55th Karpacz Winter School of Theoretical Physics
"Nuclear astrophysics in multi-messenger era "
Artus Hotel Karpacz, 24 February-2 March 2019

SUPERNOVA NEUTRINOS: WHAT CAN WE LEARN?

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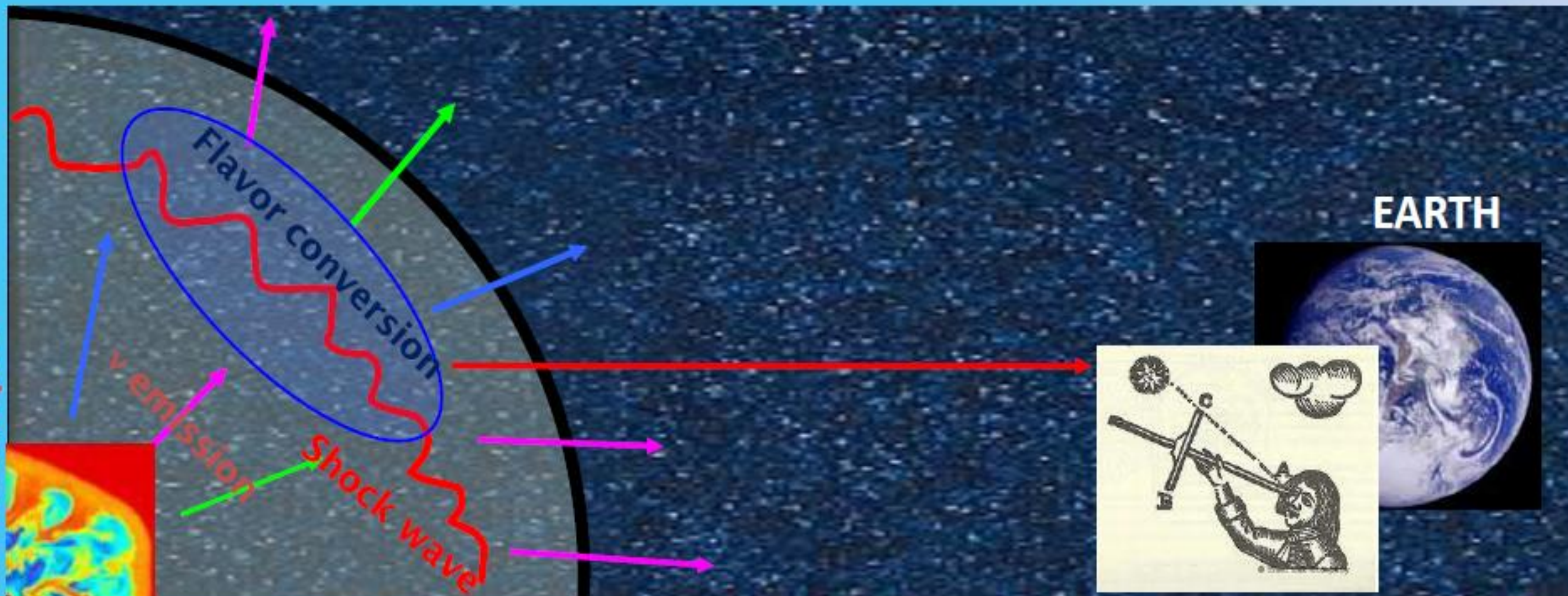
SUPERNOVA NEUTRINOS



Production (flavor)	Propagation (mass,mixing)	Detection (flavor)
$\left\| \langle \psi_i \right.$	$\int \exp(-iHt)$	$\left. \psi_f \rangle \right\|$

Production (flavor)

- Core-collapse simulation
- Microphysics of SN core
- Stellar nucleosynthesis
- Exotic particles emission

Propagation (mass,mixing)

- Flavor conversions
- Matter effects: shock wave,turbulences
- Dense neutrino bkg
- New interactions
- Decays

Detection (flavor)

- Interaction cross sections
- Different detection strategies
- Observable signatures

an *ante-litteram* APJ!

凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

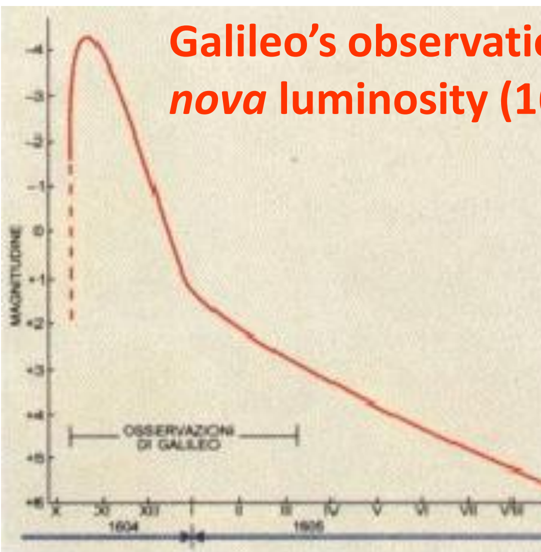
SN 1054 → Crab Nebula

Supernova 1054 Petrograph

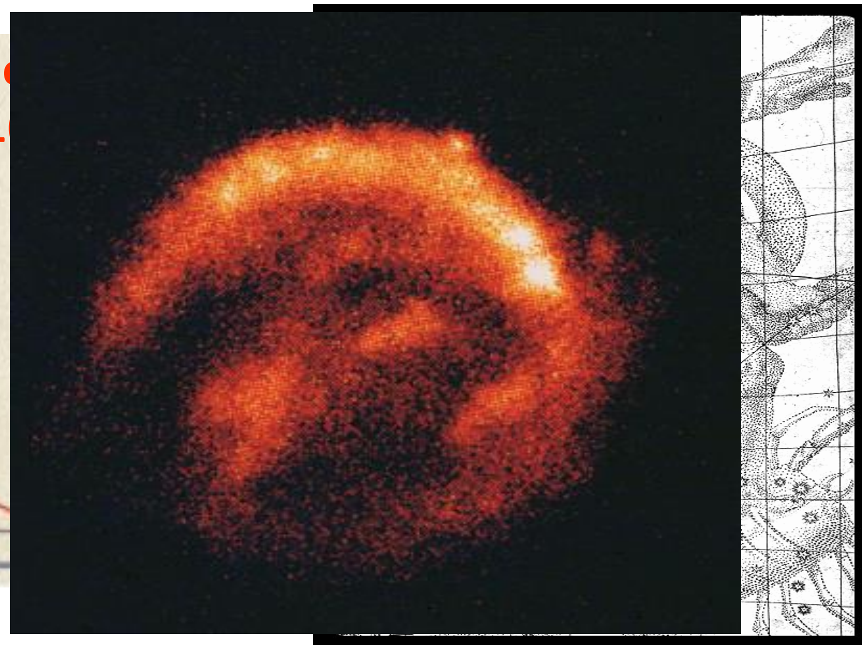
Possible SN 1054 Petrograph by the Anasazi people
(Chaco Canyon, New Mexico)

SN 1604

A **New Star *(Stella Nova)*,** as bright and as red as Mars, was discovered on **October 9 1604**. At Padua the new star was observed by Galileo, while in Prague Kepler made careful observations and the Supernova now carries his name.



Galileo's observati*nova* luminosity (1



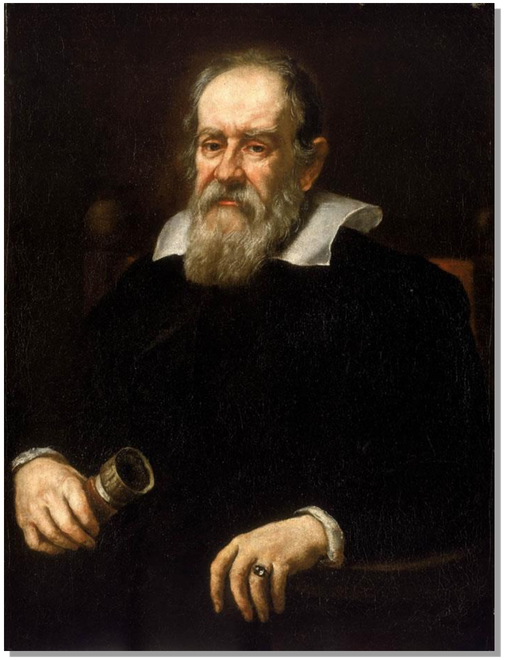
Kepler, *De Stella Nova in Pede Serpentarii,* (1606)

It is 400 years since a Supernova was last definitely observed within our own galaxy.

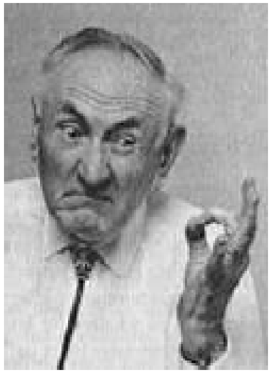
Galileo gave a course of three lectures in Padua upon SN 1604 to a great audience. The main point he brought out concerning the new star was that it upset the received Aristotelian doctrine of the immutability of the heavens.

"Che ha a che fare la filosofia col misurare? Che importa al matematico se il cielo sia corruttibile e generabile? Se anche la nuova stella fosse di polenta, chi vieta ai matematici di osservarla e misurarla? Canchero, l'ha avuto torto questa stella a rovinare così la filosofia di costoro"

G. Galilei, Dialogo de Cecco Ronchitti da Bruzene in perpuosito de la Stella Nuova



First identification of SN

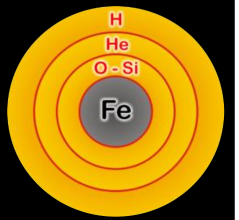


First modern identification by Baade & Zwicky (1934):

> *... at their maximum brightness they emit nearly as much light as the whole nebula in which they originate.*
>
> *... their frequency is of the order of one super-nova per stellar system (nebula) per several centuries.*
>
> *... Super-novae, initially, are quite ordinary stars whose masses are not greater than 10^{33} gr. to 10^{35} gr.*
>
> *... The total energy emitted during the existence of the super-nova therefore is of the order of ... 2.99×10^{51} ergs.*
>
> *... the phenomenon of a super-nova represents the transition of an ordinary star into a body of considerably smaller mass.*

Thermonuclear vs. Core-Collapse Supernovae

Thermonuclear (Type Ia)	Core collapse (Type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface



Chandrasekhar limit is reached – $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

C O L L A P S E S E T S I N

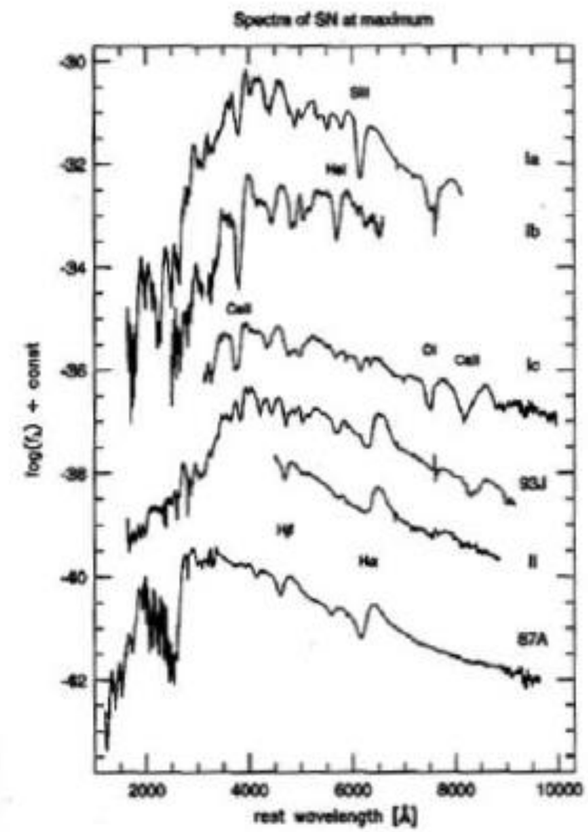
Nuclear burning of C and O ignites → Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity

Comparable "visible" energy release of ~ 3×10^{51} erg

Basic Spectral Classes

Type Ia seen in old stellar populations, while Ib, Ic & II seen in young populations → core-collapse from massive stars

- Type Ia: No H, Si II, λ6355 seen
- Type Ib: No H, He I, λ5876 seen
- Type Ic: No H, no He or Si
- Type II: H seen (e.g. Balmer Hα λ6563, Hβ λ4861 etc)



Cox (2000)

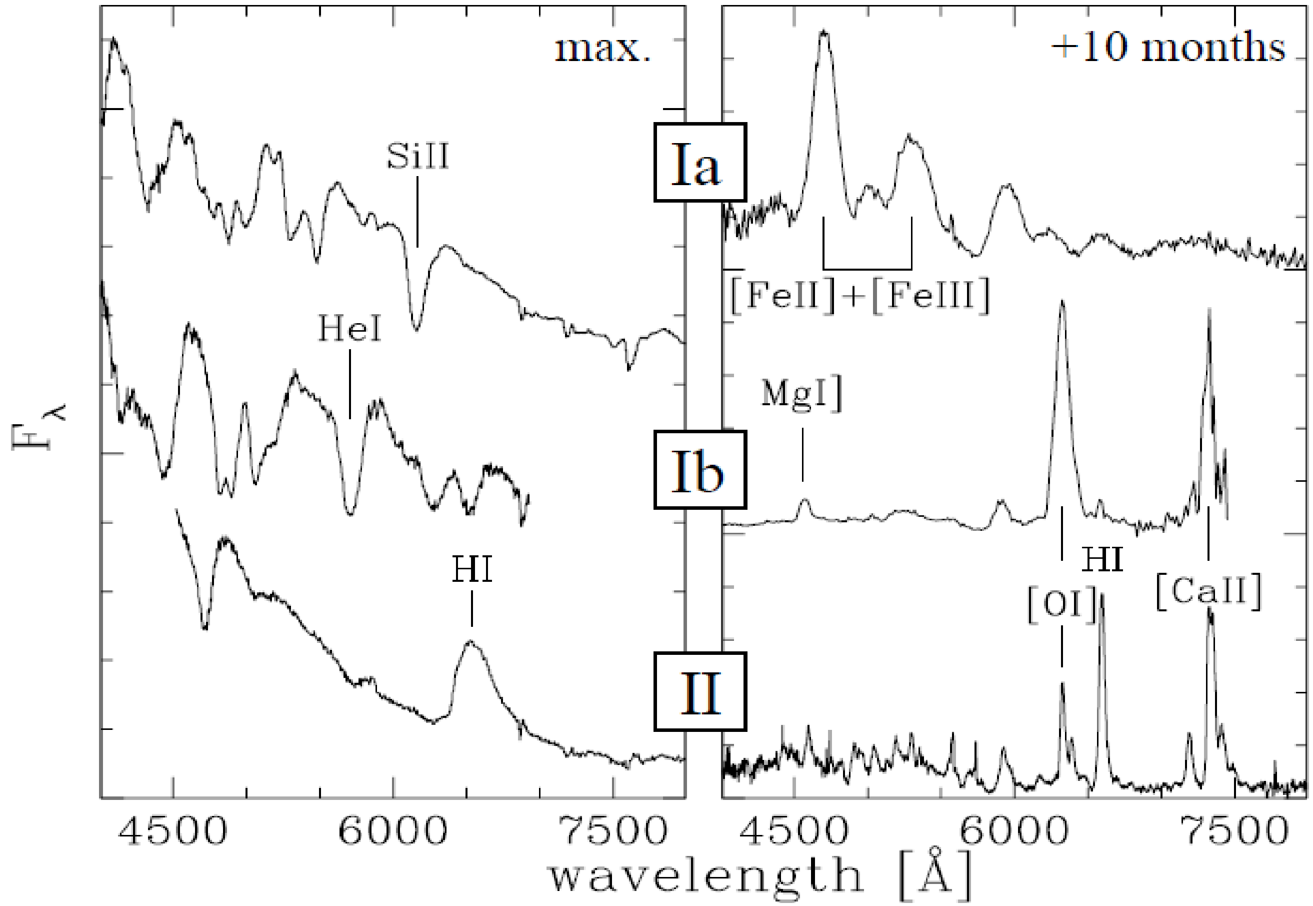
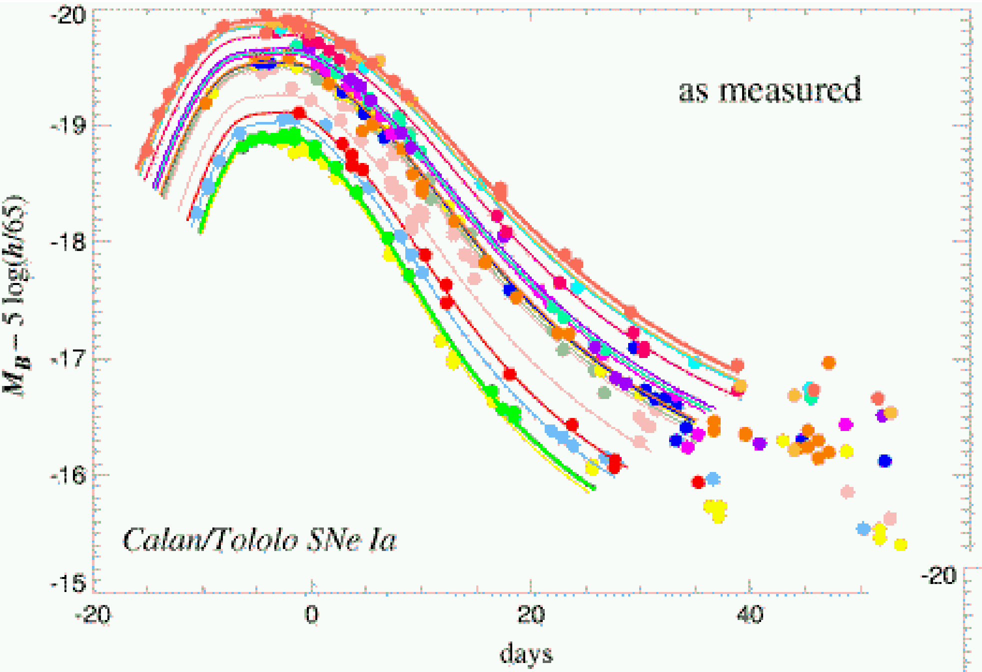


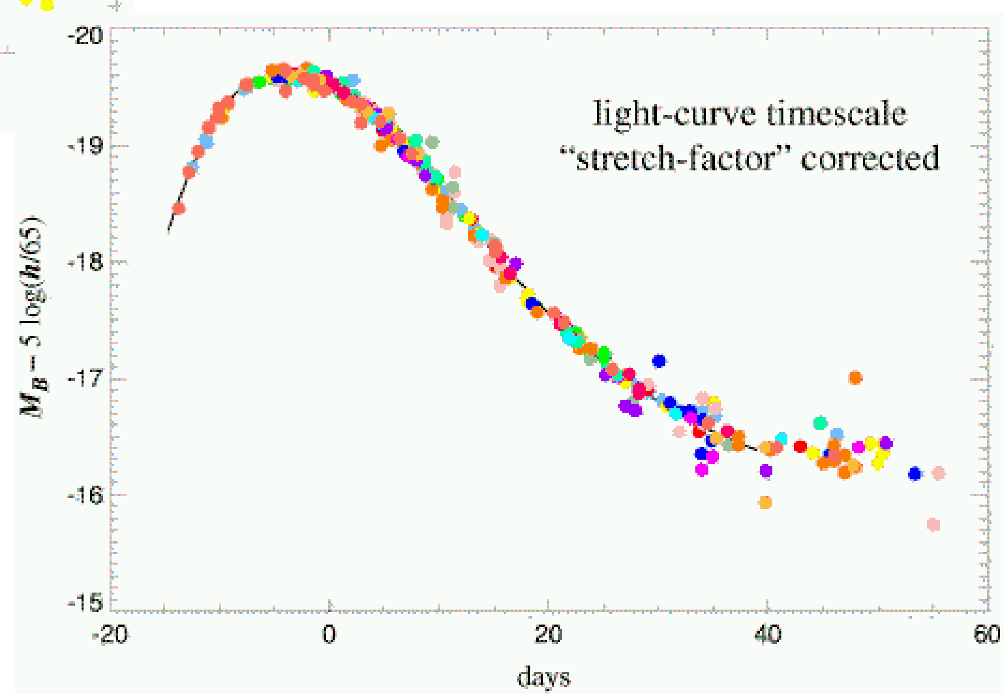
Figure 1. Basic SN types spectra. A SN which near maximum (left panel) shows clear signature of Hα is defined as type II, if it shows a strong SiII absorption at about 6150 Å is a type Ia, otherwise it is of type Ib/c (in the figure we show a SNIb characterized by strong He lines). Ten months later (right panel) SN Ia show strong emissions of [FeII] and [FeIII], SN Ib/c are dominated by [CaII] and [OI]. These same lines and strong Hα emission are typical of SNII.

UNIVERSAL SUPERNOVA Ia LIGHT CURVE



Supernova Ia lightcurves are empirically a 1-parameter family

After transformation a universal light curve, i.e. de facto standard candle



LUMINOSITY DISTANCE

Distance estimates from SNe Ia light curves are derived from the luminosity distance

$$d_L = \left(\frac{L}{4\pi F} \right)^{1/2}$$

- L intrinsic luminosity
- F observed flux

It depends on the cosmological parameters

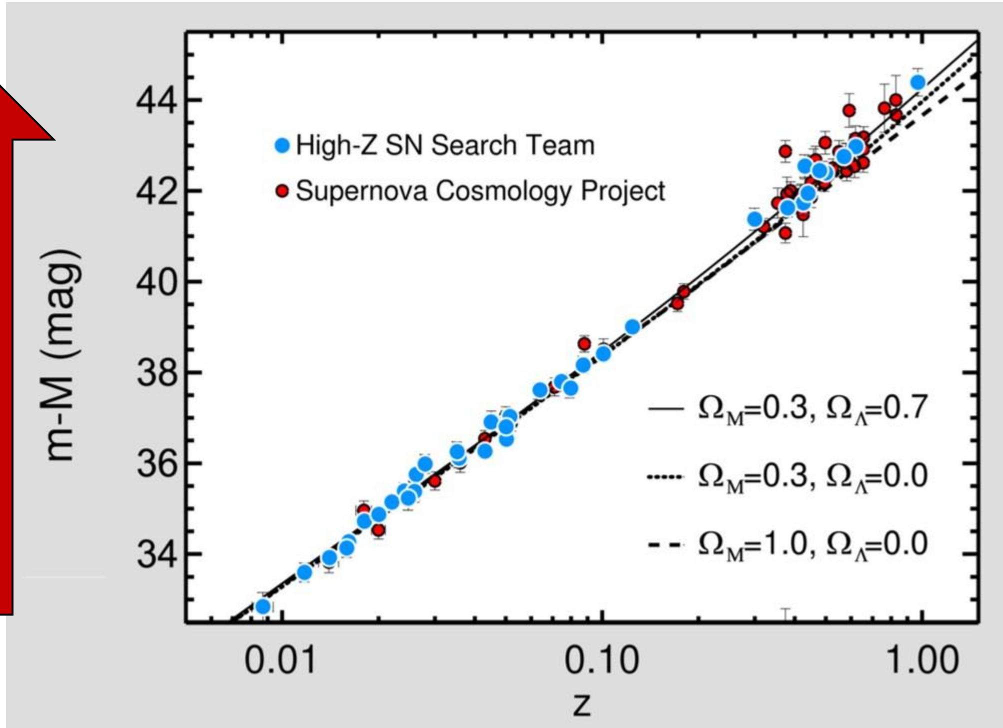
The luminosity distance is often expressed in terms of the **magnitude**

$$m = M + 5 \ \log_{10}\left(\frac{d_L}{Mpc} \right) + 25$$

M is the absolute magnitude (value at 10 pc)

HUBBLE DIAGRAM

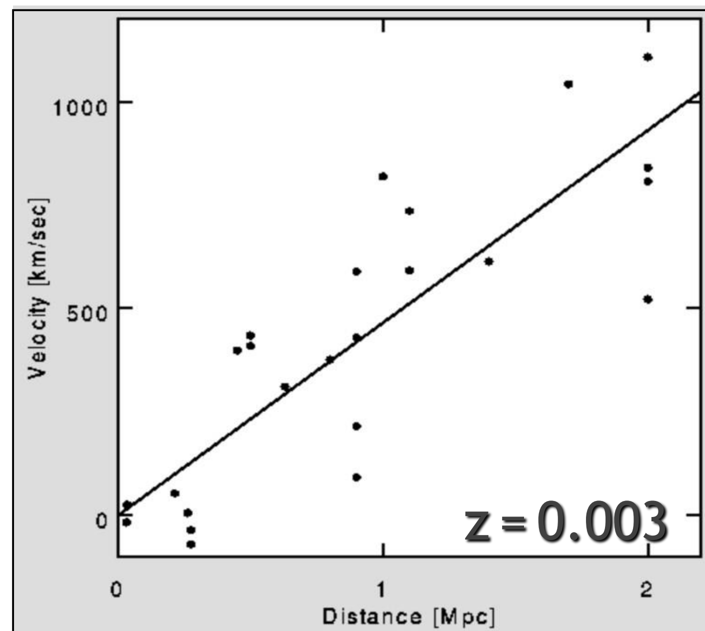
Apparent Brightness

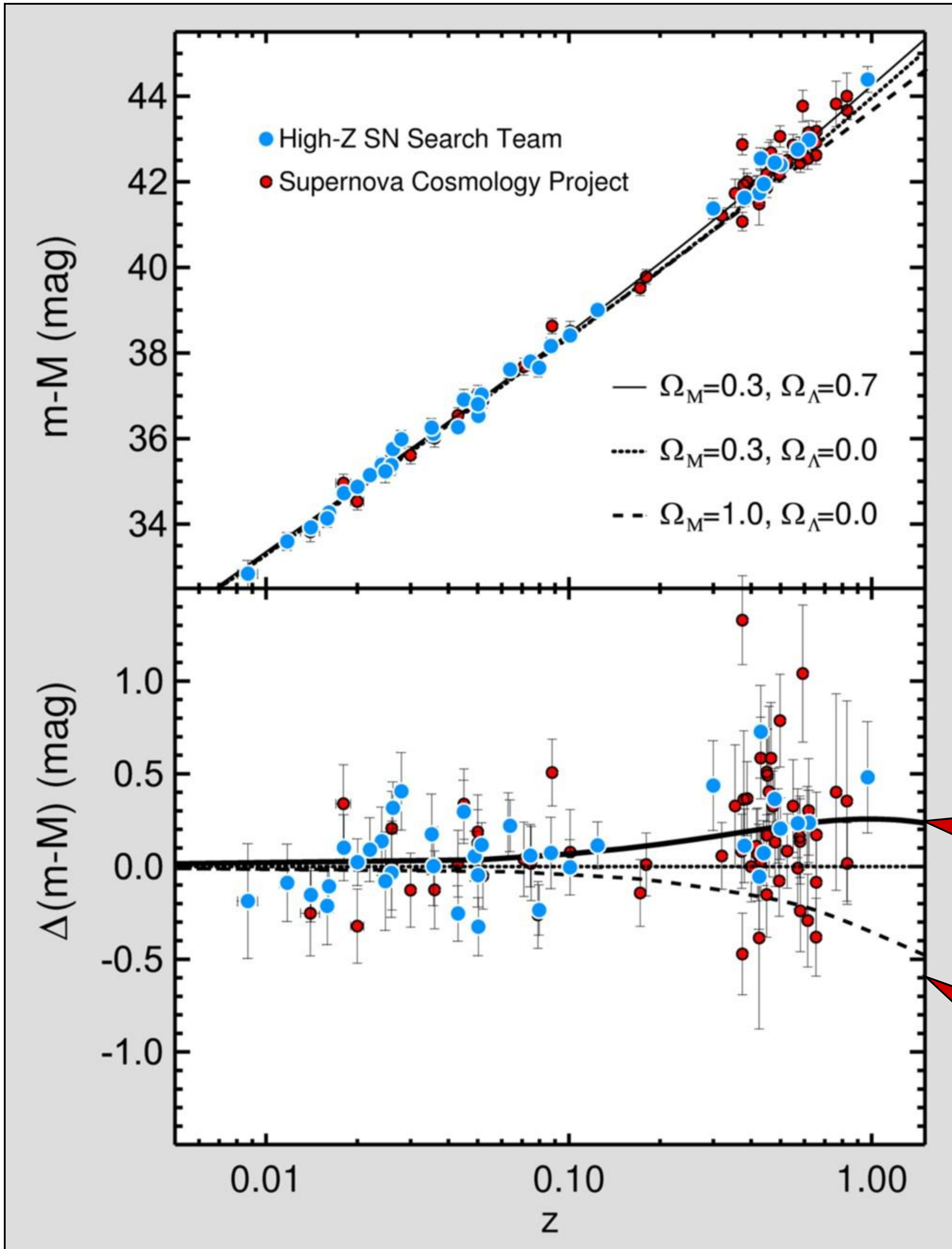


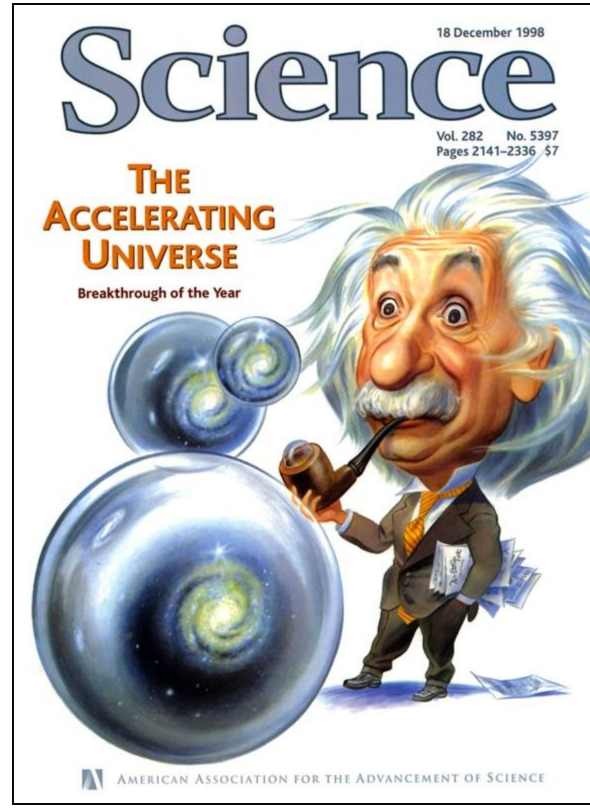
Redshift

Supernova Ia
as cosmological
standard candles

Hubble's orginal data (1929)



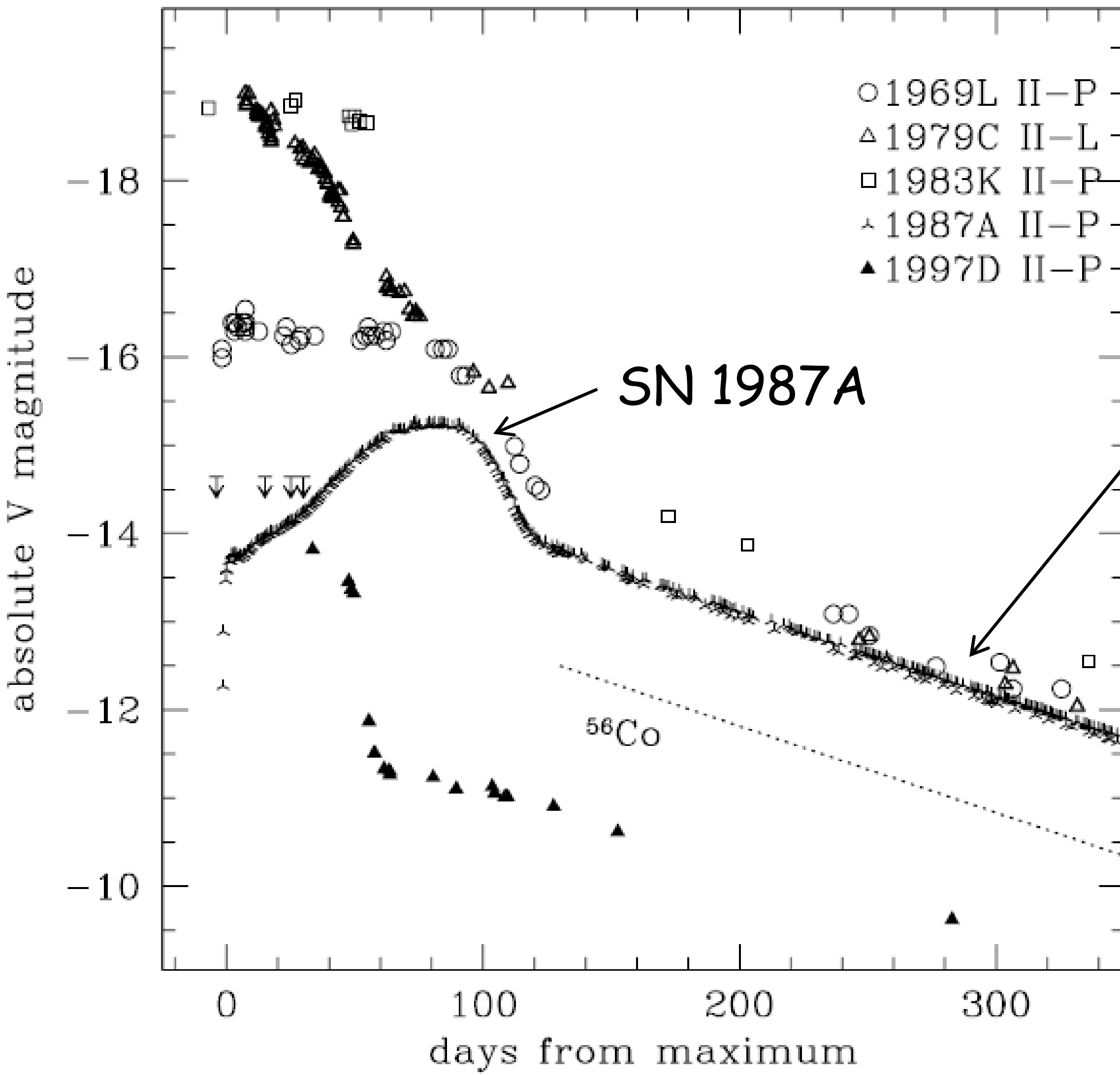




Accelerated expansion
(Ω_M = 0.3, Ω_Λ = 0.7)

Decelerated expansion
(Ω_M = 1)

EXAMPLES OF SN II LIGHT CURVES

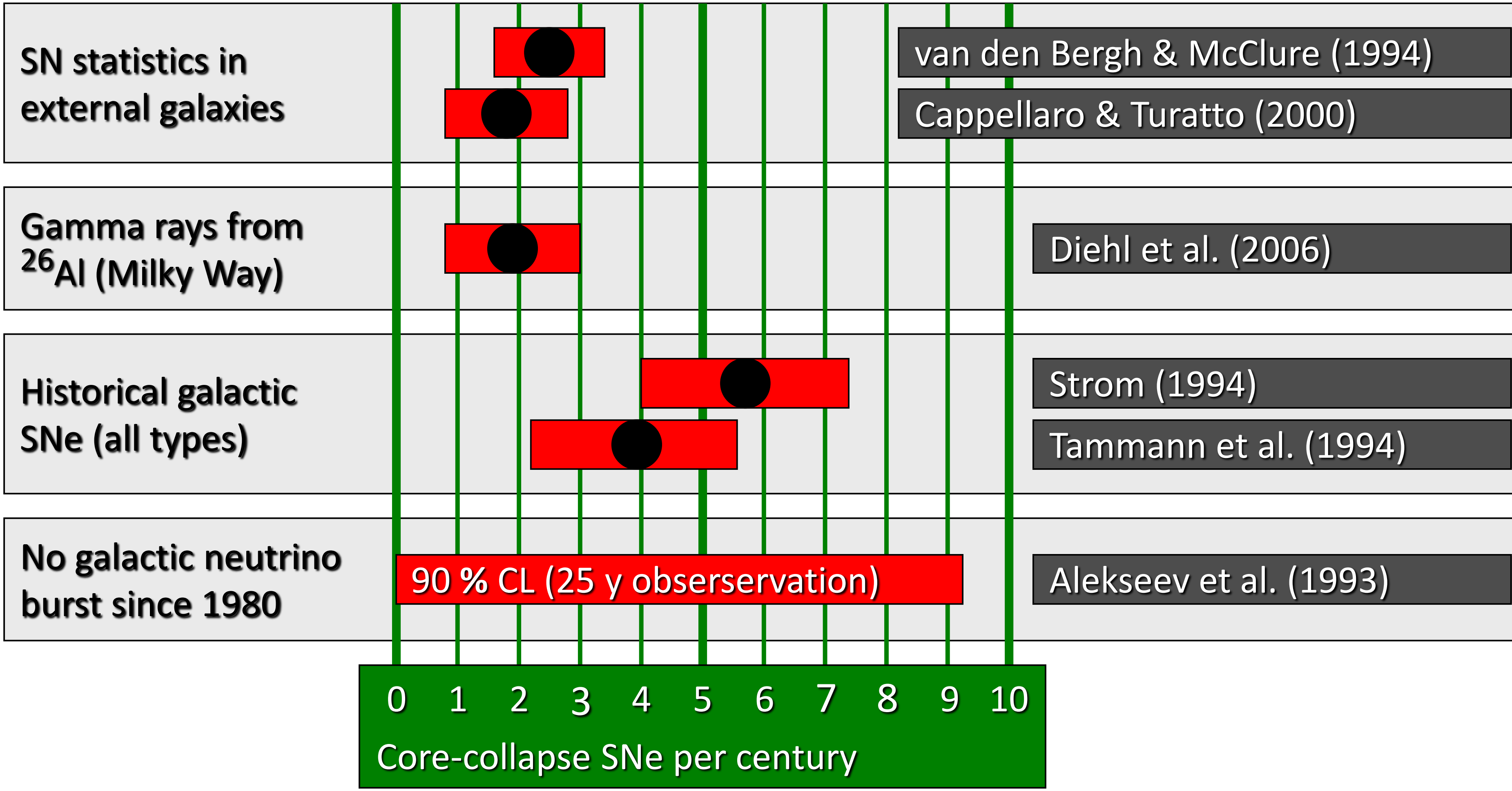


Large differences in magnitudes and spectra

Powered by radioactive decay of ^{56}Co

[Cappellaro & Turatto, astro-ph/0012455]

Core-Collapse SN Rate in the Milky Way



References: van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455. Diehl et al., Nature 439 (2006) 45. Strom, Astron. Astrophys. 288 (1994) L1. Tammann et al., ApJ 92 (1994) 487. Alekseev et al., JETP 77 (1993) 339 and my update.

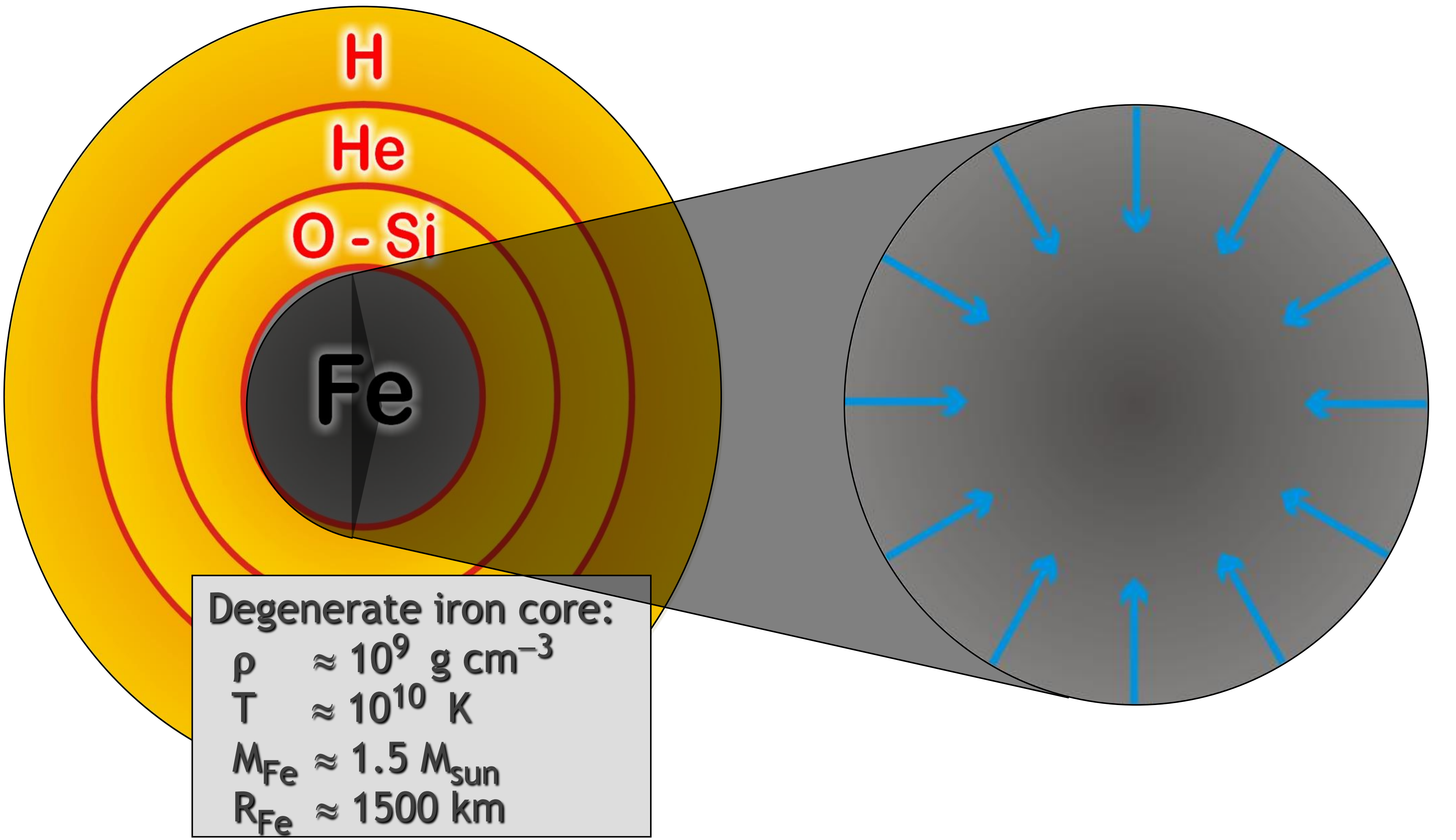
SN SUMMARY

Spectral Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light Curve	Reproducible	Large variations		
Neutrinos	Insignificant	$\sim 100 \times$ Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole		
Rate / h^2 SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total $\sim$ 5600 as of 2011 (Asiago SN Catalogue)			

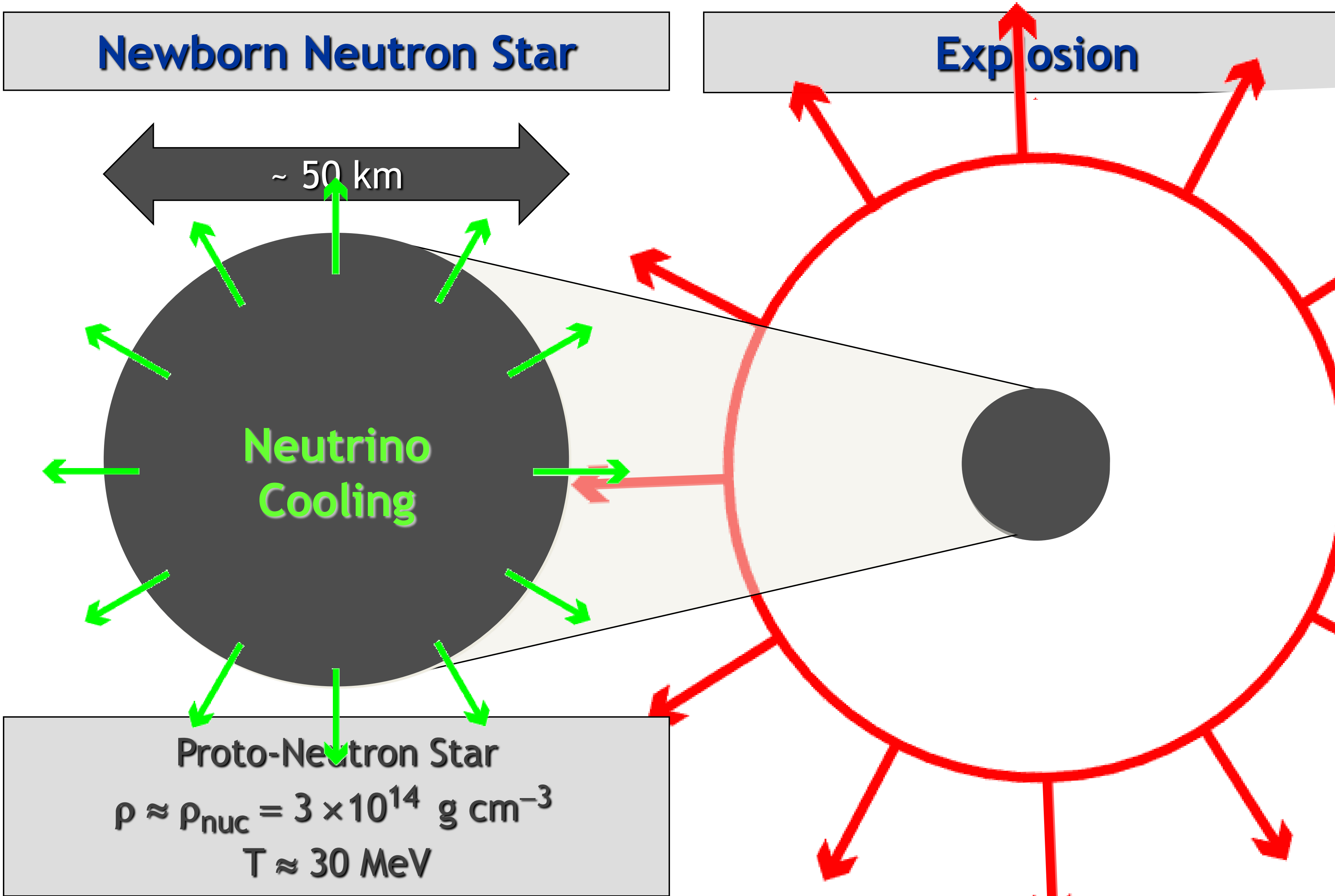
Stellar Collapse and Supernova Explosion

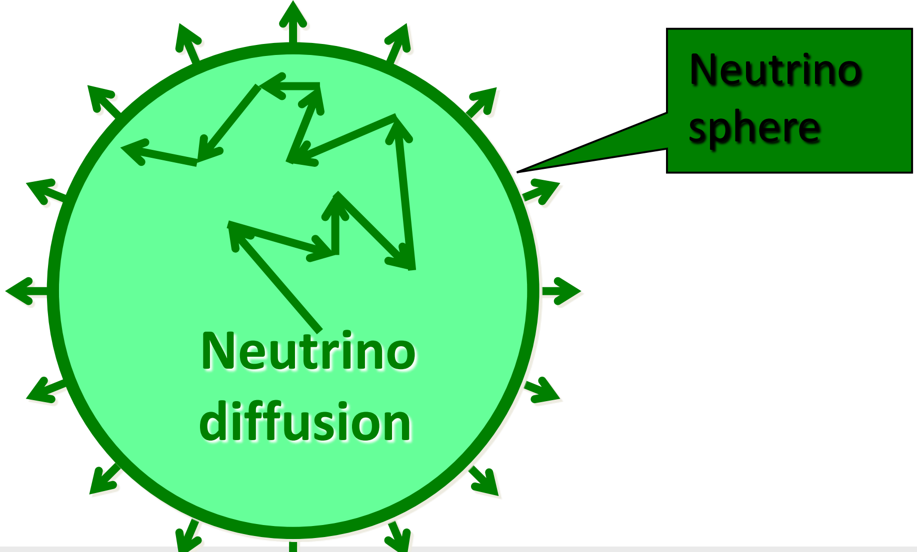
Onion structure

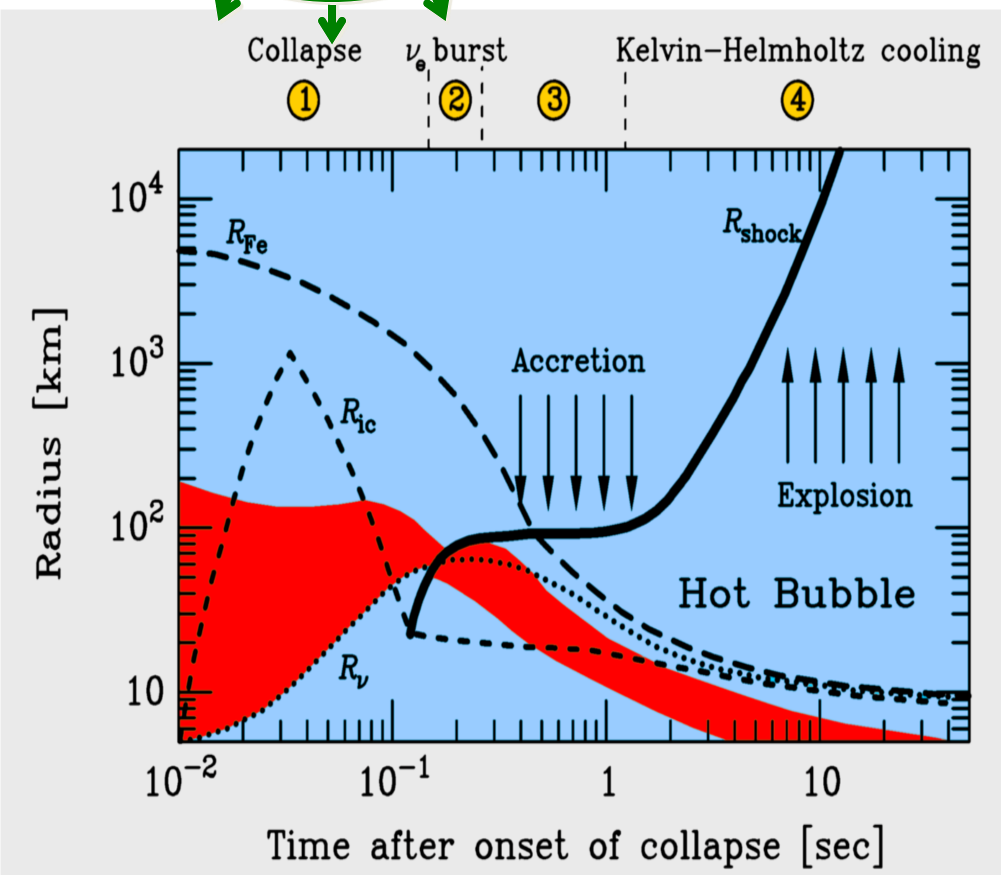
Collapse (implosion)



Stellar Collapse and Supernova Explosion







***Gravitational binding energy*:**

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}\, c^2$

Energy sharing:

99%	Neutrinos
1%	Kinetic energy of explosion
	(1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

***Neutrino luminosity*:**

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

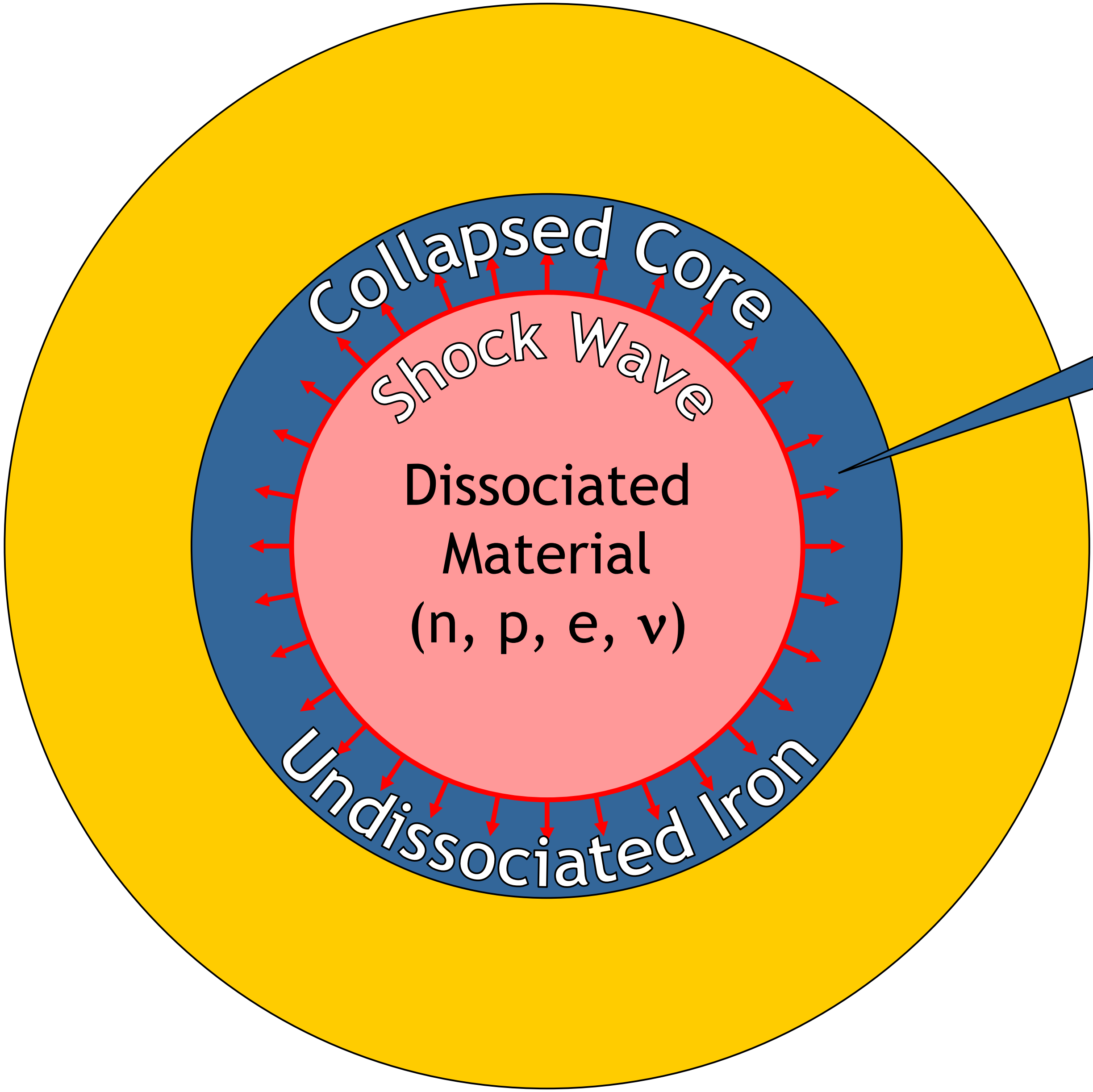
$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe!

What determines the time scale?

Main neutrino reactions	Electron flavor $\nu_e + n \to p + e^-$ $\bar{\nu}_e + p \to n + e^+$ Other flavors $\nu_e + N \to N + \nu$
Neutral-current scattering cross section	$\sigma(\nu N \to N\nu) = \frac{C_V^2 + 3C_A^2}{\pi} G_F^2 E_\nu^2 \approx 2\times 10^{-40}\,\mathrm{cm}^2 \left(\frac{E_\nu}{100\,\mathrm{MeV}}\right)^2$
Nucleon density	$n_B = \frac{\rho_{nuc}}{m_N} \approx 1.8\times 10^{38}\,\mathrm{cm}^{-3}$
Scattering rate	$\Gamma = \sigma n_B \approx 1.1\times 10^9\,\mathrm{s}^{-1} \left(\frac{E_\nu}{100\,\mathrm{MeV}}\right)^2$
Mean free path	$\lambda = (\sigma n_B)^{-1} \approx 28\,\mathrm{cm} \left(\frac{100\,\mathrm{MeV}}{E_\nu}\right)^2$
Diffusion time	$t_{diff} \approx \frac{R^2}{\lambda} \approx 1.2\,\mathrm{sec} \left(\frac{R}{10\,\mathrm{km}}\right)^2 \left(\frac{E_\nu}{100\,\mathrm{MeV}}\right)^2$

Why No Prompt Explosion?



- $0.1\ M_{sun}$ of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

- **Shock wave forms within the iron core**
- **Dissipates its energy by dissociating the remaining layer of iron**

ROLE OF NEUTRINOS

- Neutrinos produced in the hot, forming neutron star carry away the gravitational binding energy of the collapsing stellar core

$$E \approx 3\times 10^{53}\left(\frac{M}{M_{sun}}\right)^{2}\left(\frac{R}{10\ \mathrm{km}}\right)^{-1} ergs$$

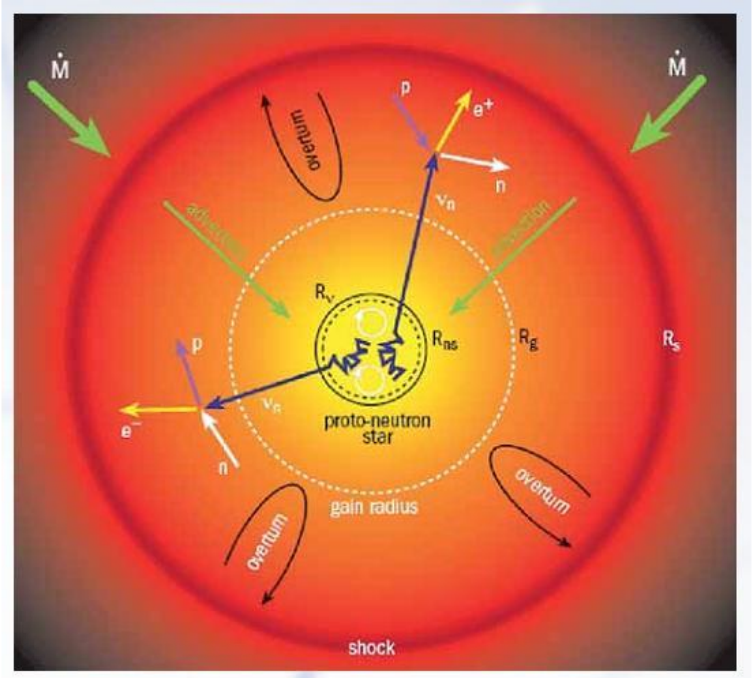
Neutrino energy $E_\nu \approx 100 \times E_{kin}$ of a SN explosion

- Neutrinos transfer energy to the collapsing stellar matter around the newly formed neutron star and could power the SN explosion

Characteristic SN energy unit: 10^{51} erg = 10^{44} J = 1 Bethe

NEUTRINOS AND EXPLOSION MECHANISM

Paradigm: Explosions by the convectively supported neutrino-heating mechanism



- "Neutrino-heating mechanism": Neutrinos "revive" stalled shock by energy deposition *[Colgate & White, 1966, Wilson, 1982, Bethe & Wilson, 1985]*

- Convective processes & hydrodynamic instabilities enhance the heating mechanism *[Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Scheck et al. 2004,06,08]*

A CONVECTIVE ENGINE

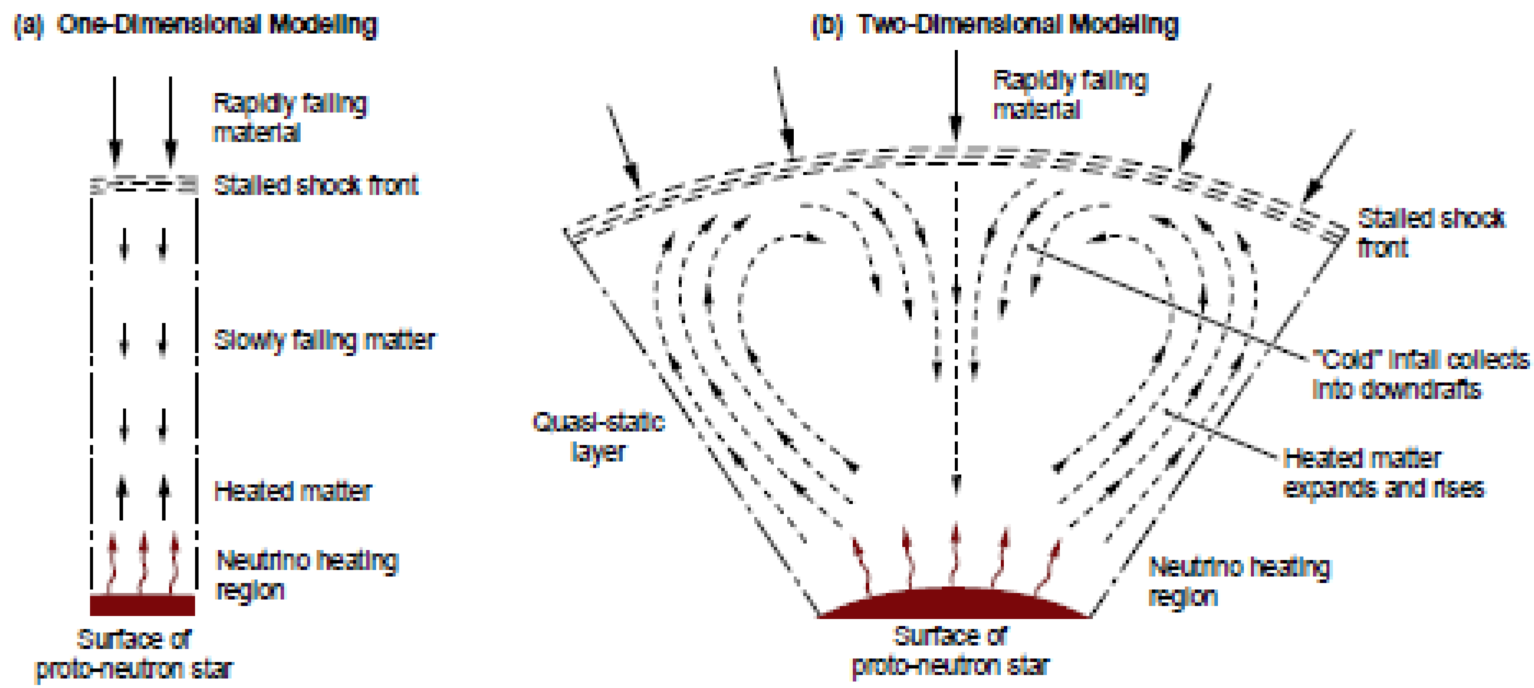
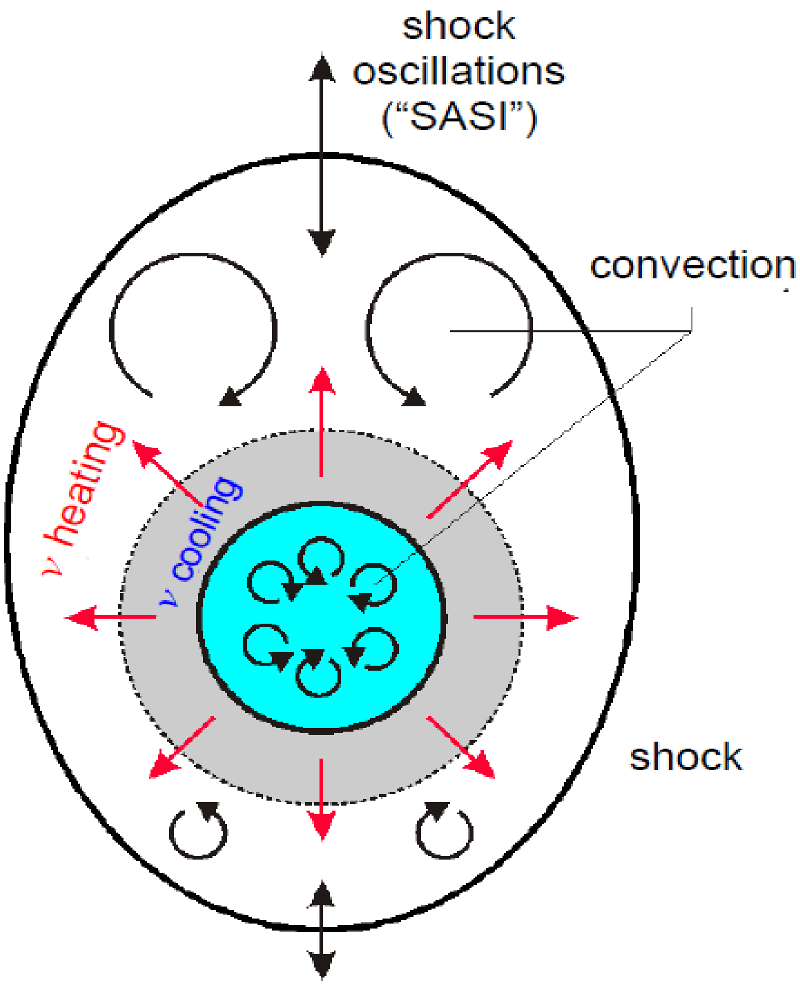


Figure 5. A Convective Engine

(a) For simplicity, supernovae were often modeled in one dimension. A star was assumed to be spherically symmetric, its radius being the only spatial parameter that mattered. Doing simulations was therefore equivalent to doing physics in a long tube, even though the transfer of heat from one end of a pipe to the other is not very effective. (b) With the advent of multidimensional models, convection could occur. Hot, buoyant material could rise in one part of the star, to be replaced by cooler material falling from some other region. An in-out circuit is established that allows for the efficient and continuous transfer of heat out of the core and into the quasi-static layer. Energy from the gravitational collapse is thus converted into mechanical work as heat is being transferred between hot and cold reservoirs. In this sense, supernovae can be thought of as being powered by a simple convective engine.

Neutrino-Driven Supernovae

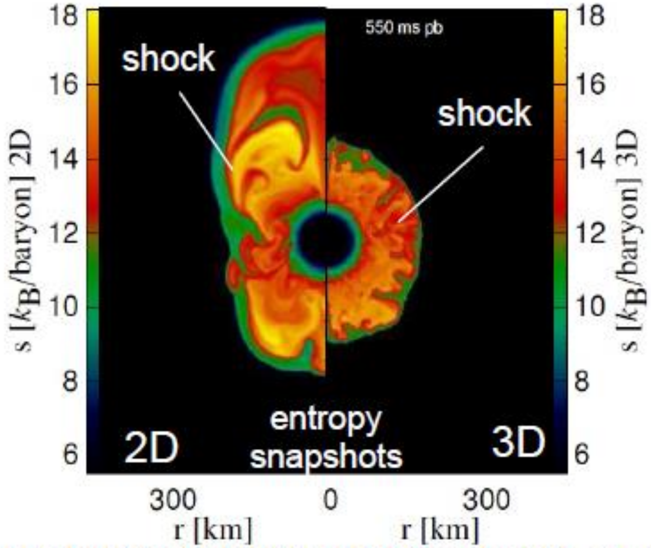
- Stalled accretion shock still pushed outward to ~150km as matter piles up on the PNS, then recedes again
- *Heating* or *gain* region develops some tens of ms after bounce
- Convective overturn & shock oscillations "SASI" enhance the efficiency of ν-heating, which finally revives the shock
- **Big challenge: Show that this works!**



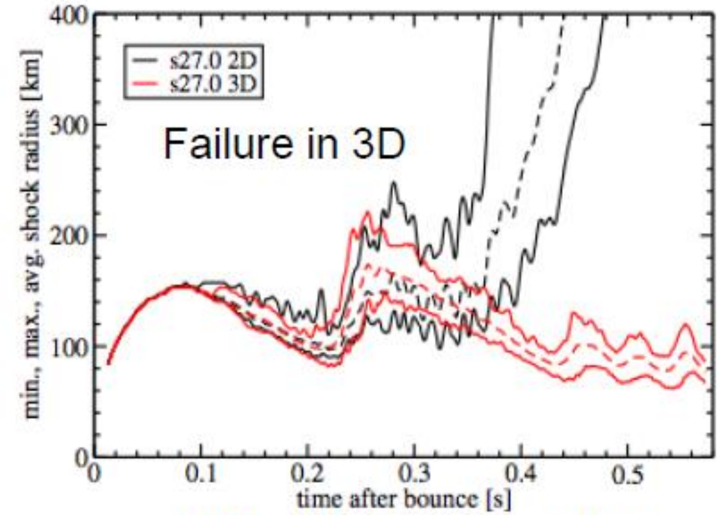
Slide by B. Müller

Problems: Shock revival by the ν-driven mechanism in 3D

Slide by B. Müller



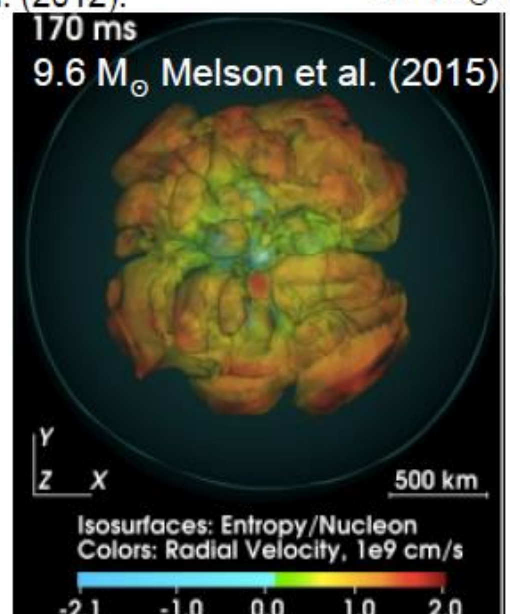
Simplified 3D “light-bulb” model from Hanke et al. (2012):
Turbulent convection in 2D and 3D

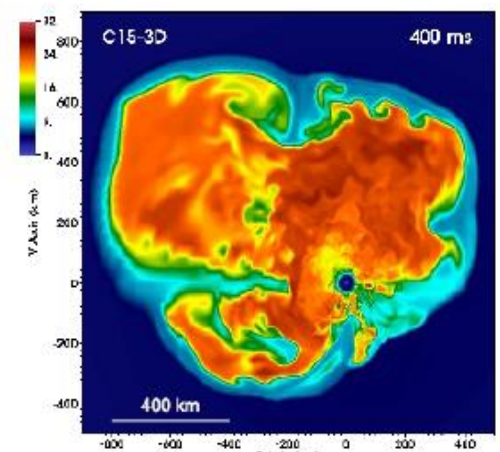


27 $M_\odot$ Hanke et al. (2013)

First-principle 3D models:

- Often failures or **delayed explosions compared to 2D**
- Models close to the threshold – not unexpected because we except failures in nature!
- Still no proof that mechanism is *robust*

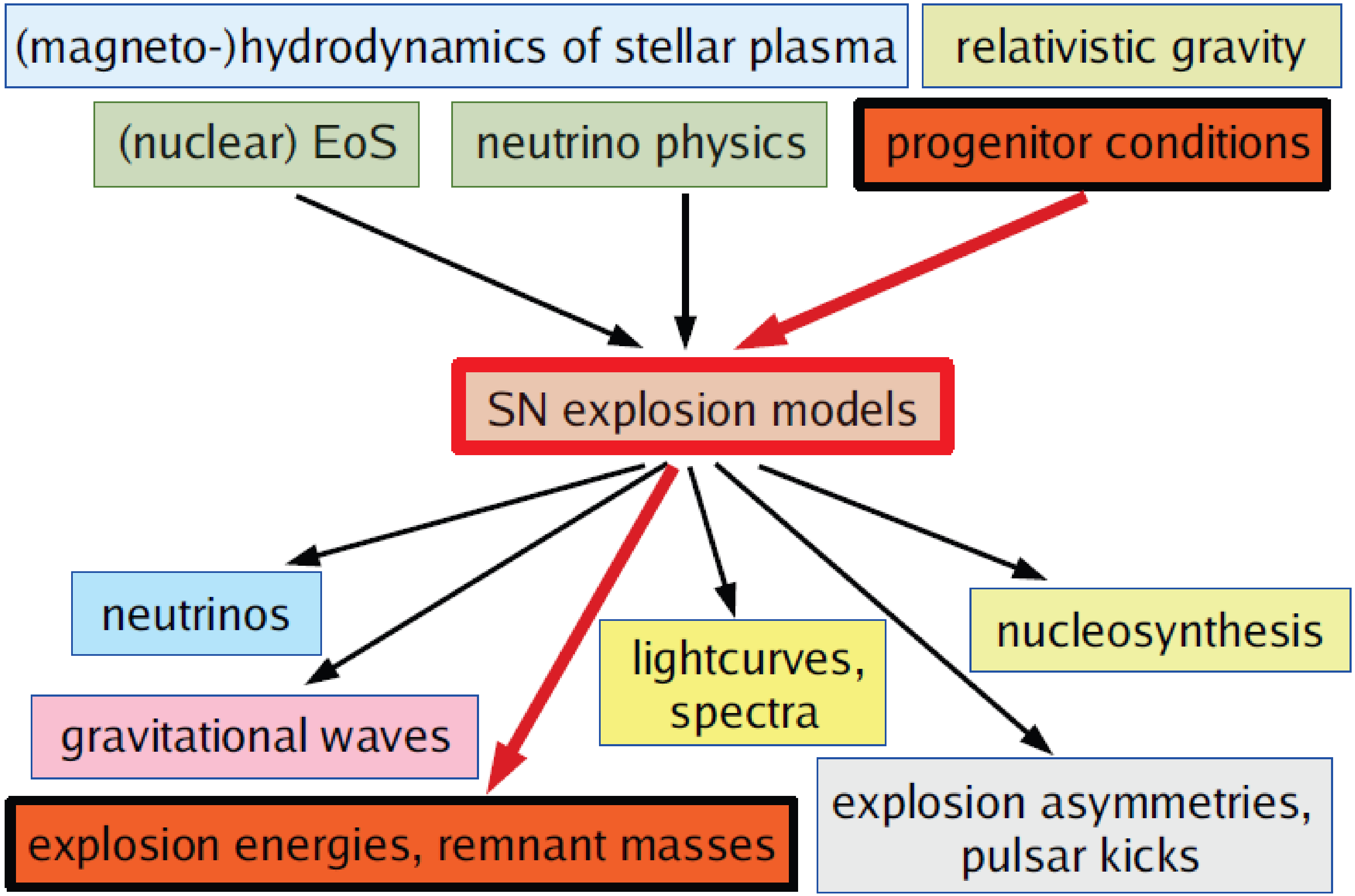




15 $M_\odot$ Lentz et al. (2015)

Or with simpler schemes: e.g. IDSA+leakage Takiwaki et al. (2014)

Predictions of Signals from Supernovae



THREE PHASES OF NEUTRINO EMISSION

[Figure adapted from *Fischer et al. (Basel group), arXiv: 0908.1871*]

10. 8 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)

Neutronization burst

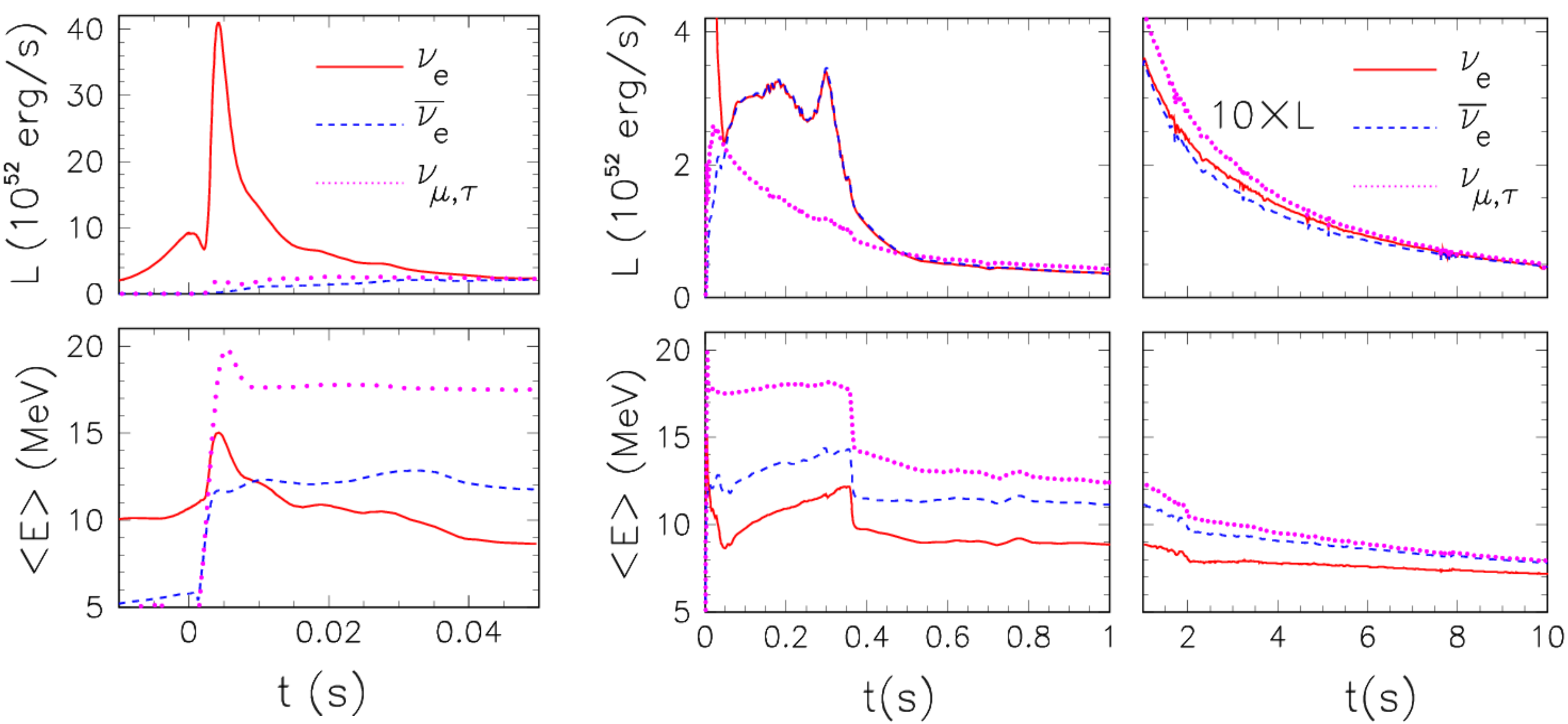
- Shock breakout
- De-leptonization of outer core layers

Accretion

- Shock stalls ~ 150 km
- ν powered by infalling matter

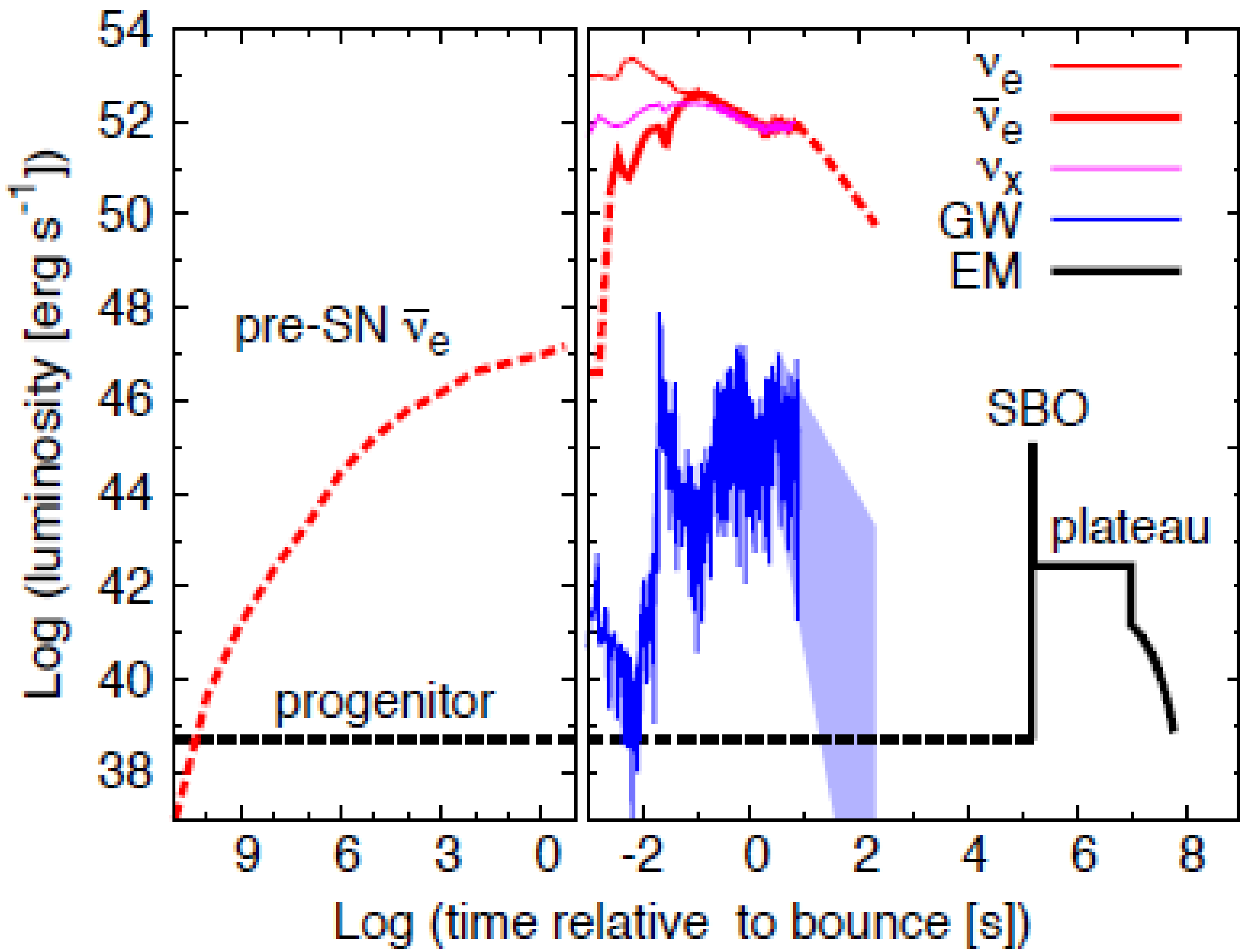
Cooling

- Cooling on ν diffusion time scale



MULTI-MESSENGER SIGNALS FROM SNE

[Nakamura, Horiuchi, Tamaka, Hayama, arXiV:1602.03028]



GW FROM SNe

Millisecond bounce time reconstruction with nu trigger

ICE-CUBE

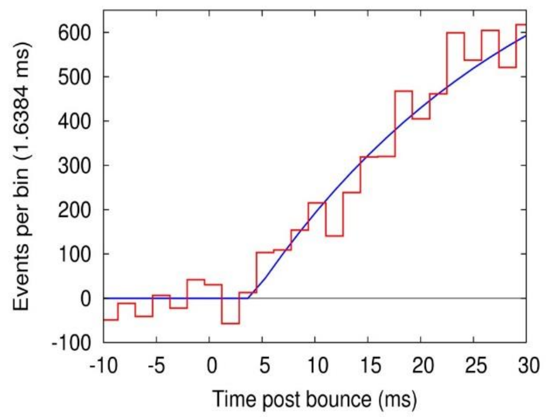


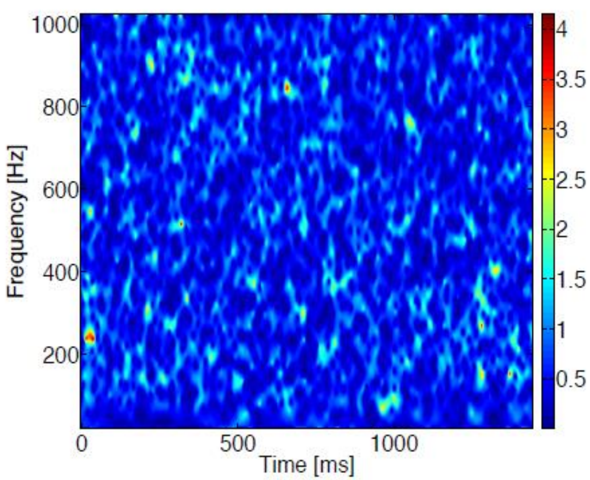
FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

[Halzen & Raffelt, arXiv:0908.2317]

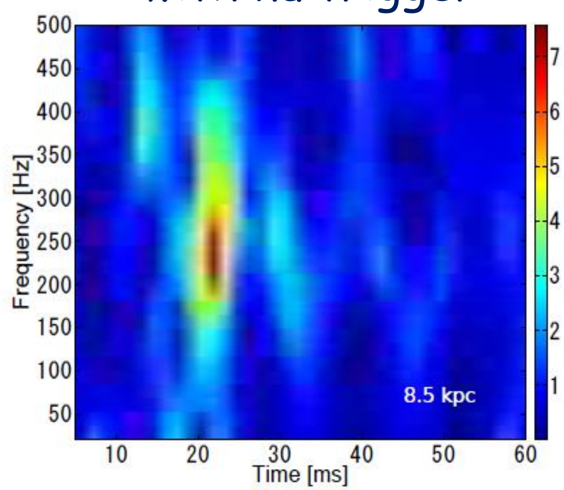
See also [Pagliaroli, Vissani, Coccia & Fulgione arXiv:0903.1191]

Signal-noise ratio

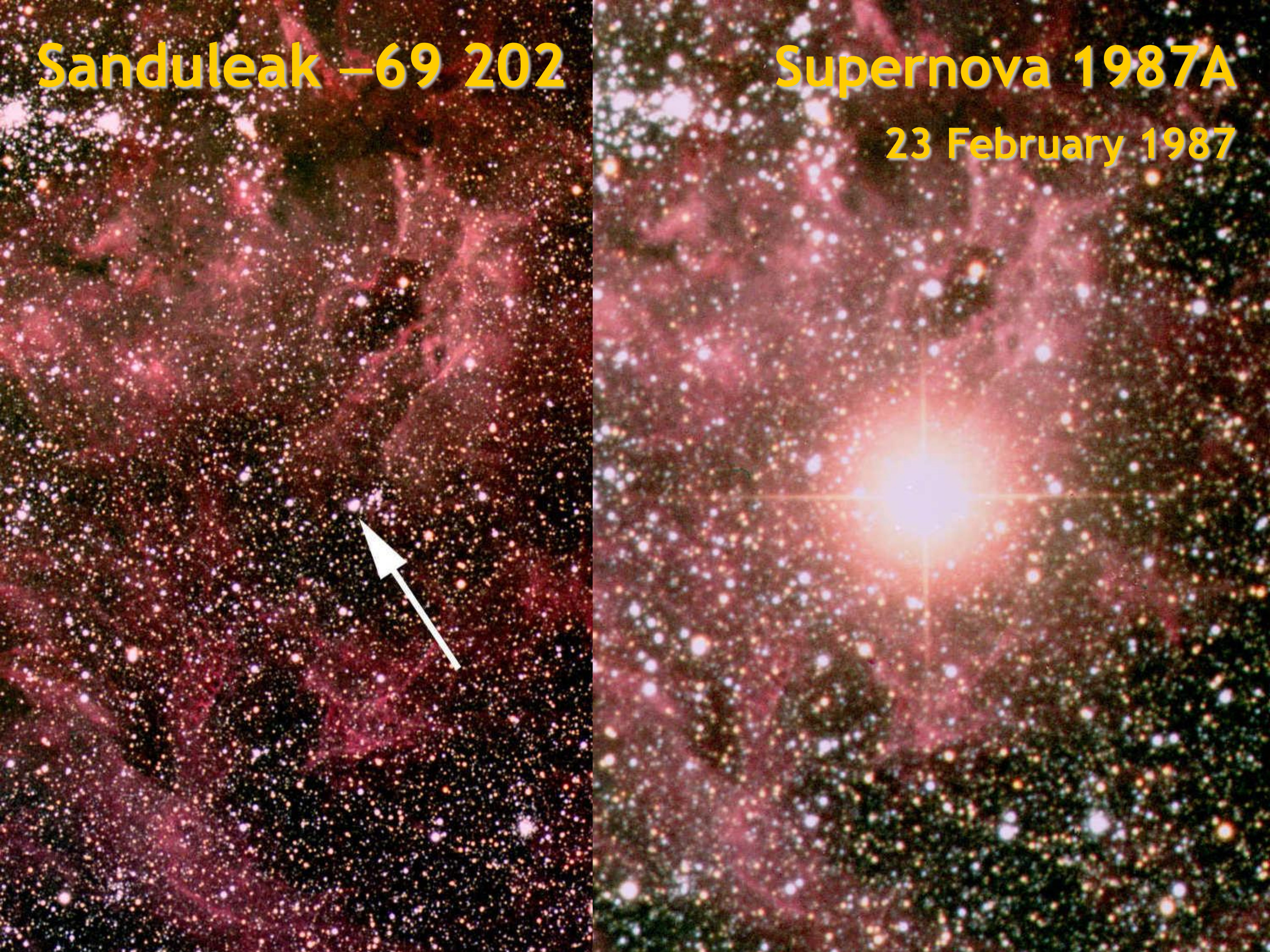
w/o nu trigger



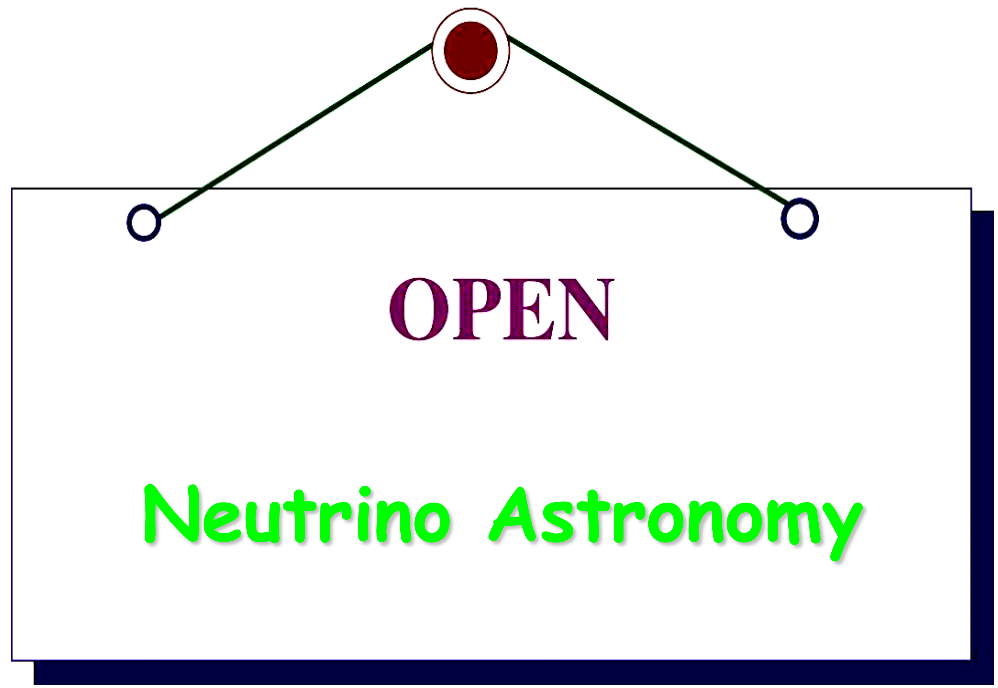
with nu trigger



SN 1987A NEUTRINOS


Sanduleak −69 202
Supernova 1987A
23 February 1987

Neutrino Burst Observation :
First verification of stellar evolution mechanism



2002 Physics Nobel Prize

“for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”

R. Davis

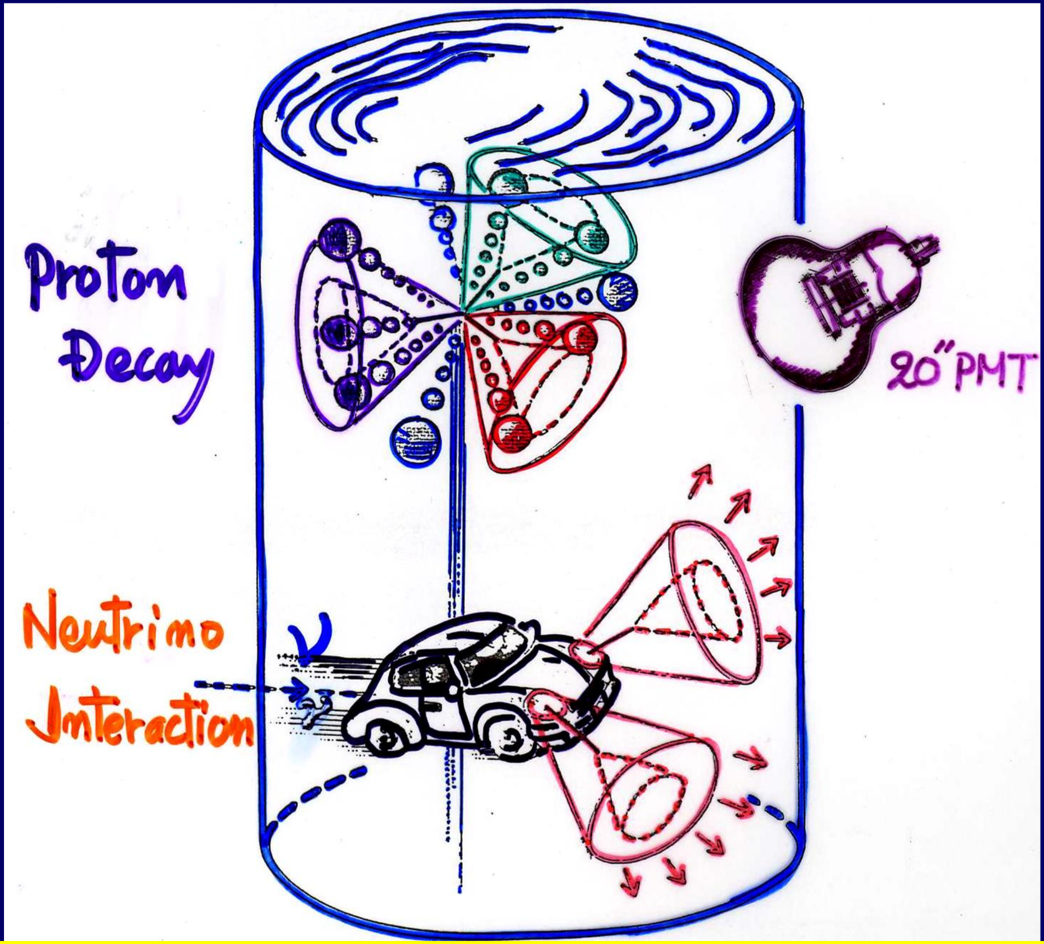
Kungliga
Svenska Vetenskapsakademien
har den 8 oktober 2002 beslutat
att med det
NOBELPRIS
som detta år tillerkännes den som inom
fysikens område gjort den viktigaste
upptäckten eller uppfinningen
med ena hälften gemensamt belöna
Masatoshi Koshiba
och Raymond Davis Jr
för banbrytande insatser inom astro-
fysiken, särskilt för detektion av
kosmiska neutriner
STOCKHOLM DEN 10 DECEMBER 2002

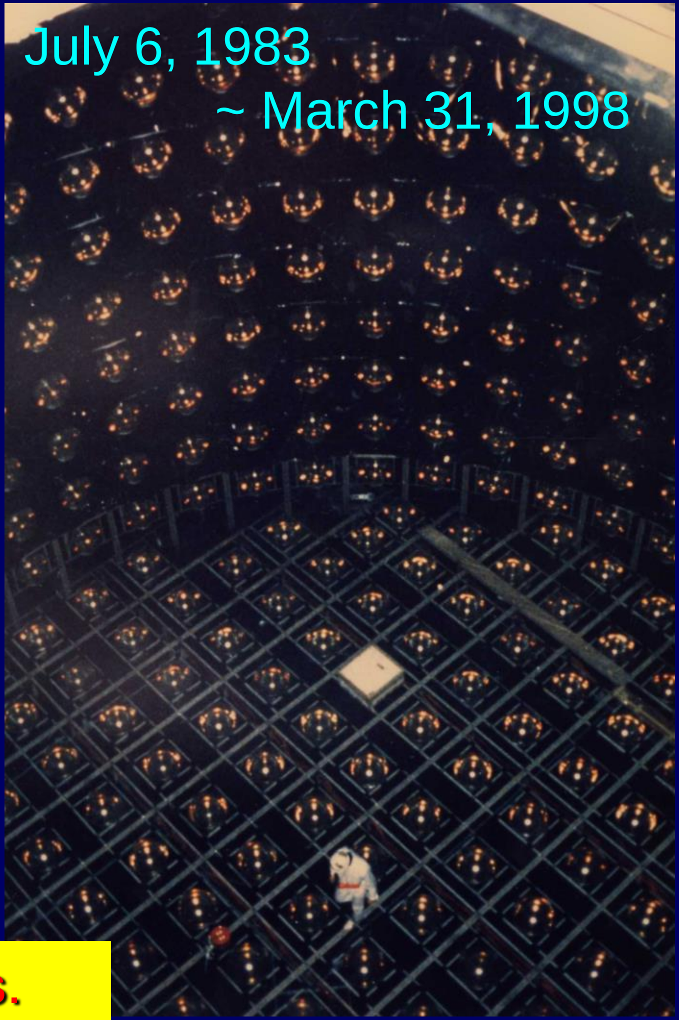
M. Koshiba

Kamiokande-I to Kamiokande-II

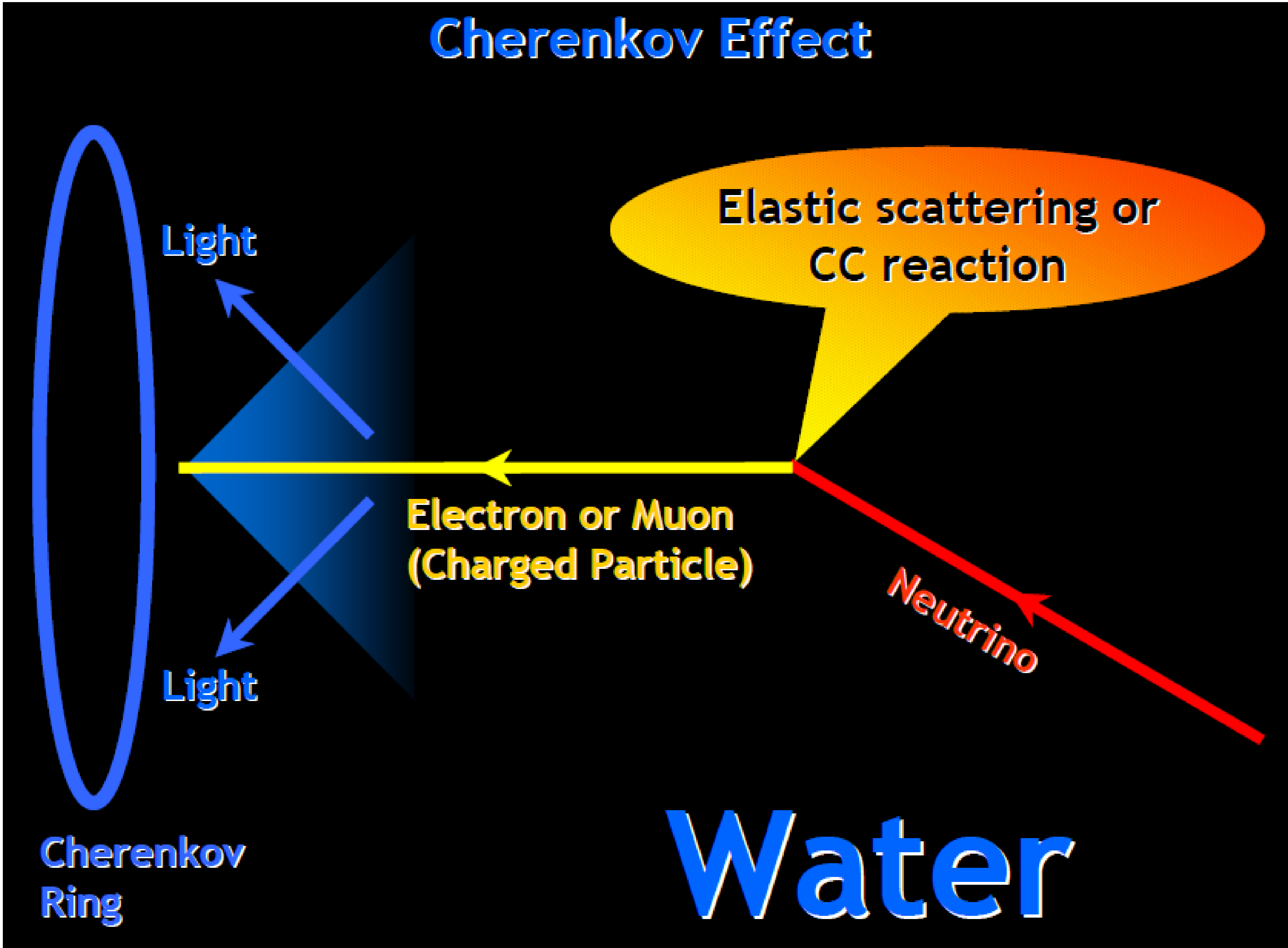
Kamiokande : Kamioka Nucleon Decay Experiment

3000-ton Imaging Water Cerenkov Detector

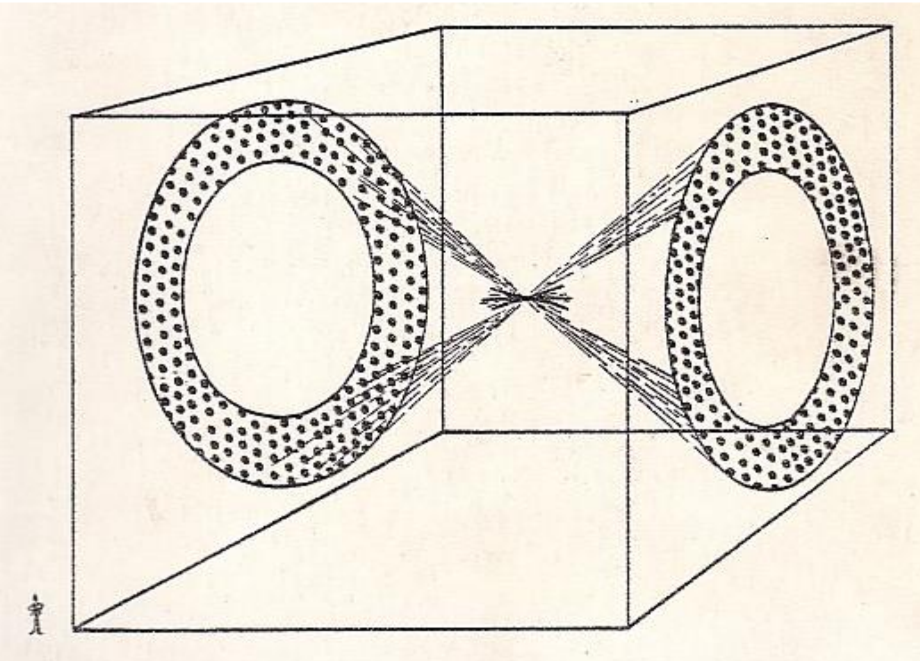




Today's backgrounds are tomorrow's signals.


Cherenkov Effect
Light
Elastic scattering or
CC reaction
Electron or Muon
(Charged Particle)
Neutrino
Light
Cherenkov
Ring
Water

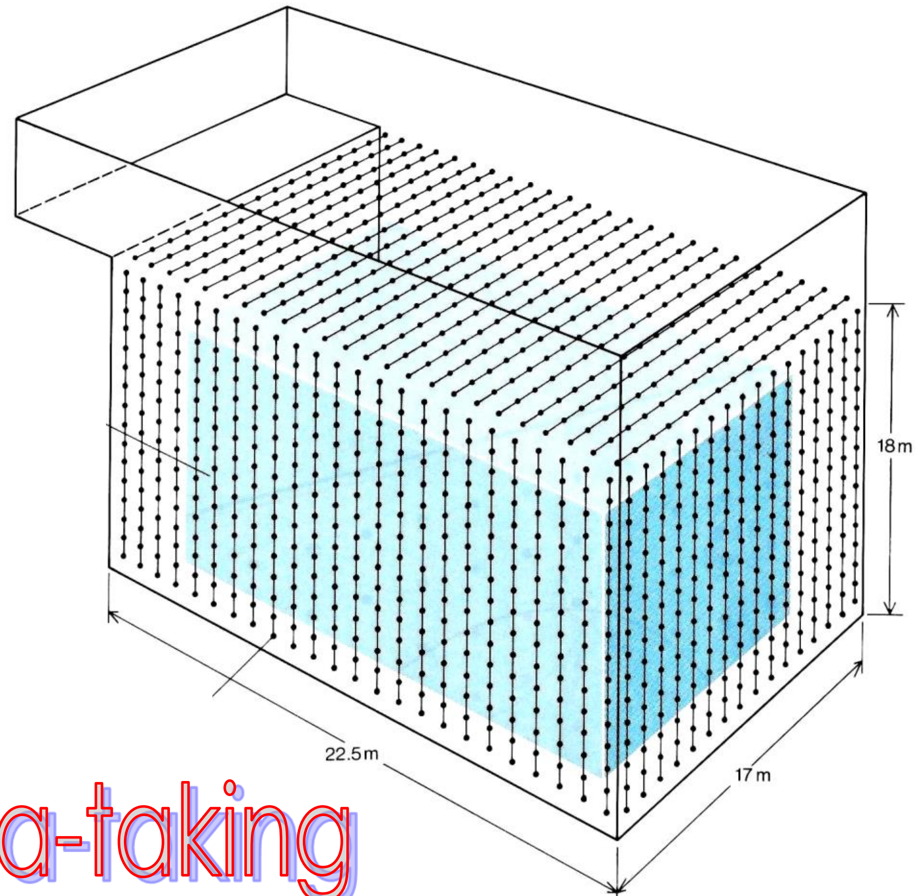
IMB: 8000 ton Water Cherenkov Detector



NUCLEON
DECAY DETECTOR

IRVINE/MICHIGAN/BROOKHAVEN

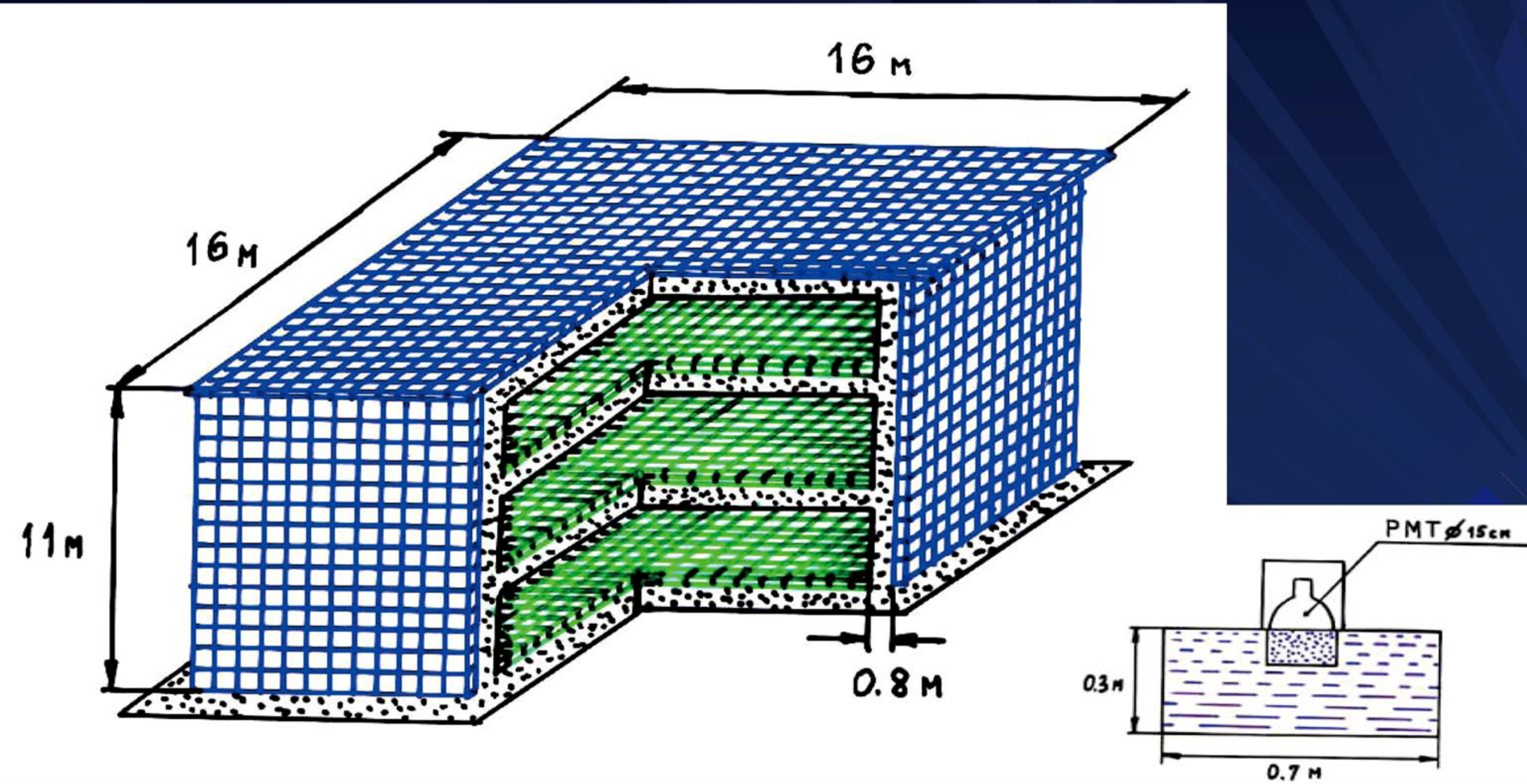
2400 x 5” PMTs



July 31, 1982 : data-taking

E. N. Alexeyev (Hawaii, 2007)

The Baksan underground scintillation telescope



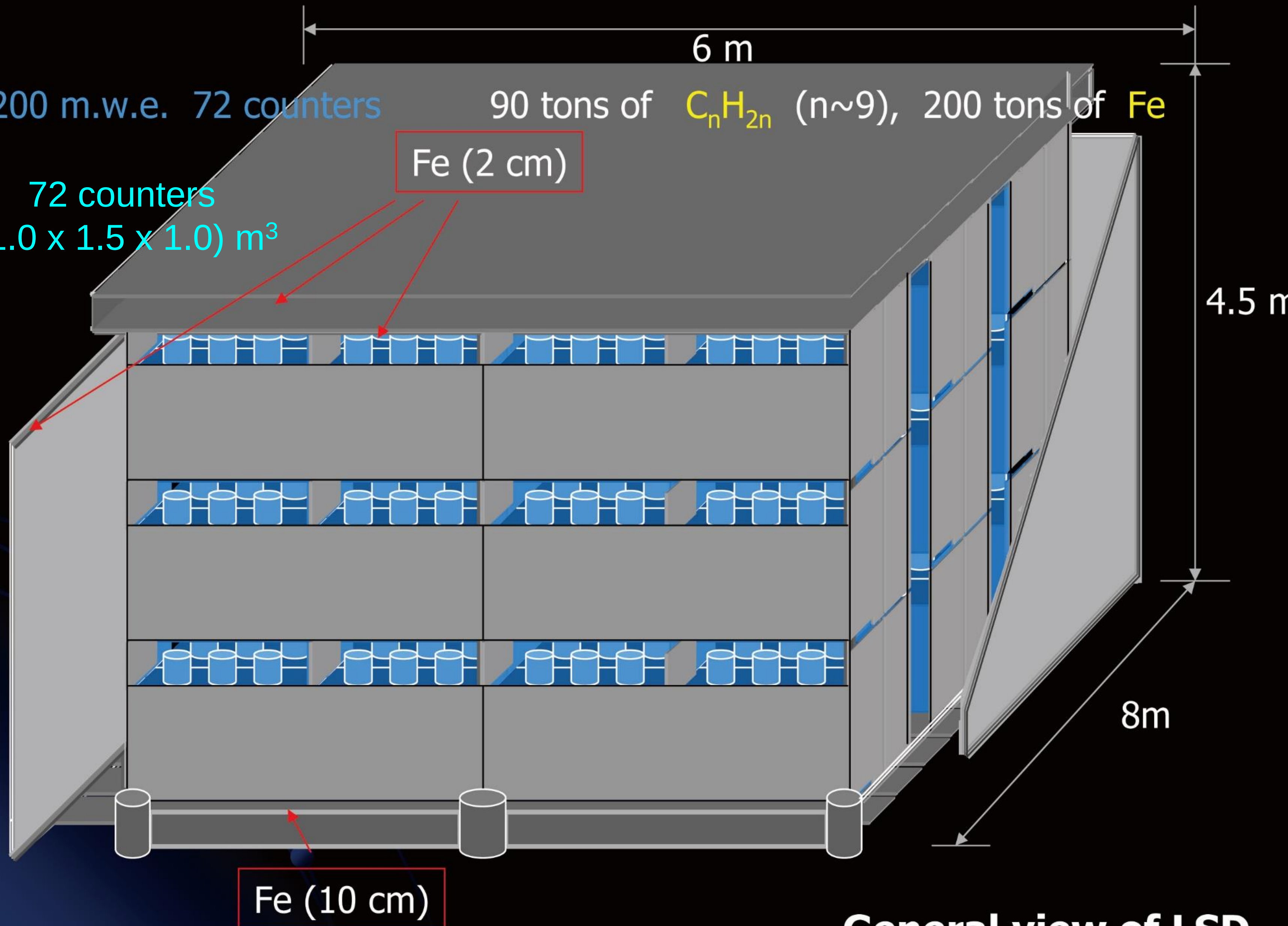
Total number of standard detectors………….3150

Total target mass…………………………...330 tons of oil-based scintillator

Liquid Scintillator Detector (LSD)

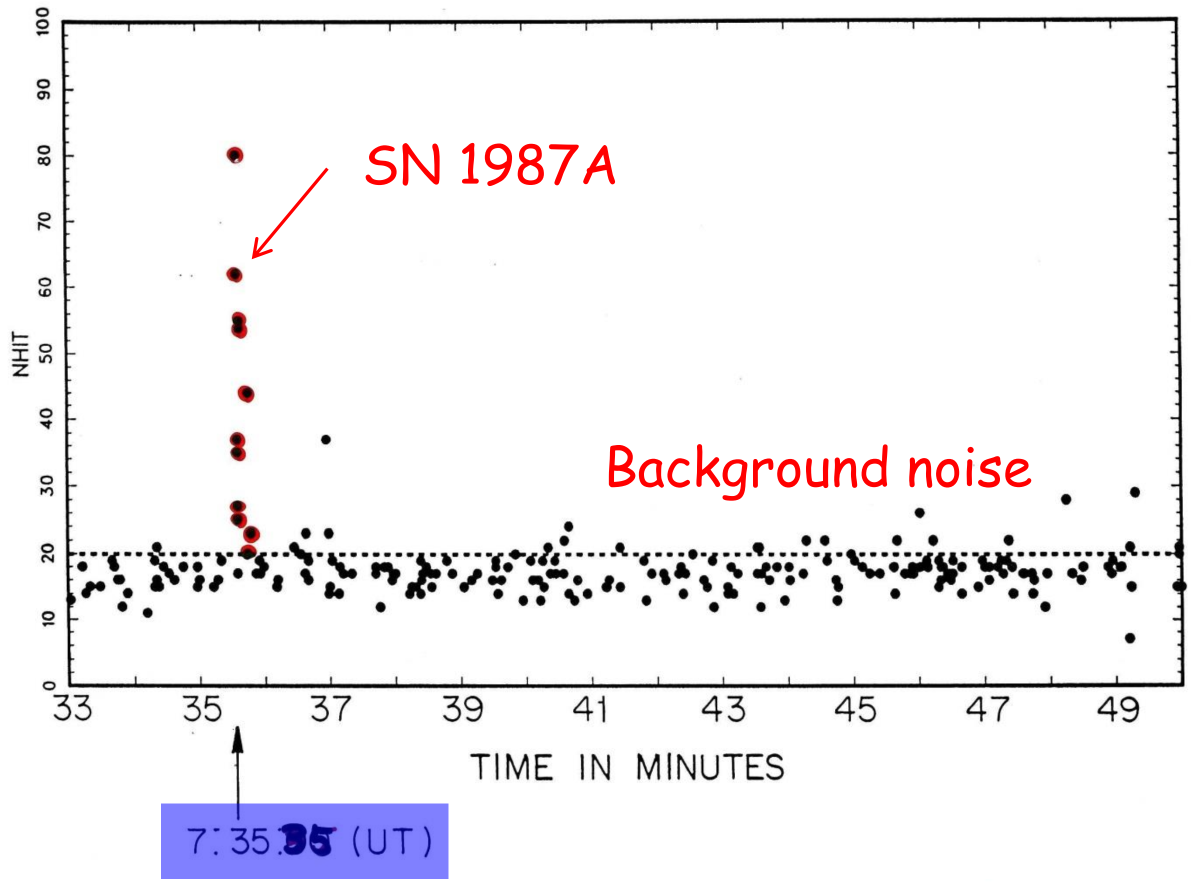
O. Saavedra (Hawaii, 2007)

H=5200 m.w.e. 72 counters 90 tons of C_nH_{2n} (n~9), 200 tons of Fe

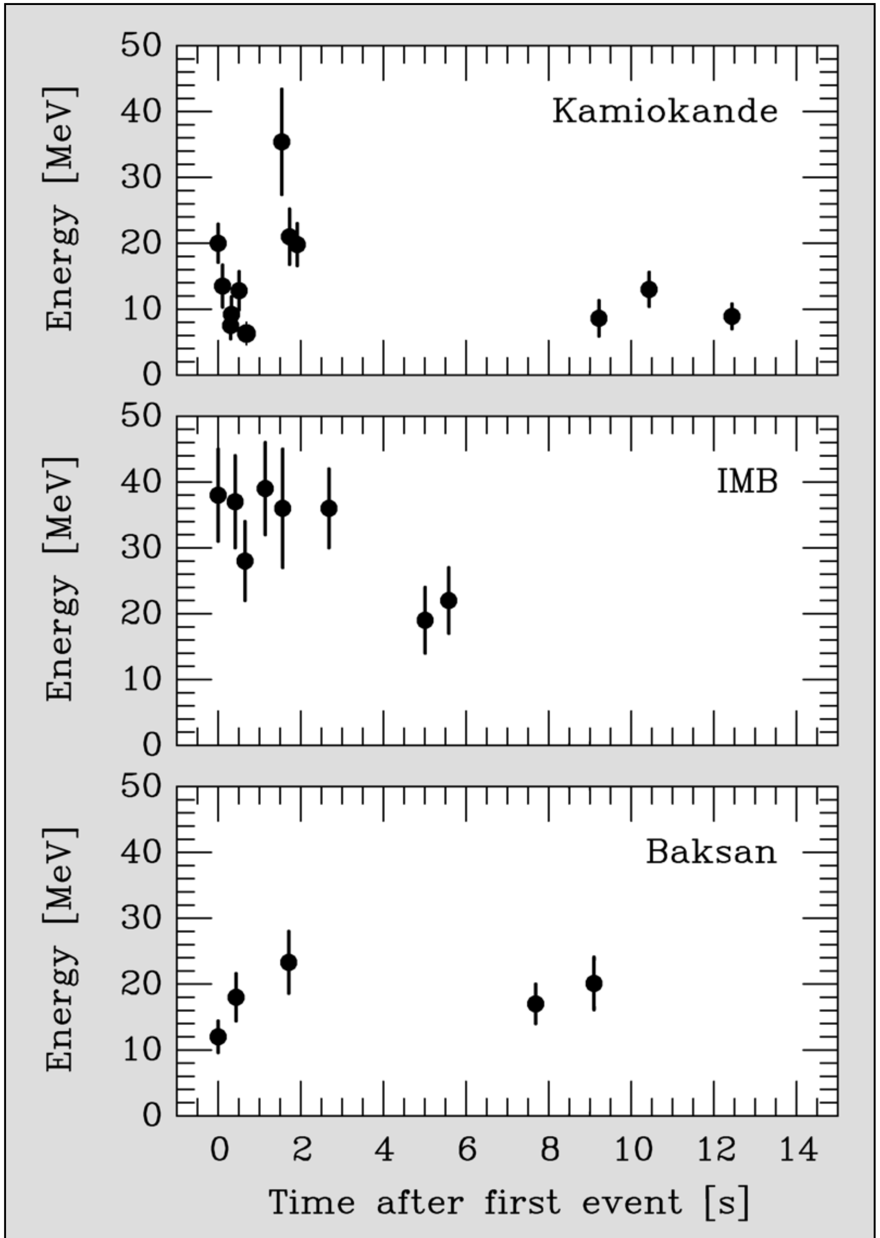


General view of LSD

NEUTRINO SIGNAL OF SN 1987A IN KAMIOKANDE



NEUTRINO SIGNAL OF SUPERNOVA 1987A



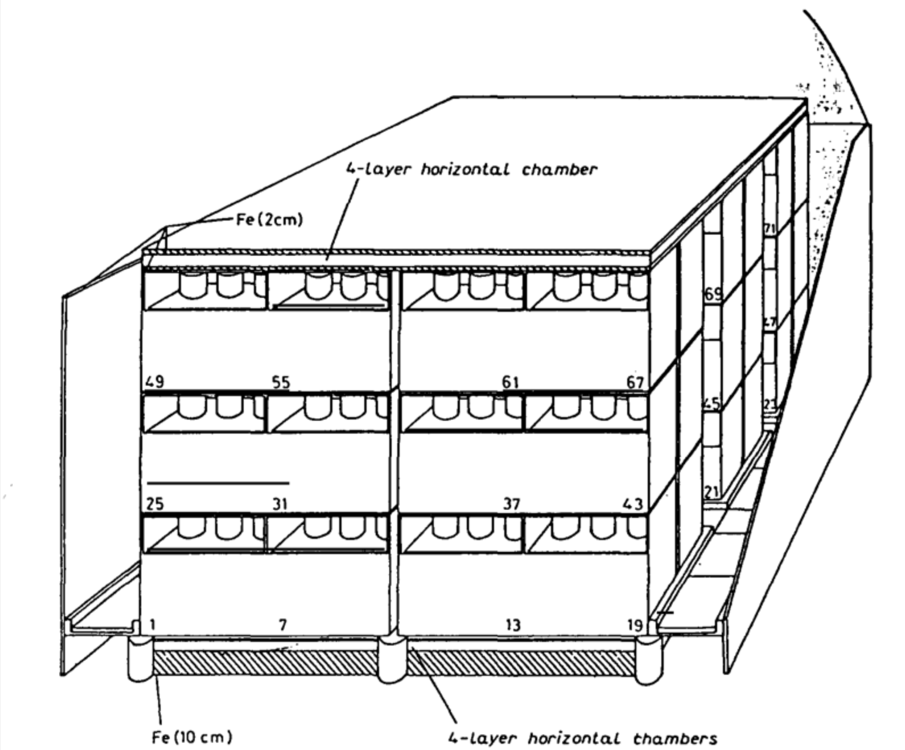
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ± 1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ± 50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

SN 1987A Signal in LSD (Mont Blanc) ?



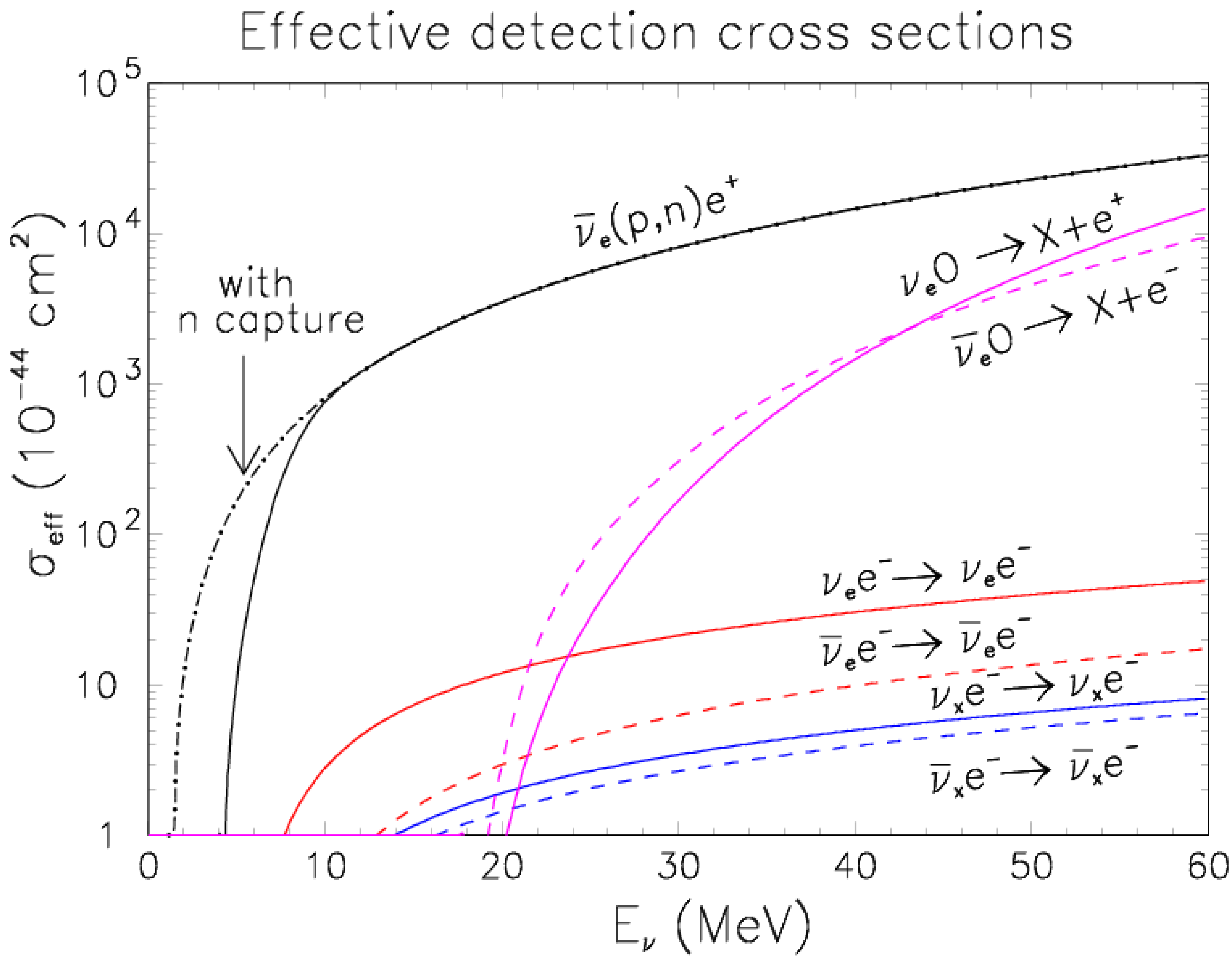
- Observed a 5-event cluster 4.72 hours before IMB/Kam-II
- Triggered autmatic SN alert
- Statistical fluctuation very unlikely
- No significant signal in IMB/Kam-II at LSD time
- No significant LSD signal at IMB time

LSD (Liquid Scintillator Detector)
in the Mont Blanc Tunnel
(Oct. 1984 - March 1999)
Supernova monitor for our galaxy
90 tons scintillator
200 tons iron (support structure)

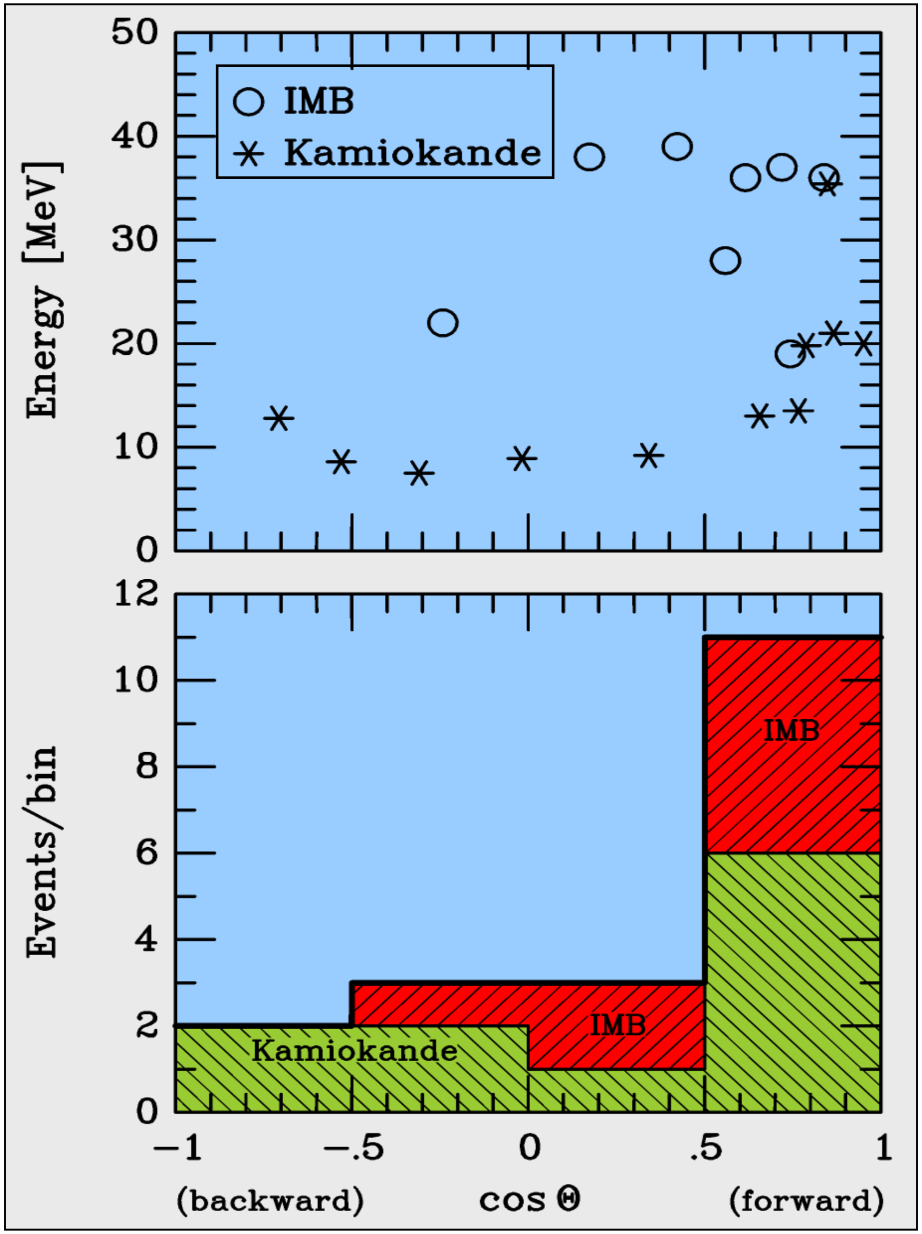
- Interpretation as “double bang”: Huge ν_e flux (~ 40 MeV) at LSD time
- LSD signal caused by interactions in iron of support structure
- Second bang ordinary multi-flavor signal

(Imshennik & Ryazhskaya, “A rotating collapsar and possible interpretation of the LSD neutrino signal from SN 1987A”, astro-ph/0401613)

CROSS SECTION IN WC DETECTOR



Angular Distribution of SN 1987A Neutrinos



Main detection reaction

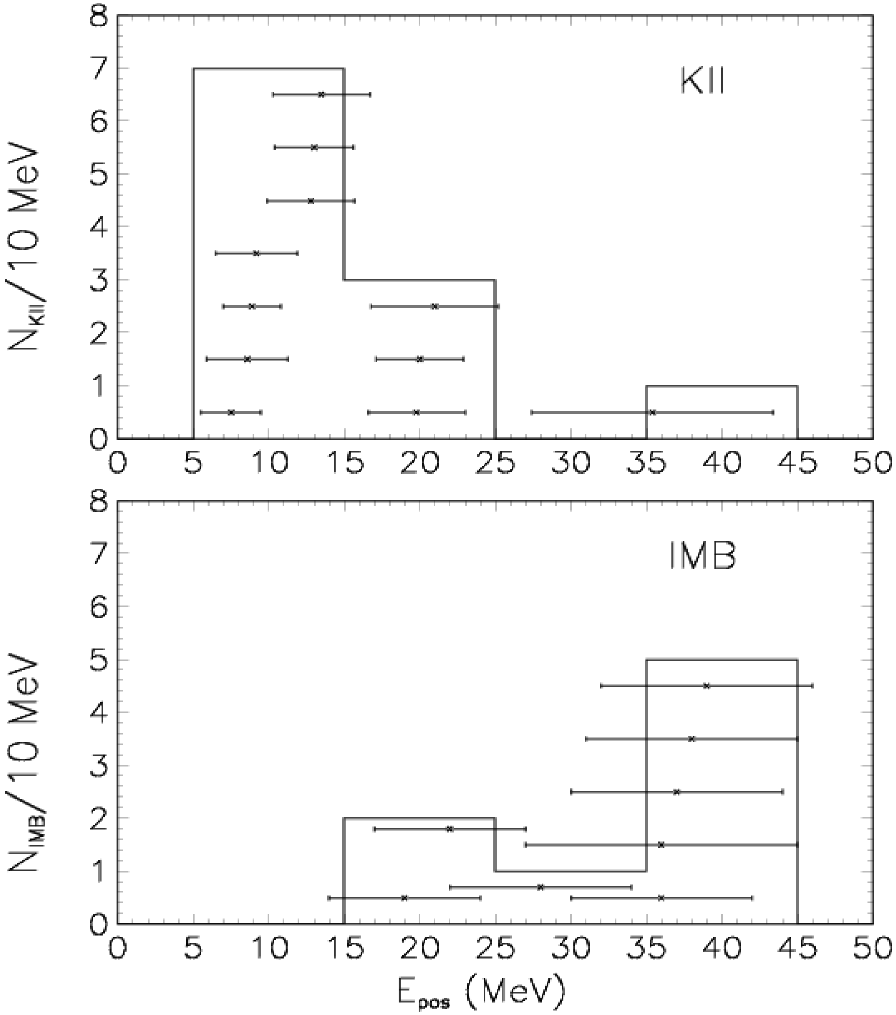
$$\bar{\nu}_e + p \rightarrow n + e^+$$

is essentially isotropic for the relevant energies.

Expect only a fraction of an event from forward-peaked reaction

$$\nu + e^- \rightarrow e^- + \nu$$

Energy Distribution of SN 1987A Neutrinos

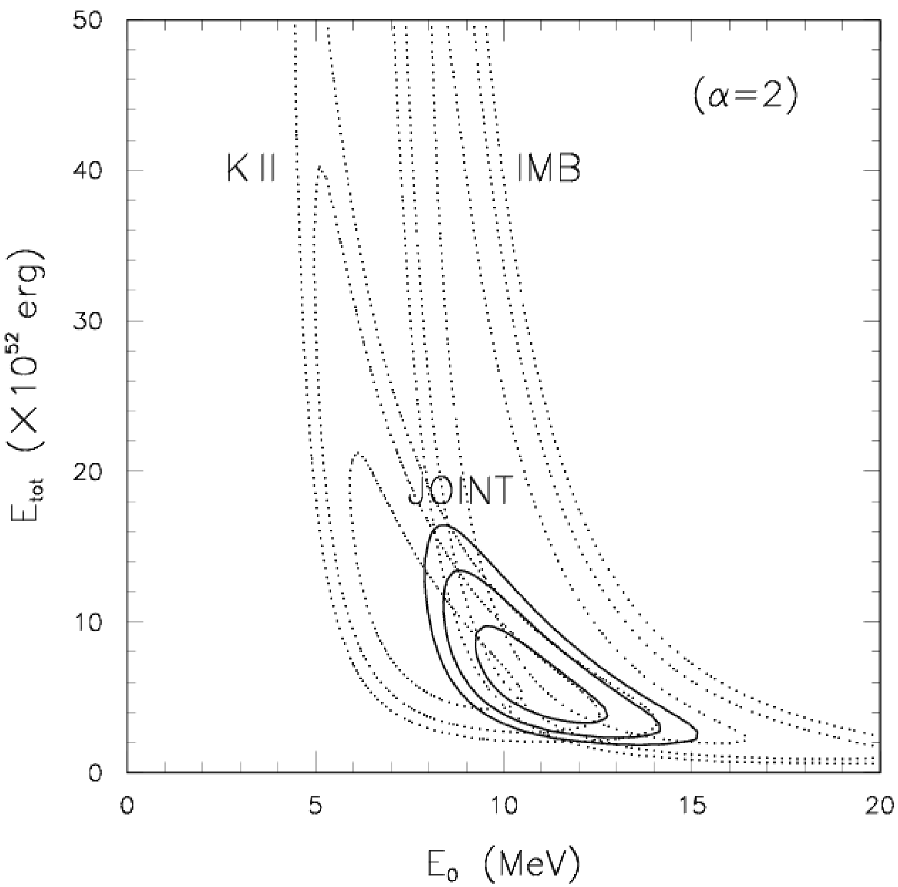


Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons

INTERPRETING SN 1987A NEUTRINOS

*[e.g.,B. Jegerlehner, F. Neubig and G. Raffelt, PRD **54**, 1194 (1996); A.M., and G. Raffelt, PRD **72**, 063001 (2005)]*



Total binding energy

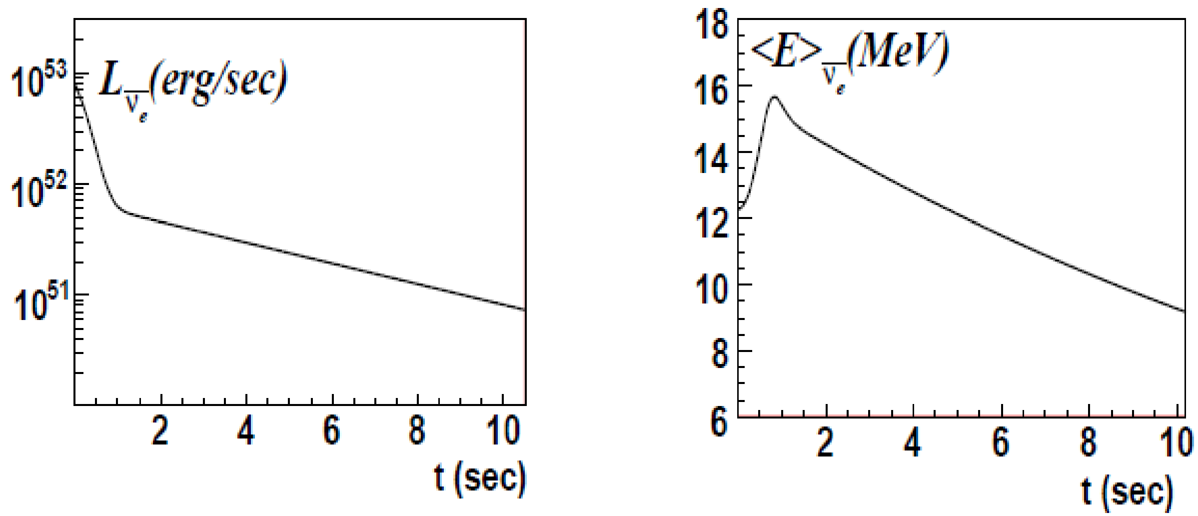
Average $\overline{\nu}_e$ energy

In agreement with the most recent theoretical predictions (i.e. Basel & Garching models)

SN NEUTRINO LIGHT CURVE FROM SN 1987A

[Loredo & Lamb, astro-ph/0107260 ; Pagliaroli, Vissani, Costantini & Ianni,arXiV:0810.0466]

Figure 6: *Pagliaroli et al. model: antineutrino luminosity and average energy in the best fit point.*



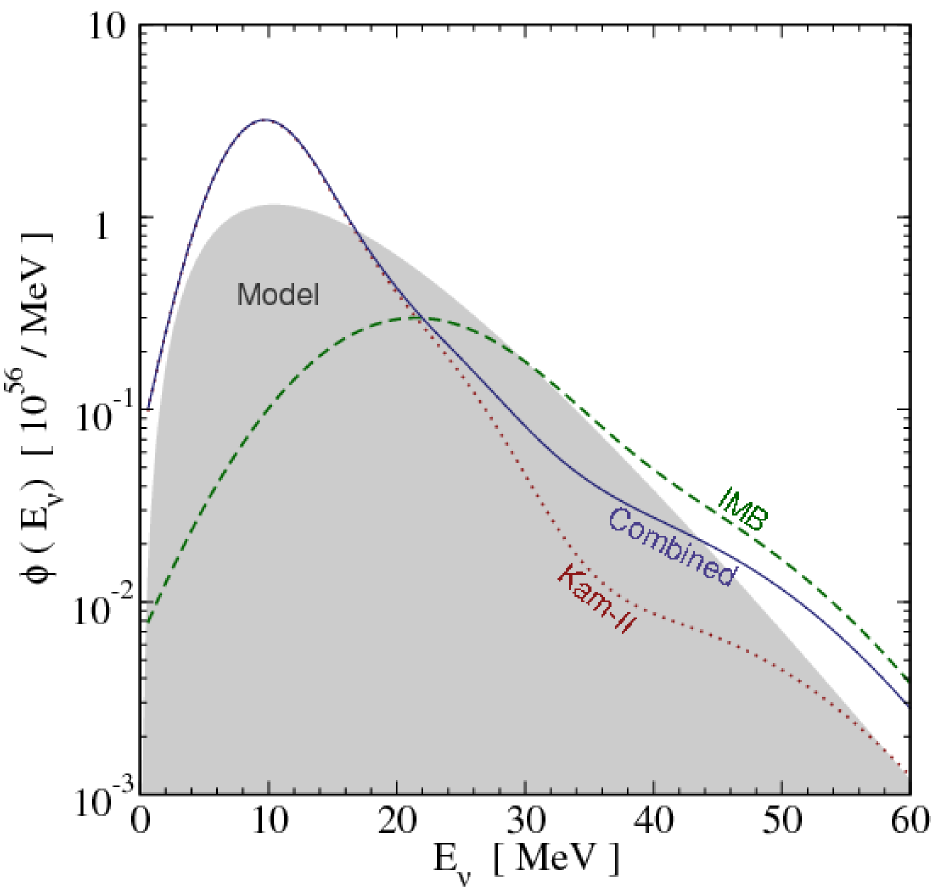
$R_c = 16$ km, $T_c = 4.6$ MeV, $\tau_c = 4.7$ s, cooling

$M_a = 0.2\ M_\odot$, $T_a = 2.4$ MeV, $\tau_a = 0.6$ s. accretion

Light curve in reasonable agreement with generic expectations of delayed explosion scenario

SN NEUTRINO SPECTRUM FROM SN1987A

[Yuksel & Beacom, astro-ph/0702613]



Original SN ν energy spectra expected to be quasi-thermal

SN1987A inferred ν energy spectrum shows strong deviations from quasi-thermal distribution:

Possible effects of:

- neutrino mixing
- ν–ν interactions
- ν decay
- nonstandard ν interactions
- additional channels of energy exchange among flavors

?

Possible to reconcile detection and theory… Still many open questions!

Based on the handful of SN neutrinos which were detected that day, approximatively <u>one theory paper has published every ten days</u>….

...for the last <u>thirty years!</u>

PARTICLE PHYSICS BOUNDS FROM SN 1987A

- Exotic neutrino properties
- Axion-like particles
- Energy-loss and novel particles

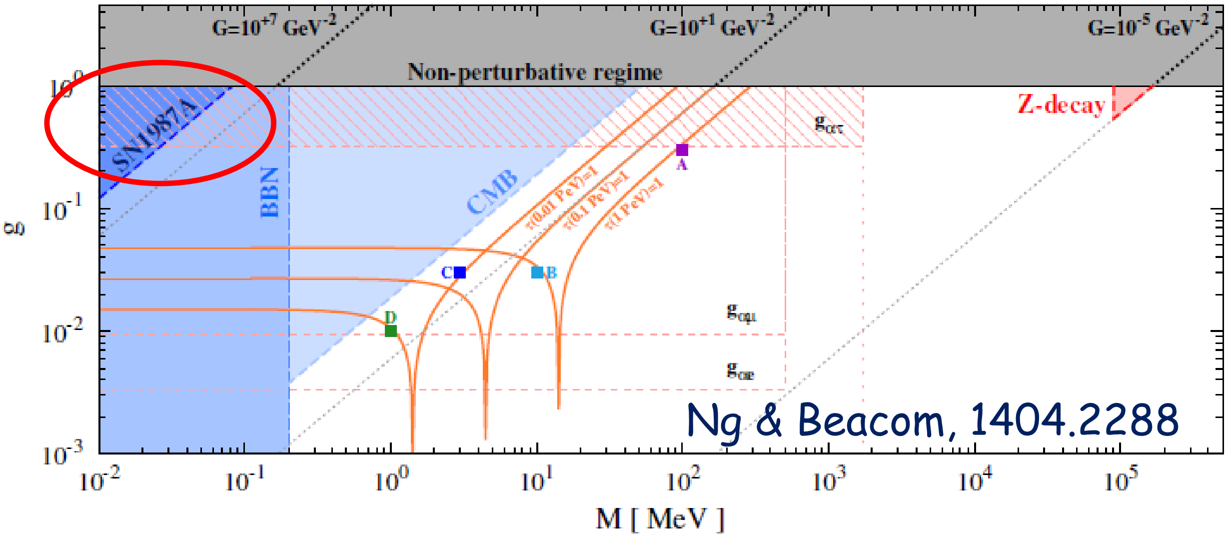
BOUND ON SECRET NEUTRINO INTERACTIONS

$$L = g\phi\nu\bar{\nu}$$

ϕ new scalar mediator with mass M

Four fermion approximation $G = \frac{1}{\sqrt{4\pi}}\frac{g^2}{M^2}$

Requiring that ν from cosmic sources travel through the CνB without scattering induced by the secret interactions leads to upper limits on the new coupling.

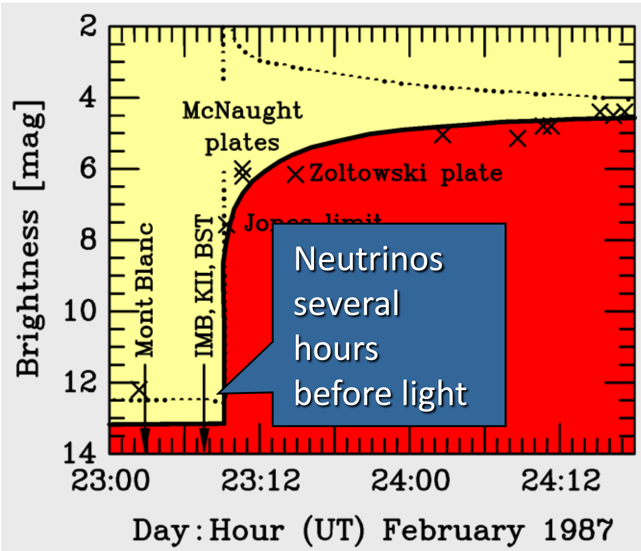


SN 1987A bound

$$G \leq\sim 10^{-8}\, GeV^{-2}$$

[Kolb & Turner, PRD 36, 2895 (1987)]

SN 1987A BOUNDS ON NEUTRINO VELOCITY



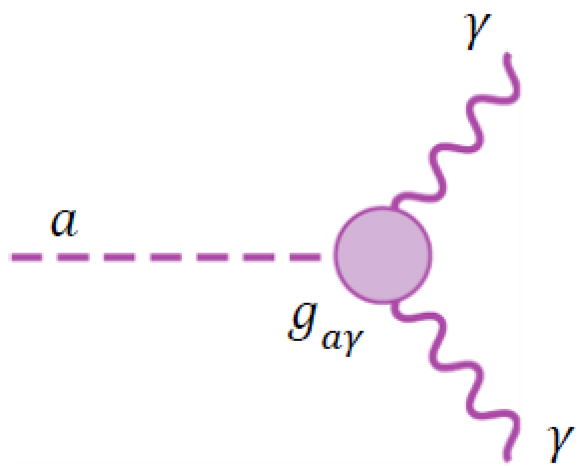
SN 1987A few events provide the most stringent constraints on ν velocity. Crucial for comparison with recent OPERA claim

Table 1. Superluminal Neutrino Velocity Observations and Bounds *[Evslin, 1111.0733]*

OPERA	2009-2011	
Energy 10-50 GeV	Neutrinos 16,111 ν's (97% ν_μ'2)	$(v-c)/c$ 2.48 ± 0.28 (stat.) ± 0.30 (syst.) $\times 10^{-5}$
Distance:	730 km from CNGS (CERN) to OPERA (Gran Sasso)	
MINOS	May 2005-February 2006	
Energy: 3 GeV (tail to 120 GeV)	Neutrinos 473 ν's (93% ν_μ's)	$(v-c)/c$ 5.1 ± 1.3 (stat.)± 2.6 (sys.)$\times 10^{-5}$
Distance:	734 km: Near Detector (FermiLab) to Soudan iron mine	
Kamiokande II	7:35 UT, February 23rd, 1987	
Energy 7.5-36 MeV	Neutrinos 12 $\bar{\nu}_e$'s	ν's $\subset$ 13 sec., $\lesssim 3$ hrs before γ's, $(v-c)/c < 3 \times 10^{-9}$ or 2×10^{-12}
Distance:	160,000 lys: Tarantula Nebula to Kamioka Observatory	
Irvine-Michigan-Brookhaven	7:35 UT, February 23rd, 1987	
Energy 20-40 MeV	Neutrinos 8 $\bar{\nu}_e$'s	ν's $\subset$ 6 sec., $\lesssim 3$ hrs before γ's, (v-c)/c$< 3 \times 10^{-9}$ or 2×10^{-12}
Distance	160,000 lys: Tarantula Nebula to Morton-Thiokol salt mine	

AXION-LIKE PARTICLES (ALPs)

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \widetilde{F}_{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$$



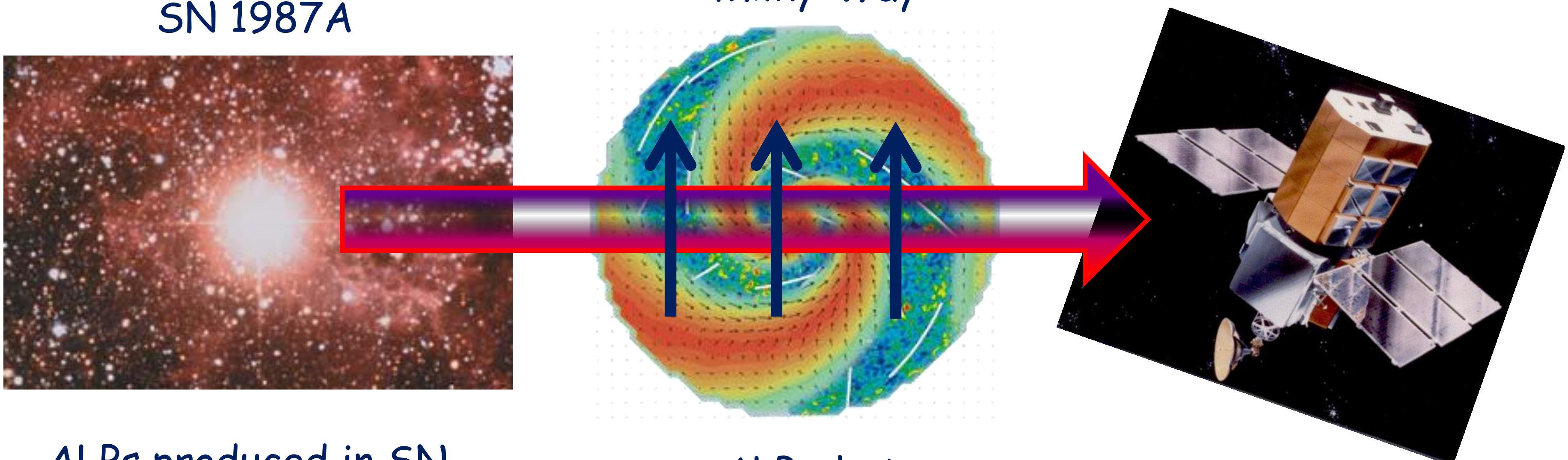
- Primakoff process: Photon-ALP transitions in external static E or B field

- Photon-ALP conversions in macroscopic B-fields

ALPs CONVERSIONS FOR SN 1987A

[*Brockway, Carlson, Raffelt, astro-ph/9605197, Masso and Toldra, astro-ph/9606028*]

SN 1987A | Milky-Way | SMM Satellite



ALPs produced in SN core by Primakoff process

ALP-photon conversions in the Galactic B-fields

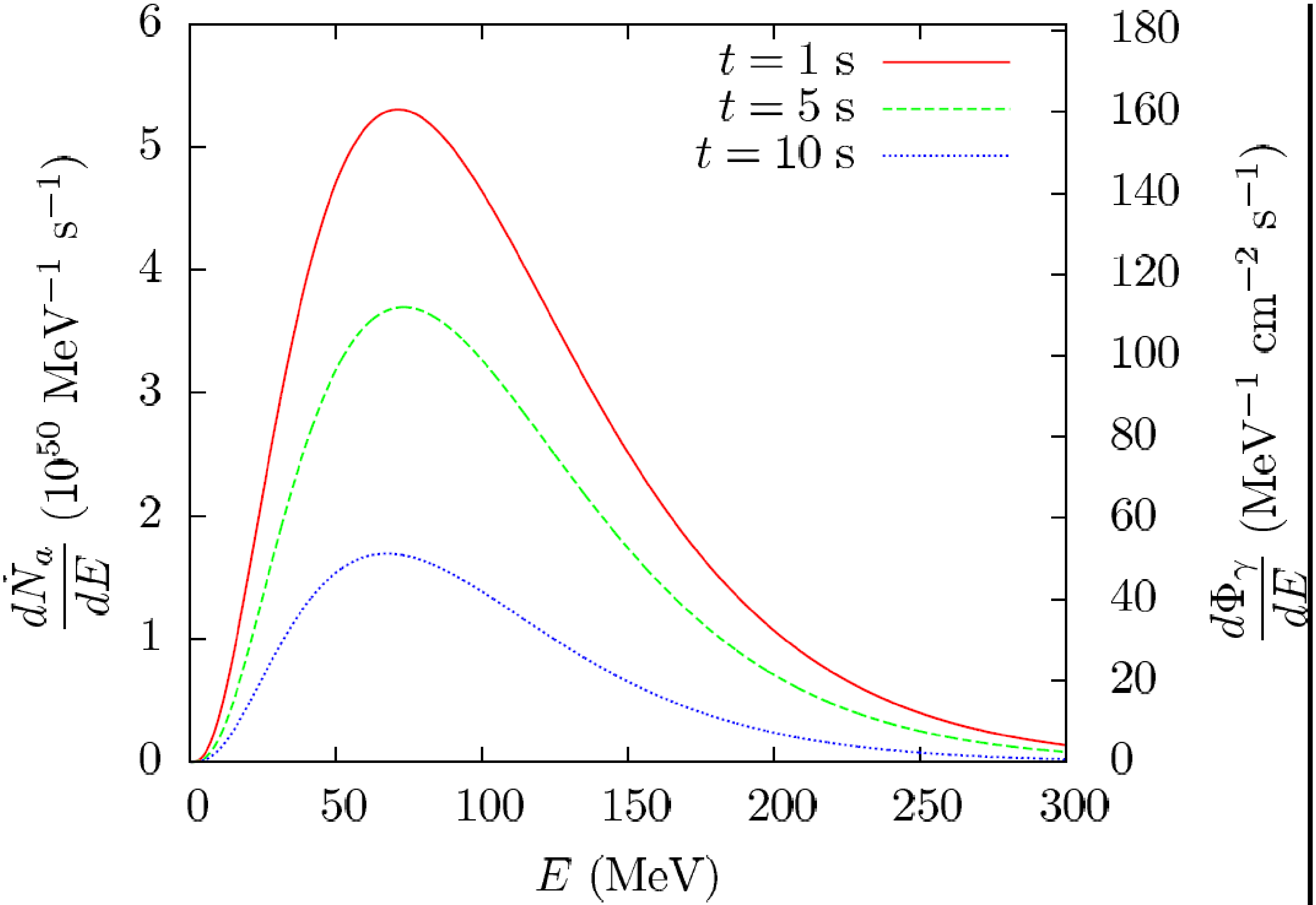
No excess gamma-rays in coincidence with SN 1987A

In [*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*] we revaluate the bound with

- state-of-art models for SNe and Galactic B-fields
- accurate microscopic description of the SN plasma

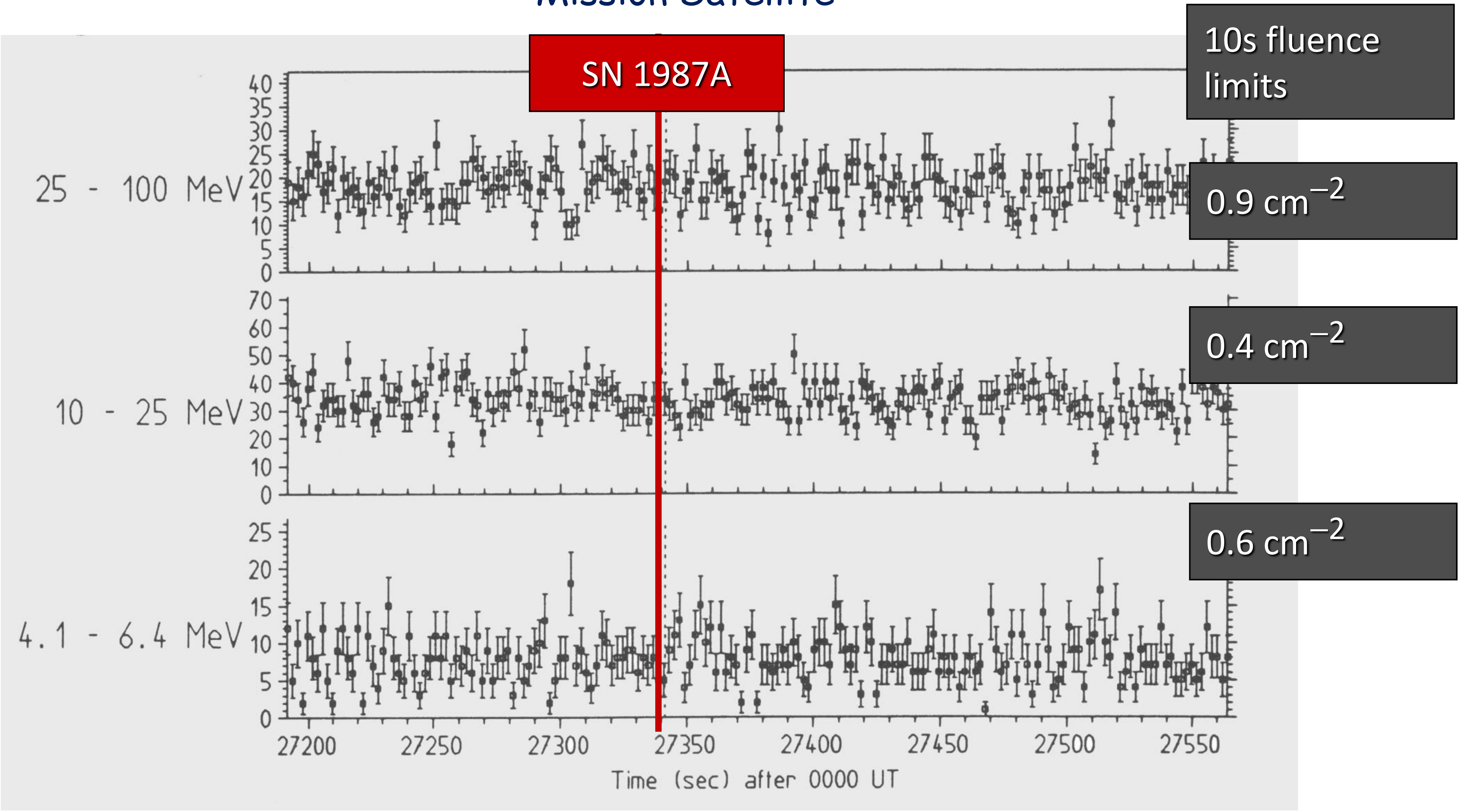
ALP-PHOTON FLUXES FOR SN 1987A

[*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*]



GAMMA-RAY OBSERVATION FROM SMM SATELLITE

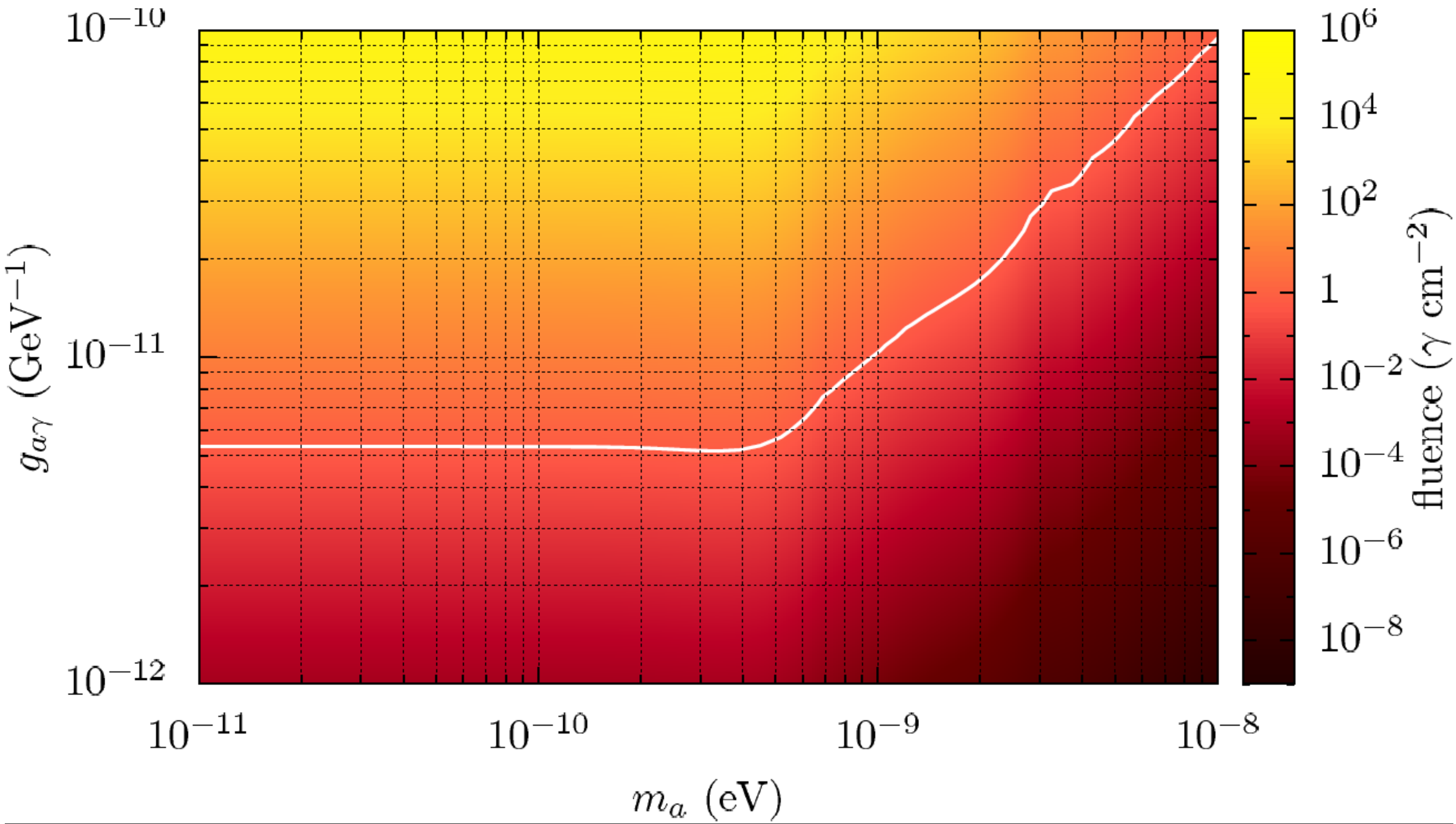
Counts in the GRS instrument on the Solar Maximum Mission Satellite



$$F(g_{a\gamma}) = 7.02 \times 10^4 \left(\frac{g_{a\gamma}}{10^{-10} GeV^{-1}}\right)^4 \gamma cm^{-2}$$

NEW BOUND ON ALPs FROM SN 1987A

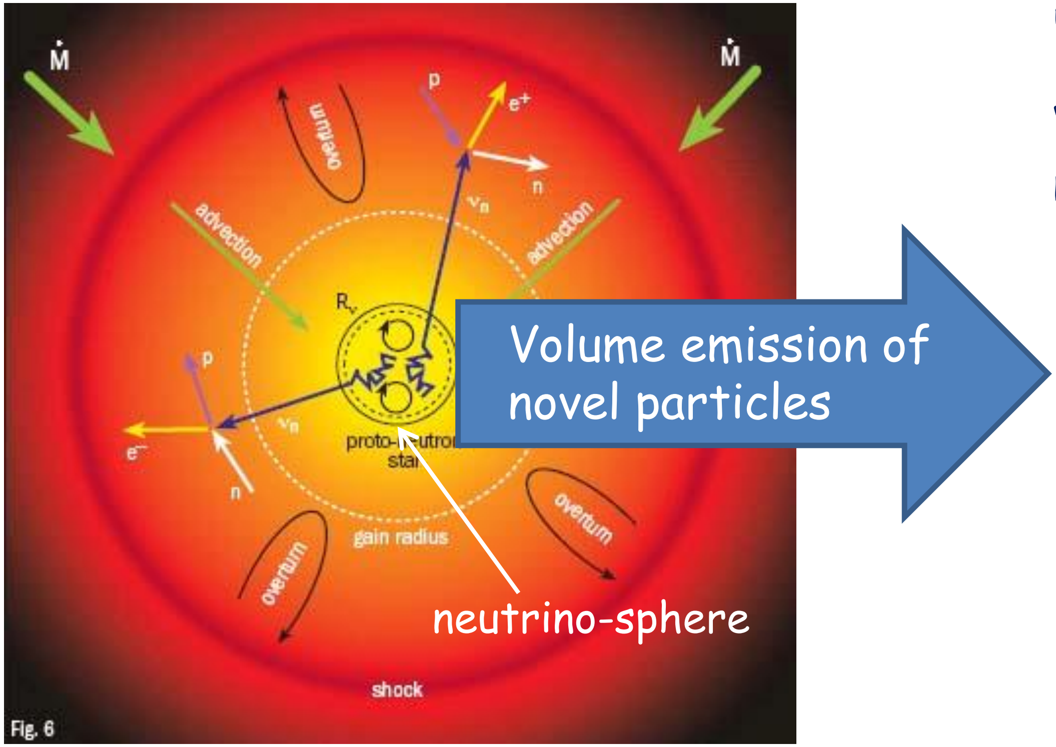
[*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*]



$$g_{a\gamma} \leq 5.3 \times 10^{-12}\ GeV^{-1} \quad \text{for} \quad m_a < 4.4 \times 10^{-10}\text{eV}$$

SN 1987A provides the strongest bound on ALP-photon coversions for ultralight ALPs

ENERGY-LOSS ARGUMENT



Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.

Assuming that the SN 1987A neutrino burst was not shortened by more than ~½ leads to an approximate requirement on a novel energy-loss rate of

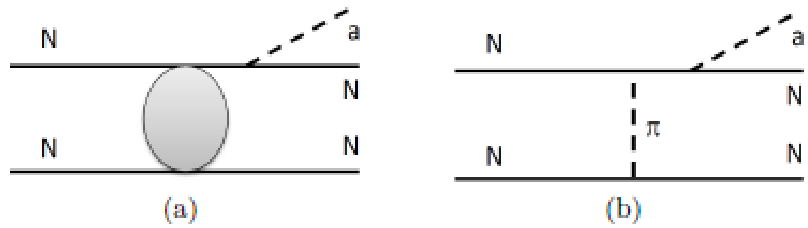
$$\varepsilon_x < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

for $\rho \approx 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$ and $T \approx 30$ MeV

AXION EMISSION FROM A NUCLEAR MEDIUM

$$NN \rightarrow NNa$$

nucleon-nucleon bremsstrahlung



Bulk nuclear interaction One pion exchange

$$\boxed{L_{aN} = \frac{g_{aN}}{2m_N} \overline{N} \gamma_\mu \gamma_5 N \partial^\mu a}$$

$$g_{aN} = C_N \frac{m}{f_a}$$

Non-degenerate energy-loss rate $\varepsilon_a = g_{aN}^2\, 2 \times 10^{39}\, \mathrm{erg\ g^{-1}\ s^{-1}} \rho_{15} T_{30}^{3.5}$

$$\begin{pmatrix} T_{30} = T / 30\ \mathrm{MeV} \\ \rho_{15} = \rho / 10^{15}\, \mathrm{g\ cm^{-3}} \end{pmatrix}$$

$$\langle \rho_{15} \rangle \approx 0.4$$

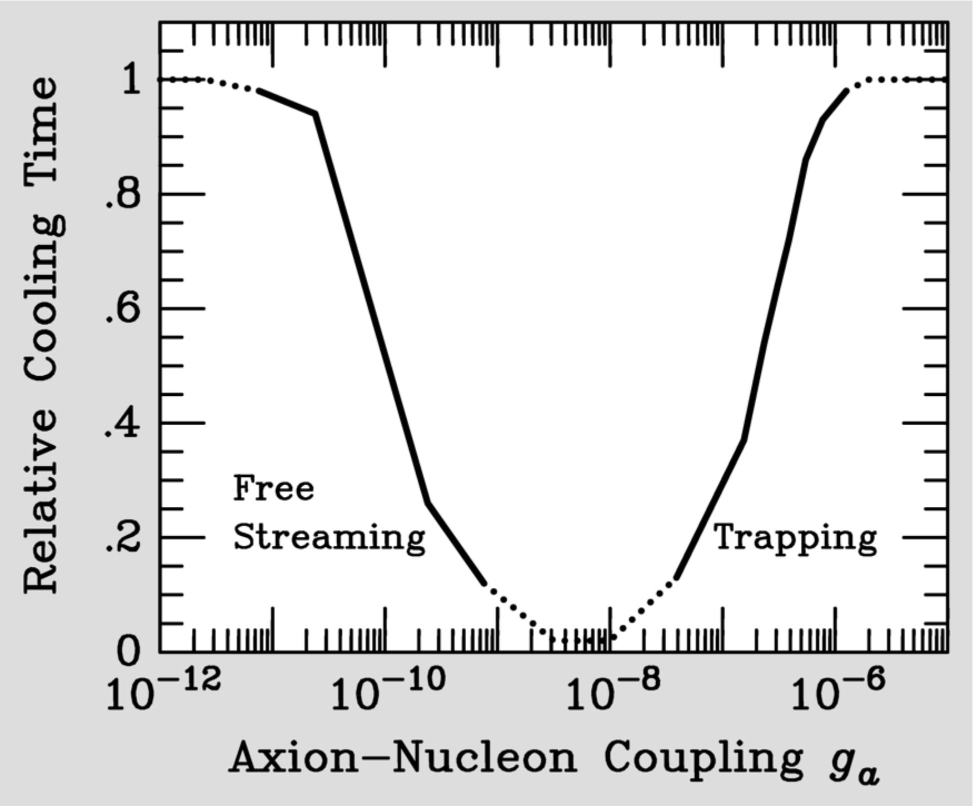
$$\langle T_{30}^{3.5} \rangle \approx 1.4$$

$$\Rightarrow \quad g_{aN} < 9 \times 10^{-10}$$

SN 1987A AXION LIMITS

Free streaming
[*Burrows, Turner & Brinkmann, PRD 39:1020,1989*]

Volume emission of axions



Trapping
[*Burrows, Ressell & Turner, PRD 42:3297,1990*]

Axion diffusion from an "axion-sphere"

Possible detection in a water Cherenkov detector via oxygen nuclei excitation

Hadronic axion (m_a ~ 1 eV, f_a~10^6 GeV) not excluded by SN 1987A. Possible hot-dark matter candidate. The "hadronic axion window" is closed by cosmological mass bounds.

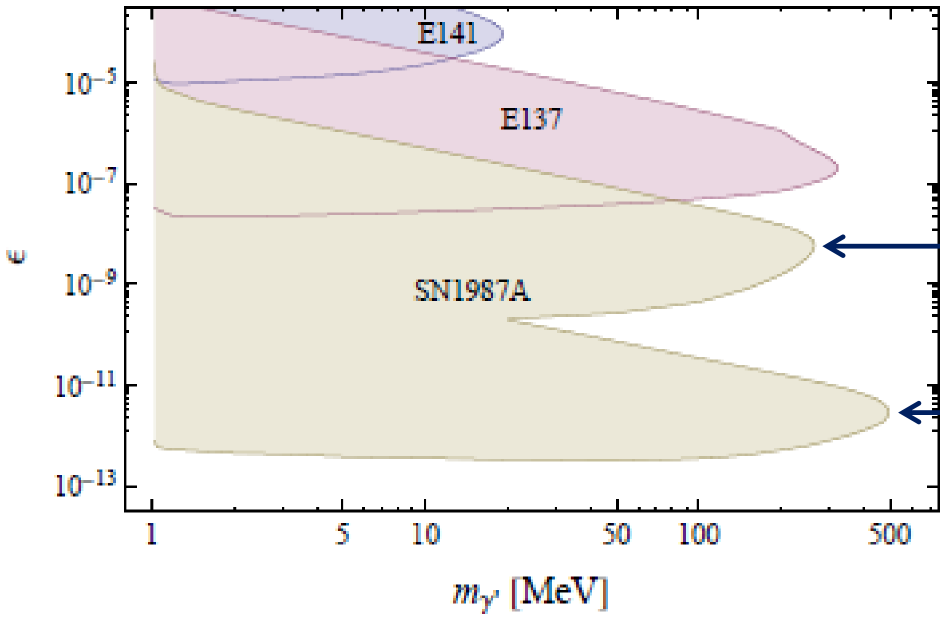
SN 1987A BOUND ON HIDDEN PHOTONS

[*Kazanas, Mohapatra et al., 1410.0221*]

$$L = \varepsilon F_{\mu\nu} F'^{\mu\nu}$$

ε mixing angle

$F'^{\mu\nu}$ U(1)' gauge field of γ'

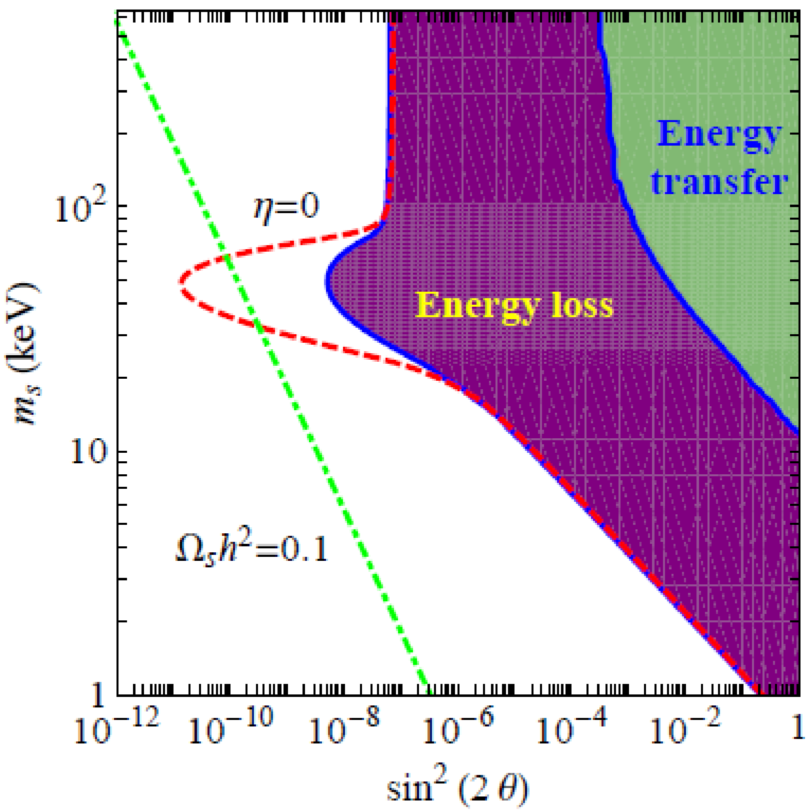


Energy-loss argument

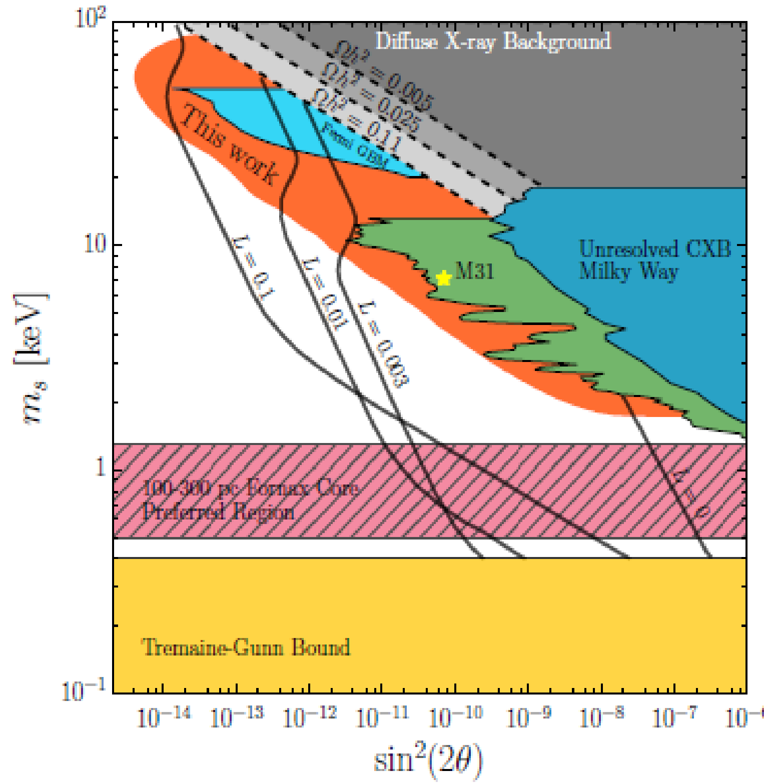
Electromagnetic decays ($\gamma' \to e^+ e^-$) [bounds of fluence of gamma-rays]

SN 1987A BOUND ON KeV STERILE NEUTRINOS

Raffelt & Zhou, 1102.5124



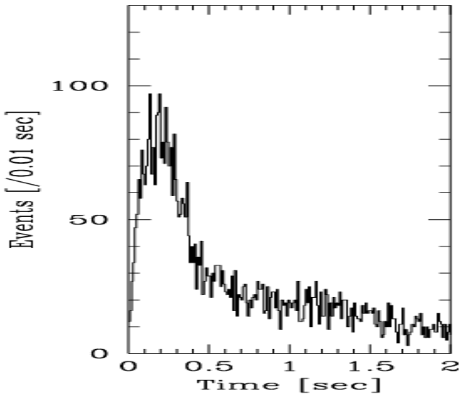
Argüelles, Brdar and Kopp, 1605.00654

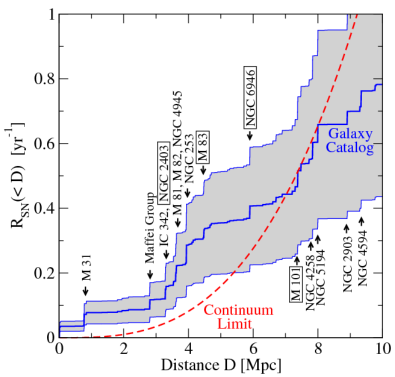


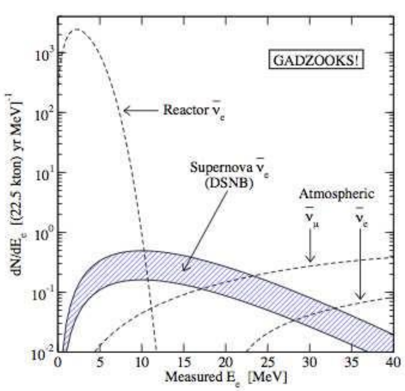
- KeV sterile ν are produced in a SN core by the mixing with active ν.
- For sufficiently small mixing θ, ν_s escape the core immediately after the production contributing to the energy-loss.

FUTURE SN NEUTRINO OBSERVATIONS

NEUTRINO DETECTION METHODS







- **Milky-Way SN**

  Excellent statistics (10^4 events for 10 kpc)
  High-sensitivity to explosion scenario
  1 SN ~ 40 years

- **SNe in nearby galaxies**

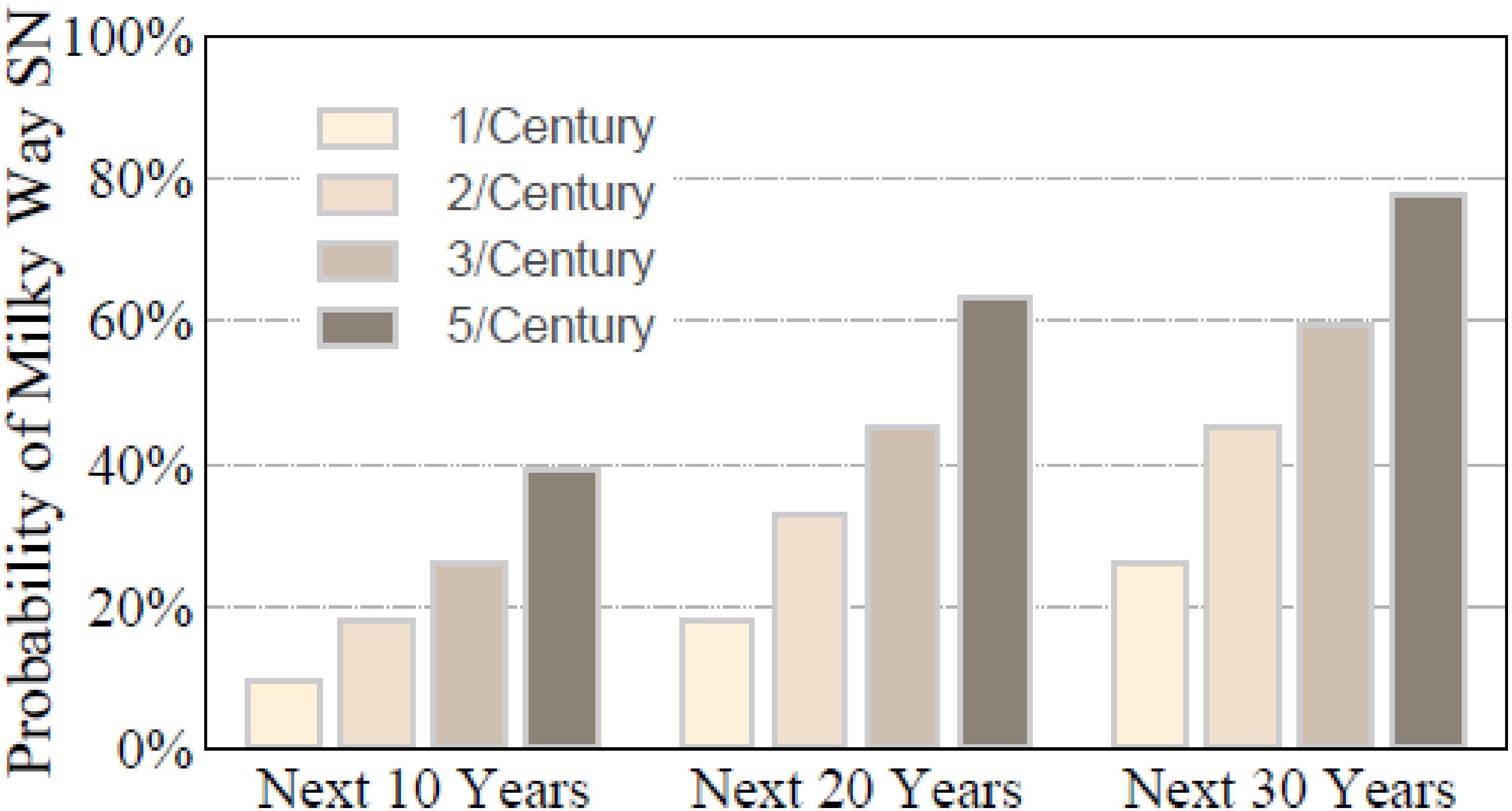
  Few to 10 neutrinos per SN, but requires a Mton-class detector
  1 SN ~ year

- **Diffuse Supernova Neutrino Background (DSNB)**

  Neutrinos from all past core-collapse SNe; emission is averaged, no timing or direction
  (faint) signal is always there

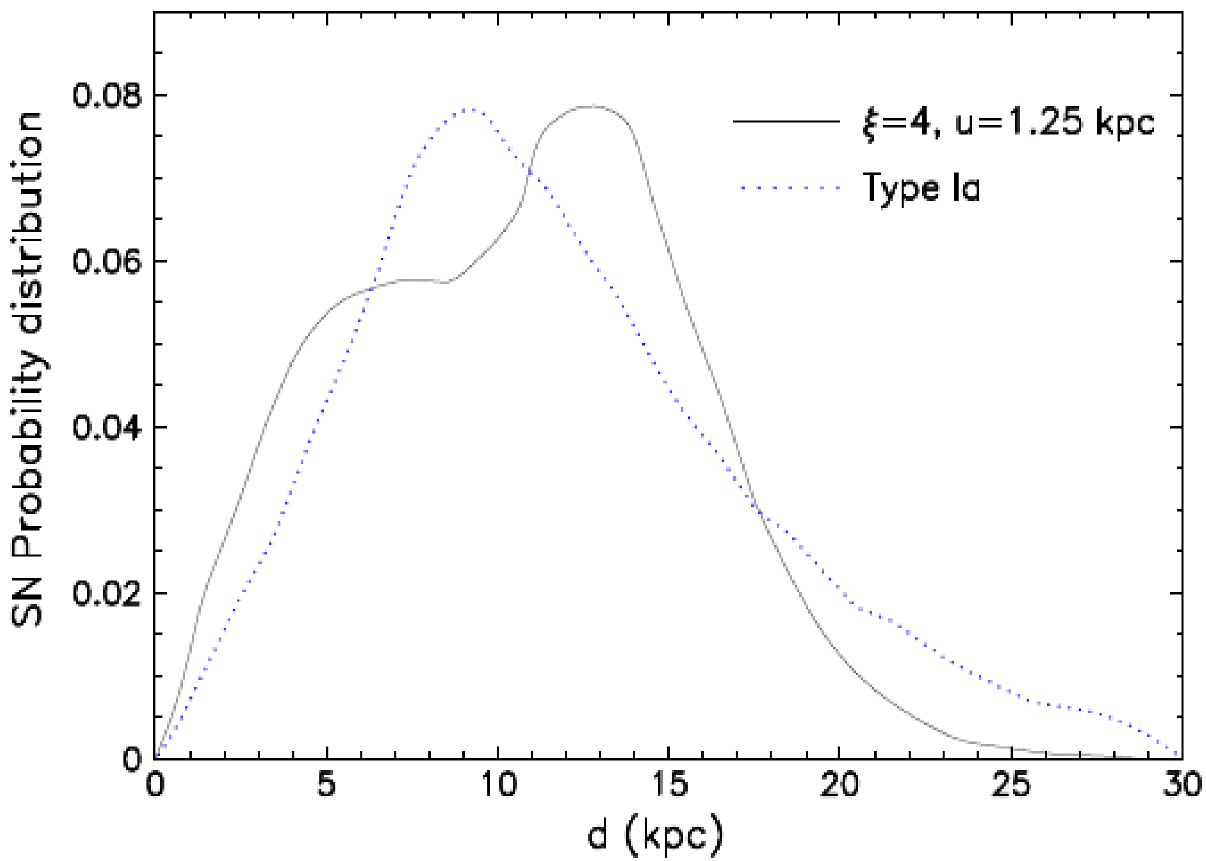
PROBABILITY OF MILKY-WAY SN

[Kistler, Yuksel, Ando, Beacom & Suzuki, 0810.1959]



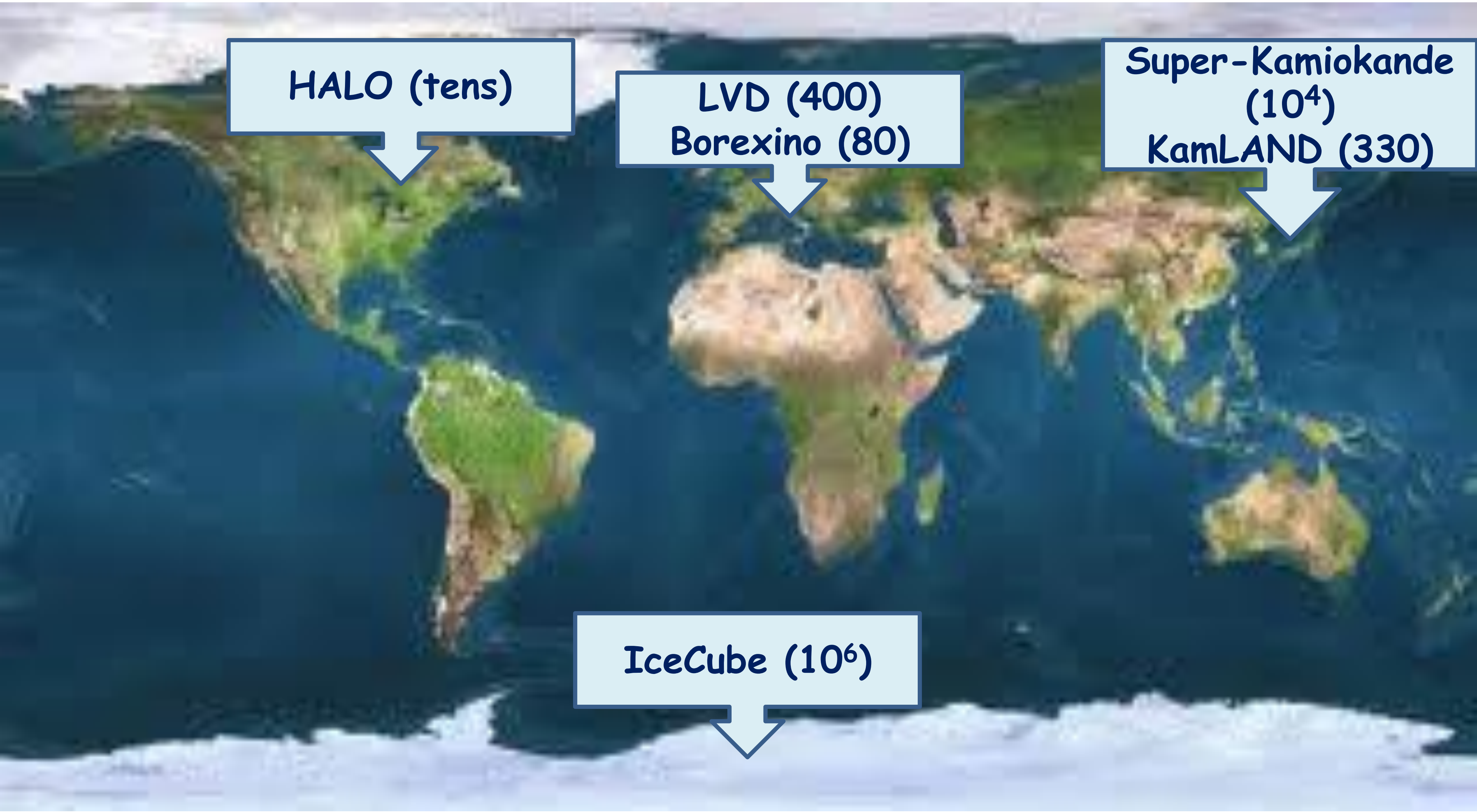
GALACTIC SUPERNOVA DISTANCE DISTRIBUTION

[A.M., Raffelt, Serpico, astro-ph/ 0604300]



Average distance 10.7 kpc, rms dispersion 4.9 kpc
(11.9 kpc and 6.0 kpc for SN Ia distribution)

Large Detectors for Supernova Neutrinos



In brackets events for a “fiducial SN” at distance 10 kpc

LARGE DETECTORS FOR SN NEUTRINOS

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]

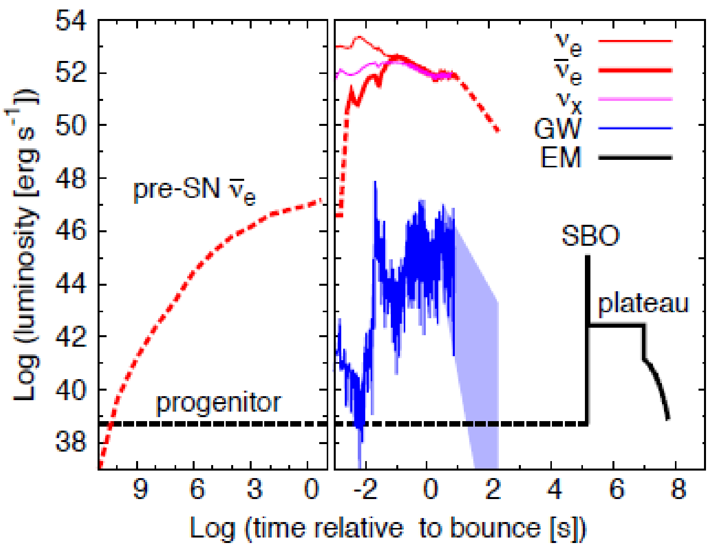
Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

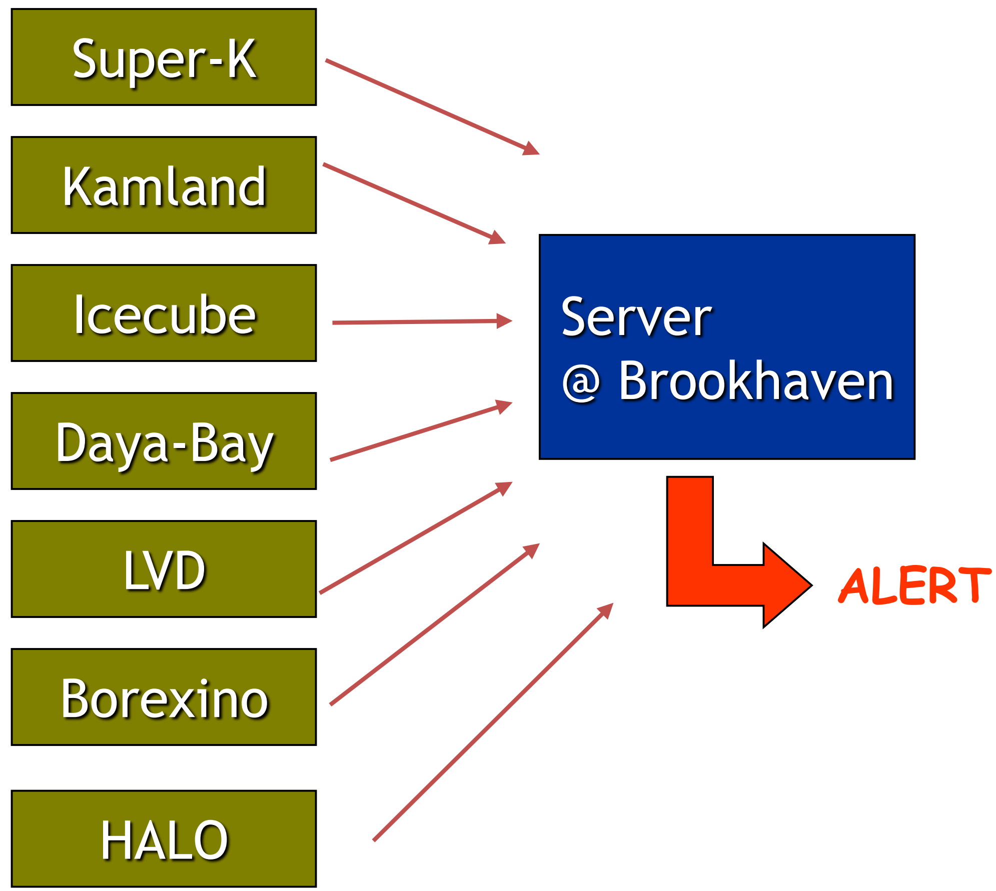
SUPERNOVA EARLY WARNING SYSTEM (SNEWS)

[P.Antonioli et al., astro-ph/0406214]

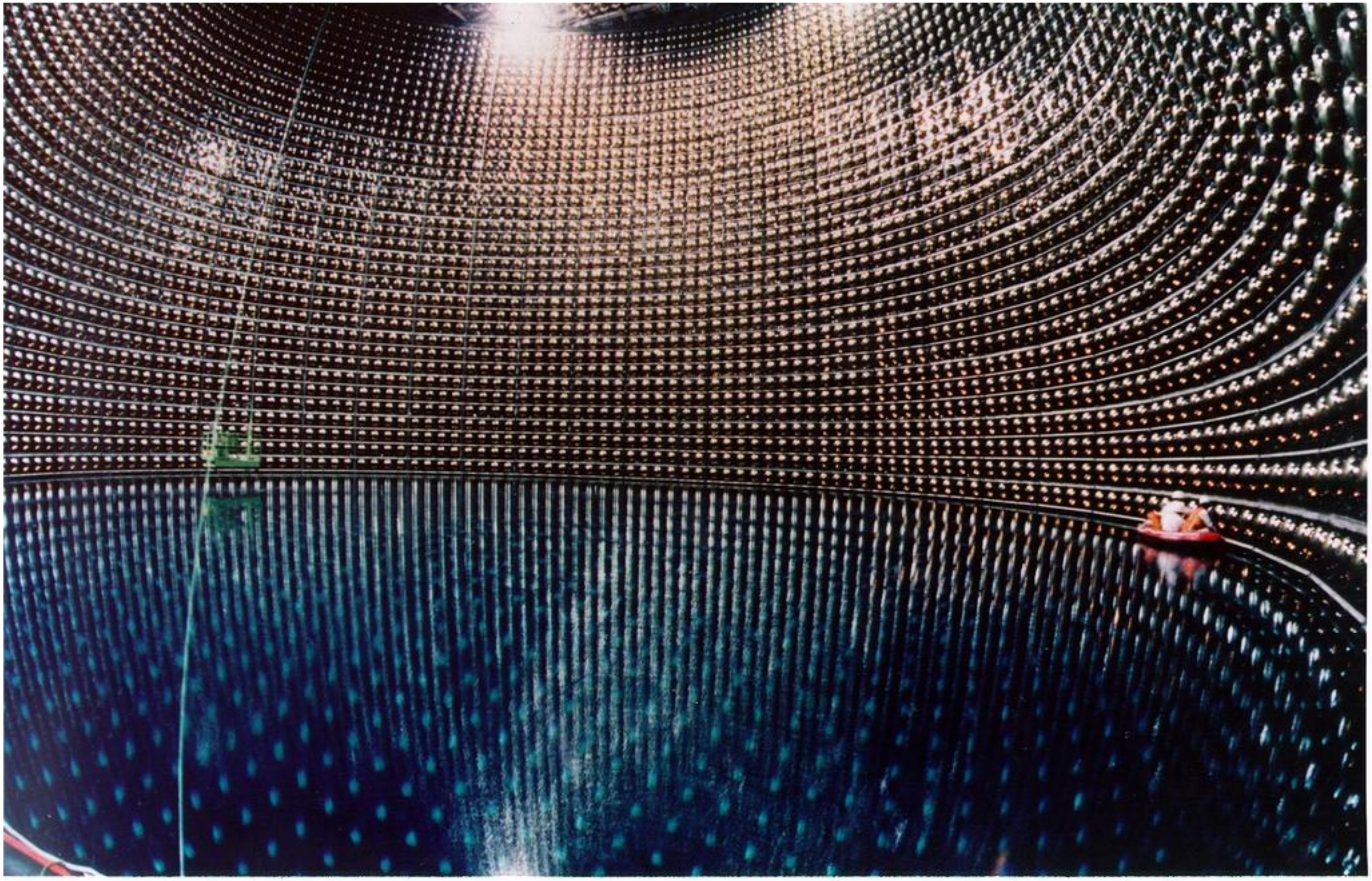
Neutrinos several hours before light

Neutrino observations can alert astronomers several hours in advance to a SN. To avoid false alarms, require alarm from at least two experiments



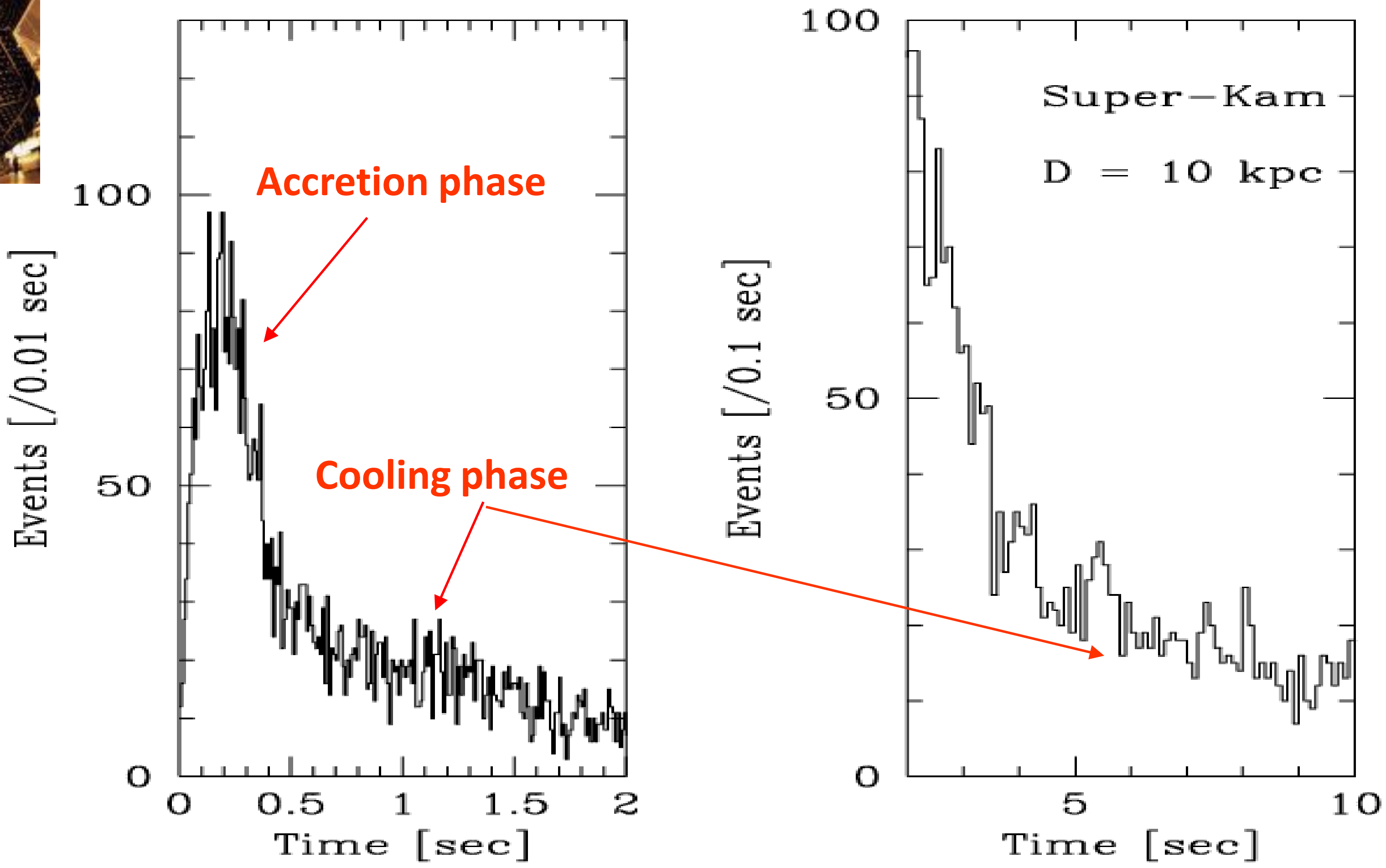


SUPER-KAMIOKANDE DETECTOR



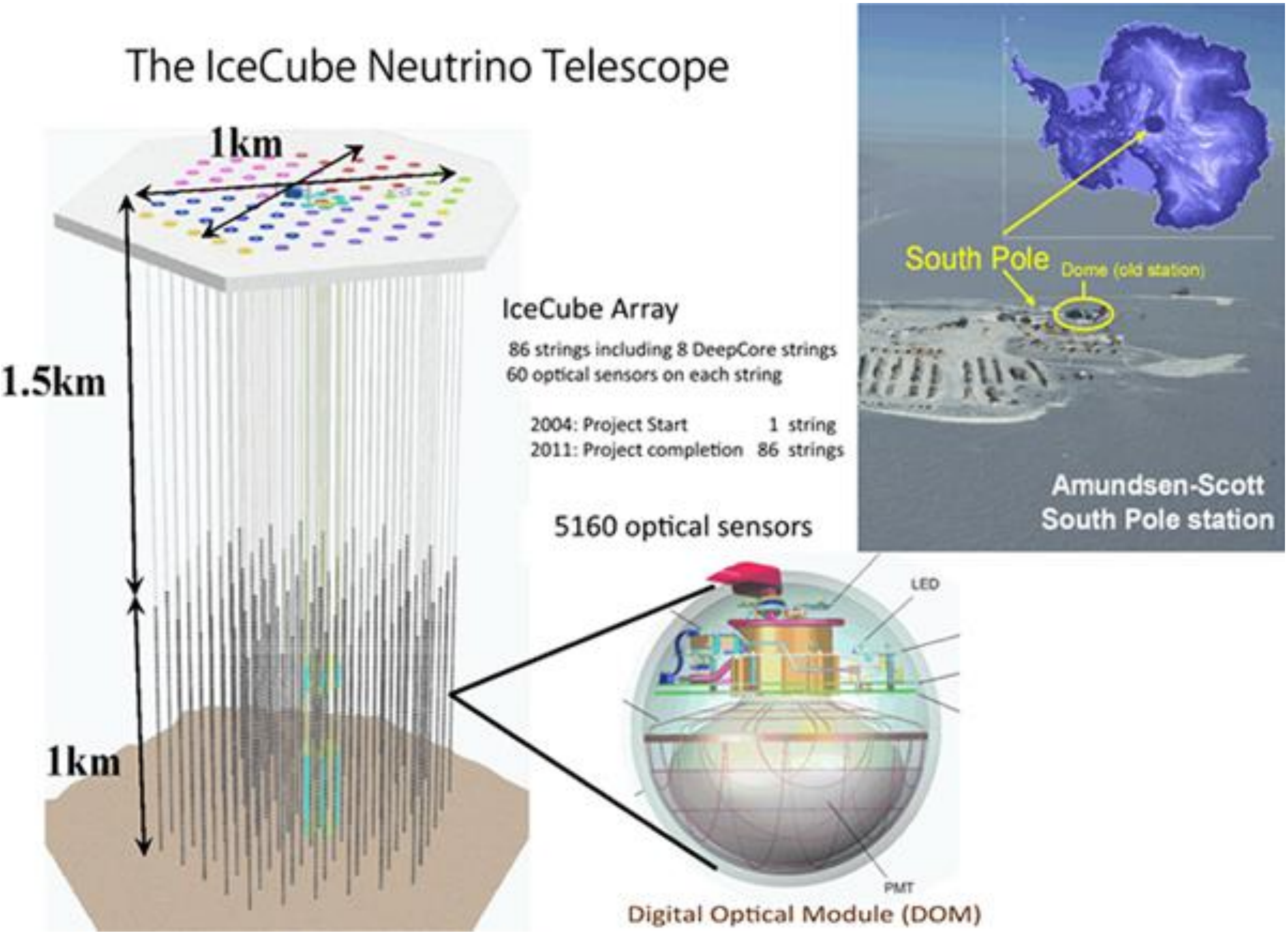
SK is a cylindrical tank containing 50000 ton of light water surrounded by photomultipliers, located underground in the Kamioka mine in Japan.

Simulated Supernova Signal at Super-Kamiokande



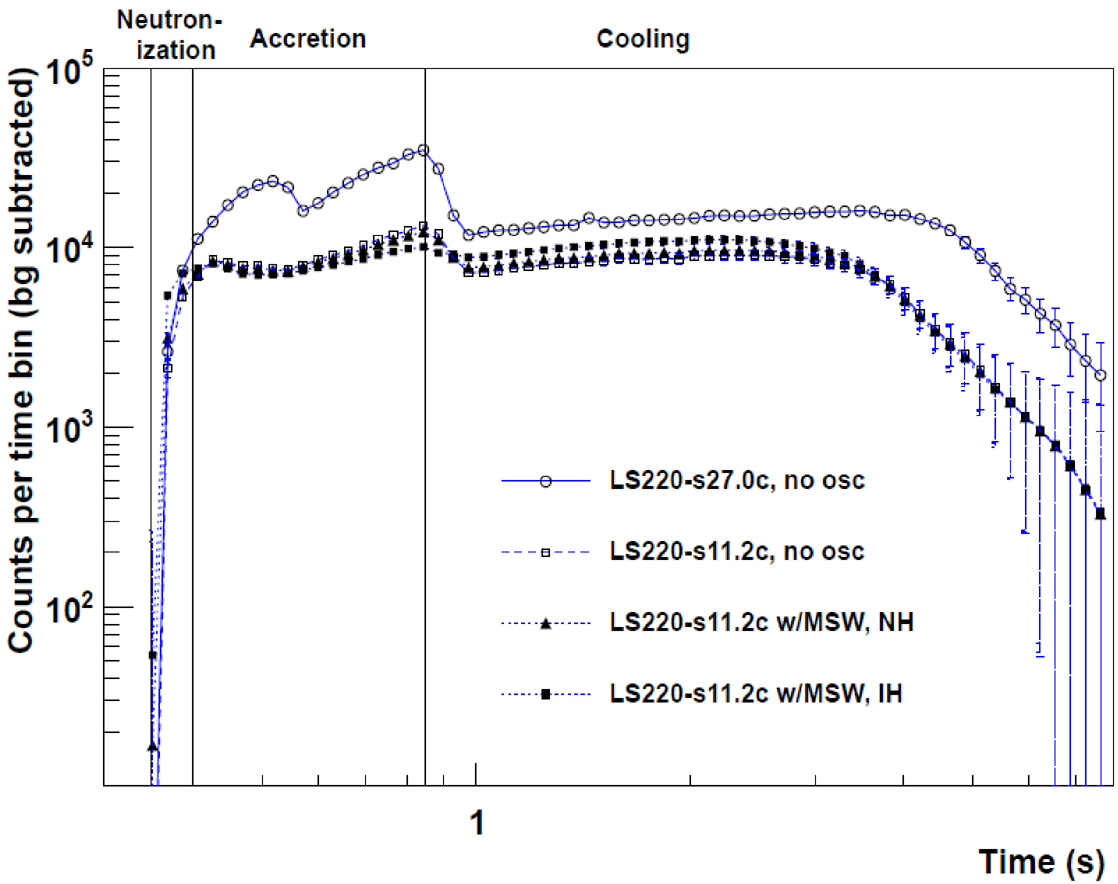
Simulation for Super-Kamiokande SN signal at 10 kpc,
based on a numerical Livermore model
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

ICECUBE NEUTRINO TELESCOPE AT SOUTH POLE



SN NU SIGNAL IN ICECUBE

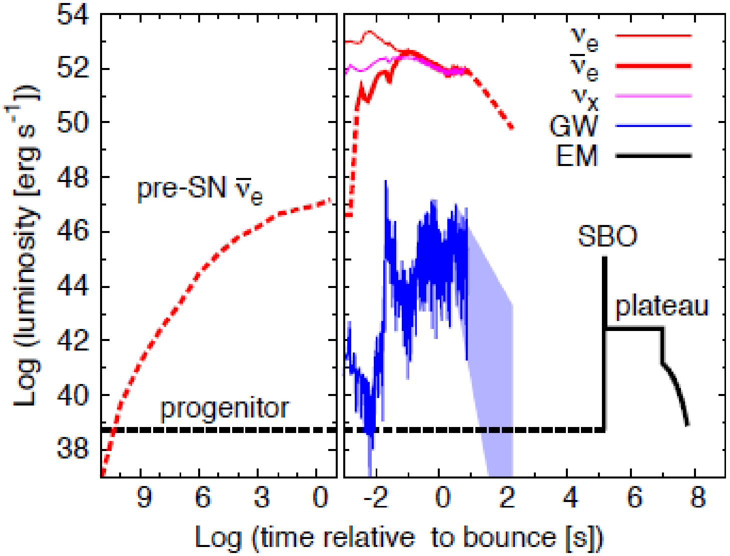
[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]



High statistics reconstruction of the nu light curve. Possible to distinguish the different post-bounce phases.

MILLISECOND BOUNCE TIME RECONSTRUCTION

External trigger for GW search



ICECUBE

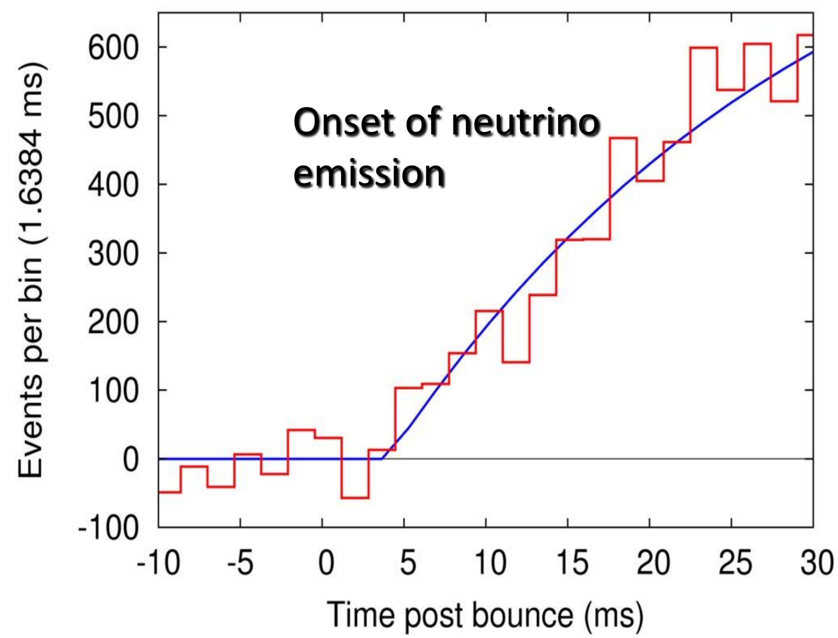
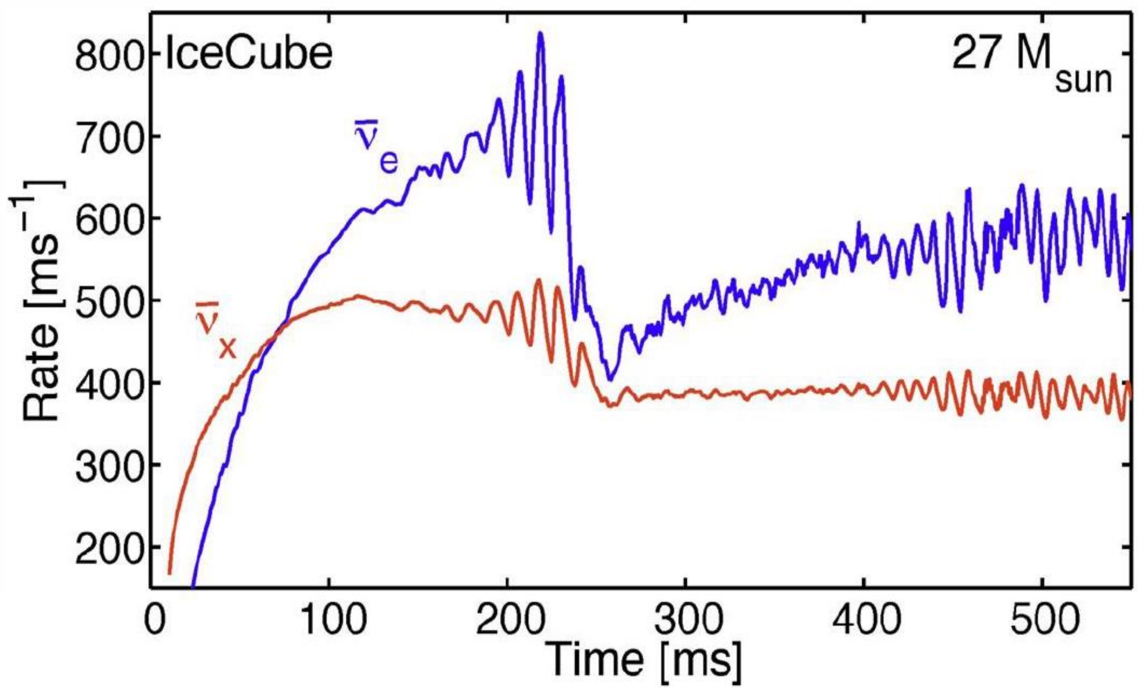


FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

[Halzen & Raffelt, arXiv:0908.2317]

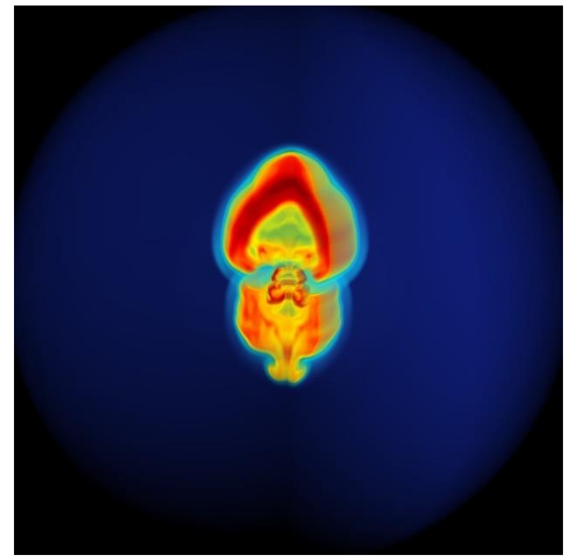
Possible also in Super-K
[see Pagliaroli, Vissani, Coccia & Fulgione arXiv:0903.1191]

SHORT TIME VARIATIONS IN SN ν SIGNAL



Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936

Convective motions lead to large-amplitude oscillations of the stalled shock with a period of ~ 10 ms



Necessary high statistics and high time resolution

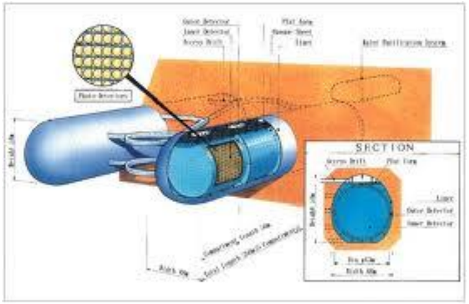
Icecube is ok!

NEXT-GENERATION DETECTORS

Mton scale water Cherenkov detectors

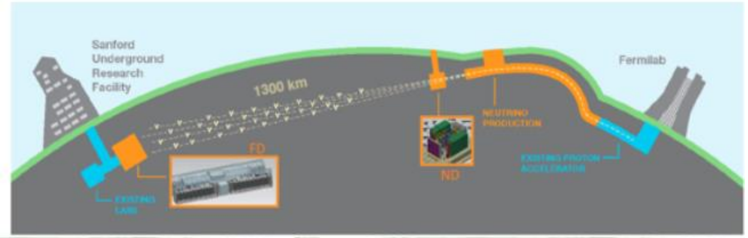
(10^5 events) $(\bar{\nu}_e)$

HYPER-KAMIOKANDE



40 kton Liquid Argon TPC

(3000 events) (ν_e)



DUNE

Dark matter detectors

DARWIN

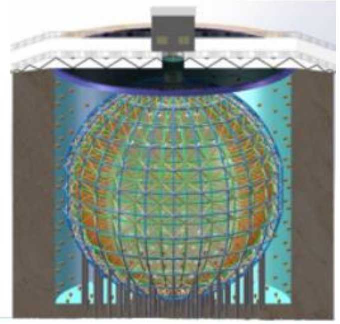
40 tons

(700 events)

$(\nu_{e,x}, \bar{\nu}_{e,x})$

20 kton scintillator

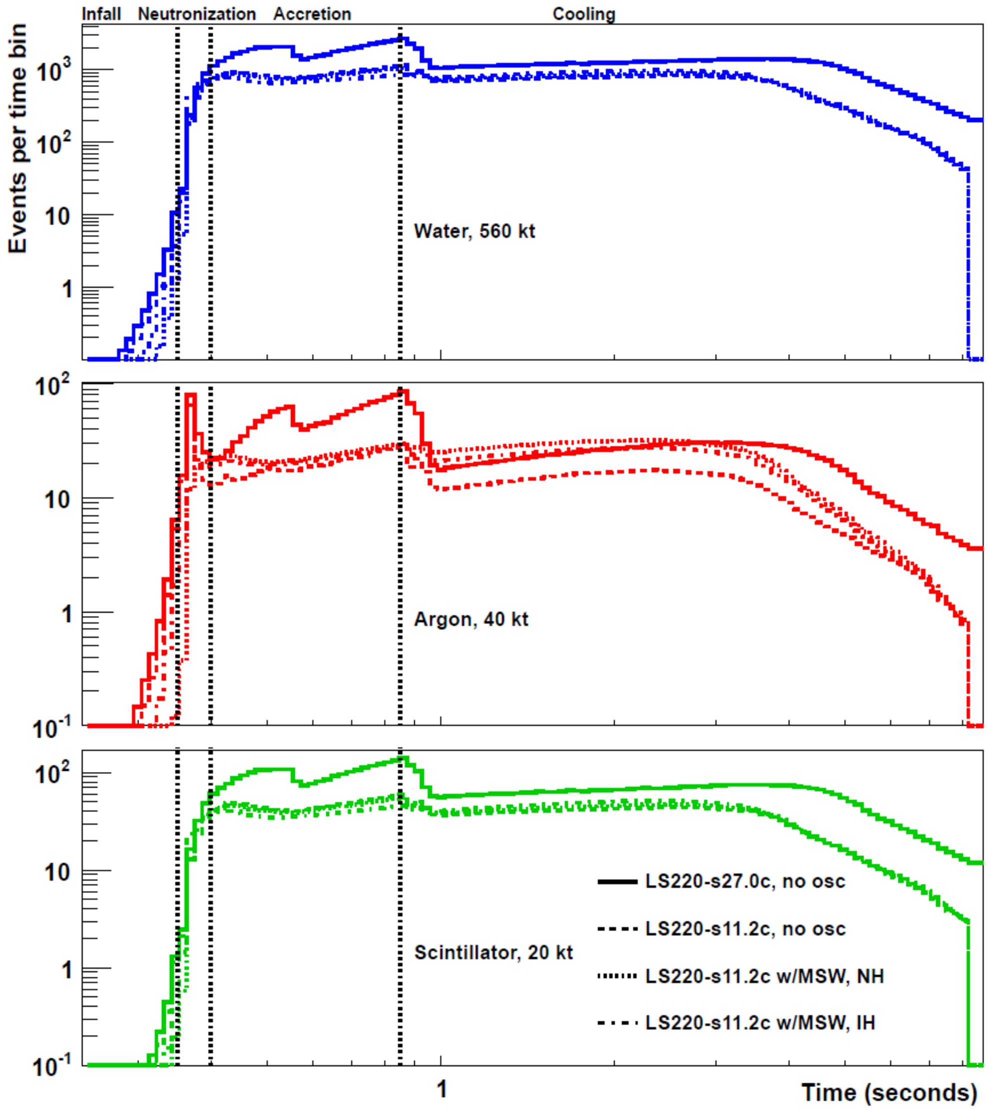
(6000 events) $(\bar{\nu}_e)$



JUNO

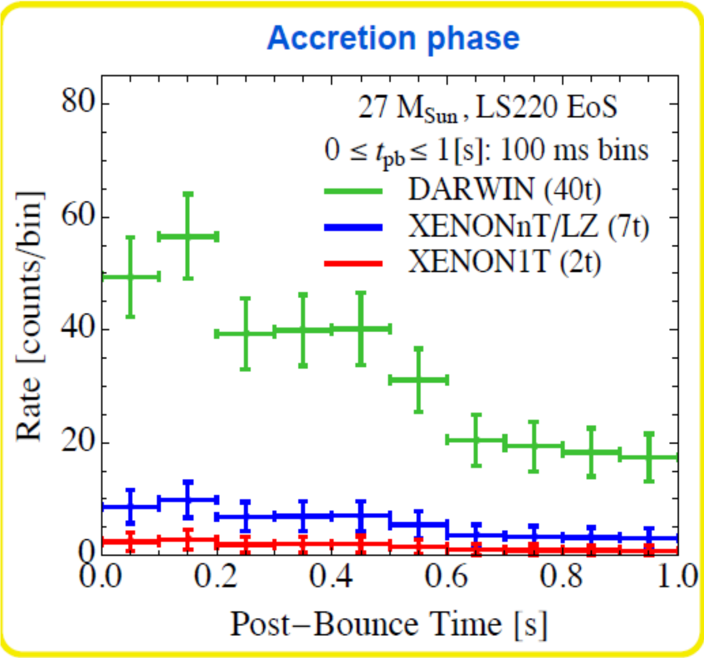
SN NU SIGNAL IN FUTURE DETECTORS

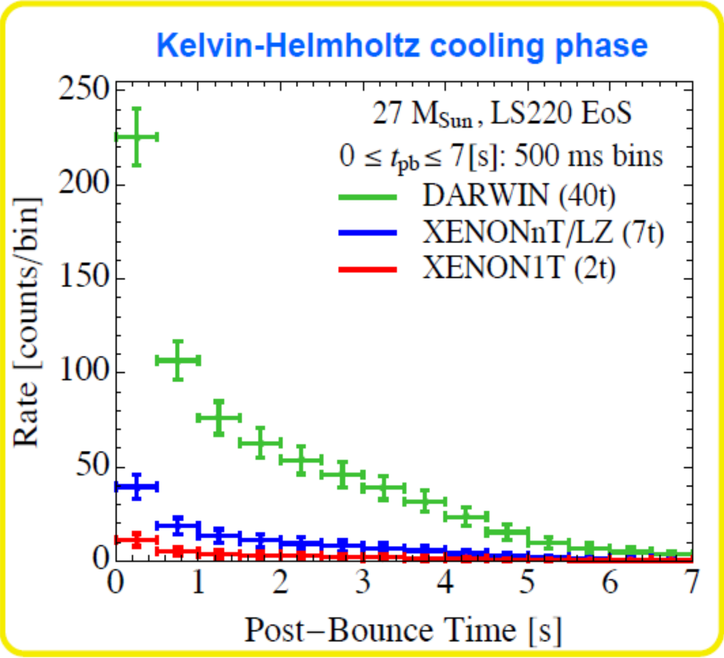
[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]



SN NU SIGNAL IN DM DETECTORS

[Lang,McCabe, Reichard, Selvi & Tamborra, arXiv:1606.09243 [astro-ph.HE]]





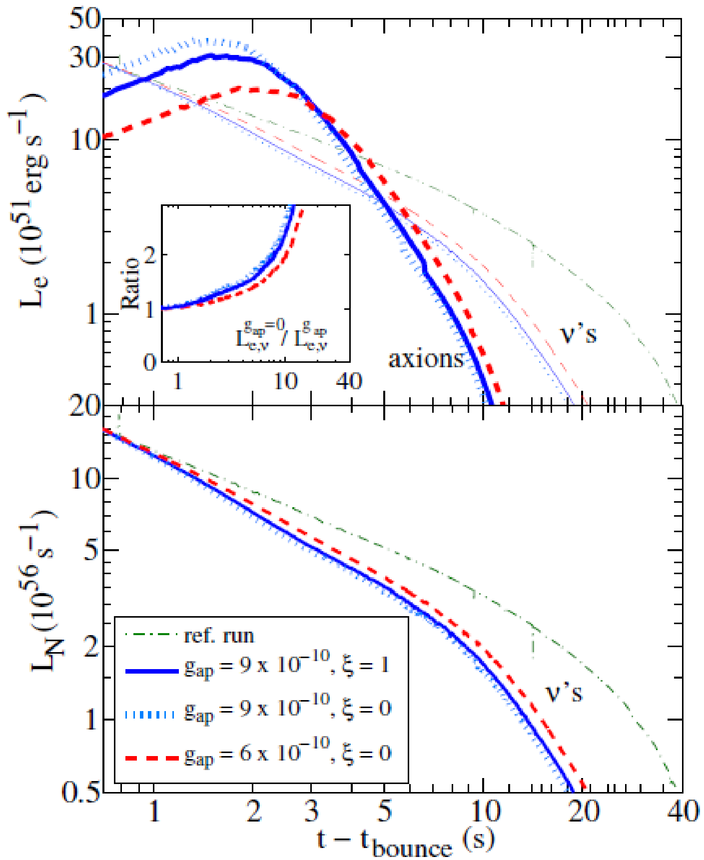
DARWIN will be able to clearly reconstruct the neutrino light-curve and to differentiate among phases of neutrino signal. Partial sensitivity with XENONnT/LZ.

A REAPPRAISAL OF AXION EMISSION WITH STATE OF ART SIMULATIONS

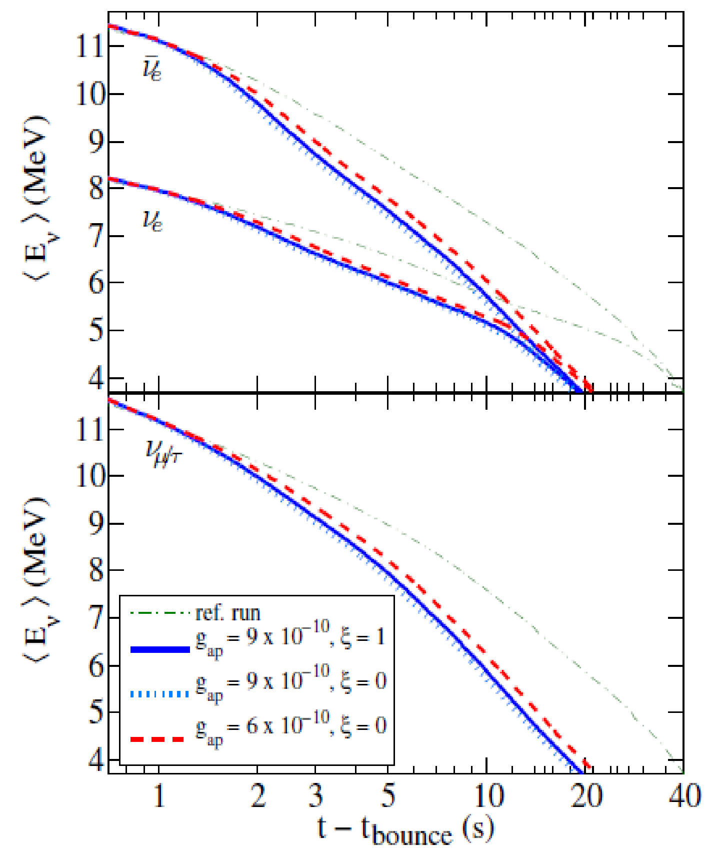
[Fischer, Chakraborty, Giannotti A.M. , Payez & Ringwald, 1605.08780]

18 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)



(a) Energy and number luminosities

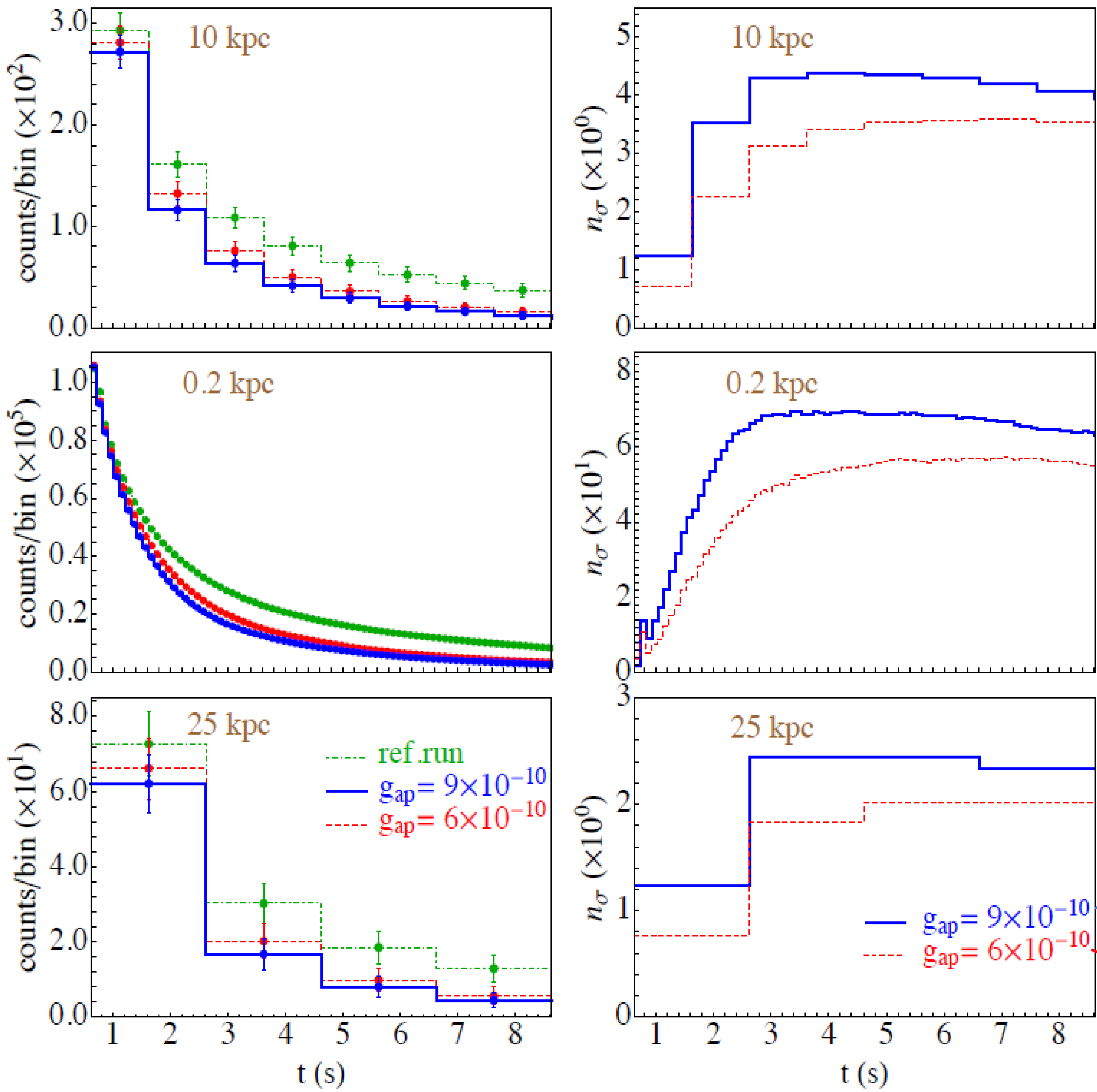


(b) Average neutrino energies

KSVZ hadronic axion model (g_{an} =0)

IMPACT ON NEUTRINO SIGNAL

@ Super-Kamiokande



(~ GC)

(Betelgeuse)

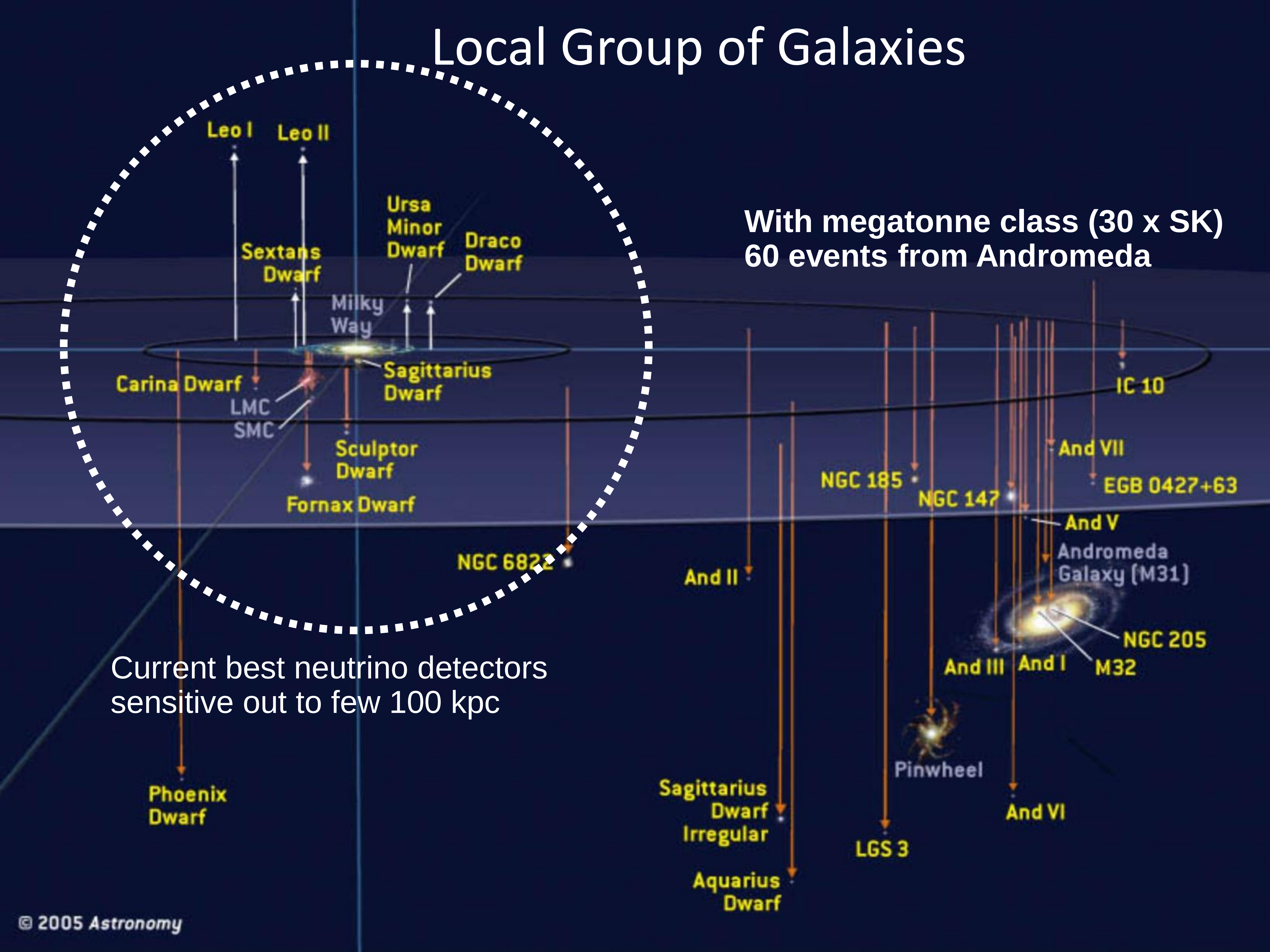
$m_a = 3 \times 10^{-2}\, eV,$
$f_a = 4.8 \times 10^{8} GeV$

$m_a = 8 \times 10^{-2}\, eV,$
$f_a = 7.3 \times 10^{8} GeV$

NEUTRINOS FROM ALL COSMIC SUPERNAVAE

Local Group of Galaxies

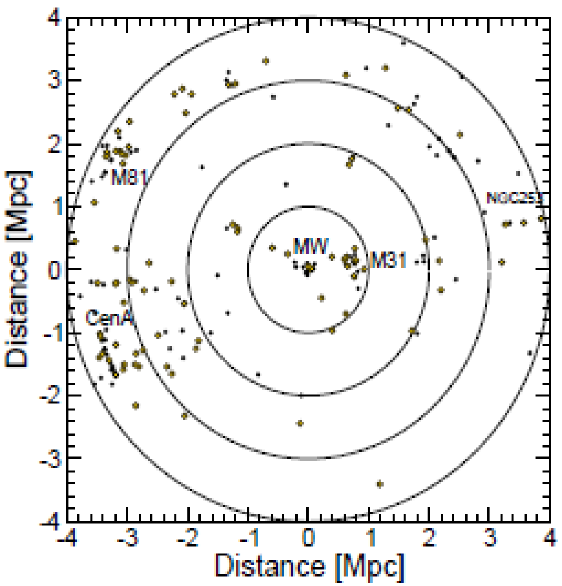
With megatonne class (30 x SK) 60 events from Andromeda

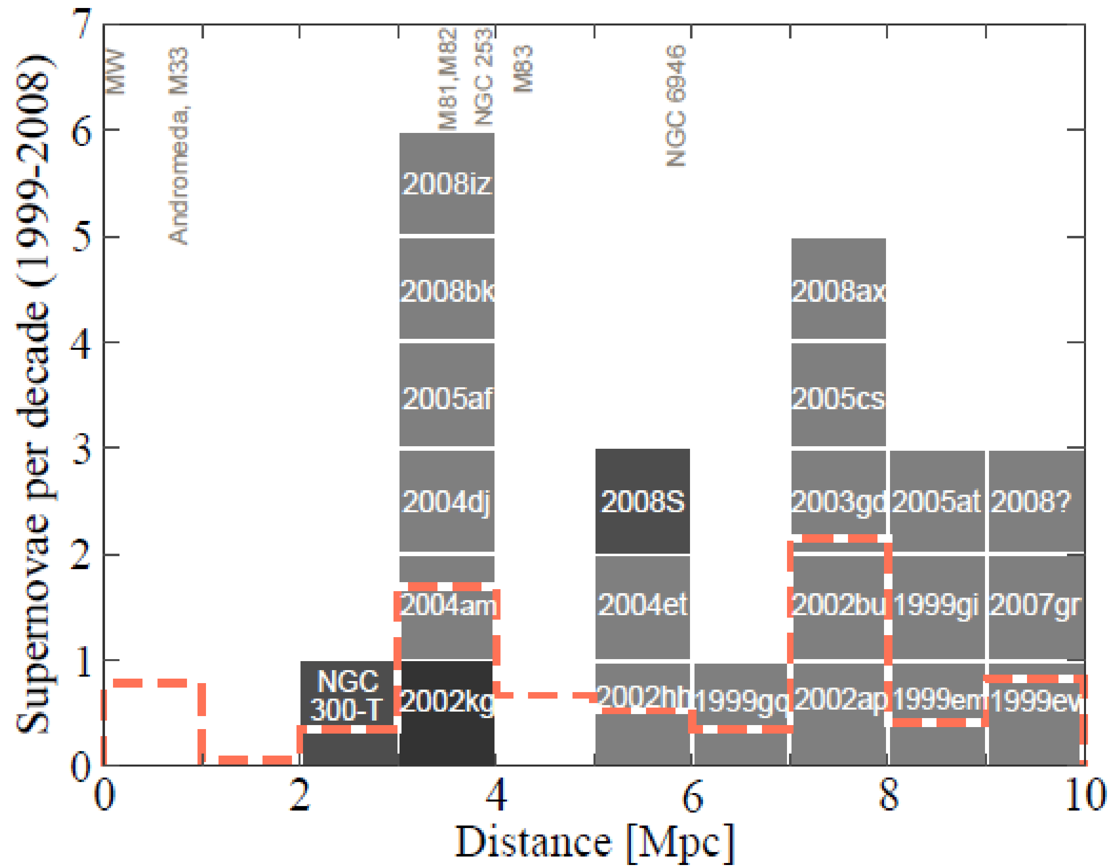


Current best neutrino detectors sensitive out to few 100 kpc

OBSERVED SUPERNOVAE IN THE LOCAL UNIVERSE

[Kistler, Yuksel, Ando, Beacom & Suzuki, 0810.1959]



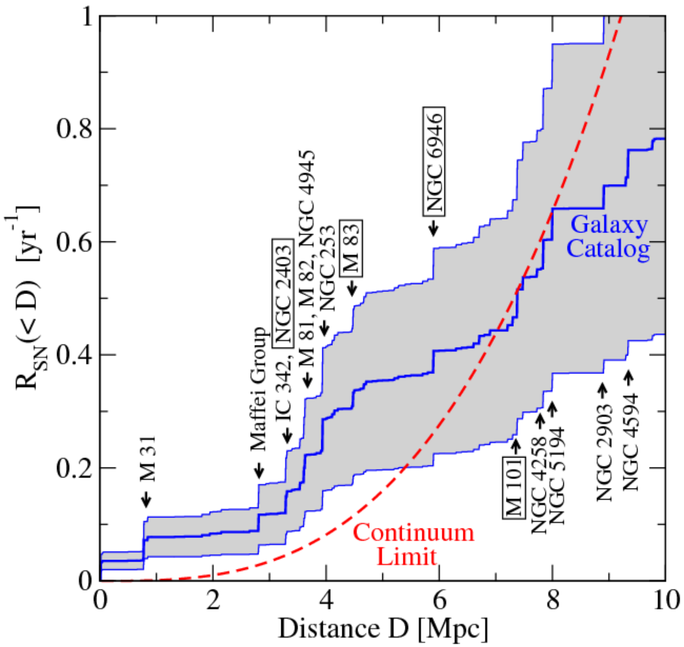


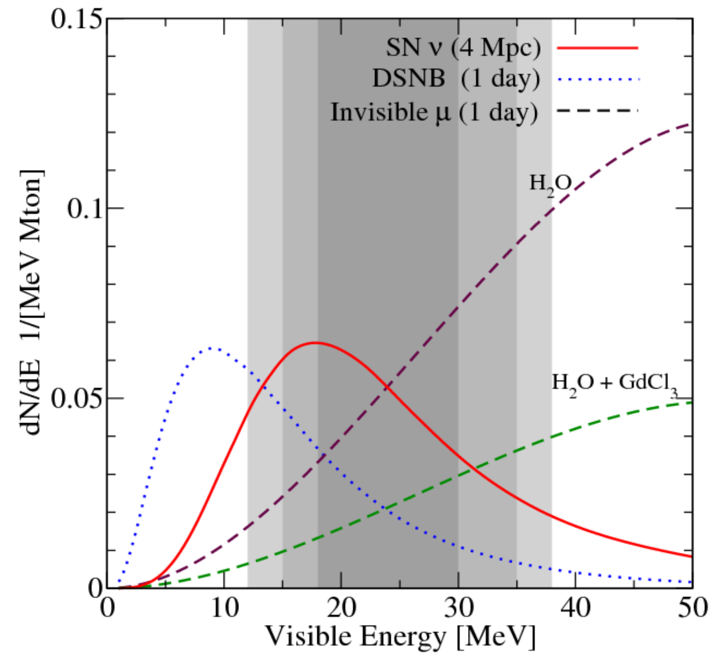
● Detection of Neutrinos from Supernovae in Nearby Galaxies

[S. Ando, J. Beacom, and Y. Yuksel, astro-ph/0503321]

Mton Cherenkov

Cumulative SN rate





Reconstruction of SN neutrino spectrum by the patient accumulation of ~1 neutrino per supernova from galaxies within 10 Mpc, in which one expects at least 1(2) SN per year.

NEUTRINO EVENTS RATE FROM EXTRAGALACTIC SNe

[Kistler et al., 0810:1959]

TABLE I: Approximate neutrino event yields for core-collapse supernovae from representative distances and galaxies, as seen in various detectors with assumed fiducial volumes. Super-Kamiokande is operating, and Hyper-Kamiokande and Deep-TITAND are proposed.

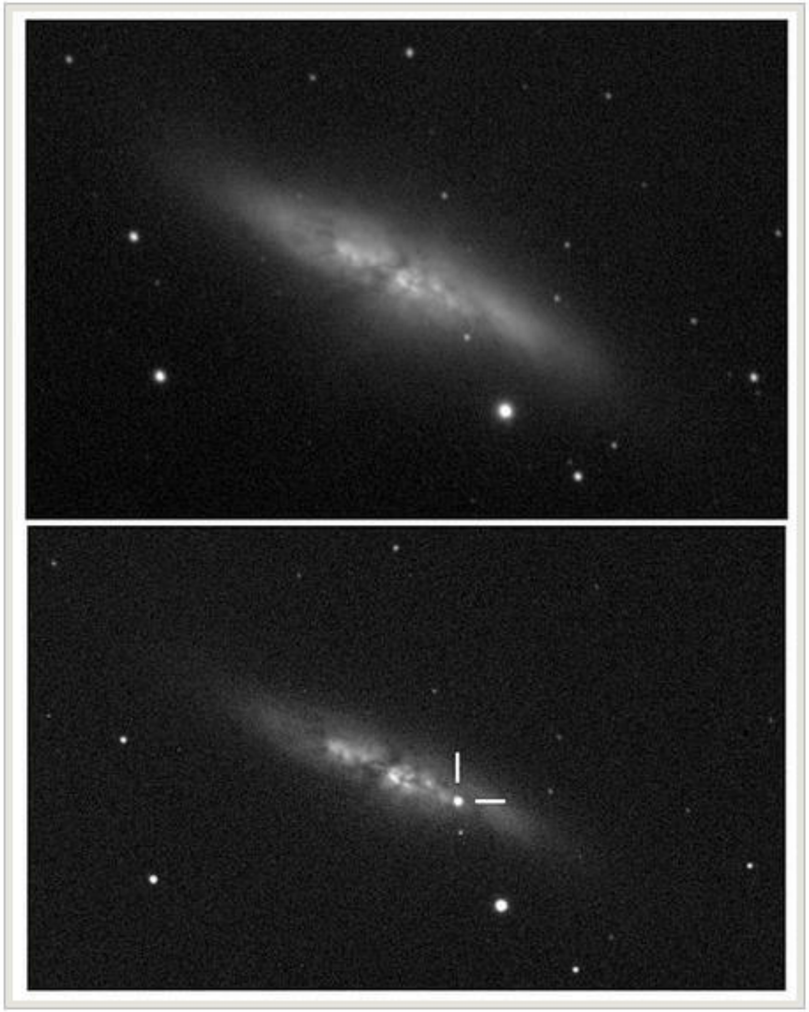
		32 kton (SK)	0.5 Mton (HK)	5 Mton (Deep-TITAND)
10 kpc	(Milky Way)	10^4	10^5	10^6
1 Mpc	(M31, M33)	1	10	10^2
3 Mpc	(M81, M82)	10^{-1}	1	10

TABLE II: Core-collapse supernova candidates from 1999-2008 within 6 Mpc, with their expected neutrino event yields ($E_{e^+} > 18$ MeV) in a 5 Mton detector.

SN	Type	Host	D [Mpc]	ν events
2002hh	II-P	NGC 6946	5.6	2.4
2002kg	IIn/LBV	NGC 2403	3.3	6.8
2004am	II-P	NGC 3034 (M82)	3.53	5.9
2004dj	II-P	NGC 2403	3.3	6.8
2004et	II-P	NGC 6946	5.6	2.4
2005af	II-P	NGC 4945	3.6	5.7
2008S	IIn	NGC 6946	5.6	2.4
2008bk	II-P	NGC 7793	3.91	4.8
2008iz	II?	NGC 3034 (M82)	3.53	5.9
NGC 300-T	II?	NGC 300	2.15	16.0

Supernova Explosion in M82: Exciting, but No Neutrinos

22 Jan. 2014



The M82 galaxy before (top) and after (bottom) its new supernova on Jan. 22 (Photo: UCL/University of London Observatory/Steve Fossey/Ben Cooke/Guy Pollack/Matthew Wilde/Thomas Wright)

By Erin Weeks

In the early morning hours of January 22, the Earth turned spectator to a celestial event the likes of which hadn't been seen in nearly three decades. The explosive death of a white dwarf star in Messier 82 (M82), a nearby galaxy, quickly ignited the astronomy world.

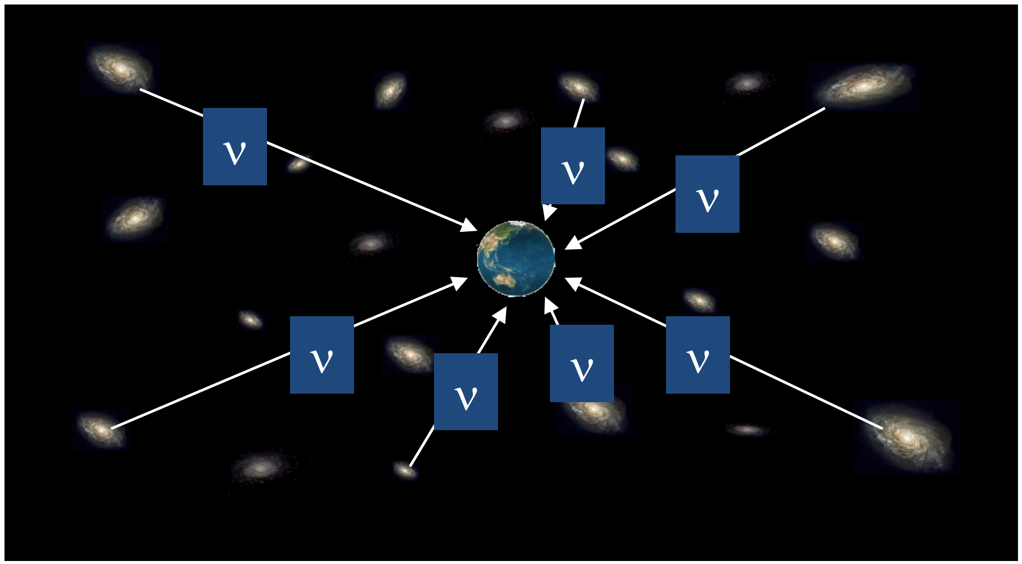
The supernova is exciting for a number of reasons that other outlets have well outlined — but unfortunately for Kate Scholberg, neutrinos are not one of them. Scholberg, a Duke University physics professor, studies the mysterious, nearly-massless particles at Super-K, a detector located deep in the mountains of Japan. Super-K was designed to spot neutrinos as they speed through Earth, revealing information about their sources, which can include the sun, cosmic rays, and supernovae.

"M82 is too far away for us to see any neutrinos from it," Scholberg wrote in an email. "It's about 11.4 million light years from us, meaning that the chance of seeing even a single neutrino from a core-collapse supernova in current detectors is probably a few percent or less (of course, we'll look)."

A galactic SN explosion is a spectacular event which will produce an enormous number of detectable ν, but it is a rare event (~ 3/century) …

.... Conversly, there is a guaranteed ν background produced by all the past Supernovae in the Universe, but leading to much less detectable events.

THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND (DSNB)



WHAT CAN WE LEARN FROM DSNB?

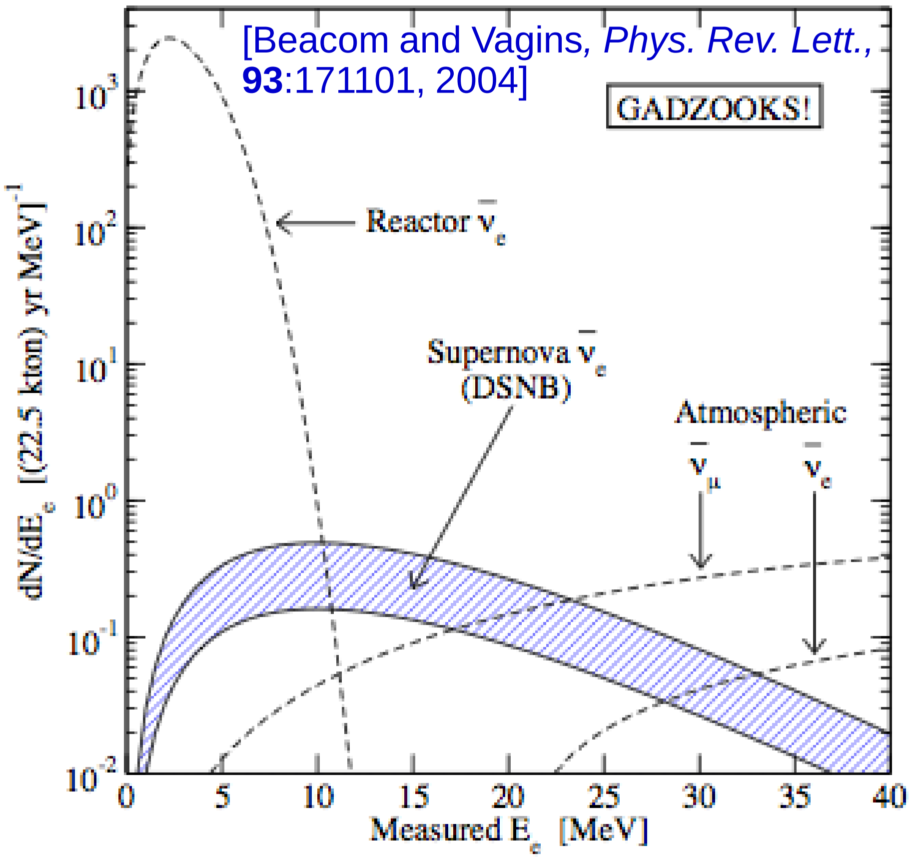
In principle, we can extract information on:

- Star formation rate
- Neutrino masses and mixing parameters
- SN neutrino energies

… not all at the same time, however!

(degeneracy of effects)

BACKGROUND IN SK FOR DSNB SIGNAL



Below ~15–20 MeV, bkgd dominated by spallation products (made by atmospheric μ) and by reactor $\bar{\nu}_e$.

For $E_\nu \in$ [20-30] MeV, the bkg of low-energy atmospheric $\bar{\nu}_e$ is relatively small.

But, in this window, there is a large background due to "invisible" μ (i.e. below Cherenkov emission threshold) decay products, induced by low energy atmospheric ν_μ and $\bar{\nu}_\mu$.

DSNB signal should manifest as distortion of the bkg spectra.

No distortion $\longrightarrow$ flux limit

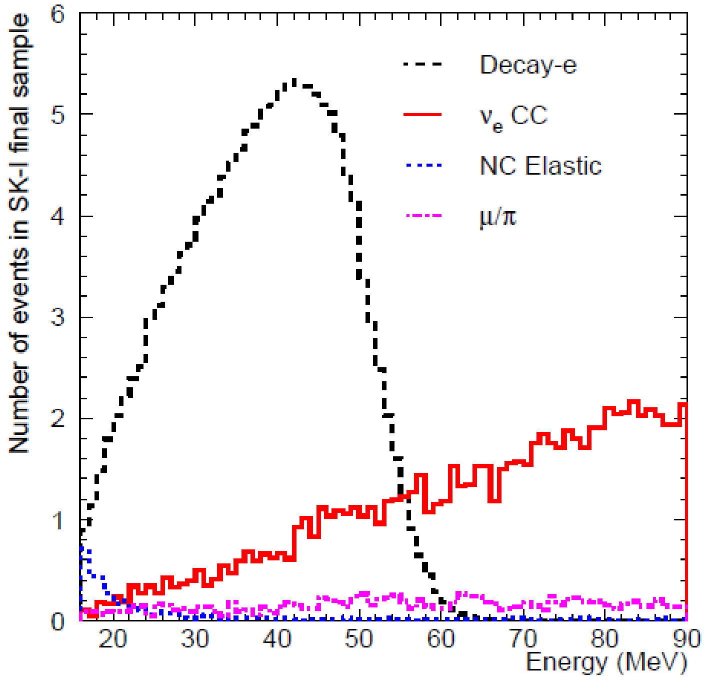


FIG. 11. Spectra of the four remaining backgrounds in the signal Cherenkov angle region with all reduction cuts applied. The ν_μ CC channel is from decay electron data; the other three are from MC. All are scaled to the SK-I LMA best fit result.

DSNB signal should manifest as distortion of the bkg spectra.

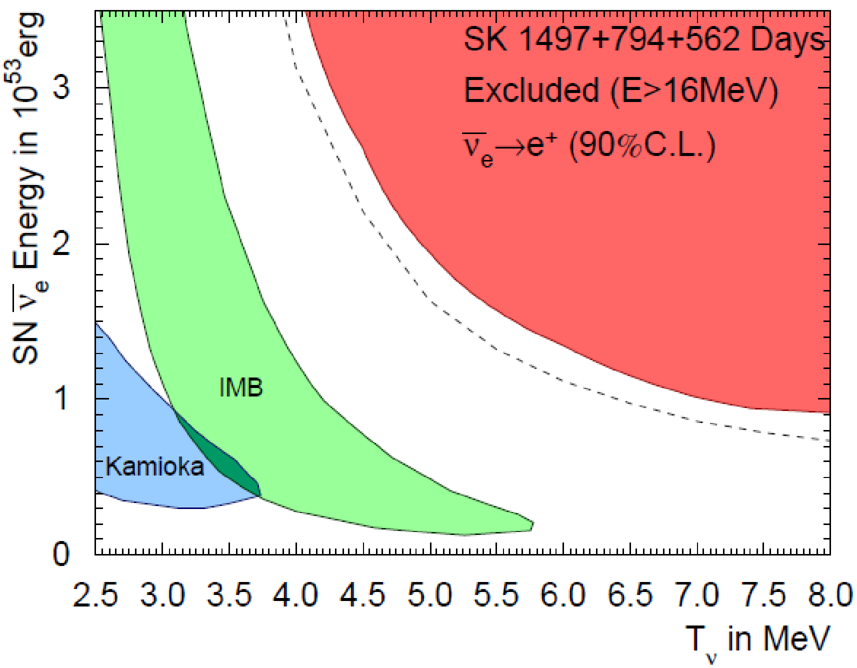
No distortion ⟶ flux limit

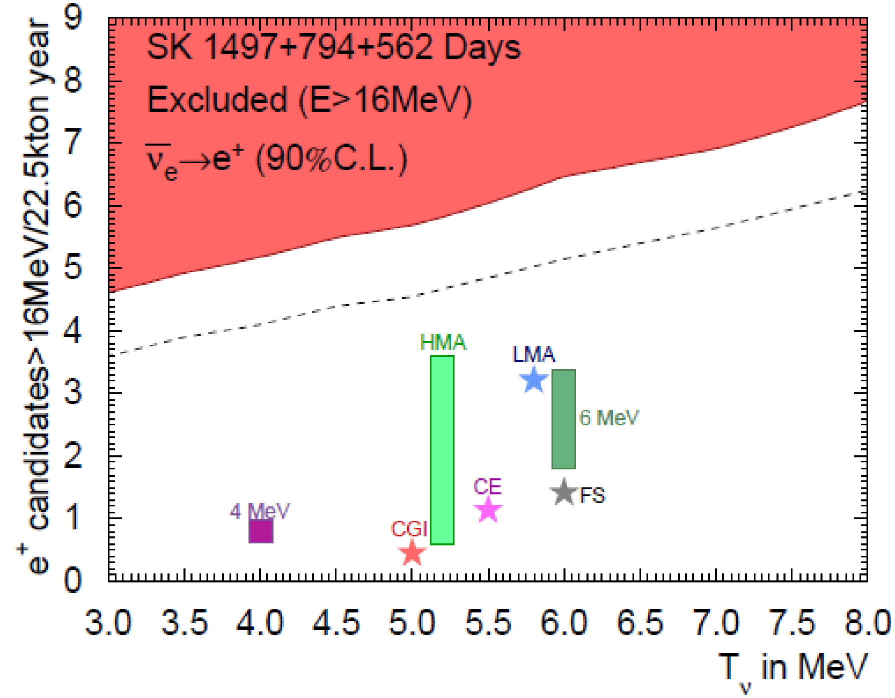
Super-Kamiokande collaboration recently investigated the DSNB flux using 2853 days of data [Bays et al., arXiV:1111:5031]. It fixed an upper bound on DSNB signal:

$$J_{\bar{\nu}_e} \leq 3 \text{ cm}^{-2} \text{ s}^{-1}$$

SN NEUTRINO EMISSION LIMIT FROM DSNB

[*Bays et al., arXiV:1111.5031, see also Vissani & Pagliaroli, 1102.0447*]



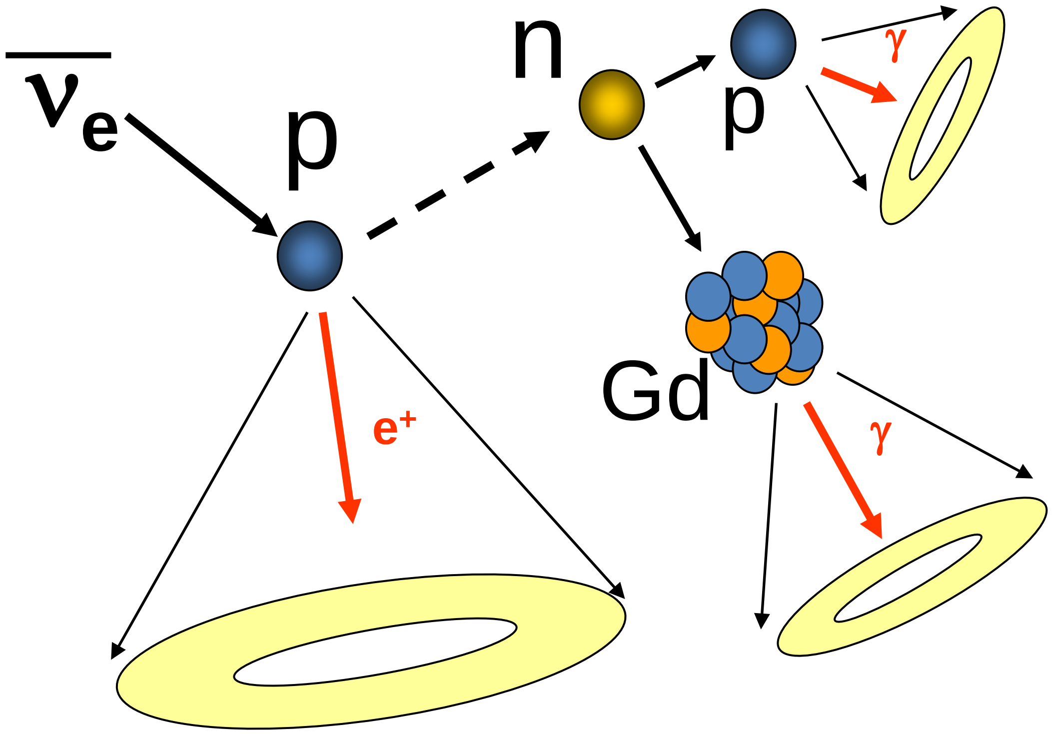


The SK limit is close to the most recent theoretical predictions

… but
Super-K is background limited.

SK-Gd Project

Neutron tagging in Gd-enriched WC Detector



Possibility 1: 10% or less

$n+p \rightarrow d + \gamma$

2.2 MeV γ-ray

Possibility 2: 90% or more

$n+Gd \rightarrow \sim 8\,\mathrm{MeV}\ \gamma$

$\Delta T = \sim 30\ \mu\mathrm{sec}$

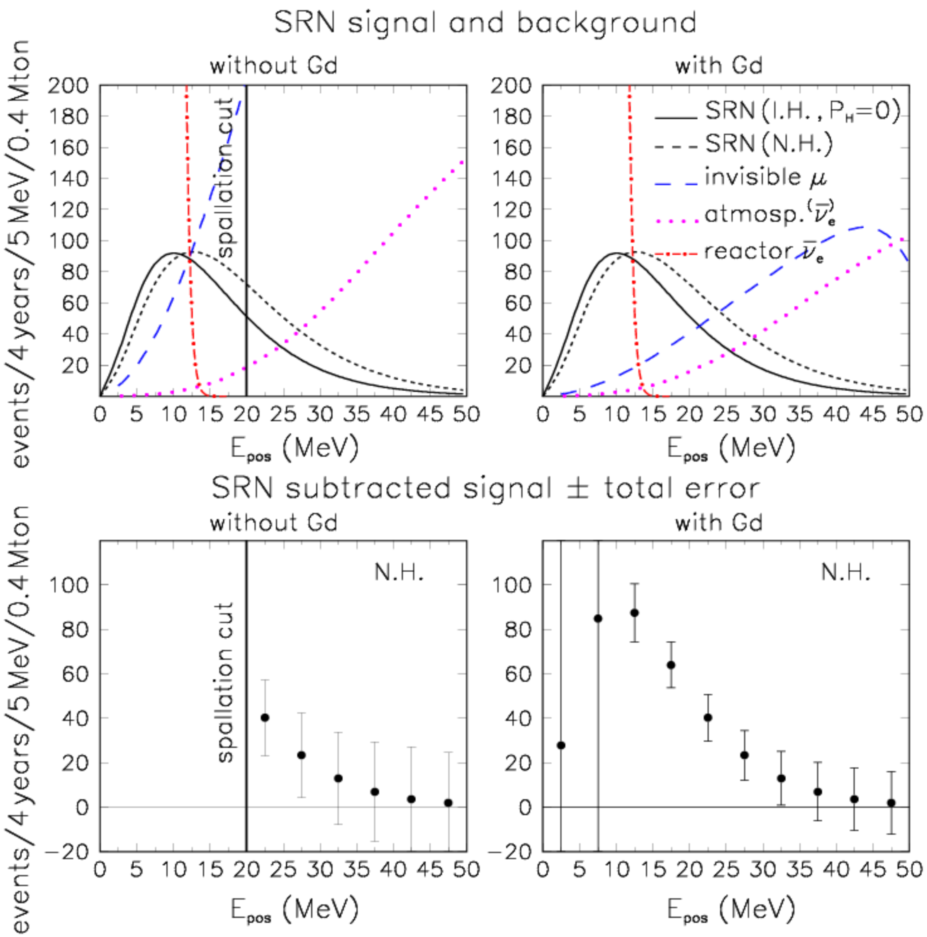
Positron and gamma ray vertices are within ~50cm.

$\bar{\nu}_e$ can be identified by delayed coincidence.

[reaction schematic by M. Nakahata]

[G.L.Fogli, E.Lisi, A.M., and D.Montanino, hep-ph/0412046]

Mton Cherenkov



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But, in this window, there is a large background due to "invisible" μ (i.e. below Cherenkov emission threshold) decay products, induced by low energy atmospheric ν_μ and $\bar{\nu}_\mu$.

Adding Gd [J.F.Beacom, and M.R.Vagins, hep-ph/0309300], spallation ~eliminated, invisible μ reduced by ~5. The analysis threshold lowered.

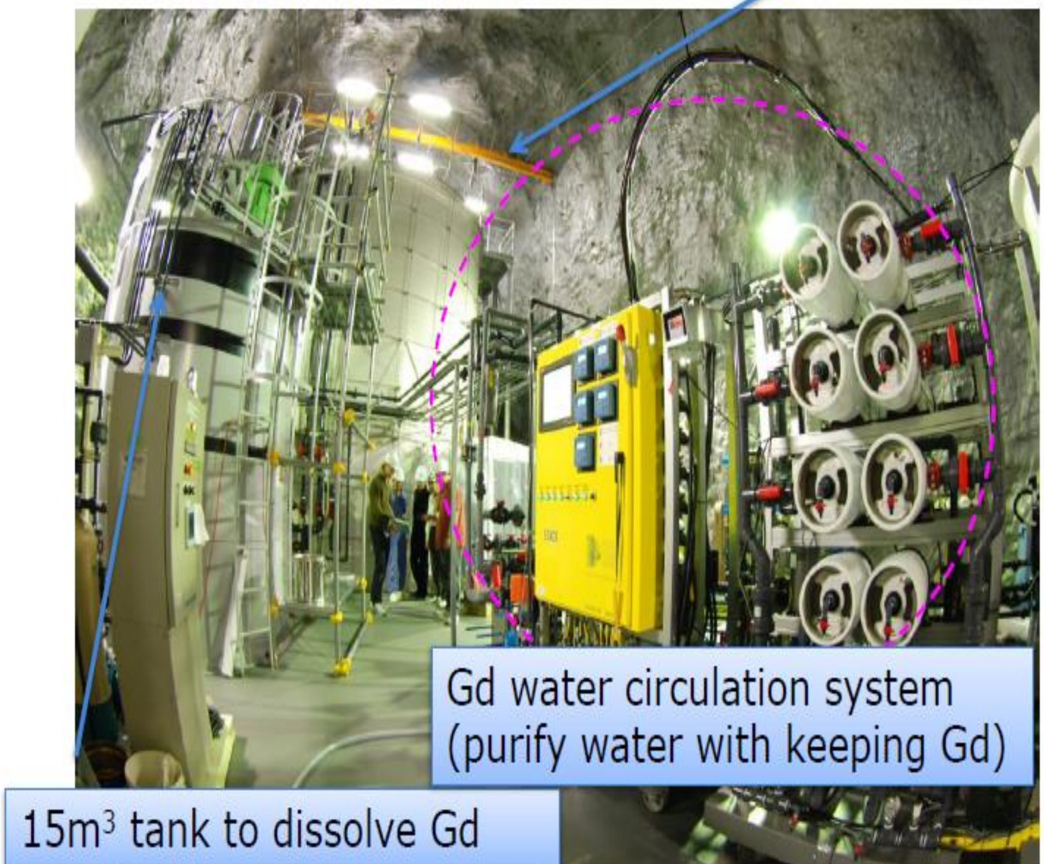
A few clean events/y in Super-K with Gd !

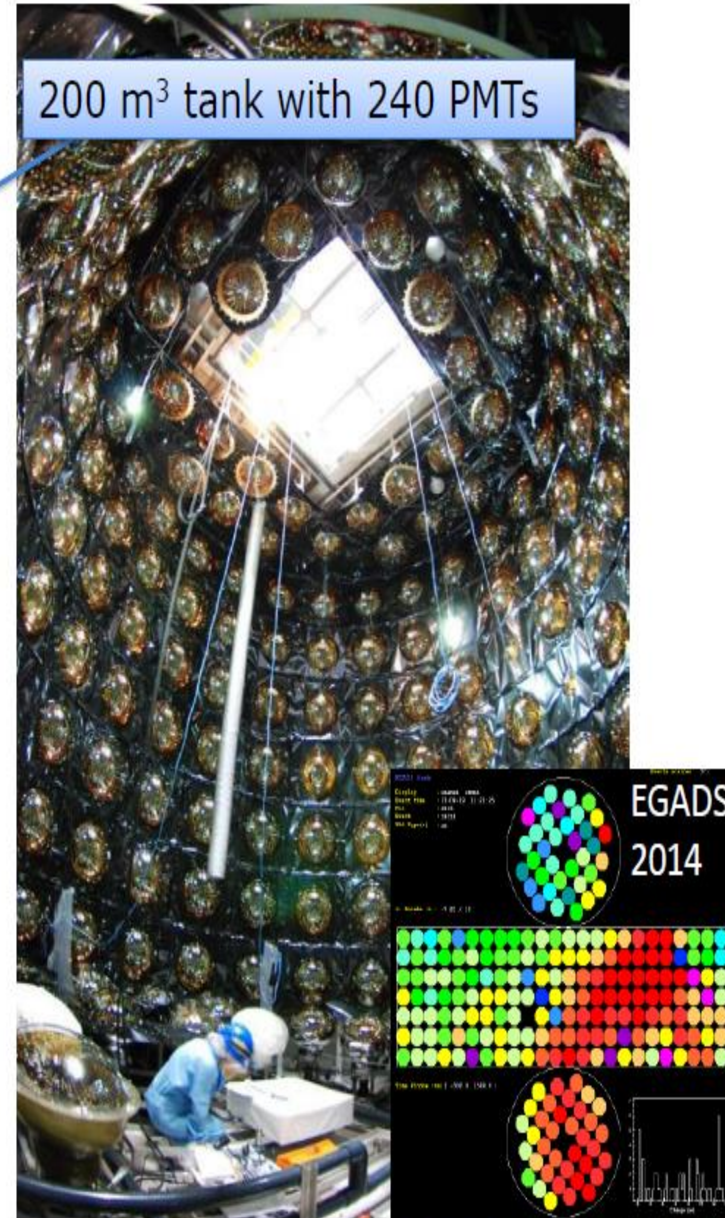
In HK after 1 year, the DSNB signal detectable at 6σ level

EGADS

Evaluating Gadolinium's Action on Detector Systems

- To study the Gd water quality with actual detector materials.
- The detector fully mimic Super-K detector;
  SUS frame, PMT and PMT case, black sheets, etc.
- Tests for Hyper-K;   13 HPDs





SK & T2K Joint Statement on "SK-Gd"

- Jan.30, 2016

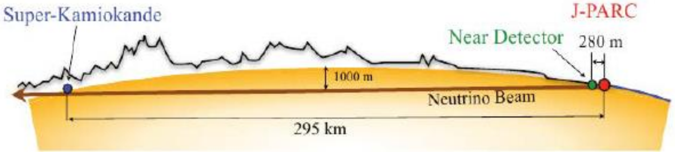
On June 27, 2015, the Super-Kamiokande collaboration approved the SK-Gd project which will enhance neutrino detectability by dissolving gadolinium in the Super-K water.

T2K and SK will jointly develop a protocol to make the decision about when to trigger the SK-Gd project, taking into account the needs of both experiments, including preparation for the refurbishment of the SK tank and readiness of the SK-Gd project, and the T2K schedule including the J-PARC MR power upgrade. Given the currently anticipated schedules, the expected time of the refurbishment is 2018.

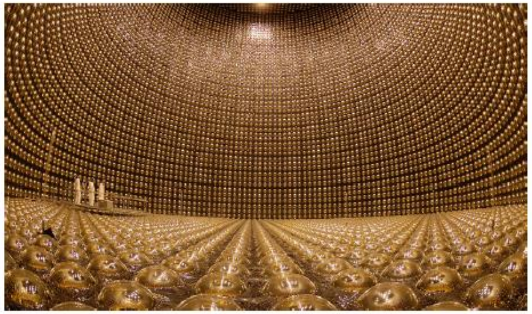
After years of testing and study
– culminating in these powerful EGADS results –
no technical showstoppers have been encountered. And so…

June 27, 2015: The Super-Kamiokande Collaboration approved the addition of gadolinium to the detector, pending discussions with T2K.

January 30, 2016: The T2K Collaboration approved addition of gadolinium to Super-Kamiokande, with the precise timing to be jointly determined based on the needs of both projects.



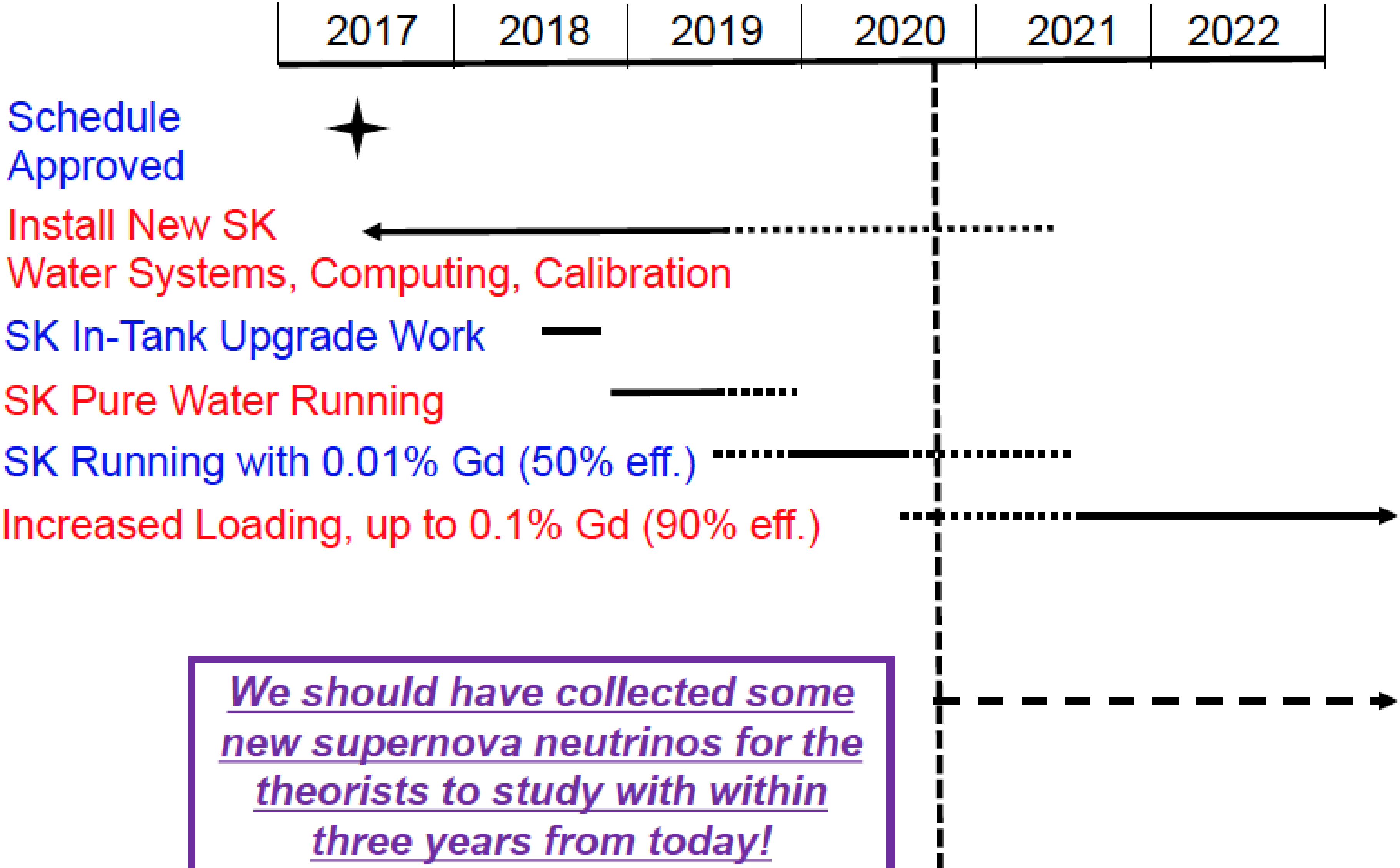
July 26, 2017: The official start time of draining the SK tank to prepare for Gd loading is decided to be <u>June 1, 2018</u>.



Slide from Mark Vagins

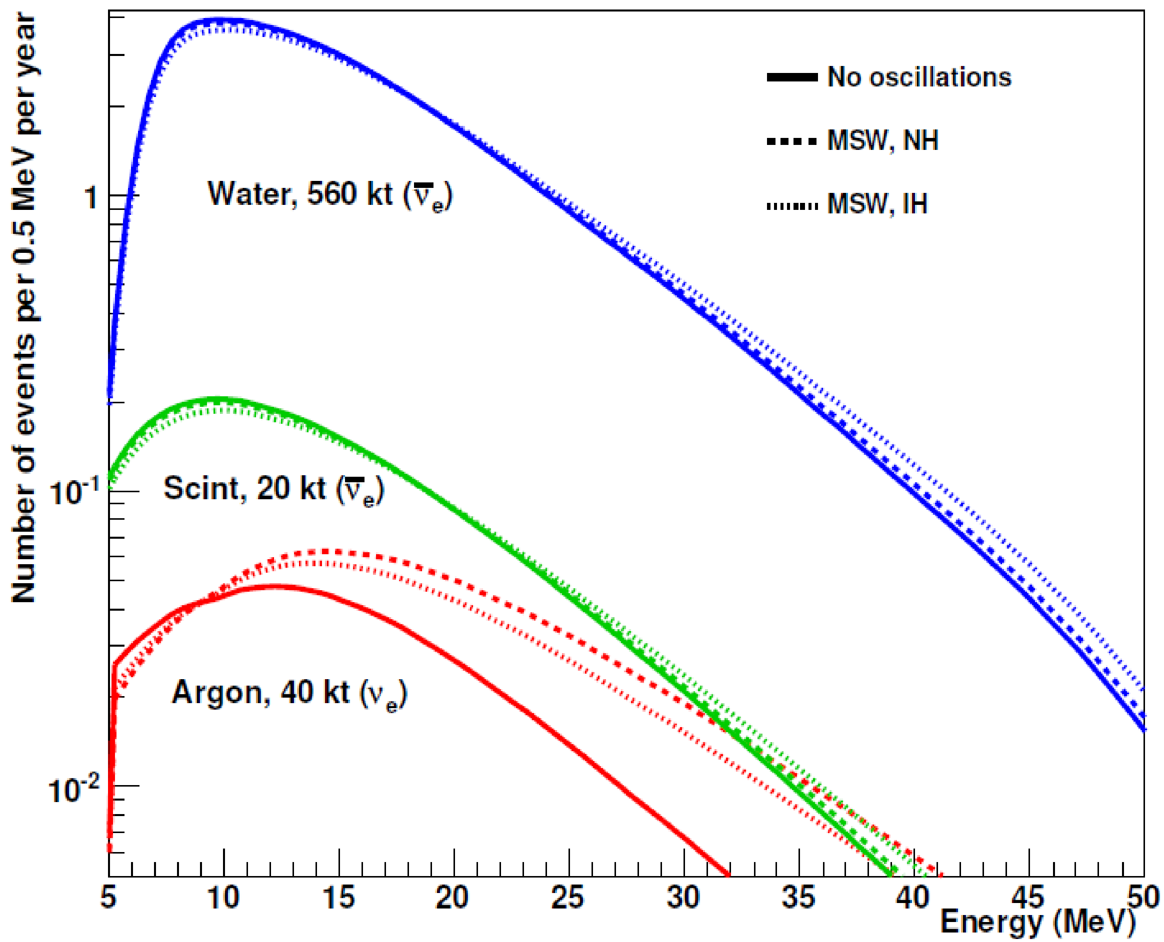
Hall G being filled with equipment for the gadolinium loading of Super-Kamiokande; January 30th, 2017

Expected timeline for SK-Gd



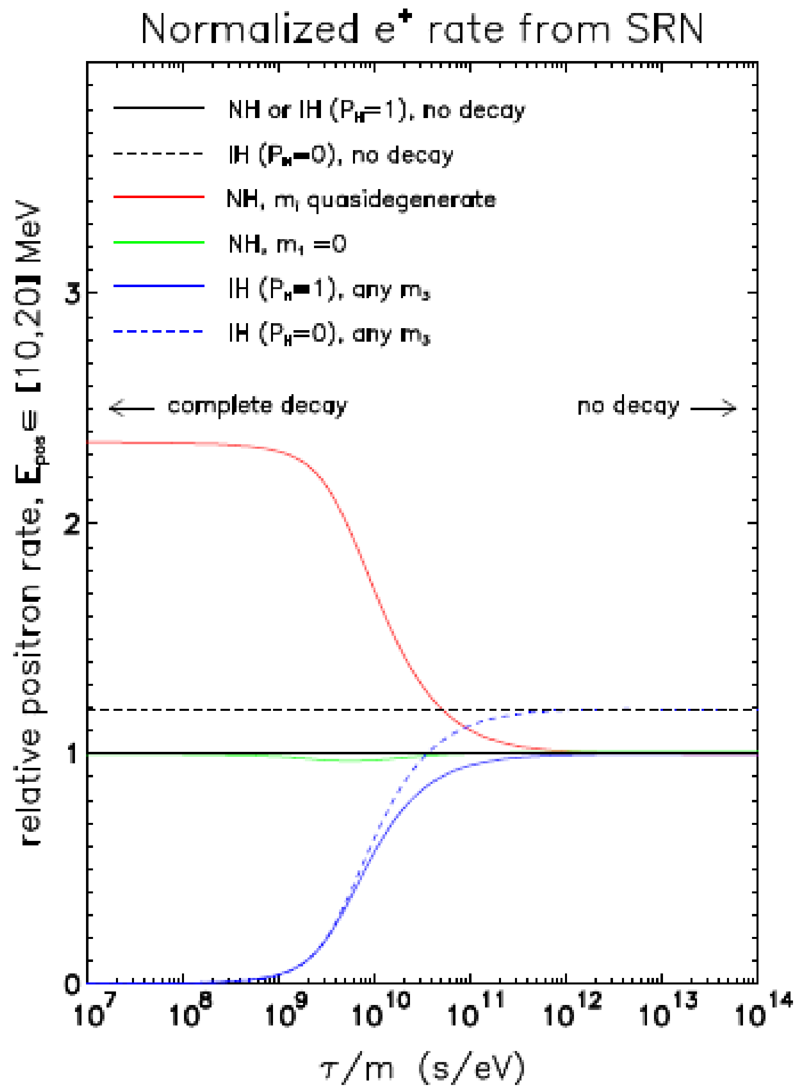
DSNB IN LARGE FUTURE DETECTORS

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]



CONSTRAINT OF NU INVISIBLE DECAY FROM DSNB

[Fogli, Lisi, A.M., Montanino, hep-ph/0401227]

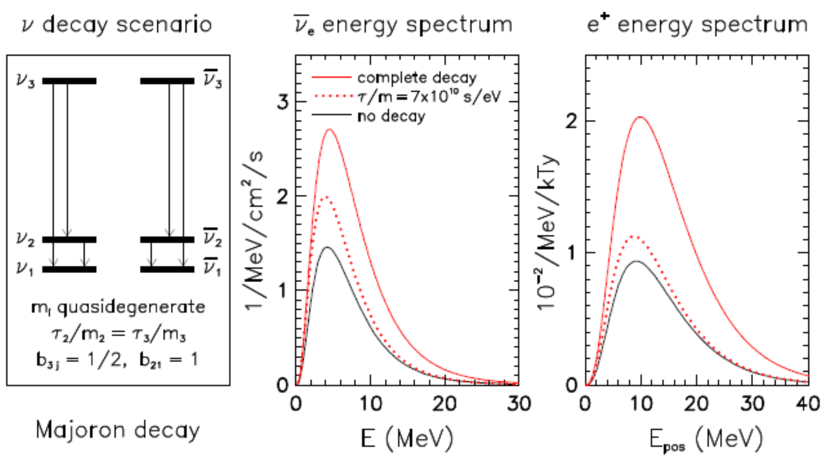


Nu decay in Majoron

$$\nu \rightarrow \nu' + \phi$$

DSNB can probe lifetimes of cosmological interest

$$\frac{\tau_i E}{m_i} \leq 1/H_0$$



DSNB spectrum larger, comparable or smaller than the standard one

SN NEUTRINO FLAVOR CONVERSIONS

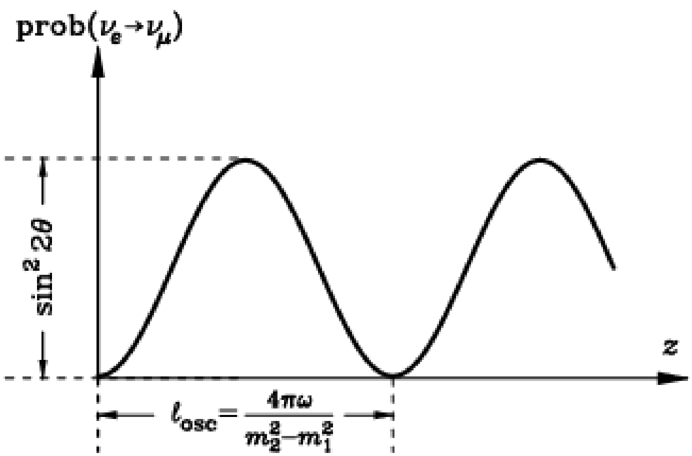
VACUUM OSCILLATIONS

- **Two flavor mixing** $$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Each mass eigenstates propagates as **e^ipz** with $p_i = \sqrt{E^2 - m^2} \approx E - \frac{m_i^2}{2E}$

$$\left|\nu_\mu(z)\right\rangle = -\sin\theta\, e^{-ip_1 z}\left|\nu_1\right\rangle + \cos\theta\, \mathrm{e}^{-\mathrm{ip}_2 z}\left|\nu_2\right\rangle$$

- **2 ν oscillation probability** $$P(\nu_e \to \nu_\mu) = \left|\left\langle \nu_\mu(z) \middle| \nu_e(0)\right\rangle\right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Bruno Pontecorvo (1967)

Dubna 1988. Neutrino oscillations.

SN ν FLAVOR TRANSITIONS

The flavor evolution in matter is described by the non-linear MSW equations:

$$i\frac{d}{dx}\psi_\nu = \left(H_{vac} + H_e + H_{\nu\nu}\right)\psi_\nu$$

In the standard 3ν framework

- $$H_{vac} = \frac{U\ M^2\ U^\dagger}{2E}$$ Kinematical mass-mixing term
- $$H_e = \sqrt{2}G_F\,\mathrm{diag}(N_e, 0, 0)$$ Dynamical MSW term (in matter)
- $$H_{\nu\nu} = \sqrt{2}G_F\int(1-\cos\theta_{pq})\left(\rho_q - \bar{\rho}_q\right)dq$$ Neutrino-neutrino interactions term (non-linear)

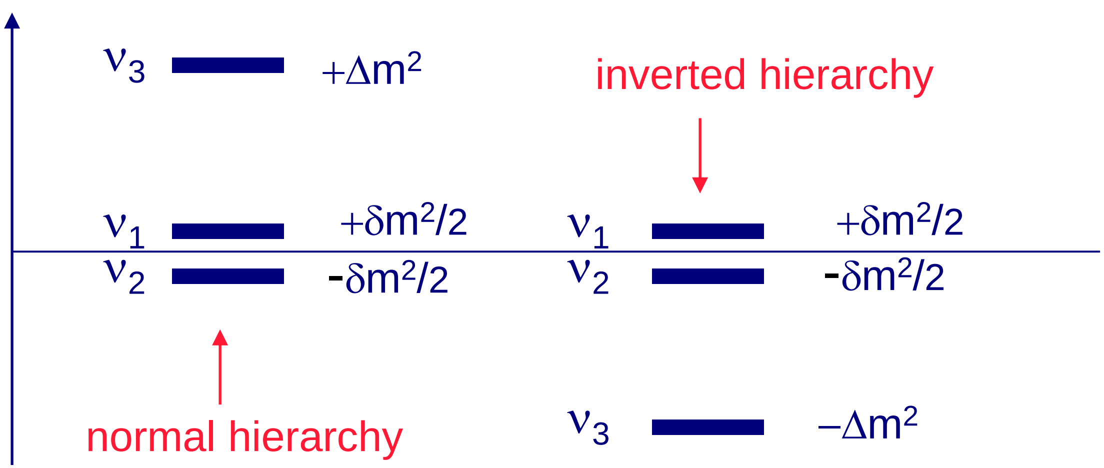
3ν FRAMEWORK

- **Mixing parameters:** $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ as for CKM matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{-i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

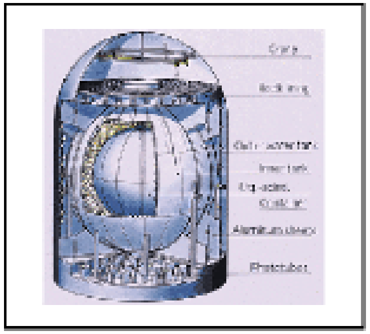
$c_{12} = \cos\theta_{12}$, etc., δ CP phase

- **Mass-gap parameters:** $M^2 = \left[\underbrace{-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}}_{\text{"solar"}}, \underbrace{\pm \Delta m^2}_{\text{"atmospheric"}}\right]$



SN neutrinos are sensitive to the unknown mass hierarchy

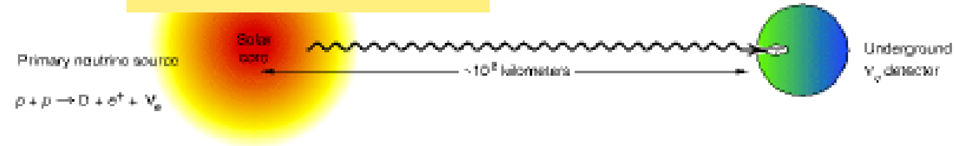
STATUS OF NEUTRINO OSCILLATIONS



Reactors: KAMLAND

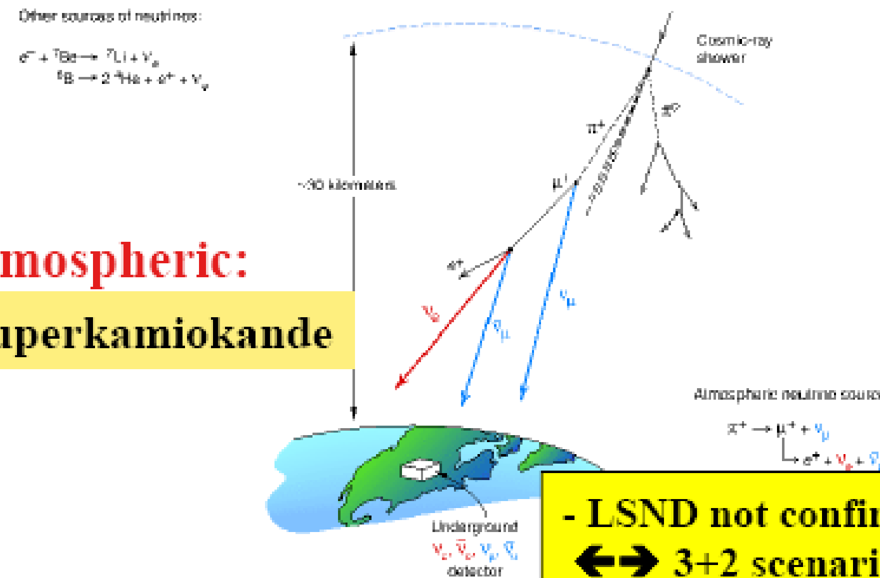
Beams: K2K → MINOS
→ OPERA

solar: GALLEX/GNO → SK, SNO



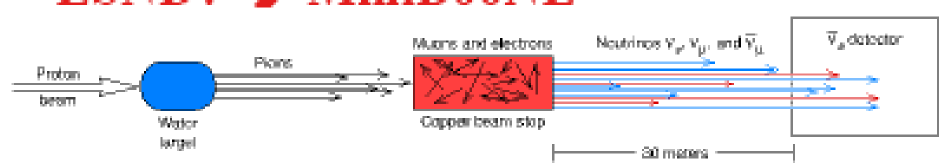
atmospheric:

Superkamiokande



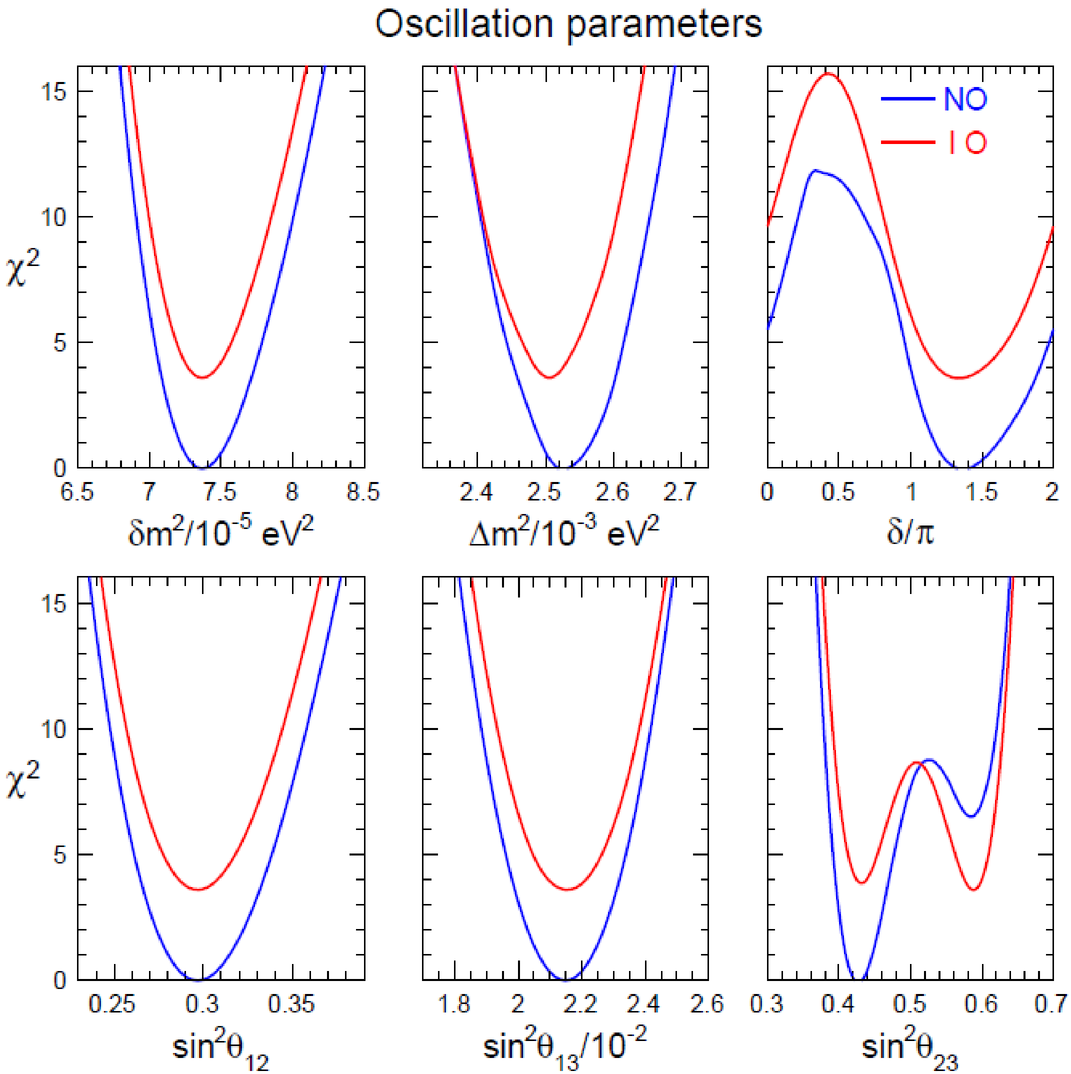
- LSND not confirmed !
↔ 3+2 scenarios?
- upturn at low E ?

LSND? → MiniBooNE



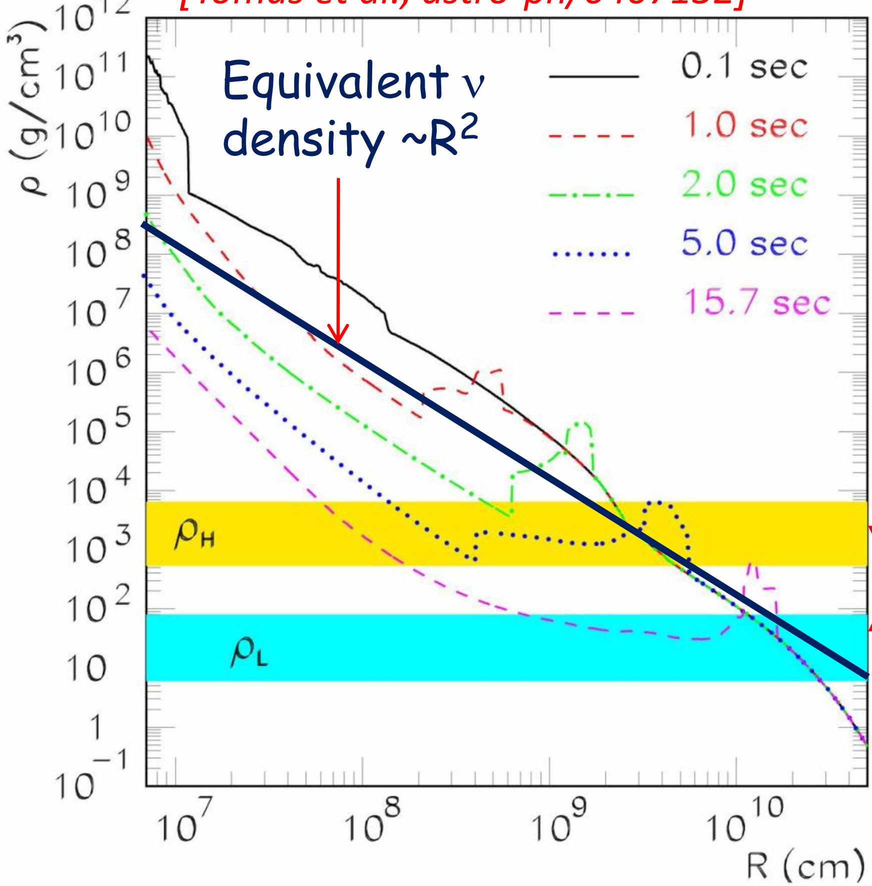
GLOBAL OSCILLATION ANALYSIS (2017)

[Capozzi et al., arXiv:1703.0447]



SNAPSHOT OF SN DENSITIES

[Tomas et al., astro-ph/0407132]



- Matter bkg potential

$$\lambda = \sqrt{2} G_F N_e \quad \sim R^{-3}$$

- ν–ν interaction

$$\mu = \sqrt{2} G_F n_\nu \quad \sim R^{-2}$$

- Vacuum oscillation frequencies

$$\omega = \frac{\Delta m^2}{2E}$$

When $\mu \gg \lambda$, SN ν oscillations dominated by ν-ν interactions

Collective flavor transitions at low-radii [O (10² – 10³ km)]

Collective Supernova Nu Oscillations since 2006

Two seminal papers in 2006 triggered a torrent of activities

Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

Balantekin, Gava & Volpe [0710.3112]. Balantekin & Pehlivan [astro-ph/0607527]. Blennow, Mirizzi & Serpico [0810.2297]. Cherry, Fuller, Carlson, Duan & Qian [1006.2175, 1108.4064]. Cherry, Wu, Fuller, Carlson, Duan & Qian [1109.5195]. Cherry, Carlson, Friedland, Fuller & Vlasenko [1203.1607]. Chakraborty, Choubey, Dasgupta & Kar [0805.3131]. Chakraborty, Fischer, Mirizzi, Saviano, Tomàs [1104.4031, 1105.1130]. Choubey, Dasgupta, Dighe & Mirizzi [1008.0308]. Dasgupta & Dighe [0712.3798]. Dasgupta, Dighe & Mirizzi [0802.1481]. Dasgupta, Dighe, Raffelt & Smirnov [0904.3542]. Dasgupta, Dighe, Mirizzi & Raffelt [0801.1660, 0805.3300]. Dasgupta, Mirizzi, Tamborra & Tomàs [1002.2943]. Dasgupta, Raffelt & Tamborra [1001.5396]. Dasgupta, O'Connor & Ott [1106.1167]. Duan, Fuller, Carlson & Qian [astro-ph/0608050, 0703776, 0707.0290, 0710.1271]. Duan, Fuller & Qian [0706.4293, 0801.1363, 0808.2046, 1001.2799]. Duan, Fuller & Carlson [0803.3650]. Duan & Kneller [0904.0974]. Duan & Friedland [1006.2359]. Duan, Friedland, McLaughlin & Surman [1012.0532]. Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl [0807.0659]. Esteban-Pretel, Pastor, Tomàs, Raffelt & Sigl [0706.2498, 0712.1137]. Fogli, Lisi, Marrone & Mirizzi [0707.1998]. Fogli, Lisi, Marrone & Tamborra [0812.3031]. Friedland [1001.0996]. Gava & Jean-Louis [0907.3947]. Gava & Volpe [0807.3418]. Galais, Kneller & Volpe [1102.1471]. Galais & Volpe [1103.5302]. Gava, Kneller, Volpe & McLaughlin [0902.0317]. Hannestad, Raffelt, Sigl & Wong [astro-ph/0608695]. Wei Liao [0904.0075, 0904.2855]. Lunardini, Müller & Janka [0712.3000]. Mirizzi, Pozzorini, Raffelt & Serpico [0907.3674]. Mirizzi & Serpico [1111.4483]. Mirizzi & Tomàs [1012.1339]. Pehlivan, Balantekin, Kajino & Yoshida [1105.1182]. Pejcha, Dasgupta & Thompson [1106.5718]. Raffelt [0810.1407, 1103.2891]. Raffelt & Sigl [hep-ph/0701182]. Raffelt & Smirnov [0705.1830, 0709.4641]. Raffelt & Tamborra [1006.0002]. Sawyer [hep-ph/0408265, 0503013, 0803.4319, 1011.4585]. Sarikas, Raffelt, Hüdepohl & Janka [1109.3601]. Sarikas, Tamborra, Raffelt, Hüdepohl & Janka [1204.0971]. Saviano, Chakraborty, Fischer, Mirizzi [1203.1484]. Wu & Qian [1105.2068]……………………….

NEUTRINO-NEUTRINO HAMILTONIAN

$$i\frac{d}{dx}\psi_{\nu}^{(i)} = \left(H_{vac} + H_{e} + \sum_{j} H_{\nu\nu}^{(ij)} \right)\psi_{\nu}^{(i)}$$

In early studies the neutrino-neutrino Hamiltonian was assumed diagonal in flavor basis: No contribution to flavor evolution!

Critical examination of this assumption by J.Pantaleone [PLB 287, 128 (1992)]

Low-energy neutral current Hamiltonian for ν-ν interactions possesses an U(N) symmetry. A diagonal $H_{\nu\nu}$ doesn't respect this symmetry.

Pantaleone proposed a modified form of $H_{\nu\nu}$ which contains non-zero off-diagonal terms

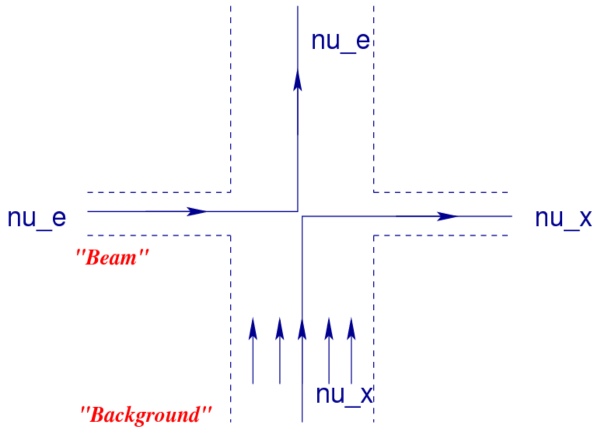
$$H_{\nu\nu} = A\begin{pmatrix} |\nu_e|^2 & \nu_e\nu_\mu^* \\ \nu_e^*\nu_\mu & |\nu_\mu|^2 \end{pmatrix}$$

It respects U(N) symmetry

$$A = \sqrt{2}G_F\left(1-\cos\theta_{ij}\right)$$

NEUTRINO FLAVOR CONVERSIONS IN A NEUTRINO BACKGROUND

Since $H_{\nu\nu}$ cannot change the *total* flavor of the system, ν-ν interactions do contribute to the flavor evolution only when the "propagating" and "background" neutrinos do exchange momenta



Momentum exchange

Pair-wise Flavor exchange by nu refraction

If all the ν in the bkg are in the same flavor state $\nu_x = \cos\alpha\,\nu_e + \sin\alpha\,\nu_\mu$

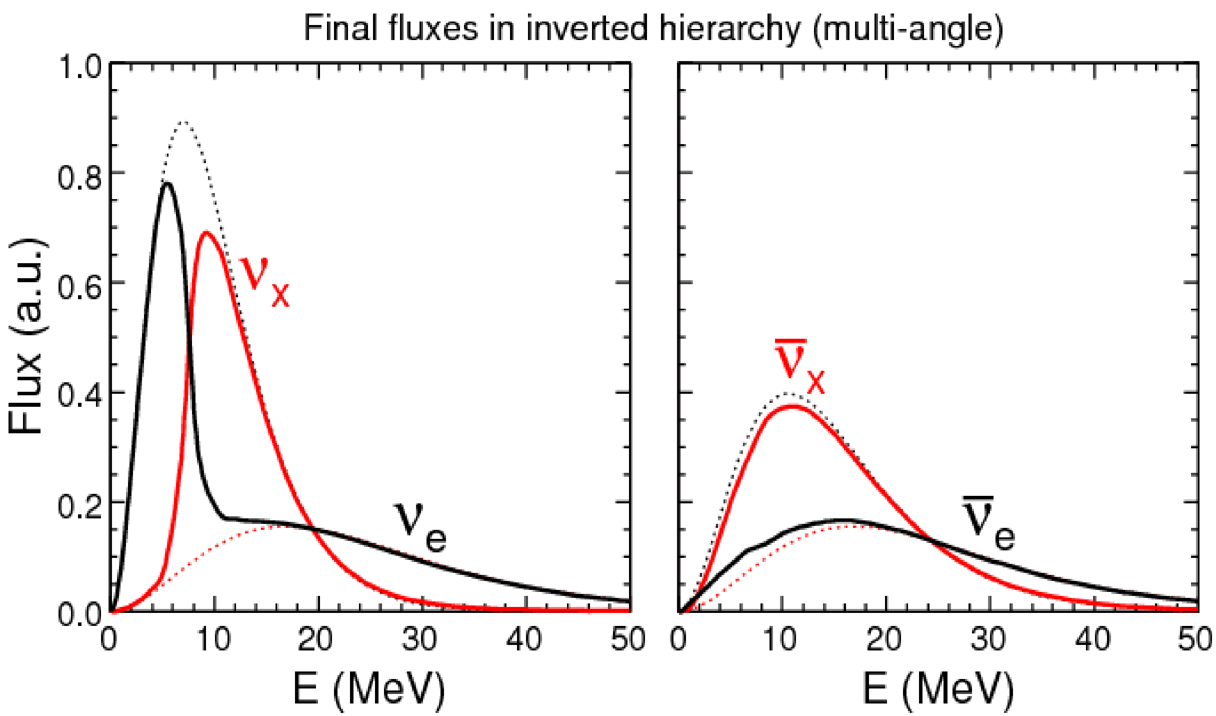
$$H_{\nu\nu} \propto \frac{\sqrt{2}G_F n_2}{2}\begin{pmatrix}\cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha\end{pmatrix} \Rightarrow P(\nu_e \to \nu_\mu) \approx \sin^2 2\alpha (G_F n_2 L)^2/2$$

[Friedland & Lunardini, hep-ph/0304055]

However, one cannot distinguish btw beam and bkg. Instrinsic non-linear problem !

SELF-INDUCED SPECTRAL SPLITS

[Fogli, Lisi, Marrone, A.M. , arXiV: 0707.1998 [hep-ph], Duan, Carlson, Fuller, Qian, astro-ph/0703776, Raffelt and Smirnov, 0705.1830 [hep-ph], Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542 [hep-ph], Duan & Friedland, arXiv: 1006.2359, A.M. & Tomas, arXiv:1012.1339, Choubey, Dasgupta, Dighe, A.M., 1008.0308....]



Swap of the original SN ν spectra in inverted mass hierarchy

Strong dependence of collective oscillations on mass hierarchy and on the energy ("splits")

Splits possible in both normal and inverted hierarchy, for ν & $\bar{\nu}$!!

SPONTANEOUS SYMMETRY BREAKING IN SELF-INDUCED OSCILLATIONS

- Symmetries have been used to reduce the complexity of the SN ν flavor evolution (e.g. the bulb model).

- However, ν can lead to a spontaneous symmetry breaking (SSB) of the symmetry inherent to the initial conditions *[Raffelt, Sarikas, Seixas, 1305.7140]* .

- Small deviations from the space/time symmetries of the bulb model have to be expected. Can these act as seed for new instabilities?

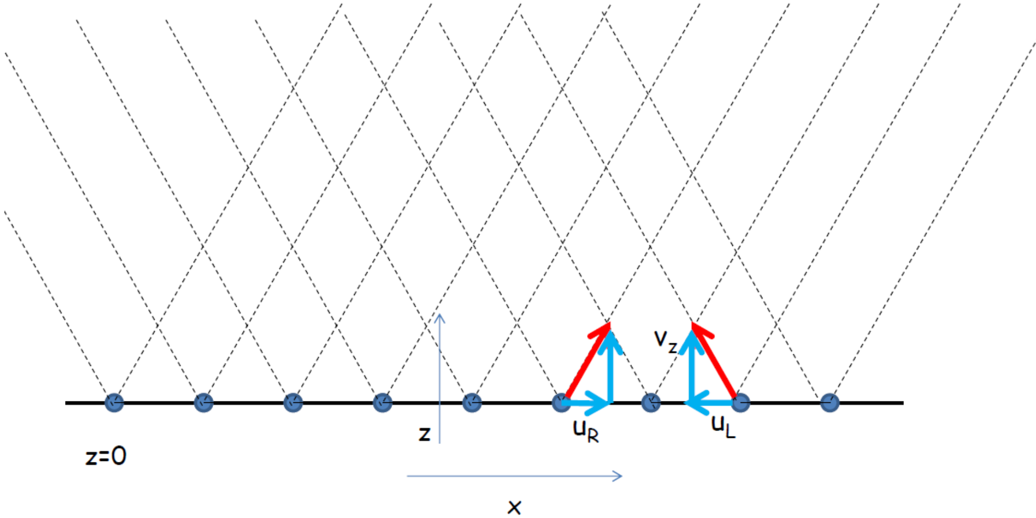
FIRST INVESTIGATIONS WITH TOY MODELS

- With a simple toy model in *[Mangano, A.M. & Saviano, 1403.1892]* it has been shown that self-interacting ν can break translational symmetries in space and time.

- By a stability analysis in *[Duan & Shalgar, 1412.7097]* is has been found that self-interacting ν can break the spatial symmetries of a 2D model.

2D MODEL FOR SELF-INTERACTING ν

[Duan & Shalgar, 1412.7097]

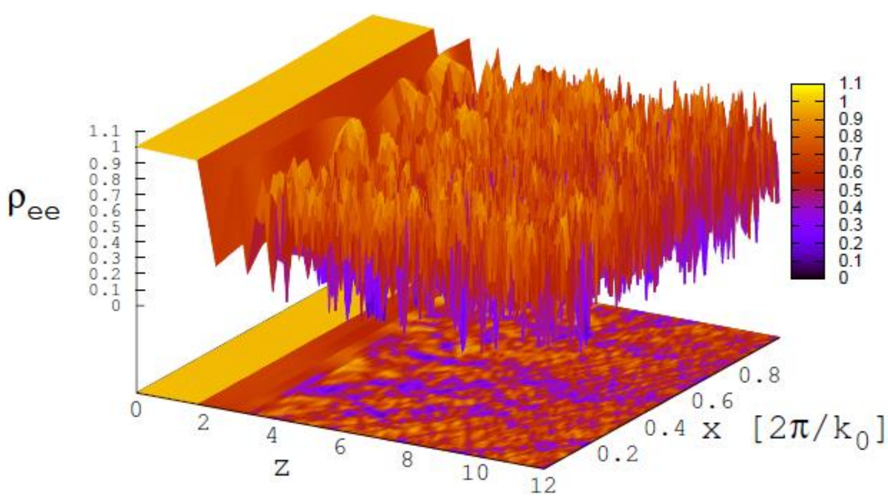


A. M., Mangano and Saviano, [arXiv:1503.03485 [hep-ph]].

Nu evolving in the plane (x,z) emitted from an infinite boundary at z=0, in only two directions (L and R). Excess of ν_e over $\bar{\nu}_e$.

~~L-R~~

~~TRANSLATIONAL~~



Large variations in the x direction at smaller and smaller scales.

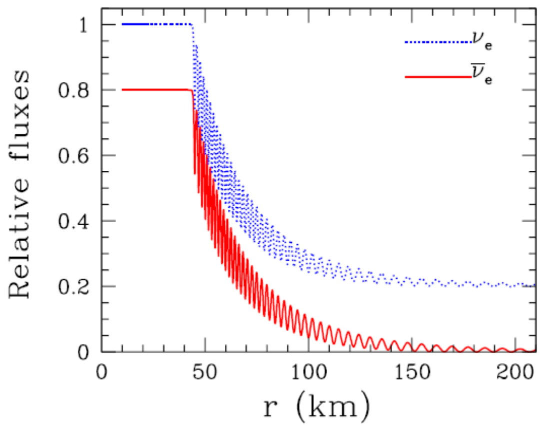
Planes of common phase broken.

Coherent behavior of oscillation lost.

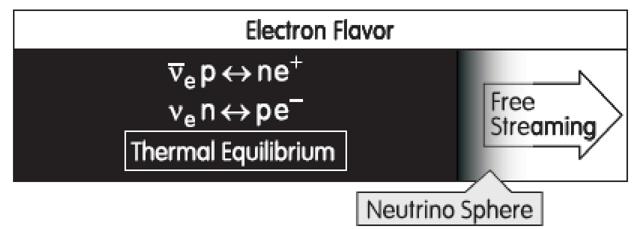
RECENT PAPERS ON SSB

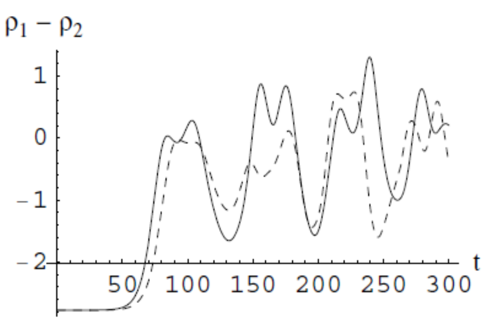
- G. Mangano, A. M. and N. Saviano, *"Damping the neutrino flavor pendulum by breaking homogeneity,"* Phys. Rev. D **89**, no. 7, 073017 (2014) [arXiv:1403.1892 [hep-ph]].
- H. Duan and S. Shalgar, *"Flavor instabilities in the neutrino line model,"* Phys. Lett. B **747**, 139 (2015) [arXiv:1412.7097 [hep-ph]].
- A. M., G. Mangano and N. Saviano, *"Self-induced flavor instabilities of a dense neutrino stream in a two-dimensional model,"* Phys. Rev. D **92**, no. 2, 021702 (2015) [arXiv:1503.03485 [hep-ph]].
- S. Chakraborty, R. S. Hansen, I. Izaguirre and G. Raffelt, *"Self-induced flavor conversion of supernova neutrinos on small scales,"* JCAP **1601**, no. 01, 028 (2016) [arXiv:1507.07569 [hep-ph]].
- S. Abbar and H. Duan, *"Neutrino flavor instabilities in a time-dependent supernova model,"* Phys. Lett. B **751**, 43 (2015) [arXiv:1509.01538 [astro-ph.HE]].
- B. Dasgupta and A. M., *" Temporal Instability Enables Neutrino Flavor Conversions Deep Inside Supernovae,"* Phys. Rev. D 92, no. 12, 125030 (2015) [arXiv:1509.03171 [hep-ph]].
- F. Capozzi, B. Dasgupta and A. M., *"Self-induced temporal instability from a neutrino antenna,"* JCAP **1604**, no. 04, 043 (2016) [arXiv:1603.03288 [hep-ph]].

FLAVOR CONVERSIONS NEAR SN CORE?



- Most of the studies assume no flavor conversion at r < 50 km (only synchronized oscillations). After self-induced conversions develop with a rate ~ $\sqrt{\omega\mu}$ *[see, e.g., Hannestad et al, astro-ph/0608695]*



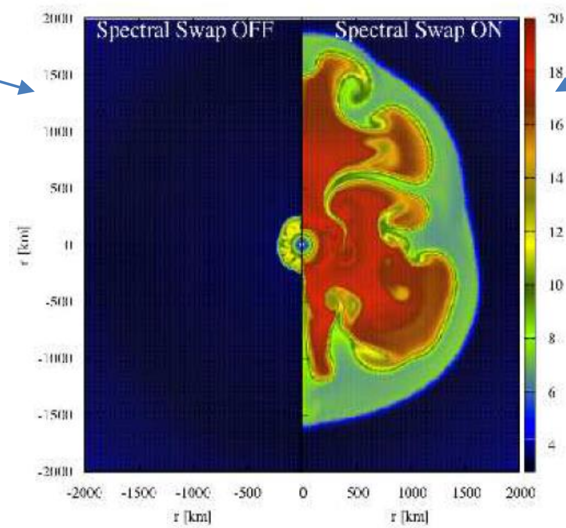


- However, since more than a decade Ray Sawyer is pointing out that close to nu-sphere nu angular distributions of different species are rather different. This would lead to a new flavor instability (absent assuming equal angular distributions). The outcome would be a possible complete flavor mixing of the outgoing stream just above the nu-sphere. Fast rate ~μ

WHY SHOULD WE WORRY ABOUT THESE EFFECTS?

- If flavor changes occur in the deepest SN regions, they would modify the neutrino heating behind the stalled shock wave, possibly helping a SN to explode.

Non-exploding



Exploding. Spectral swap (by hands) behind shock front

[Suwa et al., 1106.5487]

- If flavor equilibrium would occur close to the nu-sphere, all further oscillation effects (self-indued, matter…) would be washed-out. Crucial to predict observable SN nu signal.

FAST FLAVOR CONVERSIONS NEAR SN CORE

PHYSICAL REVIEW D **72,** 045003 (2005)

Speed-up of neutrino transformations in a supernova environment

R. F. Sawyer

Department of Physics, University of California at Santa Barbara, Santa Barbara, California 93106, USA

(Received 8 April 2005; published 5 August 2005)

When the neutral current neutrino-neutrino interaction is treated completely, rather than as an interaction among angle-averaged distributions, or as a set of flavor-diagonal effective potentials, the result can be flavor mixing at a speed orders of magnitude faster than that one would anticipate from the measured neutrino oscillation parameters. It is possible that the energy spectra of the three active species of neutrinos emerging from a supernova are nearly identical.

PHYSICAL REVIEW D **79,** 105003 (2009)

Multiangle instability in dense neutrino systems

R. F. Sawyer

Department of Physics, University of California at Santa Barbara, Santa Barbara, California 93106, USA

(Received 18 April 2008; published 6 May 2009)

We calculate rates of flavor exchange within clouds of neutrinos interacting with each other through the standard model coupling, assuming a conventional mass matrix. For cases in which there is an angular dependence in the relation among intensity, flavor, and spectrum, we find instabilities in the evolution equations and greatly speeded-up flavor exchange. The instabilities are categorized by examining linear perturbations to simple solutions, and their effects are exhibited in complete numerical solutions to the system. The application is to the region just under the neutrino surfaces in the supernova core.

PRL **116,** 081101 (2016) PHYSICAL REVIEW LETTERS week ending 26 FEBRUARY 2016

Neutrino Cloud Instabilities Just above the Neutrino Sphere of a Supernova

R. F. Sawyer

Department of Physics, University of California at Santa Barbara, Santa Barbara, California 93106, USA

(Received 7 September 2015; revised manuscript received 2 January 2016; published 25 February 2016)

Most treatments of neutrino flavor evolution, above a surface of the last scattering, take identical angular distributions on this surface for the different initial (unmixed) flavors, and for particles and antiparticles. Differences in these distributions must be present, as a result of the species-dependent scattering cross sections lower in the star. These lead to a new set of nonlinear equations, unstable even at the initial surface with respect to perturbations that break all-over spherical symmetry. There could be important consequences for explosion dynamics as well as for the neutrino pulse in the outer regions.

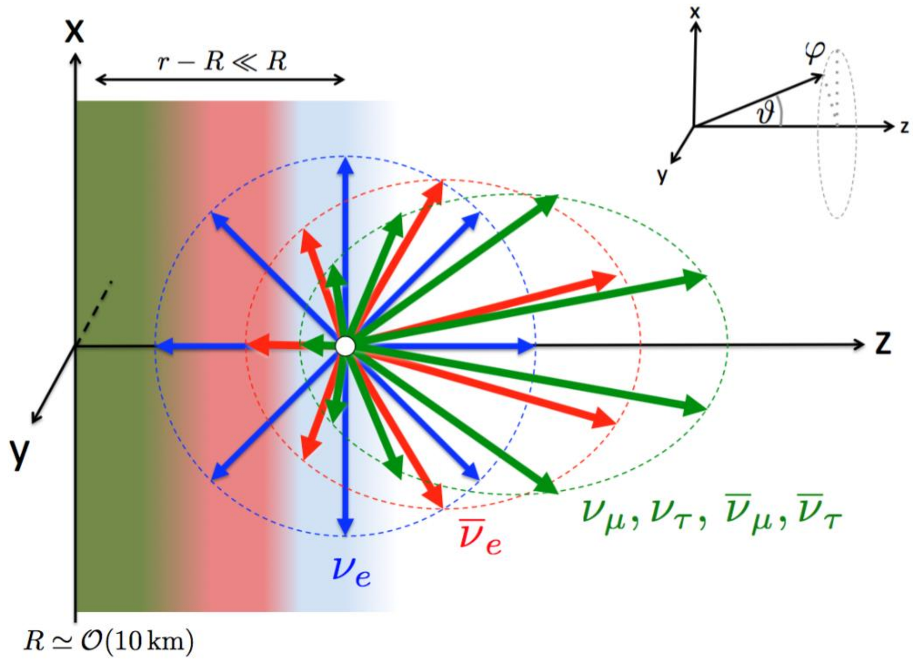
Literature on Fast Flavor Conversion

1. Speed-up of neutrino transformations in a supernova environment
   Sawyer, hep-ph/0503013
2. The multi-angle instability in dense neutrino systems
   Sawyer, arXiv:0803.4319
3. Neutrino cloud instabilities just above the neutrino sphere of a supernova
   Sawyer, arXiv:1509.03323
4. Self-induced neutrino flavor conversion without flavor mixing
   Chakraborty, Hansen, Izaguirre & Raffelt, arXiv:1602.00698
5. Fast pairwise conversion of supernova neutrinos: A dispersion-relation approach
   Izaguirre, Raffelt & Tamborra, arXiv:1610.01612
6. Fast neutrino flavor conversions near the supernova core with realistic flavor-dependent angular distributions
   Mirizzi & Dasgupta, arXiv:1609.00528
7. Fast neutrino conversions: Ubiquitous in compact binary merger remnants
   Wu & Tamborra, arXiv:1701.06580

+ new developments…

NEUTRINO ANGULAR DISTRIBUTIONS AT DECOUPLING

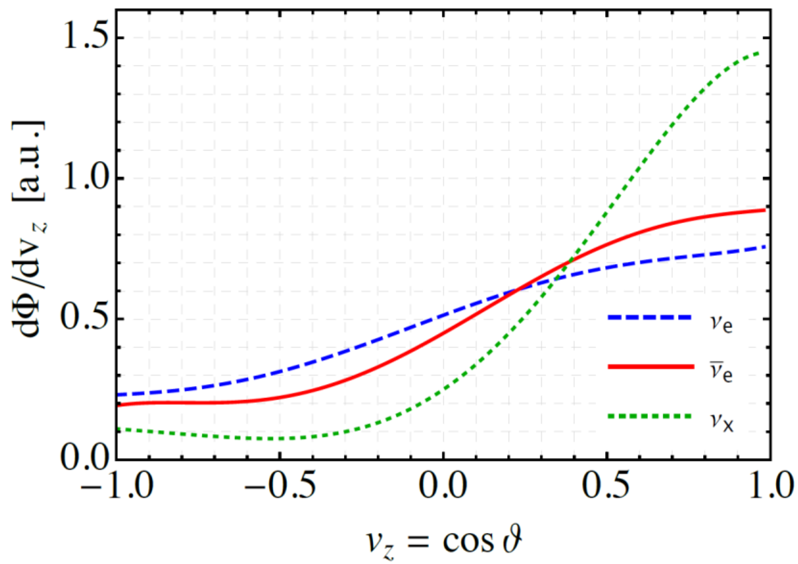
[Dasgupta, A.M., Sen, arXiV:1609.00528]



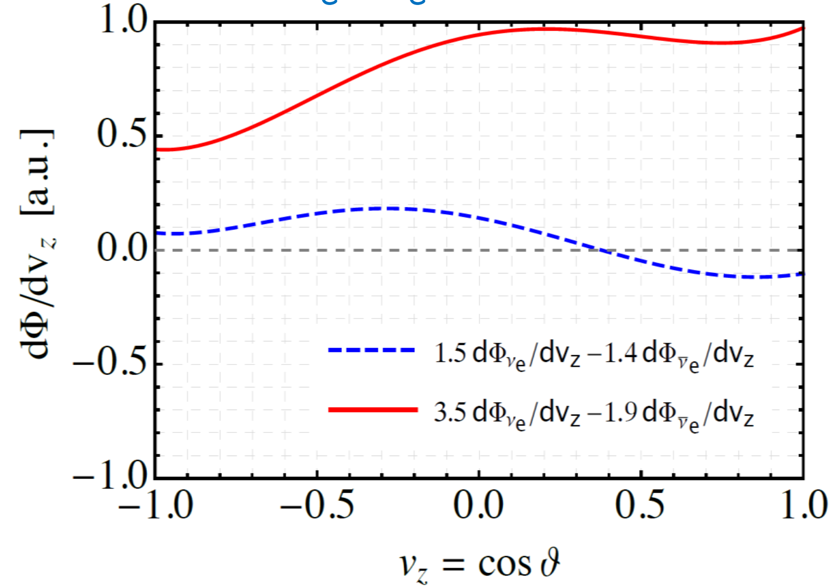
- Electron flavors remain in equilibrium with matter for a longer period than the non-electron flavors, due to the largest cross-sections of CC interactions
- Non-electron flavors decouple deeper in the star (more fwd-peaked distributions)
- Neutron-richness enhances CC interactions for ν_e keeping them more coupled to matter (more isotropic distribution) than $\overline{\nu}_e$.

FAST FLAVOR CONVERSIONS

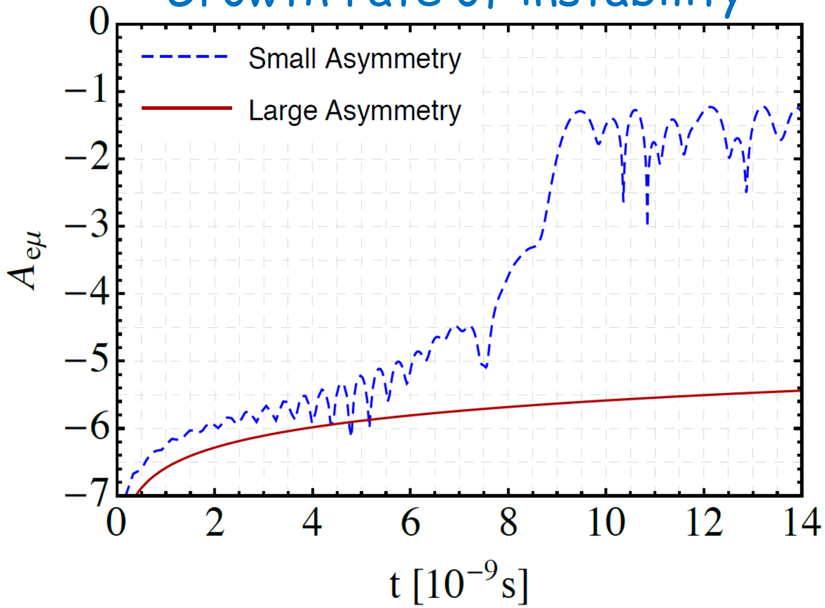
Nu angular distributions



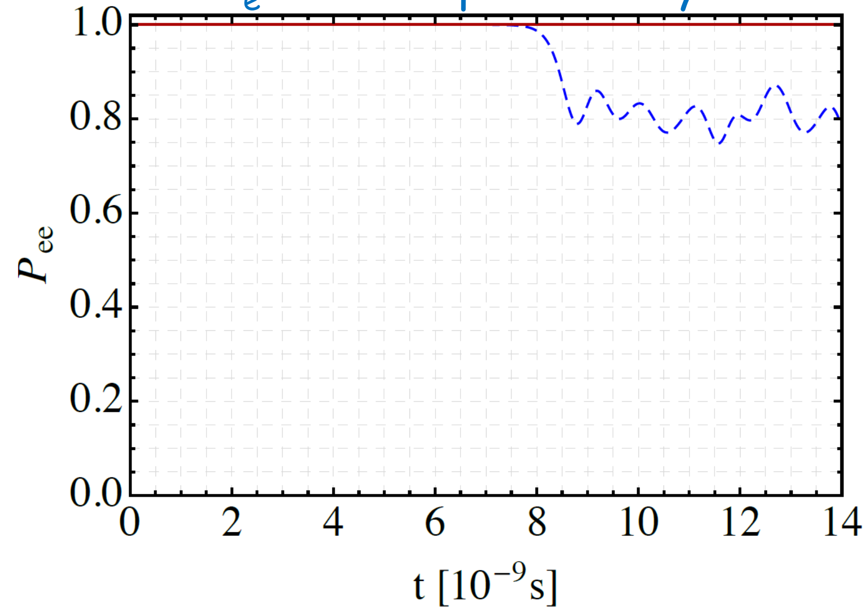
$\nu_e - \overline{\nu}_e$ difference



Growth rate of instability

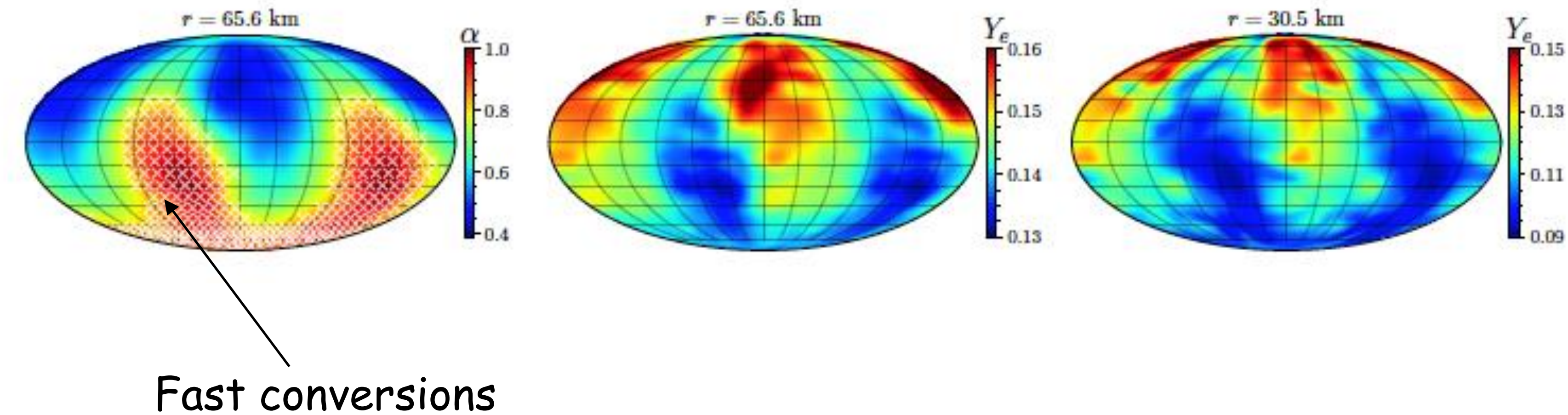


$\overline{\nu}_e$ survival probability



FAST FLAVOR CONVERSIONS IN MULTI-D SNe

[Abbar et al., arXiV:1812.06883]

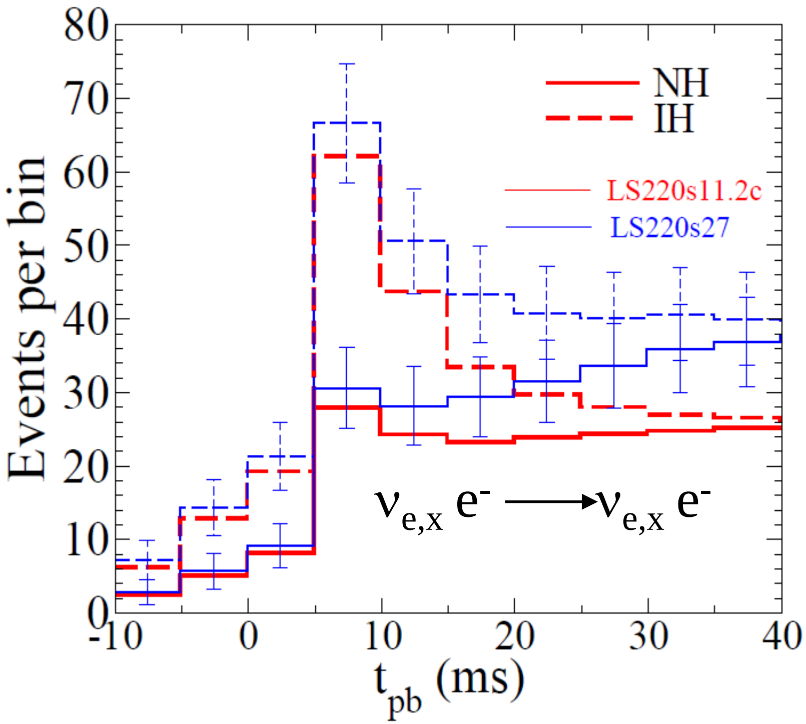


Which is the impact on the SN explosion?

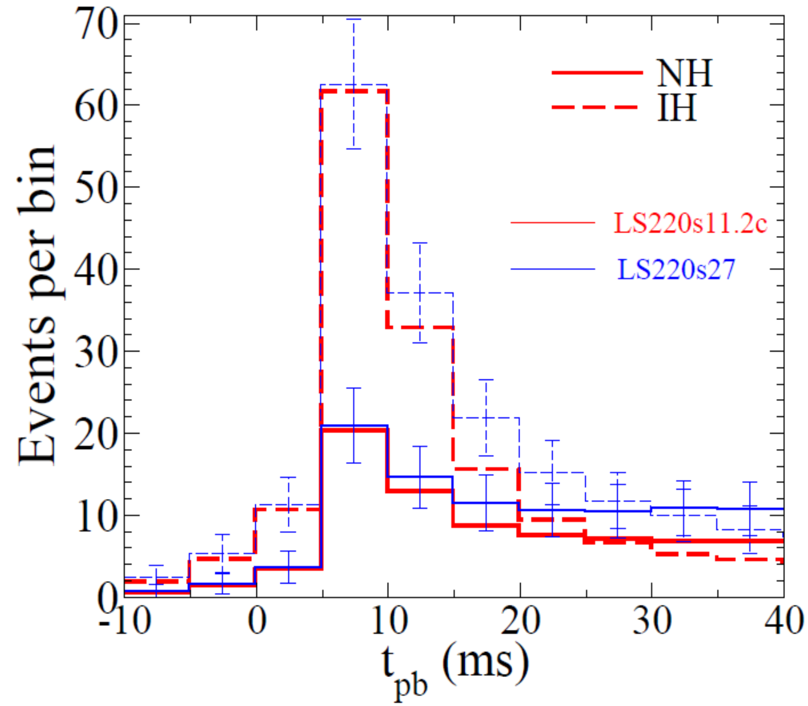
NEUTRONIZATION BURST

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]

560 kton Water Cherenkov



40 kton LAr



Robust feature of SN simulations

[Kachelriess et al., astro-ph/0412082, Gil-Botella & Rubbia, hep-ph0307244]

At "large" θ_{13} (like recently measured!):

- The peak is not seen → The hierarchy is normal (if one could see it...)
- The peak is seen → The hierarchy is inverted (more robust)

CONCLUSIONS

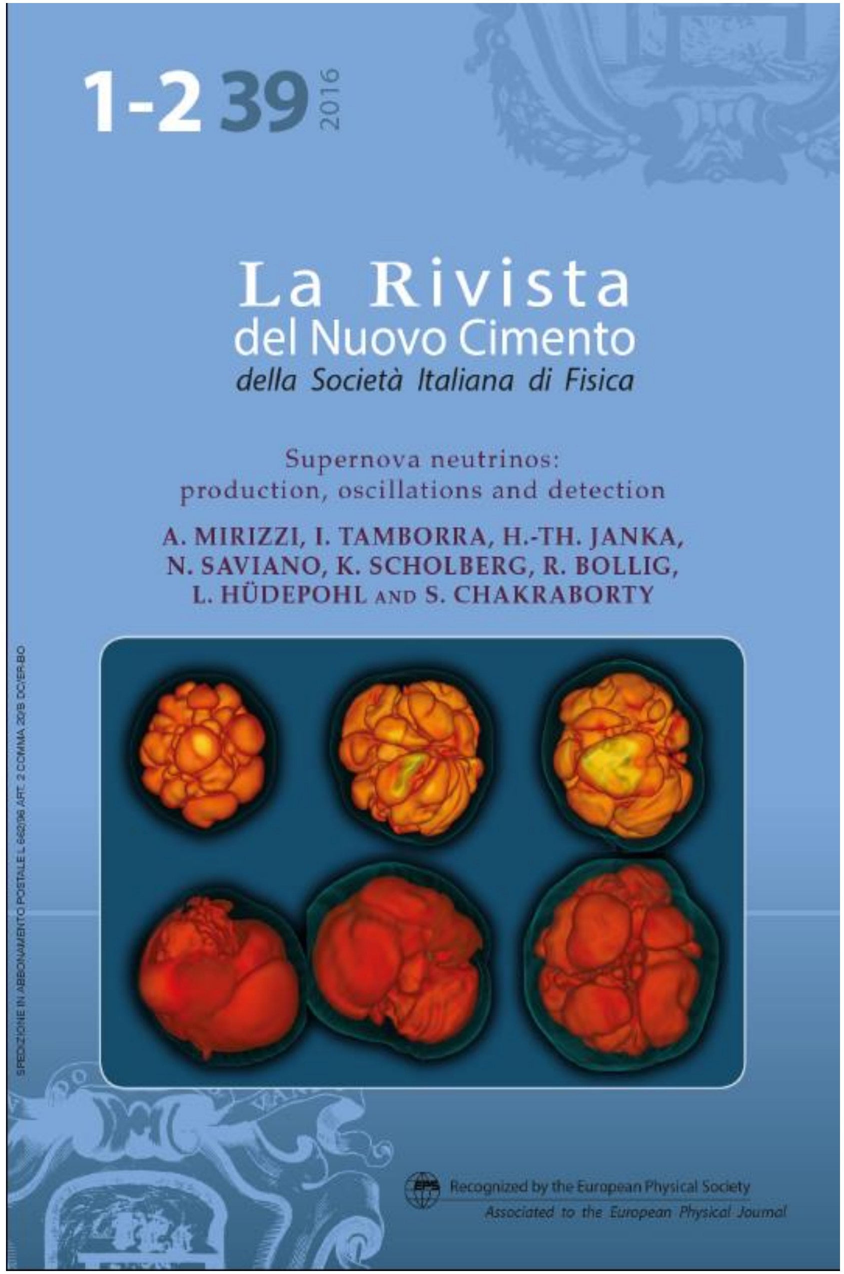
Observing SN neutrinos is the next frontier of low-energy neutrino astronomy

The physics potential of current and next-generation detectors in this context is enormous, both for particle physics and astrophysics.

Neutrino signal duration provides most useful particle-physics information. Neutrino signal from next nearby SN would make this argument much more precise.

Flavor conversions in SNe would provide valuable information on the neutrino mass hierarchy. Further investigations necessary on collective oscillations.

LOOKING FORWARD THE NEXT SN!



arXiv:1508.00785 [astro-ph.HE]

SN neutrinos at the crossroads: astrophysics, oscillations, and detection

From Monday, 13 May, 2019 - 08:00 to Friday, 17 May, 2019 - 14:00

Register Now

Location: ECT* meeting room

Abstract:
The next Galactic supernova (SN) would be a once in a lifetime event for particle astrophysics, offering a unique opportunity for a multi-messenger detection of gravitational waves, neutrinos of all flavors, and multi-wavelength photons. The aim of the workshop is to review and discuss the recent advances in the study of SN neutrinos and future perspectives, ranging from SN simulations, neutrino oscillations, nucleosynthesis, gravitational waves, and SN neutrino experimental searches. The workshop is structured to address these broad issues in a synergistic interdisciplinary way and to stimulate discussions and collaborations among scientists working on SN neutrinos from different perspectives.

SECRETARIAT

Susan Driessen
driessen@ectstar.eu
+39 0461 314722

Registration period: 25 Feb 2019 to 22 Apr 2019

Website: https://indico.ectstar.eu/e/sn-neutrinos-at-the-crossroads_astrophysics-oscillat...

Organizers

Basudeb Dasgupta	Tata Institute for Fundamental Research	basudeb@gmail.com
Alessandro Mirizzi	University of Bari	alessandro.mirizzi@ba.infn.it

Attendees

No attendees yet.