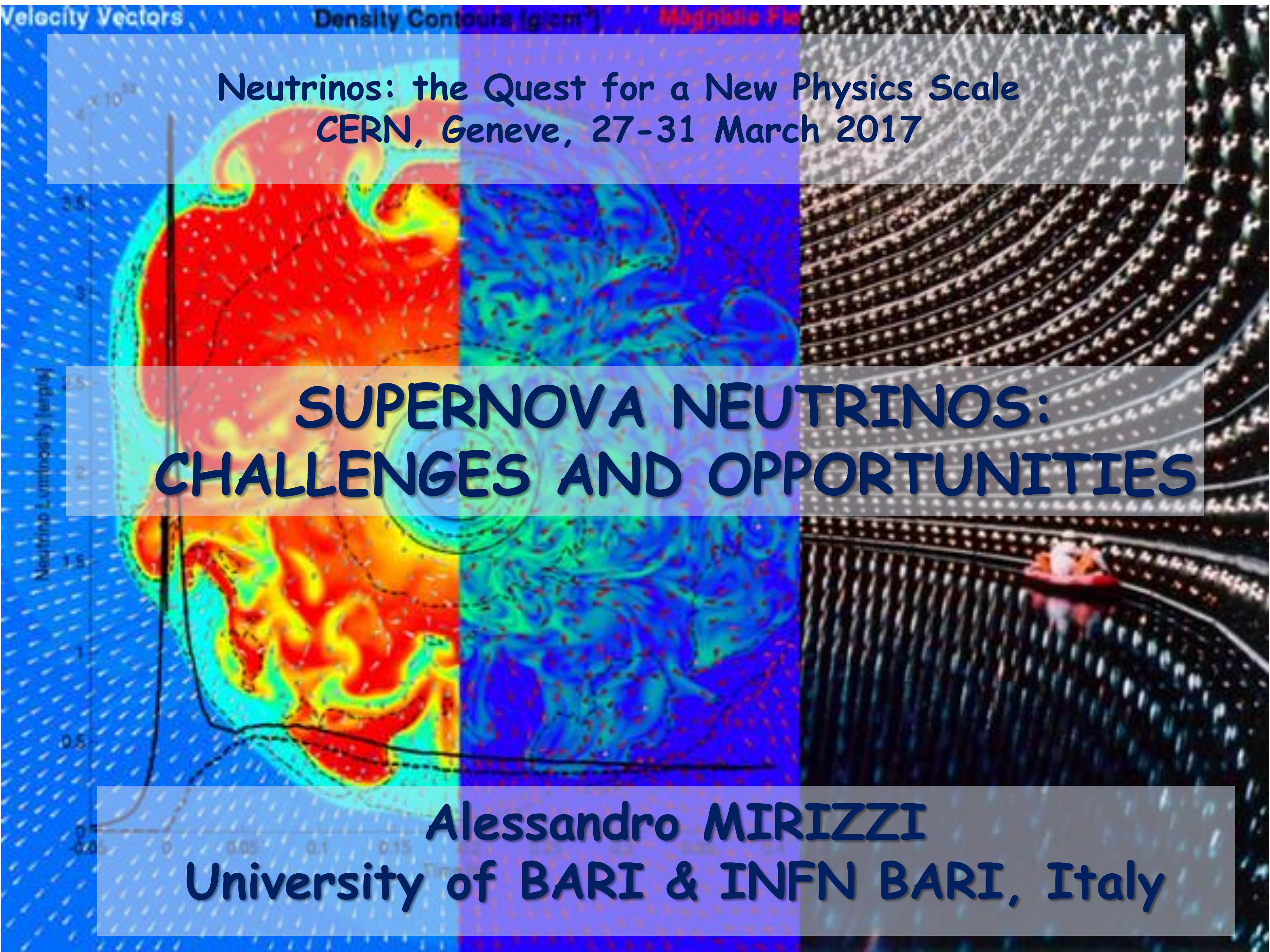
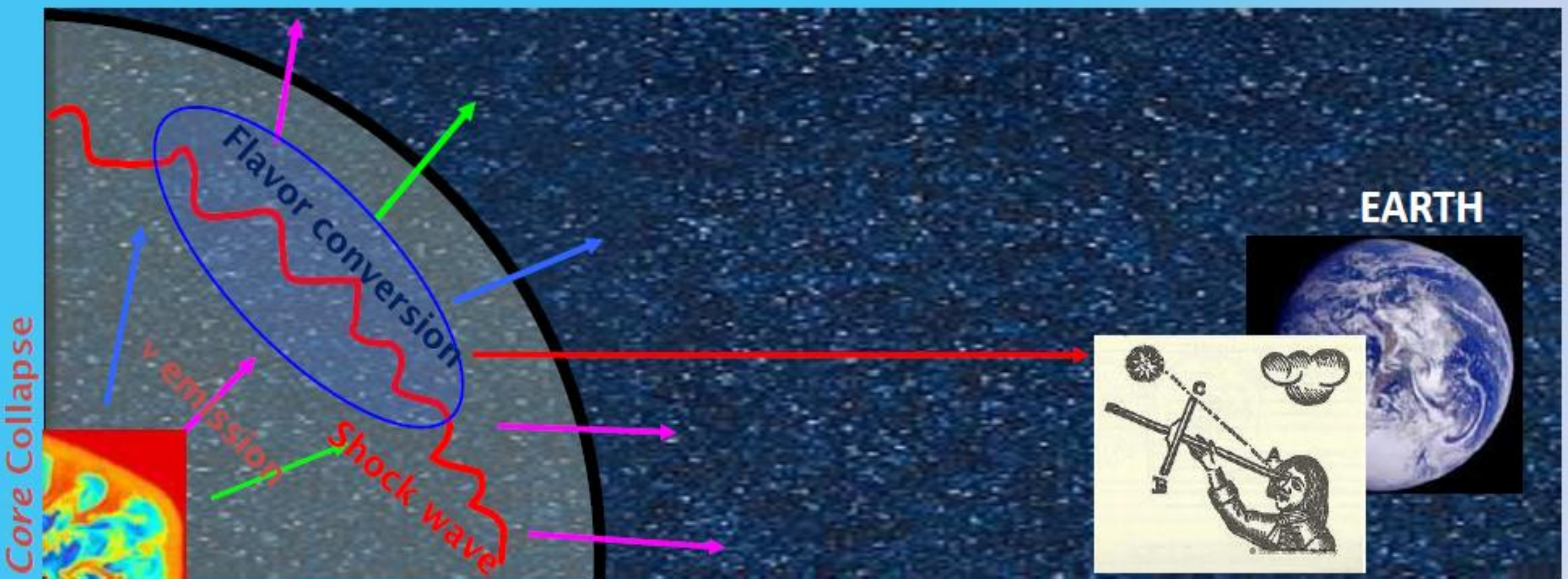


Neutrinos: the Quest for a New Physics Scale
CERN, Geneve, 27-31 March 2017

SUPERNOVA NEUTRINOS: CHALLENGES AND OPPORTUNITIES

Alessandro MIRIZZI
University of BARI & INFN BARI, Italy

SUPERNOVA NEUTRINOS



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

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

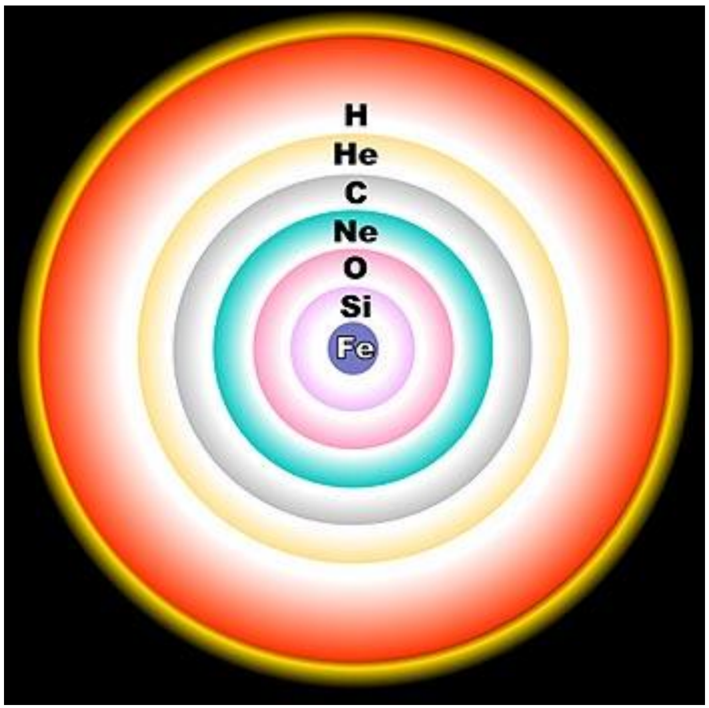
SUPERNOVA NEUTRINOS

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies $E \sim O(15\ \mathrm{MeV})$.
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED:** **1-3 SN/century** in our galaxy (d ≈ O (10) kpc).

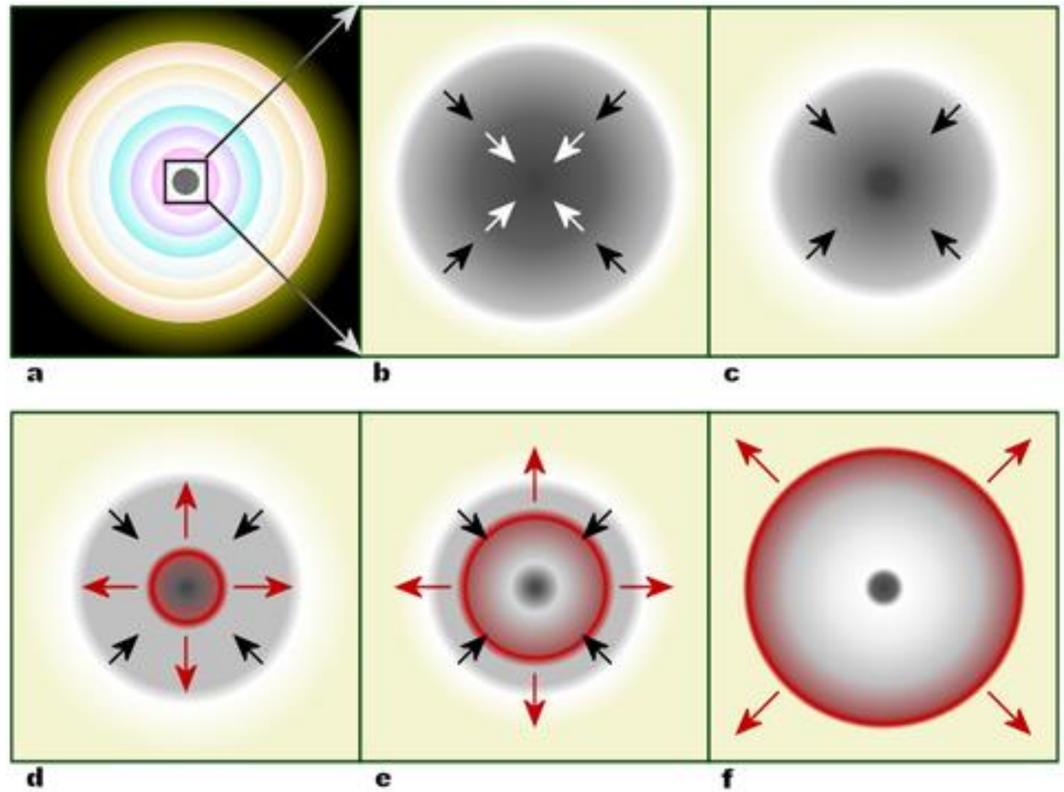
LIFE AND DEATH OF A MASSIVE STAR

Onion-like layers of a massive, evolved star just before core collapse.



Collapse

Nuclear density



Core-bounce & shock wave

shock-wave stalling

Shock revival

ROLE OF NEUTRINOS

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

$$E \approx 3\times10^{53}\left(\frac{M}{M_{sun}}\right)^{2}\left(\frac{R}{10\ \mathrm{km}}\right)^{-1} ergs$$

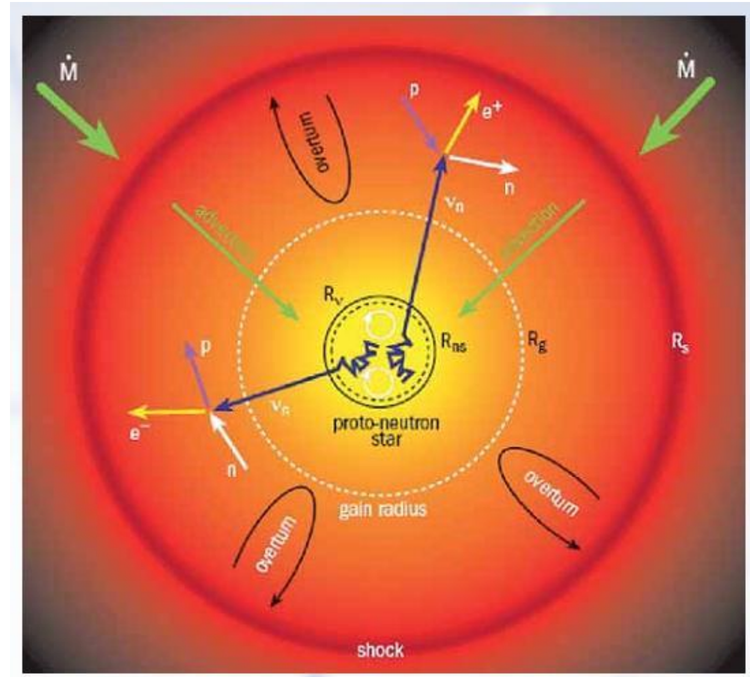
Neutrino energy $E_\nu \approx 100 \times E_{kin}$ of a SN explosion

- 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

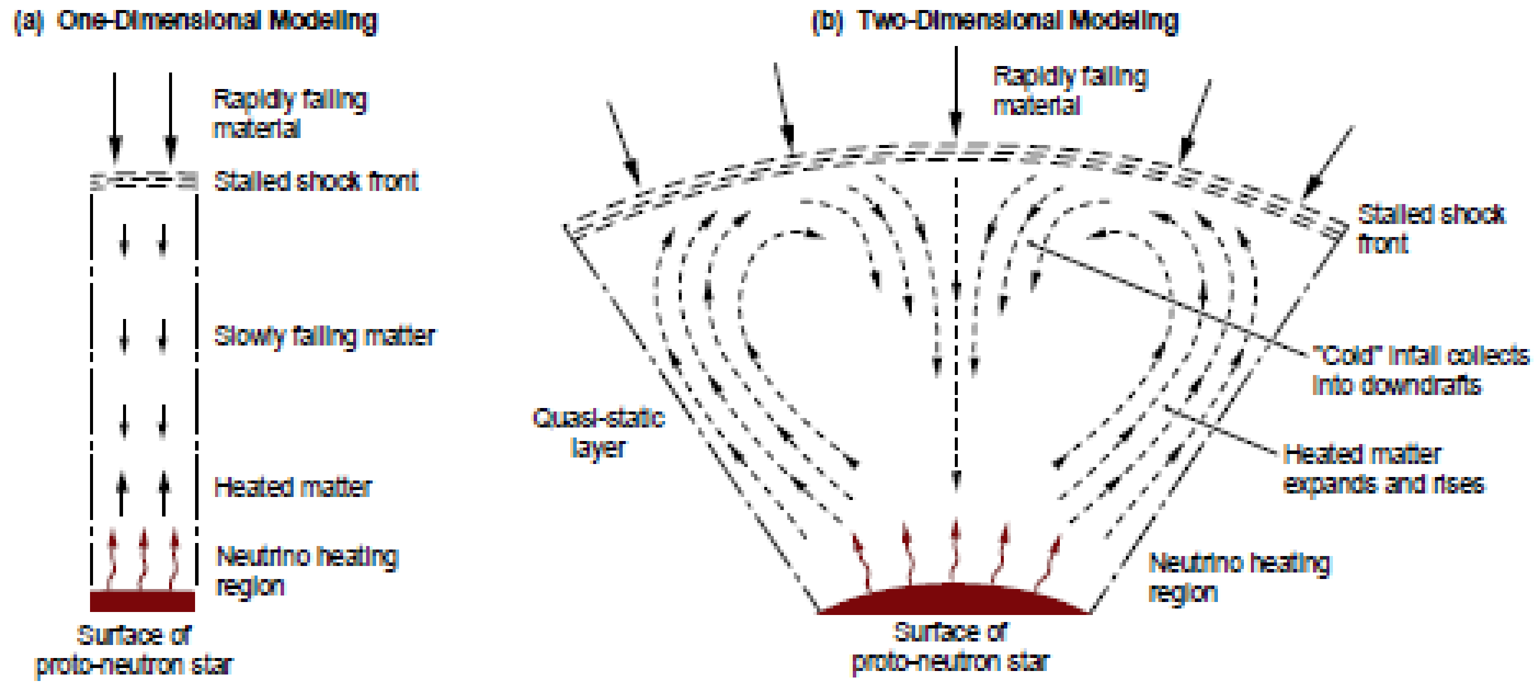
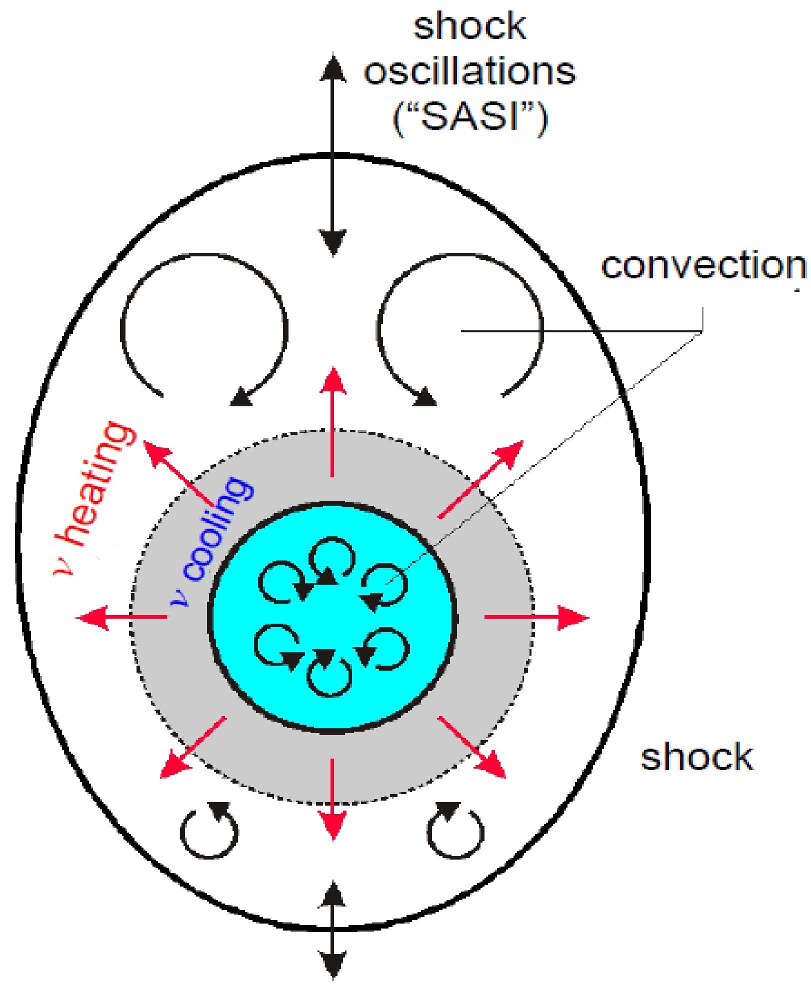


Figure 5. A Convective Engine

(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

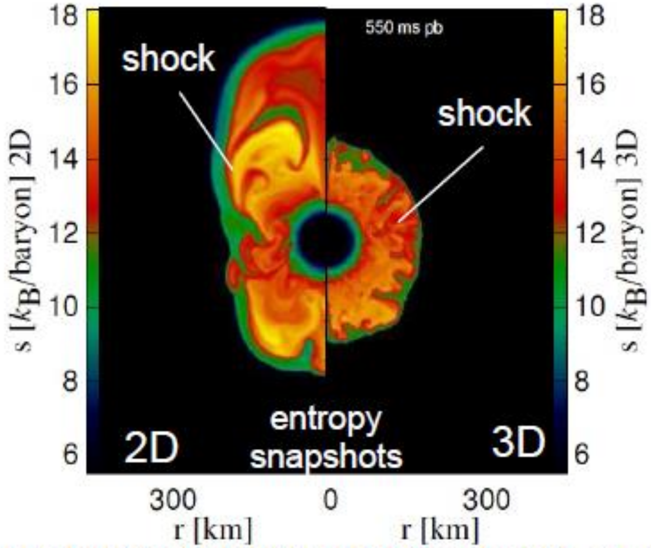
- Stalled accretion shock still pushed outward to ~150km as matter piles up on the PNS, then recedes again
- *Heating* or *gain* region develops some tens of ms after bounce
- Convective overturn & shock oscillations “SASI” enhance the efficiency of ν-heating, which finally revives the shock
- **Big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



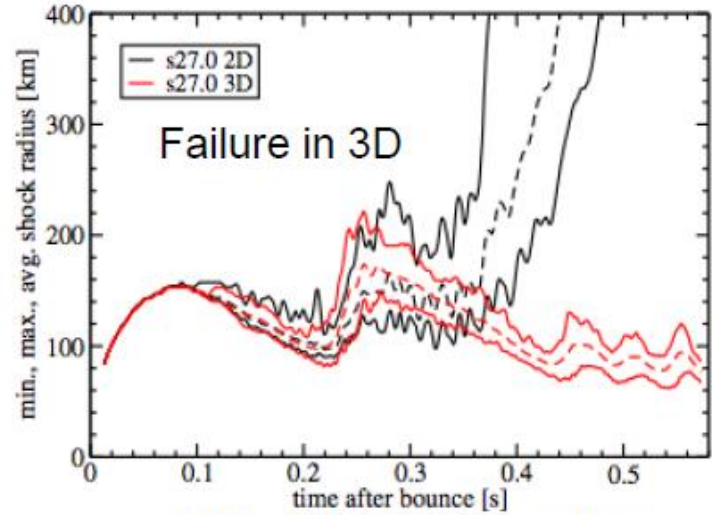
Slide by B. Müller

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

Slide by B. Müller



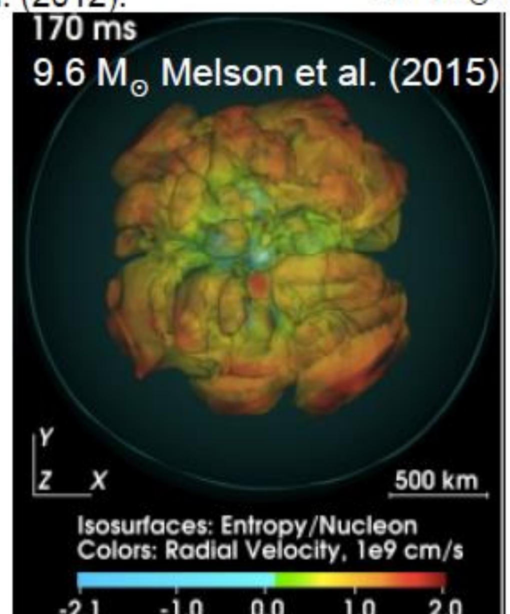
Simplified 3D "light-bulb" model from Hanke et al. (2012):
Turbulent convection in 2D and 3D

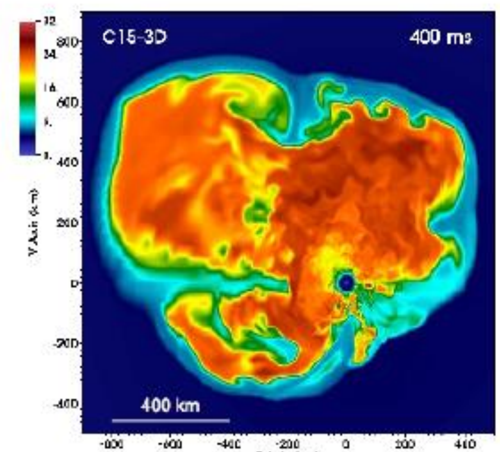


27 $M_\odot$ Hanke et al. (2013)

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)

SN AS LABORATORY FOR SM INTERACTIONS

- Up to 1973, neutrinos have been observed only participating in CC interactions. CC interactions occur so infrequently, that even at the high densities of the core collapse, ν were thought to be free-streaming from the core

- In 1973 NC interactions were experimentally observed. In 1975 Tubbs and Schramm found NC interaction scatterings would be favored under the condition of the core-collapse. Neutrinos would scatter simultaneously from all the nucleons in heavy nuclei in a coherent process. As a result neutrinos of all flavors would be trapped in the SN core.

THE ASTROPHYSICAL JOURNAL, **201**: 467–488, 1975 October 15

NEUTRINO OPACITIES AT HIGH TEMPERATURES AND DENSITIES

DAVID L. TUBBS AND DAVID N. SCHRAMM
University of Chicago, Enrico Fermi Institute
Received 1975 February 28; revised 1975 April 18

ABSTRACT

A detailed calculation is made of the major cross sections contributing to neutrino opacities at high temperatures and densities such as those encountered in gravitational collapse. These calculations include the effects of neutral currents, where applicable, and electron degeneracy. The processes considered are electron-neutrino scattering (including both electron and muon neutrinos and antineutrinos), neutrino-nucleon absorption and scattering, and coherent neutrino scattering. Results for these interactions are also given for the average energy transferred by the neutrino as well as the mean scattering angle (thus yielding momentum transfer).

Subject headings: dense matter — neutrinos — opacities

SN AS LABORATORY FOR BSM INTERACTIONS

Neutrino flavor changing neutral currents
(FCNC)

$$L = G_F \bar{\nu}^i \gamma^\mu (1-\gamma_5)\nu^j \bar{q}\gamma_\mu (\varepsilon^q_{Vij} + \varepsilon^q_{Aij}\gamma_5) q$$

Examples of FCNC:

- R_p violating SUSY
- Minimal Flavor Violation Hypothesis
- Lepto-Quark Models

Stellar environment is sensitive to neutrino flavor changing scatterings on heavy nuclei

[see Amanik & Fuller, astro-ph/0606607, Lychkovskiy, Blinnikov, Vysotsky, 0912.1395]

QUALITATIVE EFFECT

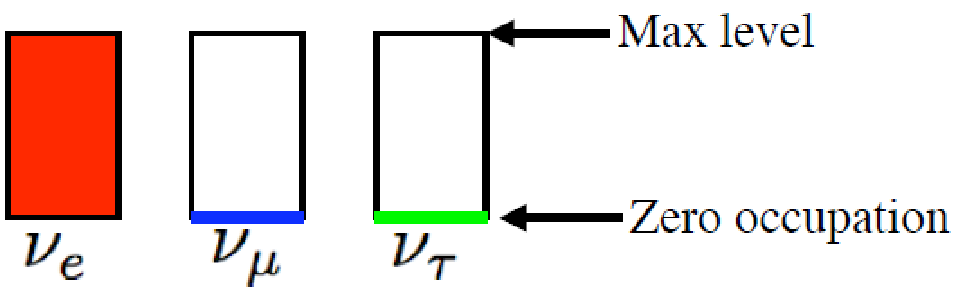
$$\nu_e \rightarrow \nu_{\mu,\tau}$$

Open holes in neutrino sea, allow electron capture to proceed

$$e^- + p \rightarrow \nu_e + n$$

Net reduction in Y_e

After trapping and before bounce, levels of the FD seas of neutrinos:



Cross section for e^- capture > cross section for FC scattering
so holes opened in the ν_e are immediately replaced by electron capture

ν_e level remains the same $\longrightarrow$ $\Delta Y_e = -(\Delta Y_{\nu_\mu} + \Delta Y_{\nu_\tau})$

- Lower Y_e

$$E_i \approx \left(Y_e^f\right)^{10/3}$$ → Lower initial shock energy

$$M_{hc} \approx 5.8 Y_e^2 M_\otimes$$ → More outer core material for the shock to pass through

Disfavour getting explosion

- Existence of ν_μ and ν_τ → More neutrinos partecipating in depositing energy behind the shock

Favour getting explosion

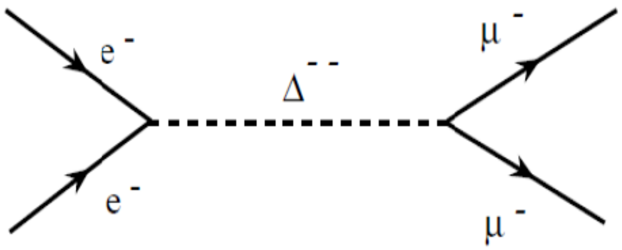
SN model is significantly changed!

LHC may see physics of this type- then it must be included in SN model

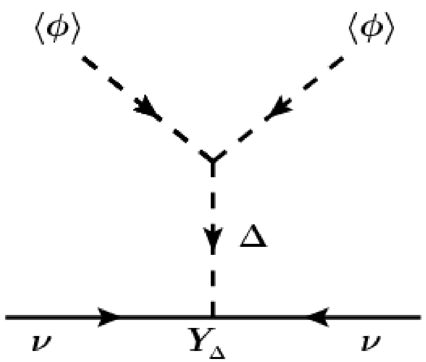
SN COLLAPSE WITH LEPTON FLAVOR VIOLATION

[Lychkovskiy, Blinnikov, Vysotsky, 0912.1395]

Assume that new heavy particles generate effective 4-fermion interactions which do not conserve lepton flavor



Type II See Saw



$$
\begin{aligned}
e^- e^- &\rightarrow \mu^- \mu^-, \\
e^- \nu_e &\rightarrow \mu^- \nu_\mu, \\
\nu_e \nu_e &\rightarrow \nu_\mu \nu_\mu, \\
\nu_e \nu_e &\rightarrow \nu_\tau \nu_\tau,
\end{aligned}
$$

⇒

$$\mu_e = \mu_\mu$$

$$\mu_{\nu_e} = \mu_{\nu_\tau}$$

Equlibrium between flavors is estabilished in the inner core. Seas of degenerate nonelectron neutrinos arise.

Even muons may appear in appreciable amount!

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

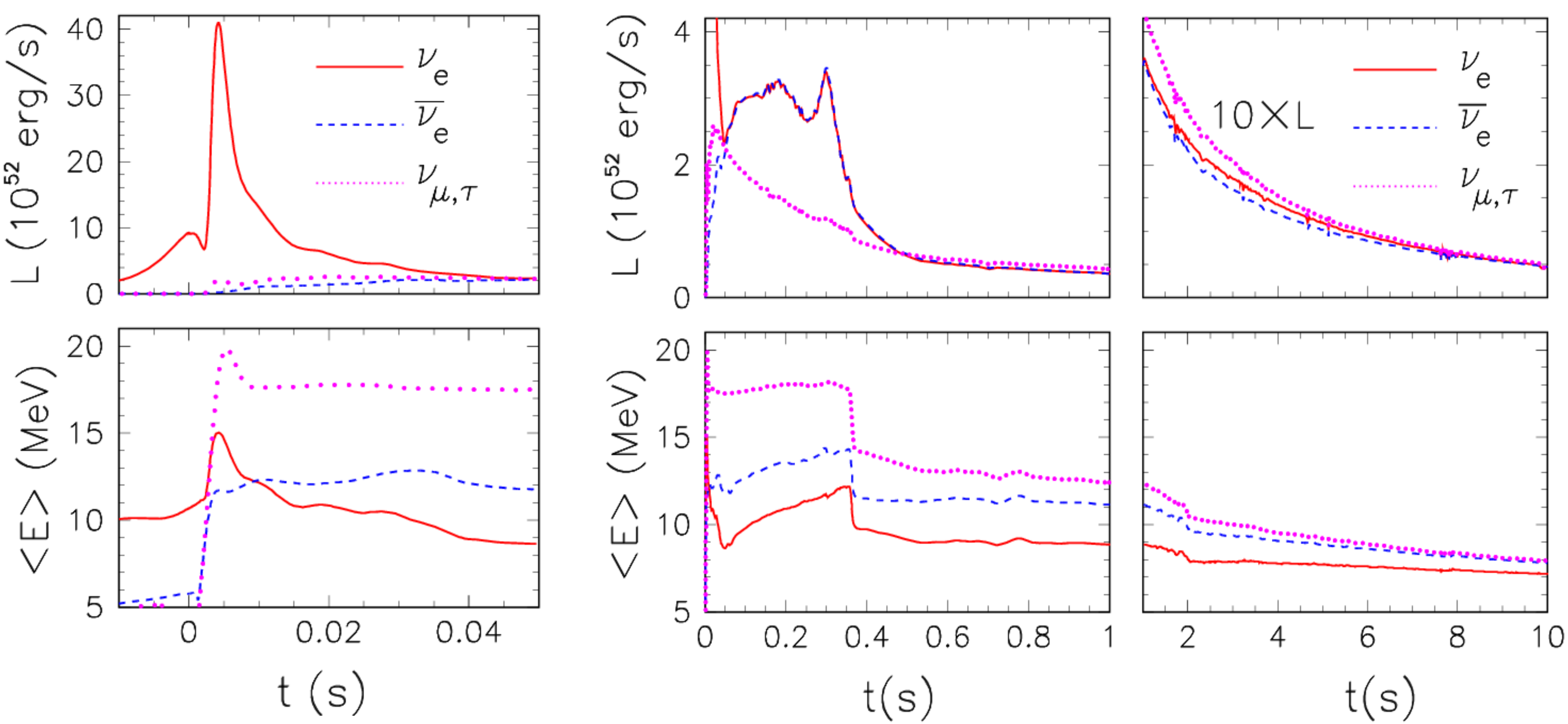
- Shock breakout
- De-leptonization of outer core layers

Accretion

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

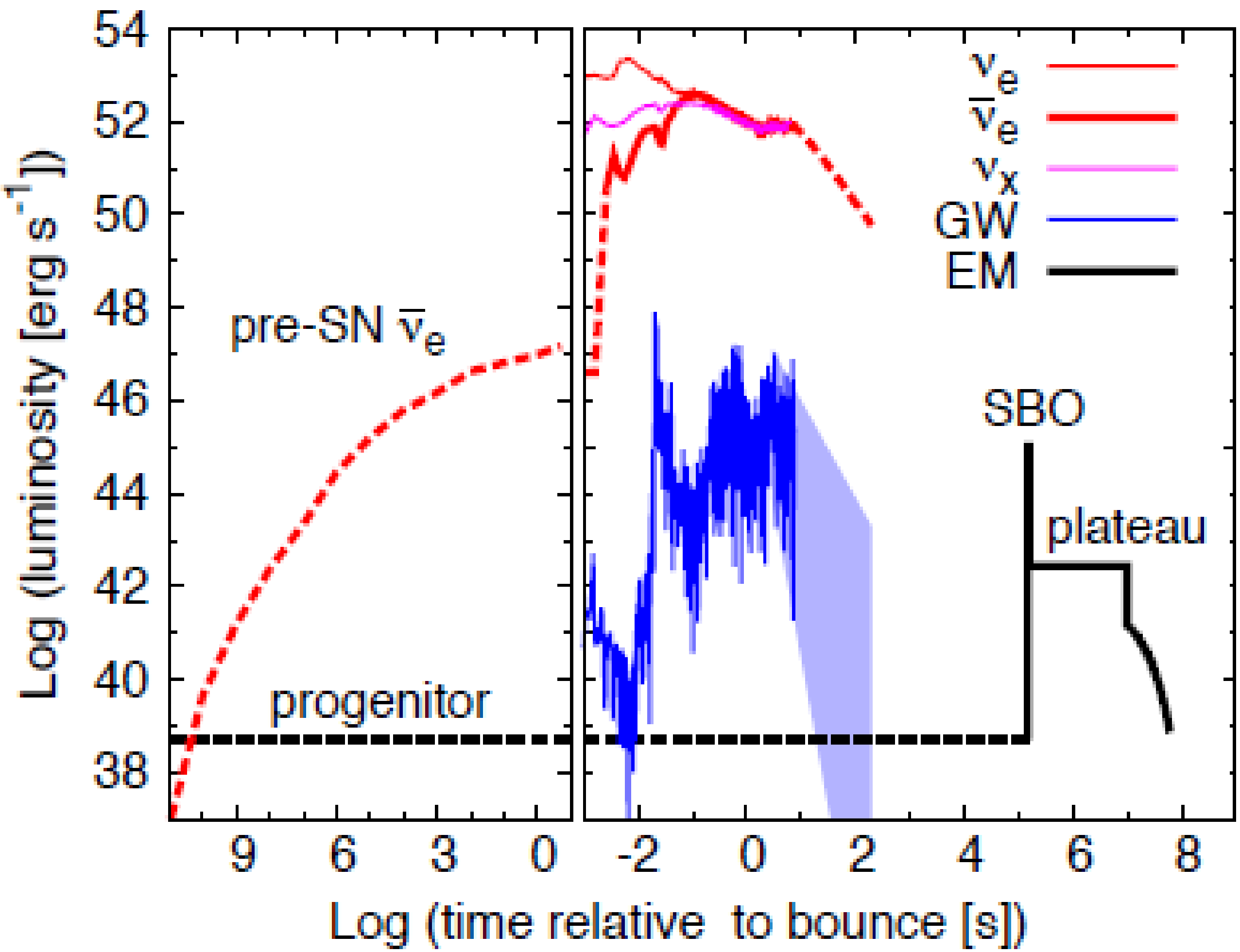
Cooling

- Cooling on ν diffusion time scale

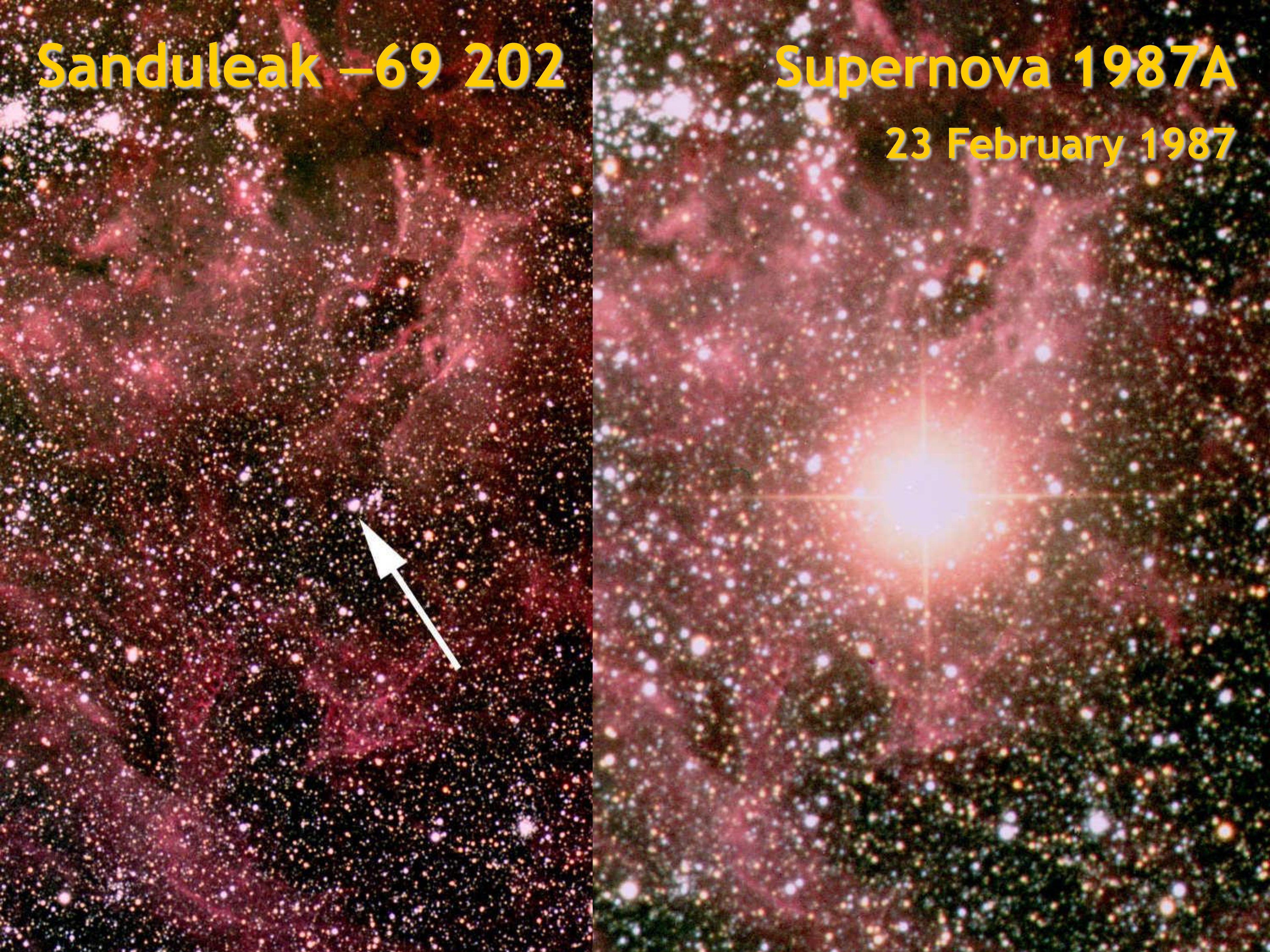


MULTI-MESSENGER SIGNALS FROM SNE

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



SN 1987A NEUTRINOS


Sanduleak –69 202
Supernova 1987A
23 February 1987

Neutrino Burst Observation :
First verification of stellar evolution mechanism

OPEN

Neutrino Astronomy

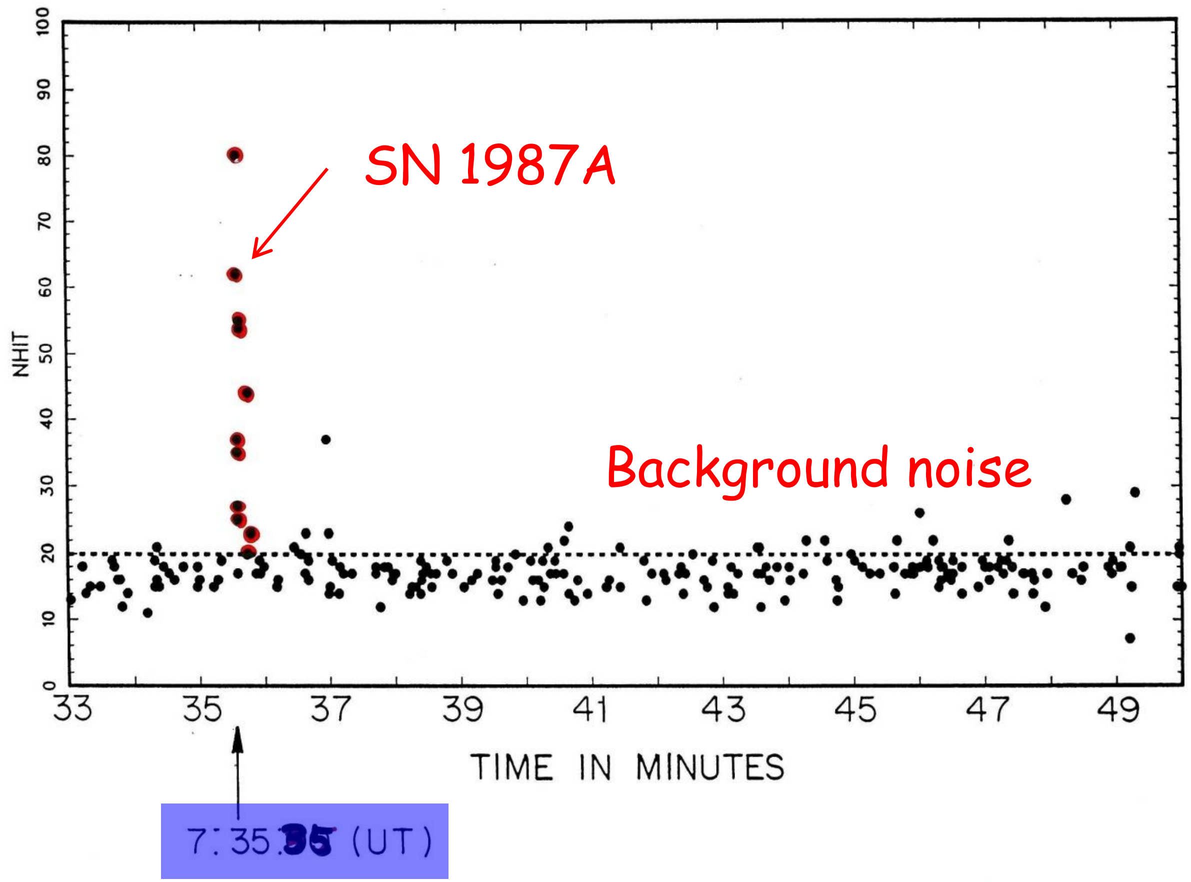
2002 Physics Nobel Prize

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

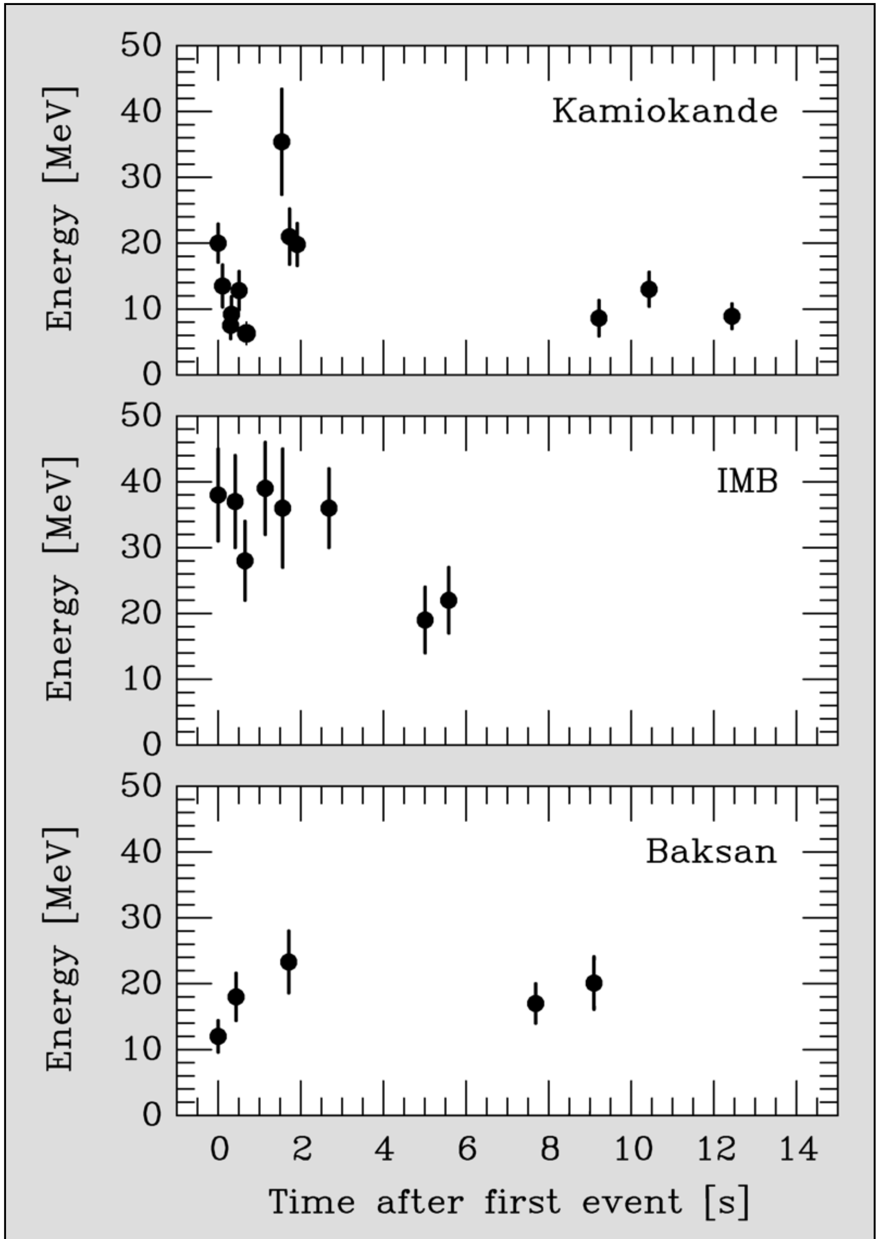
R. Davis

M. Koshiba

NEUTRINO SIGNAL OF SN 1987A IN KAMIOKANDE



NEUTRINO SIGNAL OF SUPERNOVA 1987A



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

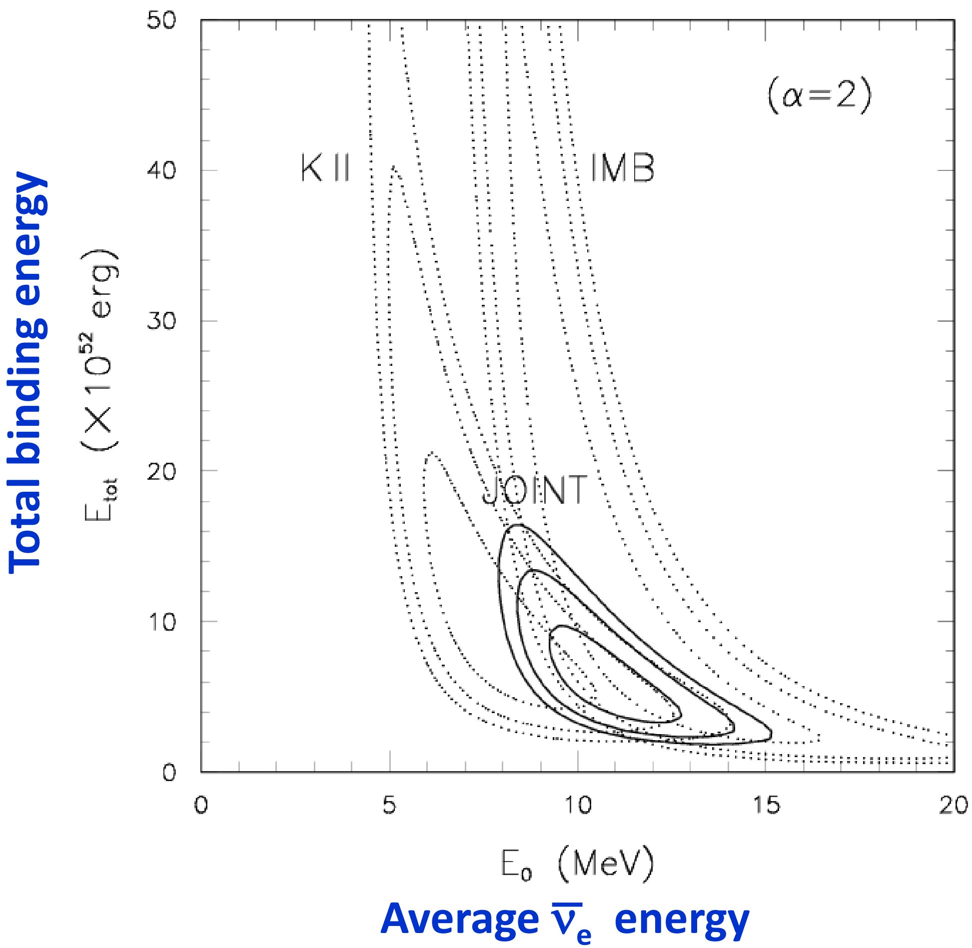
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ± 50 ms

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

Within clock uncertainties,
signals are contemporaneous

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)]*

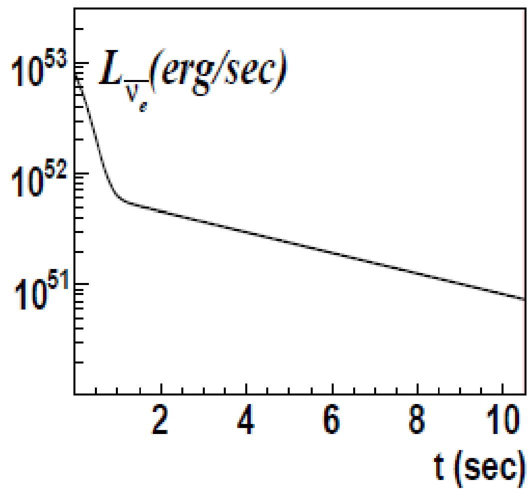


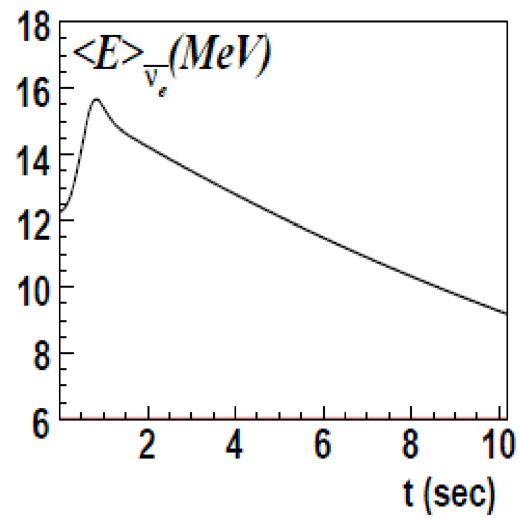
In agreement with the most recent theoretical predictions (i.e. Basel & Garching models)

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

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

...for the last thirty years!

PARTICLE PHYSICS BOUNDS FROM SN 1987A

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

BOUND ON SECRET NEUTRINO INTERACTIONS

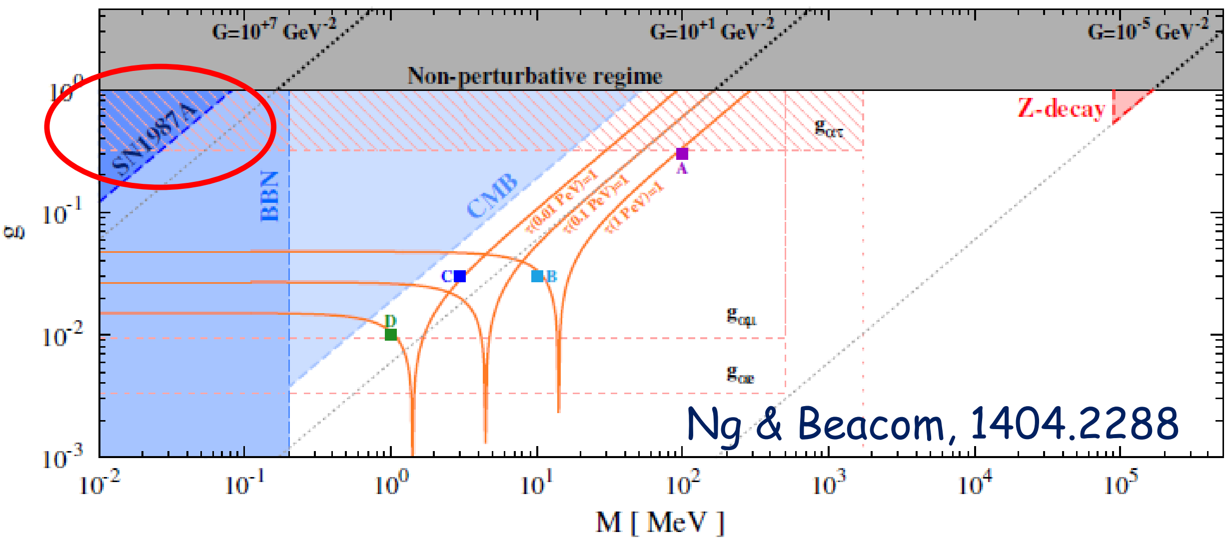
$$L = g\phi\nu\bar{\nu}$$

See talk by Ninetta Saviano (on Monday)

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.

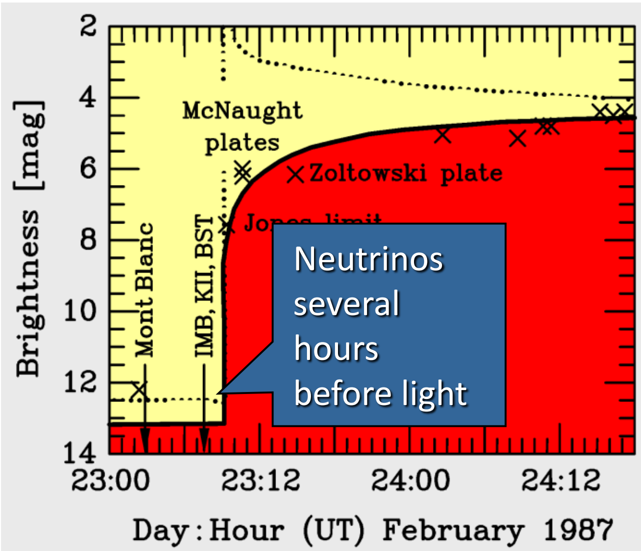


SN 1987A bound

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

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

SN 1987A BOUNDS ON NEUTRINO VELOCITY



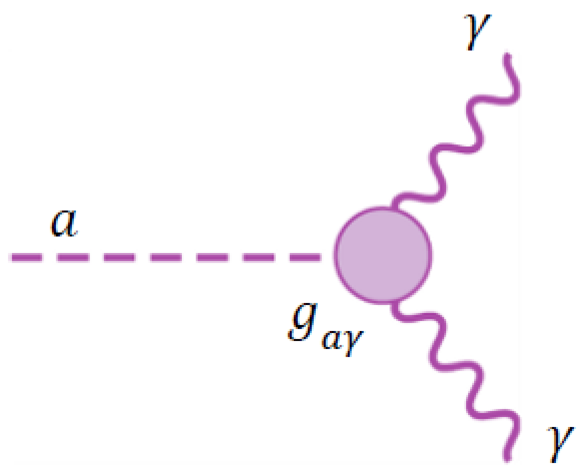
SN 1987A few events provide the most stringent constraints on ν velocity. Crucial for comparison with recent OPERA claim

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)

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



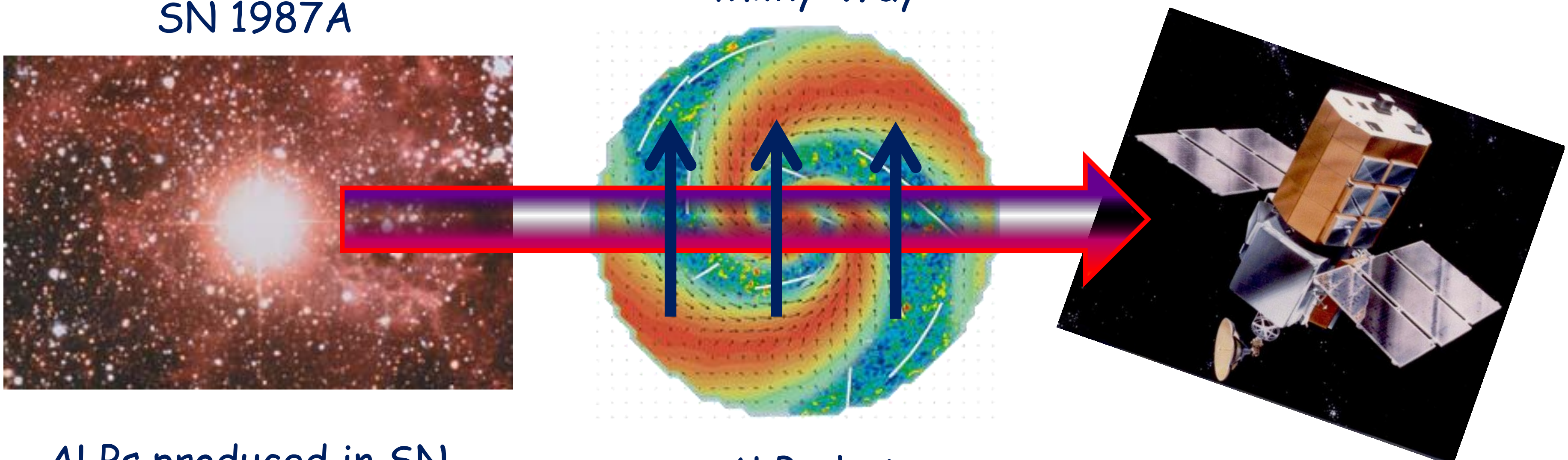
- Primakoff process: Photon-ALP transitions in external static E or B field

- 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

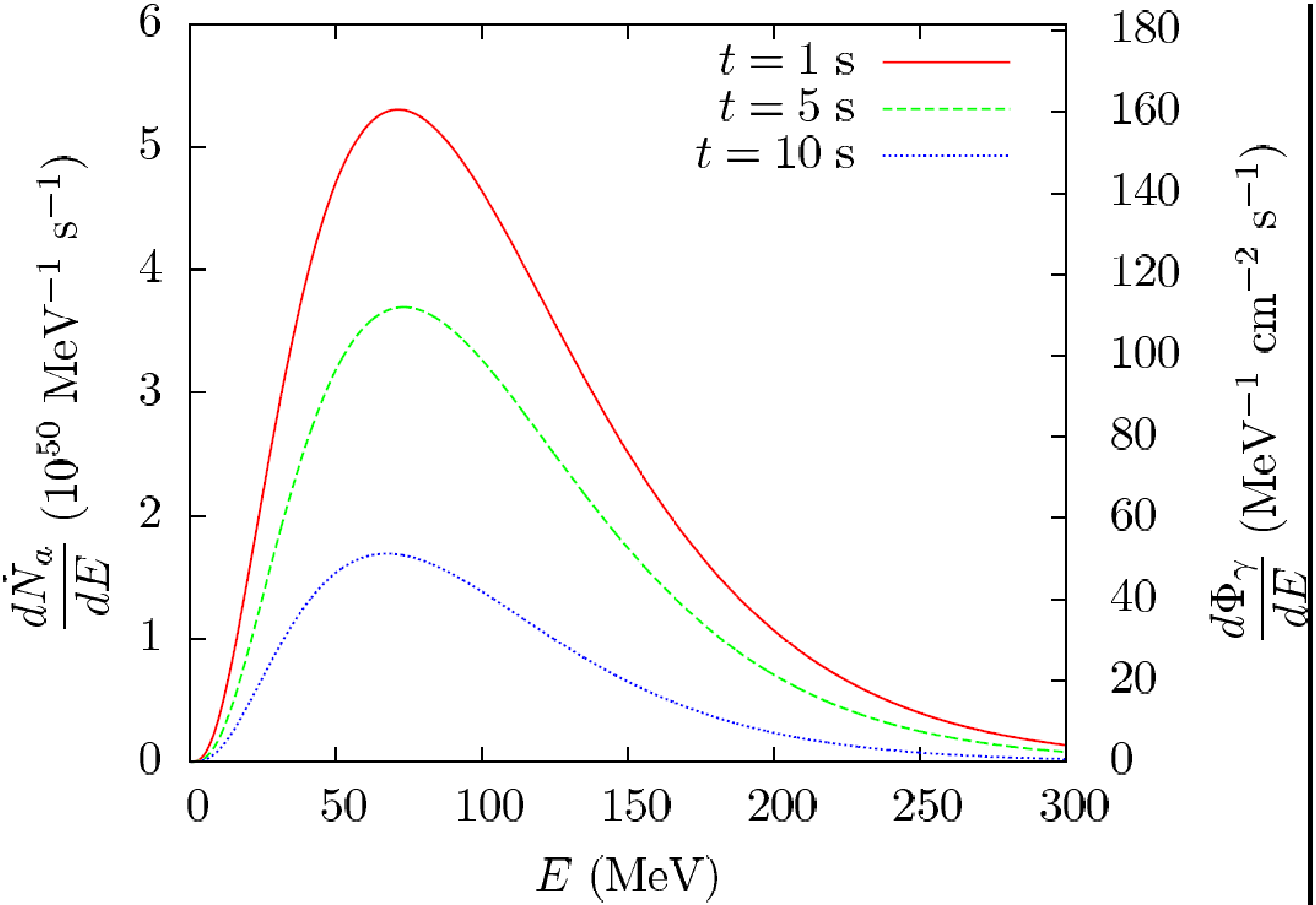
No excess gamma-rays in coincidence with SN 1987A

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

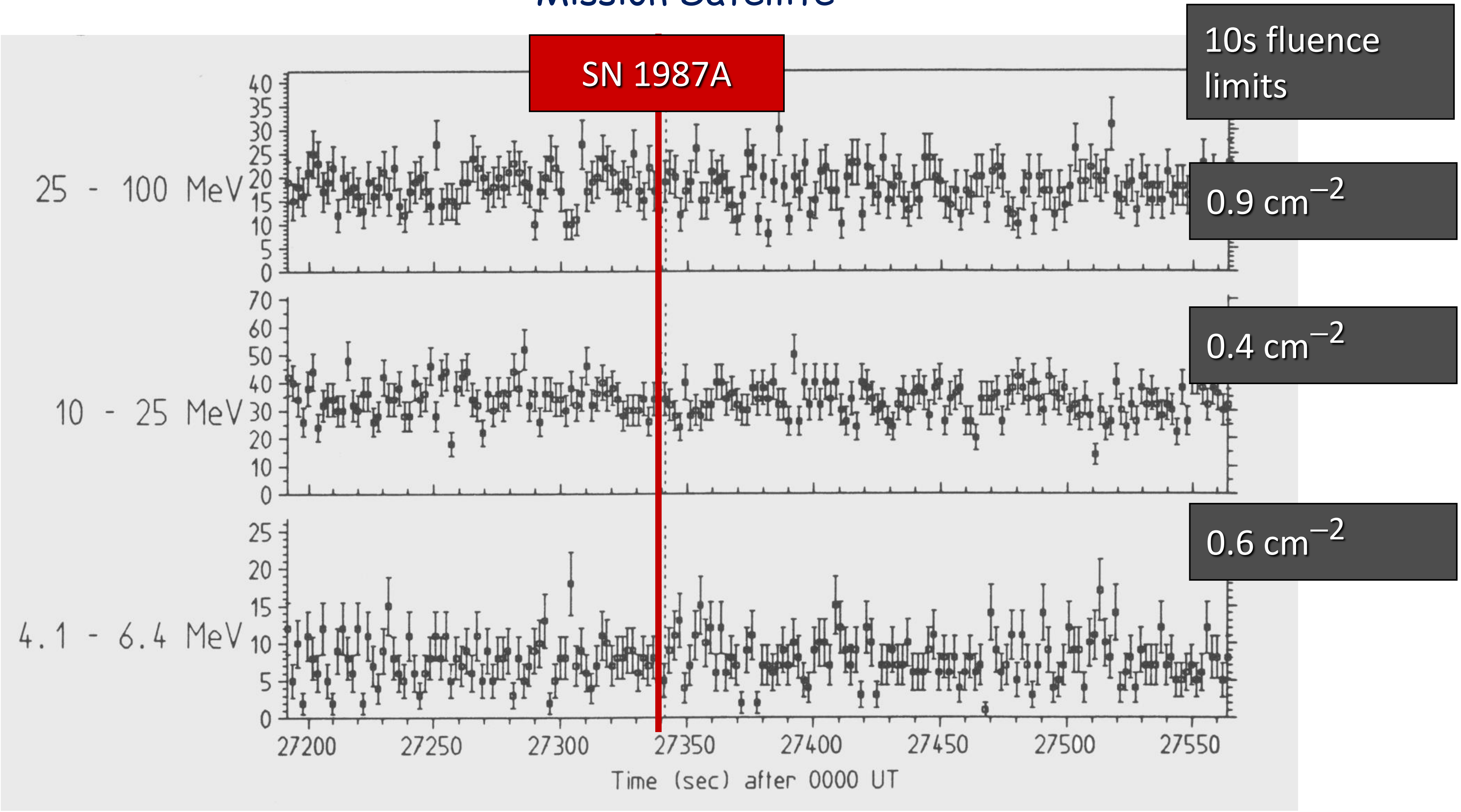
ALP-PHOTON FLUXES FOR SN 1987A

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



GAMMA-RAY OBSERVATION FROM SMM SATELLITE

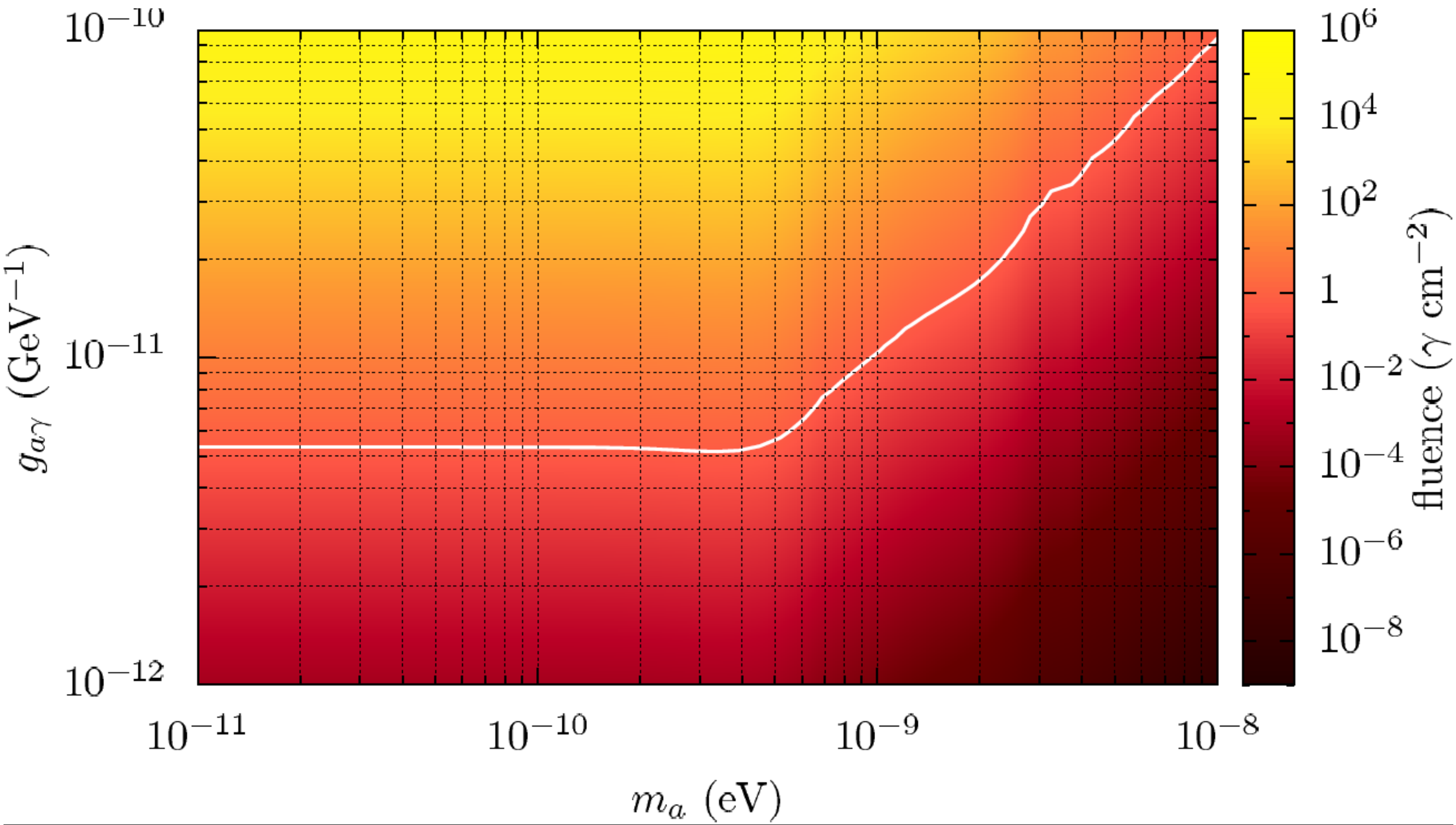
Counts in the GRS instrument on the Solar Maximum Mission Satellite



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

NEW BOUND ON ALPs FROM SN 1987A

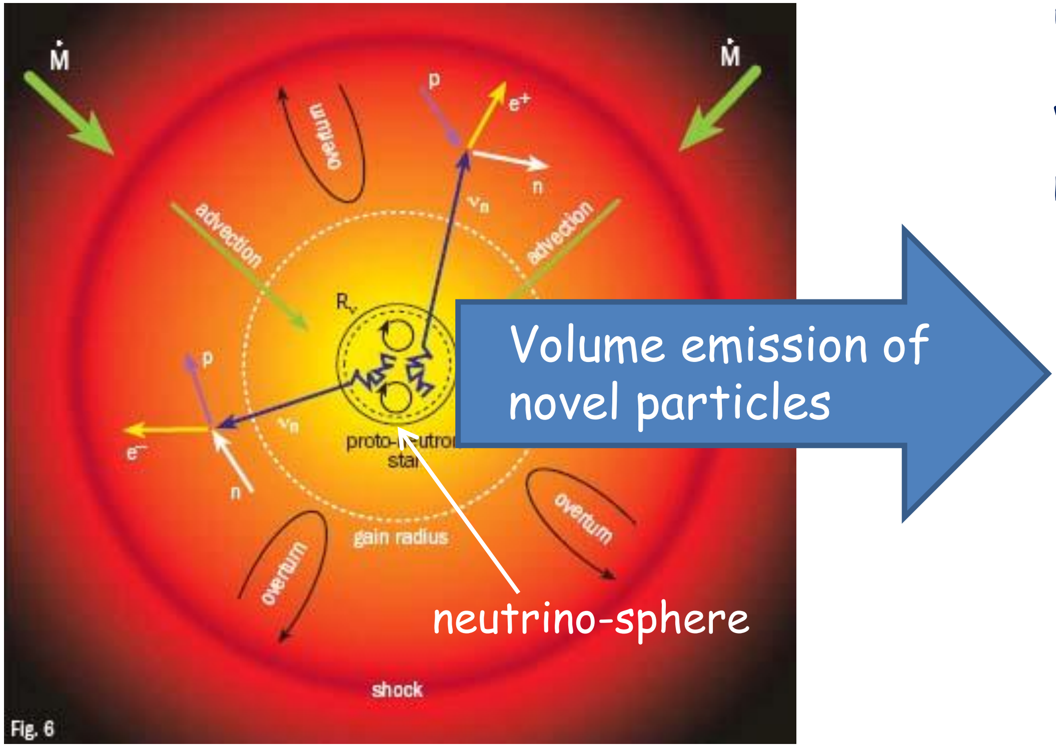
[*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*]



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

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

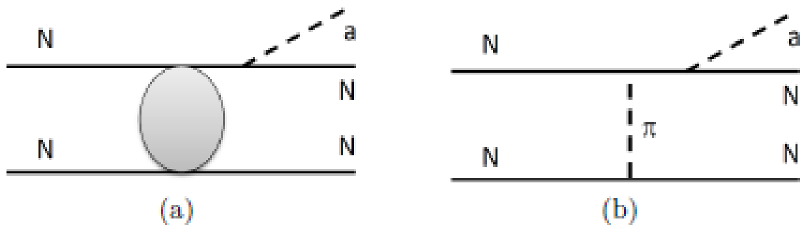
$$\varepsilon_x < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

for $\rho \approx 3 \times 10^{14}$ 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

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

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

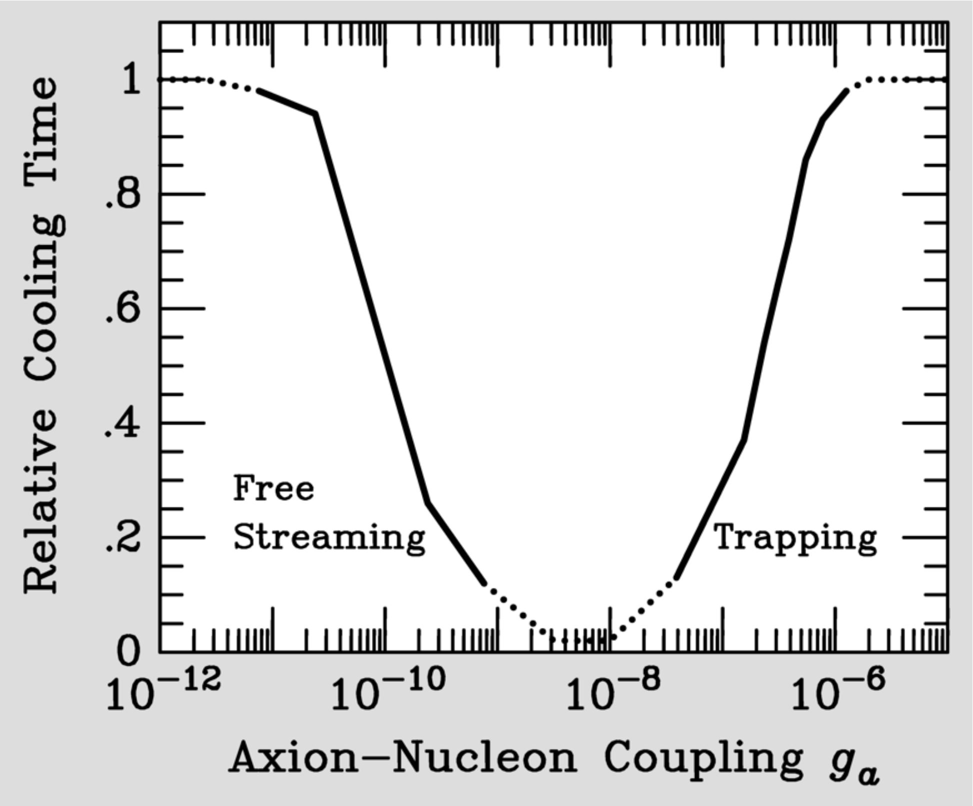
Non-degenerate energy-loss rate $\varepsilon_a = g_{aN}^2 \, 2\times 10^{39} \, \mathrm{erg\,g^{-1}\,s^{-1}} \rho_{15} T_{30}^{3.5}$

$$\begin{pmatrix} T_{30} = T/30\ \mathrm{MeV} \\ \rho_{15} = \rho/10^{15}\,\mathrm{g\,cm^{-3}} \end{pmatrix} \quad \langle \rho_{15} \rangle \approx 0.4 \quad \langle T_{30}^{3.5} \rangle \approx 1.4 \quad \Rightarrow \quad g_{aN} < 9\times 10^{-10}$$

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

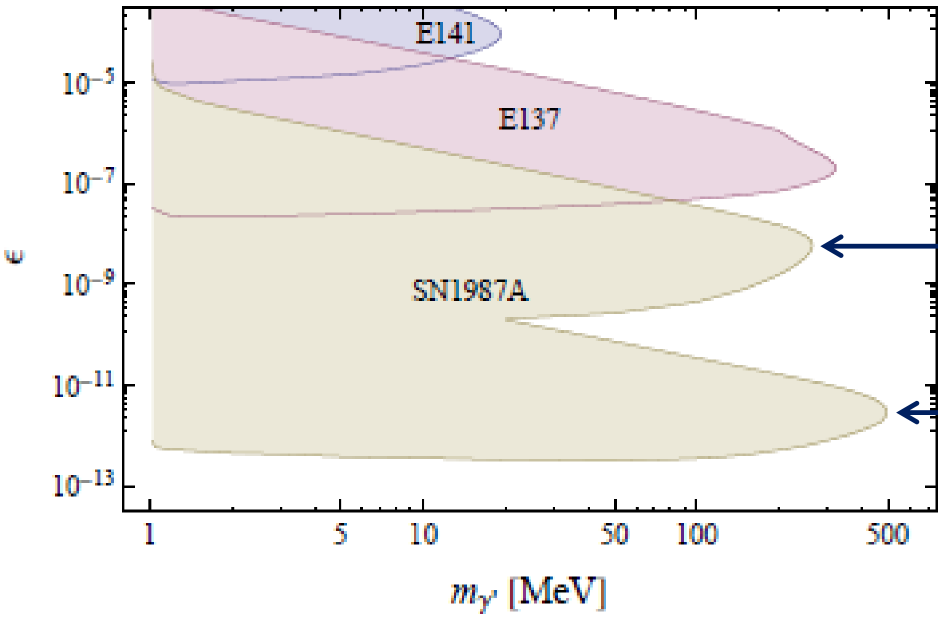
Hadronic axion (m_a ~ 1 eV, f_a~10^6 GeV) not excluded by SN 1987A. Possible hot-dark matter candidate. The "hadronic axion window" is closed by cosmological mass bounds.

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'

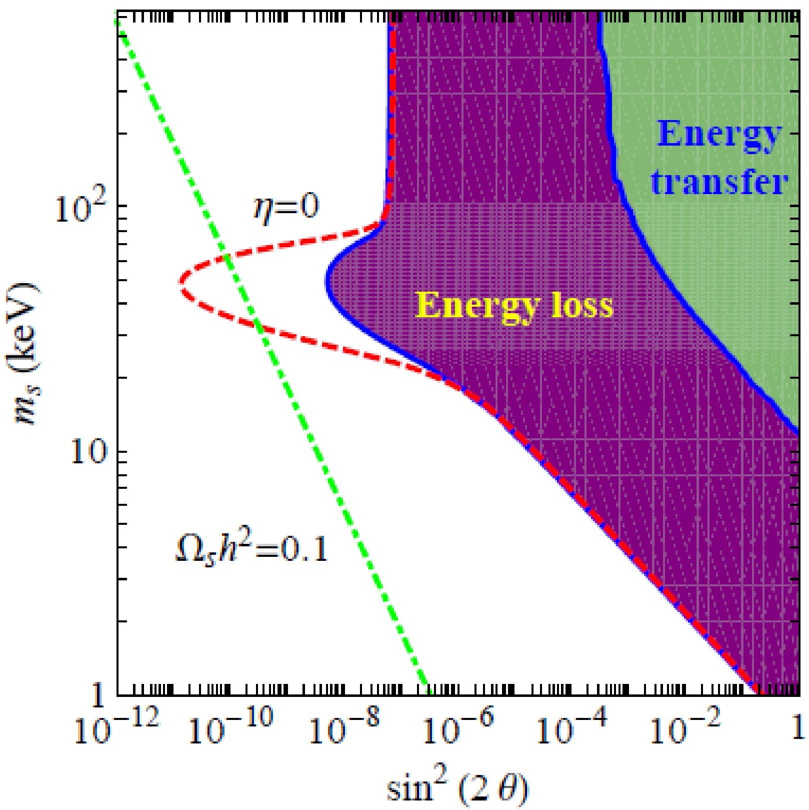


Energy-loss argument

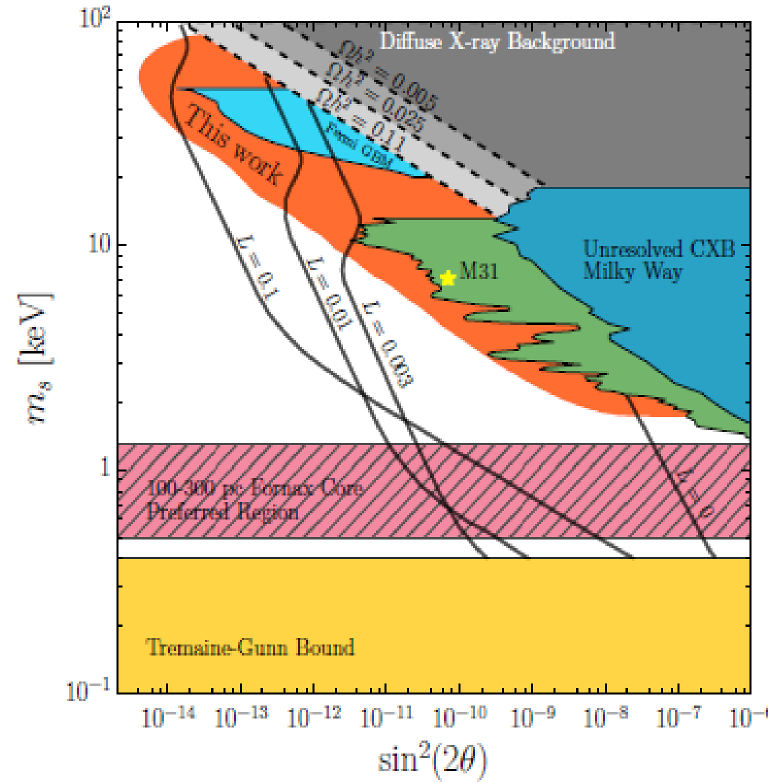
Electromagnetic decays ($\gamma' \rightarrow e^+ e^-$) [bounds of fluence of gamma-rays]

SN 1987A BOUND ON KeV STERILE NEUTRINOS

Raffelt & Zhou, 1102.5124



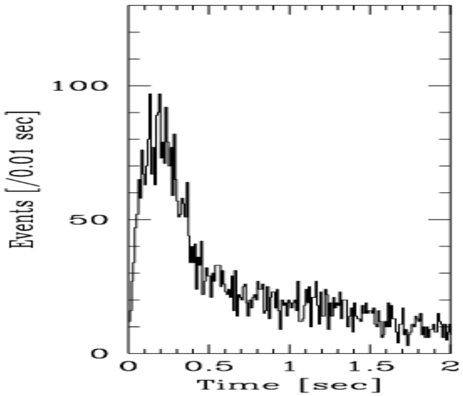
Argüelles, Brdar and Kopp, 1605.00654



- 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.

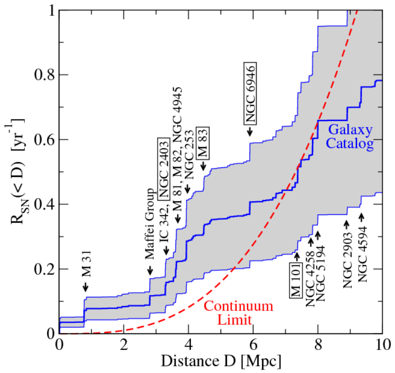
FUTURE SN NEUTRINO OBSERVATIONS

NEUTRINO DETECTION METHODS



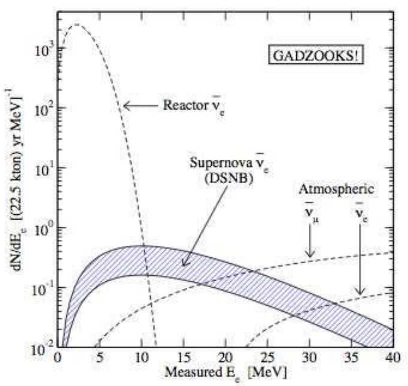
- **Milky-Way SN**

  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

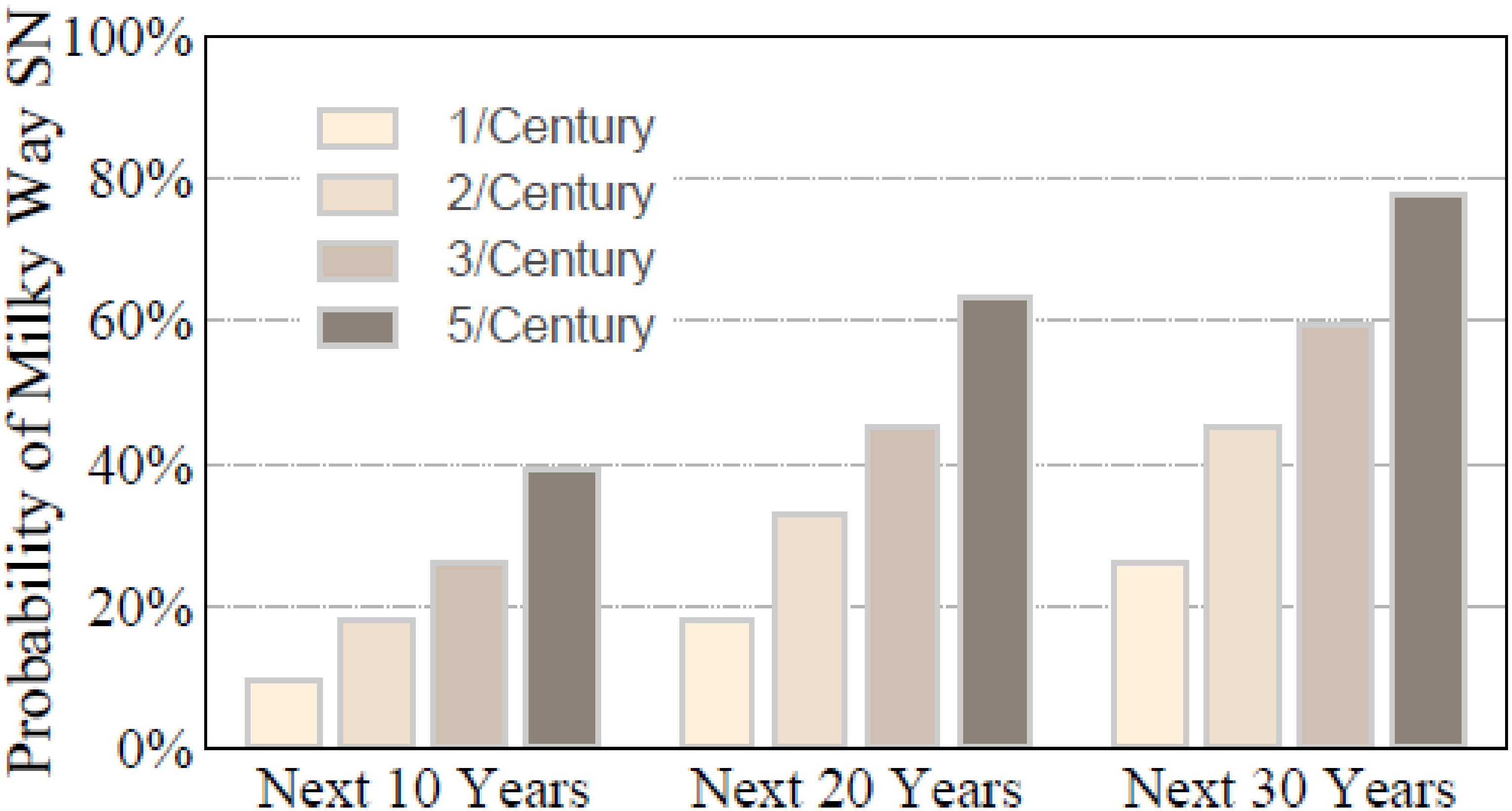


- **Diffuse Supernova Neutrino Background (DSNB)**

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

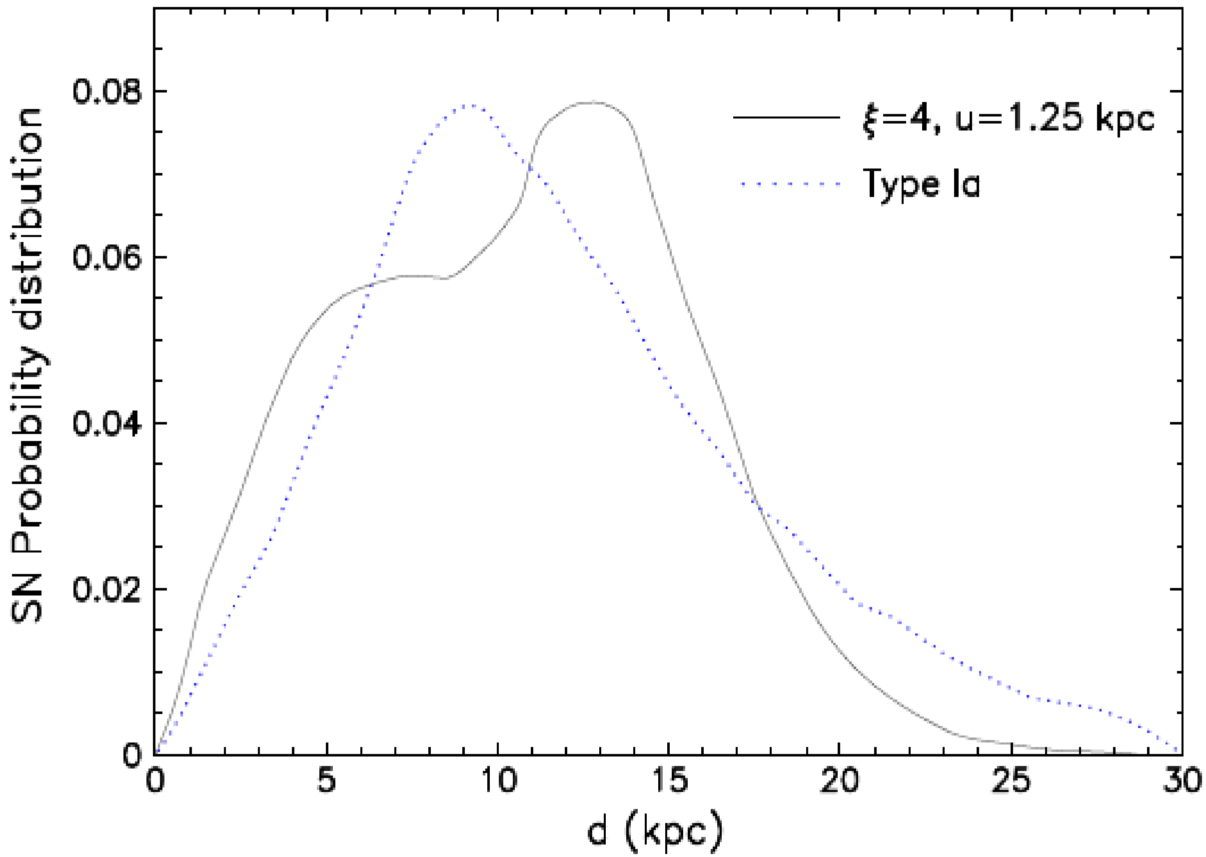
PROBABILITY OF MILKY-WAY SN

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



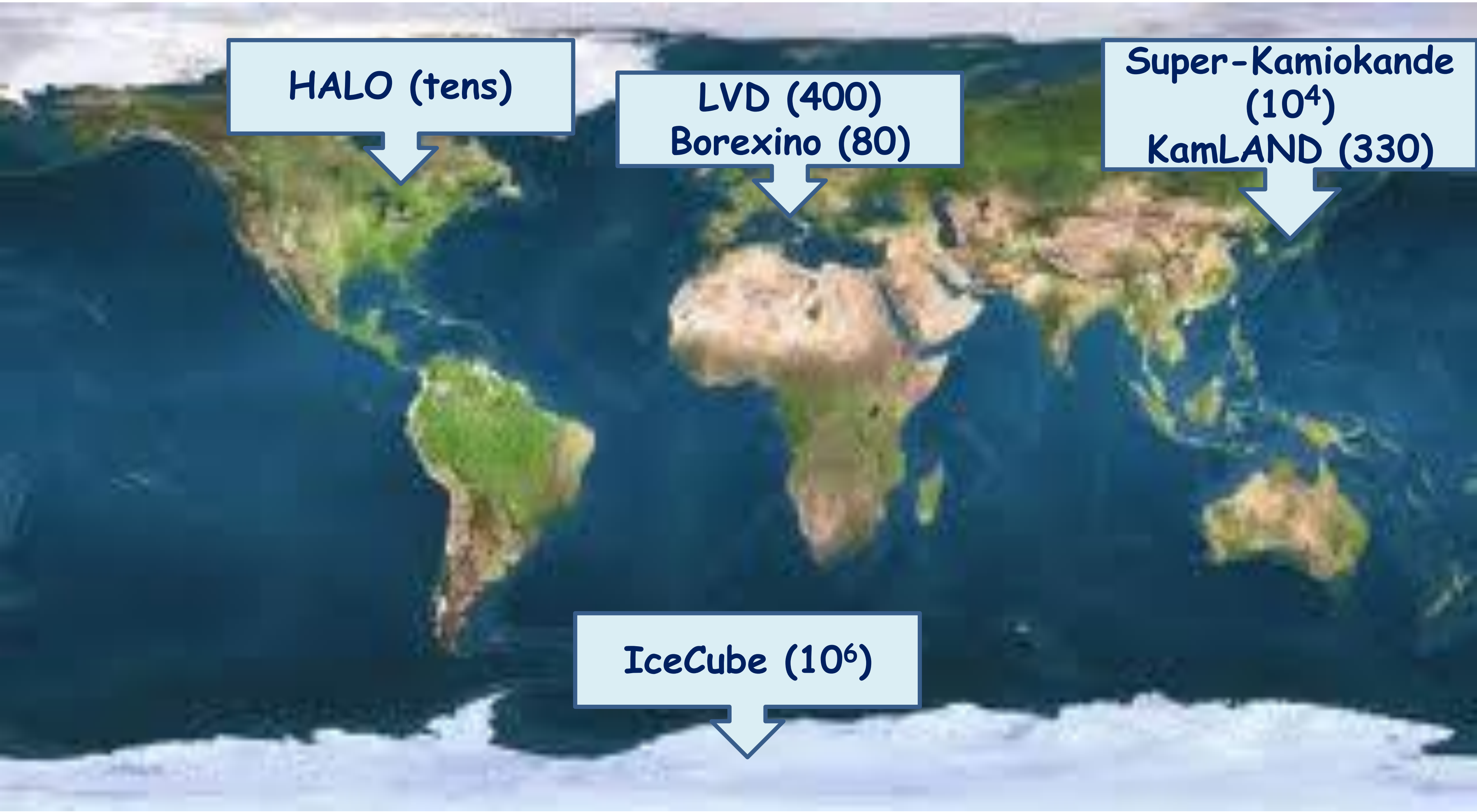
GALACTIC SUPERNOVA DISTANCE DISTRIBUTION

[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

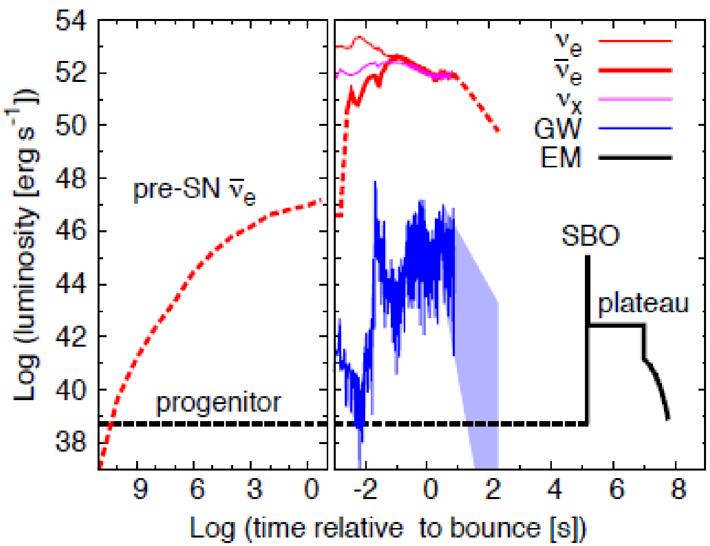
[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]

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

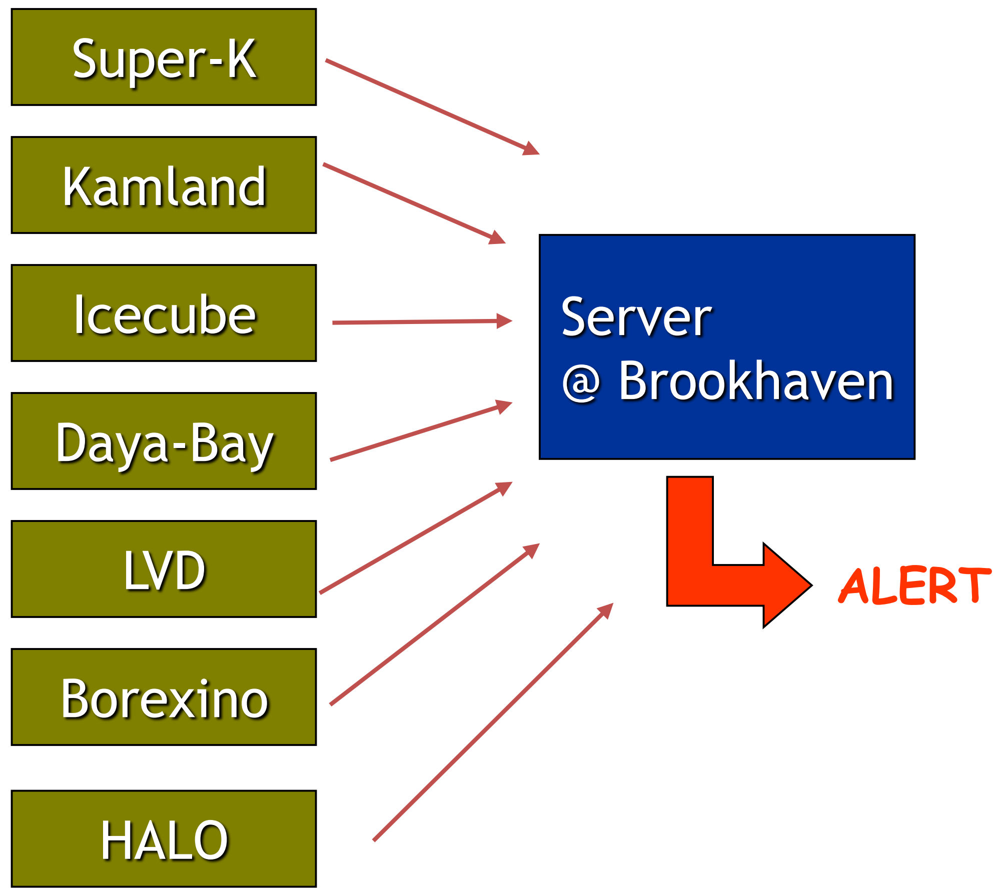
SUPERNOVA EARLY WARNING SYSTEM (SNEWS)

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

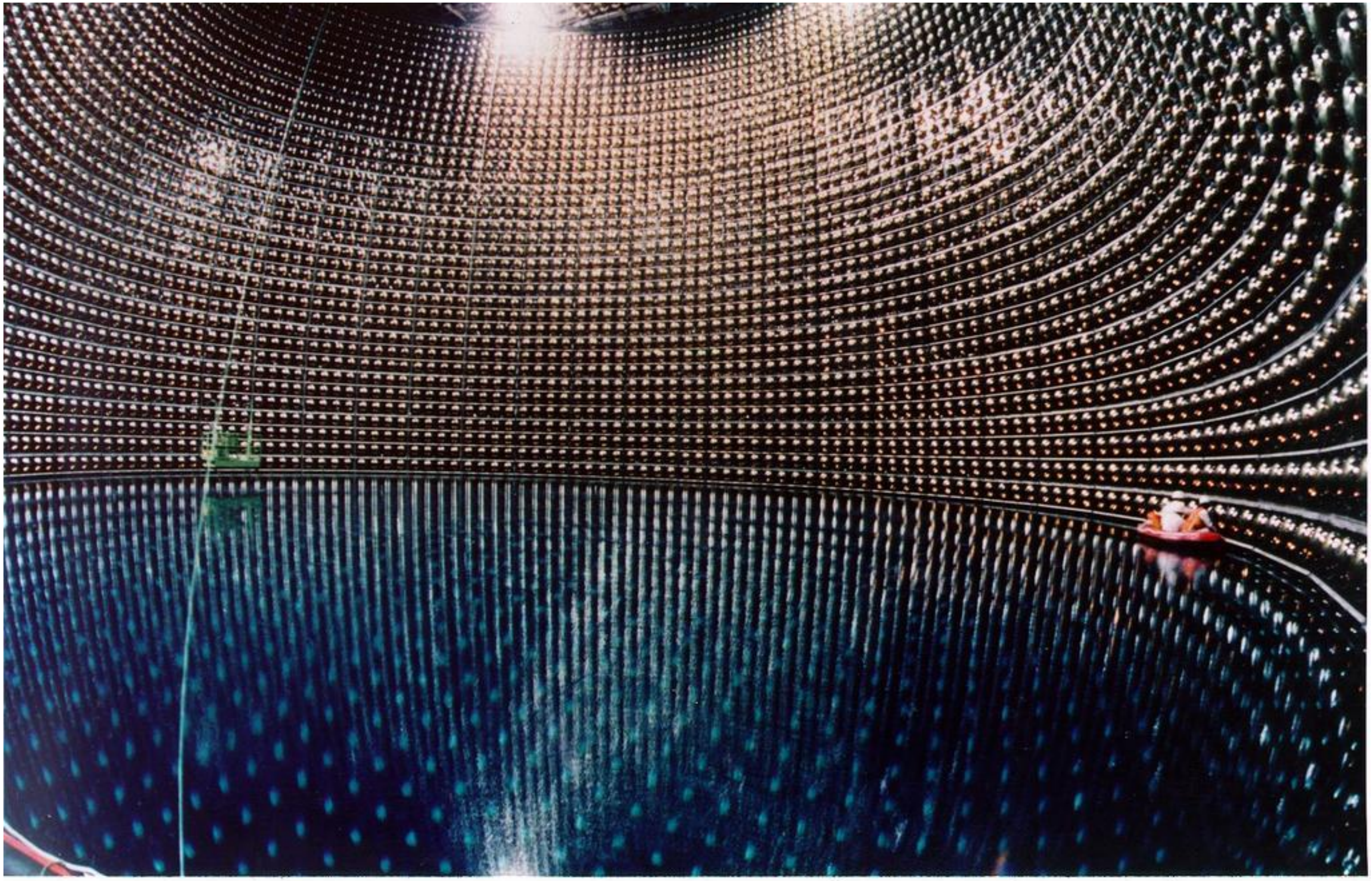
Neutrinos several hours before light



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

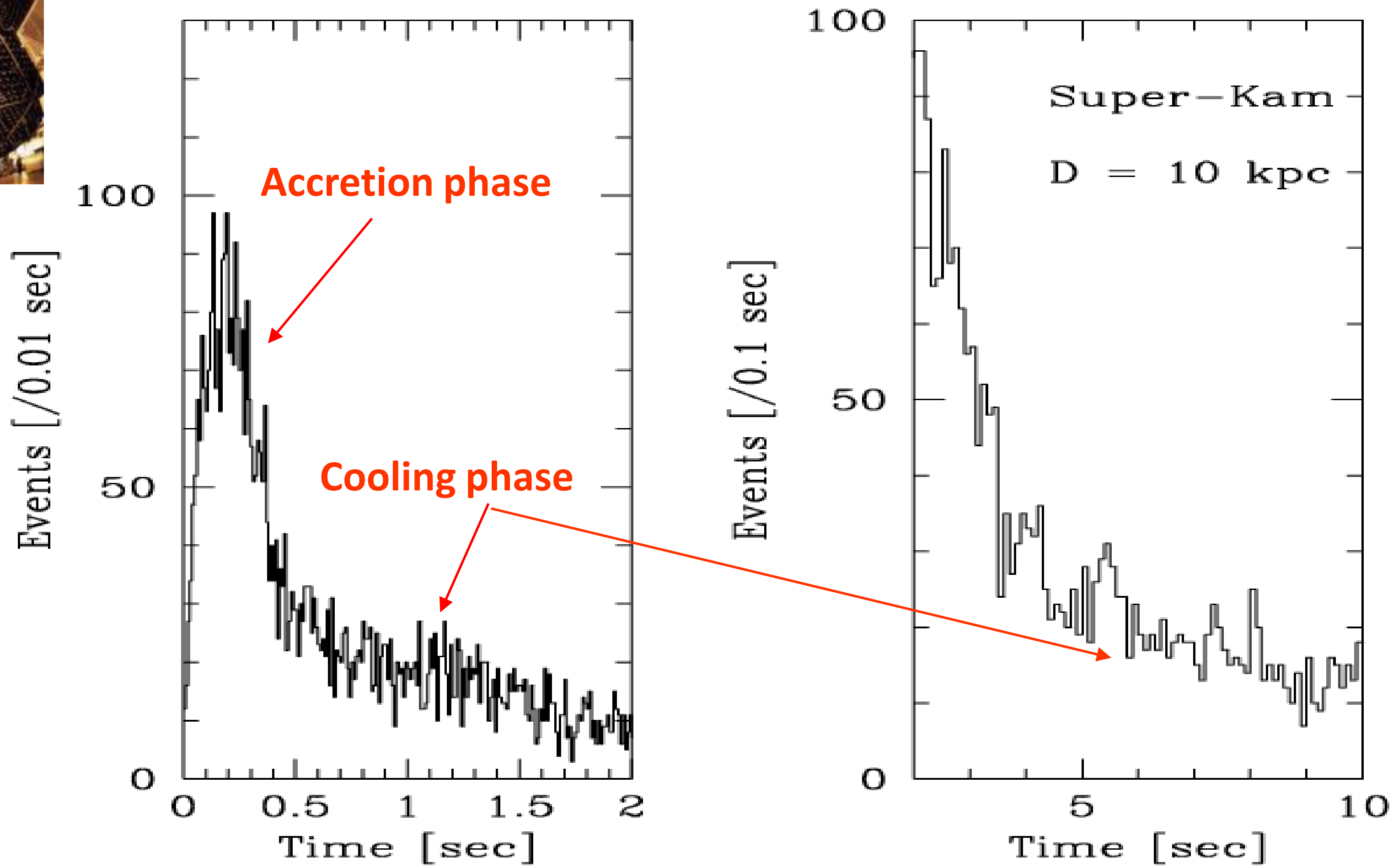


SUPER-KAMIOKANDE DETECTOR



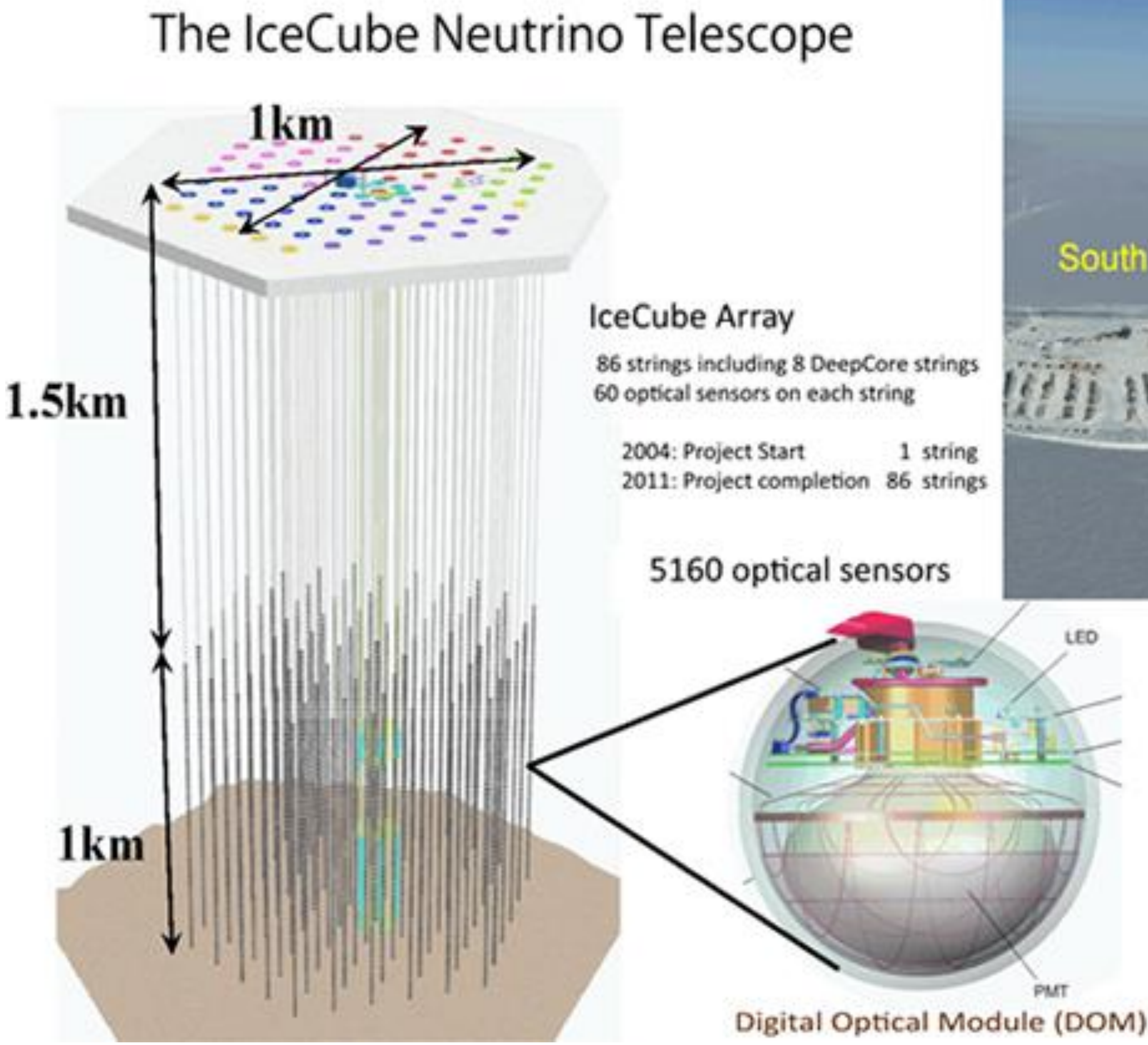
SK is a cylindrical tank containing 50000 ton of light water surrounded by photomultipliers, located underground in the Kamioka mine in Japan.

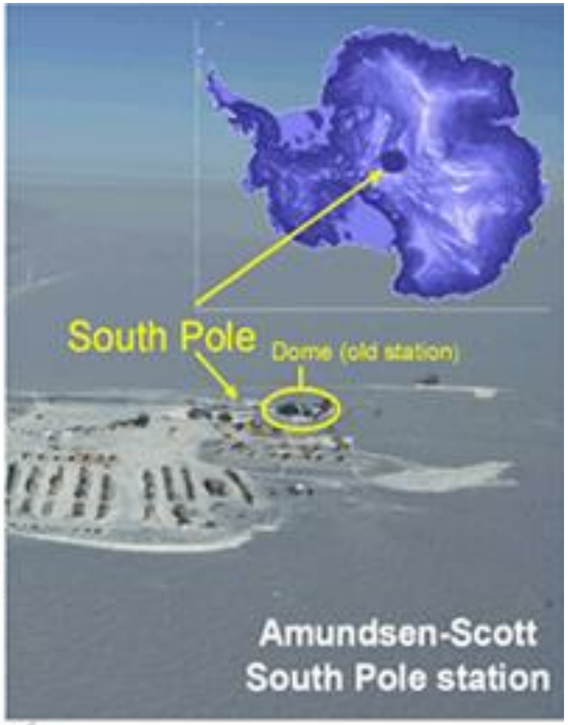
Simulated Supernova Signal at Super-Kamiokande



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

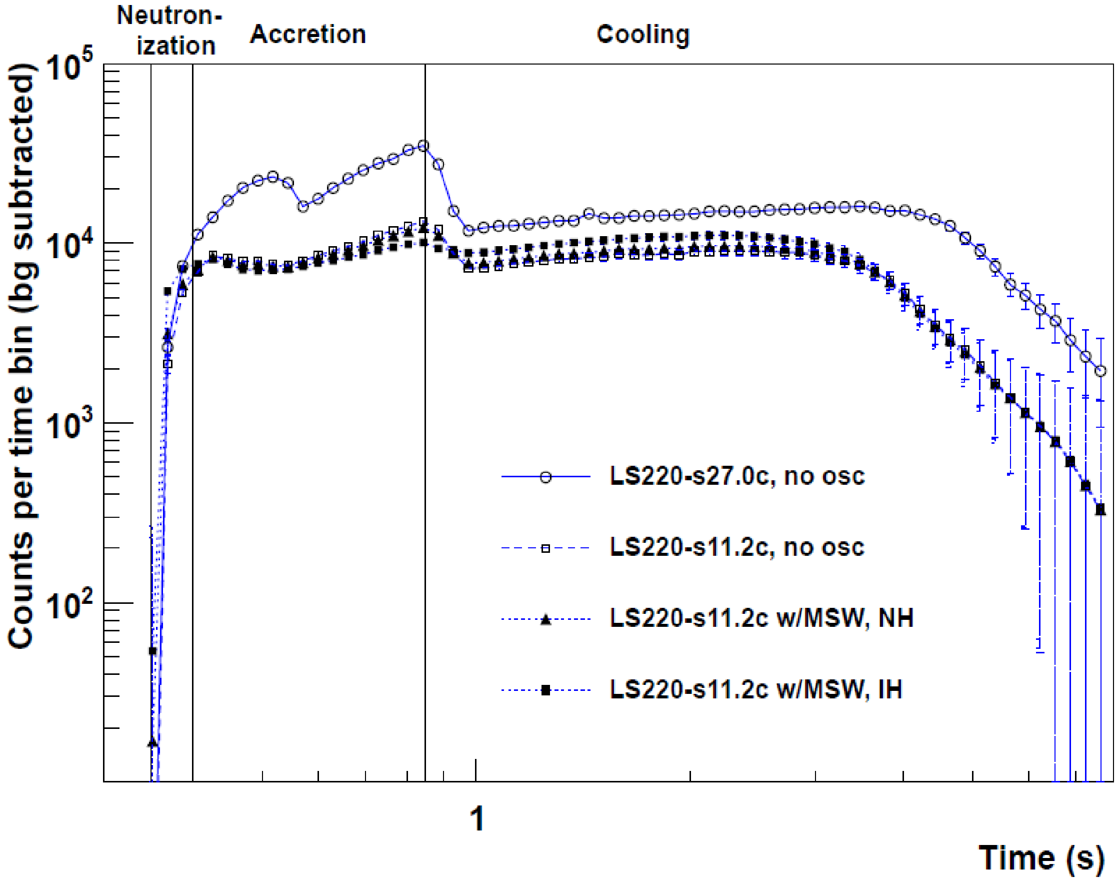
ICECUBE NEUTRINO TELESCOPE AT SOUTH POLE





SN NU SIGNAL IN ICECUBE

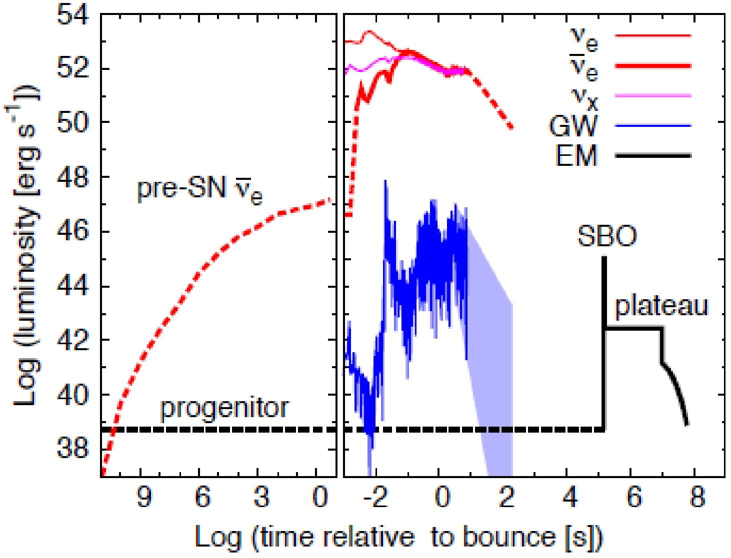
[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]



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

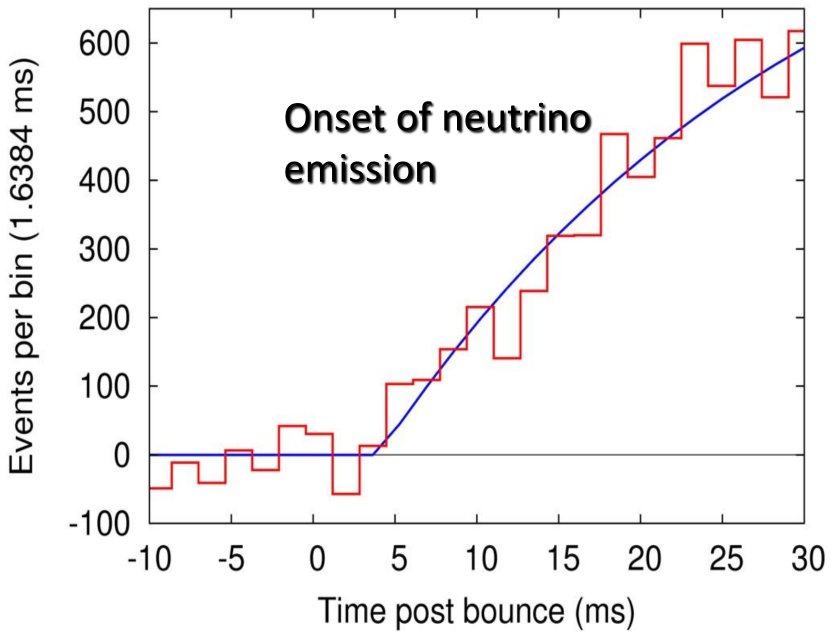
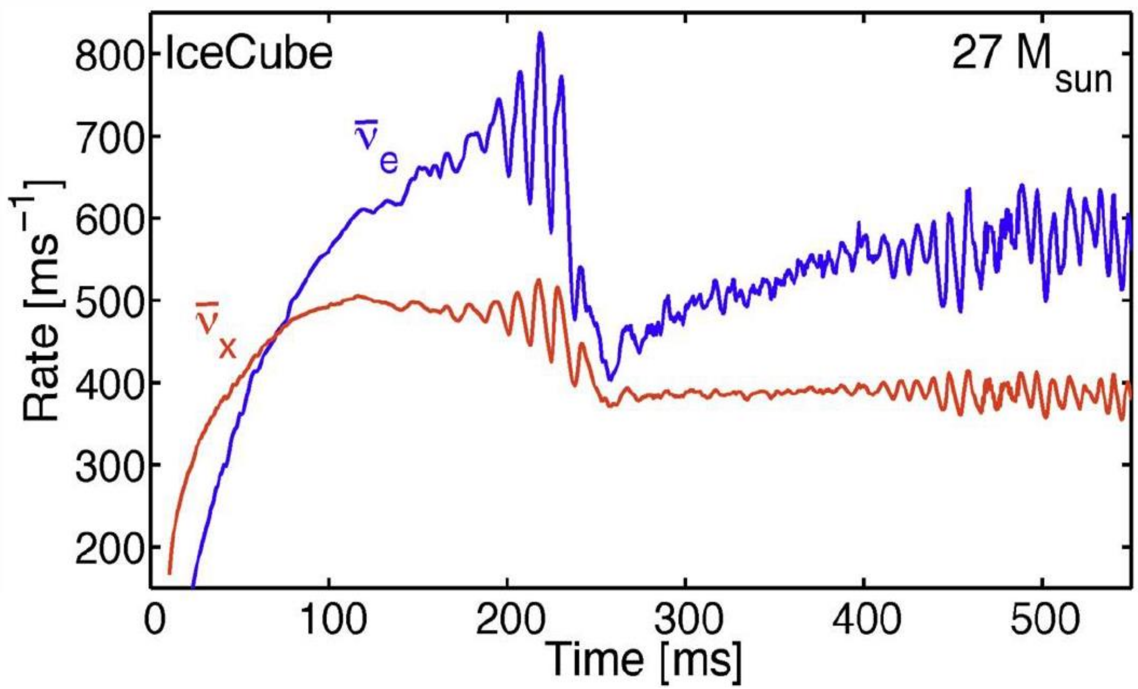


FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

[Halzen & Raffelt, arXiv:0908.2317]

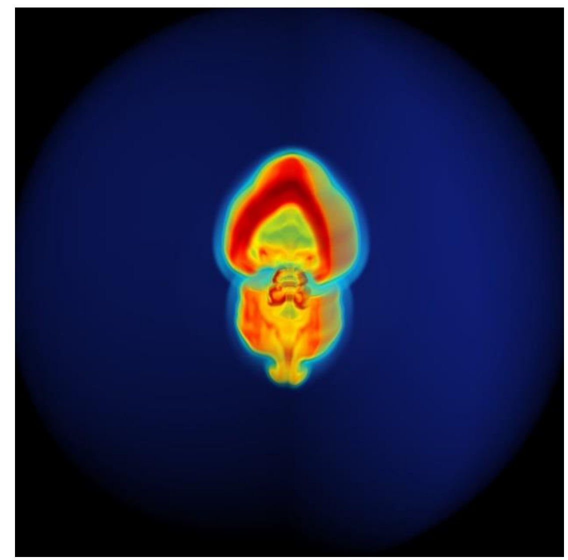
Possible also in Super-K
[see Pagliaroli, Vissani, Coccia & Fulgione arXiv:0903.1191]

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

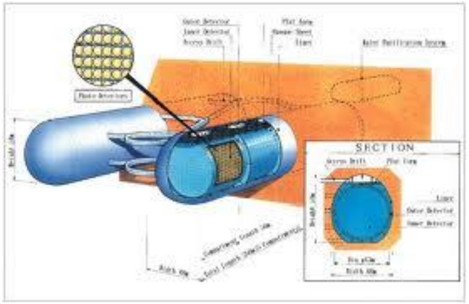
Icecube is ok!

NEXT-GENERATION DETECTORS

Mton scale water Cherenkov detectors

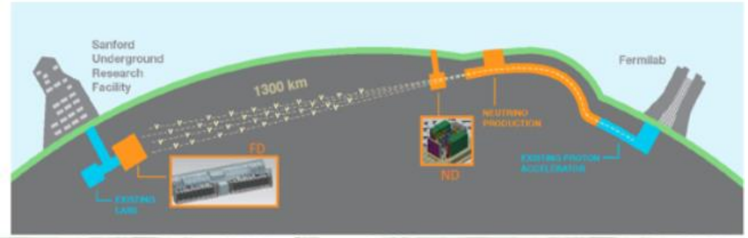
(10^5 events) $(\bar{\nu}_e)$

HYPER-KAMIOKANDE



40 kton Liquid Argon TPC

(3000 events) (ν_e)



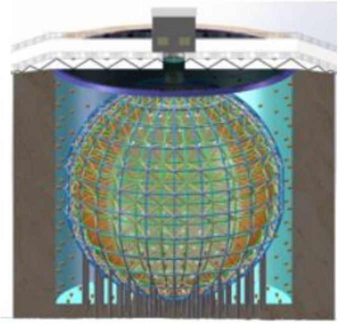
DUNE

Dark matter detectors

DARWIN
40 tons
(700 events)
$(\nu_{e,x}, \bar{\nu}_{e,x})$

20 kton scintillator

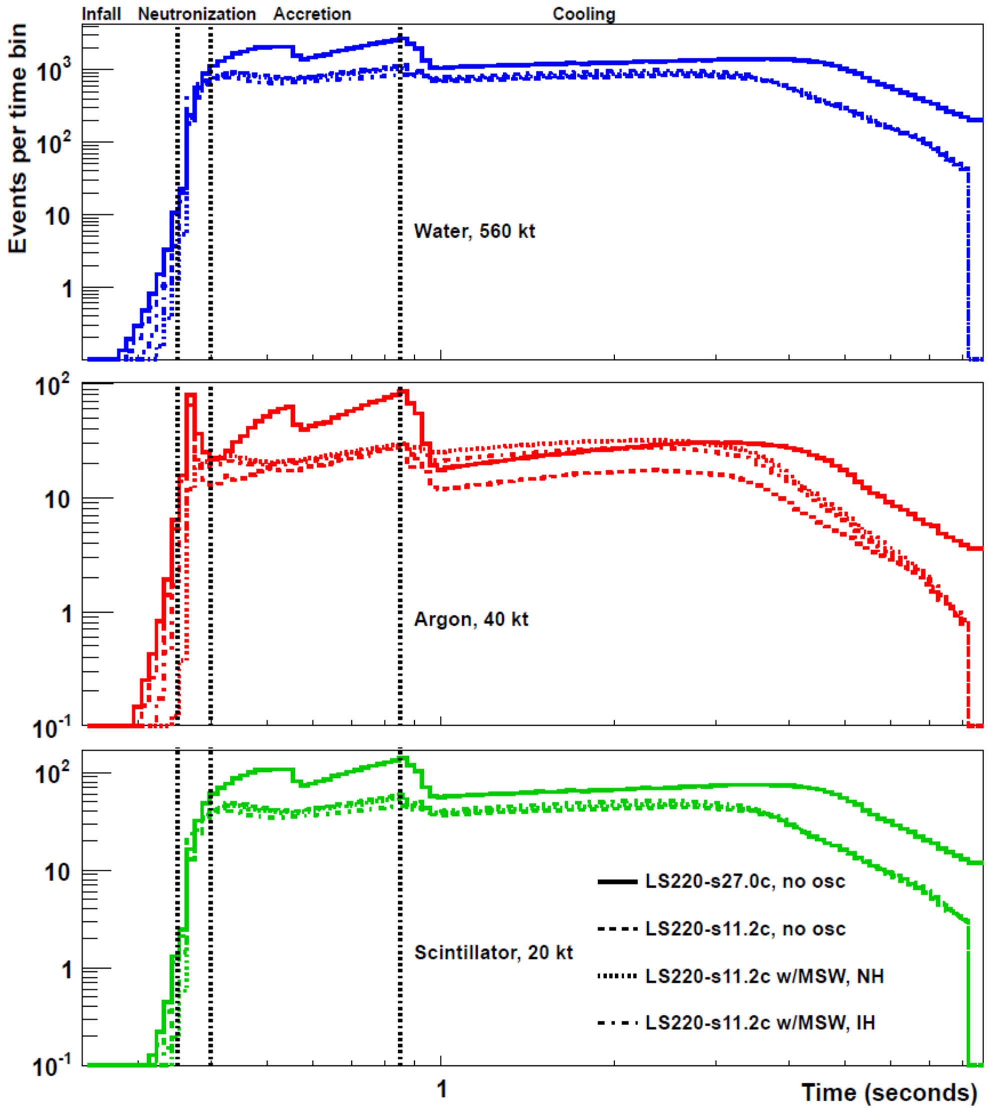
(6000 events) $(\bar{\nu}_e)$



JUNO

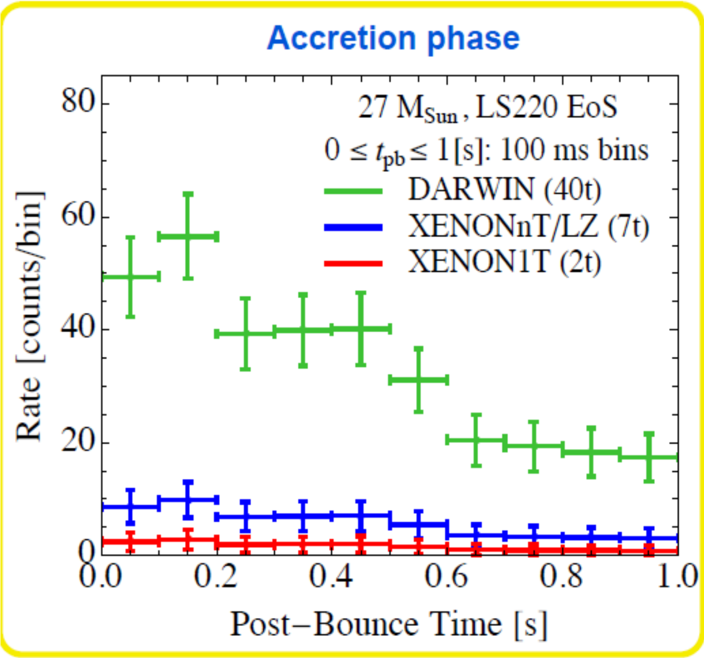
SN NU SIGNAL IN FUTURE DETECTORS

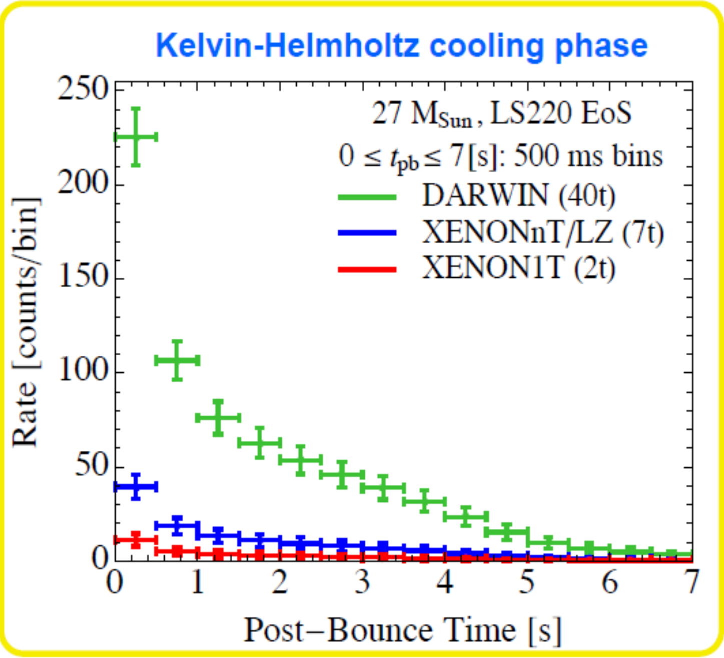
[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]



SN NU SIGNAL IN DM DETECTORS

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





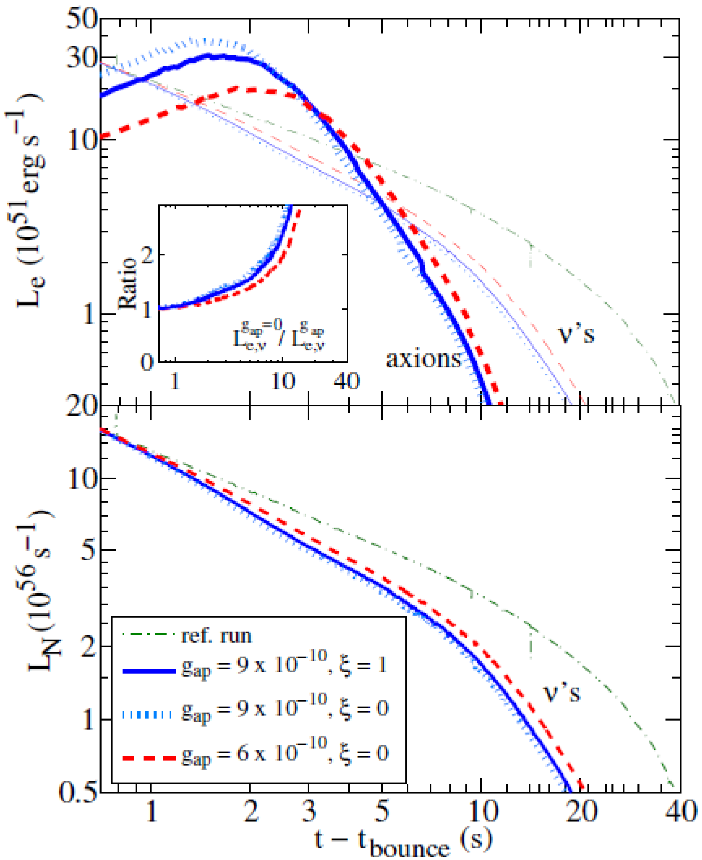
DARWIN will be able to clearly reconstruct the neutrino light-curve and to differentiate among phases of neutrino signal. Partial sensitivity with XENONnT/LZ.

A REAPPRISAL OF AXION EMISSION WITH STATE OF ART SIMULATIONS

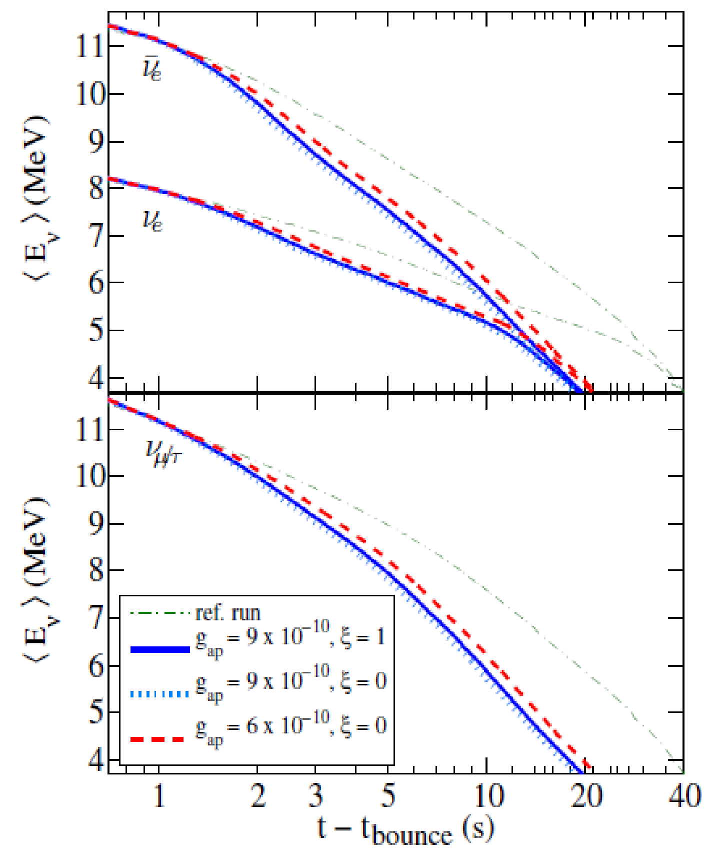
[Fischer, Chakraborty, Giannotti A.M. , Payez & Ringwald, 1605.08780]

18 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)



(a) Energy and number luminosities

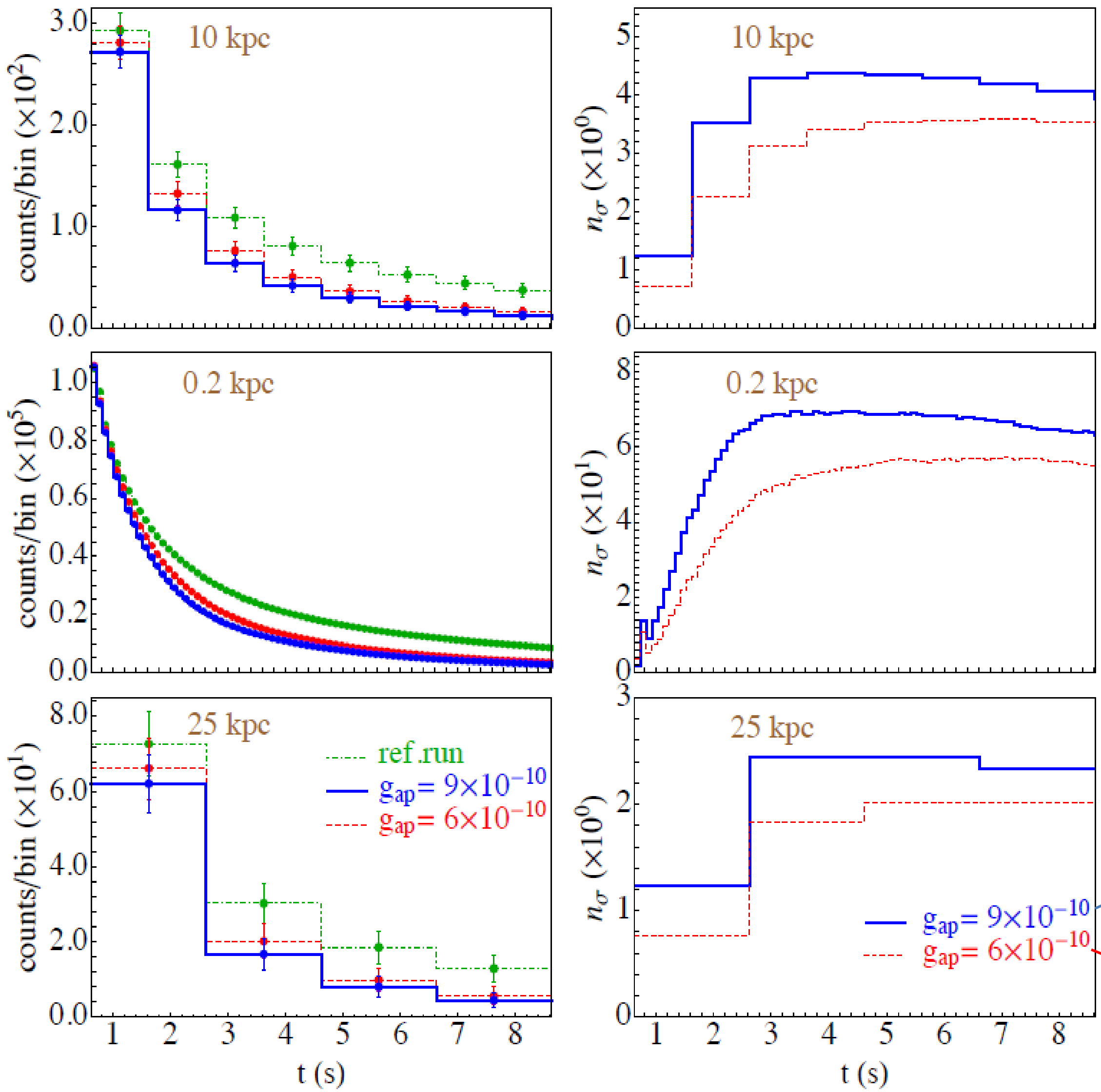


(b) Average neutrino energies

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

IMPACT ON NEUTRINO SIGNAL

@ Super-Kamiokande



(~ GC)

(Betelgeuse)

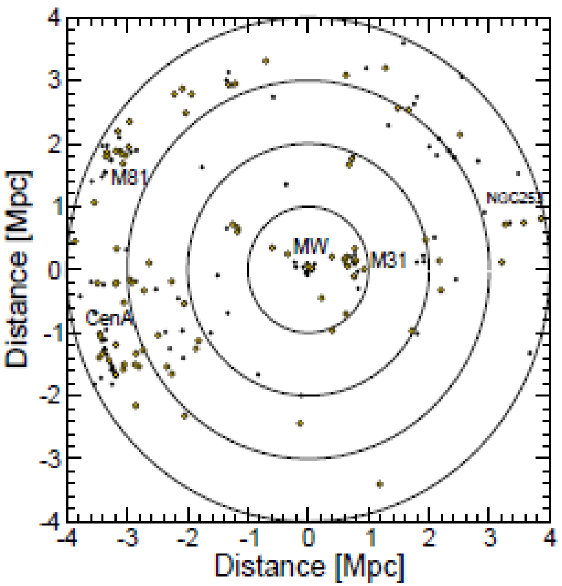
$m_a = 3 \times 10^{-2}\, eV$, $f_a = 4.8 \times 10^{8} GeV$

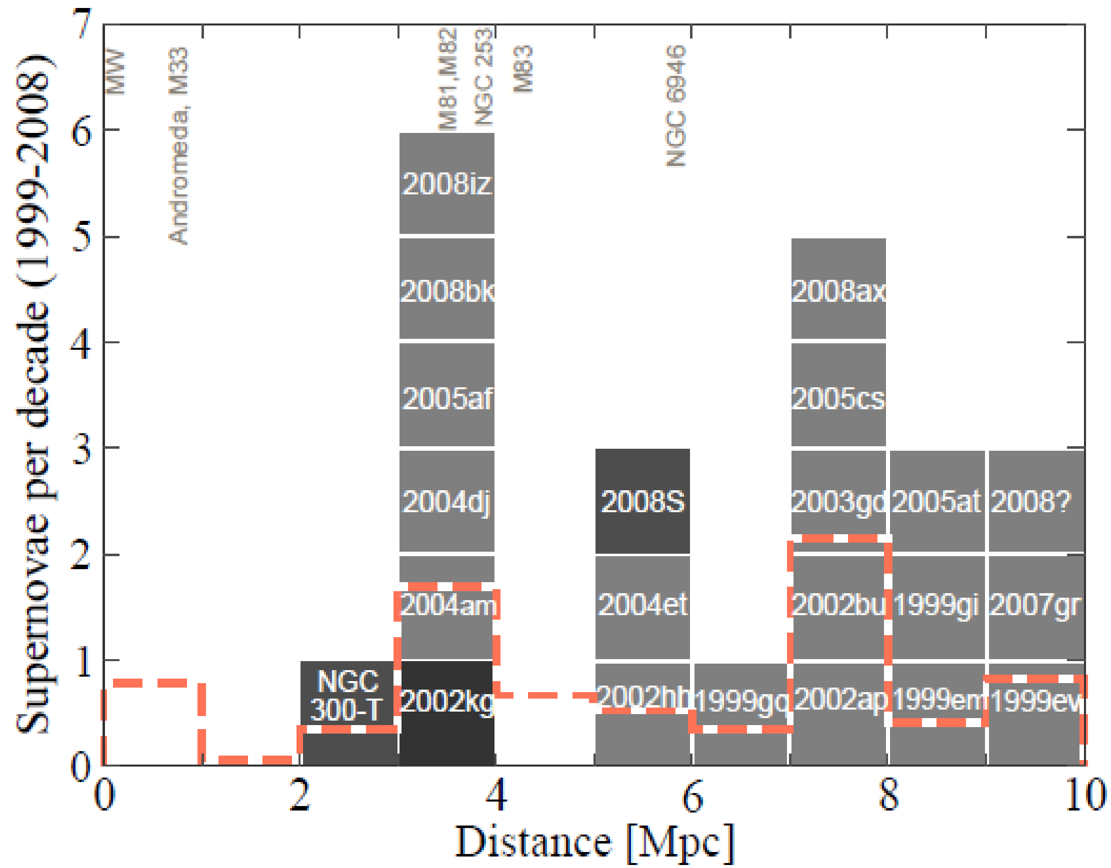
$m_a = 8 \times 10^{-2}\, eV$, $f_a = 7.3 \times 10^{8} GeV$

NEUTRINOS FROM ALL COSMIC SUPERNAVAE

OBSERVED SUPERNOVAE IN THE LOCAL UNIVERSE

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



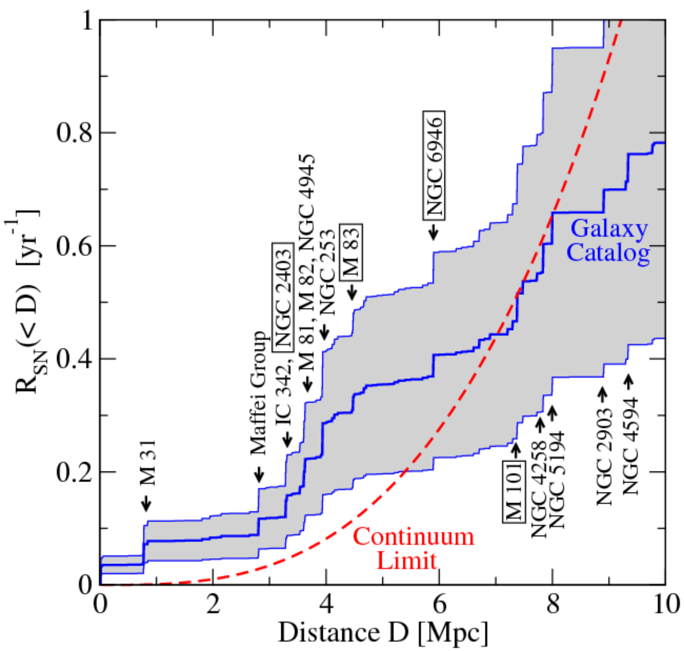


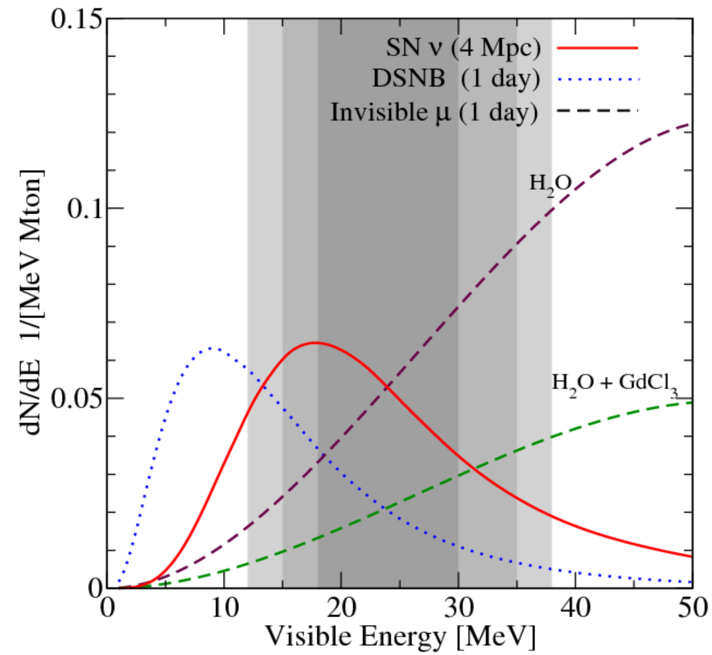
Detection of Neutrinos from Supernovae in Nearby Galaxies

[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.

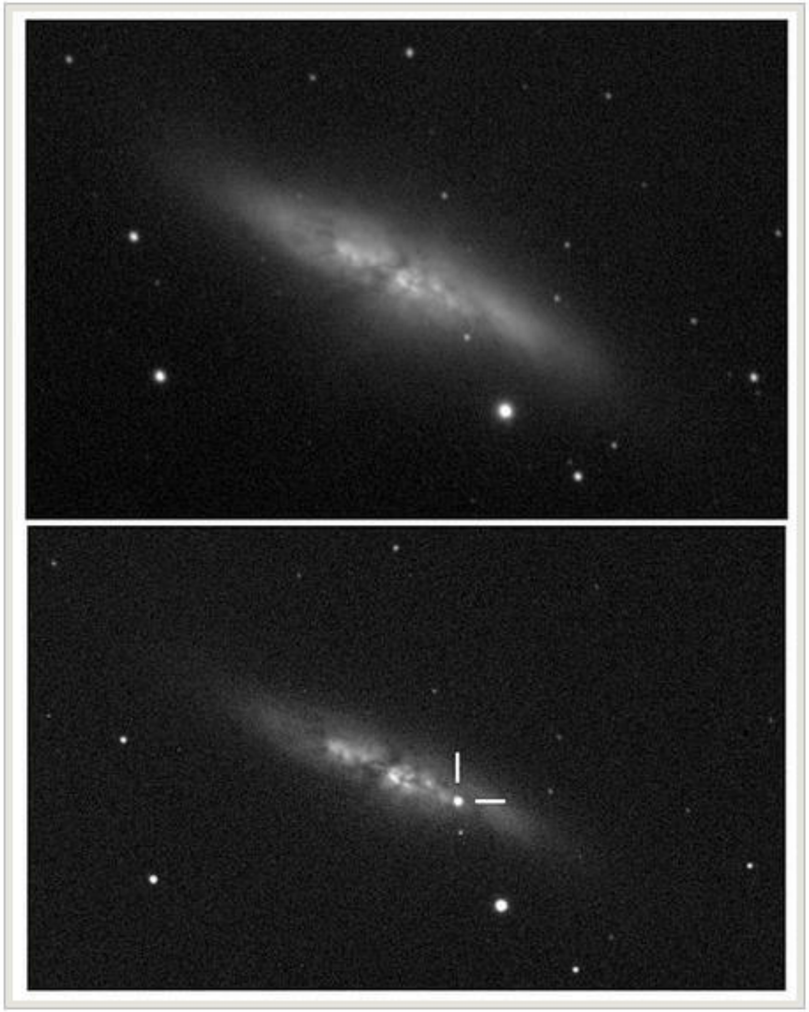
		32 kton (SK)	0.5 Mton (HK)	5 Mton (Deep-TITAND)
10 kpc	(Milky Way)	10^4	10^5	10^6
1 Mpc	(M31, M33)	1	10	10^2
3 Mpc	(M81, M82)	10^{-1}	1	10

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.

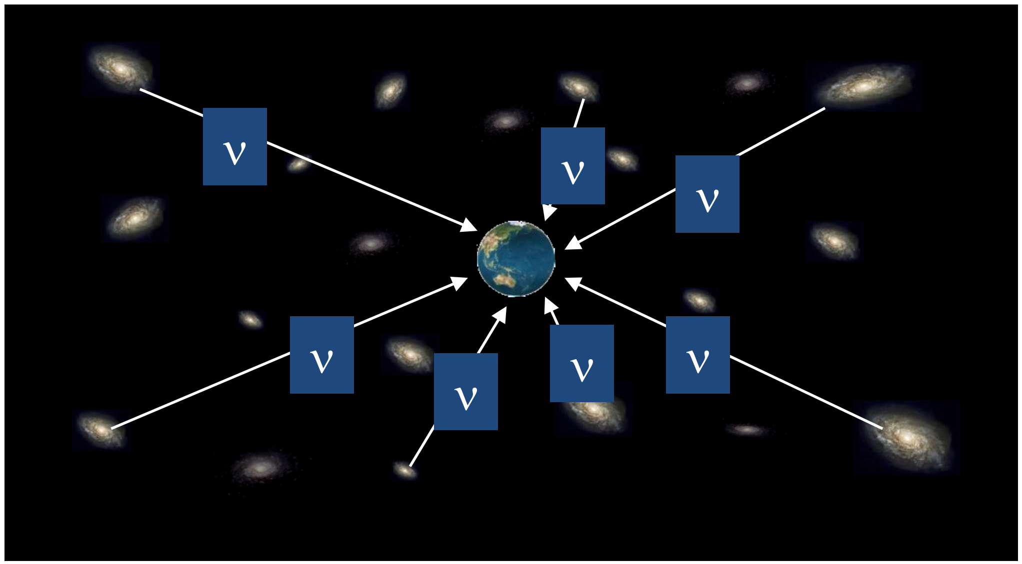
The supernova is exciting for a number of reasons that other outlets have well outlined — but unfortunately for Kate Scholberg, neutrinos are not one of them. Scholberg, a Duke University physics professor, studies the mysterious, nearly-massless particles at Super-K, a detector located deep in the mountains 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.

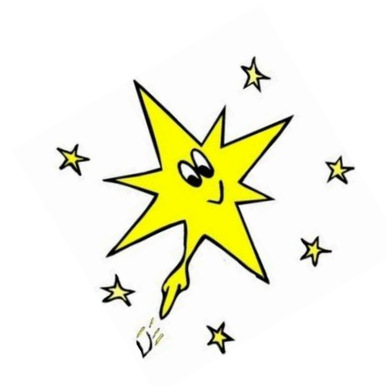
"M82 is too far away for us to see any neutrinos from it," Scholberg wrote in an email. "It's about 11.4 million light years from us, meaning that the chance of seeing even a single neutrino from a core-collapse supernova in current detectors is probably a few percent or less (of course, we'll look)."

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?

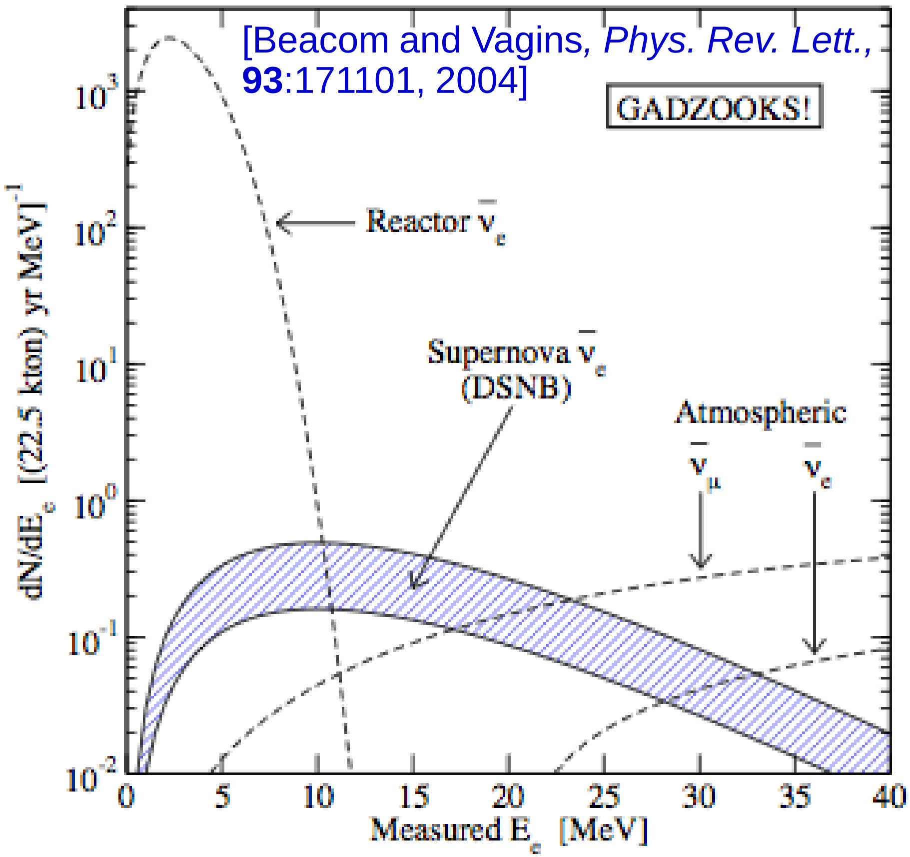
In principle, we can extract information on:

- 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 → flux limit

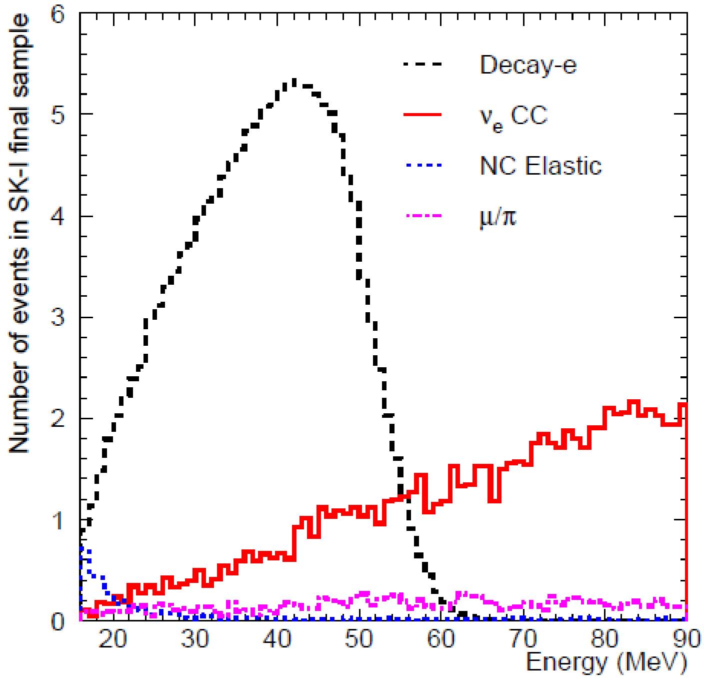


FIG. 11. Spectra of the four remaining backgrounds in the signal Cherenkov angle region with all reduction cuts applied. The ν_μ CC channel is from decay electron data; the other three are from MC. All are scaled to the SK-I LMA best fit result.

DSNB signal should manifest as distortion of the bkg spectra.

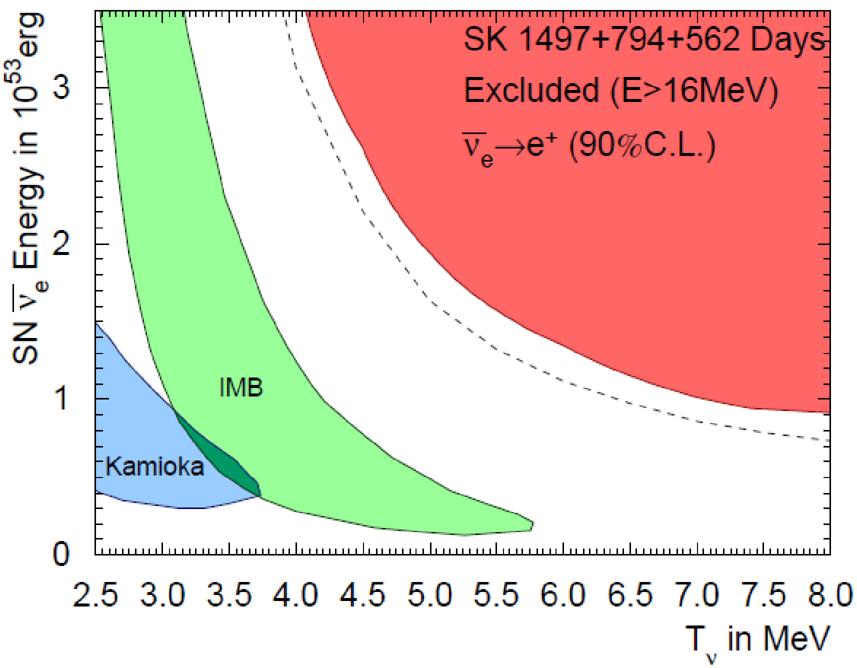
No distortion ⟶ flux limit

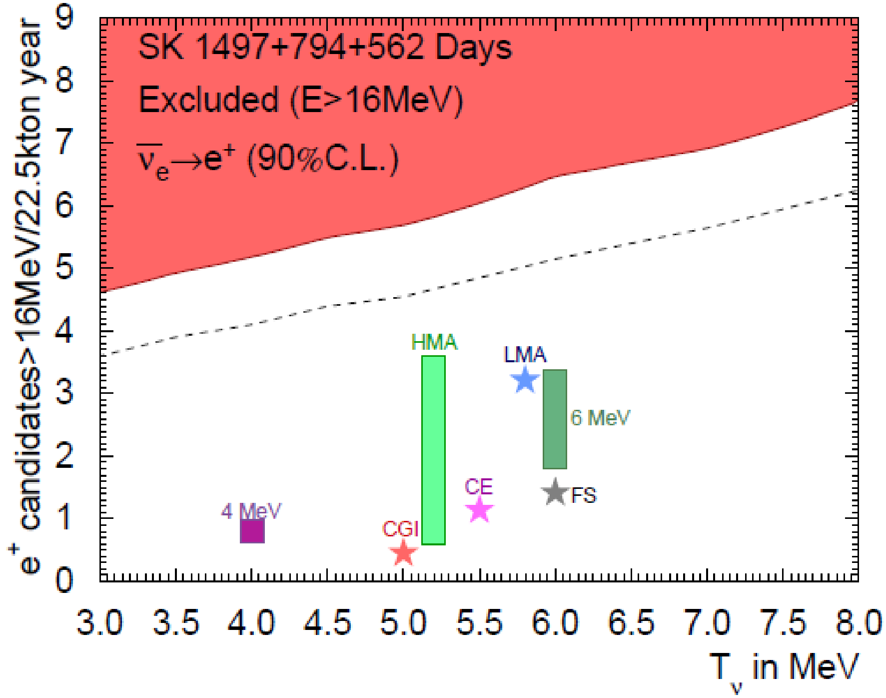
Super-Kamiokande collaboration recently investigated the DSNB flux using 2853 days of data [Bays et al., arXiV:1111:5031]. It fixed an upper bound on DSNB signal:

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

SN NEUTRINO EMISSION LIMIT FROM DSNB

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



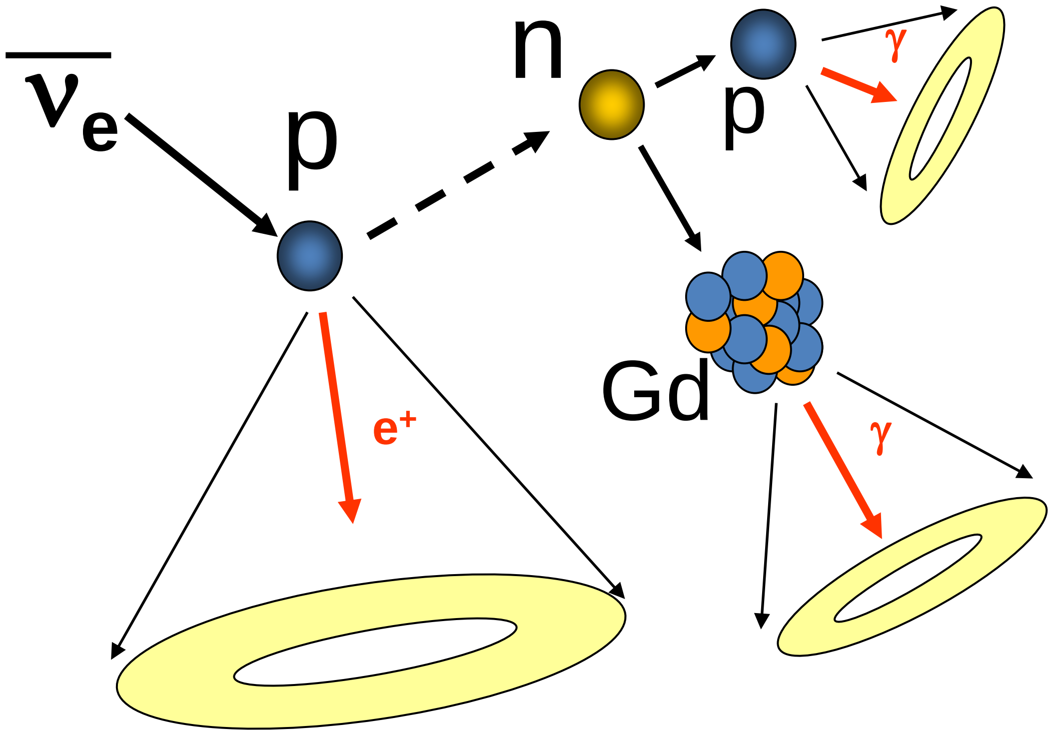


The SK limit is close to the most recent theoretical predictions

… but
Super-K is background limited.

SK-Gd Project

Neutron tagging in Gd-enriched WC Detector



Possibility 1: 10% or less

n+p→d + γ

2.2 MeV γ-ray

Possibility 2: 90% or more

n+Gd →~8MeV γ

ΔT = ~30 μsec

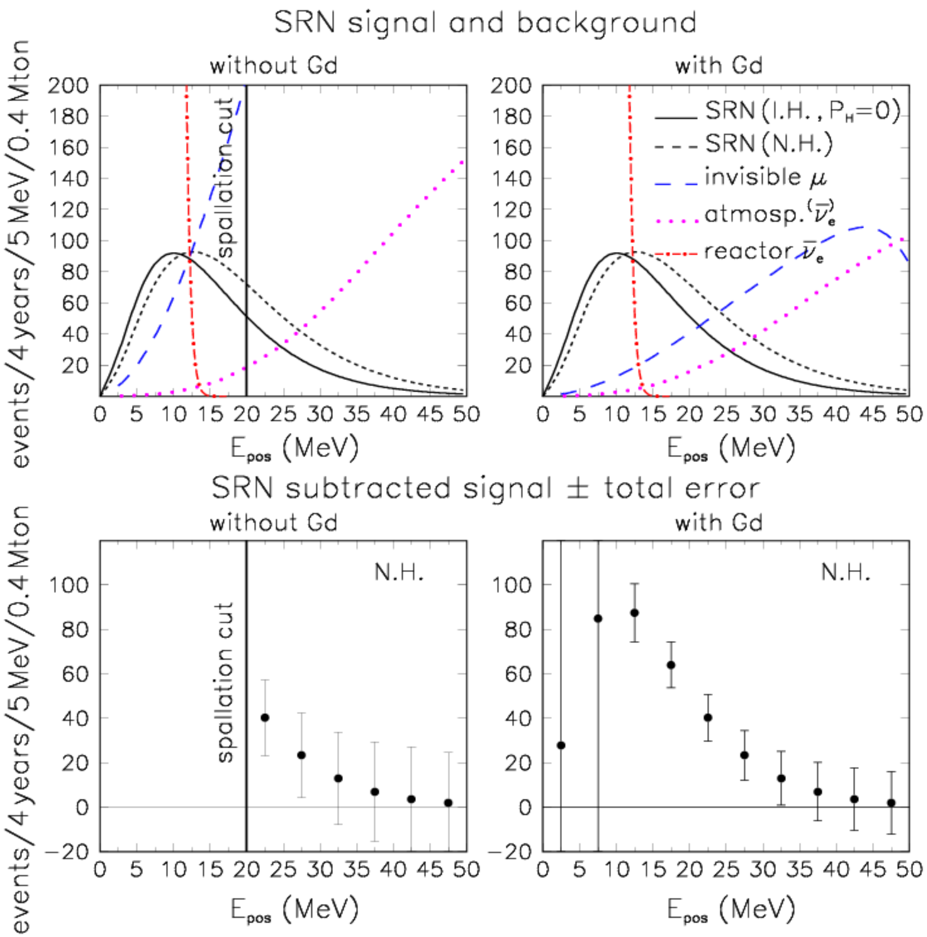
Positron and gamma ray vertices are within ~50cm.

$\overline{\nu}_e$ 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



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 $\bar{\nu}_\mu$.

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

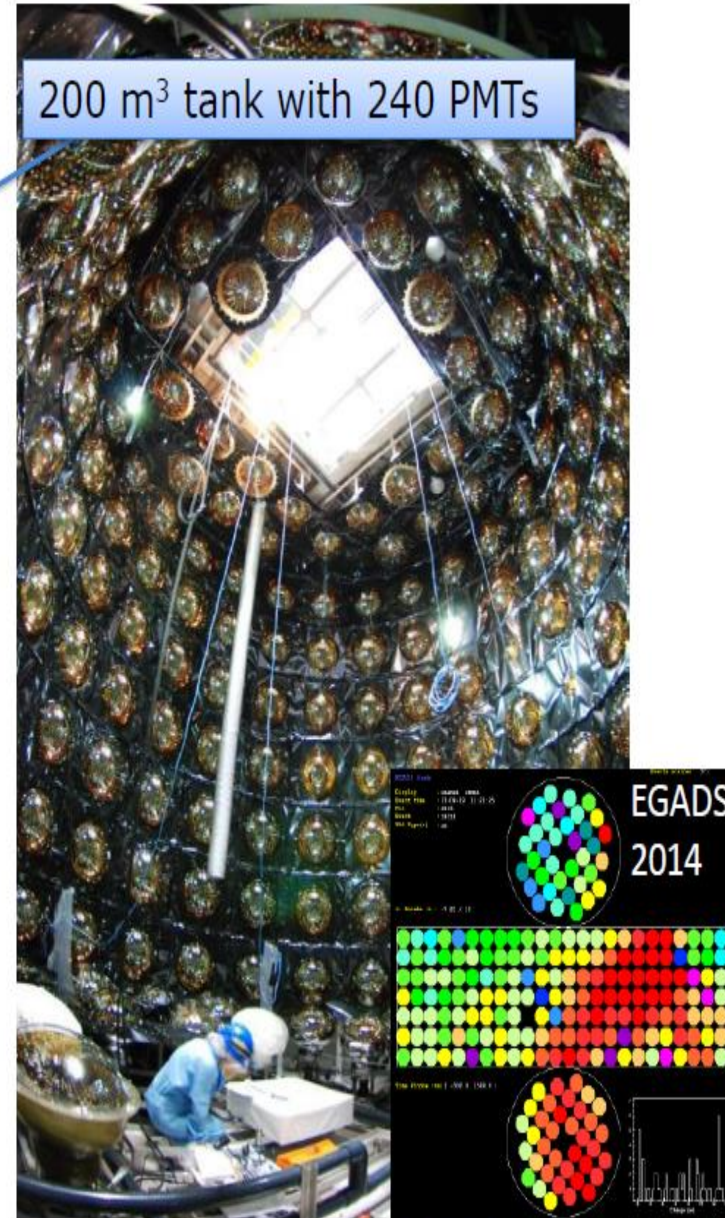
Evaluating Gadolinium's Action on Detector Systems

- 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

Gd water circulation system
(purify water with keeping Gd)

15m^3 tank to dissolve Gd

200 m^3 tank with 240 PMTs



SK & T2K Joint Statement on "SK-Gd"

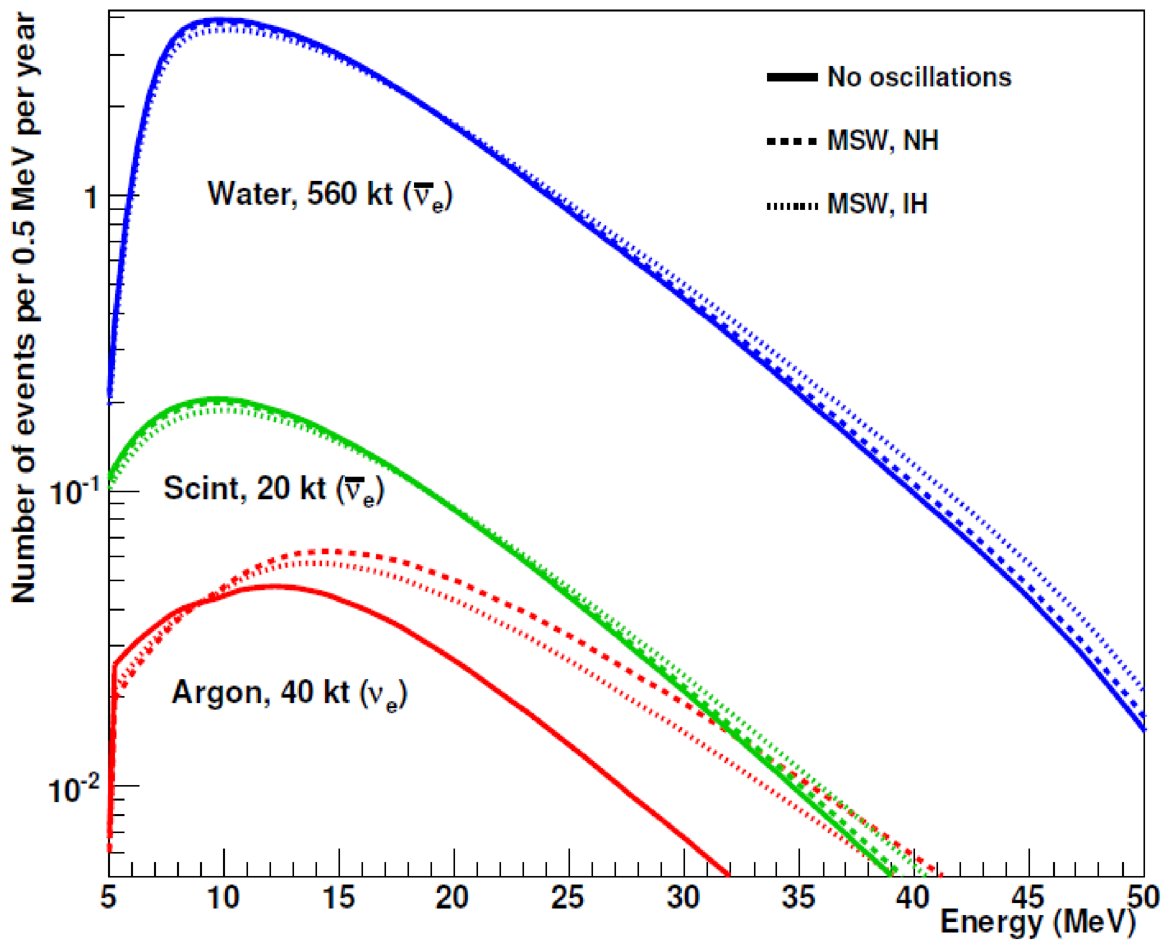
- Jan.30, 2016

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.

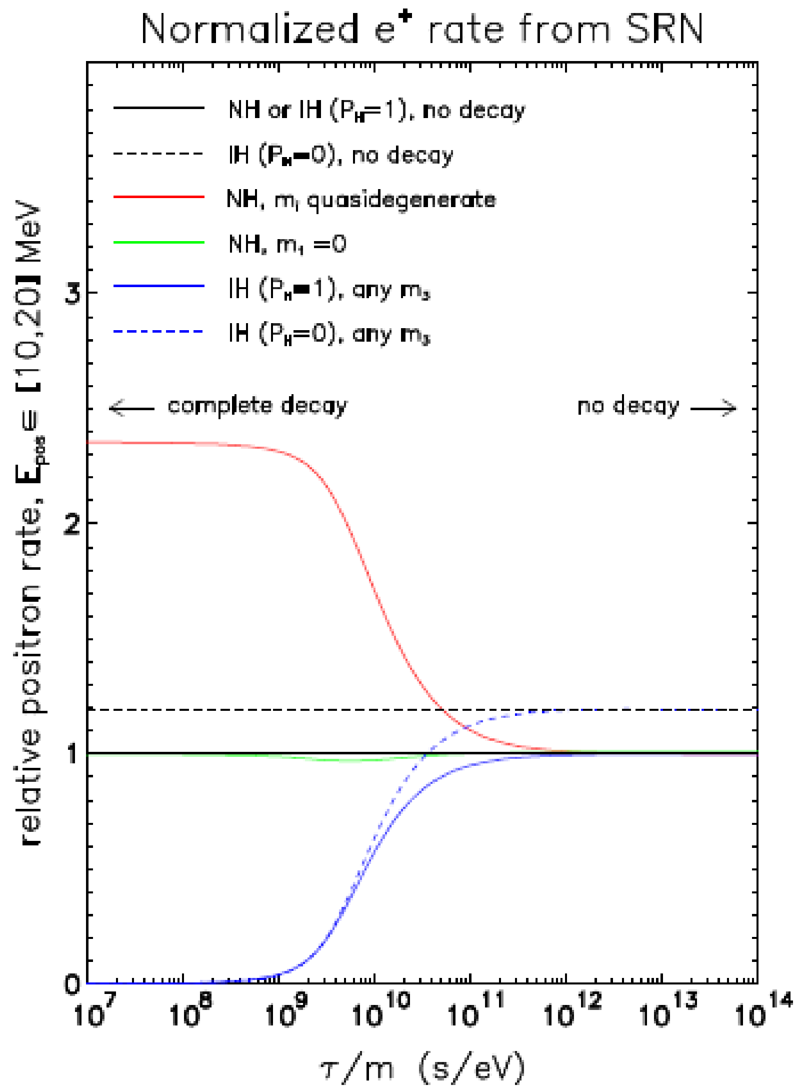
DSNB IN LARGE FUTURE DETECTORS

[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]

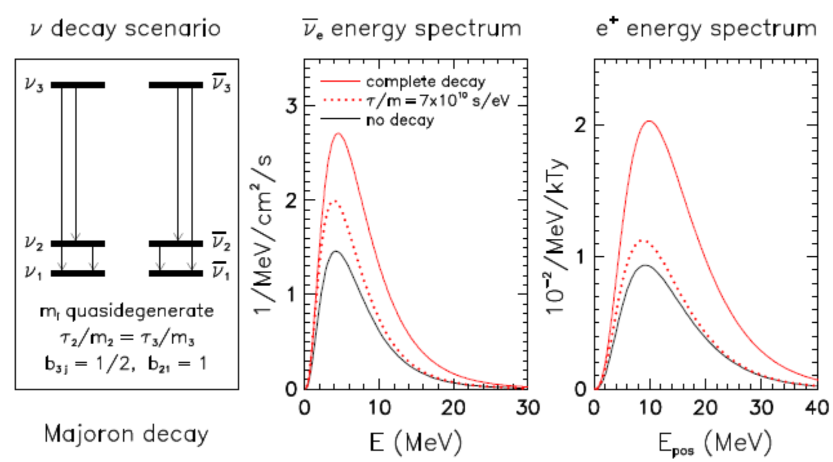


Nu decay in Majoron

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

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

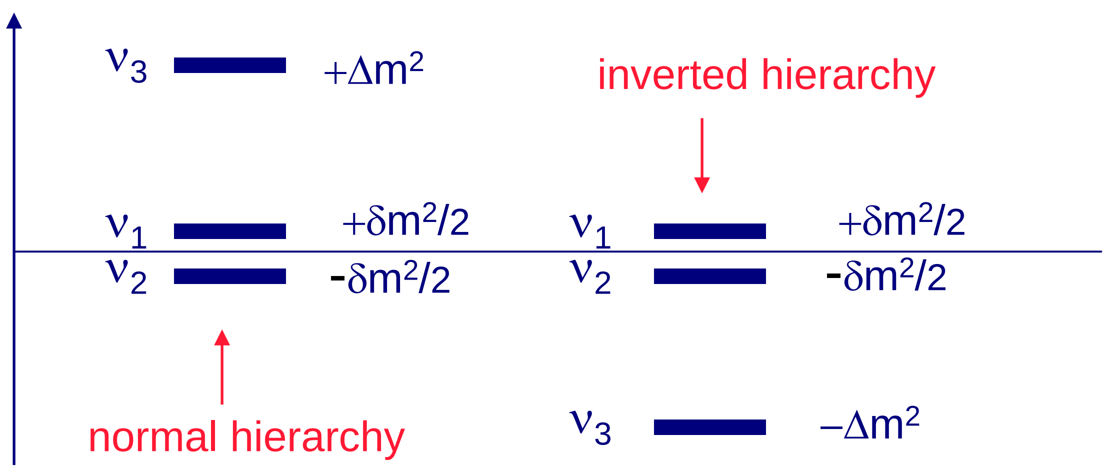
3ν FRAMEWORK

- **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

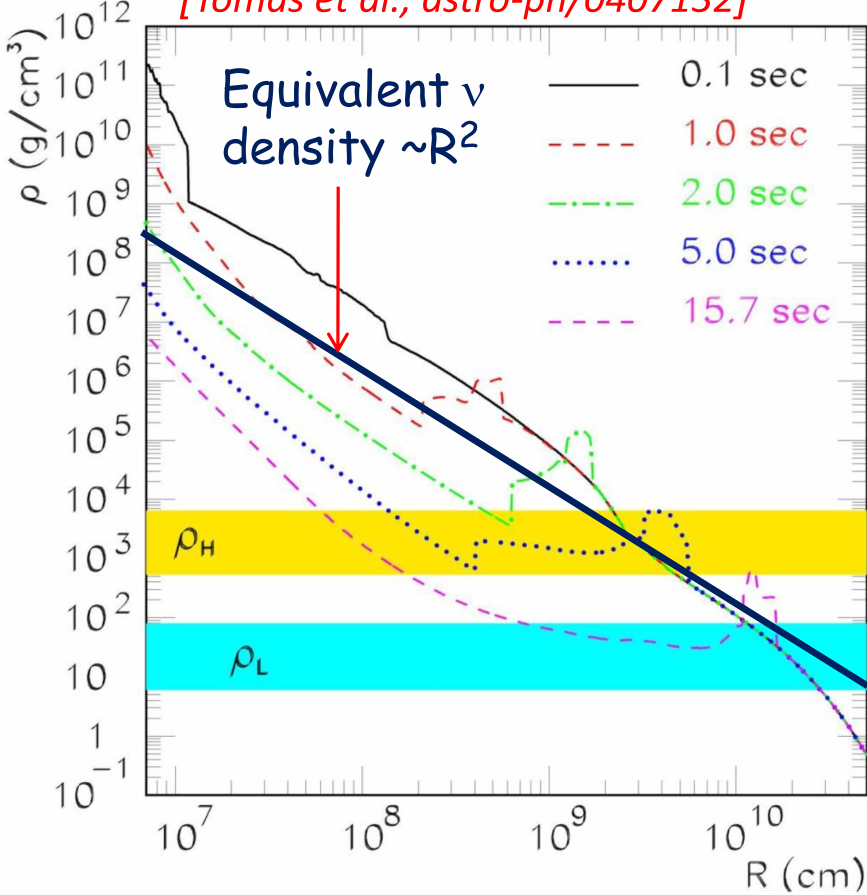
- **Mass-gap parameters:** $M^2 = \left[\underbrace{-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}}_{\text{“solar”}}, \underbrace{\pm \Delta m^2}_{\text{“atmospheric”}} \right]$



SN neutrinos are sensitive to the unknown mass hierarchy

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 μ >> λ, SN ν oscillations dominated by ν-ν interactions

Collective flavor transitions at low-radii [O (10^2 – 10^3 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

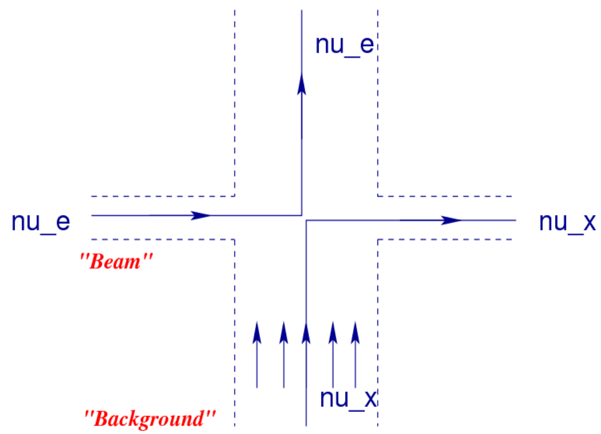
$$H_{\nu\nu} = A\begin{pmatrix} |\nu_e|^2 & \nu_e \nu_\mu^* \\ \nu_e^* \nu_\mu & |\nu_\mu|^2 \end{pmatrix}$$

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 $\nu_x = \cos\alpha\,\nu_e + \sin\alpha\,\nu_\mu$

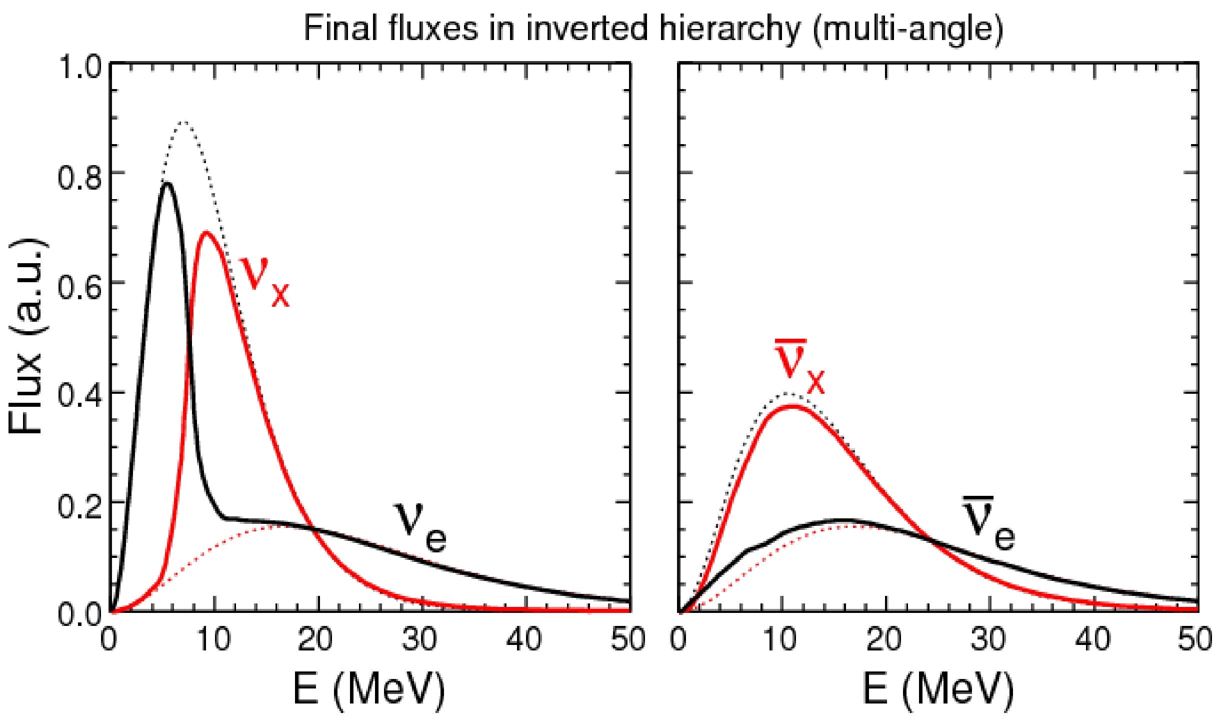
$$H_{\nu\nu} \propto \frac{\sqrt{2}G_F n_2}{2}\begin{pmatrix}\cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha\end{pmatrix} \Rightarrow P(\nu_e \to \nu_\mu) \approx \sin^2 2\alpha (G_F n_2 L)^2/2$$

[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

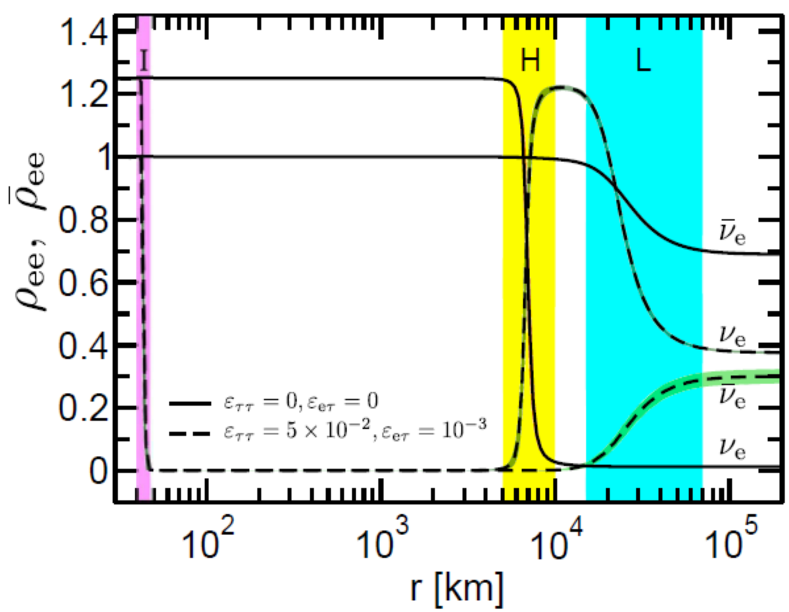
Strong dependence of collective oscillations on mass hierarchy and on the energy ("splits")

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

NSI AND NU-NU INTERACTIONS

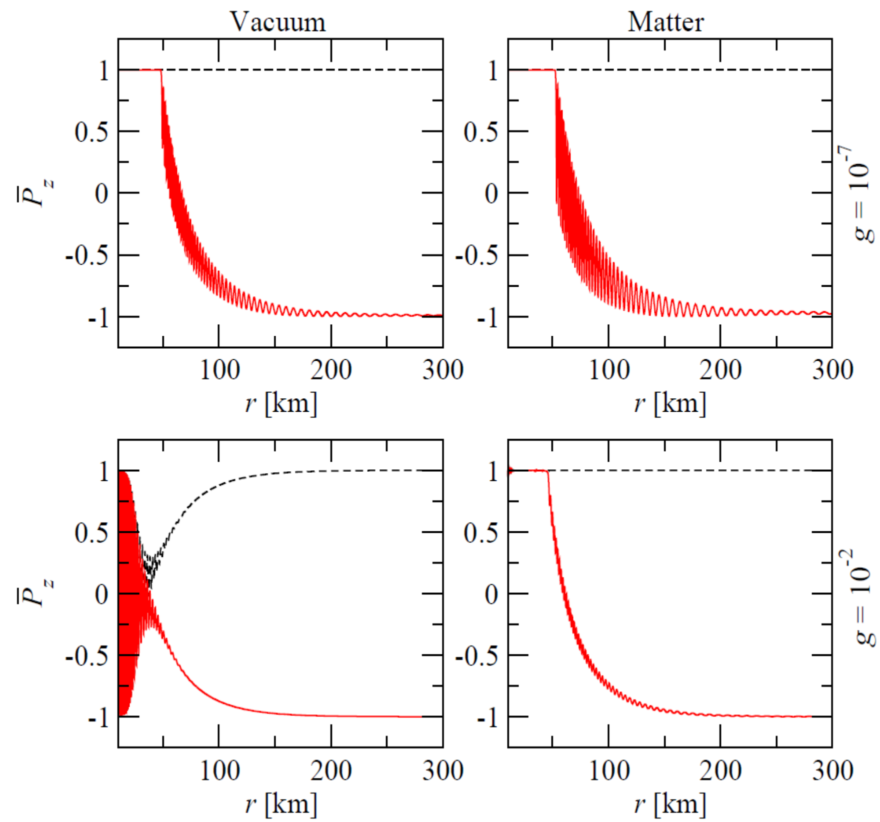
$$\mathcal{O}_{\alpha\beta} \sim [\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta][f \gamma_\mu P_L f]$$

f=e,u,d



[Esteban Pretel, Tomas & Valle, 0909.2196]

f=ν



[Blennow, A.M., Serpico, 0810.2297]

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

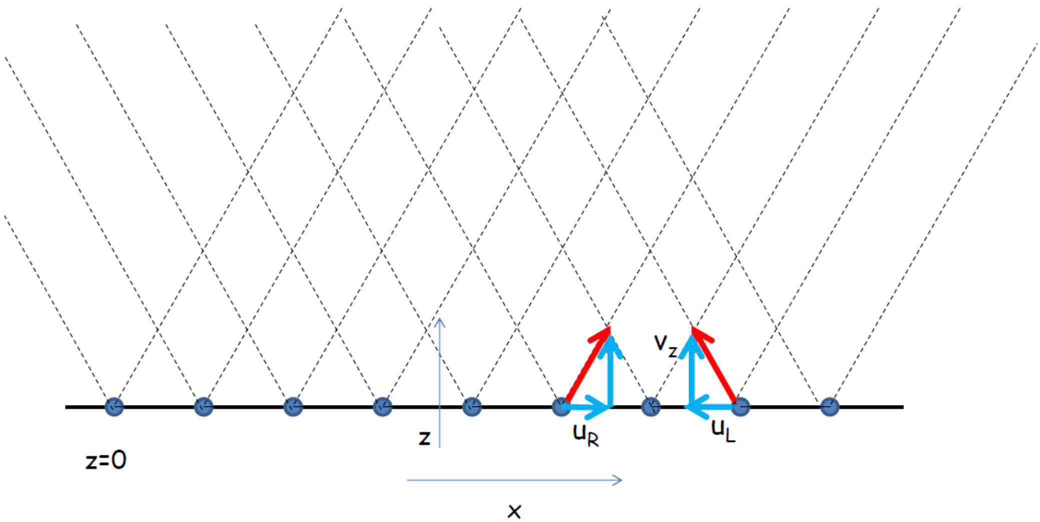
- With a simple toy model in *[Mangano, A.M. & Saviano, 1403.1892]* it has been shown that self-interacting ν can break translational symmetries in space and time.

- 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]

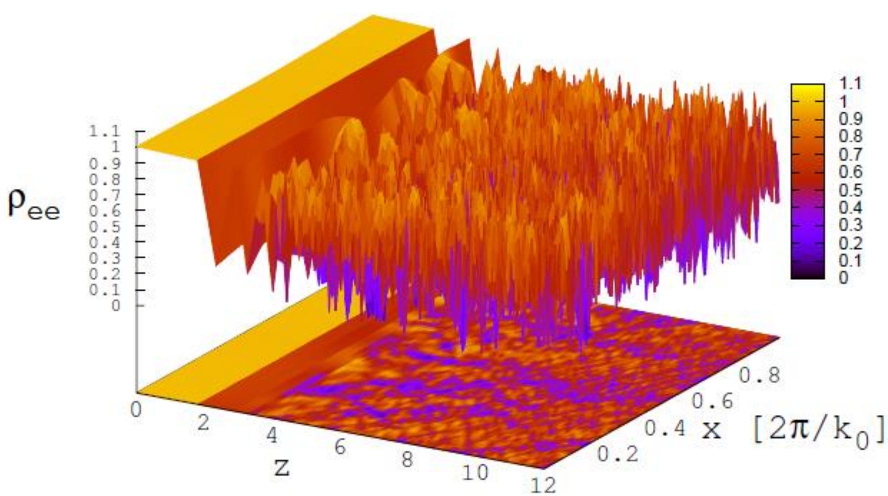
Nu evolving in the plane (x,z) emitted from an infinite boundary at z=0, in only two directions (L and R). Excess of ν_e over $\bar{\nu}_e$.



~~L-R~~

~~TRANSLATIONAL~~

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



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]].

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

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

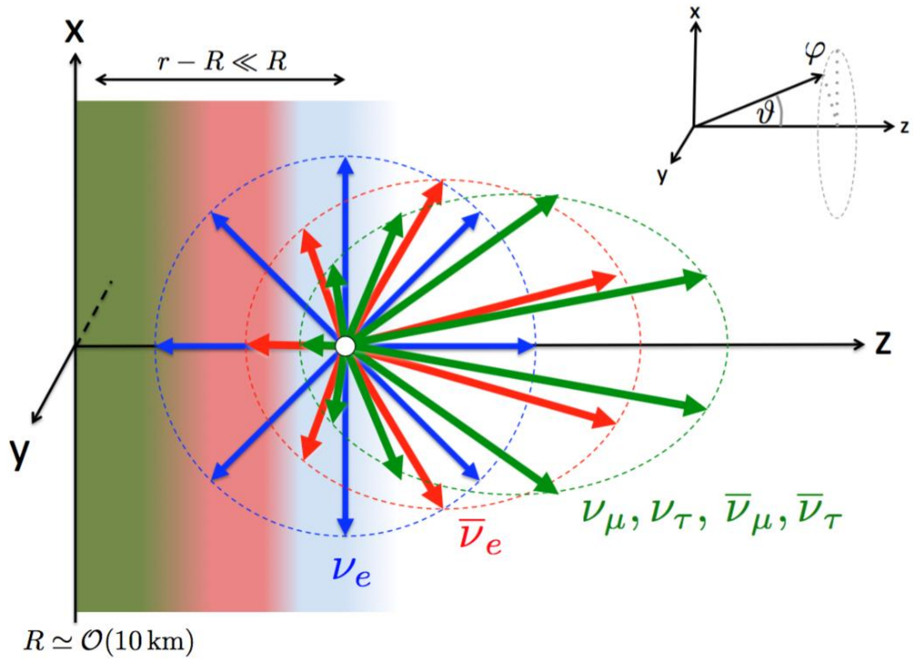
Most treatments of neutrino flavor evolution, above a surface of the last scattering, take identical angular distributions on this surface for the different initial (unmixed) flavors, and for particles and antiparticles. Differences in these distributions must be present, as a result of the species-dependent 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

NEUTRINO ANGULAR DISTRIBUTIONS AT DECOUPLING

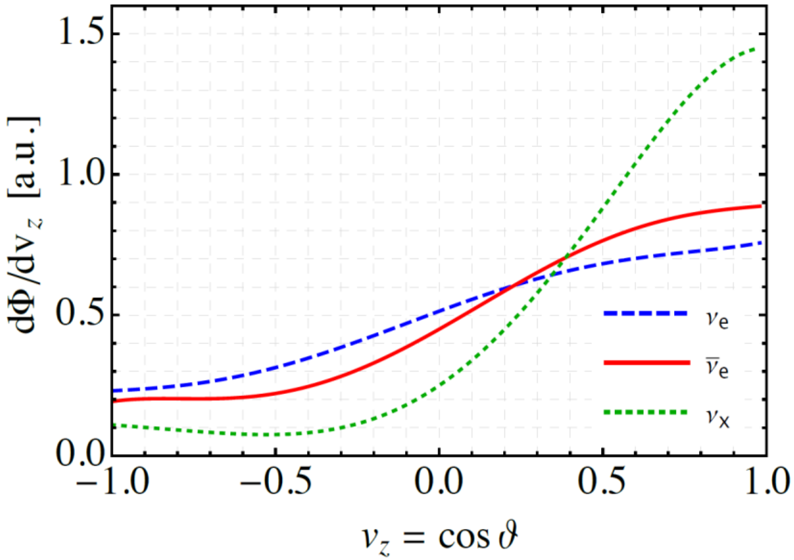
[Dasgupta, A.M., Sen, arXiV:1609.00528]



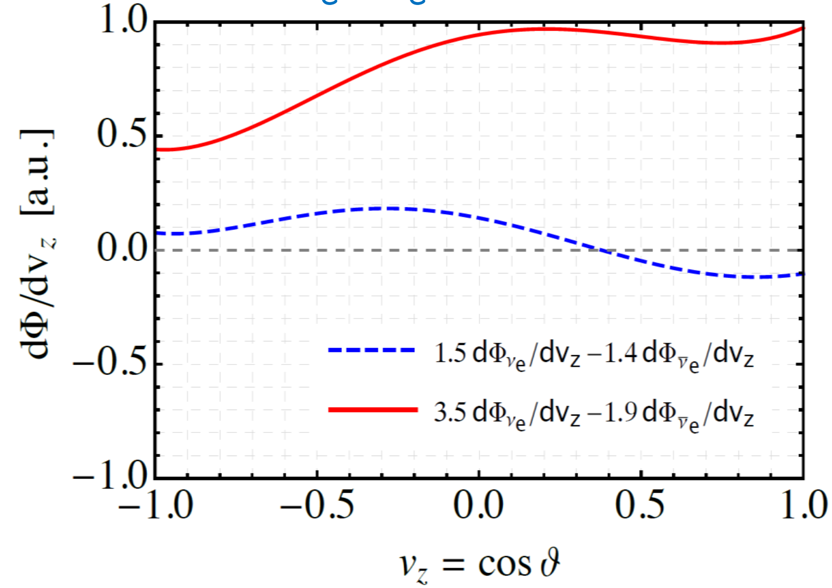
- Electron flavors remain in equilibrium with matter for a longer period than the non-electron flavors, due to the largest cross-sections of CC interactions
- Non-electron flavors decouple deeper in the star (more fwd-peaked distributions)
- Neutron-richness enhances CC interactions for ν_e keeping them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

FAST FLAVOR CONVERSIONS

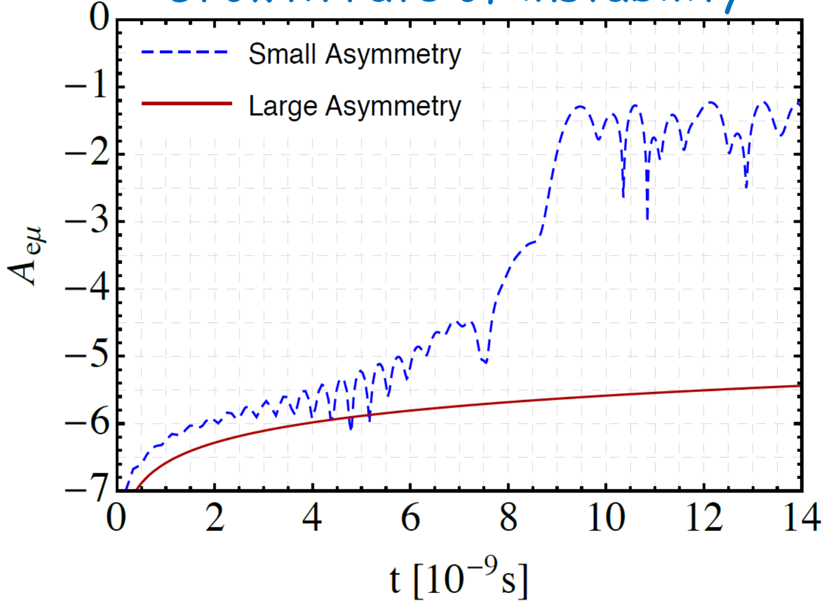
Nu angular distributions



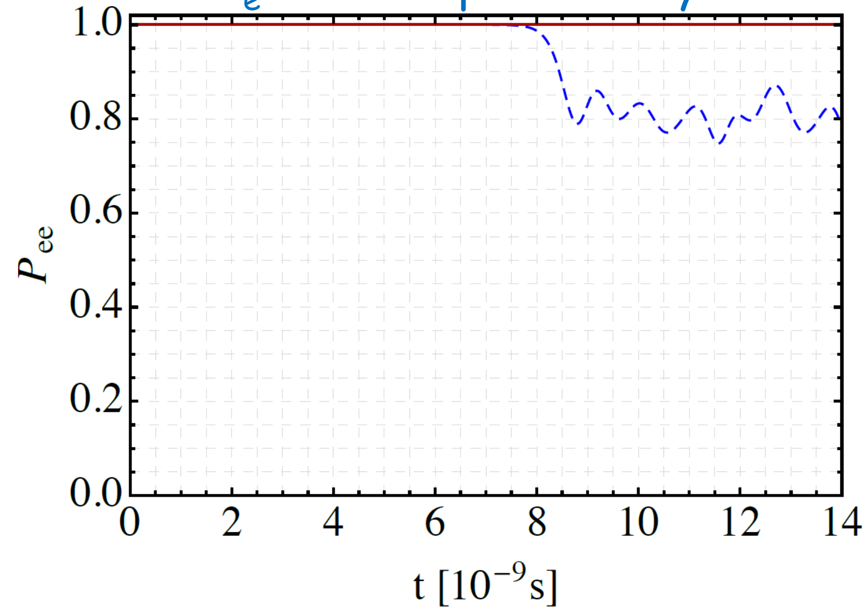
$\nu_e - \overline{\nu}_e$ difference



Growth rate of instability

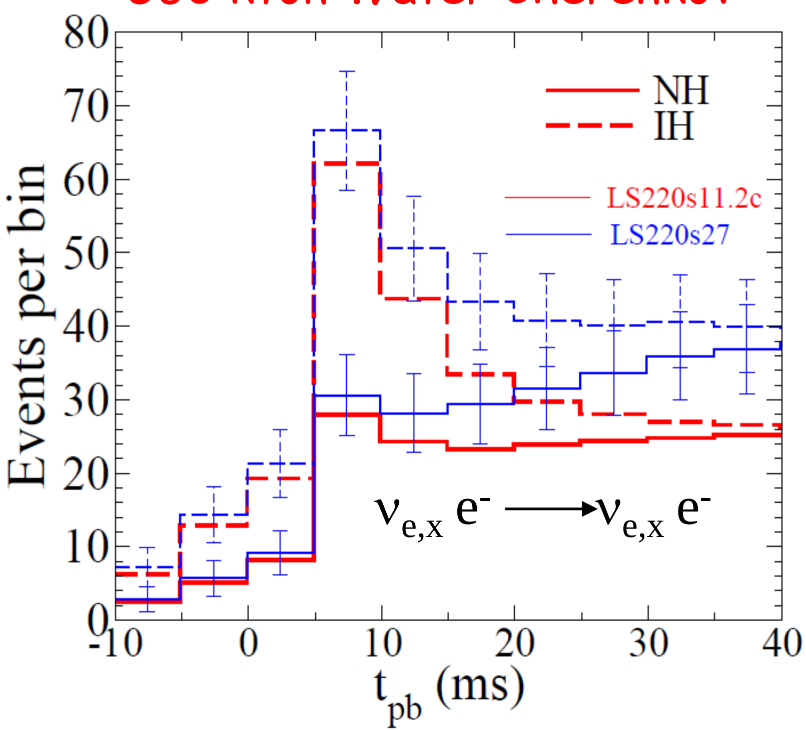


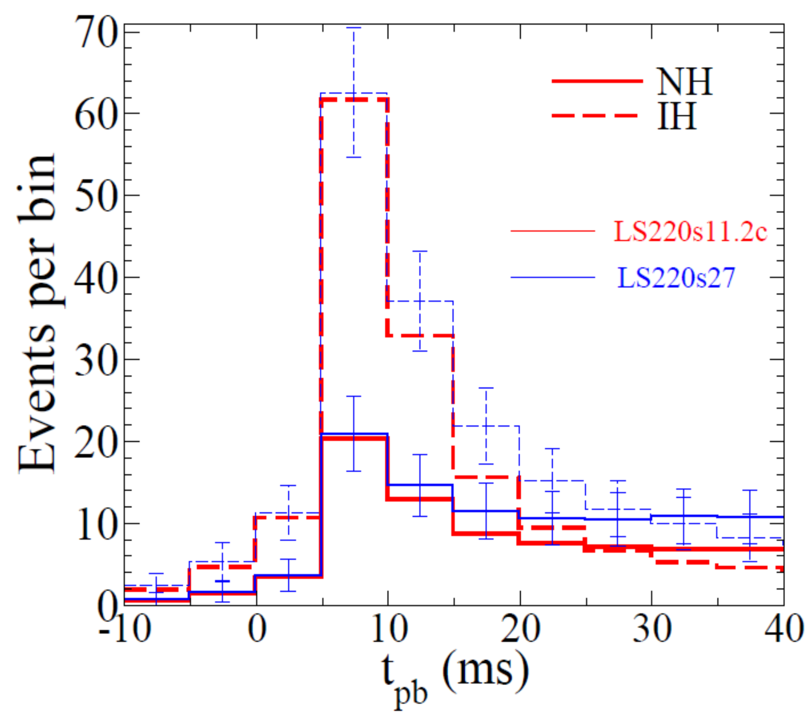
$\overline{\nu}_e$ survival probability



NEUTRONIZATION BURST

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





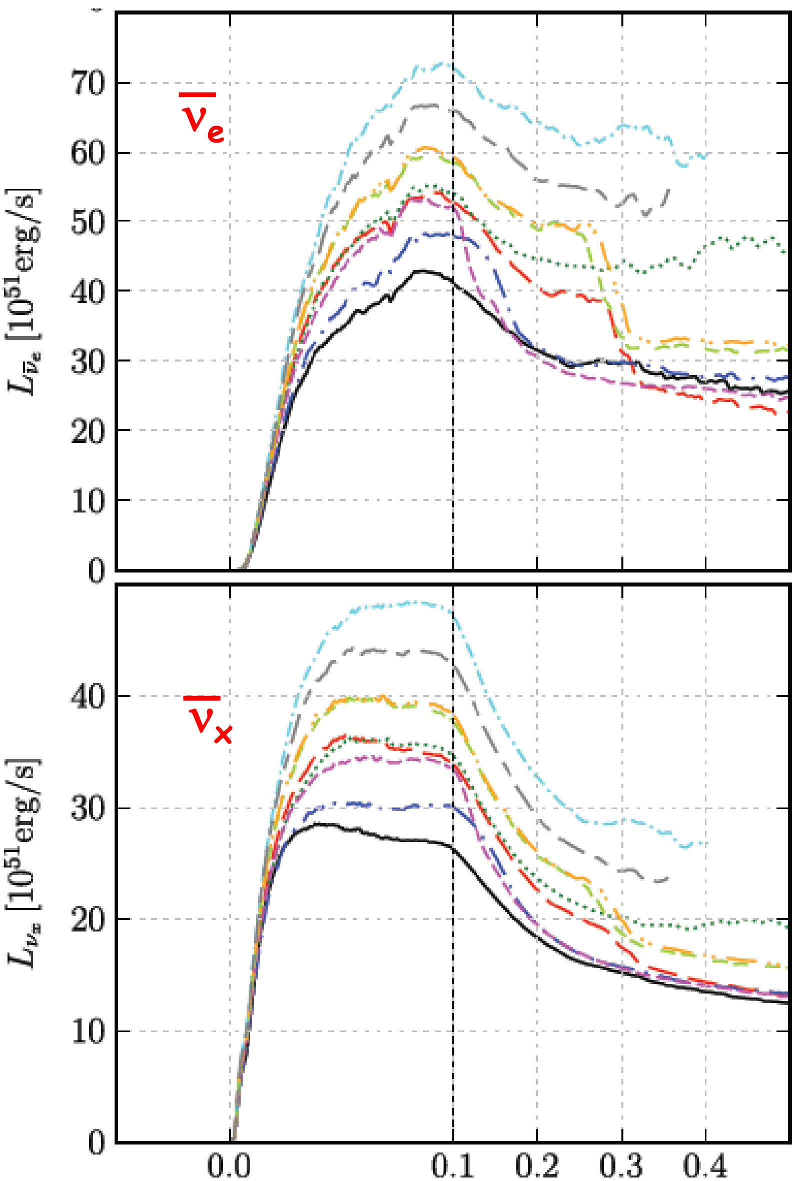
Robust feature of SN simulations

[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)

RISE TIME OF SN NEUTRINO SIGNAL IN ANTI-NU



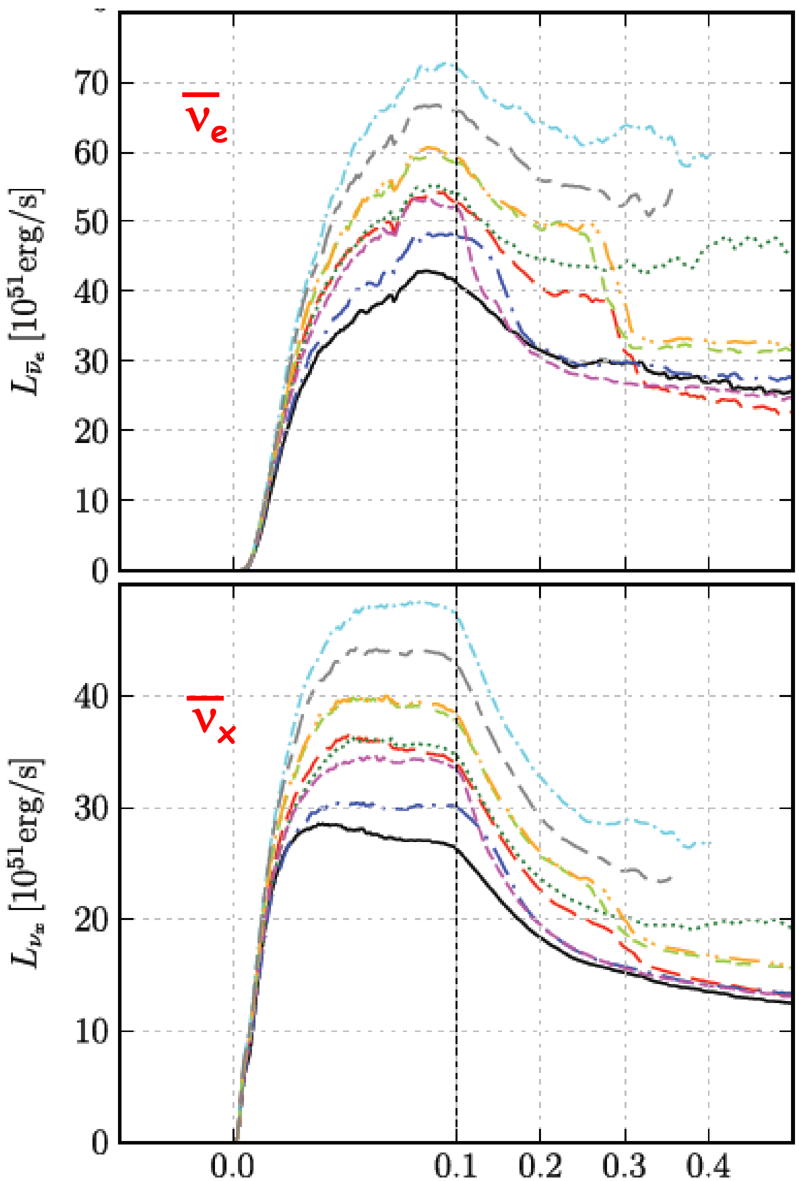
Garching group, 2011

- The production of $\overline{\nu}_e$ is more strongly suppressed than that of ν_x during the first tens of ms after bounce because of the high degeneracy of e and ν_e.

- $\overline{\nu}_e$ are produced more gradually via cc processes (e captures on free nucleons) in the accreting matter; ν_x come fastly from a deeper region

The lightcurves of the two species in the first O(100) ms are quite different.

RISE TIME OF SN NEUTRINO SIGNAL IN ANTI-NU



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RISE TIME ANALYSIS: HIERARCHY DETERMINATION

[see Serpico, Chakraborty, Fischer, Hudepohl, Janka & A.M., 1111.4483]

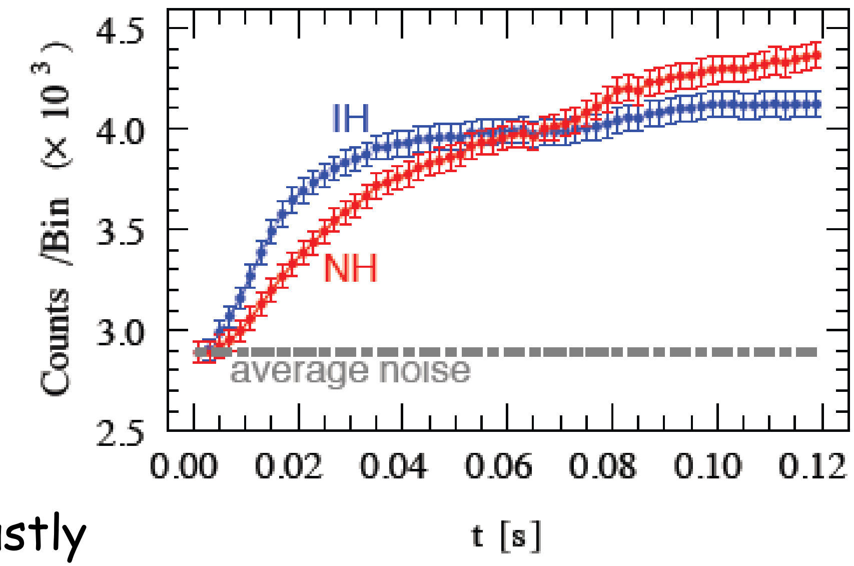
In accretion phase one has

$$F^D_{\bar{\nu}_e} = \cos^2\theta_{12} F_{\bar{\nu}_e} + \sin^2\theta_{12} F_{\bar{\nu}_x}$$ NH

$$F^D_{\bar{\nu}_e} = F_{\bar{\nu}_x}$$ IH

A high-statistics measurment of the rise time shape may distinguish the two scenarios

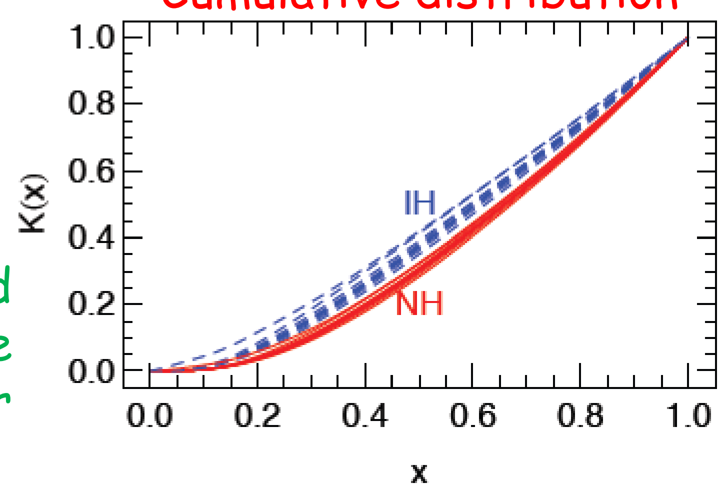
SN ν signal in Icecube



- Are the rise time shapes enough robustly predicted to be useful?

Models with state-of-the art treatment of weak physics (Garching simulations) suggest so: one could attribute a "shape" to NH and IH.

Cumulative distribution



Given these promising early results, it would be mandatory in future to explore the robusteness of the signature with other simulations. *[see Ott et al., 1212.4250]*

CONCLUSIONS

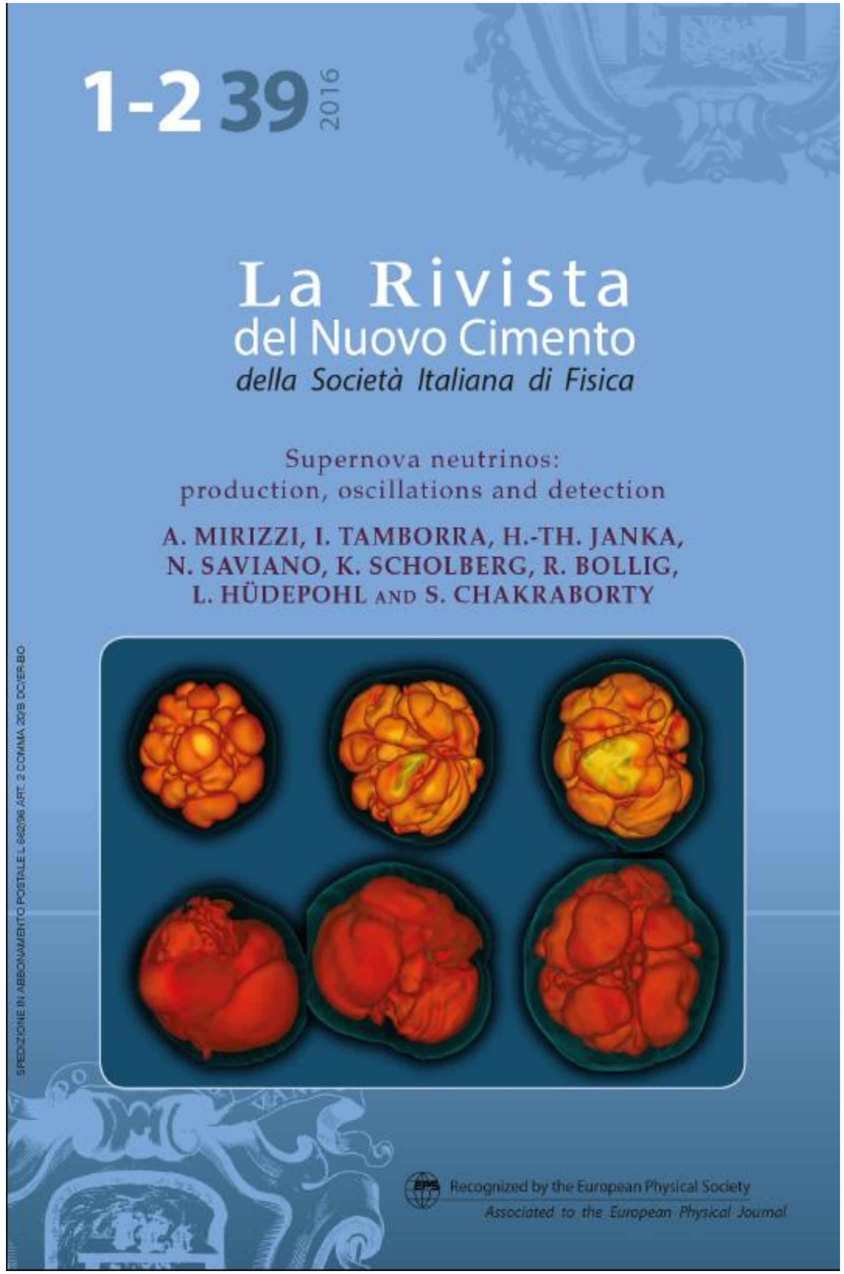
Observing SN neutrinos is the next frontier of low-energy neutrino astronomy

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](https://arxiv.org/abs/1508.00785) [astro-ph.HE]