Workshop on
Off-the-Beaten-Track Dark Matter and Astrophysical Probes of Fundamental Physics
ICTP, Trieste 13-17 April 2015

PARTICLE PHYSICS LESSON FROM CORE-COLLAPSE SUPERNOVAE

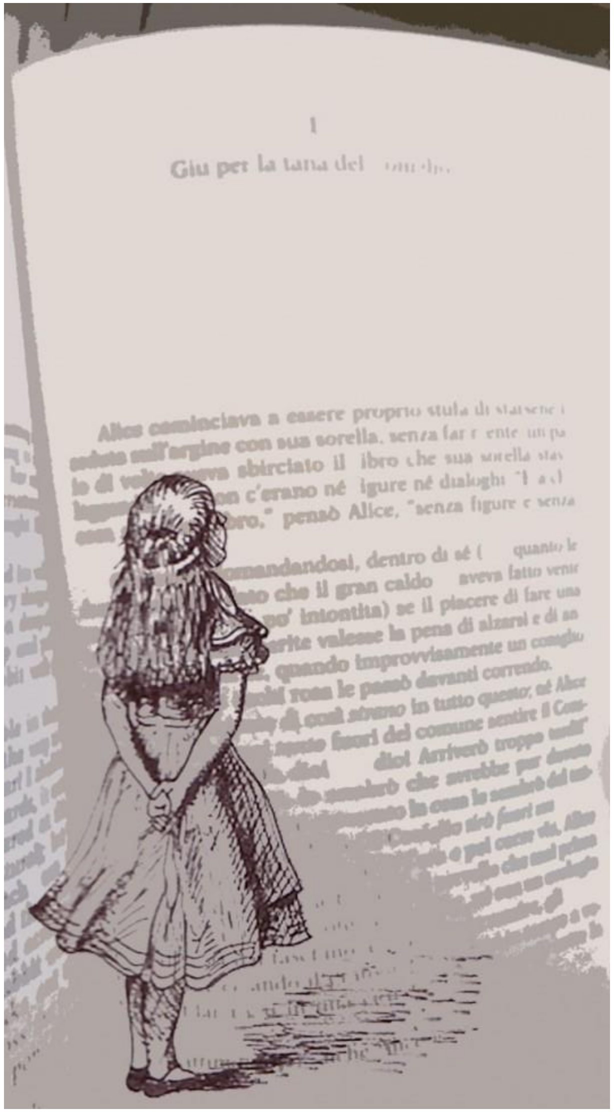
Alessandro MIRIZZI
University of BARI, Italy

OUTLINE

- Introduction to SN neutrinos
- SN neutrinos & NSI
- SN1987A neutrinos
- Particle physics lesson from SN1987A
- SN neutrino oscillations
- Diffuse SN neutrino background (DSNB)
- Conclusions

OUTLINE

- Introduction to SN neutrinos
- SN neutrinos & NSI
- SN 1987A neutrinos
- Particle physics lesson from SN 1987A
- SN neutrino oscillations
- Diffuse SN neutrino background (DSNB)
- Conclusions



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.

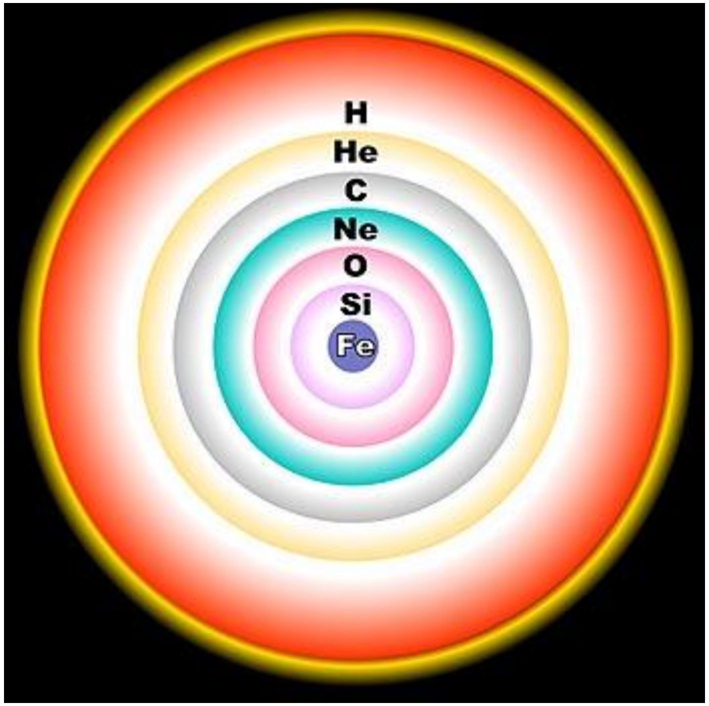
- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).

- **TIME SCALES:** Neutrino emission lasts **~10 s**

- **EXPECTED:** **1-3 SN/century** in our galaxy (d ≈ O (10) kpc).

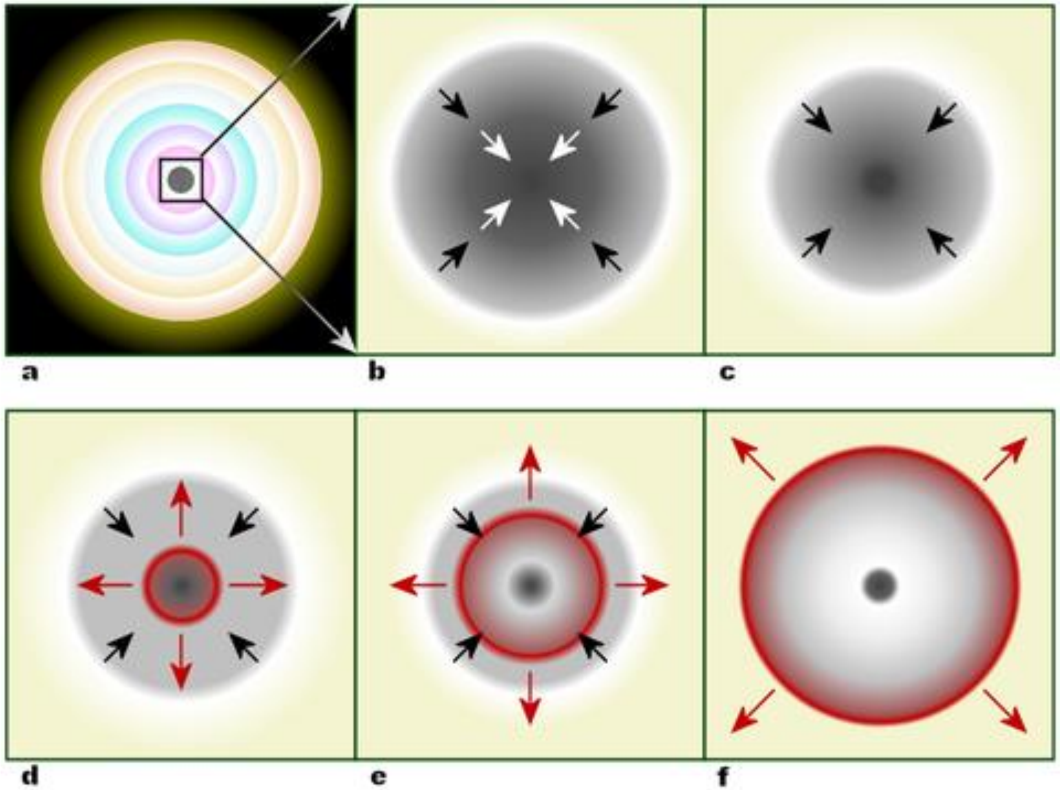
LIFE AND DEATH OF A MASSIVE STAR

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



Collapse

Nuclear density



Core-bounce & shock wave

shock-wave stalling

Shock revival

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

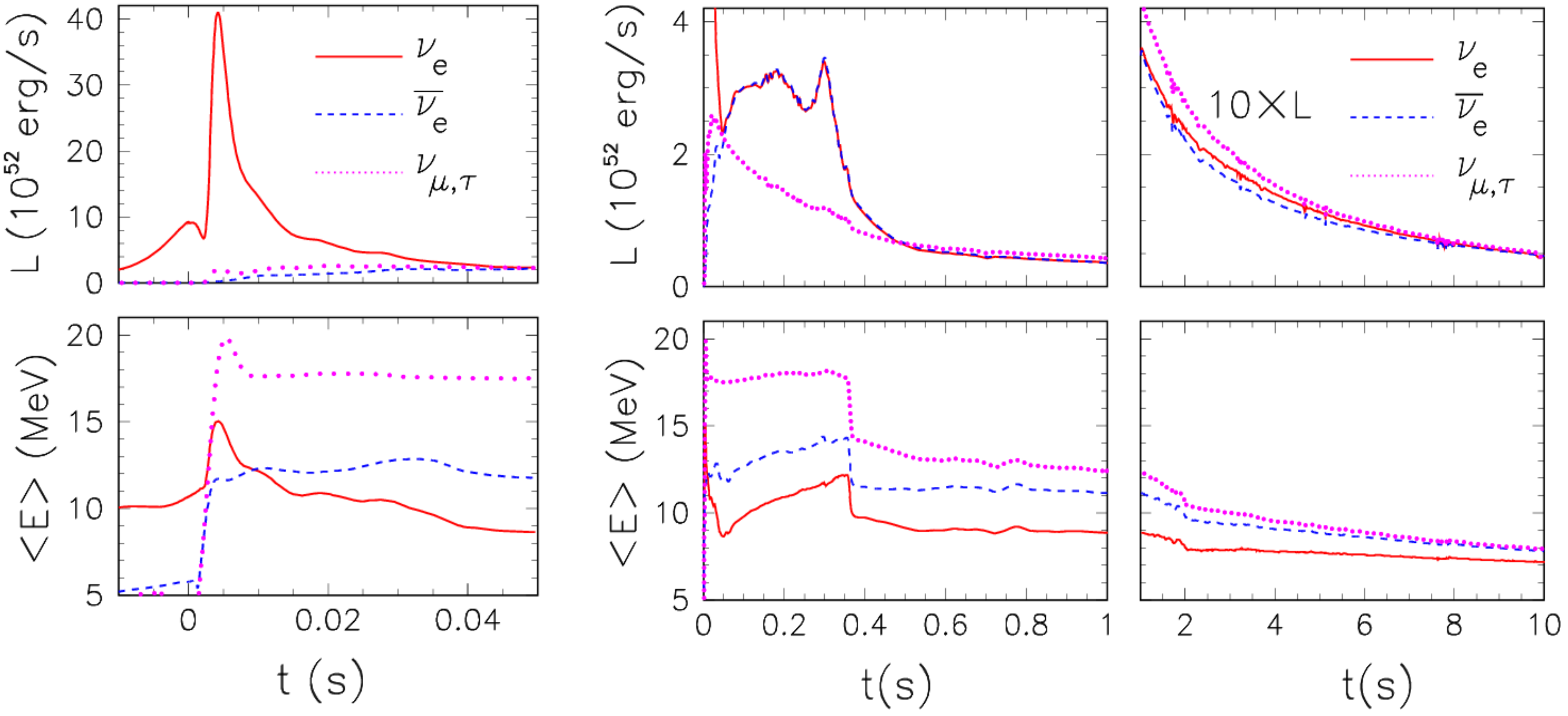
- Shock breakout
- De-leptonization of outer core layers

Accretion

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

Cooling

- Cooling on ν diffusion time scale



OUTLINE

- Introduction to SN neutrinos
- **SN neutrinos & NSI**
- SN 1987A neutrinos
- Particle physics lesson from SN 1987A
- SN neutrino oscillations
- Diffuse SN neutrino background (DSNB)
- Conclusions

SN AS LABORATORY FOR NEUTRINO NSI

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

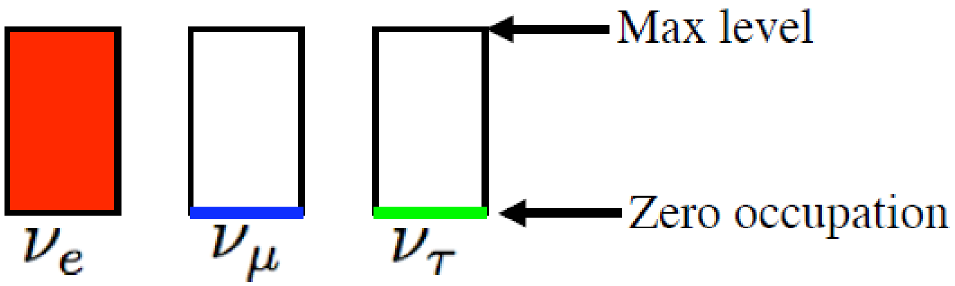
$$\nu_e \to \nu_{\mu,\tau}$$

Open holes in neutrino sea, allow electron capture to proceed

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

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 ⟶ $\Delta Y_e = -(\Delta Y_{\nu_\mu} + \Delta Y_{\nu_\tau})$

- 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

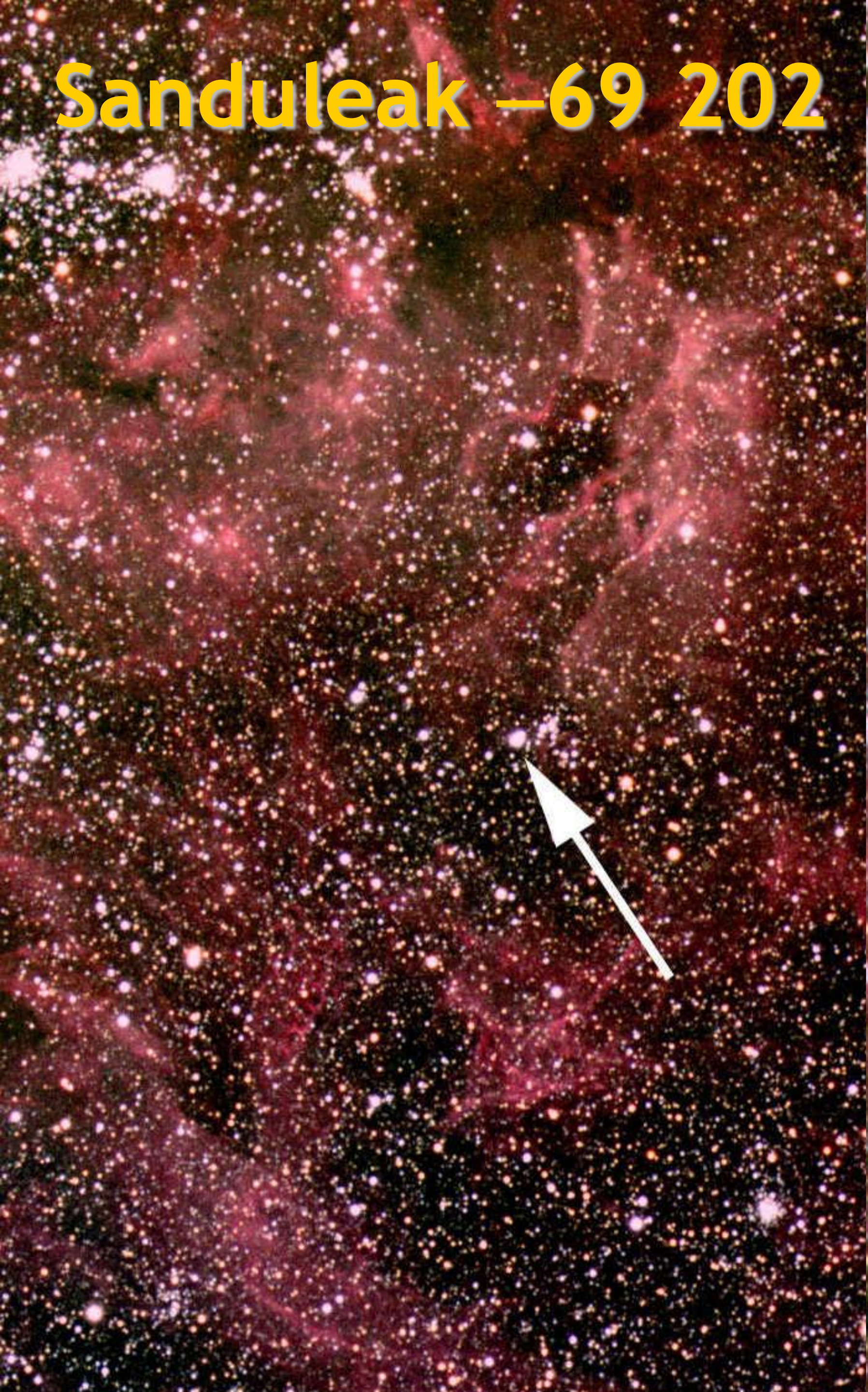
Favour getting explosion

SN model is significantly changed!

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

OUTLINE

- Introduction to SN neutrinos
- SN neutrinos & NSI
- SN 1987A neutrinos
- Particle physics lesson from SN 1987A
- SN neutrino oscillations
- Diffuse SN neutrino background (DSNB)
- Conclusions



Sanduleak −69 202

Supernova 1987A

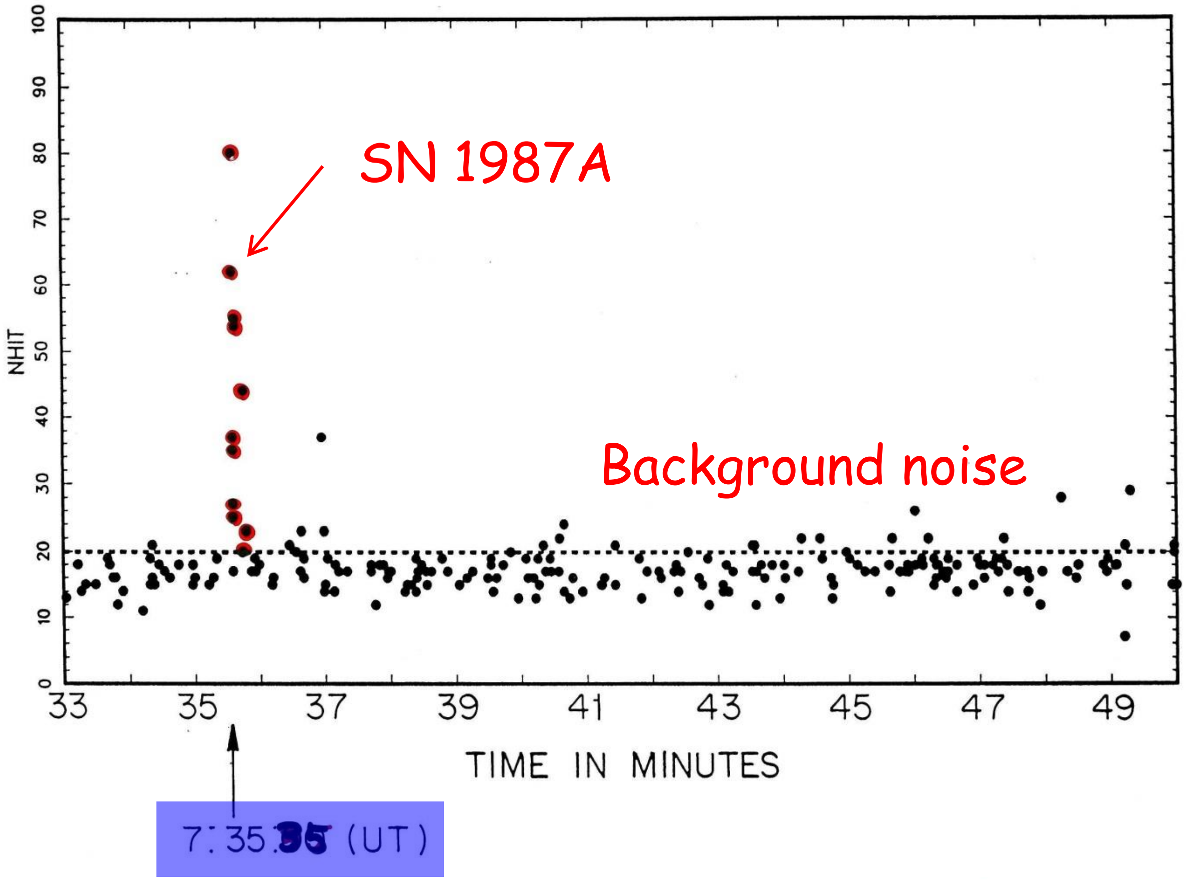
23 February 1987

Neutrino Burst Observation : First verification of stellar evolution mechanism

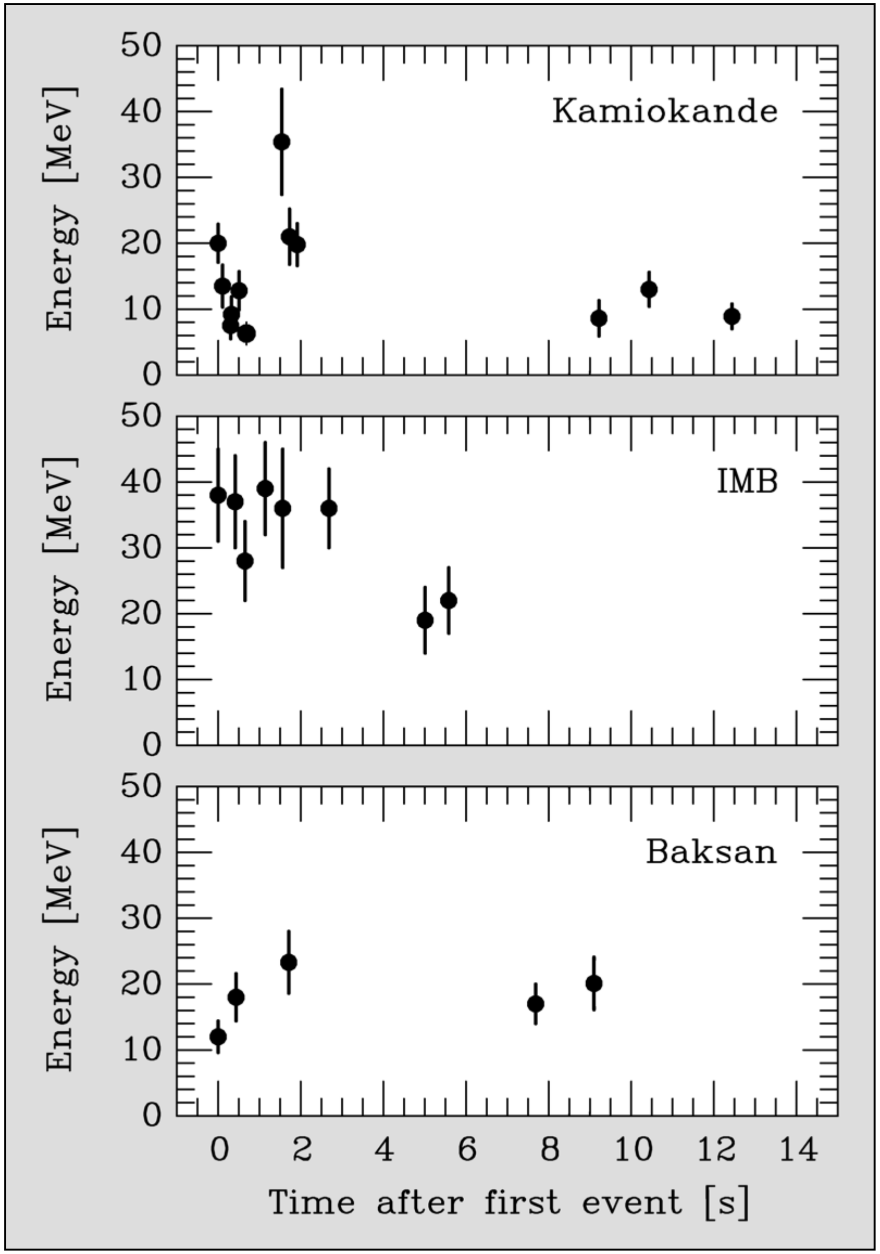
OPEN

Neutrino Astronomy

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

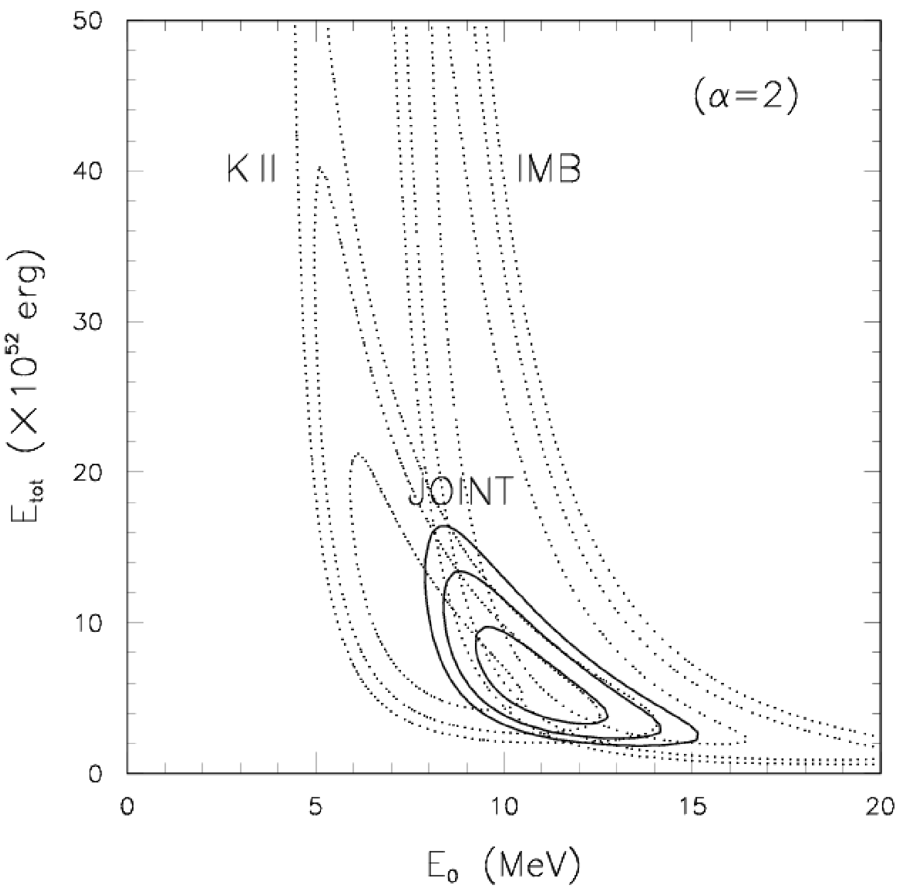
Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

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)**]**

Total binding energy



Average $\overline{\nu}_e$ energy

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

OUTLINE

- Introduction to SN neutrinos
- SN neutrinos & NSI
- SN 1987A neutrinos
- **Particle physics lesson from SN 1987A**
- SN neutrino oscillations
- Diffuse SN neutrino background (DSNB)
- Conclusions

PARTICLE PHYSICS LESSON FROM SN 1987A

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

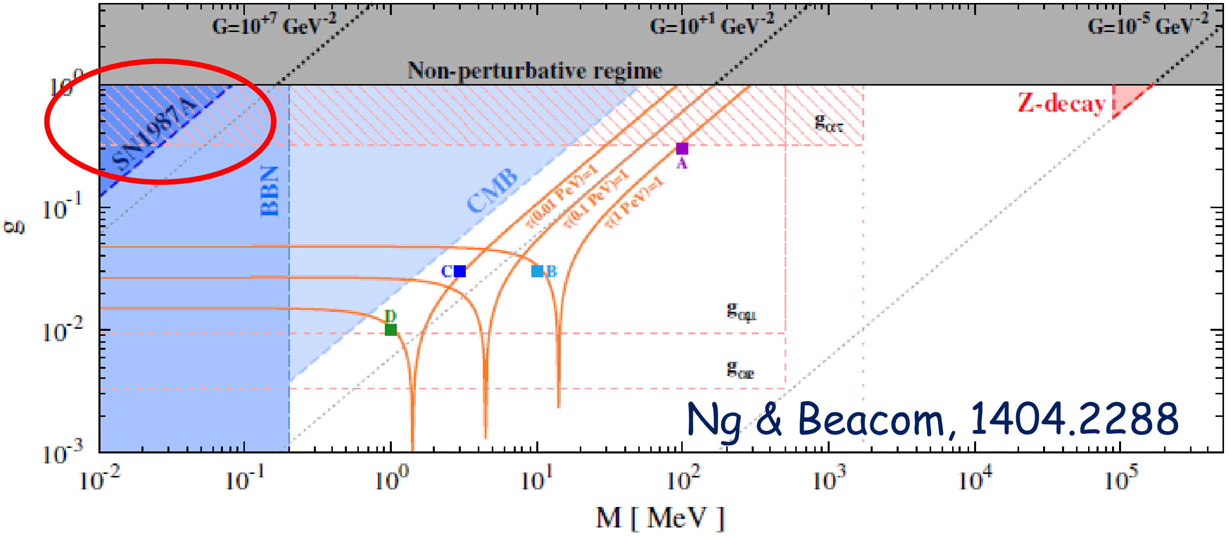
BOUND ON SECRET NEUTRINO INTERACTIONS

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

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.



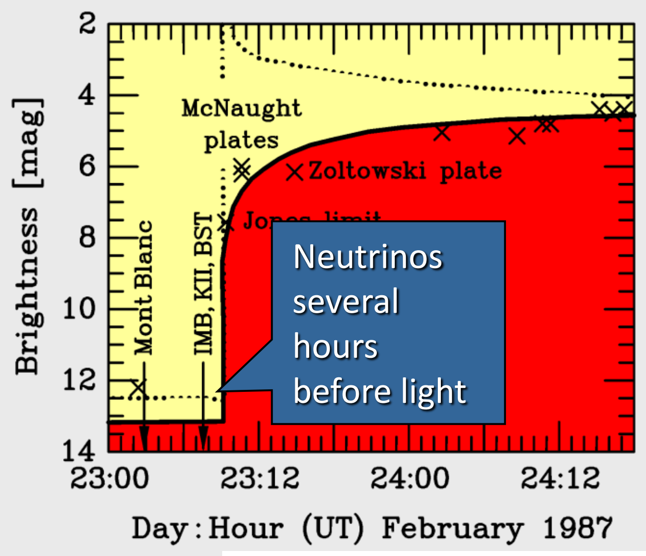
Ng & Beacom, 1404.2288

SN1987A bound

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

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

SN1987A BOUNDS ON NEUTRINO VELOCITY

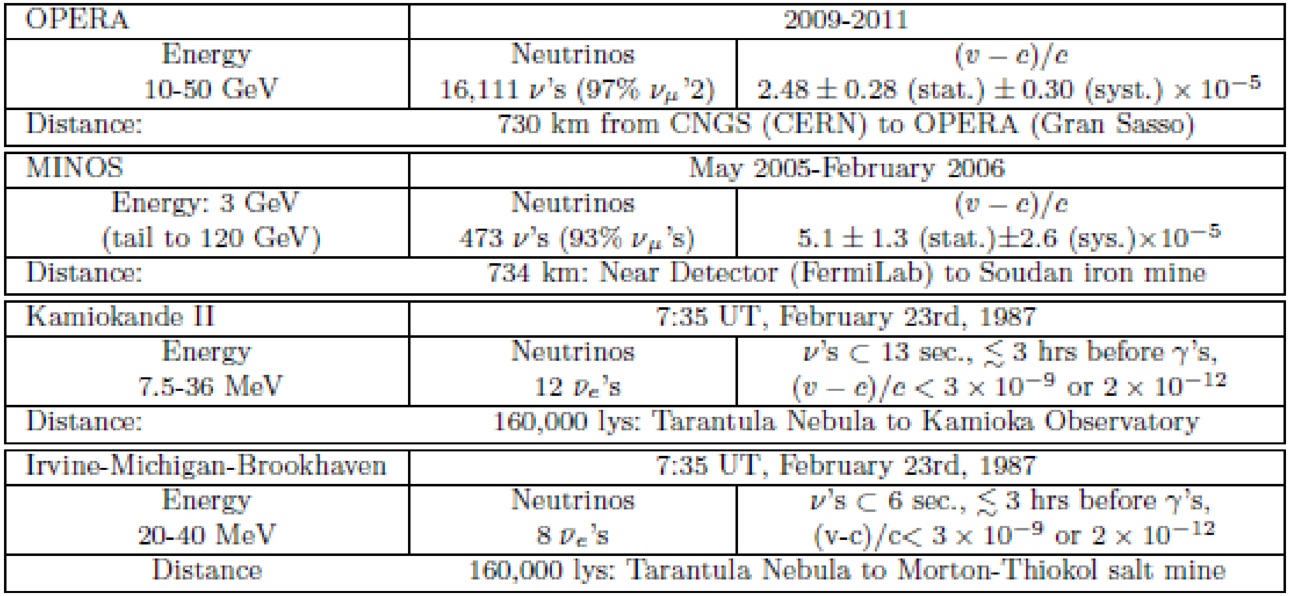


Neutrinos several hours before light

SN1987A few events provide the most stringent constraints on ν velocity. Crucial for comparison with recent OPERA claim

[Evslin, 1111.0733]

Table 1. Superluminal Neutrino Velocity Observations and Bounds



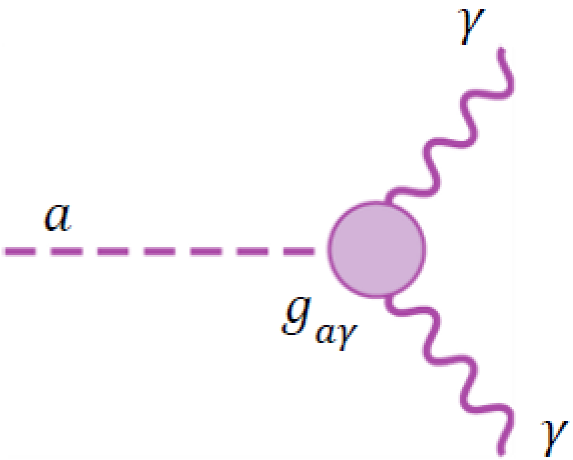
OPERA	2009-2011	
Energy 10-50 GeV	Neutrinos 16,111 ν's (97% ν_μ'2)	$(v-c)/c$ 2.48 ± 0.28 (stat.) ± 0.30 (syst.) $\times 10^{-5}$
Distance:	730 km from CNGS (CERN) to OPERA (Gran Sasso)	
MINOS	May 2005-February 2006	
Energy: 3 GeV (tail to 120 GeV)	Neutrinos 473 ν's (93% ν_μ's)	$(v-c)/c$ 5.1 ± 1.3 (stat.)± 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	

PARTICLE PHYSICS LESSON FROM SN 1987A

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

AXION-LIKE PARTICLES (ALPs)

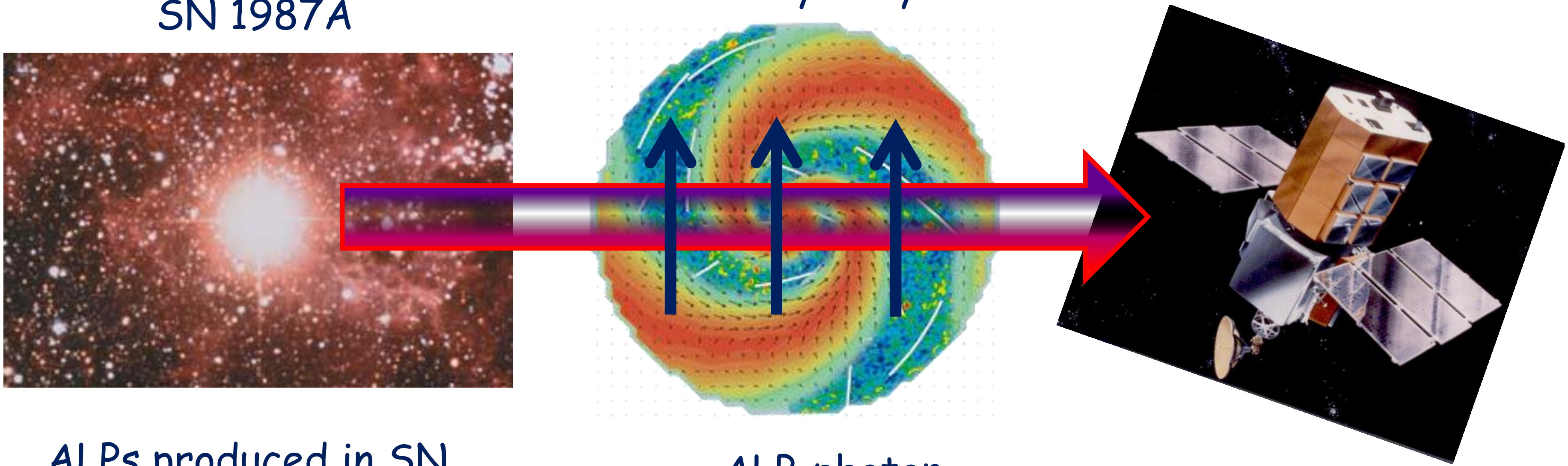
$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}_{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$$



- 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

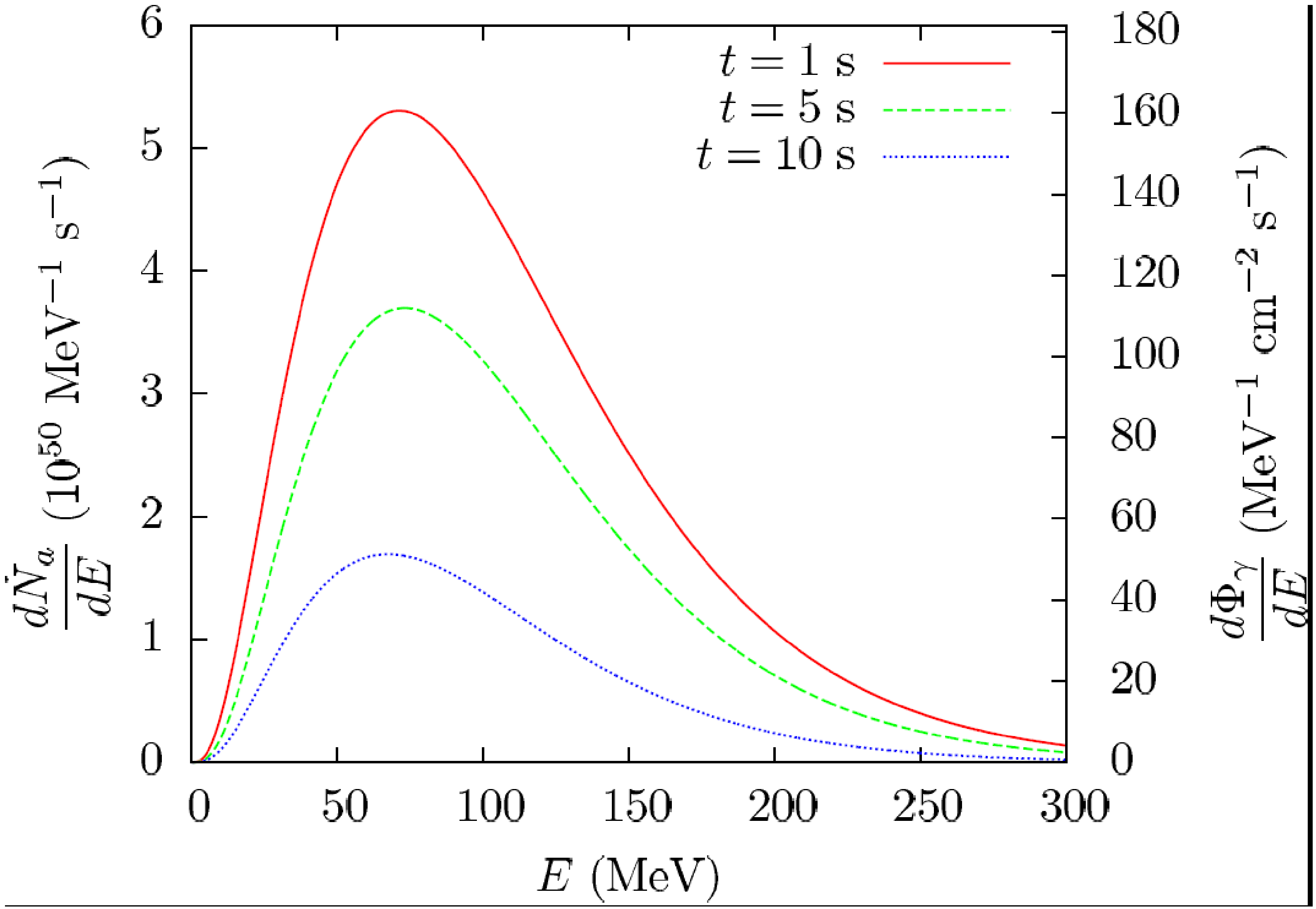
No excess gamma-rays in coincidence with SN 1987A

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

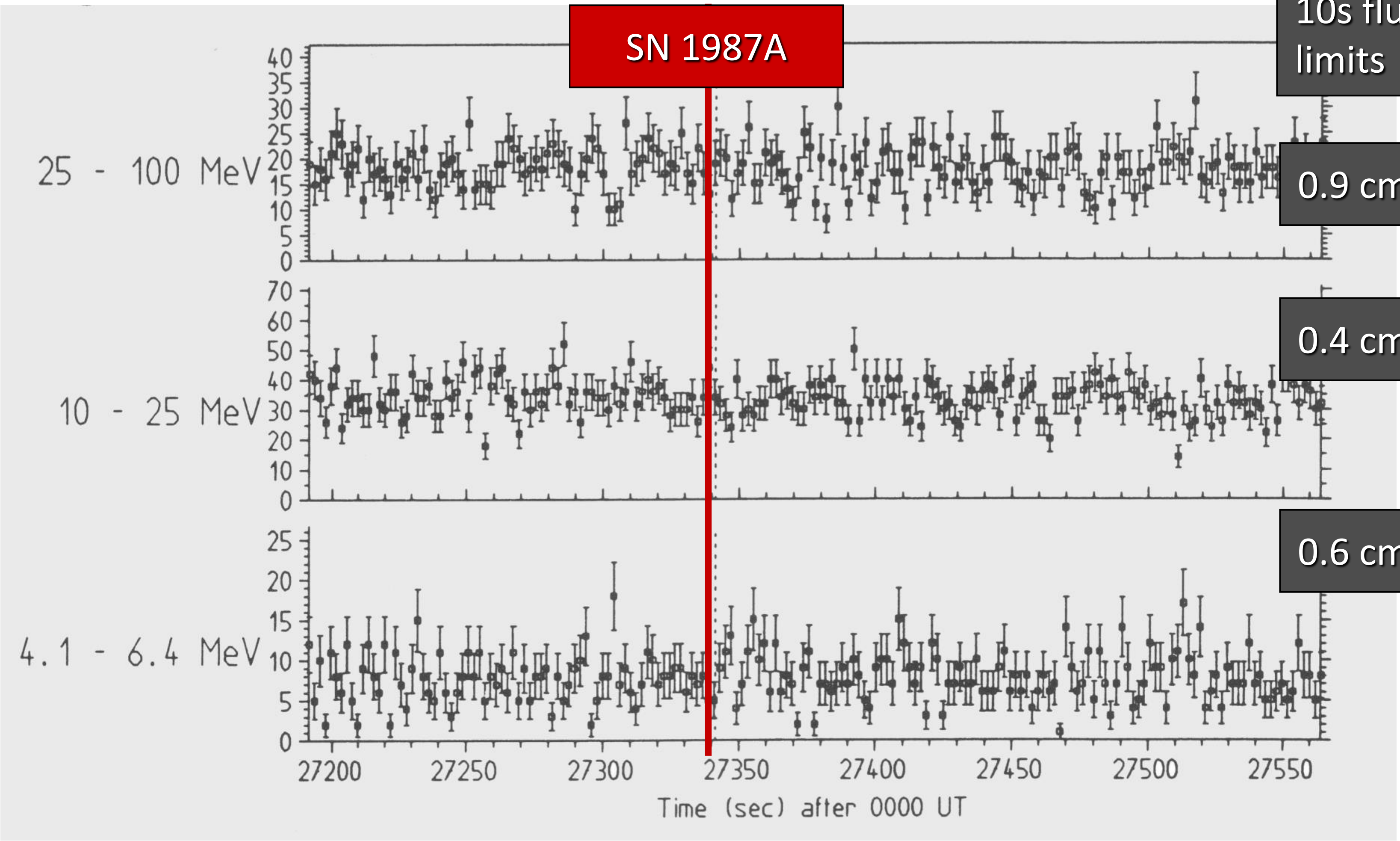
ALP-PHOTON FLUXES FOR SN 1987A

[*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



10s fluence limits

$0.9\ cm^{-2}$

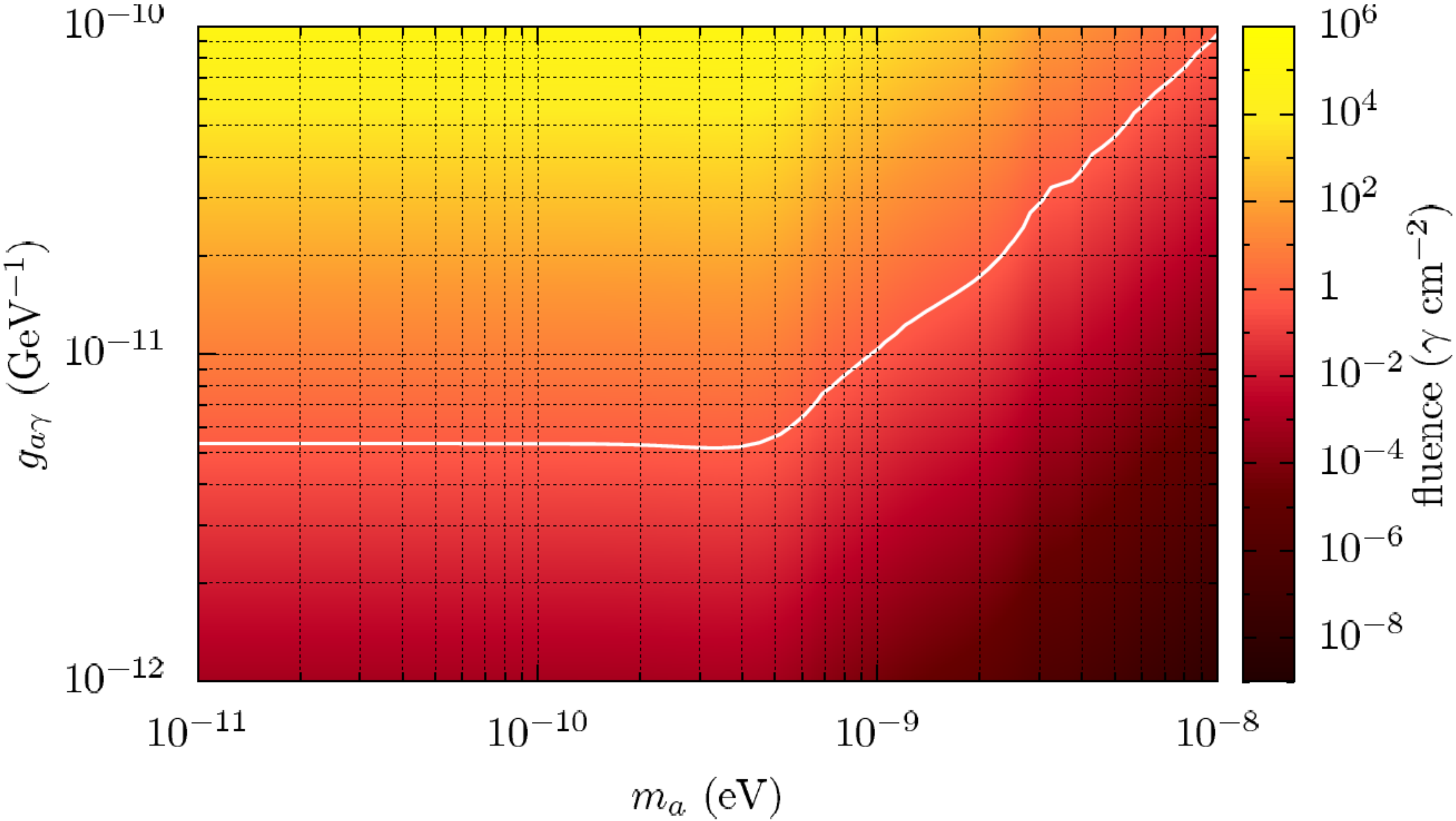
$0.4\ cm^{-2}$

$0.6\ cm^{-2}$

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

NEW BOUND ON ALPs FROM SN 1987A

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



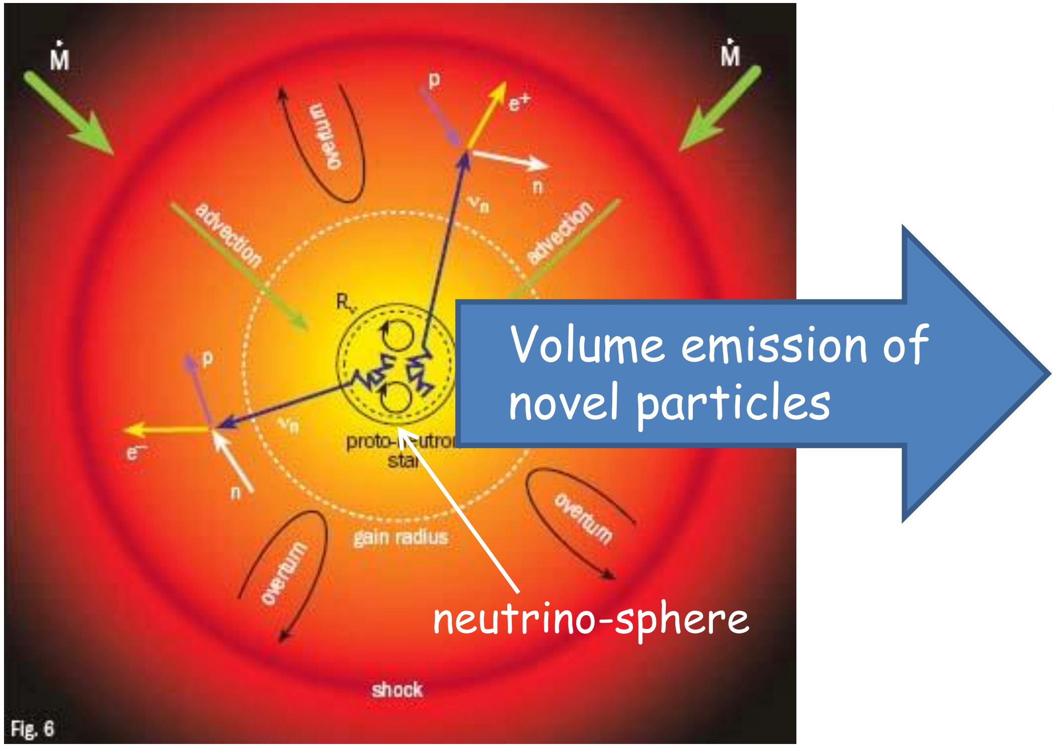
$$g_{a\gamma} \leq 5.3 \times 10^{-12}\ GeV^{-1} \quad \text{for} \quad m_a < 4.4 \times 10^{-10}\text{eV}$$

SN1987A provides the strongest bound on ALP-photon coversions for ultralight ALPs

PARTICLE PHYSICS LESSON FROM SN 1987A

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

ENERGY-LOSS ARGUMENT



Volume emission of novel particles

neutrino-sphere

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

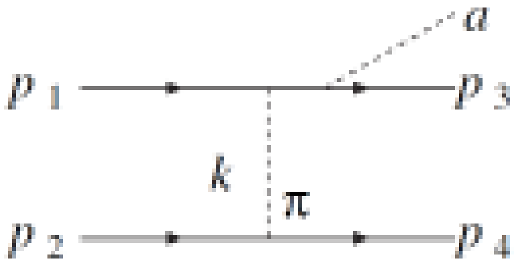
Assuming that the SN 1987A neutrino burst was not shortened by more than ~$\frac{1}{2}$ leads to an approximate requirement on a novel energy-loss rate of

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

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

AXION EMISSION FROM A NUCLEAR MEDIUM

$$NN \to NNa$$



nucleon-nucleon bremsstrahlung

$$L_{\text{int}} = \frac{C_N}{2 f_a} \bar{\psi}_N \gamma_\mu \gamma_5 \psi_N \partial^\mu a = \frac{C_N}{2 f_a} j_\mu^A \partial^\mu a$$

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

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

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

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

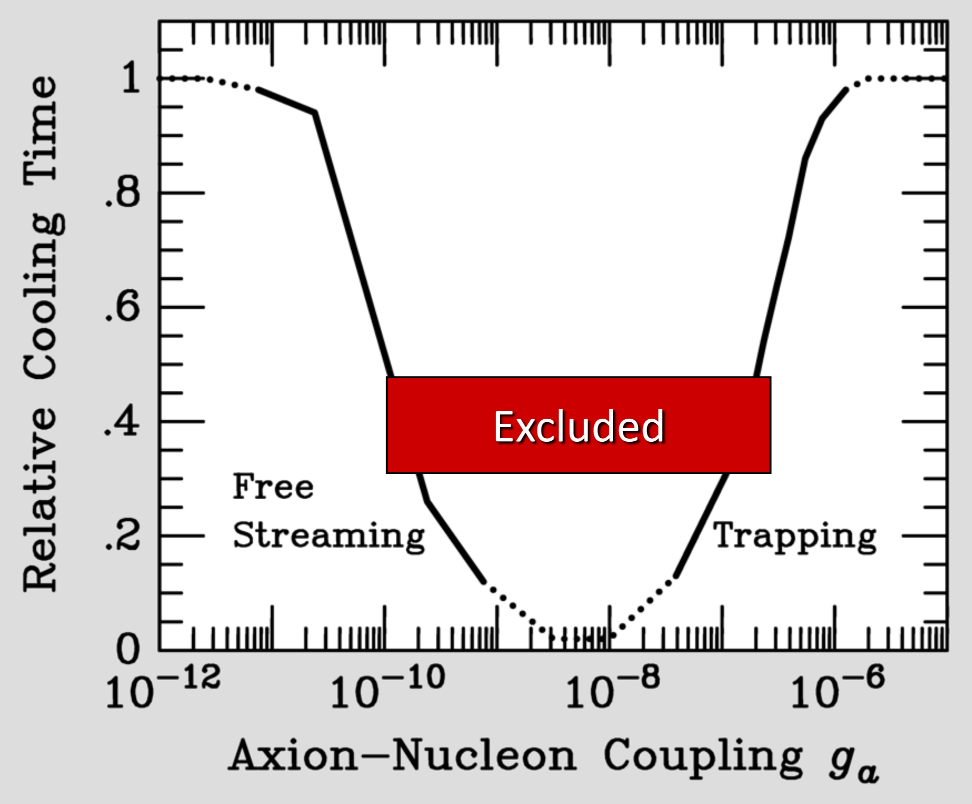
$$\Rightarrow \quad g_{aN} < 10^{-10}$$

SN1987A 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 SN1987A. Possible hot-dark matter candidate. The "hadronic axion window" is closed by cosmological mass bounds.

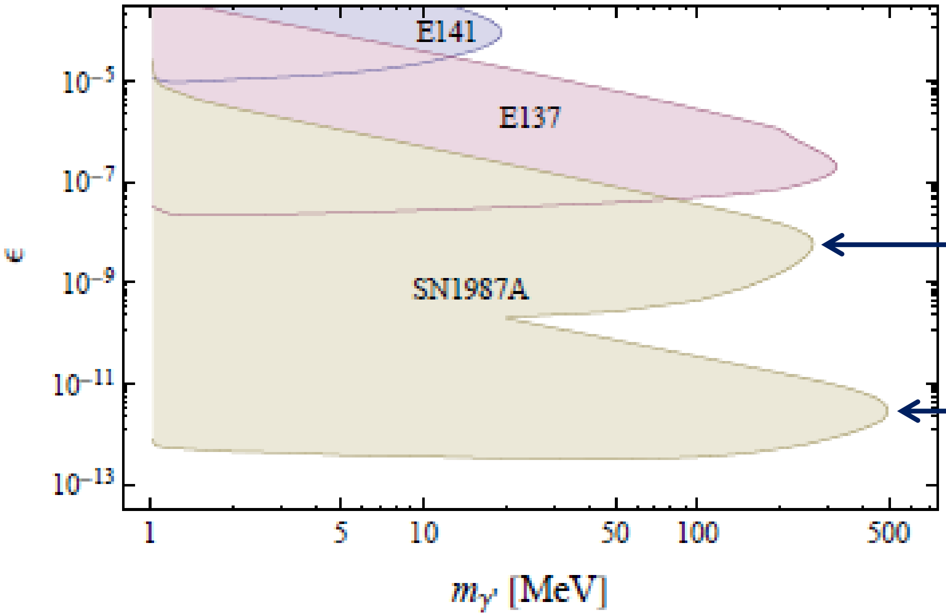
SN1987A BOUND ON HIDDEN PHOTONS

[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'

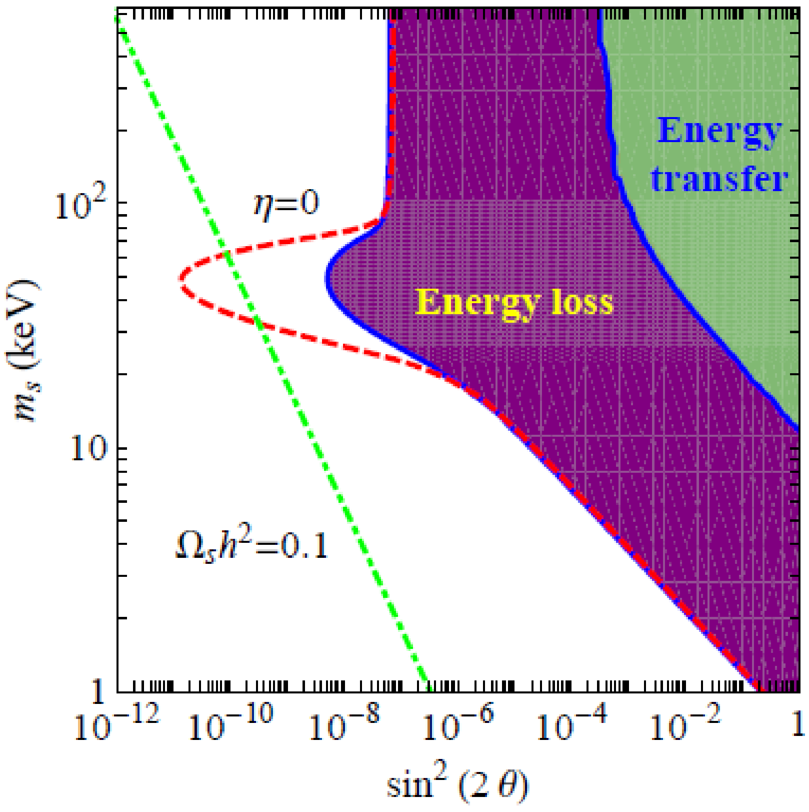


Energy-loss argument

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

SN1987A BOUND ON KeV STERILE NEUTRINOS

[Raffelt & Zhou, 1102.5124]



- 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.
- When both θ and m_s are sufficiently large ν_s are trapped in the SN core. However, since they have the largest free-path they contribute to the energy transfer, reducing once more the duration of the ν signal.

Warm Dark Matter range is essentially unconstrained.

WHAT WE LEARNT FROM SN1987A?

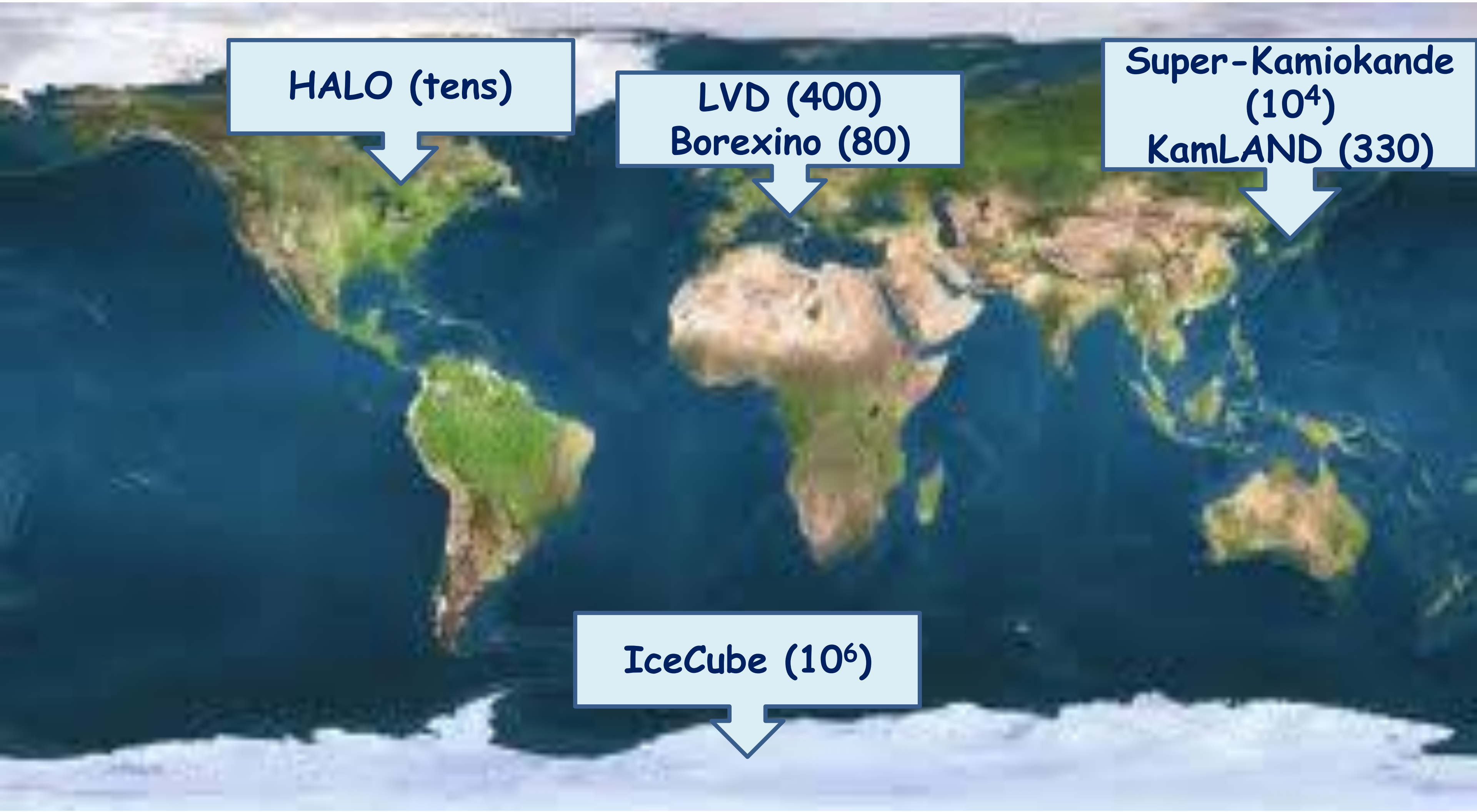
- General confirmation of core-collapse paradigm (total energy, spectra, time scale)

- No unexpected energy-loss channel: Restrictive limits on axions, large extra-dimensions, right-handed neutrinos, etc…..

- Improving Energy-Loss Limits with Next Supernova?

  Even a relatively low-statistics new measurement could confirm general validity of SN 1987A energy-loss limits

Large Detectors for Supernova Neutrinos

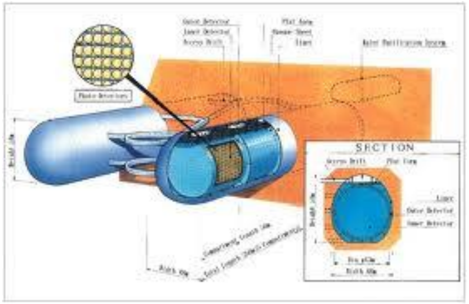


In brackets events for a "fiducial SN" at distance 10 kpc

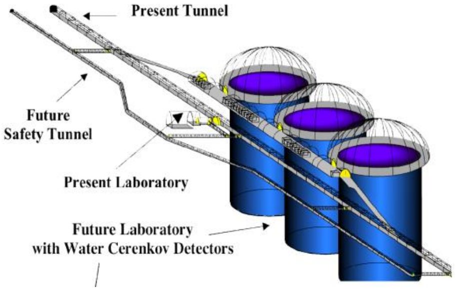
NEXT-GENERATION DETECTORS

Mton scale water Cherenkov detectors

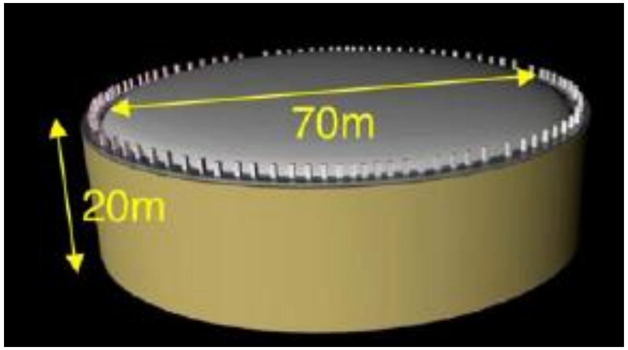
HYPER-
KAMIOKANDE



MEMPHYS



30-100 kton Liquid Argon TPC



GLACIER, LBNE

20-50 kton scintillator

JUNO

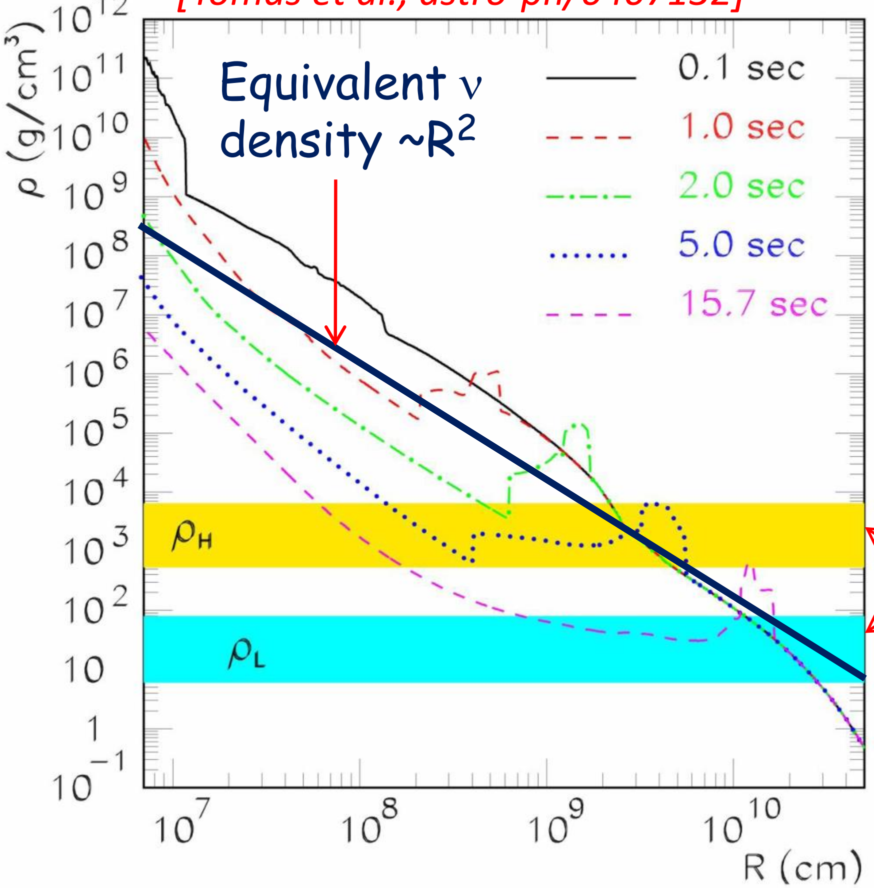
LENA

OUTLINE

- Introduction to SN neutrinos
- SN neutrinos & NSI
- SN 1987A neutrinos
- Particle physics lesson from SN 1987A
- **SN neutrino oscillations**
- Diffuse SN neutrino background (DSNB)
- Conclusions

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

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

Far more complicated than expected

Spontaneous symmetry breaking in collective oscillations!

SUPPRESSION OF COLLECTIVE OSCILLATIONS

At the moment, predictions are more robust in the phases where collective effects are suppressed, i.e.:

- Neutronization burst ($t < 20$ ms): large ν_e excess and ν_x deficit *[Hannestad et al., astro-ph/0608695]*

- Accretion phase ($t < 500$ ms): dense matter term dominates over nu-nu interaction term *[Chakraborty, A.M. , Saviano et al., 1104.4031, 1105.1130, 1203.1484, Sarikas et al., 1109.3601]*

Large flux differences during the neutronization and accretion phase

Best cases for ν oscillation effects !

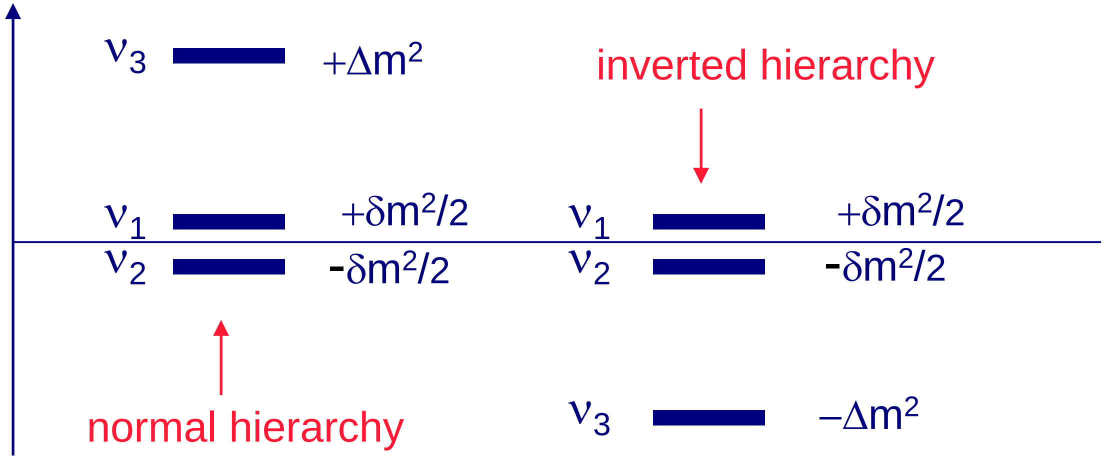
3ν FRAMEWORK

- **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

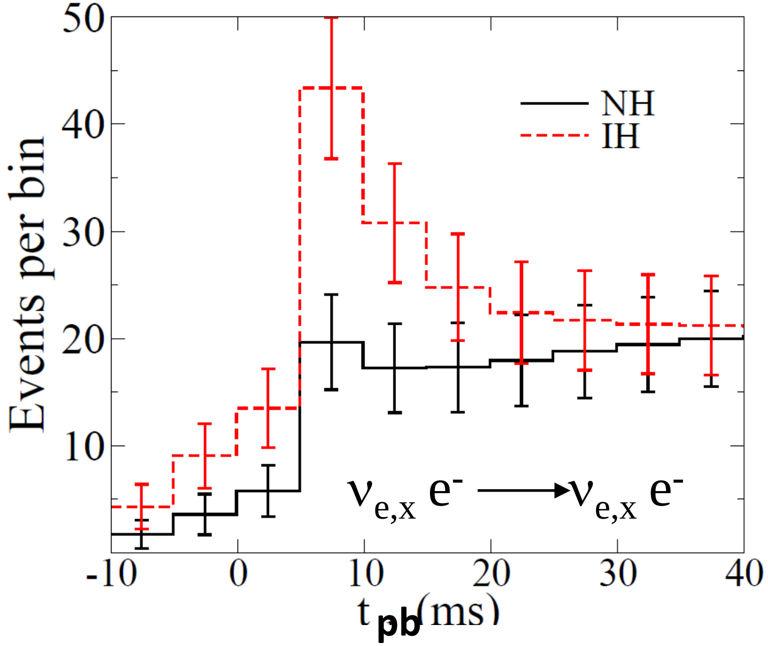
- **Mass-gap parameters:** $M^2 = \left(\underbrace{-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}}_{\text{“solar”}}, \underbrace{\pm \Delta m^2}_{\text{“atmospheric”}} \right)$



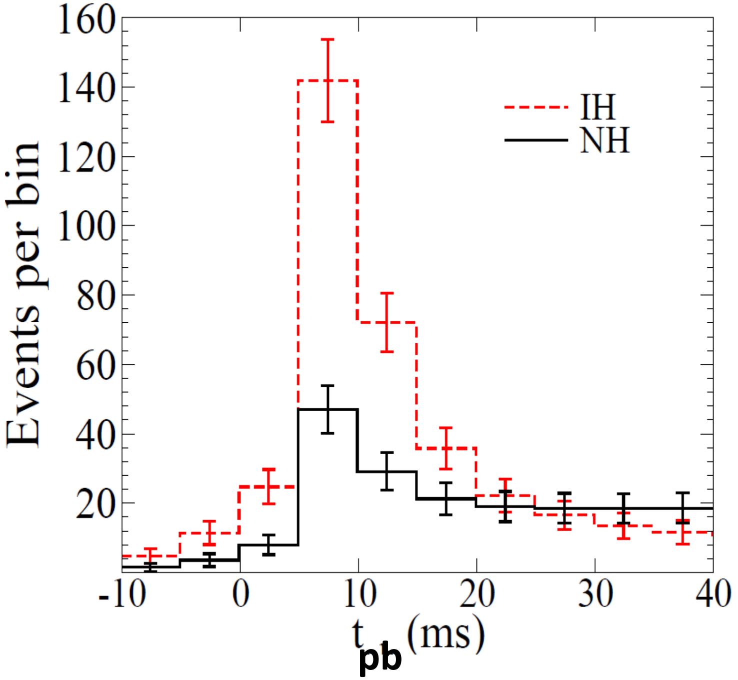
SN neutrinos are sensitive to the unknown mass hierarchy

NEUTRONIZATION BURST

0.4 Water Cherenkov



100 kton LAr



Robust feature of SN simulations

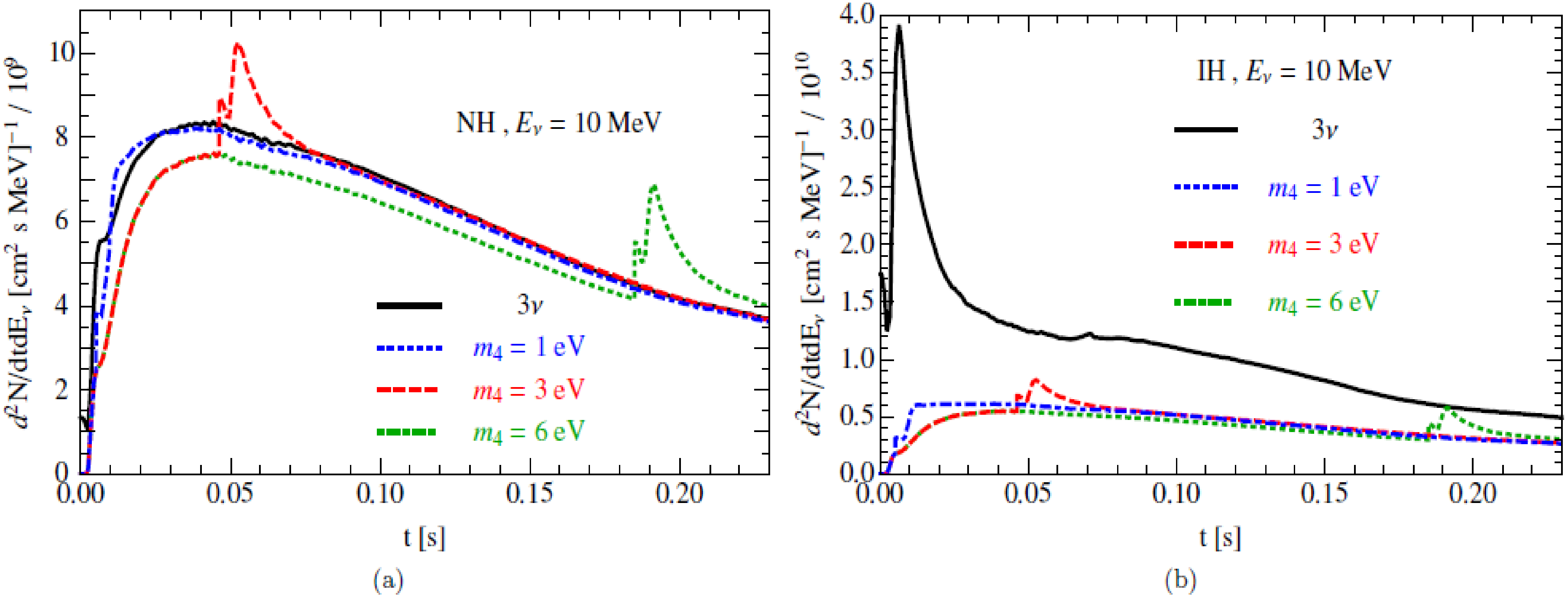
[Kachelriess et al., astro-ph/0412082, Gil-Botella & Rubbia, hep-ph0307244]

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

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

PROBING eV STERILE NU WITH NEUTRONIZATION BURST

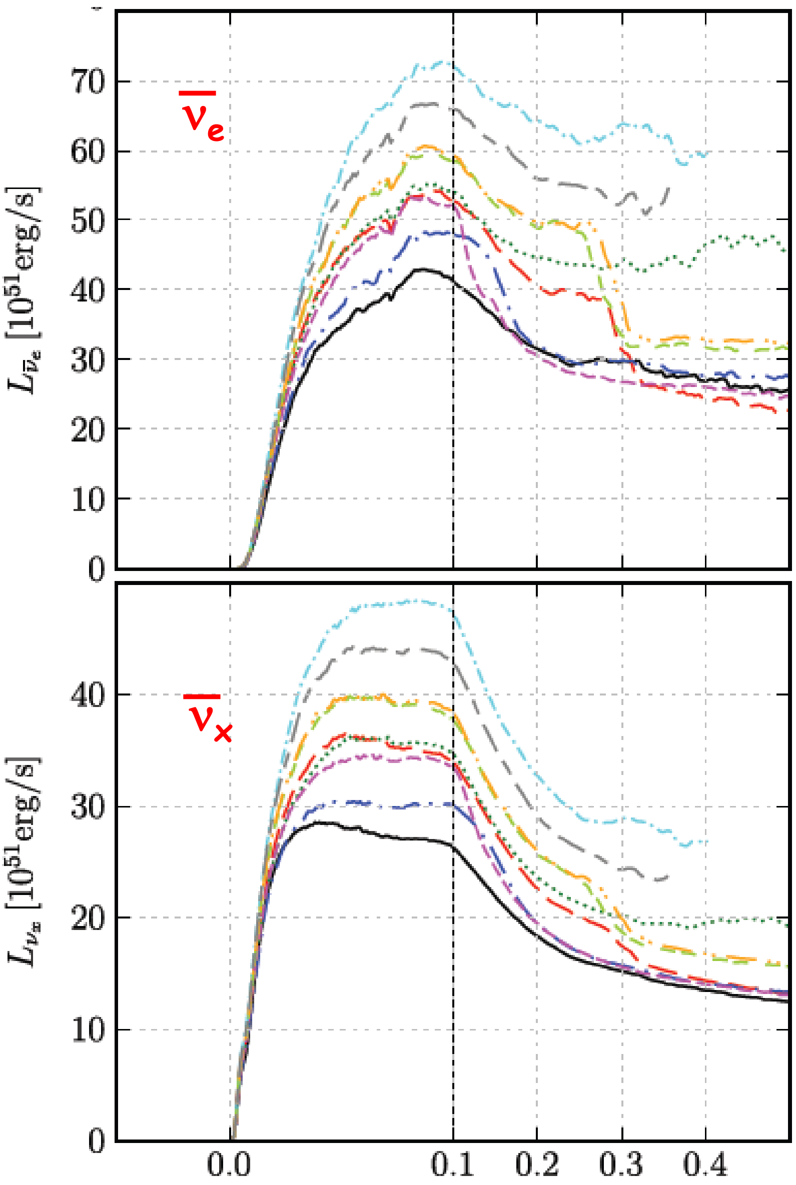
[Esmaili, Peres & Serpico, 1402.1453]



3+1 scheme

- IH: disappearence of neutronization peak. Possible appearence of delayed peak due to the fraction of heavy ν_4 component in ν_e (kinematical reason).
- Peculiar time-energy distribution in LAr TPC.

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 ANALYSIS: HIERARCHY DETERMINATION

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

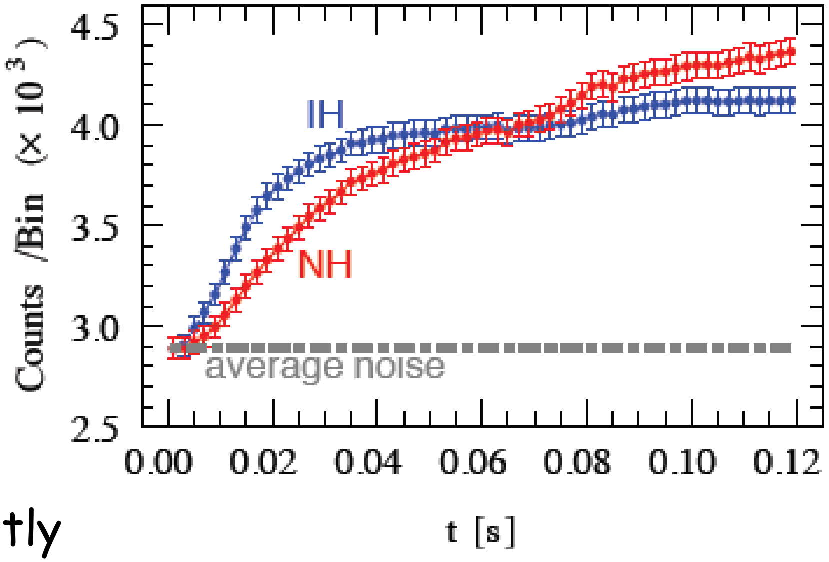
In accretion phase one has

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

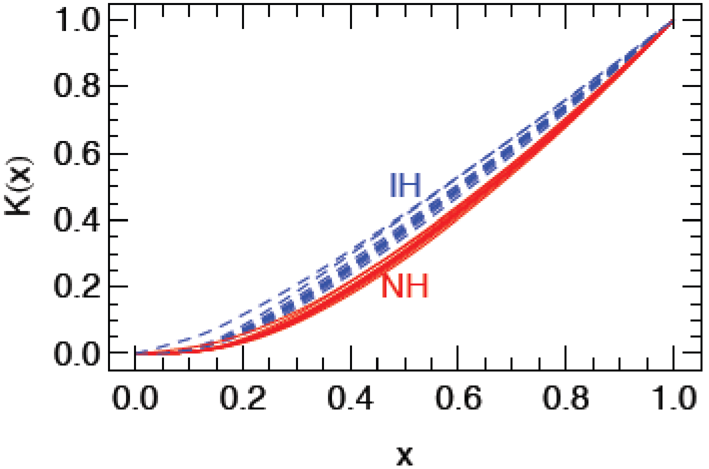
SN ν signal in Icecube



- 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]*

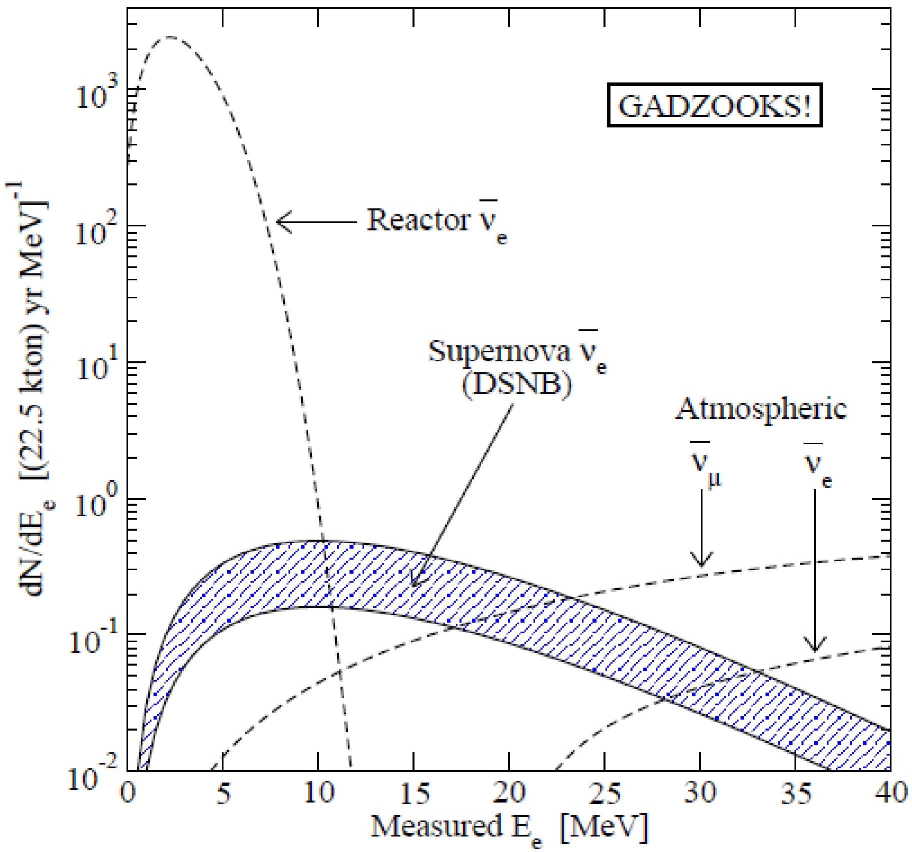
OUTLINE

- Introduction to SN neutrinos
- SN neutrinos & NSI
- SN 1987A neutrinos
- Particle physics lesson from SN 1987A
- SN neutrino oscillations
- Diffuse SN neutrino background (DSNB)
- Conclusions

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

- Approx. 10 core collaspes/sec in the visible universe
- Emitted ν energy density
  ~extra galactic bkg light
  ~ 10% of CMB density
- Detectable $\overline{\nu}_e$ flux at Earth
  ~ 10 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  mostly from redshift z~1
- Confirm the star formation rate
- Nu emission from average core-collapse & black-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances!

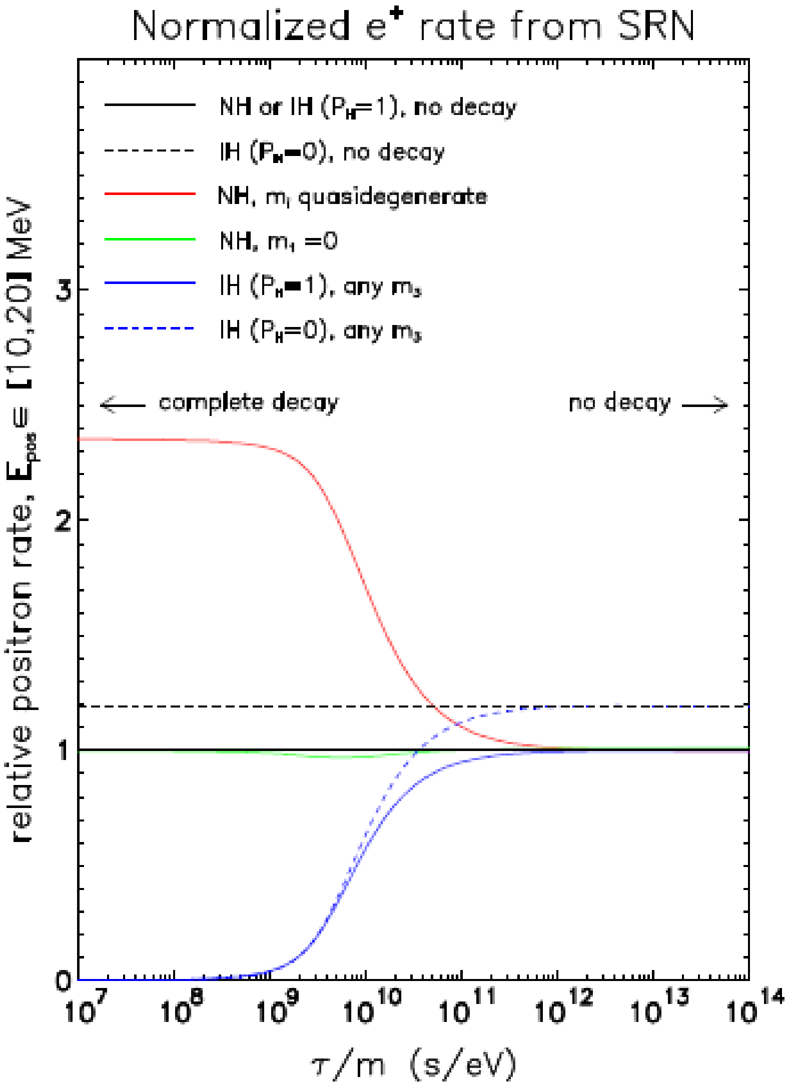
[Beacom & Vagins, hep-ph/0309300]



Windows of opportunity btw reactor $\overline{\nu}_e$ and atmospheric ν bkg

CONSTRAINT OF NU INVISIBLE DECAY FROM DSNB

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

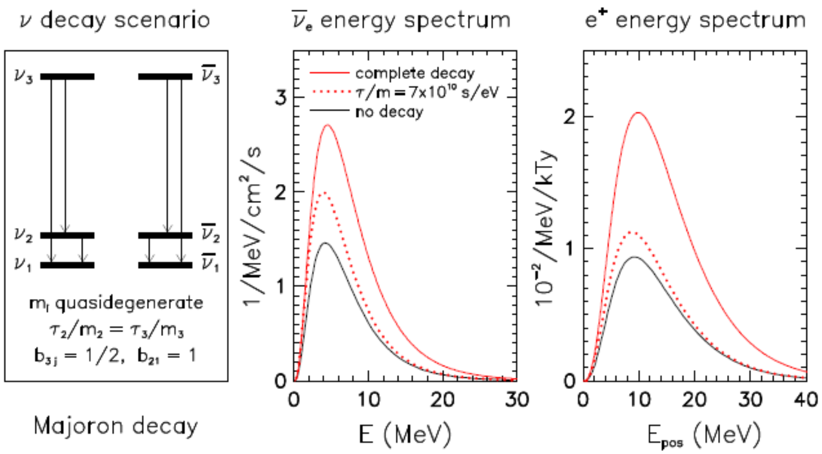


Nu decay in Majoron

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

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

OUTLINE

- Introduction to SN neutrinos
- SN neutrinos & NSI
- SN 1987A neutrinos
- Particle physics lesson from SN 1987A
- SN neutrino oscillations
- Diffuse SN neutrino background (DSNB)
- **Conclusions**

CONCLUSIONS

Observing SN neutrinos is the next frontiers 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.

THANK YOU!