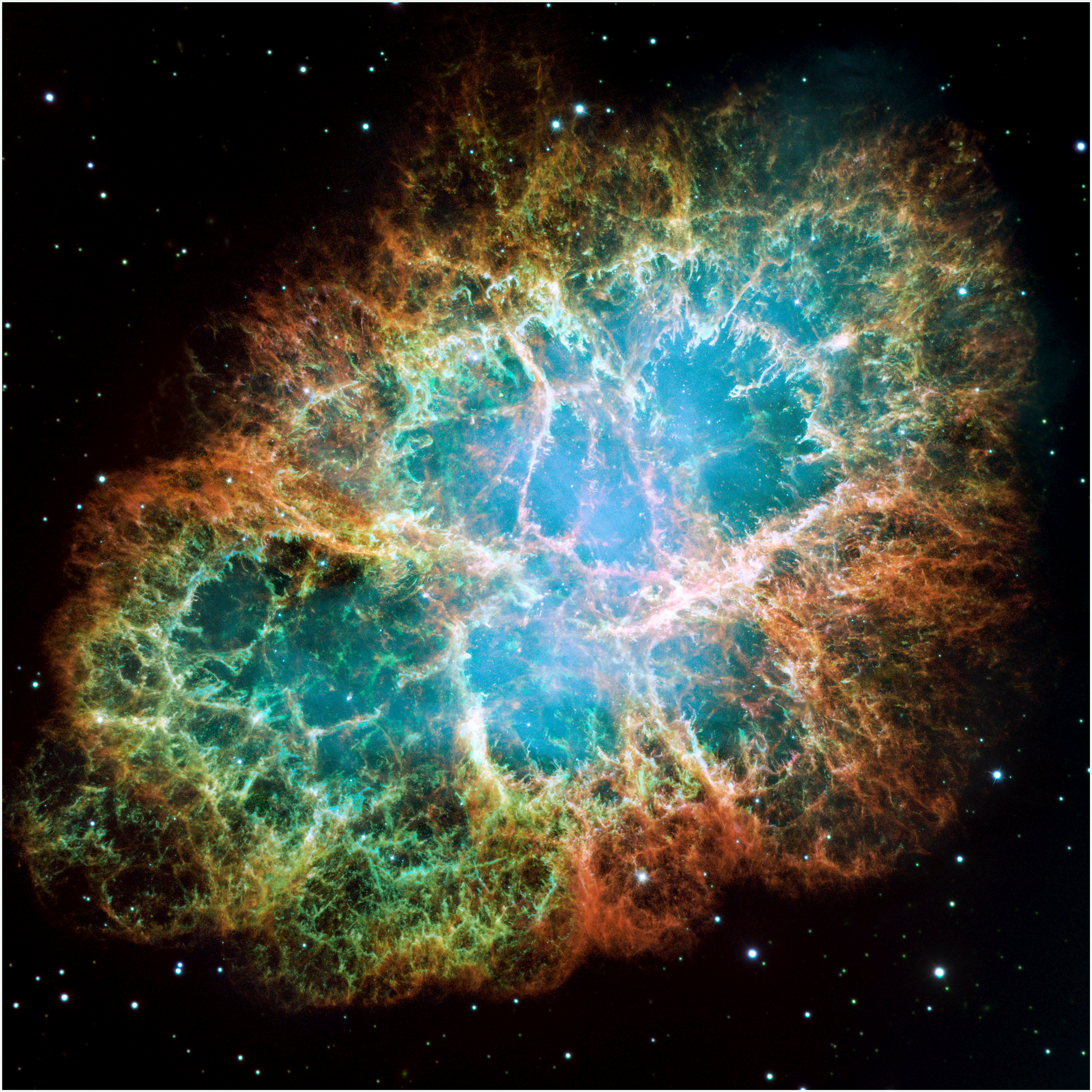


WHAT SHALL WE LEARN FROM A FUTURE CORE-COLLAPSE SUPERNOVA?

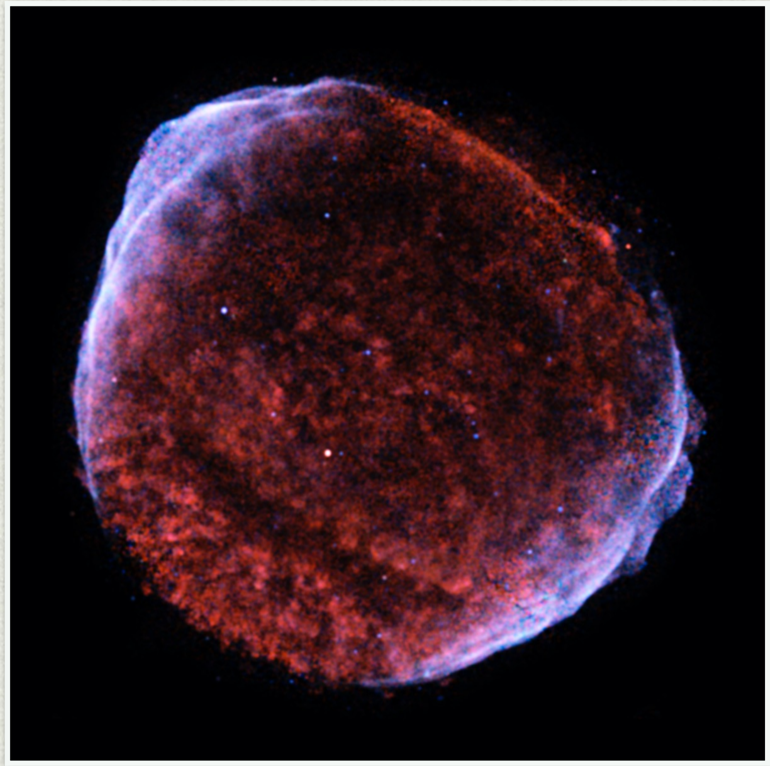
Maria Cristina Volpe
CNRS, Astroparticle and Cosmology Laboratory, Paris

OUTLINE

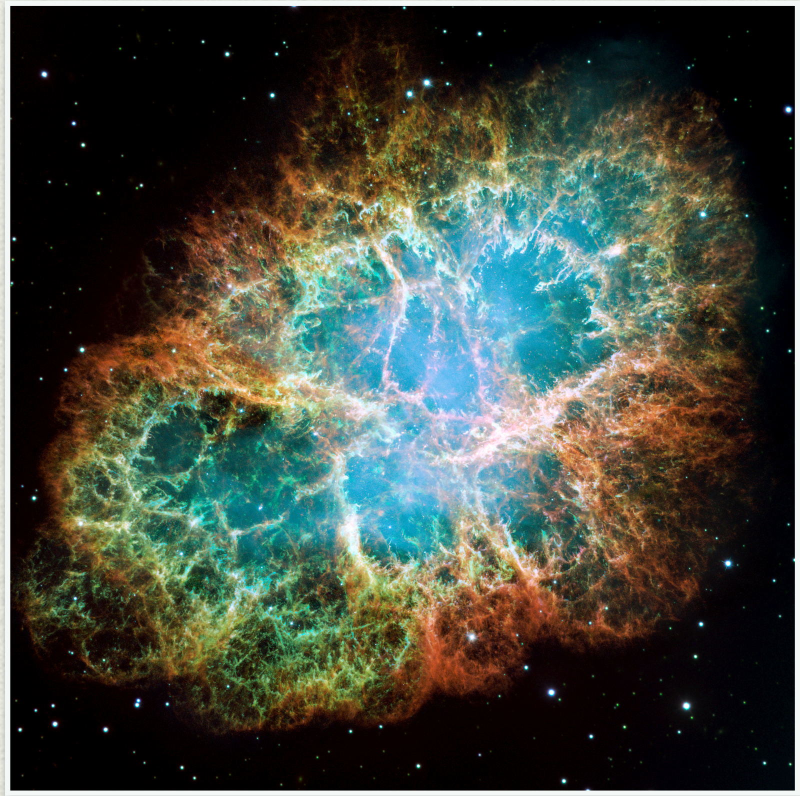
- ★ Core-collapse supernovae
- ★ Theoretical aspects of neutrinos from dense environments
- ★ A future supernova
- ★ The diffuse supernova neutrino background
- ☆ Conclusions

SUPERNOVAE IN THE MILKY WAY - since 1000 y

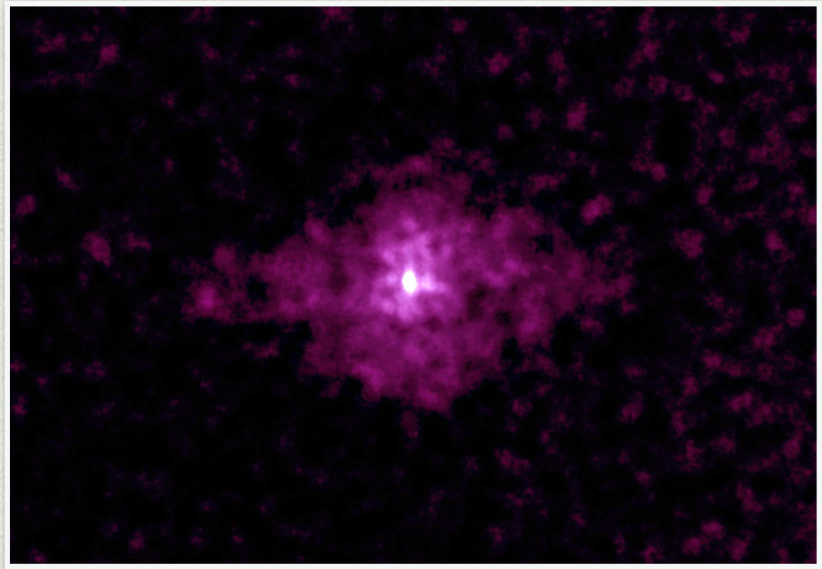
SN 1006


Smithsonian Institution

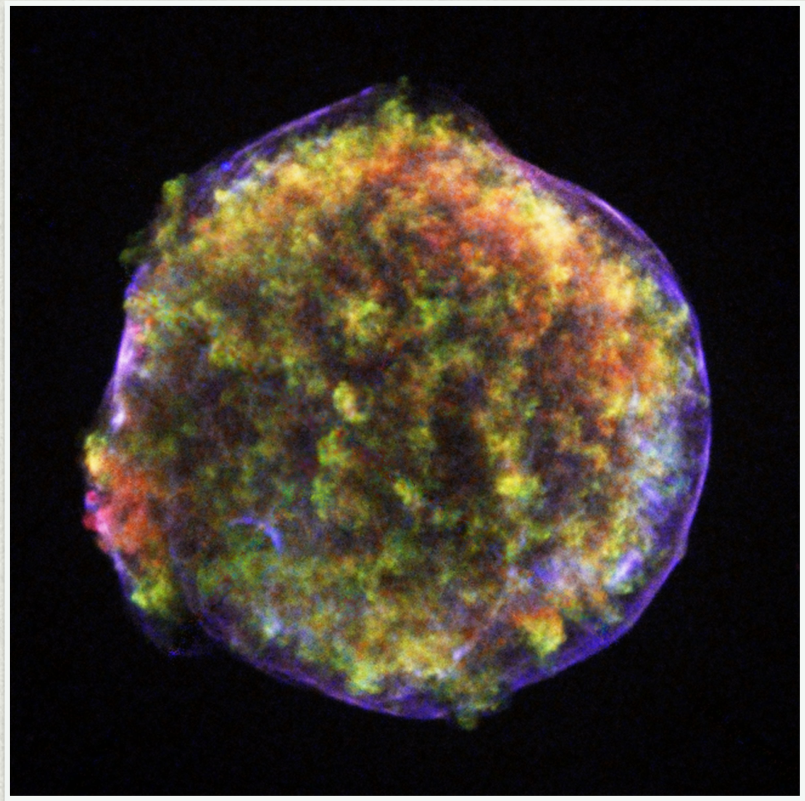
SN 1054
Crab Nebula


NASA, ESA, J. Hester and A. Loll

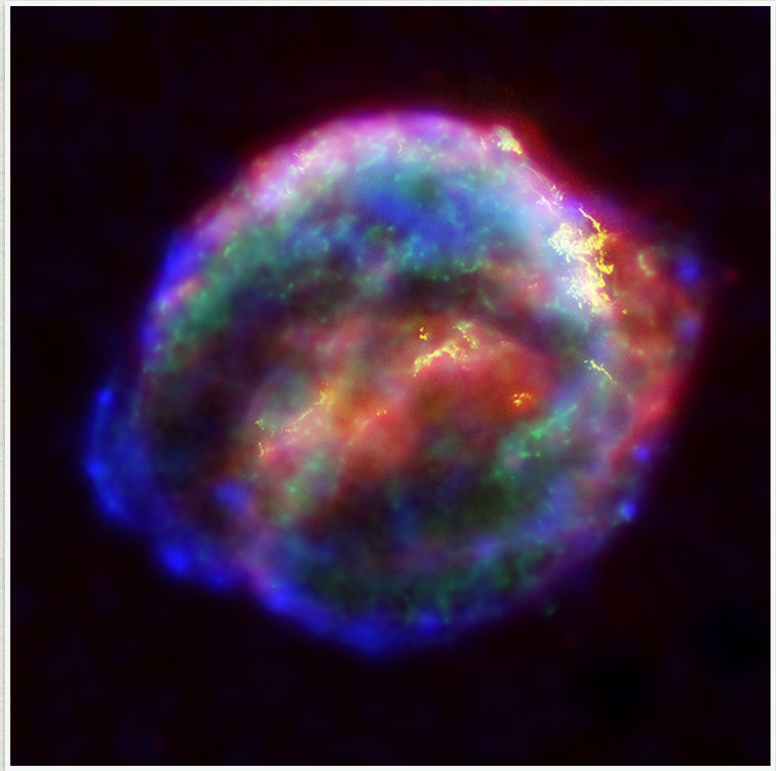
SN 1181


NASA/CXC/SAO/S.Murray et al.

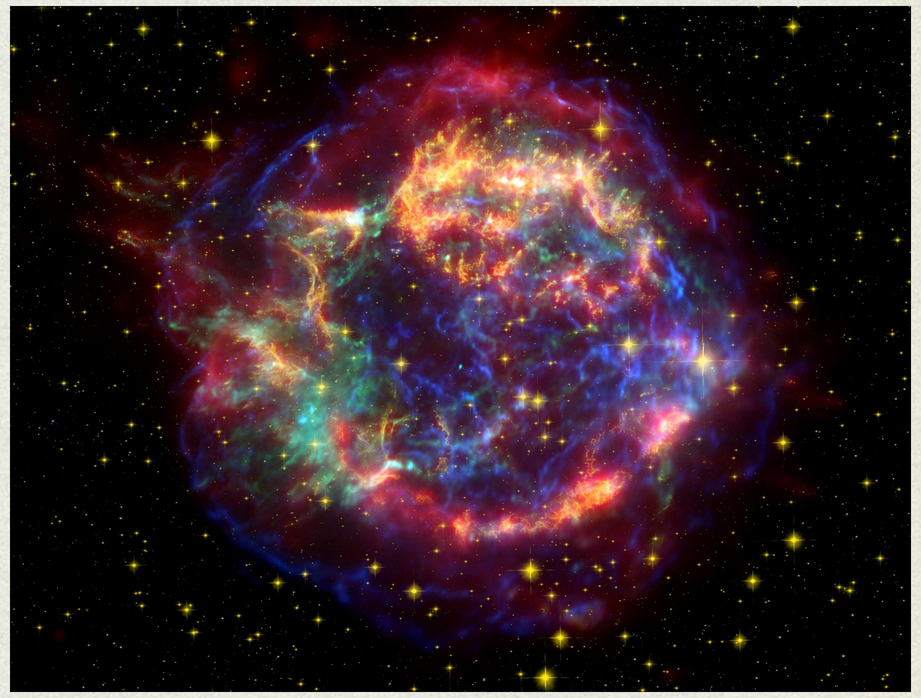
SN 1572


NASA/CXC/Rutgers/J.Warren & J.Hughes et al.

SN 1604


NASA/ESA/JHU/R.Sankrit & W.Blair

SN 1667 (Cas A)


Courtesy NASA/JPL-Caltech

THE LOCAL GROUP

- **Largest galaxies :** Small Magellanic Cloud (SMC), NGC 3109, Large Magellanic Cloud (LMC), Triangulum Galaxy, Milky Way, Andromeda (M31).
- In the last century, in the Local Group, SN1987A (LMC) and SN 1885 (Andromeda)
- **Supernovae** are rare events. Evaluations of the Galactic core-collapse supernova rate include

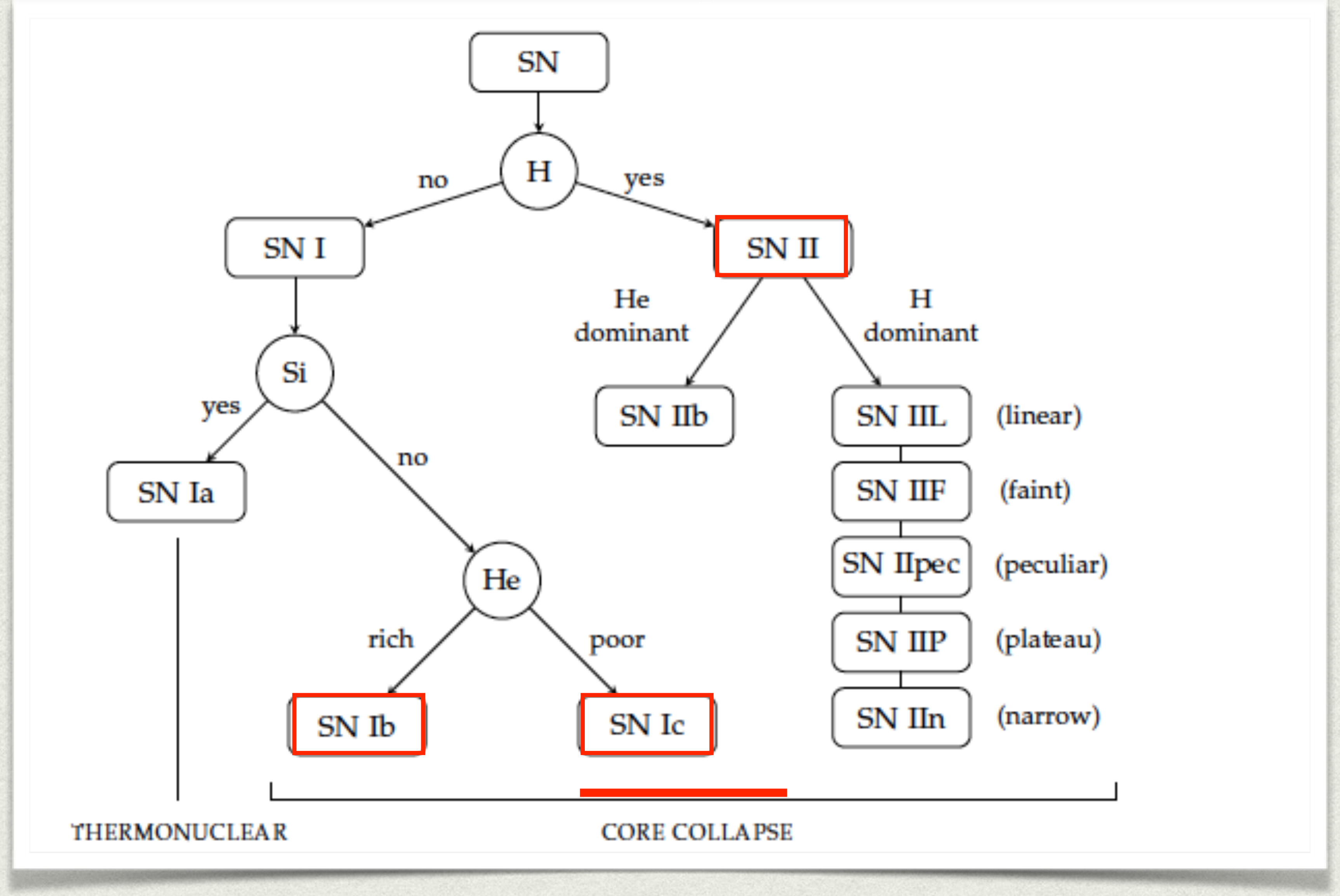
$\mathrm{CORE - COLLAPSESUPERNOVARATES(MilkyWay)}(100y)^{-1}$

1.9 ± 1.1	^{26}Al in our Galaxy	Diehl et al, Nature, 2006
$3.2^{+7.3}_{-2.6}$	historical SNe	Adams et al, Astr. Journ., 2013
1.7 ± 0.74	observed SNe	Cappellaro et al 1993, Abrahim et, 2020
7.2 ± 2.7	observed NS	Keane, Kramer, Mon. N. Roy. Ac., 2008 Rozwadowska et al, New Astr., 2021
$1 - 2$	1.5 kpc from Sun	Reed, Astr. J., 2005
1.63 ± 0.46	combining some observations	Rozwadowska et al, New Astr., 2021

In the Milky Way, the core-collapse supernova rate is about 1-2 or 1-3 per century.

CORE-COLLAPSE SUPERNOVAE

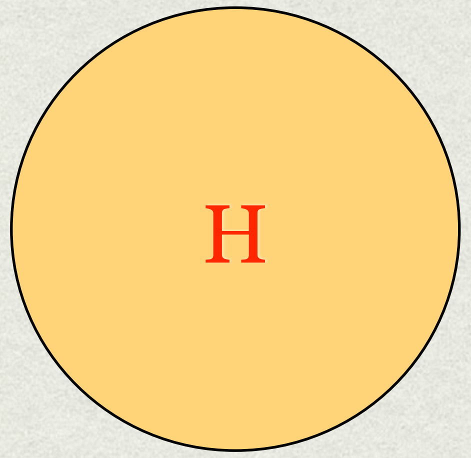
- Spectral classification of supernovae



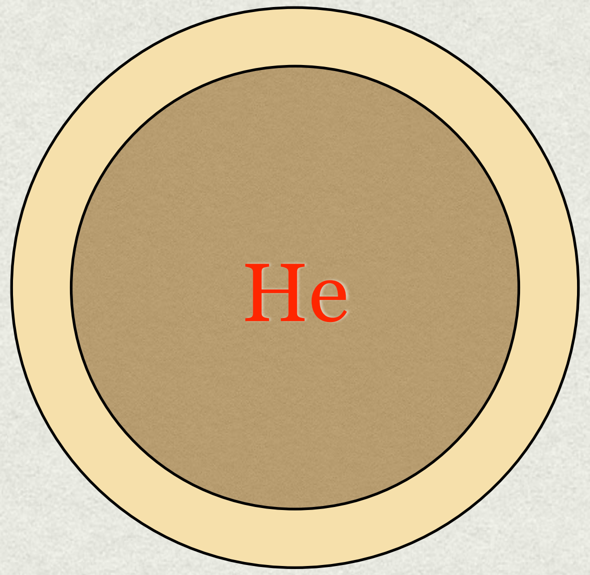
Schematic evolution of a massive star (25 Msun)

Energy : 99 % neutrinos, 0.01% photons
about 1% explosion kinetic energy

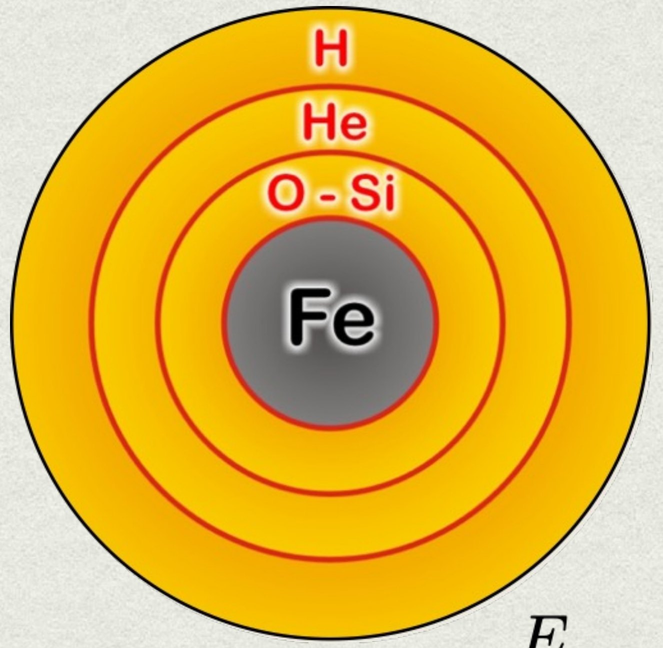
INITIAL STAGES



H burning
T= 0.09 10^9 K
Burning time = 7 My

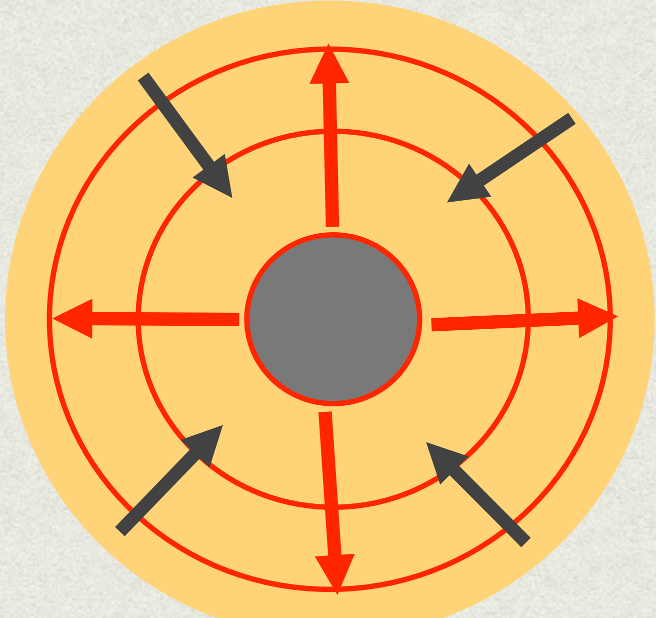


He burning
T= 0.2 10^9 K
Burning time = 5 10^5 y

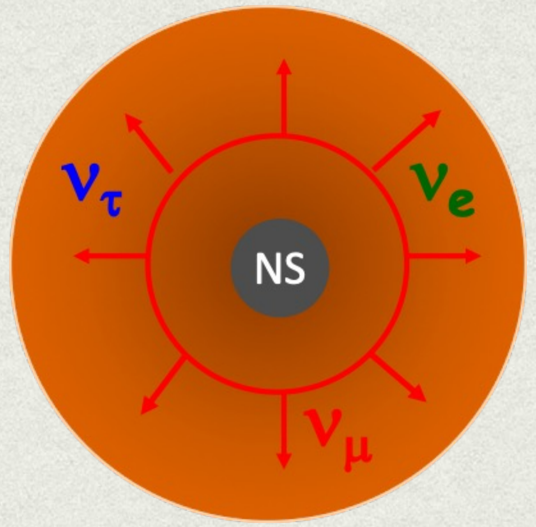


C (Si) burning
T= 0.8 (3.5) 10^9 K
Burning time = 600 y (1 d)

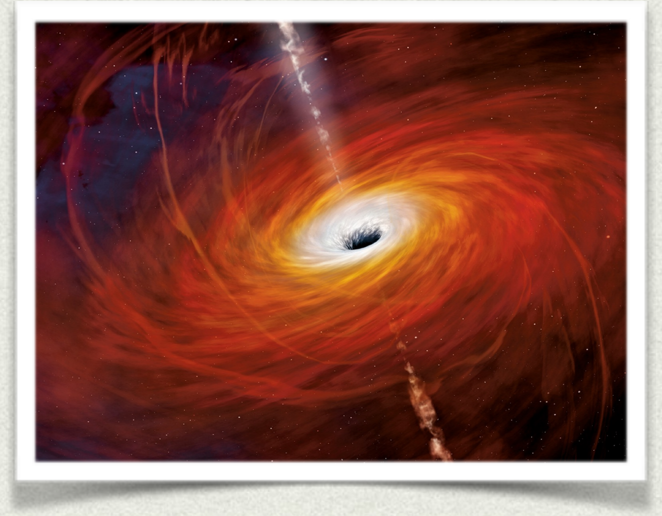
$$E_{grav} \approx \frac{GM^2}{R} \approx 10^{53} ergs$$



Supernova
(core-collapse and explosion)
Weaver, Woosley (1980)



neutron star (NS) formed



black-hole (BH)
Artist image

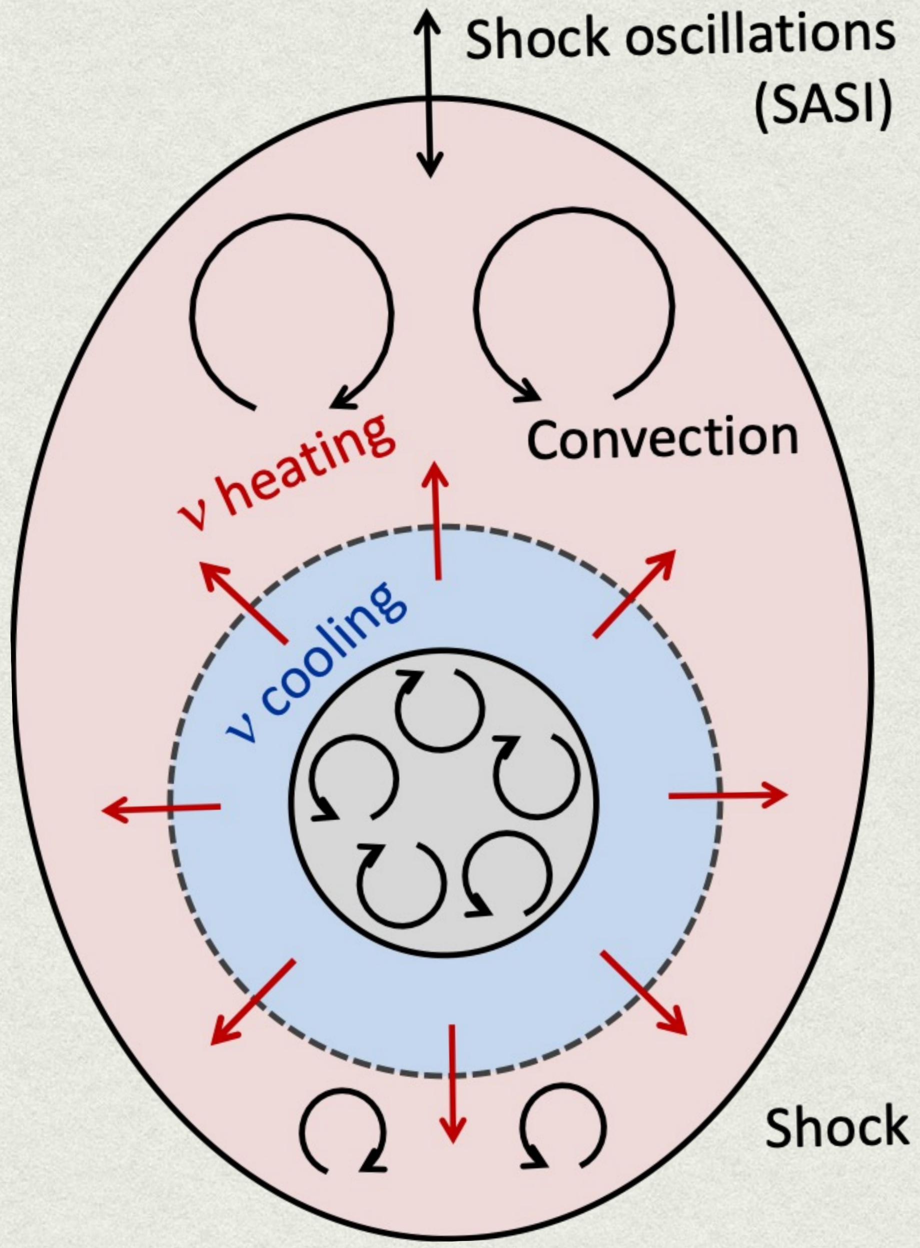
+ FAILED SUPERNOVAE

FINAL STAGES

SUPERNOVA EXPLOSION MECHANISM

Elucidating the core-collapse supernova mechanism is six-decade quest:

- Colgate and White (1966) neutrinos deposit energy behind the shock triggering the explosion: *prompt explosion mechanism*.
- Wilson (1982), Bethe and Wilson (1985) : neutrino heating render the accretion shock a dynamical shock.
- Herant et al (1992) performed the first 2D-simulations.
- Blondin et al (2003) : shock wave unstable to non-radial perturbations.
- Murphy et al (2013) : turbulent ram pressure contributes pushing the shock outward.
- the progenitor dependence, rotation (Summa et al, 2018), and magnetic fields (Obergaulinger et al, 2015, Kuroda et al, 2020) also important.



see Mezzacappa (2022), arXiv: 2205.13438,
T. Janka's talk at « Neutrino Frontiers » (GGI, 2023)

A MAJOR STEP FORWARD EVERY DECADE

SN1987A today


Hubble Space Telescope

On the 23rd February, Sanduleak $69^0$202 (blue supergiant) exploded, in the Large Magellanic Cloud

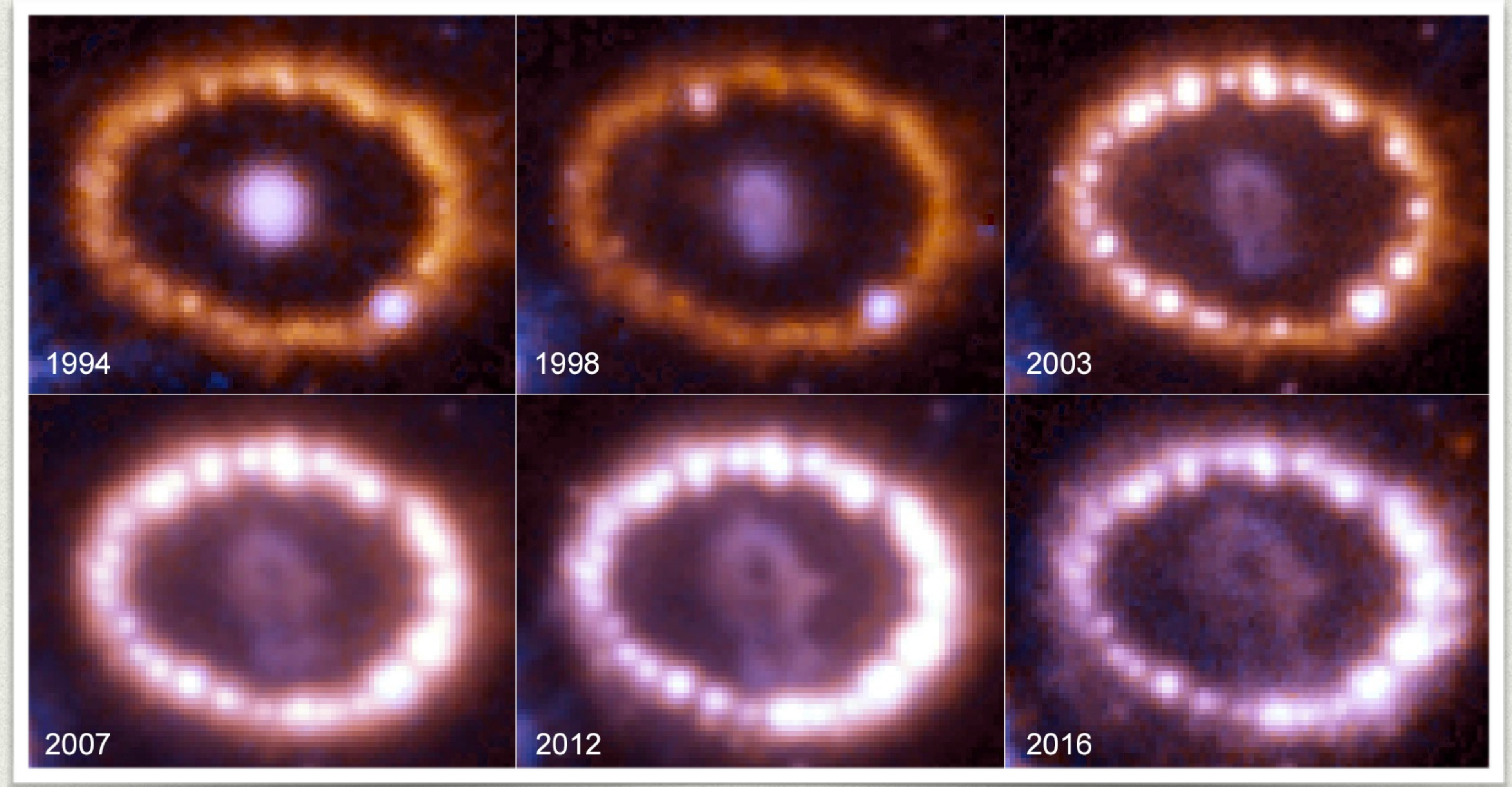
50 ± 5 kpc (163,000 light-years)

Schmidt et al, 1992

distance to LMC now known with 1% precision

49.59 ± 0.09 (stat) ± 0.54 (sys) kpc

Pietrzynski et al., 2019



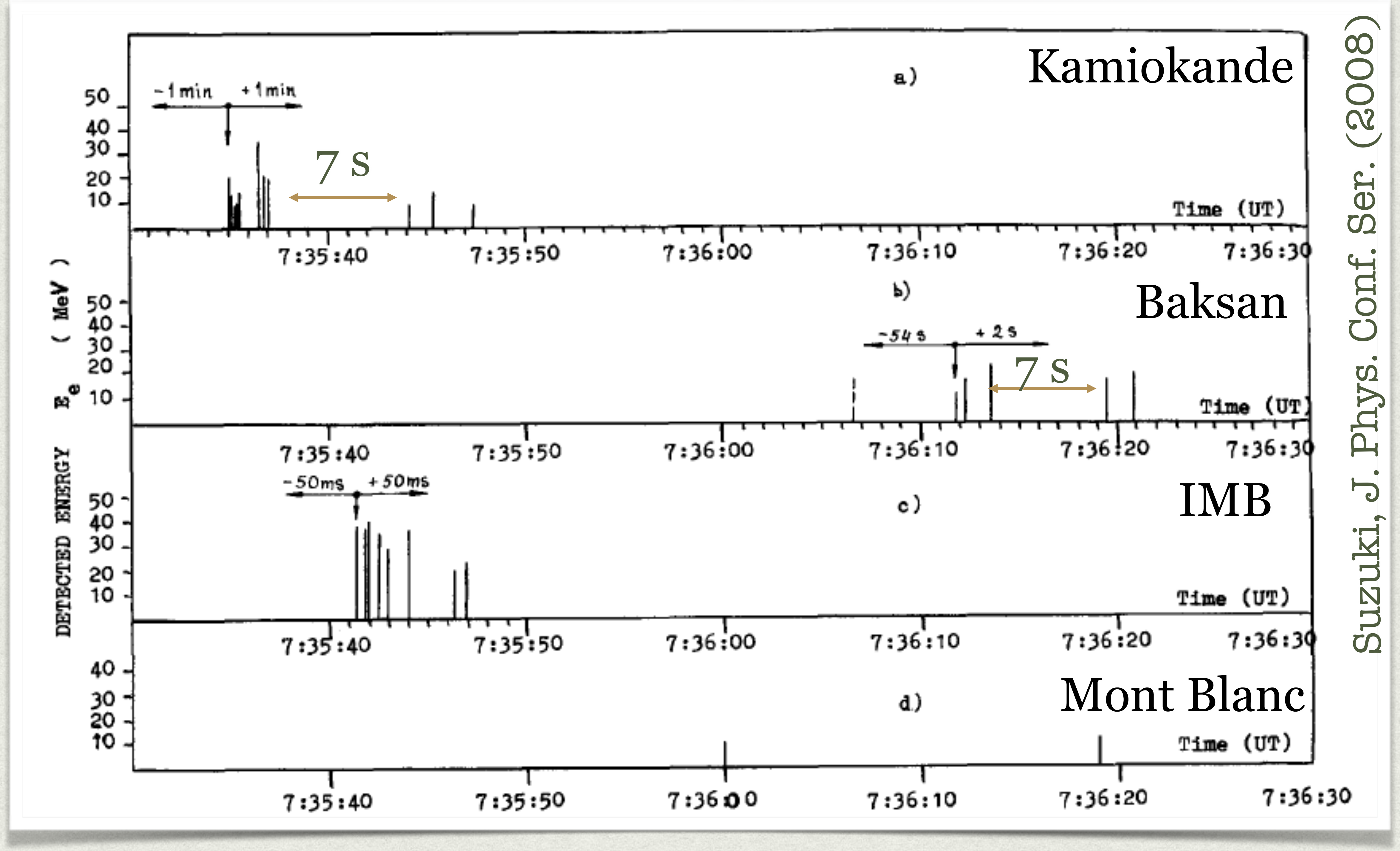
Hubble Space Telescope

- After 30 years, the remnant has been identified: a dust-obscured thermally emitting **neutron star**.

Alp et al, 2018, Cigan et al, 2019,
Page et al., Astroph. Journ. 898, 2020

SN1987A NEUTRINO EVENTS

- First observation of neutrinos from the core of an exploding massive star. Observed in all wavelengths.
  24 events detected (+5 events in Mont Blanc debated).



Suzuki, J. Phys. Conf. Ser. (2008)

Consistent with predicted time window, average energies

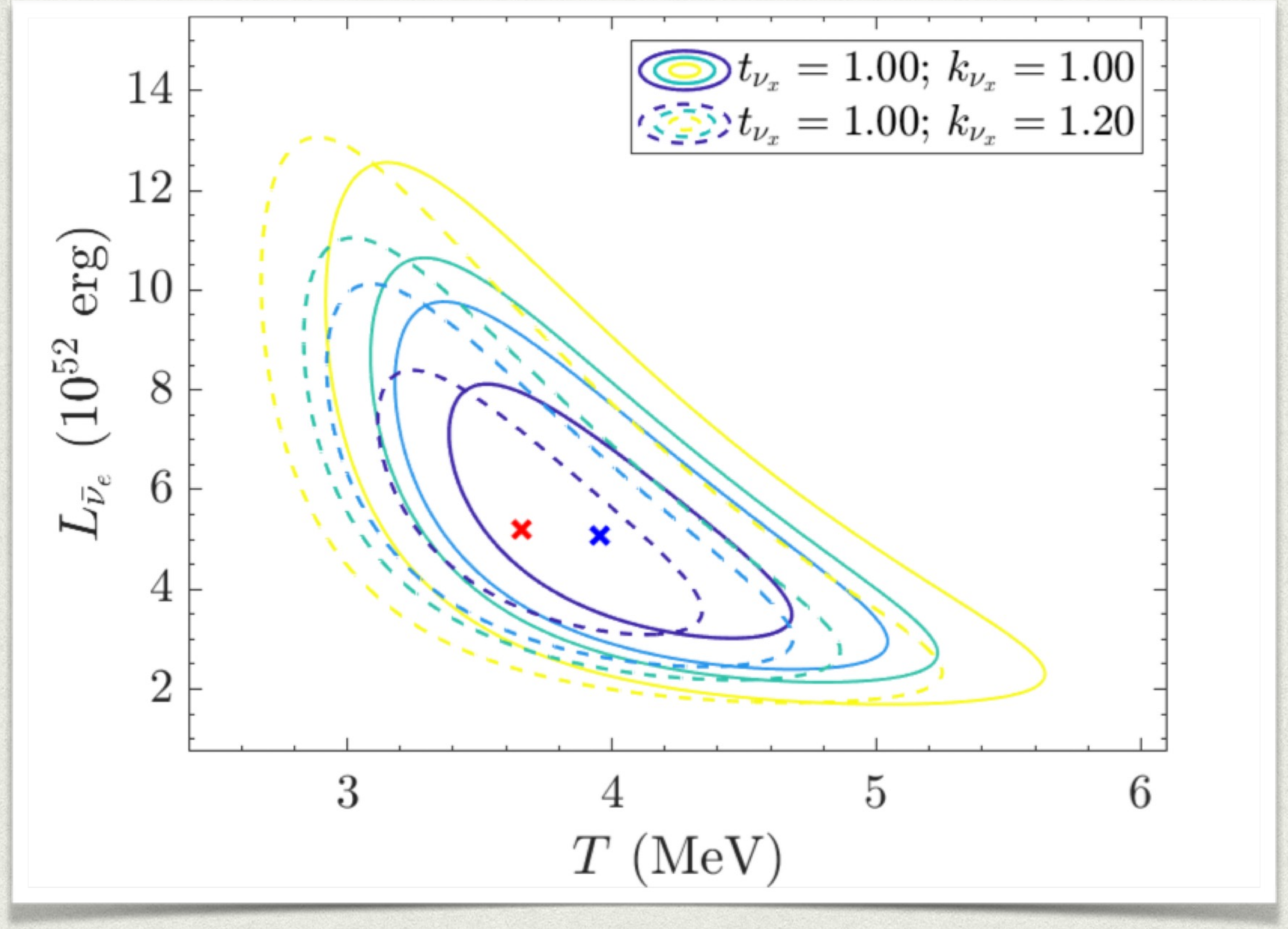
- Bayesian analysis considering only cooling models or accretion+cooling models.

«*We find two-component models* to be 100 more probable than *single-model component*. »

Loredo and Lamb, PLB 205 (1988)

Accretion+cooling SN model favored, prompt model rejected

SN1987A and the Mikheev-Smirnov-Wolfenstein (MSW) effect



Ivanez-Ballesteros and Volpe, PLB 2023, 2307.03549

- First analysis found strong sensitivity,

  Lunardini and Smirnov , Astrop. Phys. 2004

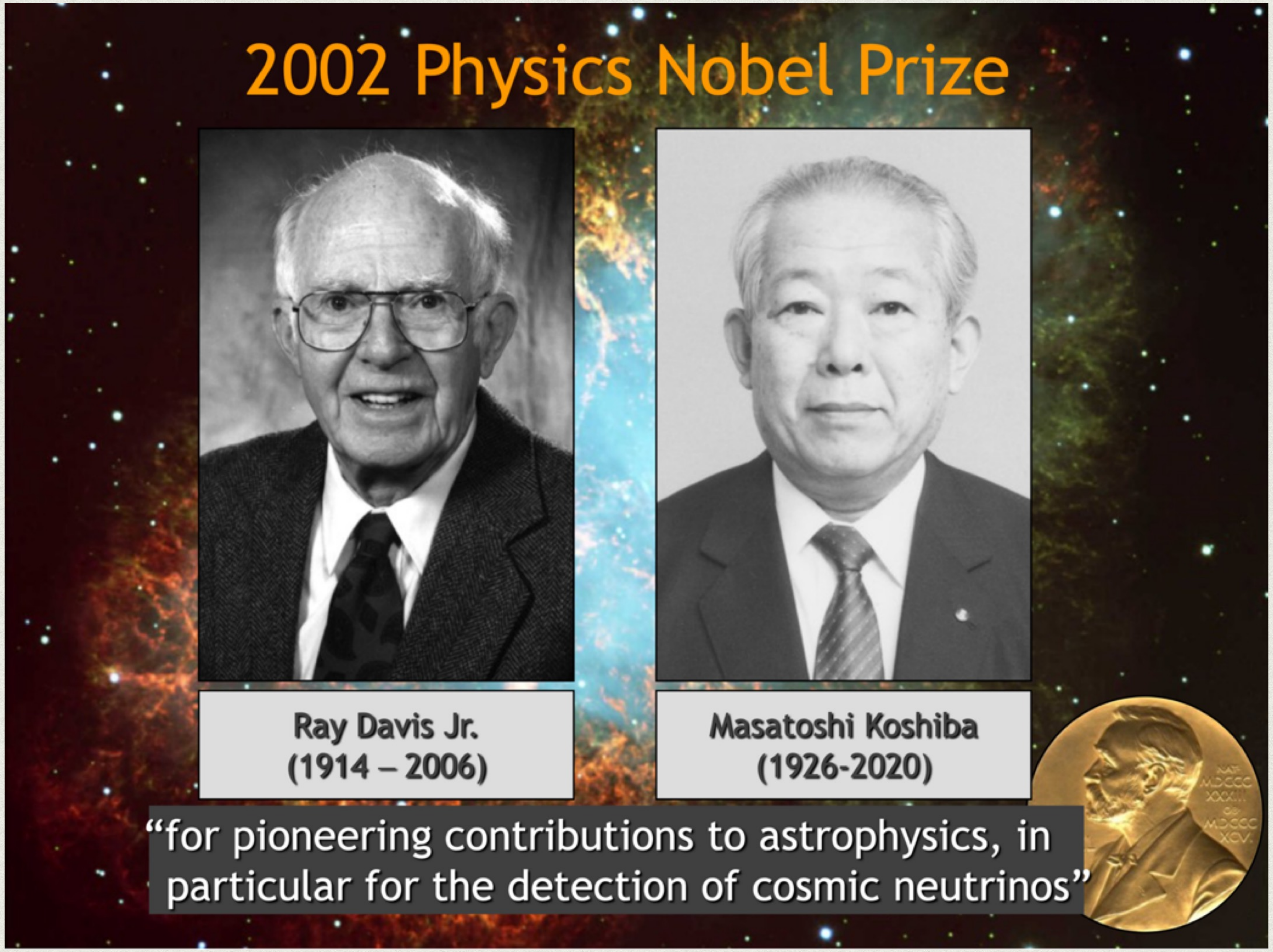
  or indicated a conflict with average neutrino energies from simulations.

  Jegerlherer, Neubig, Raffelt, PRD 54, 1996

- More recent found sensitivity at the level of 10%, from the spectral analysis

  Vissani, J.Phys.G 42, 2015

At the same level of several uncertainties
in the analysis (energy thresholds, efficiencies, …)



2002 Physics Nobel Prize

Ray Davis Jr.
(1914 – 2006)

Masatoshi Koshiba
(1926-2020)

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

Prix Nobel en 2002 avec R. Giacconi (1/2)

NEUTRINO NON-RADIATIVE DECAY

- Since neutrinos are massive they can decay. Neutrino non-radiative two-body decay:

$$\nu_i \rightarrow \nu_j + \phi \quad \text{or} \quad \nu_i \rightarrow \bar{\nu}_j + \phi$$

ϕ a massless (pseudo)scalar particle

due to tree-level (pseudo)scalar couplings.

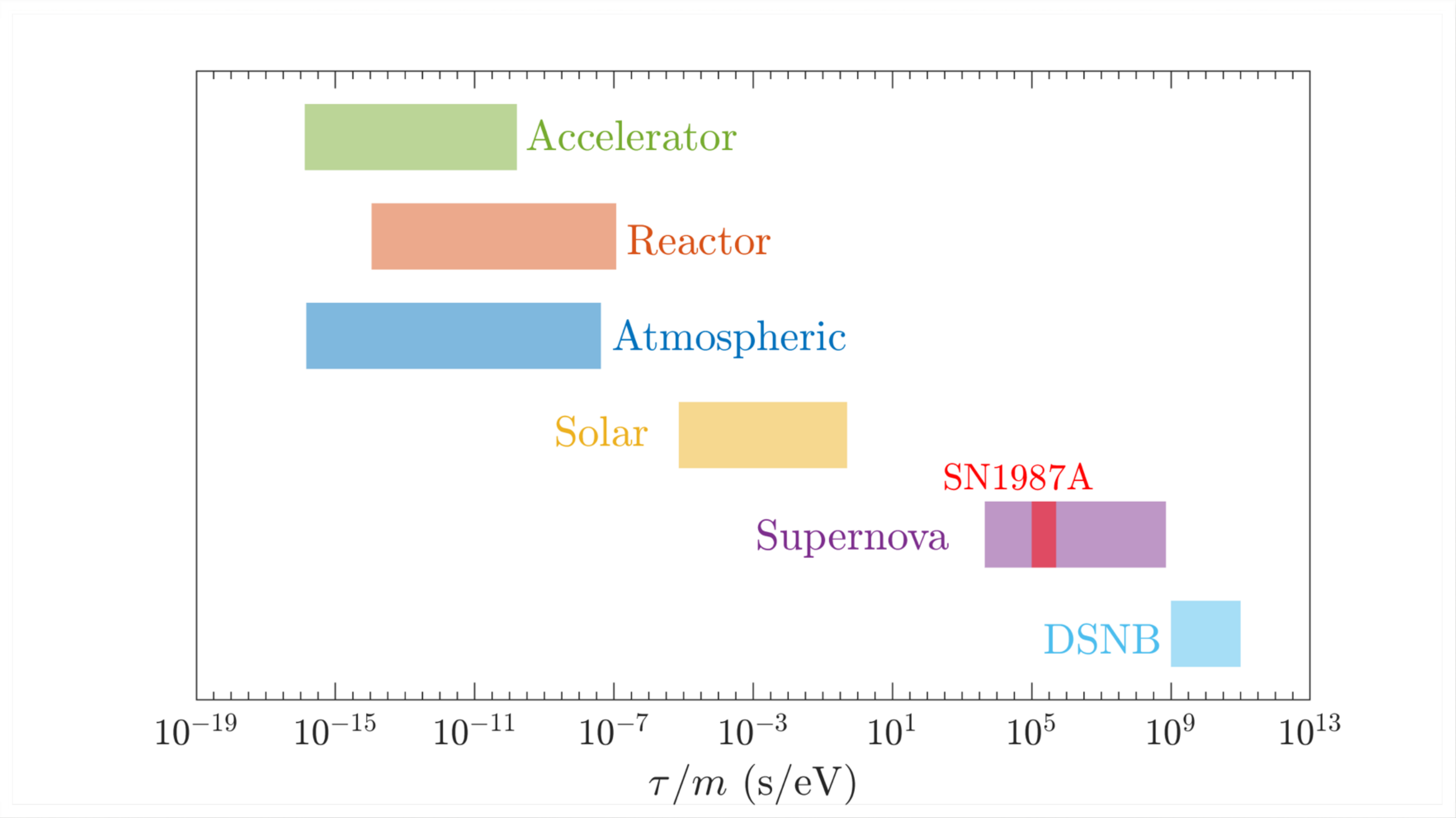
$$\mathcal{L} = g_{ij}\bar{\nu}_i \nu_j \phi + h_{ij}\bar{\nu}_i \gamma_5 \nu_j \phi + H.c. \ ,$$

- The neutrino fluxes get suppressed by the factor

$$\exp(-\frac{L}{\tau} \times \frac{m}{E})$$

L - souce-detector distance
E - neutrino energy
m - neutrino mass
τ - lifetime

Sensitivity from different neutrino sources



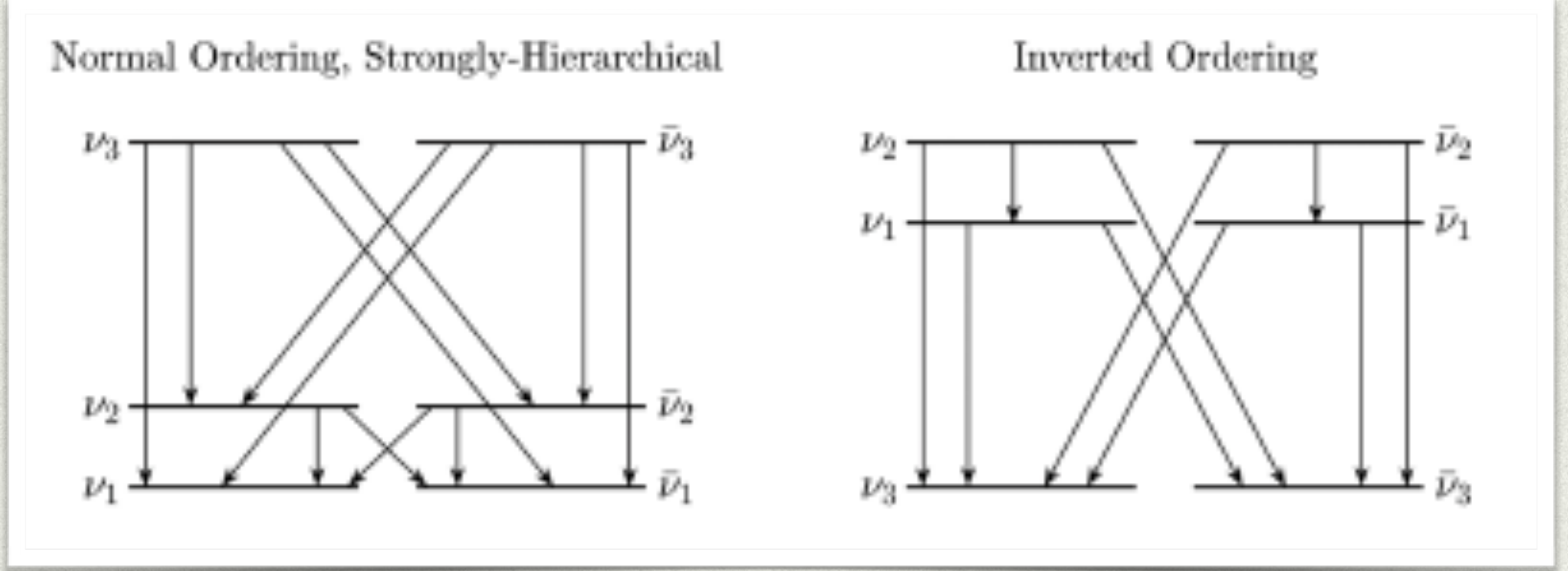
Ivanez-Ballesteros, Volpe, PLB 2023, 2307.03549

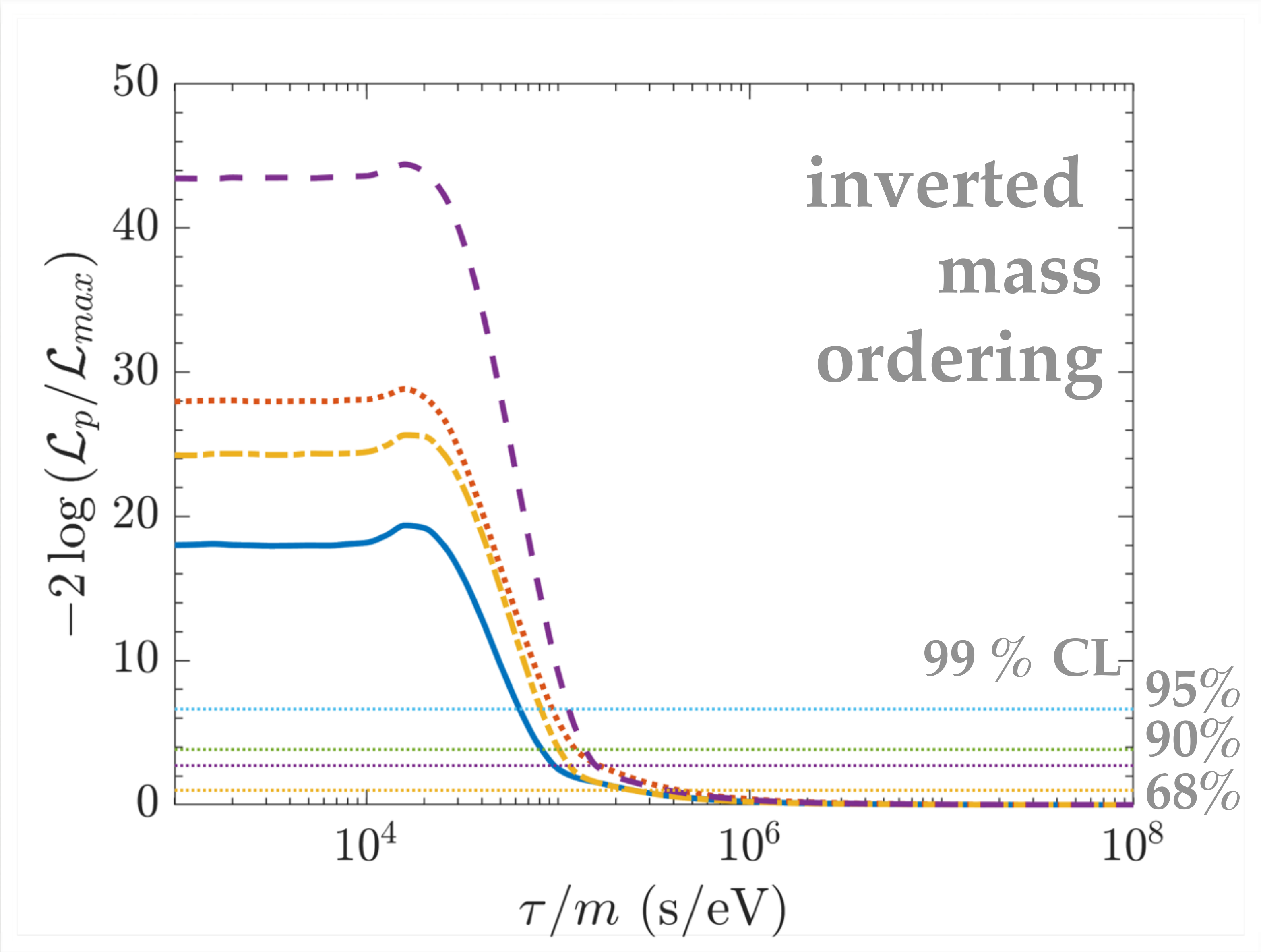
Unique sensitivity to tau/m from CCSNe and the diffuse supernova neutrino background

SN1987A and NEUTRINO NON-RADIATIVE DECAY

- A likelihood analysis (7D) of the 24 SN1987 neutrino events in Kamiokande, IMB and Baksan, with non-radiative decay yields

- Full 3 neutrino framework, three possible decay patterns (NO and SH or QD, IO) .





Ivanez-Ballesteros, Volpe, PLB 2023, 2307.03549

$$\tau/m > 1.2\times10^5(90\%\mathrm{C.L.})\mathrm{for}\nu_1\mathrm{and}\nu_2(\mathrm{IO})$$

Excludes previous bounds on tau/m (PDG), competitive with cosmology

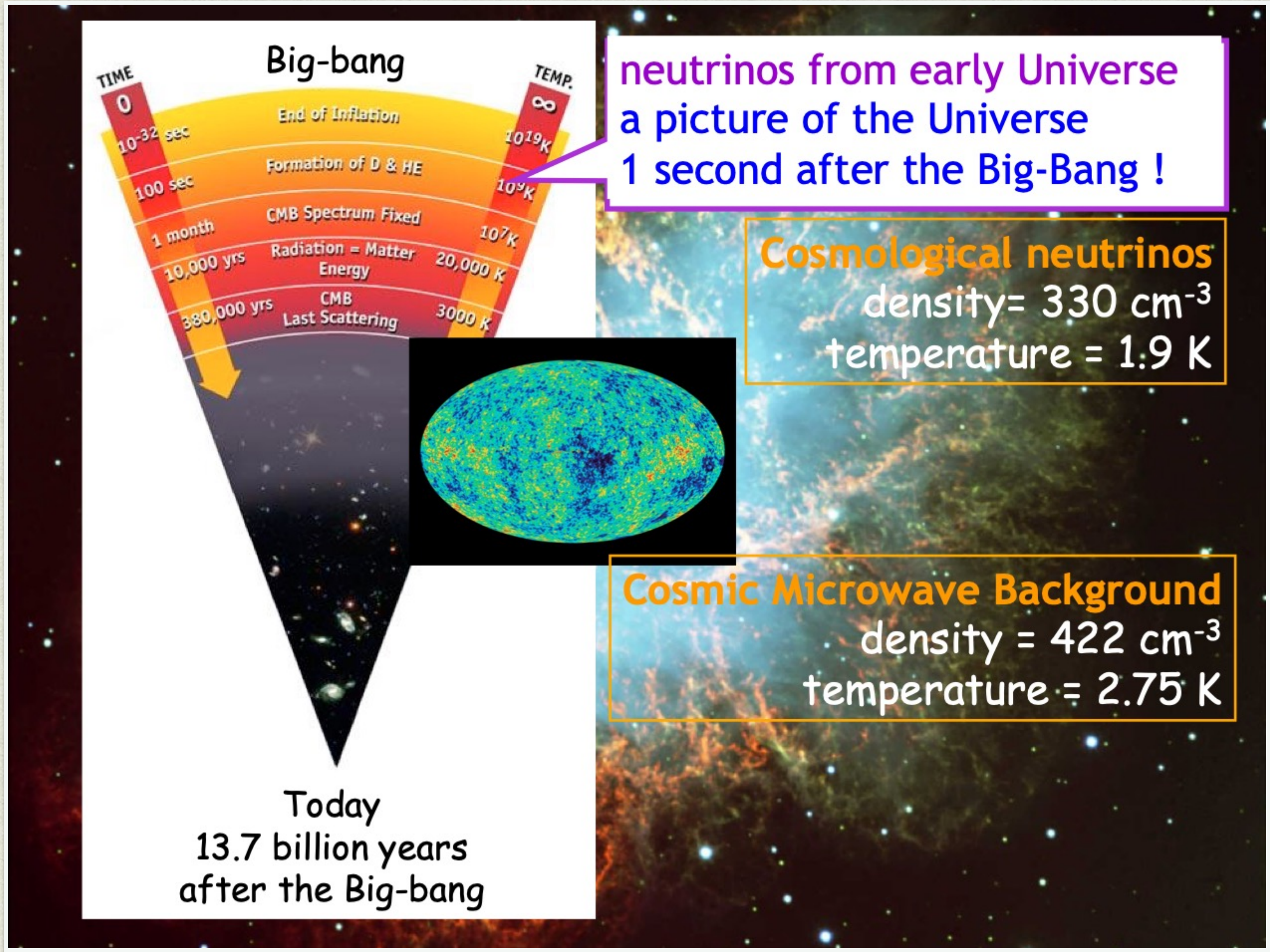
WHAT ARE WE LEARNING WAITING FOR THE NEXT SUPERNOVA?

see talks by Manibrata Sen (Wednesday), Nagakura (Wednesday), Johns (Wednesday), Abbar (Saturday), Lella (Saturday), Beauchêne (Saturday)

See C. Volpe, «Neutrinos from dense: flavor mechanisms, theoretical approaches, observations, new directions »,
Review of Modern Physics . 96 (2024) 2, 025004, arXiv: 2301.11814

See also the reviews Duan et al 2010, Scholberg 2012, Volpe, 2015, Mirizzi et al 2016, Horiuchi and Kneller 2018, Tamborra and Shalgar 2021, Kato et el 2020, Manibrata Sen 2024, Volpe, 2024, …

NEUTRINOS FROM DENSE ENVIRONMENTS

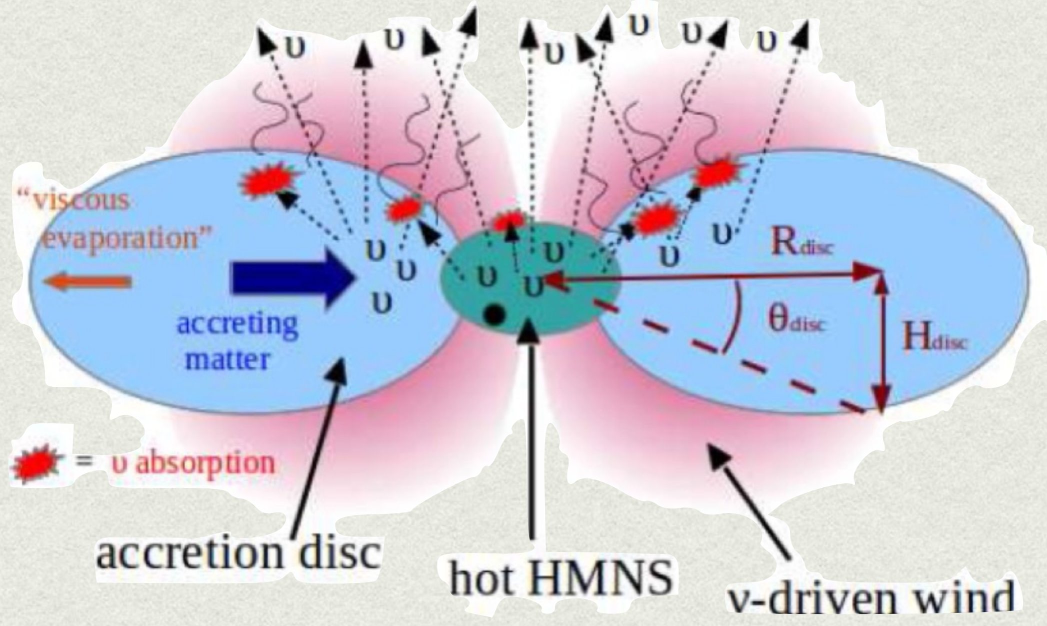


neutrinos from early Universe
a picture of the Universe
1 second after the Big-Bang !

Cosmological neutrinos
density= 330 cm^{-3}
temperature = 1.9 K

Cosmic Microwave Background
density = 422 cm^{-3}
temperature = 2.75 K

BINARY NEUTRON STAR MERGERS

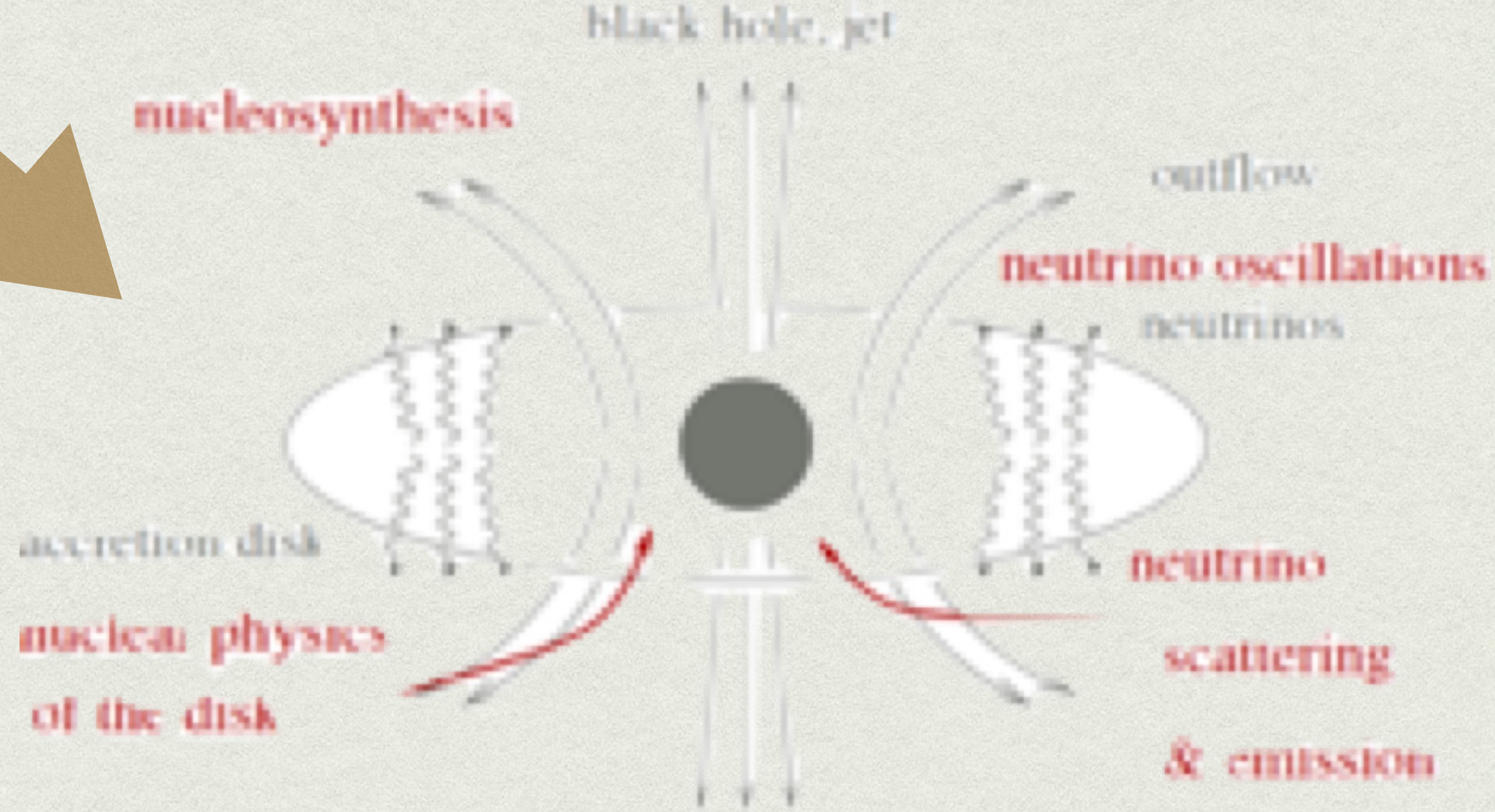


GW170817

CORE-COLLAPSE SUPERNOVAE

SN1987A

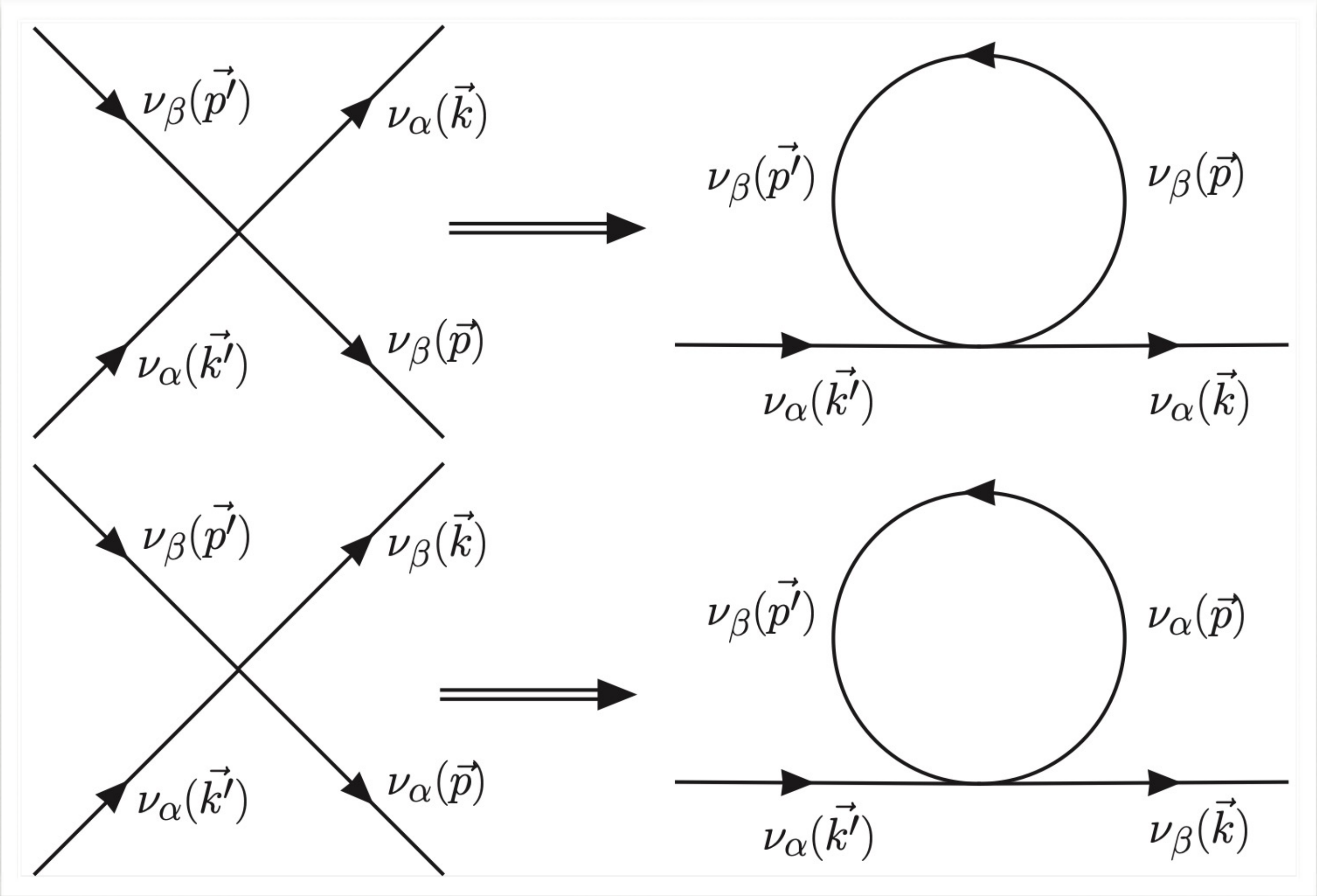
ACCRETION DISKS AROUND BLACK HOLES



DENSE ENVIRONMENTS

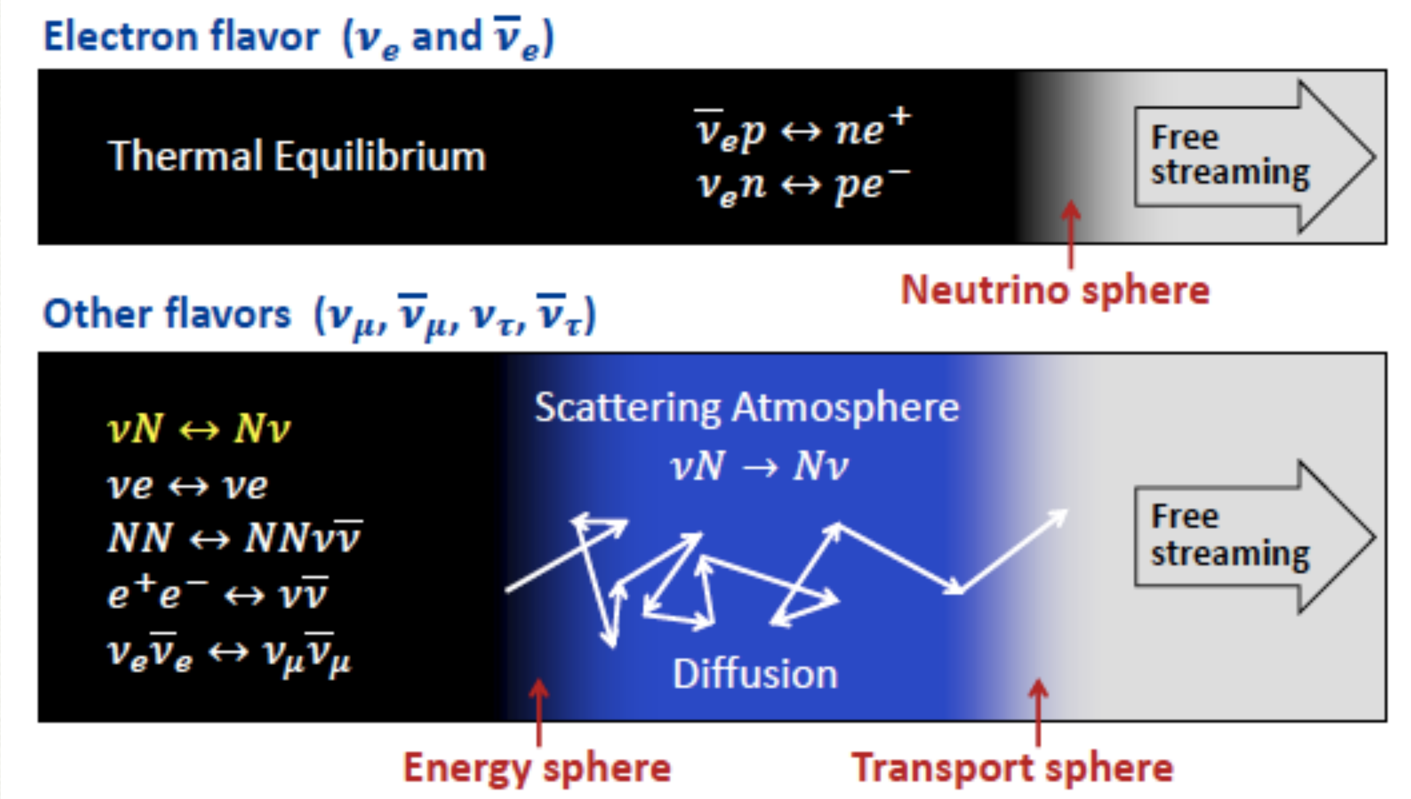
- **« Dense» =** a medium that can reach 10^{10} g/cm^3 and more, 10^{15} - 10^{16} g/cm^3 (limits of matter compressibility),.

- But « dense » also means in neutrinos. In a supernova explosion about 10^{58} neutrinos with an average energy of 10 MeV produced.



« Neutrino propagation in supernovae is a ***non-linear many-body problem*** *due to a sizeable neutrino-neutrino interaction. »*

Pantaleone, PLB 1992



Raffelt, 2001

Dense in matter and neutrinos

NEUTRINO EVOLUTION EQUATIONS IN DENSE MEDIA

In astrophysical and cosmological environments, neutrinos interact with the particles in the medium.

- One-body density matrix in 2nu framework :

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$

Diagonal elements are the expectation value of the number operator :

$$\alpha = \beta \qquad \rho_{\alpha\alpha} = \langle a^\dagger_\alpha a_\alpha \rangle$$

$$N_\alpha = \int \frac{d\vec{p}}{(2\pi)^3} \rho_{\alpha\alpha}$$

Non-diagonal elements account for the mixings (flavor modification)

$$\alpha \neq \beta \qquad \rho_{\alpha\beta} = \langle a^\dagger_\beta a_\alpha \rangle$$

- The full description employs the neutrino quantum kinetic equations:

$$i(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}} + \mathbf{F} \cdot \nabla_{\mathbf{p}})\varrho_{\mathbf{x},\mathbf{p}} = [h_{\mathbf{x},\mathbf{p}}, \varrho_{\mathbf{x},\mathbf{p}}] + iC[\varrho, \overline{\varrho}],$$

The full Liouville operator is 7-dimensional.

Necessary for the early Universe - primordial nucleosynthesis (10 MeV - 0.1 MeV, neutrinos set n/p ratio key for the build up to He4, D, He3, Li7).

Solved in the early Universe (isotropy, homogeneity).
A precise value for Neff = 3.0440 (BBN epoch)

Froustey, Pitrou, Volpe, JCAP 12, 2020; Bennet et al, JCAP 04, 2021

NEUTRINO HAMILTONIAN (MEAN-FIELD)

- Neutrinos propagating in a dense astrophysical environments :
  A weakly interacting many-body problem.

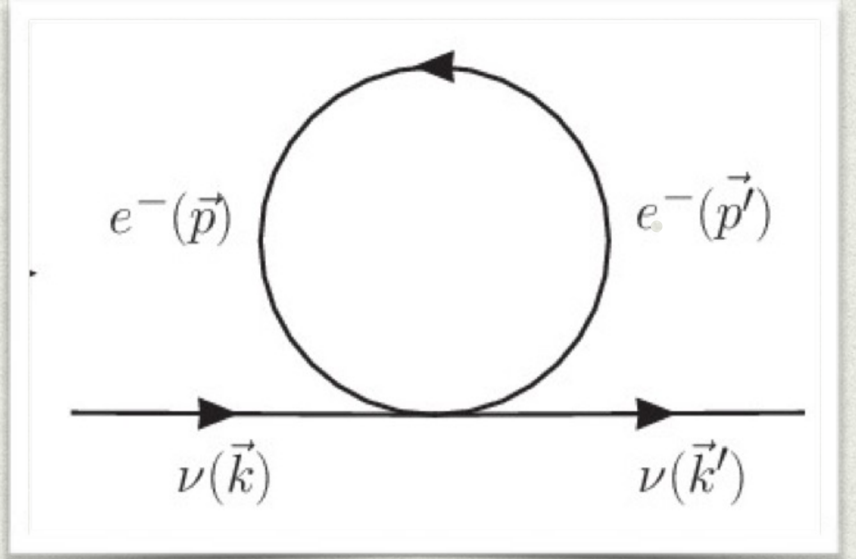
- $$h = h_{vac} + h_{mat} + h_{\nu\nu} + h_{NSI}$$

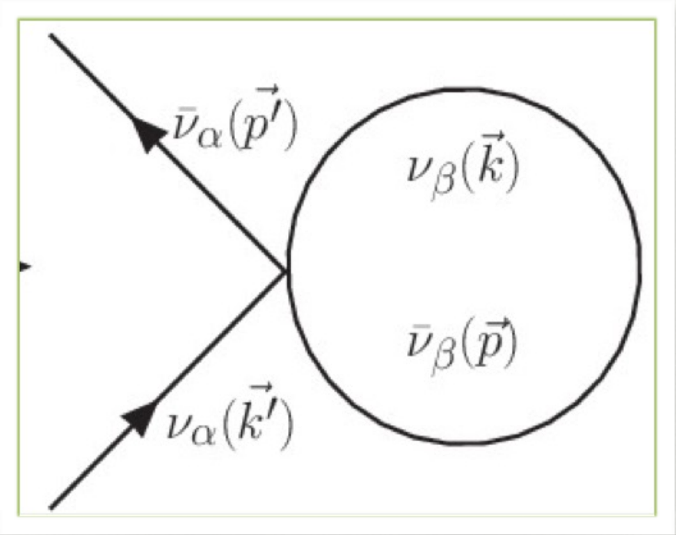
$$h_{vac} = \omega \begin{pmatrix} -c_{2\theta} & s_{2\theta} \\ s_{2\theta} & c_{2\theta} \end{pmatrix}$$

responsible for vacuum oscillations

$$h_{mat} = \sqrt{2} G_F \begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2} \end{pmatrix}$$

Matter term, MSW effect





Neutrino-neutrino interactions

$$h_{\nu\nu} = \sqrt{2} G_F \sum_\alpha [\int (1 - \hat{q} \cdot \hat{p}) \times [\mathrm{d}n_{\nu_{\underline{\alpha}}} \rho_{\nu_{\underline{\alpha}}}(\vec{p}) - \mathrm{d}n_{\bar{\nu}_{\underline{\alpha}}} \bar{\rho}_{\bar{\nu}_{\underline{\alpha}}}(\vec{p})]],$$

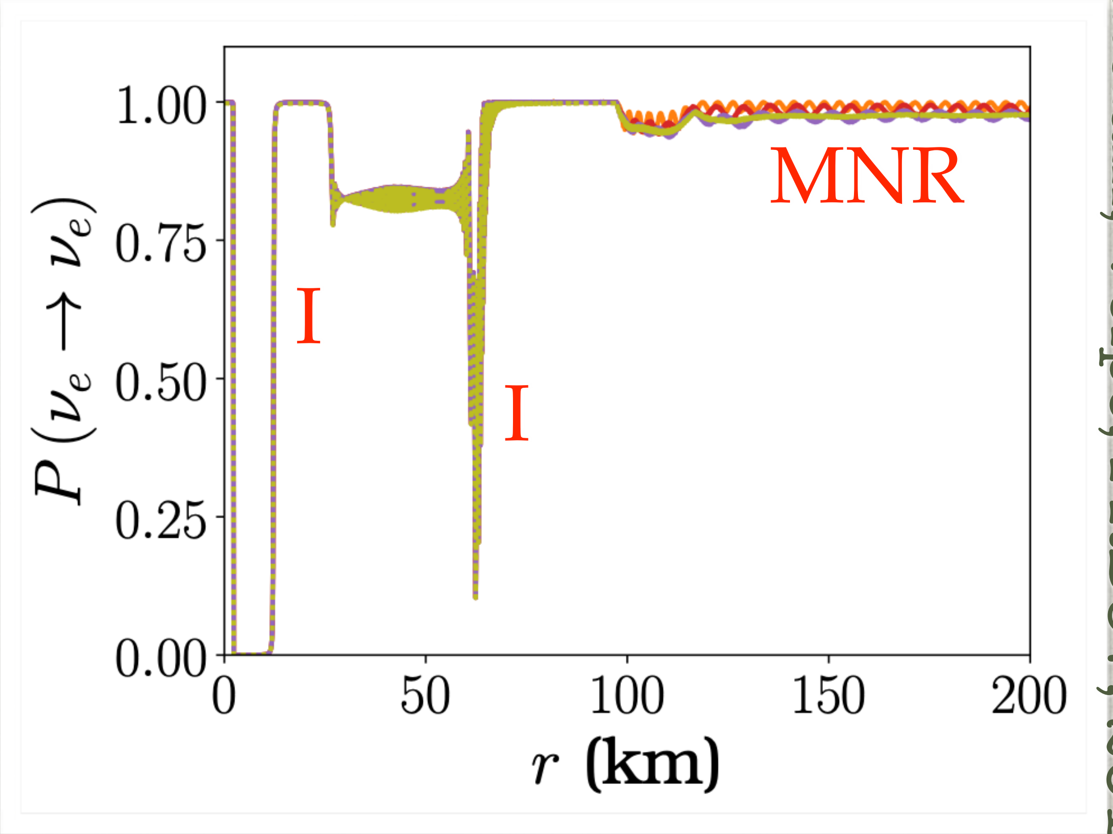
$$h_{NSI} = \sqrt{2} G_F \sum_f N_f \epsilon^f \quad f = e, d, u$$

Non-standard interactions

$$\begin{pmatrix} \mid \epsilon_{ee} \mid < 2.5 & \mid \epsilon_{e\tau} \mid < 1.7 \\ & \mid \epsilon_{\tau\tau} \mid < 9.0 \end{pmatrix}$$

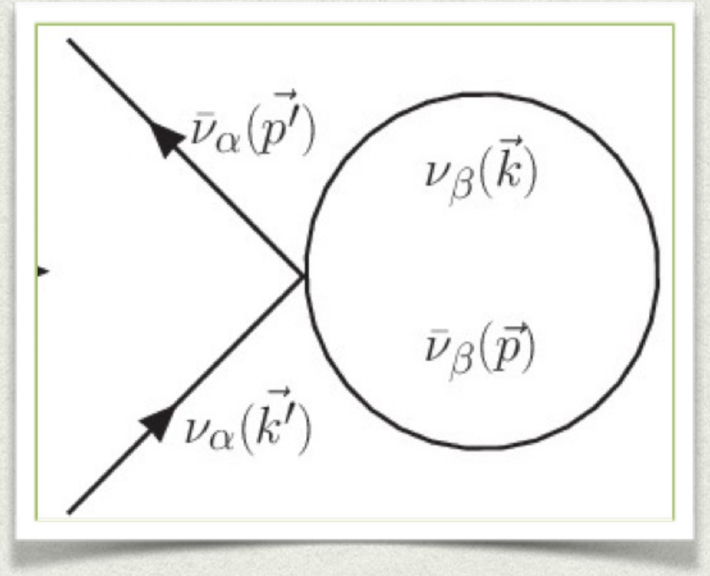
limits for neutral solar-like matter

NSI in BNS



Chatelain, Volpe, PRD97, 2018.

FLAVOR CONVERSION IN DENSE ENVIRONMENTS

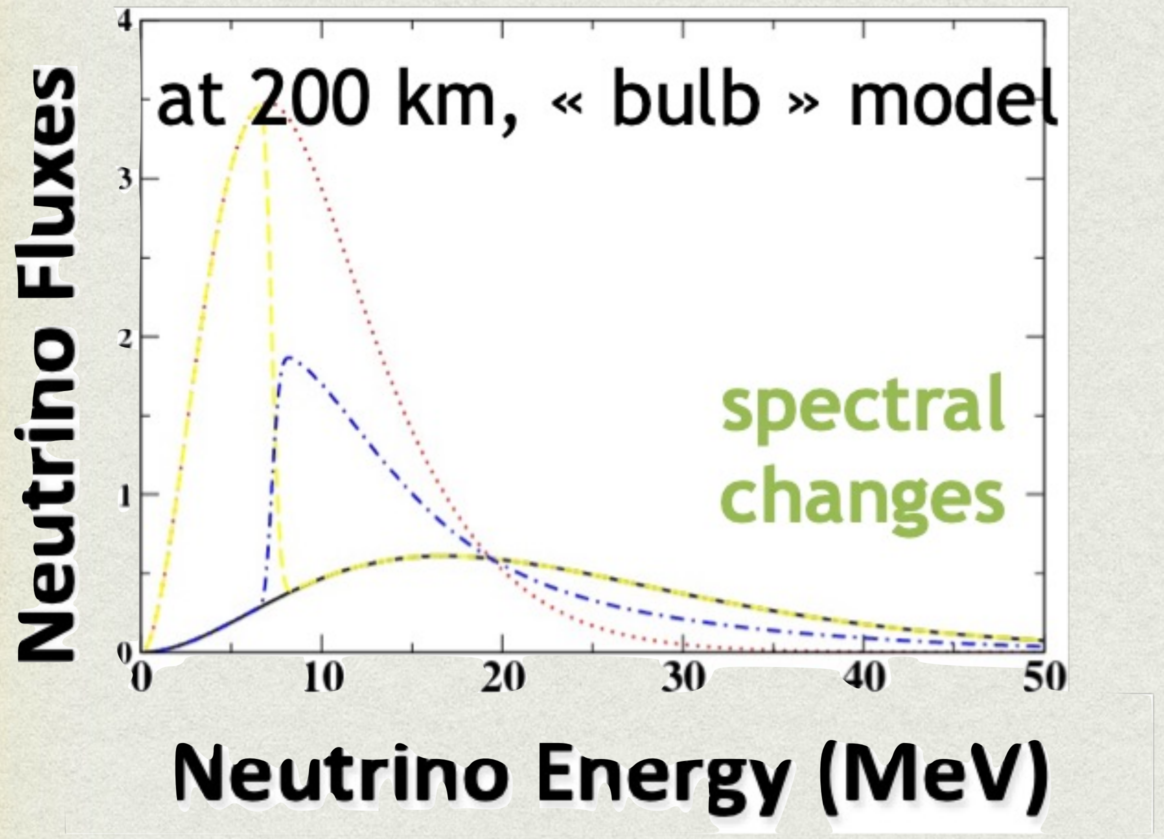


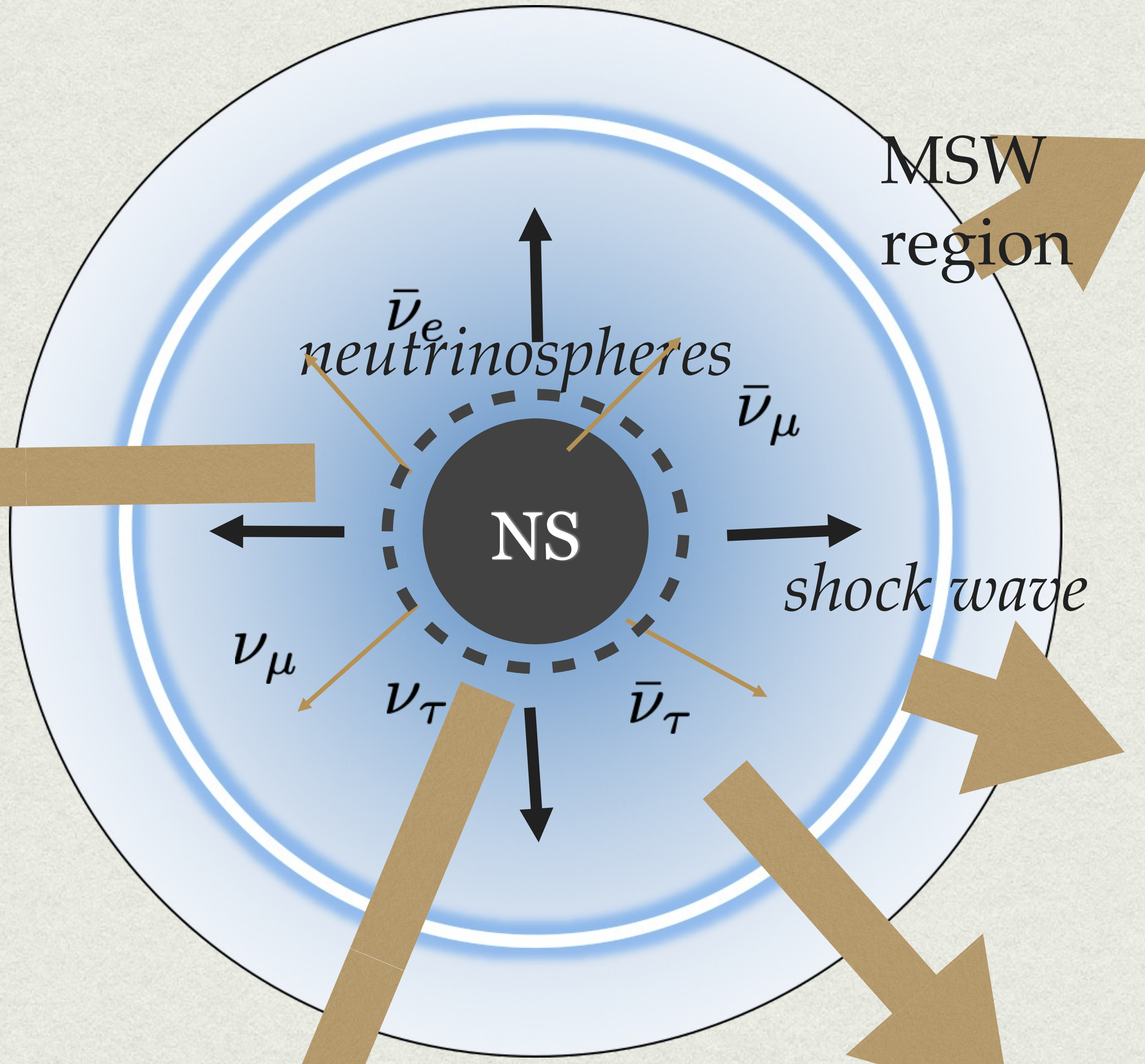
Neutrino-neutrino interactions

Pantaleone, PLB287 (1992).
Duan et al, PRD, 2006

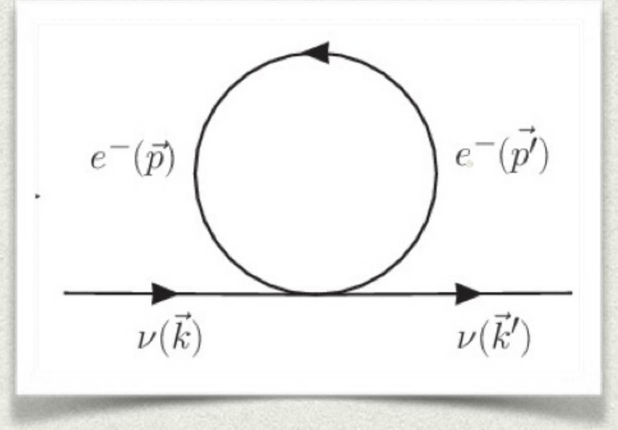
slow **modes**
fast **modes (m scale or less)**

Sawyer PRD 2005, PRL 2016.





MSW effect



Shock wave effects (multiple MSW)

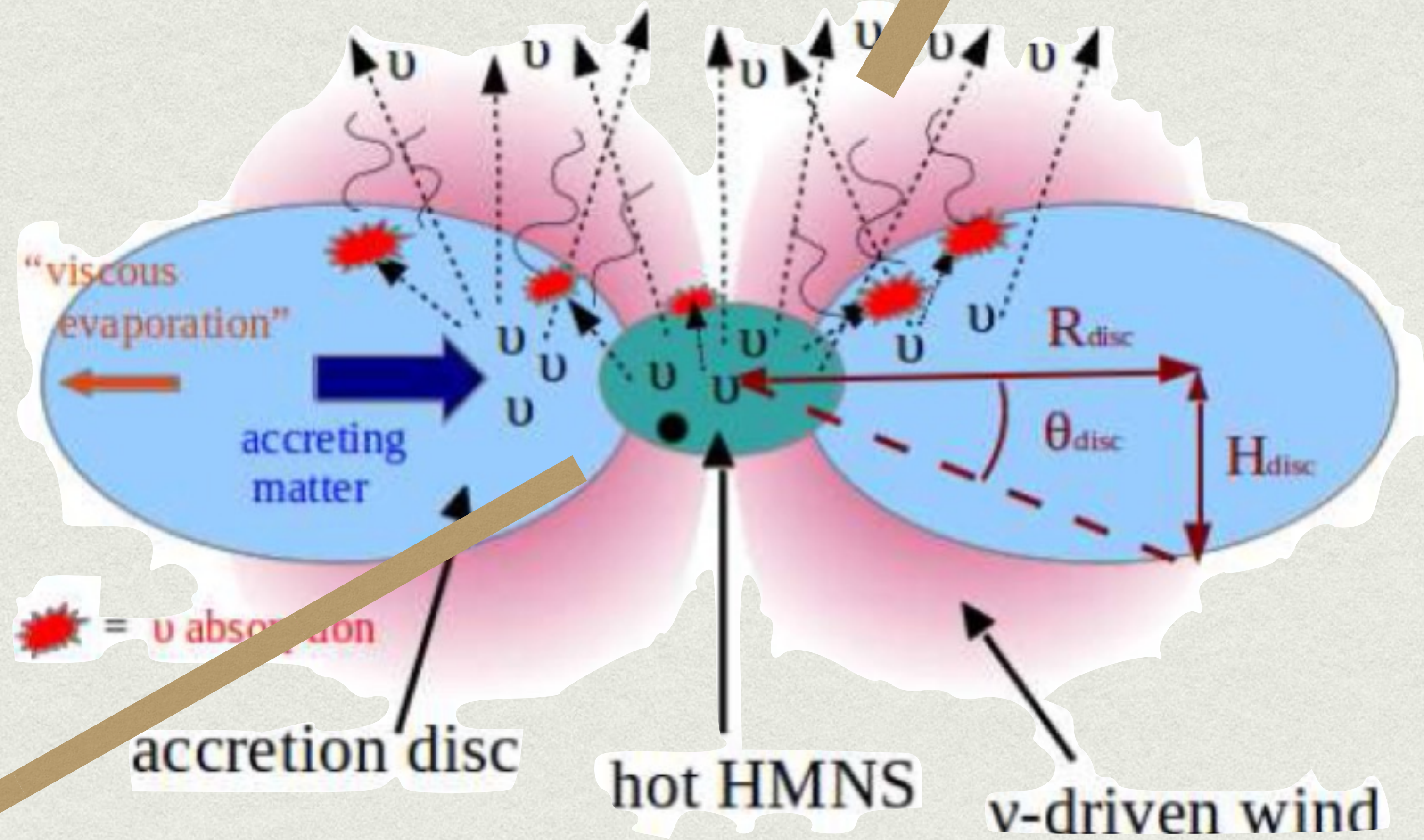
Schirato and Fuller,
hep-ph/0205390

Turbulence effects
Loreti et al, PRD 52 (1995)

Collisional instabilities

Johns, PRL 19 (2023)

MSW effect



Neutrino-neutrino interactions

« It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are. If it doesn’t agree with experiment, it’s wrong. »

R. Feynman

From C. Giunti and C. W. Kim, « Fundamentals of neutrino physics and astrophysics », Oxford U Press

NEUTRINOS from NEXT SUPERNOVA

- Supernova Early Warning System (SNEWS 1.0) - prompt, positive, pointing
  Scholberg 1999, 2008; Antonioli et al, 2004
  pre-SN neutrinos, dark matter detectors, multimessenger astronomy
  SNEWS 2.0, 2021

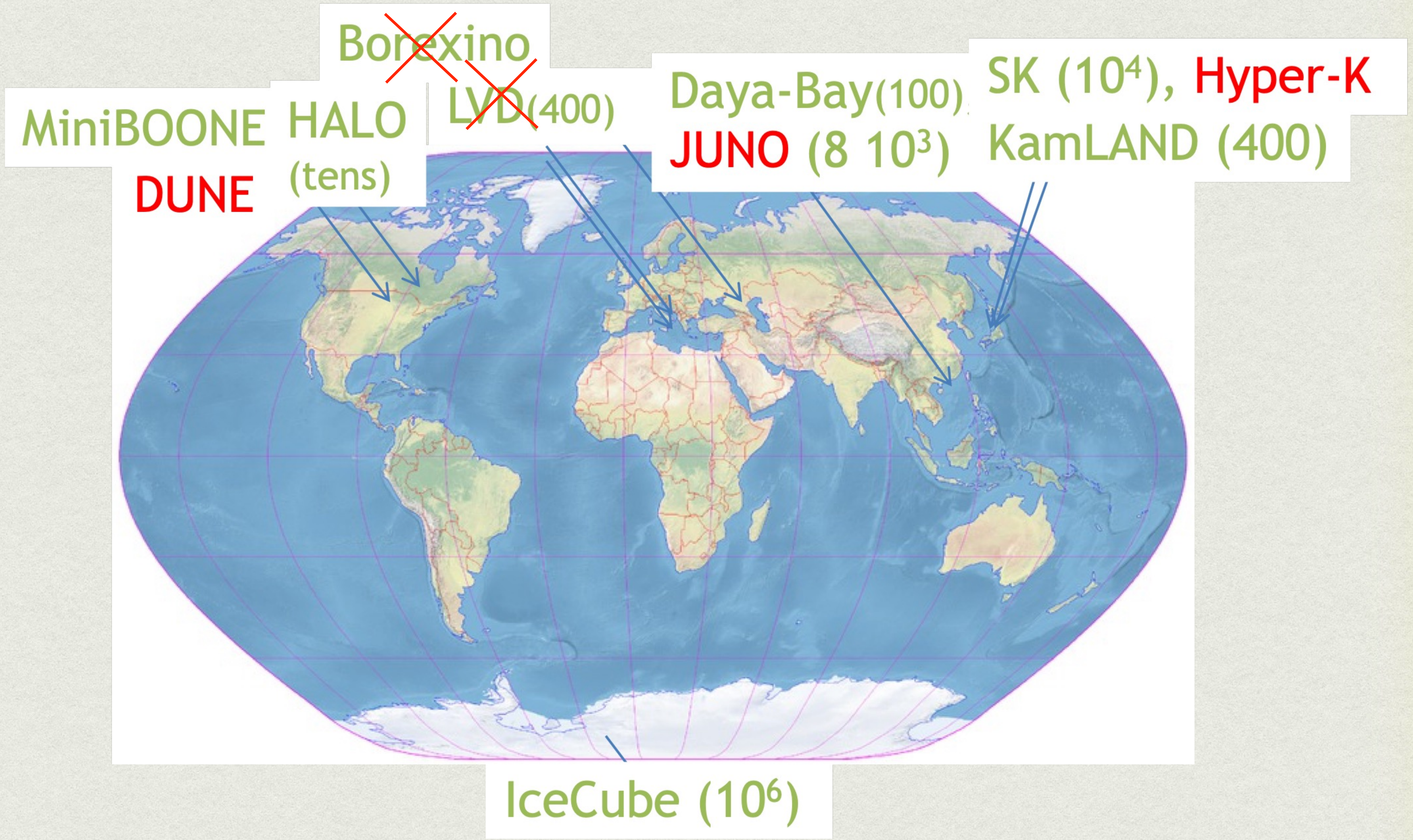
- Expected events (SN at 10 kpc):
  540 in HALO-2, hundreds in KamLAND,
  3000 in DUNE, 8000 (JUNO), 10000 in Super-K,
  10^5 in Hyper-K, 10^6 in IceCube.

Sensitivity to electron neutrinos from neutrino-nucleus inelastic scattering

See also SNEWPY (Baxter et al., 2022).

- Dark matter detectors:
  120 (Xenon nT, 7 tons), 700 (DARWIN, 40 tons),
  336 events (Darkside-20k (50 tons)

Lang et al, 2016; Agnes 2021



Sentivity to all flavors, time and energy signal through nu-electrons, nu-nucleus incoherent, nu-proton and coherent nu-nucleus scattering
(CEνNS, Akimov, 2017)

SN NEUTRINO TIME SIGNAL

- **Pre-SN neutrinos** (1-a few days before the SN)
  information on the late stages before SN collapse (stellar evolution theory), on the progenitor and early alert.

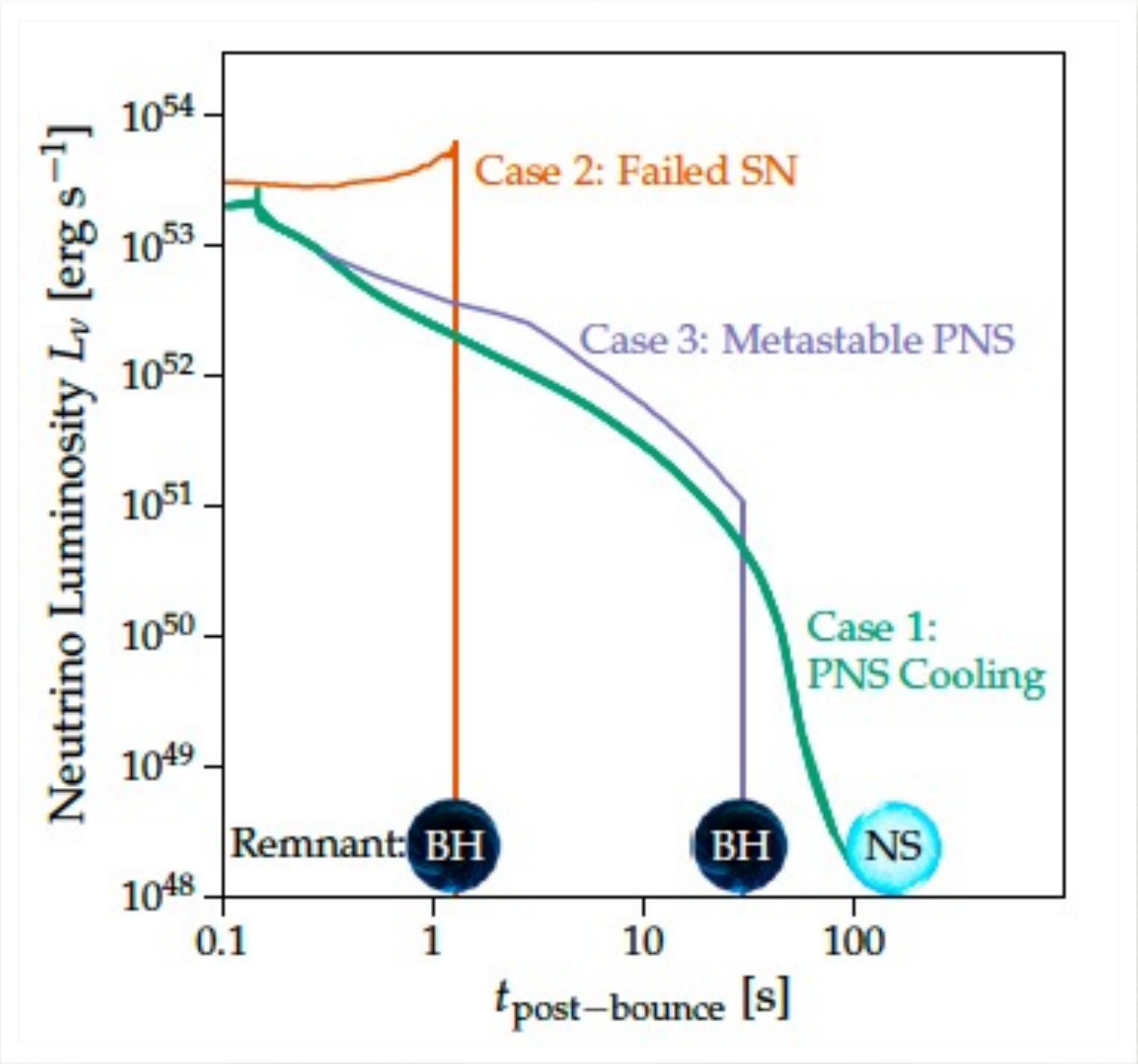
Neutrino emission from e.g. the Si-burning phase lasts about 2 days (M = 20 Msun).

Odrzylowek et al, Astrop. Phys. (2004);
Patton et al, 2017; Kato et al 2020

Pre-SN neutrinos (3 sigma, 2d before exp.) could be detected in KamLAND for M = 25 Msun up to 690 pc.

Asakura et al., Astrophys. Journ. (2016)

- **Late-time neutrinos from PNS cooling** (10-100 s)
  about the PNS EOS, fate of the SN, total radiated energy and lepton number, non-standard cooling

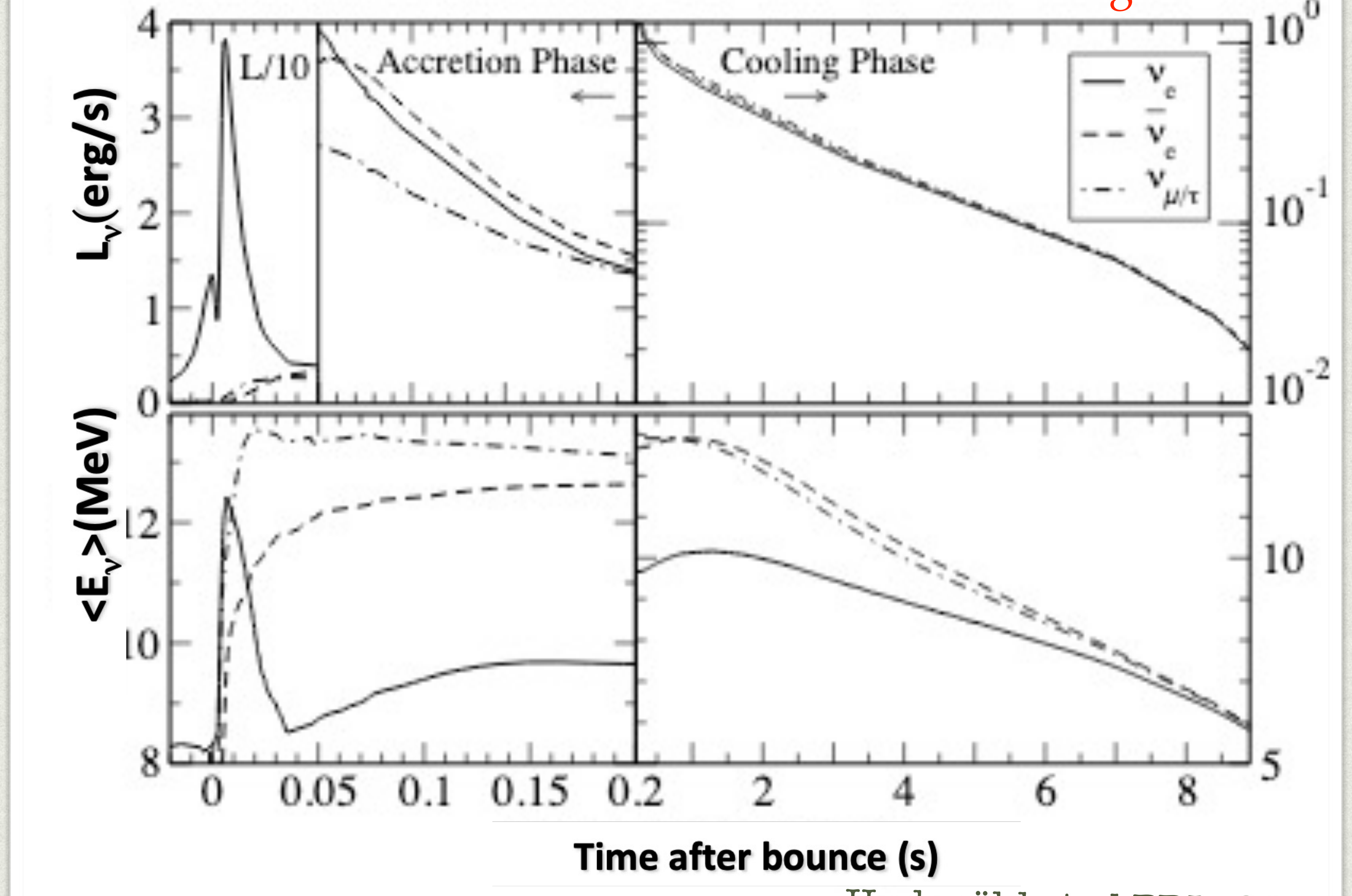


250 antinue over 50 s in Super-K,
110 nue over 40 s in DUNE
10 (anti)numu, (anti)tau over 20 s in JUNO
- SN at 10 kpc.

Li, Roberts, Beacom., PRD (2021)

SN NEUTRINO 10 s TIME SIGNAL

Neutronization Accretion Neutron star cooling



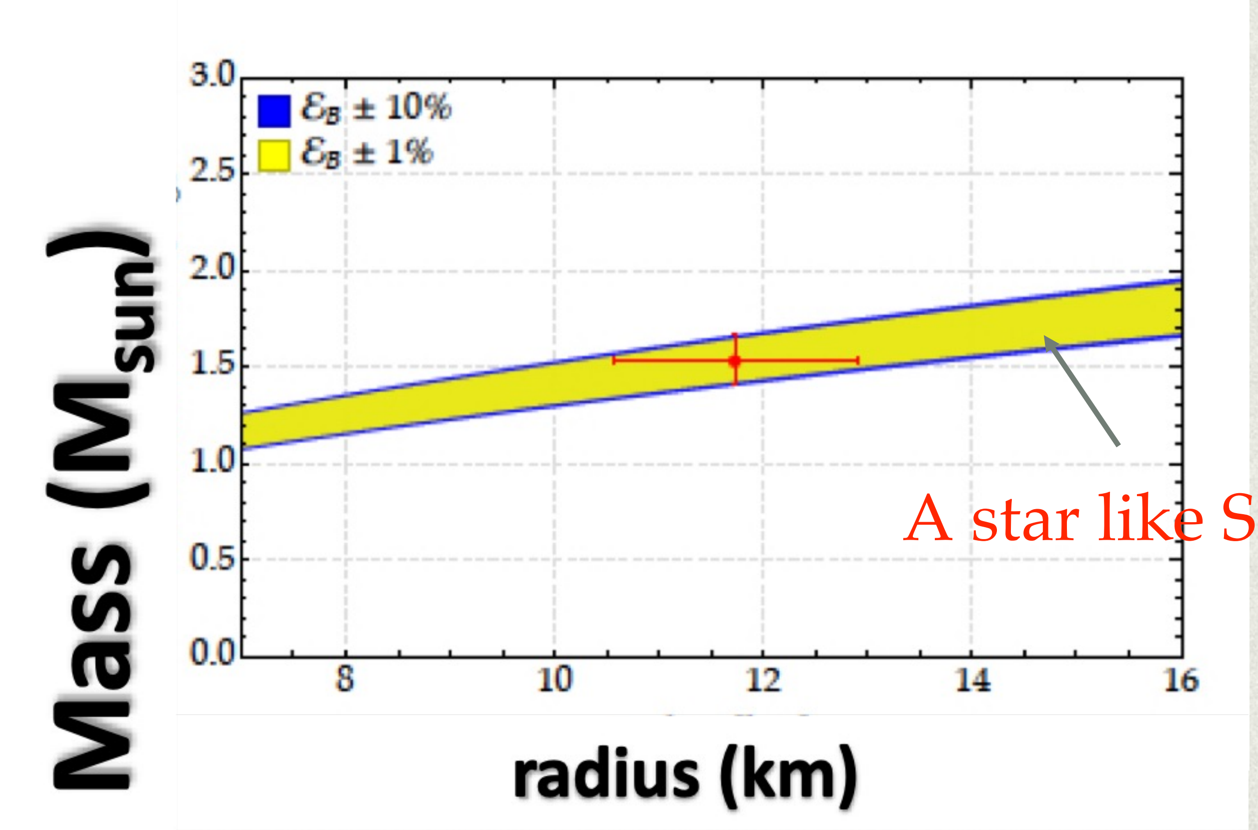
Hudepöhl et al PRL, 2011

Detection of each phase crucial

- Neutronization peak:
  > only MSW effect operates
  > non-standard properties, ex. decay or NSI
  De Gouvea et al, PRD101, 2020; Das et al, JCAP 05, 2017; etc…

  see talk by Manibrata Sen

- Total gravitational energy emitted in neutrino luminosity ((SN at 10 kpc):
  > 11% (SK) and 3% (HK) precision



A star like SN1987A

Gallo Rosso, Vissani, Volpe, JCAP 11, 2017

fit to numerous EOS for NS

$$\frac{\mathcal{E}_B}{Mc^2} \approx \frac{(0.60 \pm 0.05)\,\beta}{1-\beta/2},$$

Lattimer & Prakash, Phys. Rep. 2007

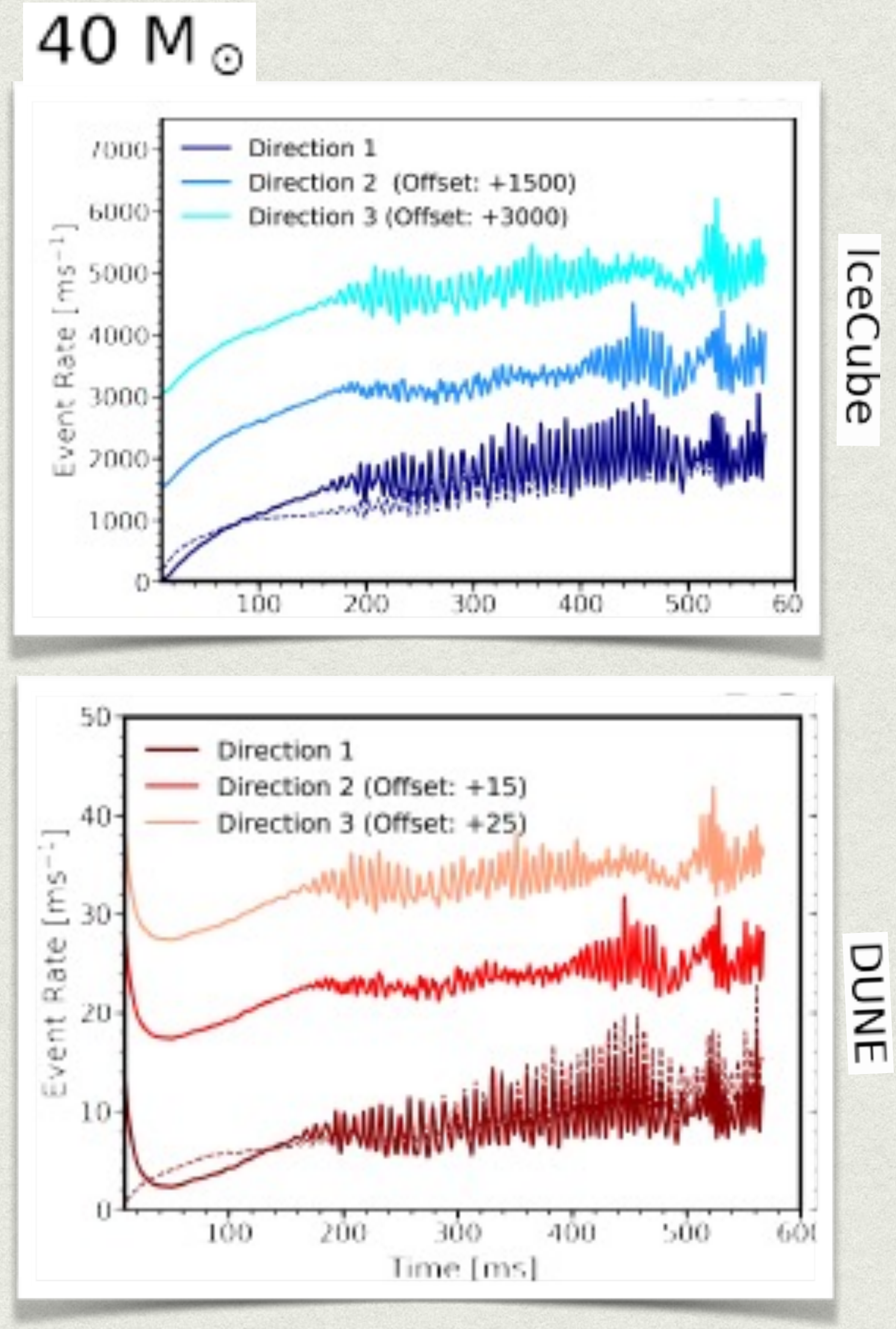
$$\beta = \frac{GM}{Rc^2},$$

Compactness of newly born neutron star

SUPERNOVA EXPLOSION MECHANISM

- *Since a decade, there is an emerging consensus : the majority of supernovae explodes due to the* ***delayed neutrino-heating mechanism*** *neutrinos efficiently reheat the shock aided by convection,* **turbulence and hydrodynamic instabilities (SASI).**

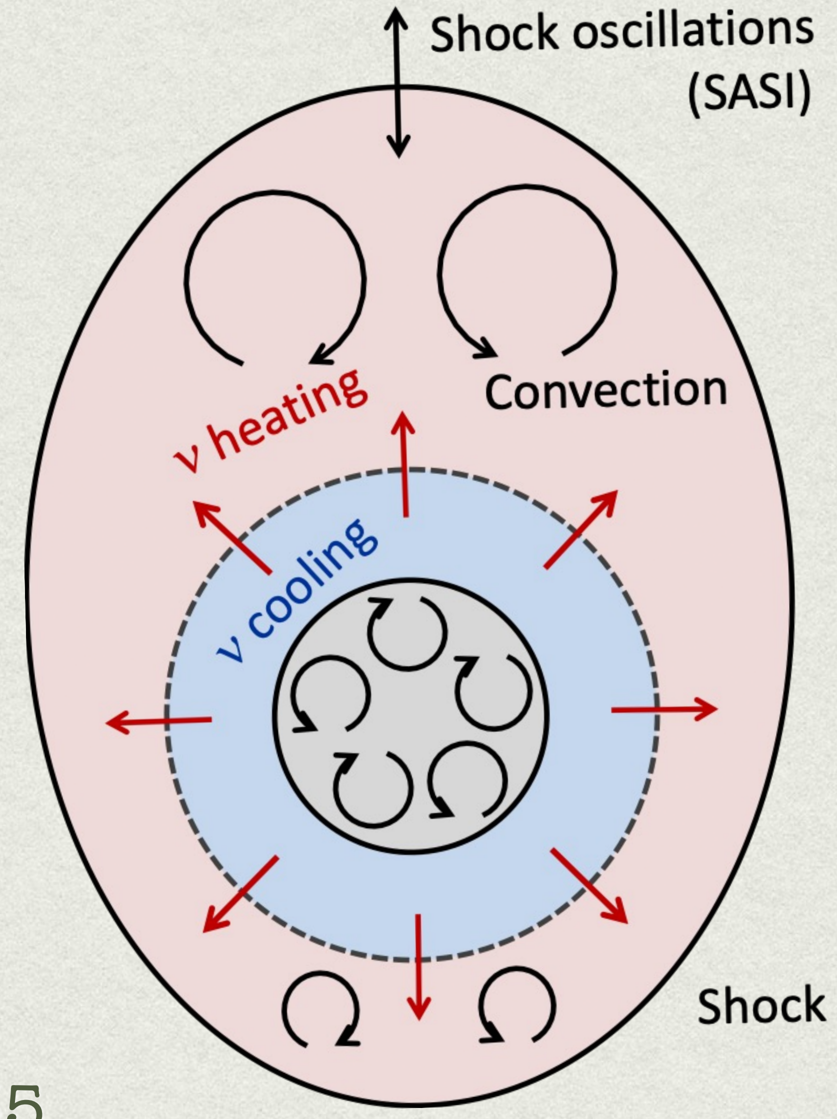
see Mezzacappa (2022), arXiv: 2205.13438.



Walk et al (2020)

GW signatures (different frequencies) from

- *core bounce (rotating progenitor);*
- *neutrino-driven convection (PNS);*
- *neutrino-heating in the gain layer;*
- *SASI;*
- *explosion.*



see e.g. Mezzacappa and Zaolin, 2401.11635,
G. Pagliaroli's talk at « Neutrino Frontiers » (2023, GGI)

see also Mueller, Janka, Astr. J. (2014),
Tamborra et al, Ast. Journ.(2014)

OBSERVING THE NEXT SUPERNOVA CRUCIAL to CONFIRM/REFUTE

FLAVOR MECHANISMS

- First Bayesian analysis to explore our capacity to discriminate among models.

  Five (one-dimensional or multi- dimensional) supernova models from different groups, 500 ms, MSW.

  Abe et al, 2021

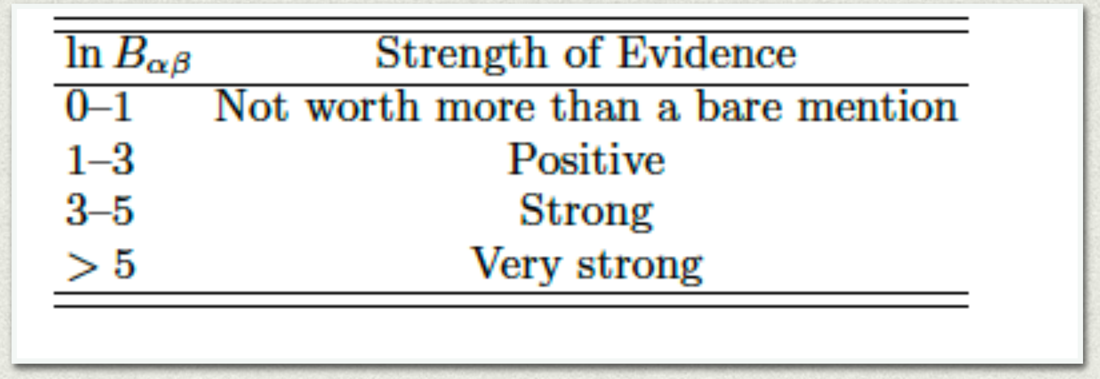
  Seven one-dimensional models (different progenitor mass, EOS), 9s, MSW.

  Olsen and Qian 2022

  18 2D and 3D supernova models (9 M to 60 M), 300 ms, MSW

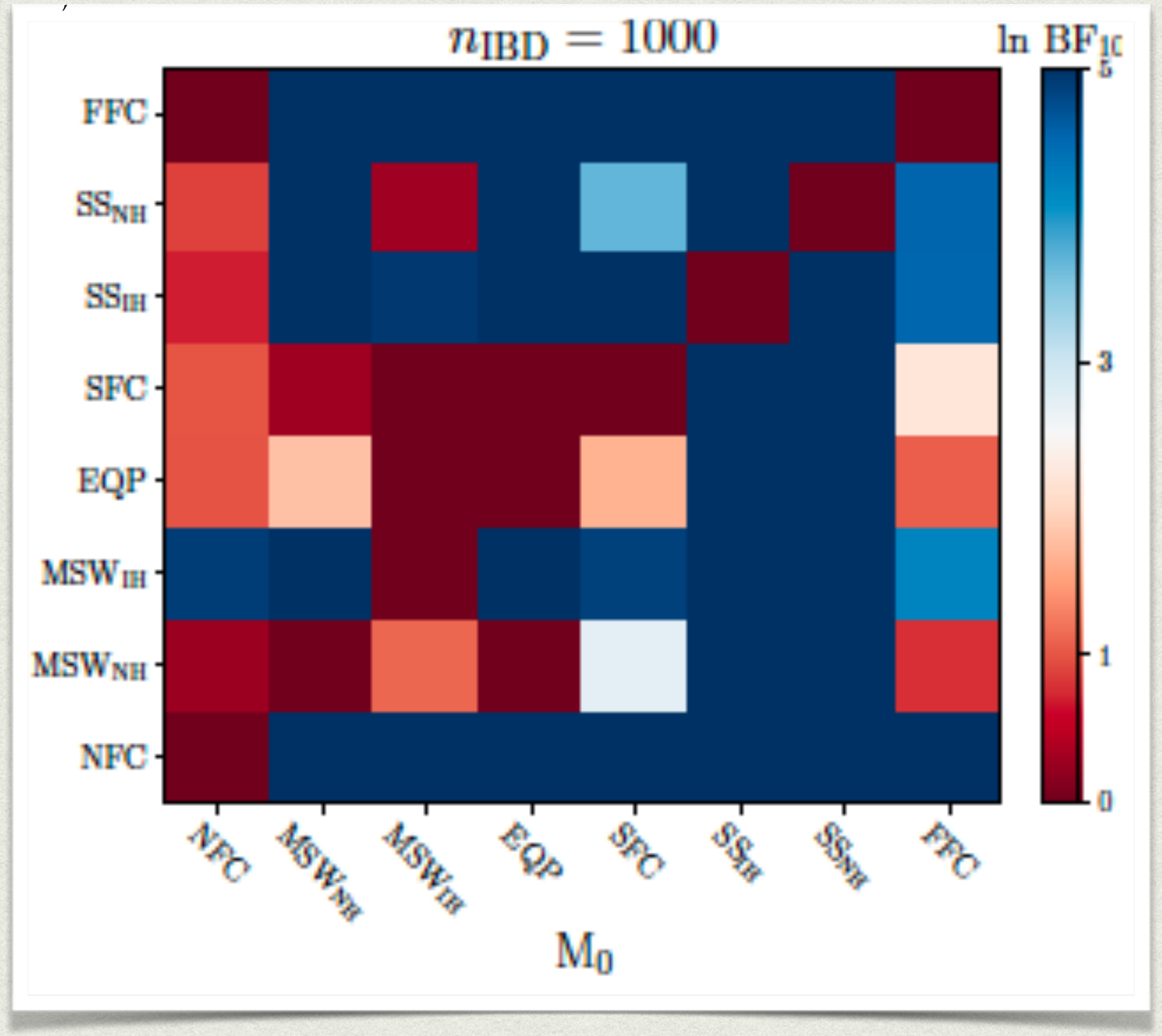
  Saez et al 2024

$$\mathrm{BF}_{10} = \frac{P(\{E_i\}|\mathrm{M}_1)}{P(\{E_i\}|\mathrm{M}_0)},$$



$\ln B_{\alpha\beta}$	Strength of Evidence
0–1	Not worth more than a bare mention
1–3	Positive
3–5	Strong
> 5	Very strong

- First Bayesian analysis to discriminate among flavor mechanisms.
  Supernova distance not know,
  neutrino flux parameters not fixed.

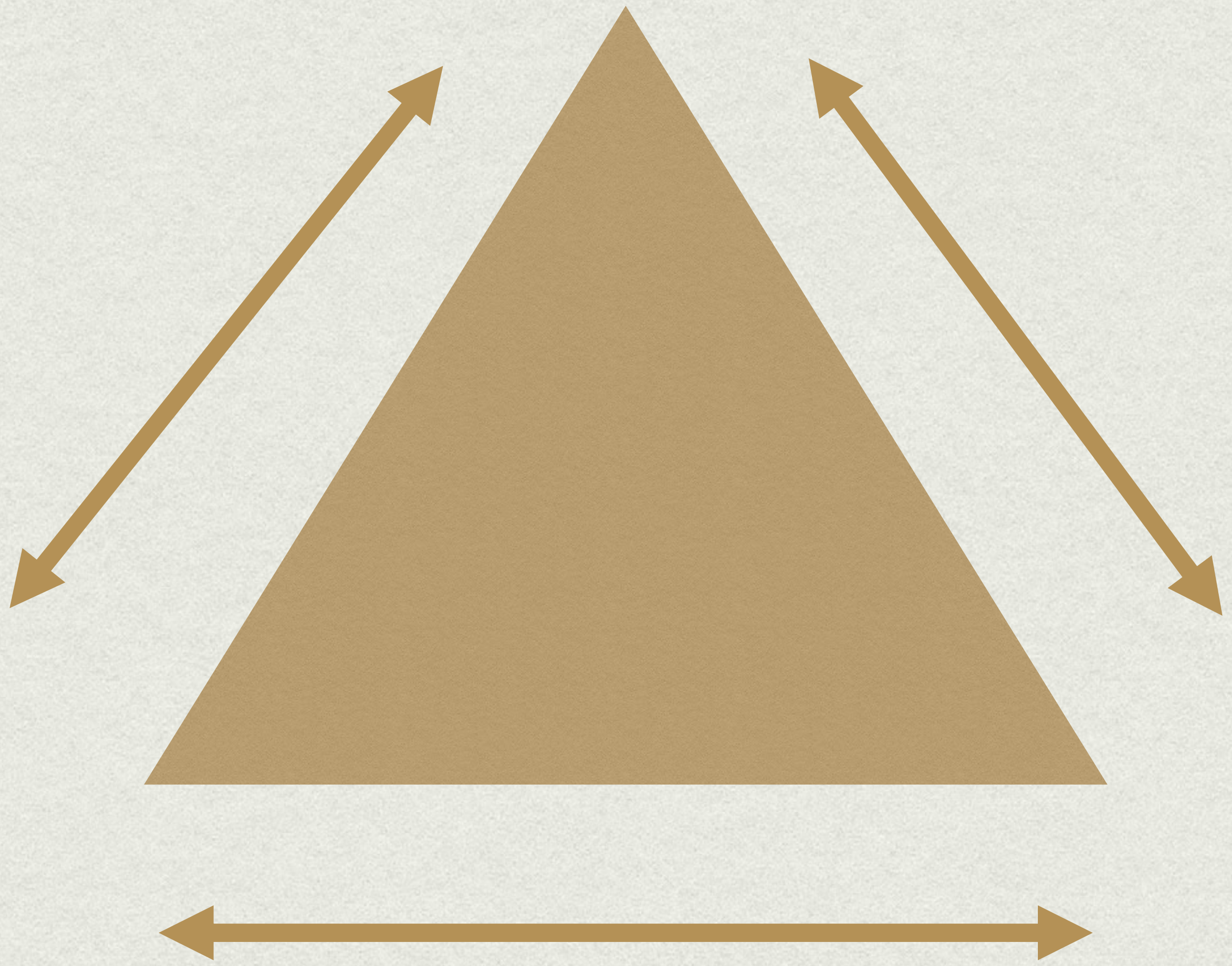


Abbar and Volpe, 2401.10851

DISCRIMINATING FLAVOR MECHANISMS COULD BE POSSIBLE

SUPERNOVA SIGNALS

Neutrinos - SN fate (BH vs NS), explosion mechanism,
EOS and compactness of the PNS, PNS cooling,
progenitor structure, stellar evolution (pre-SN neutrinos),
localization via triangulation, flavor mechanisms in dense media,
neutrino properties - magnetic moment, non-radiative decay,…



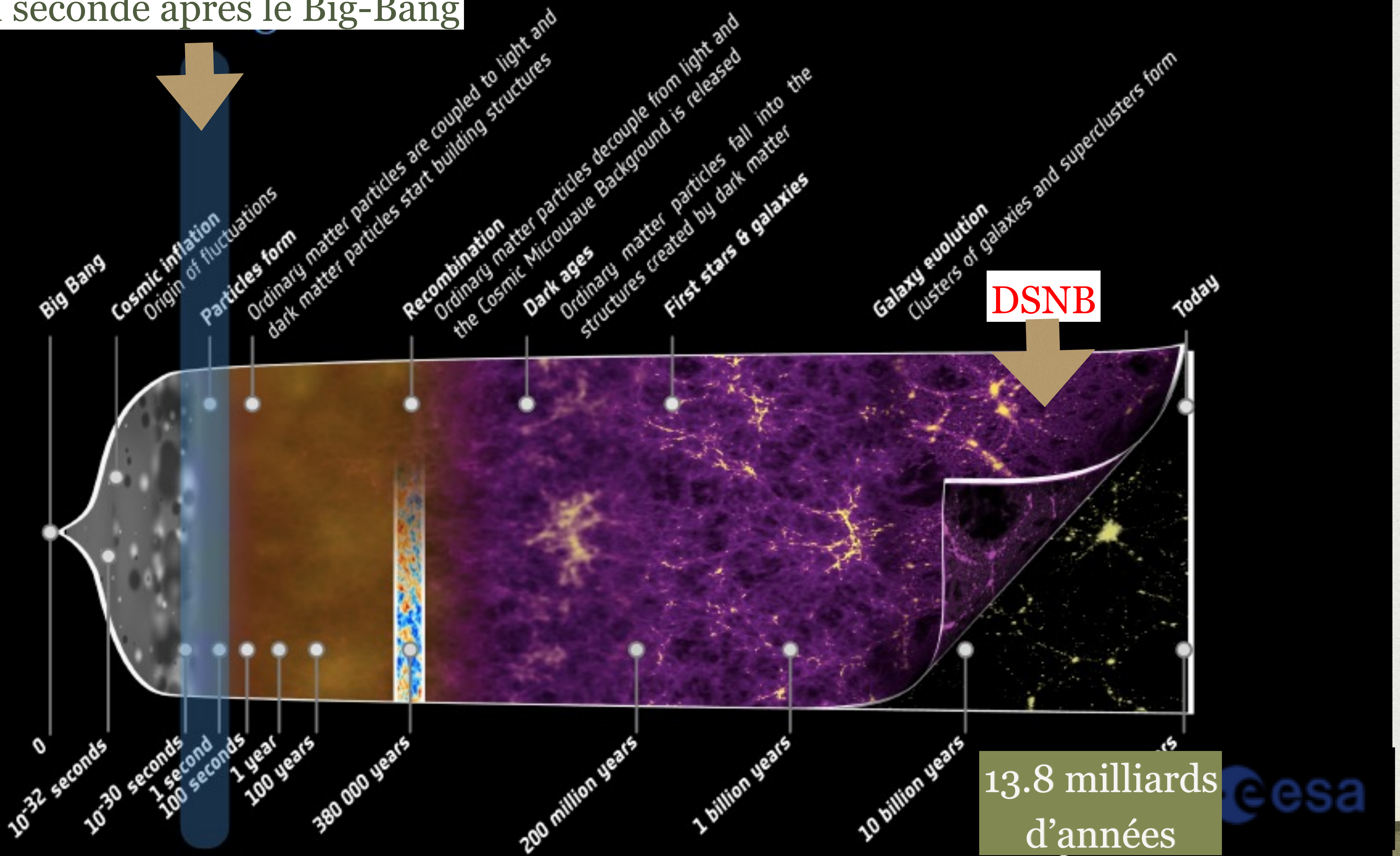
Optical- localization and distance,
progenitor, …

ex. All Sky Automated Survey
for Supernovae (ASAS-SN)

Gravitational waves - explosion mechanism,
M-R, …

EVOLUTION DE L'UNIVERS

1 seconde après le Big-Bang



DSNB

13.8 milliards d'années

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

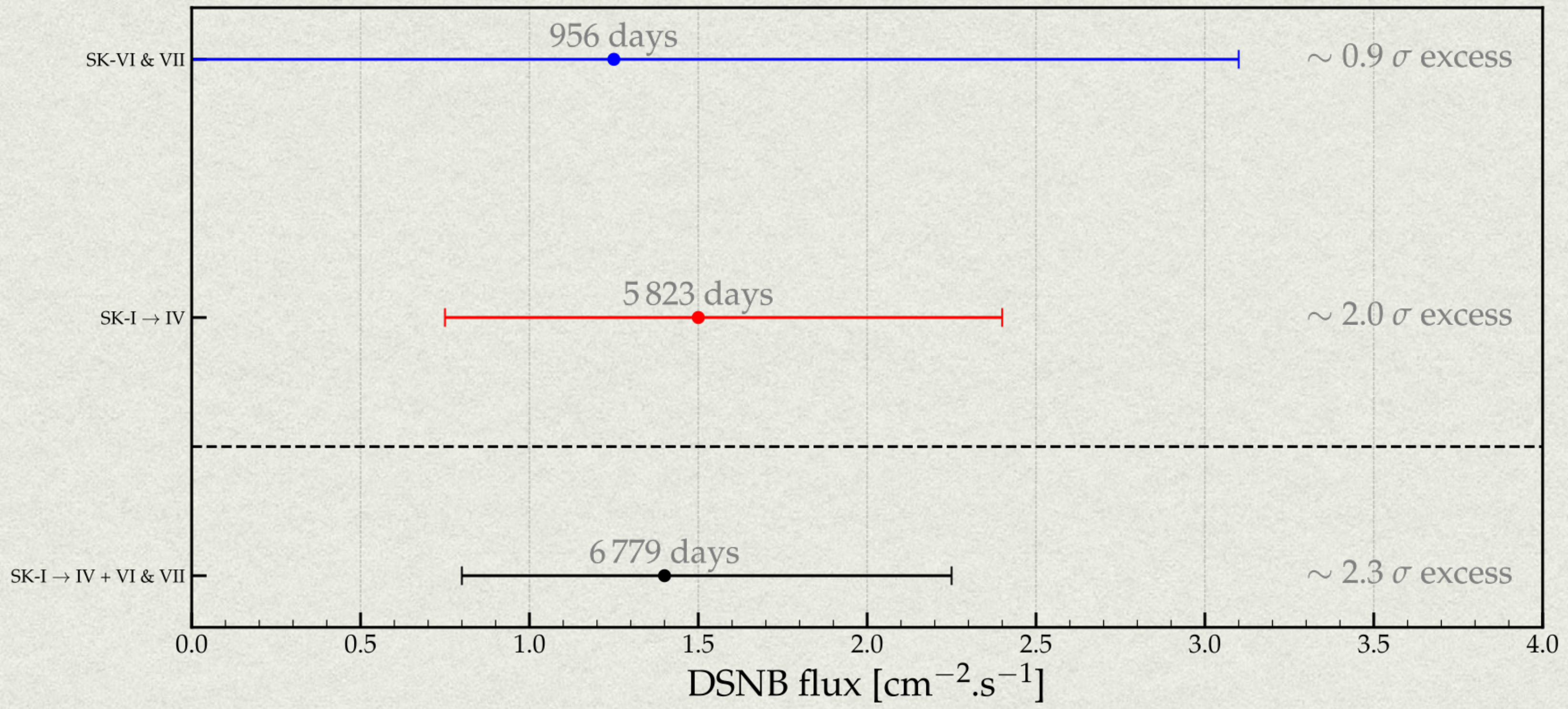
- The DSNB flux depends on the evolving core-collapse supernova rate, the neutrino fluxes from a supernova, integrated over time

$$\phi^{\mathrm{DSNB}}_{\nu_\alpha}(E_\nu) = c\int\int \mathrm{dM}\ dz\ \left|\frac{dt}{dz}\right|\ R_{\mathrm{SN}}(z,\ \mathrm{M})\ \phi_{\nu_\alpha,SN}(E'_\nu,\ \mathrm{M})$$

M - progenitor mass giving a neutron star or a black hole

See Beauchêne's talk on Saturday

- **First results of SK+Gadolinium (SK VI and VII)**



Courtesy of A. Beauchêne

Super-Kamiokande
50 kton water (Japan)
Running (2020) + Gd

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

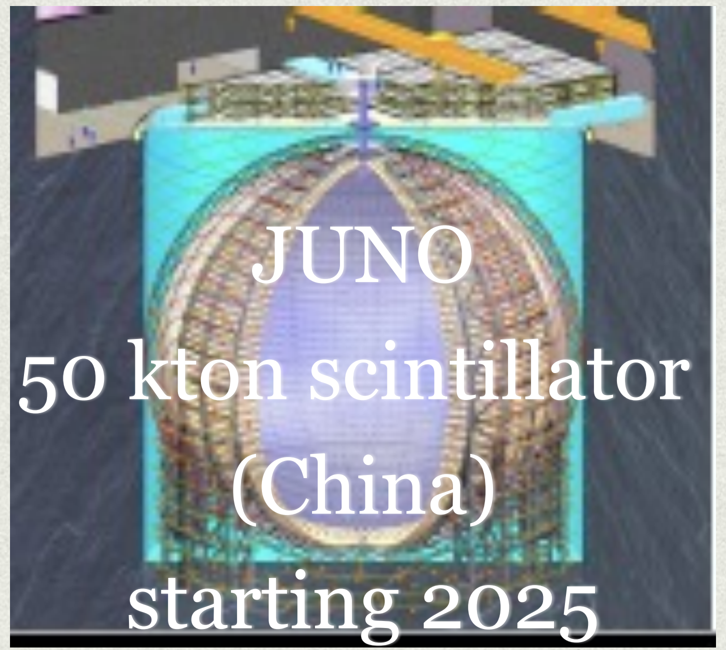
Hyper-Kamiokande
178 kton (FV) water (Japan)
Starting 2027

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

- **Expected DSNB events**

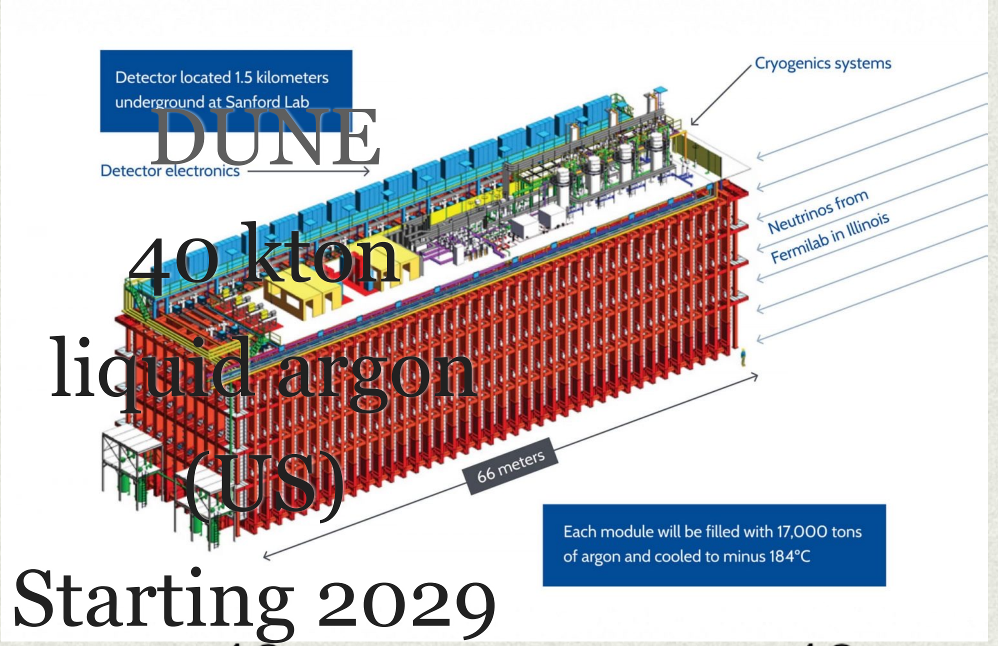
10 anti-nue for SK-Gd (10 year), and nue in DUNE (20 years), 10-40 anti-nue for JUNO (20 years) hundreds anti-nue for Hyper-Kamiokande (10-20 years)

10 nux (antinux) in dark matter detectors



JUNO
50 kton scintillator
(China)
starting 2025

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



DUNE
40 kton
liquid argon
(US)
Starting 2029

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$$

DSNB ENCODES CRUCIAL INFORMATION

The DSNB is sensitive to :

- \- the cosmic core-collapse supernova rate, the fraction of failed supernovae, the EOS;

  see e.g. Priya and Lunardini 2017,
  Moller et al 2018, Kresse et al 2021,
  Horiuchi et al 2021, …

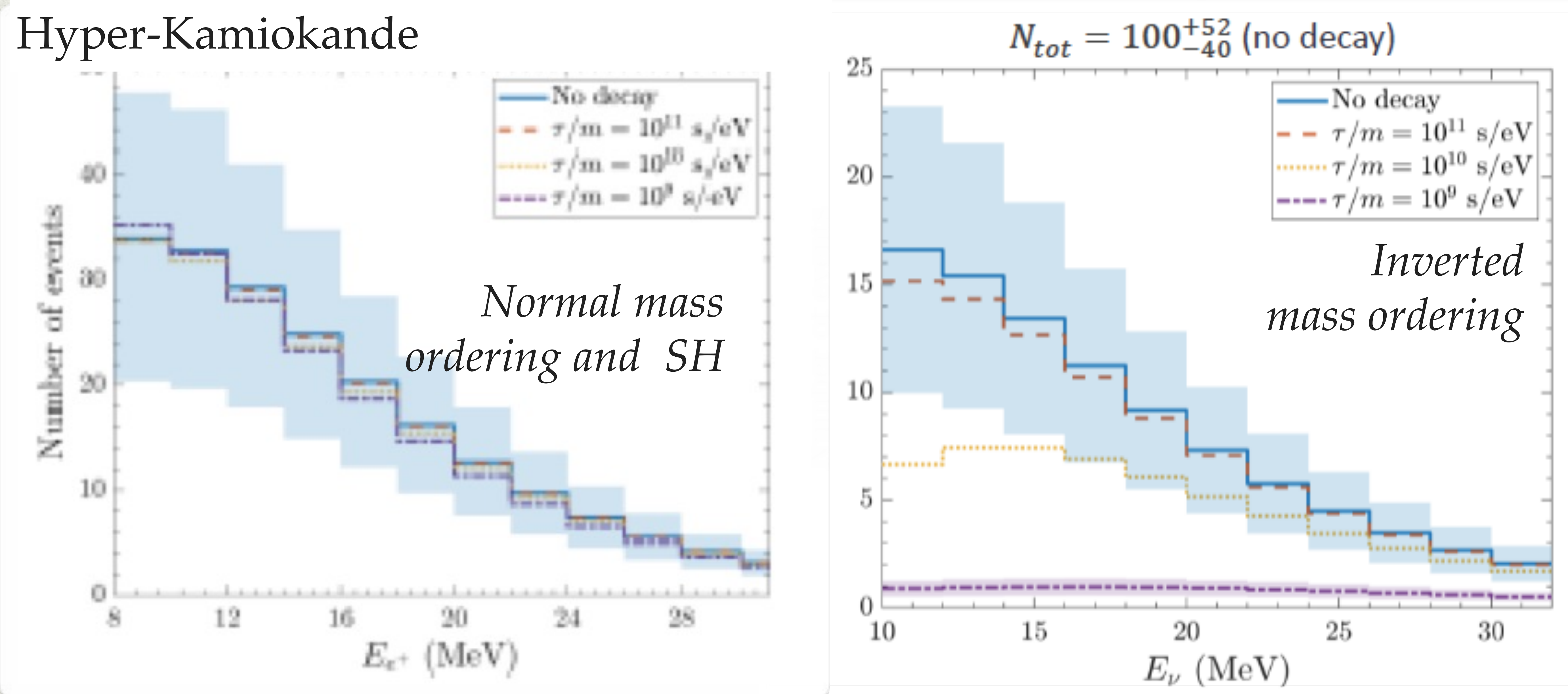
- \- flavor conversion phenomena beyond MSW, e.g. shock waves and self-interaction.
  Event rates can be modified by 10-20 %.

  Galais, Kneller, Gava, Volpe, PRD81, 2010

- \- non-standard neutrino properties such as neutrino decay.

$$\nu_i \to \nu_j + \phi \quad \text{or} \quad \nu_i \to \bar{\nu}_j + \phi$$

Ando 2003, Lisi et al 2004, De Gouvea et al 2020,
Tabrizi et Horiuchi 2021, Ivanez-Ballesteros, Volpe, 2023.



Ivanez-Ballesteros, Volpe, PRD107 (2023), arXiv:2209.12465

In case DSNB not observed, it could be due to neutrino non-radiative two-body decay (IO); significant degeneracies with no decay case (NO)

Conclusions and Perspectives

- *Core-collapse supernova are rare spectacular events and a unique laboratory for astrophysics, particle physics and the search for new physics.*

- How neutrinos evolve in dense matter is a unique weakly interacting many-body system. **Many ongoing developments**, ***e.g.* on the** *impact of fast modes on the explosion*, on the *role of flavor conversion on stellar nucleosynthesis*, on the interplay between flavor terms and collisions, on SN dynamics and many-body correlations.

- **Two crucial features we might learn - answer the six-decade quest of how massive stars undergoing gravitational collapse explode and how neutrinos change flavor in dense environments.**

- **The upcoming detection of the diffuse supernova neutrino background will open a unique low-energy observational window in neutrino astronomy.**

M.C. Volpe, «Neutrinos from dense: flavor mechanisms,
theoretical approaches, observations, new directions »,
Review of Modern Physics . 96 (2024) 2, 025004, arXiv: 2301.11814

« *Une femme jouant de guitare* », Vermeer, 1672

SN NEUTRINO TIME SIGNAL

- **Pre-SN neutrinos** (1-a few days before the SN)

information on the late stages before SN collapse (stellar evolution theory), on the progenitor and early alert.

First pointed out that neutrino pair emission from e.g. the Si-burning phase lasts about 2 days (M = 20 Msun). Average neutrino energies about 2 MeV (thermal emission). Possible detection of pre-SN neutrinos from 1 kpc. Weak interactions

Odrzylowek et al, Astrop. Phys. (2004)

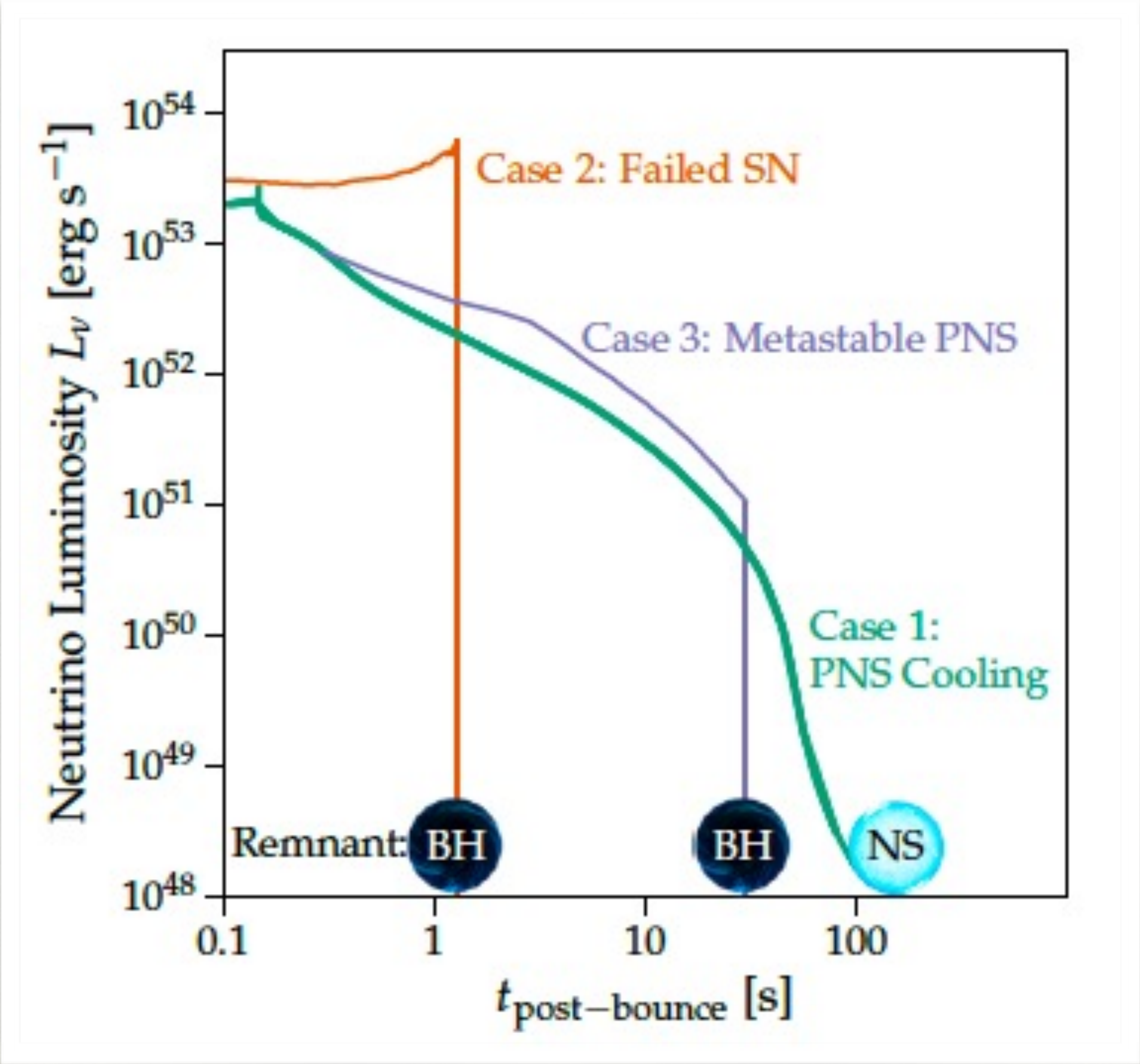
Pre-SN neutrinos (3 sigma detection, 48 h before exp.) could be detected in KamLAND for M = 25 Msun up to 690 pc.

Asakura et al., Astrophys. Journ. (2016)

- **Late-time neutrinos from PNS cooling** (10-100 s)

Late time neutrino emission tells us about the PNS, e.g. equation of state, fate of the SN, total radiated energy and lepton number, new physics.

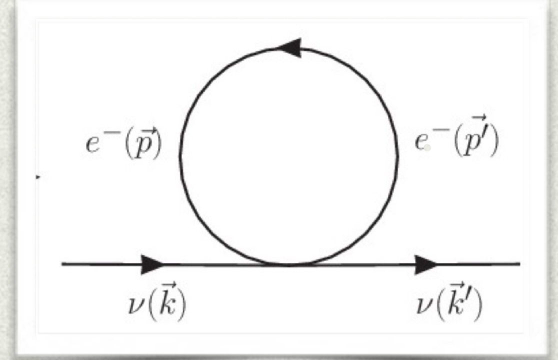
Li, Roberts, Beacom., PRD (2021)



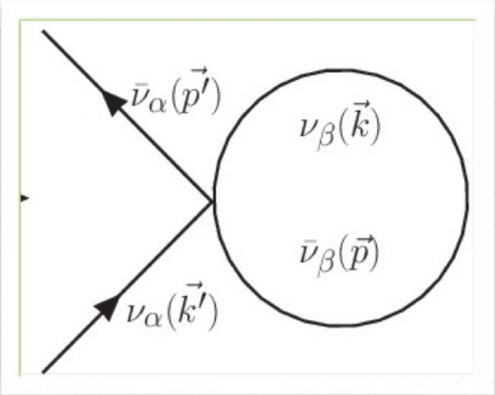
SN at 10 kpc : 250 antinue over 50 s in Super-K, 110 nue over 40 s in DUNE
10 (anti)numu, (anti)tau over 20 s in JUNO

NS cooling goes through different phases -
1 s after bounce - cooling and contraction of the high entropy, shock heated outer layers of the PNS (radius from 50 to 10 km)
1-15 s after bounce - inward diffusion of neutrinos and cooling (T gradient and lepton number)
several tens of s - thermal cooling, neutrinos remove energy from the star (T gradient)

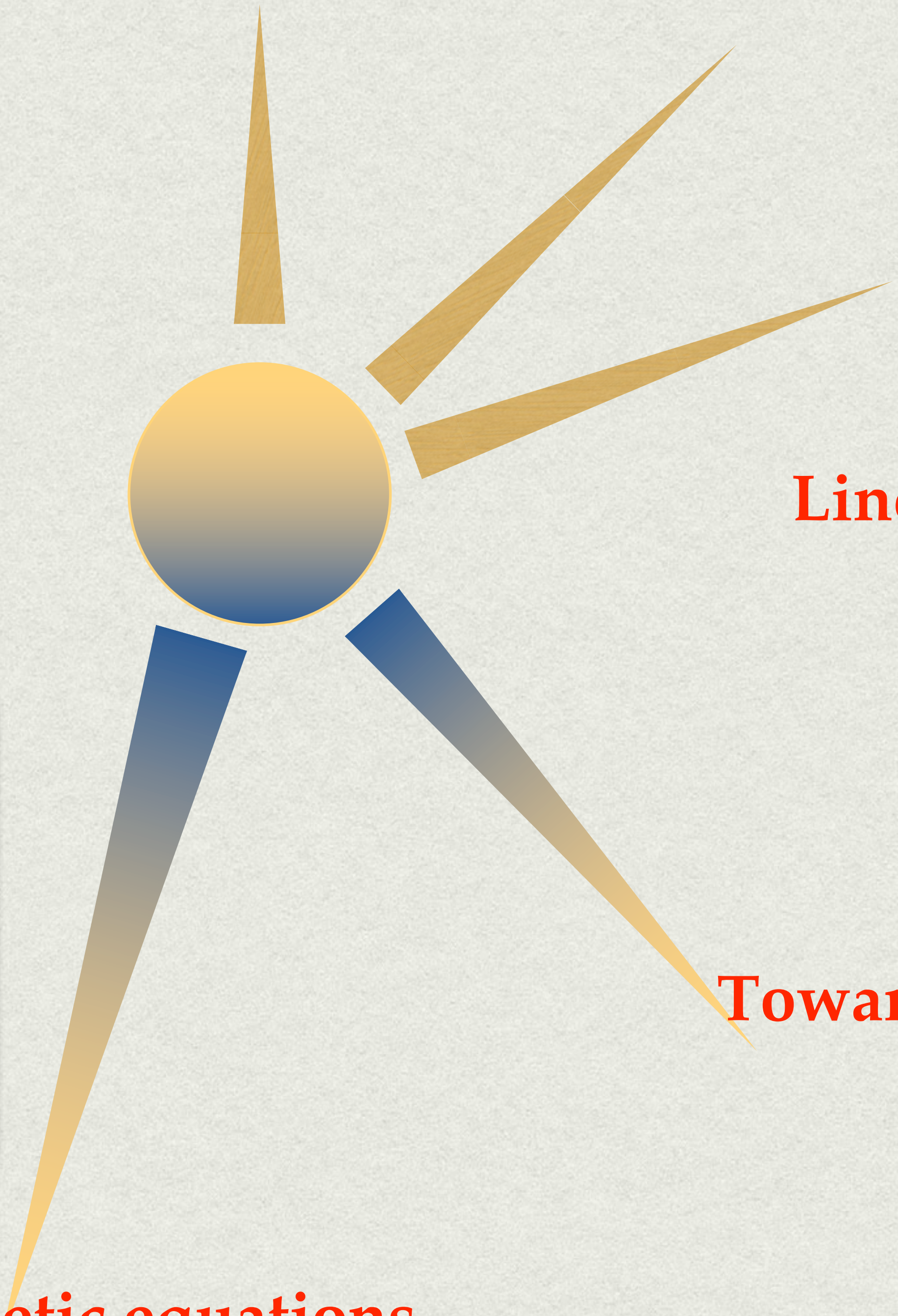
THEORETICAL APPROACHES

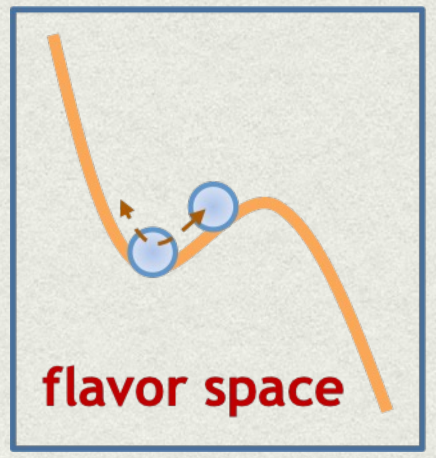


Mean-field approximation



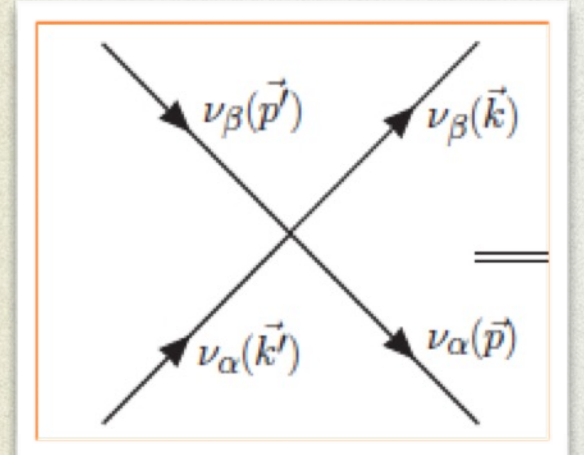
Mean-field and extended mean-field





Linearised mean-field equations

Towards the many-body solution



Quantum kinetic equations

- **Mean-field equations**

$$i(\partial_t + \mathbf{v} \cdot \nabla_\mathbf{x})\varrho_{\mathbf{x},\mathbf{p}} = [h_{\mathbf{x},\mathbf{p}}, \varrho_{\mathbf{x},\mathbf{p}}],$$

- **Extended mean-field equations**

$$i\dot{\mathcal{R}} = [\mathcal{H}, \mathcal{R}],$$

$k_{\alpha\beta} = \langle b_\beta a_\alpha \rangle$- pairing correlators

$\zeta = \langle a_+^\dagger a_- \rangle$ - spin or helicity coherence

- **Linearised equations**

$$\delta\rho = \rho_0 + \delta\rho(t) = \rho^0 + \rho' e^{-i\omega t} + \rho'^\dagger e^{i\omega^* t}.$$

$$\begin{pmatrix} A & B \\ \bar{B} & \bar{A} \end{pmatrix} \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix} = \omega \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix}$$

S eigenvalues :
-> real : stable collective
-> imaginary : instabilities

- **Quantum kinetic equations**

$$i(\partial_t + \mathbf{v} \cdot \nabla_\mathbf{x})\varrho_{\mathbf{x},\mathbf{p}} = [h_{\mathbf{x},\mathbf{p}}, \varrho_{\mathbf{x},\mathbf{p}}] + i\mathcal{C}[\varrho, \overline{\varrho}],$$

-full collision term

DNSB LIMITS

- Flux upper limits from SKI-IV and SNO data

$$2.8 - 3 \quad \bar{\nu}_e \quad \mathrm{cm}^{-2} s^{-1} \quad (E_\nu > 17.3 \quad \mathrm{MeV})$$

Abe et al, 2109.11174

$$19 \quad \nu_e \quad \mathrm{cm}^{-2} s^{-1} \quad (E_\nu \in [22.9, 36.9] \quad \mathrm{MeV})$$

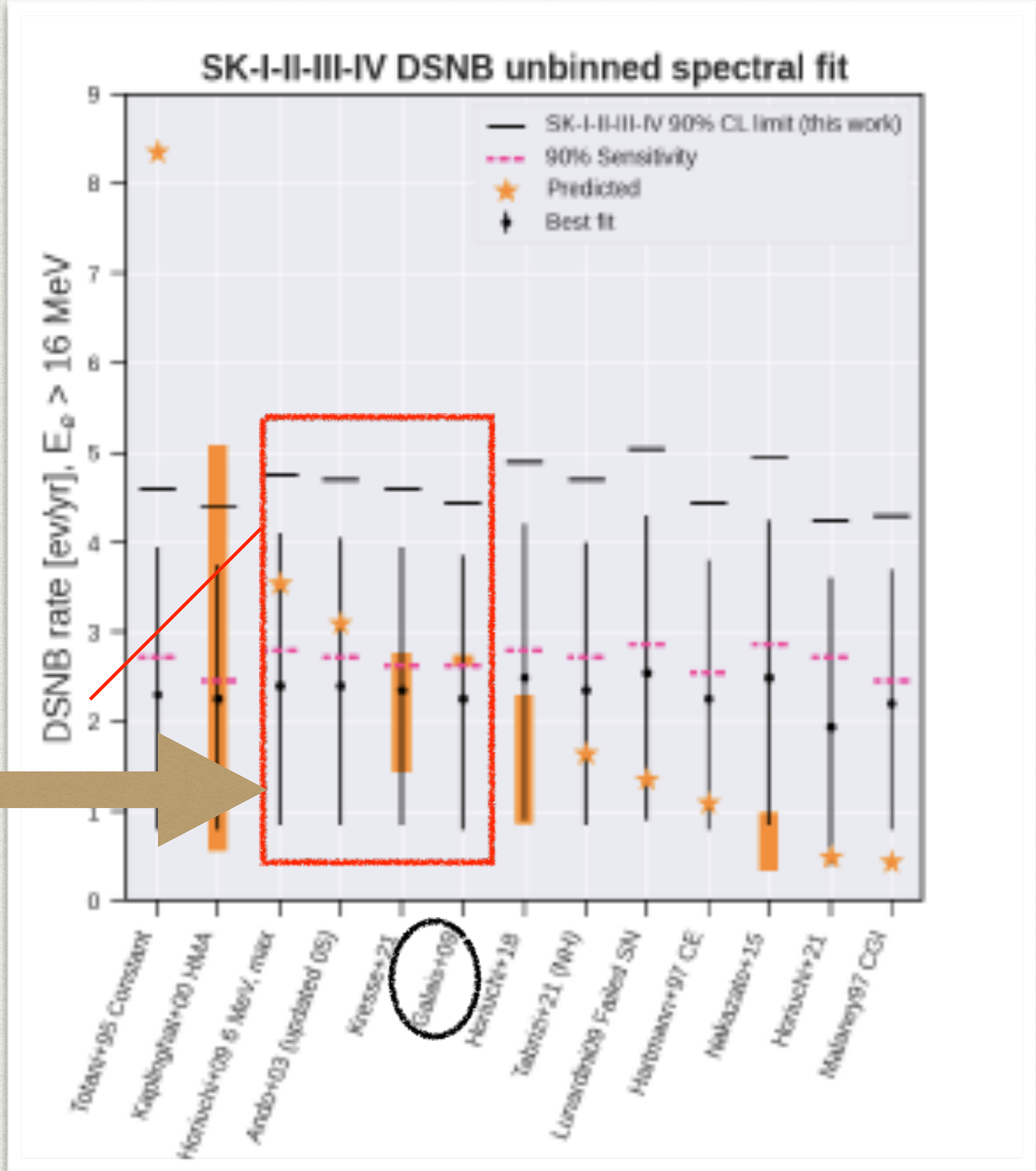
SNO data, Aharmim et al, Astrophys. J. 2006

$$10^3 \nu_x \; cm^{-2} s^{-1}$$

Peres and Lunardini,. JCAP 2008

The sensitivity of the combined analysis (90 % C.L.) is on par with 4 predictions.

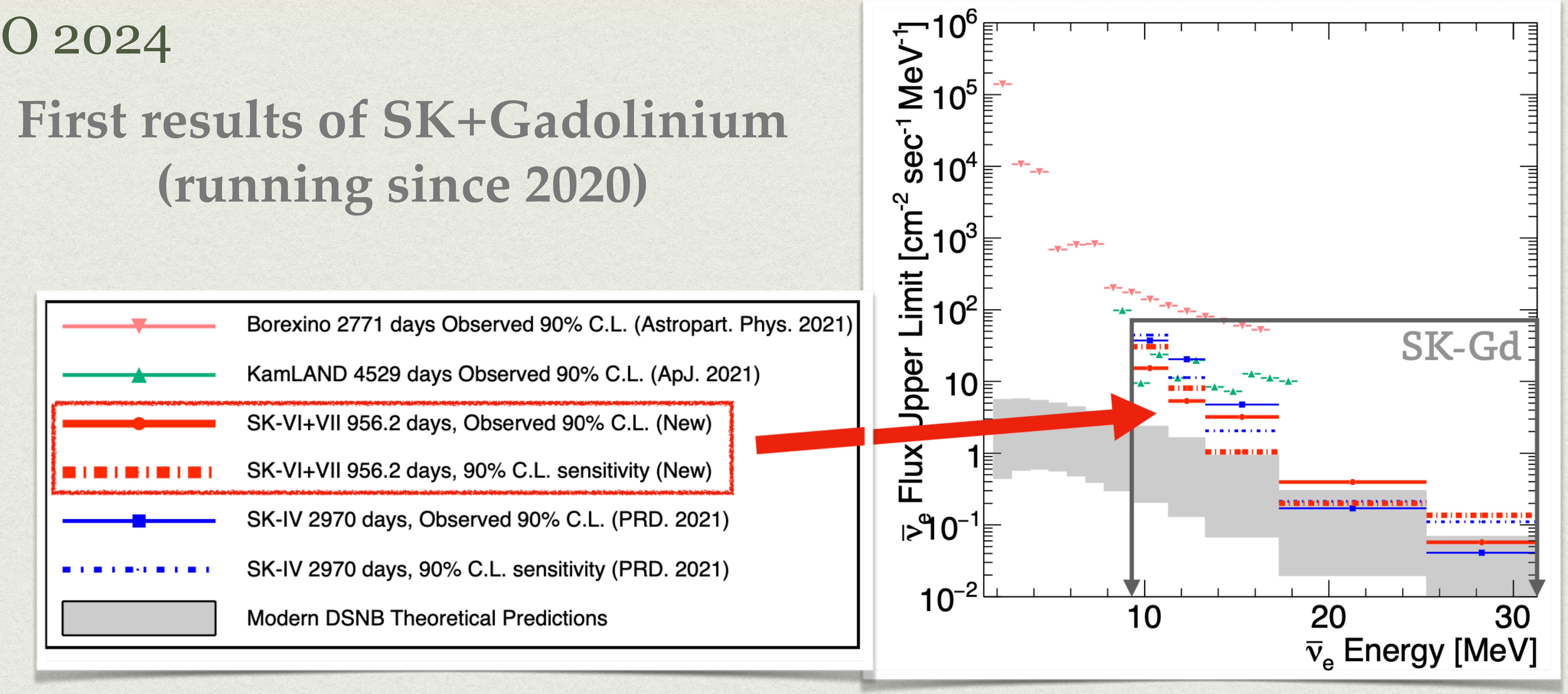
EXCESS (1.5 sigma) over BACKGROUND OBSERVED

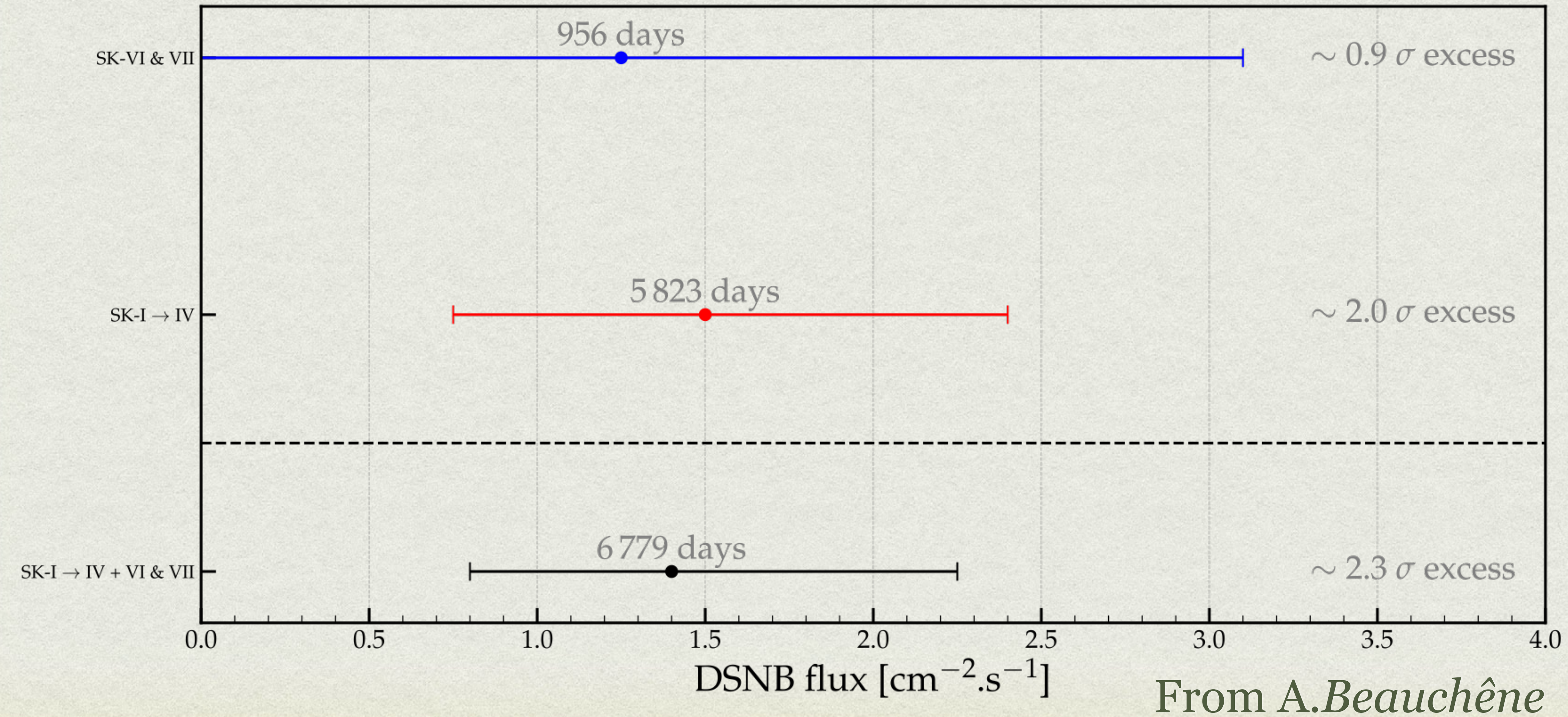


Expected rates, 90% C.L. upper limits, best fit values (1 sig.) and expected sensitivity from SK-I and SK-IV data

Abe et al, 2109.11174

First results of SK+Gadolinium (running since 2020)





From A.*Beauchêne*

Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is **$1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1}** for E_ν> 17.3 MeV

➡ **exhibit ~2.3 σ excess!!**

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

- The DSNB flux depends on the evolving core-collapse supernova rate, the neutrino fluxes from a supernova, integrated over time

$$\phi^{\rm DSNB}_{\nu_\alpha}(E_\nu) = c \int\int {\rm dM}\ dz \left|\frac{dt}{dz}\right| \underleftrightarrow{R_{\rm SN}(z,\ {\rm M})}\ \underleftrightarrow{\phi_{\nu_\alpha,SN}(E'_\nu,\ {\rm M})}$$

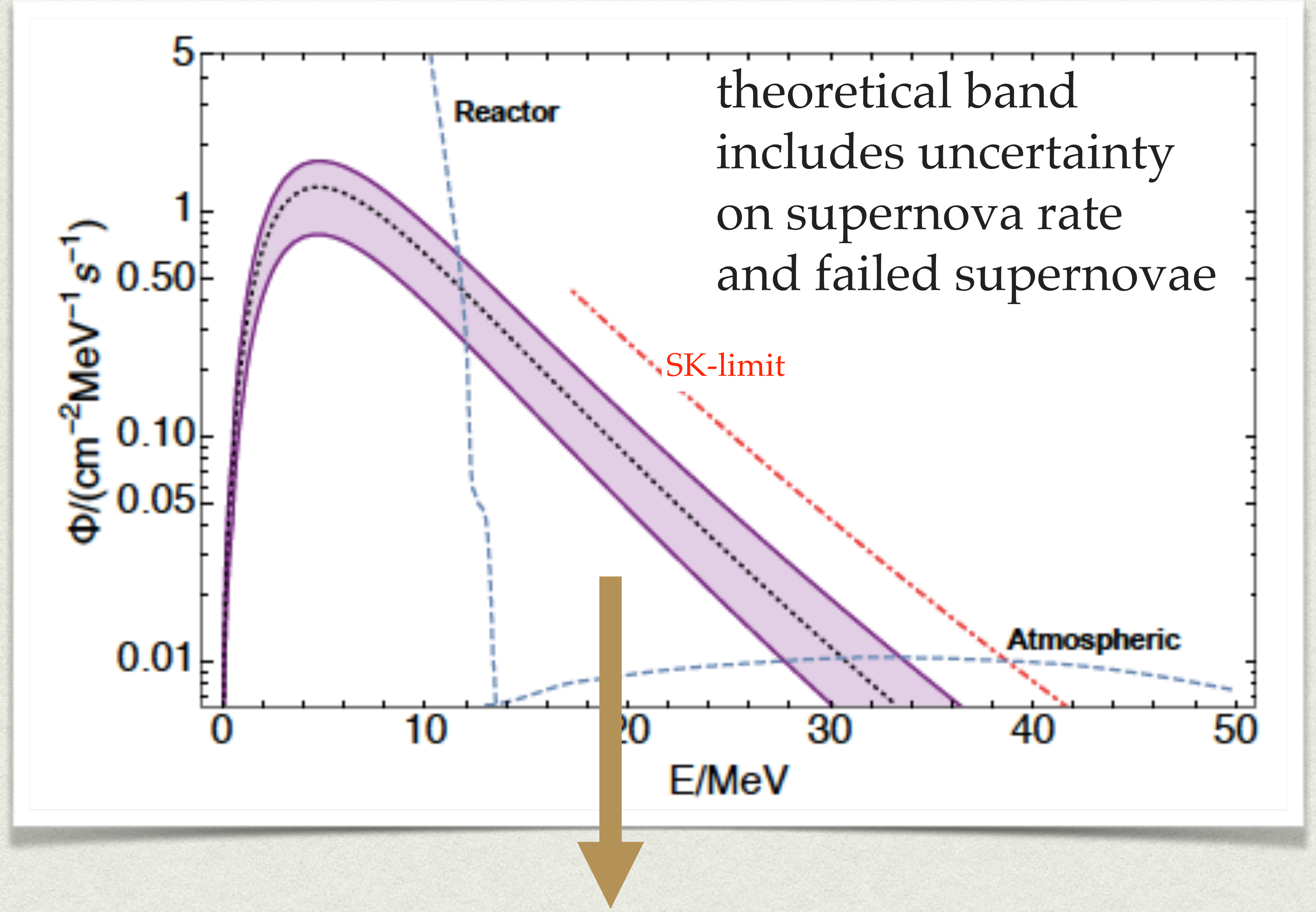
$E'_\nu = E_\nu(1+z)$ redshifted neutrino energies

M mass of the supernova progenitor giving either a neutron star or a black hole

Contribution from failed supernovae (black-hole): hotter energy spectrum determines the relic flux tail.

Lunardini, PRL 2009

The BH fraction is a debated astrophysical input.



theoretical band includes uncertainty on supernova rate and failed supernovae

Priya and Lunardini JCAP 2017

DSNB detection window

NEUTRINO FLUX from a SN of the main UNCERTAINTIES

- Dependence on the cosmological model ΛCDM

$$\left|\frac{dz}{dt}\right| = H_0(1+z)\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m}$$

$\Omega_\Lambda = 0.7 \quad \Omega_m = 0.3$ dark energy and matter cosmic energy densities

$H_0 = 67.4\ \mathrm{km\ s^{-1}Mpc^{-1}}$ Hubble constant

COSMIC CORE-COLLAPSE SUPERNOVA RATE

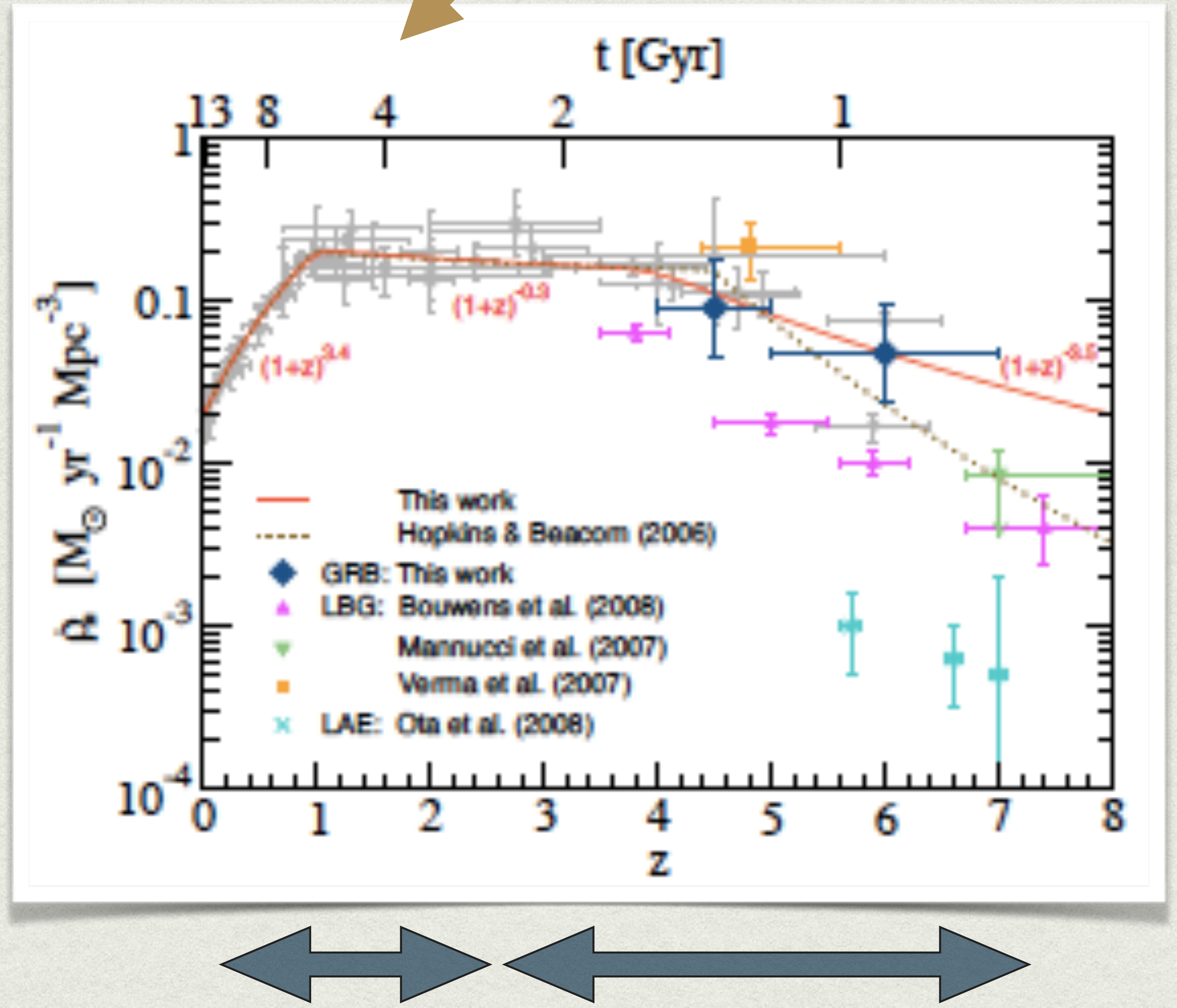
- The cosmic core-collapse supernova rate history can be deduced from the cosmic star formation rate history.

$$R_{\rm SN}(z,{\rm M}) = \dot\rho_*(z)\frac{\phi({\rm M})d{\rm M}}{\int_{0.5\ {\rm M}_\odot}^{125\ {\rm M}_\odot}\phi({\rm M}){\rm M}d{\rm M}}$$

- $\phi({\rm M}){\rm dM}$ is the number of stars with progenitor mass $[{\rm M},{\rm M}+{\rm dM}]$

$$\phi({\rm M}) \sim {\rm M}^{\chi} \qquad \chi = -2.35 \qquad {\rm M} \geq 0.5{\rm M}_\odot$$

Salpeter Initial Mass Function (IMF)



Yuksel et al, i Astrophys. J(2008)

relevant for the DSNB

below detection threshold

- **Local SN rate uncertain by a factor of 2:**

$$R_{SN}(0) = \int_{8\ {\rm M}_\odot}^{125\ {\rm M}_\odot} R_{\rm SN}(0,{\rm M})d{\rm M}$$

$$= 1.25 \pm 0.5 \times 10^{-4} yr^{-1} Mpc^{-3}$$

ONE of the main UNCERTAINTIES

SN NEUTRINO TIME SIGNAL

- **Pre-SN neutrinos** (1-a few days before the SN)

  information on the late stages before SN collapse, on the progenitor and early alert.

  First pointed out that neutrino emission from e.g. the Si-burning phase lasts about 2 days (M = 20 Msun).
  Average neutrino energies about 2 MeV (thermal emission). Possible detection of pre-SN neutrinos from 1 kpc.

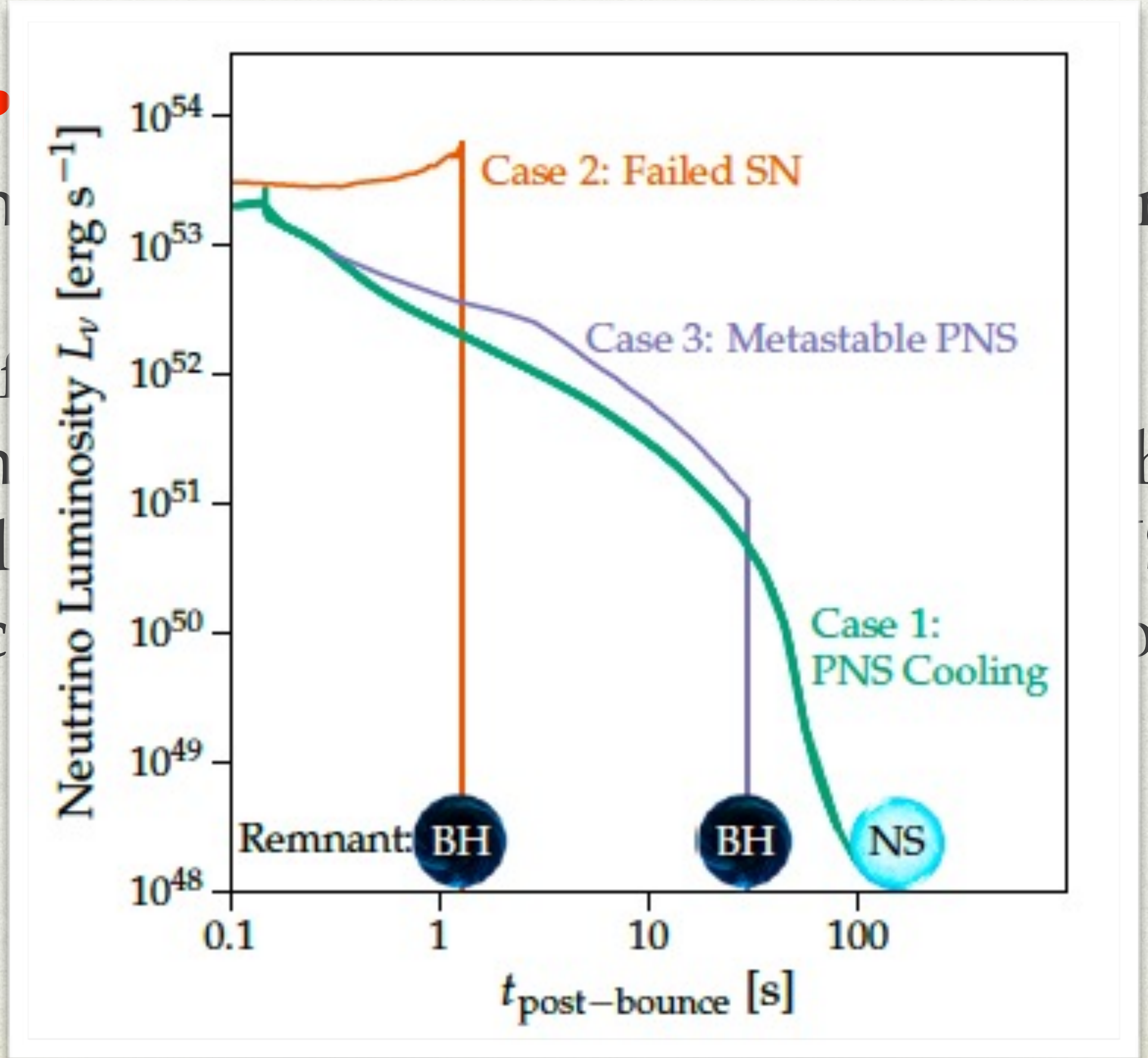
  Weak interactions

  Odrzylowek et al, Astrop. Phys. (2004)

  Pre-SN neutrinos could be detected in KamLAND for M = 25 Msun up to 690 pc.

  Asakura et al., Astrophys. Journ. (2016)

  Super-K



- **Late-time neutrinos from P**

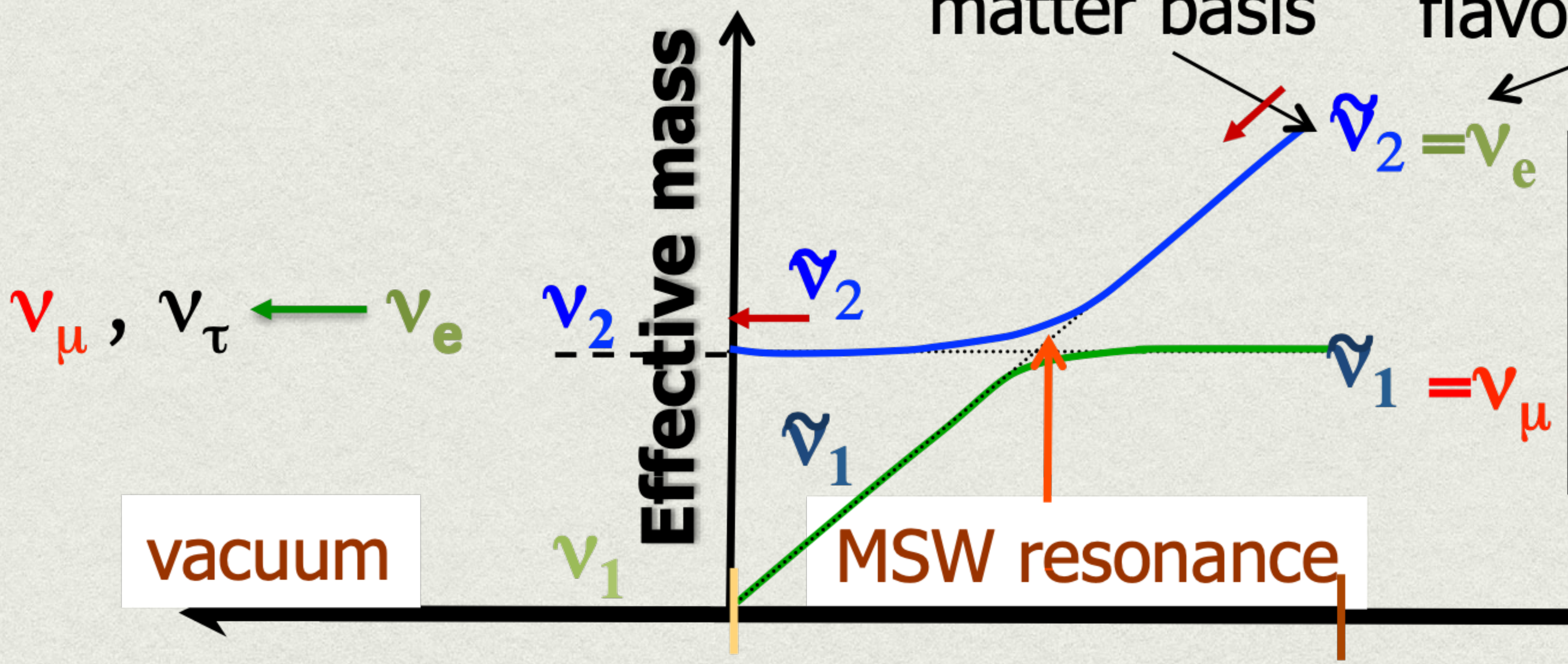
  Late time neutrino emission n of state, new physics.

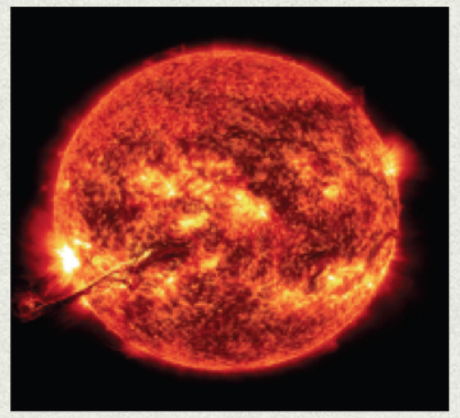
  NS cooling goes through di
  1 s after bounce - cooling an hock heated outer layers of the PNS (radius from 50 to 10 km)
  5-15 s after bounce - inward S, and cooling, tends to zero net neutrino number
  several tens of s - thermal c om the star (temperature gradients).

  Li, Roberts, Beacom., PRD (2021)

Mikheev-Smirnov-Wolfenstein (MSW) EFFECT

Wolfenstein, 1978; Mikheev and Smirnov, 1985

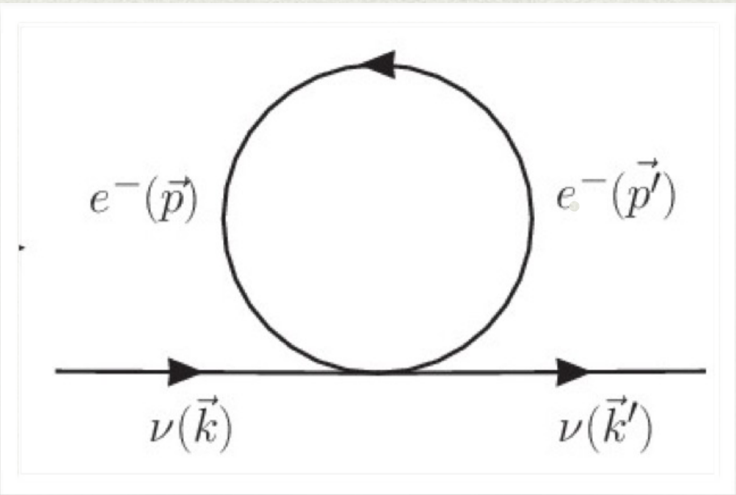




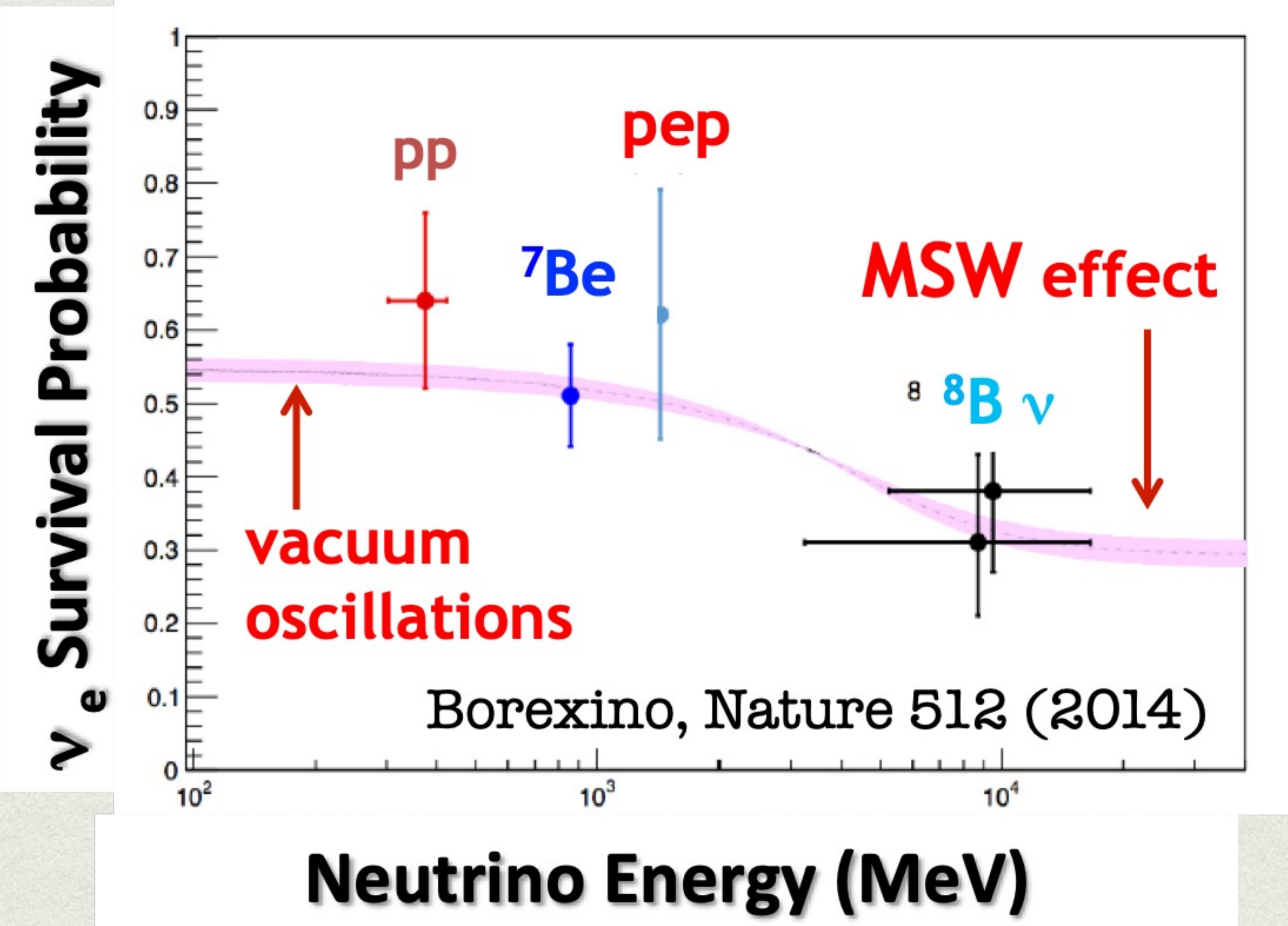
$$\frac{\Delta m2}{2E} cos2\theta = \sqrt{2}G_F N_e$$

Electron neutrinos adiabatically (efficiently) convert into other flavors at the resonance location

- The neutrino-matter interaction term responsible for the MSW effect

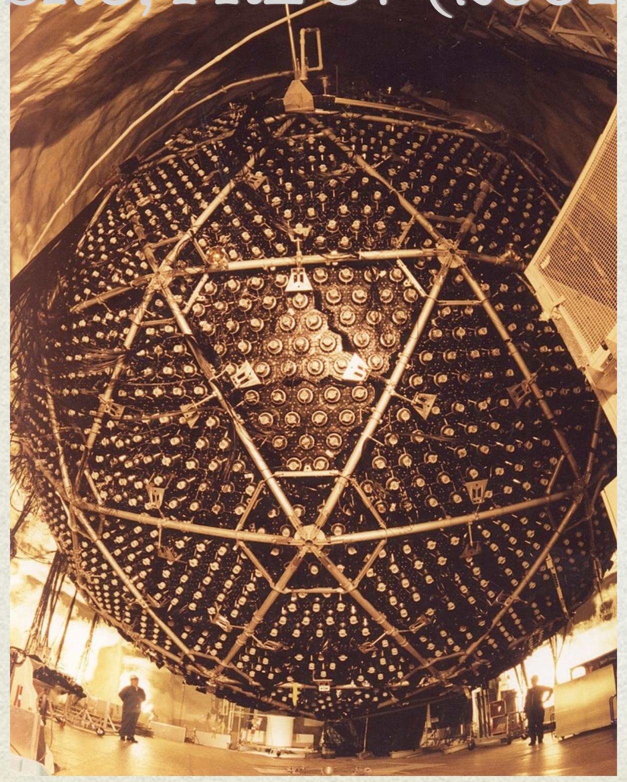


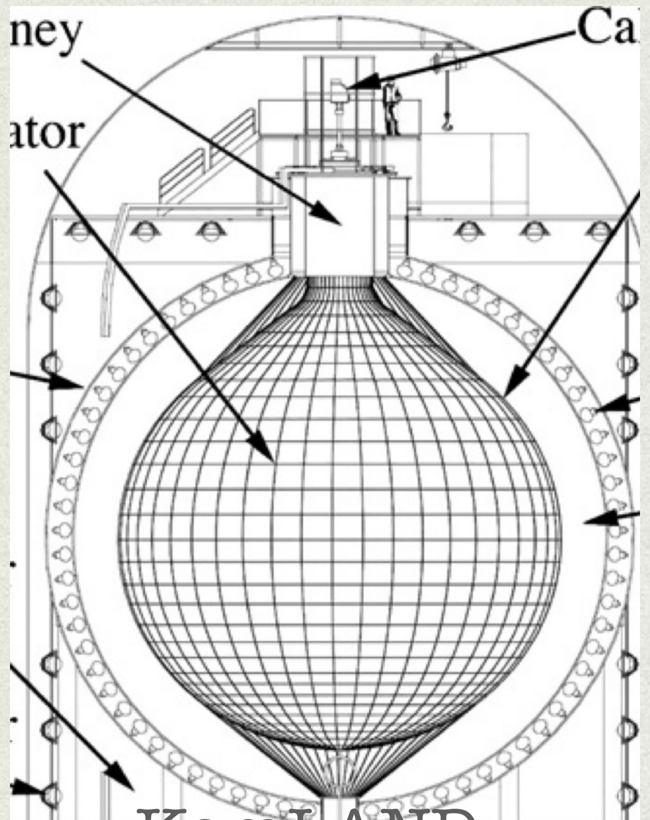
- Established by experiments



Borexino, Nature 512 (2014)

SNO, PRL 87 (2001)

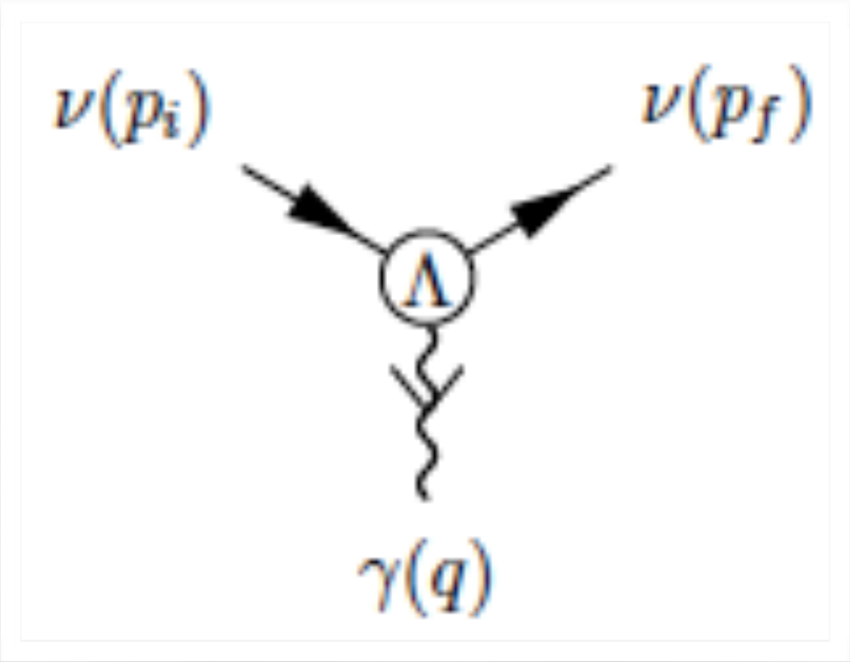




KamLAND, PRL 90 (2003)

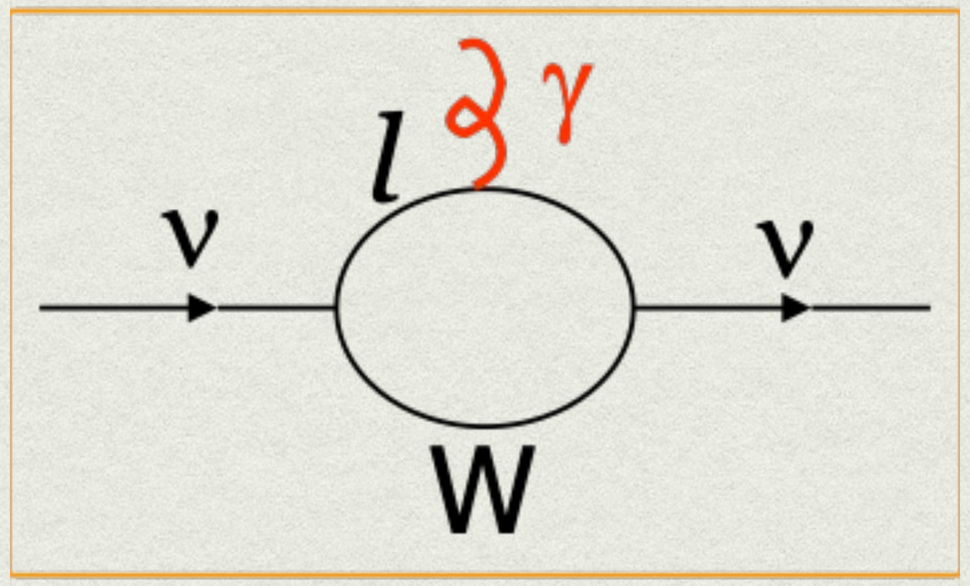
MSW occurs in supernovae, binary neutron star mergers, Earth and early Universe

SN1987A: an incredible laboratory for particle physics



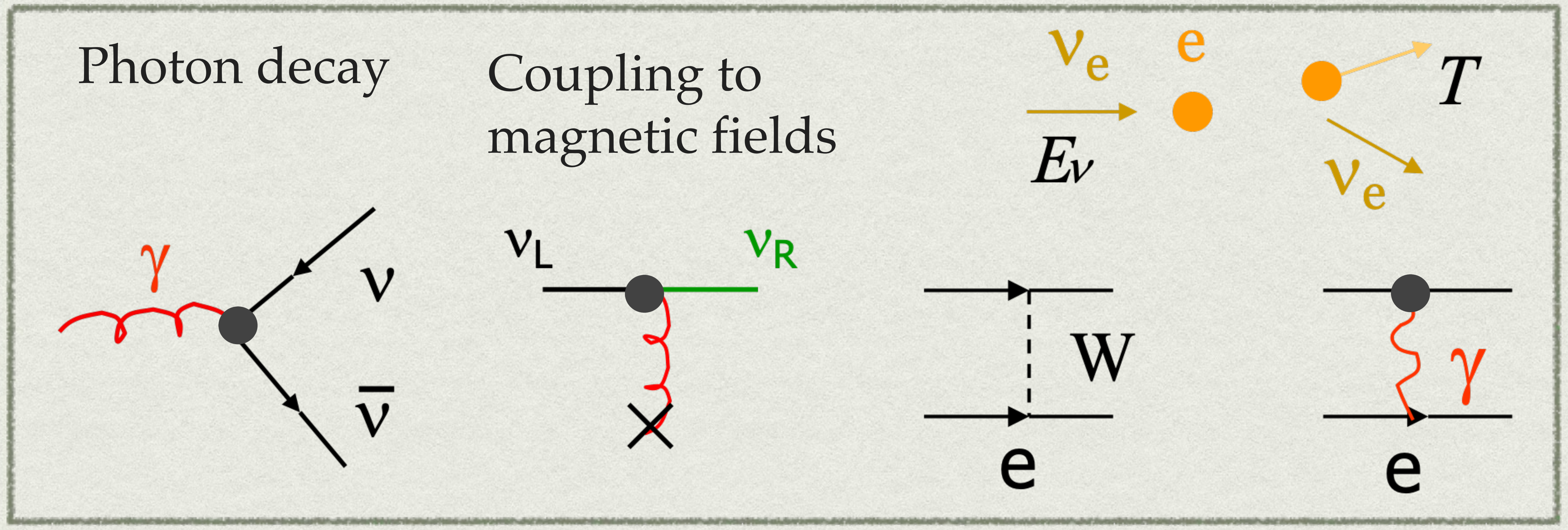
Effective one-photon coupling of a neutrino with a photon

$$\mathcal{L}_{eff} = \bar{\psi} O_\lambda \psi A^\lambda$$



Neutrino magnetic moment from quantum loops

$\mu_\nu = 3.2 \times 10^{-19}\,(m_\nu/1\text{ eV})\,\mu_B$



Photon decay

Coupling to magnetic fields

- Neutrinos have electromagnetic properties from effective one-photon couplings.
- The most general vertex form, consistent with Lorentz invariance includes

$$\Gamma_\lambda(p_i, p_f) = D_M(q^2)\sigma_{\lambda\rho}q^\rho$$ Magnetic form factor

- Limits on the electron **neutrino magnetic moment**

$1.1 \times 10^{-9}\mu_B$ to $2.9 \times 10^{-11}\mu_B$ reactor, accelerator experiments

$\mu_\nu < 1.5\text{-}5 \times 10^{-12}\,\mu_B$ **SN1987A**

Lattimer and Cooperstein (1988), Goldman et al. (1988), Notzold (1988),...

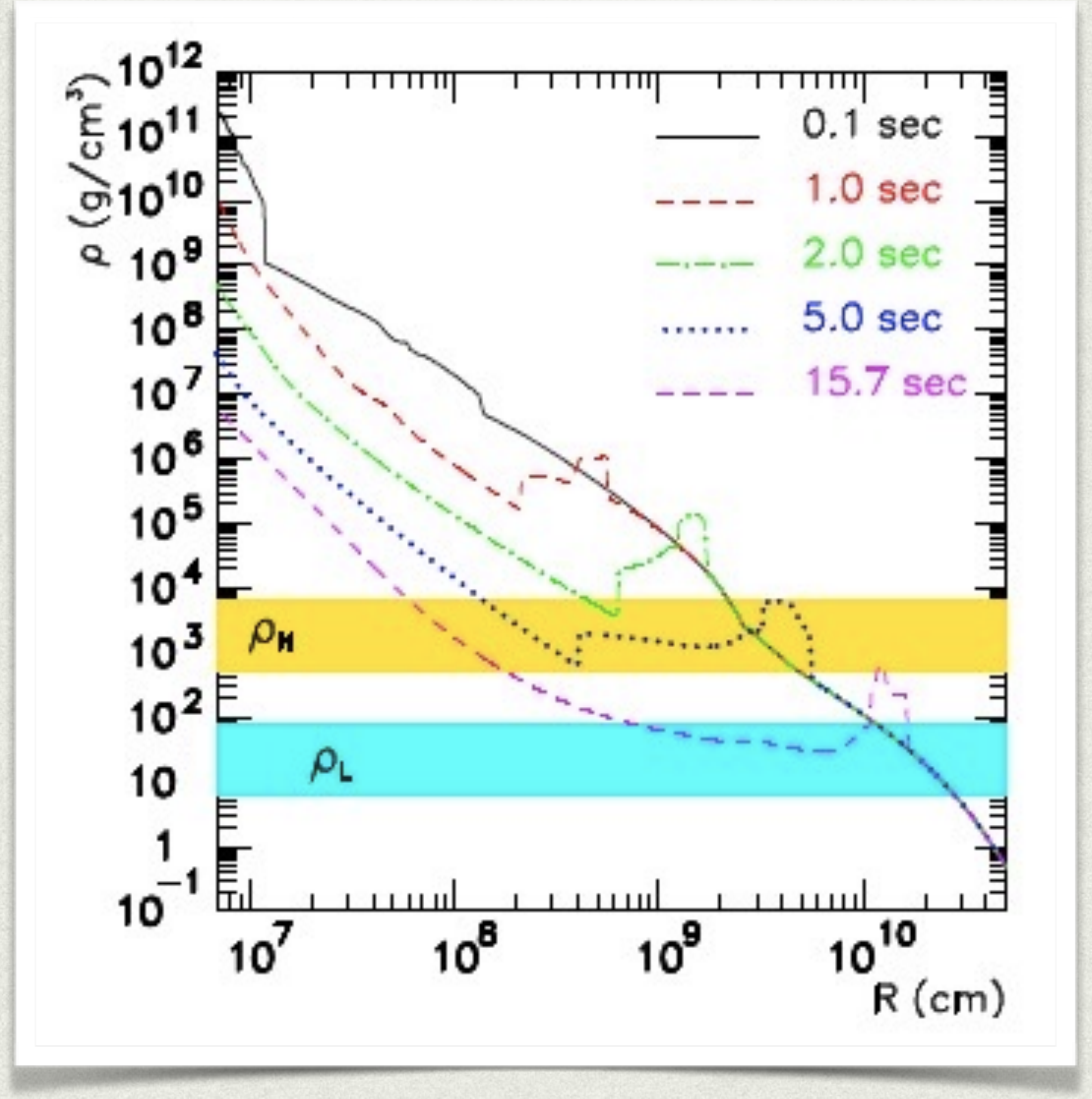
$\mu_\nu < 1 - 3 \times 10^{-12}\mu_B$ $(95\%\ C.L.)$ stellar cooling

See the review Giunti and Studenikin, RMP 87 (2015)

Numerous limits on non-standard properties, particles and interactions

NEUTRINO MASS ORDERING

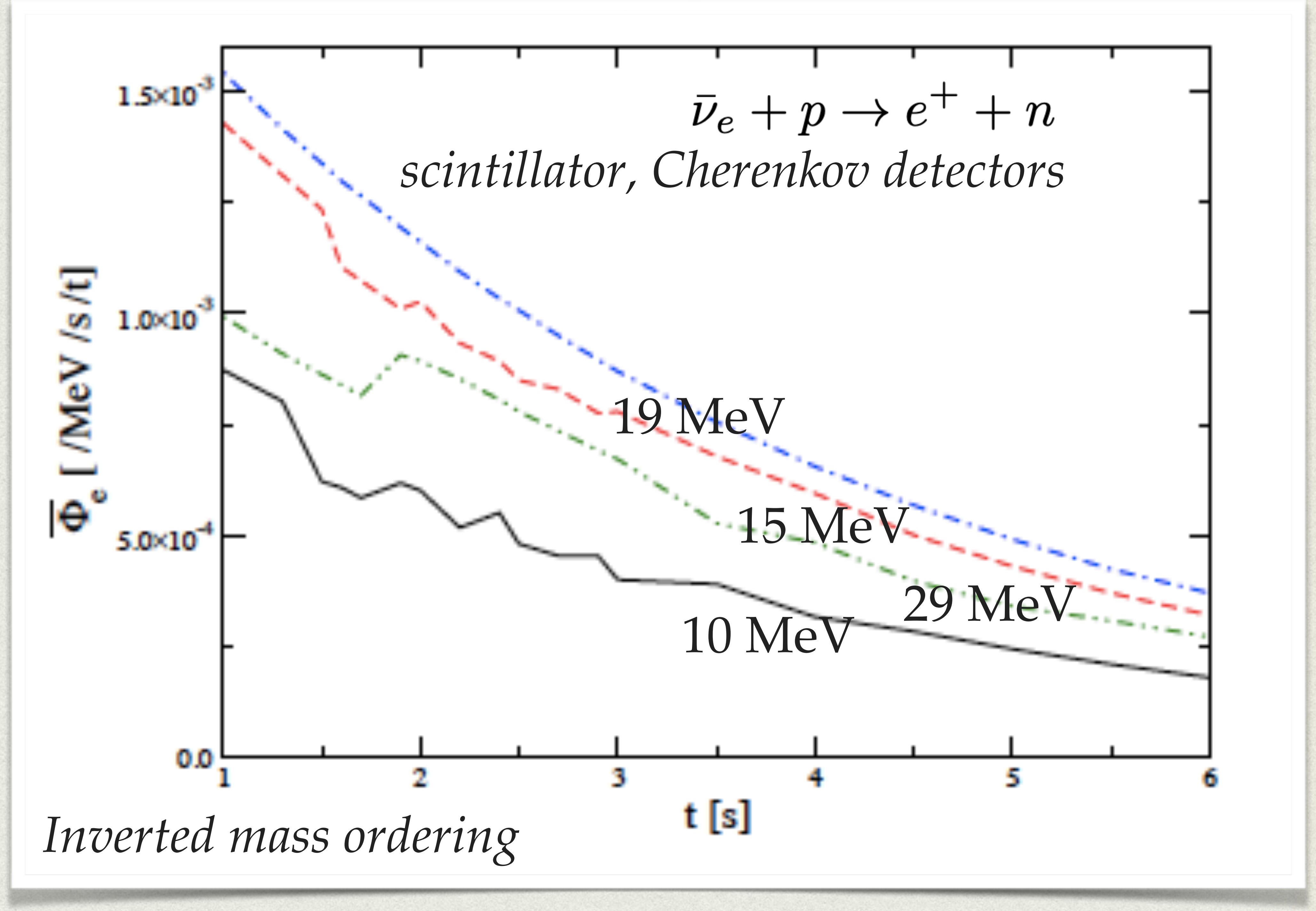
- Presence of front and reverse shocks .



Tomas et al, JCAP 09 (2004)

MSW resonance can be met multiple times.

- *Time signal in Cherenkov and scintillator detectors of a supernova in our galaxy (10 kpc)*

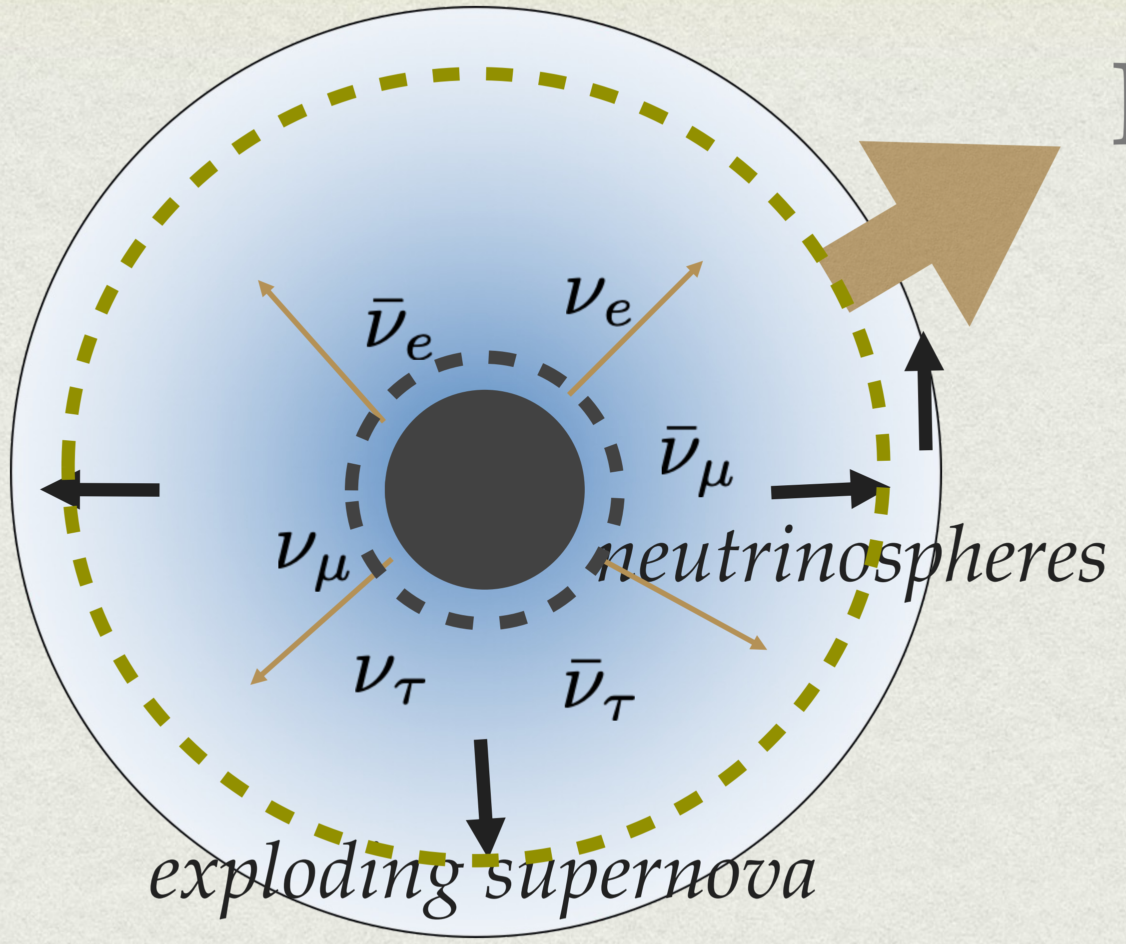


Gava, Kneller, Volpe, McLaughlin, PRL 103 (2009)

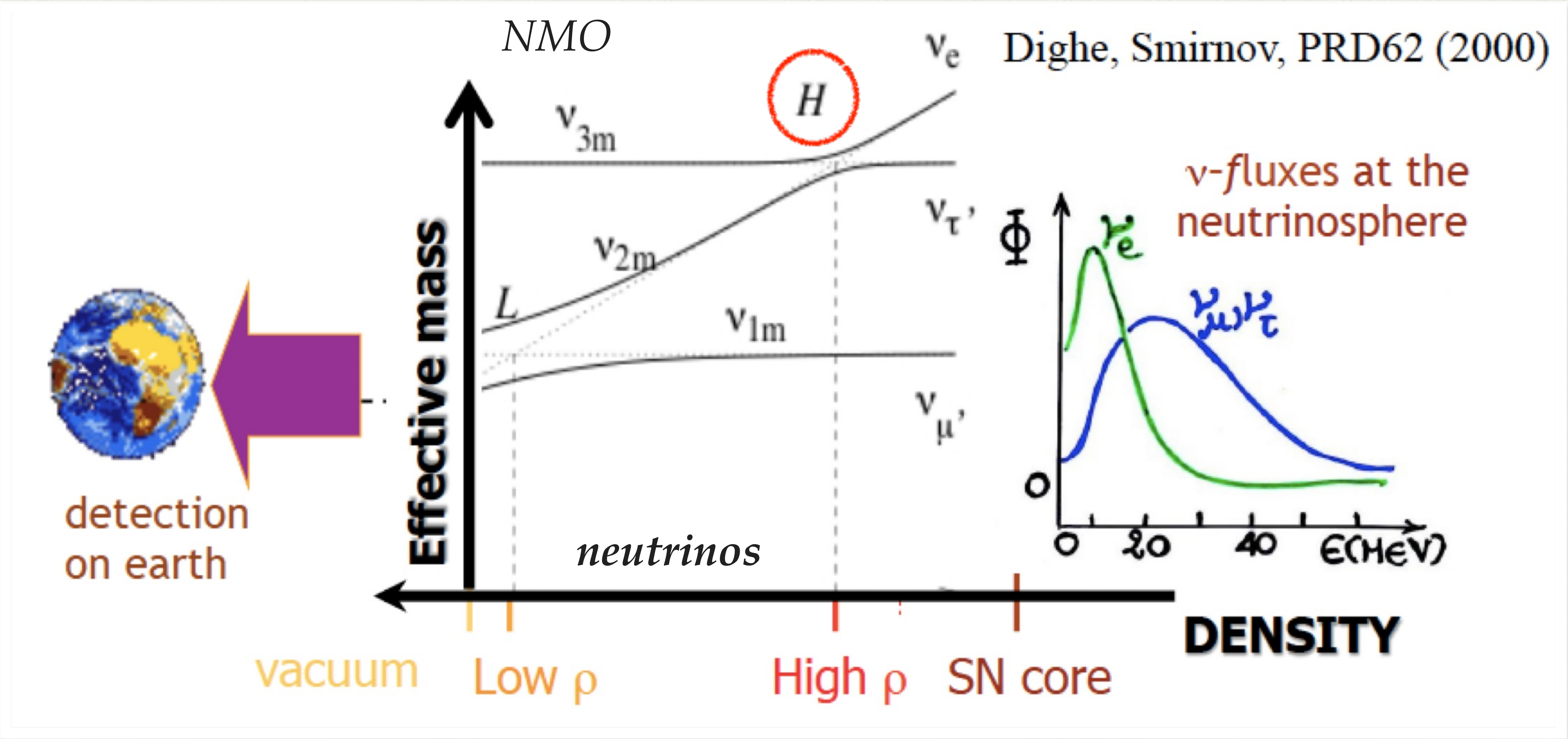
Positron time signal from $\bar{\nu}_e$ per unit tonne.
Prediction includes $\nu\nu$ interactions and shock wave effects.

Picture of the shock wave passage in the MSW region. Similar for electron neutrinos in DUNE for NMO.

If the mass ordering determined by experiments, it will confirm/refute that we understand.



MSW EFFECT IN DENSE MEDIA

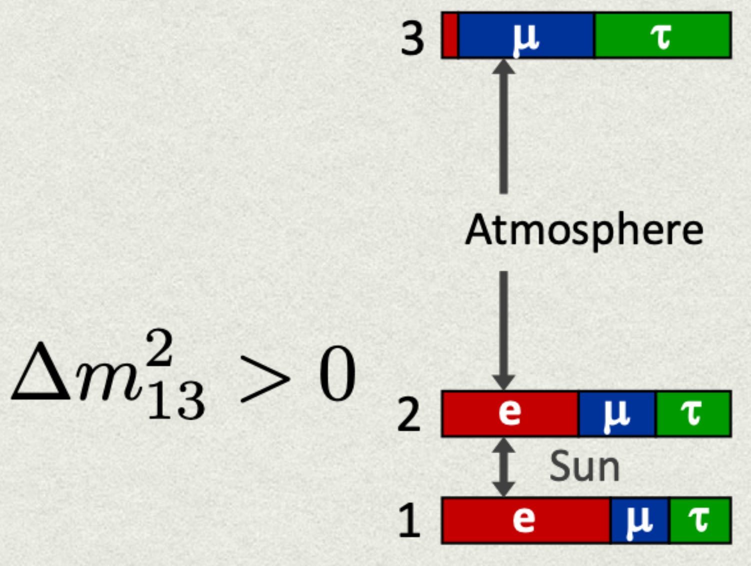


- Main resonances :
  High (H) $(\theta_{13}, \Delta m^2_{13})$
  Low (L) $(\theta_{12}, \Delta m^2_{12})$
- Modifies supernova neutrino spectra (spectral swapping) and the time signal

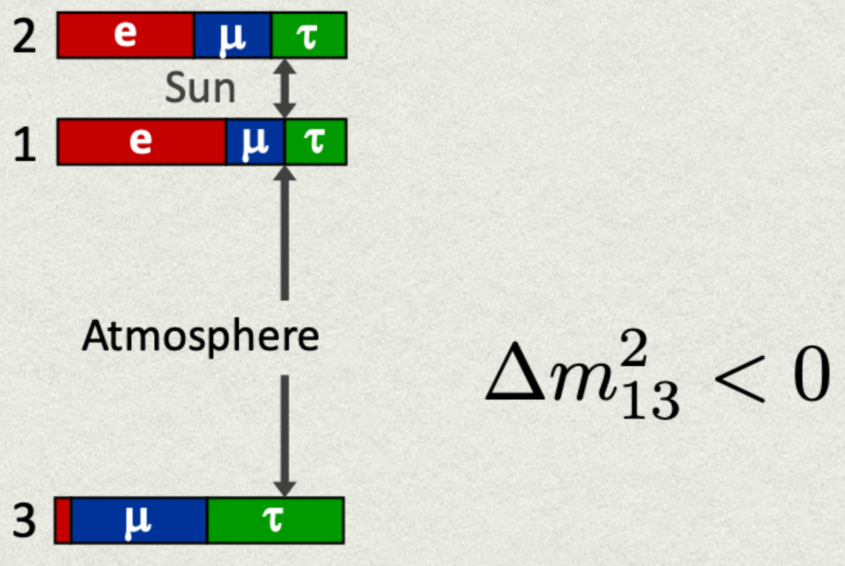
$$\phi_{\bar{\nu}_e} = p\phi^0_{\bar{\nu}_e} + (1-p)\phi^0_{\bar{\nu}_x}$$

$$p = 0.68 \quad NMO \qquad p = 0 \quad IMO$$

Evolution at the H-resonance depends on the unknown sign of Δm^2_{13}



Normal mass ordering (NMO)



Inverted mass ordering (IMO)

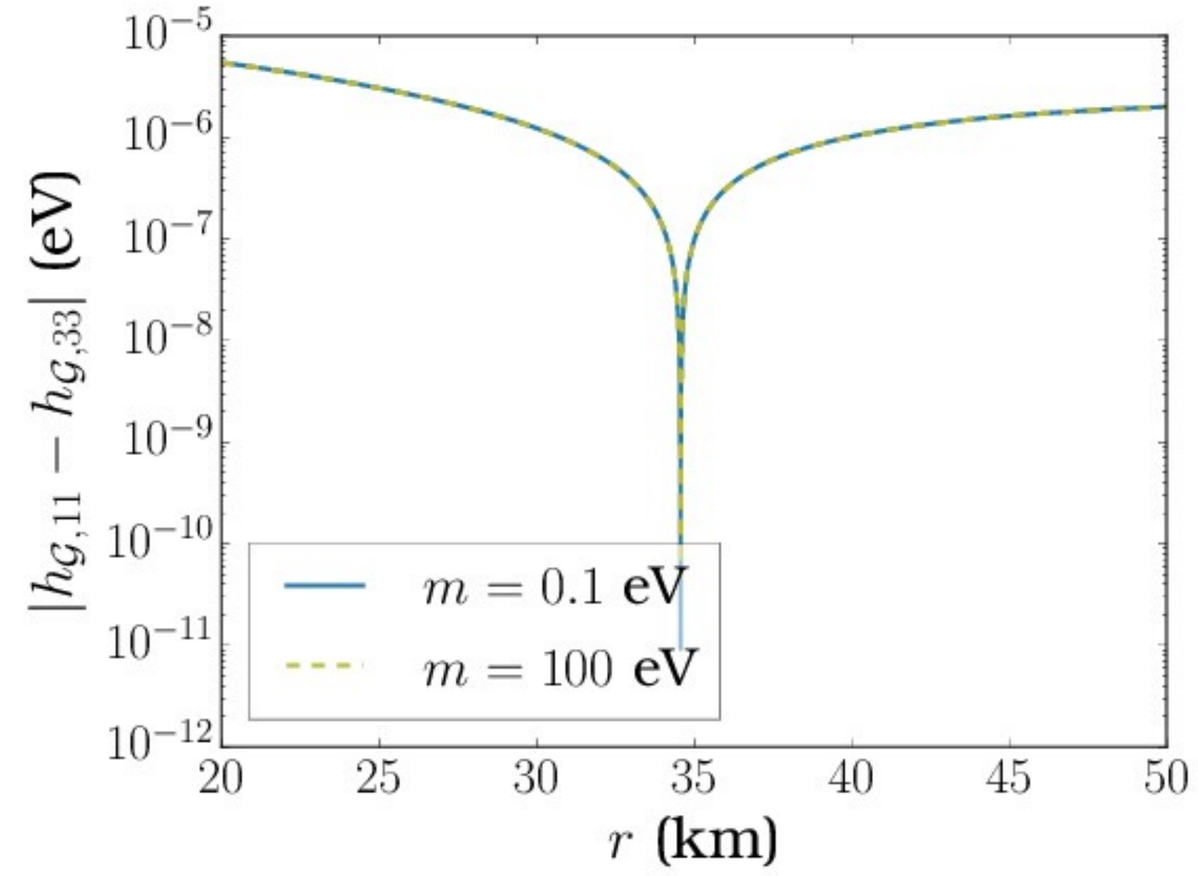
Flavor evolution in presence of helicity coherence

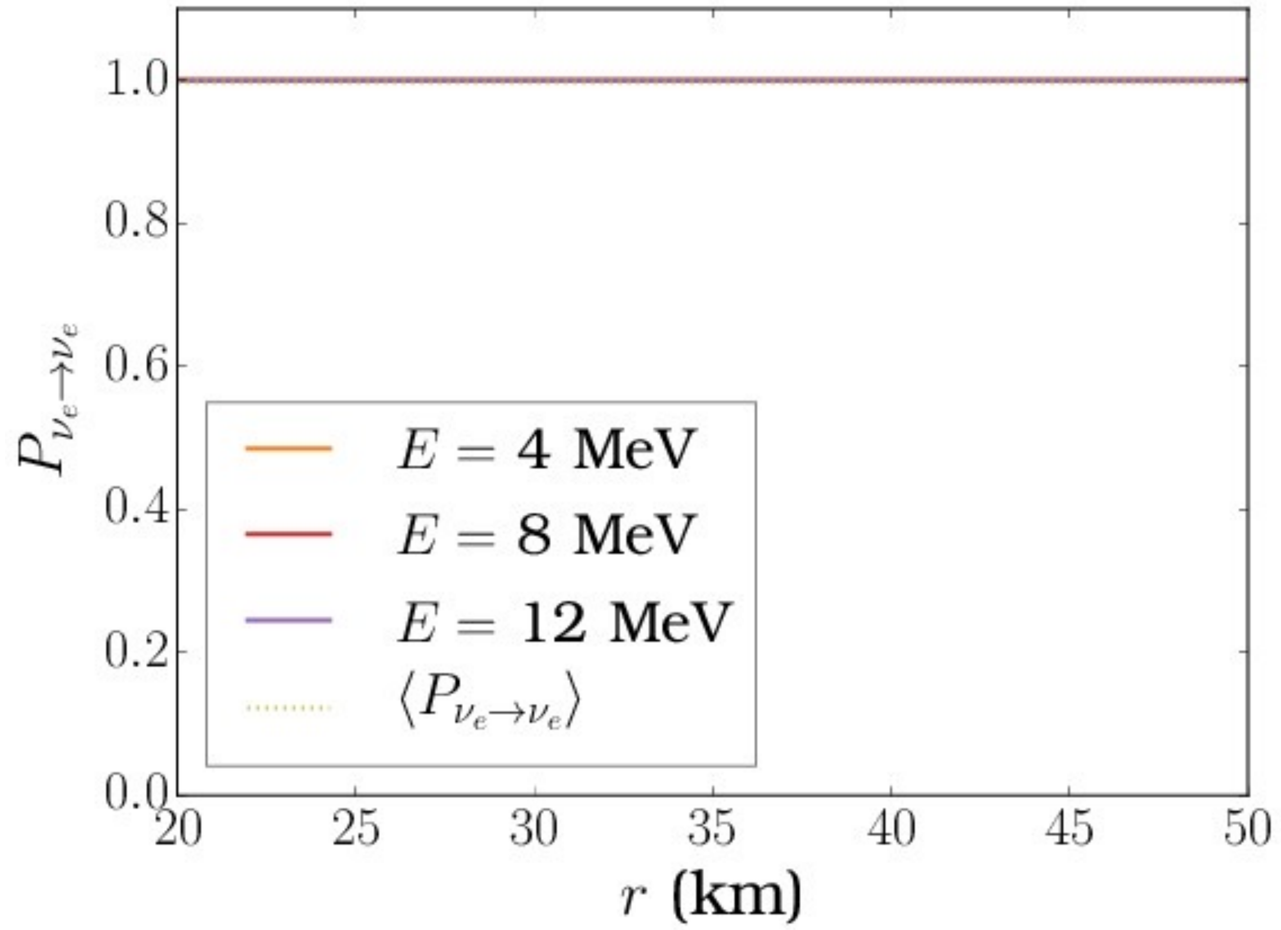
For Majorana neutrinos, the 2ν Hamiltonian $\mathcal{H} = \begin{pmatrix} h & \Phi \\ \Phi^* & \bar{h} \end{pmatrix}$

Resonance (MSW-like) conditions :

- Helicity Coherence

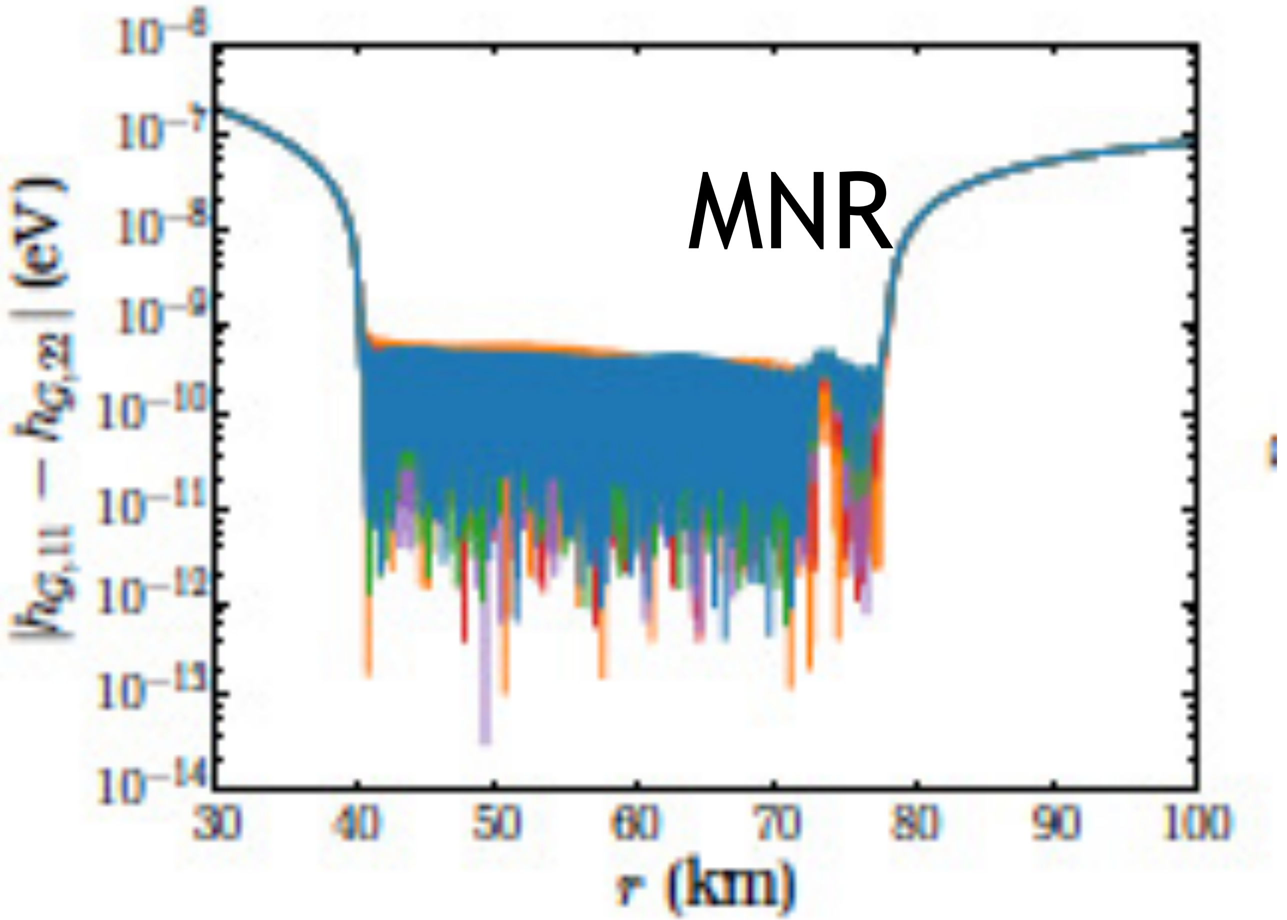
$$h_{\mathcal{G},11} - h_{\mathcal{G},33} = \sqrt{2} G_F n_B (3Y_e - 1) + 2h_{\nu\nu}^{ee} \simeq 0,$$

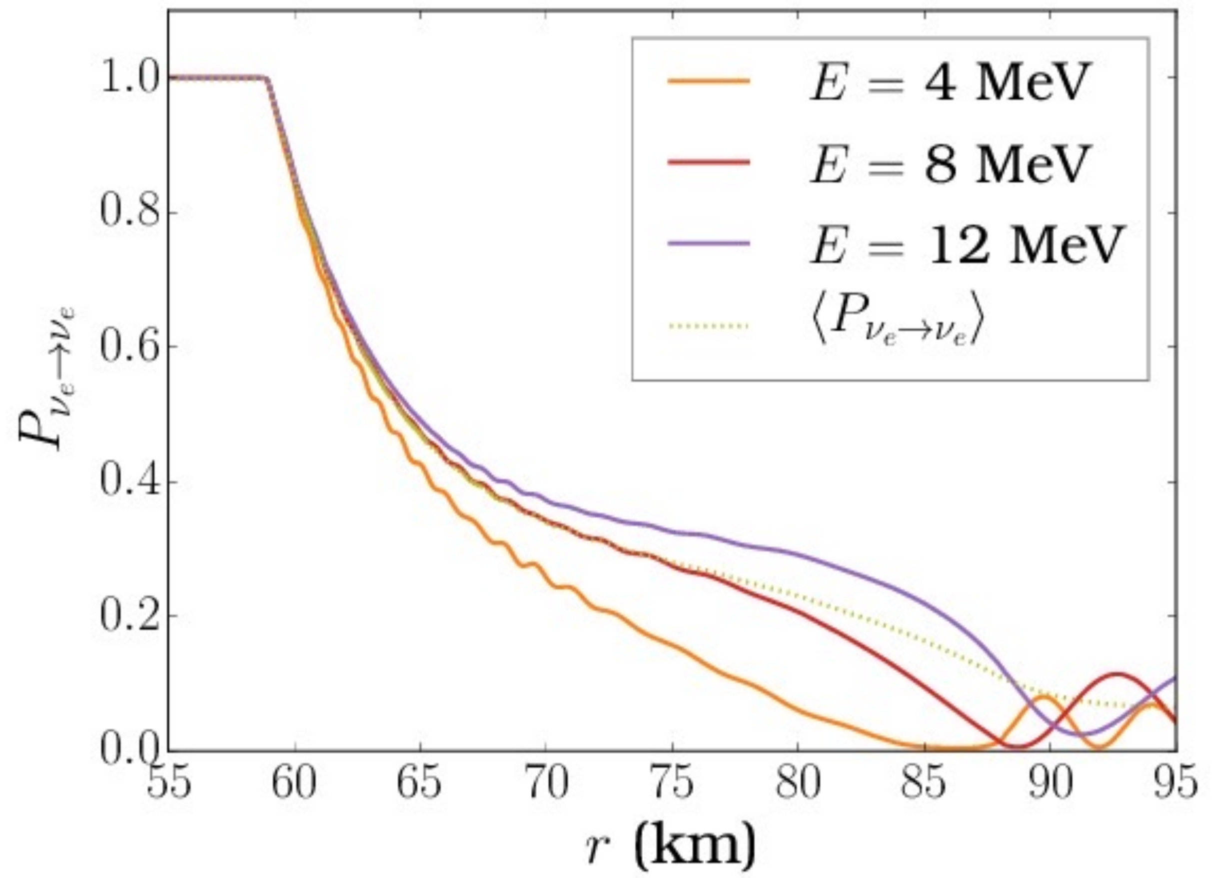




- Matter-Neutrino Resonance

$$h_{\mathcal{G},11} - h_{\mathcal{G},22} = 2\omega c_\theta + \sqrt{2} G_F n_B Y_e + h_{\nu\nu}^{ee} - h_{\nu\nu}^{xx} \simeq 0.$$



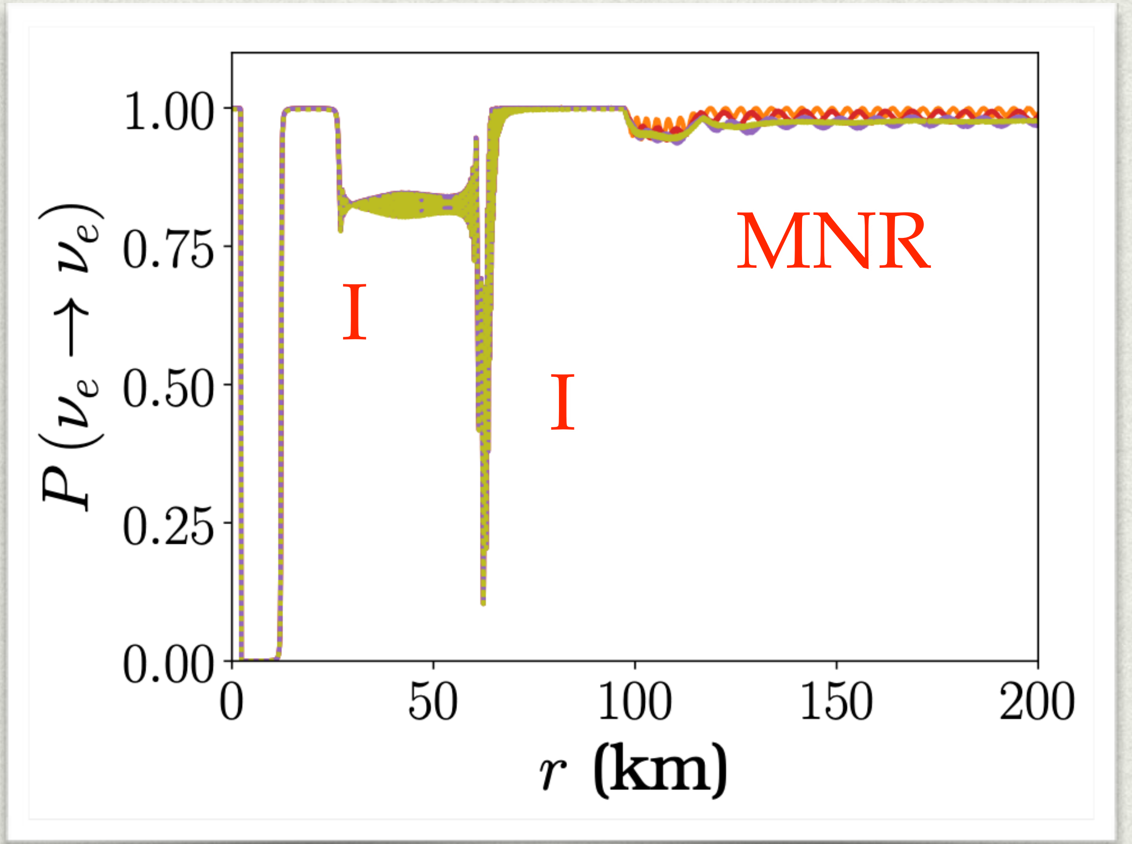


Resonance conditions met, adiabaticity not enough

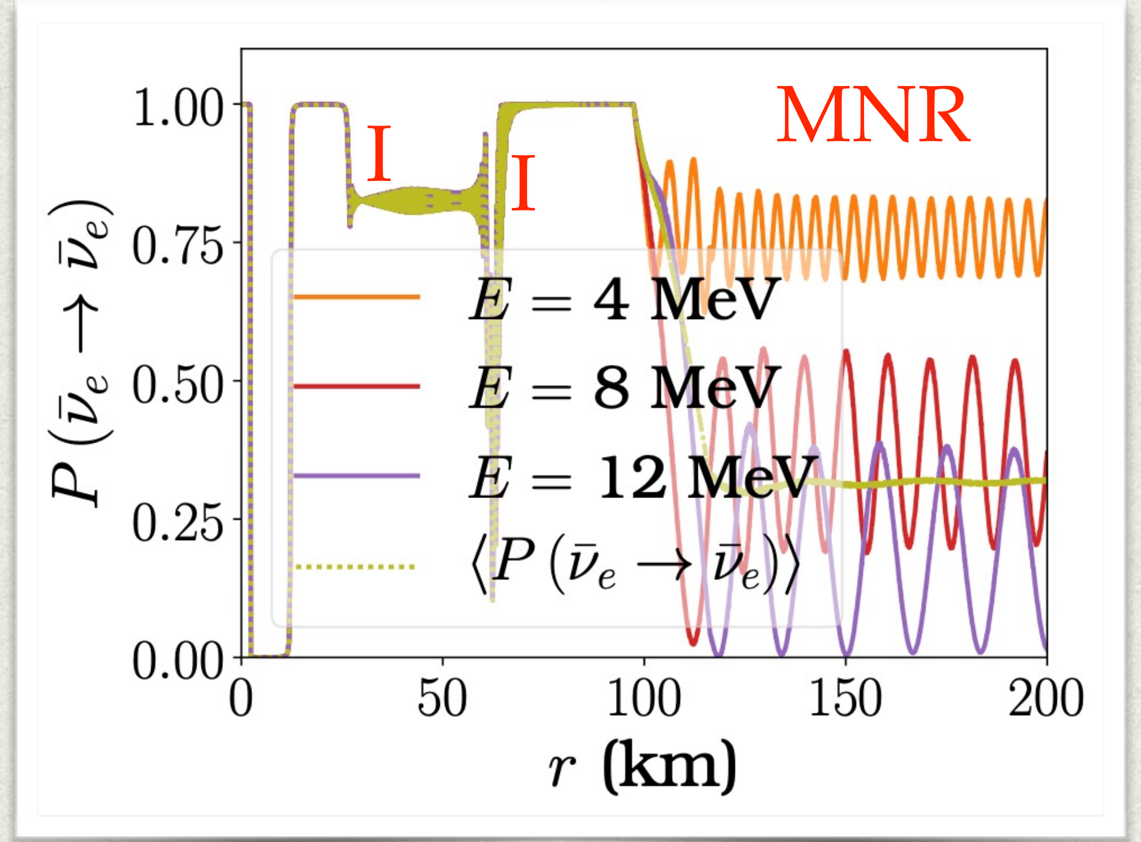
contrary to the findings in Vlasenko, Fuller, Cirigliano, 1406.6724

NON-STANDARD INTERACTIONS in Binary Neutron Star Mergers

- A large set of neutrino trajectories investigated : an example..



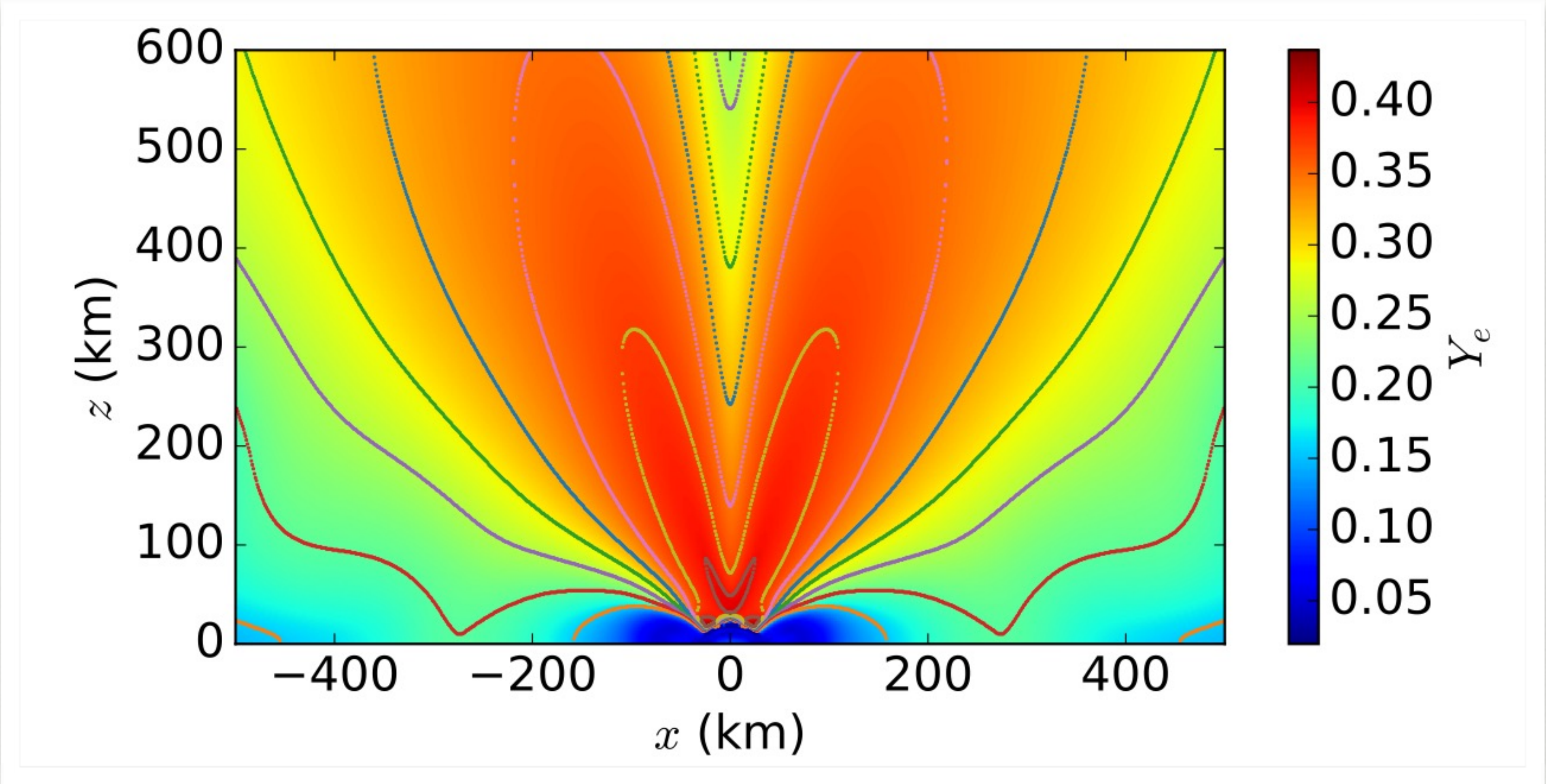
Neutrinos



Antineutrinos

Complex patterns of flavor evolution mechanisms emerge, even for small NSI couplings which produces spectral modifications, with a possible impact on Ye.

I-resonance locations in a BNS remnant



Chatelain and Volpe PRD97 (2018)

$$Y_e = \frac{p}{p+n}$$

electron fraction
Key parameter for the r-proces

IMPACT OF SPECTRAL SWAPPING

In matter (neutrino-driven winds), neutrinos interact with p/n

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

The **capture rates** are modified by spectral swappings due to flavor mechanisms and neutrino properties :

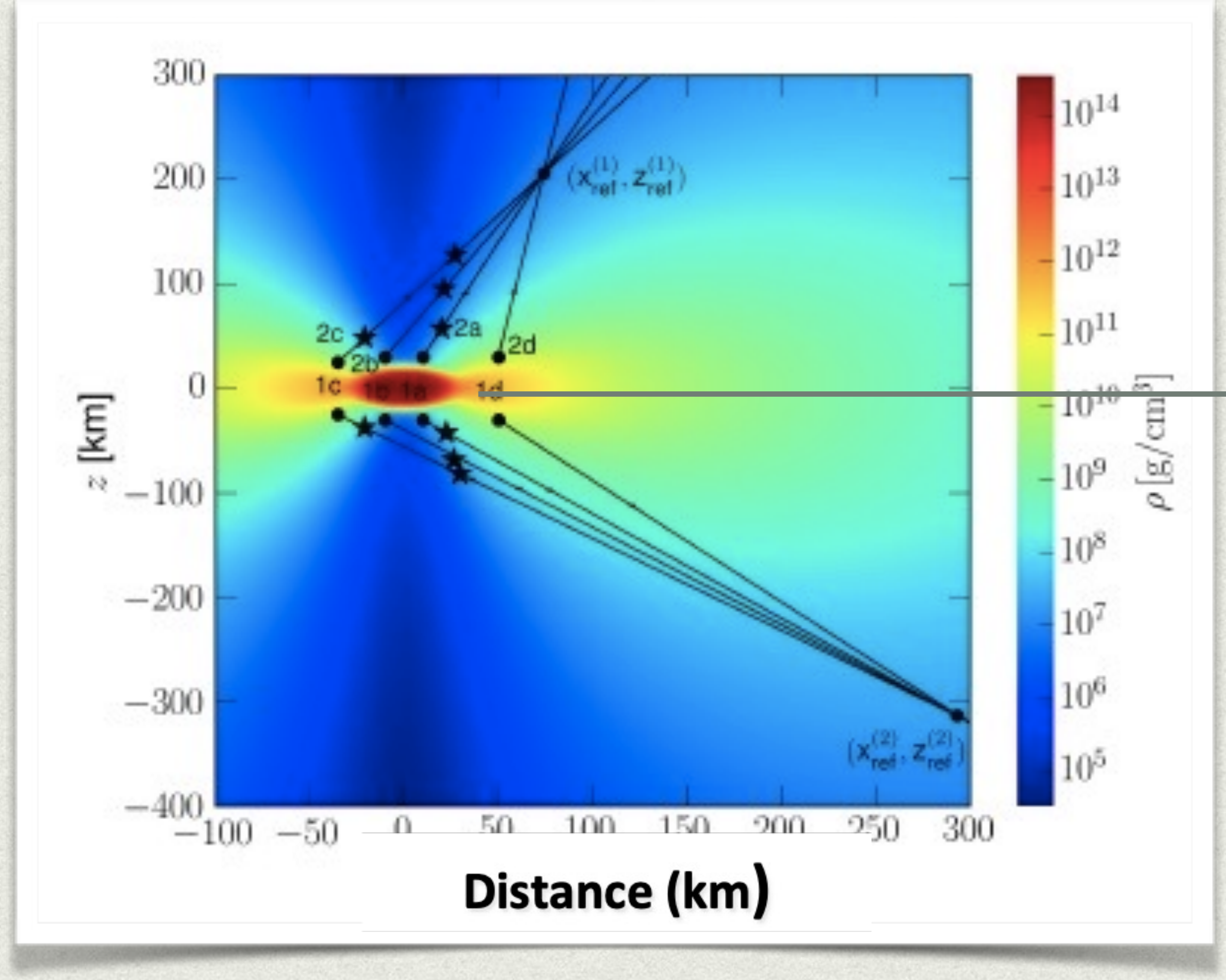
$$\frac{\lambda_{\nu_e n}}{\lambda_{\bar{\nu}_e p}} = \frac{<\sigma_{\nu_e n}>}{<\sigma_{\bar{\nu}_e p}>} \qquad <E_{\nu_e}> << E_{\bar{\nu}_e}> << E_{\nu_{\mu,\tau}}>$$

- This determines the electron fraction Ye and the number of available neutrons (1- Ye). $Y_e = \frac{p}{p+n}$

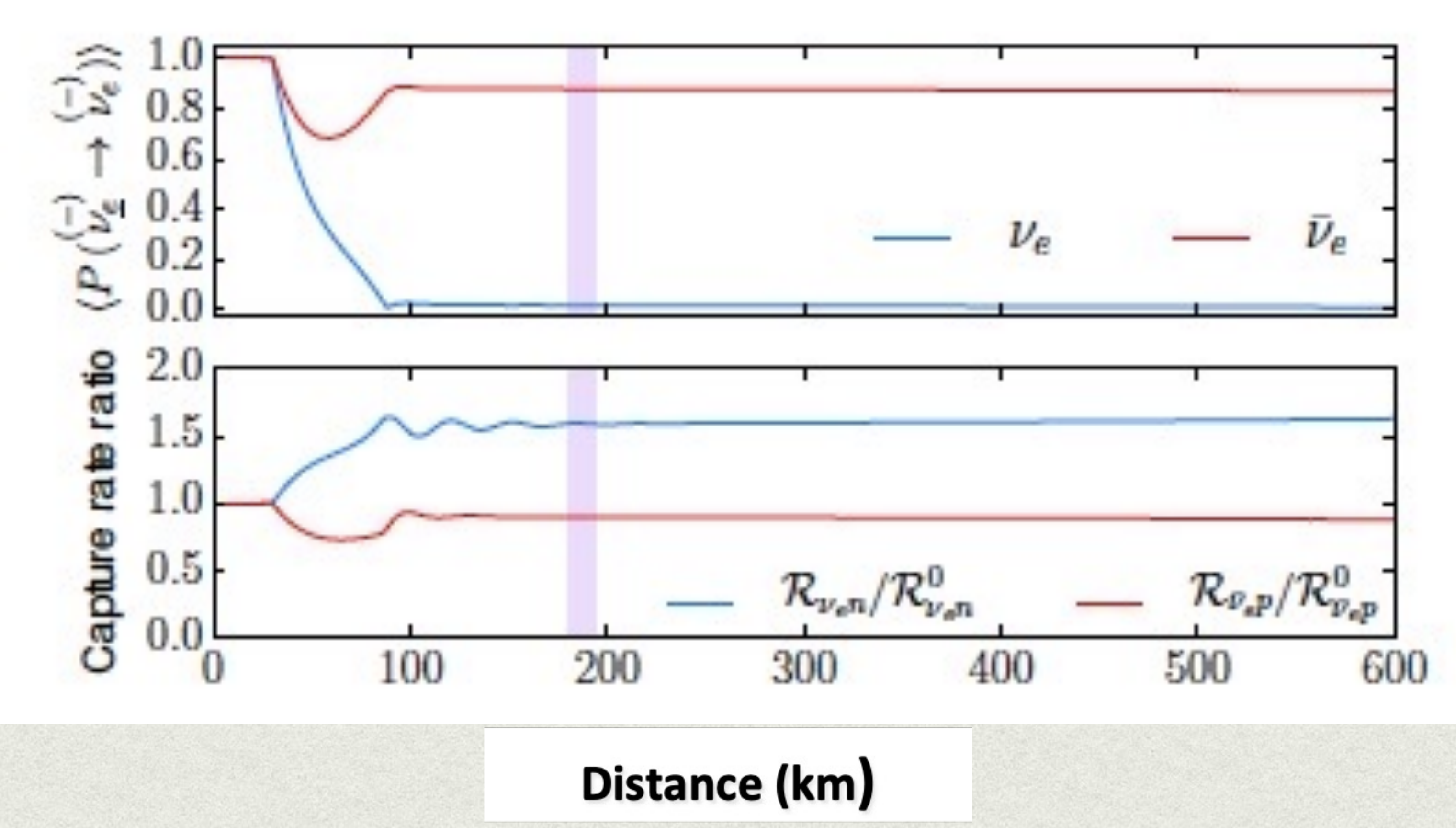
  Key parameter for the r-proces (elements heavier than iron)

  Ye > 0.5 no r-process, Ye < 0.2 strong r-process

- Important for the SN dynamics :
  Enhanced heating behind the shock.



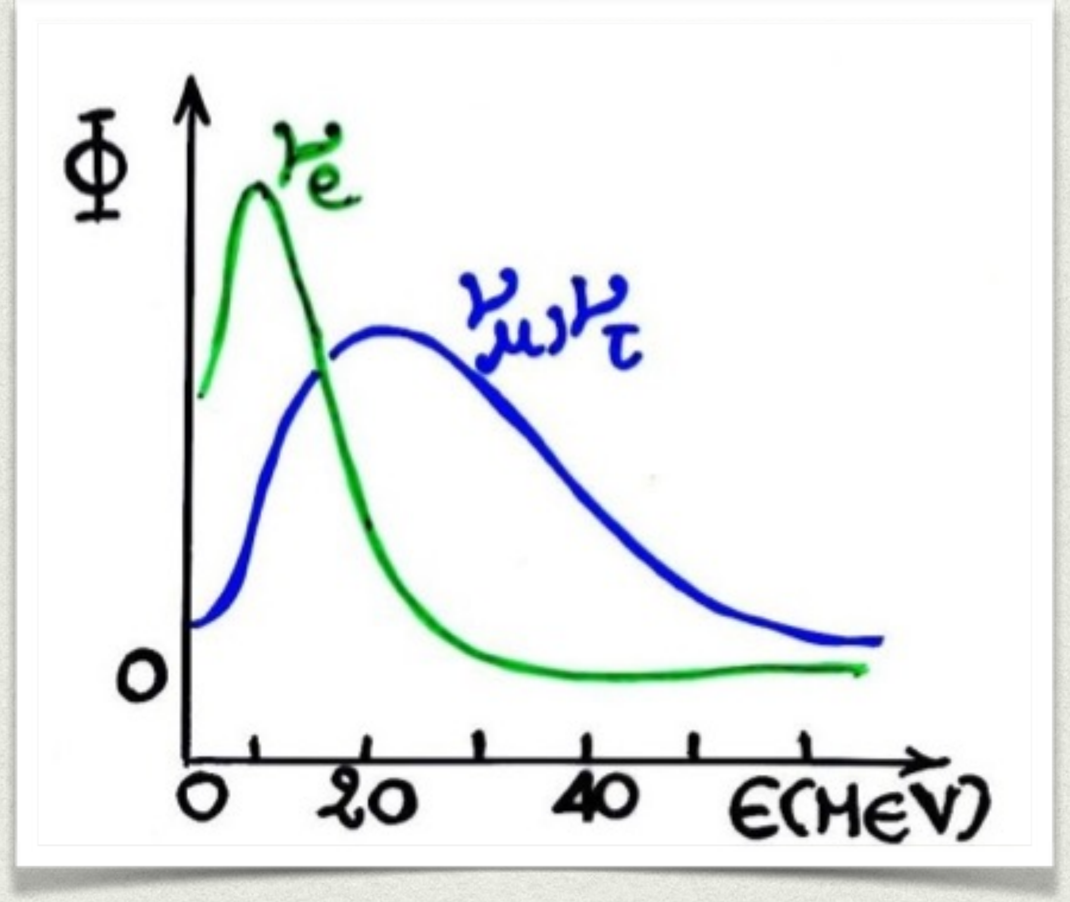
BNS remnant

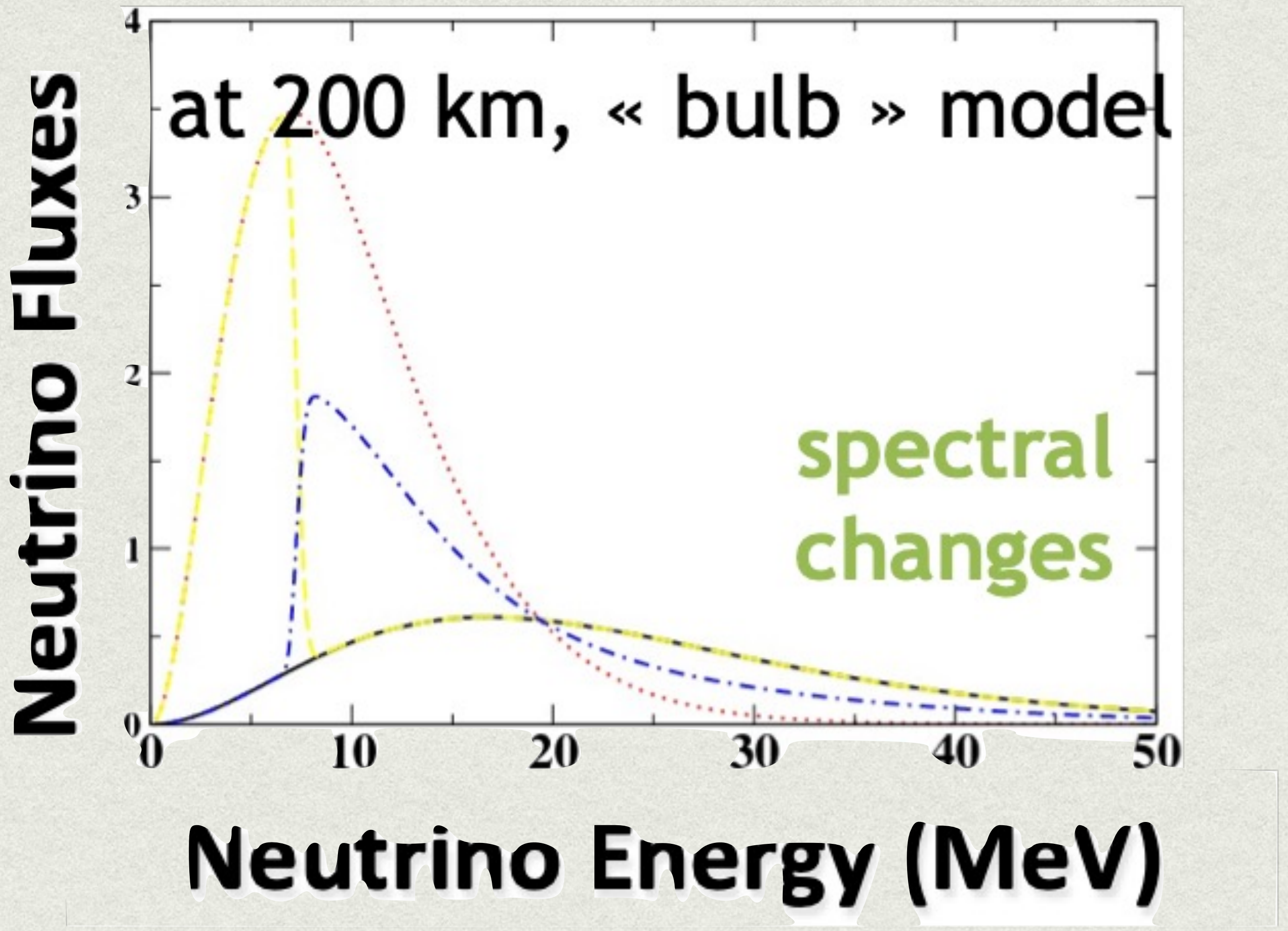


Frensel et al PRD95 (2017)

Flavor evolution and neutrino properties impact
the n/p ratio (nucleosynthesis), neutrino heating (SN dynamics) and observations

SPECTRAL SWAPPING DENSE MEDIA





An example due to the neutrino-neutrino interaction

THE Mikheev-Smirnov-Wolfenstein (MSW) EFFECT

Wolfenstein, 1978; Mikheev and Smirnov, 1985

- The total Hamiltonian in 2 neutrino flavors

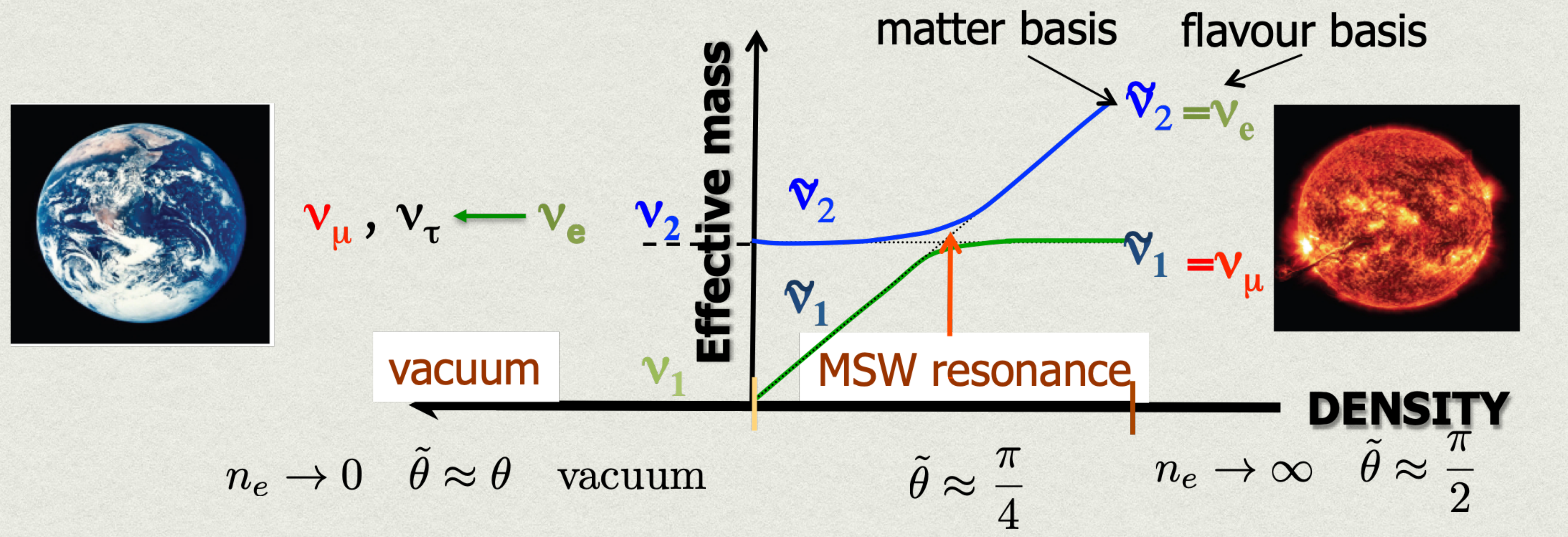
$$\mathcal{H}^f = \mathcal{H}^f_{\rm vac} + \mathcal{H}^f_{\rm mat} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos^2 2\theta + \sqrt{2}G_{\rm F}n_e & \frac{\Delta m^2}{4E}\sin^2 2\theta \\ \frac{\Delta m^2}{4E}\sin^2 2\theta & \frac{\Delta m^2}{4E}\cos^2 2\theta \end{pmatrix}$$

- It can be made diagonal with the rotation (giving the so called « matter basis ») :

$$\tan 2\tilde{\theta} = \frac{2|H_{12}|}{H_{11} - H_{22}} = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\sqrt{2}G_{\rm F}n_e - \frac{\Delta m^2}{2E}\cos 2\theta}$$

MSW resonance condition $\sqrt{2}G_{\rm F}n_e - \frac{\Delta m^2}{2E}\cos 2\theta = 0$

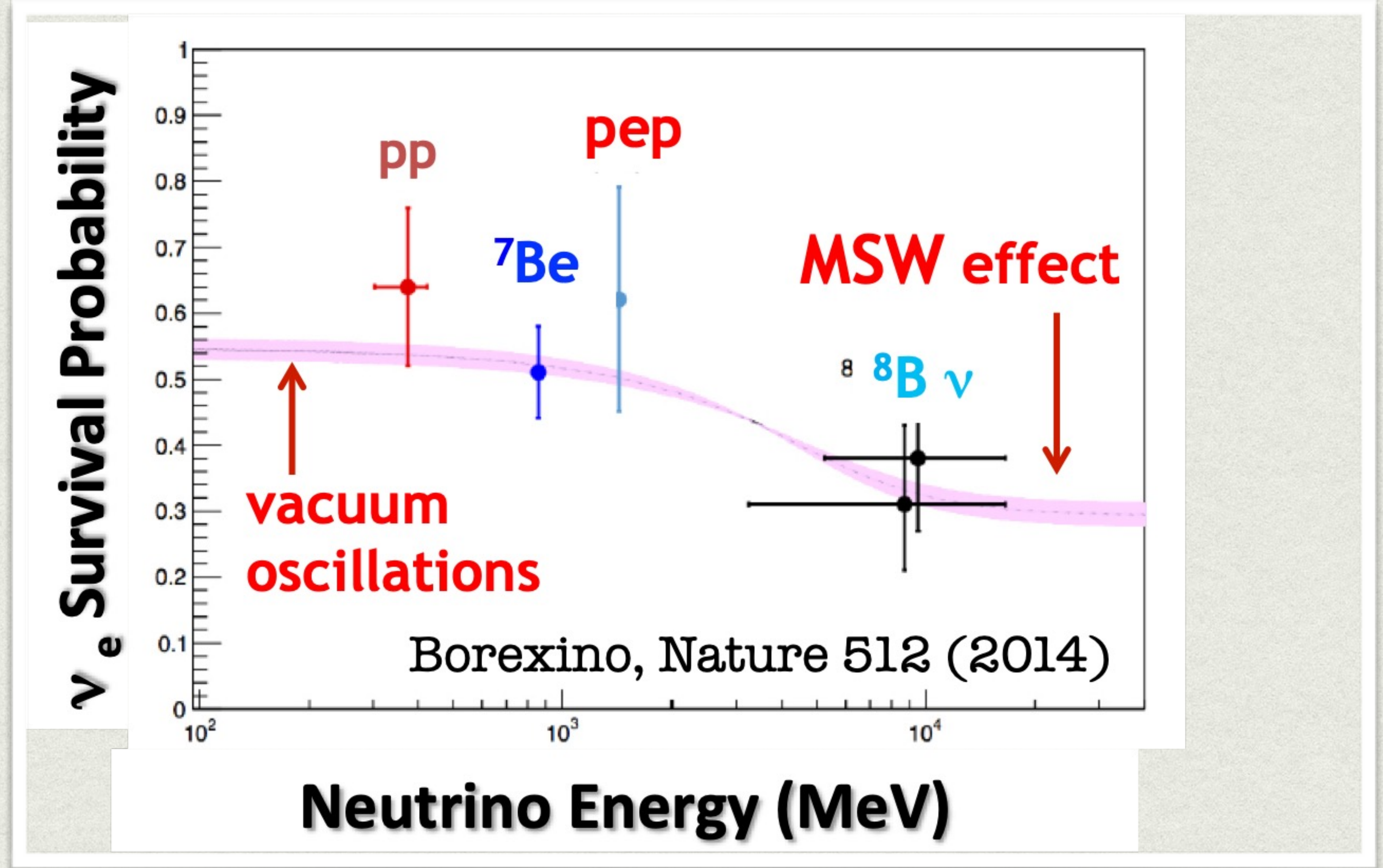
Two-level problem in quantum mechanics



If the MSW resonance is fulfilled, the resonance width is large and the evolution through resonance adiabatic, an electron neutrino will come out as a nu2.

SOLUTION OF THE SOLAR NEUTRINO PROBLEM

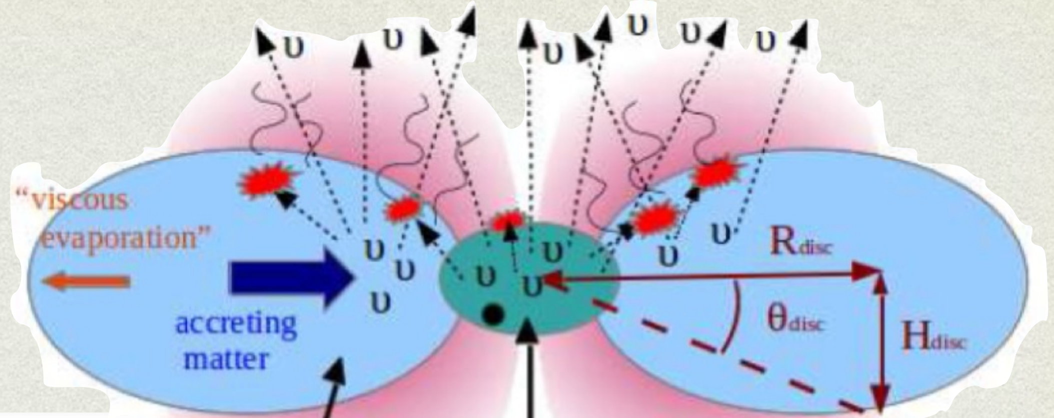
- Borexino experiment (Gran Sasso) measured for the first time solar neutrinos from pp, pep, 7Be… and the CNO cycle suggested by Bethe (1939) (1% of solar energy).



thanks for Super-Kamionande discovery of neutrino oscillations in vacuum, SNO measurement of the total solar neutrino flux, KamLAND measurement, but also thirty years of searches and combined data fit and Borexino results for low energy solar neutrinos

A reference phenomenon for the study of how neutrinos change flavor in dense media.

A UNIQUE EVENT : GW170817



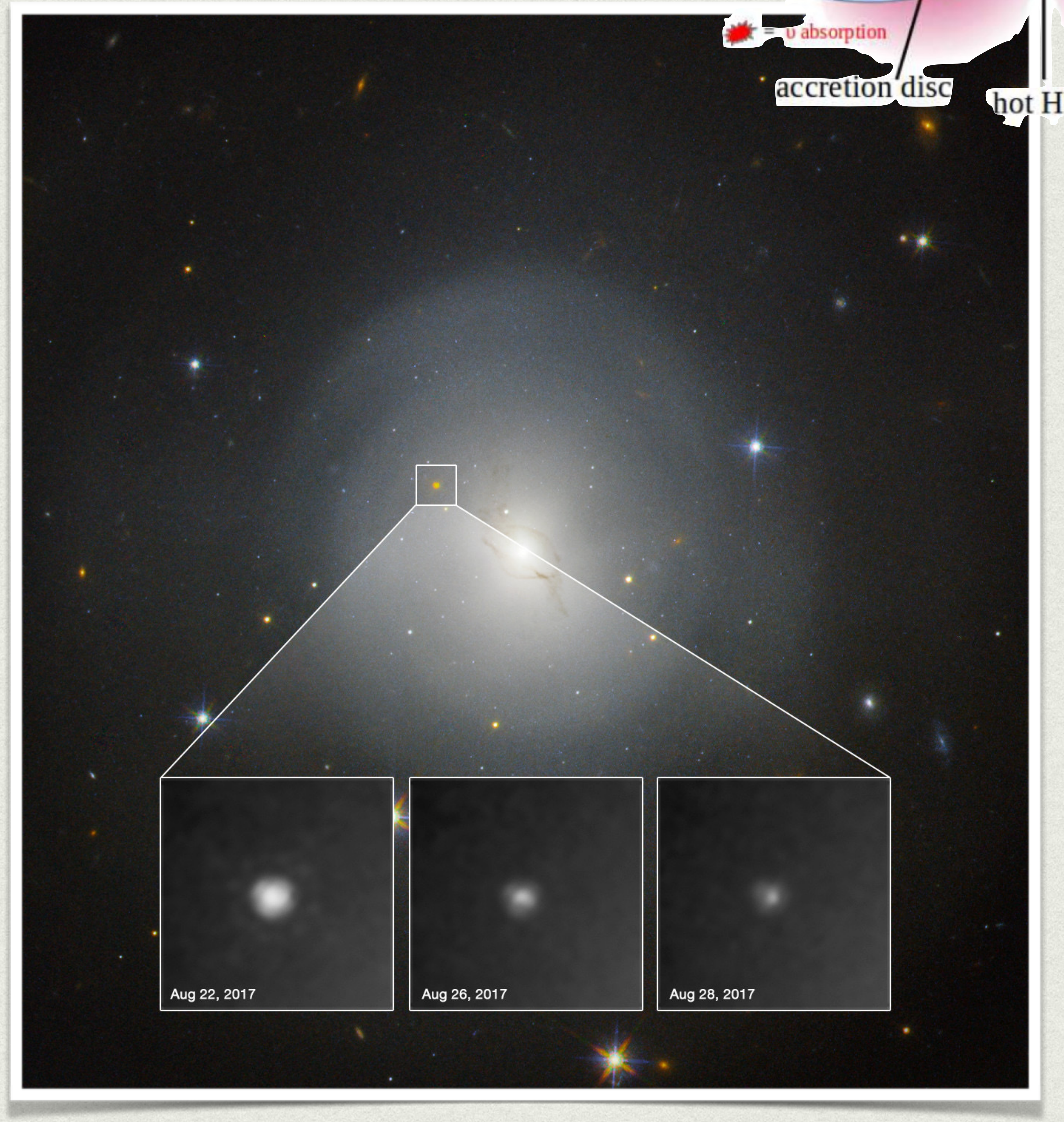
- 🟩 First measurement of gravitational waves from binary neutron star mergers, in coincidence with a short gamma ray burst and a kilonova.

Abbot et al, PRL 2017

- 🟩 From the electromagnetic signal, indirect evidence for r-process elements in the ejecta

Vilar et al, 2017; Tanaka et al, 2017;
Aprahamian et al, 2018;
Nedora et al, 2021, ...

→ Binary neutron star mergers :
powerful sources of tens of MeV neutrinos



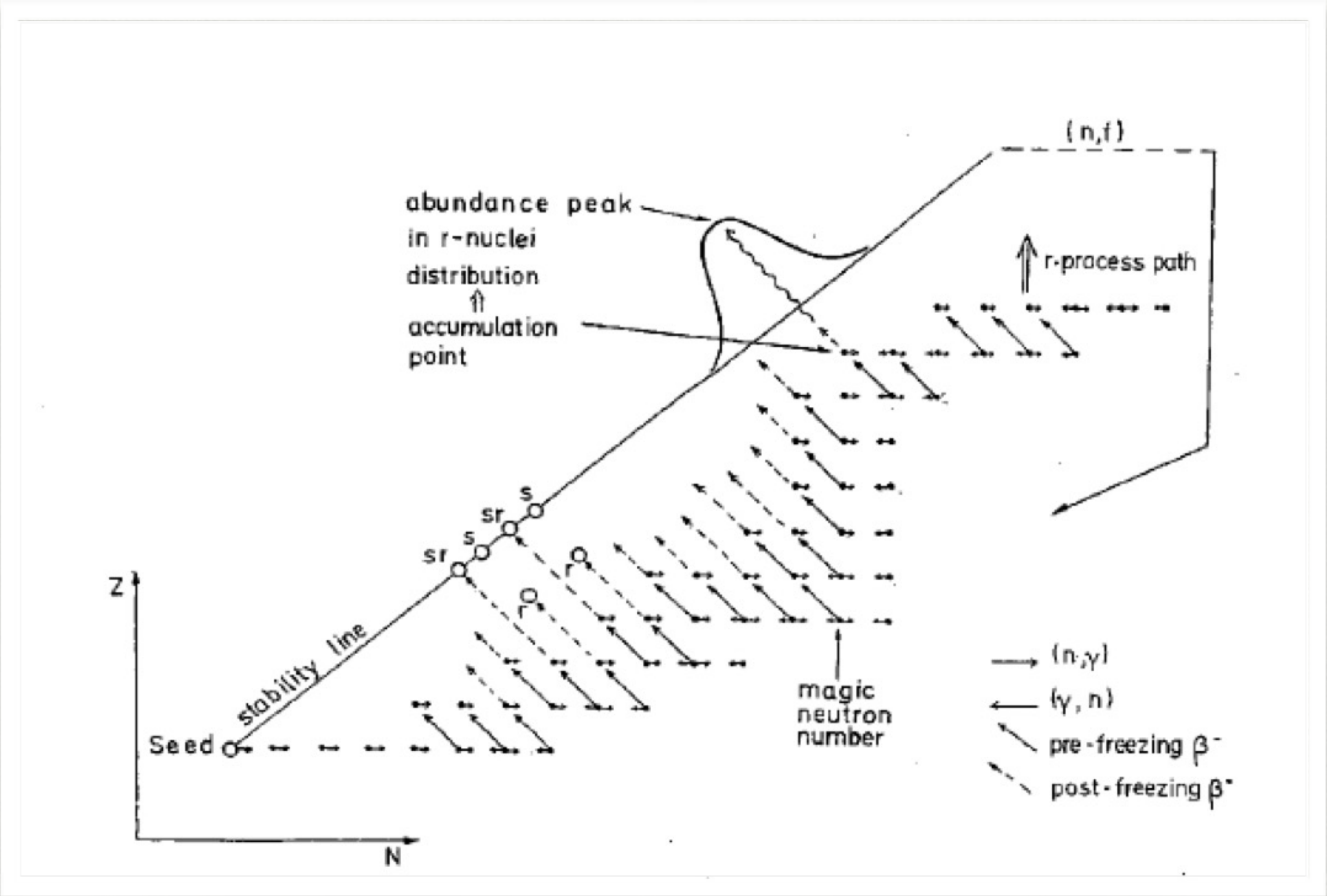
Hubble Space Telescope

Kilonova, gradually fading away, in NGC 4993,
40 Mpc, 140 million light-years

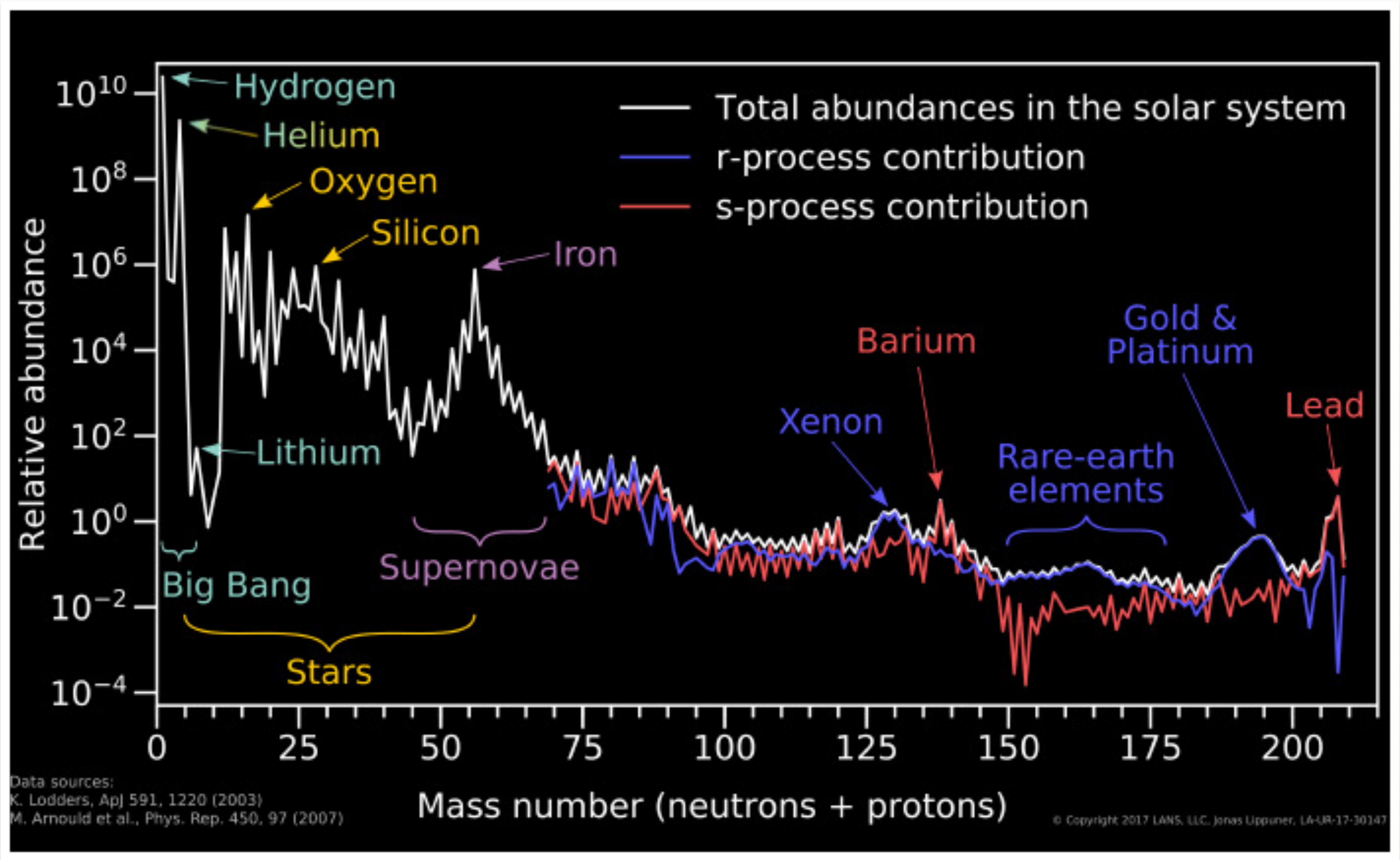
r-PROCESS NUCLEOSYNTHESIS

- Key open question in astrophysics : the origin (i.e. the sites and conditions) of elements heavier than iron.

- Two main mechanisms : s-process (s for slow), r-process (r for rapid neutron capture) where neutron rich nuclei capture neutrons faster than beta-decay to the stability valley.



Nucleosynthetic abundances in the solar system



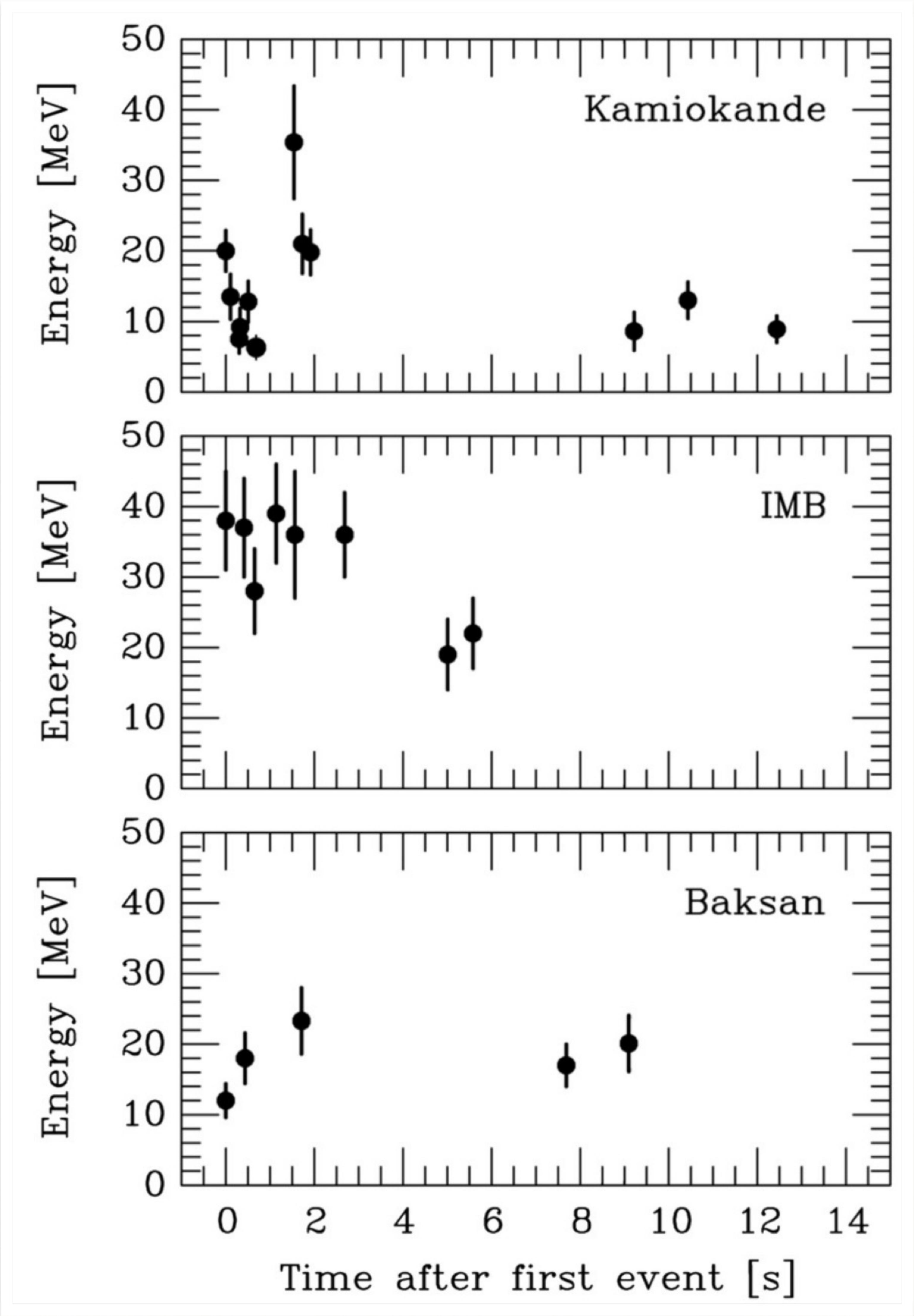
Data sources:
K. Lodders, ApJ 591, 1220 (2003)
M. Arnould et al., Phys. Rep. 450, 97 (2007)

© Copyright 2017 LANS, LLC, Jonas Uppuner, LA-UR-17-30147

Main candidate sites : supernovae and neutron star-neutron star mergers

A UNIQUE EVENT : SN1987A

→ First observation of neutrinos from the death of a massive star: 24 events detected.



Water Cherenkov detector, 2140 tons

Irvine-Michigan-Brookhaven, Water Cherenkov, 6800 tons

Baksan Scintillator Telescope, 200 tons

A wonderful laboratory for particle physics and astrophysics.

DENSE ENVIRONMENTS: FROM TRAPPED TO FREE-STREAMING

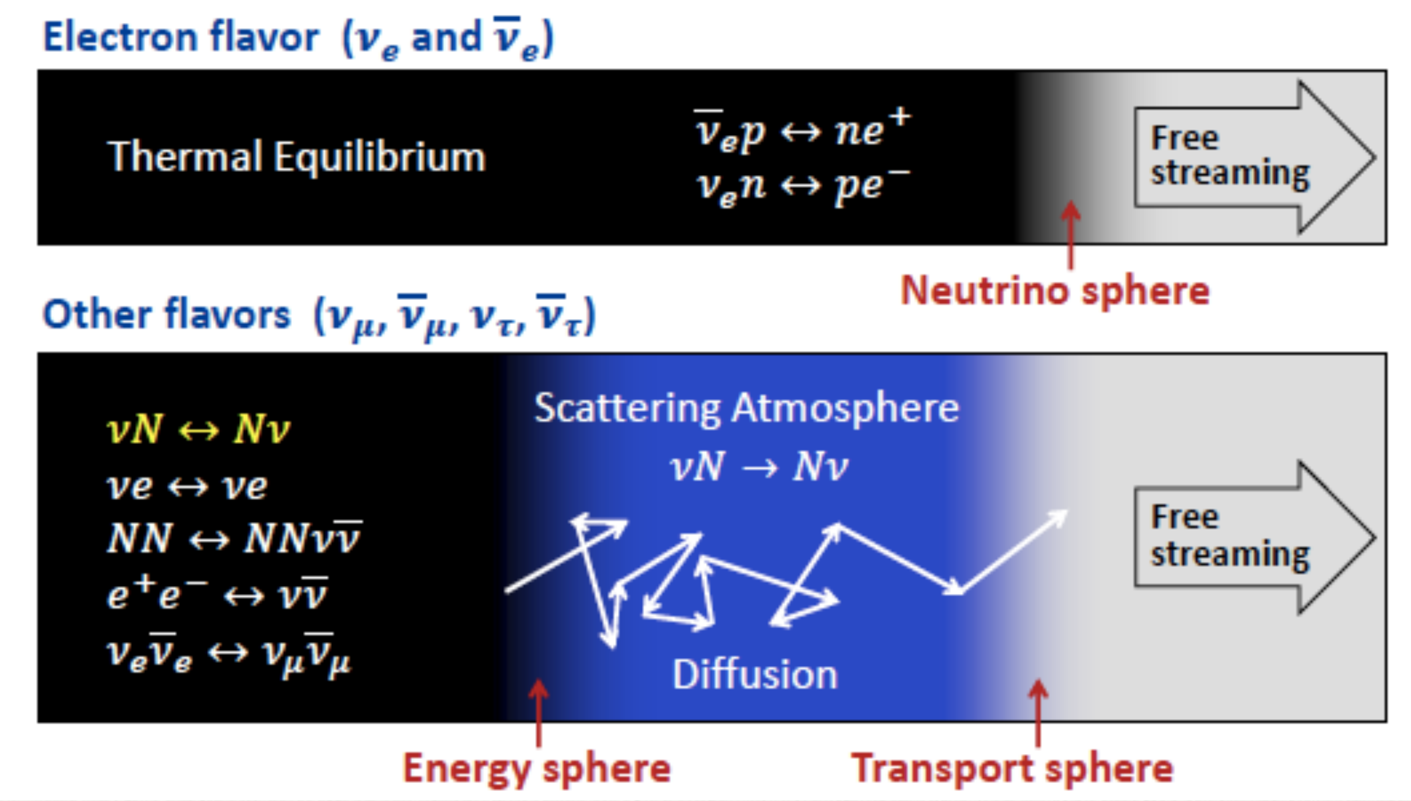
- In such environments neutrinos are trapped.
  $E = 10$ MeV
  Typical cross section Density Mean free path $\lambda = \frac{1}{\sigma\rho}$

  $\sigma = 6\ 10^{-41}\mathrm{cm}^2$ $\rho = 10^{14}\mathrm{g/cm}^3$ $\lambda \approx \mathrm{m}$

  $\rho = 10^{12}\mathrm{g/cm}^3$ $\lambda \approx \text{tens of km}$

  The region where neutrinos start free-streaming is called the neutrinosphere. It is energy and flavor dependent. In flavor studies, usually taken as a a sharp boundary.

- Neutrinos are emitted with quasi-thermal spectra (Fermi-Dirac distributions)

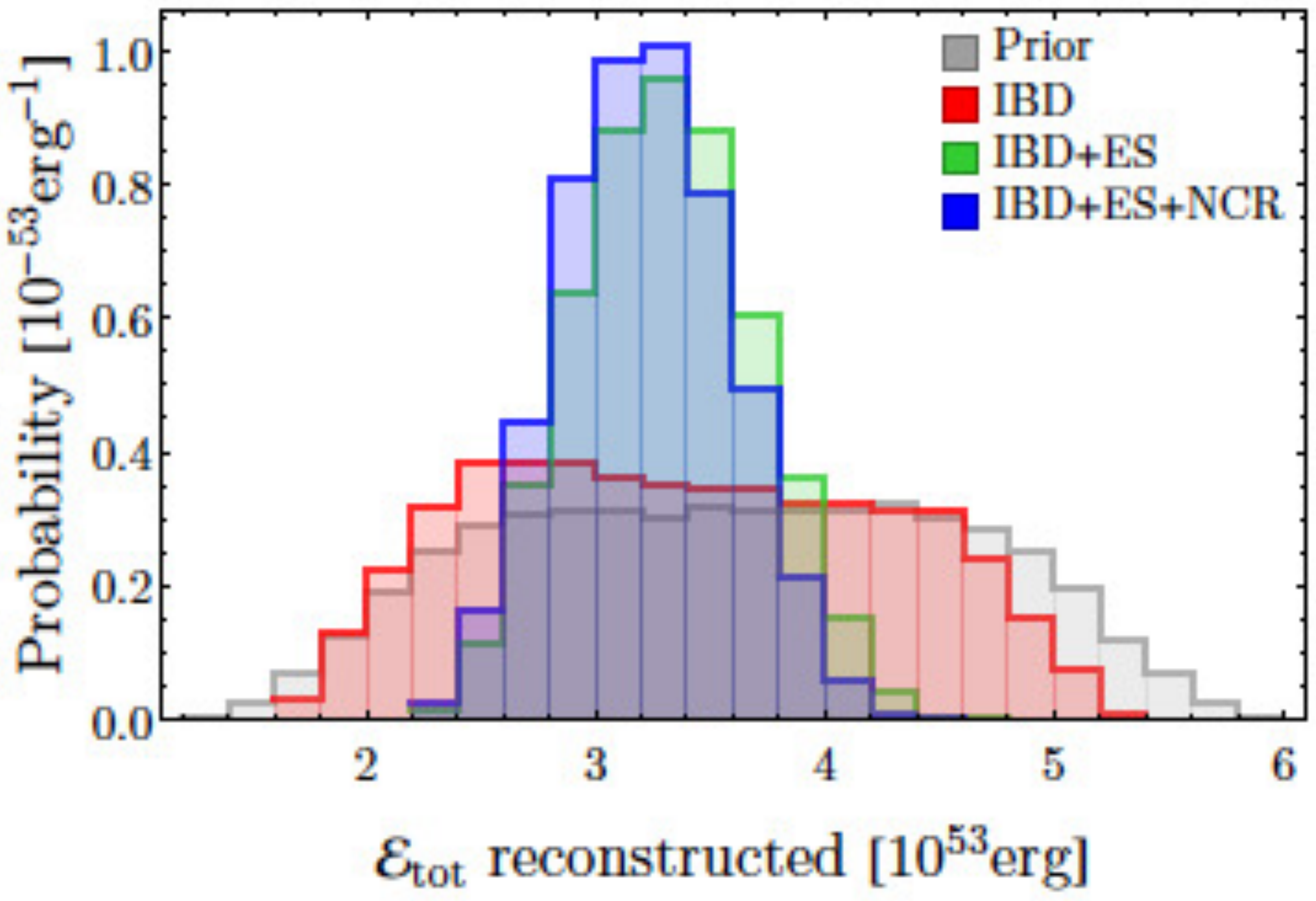


Raffelt (2012)

Reconstrucing the gravitational binding energy

Gallo Rosso, Vissani, Volpe, arXiv:1708.00760

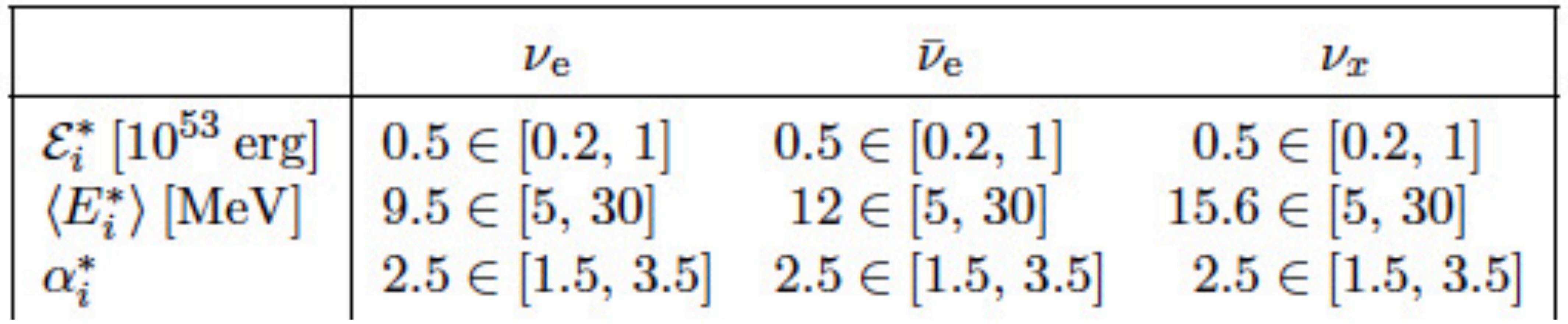
For a galactic supernova at 10 kpc. Signal in Super-Kamiokande.



Likelihood without any priors
(9 free parameters)

Fluence described by a power-law,
MSW included, NH

Combined IBD, elastic scattering
(100% tagging efficiency on IBD
and ES for E_{thr} = 5 MeV) and
NC on oxygen ($E\gamma$ 5–7 MeV)



	ν_e	$\bar{\nu}_e$	ν_x
$\mathcal{E}_i^*$ $[10^{53}$ erg$]$	$0.5 \in [0.2, 1]$	$0.5 \in [0.2, 1]$	$0.5 \in [0.2, 1]$
$\langle E_i^* \rangle$ [MeV]	$9.5 \in [5, 30]$	$12 \in [5, 30]$	$15.6 \in [5, 30]$
α_i^*	$2.5 \in [1.5, 3.5]$	$2.5 \in [1.5, 3.5]$	$2.5 \in [1.5, 3.5]$

True parameters used in the
analysis and parameters range
In the analysis

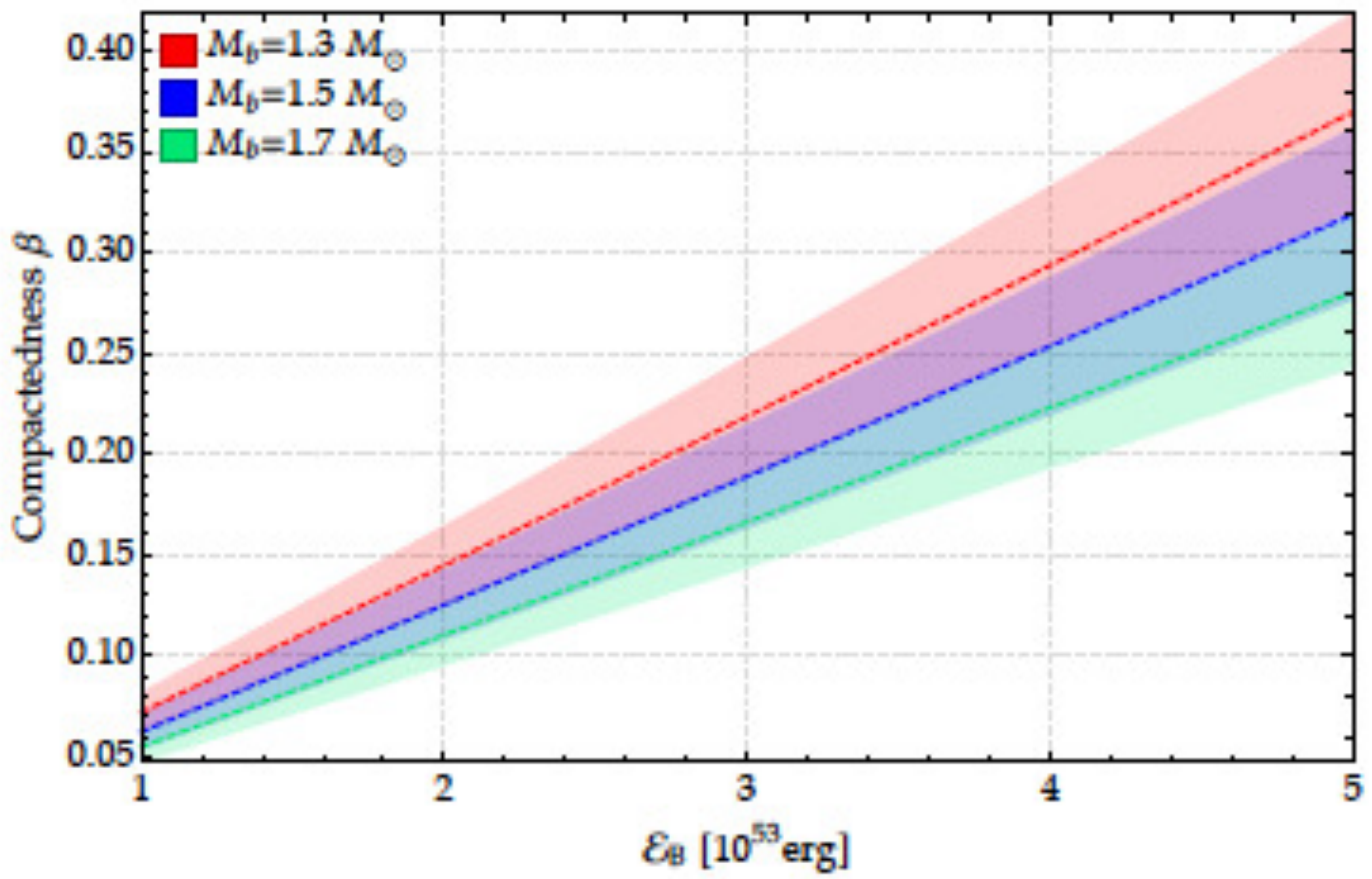
E_b reconstructed with 11% accuracy.

Compactness and M-R of the newly born neutron star

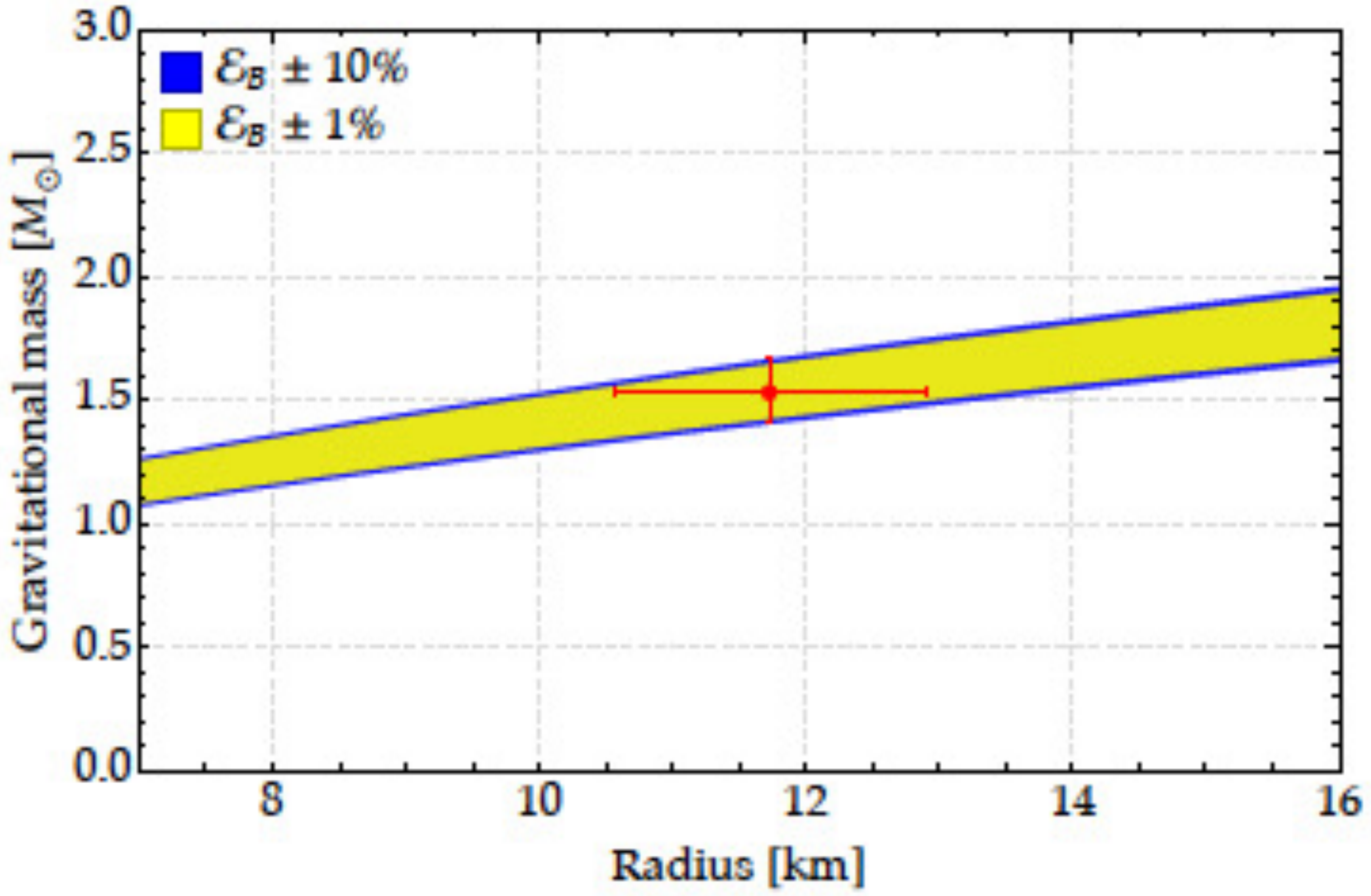
$$\frac{\mathcal{E}_{\rm B}}{Mc^2} \approx \frac{(0.60 \pm 0.05)\,\beta}{1-\beta/2}, \qquad \beta = \frac{GM}{R\,c^2},$$

Lattimer & Prakash,
Phys. Rep. 2007

fit to numerous EOS for NS



(a) Compactness–$\mathcal{E}_{\rm B}$ constraint



(b) Mass–Radius constraint

$$\beta = \frac{\mathcal{E}_{\rm B}}{0.6\,M_b c^2 - 0.1\,\mathcal{E}_{\rm B}}.$$

$$M = \sqrt{\frac{\mathcal{E}_{\rm B} R}{0.6\,G}}\left[\sqrt{1+\epsilon^2} - \epsilon\right]$$

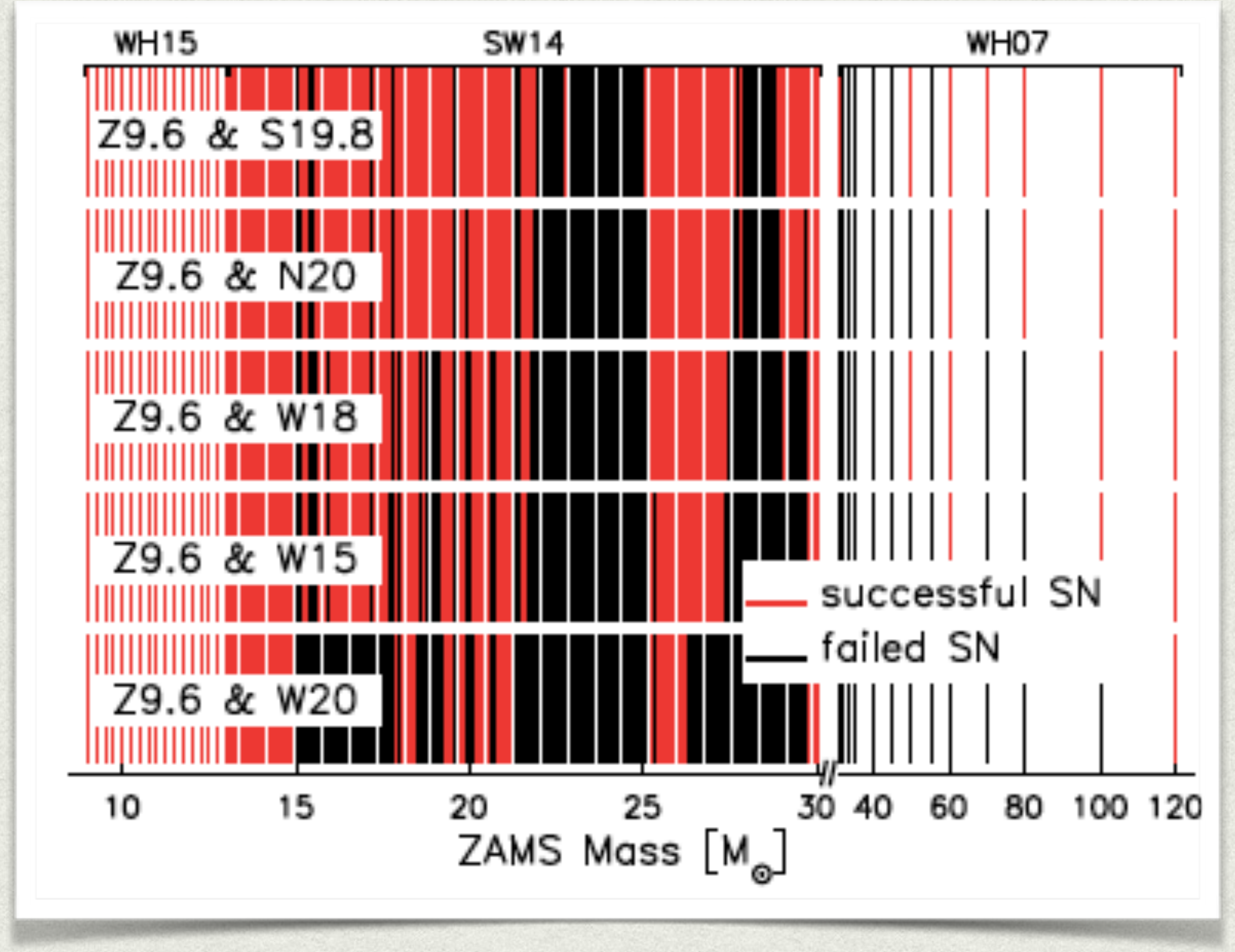
$$\text{with} \quad \epsilon = \frac{1}{4}\sqrt{\frac{\mathcal{E}_{\rm B} G}{0.6\,R\,c^4}}.$$

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

- DSNB sensitive to the fraction of failed supernovae, (hotter energy spectrum determines the relic flux tail)

Lunardini, PRL 2009

- The fraction of « dark » collapses is debated.



Kresse et al 2021

- The DSNB is also sensitive to the EOS, non-standard neutrino properties such as neutrino decay.

Moller et al 2018, De Gouvea et al 2020,
Kresse et al 2021, Horiuchi et al 2021,
Ivanez-Ballesteros and Volpe, 2022…

and flavor conversion phenomena beyond MSW, e.g. shock waves and self-interaction. Event rates can be modified by 10-20 %.

Galais, Kneller, Gava,

A laboratory for astrophysics a
complementary to one supern

« *Une femme jouant de guitare* », Vermeer, 1672