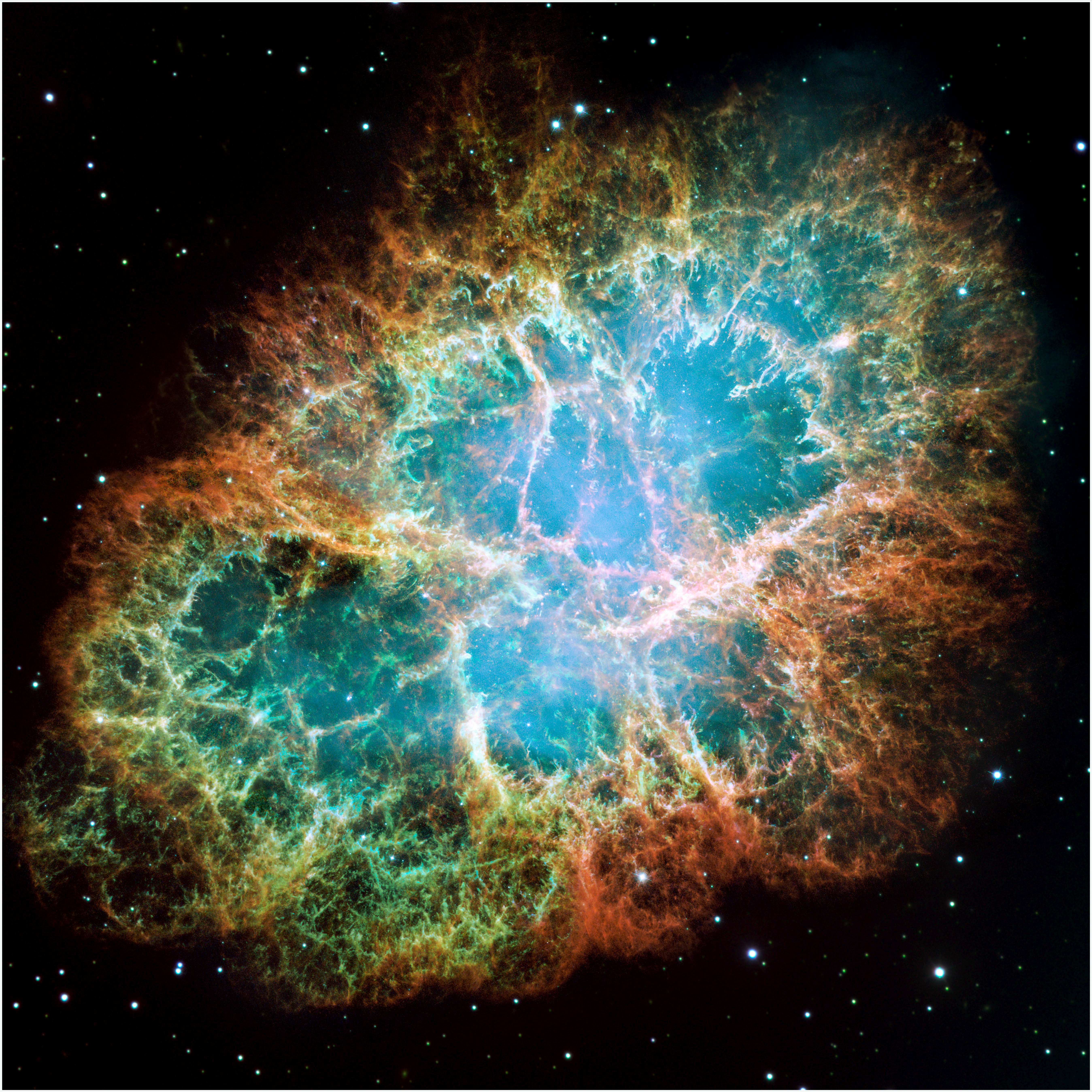


NEUTRINOS
FROM DENSE ENVIRONMENTS

Maria Cristina Volpe
CNRS, Astroparticle and Cosmology
Laboratory, Paris

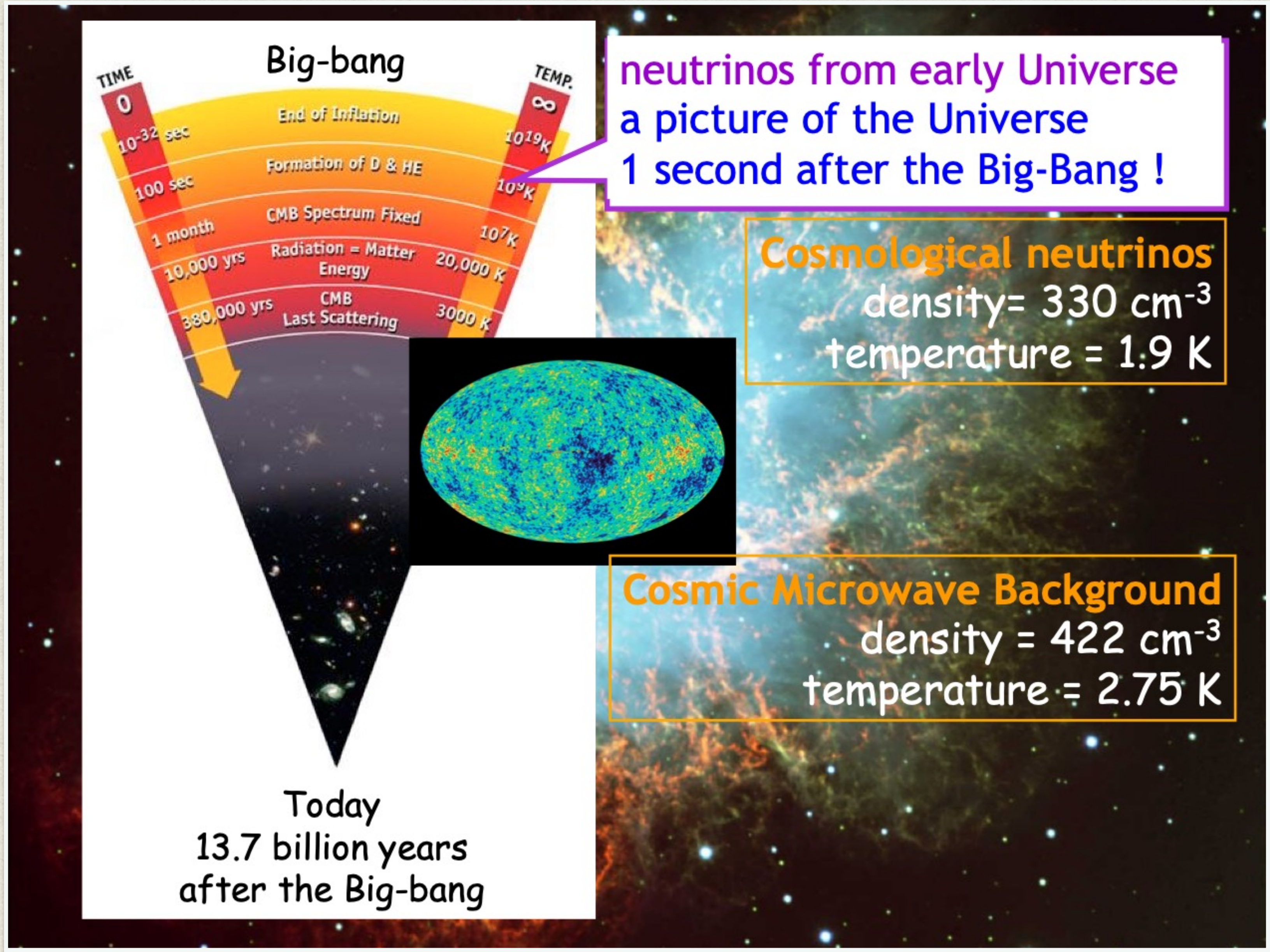
OUTLINE

- Neutrino from dense environments :
  - What are they?
  - Why are they interesting?

  Two unique events : SN1987A, GW170817
- Theoretical aspects on neutrinos and flavor evolution
- Future: supernova and diffuse supernova neutrino background
- Conclusions

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

EARLY UNIVERSE

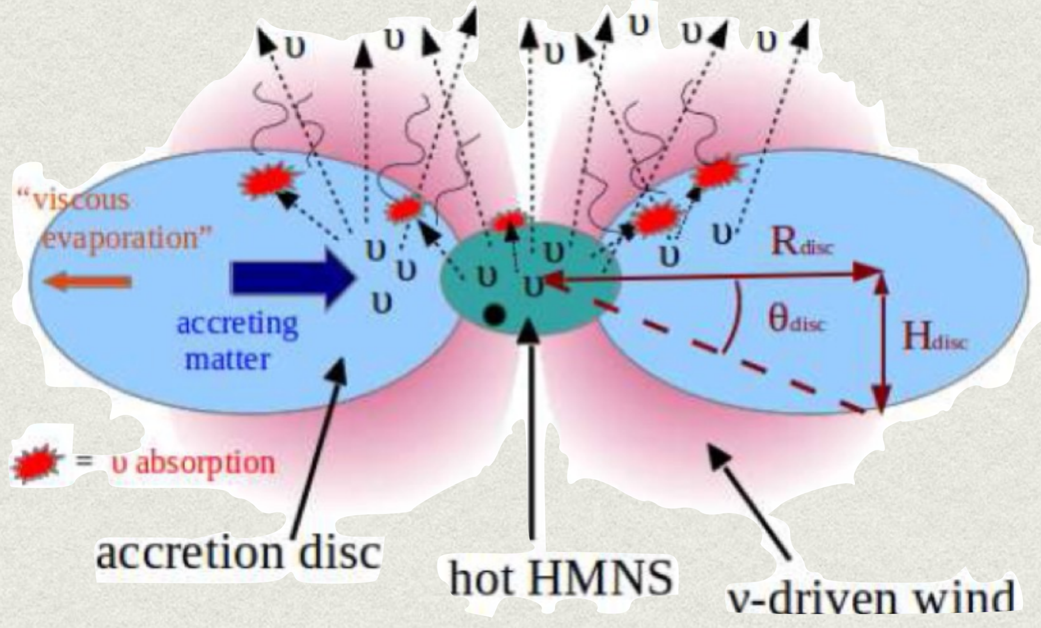


neutrinos from early Universe
a picture of the Universe
1 second after the Big-Bang !

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

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

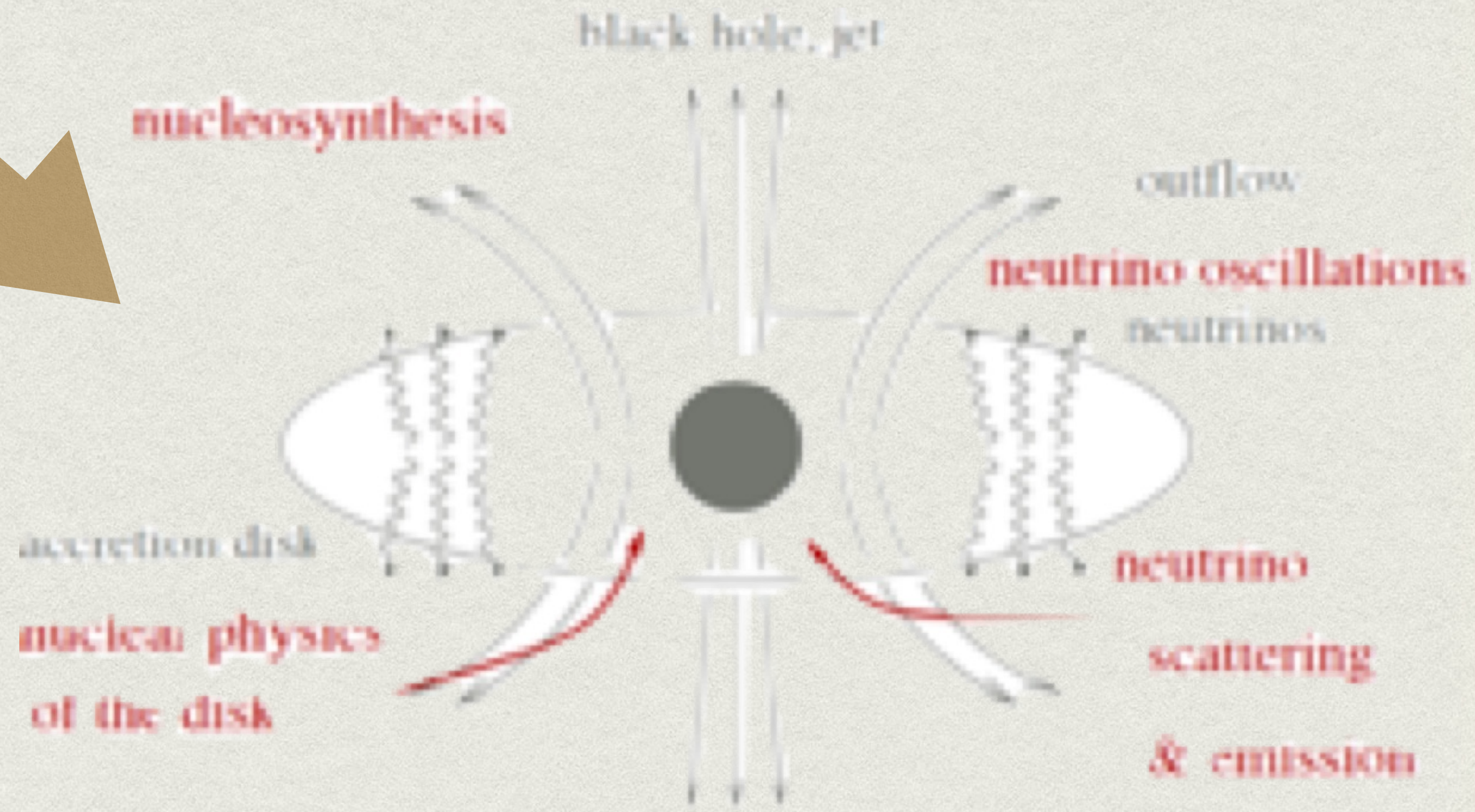
BINARY NEUTRON STAR MERGERS



GW170817

NEUTRINOS FROM
DENSE
ENVIRONMENTS

ACCRETION DISKS AROUND BLACK HOLES



CORE-COLLAPSE SUPERNOVAE

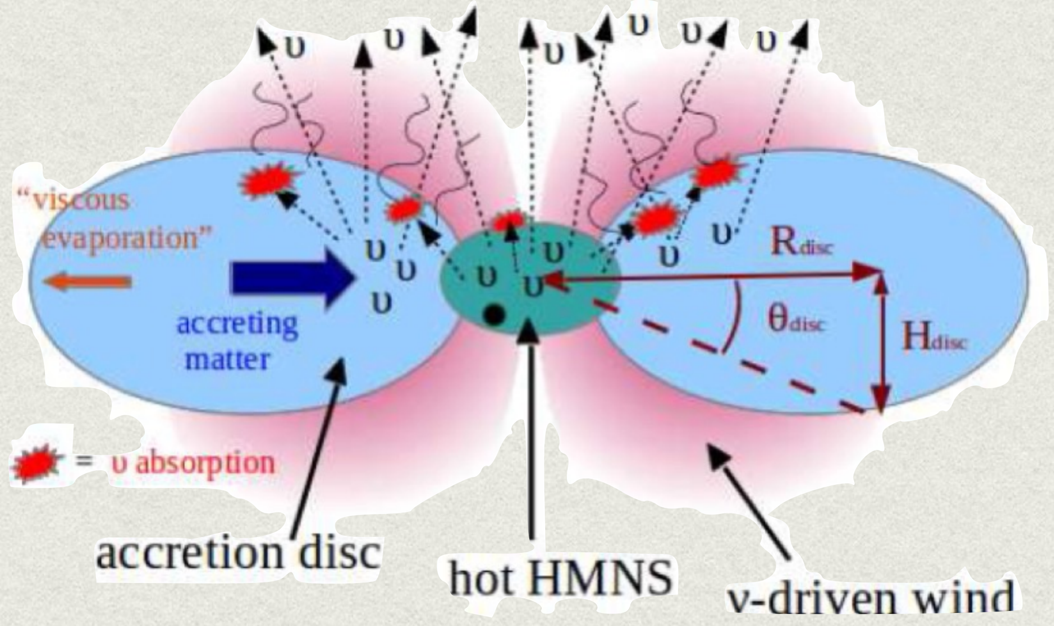
SN1987A

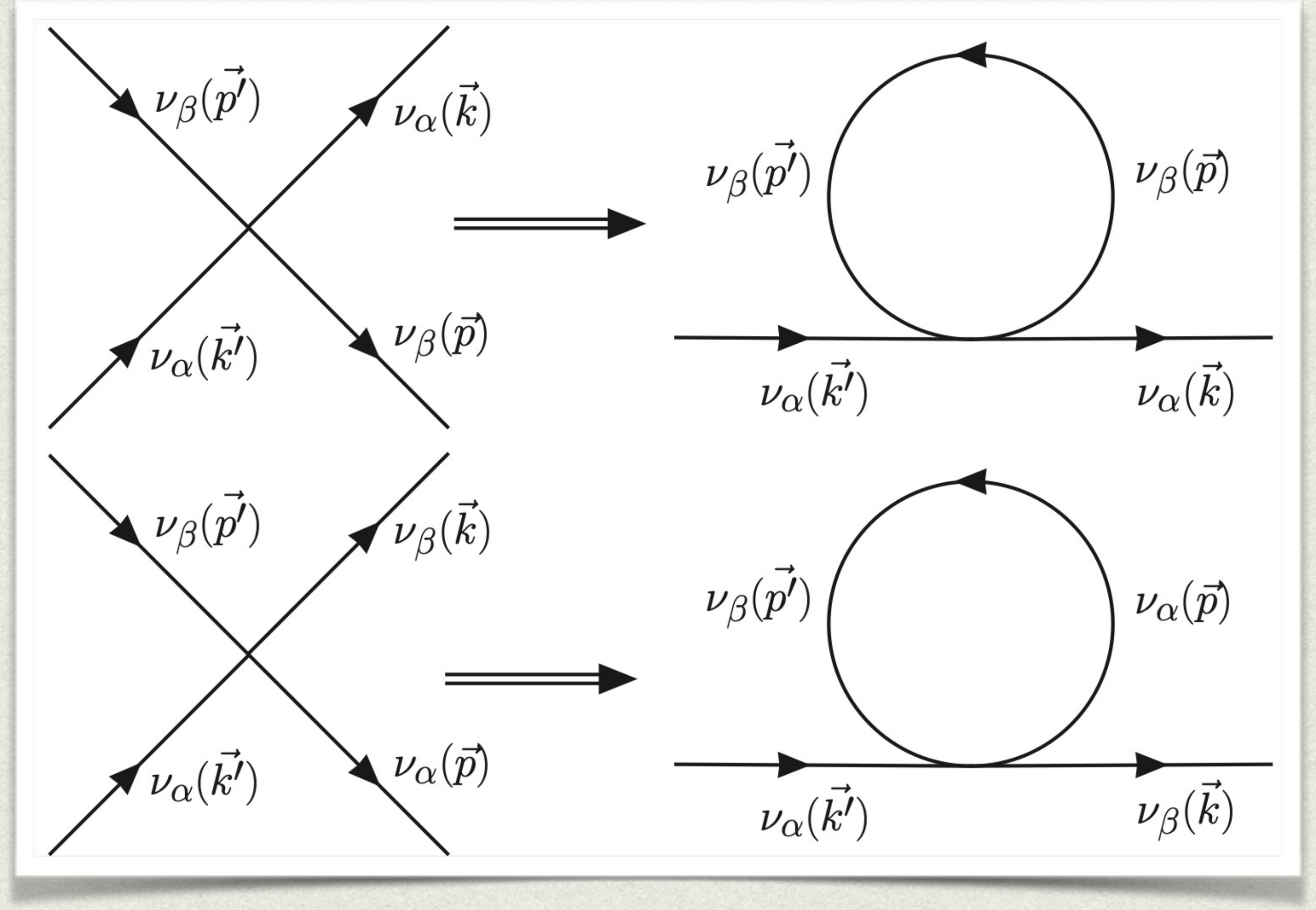
M. Cristina Volpe, « Rencontres de Blois», 2024

DENSE ENVIRONMENTS

- **« Dense» =** a medium that can reach 10^{10} g/cm^3 and more, about 10^{14} 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. »*

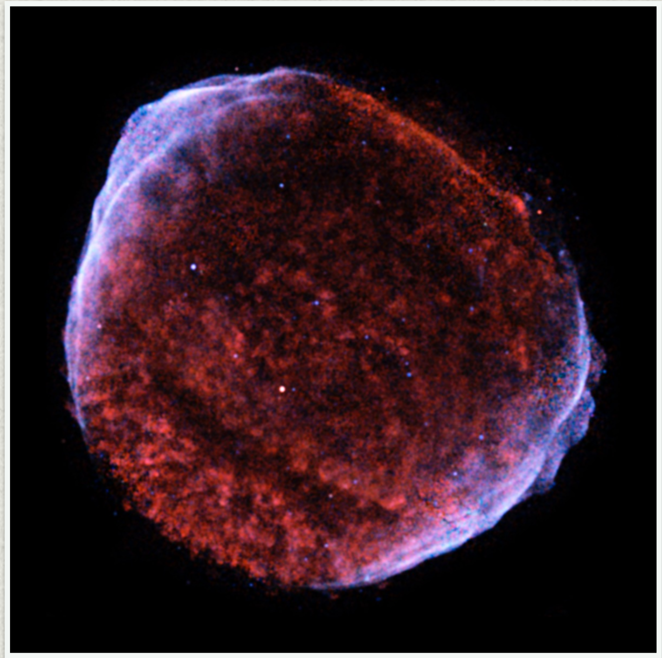
Pantaleone, PLB 1992

Dense in matter and neutrinos

SUPERNOVAE IN THE MILKY WAY and in THE LOCAL GROUP

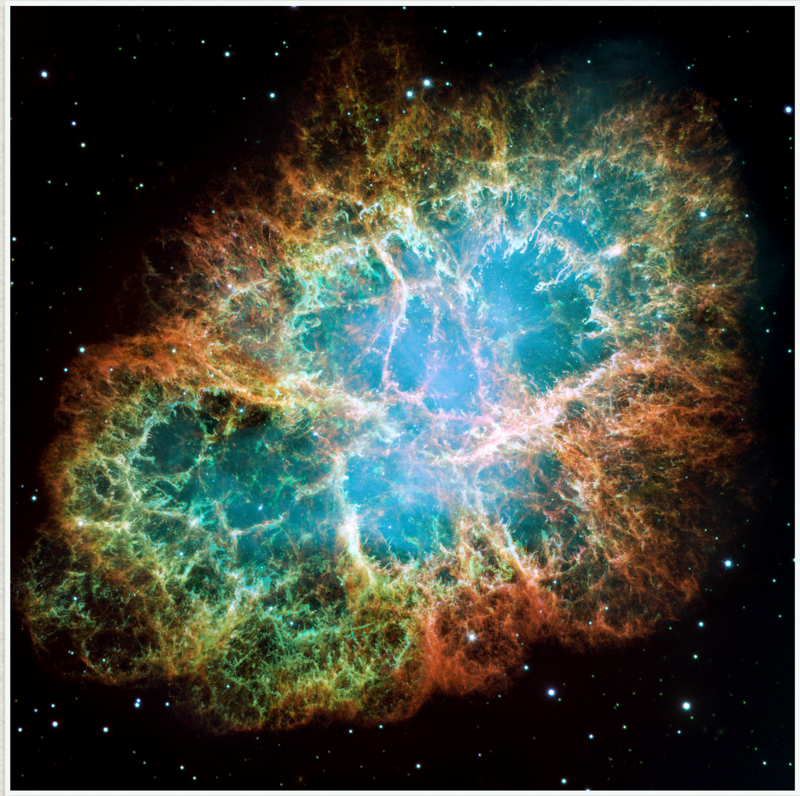
- **Since 1000 y, Milky Way**

SN 1006



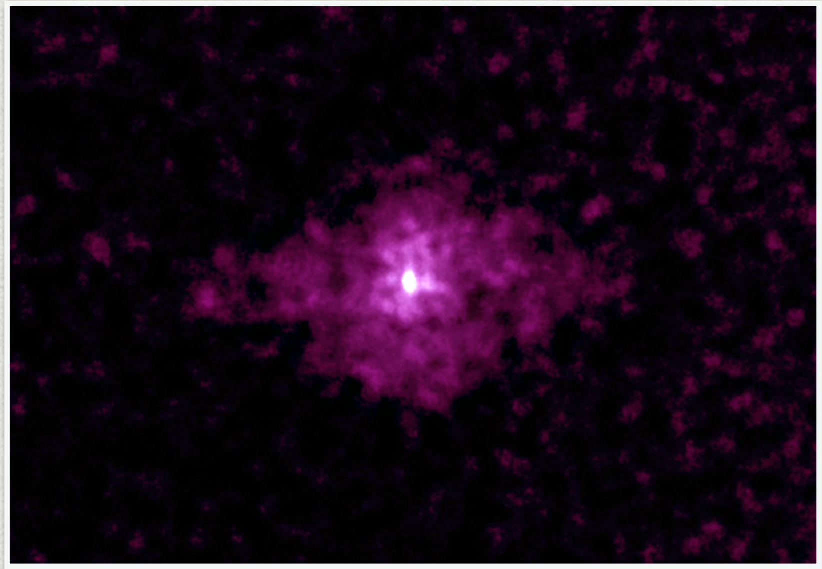
Smithsonian Institution

SN 1054
Crab Nebula



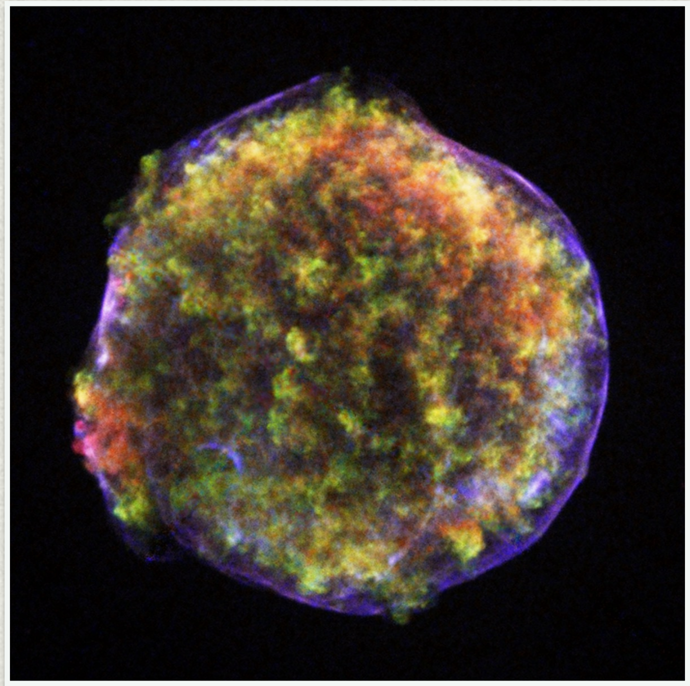
NASA, ESA, J. Hester and A. Loll

SN 1181



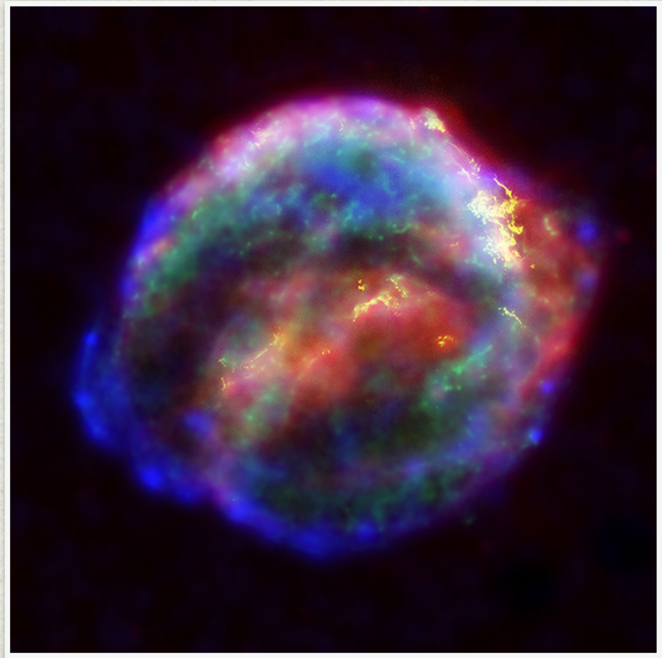
NASA/CXC/SAO/S.Murray et al.

SN 1572



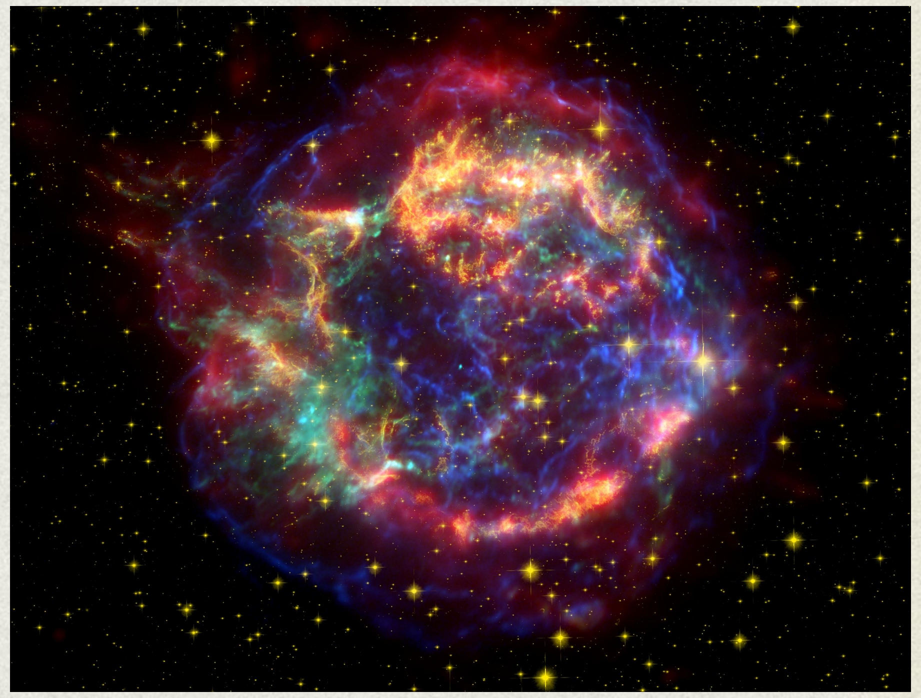
NASA/CXC/Rutgers/J.Warren & J.Hughes et al.

SN 1604



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

SN 1667 (Cas A)



Courtesy NASA/JPL-Caltech

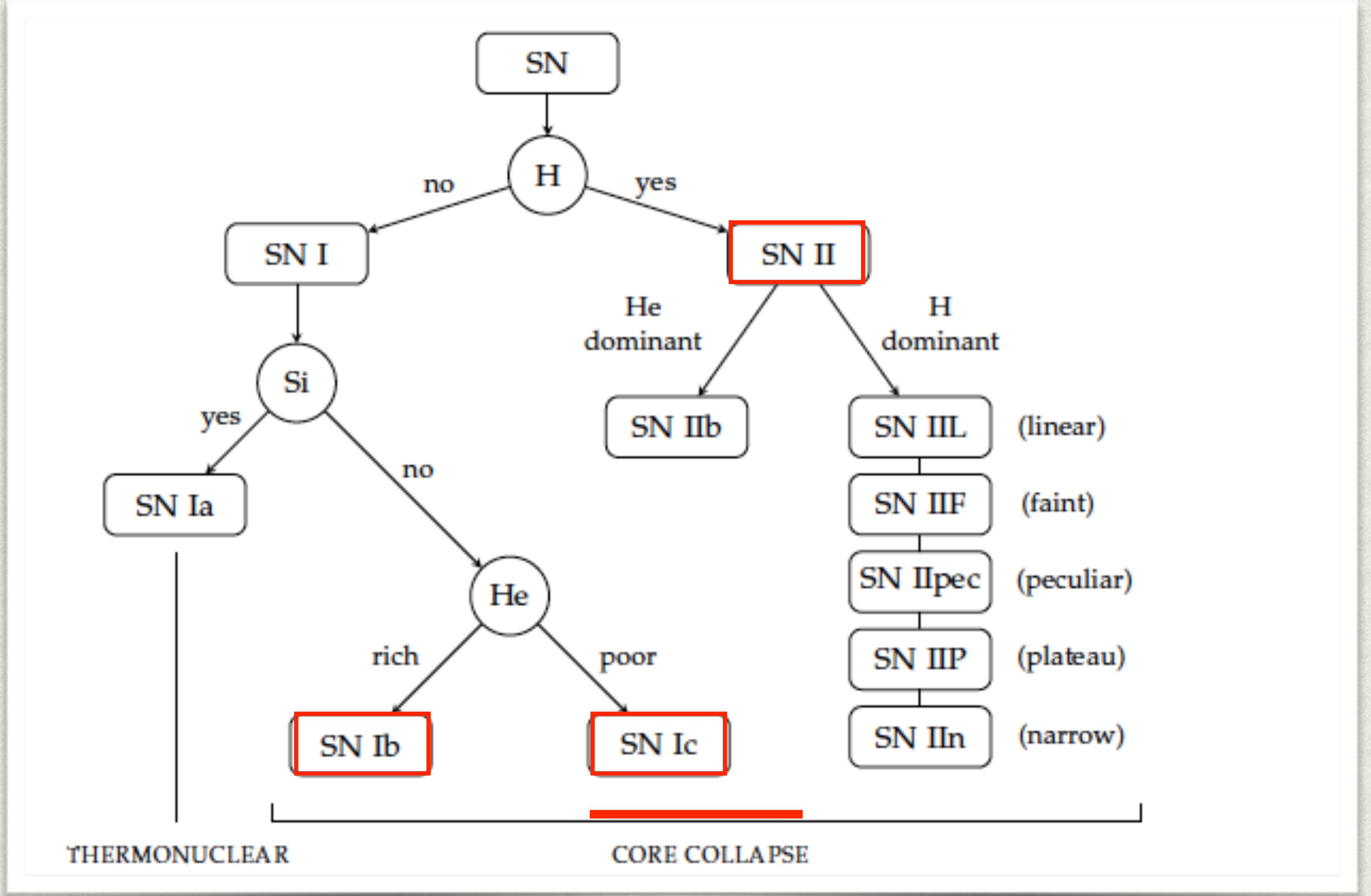
- **Since 100 y, Local Group :** SN1987A (LMC) and SN 1885 (Andromeda)
  Supernovae are rare events. Evaluations of the Galactic core-collapse supernova rate include

$3.2^{+7.3}_{-2.6}$ historical SNe Adams et al, Astr. Journ., 2013 1.63 ± 0.46 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

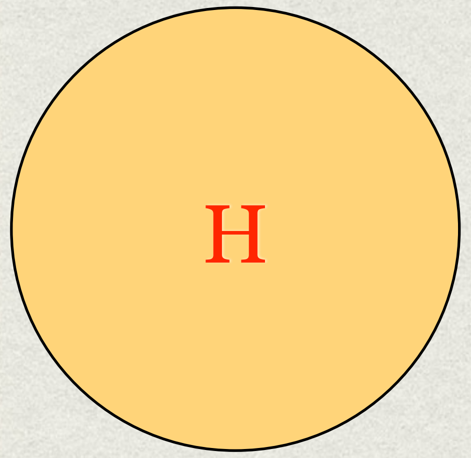


$$E_{grav} \approx \frac{GM^2}{R} = 3\times10^{53}\text{erg}$$

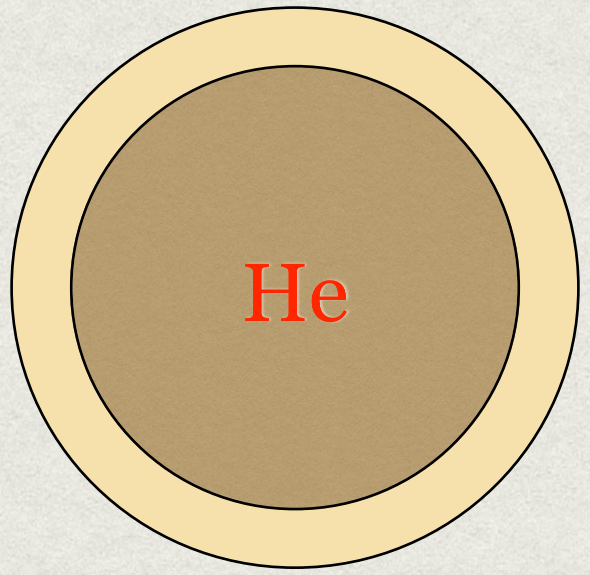
Energy : 99 % neutrinos,
0.01% photons
about 1% explosion kinetic energy

Schematic evolution of a massive star (25 Msun)

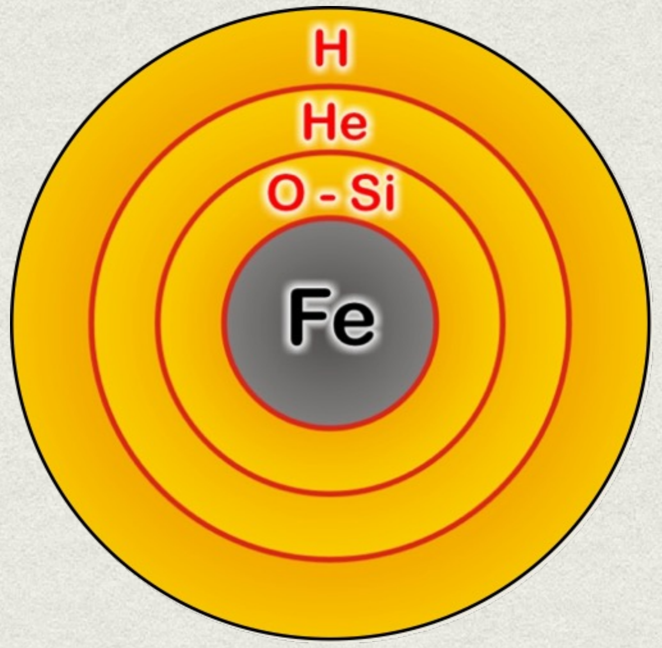
INITIAL STAGES



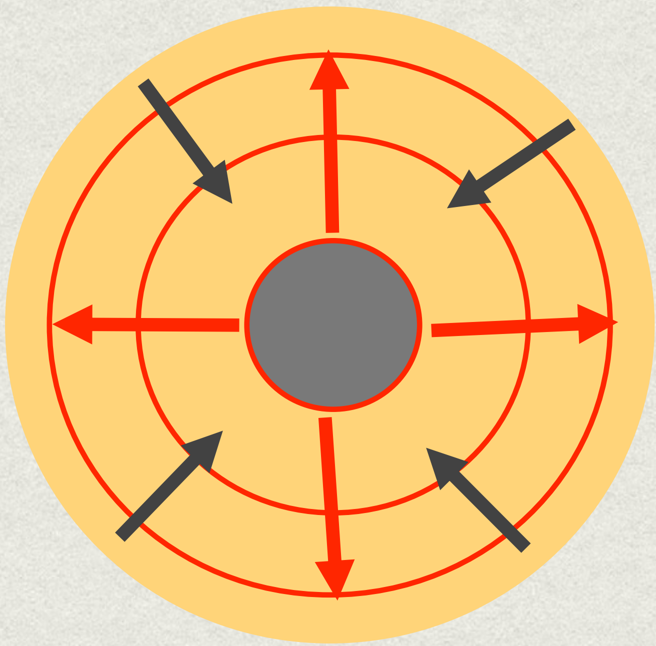
H burning
$T= 0.09\ 10^9$ K
Burning time = 7 My



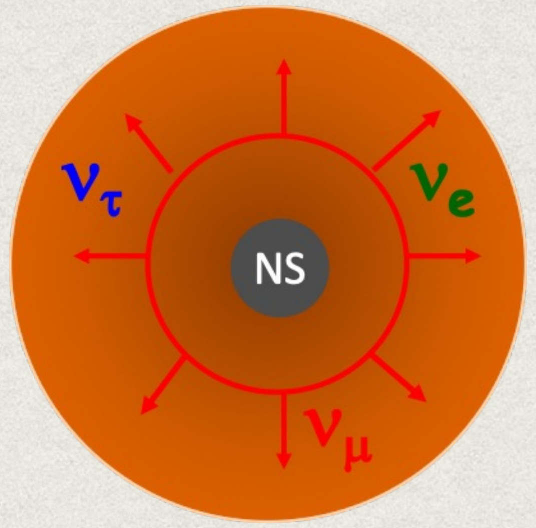
He burning
$T= 0.2\ 10^9$ K
Burning time = $5\ 10^5$ y



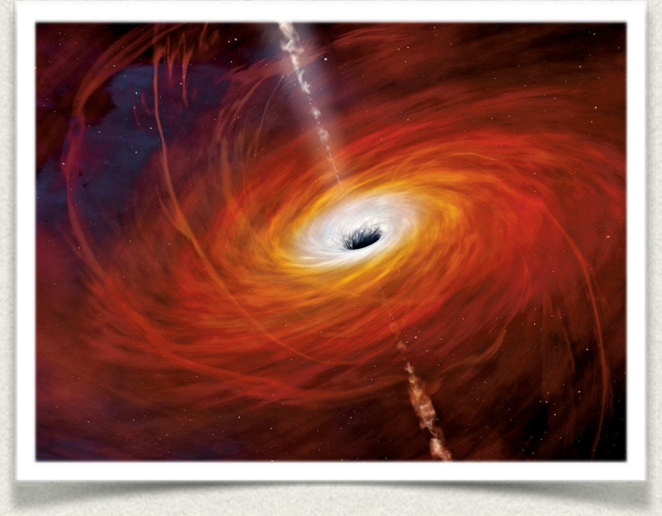
C (Si) burning
$T= 0.8\ (3.5)\ 10^9$ K
Burning time = 600 y (1 d)



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



neutron star (NS) formed



black-hole (BH)
Artist image

+ FAILED SUPERNOVAE

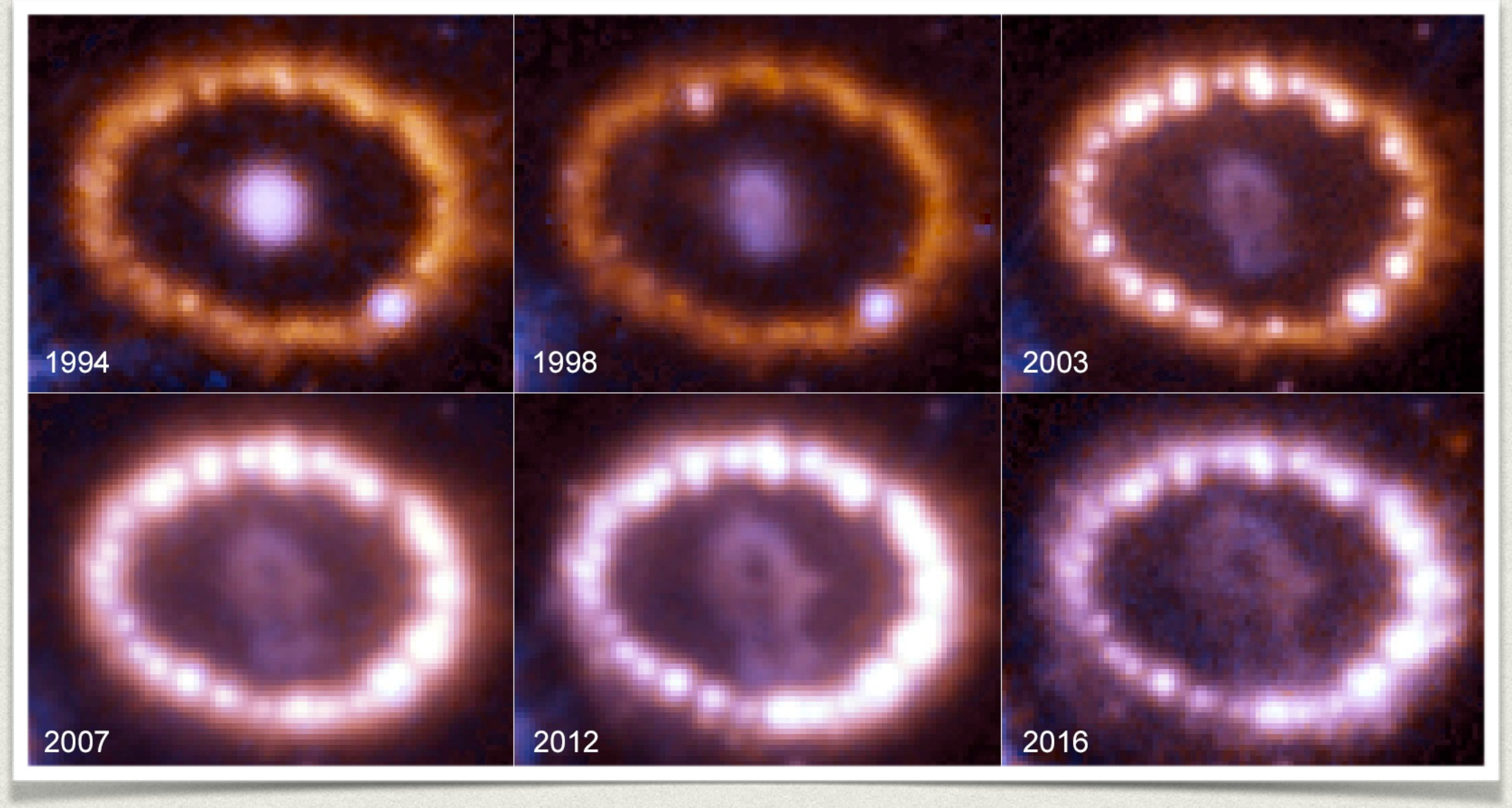
FINAL STAGES

A UNIQUE EVENT : SN1987A

- On the 23rd February, Sanduleak 69^0202 (blue supergiant) exploded, in the Large Magellanic Cloud

50 ± 5 kpc (163,000 light-years)

Schmidt et al, 1992

- 

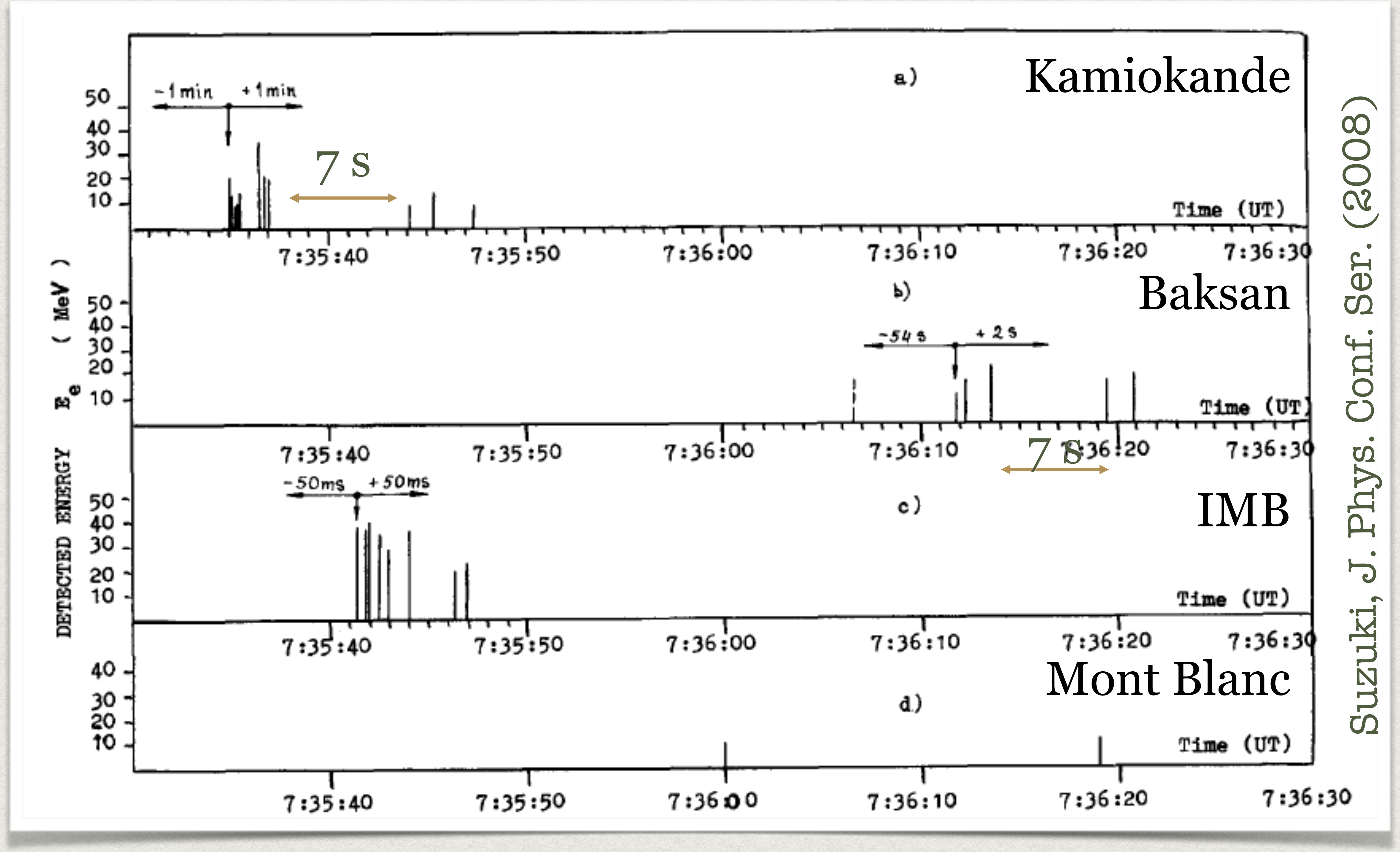
Hubble Space Telescope

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., 2020

SN1987A NEUTRINO EVENTS

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



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

Water Cherenkov detector, 2140 tons

Baksan Scintillator Telescope, 200 tons

Irvine-Michigan-Brookhaven, Water Cherenkov, 6800 tons

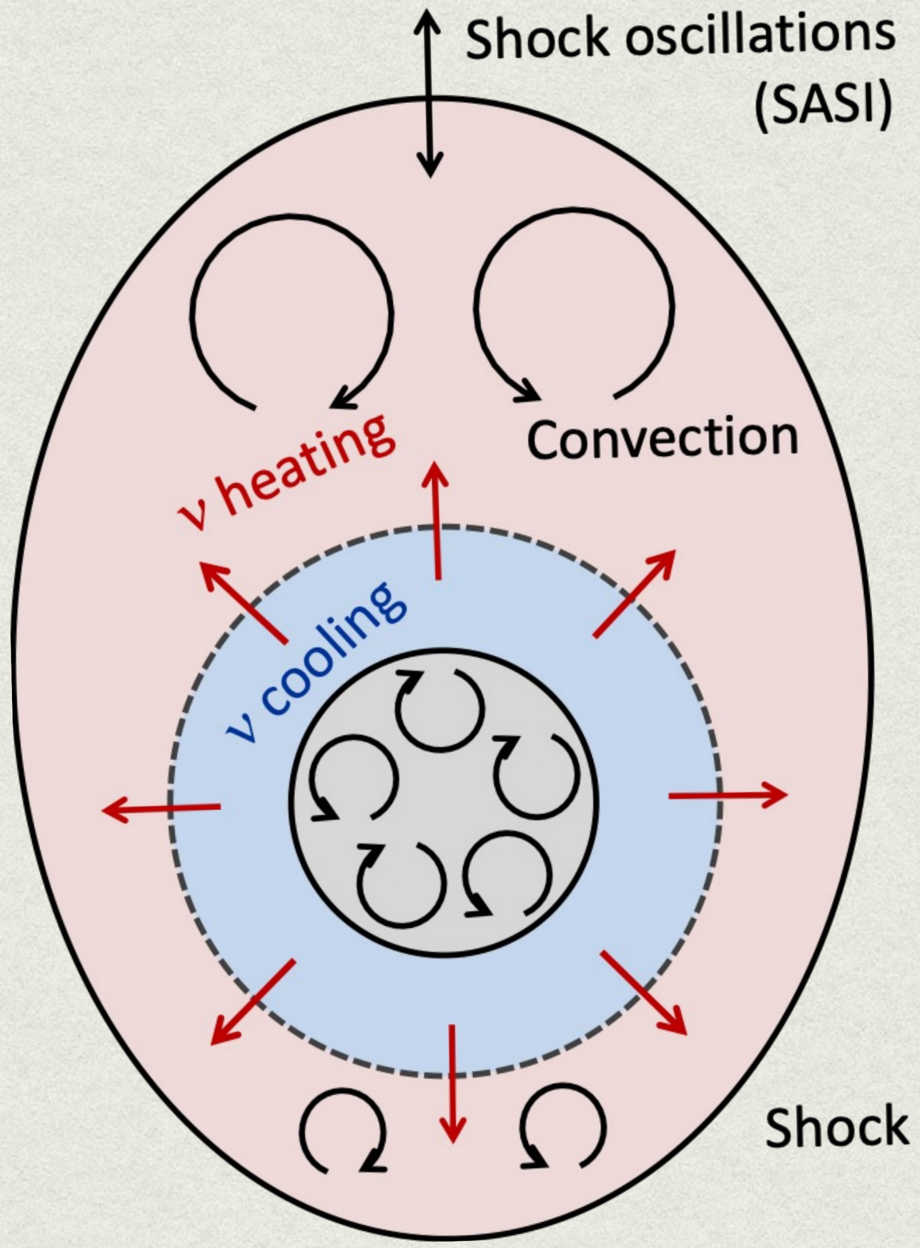
A wonderful laboratory for particle physics and astrophysics

SUPERNOVA EXPLOSION MECHANISM

- Elucidating the core-collapse supernova mechanism a 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: *delayed neutrino-heating mechanism,*

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



see Mezzacappa (2022), arXiv: 2205.13438,
T. Janka's talk at « Neutrino Frontiers » (GGI, 2024)

A MAJOR STEP FORWARD EVERY DECADE

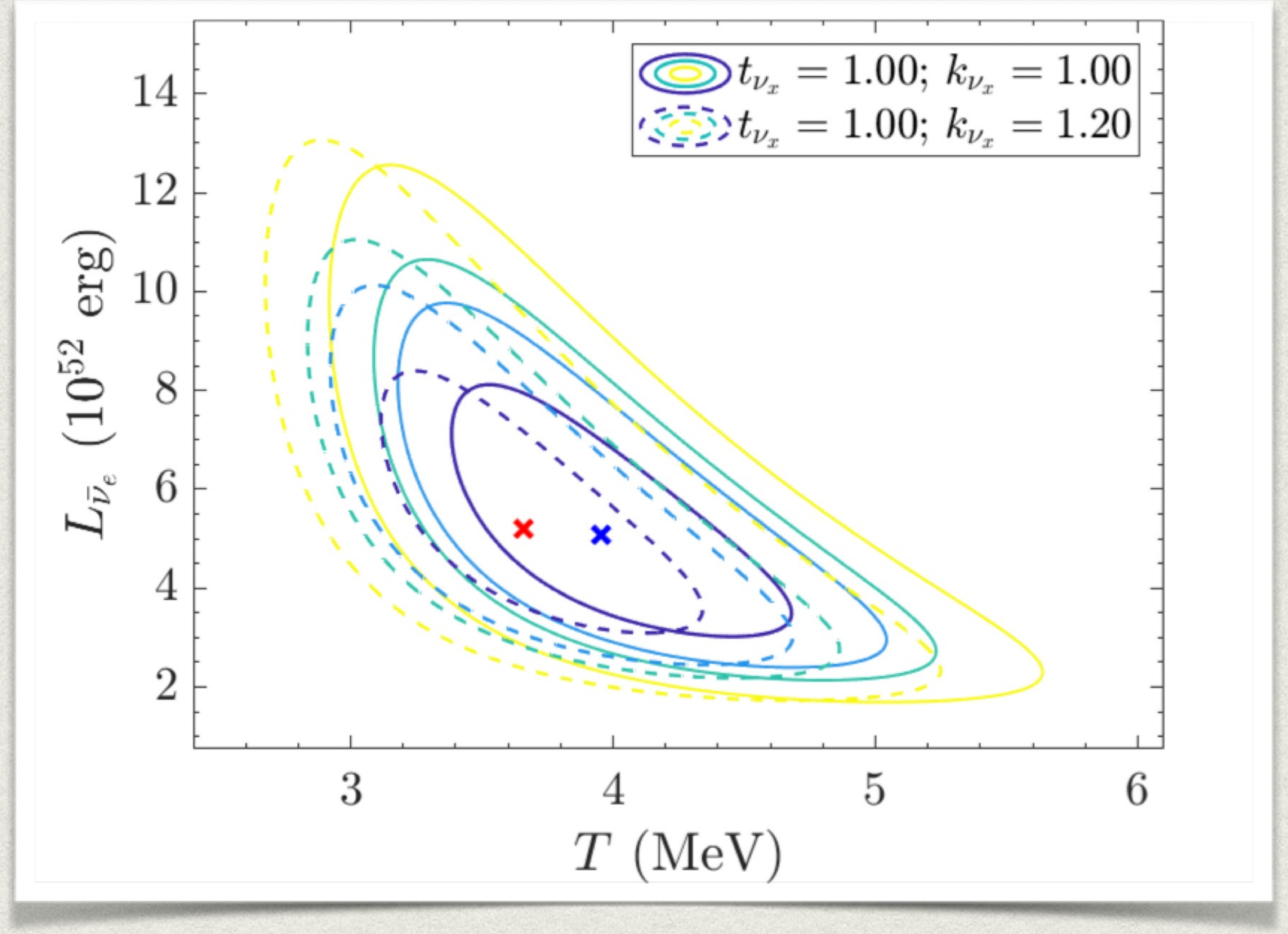
SN1987A NEUTRINO EVENTS

- Bayesian analysis of neutrino time signal considering with cooling or accretion+cooling supernova models.

«*We find two-component models* to be 100 more probable than *single-model component*. » Loredo and Lamb, PLB 205 (1988)

Delayed neutrino-heating mechanism favored

- 2D-likelihood analysis of the neutrino spectra



Ivanez-Ballesteros,Volpe, PLB 2023, 2307.03549

Average neutrino energies and total neutrino luminosity agree with expectations. $E_{\mathrm{grav}} = 3\times10^{53}$ergs

see also, Vissani, *J.Phys.G* 42, 2015

Good agreement with expected supernova neutrino signals

AN EXAMPLE: Neutrino non-radiative decay

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

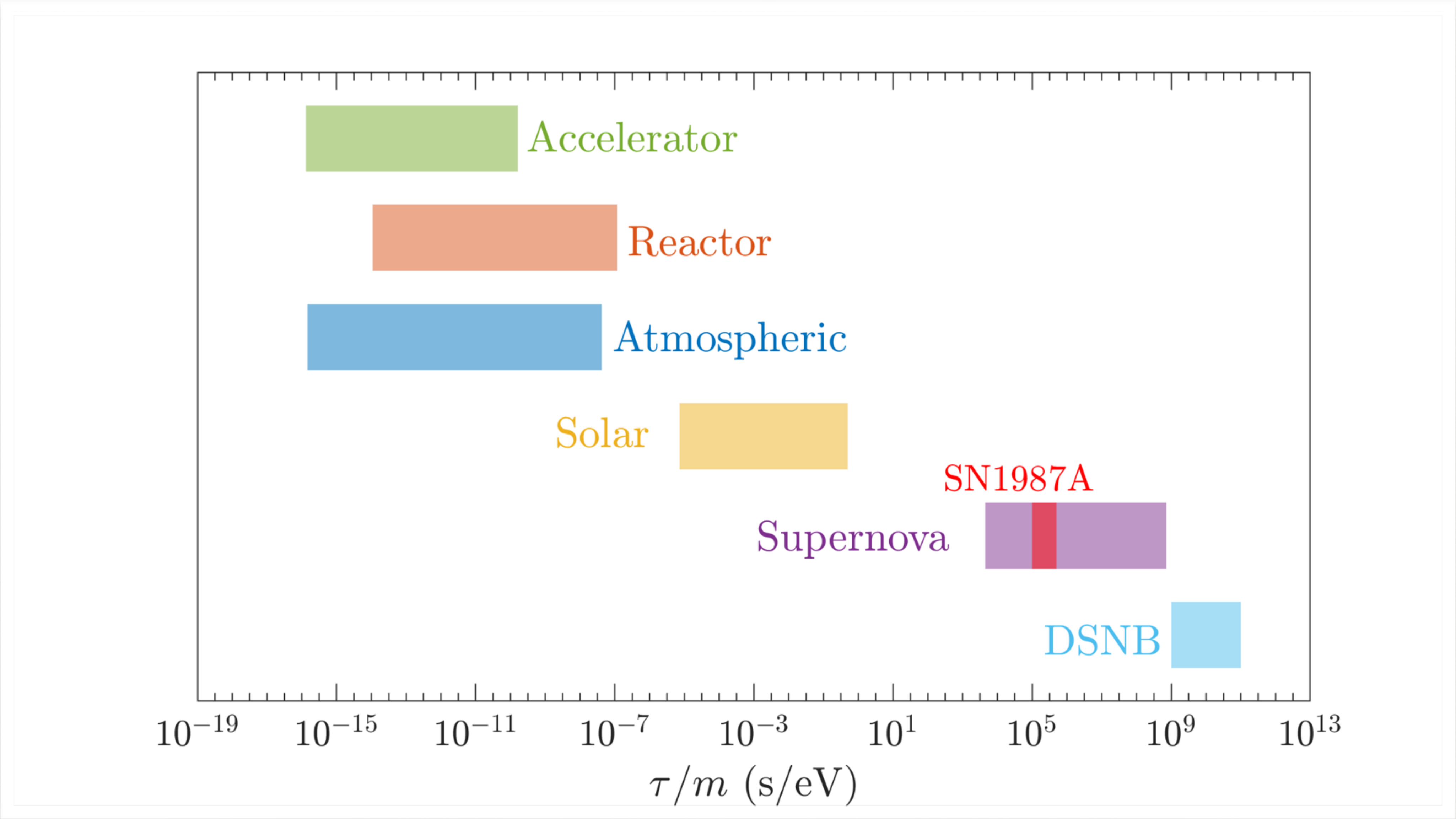
$$\nu_i \rightarrow \nu_j + \phi \quad \text{or} \quad \nu_i \rightarrow \bar{\nu}_j + \phi$$

ϕ a massless (pseudo)scalar particle

due to tree-level (pseudo)scalar couplings.

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

Sensitivity from different neutrino sources



Ivanez-Ballesteros, Volpe, PLB 2023, 2307.03549

- The neutrino fluxes get suppressed by the factor

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

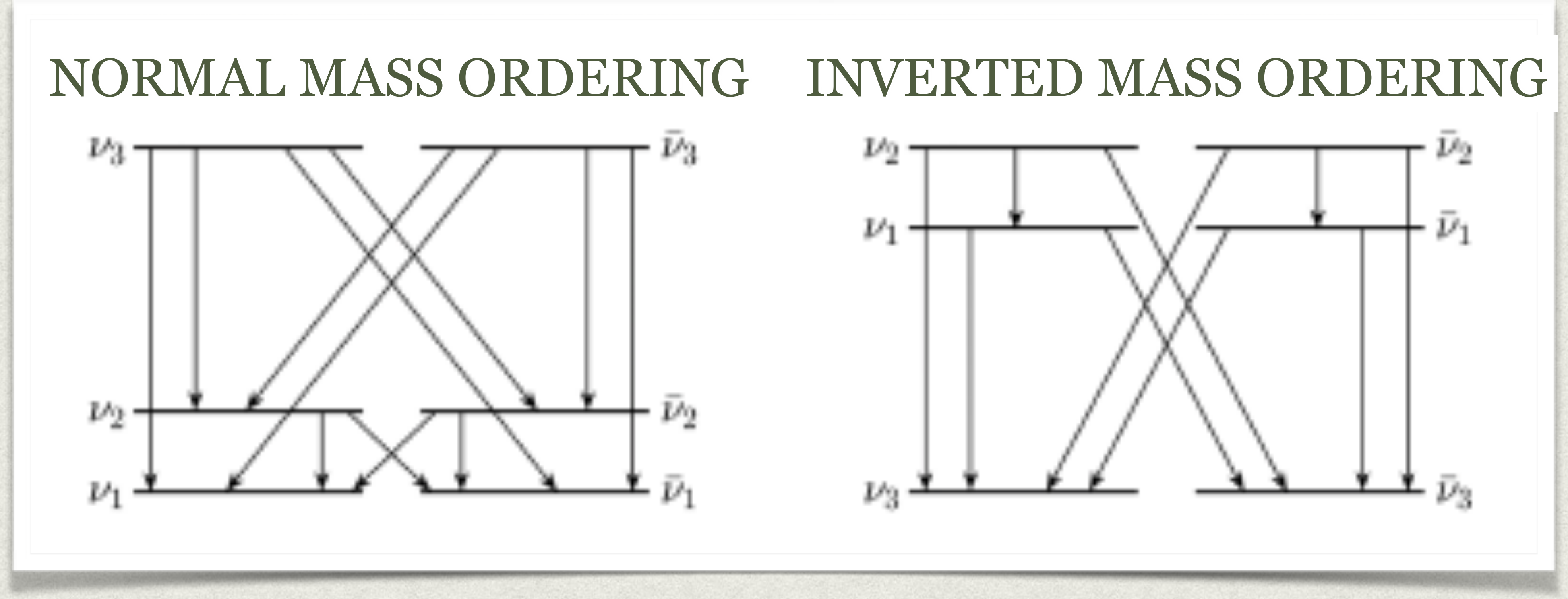
L - souce-detector distance
E - neutrino energy
m - neutrino mass
τ - lifetime

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

SN1987A and NEUTRINO NON-RADIATIVE DECAY

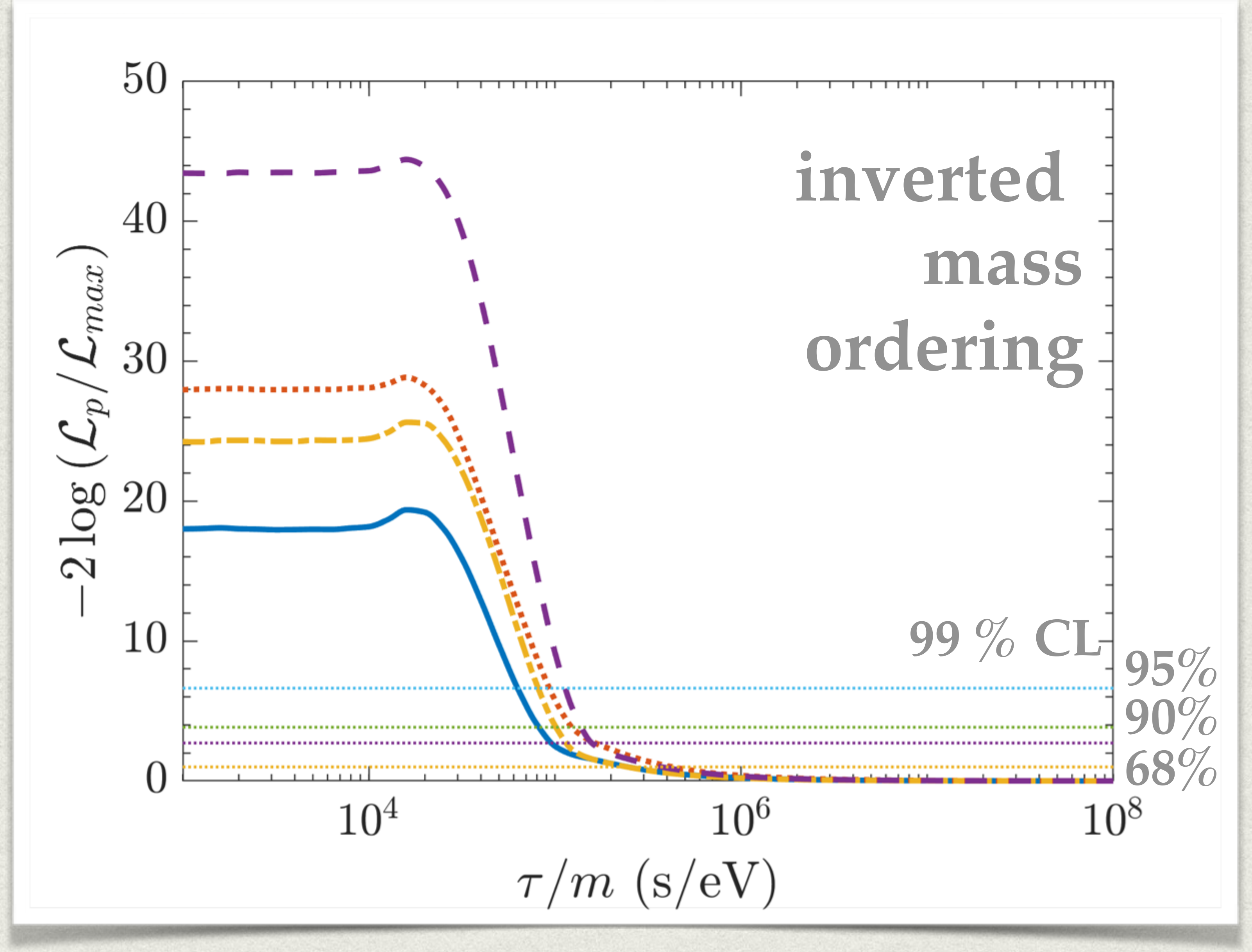
- A likelihood analysis (7D) of the 24 SN1987 neutrino events in Kamiokande, IMB and Baksan, with non-radiative decay yields

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



$\Delta m^2_{32} > 0$

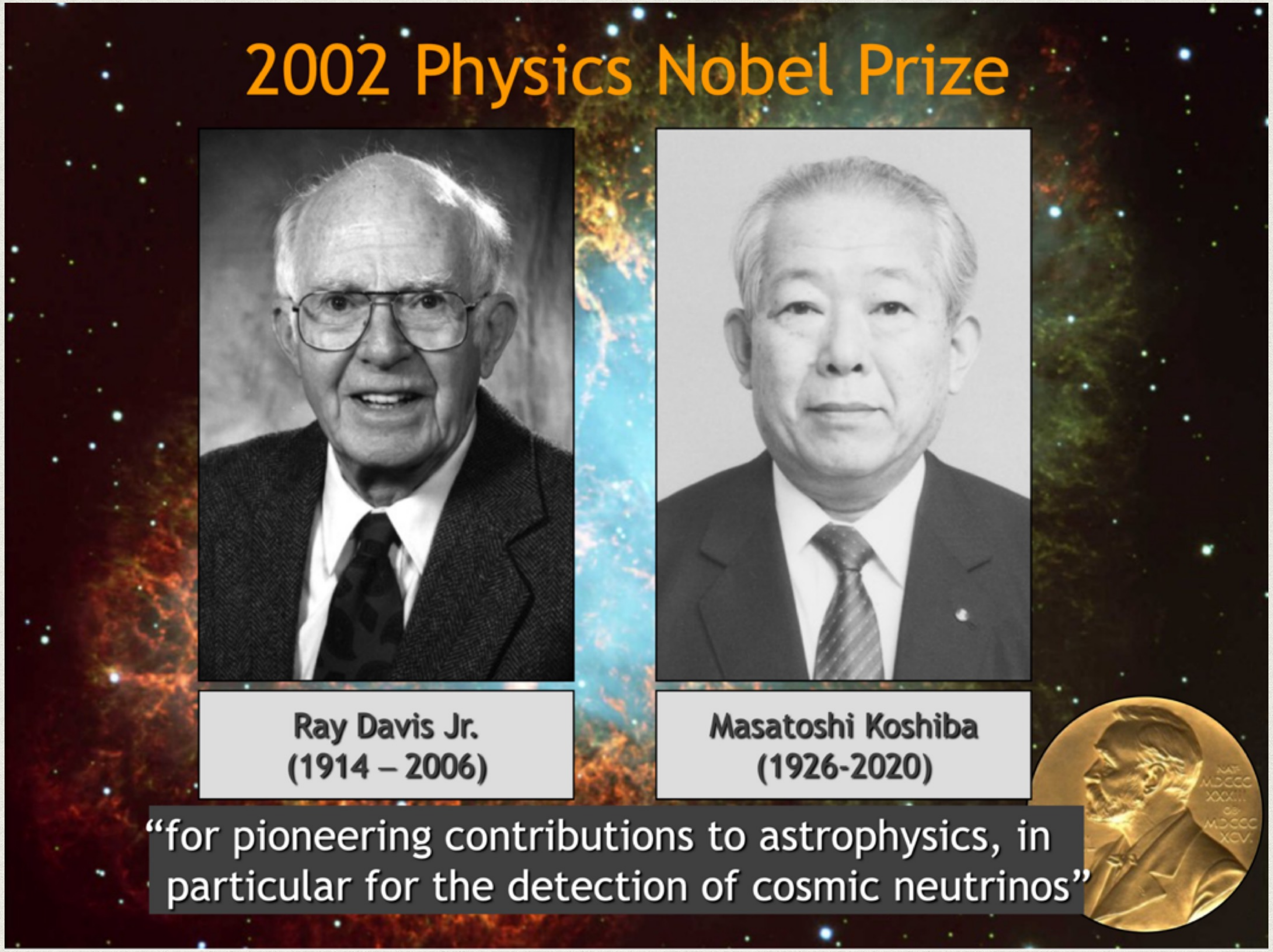
$\Delta m^2_{32} < 0$



Ivanez-Ballesteros, Volpe, PLB 2023, 2307.03549

$\tau/m > 1.2{\times}10^5 (90\% \mathrm{C.L.}) \mathrm{for} \nu_1 \mathrm{and} \nu_2 (\mathrm{IO})$

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



2002 Physics Nobel Prize

Ray Davis Jr.
(1914 – 2006)

Masatoshi Koshiba
(1926-2020)

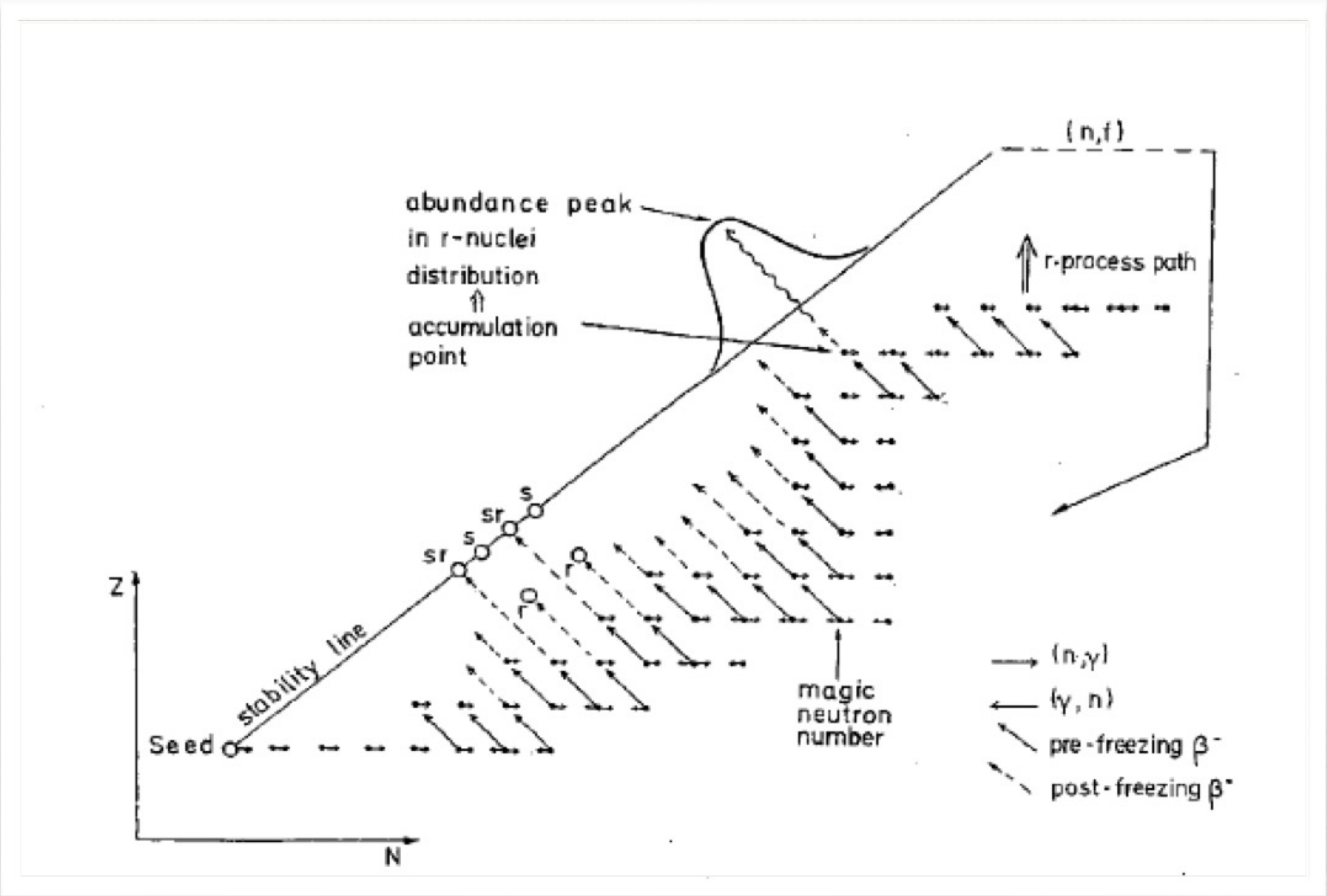
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

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

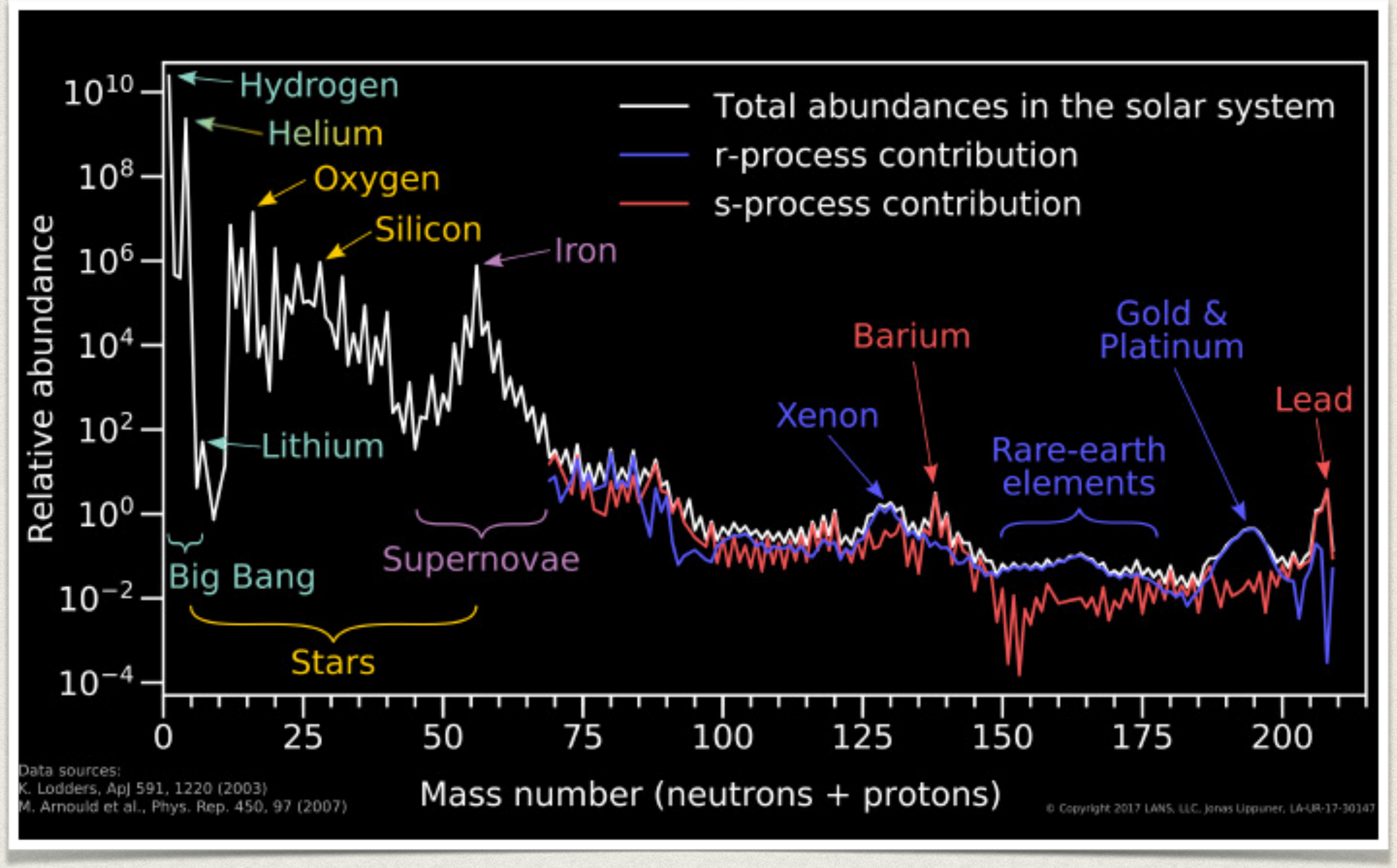
r-PROCESS NUCLEOSYNTHESIS

- 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.

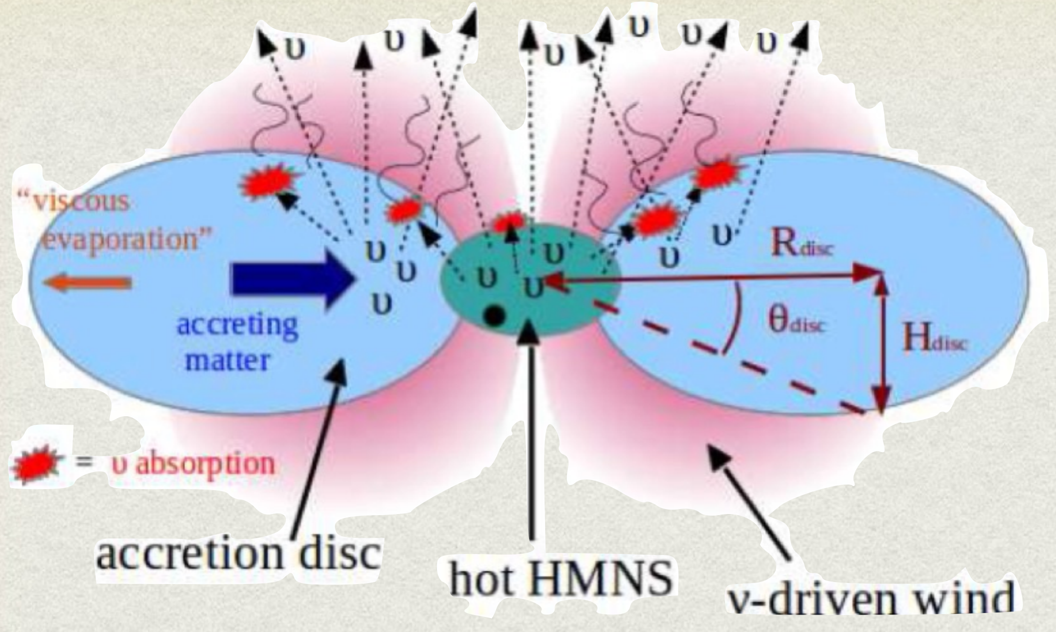


Nucleosynthetic abundances in the solar system



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

Main candidate sites : supernovae and binary neutron star mergers



A UNIQUE EVENT : GW170817

- First measurement of gravitational waves, in coincidence with a short gamma ray burst and a kilonova.

Abbot et al, PRL 2017

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

- From the electromagnetic signal, indirect evidence for r-process elements (lanthanides, actinides) in the ejecta and neutrino impact

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

see works e.g. by Balantekin, Chatelain, Fuller, Kneller, Qian, Frensel,
Yuksel, Malkus, Pastor, Raffelt, Surman, McLaughlin, Tamborra, Volpe, Wu, ...

Hubble Space Telescope

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

Neutrinos and neutrino flavor conversion impact r-process abundances

WHAT ARE WE LEARNING
WAITING FOR THE NEXT SUPERNOVA AND KILONOVA?

We face complexity *since neutrinos propagating*
in a dense astrophysical environments :
A weakly interacting many-body problem.

NEUTRINOS EVOLUTION EQUATIONS

- In such environments neutrinos are trapped.

  $E = 10$ MeV $\sigma = 6\ 10^{-41}\mathrm{cm}^2$ Typical cross section

  Mean free path $\lambda \approx \mathrm{m}$ $\lambda \approx$ tens of km

- Density matrix in 2nu framework $\rho_{\alpha\beta} = \langle a^\dagger_\beta a_\alpha \rangle$

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

The full description requires neutrino quantum kinetic equations:

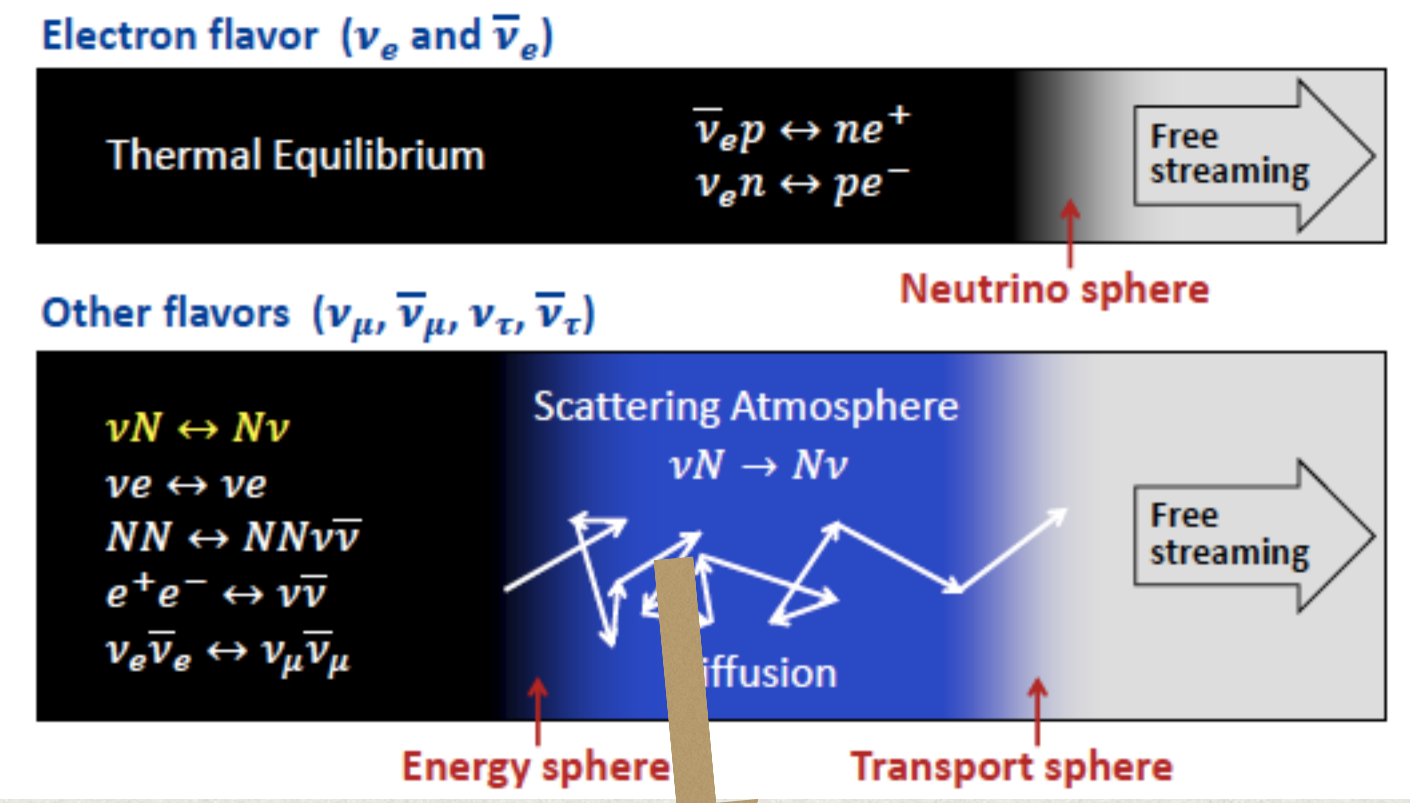
$$\underbrace{i(\partial_t + \mathbf{v}\cdot\nabla_{\mathbf{x}} + \mathbf{F}\cdot\nabla_{\mathbf{p}})}_{\text{Liouville operator}}\varrho_{\mathbf{x},\mathbf{p}} = \underbrace{[h_{\mathbf{x},\mathbf{p}}, \varrho_{\mathbf{x},\mathbf{p}}]}_{\text{mean-field}} + \underbrace{iC[\varrho,\bar{\varrho}]}_{\text{collisions}},$$

The full problem is 7-dimensional.

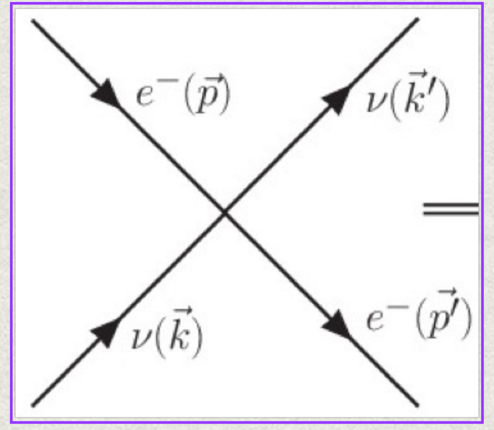
- Same in the early Universe, at primordial nucleosynthesis epoch.

  Solved, a precise value for Neff = 3.0440 .

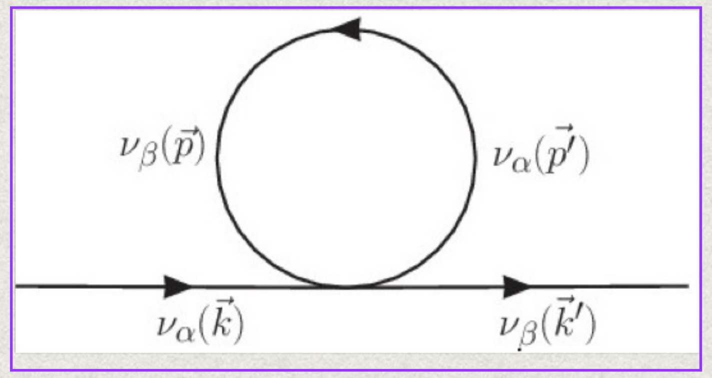
  Froustey, Pitrou, Volpe, JCAP 12, 2020; Bennet et al, JCAP 04, 2021



Raffelt (2012)



collisions



mean-field

Flavor conversion occurs in the trapping and the free-streaming regions

NEUTRINO (MEAN-FIELD) HAMILTONIAN

- The neutrino Hamiltonian contains different contributions

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

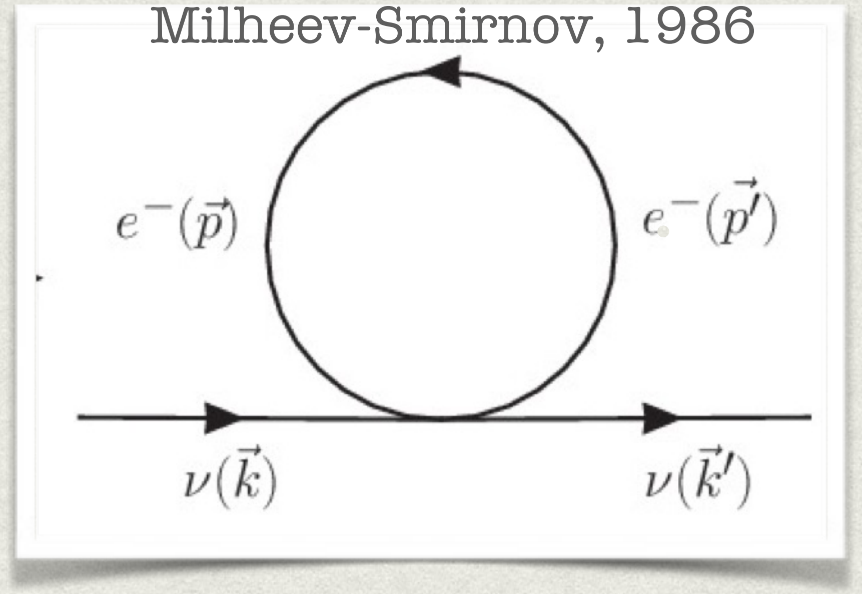
$$h_{vac} = \omega \begin{pmatrix} -c_{2\theta} & s_{2\theta} \\ s_{2\theta} & c_{2\theta} \end{pmatrix}$$

responsible for vacuum oscillations

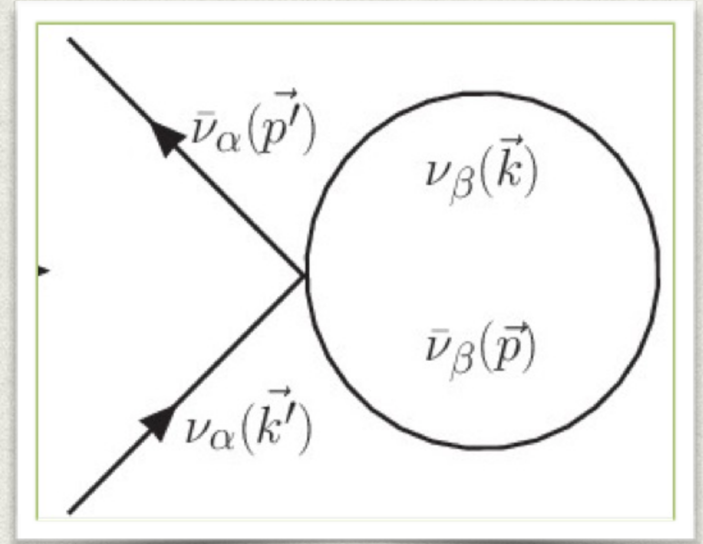
$$h_{mat} = \sqrt{2} G_F \begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2} \end{pmatrix}$$

Matter term, responsible for the Mikheev-Smirnov-Wolfenstien effect

Wolfenstein, 1978;
Milheev-Smirnov, 1986



Explains solar 8B neutrino reduced to 1/3 the Standard Solar model predictions



Neutrino-neutrino interactions

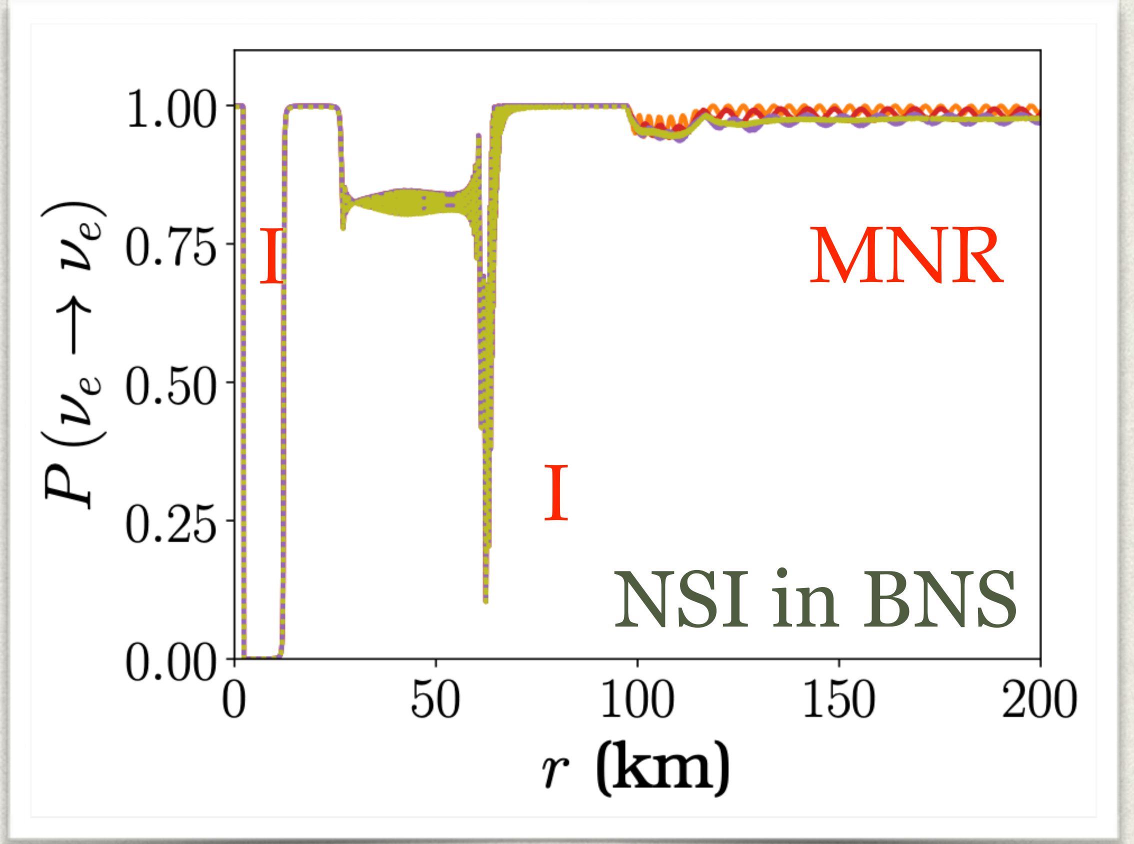
$$h_{\nu\nu} = \sqrt{2} G_F \sum_\alpha [\int (1 - \hat{q} \cdot \hat{p}) \times [\mathrm{d}n_{\nu_{\underline{\alpha}}} \rho_{\nu_{\underline{\alpha}}}(\vec{p}) - \mathrm{d}n_{\bar{\nu}_{\underline{\alpha}}} \bar{\rho}_{\bar{\nu}_{\underline{\alpha}}}(\vec{p})]],$$

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

Non-standard interactions

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

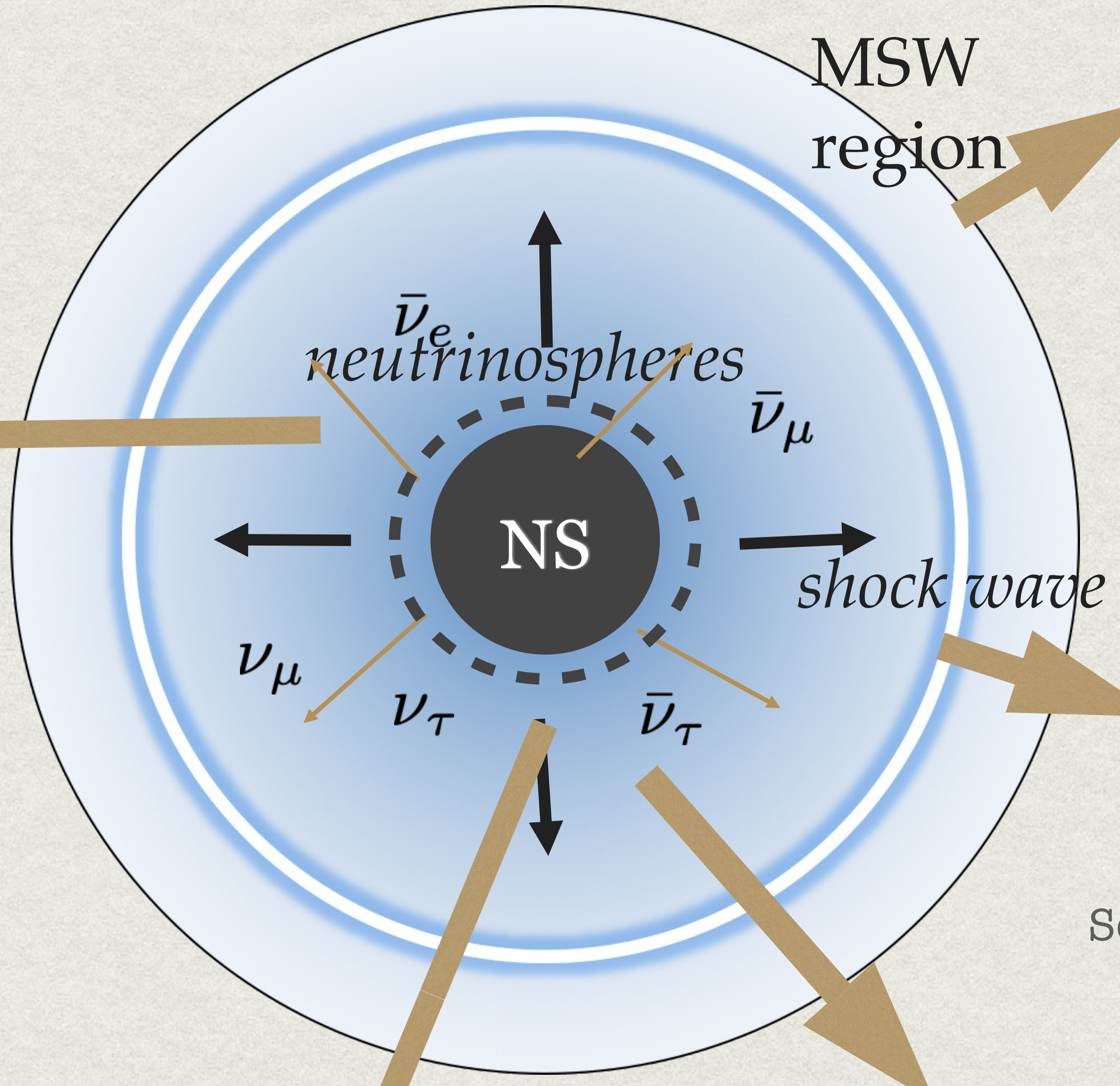
limits for neutral solar-like matter

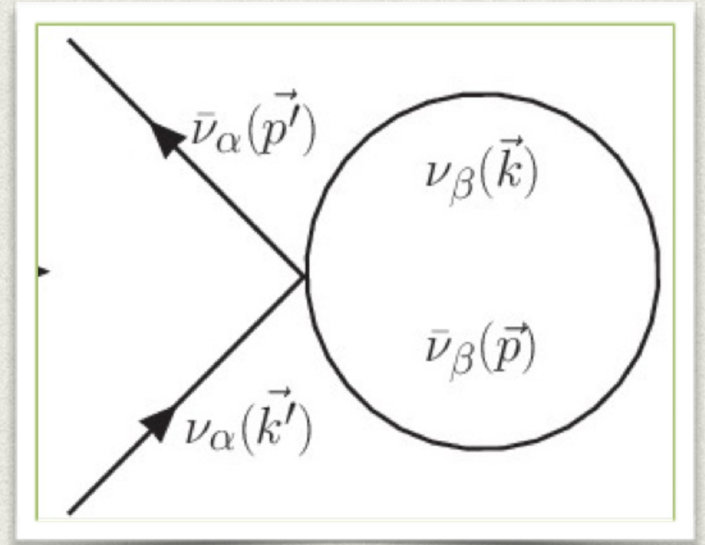


Chatelain, Volpe, PRD97, 2018.

The solution of the full kinetic equations very challenging

FLAVOR MECHANISMS IN DENSE ENVIRONMENTS



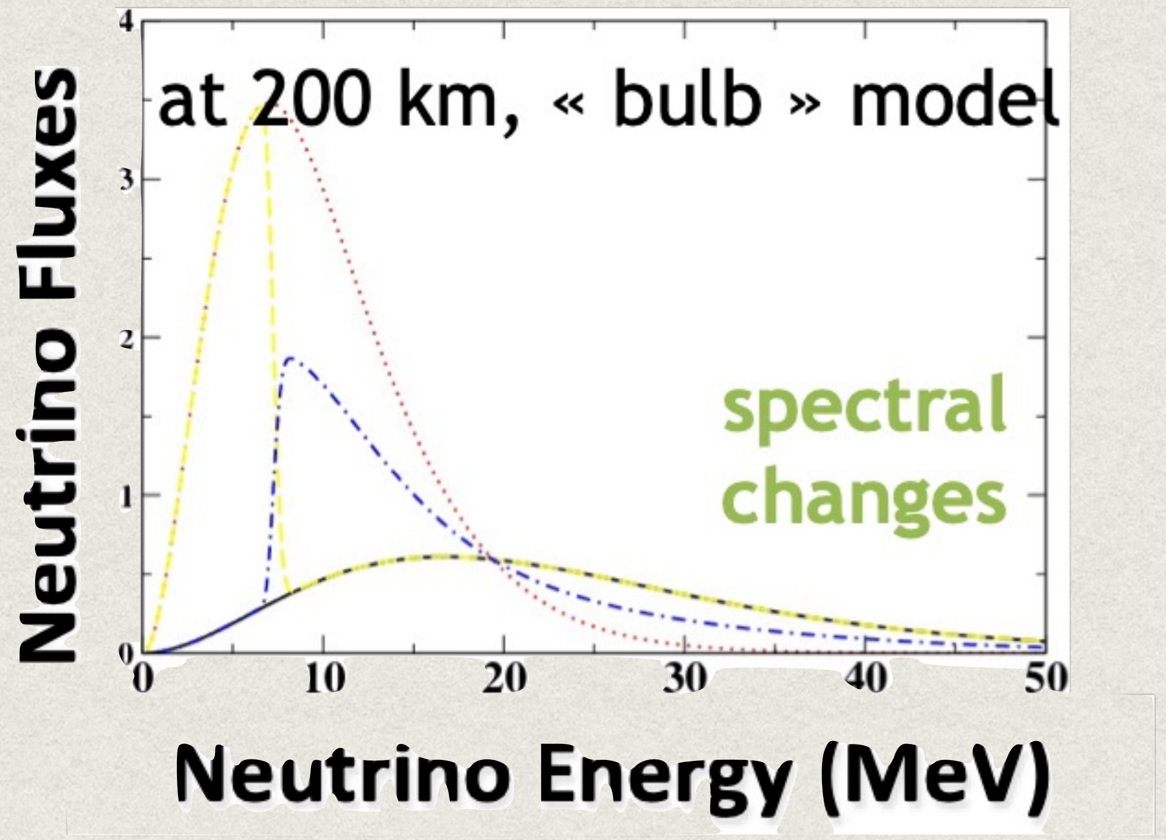


Neutrino-neutrino interactions

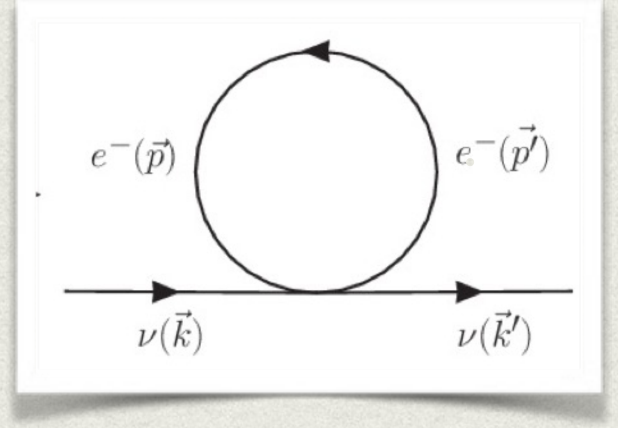
Pantaleone,1992, Duan et al, 2006

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

Sawyer PRD 2005, PRL 2016



Mikheev-Smirnov-Wolfenstein effect



Wolfenstein, 1978;
Milheev-Smirnov, 1986

Shock wave effects (multiple MSW)

Schirato and Fuller, hep-ph/0205390

Turbulence effects

Loreti et al, 1995

Collisional instabilities

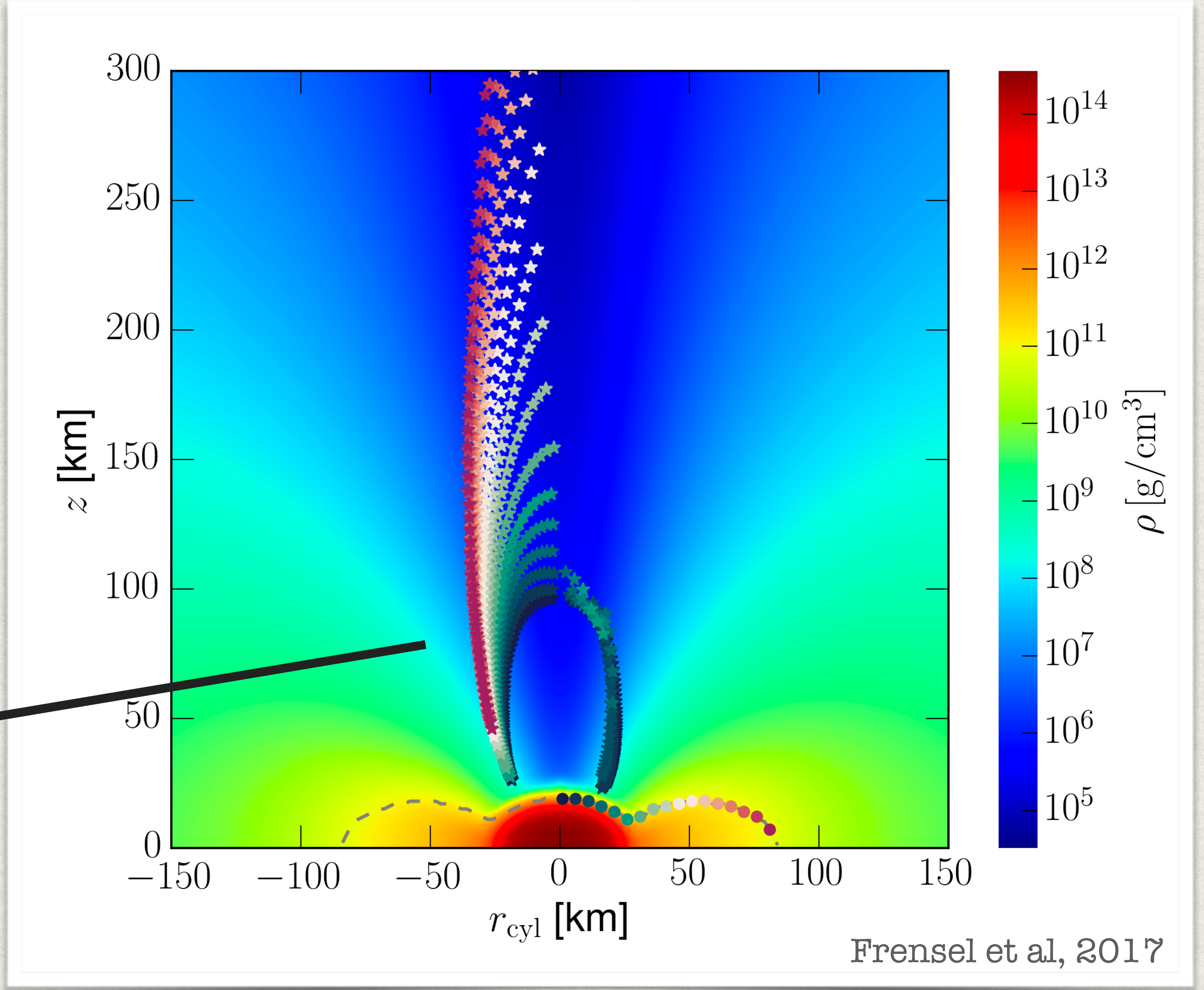
Johns, 2023

They produce modifications of the neutrino spectra

FLAVOR MECHANISMS IN DENSE ENVIRONMENTS

An example :
neutrino-neutrino
interactions in BNS

Stars indicate the so-called matter-neutrino resonance (MSW-like)



Frensel et al, 2017

BINARY NEUTRON STAR MERGER REMNANT

Major progress in about two decades - mechanisms, conditions, impact on supernova explosions, r-process nucleosynthesis and future observations

« 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

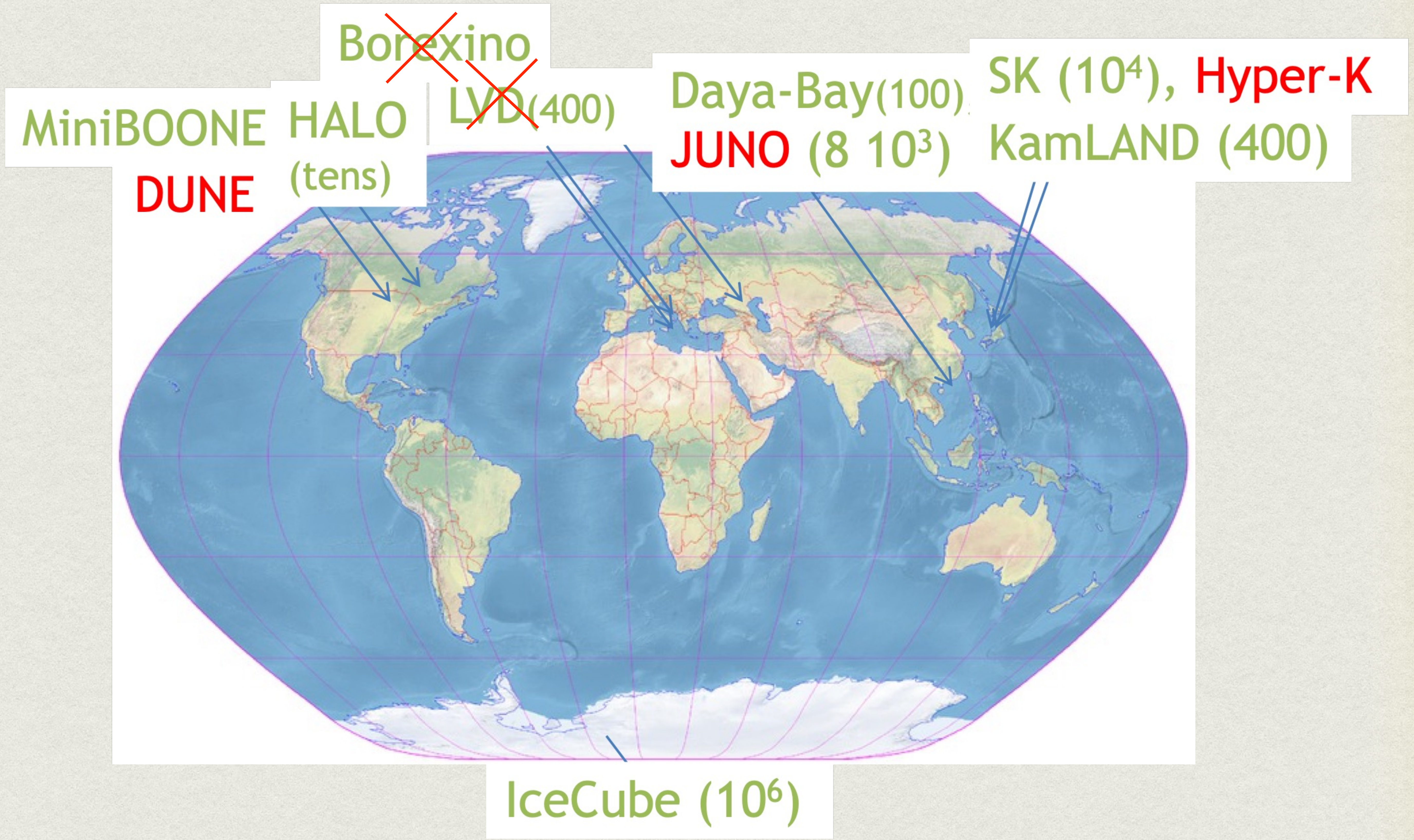
- Supernova Early Warning System (SNEWS 1.0) - prompt, positive, pointing
  Scholberg 1999, 2008; Antonioli et al, 2004
  pre-SN neutrinos, dark matter detectors, multimessenger astronomy
  SNEWS 2.0, 2021

- Expected events (supernova 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.

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

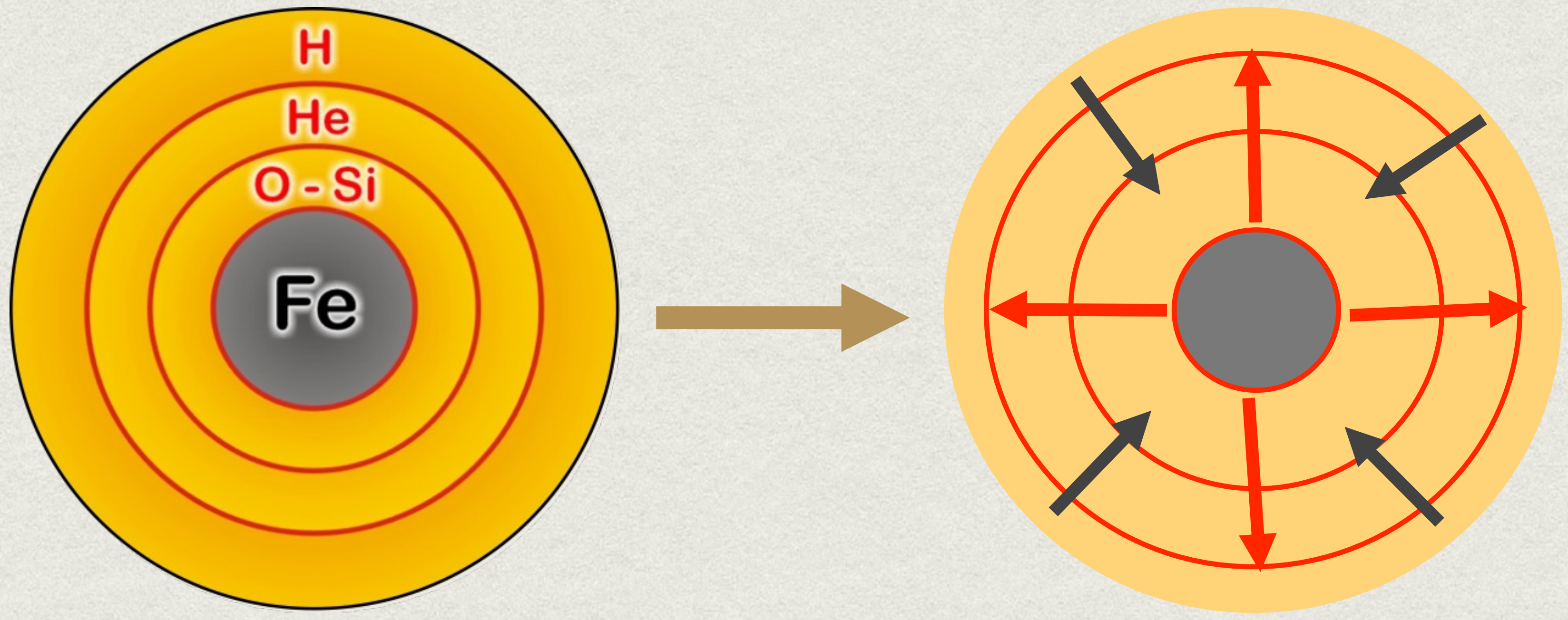
- Dark matter detectors:
  120 (Xenon nT, 7 tons), 700 (DARWIN, 40 tons),
  336 events (Darkside-20k (50 tons)

  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

IMPORTANCE of NEUTRINO TIME SIGNAL



Si burning : 2 d (20 Msun).
T= 3.5 10^9 K

Supernova
(core-collapse and explosion)

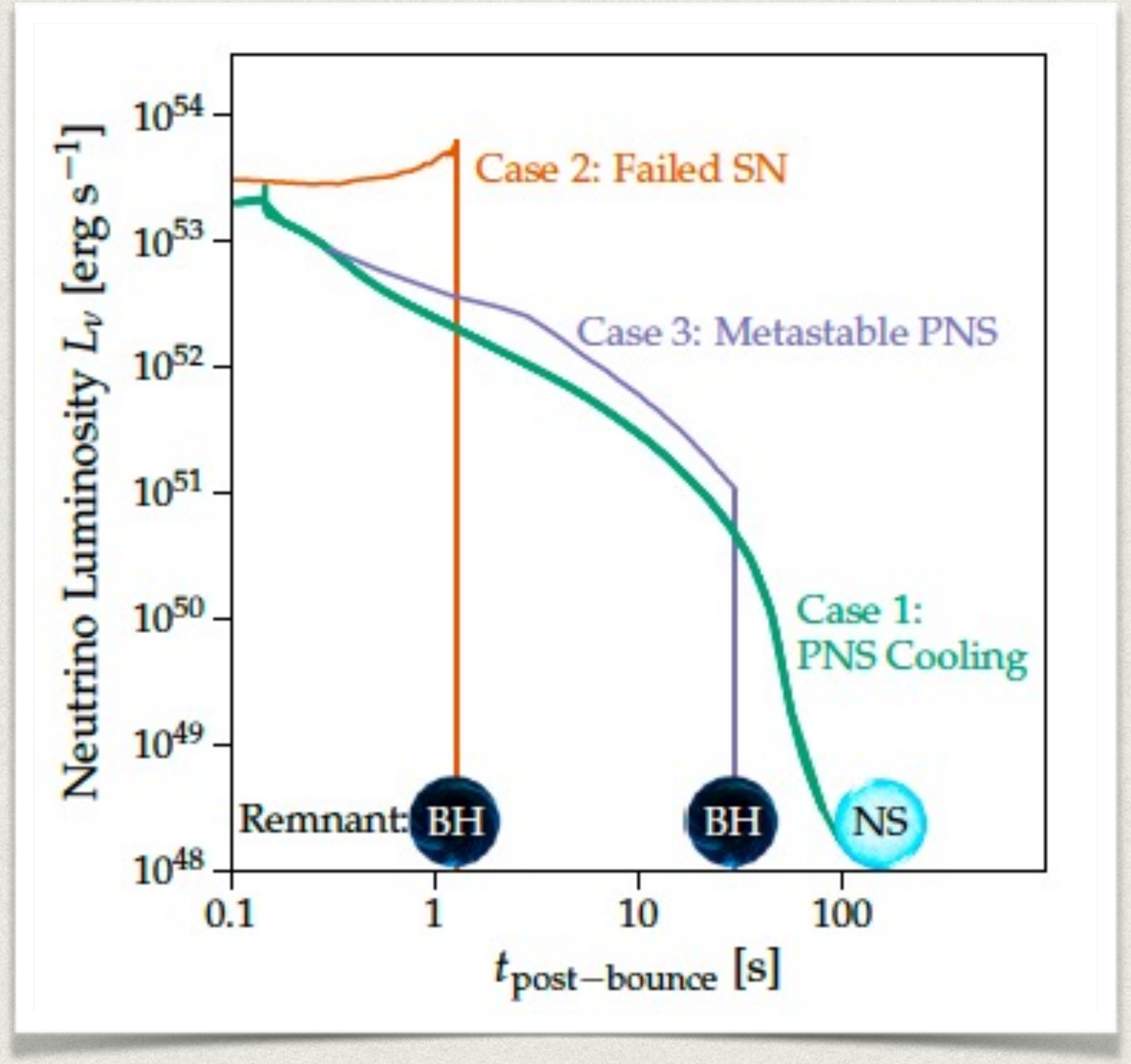
Pre-SN neutrinos (1-a few days before the SN)
information on the late stages before SN collapse (stellar evolution theory), the progenitor, early alert.

Odrzylowek et al, 2004; Patton et al, 2017; Kato et al 2020

Example: pre-SN neutrinos (3 sigma, 2d before exp.) in KamLAND for M = 25 Msun up to 690 pc.

Asakura et al., 2016

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

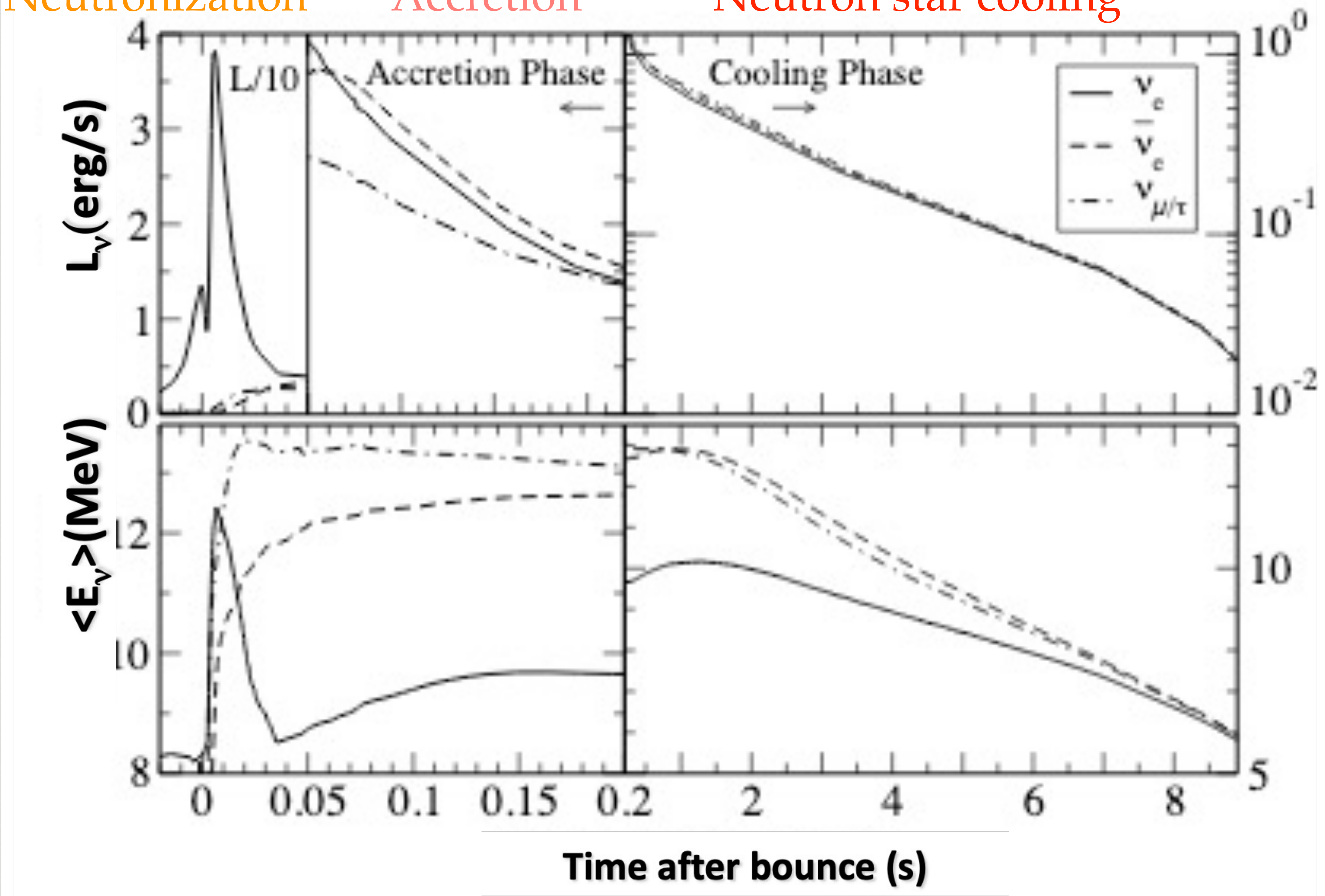


Li, Roberts, Beacom, PRD (2021)

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

SN NEUTRINO 10 s TIME SIGNAL

Neutronization Accretion Neutron star cooling



Hudepöhl et al PRL, 2011

Detection of each phase crucial

- <u>Neutronization peak:</u>

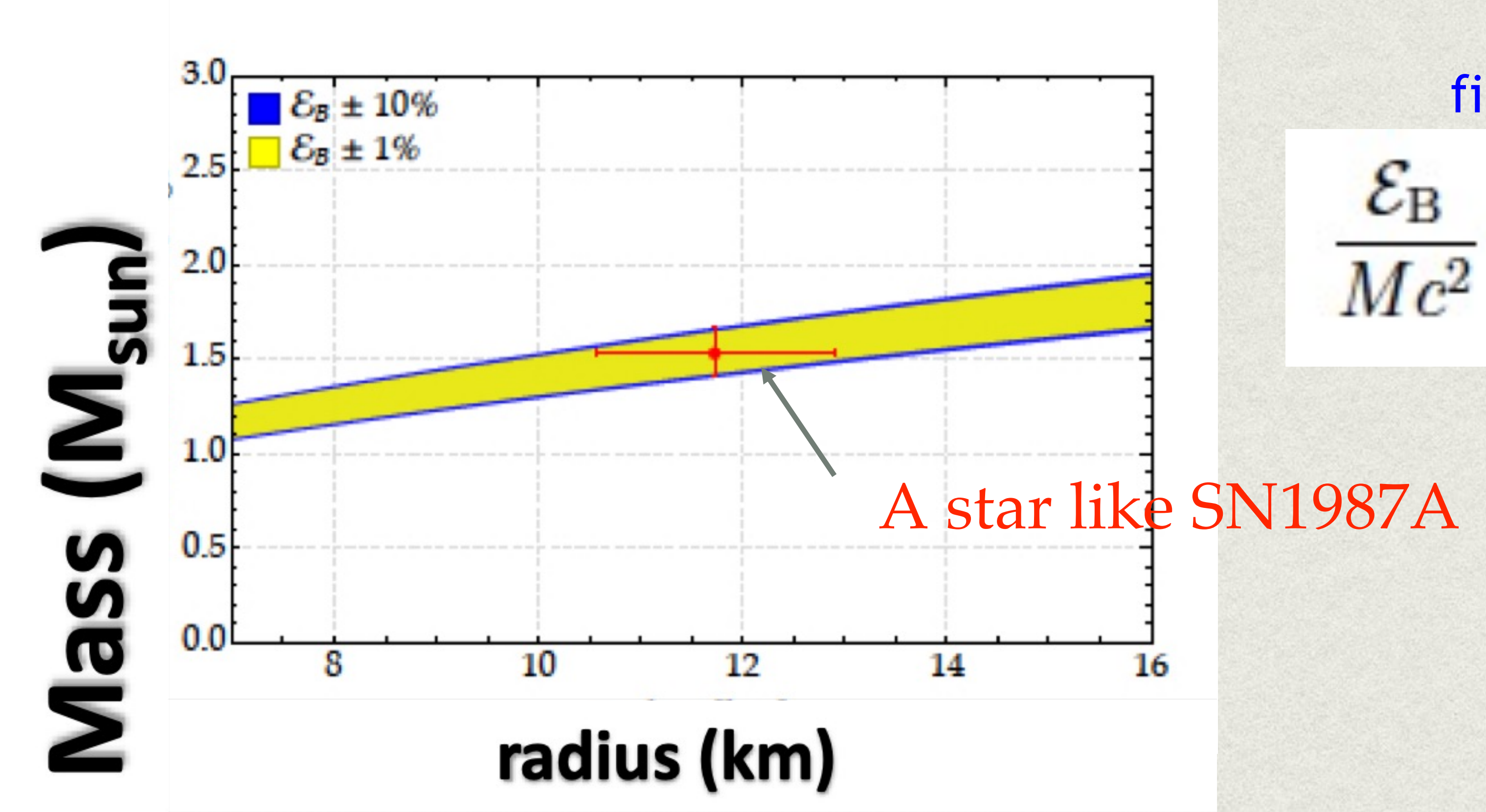
  > only MSW effect operates

  > non-standard properties, ex. decay or NSI

  De Gouvea et al, PRD101, 2020; Das et al, JCAP 05, 2017; etc...

- <u>Total neutrino luminosity (SN at 10 kpc):</u>

  > 11% (SK) and 3% (HK) precision



Gallo Rosso, Vissani, Volpe, JCAP 11, 2017

fit to numerous EOS for NS

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

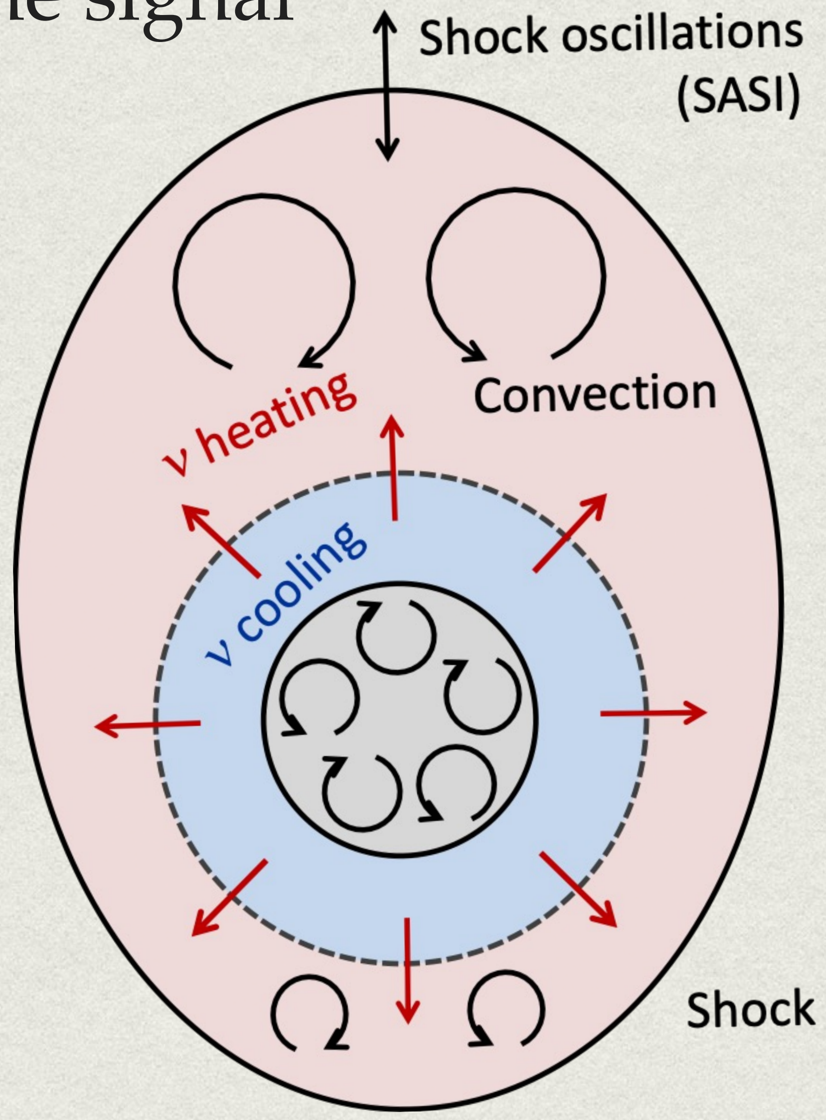
Lattimer & Prakash, Phys. Rep. 2007

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

Compactness of newly born neutron star

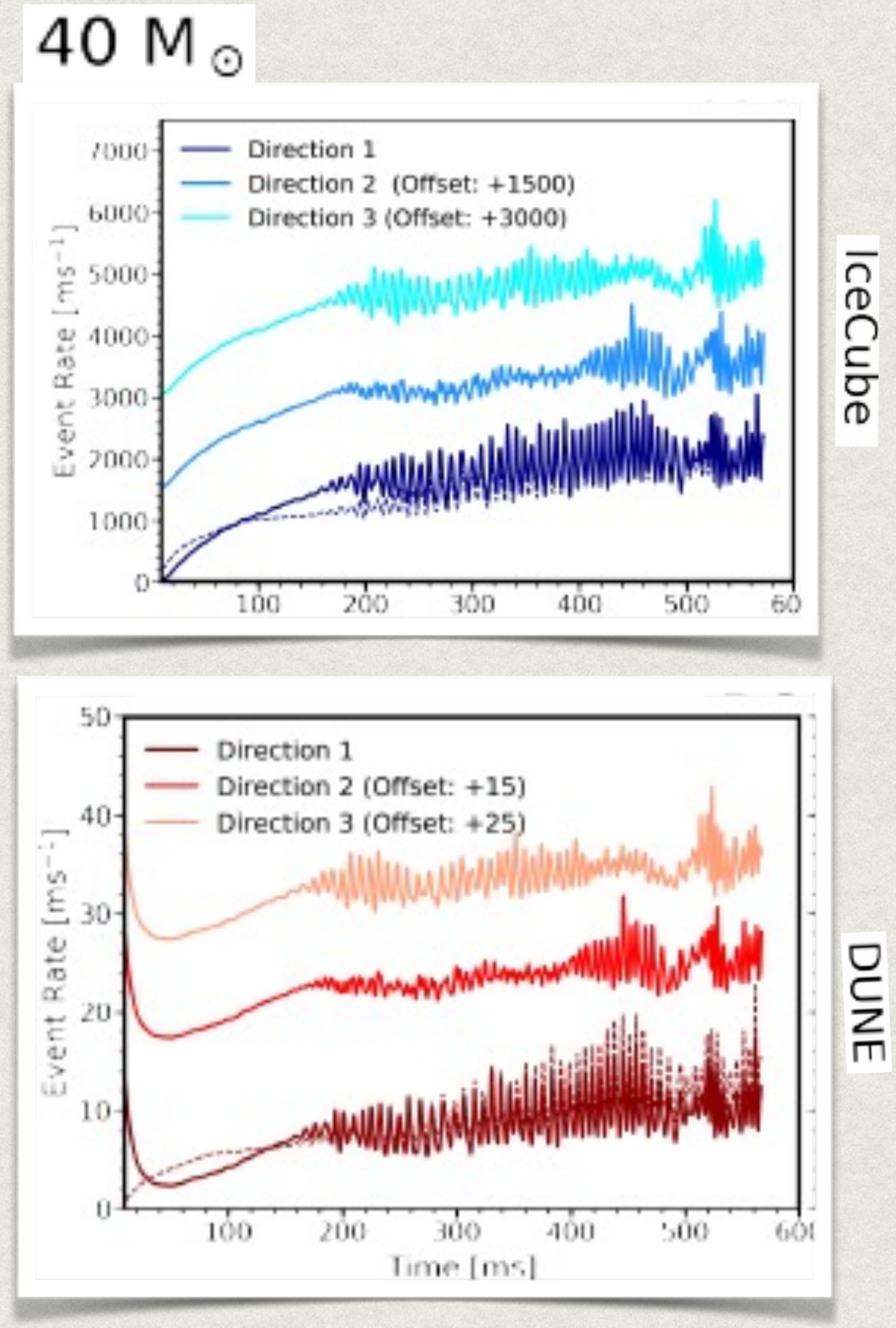
SUPERNOVA EXPLOSION MECHANISM

- Delayed neutrino-heating mechanism:
  the hydrodynamic instabilities (SASI) have
  a characteristic imprint on the neutrino time signal



- ***GW signatures** (different frequencies) from*
  - *core bounce (rotating progenitor);*
  - *neutrino-driven convection (PNS);*
  - *neutrino-driven convection in the gain layer;*
  - *SASI;*
  - *explosion.*

see e.g. Mezzacappa and Zaolin, 2401.11635,
G. Pagliaroli's talk at « Neutrino Frontiers » (2024, GGI)



Walk et al (2020)

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

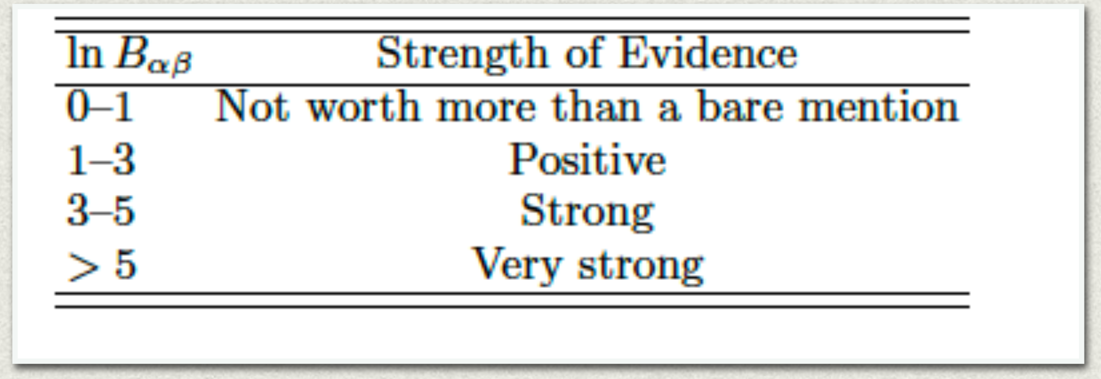
OBSERVING THE NEXT SUPERNOVA CRUCIAL to CONFIRM/REFUTE

FLAVOR MECHANISMS

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

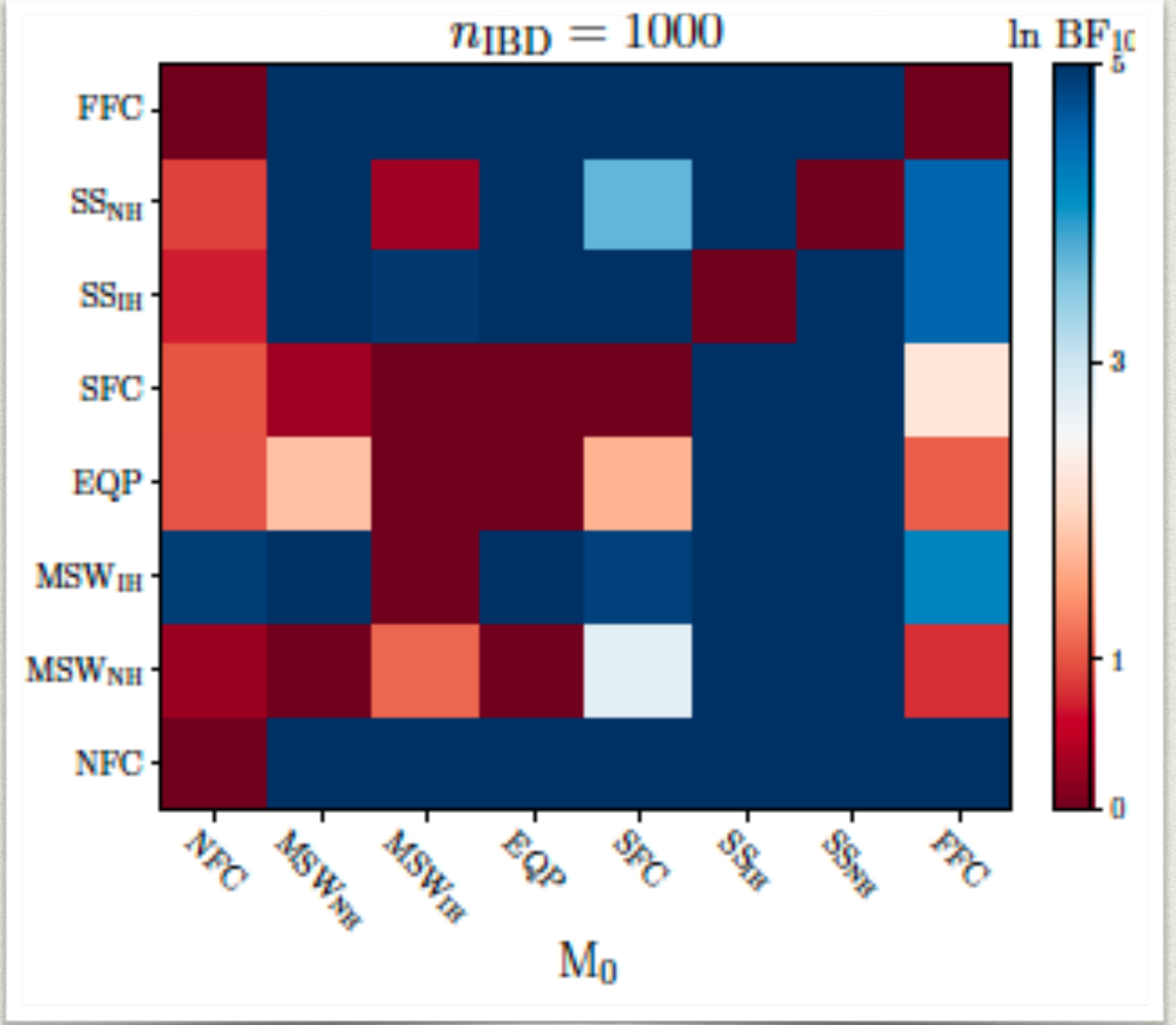
Abe et al, 2021 Olsen and Qian 2022 Saez et al 2024

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



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

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

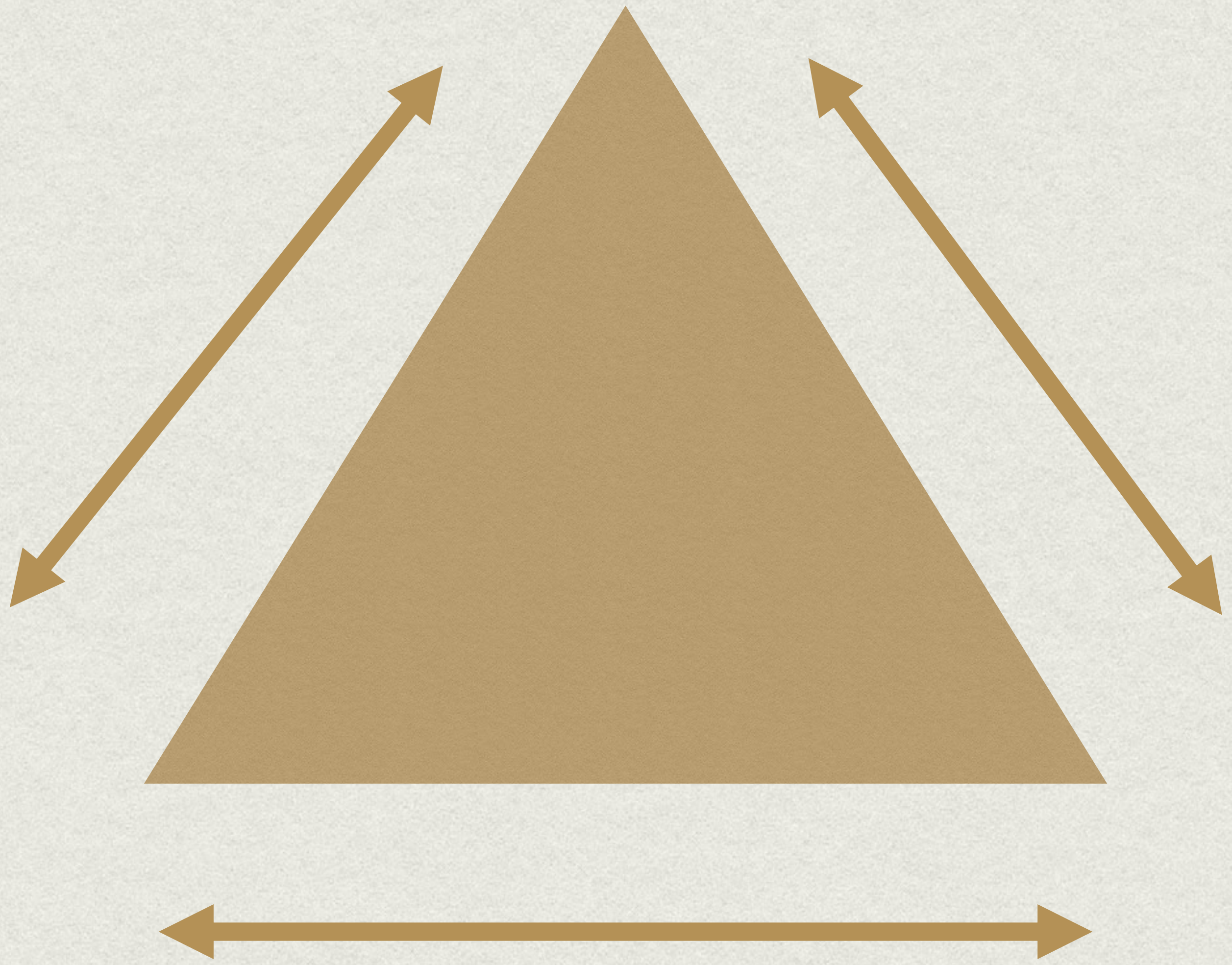


Abbar and Volpe, 2401.10851

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,…



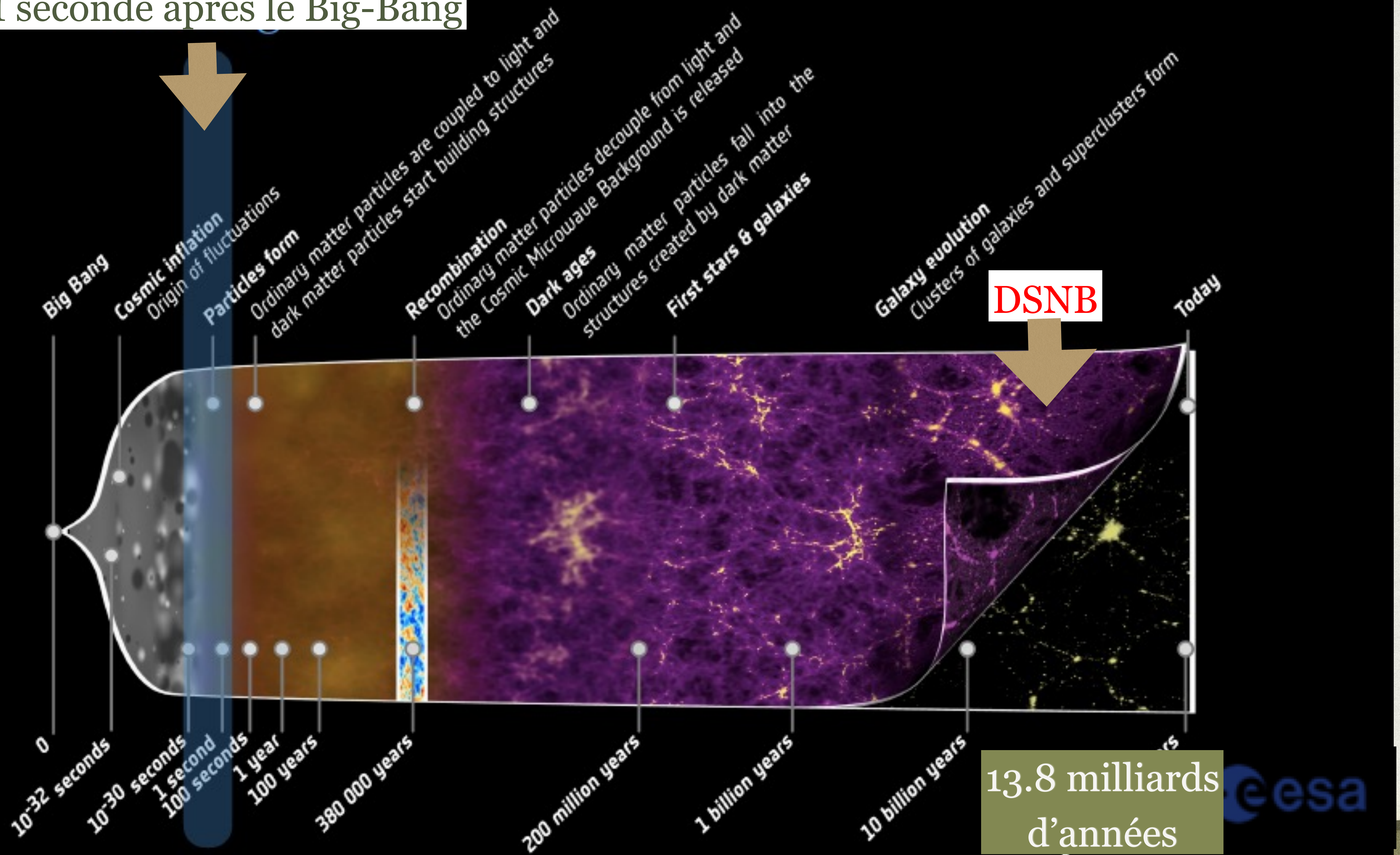
Optical- localization and distance,
progenitor, …

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

Gravitational waves -
explosion mechanism,
M-R and EOS, …

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

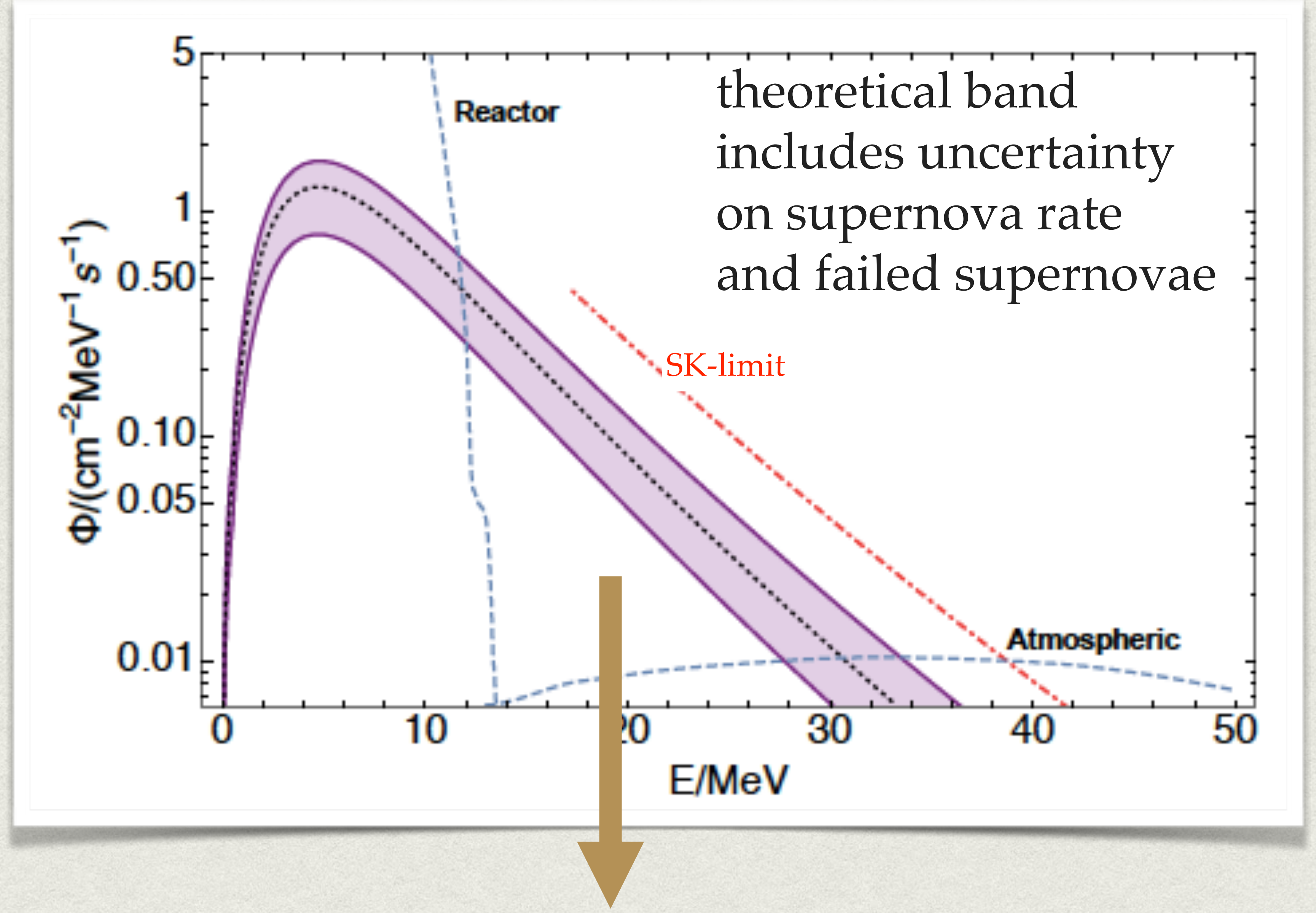
$$\phi^{\rm DSNB}_{\nu_\alpha}(E_\nu) = c \int \int {\rm dM}\, dz \left|\frac{dt}{dz}\right| \underleftrightarrow{R_{\rm SN}(z,\ {\rm M})}\ \underleftrightarrow{\phi_{\nu_\alpha, SN}(E'_\nu,\ {\rm M})}$$

$E'_\nu = E_\nu(1+z)$ redshifted neutrino energies $z \in [0,3]$

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

- There is a contribution from failed supernovae (black-hole): hotter energy spectrum determines the relic flux tail

Lunardini, PRL 2009



theoretical band includes uncertainty on supernova rate and failed supernovae

Priya and Lunardini JCAP 2017

DSNB detection window

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

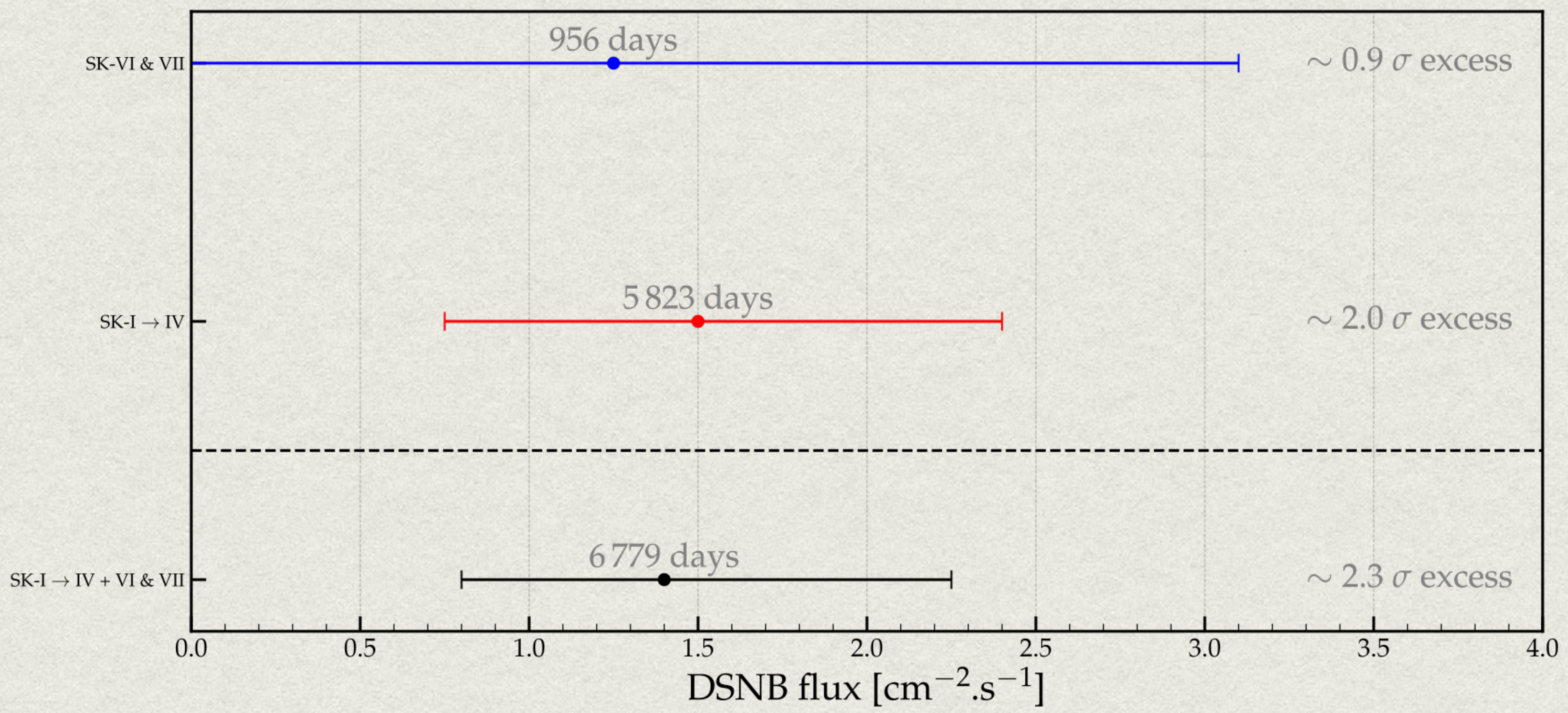
$\Omega_\Lambda = 0.7 \quad \Omega_m = 0.3$ dark energy and matter cosmic energy densities

$H_0 = 67.4\ {\rm km\ s^{-1} Mpc^{-1}}$ $\quad \Lambda CDM$

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

See Santos's talk

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



Courtesy of A. Beauchêne

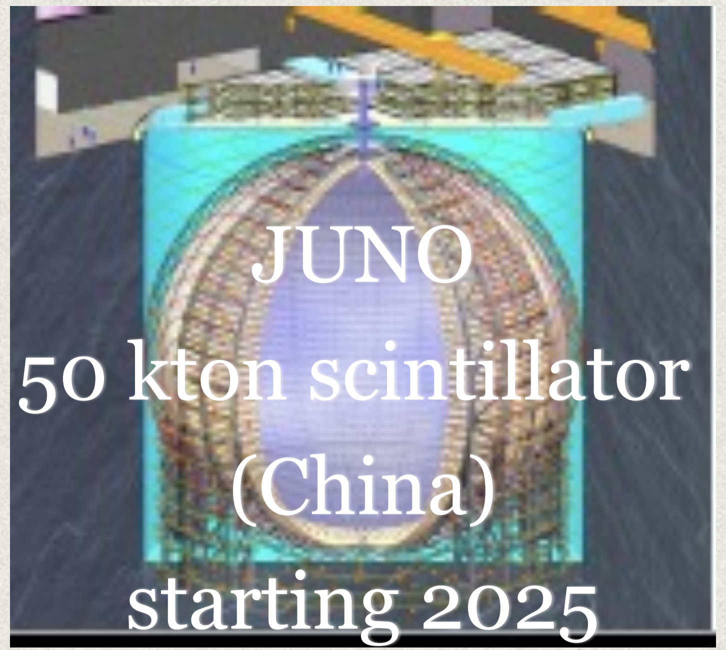
- **Expected DSNB events**
  10 anti-nue for SK-Gd (10 year), and nue in DUNE (20 years), 10-40 anti-nue for JUNO (20 years)
  hundreds anti-nue for Hyper-Kamiokande (10-20 years)
  10 nux (antinux) in dark matter detectors

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

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

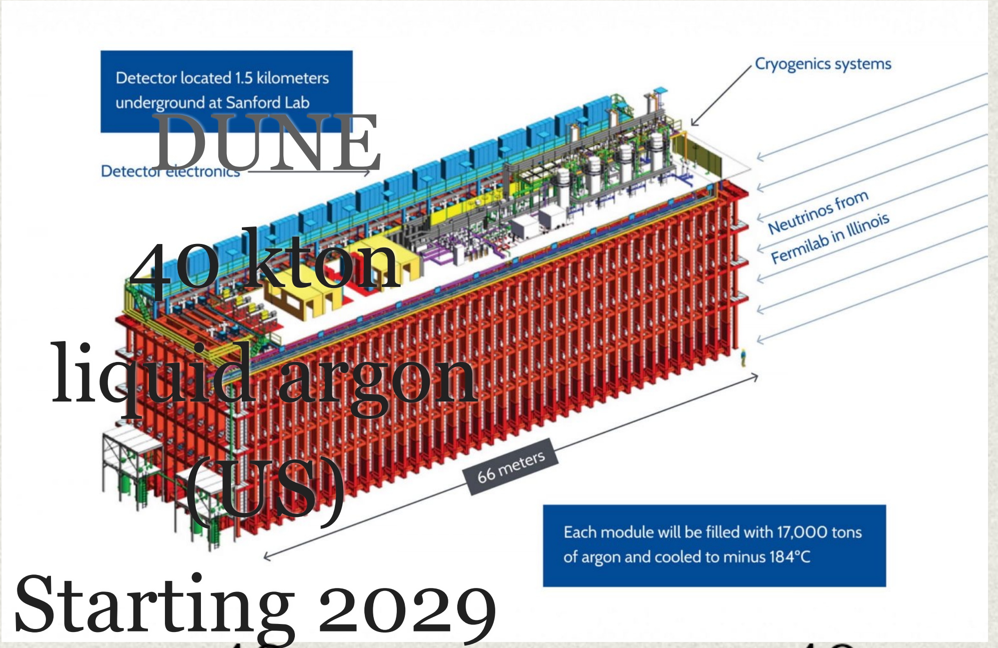
Hyper-Kamiokande
178 kton (FV) water (Japan)
Starting 2027

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



JUNO
50 kton scintillator
(China)
starting 2025

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



DUNE
40 kton
liquid argon
(US)
Starting 2029

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

Discovery could be imminent

STATUS on the DSNB

- 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

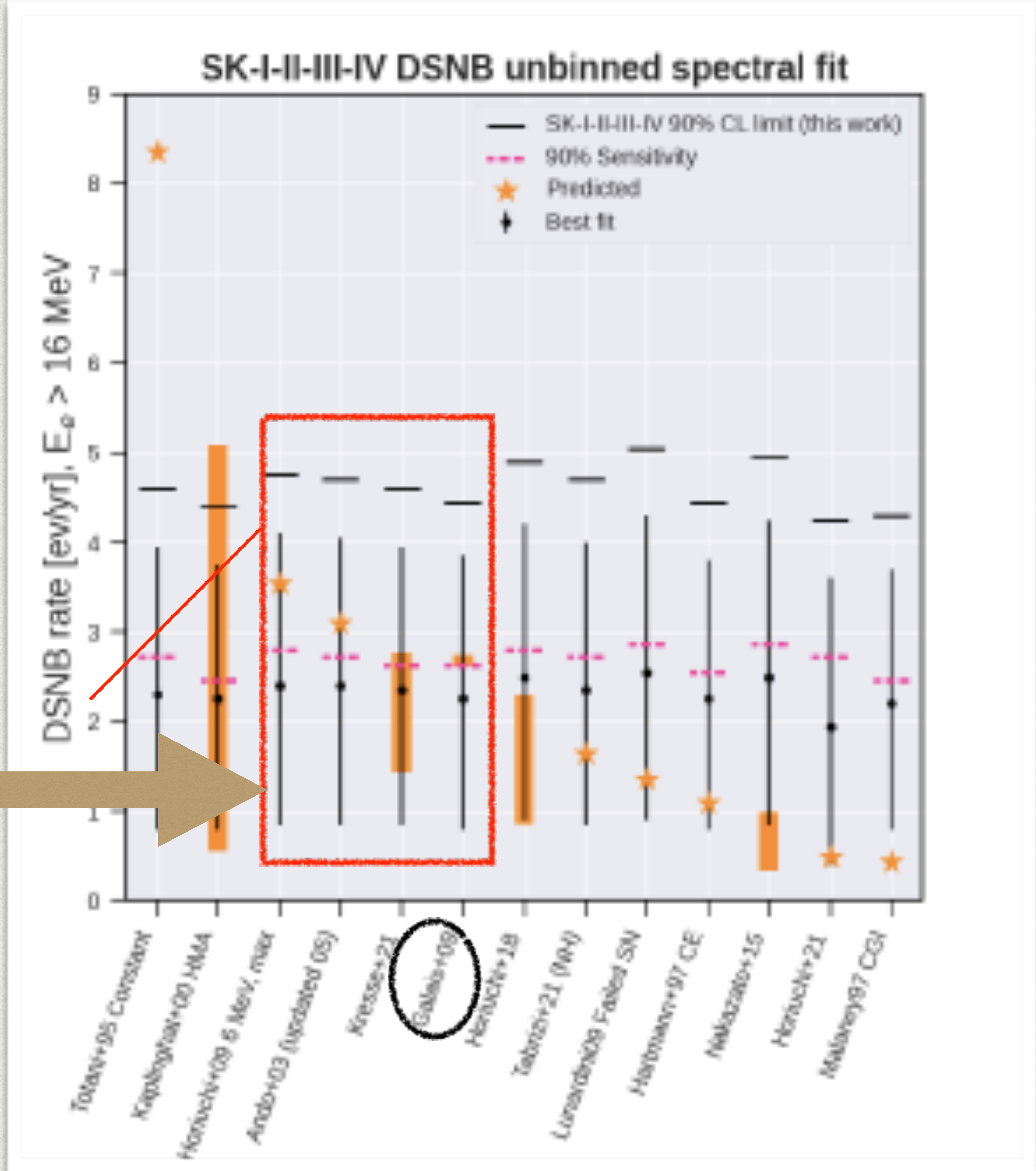
$19 \quad \nu_e \quad \mathrm{cm}^{-2} s^{-1} \quad (E_\nu \in [22.9, 36.9] \quad \mathrm{MeV})$

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

DSNB ENCODES CRUCIAL INFORMATION

- 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, ...

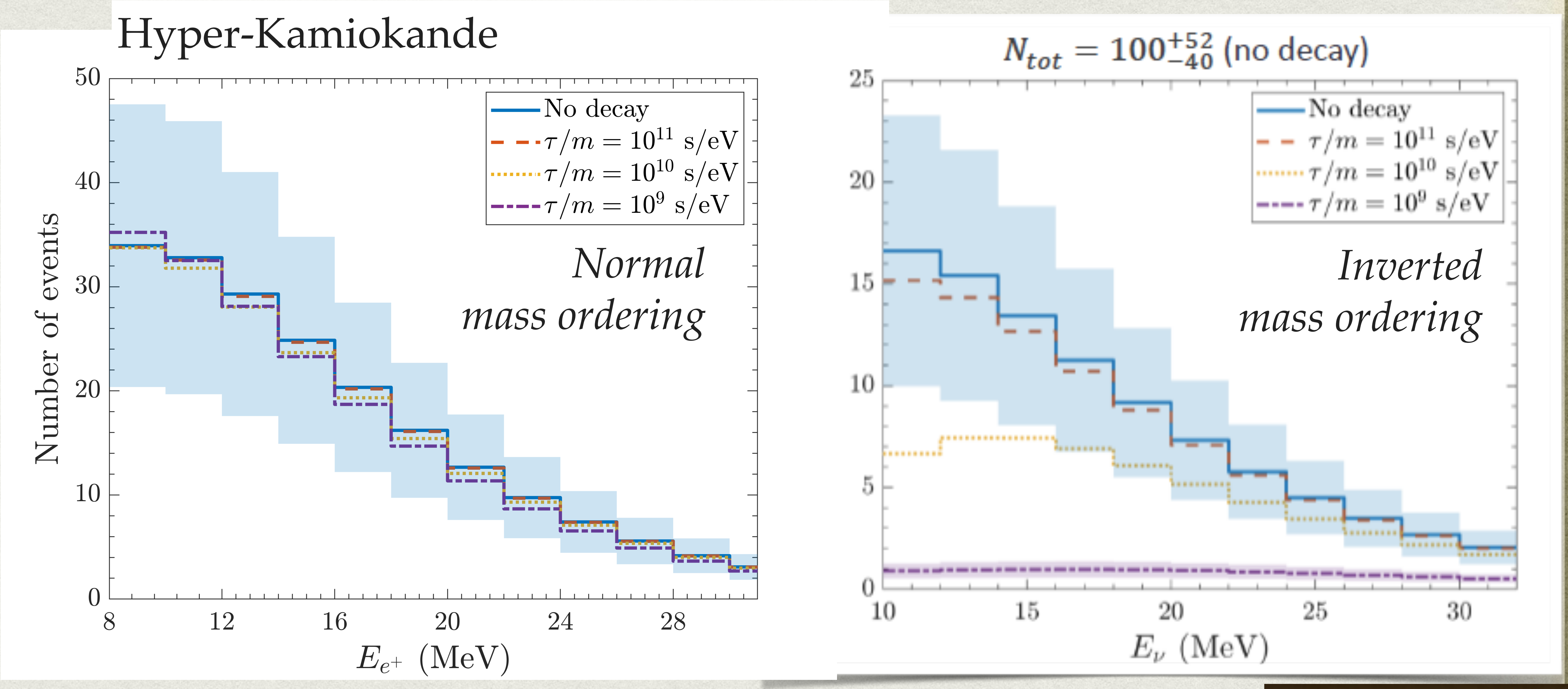
- flavor conversion phenomena beyond MSW, e.g. shock waves and self-interaction. Event rates can be modified by 10-20 %.

  Galais, Kneller, Gava, Volpe, PRD81, 2010

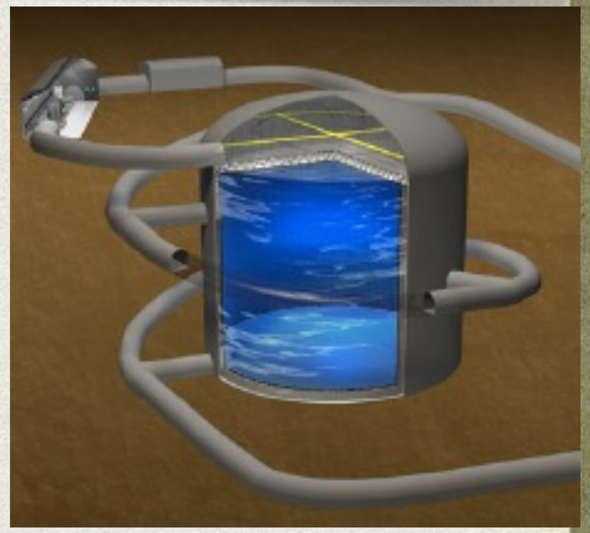
- non-standard neutrino properties such as neutrino decay.

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

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



Ivanez-Ballesteros, Volpe, 2023; 2209.12465



If DSNB not observed & mass ordering inverted, it could come from neutrino decay.
If DSNB observed & mass ordering normal, rates are degenerate with those in absence of decay.

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 astrophysics.

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

« *Femme jouant de guitare* », Renoir, 1879

NON-STANDARD INTERACTIONS (NSI) in SNe and BNS

- Current limits on NSI from solar, oscillations and as coherent neutrino-nucleus scattering.

see e.g. Biggio et al 2009, Ohlsson, 2013, Davidson et al 2013, Farzan and Tortola 2018, Bhupal-Dev et al 2019, Giunti 2020,
Barbeau, Efremenko, Scholberg, 2111.07033, Coherent coll….

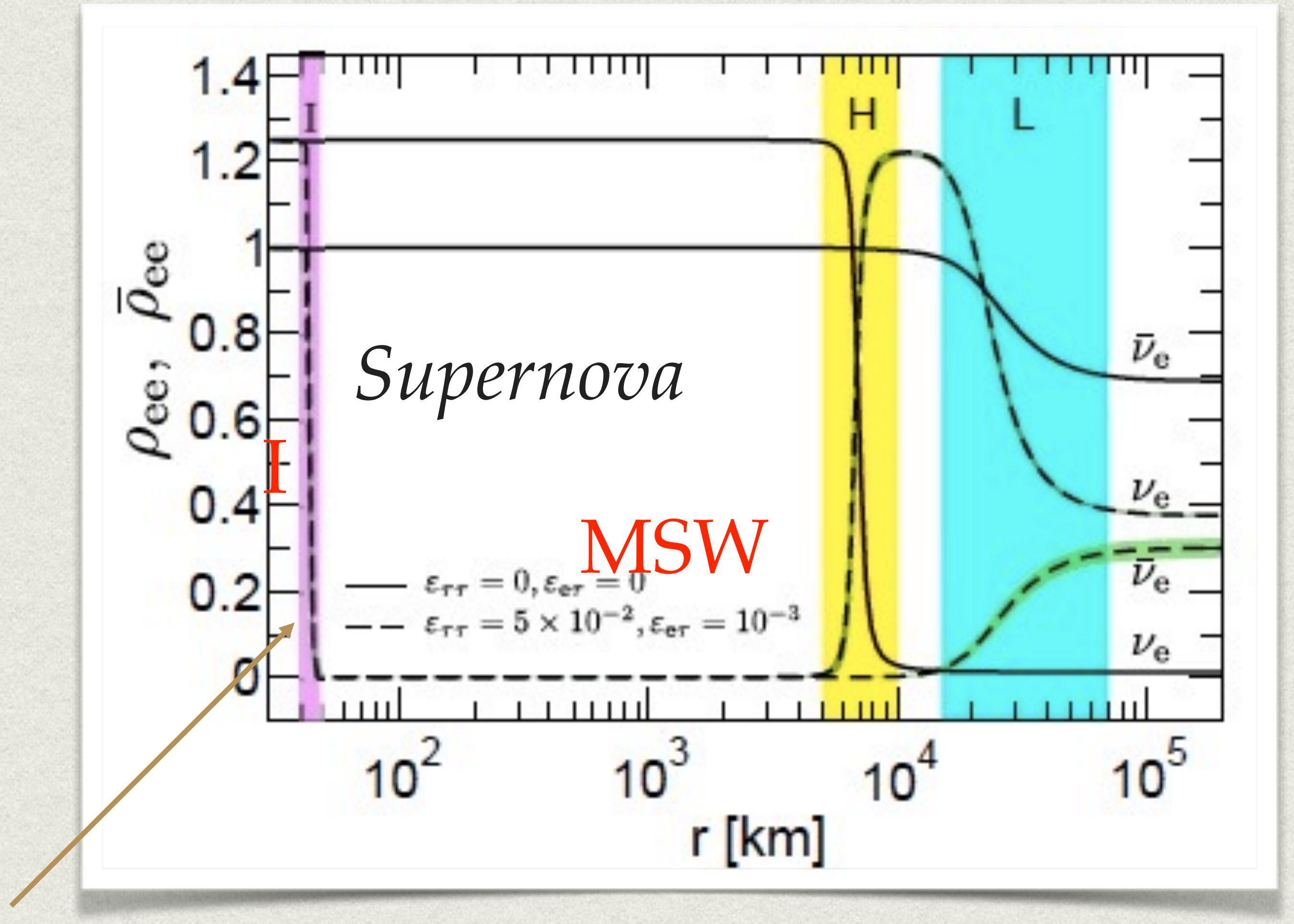
- NSI impact studied in core-collapse supernovae and BNS.

$$\mathcal{H}_{\rm NSI} = \sqrt{2} G_F \sum_f n_f \epsilon^f \qquad f = e, d, u$$

$$\epsilon^f \quad \text{NSI couplings}$$

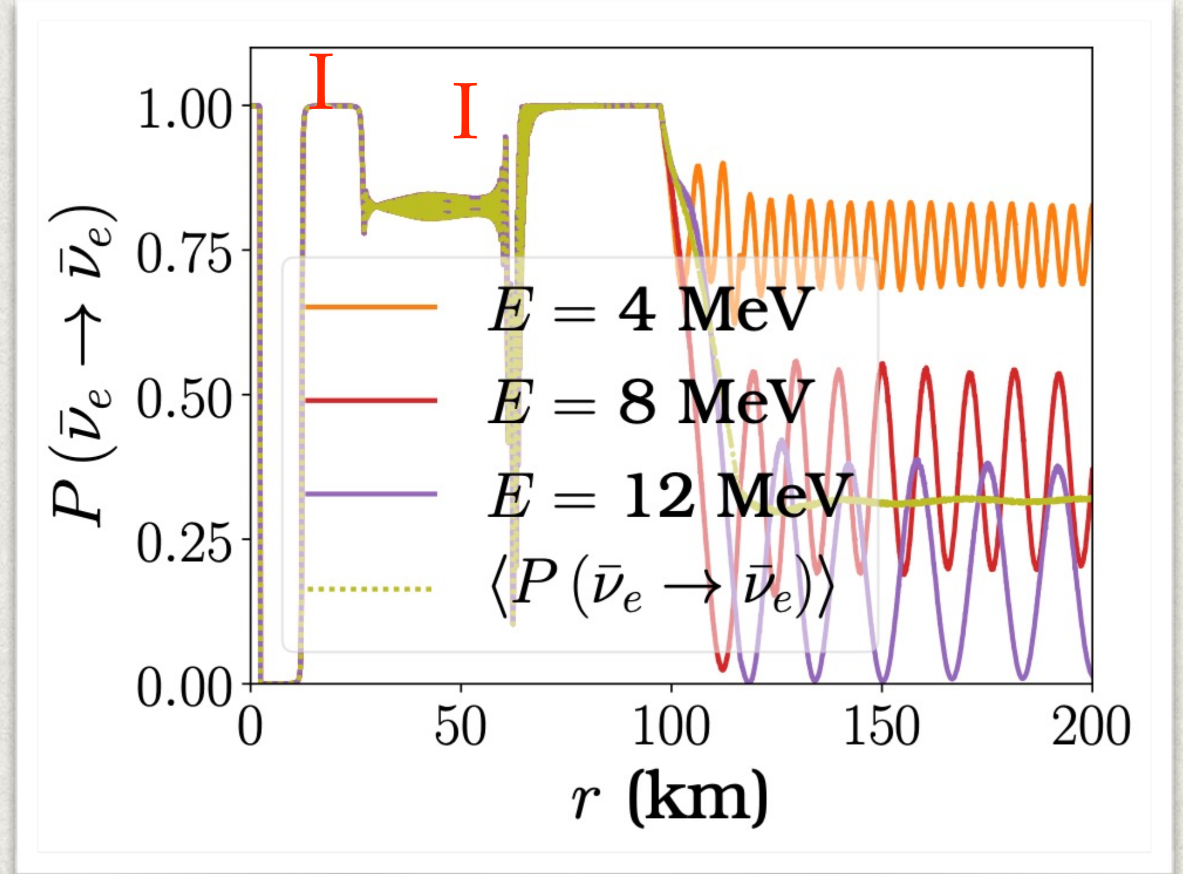
see e.g. Fogli et al, 2002, Esteban-Pretel et al 2007, Stapleford et al 2016, …

Impact flavor evolution and potentially r-process nucleosynthesis, even for very small NSI couplings



Esteban-Pretel et al, 2010

I-resonance : MSW-like resonance due to NSI



Antineutrinos

Chatelain and Volpe PRD97 (2018)

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

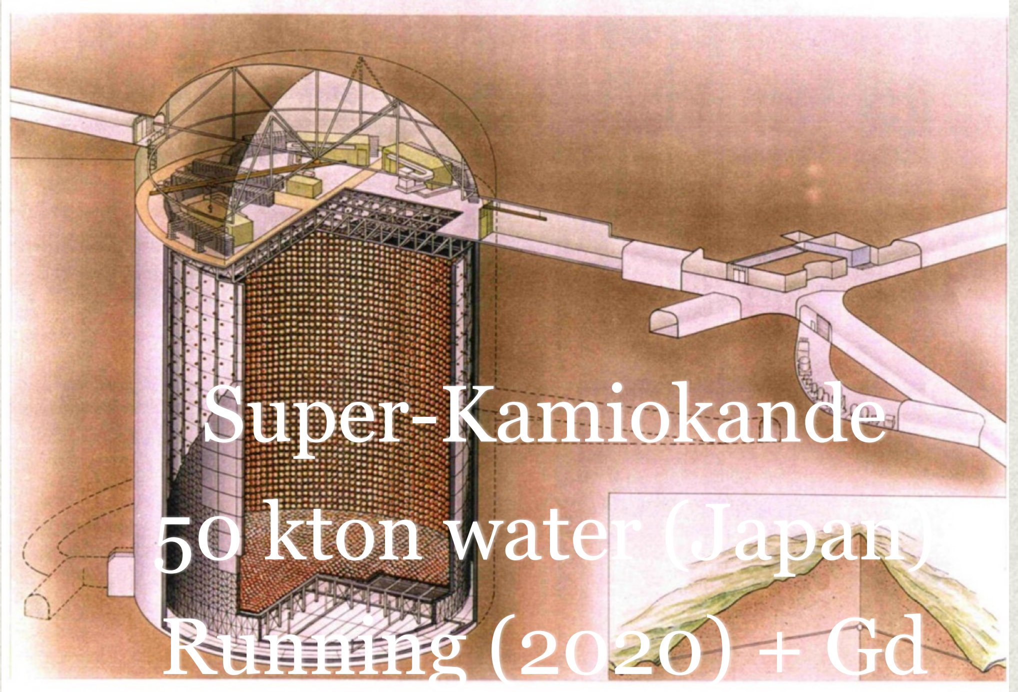
$\mathrm{CORE-COLLAPSESUPERNOVARATES(MilkyWay)}(100y)^{-1}$

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.

THE DSNB DISCOVERY

- **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

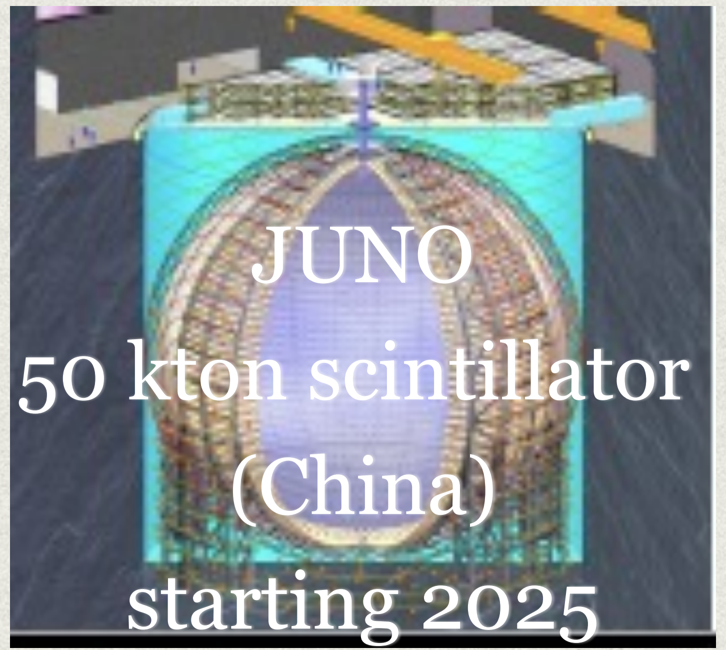


Super-Kamiokande
50 kton water (Japan)
Running (2020) + Gd

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

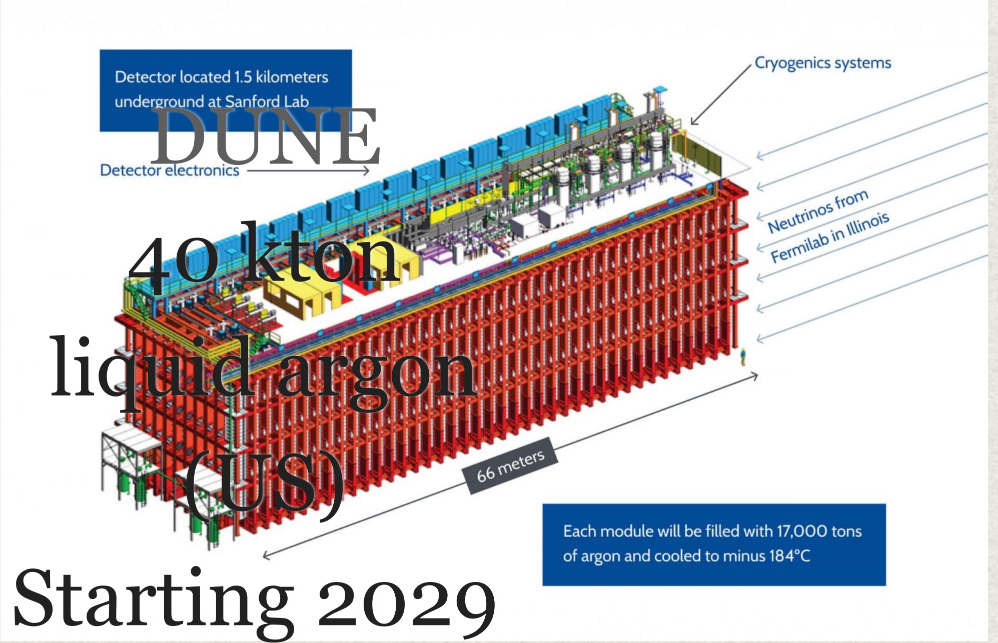
Hyper-Kamiokande
178 kton (FV) water (Japan)
Starting 2027

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



JUNO
50 kton scintillator
(China)
starting 2025

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



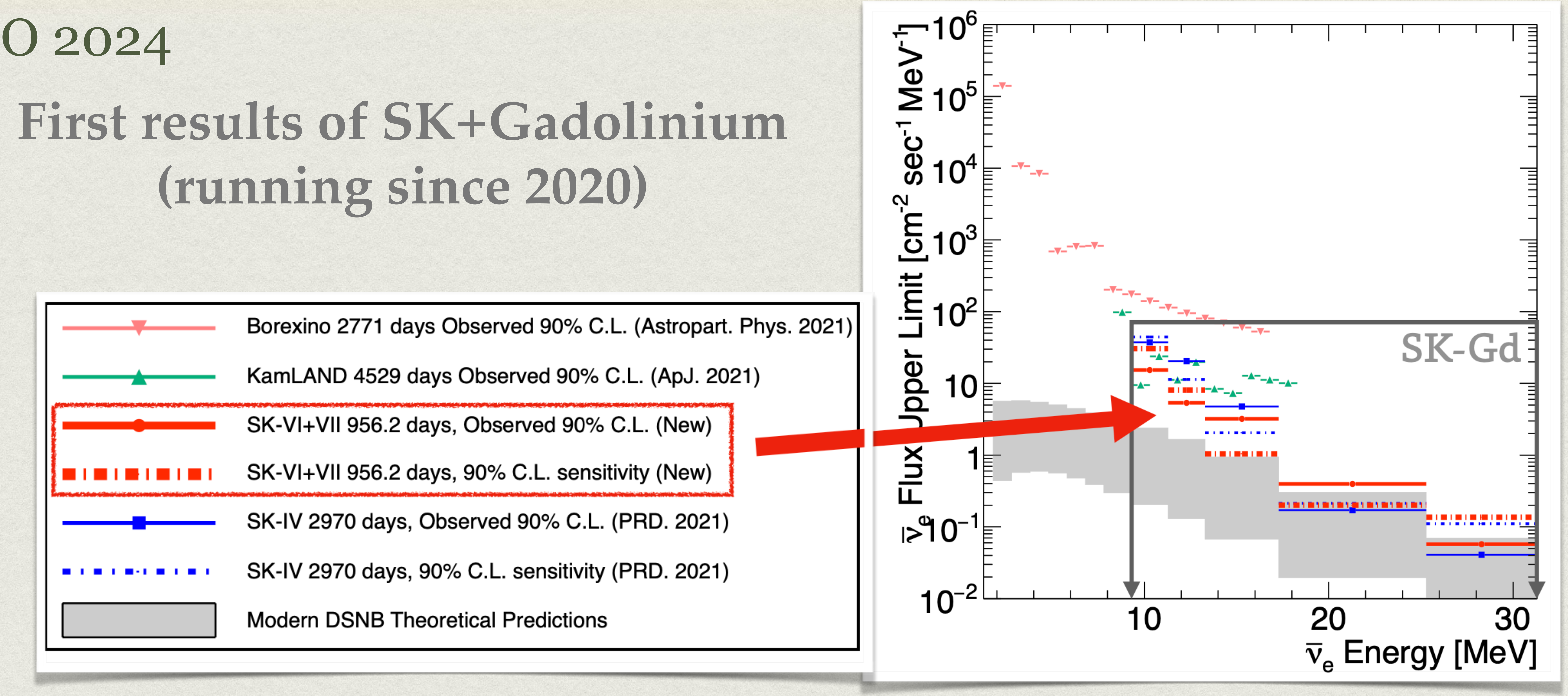
DUNE
40 kton
liquid argon
(US)
Starting 2029

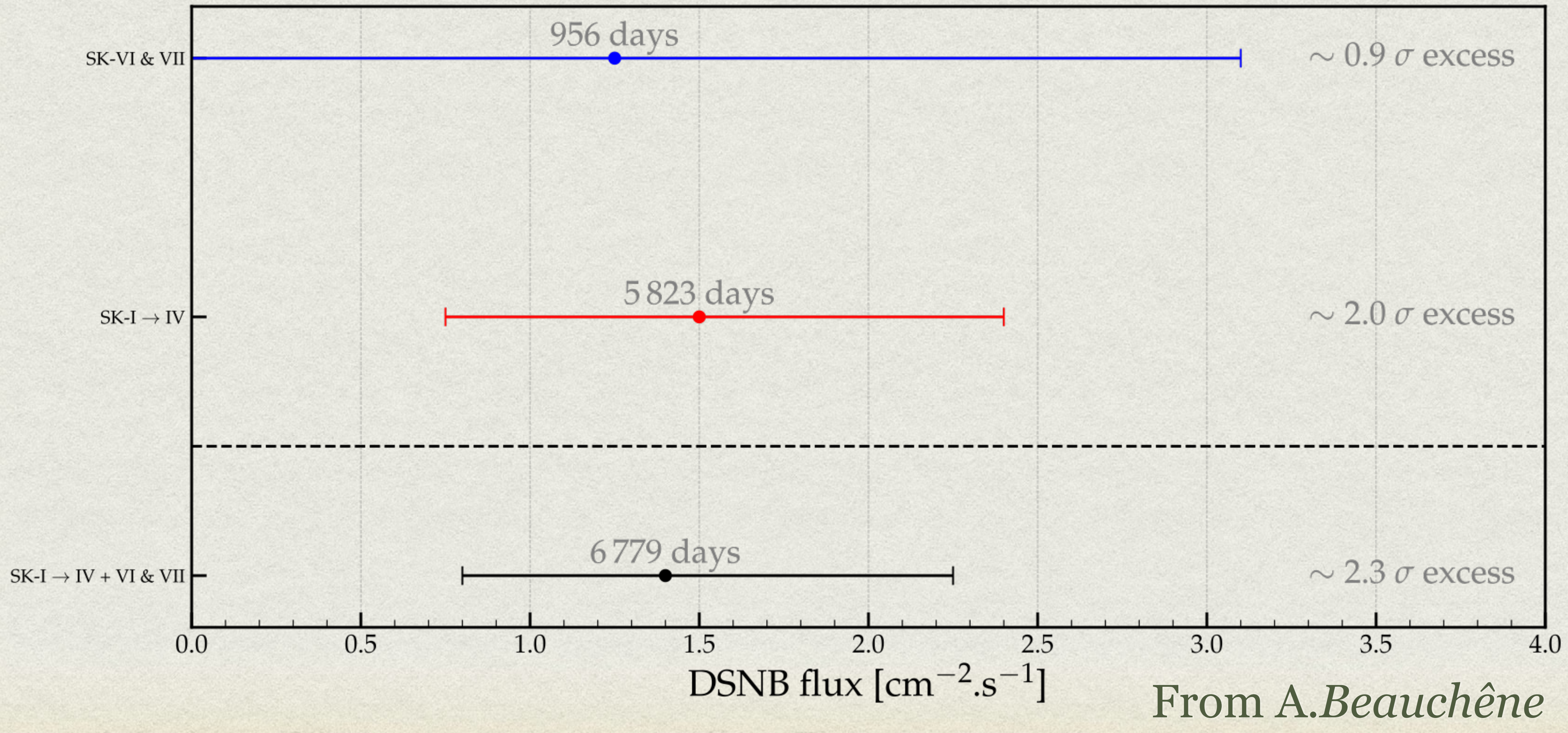
$$\nu_e +^{40} Ar \rightarrow e^- +^{40} K$$

and DARK MATTER DETECTORS
DSNB is part of the neutrino floor

NEUTRINO 2024

First results of SK+Gadolinium (running since 2020)





From A.*Beauchêne*

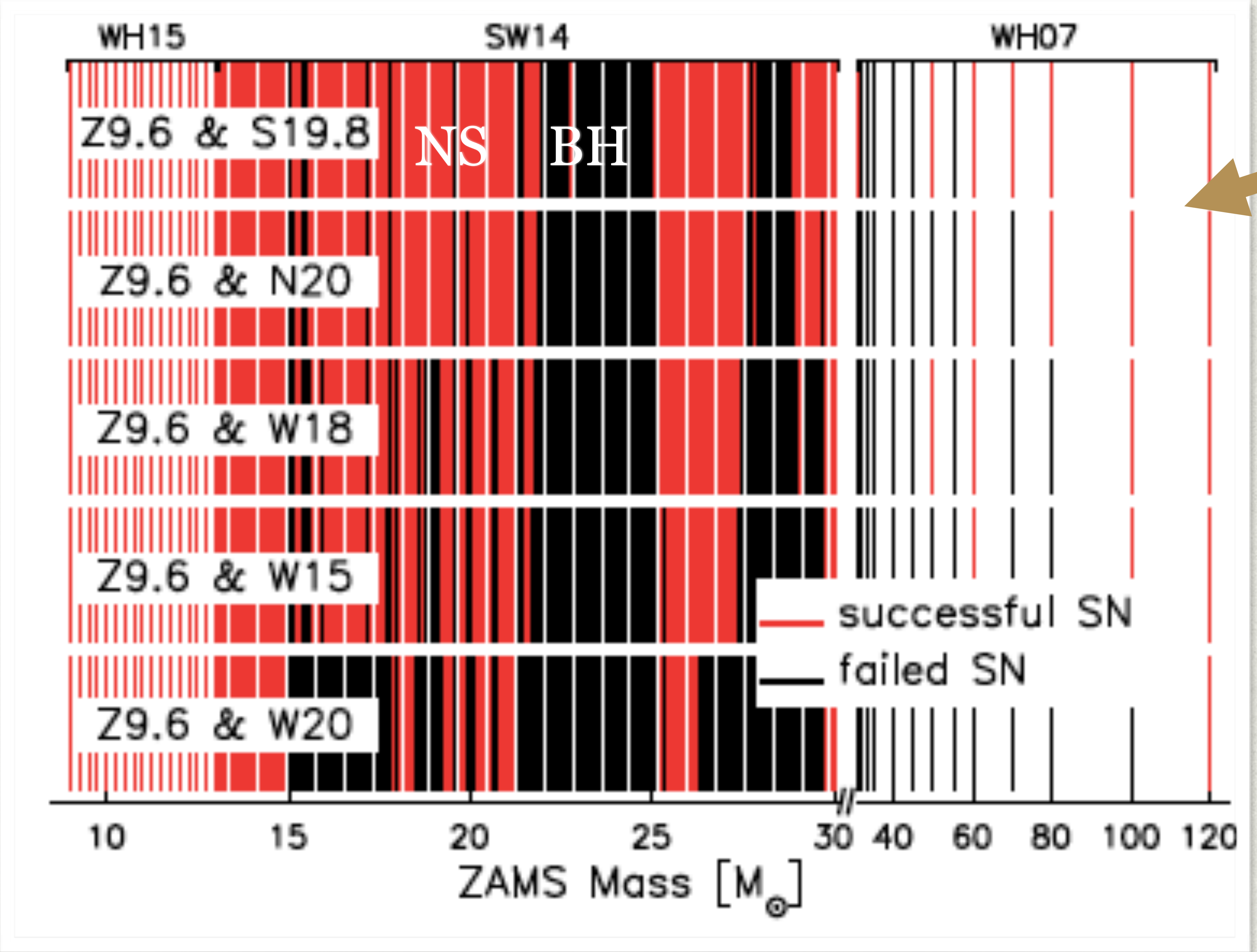
Highlight:

- 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!!**

DSNB IMPORTANT

Fraction of black-hole forming supernovae versus neutron-star forming supernovae debated



Kresse et al 2021

Therefore 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.

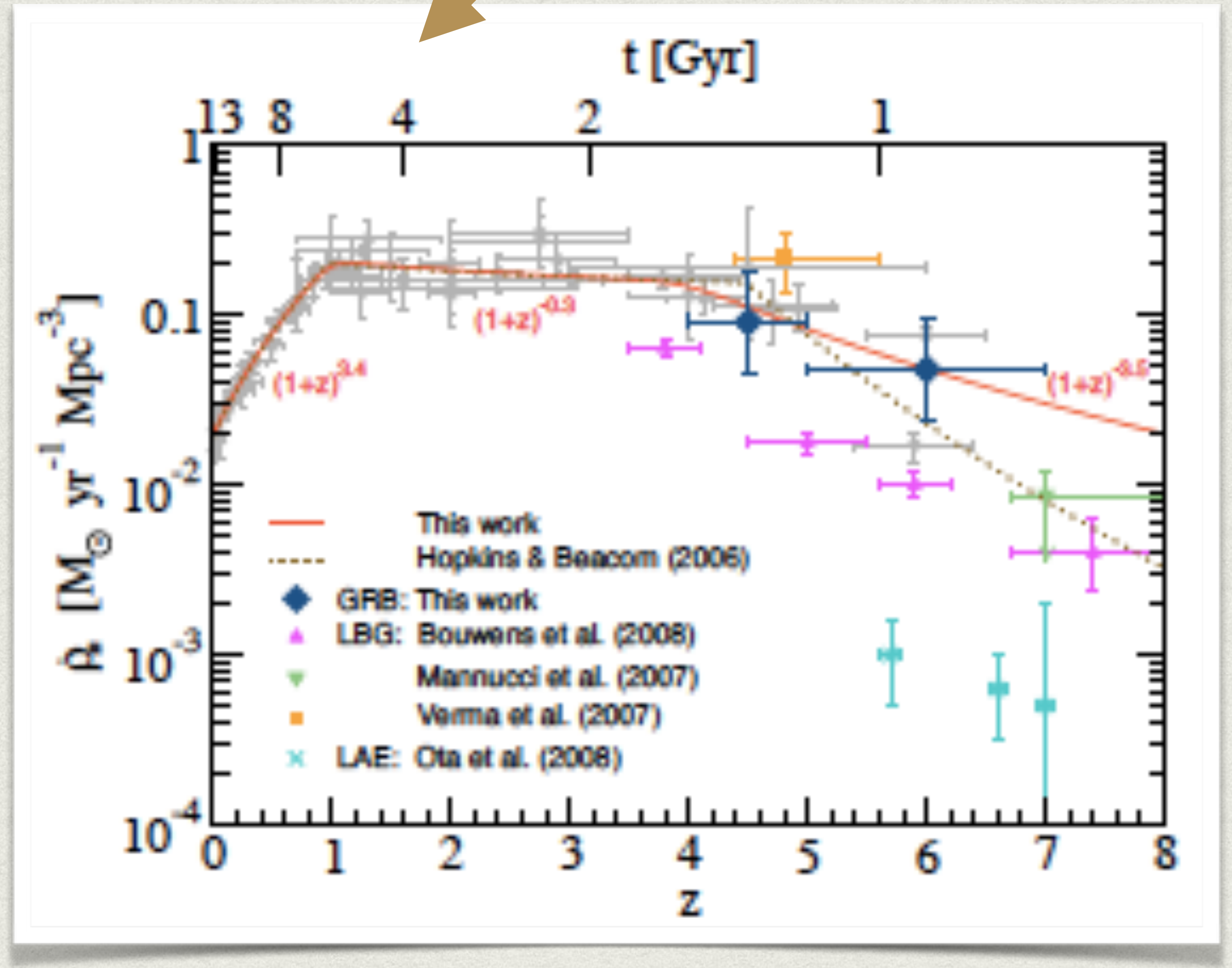
Ando 2003, Lisi et al 2004,
De Gouvea et al 2020,
Tabrizi et Horiuchi 2021,
Ivanez-Ballesteros and Volpe, 2022.

FOR ASTROPHYSICS AND PARTICLE PHYSICS

CORE-COLLAPSE SUPERNOVA RATE

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

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



Yuksel et al, i Astrophys. J(2008)

relevant for the DSNB

below detection threshold

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

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

Salpeter Initial Mass Function (IMF)

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

$$R_{SN}(0) = \int_{8\ \mathrm{M}_\odot}^{125\ \mathrm{M}_\odot} R_{\mathrm{SN}}(0,\mathrm{M})d\mathrm{M}$$
$$= 1.25 \pm 0.5 \times 10^{-4} yr^{-1} Mpc^{-3}$$

ONE of the main UNCERTAINTIES

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

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

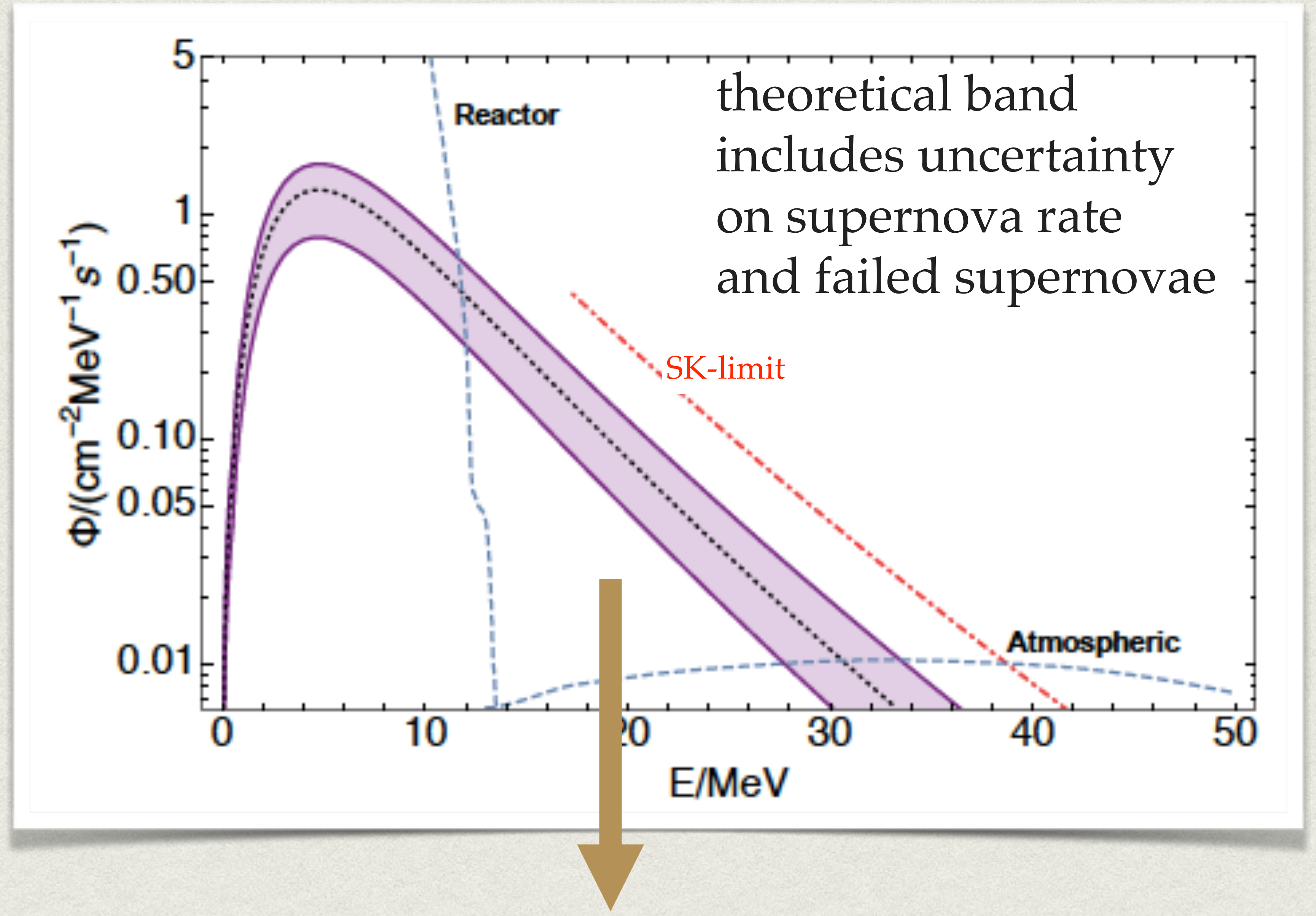
$$\phi^{\mathrm{DSNB}}_{\nu_\alpha}(E_\nu) = c \int\int \mathrm{dM}\; dz \left|\frac{dt}{dz}\right| \underleftrightarrow{R_{\mathrm{SN}}(z,\ \mathrm{M})}\ \underleftrightarrow{\phi_{\nu_\alpha,SN}(E'_\nu,\ \mathrm{M})}$$

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

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

- There is a contribution from failed supernovae (black-hole): hotter energy spectrum determines the relic flux tail

Lunardini, PRL 2009



theoretical band includes uncertainty on supernova rate and failed supernovae

Priya and Lunardini JCAP 2017

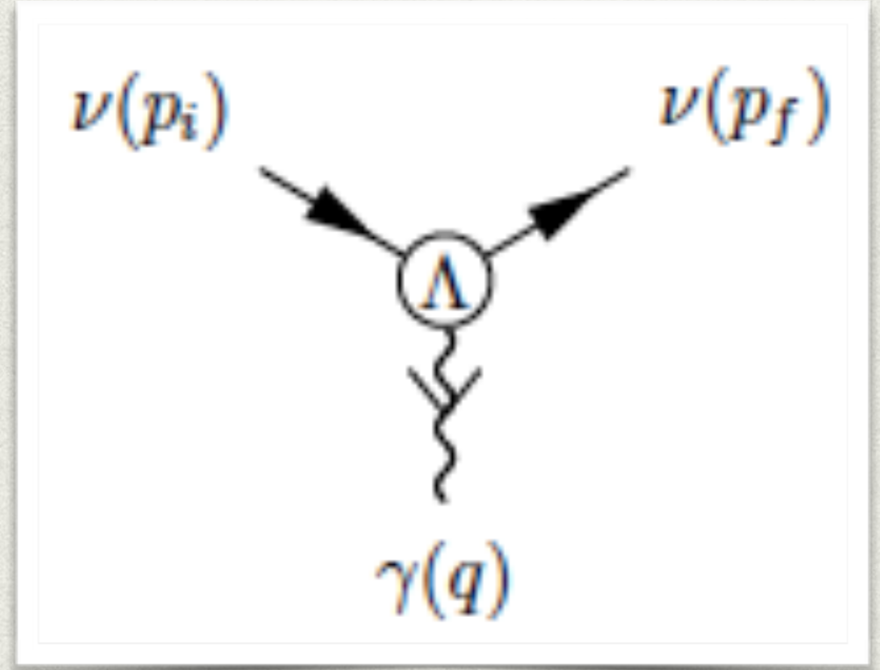
DSNB detection window

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

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

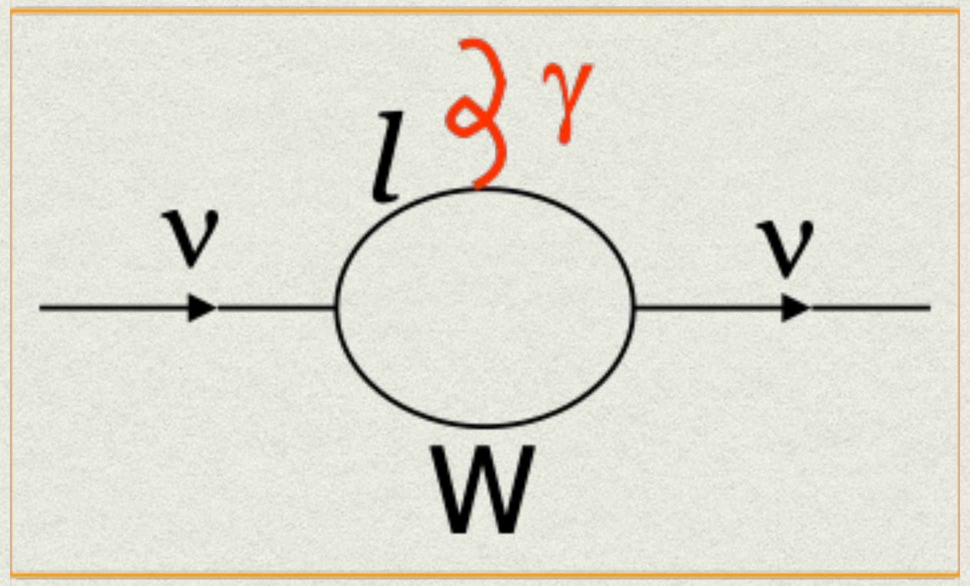
$H_0 = 67.4\ \mathrm{km\ s^{-1}Mpc^{-1}}$ $\quad \Lambda CDM$

SN1987A: an incredible laboratory for particle physics



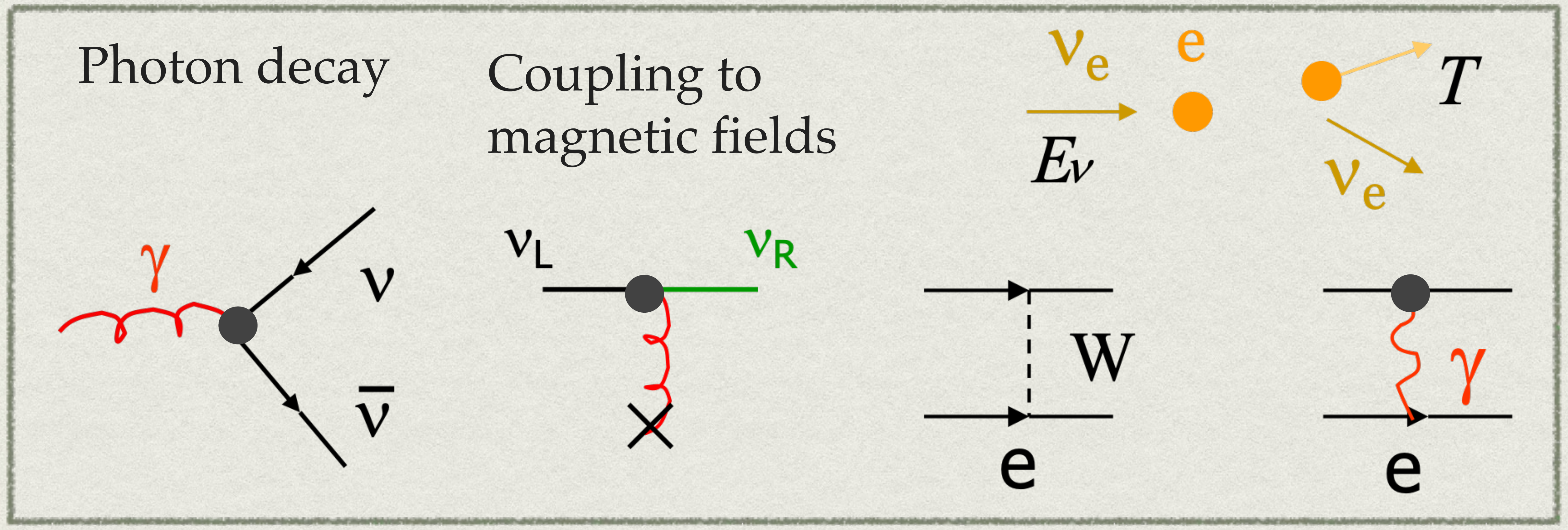
Effective one-photon coupling of
a neutrino with a photon

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



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

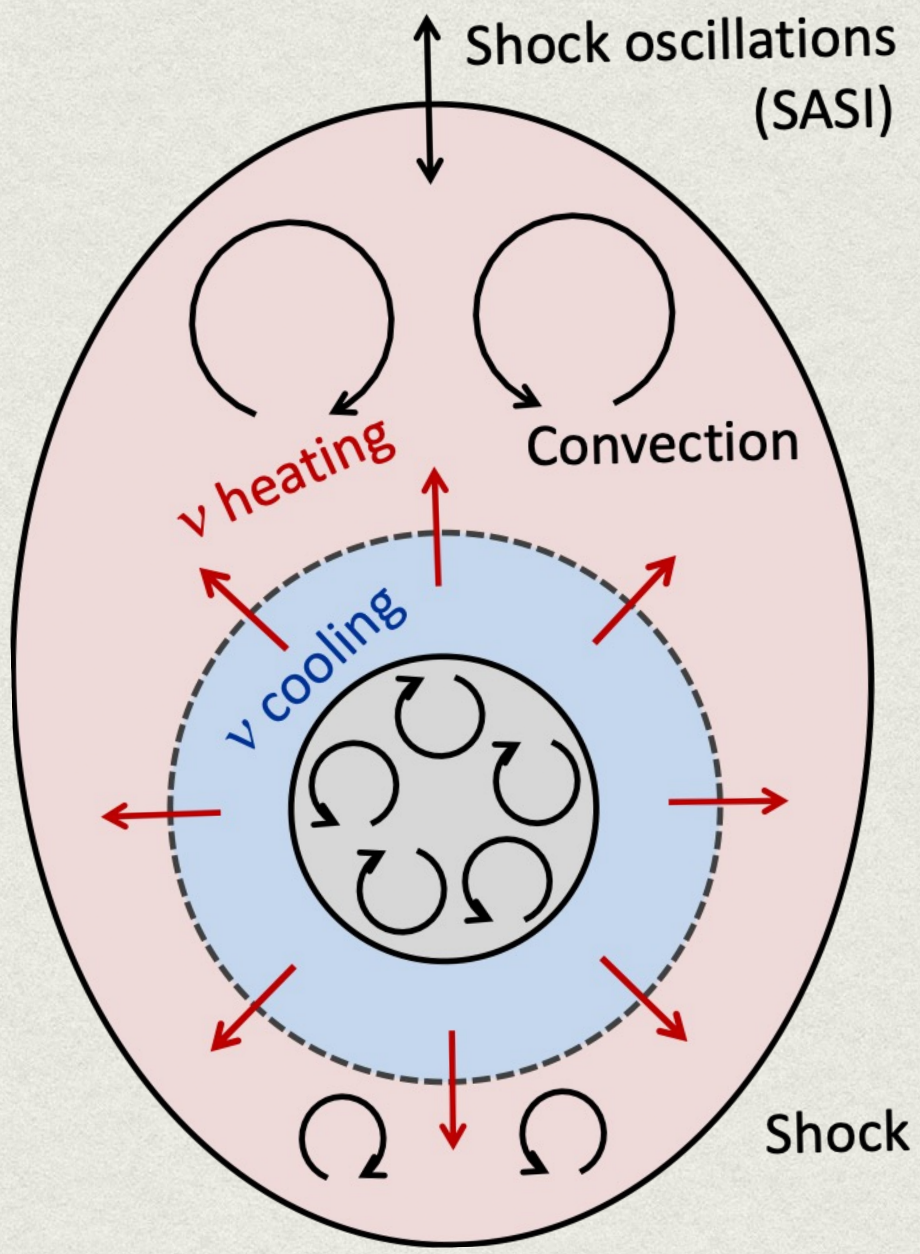
See the review Giunti and Studenikin, RMP 87 (2015)

Numerous limits on non-standard properties, particles and interactions

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, 2024)

A MAJOR STEP FORWARD EVERY DECADE

THE Mikheev-Smirnov-Wolfenstein (MSW) EFFECT

Wolfenstein, 1978; Mikheev and Smirnov, 1985

- The total Hamiltonian in 2 neutrino flavors

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

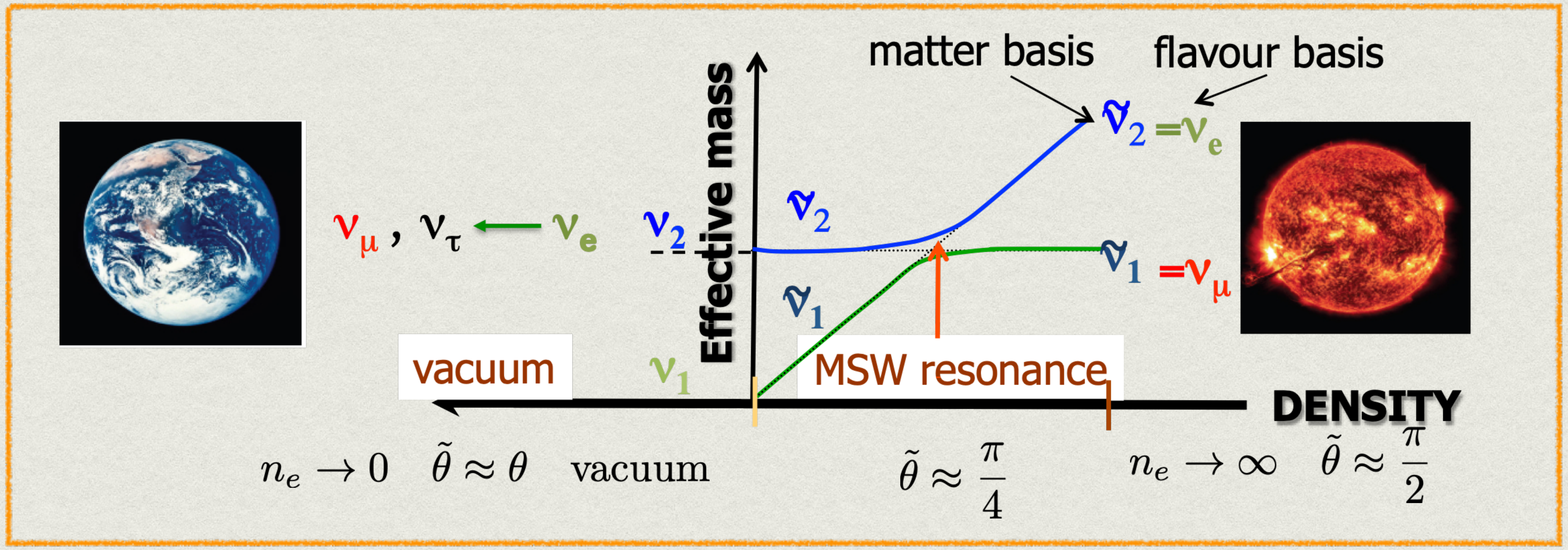
- It can be made diagonal with the rotation (giving the so called « matter basis ») :

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

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.

FLAVOR MECHANISMS

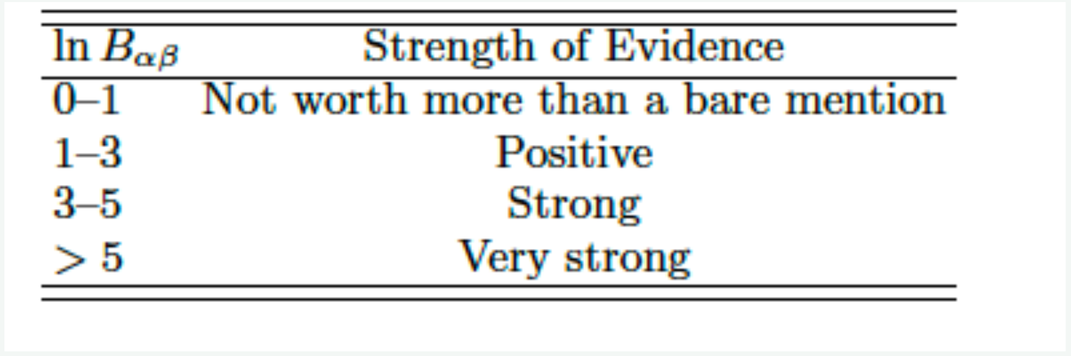
- First Bayesian analysis to explore our capacity to discriminate among models.

  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

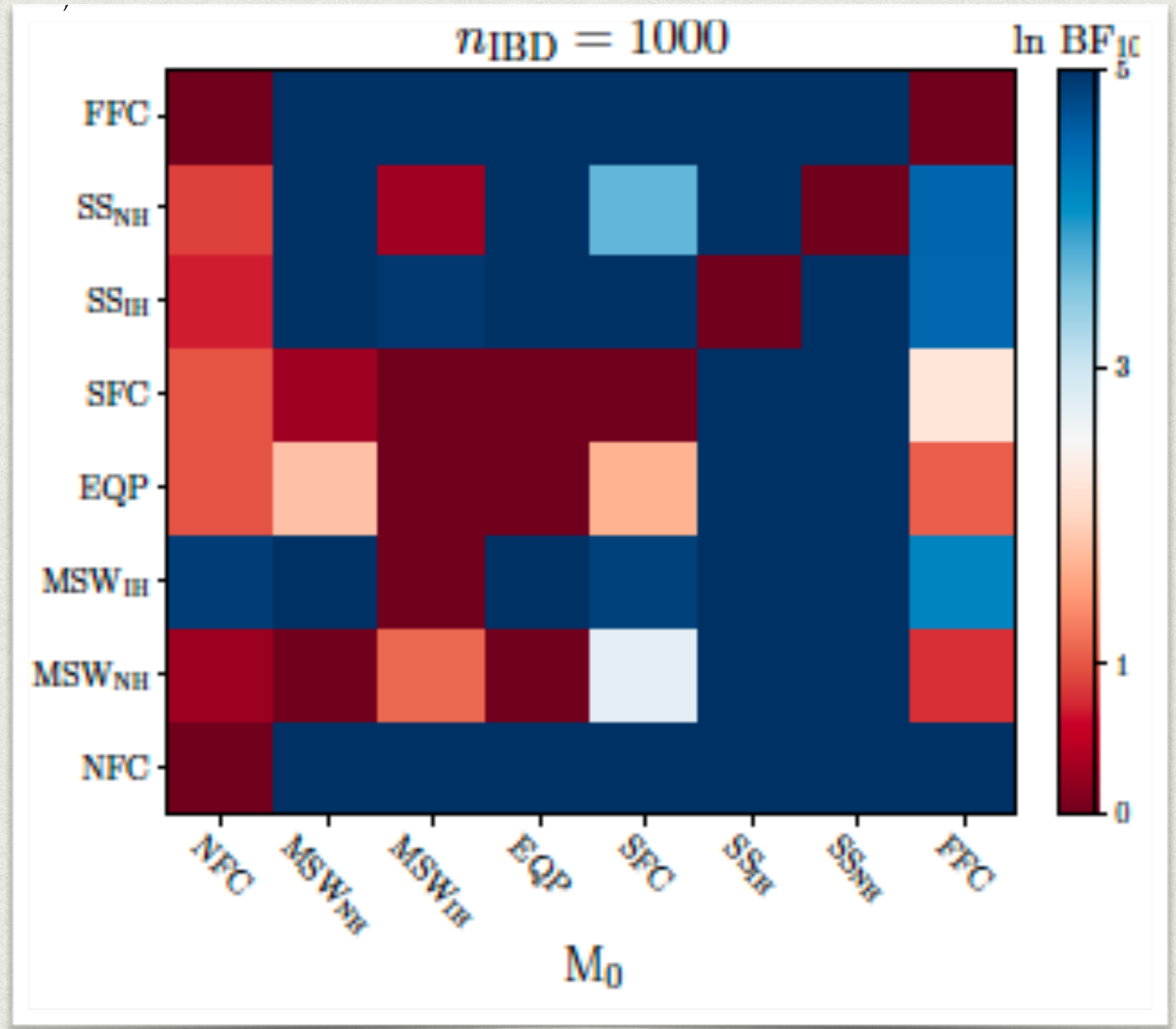
  18 2D and 3D supernova models (9 M to 60 M), 300 ms, MSW
  Saez et al 2024

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



$\ln B_{\alpha\beta}$	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