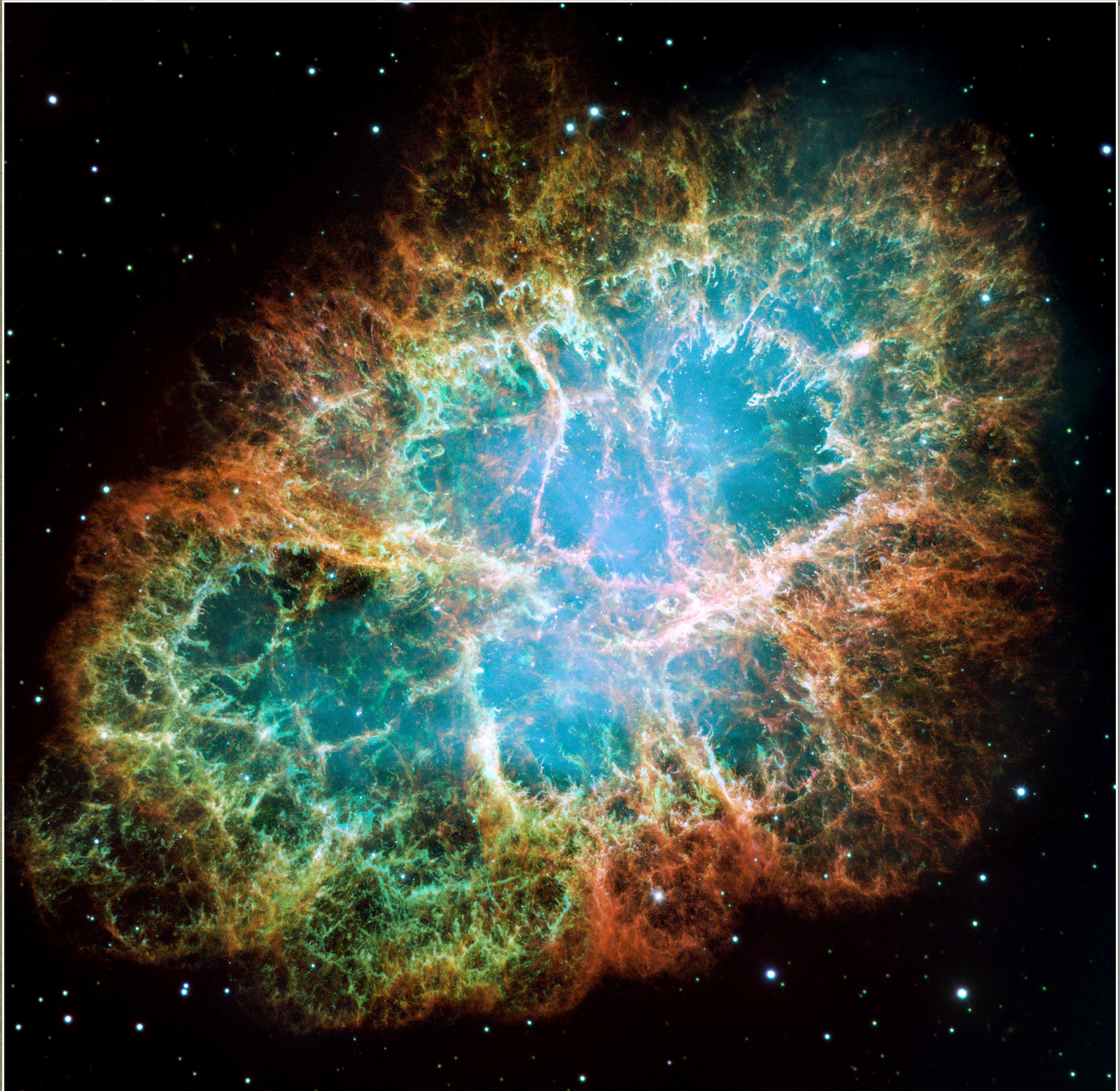


https://science.nasa.gov/asset/hubble/a-giant-hubble-mosaic-of-the-crab-nebula/

NEUTRINO ASTROPHYSICS:
A window to new physics

Lecture II

M. Cristina VOLPE

French National Center for Research (CNRS) and Astroparticle and Cosmology (APC) Laboratory,
email: volpe@apc.in2p3.fr

OUTLINE OF THE SECOND LECTURE

- **Neutrinos vacuum oscillations**

- **Neutrinos and stars**
  > Stars and neutrinos
  > SN1987A
  > The core-collapse supernova mechanism

- > Dense environments
  > Neutrino evolution in dense environments

REFERENCES

- C. Giunti and C.W Kim, «*Fundamentals of neutrino physics and astrophysics*», Oxford University Press (2007)
- Georg G. Raffelt, « *Stars as laboratories for fundamental physics*», The University of Chicago press (1996)
- R.N. Mohapatra and P.B. Pal, «*Massive neutrinos in physics and astrophysics*», World Scientific (1998)
- M. Cristina Volpe, «*Neutrinos from dense environments: Flavor mechanisms, theoretical approaches, observations and new directions*», Review of Modern Physics 96 (2024) 2, 025004arXiv: 2301.11814

The weak CC Lagrangian

- Let us consider the weak charged-current leptonic interaction $\mathcal{L}$

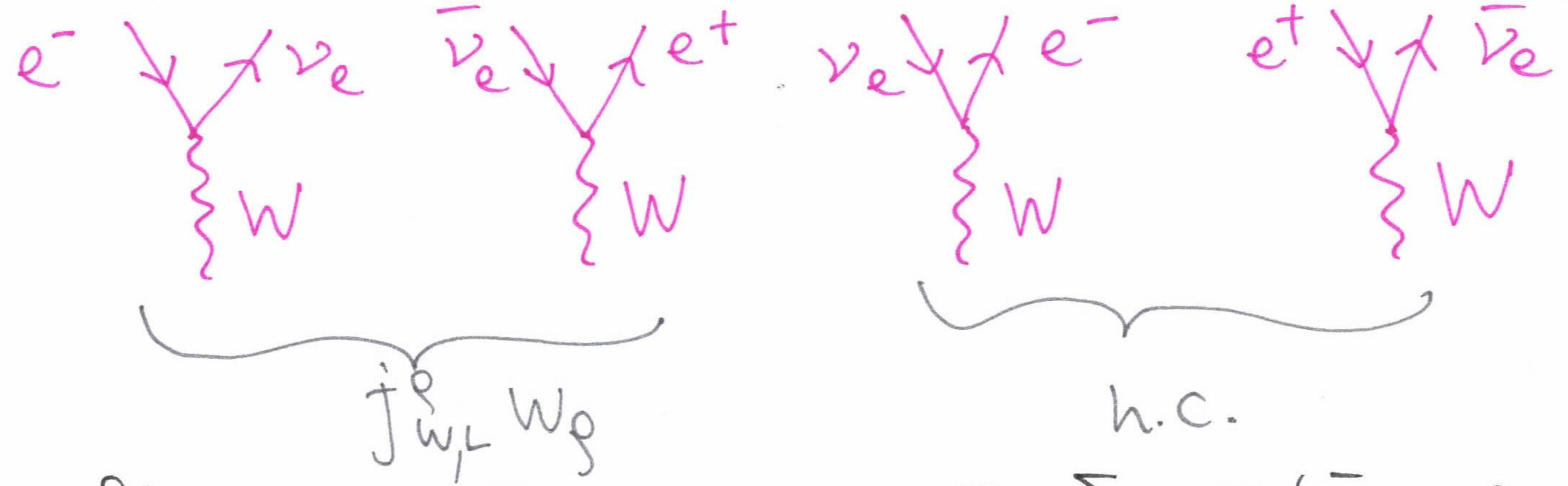
$$\mathcal{L}^{CC} = -\frac{g}{2\sqrt{2}}\left(j^{\rho}_{W,L} W_{\rho} + h.c.\right)$$

with

$$j^{\rho}_{W,L} = 2\sum_{\alpha=e,\mu,\tau}\left(\bar{\nu}_{\alpha L}\gamma^{\rho} l_{\alpha L}\right) = 2\sum_{\alpha=e,\mu,\tau}\sum_{k} U^{*}_{\alpha k}\left(\bar{\nu}_{kL}\gamma^{\rho} l_{\alpha L}\right)$$

(leptonic charged-current)

For example



and

$$j^{\rho +}_{W_L} = 2\sum_{\alpha=e,\mu,\tau}\bar{l}_{\alpha L}\gamma^{\rho}\nu_{\alpha L} = 2\sum_{\alpha=e,\mu,\tau}\sum_{k} U_{\alpha k}\left(\bar{l}_{\alpha L}\gamma^{\rho}\nu_{kL}\right)$$

- $|\nu_{\alpha}\rangle = U^{*}_{\alpha k}\,|\nu_{k}\rangle$ (flavor states) while $\nu_{\alpha L}(x) = U_{\alpha k}\,\nu_{kL}(x)$ (flavor fields)

Vacuum oscillations : the parameters

- $\sum \Delta m^2 = 0 \qquad m_1^2 - m_1^2 + m_2^2 - m_2^2 + m_3^2 - m_3^2 = 0$

  $\Delta m^2_{21} \sim 10^{-5}\mathrm{eV}^2(\mathrm{solar})$

  $\Delta m^2_{32} \sim 10^{-3}\mathrm{eV}^2(\mathrm{atmospheric})$

  Only two Dm² are independent for 3 active neutrinos.

- An NxN matrix is defined by $2N^2$ real elements, with unitarity conditions N^2 are left. out of which $\frac{N(N-1)}{2}$ angles, $\frac{N(N+1)}{2}$ are phases. For N = 3, there are 3 angles and 6 phases.

$U_{\alpha k} e^{-i\theta_k} \rightarrow U_{\alpha k}$ $\nu_{kL} \rightarrow e^{i\theta_k}\nu_{kL}$ rephasing of the neutrinos fields

$U_{\alpha k} e^{i\eta_\alpha} \rightarrow U_{\alpha k}$ $l_\alpha \rightarrow e^{-i\eta_\alpha} l_\alpha$ rephasing of the charged leptons fields

By a redefinition of the lepton fields we can absorb 5 out of the 6 phases if neutrinos are Dirac particles. If they are Majorana particles, only the charged lepton fields can reabsorb phases because of the Majorana mass term. So, there are two extra phases in the Majorana case.

The PMNS matrix

- For three neutrino flavors the PMNS matrix depends on three mixing angles, one Dirac and two Majorana phases (not shown):

$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

THE CP violating phase INTRODUCES A ν-$\bar{\nu}$ ASYMMETRY.

→ For three mixing angles are precisely known, for the Dirac phase we have a hint (1.5-2 sigma), the Majorana phases are unknown (not important for oscillations).

Oscillation parameters: current status

	Ref. [181] w/o SK-ATM	
NO	Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.72^{+0.18}_{-0.23}$	$4.06 \to 6.20$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.203^{+0.056}_{-0.059}$	$2.029 \to 2.391$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$
$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$2.437^{+0.028}_{-0.027}$	$2.354 \to 2.523$

S. Salas et al (PDG), PRD 110, 030001(2024).

Current values of the oscillation parameters from the PDG.

Crucial open questions include

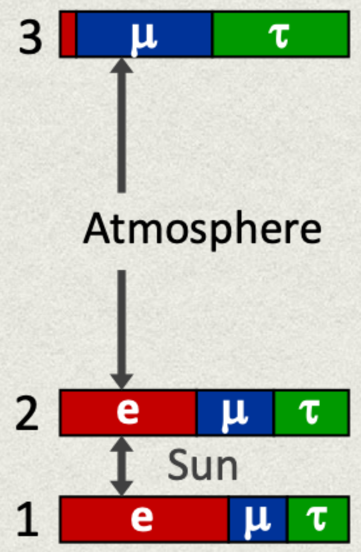
> Only two Dm^2 are independent for 3 active neutrinos.

More oscillation frequencies (anomalies in oscillation experiments) need physics beyond the three neutrino framework, e.g. *sterile* neutrinos *(that do not couple to the gauge bosons and do not interact with matter)*.

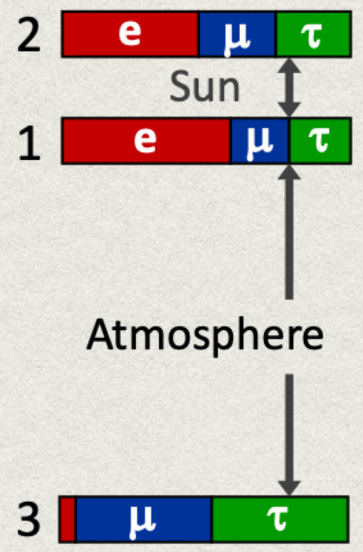
> *The sign of the Dm^2 atmospheric is not known, while the solar one is known because of the occurrence of the MSW effect in the Sun (^{8}B neutrinos).*

Two neutrino mass orderings are possible -

$$\Delta m^2_{13} > 0$$



Normal mass ordering (NMO)



$$\Delta m^2_{13} < 0$$

Inverted mass ordering (IMO)

The upcoming JUNO, Hyper-K, DUNE, ORCA will tell us about the neutrino mass ordering.

Crucial open questions include

> Origin and smallness of neutrino masses

> CP violation in the lepton sector, hints *Upcoming Hyper-K (beam), DUNE will measure the Dirac phase*

> the neutrino nature (Dirac versus Majorana) is unknown *Neutrinoless double-beta decay searches*

See e.g. Agostini et al, Rev.Mod.Phys. 95 (2023), 2202.01787 [

> the absolute neutrino mass - KATRIN experiment, model dependent information from cosmology

$$\langle m_{\nu_e} \rangle < 0.45 \text{eV} (90\% \text{C.L.})$$

> the neutrino magnetic moment, ….

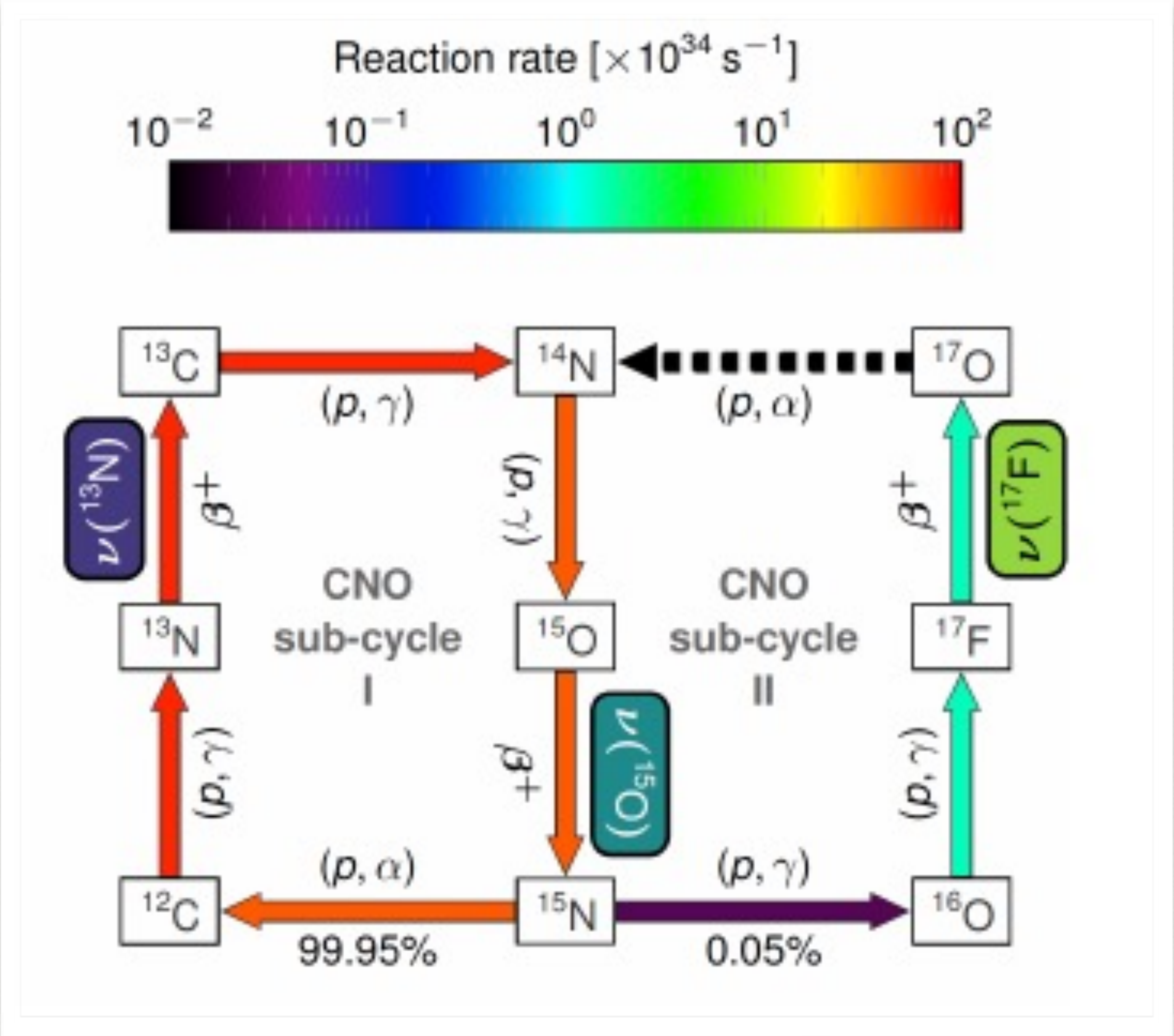
> neutrino flavor evolution in dense environments

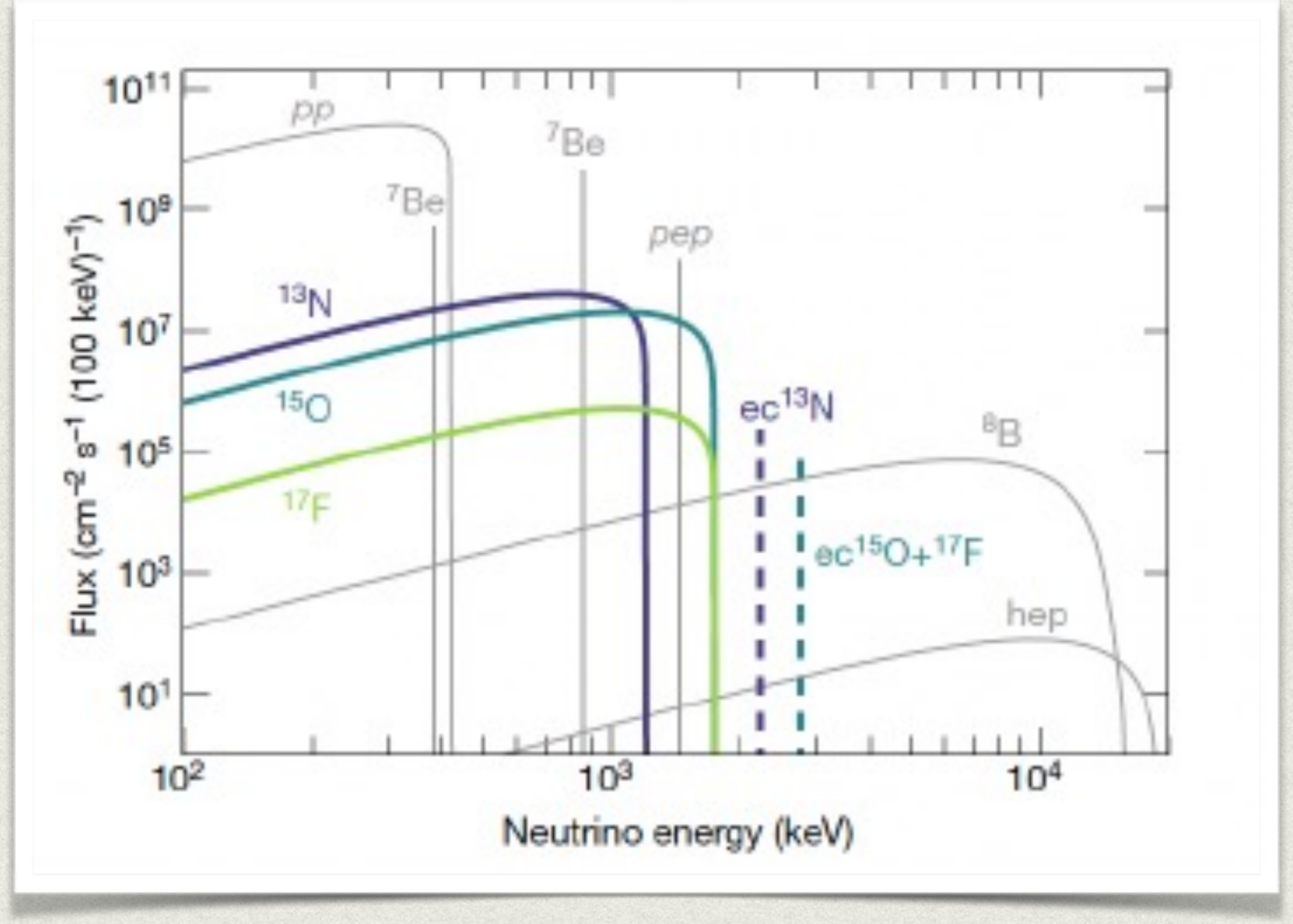
Several key open questions intertwined with neutrino propagation, or on how neutrinos change flavor, in astrophysical environments or the early Universe.

The Carbon-Nitrogen-Oxygen cycle

- Responsible for 1% energy production in the Sun. The dominant mode for hydrogen burning into helium in more massive main sequence stars.

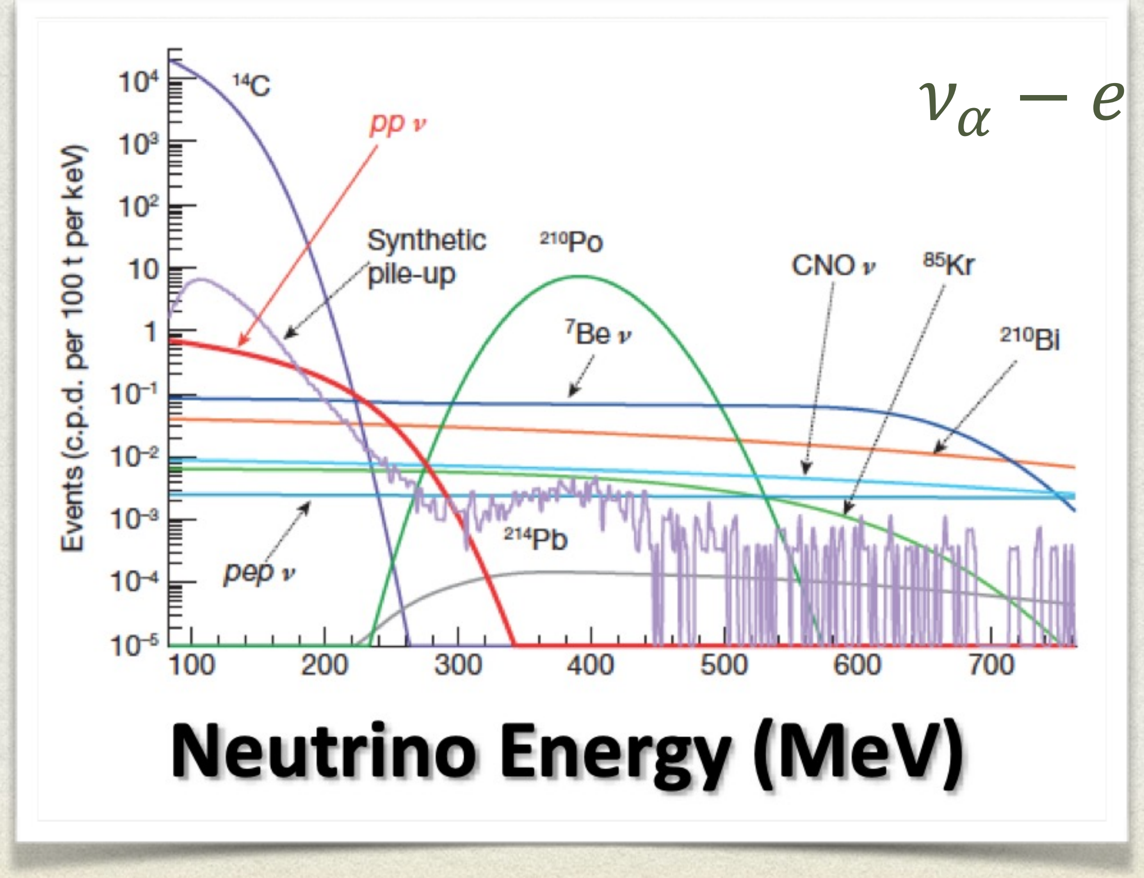
Borexino, POS (ICRC 2023)

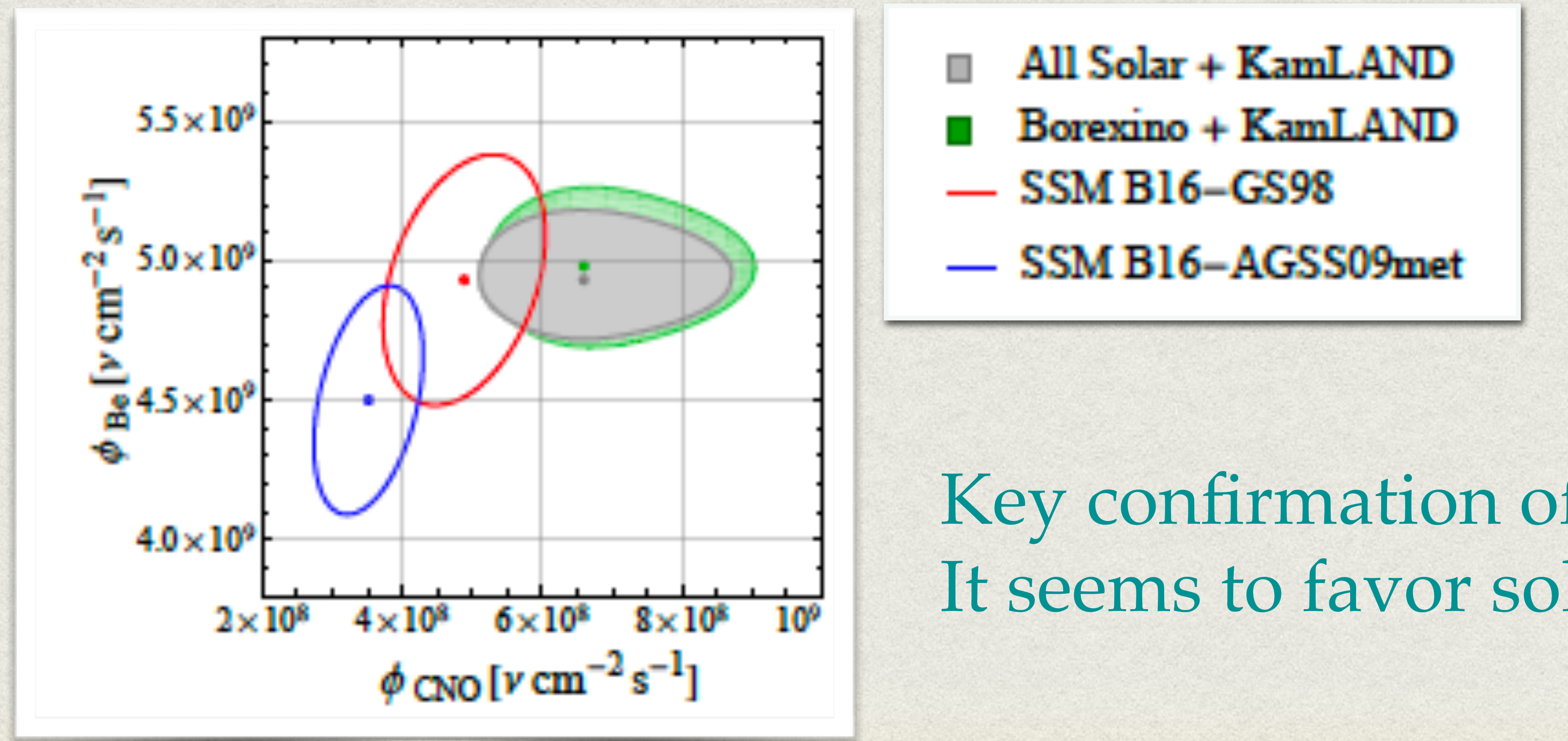




A confirmation of Bethe's prediction in 1939 !

- The neutrinos from the CNO cycle measured by the Boxexino experiment.



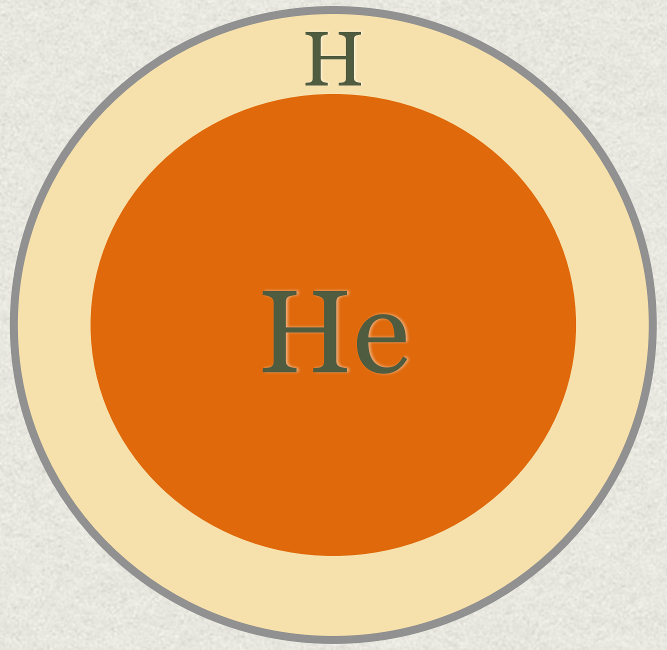


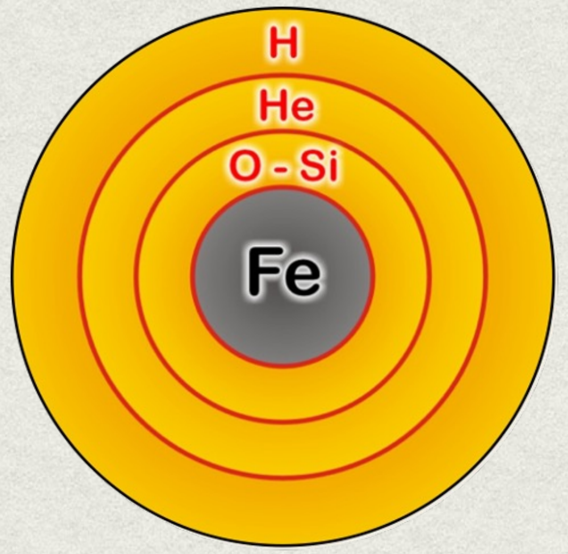
Key confirmation of evolutionary models.
It seems to favor solar models with high metallicity.

Stars and neutrinos: tightly linked

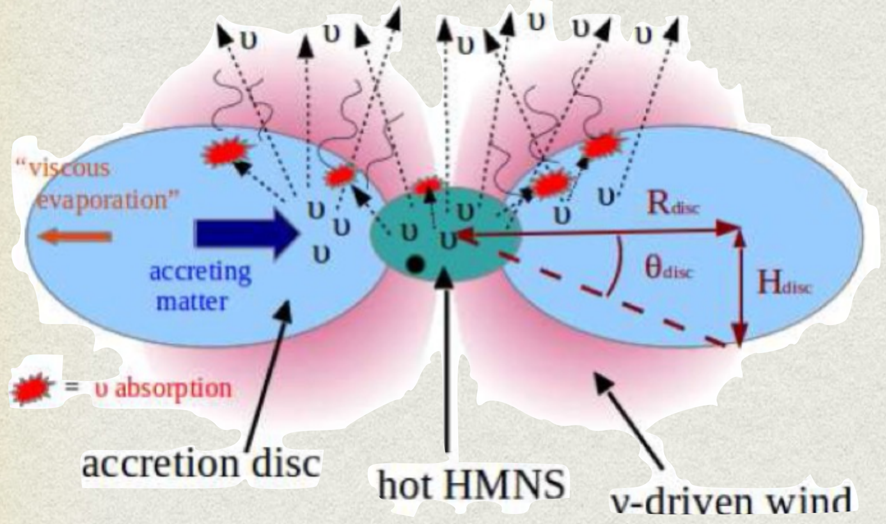
Main sequence stars ⟷ pp-nuclear reaction chain, CNO cycle

Red giants ⟷ cooling via neutrinos



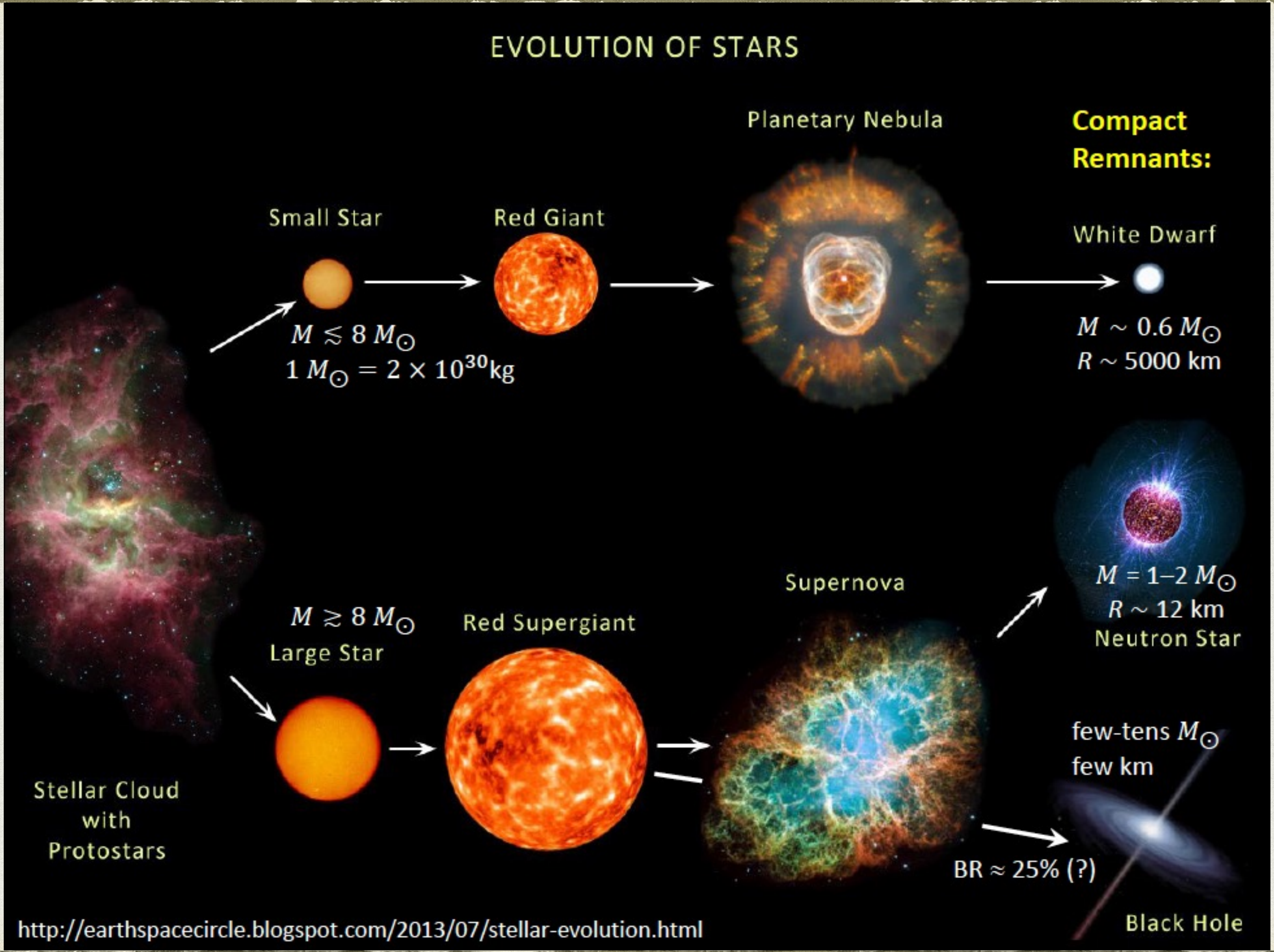


Core-collapse supernovae, neutron stars (and binary neutron star mergers) ⟷ supernova explosion mechanism, cooling, nucleosynthesis (r-process)



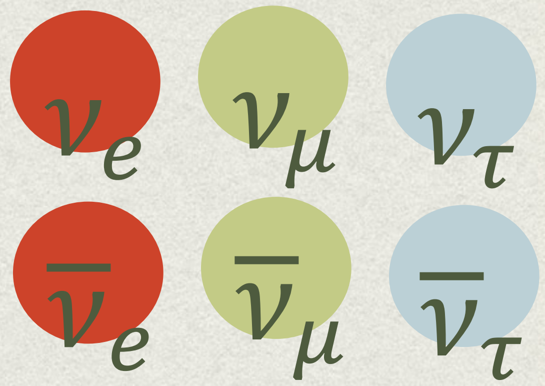
Non standard neutrino properties can play a role: neutrino magnetic moment, sterile neutrinos, x, … as well as dark matter particles and new interactions (ex. non-standard neutrino matter interactions).

Neutrinos play an important role in astrophysical contexts, linked to new particles and interactions


EVOLUTION OF STARS
Planetary Nebula
Compact Remnants:
Small Star
Red Giant
White Dwarf
$M \lesssim 8\ M_\odot$
$1\ M_\odot = 2 \times 10^{30}$kg
$M \sim 0.6\ M_\odot$
$R \sim 5000$ km
$M = 1$–$2\ M_\odot$
$R \sim 12$ km
Neutron Star
Supernova
$M \gtrsim 8\ M_\odot$
Large Star
Red Supergiant
few-tens $M_\odot$
few km
Stellar Cloud with Protostars
BR ≈ 25% (?)
Black Hole
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

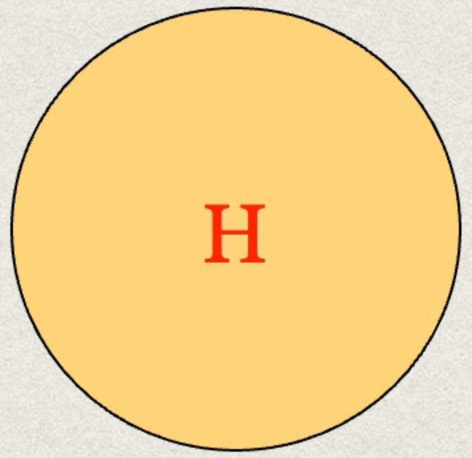
Neutrinos from core-collapse supernovae

The core-collapse and explosion lasts 10 seconds. Neutrinos of all flavors take away 99% of the gravitational binding energy of the newly formed neutron-star.



Schematic evolution of a massive star (25 Msun)

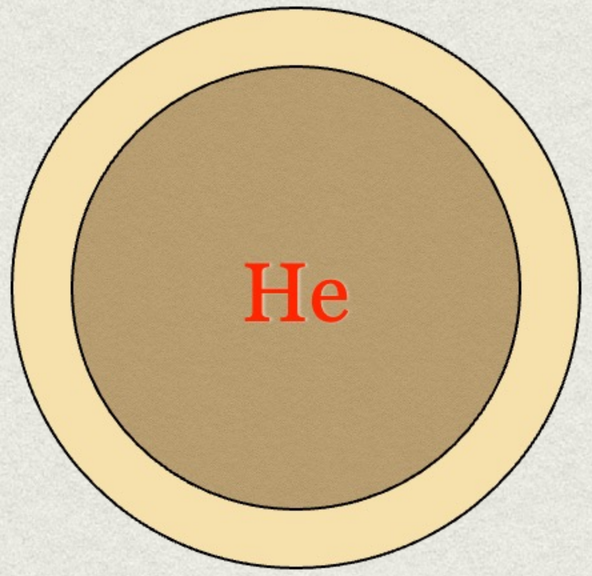
INITIAL STAGES



H burning

T= 0.09 10^9 K

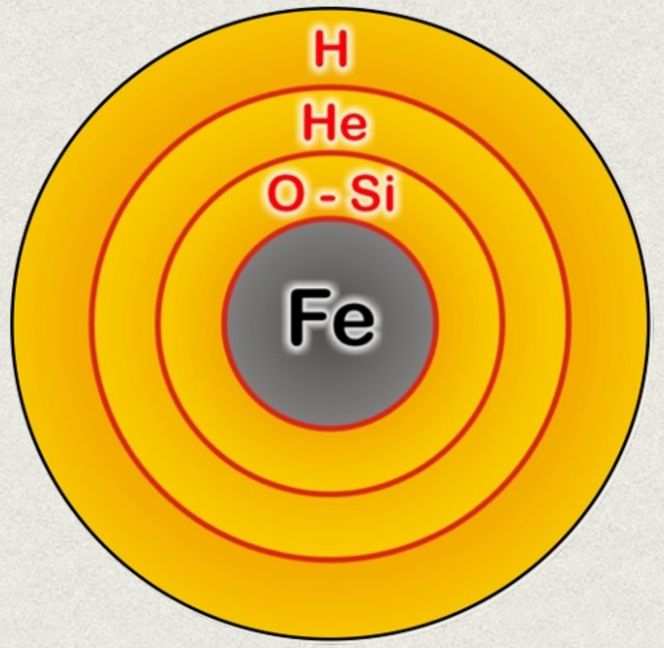
Burning time = 7 My

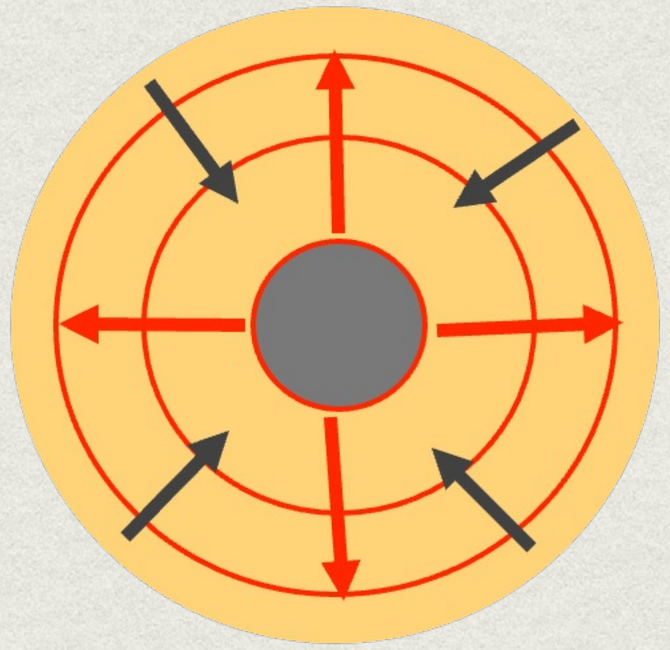


He burning

T= 0.2 10^9 K

Burning time = 5 10^5 y

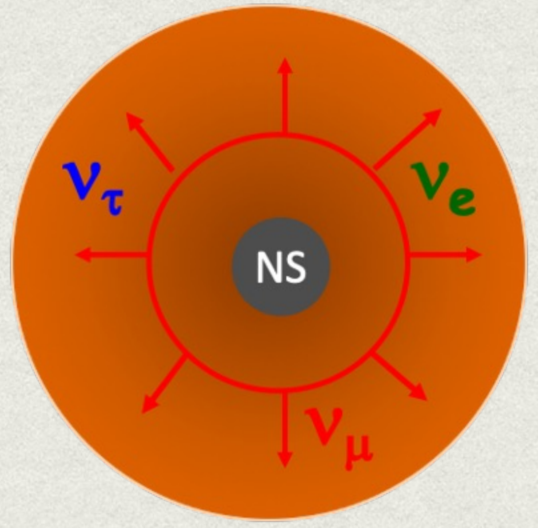




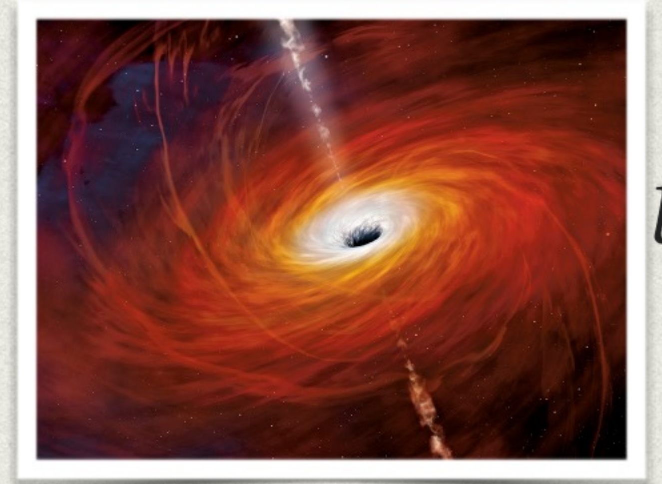
Supernova

(core-collapse and explosion)

Weaver, Woosley (1980)



neutron star (NS) formed



black-hole (BH)

Artist image

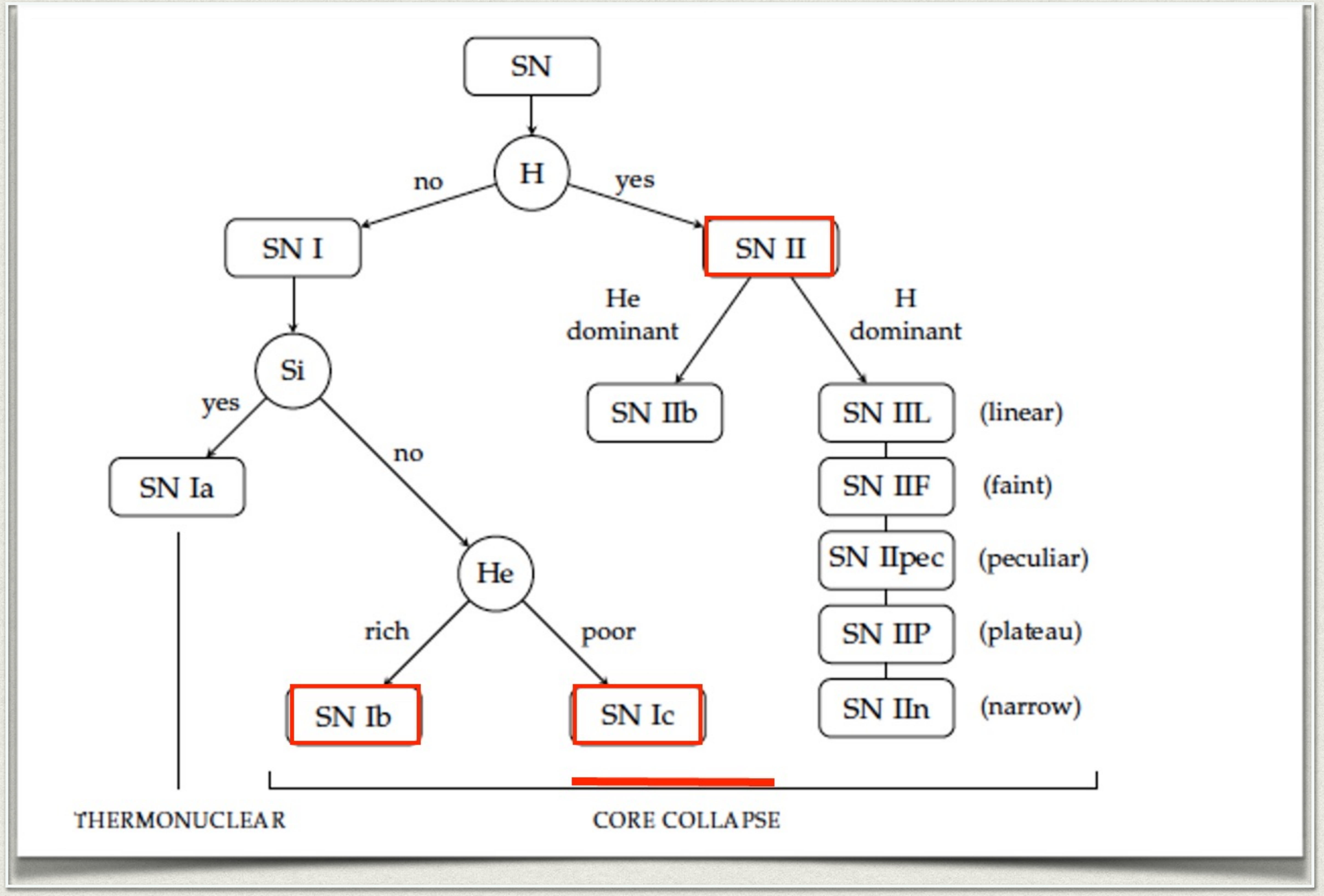
Energy : 99 % neutrinos, 0.01% photons
about 1% explosion kinetic energy

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

Core-collapse supernovae are gigantic neutrino sources in the tens of MeV energy range.

- What is a core-collapse supernova? More generally a dense environment?
  - Why are neutrinos from dense media interesting?

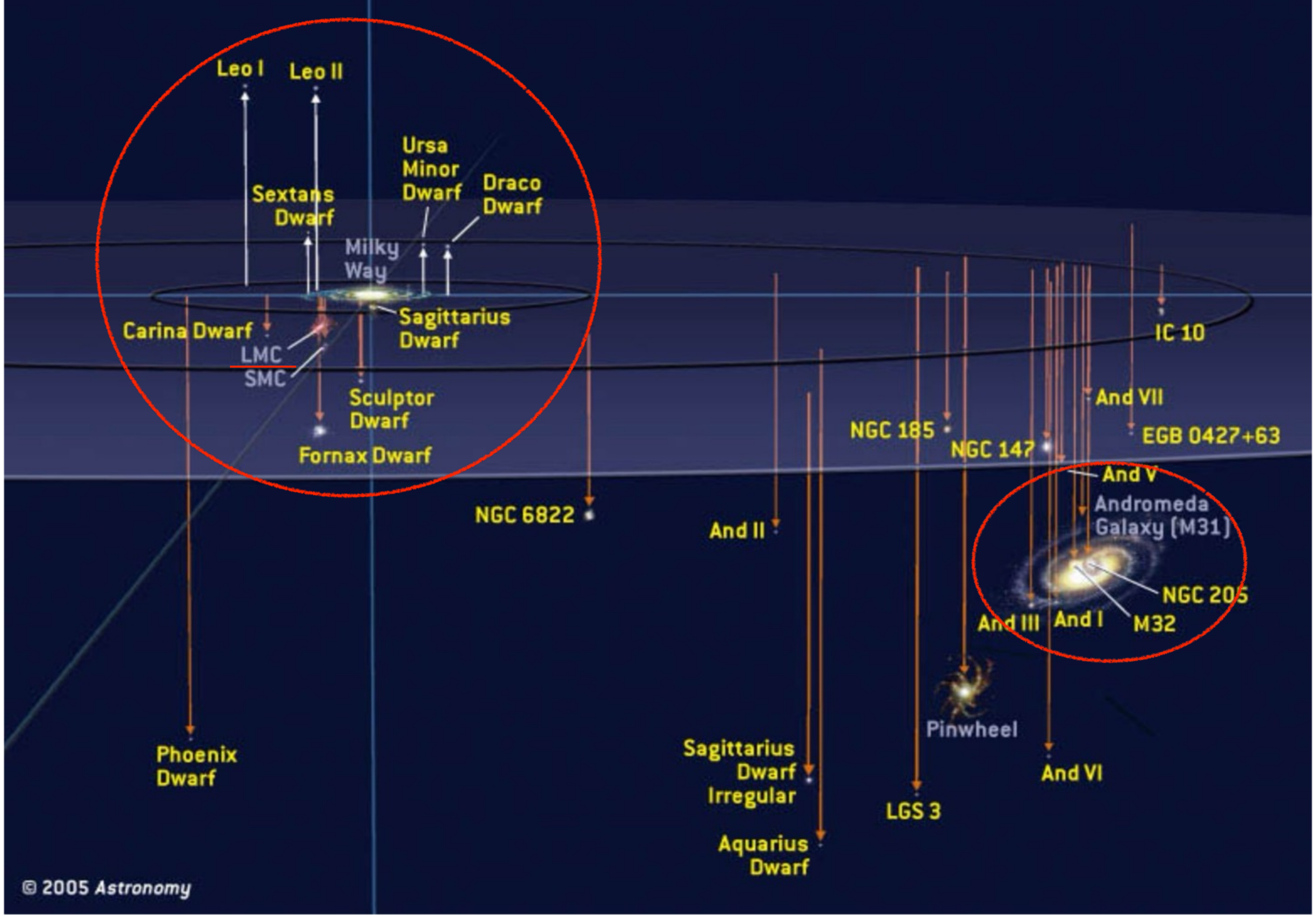
CORE-COLLAPSE supernovae



Spectral classification of supernovae

Core-collapse supernovae include supernovae type II, Ib and Ic.

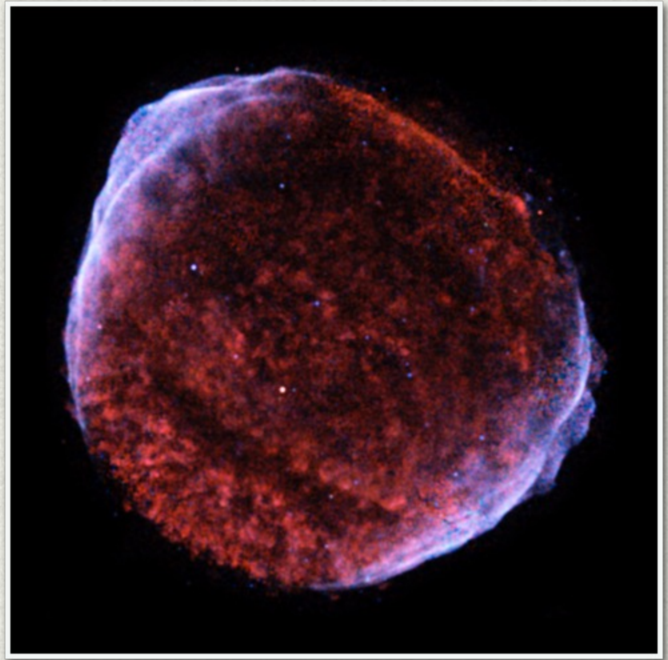
LOCAL GROUPs



Core-collapse supernovae in our Galaxy

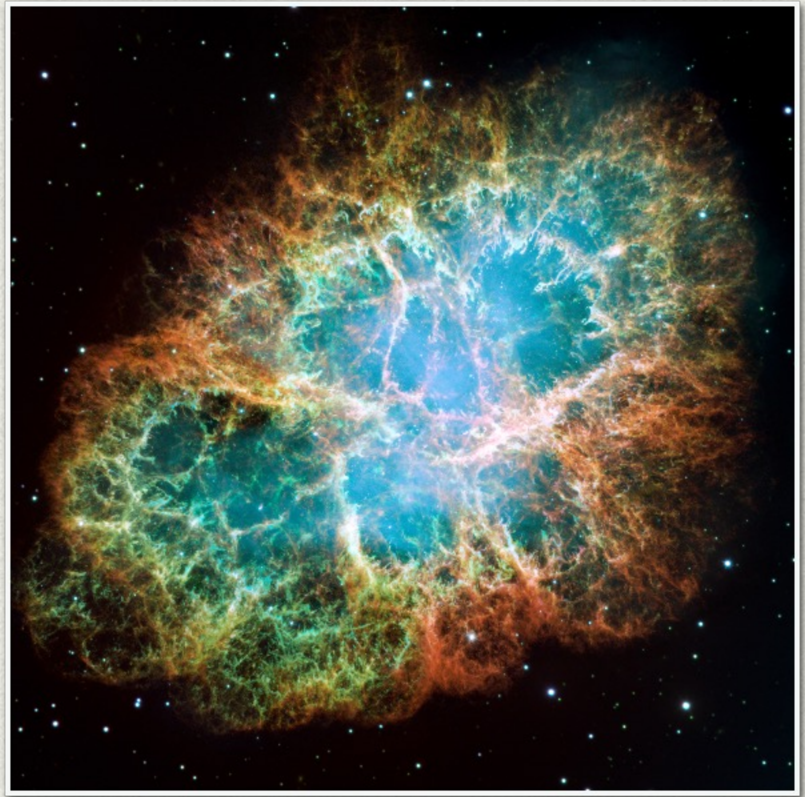
- **Since 1000 y, Milky Way**

SN 1006



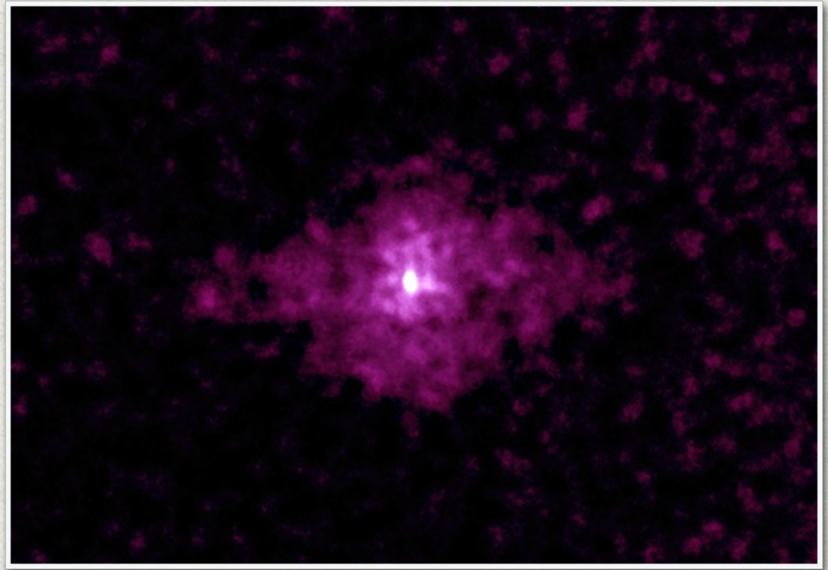
Smithsonian Institution

SN 1054
Crab Nebula



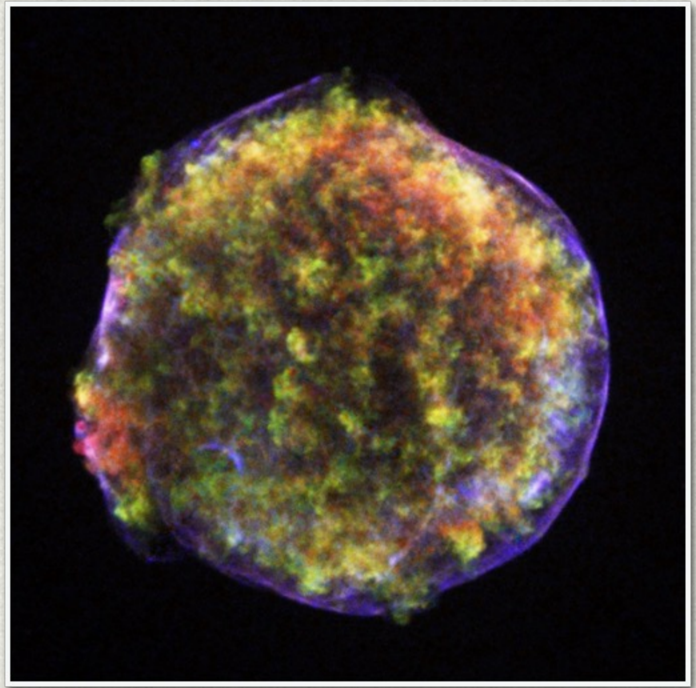
NASA, ESA, J. Hester and A. Loll

SN 1181



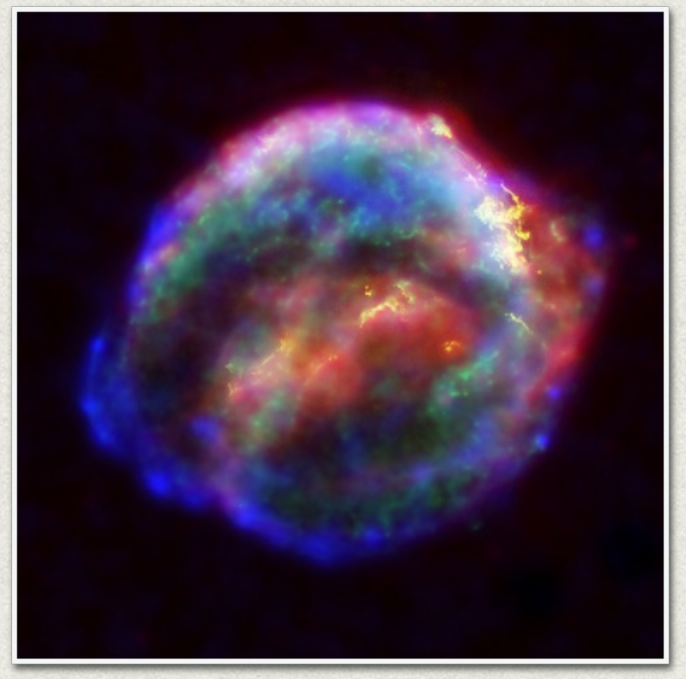
NASA/CXC/SAO/S.Murray et al.

SN 1572



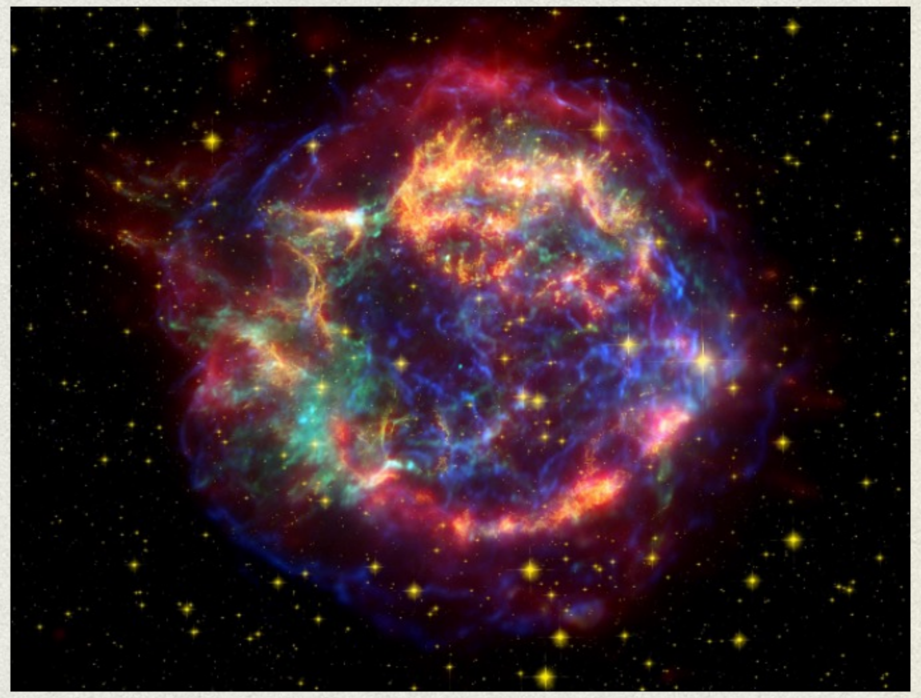
NASA/CXC/Rutgers/J.Warren & J.Hughes et al.

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 their rate is 1-2 (conservative) to 1-3 (more optimistic) event/century.

Supernova 1054

Crab Nebula at 1.9 kpc

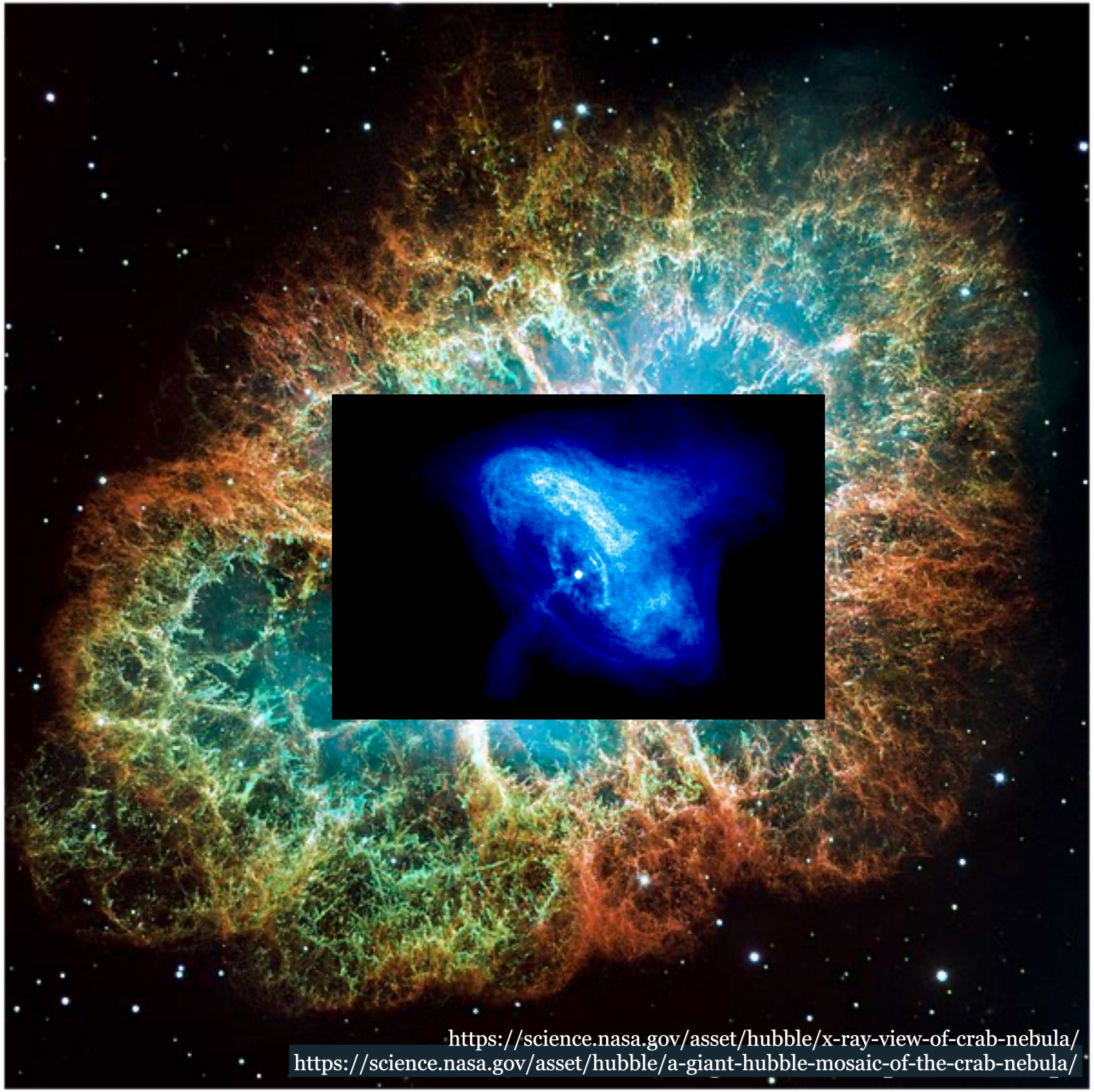
(6.200 light years),

so luminous that was

seen by Chinese astronomers

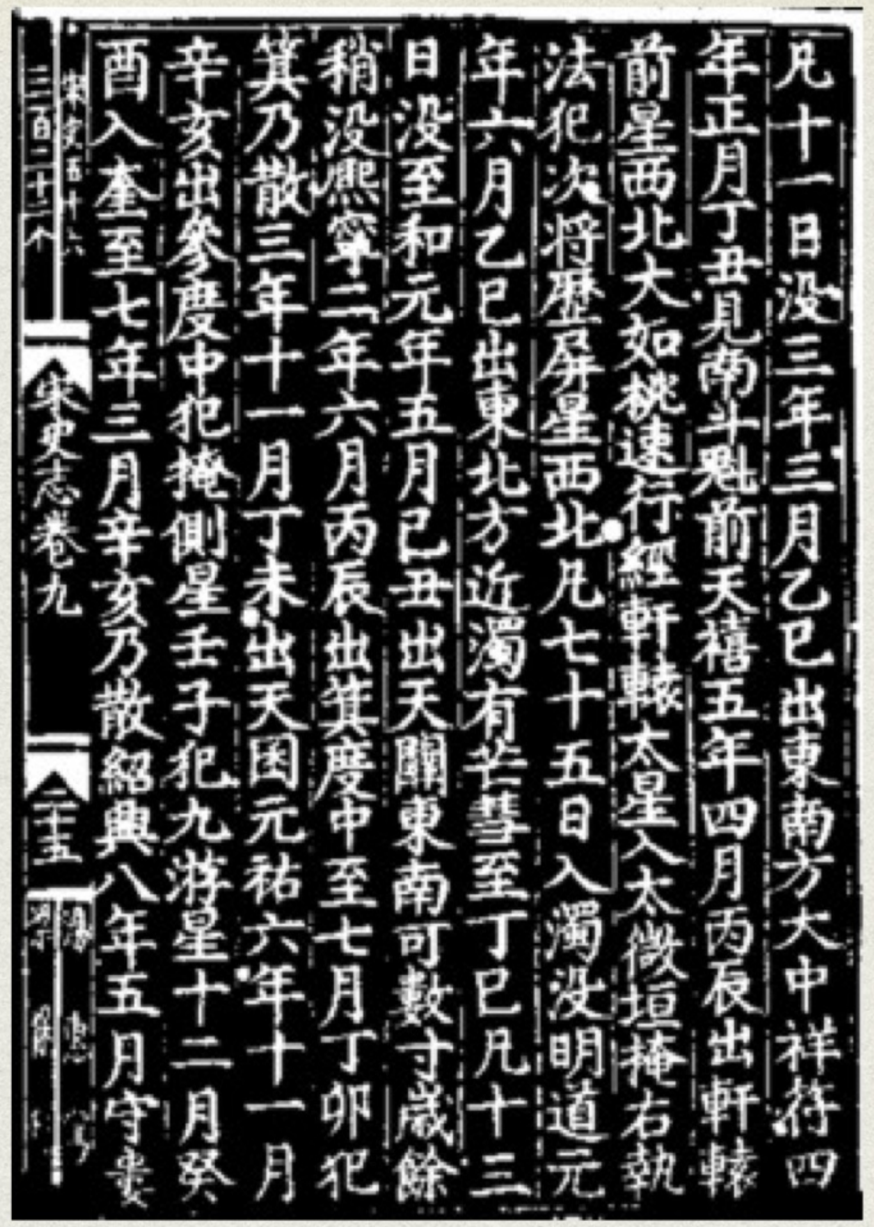
1 light year = $9.5 \; 10^{12}$ km

1 kpc = $3.26 \; 10^{3}$ light years



https://science.nasa.gov/asset/hubble/x-ray-view-of-crab-nebula/

https://science.nasa.gov/asset/hubble/a-giant-hubble-mosaic-of-the-crab-nebula/

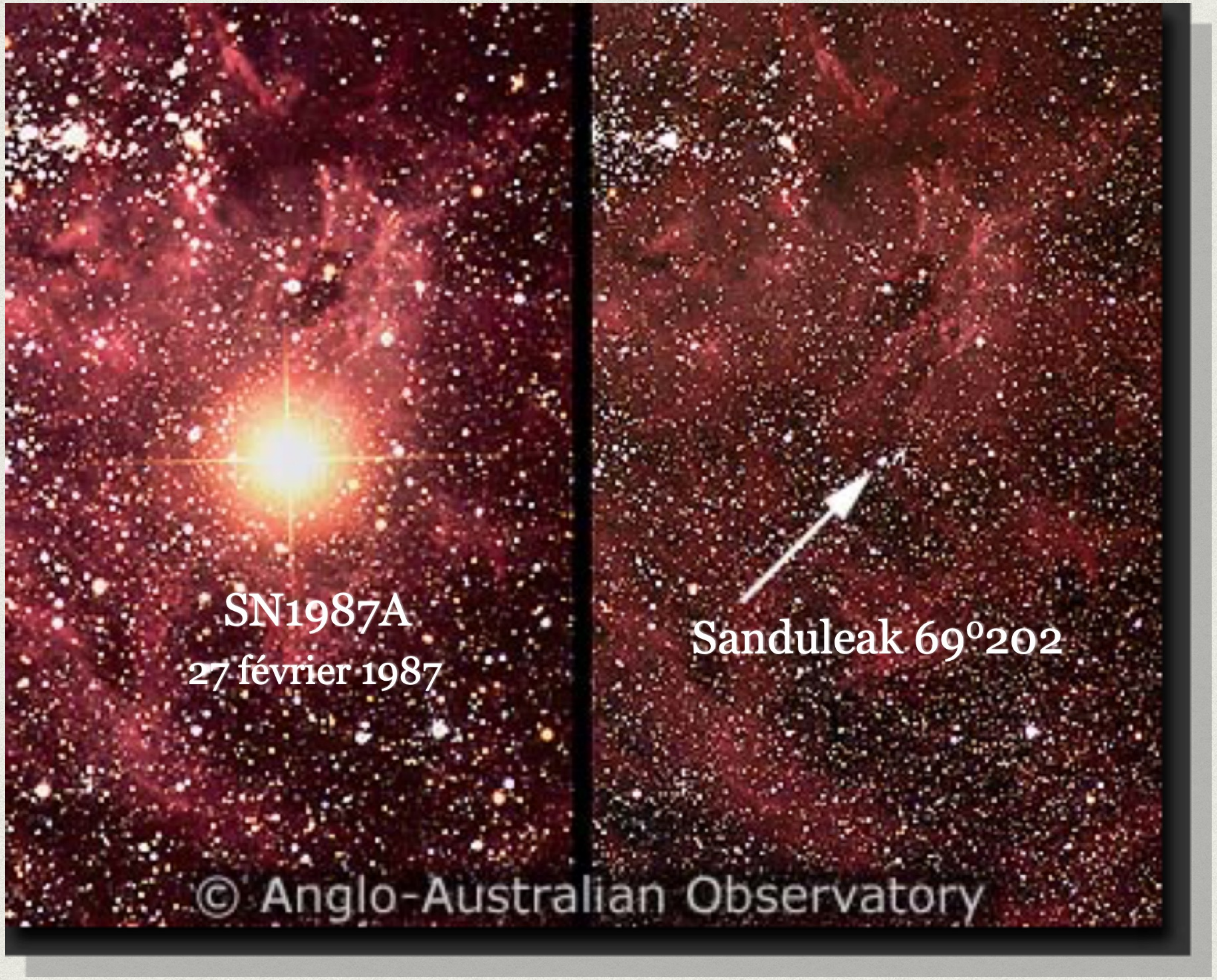


凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屛星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

A spinning neutron-star as a remnant

SN1987A



Large Magellanic Cloud, satellite galaxy of the Milky Way,
50 kpc (163,000 light-years)

The first multimessenger event : SN1987A

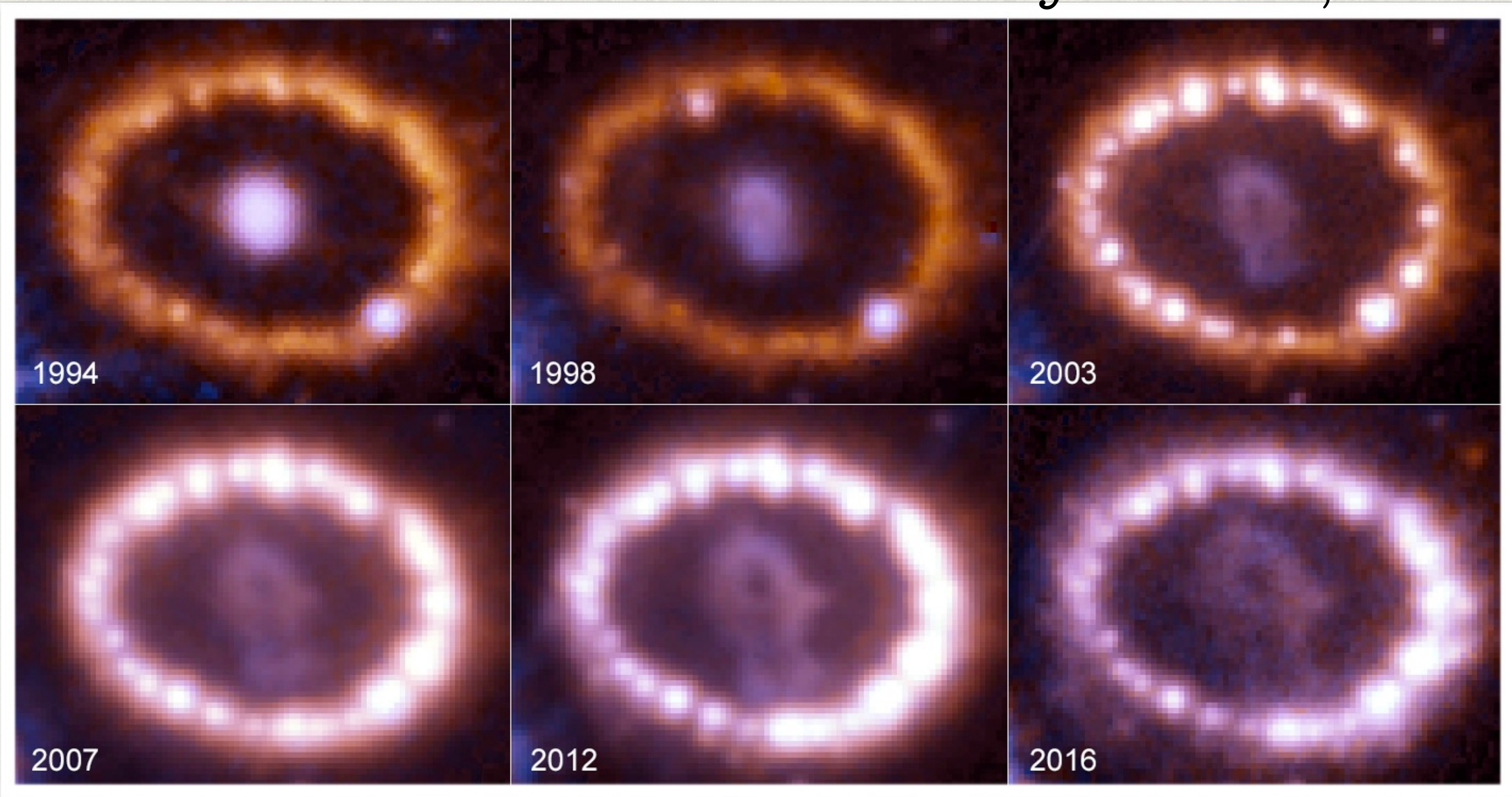
- On the 23rd February, Sanduleak 69^0202 (blue supergiant) exploded, in the Large Magellanic Cloud

50 ± 5 kpc (163,000 light-years)

Schmidt et al, 1992

distance to LMC : 49.59 ± 0.09 (stat) ± 0.54 (sys) kpc

Pietrzynski et al., 2019

- 

Hubble Space Telescope

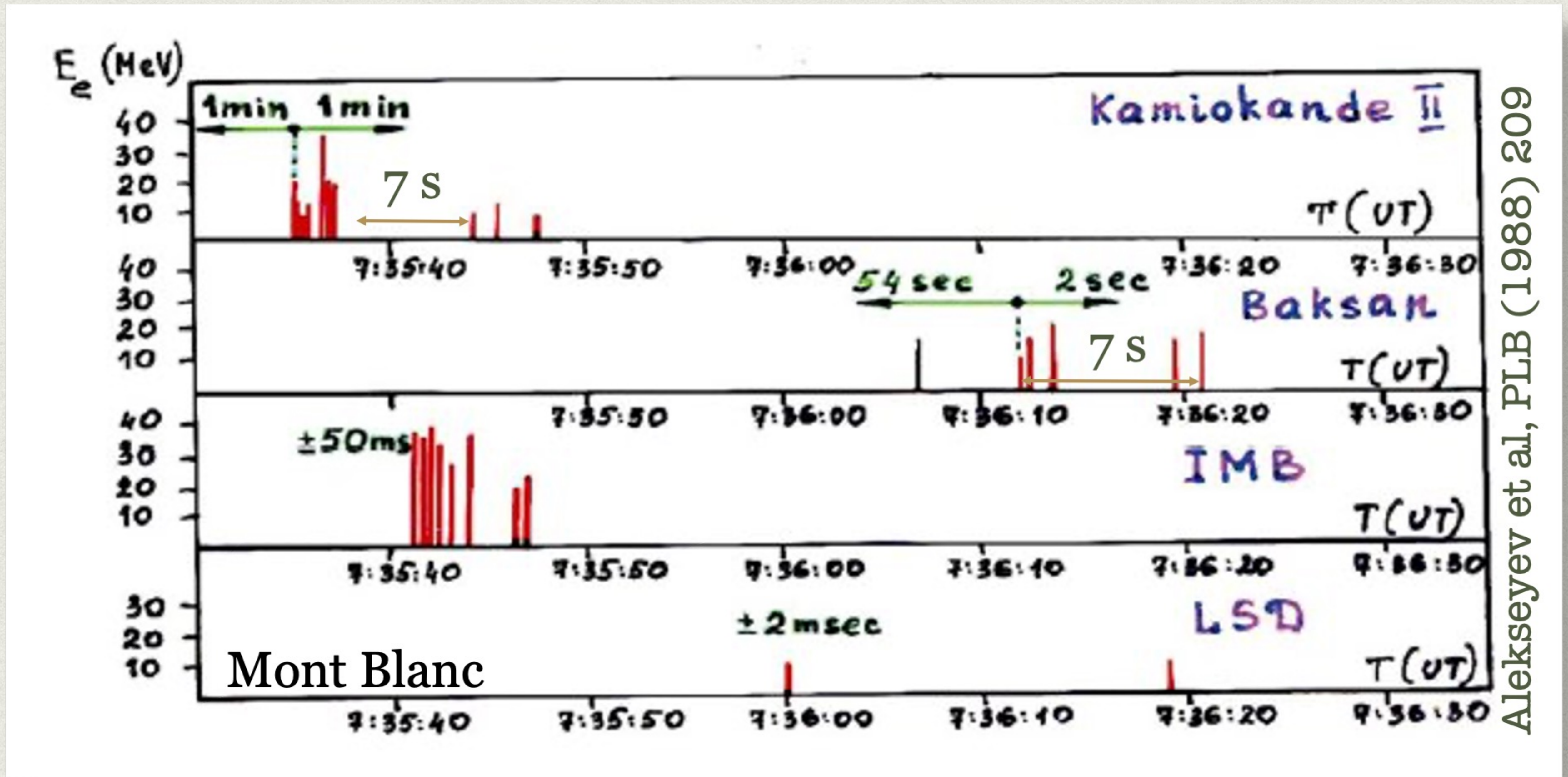
After 30 years, the remnant has been identified: a dust-obscured thermally emitting **neutron star**.

Alp et al, 2018, Cigan et al, 2019, Page et al., 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).

> *« With the above mentioned stories, people might say that Kamiokande and IMB would be so lucky. However according to the Japanese proverb, catching good luck is a kind of ability. »*
>
> Suzuki, J. Phys. Conf. Ser. (2008)



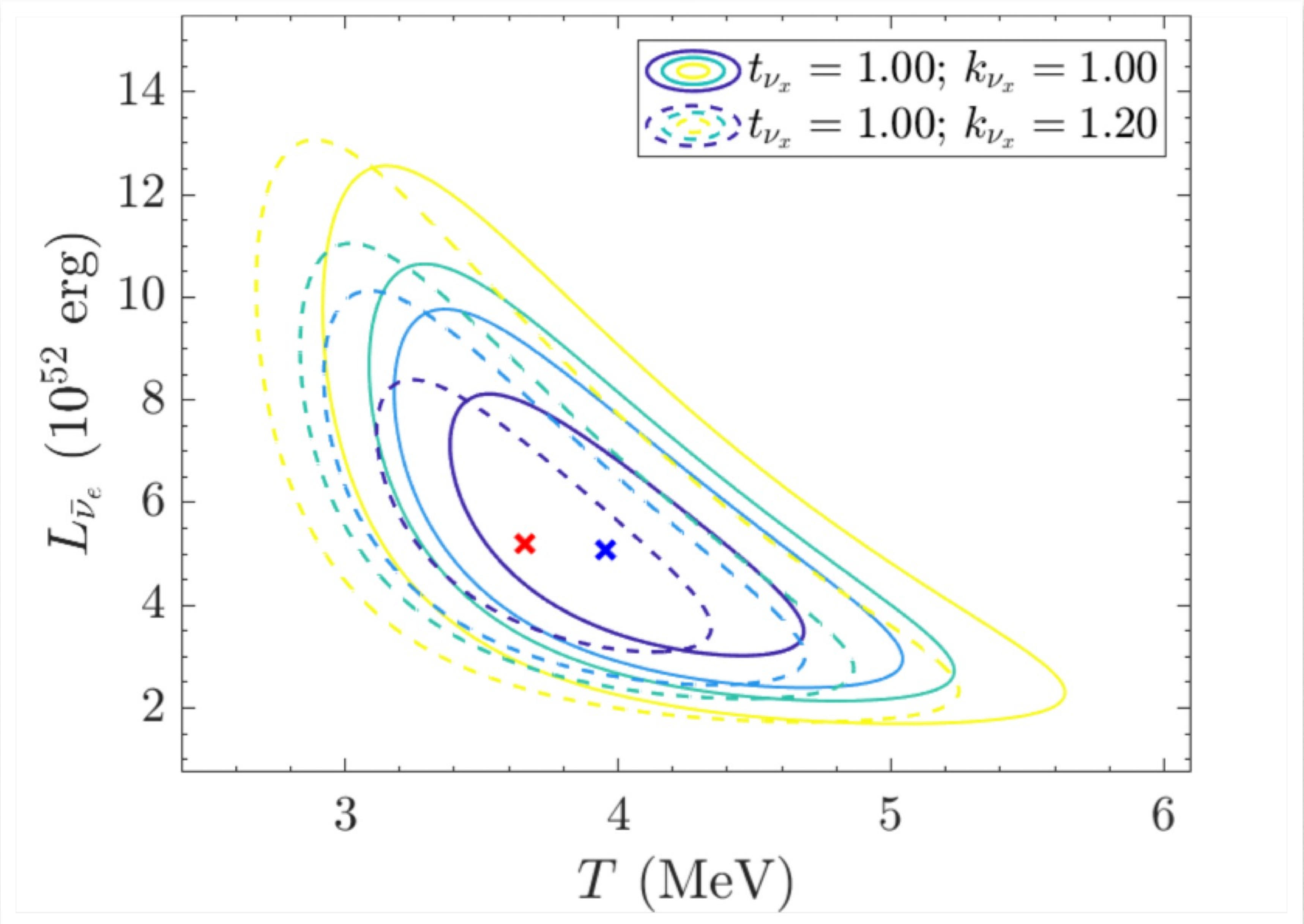
Water Cherenkov detector, 2140 tons

Baksan Scintillator Telescope, 200 tons

Irvine-Michigan-Brookhaven, Water Cherenkov, 6800 tons

A wonderful laboratory for particle physics and astrophysics

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



Ivanez-Ballesteros and Volpe, PLB 2023, 2307.03549

- Recent analysis found sensitivity at the level of 10%, from the spectral analysis
  Vissani, J.Phys.G 42, 2015

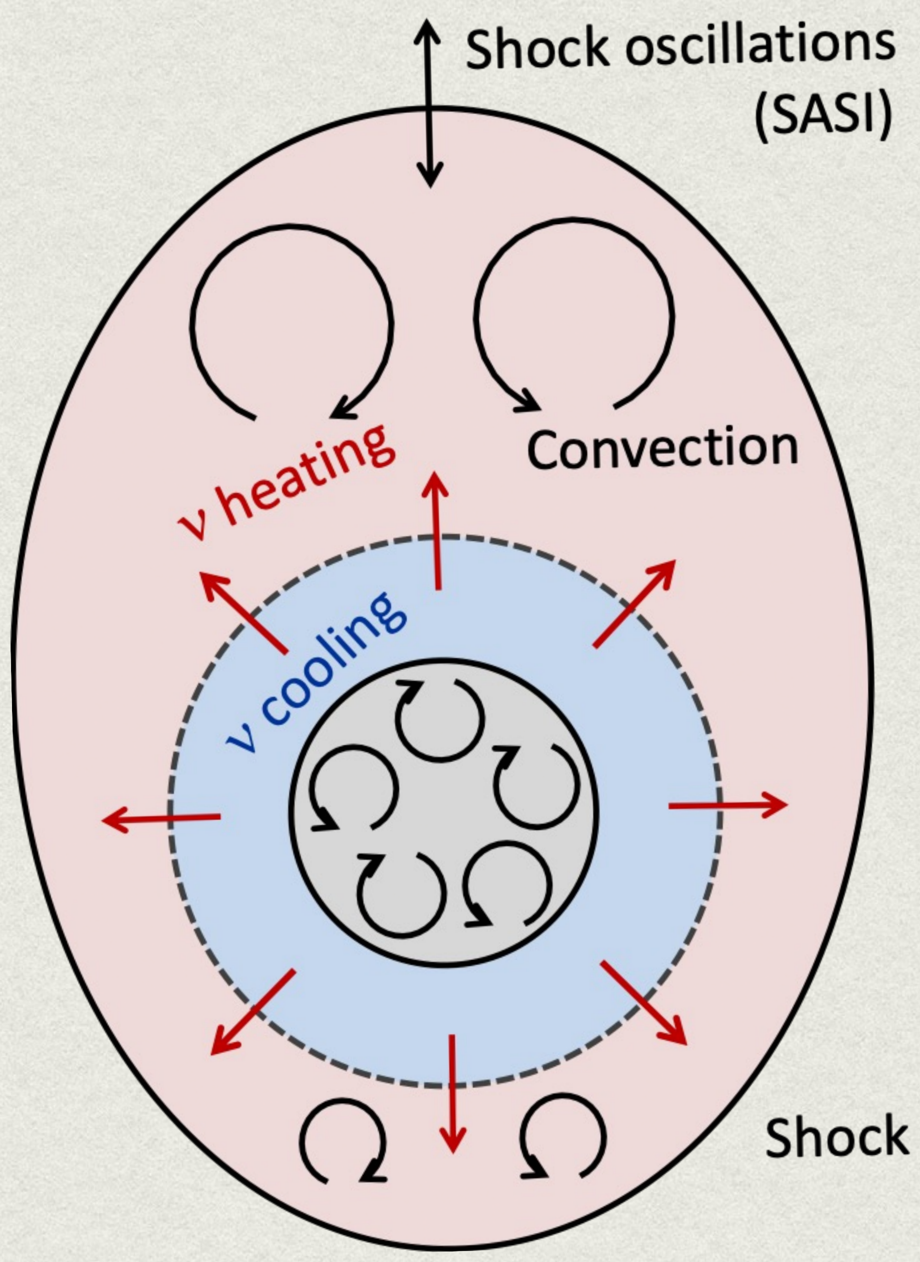
- Luminosity and average energies of the electron antineutrinos in agreement with expectations (under the equipartition Assumption).

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*.
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)

- 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.



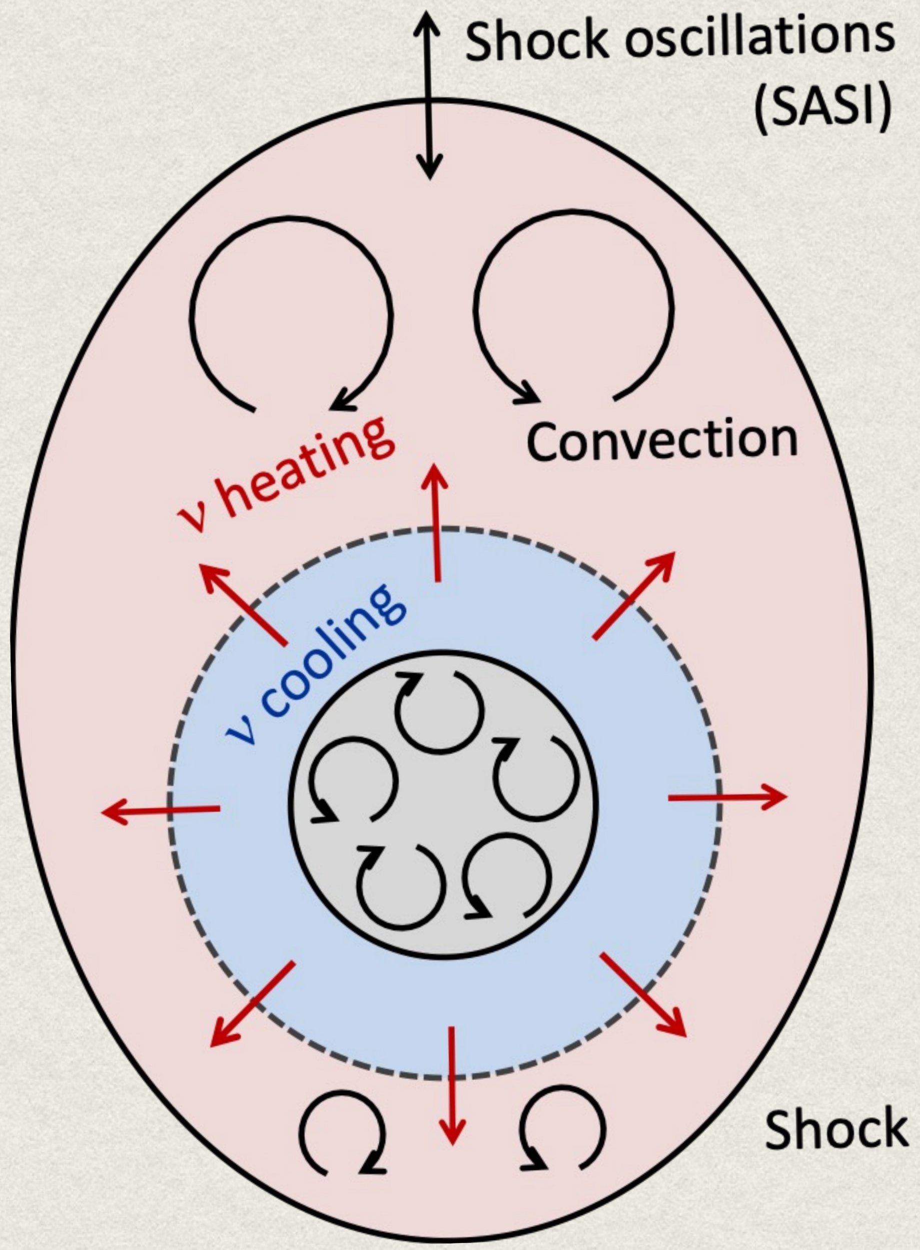
see Mezzacappa (2022), arXiv: 2205.13438,
T. Janka's talk at « Neutrino Frontiers » (GGI, 2023)

PROMPT SUPERNOVA MODEL REJECTED
A MAJOR STEP FORWARD EVERY DECADE

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).**

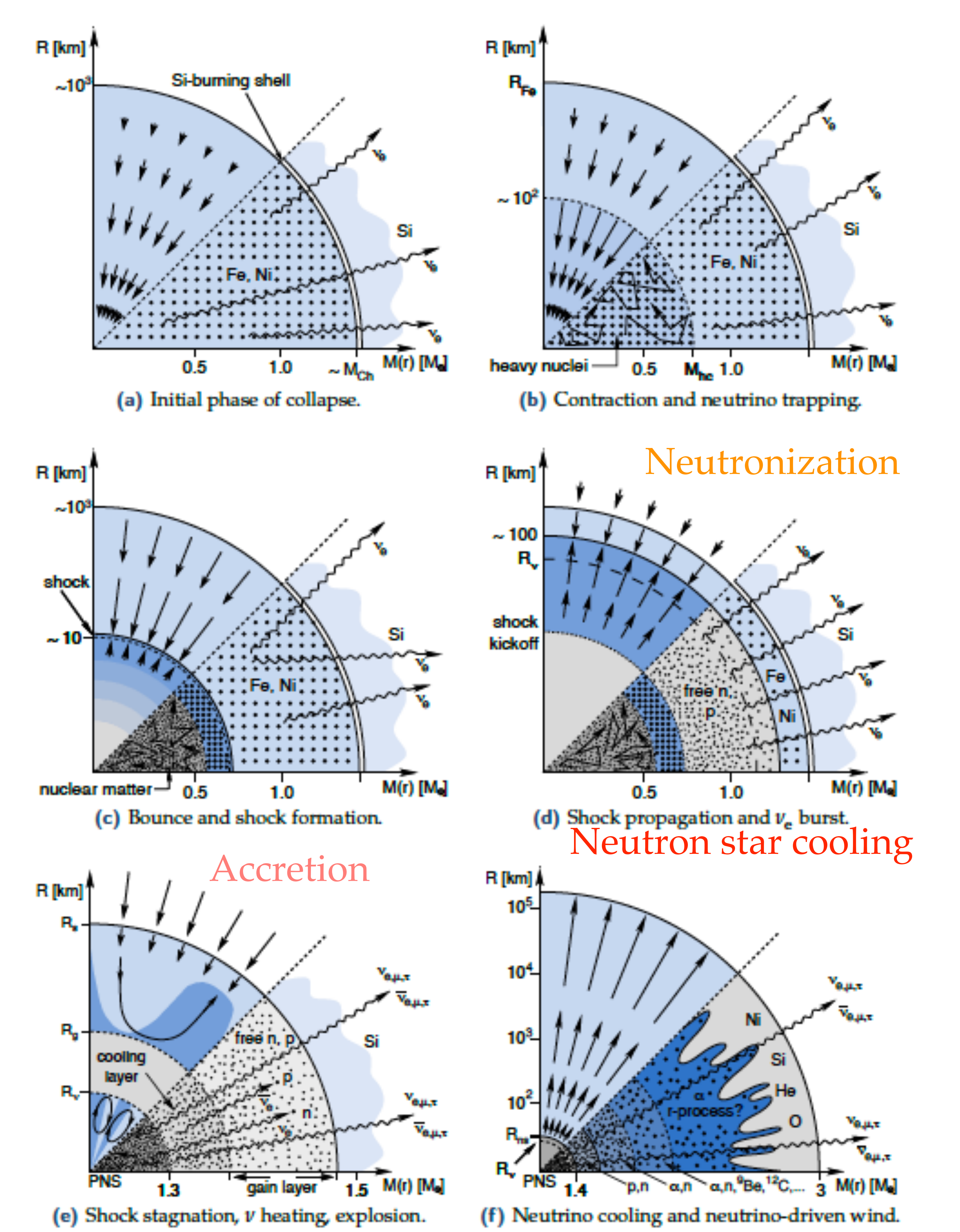
see Mezzacappa (2022), arXiv: 2205.13438.



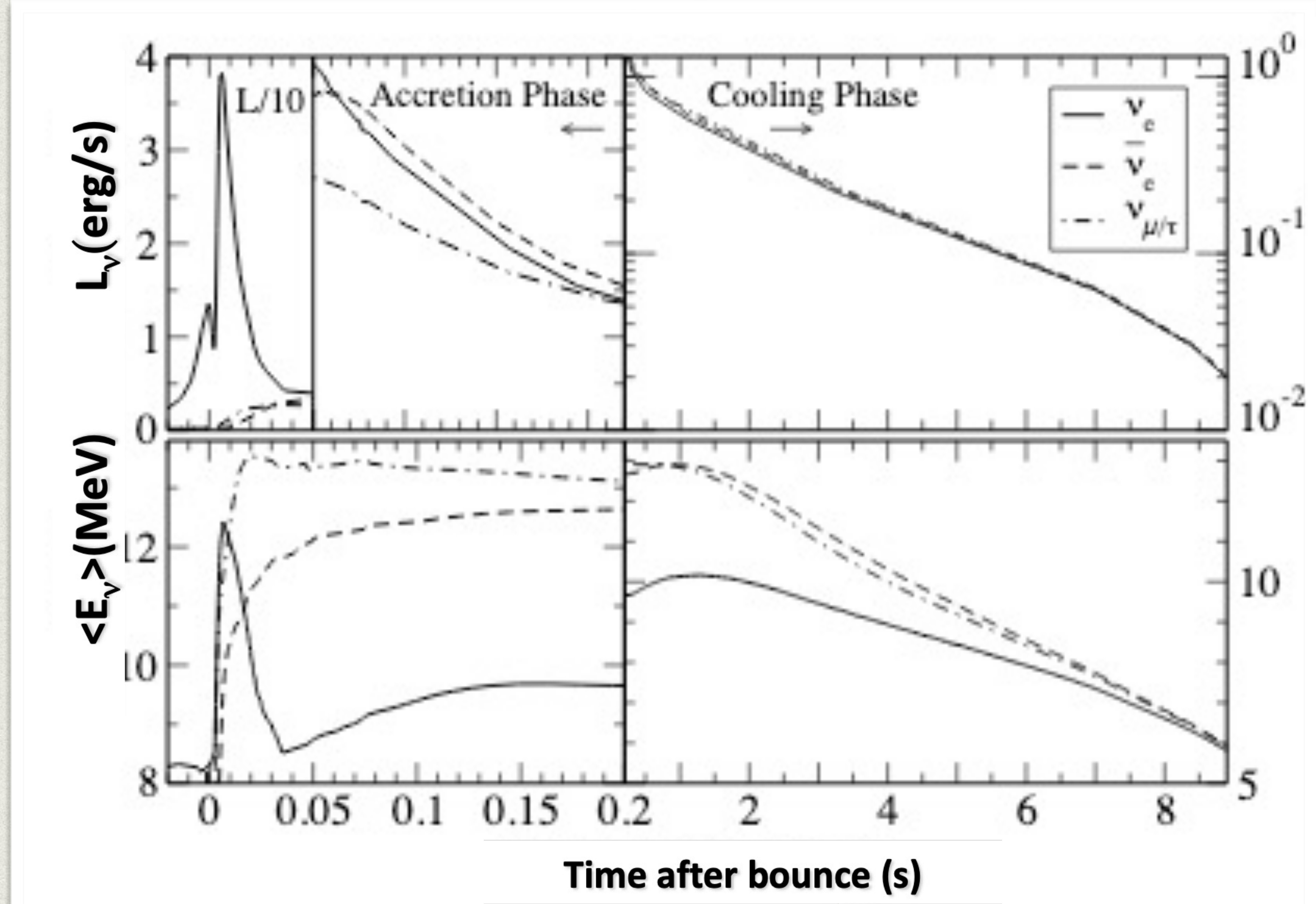
see Mezzacappa (2022), arXiv: 2205.13438,
T. Janka's talk at « Neutrino Frontiers » (GGI, 2023)

THE CURRENT PARADIGM

SN EXPLOSION MECHANISM and NEUTRINO TIME SIGNAL



T. Janka, Phys. Rep. 442, (2007) (and A.Gallo Rosso, PhD Thesis)



Hudepöhl et al PRL, 2011

Delayed neutrino-driven explosions:
Current paradigm for supernova explosion by Bethe and Wilson (1985).

Detection of each phase crucial

Neutrino non-radiative decay and SN1987A

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

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

  ϕ a massless (pseudo)scalar particle

  due to tree-level (pseudo)scalar couplings.

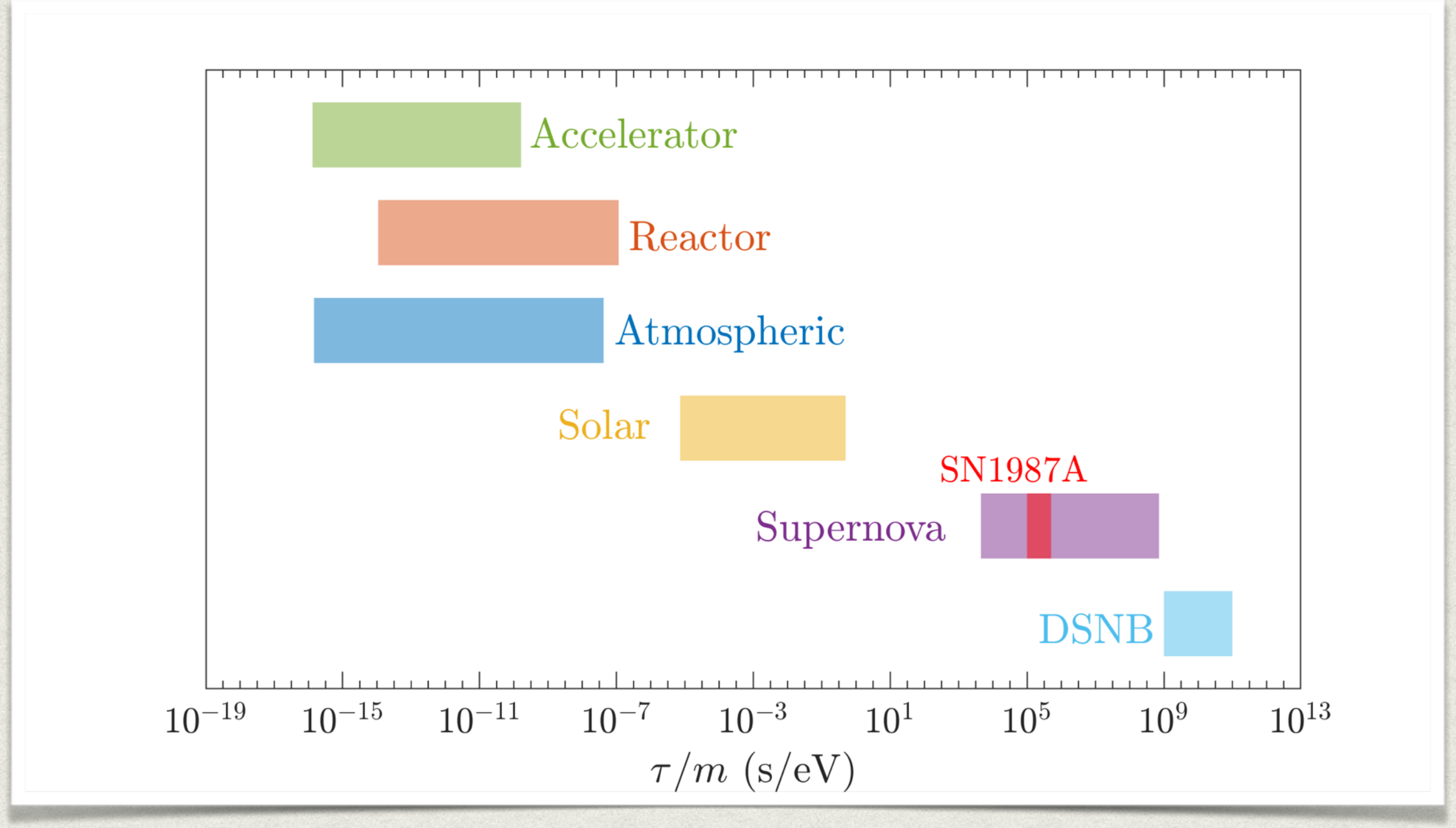
  $\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + H.c.$,

- 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

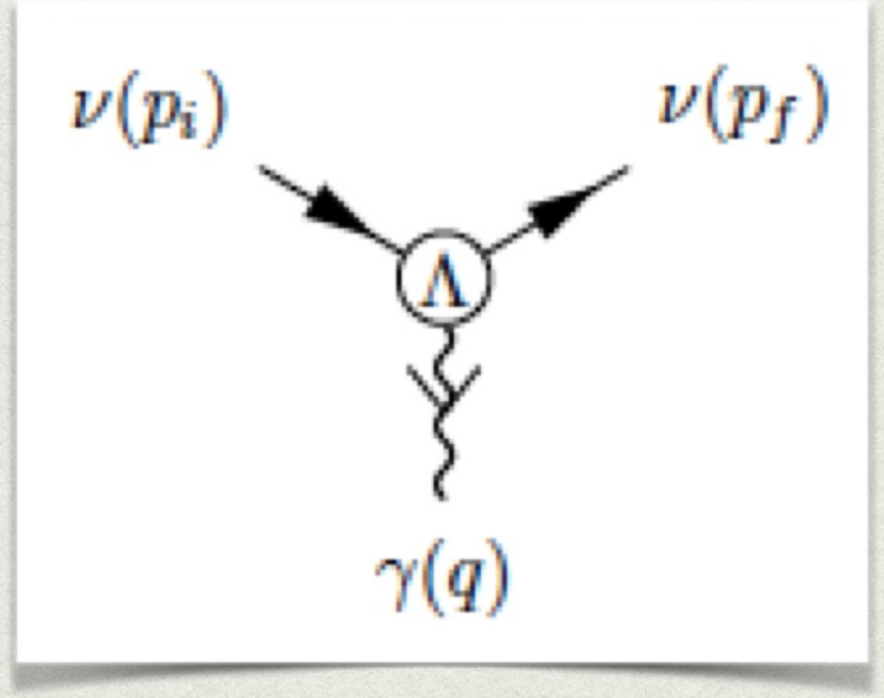


Ivanez-Ballesteros, Volpe, PLB 2023, 2307.03549

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

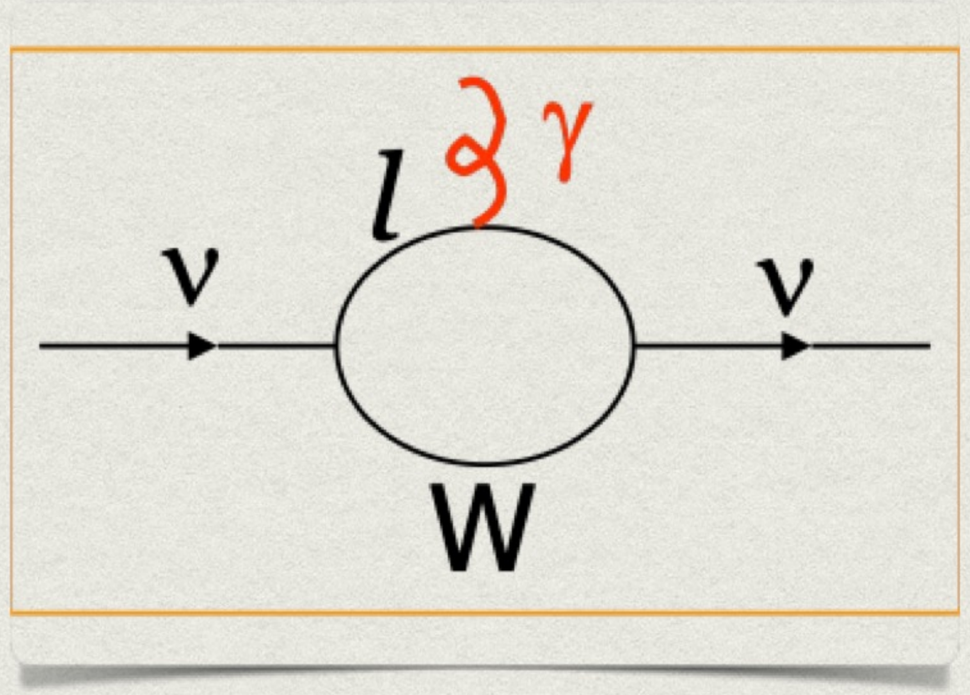
Unique sensitivity to tau/m from supernovae and the diffuse supernova neutrino background

Unknown neutrino properties: the neutrino magnetic moment



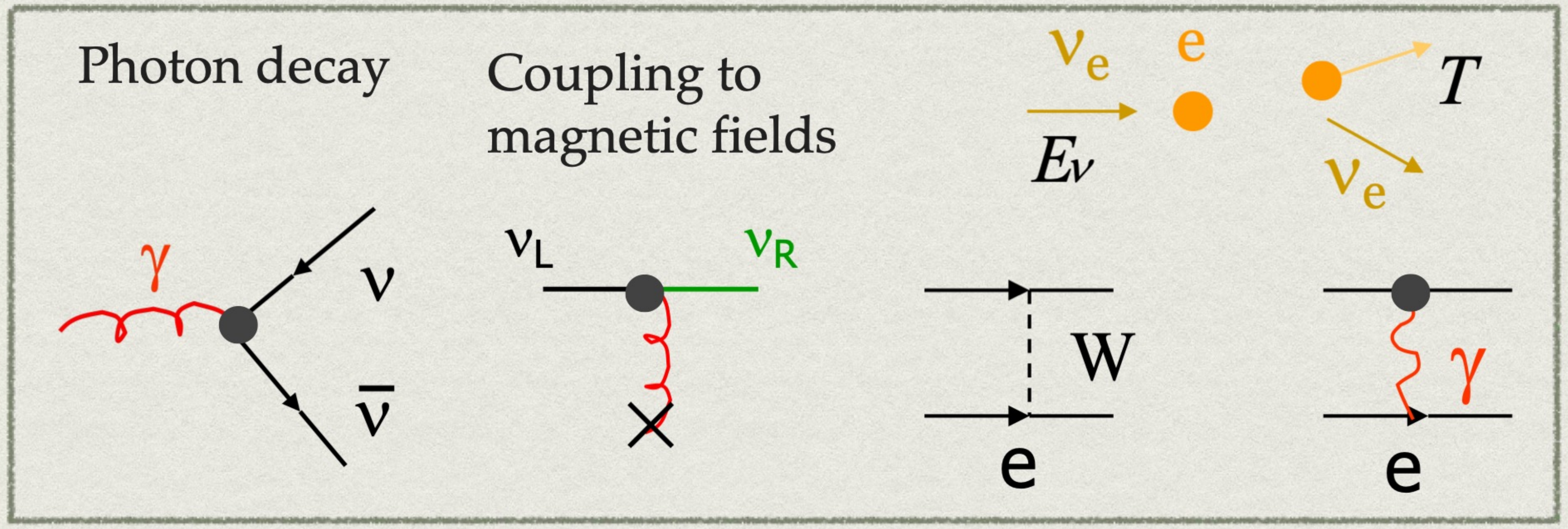
Effective one-photon coupling of a neutrino with a photon

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



Neutrino magnetic moment from quantum loops

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



- 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

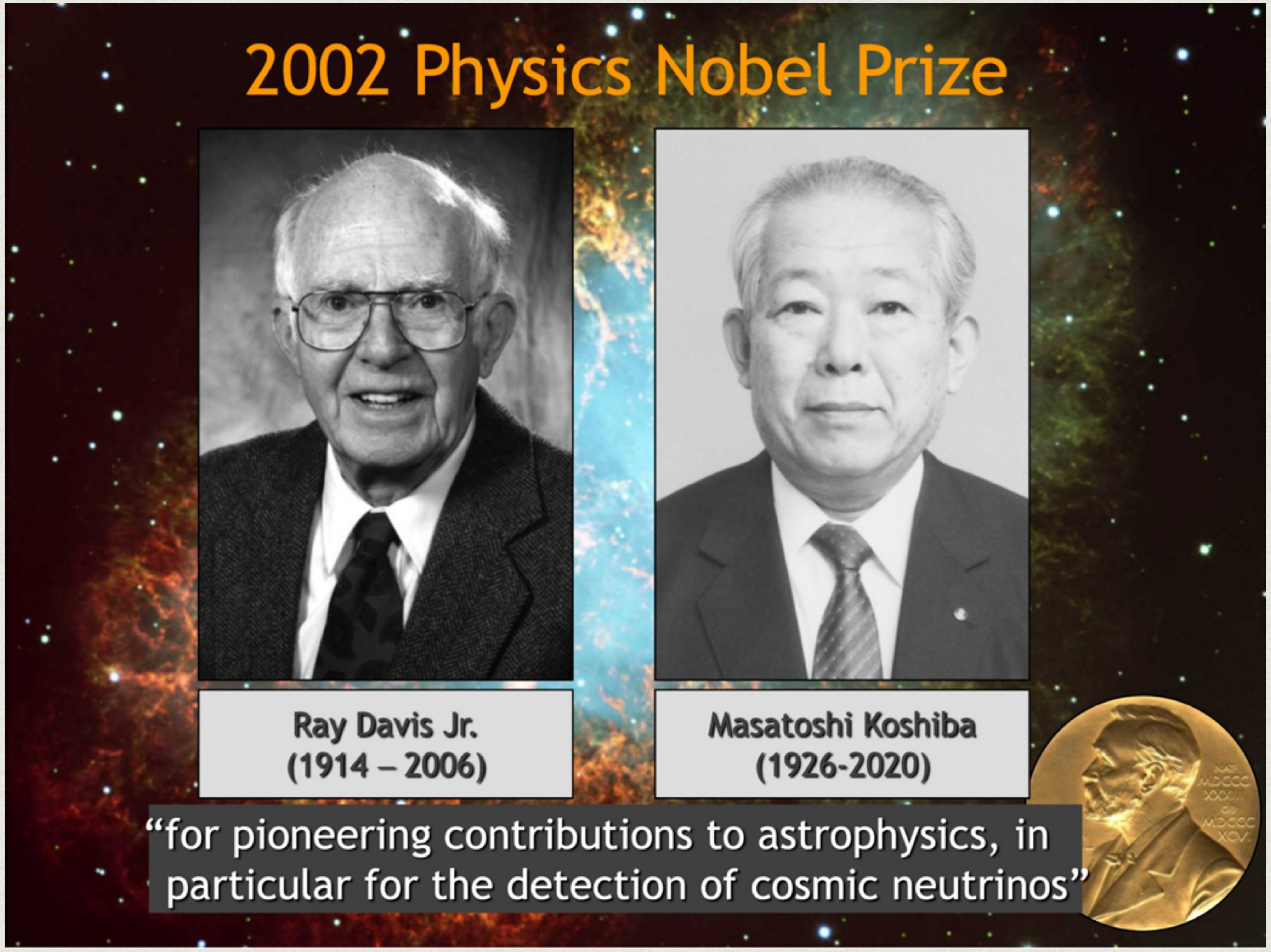
$\mu_\nu < 1.5\text{-}5 \times 10^{-12}\ \mu_B$ **SN1987A**

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)

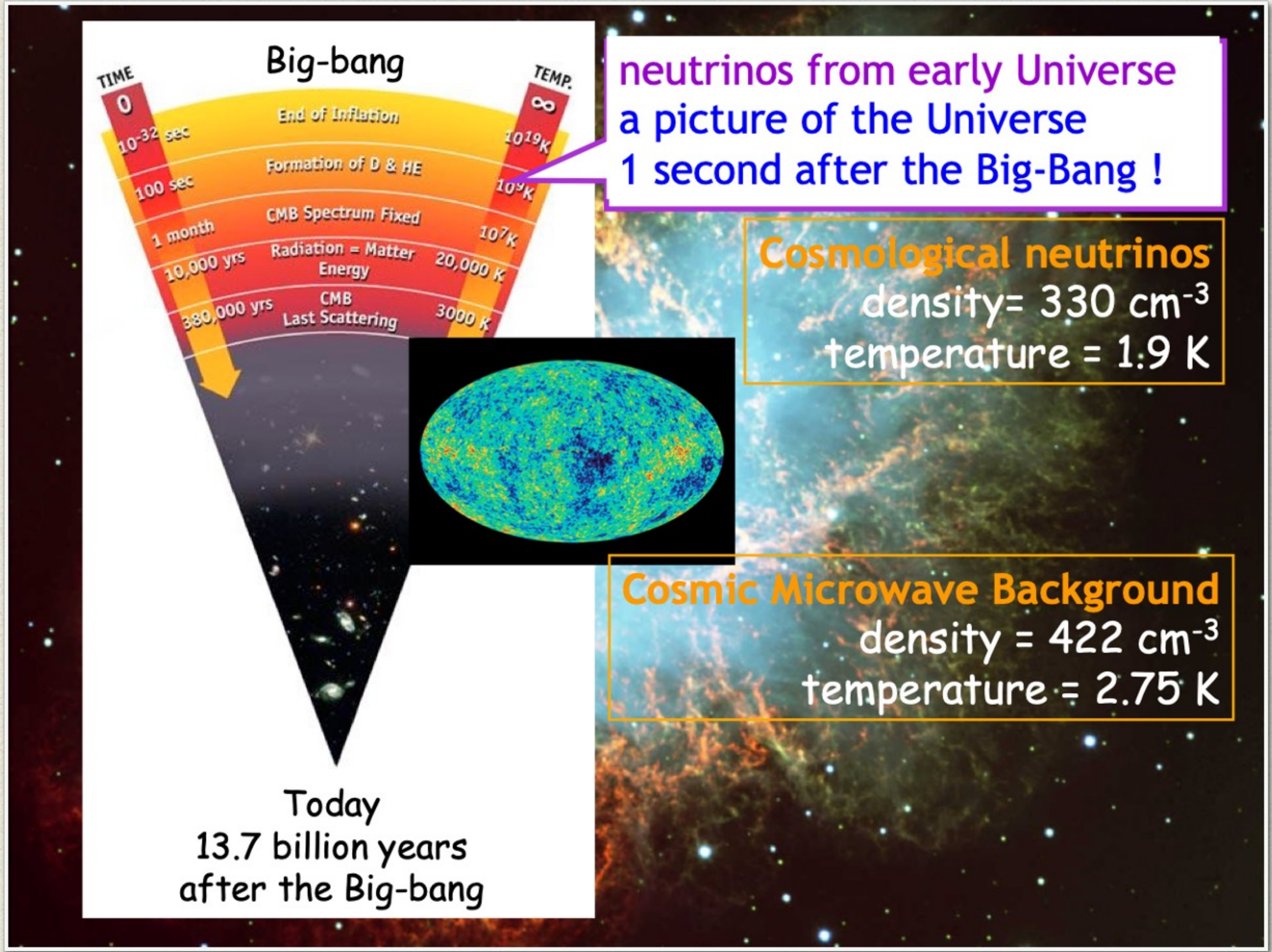
Numerous limits on non-standard properties, particles and interactions



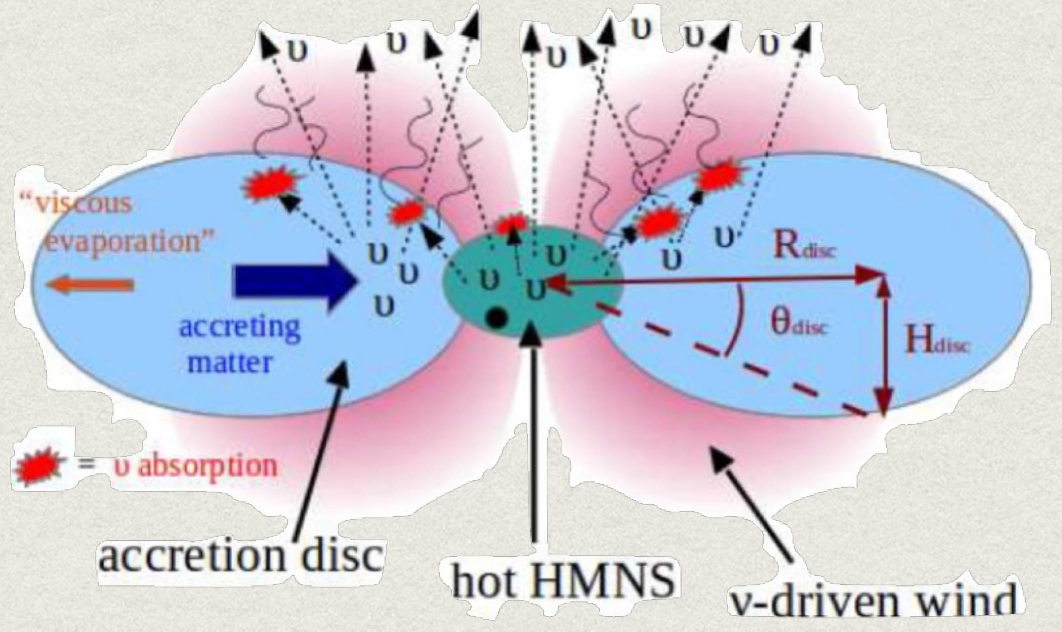
Prix Nobel en 2002
avec R. Giacconi (1/2)

« For pioneering works in the astrophysical domain that brought to the discovery of cosmic X-ray sources»

EARLY UNIVERSE



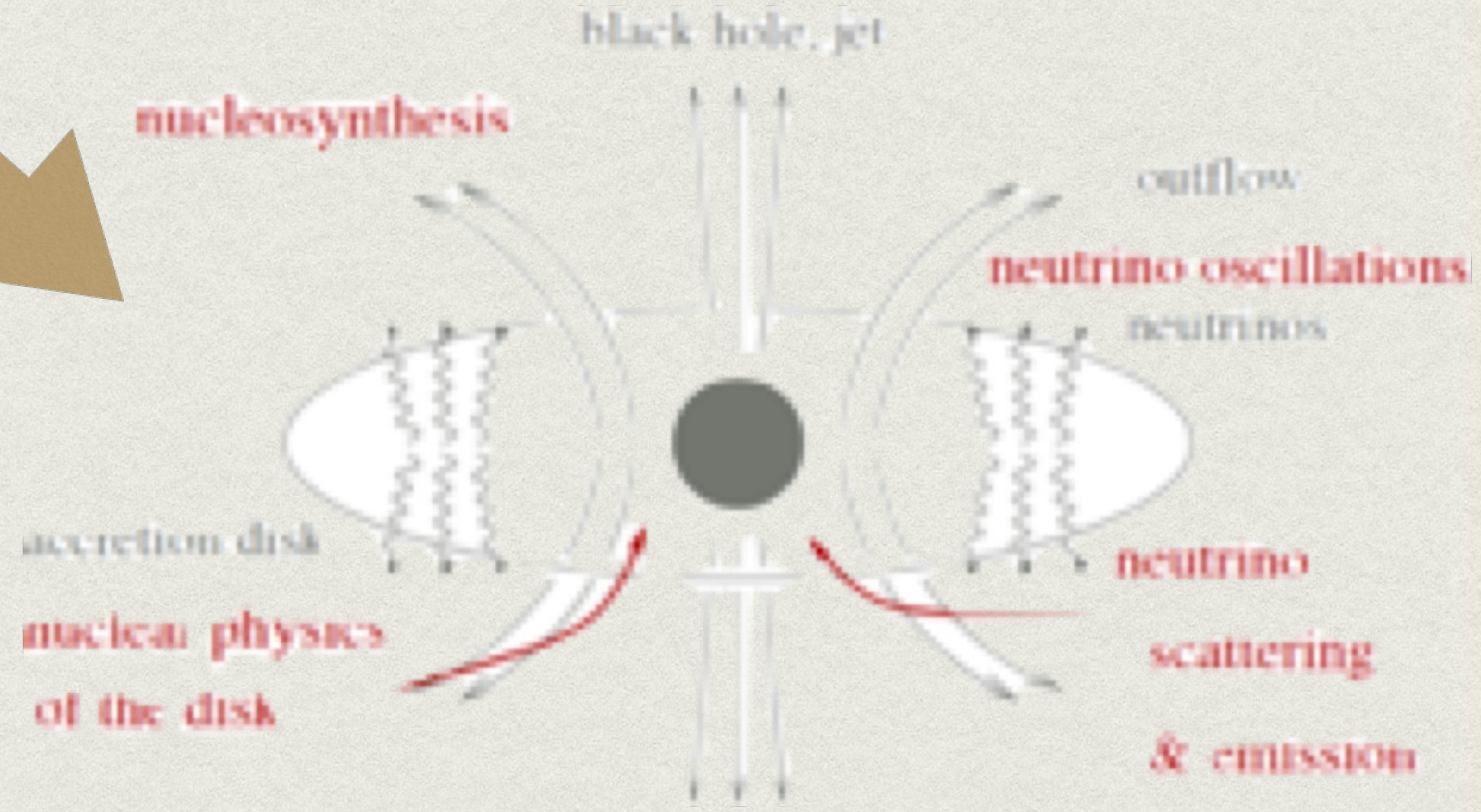
BINARY NEUTRON STAR MERGERS



GW170817

NEUTRINOS FROM DENSE ENVIRONMENTS

ACCRETION DISKS AROUND BLACK HOLES

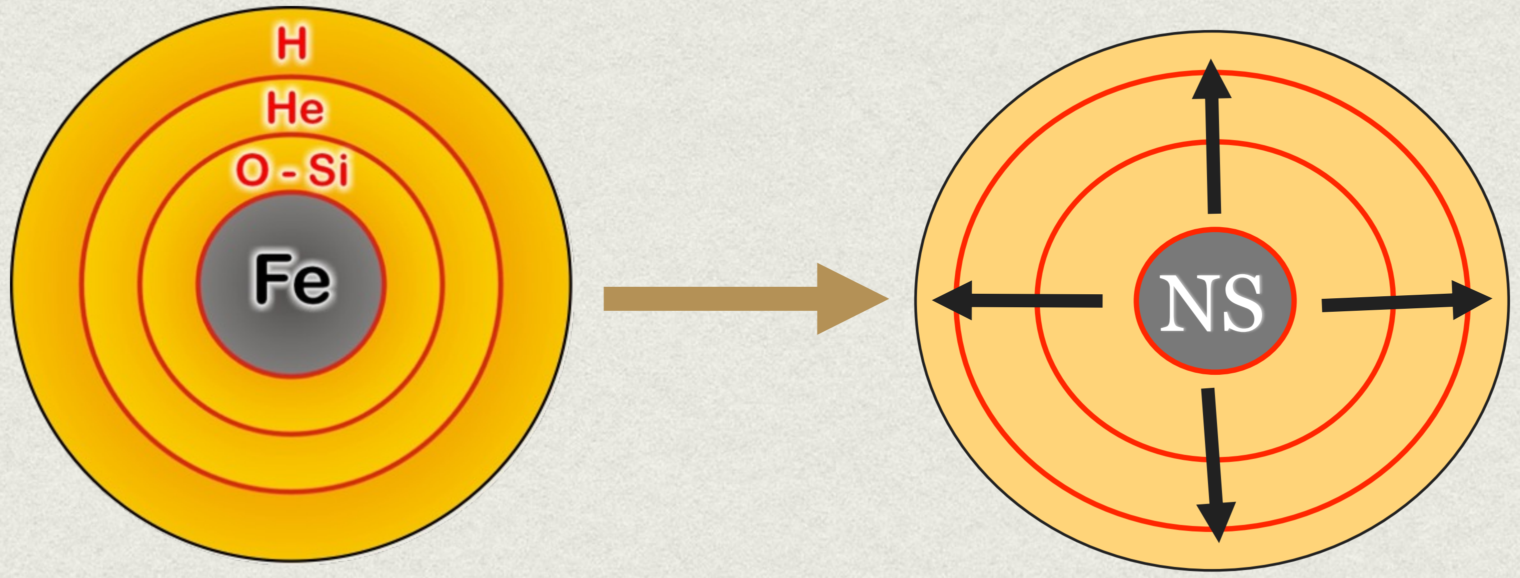


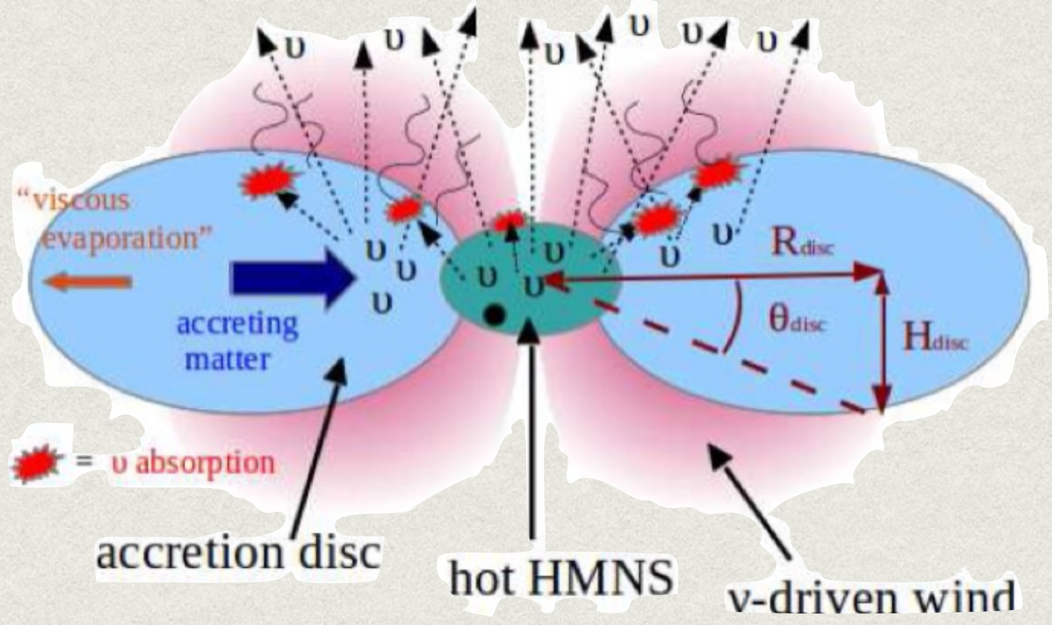
CORE-COLLAPSE SUPERNOVAE

SN1987A

DENSE ENVIRONMENTS

- « Dense » here means media that can reach 10^{10} g/cm^3 and more, A few 10^{15} g/cm^3 (limits of matter compressibility), e.g. massive stars called core-collapse supernovae or binary neutron star merger remnants, or accretion-disks around black holes, or the Early Universe.



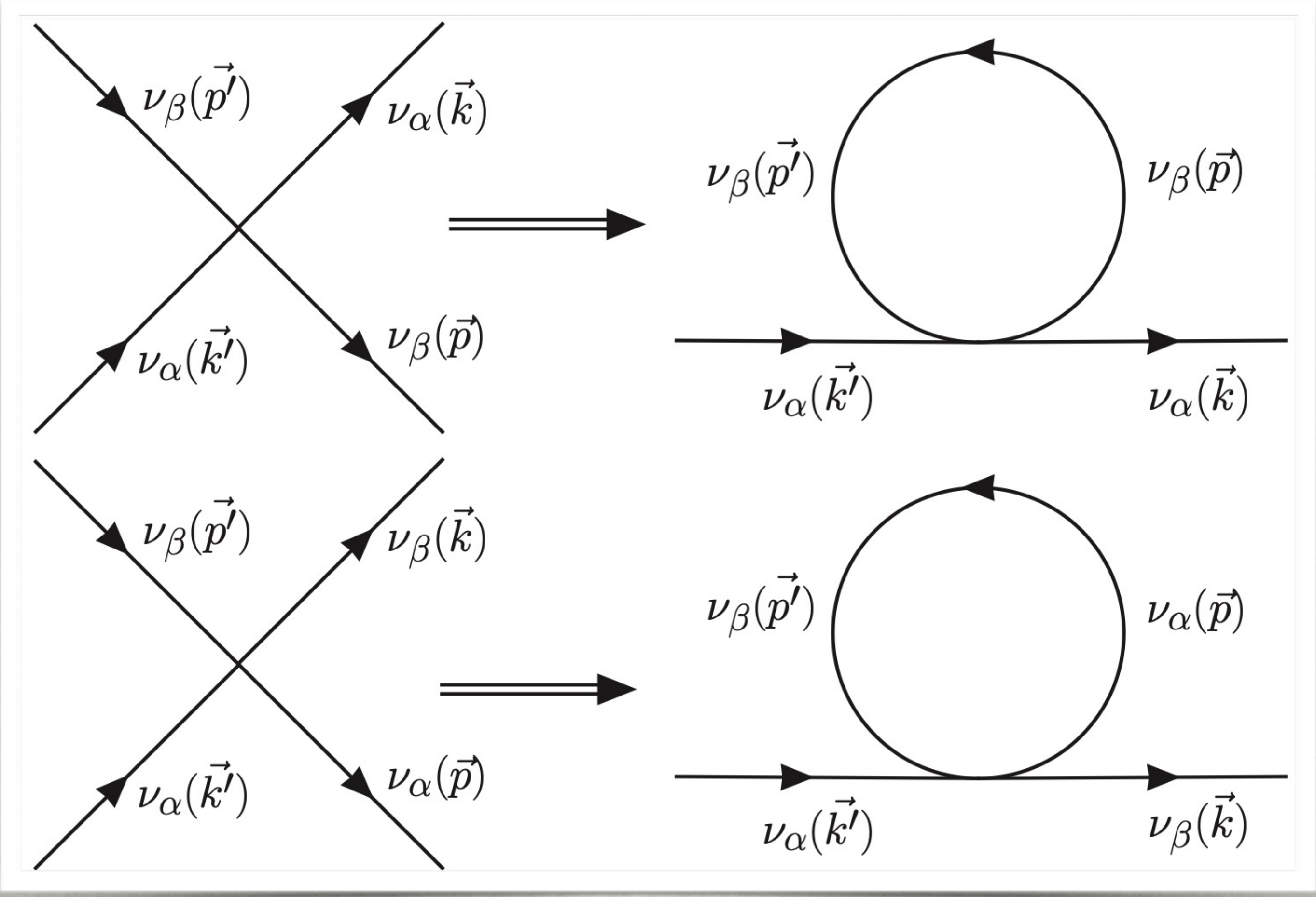


MATTER

DENSE ENVIRONMENTS

- « Dense » here also means in neutrinos. In a supernova explosion about 10^{58} neutrinos with an average energy of 10(-20) MeV produced.

→ These neutrinos interact with each other making the neutrino-neutrino interaction sizable:



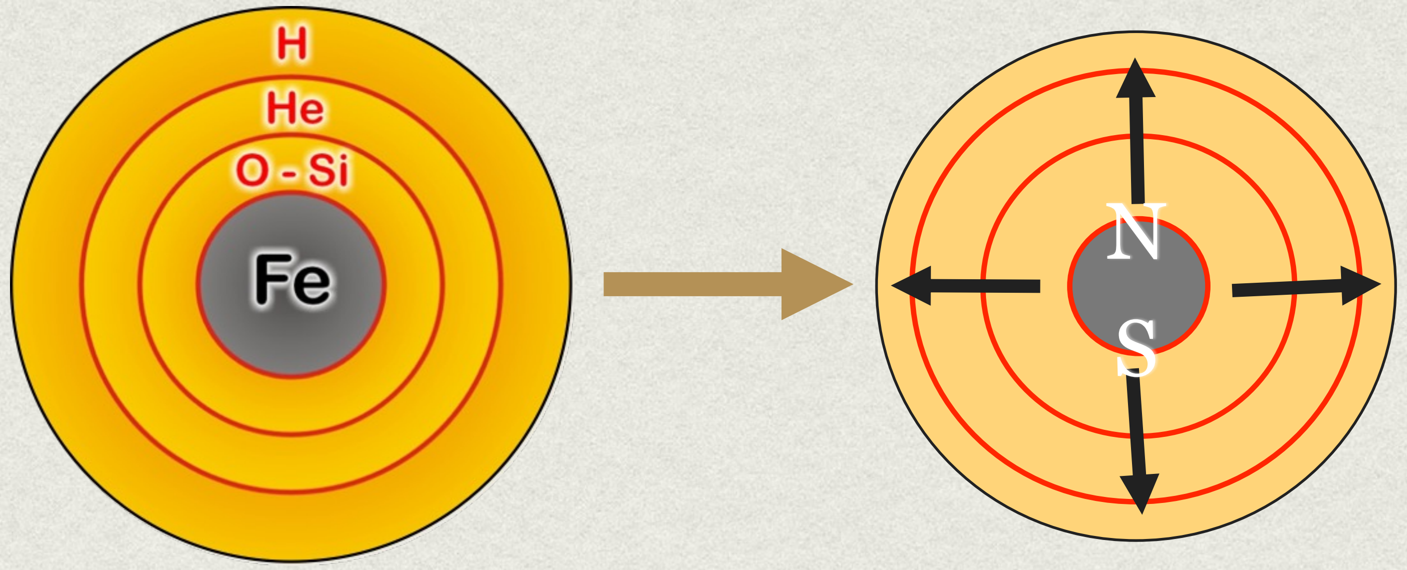
diagonal in flavor

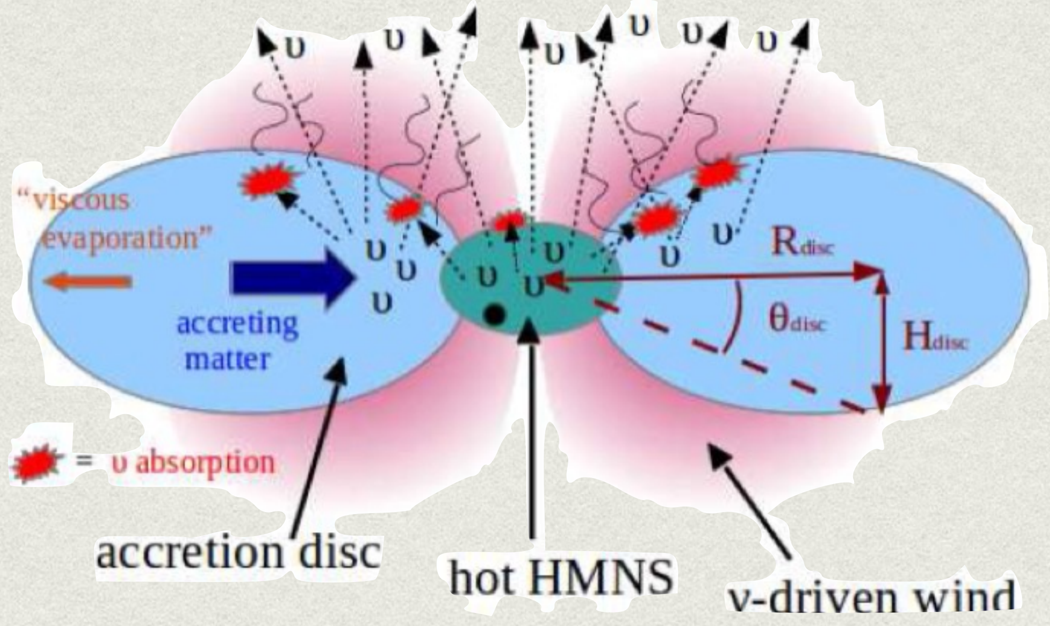
$k = k'p = p'$

non-diagonal in flavor

$k = k'p = p'$

Pantaleone, PLB 1992

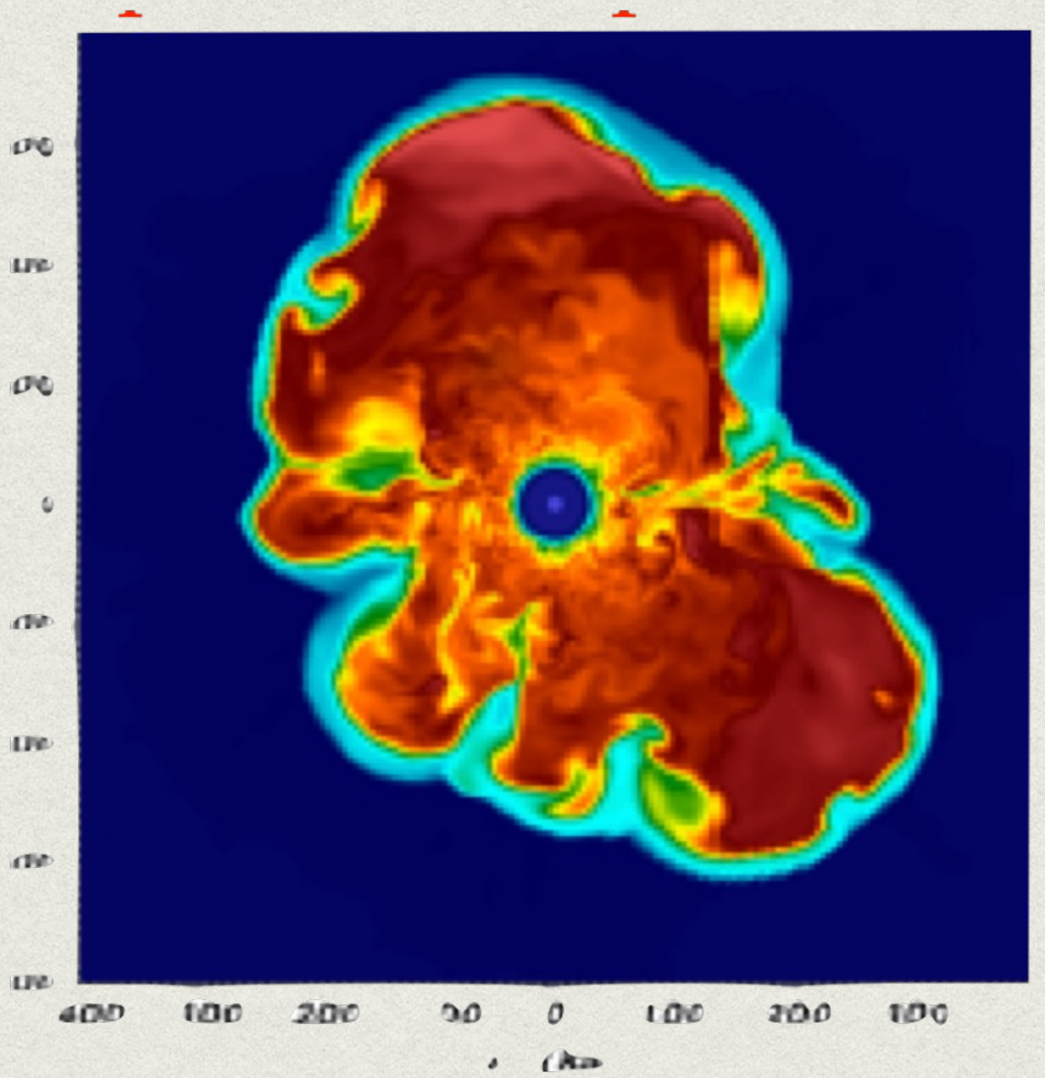




« Neutrino propagation in supernovae is a non-linear many-body problem. »

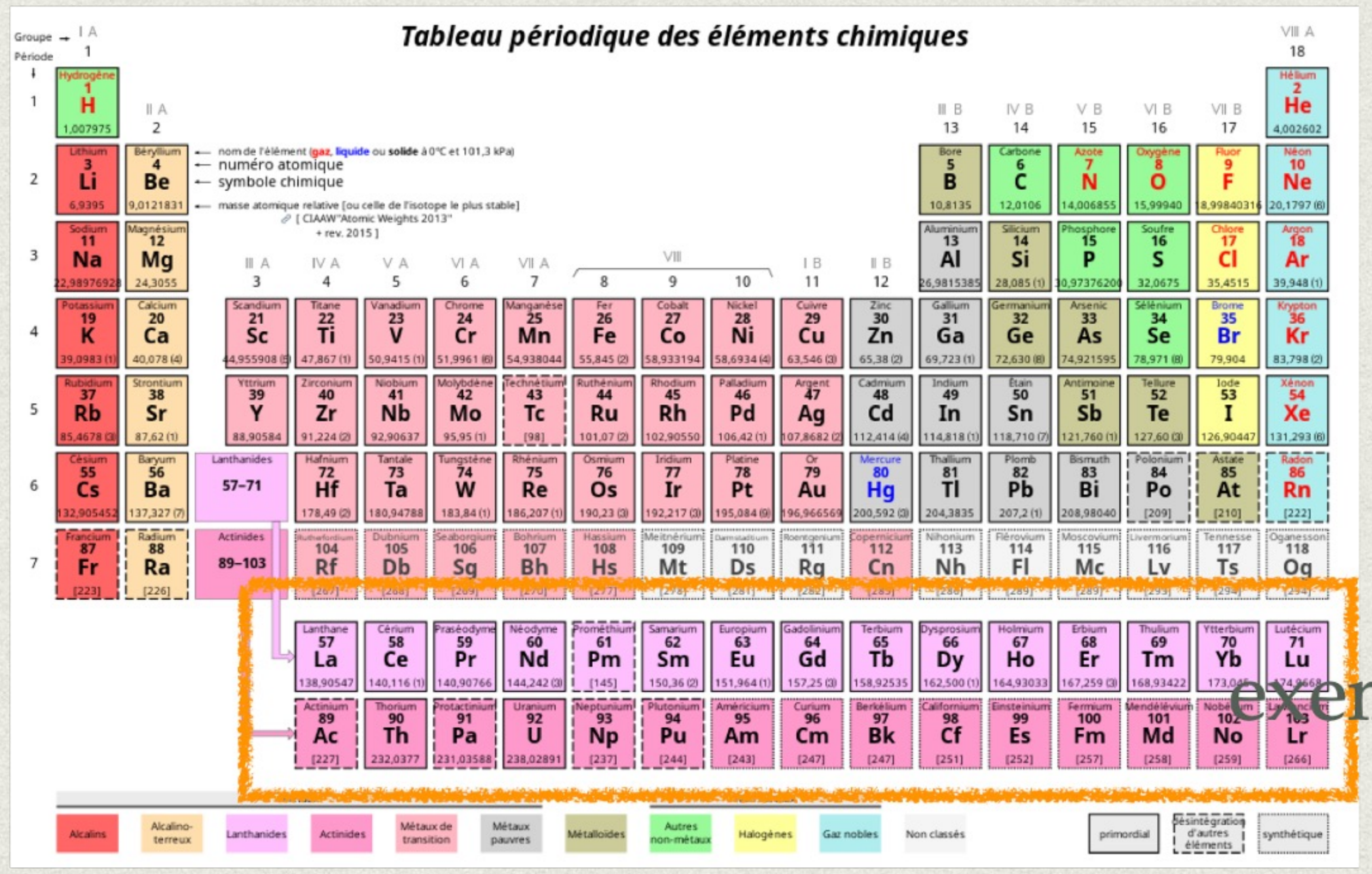
MATTER AND NEUTRINOS

WHY are we *interested* in **neutrinos from dense environments**?



Mueller et al, 1705.00620

How do supernovae explode?



exemple

Where are the heavy elements made?

Neutrinos from dense environments

Future observations of core-collapse supernova neutrinos and the diffuse supernova neutrino background (DSNB)

Search for new physics, e.g. dark matter particles, and multimessenger physics

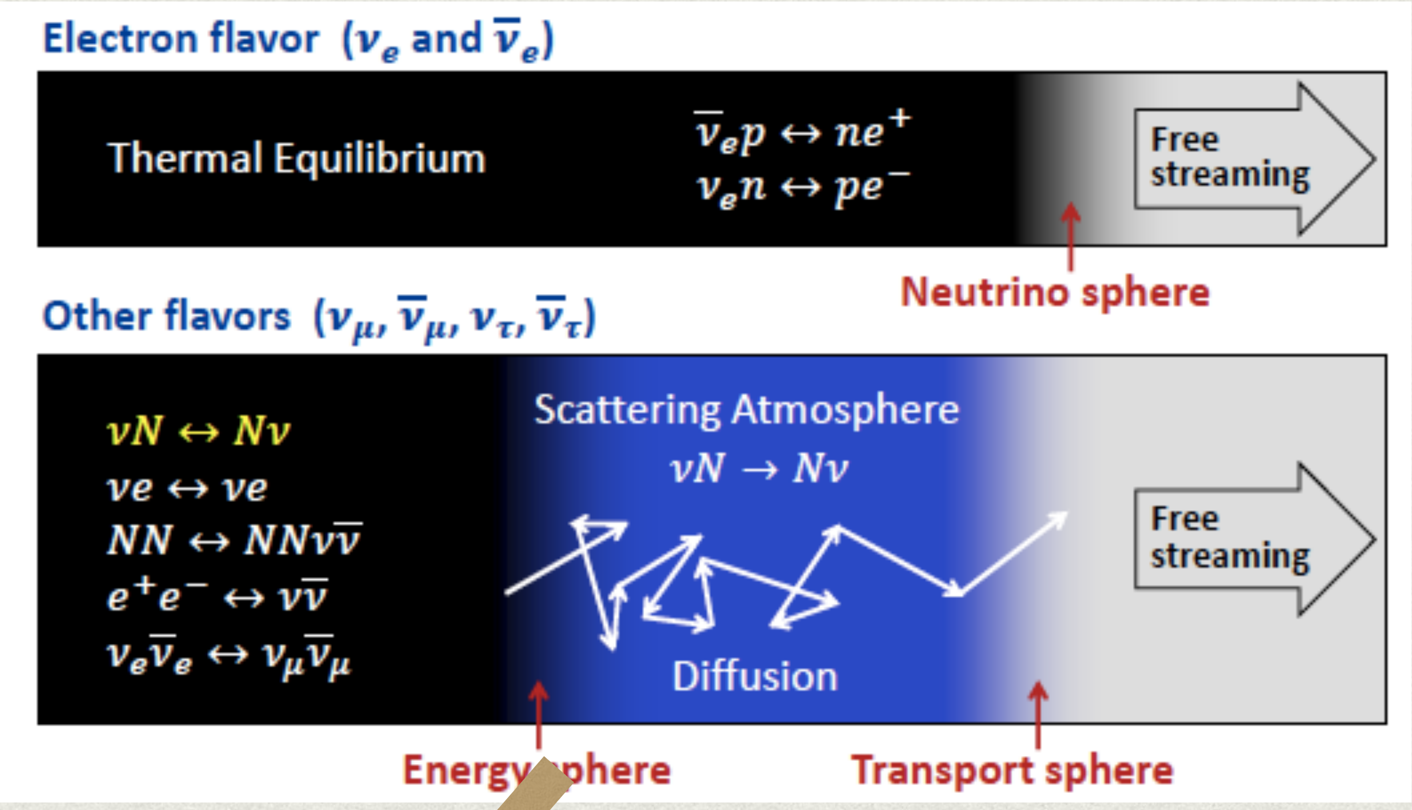
FROM TRAPPED TO FREE-STREAMING

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

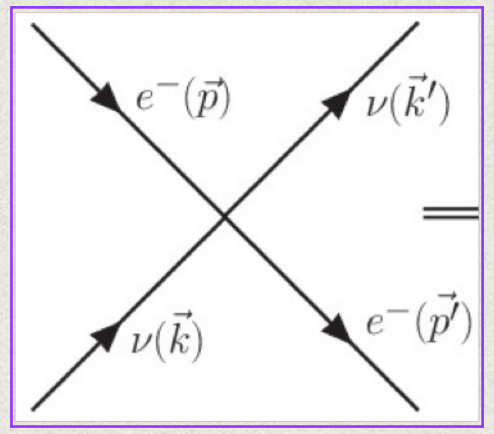
  $\sigma = 6\ 10^{-41}\mathrm{cm}^2$ $\rho = 10^{14}\mathrm{g/cm}^3$ $\lambda \approx \mathrm{m}$

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

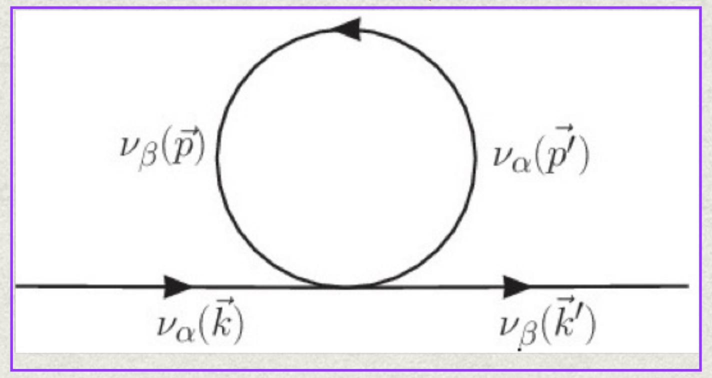
  The region where neutrinos start free-streaming is called the neutrinosphere. It is energy and flavor dependent. In flavor studies, up to 2016 it was always taken as a a sharp boundary.



Raffelt (2012)



collisions dominated
Boltzmann approximation



flavor conversion
mean-field approximation

NEUTRINO EVOLUTION EQUATIONS IN DENSE MEDIA

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

- <u>One-body density matrix in 2nu framework :</u>

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

Diagonal elements are the expectation value of the number operator :

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

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

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

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

- 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 (MEAN-FIELD) HAMILTONIAN

- The neutrino Hamiltonian contains different contributions

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

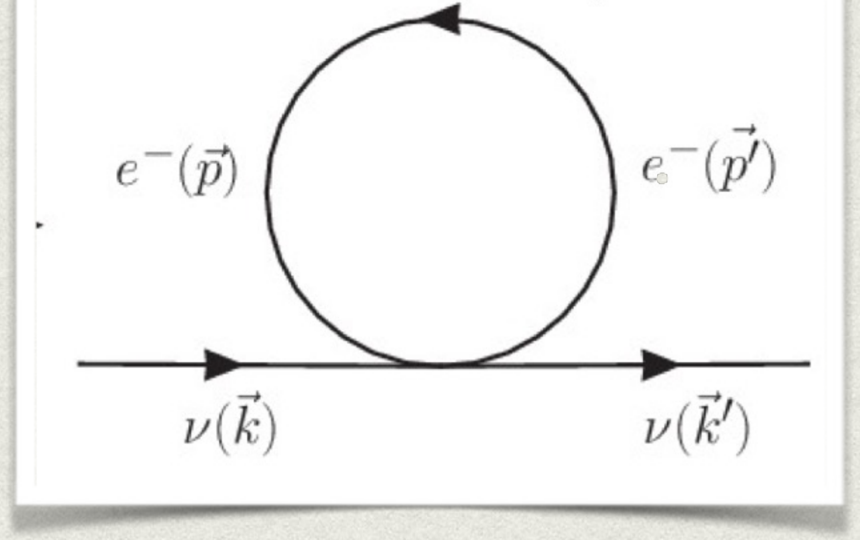
$$h_{vac} = \omega \begin{pmatrix} -c_{2\theta} & s_{2\theta} \\ s_{2\theta} & c_{2\theta} \end{pmatrix}$$

responsible for vacuum oscillations

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

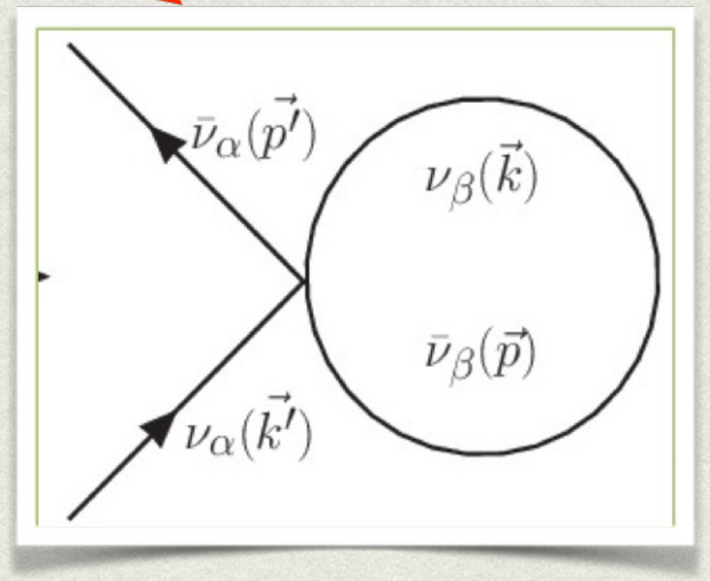
Matter term, responsible for the Mikheev-Smirnov-Wolfenstien effect

Wolfenstein, 1978; Milheev-Smirnov, 1986



$k = k'p = p'$

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



$k = k'p = p'$

Neutrino-neutrino interactions

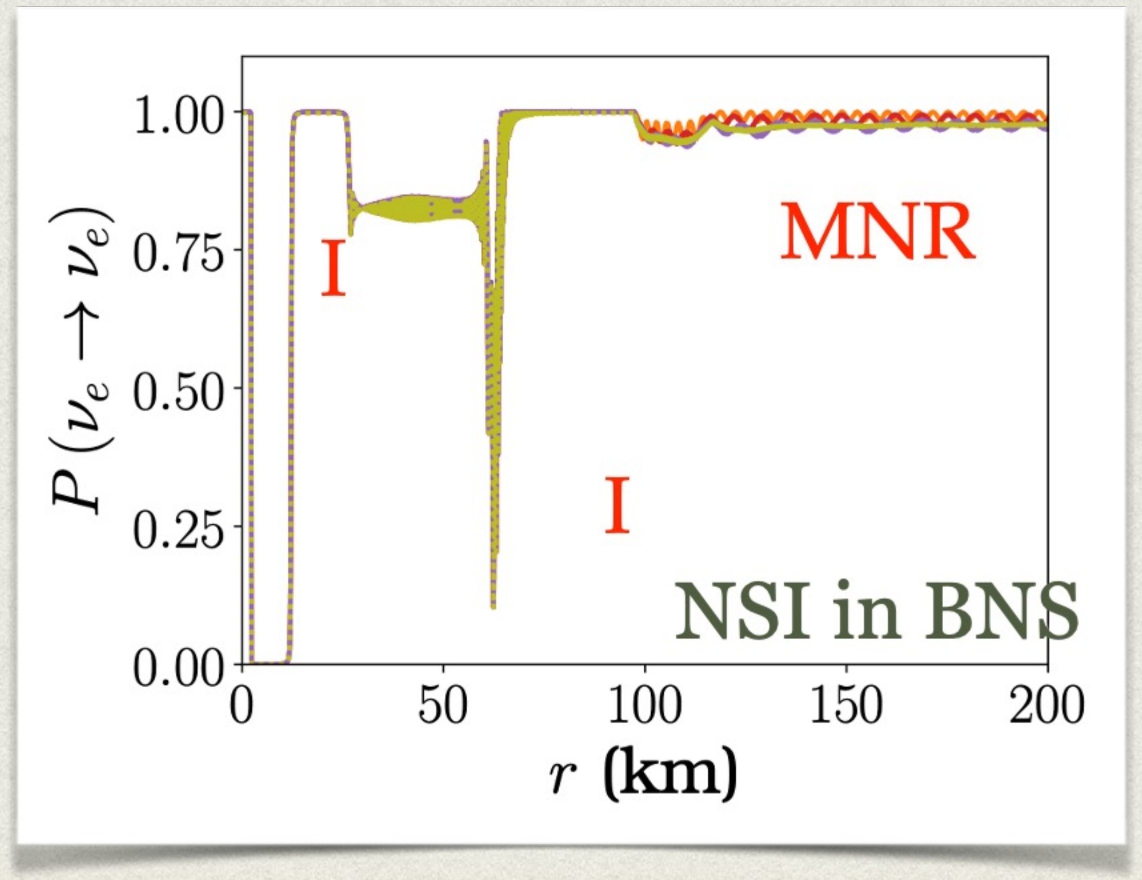
$$h_{\nu\nu} = \sqrt{2} G_F \sum_\alpha [\int (1 - \hat{q} \cdot \hat{p}) \times [dn_{\nu_\alpha} \rho_{\nu_\alpha}(\vec{p}) - dn_{\bar{\nu}_\alpha} \bar{\rho}_{\bar{\nu}_\alpha}(\vec{p})]],$$

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

Non-standard interactions

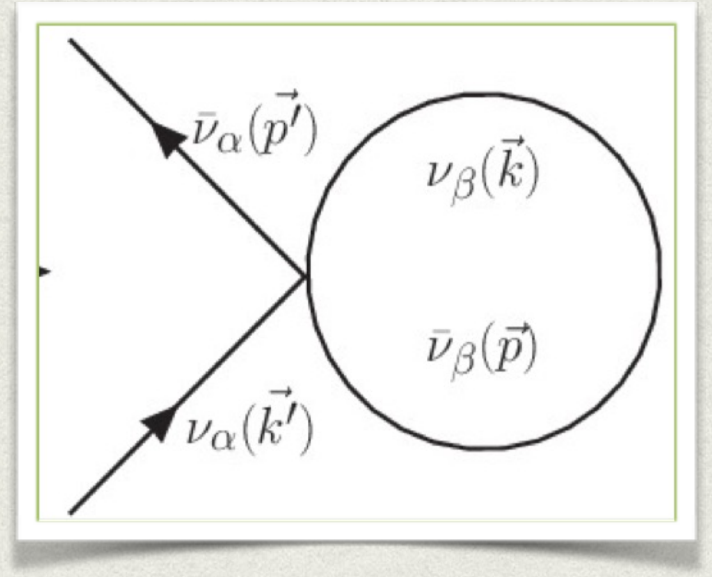
$$\begin{pmatrix} |\epsilon_{ee}| < 2.5 & |\epsilon_{e\tau}| < 1.7 \\ & |\epsilon_{\tau\tau}| < 9.0 \end{pmatrix}$$

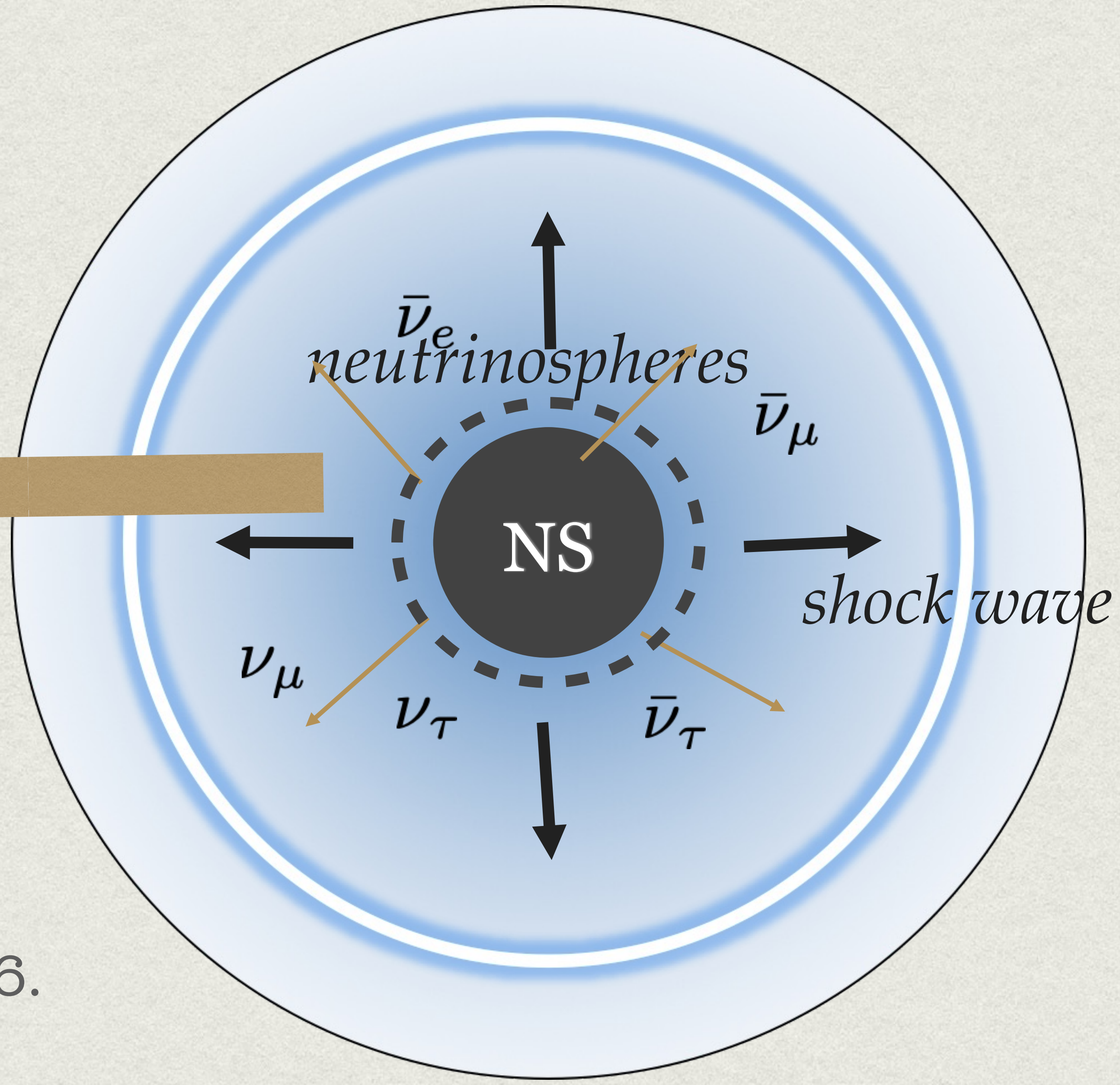
limits for neutral solar-like matter



Chatelain, Volpe, PRD97 (2018), 023014, 1710.11518

FLAVOR CONVERSION IN DENSE ENVIRONMENTS





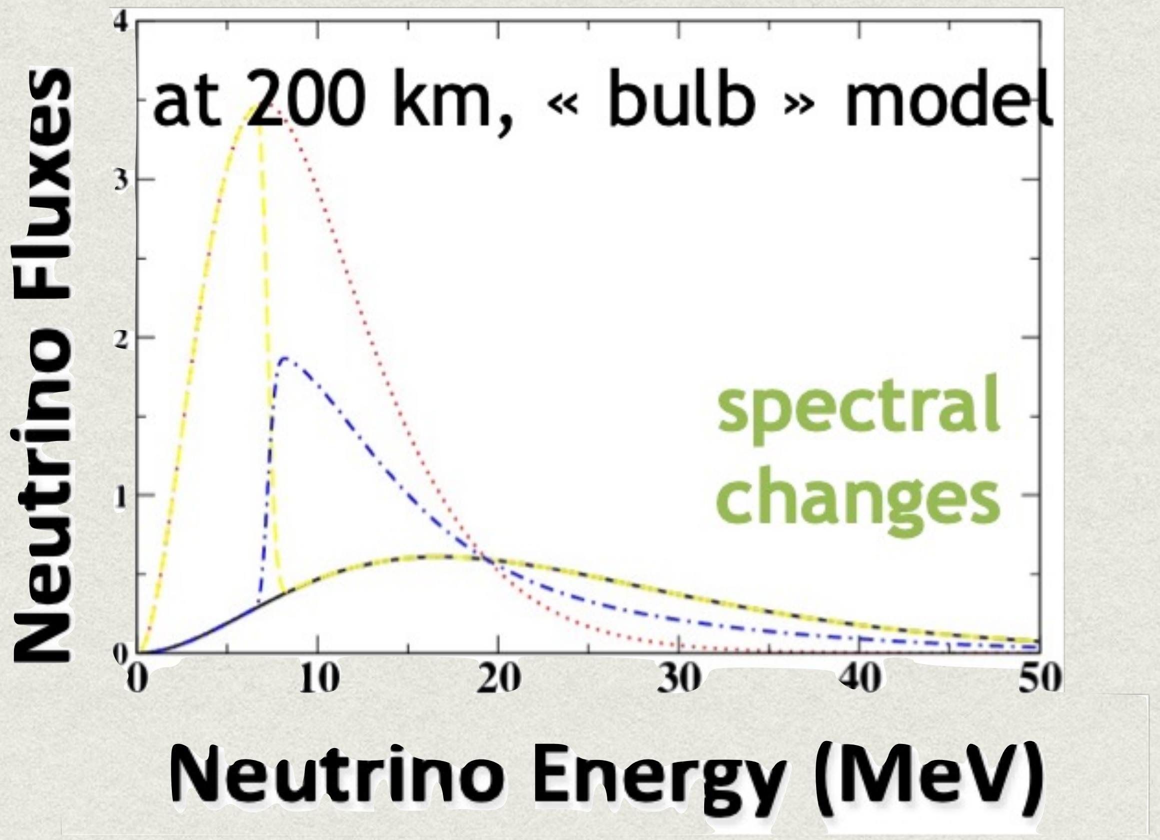
Neutrino-neutrino interactions

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

slow **modes**

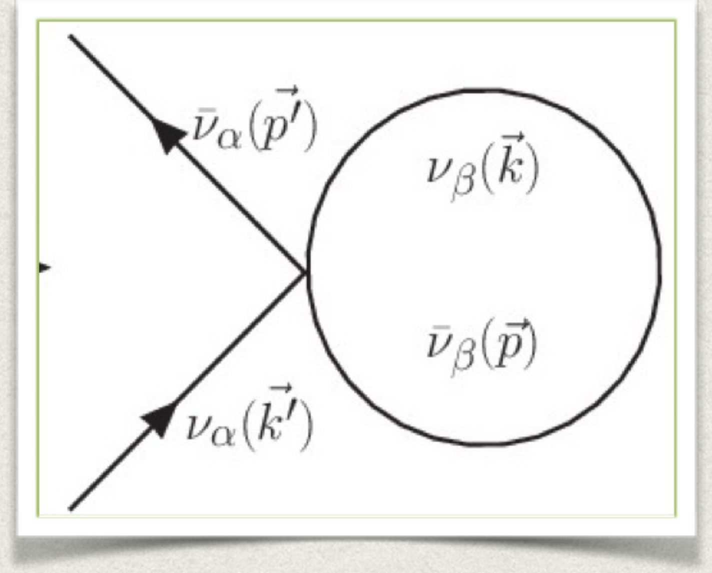
fast **modes (m scale or less)**

Sawyer PRD 2005, PRL 2016.



Balantekin, Gava, Volpe, PLB 662 (2008)

FLAVOR CONVERSION IN DENSE ENVIRONMENTS

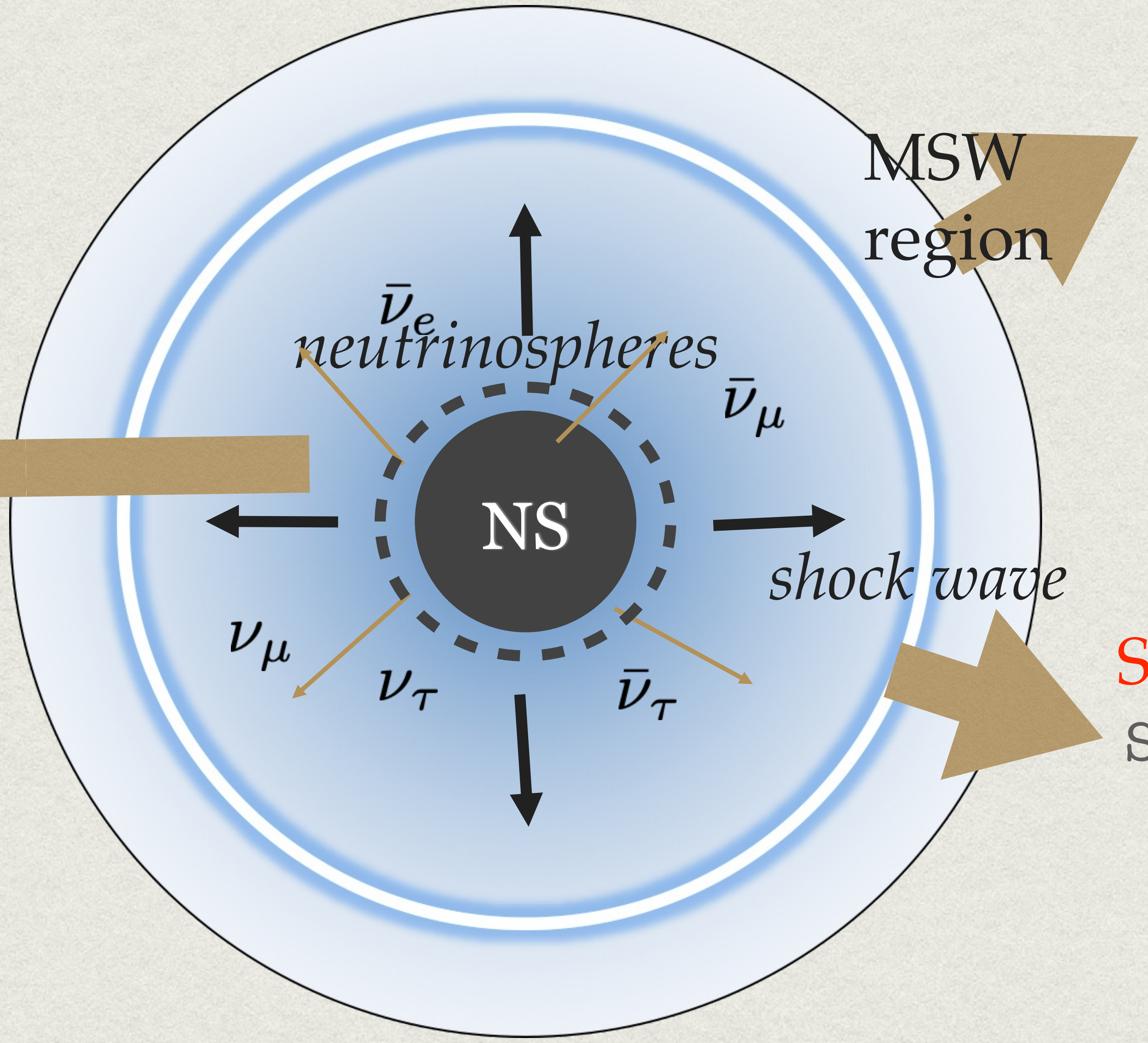


Neutrino-neutrino interactions

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

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

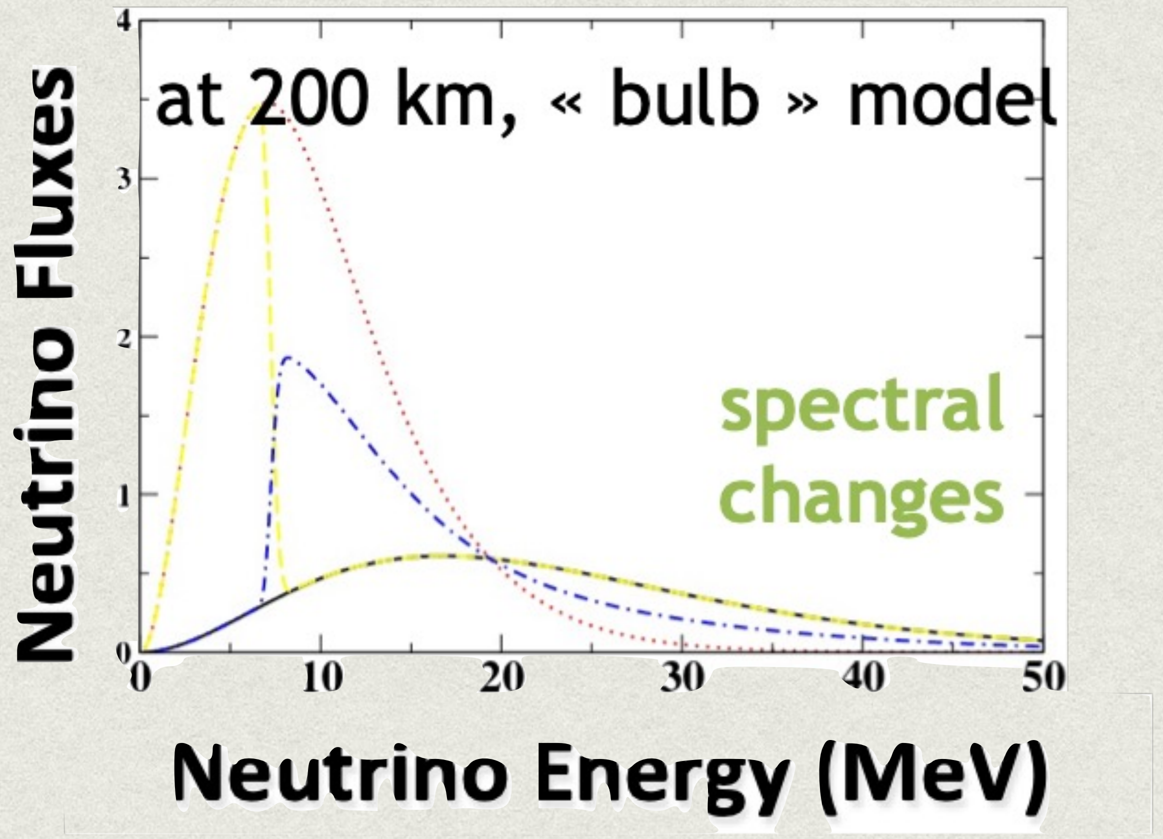
Sawyer PRD 2005, PRL 2016.



MSW effect

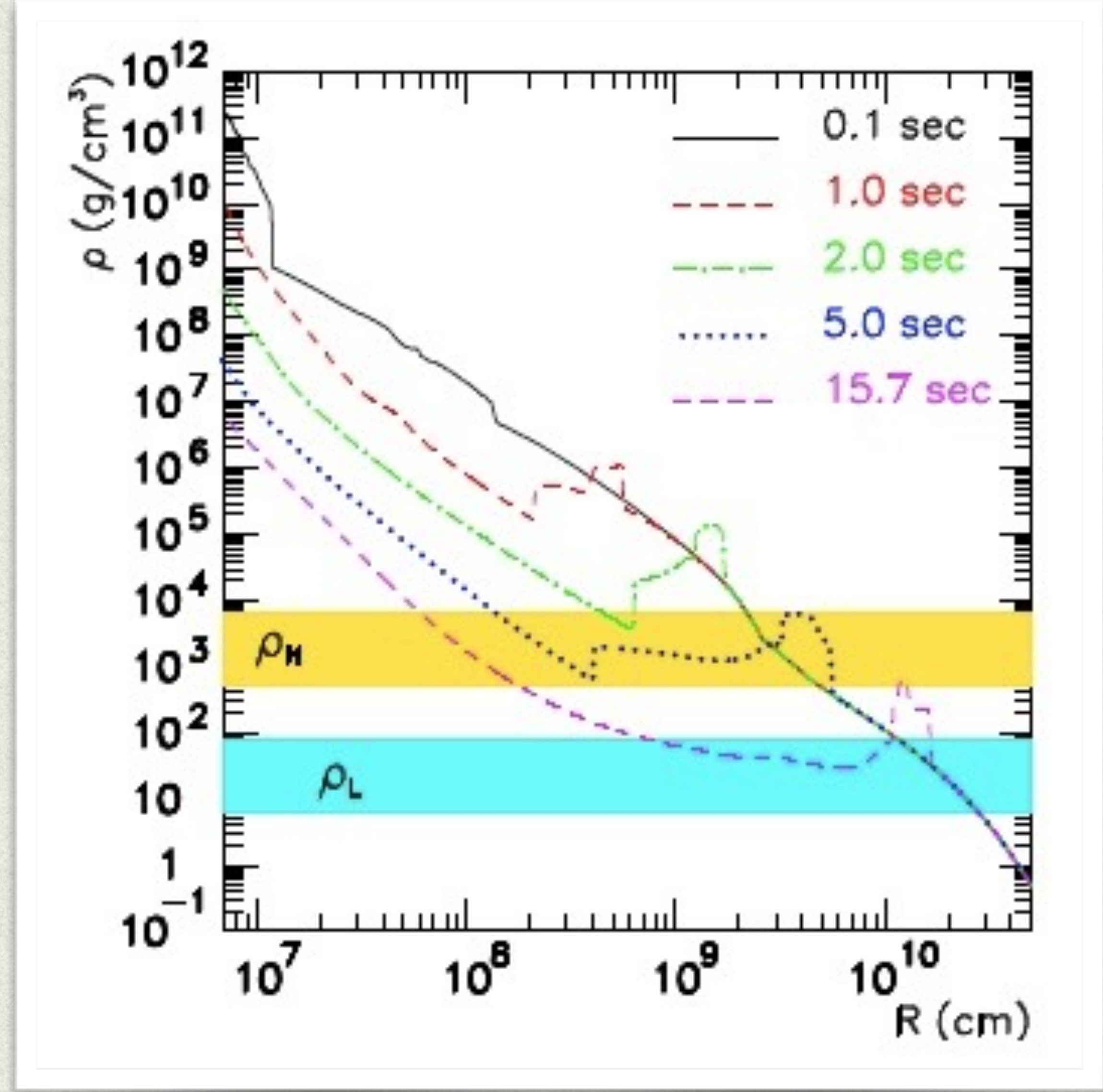
Shock wave effects

Schirato and Fuller, hep-ph/0205390



Balantekin, Gava, Volpe, PLB 662 (2008)

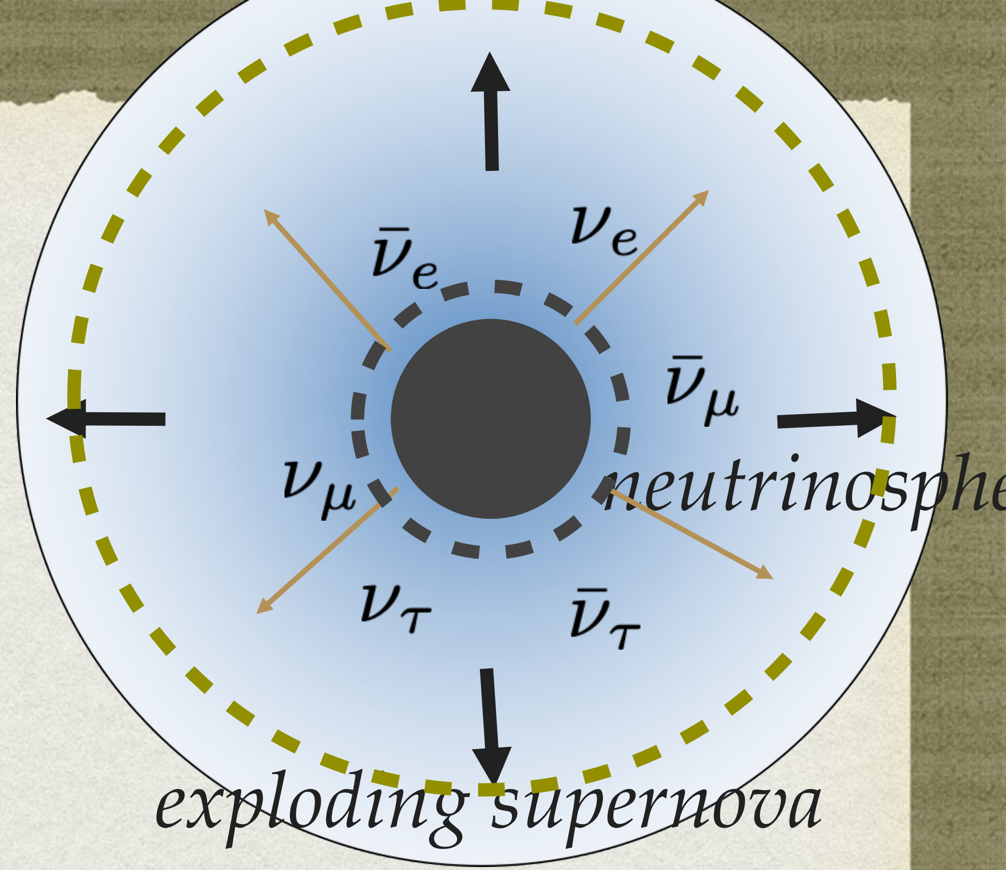
Tomas et al, JCAP 09 (2004)



Presence of front and reverse shocks .

MSW resonance can be met multiple times.

MSW EFFECT IN SUPERNOVAE



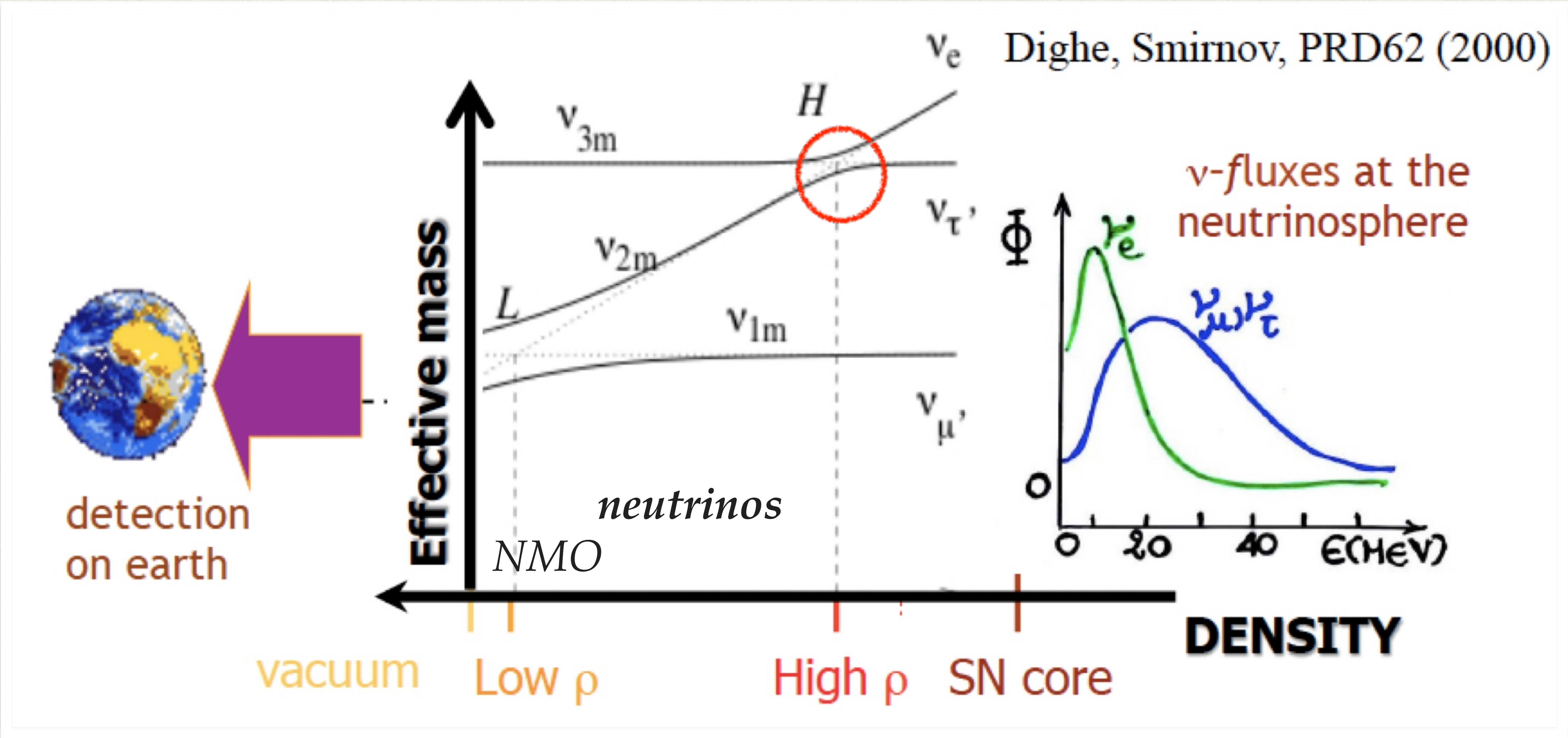
MSW resonance condition $\sqrt{2}G_F n_e - \frac{\Delta m^2}{2E}\cos 2\theta = 0$

Main resonances :
High (H) $(\theta_{13}, \Delta m^2_{13})$
Low (L) $(\theta_{12}, \Delta m^2_{12})$

Spectral swapping: Modification of the neutrino spectra due to flavor conversion mechanisms

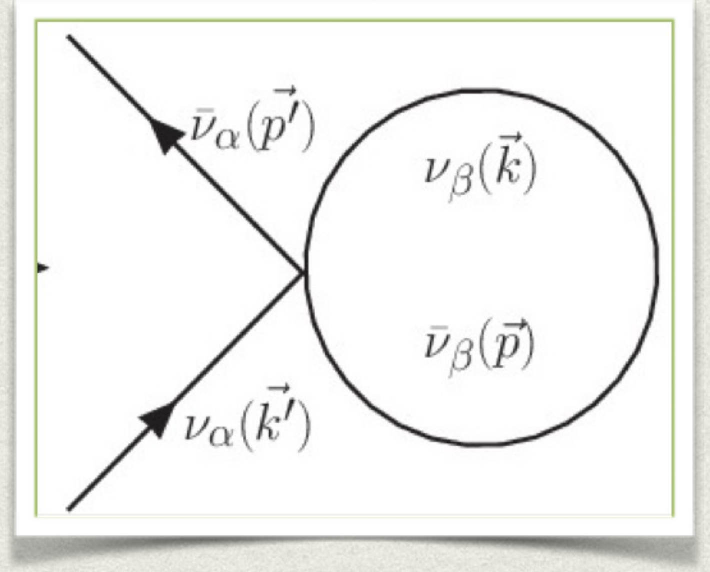
$$\phi_{\bar{\nu}_e} = p\phi^0_{\bar{\nu}_e} + (1-p)\phi^0_{\bar{\nu}_x}$$

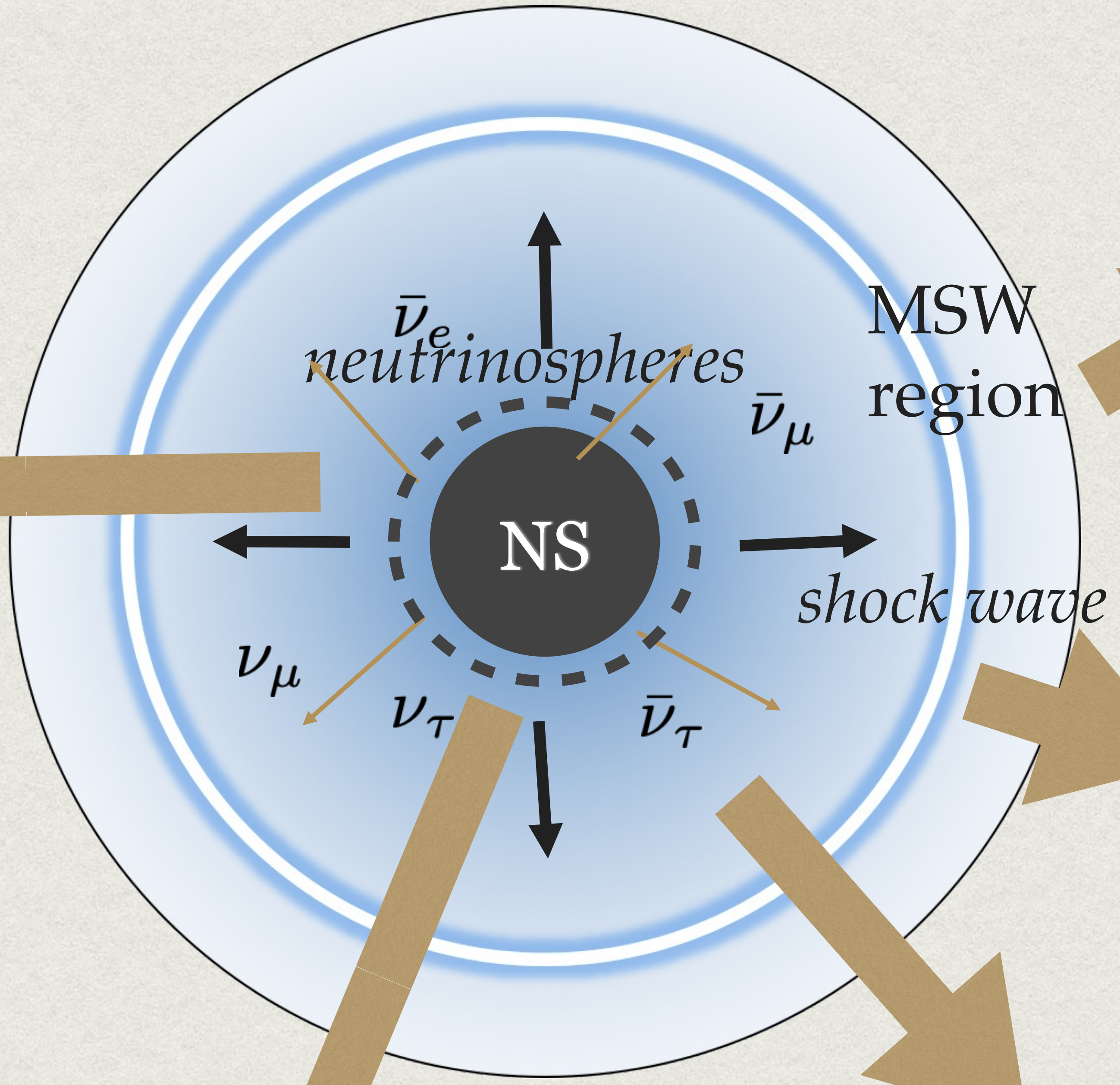
$p = 0.68 \quad NMO$ $\qquad p = 0 \quad IMO$



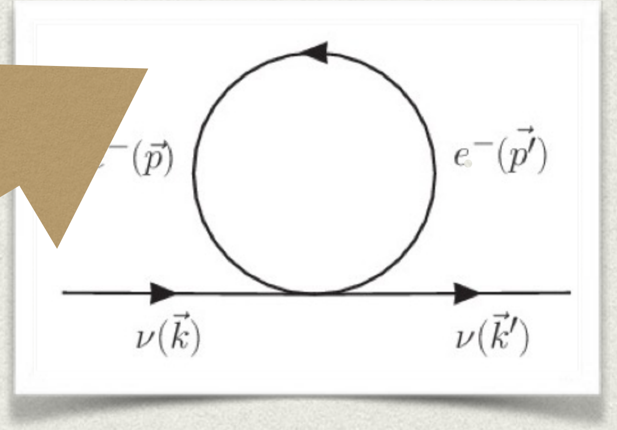
→ Evolution at the H-resonance depends on the unknown sign of Δm^2_{13}

FLAVOR CONVERSION IN DENSE ENVIRONMENTS





MSW effect

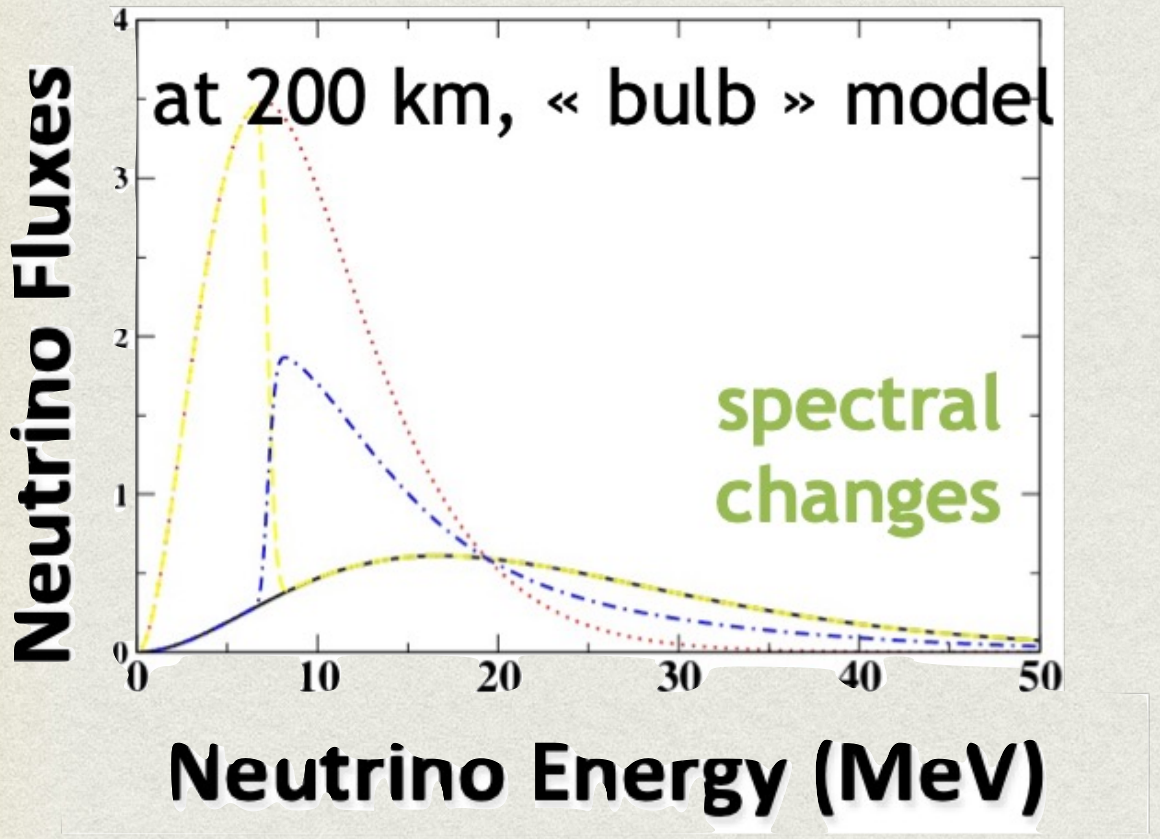


Neutrino-neutrino interactions

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

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

Sawyer PRD 2005, PRL 2016.



Balantekin, Gava, Volpe, PLB 662 (2008)

Shock wave effects (multiple MSW)

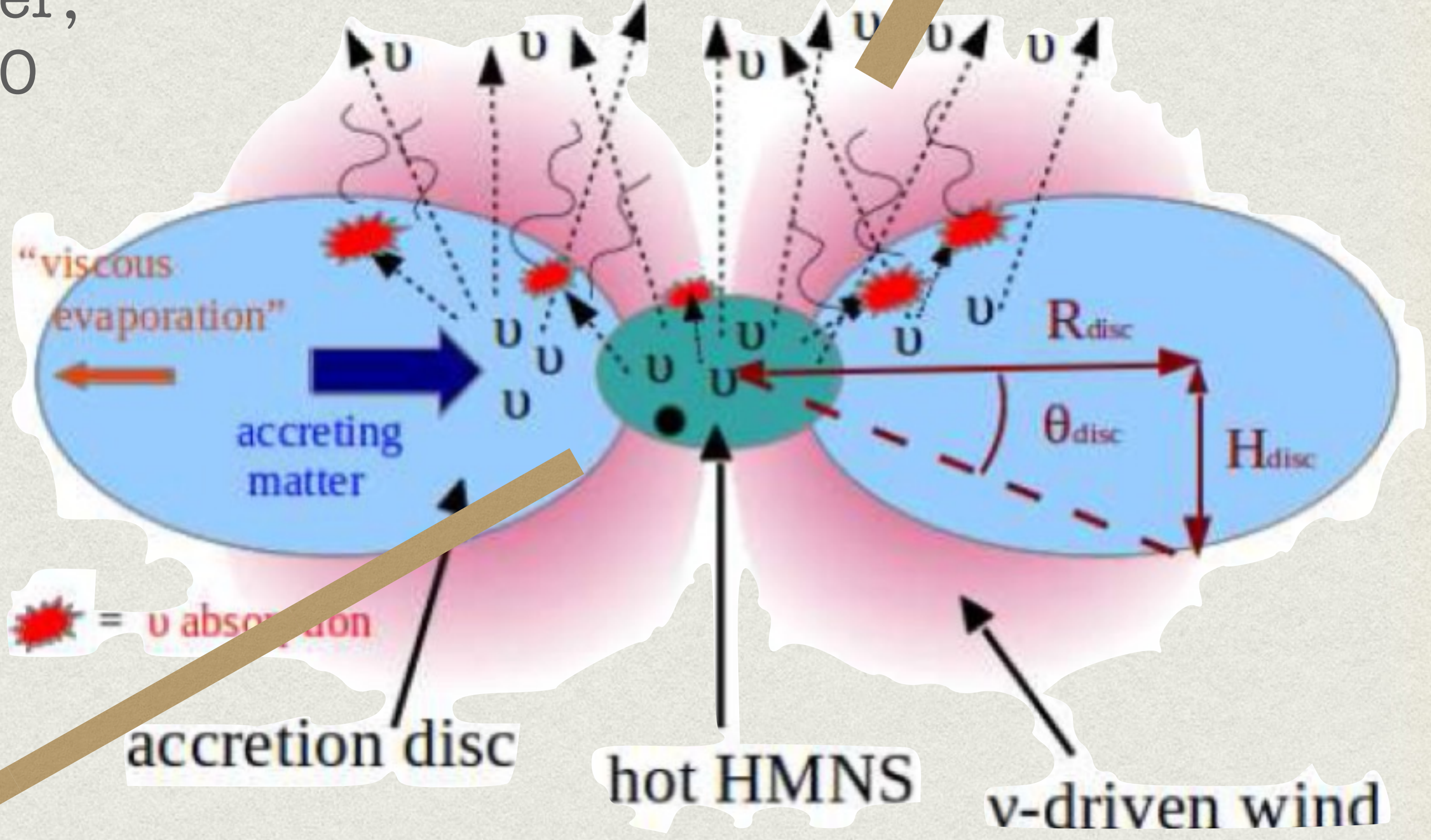
Schirato and Fuller,
hep-ph/0205390

Turbulence effects
Loreti et al, PRD 52 (1995)

Collisional instabilities

Johns, PRL 19 (2023)

MSW effect



Neutrino-neutrino interactions

Many aspects understood (MSW, shock wave effects, ...)
but important questions remain (neutrino-neutrino interaction, interplay with collisions, role of correlations)

CONCLUSIONS

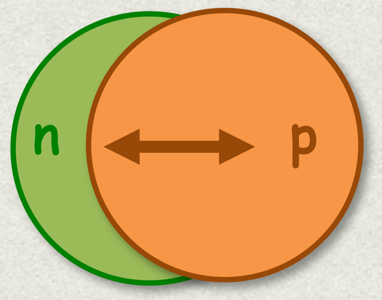
Oscillation parameters measured precisely, except Majorana CP violating phases and the Dirac one. **Key open questions include** the neutrino nature, the neutrino absolute mass and mass ordering, the origin of the neutrino mass, the neutrino magnetic moment, …

Neutrinos from dense environments are tightly linked to key open questions, in particular the core-collapse supernova mechanism, the sites for heavy elements (r-process), **and from stars are unique laboratories for the search for unknown neutrino properties, new particles and interactions.**

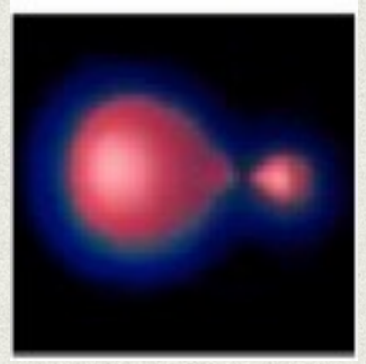
How neutrinos evolve in dense environments is an open question, where important developments are ongoing and an active theoretical field since almost twenty years. Numerous aspects understood (MSW, shock wave and turbulence effects) but many open questions remain - interplay between collisions and flavor mechanisms, role of correlations.

Connections to other domains

ATOMIC NUCLEI and CONDENSED MATTER



giant resonances



nuclear collision

phonons

metallic clusters

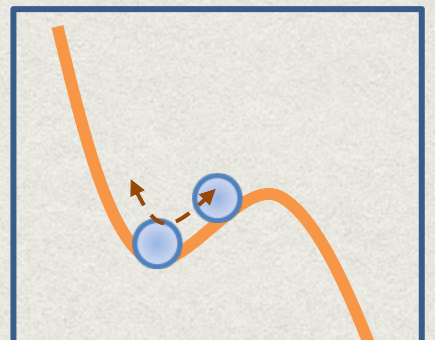
MEAN-FIELD level: there are also correlators of the pairing-type.

$$\kappa_{ik} \equiv \langle b_k a_j \rangle$$

$$\kappa = \begin{pmatrix} \langle b_{\nu_e} a_{\bar{\nu}_e} \rangle & \langle b_{\nu_x} a_{\bar{\nu}_e} \rangle \\ \langle b_{\nu_e} a_{\bar{\nu}_x} \rangle & \langle b^{\dagger}_{\nu_x} a_{\bar{\nu}_x} \rangle \end{pmatrix}$$

Volpe, Väänänen, Espinoza, PRD87 (2013), 1302.2374

Linearized theory (Random-Phase-Approximation)



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

Eigenvalue equations tell us about the occurrence of flavor instabilities.

Väänänen, Volpe, PRD88 (2013), arXiv: 1306.6372

Linearised equations first introduced by
Sawyer PRD79 (2009), Banerjee , Dighe, Raffelt, PRD 84 (2011)