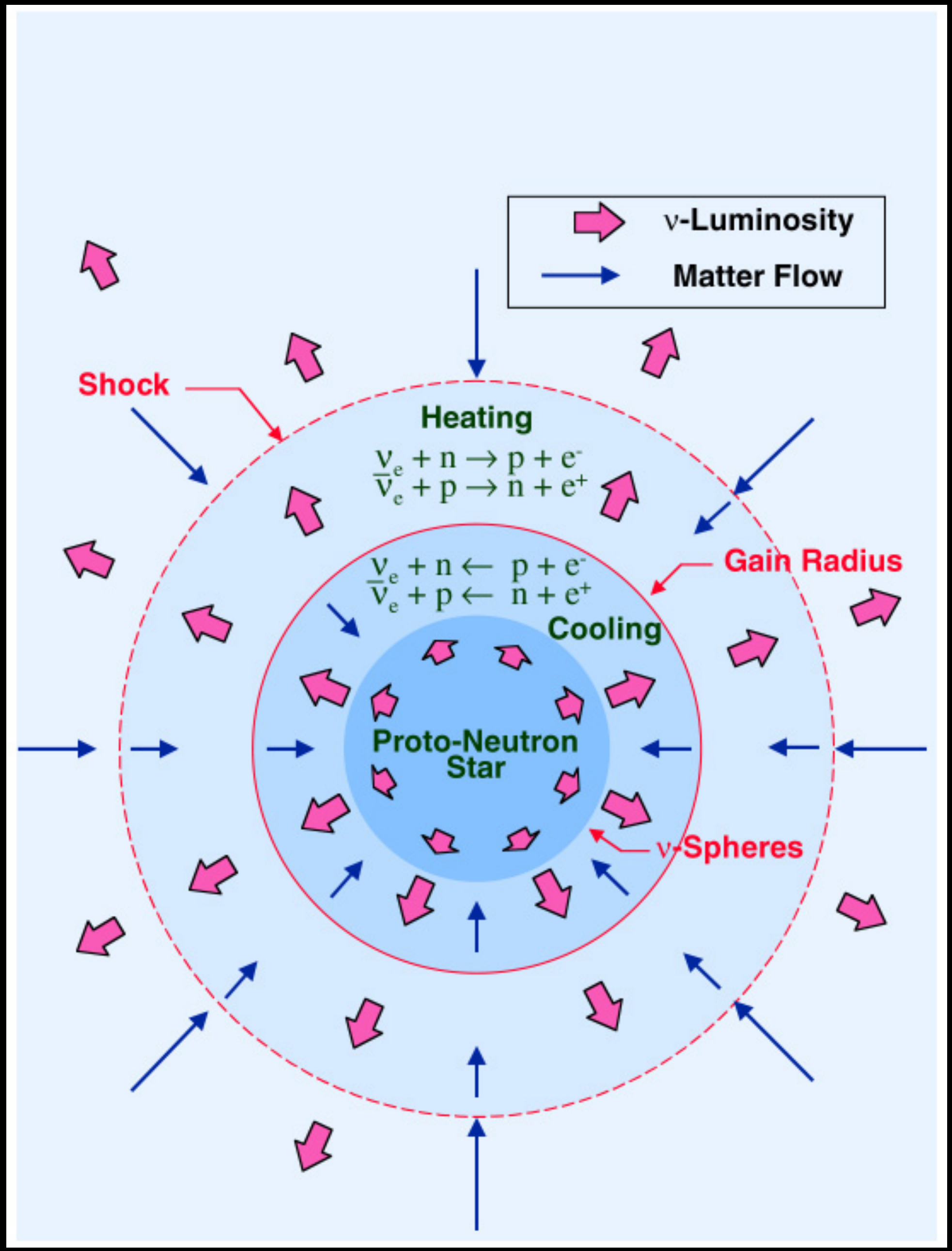
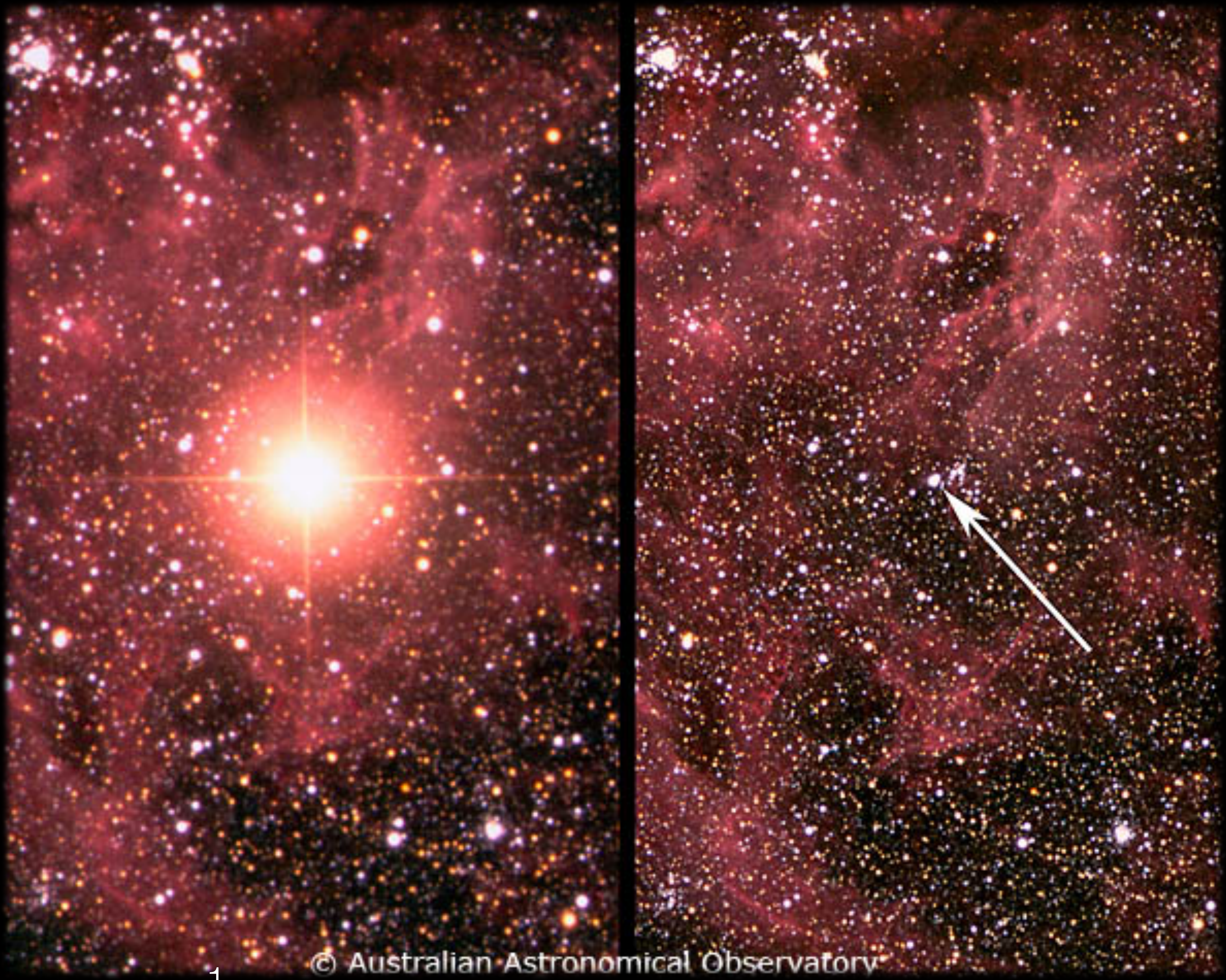
Collective Neutrino Oscillations in Core-Collapse Supernovae

Sajad Abbar

MPP Project Review 2021





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SFB 1258

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Core-Collapse Supernova

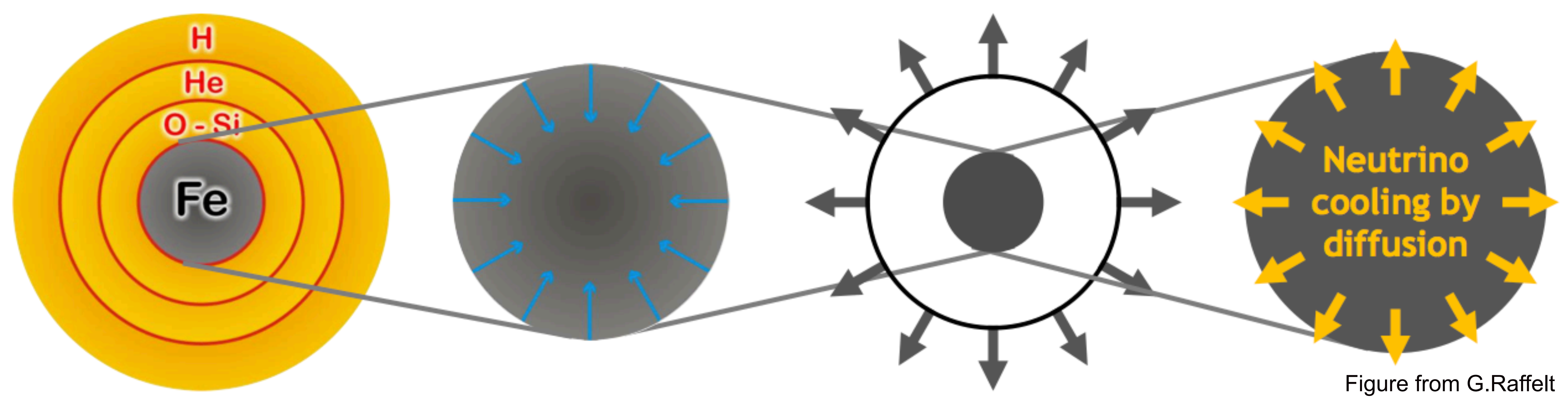


Figure from G.Raffelt

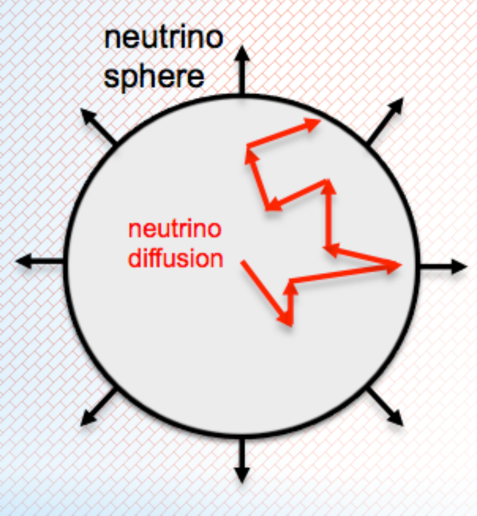
Stars burn lighter elements into heavier ones until the core reaches **Iron**.

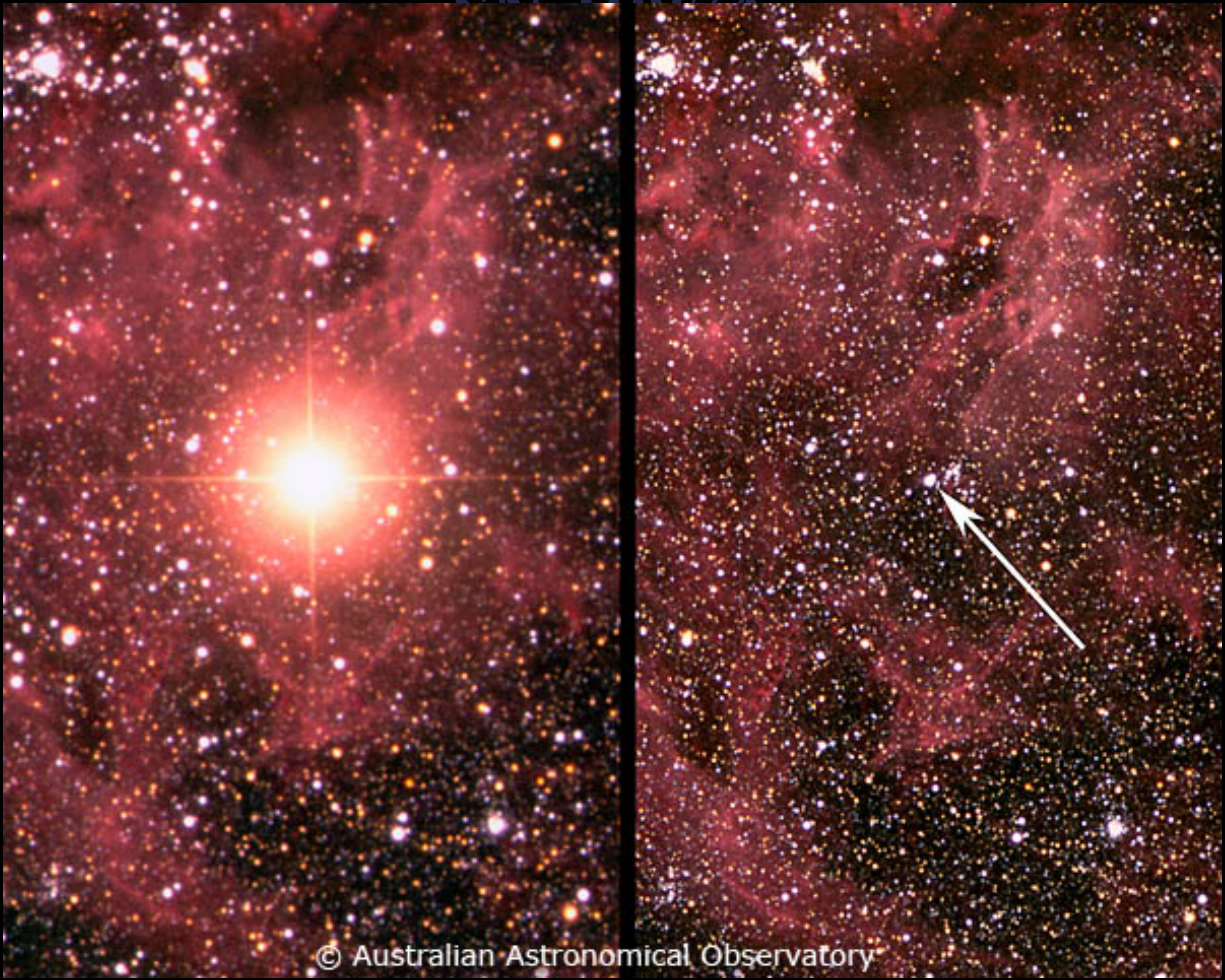
When the mass of the core becomes larger than the **Chandrasekhar** mass the collapse starts.

The collapse is **halted** when the inner core reaches density of order nuclear density.

Neutrinos are trapped inside the **neutrino sphere**.

- A huge amount of energy (~10^{53} ergs (10^{46} joule), 99% of the total released energy) is released in the form of neutrinos of all flavors.
- The explosion can outshine the host galaxy.





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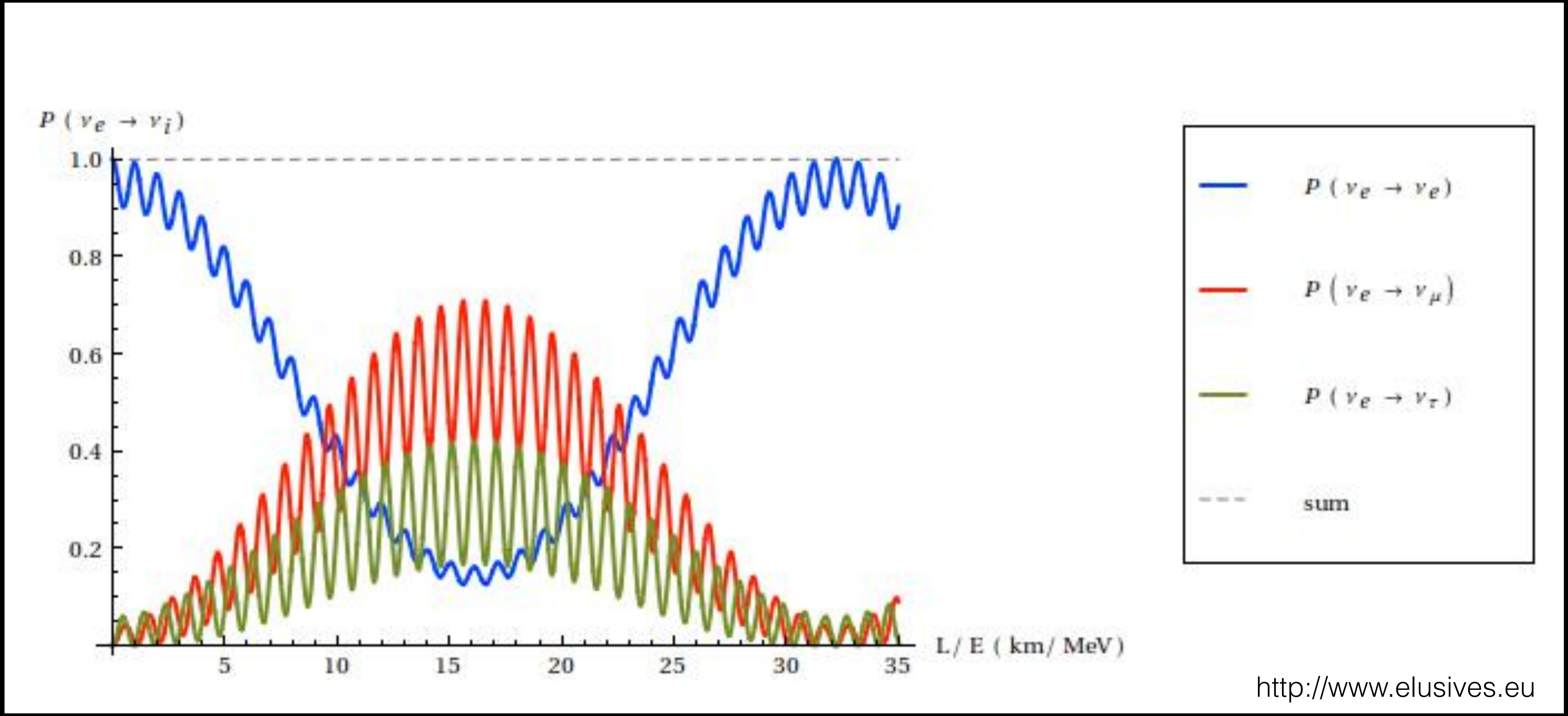
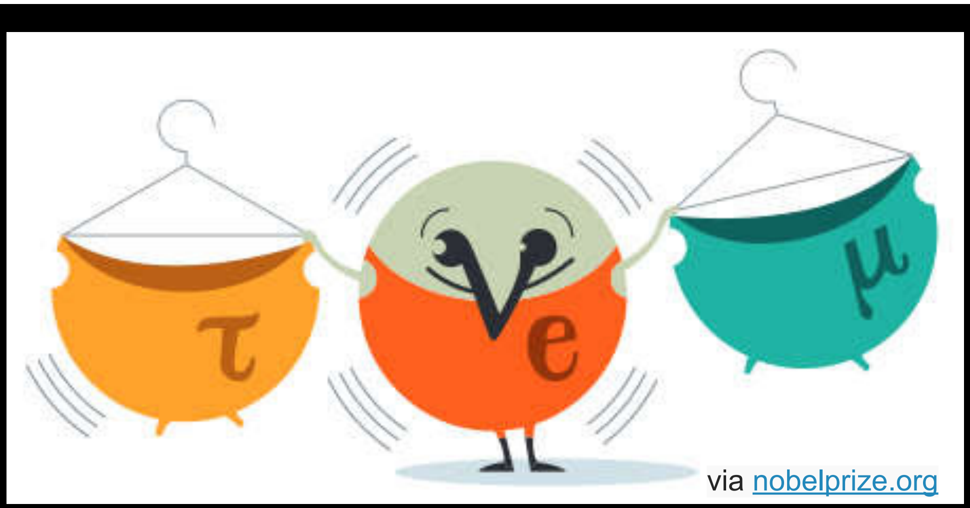
Supernova 1987A that exploded on 23 February 1987 in the Large Magellanic Cloud (LMC)

Neutrino Oscillations

- Neutrinos can experience flavor oscillations



http://www.elusives.eu



via nobelprize.org

Figure from wikipedia

Neutrino Oscillations

- Neutrinos can experience flavor oscillations governed by

$$\mathrm{i}(\partial_t + \mathbf{v}\cdot\nabla)\rho = [H, \rho] \qquad \rho = \begin{bmatrix} f_{\nu_e} & f_{<\nu_e|\nu_x>} \\ f_{<\nu_x|\nu_e>} & f_{\nu_x} \end{bmatrix}$$

- In the two-flavor scenario, the Hamiltonian can be written as

$$H = \frac{1}{2}\begin{bmatrix} -\omega\cos 2\theta & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta \end{bmatrix}, \quad \omega = \pm\frac{\Delta m^2}{2E}$$

- In the two flavor scenario, the transition probability for a neutrino produced in flavor alpha after traveling the distance *L*

$$P_{\nu_\alpha\rightarrow\nu_\beta}(L) = \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{4E})$$

Figure from wikipedia

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- When there is matter, we have a new term in the Hamiltonian

$$H = \frac{1}{2}\begin{bmatrix} -\omega\cos 2\theta + \sqrt{2}G_{\mathrm{F}}n_e & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta - \sqrt{2}G_{\mathrm{F}}n_e \end{bmatrix}$$

- Note that there is **resonance** in which the diagonal term can become zero and we can have maximal mixing. This can cause **significant flavor conversion**. This is called the **MSW** effect.

Neutrino Oscillations in Dense Media

- Neutrino evolution in dense neutrino media is very different from the one in vacuum and matter

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$$\sqrt{2} G_{\mathrm{F}} \int \underbrace{d^3}_{\text{correlation}} q (1 - \mathbf{v_P} \cdot \mathbf{v_q})(\underbrace{\rho_\nu}_{\text{nonlinearity}} - \rho_{\bar{\nu}})$$

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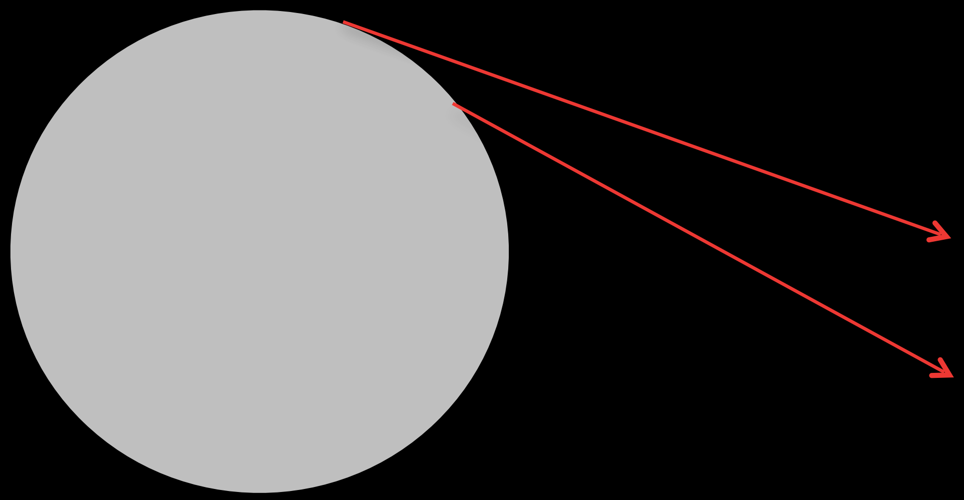
- This new term is **different** from the vacuum and matter terms in the sense that: It **correlates** neutrinos with trajectories and energies
  It brings up **nonlinearity**



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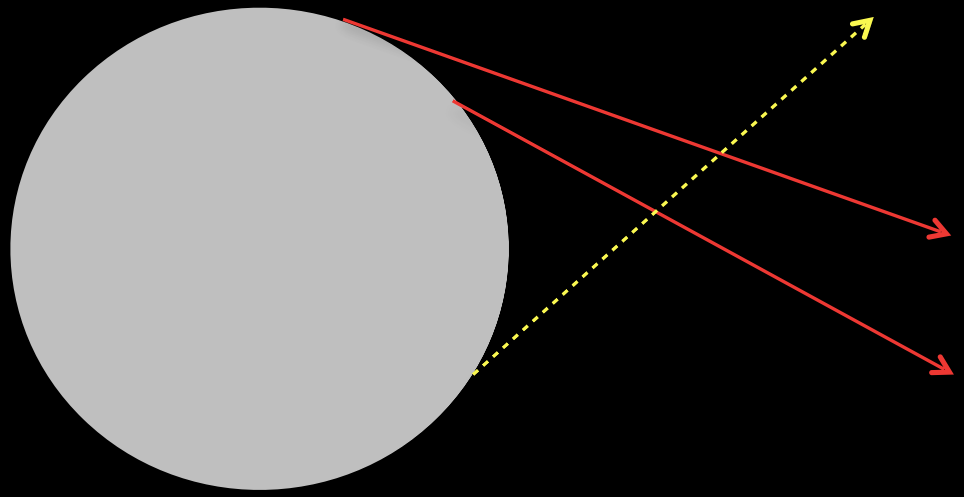


Why Studying Neutrino Oscillations?

- Nearly half of elements with A>70 are produced in r-process
  CCSNe are among the most promising candidate sites

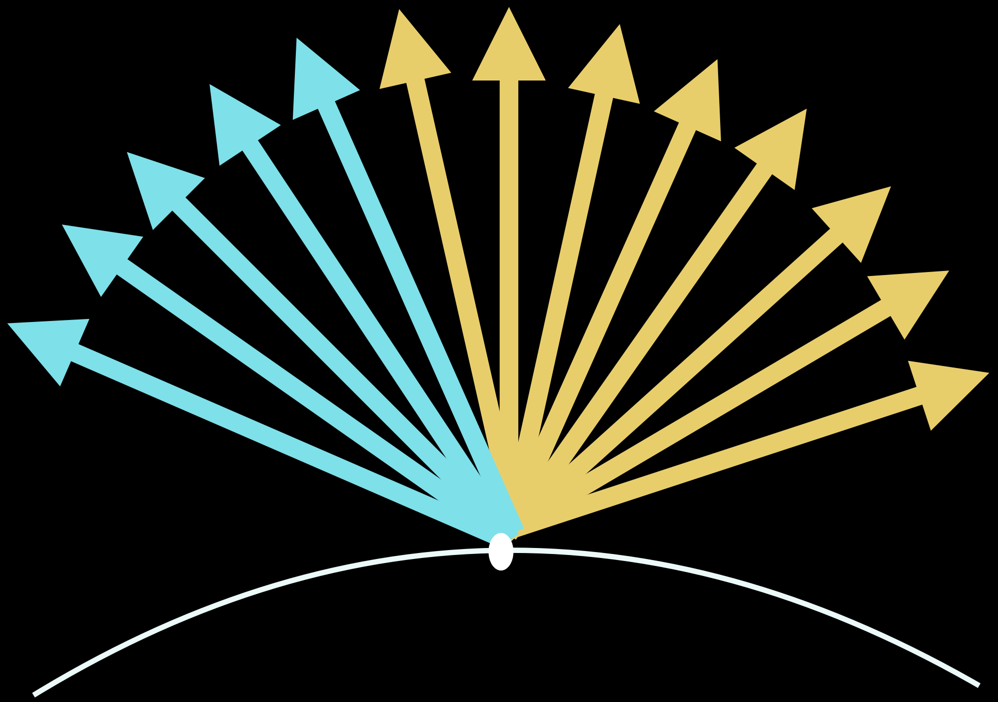
- Understanding neutrino flavor evolution can also be important to the understanding of the SN dynamics

  In the delayed supernova explosion mechanism,
  shock wave is revived by the aid of neutrinos

- Observation of a galactic supernova explosion

Fast Flavor Conversion Modes

- Our initial understanding was based on simplistic symmetric models, but we recently realized that such models are not reliable



- Fast neutrino flavor conversions could occur when there is crossing in $f_{\nu_e}(\theta)$ - $f_{\bar{\nu}_e}(\theta)$

- Scales on which flavor conversion can occur is now proportional to n_ν and could be < 10 cm on the surface of proto-neutron star

- Neutrino oscillations could now occur at densities that had been long thought to be the realm of collisional and scattering processes

Important questions:

- Do fast modes really occur in supernovae environments?

- How do they impact the physics of core-collapse supernovae?

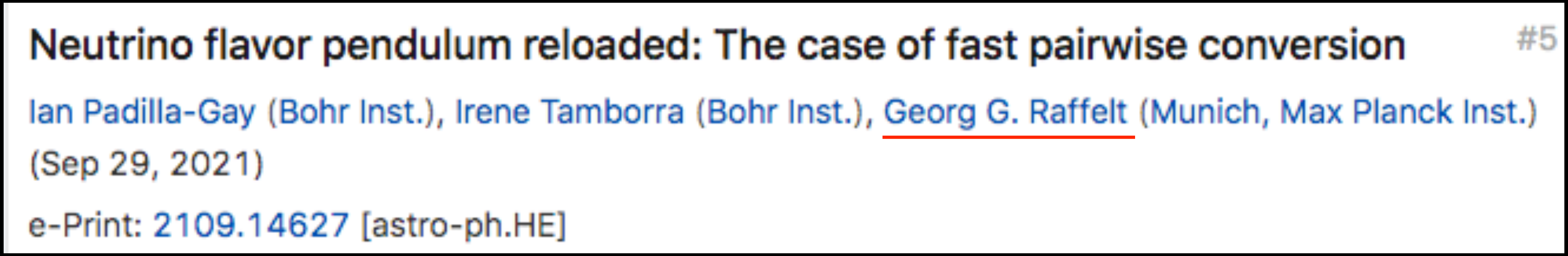
Projects at MPP

- We have studied a number of SN simulations by the Garching group
  - Fast instabilities can actually occur in the SN environment
  - Fate of the SN explosions matters
  - Fast instabilities can also occur in the muon channel

2012.08525, 2012.06594, 2003.00969

Projects at MPP

- We have also develop our understanding of fast conversion modes

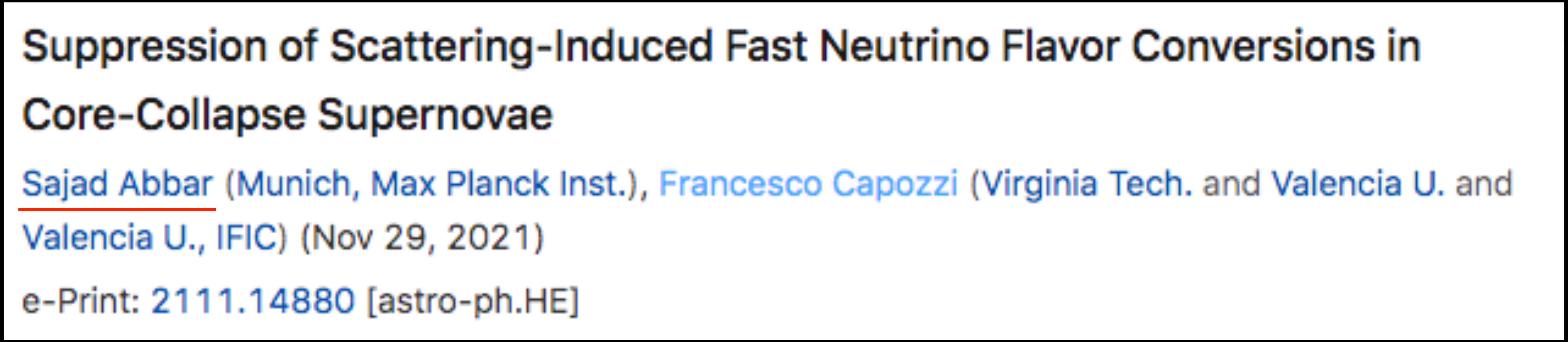


Neutrino flavor pendulum reloaded: The case of fast pairwise conversion

#5

Ian Padilla-Gay (Bohr Inst.), Irene Tamborra (Bohr Inst.), Georg G. Raffelt (Munich, Max Planck Inst.)
(Sep 29, 2021)

e-Print: 2109.14627 [astro-ph.HE]



Suppression of Scattering-Induced Fast Neutrino Flavor Conversions in Core-Collapse Supernovae

Sajad Abbar (Munich, Max Planck Inst.), Francesco Capozzi (Virginia Tech. and Valencia U. and Valencia U., IFIC) (Nov 29, 2021)

e-Print: 2111.14880 [astro-ph.HE]

Projects at MPP

- If fast modes really exist in the SN environment, then the next question would be how they impact the physics of CCSNe.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- We have addressed this problem for the first time in a sort of self consistent way in the SN simulations (in preparation)

Neutron Star Mergers

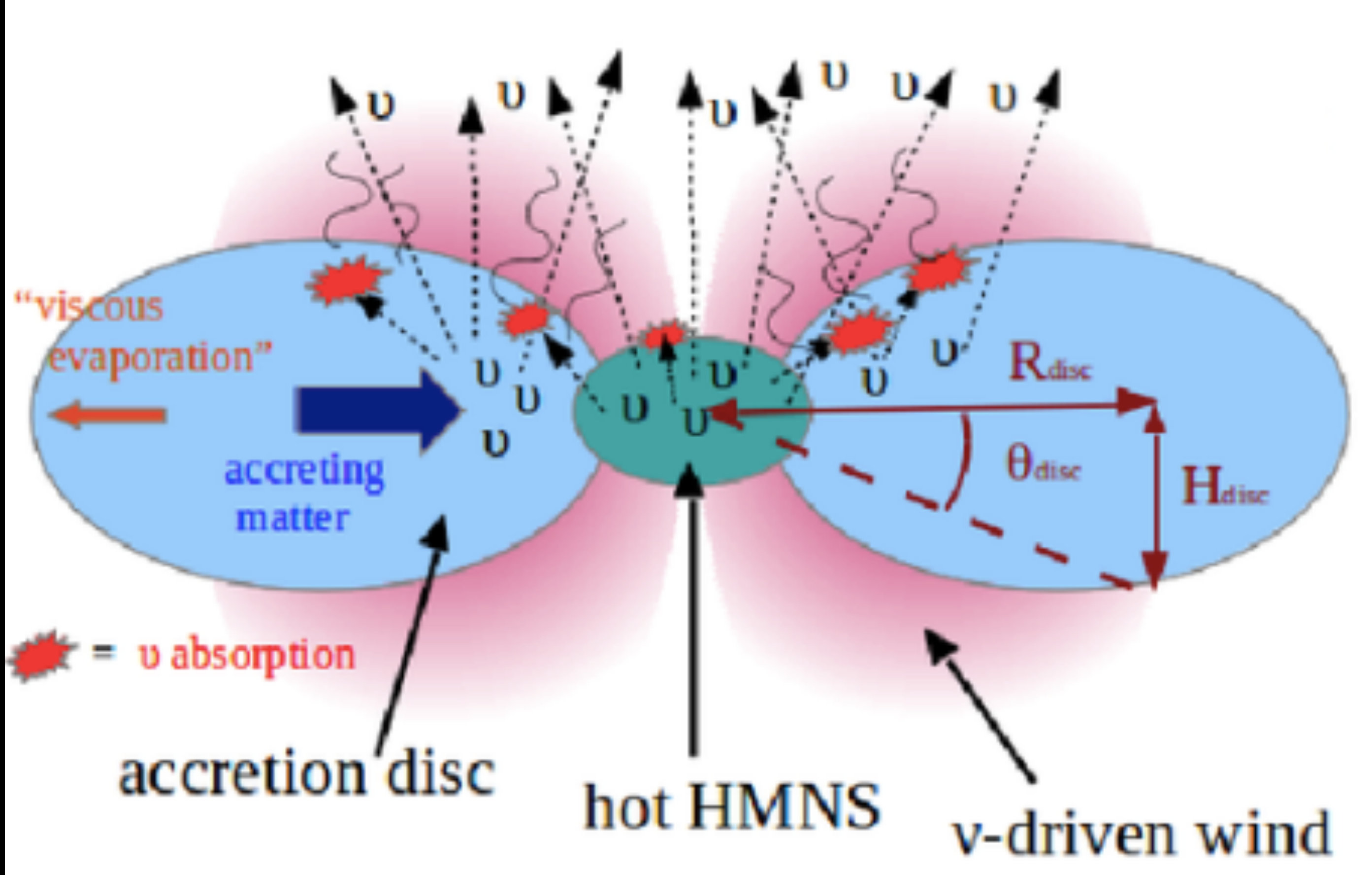
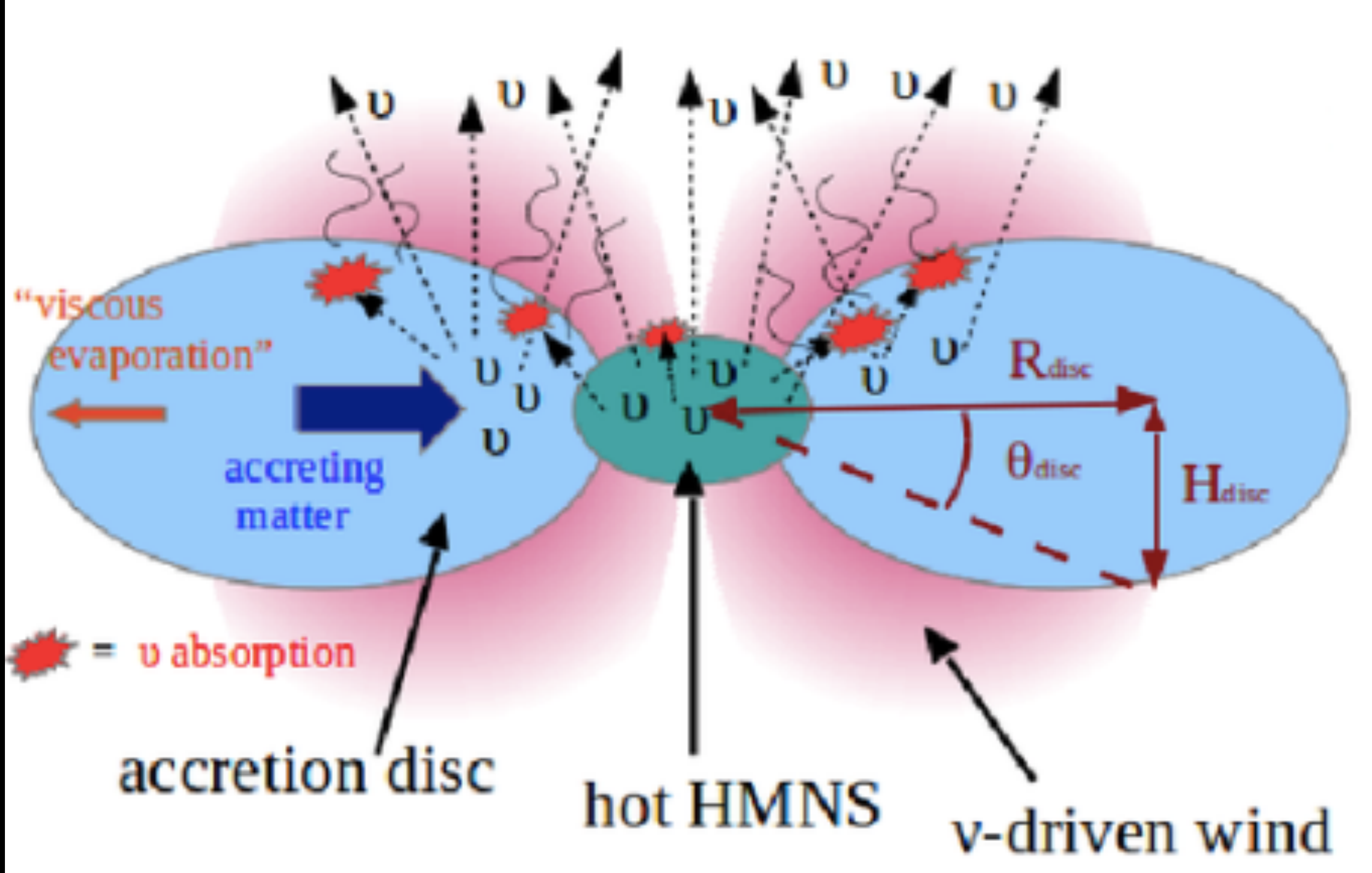


Figure from Perego et. al., arxiv: 1405.6730

- Hot hyper massive NS and the accretion disk emit a huge number of neutrinos

Neutron Star Mergers



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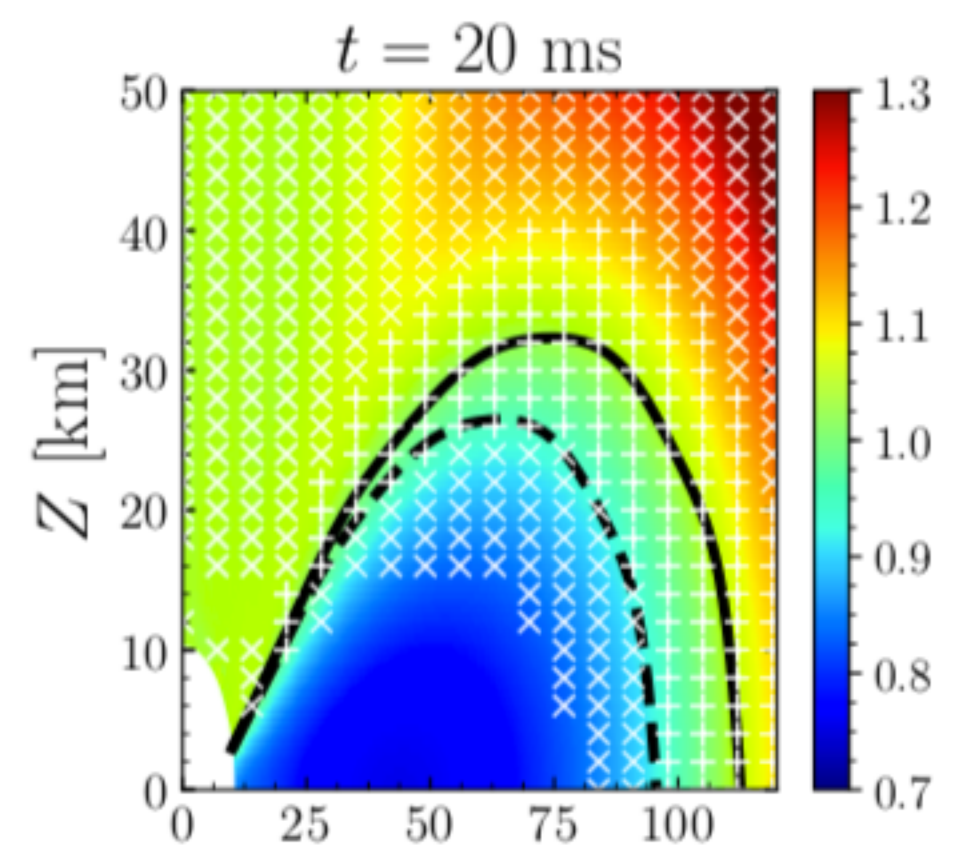
- Hot hyper massive NS and the accretion disk emit a huge number of neutrinos

Abbar+2021 (In preparation)



- Fast modes can occur in a wide region even inside the disk

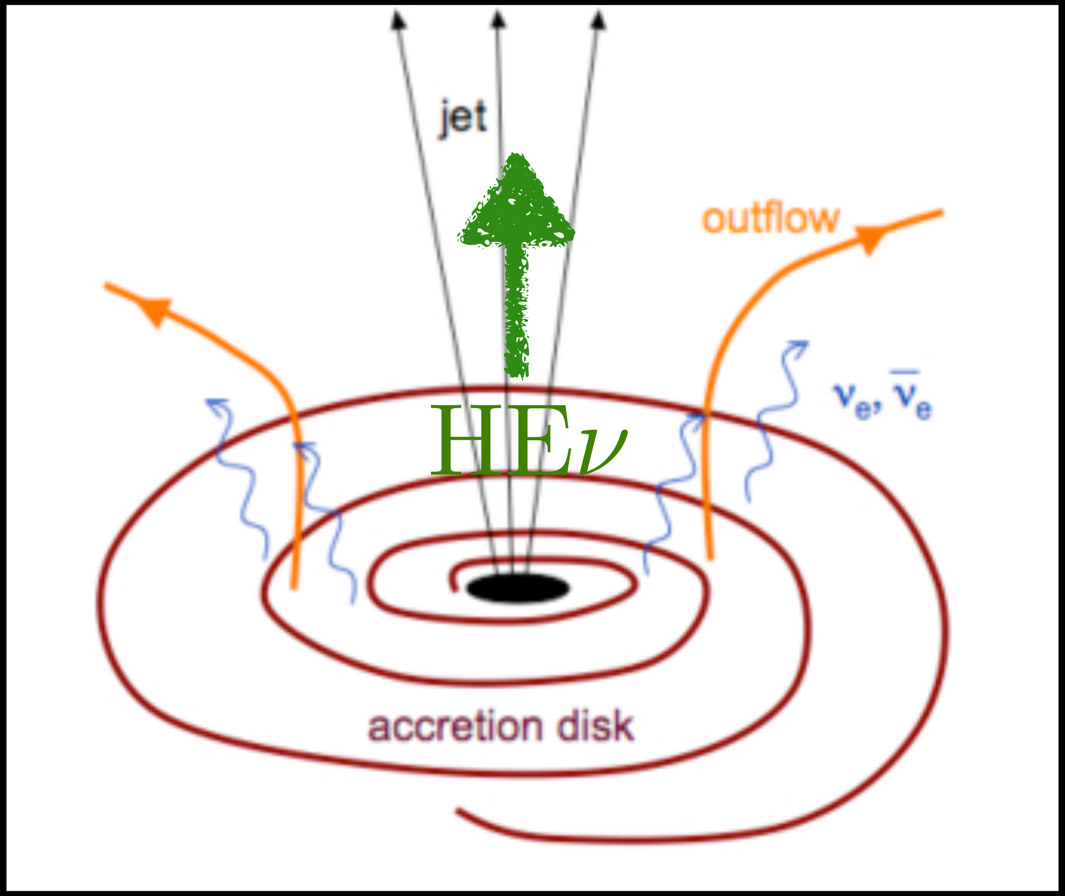
- Any self-consistent neutrino transport should implement fast conversions.

Neutron Star Mergers

- We perform simulations with self-consistent neutrino transport
- The presence of fast conversions inside the torus opens up a new cooling channel
- The impact of the fast modes remains small on the Y_e due to a sort of self-regulating mechanism

The case of High Energy Neutrinos

- High energy neutrinos can interact with the bath of lower energy neutrino
- The number density of the low energy neutrinos can be relatively small so that it does not lead to their collective oscillations. But the story is different for high energy neutrinos!



Surman+2006

Summary

- Neutrino oscillations in dense neutrino media such as core-collapse supernovae and neutron star mergers is a very rich phenomenon

- Fast neutrino flavor conversions on cm scales can occur in a dense neutrino medium

- We have shown that fast modes can be generic in core-collapse supernovae and neutron star mergers

- We have investigated the impact of fast modes on the physics of core-collapse supernovae