(Selected topics on) Neutrino in astrophysics

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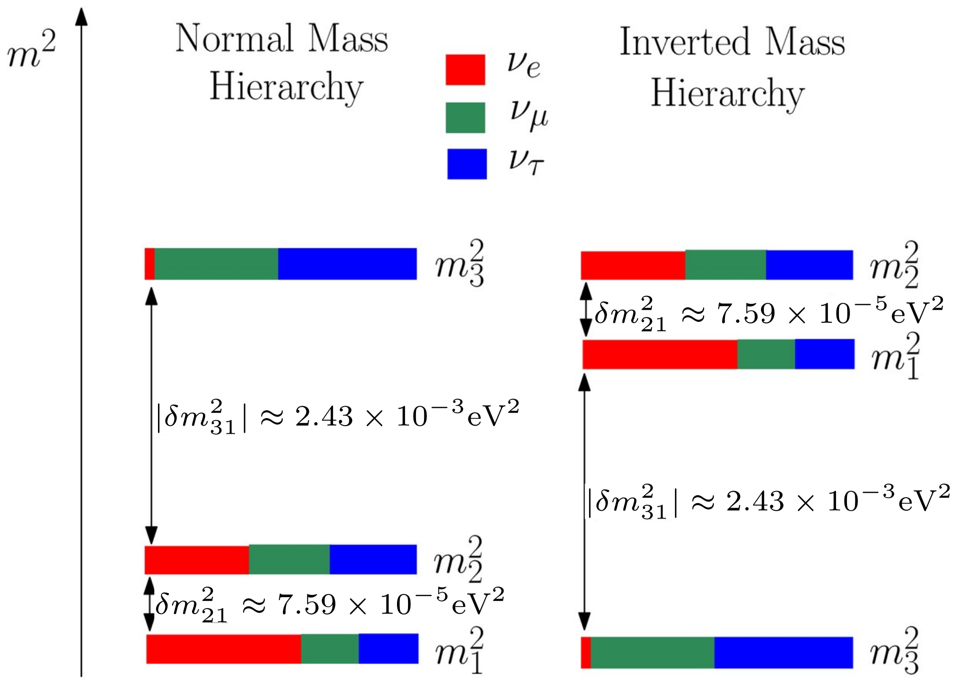
Neutrino

knowns:

- spin 1/2 fermions, (electric) charge neutral, weakly-interacting particles
- three different weak interaction eigenstates ν_e, ν_μ, ν_τ
- have different mass eigenstates and weak-interaction (flavor) eigenstates
  $|\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle$

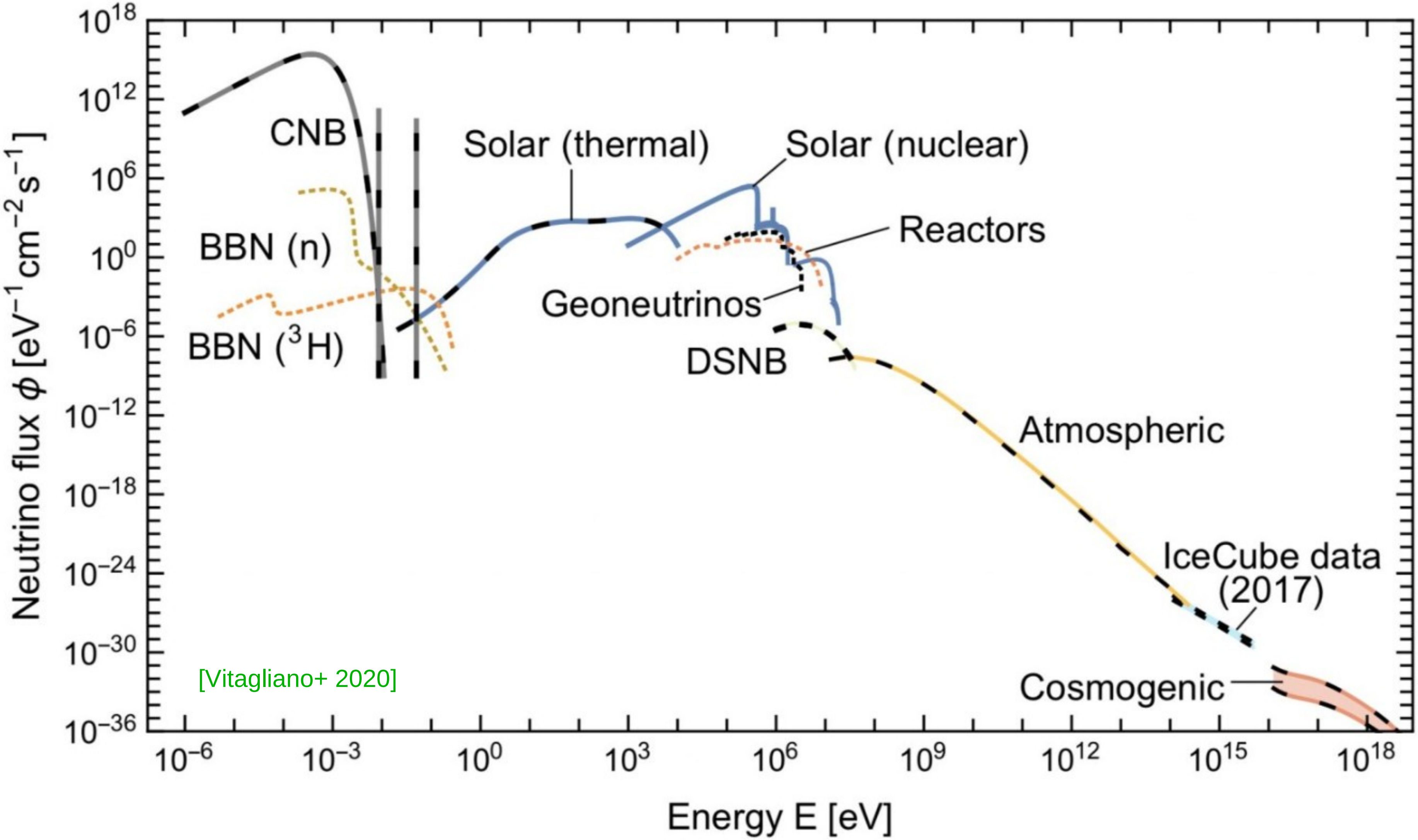
unknowns:

- ordering of their mass eigenstates?
- masses of neutrinos?
- CP-violating phase(s)?
- Dirac or Majorana particles?



$$\theta_{12} \approx 34^\circ,\ \theta_{13} \approx 9^\circ,\ \theta_{23} \approx 45^\circ$$

Neutrino sources



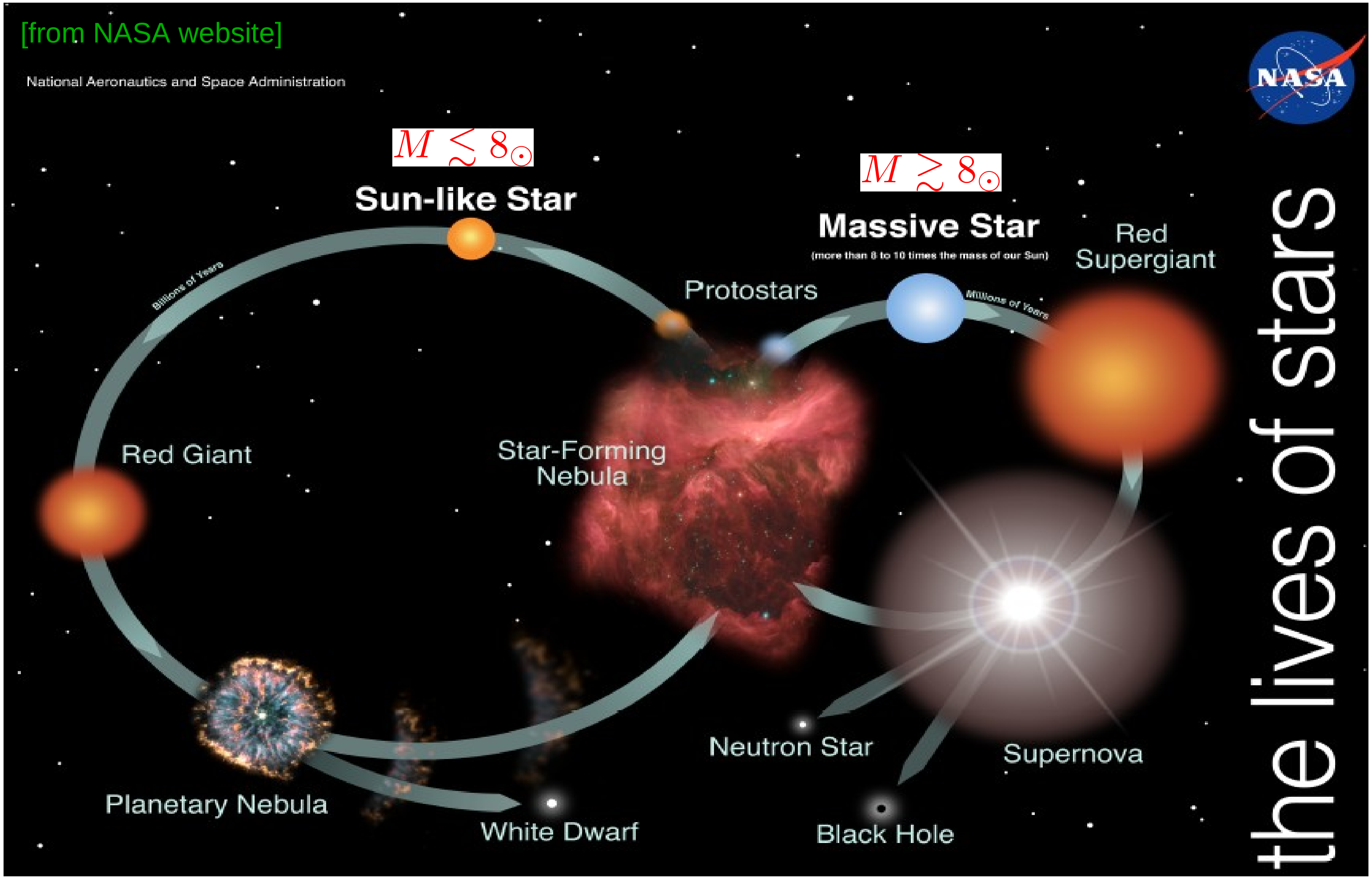
Offers great possibilities to study unknown neutrino property and to explore astrophysical conditions that produce them

Outline

- Neutrinos from stars (a little bit)
- Supernova neutrinos – flavor oscillations and upscattered dark matter
- High-energy neutrinos from stellar explosions
- Summary

Neutrinos from stars

Stars live, die and produce neutrinos



Neutrinos are produced by nuclear burning that converts protons to neutrons (ν_e), by pairs ($\nu\bar{\nu}$), and by $e^{\pm}$ captures (ν_e & $\bar{\nu}_e$)

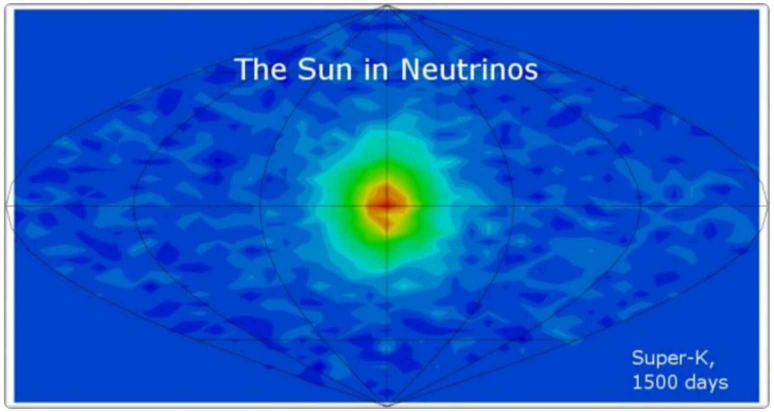
$\rightarrow$ One can study stellar interiors by detecting these neutrinos or probe fundamental properties of neutrinos in environments beyond laboratory experiments

Solar neutrinos

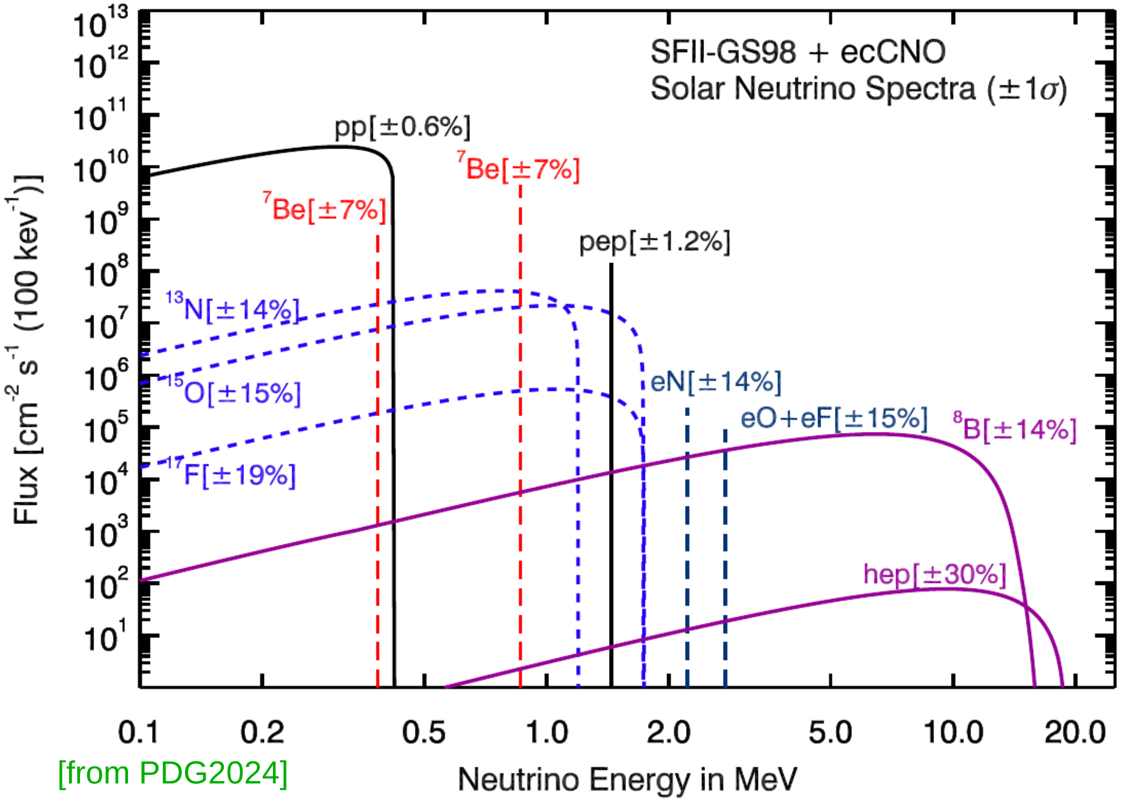
neutrinos won four Nobel Prizes (1988, 1995, 2002, 2015), solar neutrinos contributed two!

The Sun produces ν_e through various nuclear reactions in p-p chain and in CNO cycle, which effectively do:

$$4p \rightarrow {}^4\text{He} + 2e^- + 2\nu_e$$



[from T2K website]

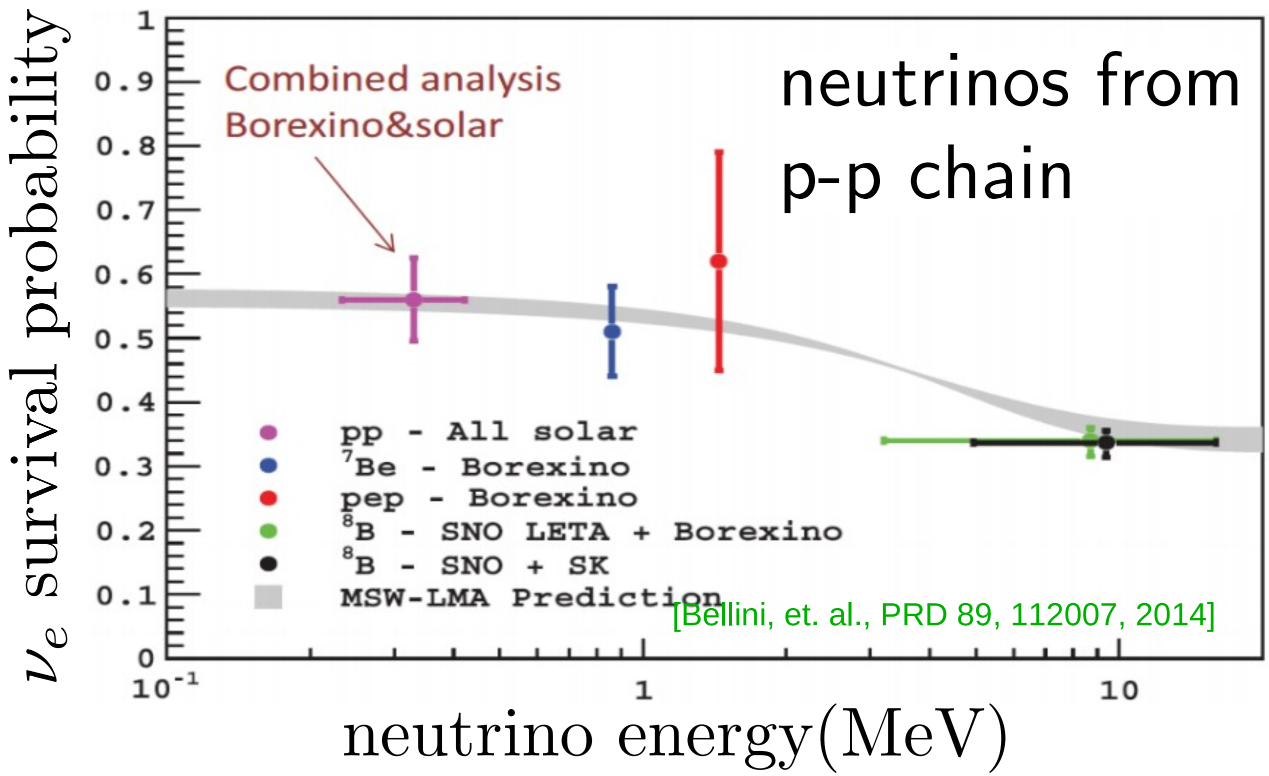


[from PDG2024]

Solar neutrinos

The solar ν_e flux at earth are smaller than model prediction: evidence of neutrino flavor oscillations!

Energy dependence of survival probability: confirming that the presence of matter affects flavor transformation of neutrinos (Mikheyev-Smirnov-Wolfenstein effect)



[Bellini, et. al., PRD 89, 112007, 2014]

Nuclear burning stages for a massive star $(20 M_\odot)$

[from A. Heger]

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,\mathrm{H} \xrightarrow{\mathrm{CNO}} {}^4\mathrm{He}$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,\mathrm{He}^4 \rightarrow {}^{12}\mathrm{C}$ $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$
C	Ne, Mg	Na	0.8	10^3	$^{12}\mathrm{C} + {}^{12}\mathrm{C}$
Ne	O, Mg	Al, P	1.5	3	$^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$ $^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}\mathrm{O} + {}^{16}\mathrm{O}$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}\mathrm{Si}(\gamma,\alpha)\ldots$

much shorter due to strong ν energy loss from pair processes

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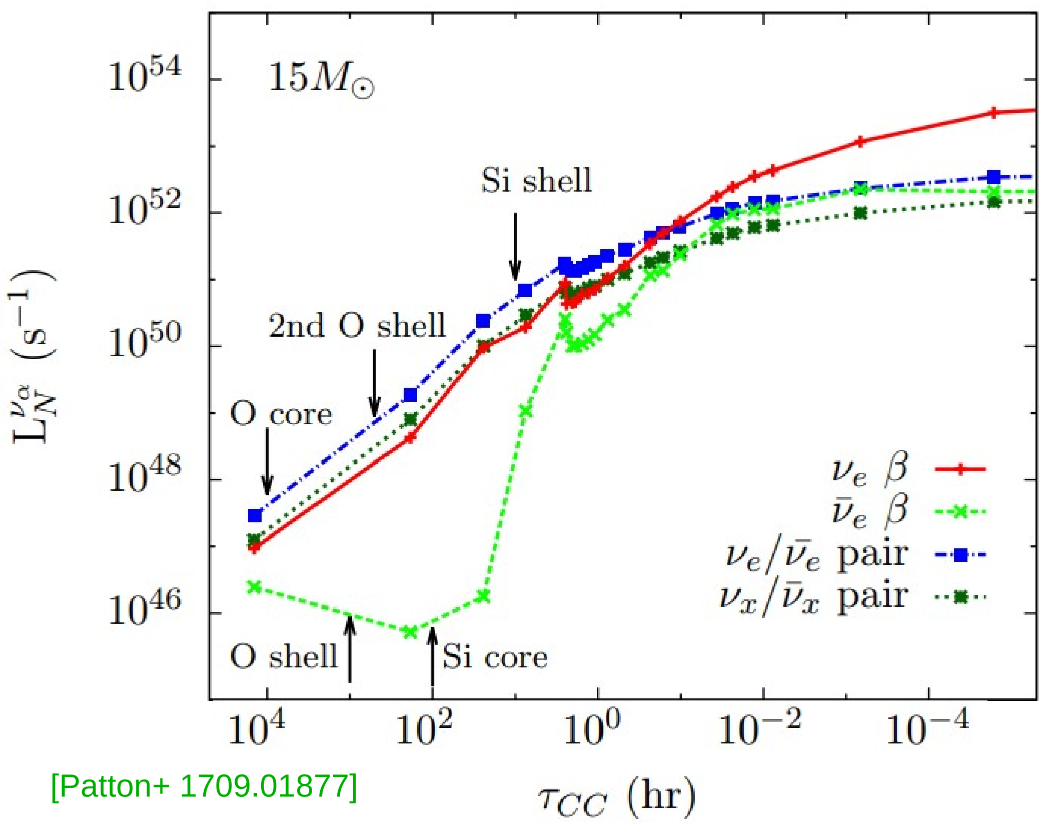

[Patton+ 1709.01877]

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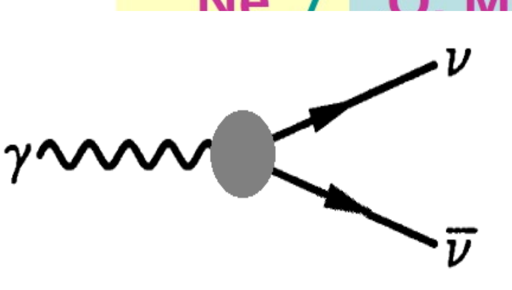
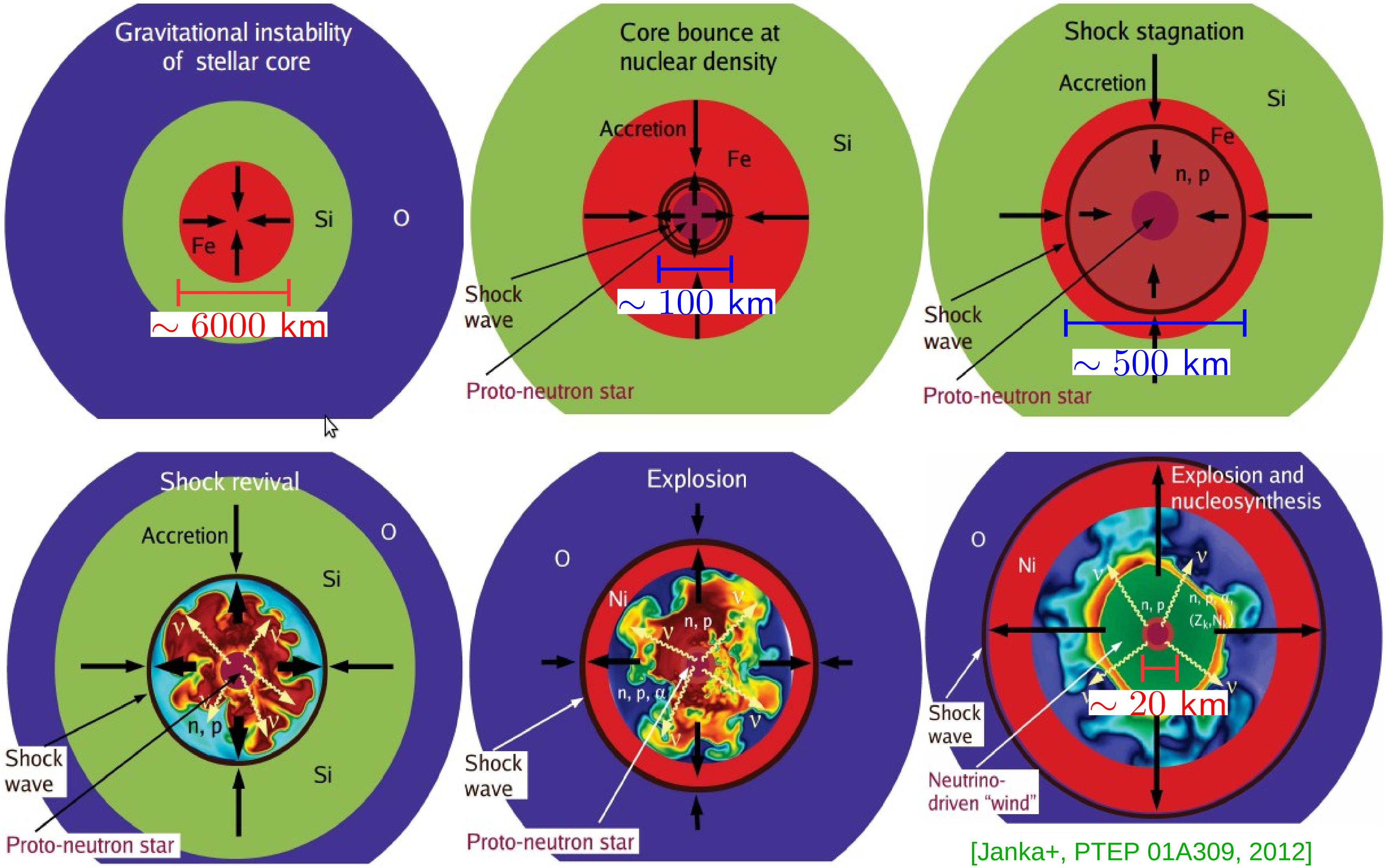


large ν magnetic moment $\rightarrow$ ν energy loss $\rightarrow$ larger Helium core at the beginning of core Helium burning$\rightarrow$ temperature-luminosity relation of stars

the best constraint on ν magnetic moment, $\mu_\nu \lesssim 3 \times 10^{-12} \mu_B$, comes from observations of stars in globular clusters [Raffelt, ApJ 365 (1990) 559, Arceo-Diaz+, Astro. Part. Phys. 70 (2015) 1]

Supernova neutrinos

Core-collapse supernovae – the death of massive stars

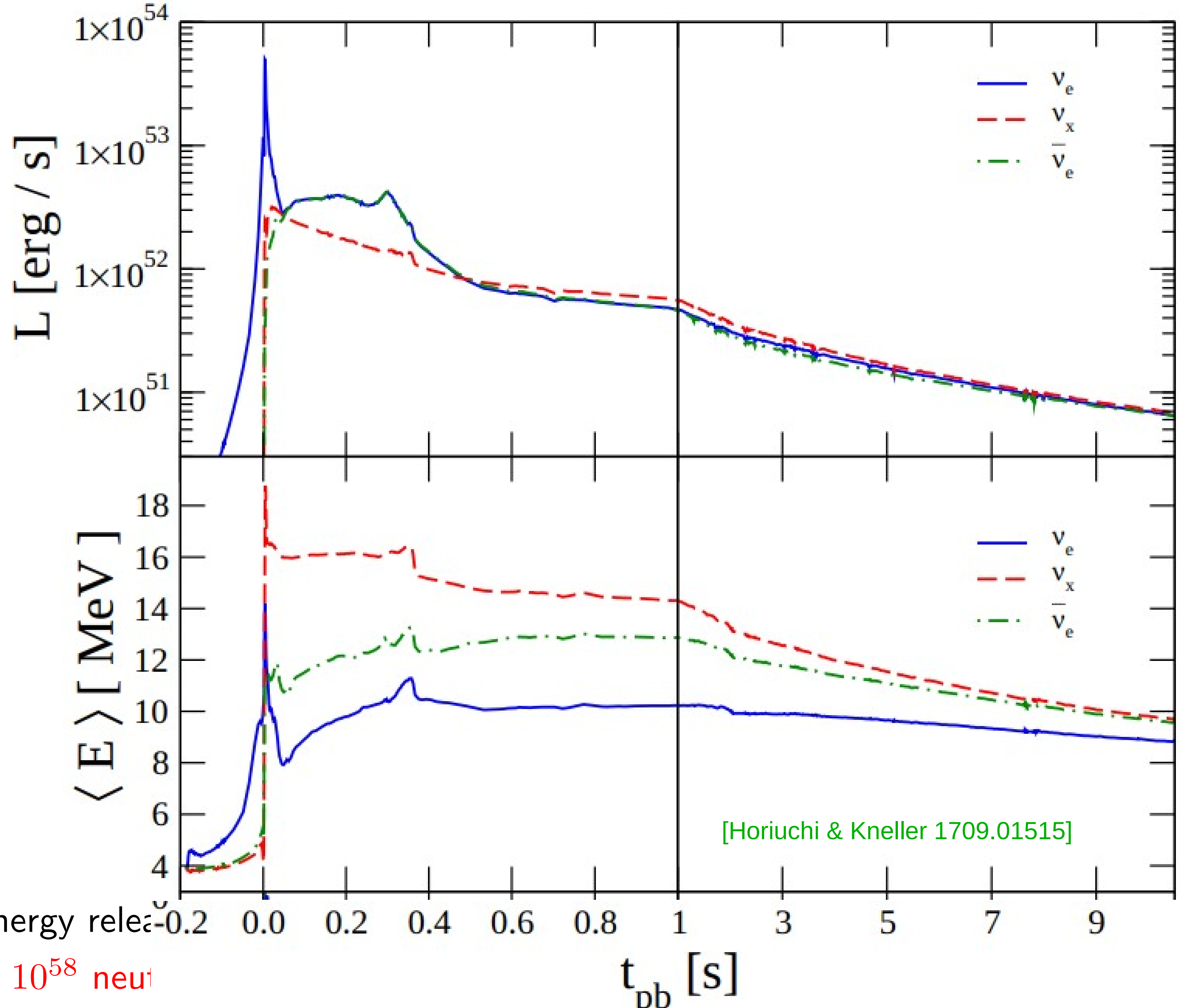


[Janka+, PTEP 01A309, 2012]

energy released: $E_\gamma \sim 10^{49}$ ergs, $E_{\mathrm{kinetic}} \sim 10^{51}$ ergs, $E_\nu \sim 10^{53}$ ergs.

$\sim 10^{58}$ neutrinos carry away nearly all the gravitational binding energy in ~ 10 s!

Core-collapse supernovae – the death of massive stars



Shock wave

Proto-r

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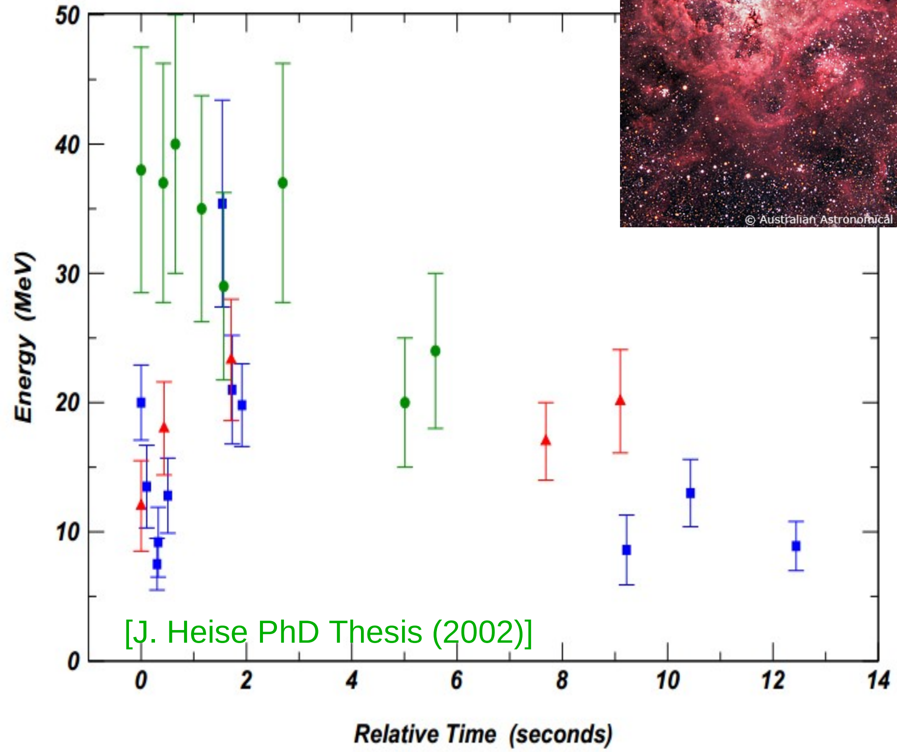
$\sim 10^{58}$ neu

s!

Supernova neutrinos

~ 20 SN $\bar{\nu}_e$ detected from SN1987a in ~ 10 seconds,

$E_{\mathrm{tot},\bar{\nu}_e} \sim 5 \times 10^{52}$ erg
$\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV



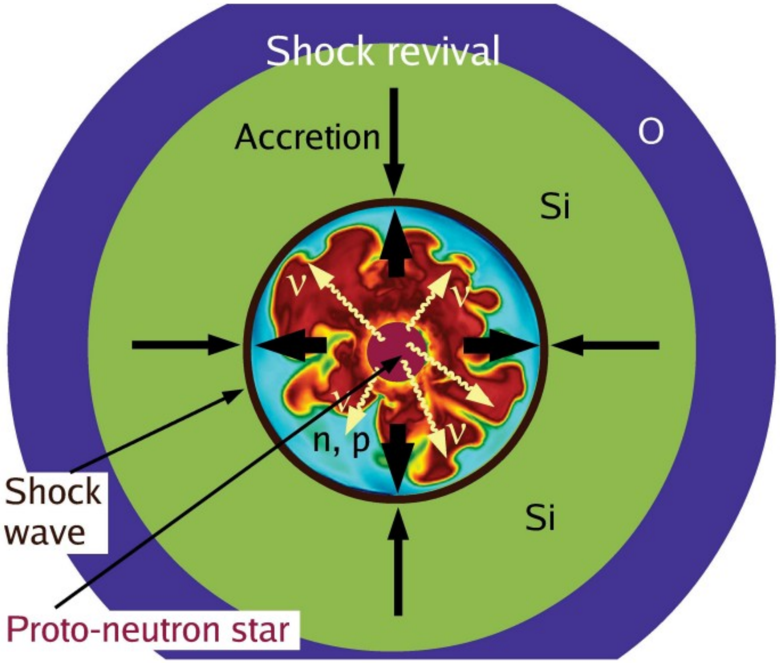
$\mathcal{O}(10^4)$ events (all flavors!) expected for the next galactic supernova ($\sim$ 0.5-2 per century).

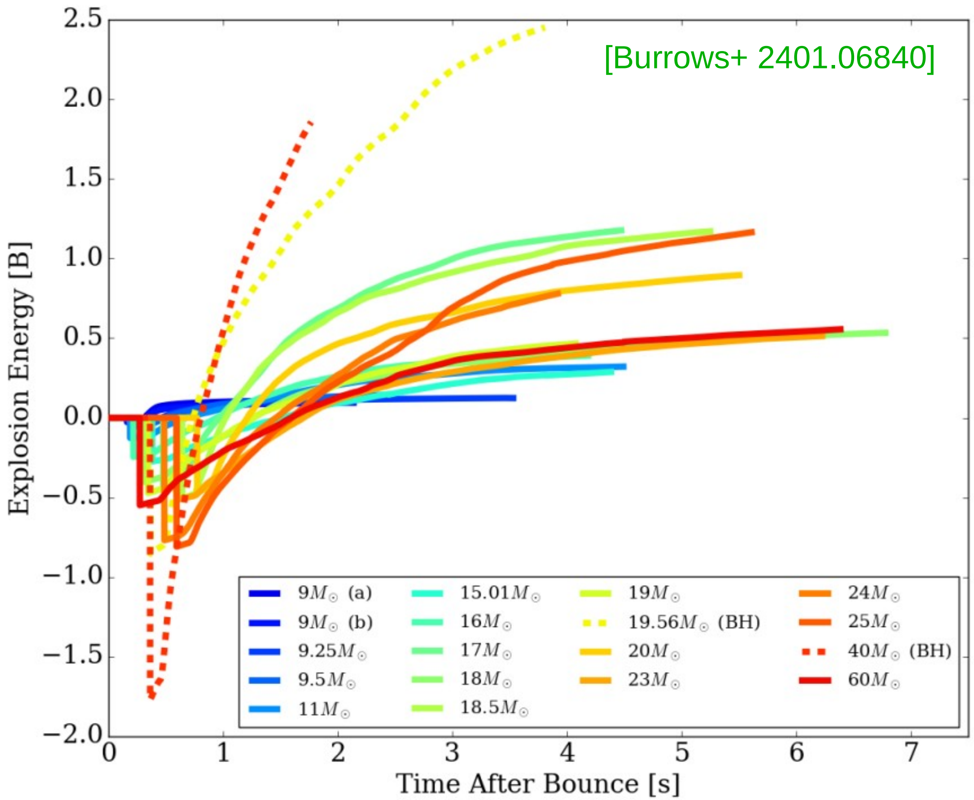
moreover, the detection of the diffuse supernova neutrino background is around the corner [Super-K]

$\rightarrow$ unique opportunities to understand questions related to supernova explosion, the properties of neutron star, the properties of neutrinos, and various light beyond-the-Standard-Model candidates!

Do we know how core-collapse supernovae explode?

Simulating core-collapse supernovae is a daunting task – involving all four fundamental forces, fluid dynamics, and non-equilibrium neutrino radiation transport



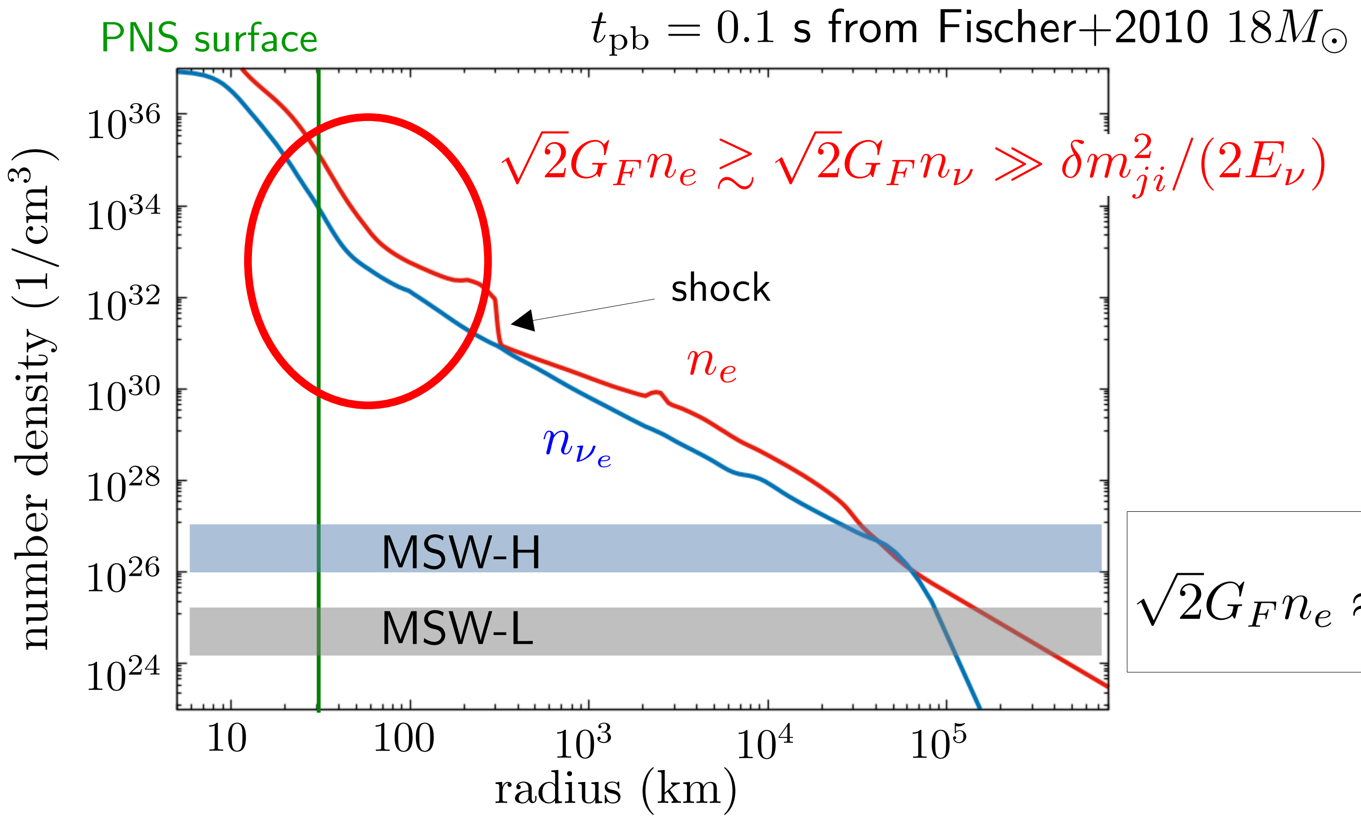


Neutrino energy deposition by $\nu_e + n \to p + e^-$ and $\bar{\nu}_e + p \to n + e^+$ holds the key to turn implosion to explosion

During the accretion phase, $\langle E_{\nu_\mu,\nu_\tau} \rangle > \langle E_{\nu_e,\bar{\nu}_e} \rangle \to$ neutrino flavor oscillations?

how? when? where? and how much?

Neutrinos flavor oscillations in supernovae



$$\sqrt{2} G_F n_e \approx \frac{\delta m^2_{ji}}{2E_\nu}$$

typical MSW resonances occur far away from the PNS – irrelevant to shock revival

Can flavor oscillations happen between PNS surface shock?

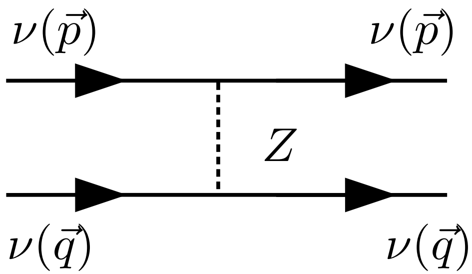
Collective neutrino flavor oscillations

Wigner-transformed density matrix

$$\varrho(t,\mathbf{x},\mathbf{p}) = \begin{bmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{bmatrix}$$

It requires neutrino quantum kinetic transport equation (νQKE):

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}})\varrho(\mathbf{x},\mathbf{p},t) = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho(\mathbf{x},\mathbf{p},t)] + \mathcal{C}(\varrho)$$



$$H_{\rm vac}(p) = UM^2U^\dagger/(2|\mathbf{p}|),$$

$$H_m(\mathbf{x},t) = \sqrt{2}G_F n_e \times {\rm diag}(1,0,0)$$

$$H_{\nu\nu}(\mathbf{x},\mathbf{p},t) = \frac{\sqrt{2}G_F}{(2\pi)^3}\int d^3q(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})[\varrho - \bar{\varrho}^*]$$

[Fuller+1987, Pantaleone 1992, Sigl & Raffelt 1992]

When $G_F n_\nu \gg \frac{\delta m^2_{ji}}{2E_\nu}$ in supernova interior

$\rightarrow$ flavor evolution of neutrinos with different momenta strongly coupled in a non-linear way

$\rightarrow$ collective oscillations [see recent reviews: Volpe 2301.11814, Johns, Richers, MRW 2503.05959]

Collective neutrino flavor oscillations

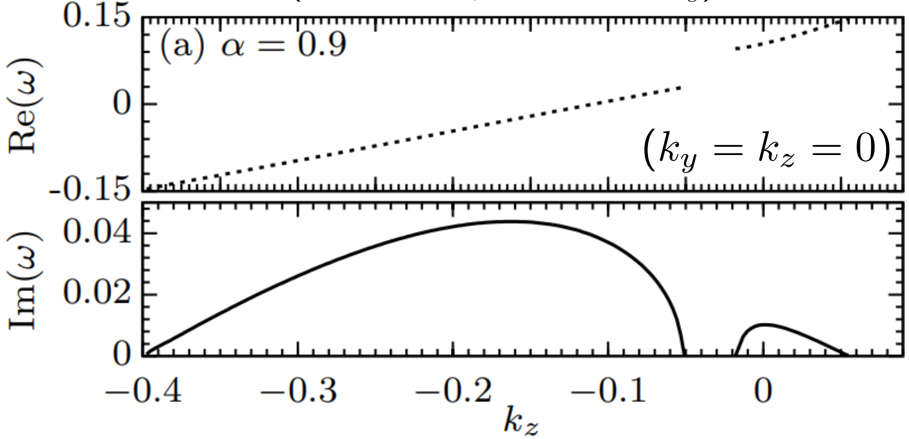
Assuming $|\rho_{\alpha\beta}|/f_{\nu_\alpha} \ll 1$, linearization of the EoM allows to find the dispersion relation of collective modes:

[Banerjee+ 2011, Raffelt+ 2013, Izaguirre+ 2017...]

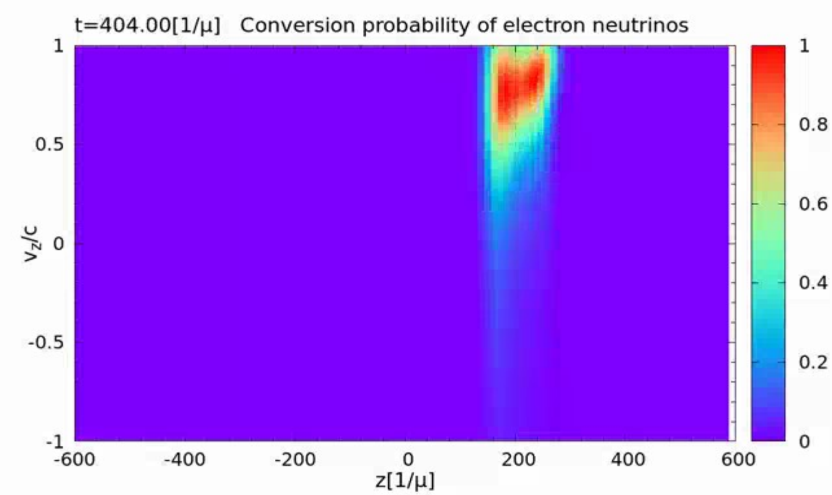
$$|\varrho_{\alpha\beta}| \propto \exp(ik^\mu x_\mu) \longrightarrow \text{EoM} \longrightarrow \mathcal{D}(\omega, \vec{k}) = 0$$

complex frequency $\leftrightarrow$ unstable collective modes

(in units of $\mu \equiv \sqrt{2} G_F n_{\nu_e}$)



[MRW, George, Lin, Xiong 2108.09886]



these collective unstable modes can grow in nanoseconds and lead to "flavor waves" of centimeter wavelengths

(mesoscopic scale!)

[See Fiorillo & Raffelt, 2502.06935 for the language of "flavomon"]

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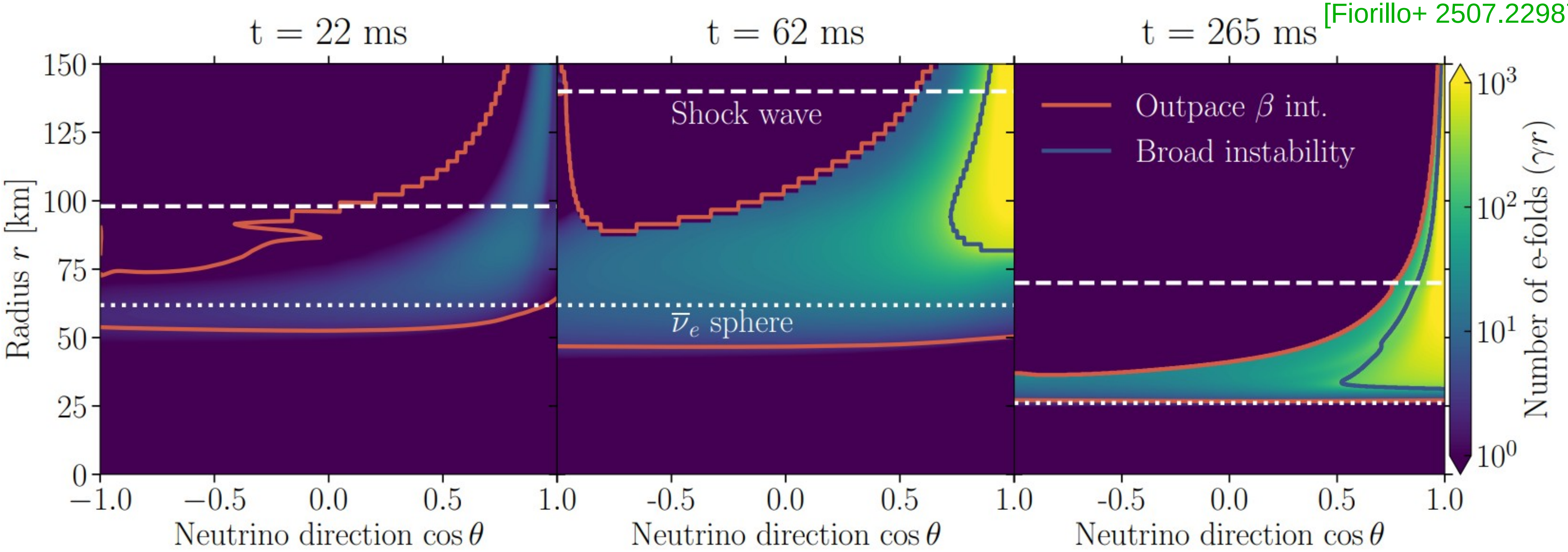
[Fiorillo+ 2507.22987]



they can apprear shortly after core-bounce at regions between ν-sphere and shock

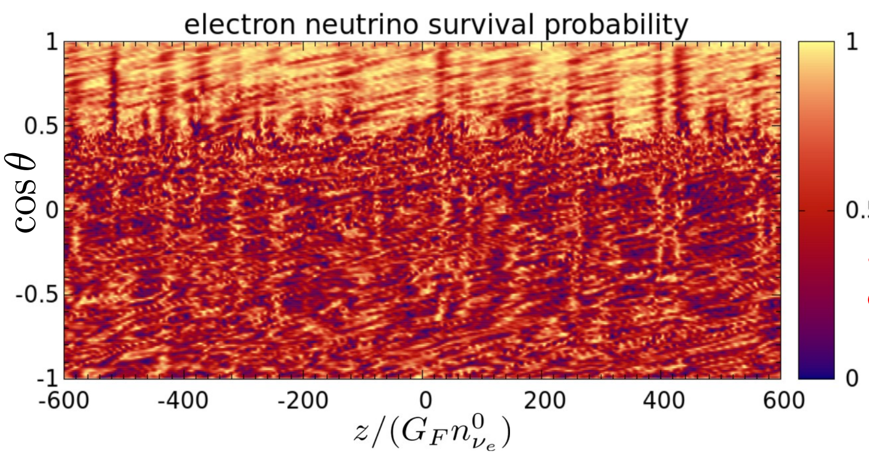
how to understand them? whats the potential impact? how to include them in multi-D SN simulations?

Local quasi-equilibrium state of collective oscillations

We numerically solve the νQKE in periodic boxes that represent small volumes in supernova interior [Bhattacharyya+, Richers+, MRW+, Martin+, Nagakura+...]

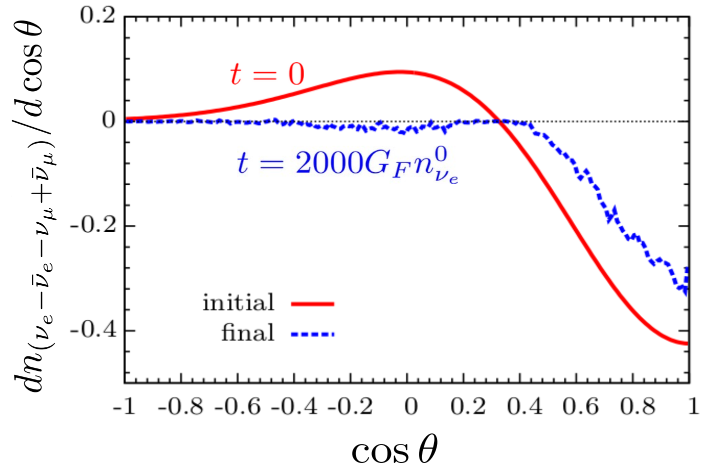
$\rightarrow$ unstable collective modes drive the system to reach a "quasi-equilibraium" state, where phase-space kinematic decoherence leads to almost coarse-grained flavor equipartition in certain phase space

[MRW, George, Lin, Xiong 2108.09886]



averaging over space

$$\langle \frac{dn_{\nu_e}}{d\cos\theta}\rangle_z \simeq \langle \frac{dn_{\nu_\mu}}{d\cos\theta}\rangle_z,\ \langle \frac{dn_{\bar\nu_e}}{d\cos\theta}\rangle_z \simeq \langle \frac{dn_{\bar\nu_\mu}}{d\cos\theta}\rangle_z \text{ for } \cos\theta \lesssim 0.35$$



https://github.com/COSEnu/

Moreover, the equilibrated state can approximated by simple analytical formulas if one knows the initial state of the system [Zaizen+, Xiong+, Richers+, George+...]

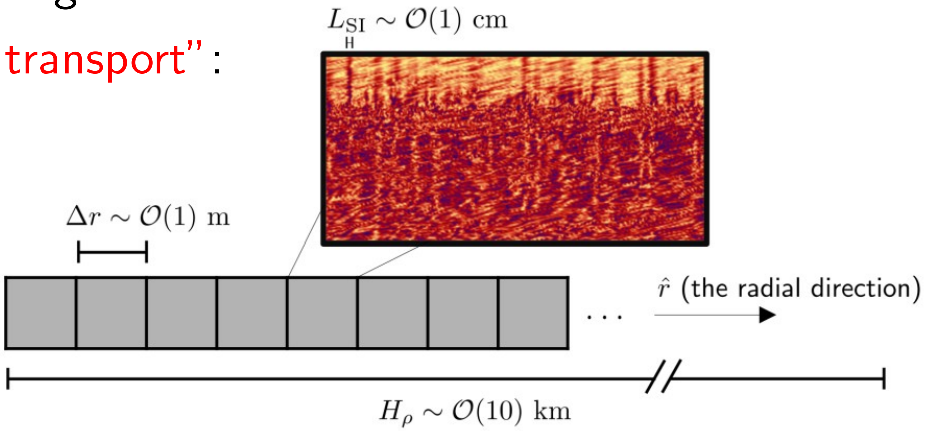
Sub-grid effective classical model for global transport

Kinematic decoherence induced coarse-grained equilibration + scale separation

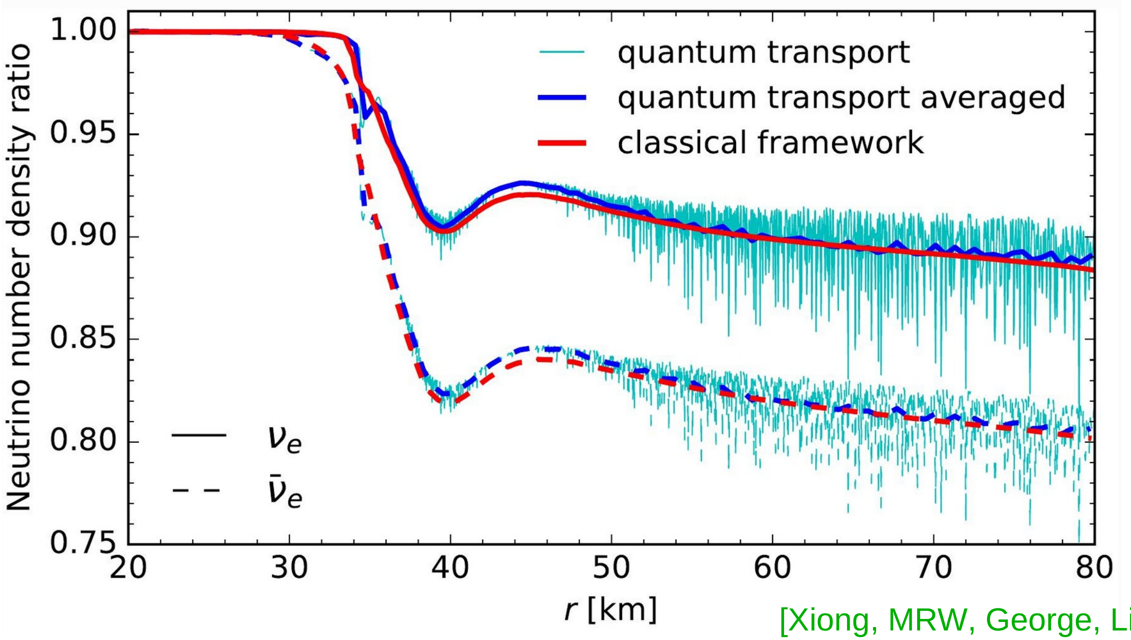
$\to$ vanishing quantum correlation $\langle \rho_{ex} \rangle$ on larger scales

$\to$ sub-grid model for "effective classical ν transport":

at every spatial grid where an $e - \mu$ crossing is found, use the analytical equilibration solution to redistribute neutrino occupation numbers



global νQKE v.s. effective classical transport



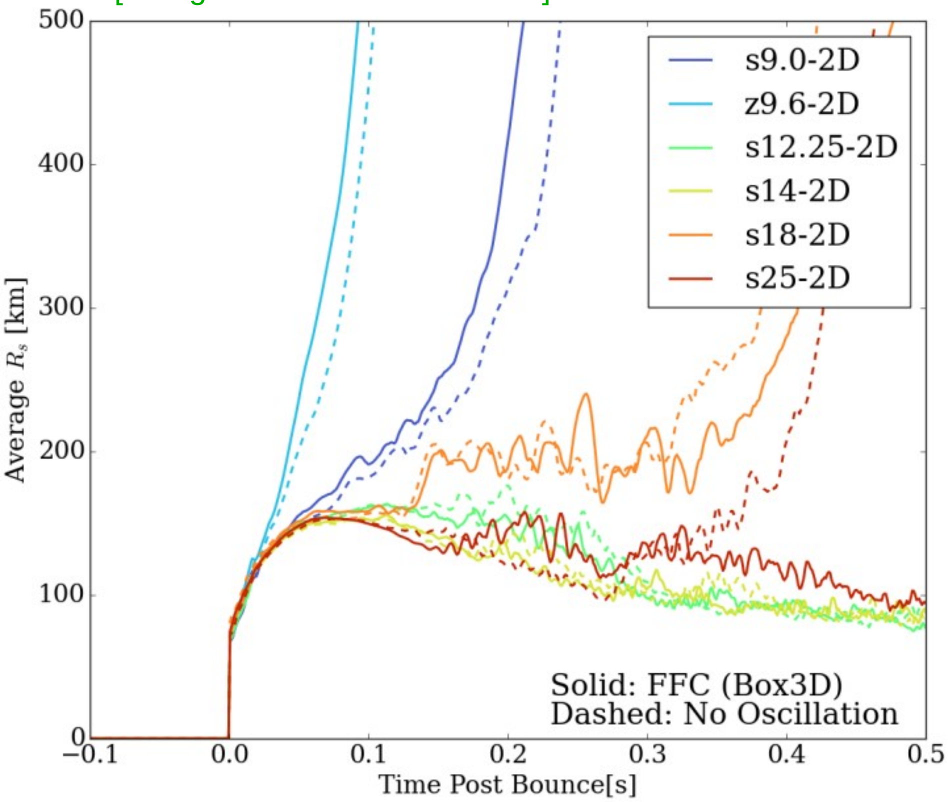
The effective model well captures the coarse-grained neutrino properties!

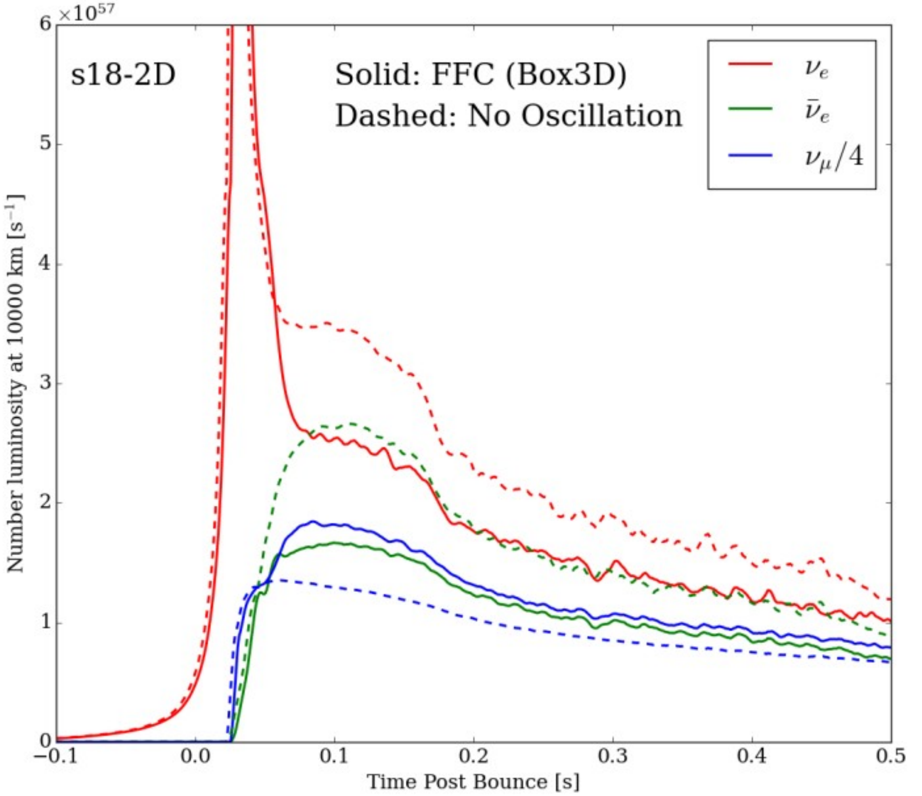
[Xiong, MRW, George, Lin 2403.17269]

Potential impact?

Recent exploratory works suggest that shock revival and the emerging neutrino fluxes of different flavors can be affected [see also Ehring+, Mori+, Wang+]

[Wang & Burrows 2503.04896]





Issues ahead...

– Does the effective classical method work without knowing the full phase-space distribution of neutrinos? Can machine learning help?

[Abbar+2311.15656, 2401.17424, Richers+ 2409.04455]

– Limitation of the effective models? Do the separation of scales and coarse-graining always work? Any non-vanishing quantum correlations over macroscopic scales?

[Fiorillo+ 2403.12189, Liu+ 2411.01503]

– Slow flavor conversions and collision-induced flavor conversions?

[Xiong, 2210.08254, Padilla-Gay+ 2505.11588, Fiorillo+ 2507.22985]

– Potential effect due to global inhomogeneity and non-stationarity?

[Bhattacharyya+ 2504.11316]

– Any potential role of helicity and pair correlations?

[Vlasenko+ 1309.2628, Volpe+ 1302.2374, Kartavtev+ 1504.03230]

– Any potential role of many-body (beyond mean-field) effect?

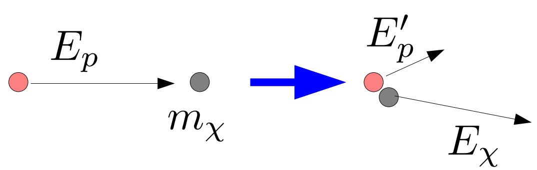
[Kost+ 2402.05022, Laraib+ 2507.02040]

Upcattering light dark matter with SN neutrinos

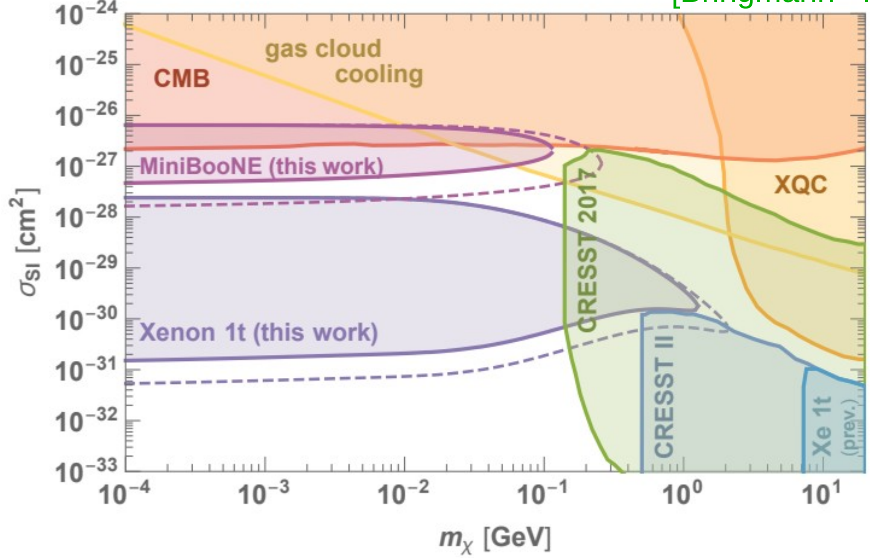
Light dark matter boosted by supernova neutrinos?

[Bringmann+ 2018, Ema+ 2018, Cappiello+ 2019,...]

It's realized in recent years that light (sub-GeV) DM particles can be "boosted" by energetic cosmic rays, which can probe the dark matter – nucleon interaction cross section ($\sigma_{\chi N}$) or that of dark matter – electron interaction ($\sigma_{\chi e}$)



[Bringmann+ PRL '18]



[Zhang+, Jho+, Das+, Ghosh+, Lin+,...]

What if DM interacts with neutrinos? Can supernova neutrinos lead to any interesting new constraints?

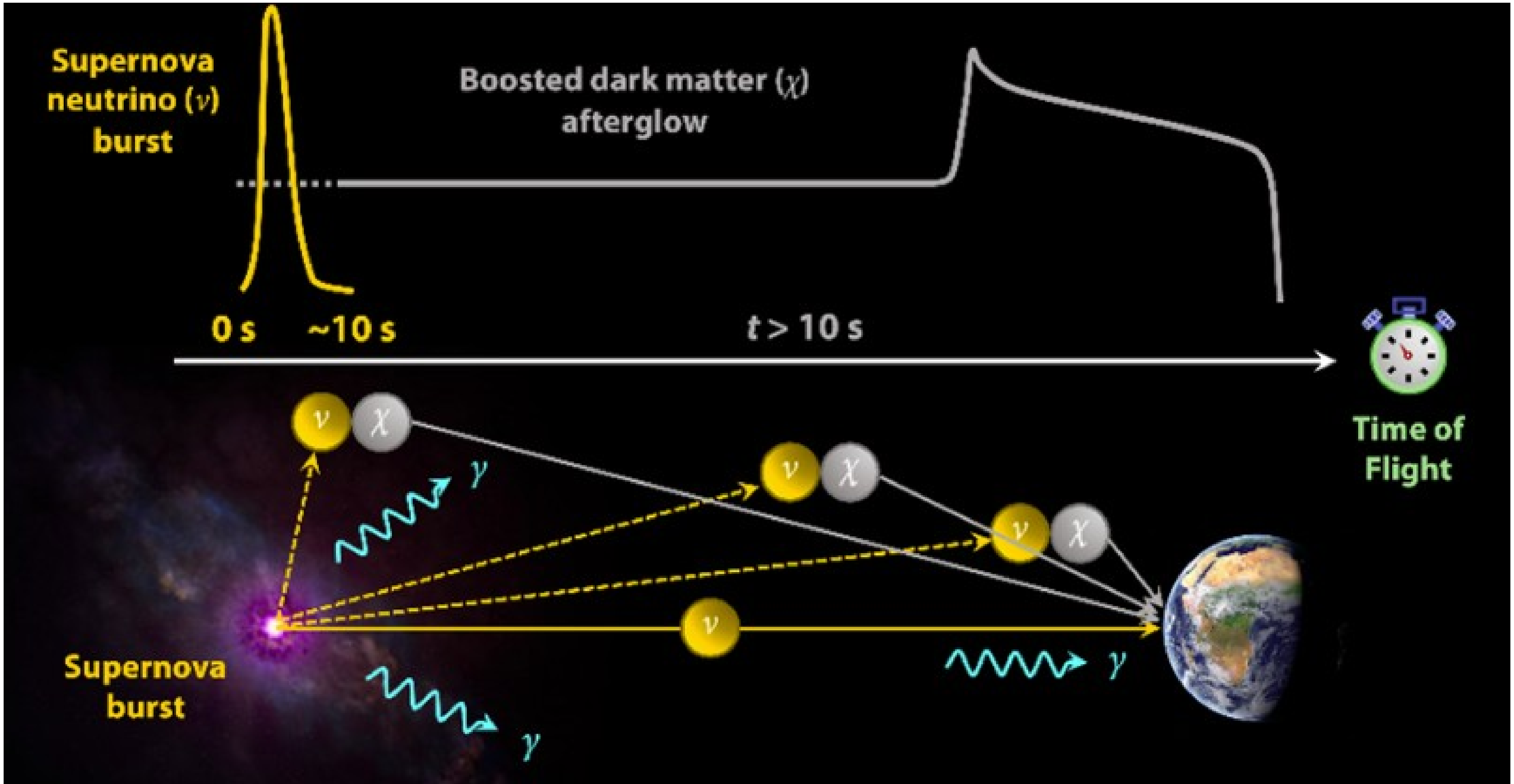
Light dark matter boosted by supernova neutrinos

For light DM ($m_\chi \sim 10$ keV), if it obtains an energy of ~ 10 MeV (kicked by SNν)

$\rightarrow$ arrives the Earth ~ 10 days $\times [d/(8\ \mathrm{kpc})][m_\chi/(10\ \mathrm{keV})]^2[E_\chi/(10\ \mathrm{MeV})]^{-2}$ after the arrival of SNν $\rightarrow$ afterglow events

($t = 0$ is calibrated by SNν)

[Lin, Wu, MRW, Wong 2206.06864]



Light dark matter boosted by supernova neutrinos

Two major features:

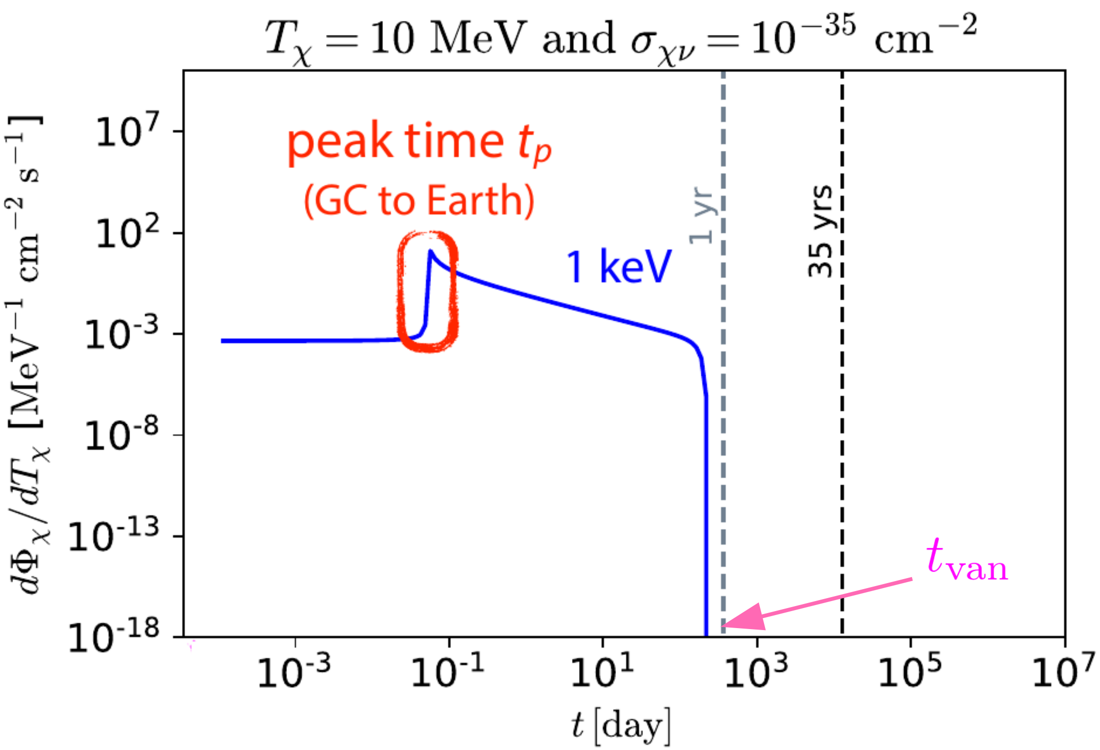
- sharp rise at $t_p = \frac{R_s}{v_\chi} - t_\nu$
  $\approx \frac{m_\chi^2}{2T_\chi^2}\frac{R_s}{c}$

  → arrival time of BDM from SN location to Earth

- cut-off at $t_{\rm van} \approx \frac{m_\chi}{4T_\chi}\frac{R_s}{c}$

  → longest arrival time for BDM

for a SN exploded in the MW center

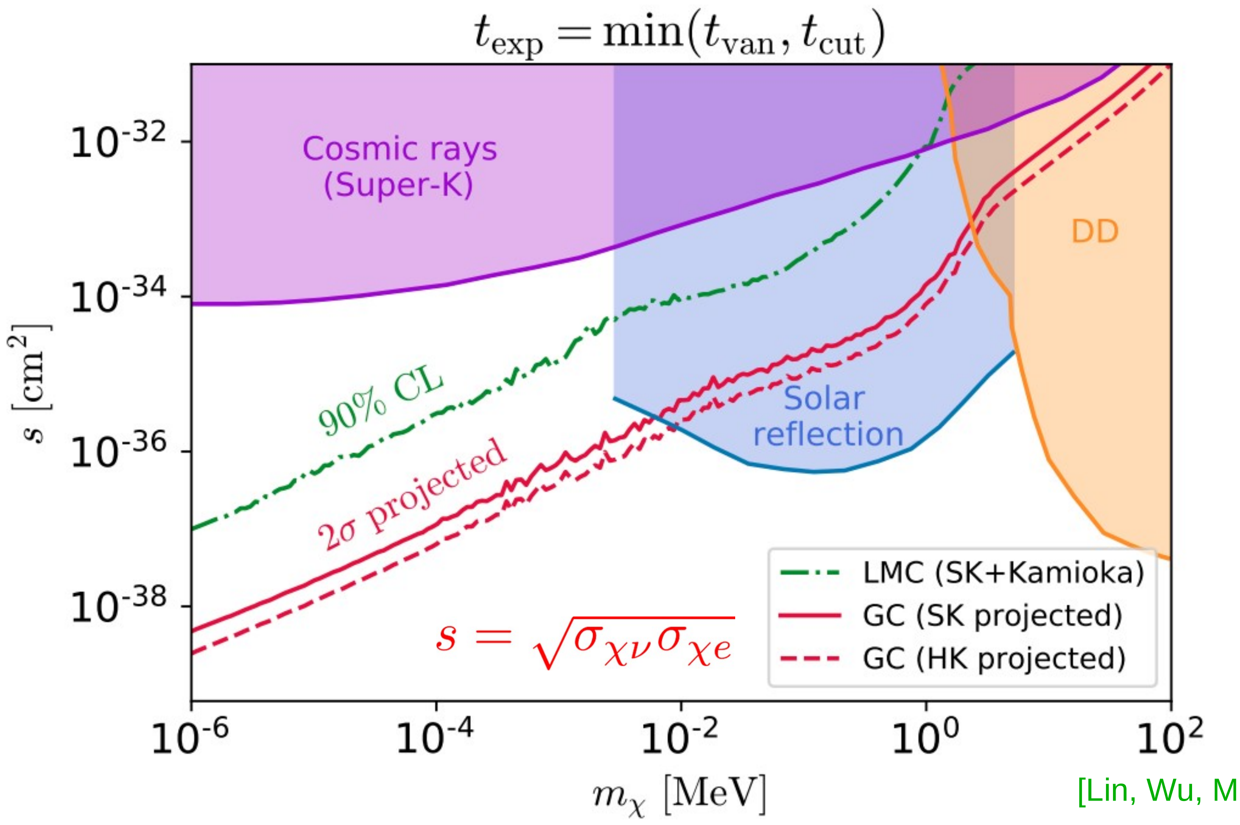


[Lin, Wu, MRW, Wong 2206.06864]

→ For non-zero χ-e interaction, it allows neutrino or DM detectors to measure m_χ if these time-dependent features are detected, or place constraint on $\sigma_{\chi\nu}\sigma_{\chi e}$ with nearby SN explosions

SNν boosted DM events and constraints

Consider total event and background counts within an exposure time $t_{\rm exp}$ =min($t_{\rm van}$, 35 years) with Kamiokande from 1987-1996 and Super-Kamiokande from 1996 on

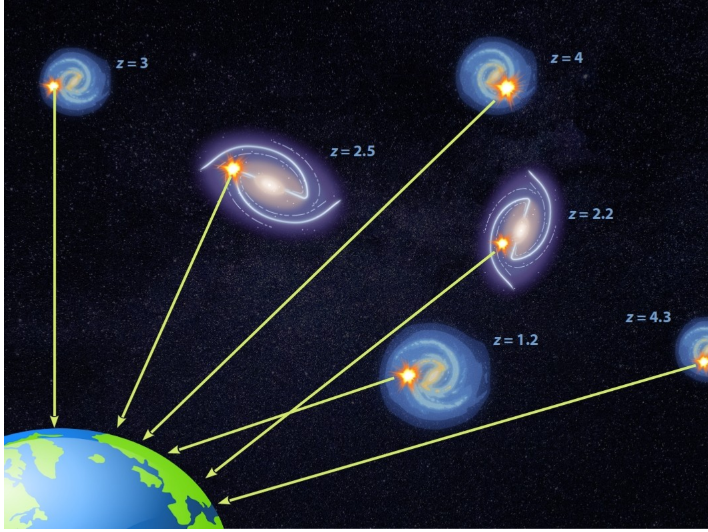


($s = \sigma_{\chi e}$ for shaded region from other considerations)

[Lin, Wu, MRW, Wong 2206.06864]

**can also provide complementary constraint to models that couple the dark sector to SM leptons [Lin+ 2307.03522]

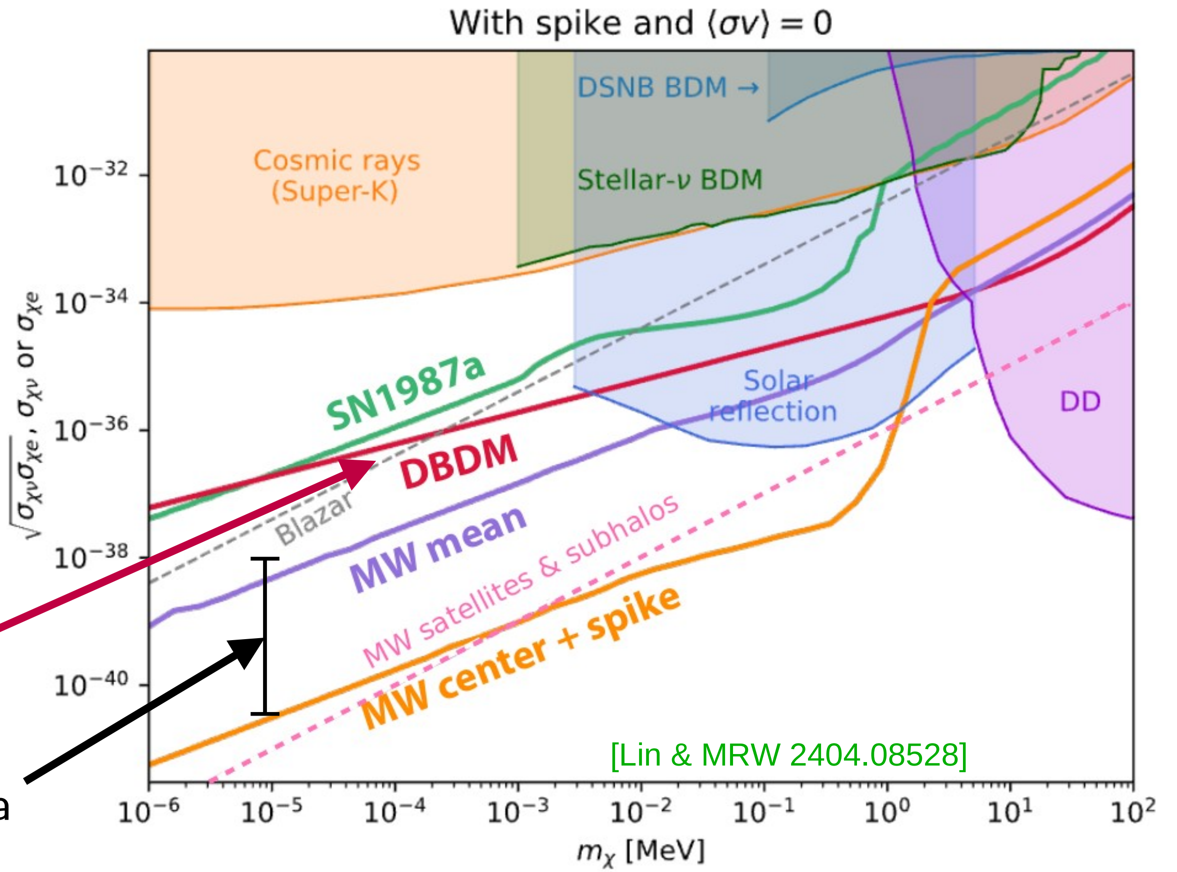
Diffuse SNν boosted DM



Beyond single SN, one can also consider SNν boosted DM from all galaxies at different redshifts that arrive at Earth

$\rightarrow$ a persistent diffuse boosted DM flux

$\rightarrow$ makes immediate measurements possible with current or upcoming neutrino and DM detectors



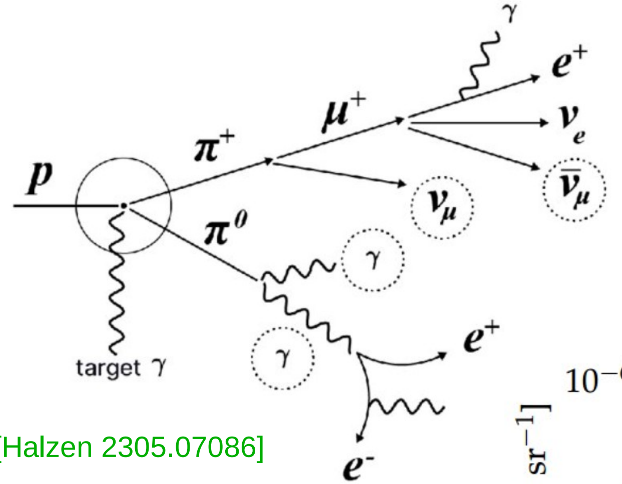
5-year of Hyper-Kamiokande data

next galactic supernova

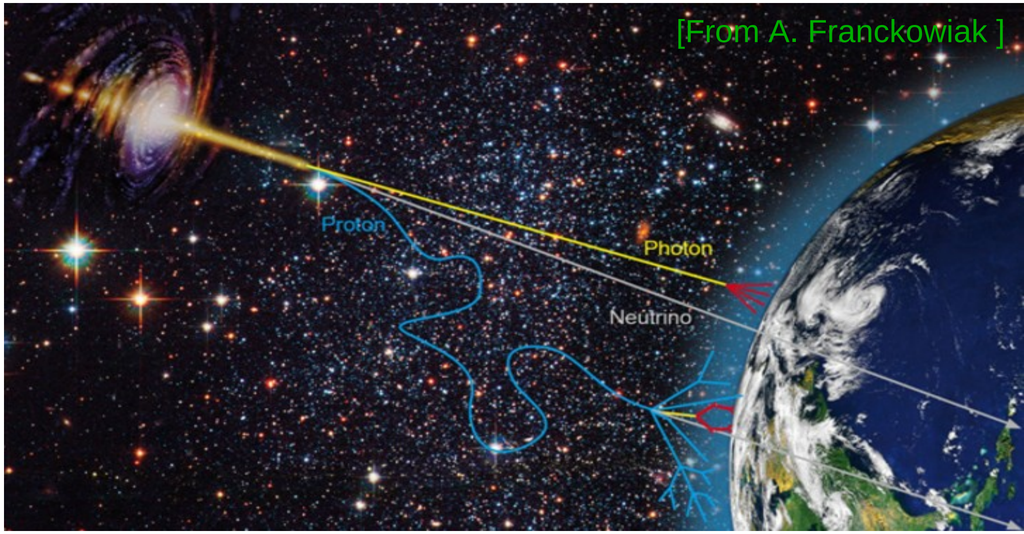
High-energy neutrinos from stellar explosions

Multimessenger of the high energy sky?

High-energy neutrinos and γ-rays can be (co)-produced when high energy cosmic rays interact with target protons or photons

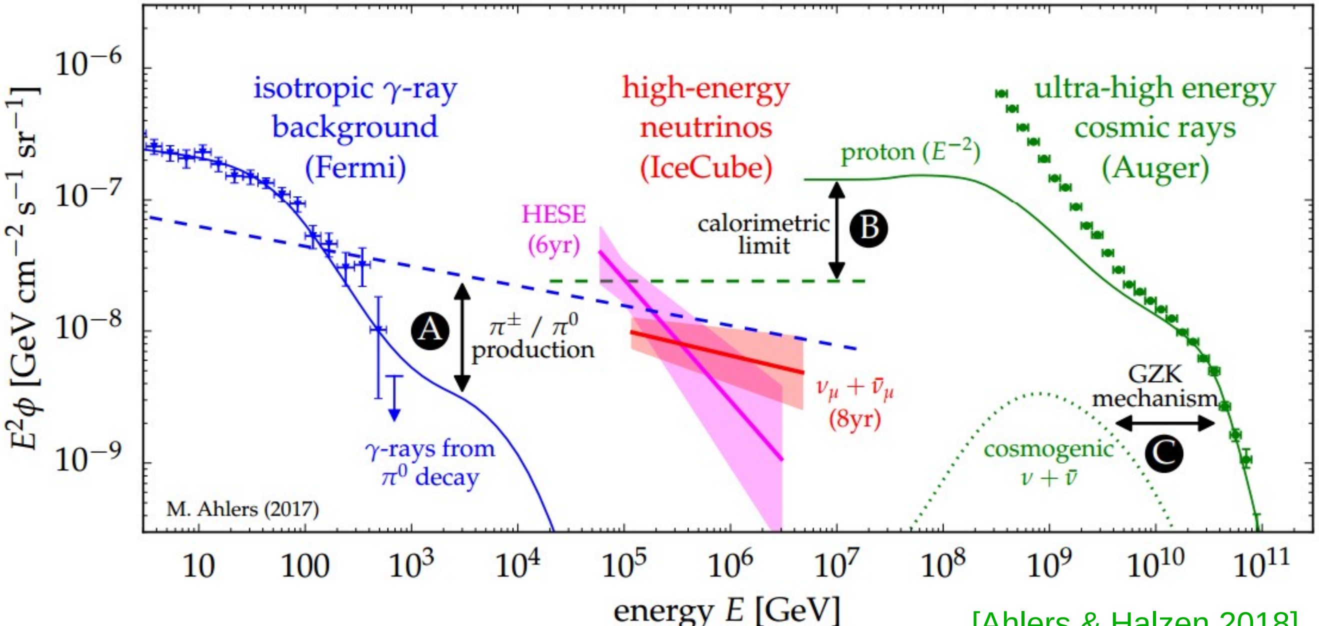


[Halzen 2305.07086]



Astrophysical sources?

active galactic nuclei?
gamma-ray bursts?
tidel disruption events?
starburst galaxies?
galaxy clusters?
magnetar?...?

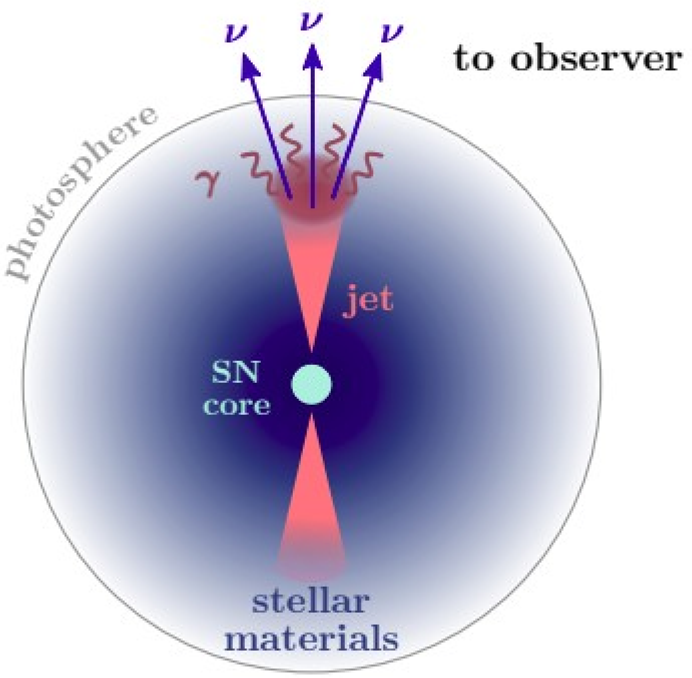


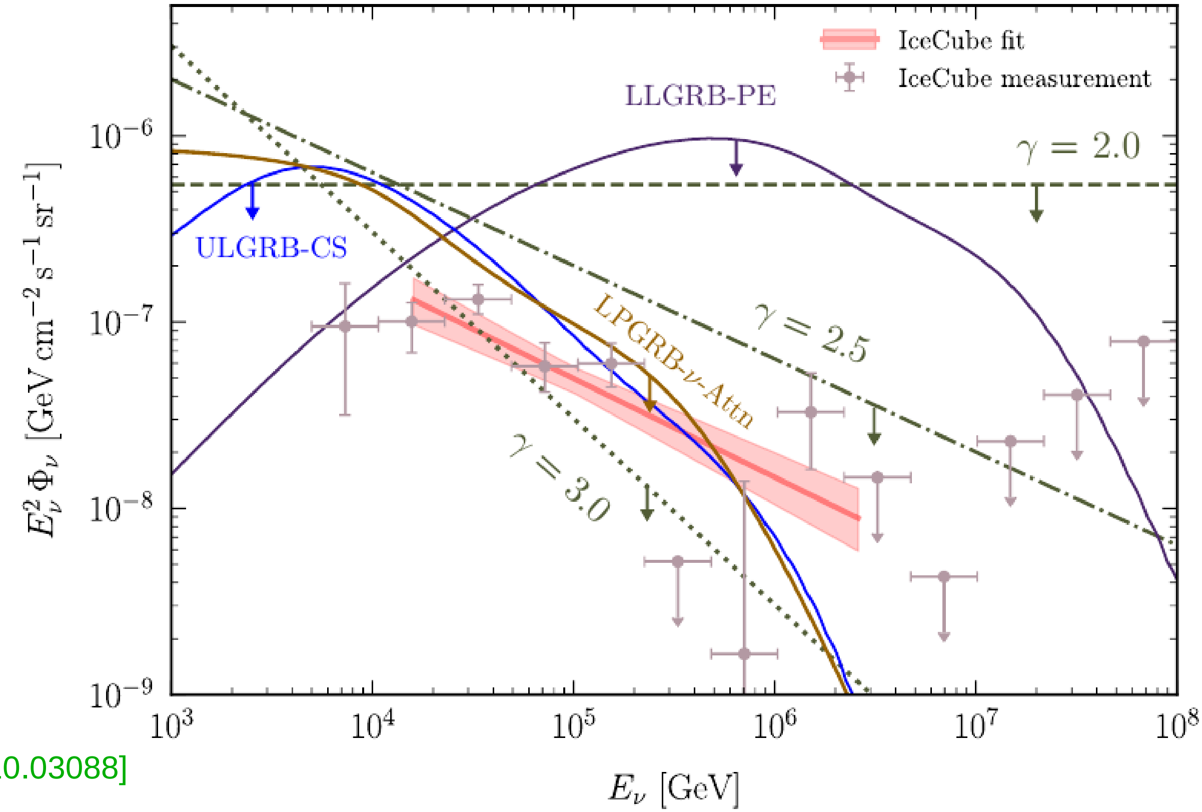
[Ahlers & Halzen 2018]

Gamma-ray-dim explosions as HE neutrino sources?

Non-association of diffuse high-energy neutrinos with GRBs put stringent bound on their overall contribution to those detected by IceCube ($\lesssim 1 - 24\%$ depending on the assumed emission phase) [IceCube 2022]

However, choked jets or interacting supernovae with thick circumstellar medium remain possible to account for some non-neglible fraction of diffuse HE neutrino flux





[Chang+ 2210.03088]

Gamma-ray-dim explosions as HE neutrino sources?

SN 2023uqf: An Interacting Supernova Coincident with a High-Energy Neutrino

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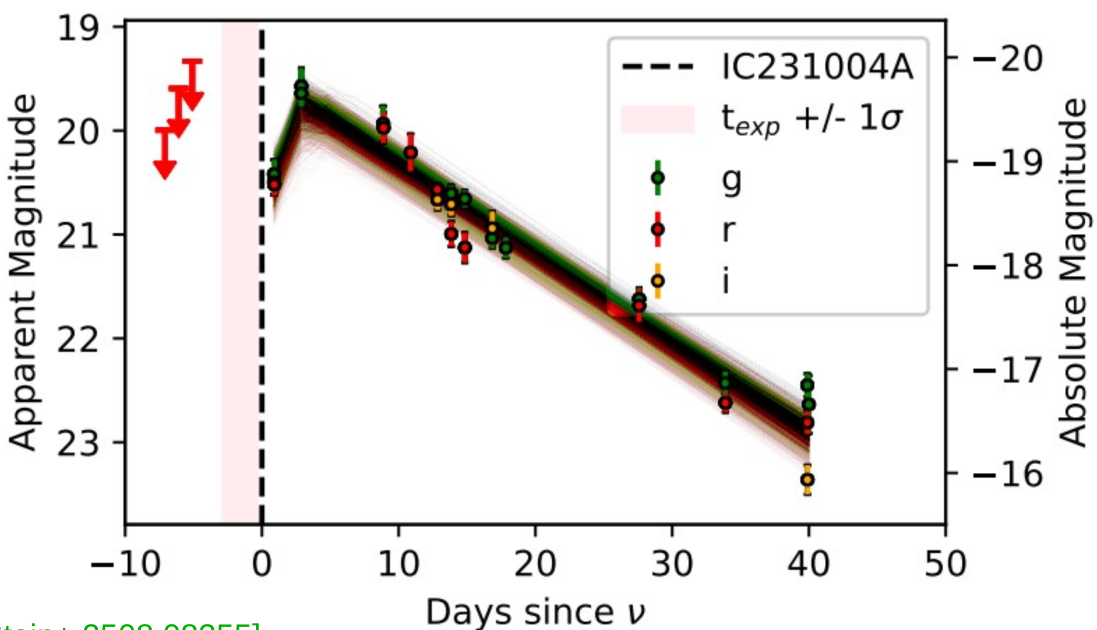


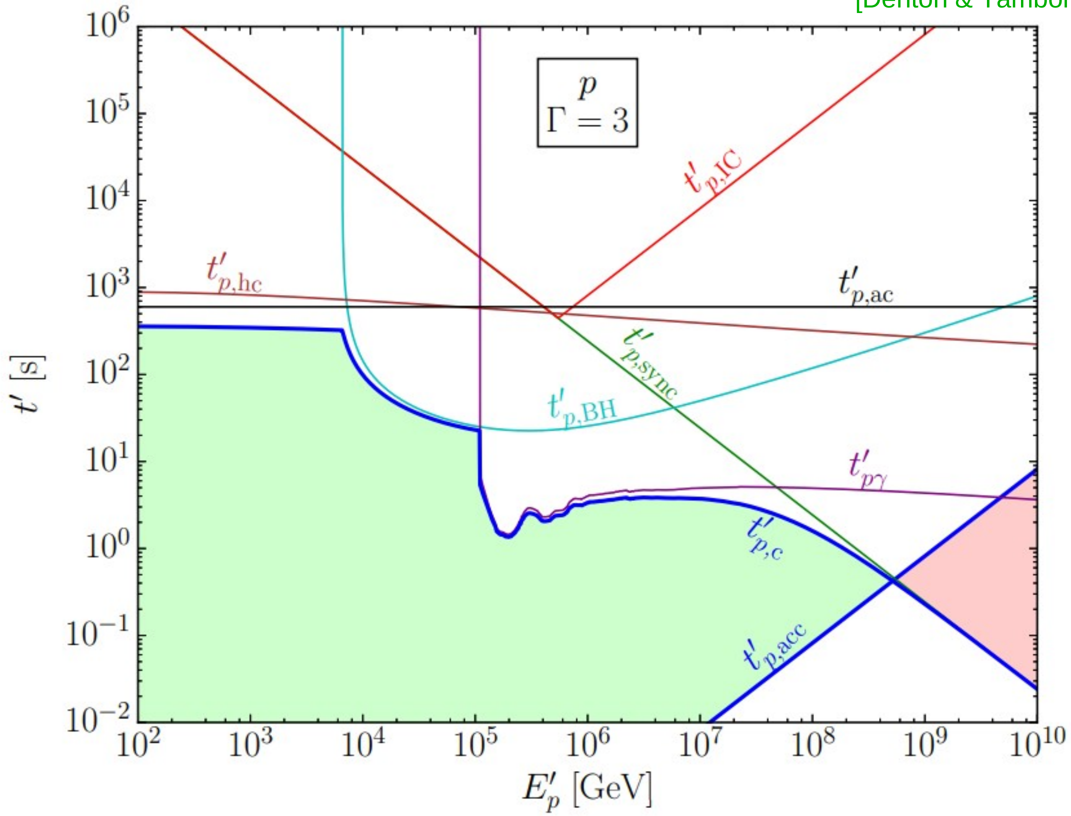
[Stein+ 2508.08355]

a potential $\sim 3\sigma$ association of a Type-Ibn SN with a IceCube neutrino!

High-energy neutrino production in stars

Typical calculations of HE neutrino production assume:
– protons are being shock-accelerated to $\phi_p(E_p) \propto E_p^{-2} \exp(-E_p/E_{p,\max})$
– $E_{p,\max}$ determined by the comparison of acceleration time scale v.s. all possible cooling time scales

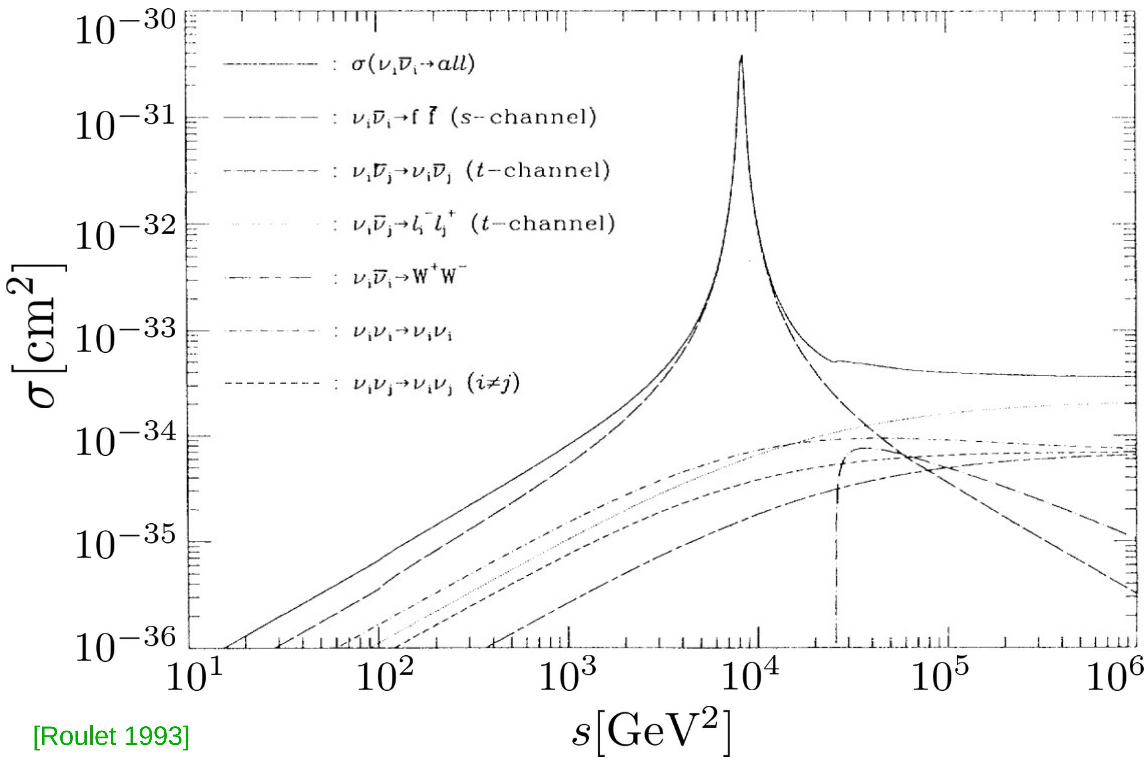
[Denton & Tamborra 1711.00470]



$\rightarrow$ corresponding HE neutrino energy spectrum is then computed from pp and $p\gamma$ reactions, taking into account meson cooling

Pair-annihilation effect?

Low-energy (anti)neutrinos of $\sim \mathcal{O}(10)$ MeV are copiously present in stellar explosions, under what conditions can they affect high-energy neutrinos spectrum?



[Roulet 1993]

$$\sigma_{\rm res} \simeq G_F^2 M_Z^4 \Gamma_Z^{-2} \sim 10^{-30}\ \text{cm}^2$$

for $s \ll M_{Z/W}^2$

$$\sigma_{\rm non-res} \sim G_F^2 s \sim 10^{-38}\ \mathrm{cm}^2 (\mathrm{s}/\mathrm{GeV}^2)$$

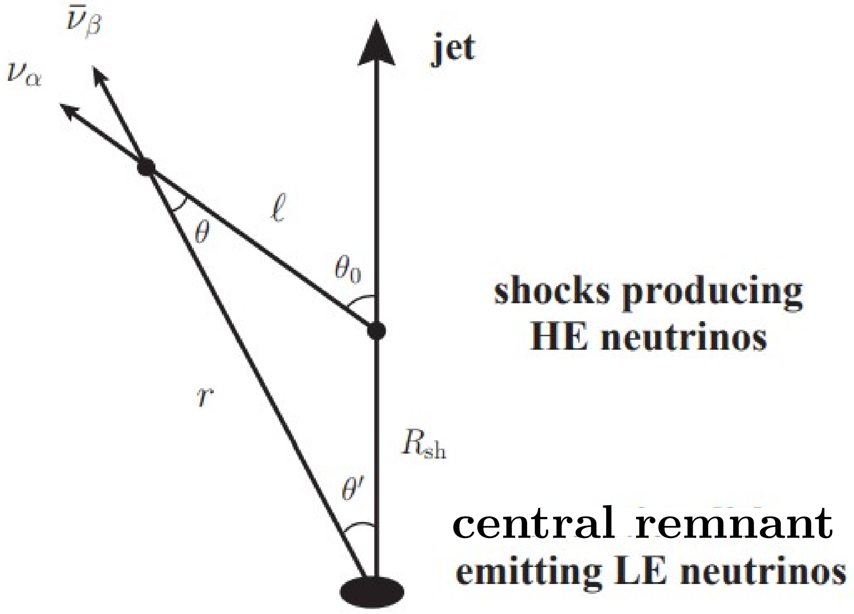
For $E_H = 0.5$ PeV, $E_L = 10$ MeV, $s = 2E_H E_L(1-\cos\theta) = 10^4$ GeV$^2(1-\cos\theta)$

$\rightarrow$ annihilation is dominated by non-resonant and resonant part for $\theta \ll \mathcal{O}(1)$ and $\theta \sim \mathcal{O}(1)$, respectively

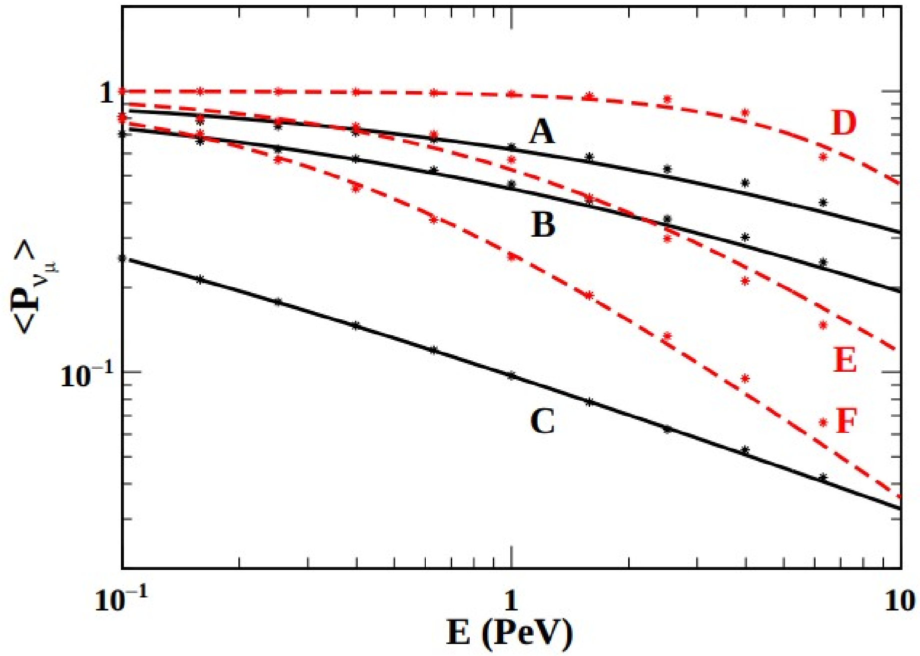
Pair-annihilation effect?

For thermal neutrinos of $\mathcal{O}(10)$ MeV emitted from central remnants, $n_\nu \sim 10^{25-26}$ cm^{-3} at $R_{\rm sh} \sim 10^{9-10}$ cm

$\rightarrow$ non-resonant annihilation can be important for slow jets (Lorentz factor $\Gamma \sim 3-10$) with opening angle $\theta_0 \sim 0.1 - 0.3$ for $E_\nu \gtrsim 100$ TeV



[Guo, Qian, MRW, 2310.05137]



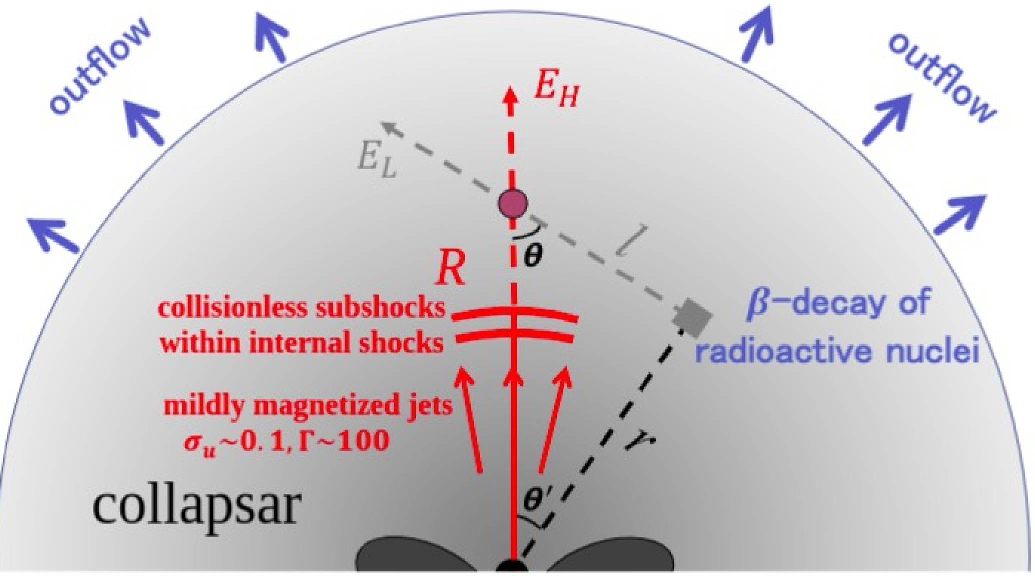
potentially relevant for various chocked jet scenario associated with stellar collapses

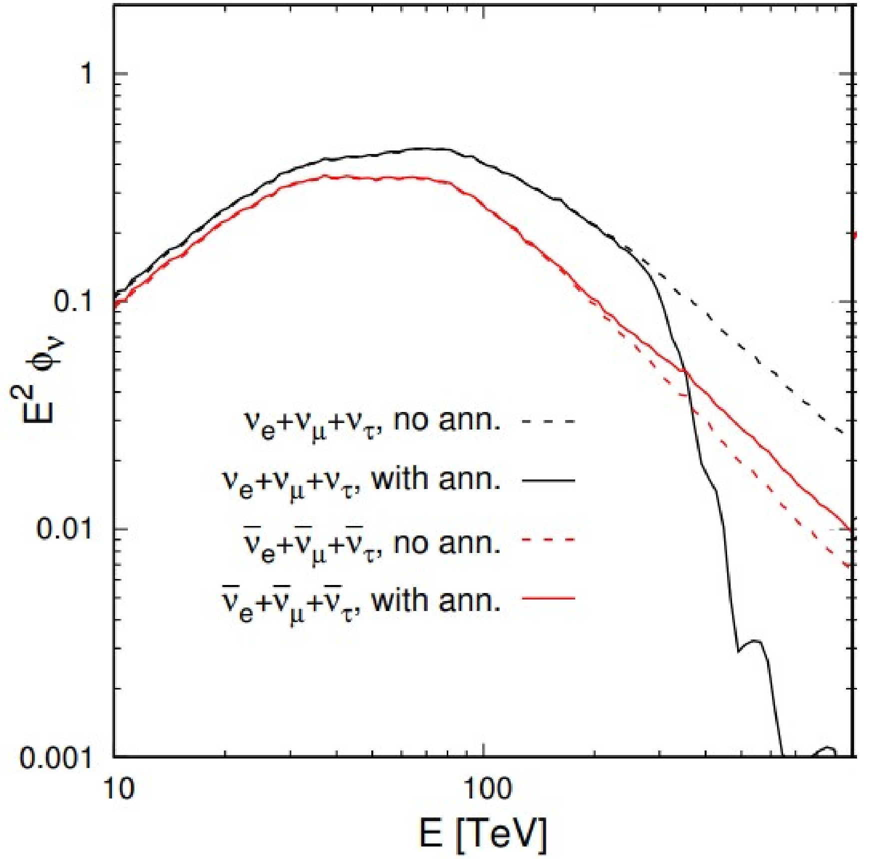
Pair-annihilation effect?

For massive star explosion ejecta containing unstable nuclei that undergo weak decays, resonnat annihilation of the decay (anti-)neutrinos with HE neutrinos may be possible

[Guo, Qian, MRW, PRD-L '23 (2212.08266)]

$$R \sim 10^{10}\ \mathrm{cm},\ n_{\bar{\nu},\mathrm{decay}} \sim 10^{23}\ \mathrm{cm}^{-3}$$





Summary

• Neutrinos affect stellar evolution and dominate explosion of massive stars. Their detection not only offers unique probes for stellar interior, but also can be used to infer fundamental properties of neutrinos

• In neutrino-dense environments (e.g., supernovae), collective phenomena emerge in flavor space, leading to challenging problems that must be taken care of for understanding how supernovae explode

• Supernova neutrinos can potentially upscatter light dark matter, capable of producing unique time-dependent boosted dark matter profile from nearby sources as well as a steady component from all past supernovae in the universe

• For high-energy neutrinos that are produced in stellar explosions, their annihilation with low-energy neutrinos from central remnants or from unstable nucleear decays in the ejecta may need to be considered.