

Neutrinos in Stellar Evolution and Explosions

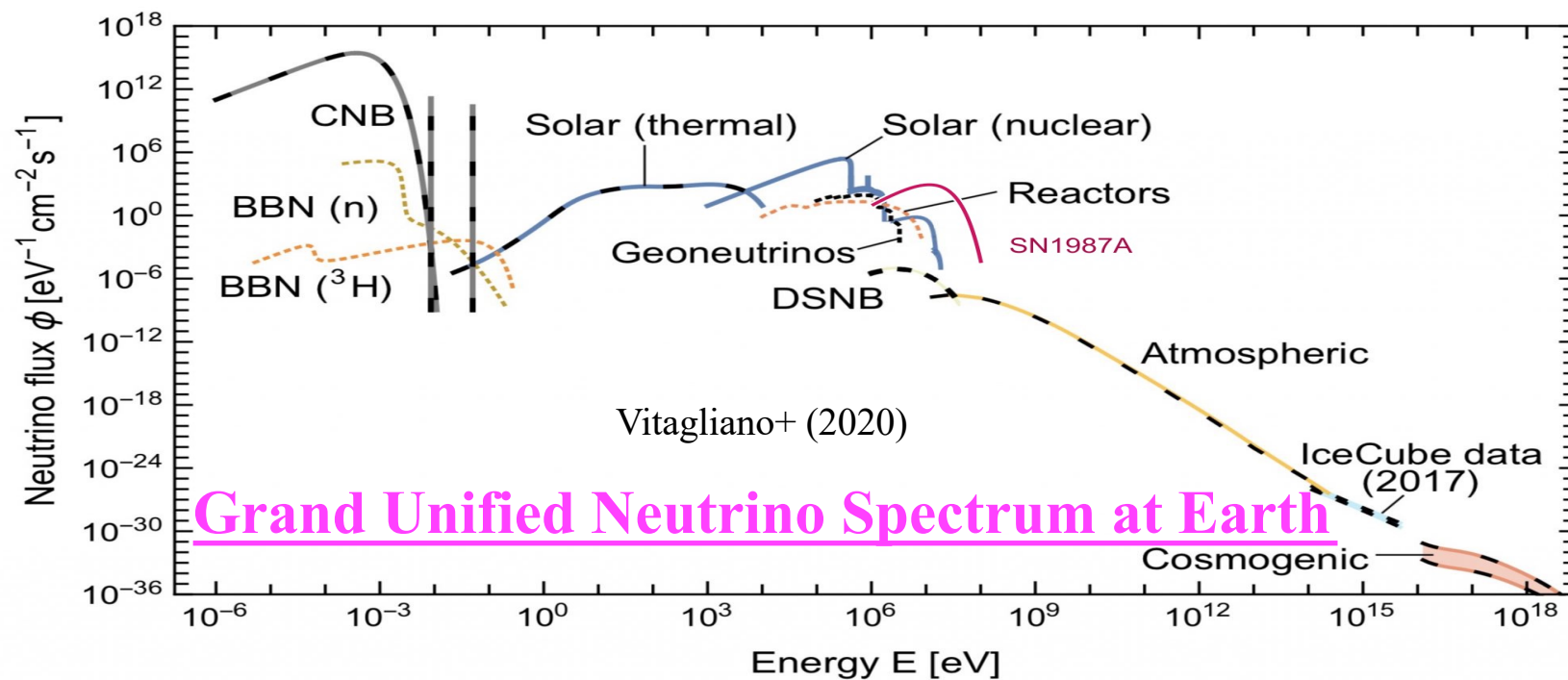
An overview from microphysics to neutrino signatures

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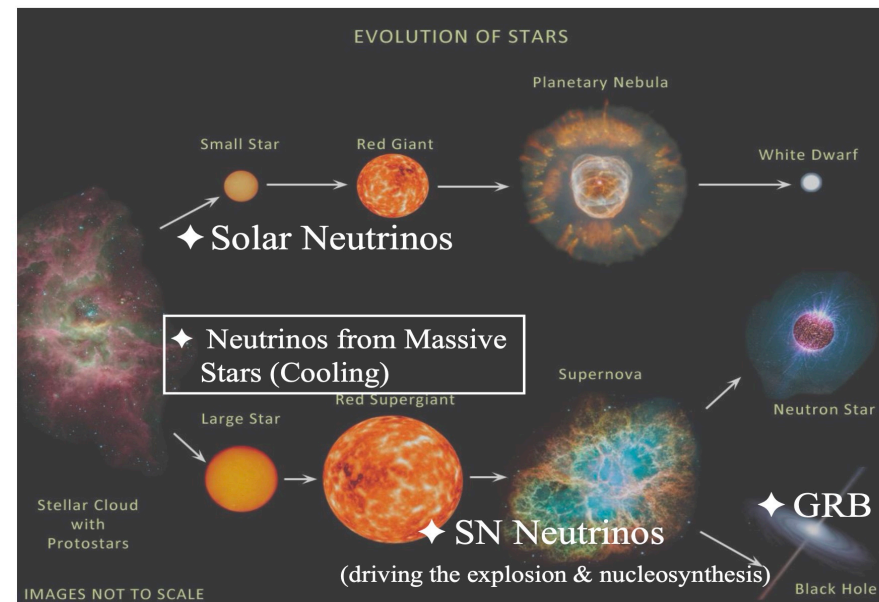
The 7th Joint Workshop on the Standard Model and Beyond,
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Major collaborators: Yong-Zhong Qian, Gabriel Martinez-Pinedo, Meng-Ru Wu, Tobias Fischer



Three topics in this talk neutrinos astronomy & stellar evolution

- 1) Neutrinos from stars: **keV-MeV**
- 2) Neutrinos from regular core-collapse supernovae (CCSNe): **10-100 MeV**
- 3) High-energy neutrinos (**TeV-PeV**) from violent stellar explosions: gamma-ray bursts (GRBs); newborn pulsars/magnetars; interacting SNe



Supernova (SN)

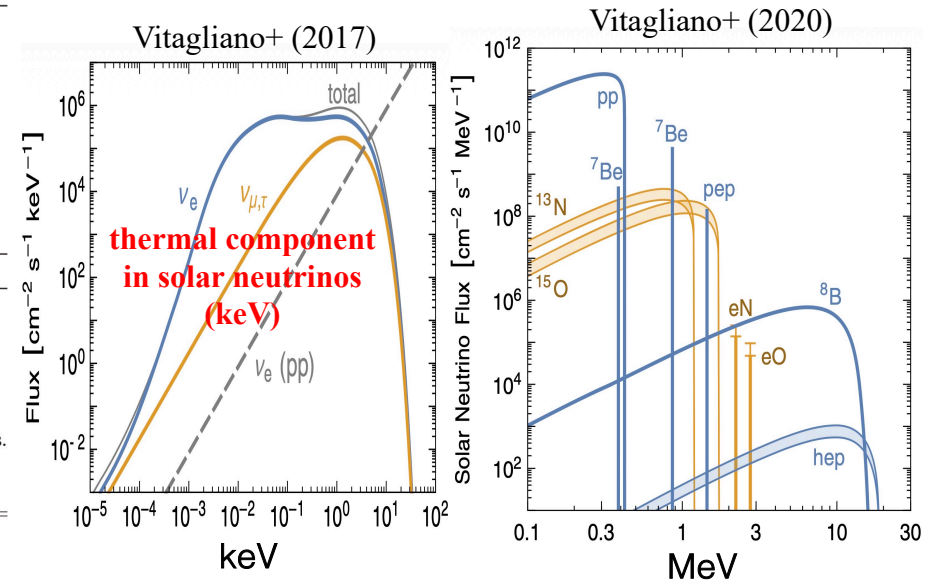
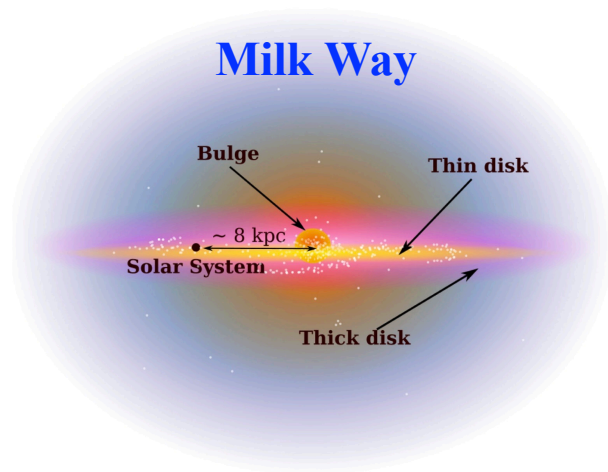
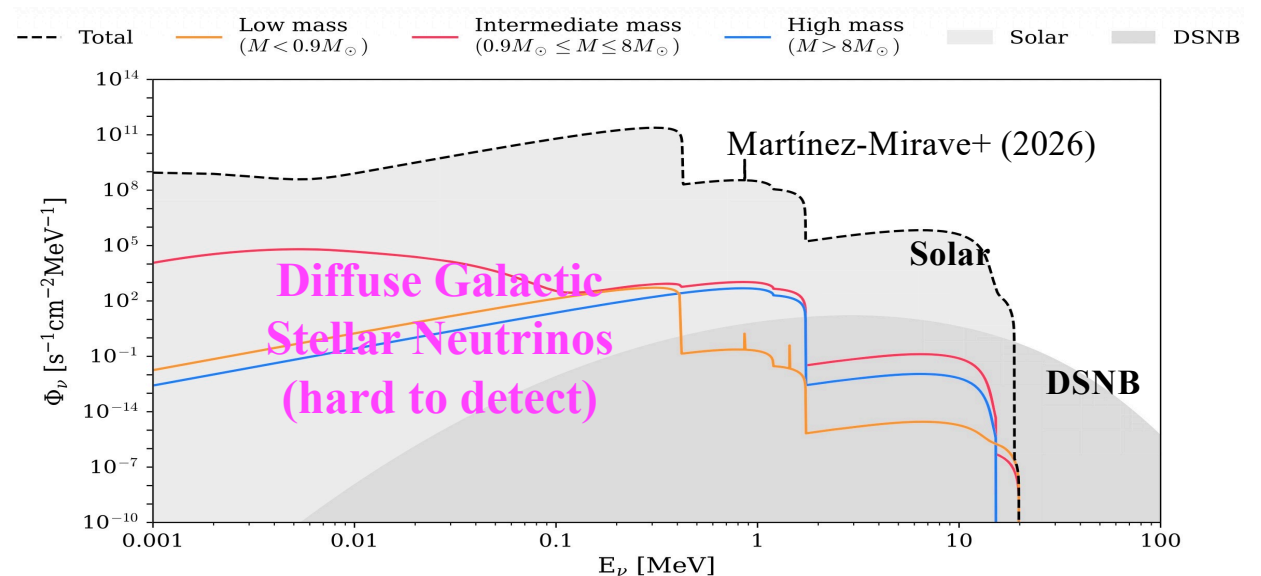
gamma-ray burst (GRB)

Neutrinos [TeV-PeV]

neutrino emission in stars

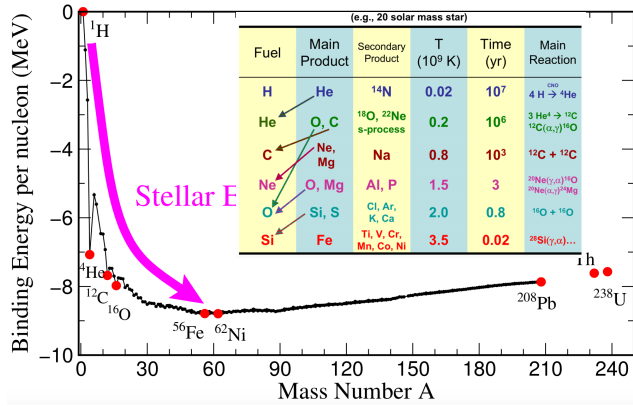
Thermonuclear reactions			
pp chain	pp Pep ${}^7\text{Be}$ ${}^8\text{B}$ hep	$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$ $p + e^- + p \rightarrow {}^2\text{H} + \nu_e$ ${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \gamma + \nu_e$ ${}^8\text{B} \rightarrow 2\alpha + e^+ + \nu_e$ ${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$	Dominant for $T \lesssim 1.9 \times 10^7$ K, in main-sequence low-mass stars.
CNO cycle	${}^{13}\text{N}$ ${}^{15}\text{O}$ ${}^{17}\text{F}$	${}^{13}\text{N} \rightarrow {}^{13}\text{C} + e^+ + \nu_e$ ${}^{15}\text{O} \rightarrow {}^{15}\text{N} + e^+ + \nu_e$ ${}^{17}\text{F} \rightarrow {}^{17}\text{O} + e^+ + \nu_e$	Dominant for $T \gtrsim 1.9 \times 10^7$ K, in main sequence intermediate- and high-mass stars.
Others	${}^{18}\text{F}$ neutrinos	${}^{18}\text{F} \rightarrow {}^{18}\text{O} + e^+ + \nu_e$	Relevant during He burning
Thermal reactions			
Plasmon decay		$\gamma^* \rightarrow \nu + \bar{\nu}$	Dominant during early stages of white-dwarf cooling and main thermal process during H-burning for $M \lesssim 3M_\odot$.
Photoneutrinos*		$e^- + \gamma \rightarrow e^- + \nu_e + \bar{\nu}_e$	Main thermal process during H-burning for $M \gtrsim 3M_\odot$ and during He burning.
Pair annihilation*		$e^+ + e^- \rightarrow \nu + \bar{\nu}$	Relevant in the late stages of evolution of high-mass stars.
Bremsstrahlung*		$N + e^- \rightarrow N + e^- + \nu + \bar{\nu}$	Subdominant
Recombination*		$e^-_{\text{continuum}} \rightarrow e^-_{\text{bound}} + \nu_e + \bar{\nu}_e$	

Solar neutrinos

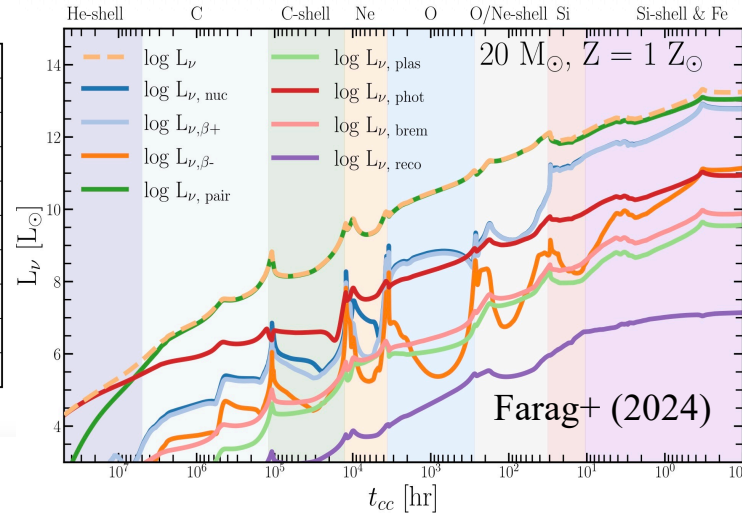
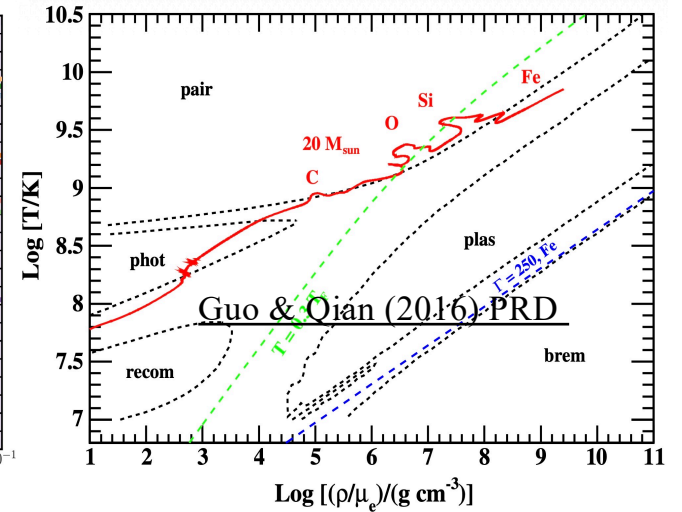


Steady stellar neutrinos, apart from solar nuclear neutrinos, remain beyond the reach of current detectors !

neutrinos during late stages of massive stars ($\geq 10M_{\odot}$)

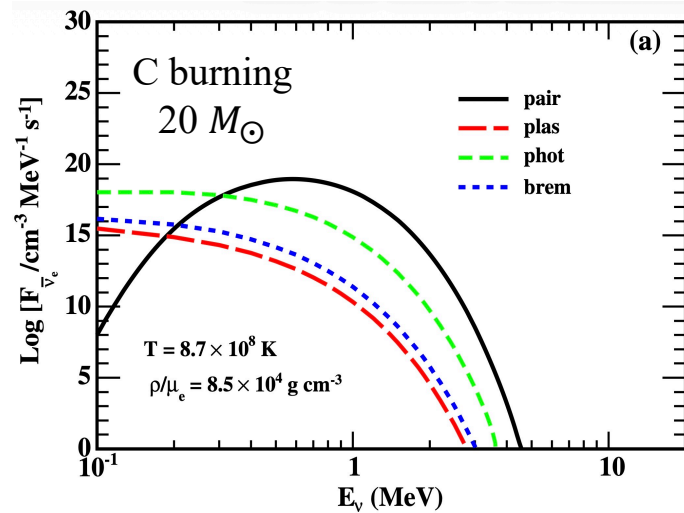
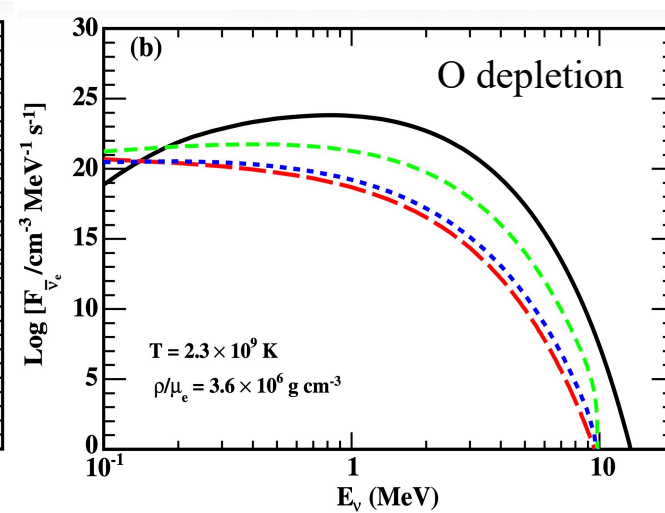
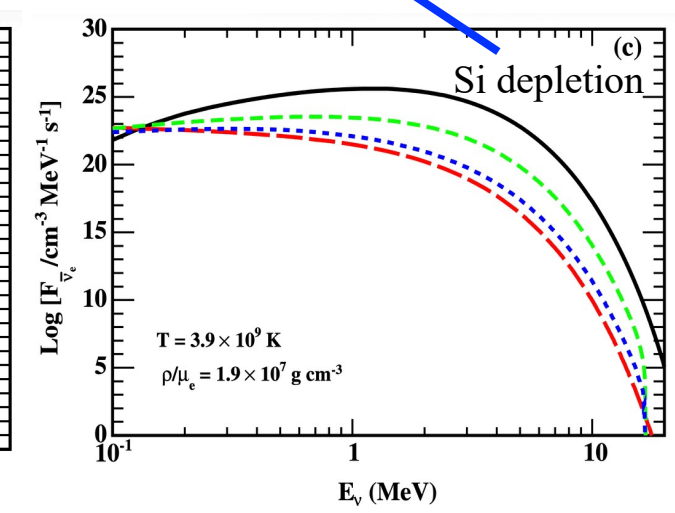


photon star → neutrino star
after core C burning



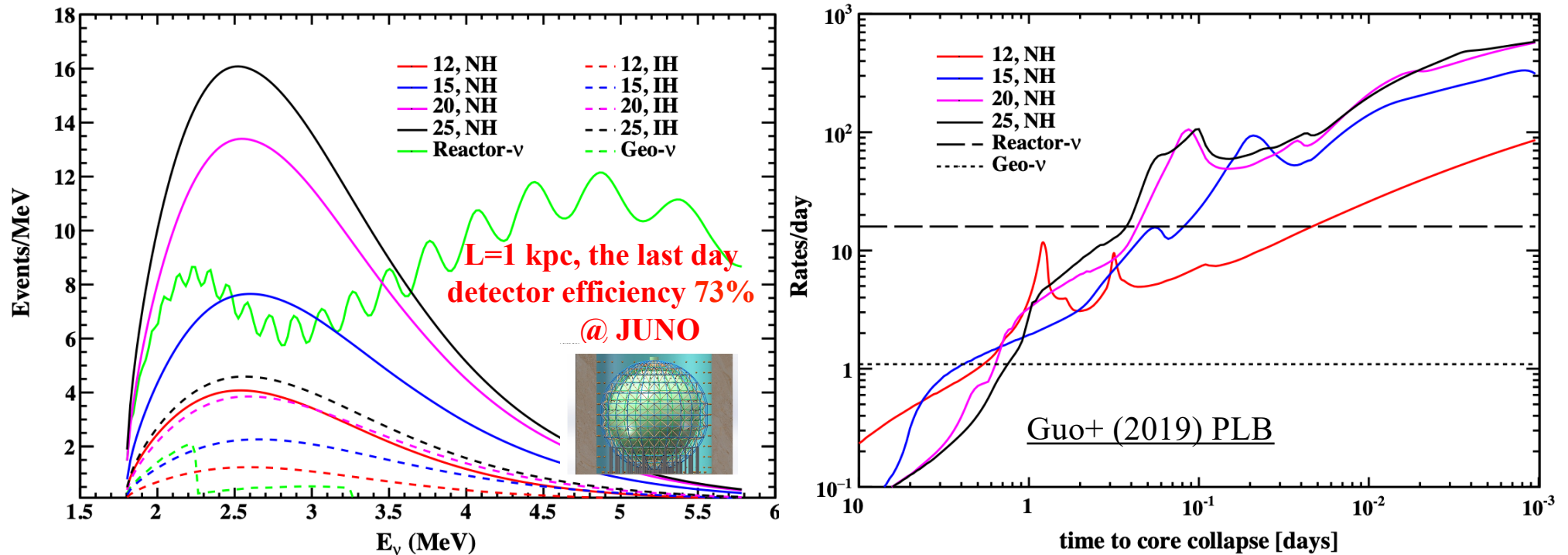
$e^{\pm}$ pair annihilation dominating

the very last day prior to core collapse
Pre-SN neutrinos



Guo & Qian (2016) PRD

Pre-SN neutrino events expected at JUNO



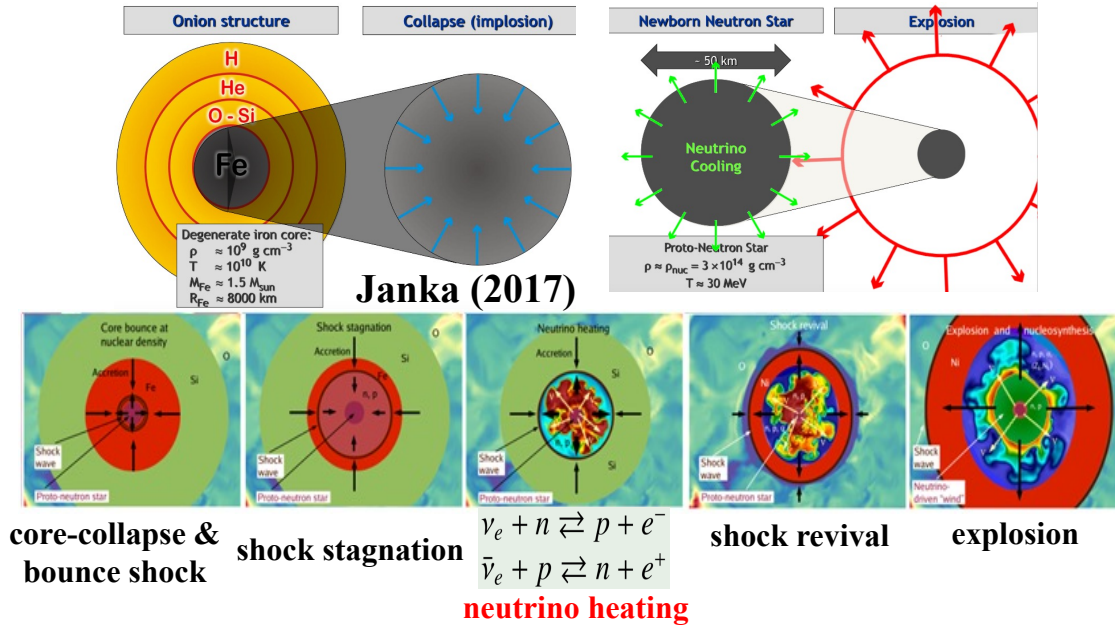
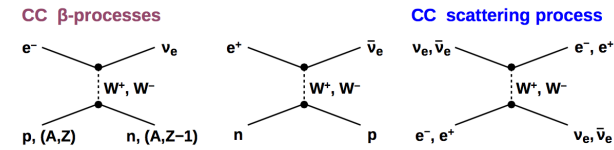
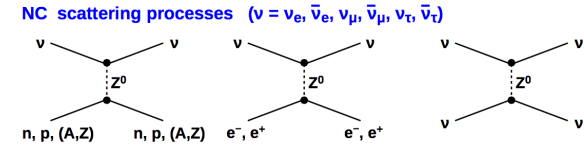
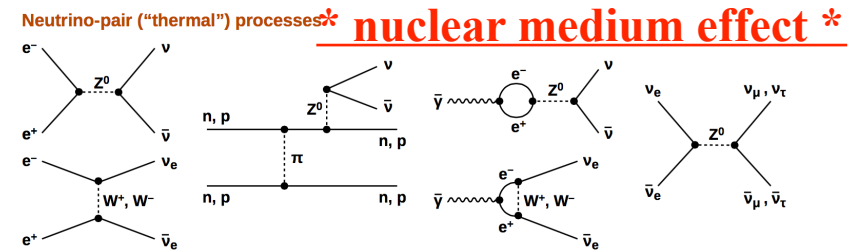
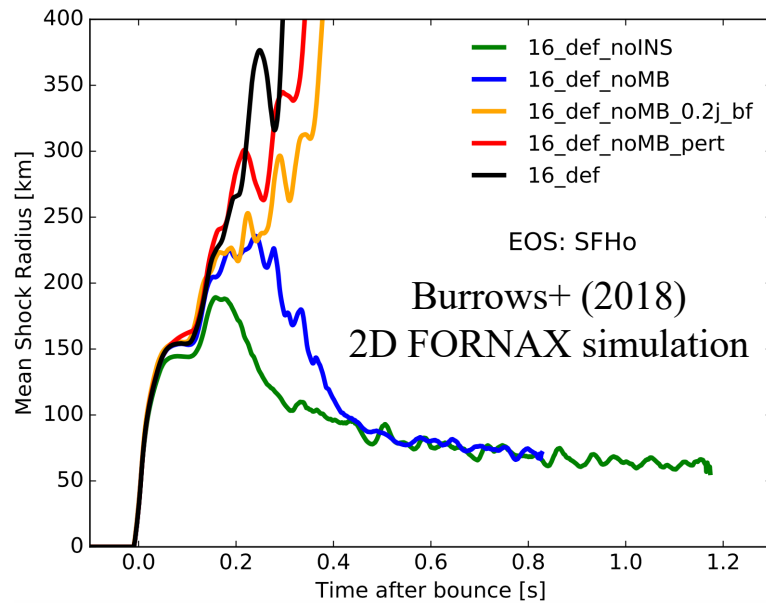
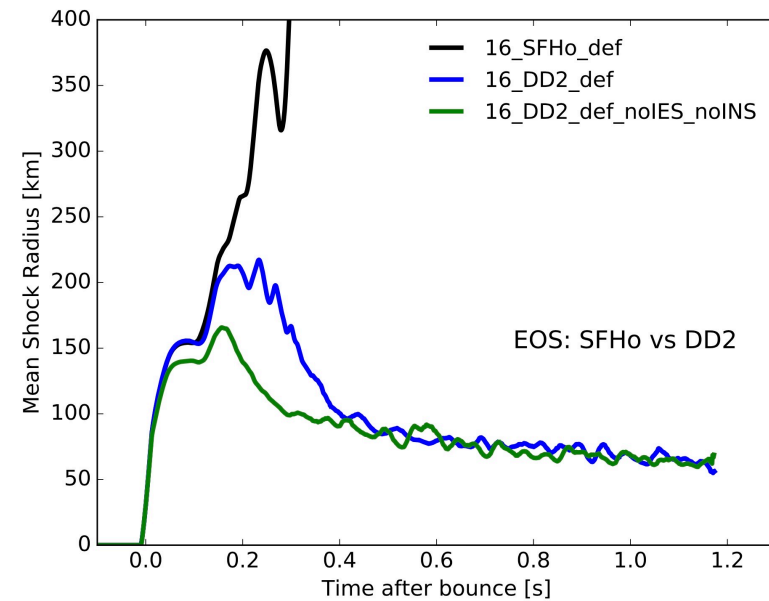
**~6.2, 12.3, 21.0 and 25.0 IBD events for normal hierarchy;
~16 and 1 background events from reactor and geo-neutrinos.**

Detectable at underground dark matter detectors via coherent scattering on heavy nuclei

Potential lessons from future pre-SN neutrino observations, see Kato+ (2020)

- Unique probe of stellar physics (maybe the only one to probe inner structure);
- Alarm for SN explosion (~a few days prior to core collapse for **Betelgeuse, 200 pc**);
- Probe neutrino mass hierarchy (oscillation depends on mass hierarchy), Guo+ (2019) PLB;
- Test BSM physics (clean compared to CCSNe): axion, dark photon, Z' boson, dark matter;
-

Neutrinos Driving Core-Collapse Supernova



The SN explodability depends sensitively on the **neutrino rates** & **nuclear equation of state**

Theoretical calculation of neutrino-nucleon rates

Neutrino-nucleon scattering or absorption rates at **mean field level**

$$\nu + N \rightarrow \nu + N$$

$$\nu + N \rightarrow l^- + N$$

$$E_{n,p} = \sqrt{m_{n,p}^{*2} + p^2} + U_{n,p}$$

Depending on EoS

$$\bar{\psi}_4 \left\{ \gamma^\mu [G_V(q^2) - G_A(q^2) \gamma^5] + \frac{iF_2(q^2)}{2M_N} \sigma^{\mu\nu} q_\nu^* - \frac{G_P(q^2)}{M_N} \gamma^5 q^{*\mu} \right\} \psi_2$$

Full hadronic currents + relativistic kinematics;

Inclusion of inverse beta decay;

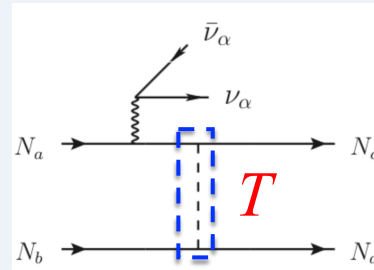
Valid for muonic reactions.

Fischer+ (2020) PRC

Guo+ (2020) PRD

Neutrino pair process from **nucleon-nucleon bremsstrahlung**

$$N_a + N_b \rightarrow N_c + N_d + \nu_\alpha + \bar{\nu}_\alpha$$



T-matrix elements obtaining using the chiral effective nucleon potential

Leading to enhanced (suppressed) rates at low (high) density regions

Generally minor effects on SN dynamics & neutrino signals

Guo+ (2019) ApJ

Neutrino-nucleon scattering with **nucleon-nucleon correlation**

$$\nu + N^* \rightarrow \nu + N^*$$

➤ **Random phase approximation**

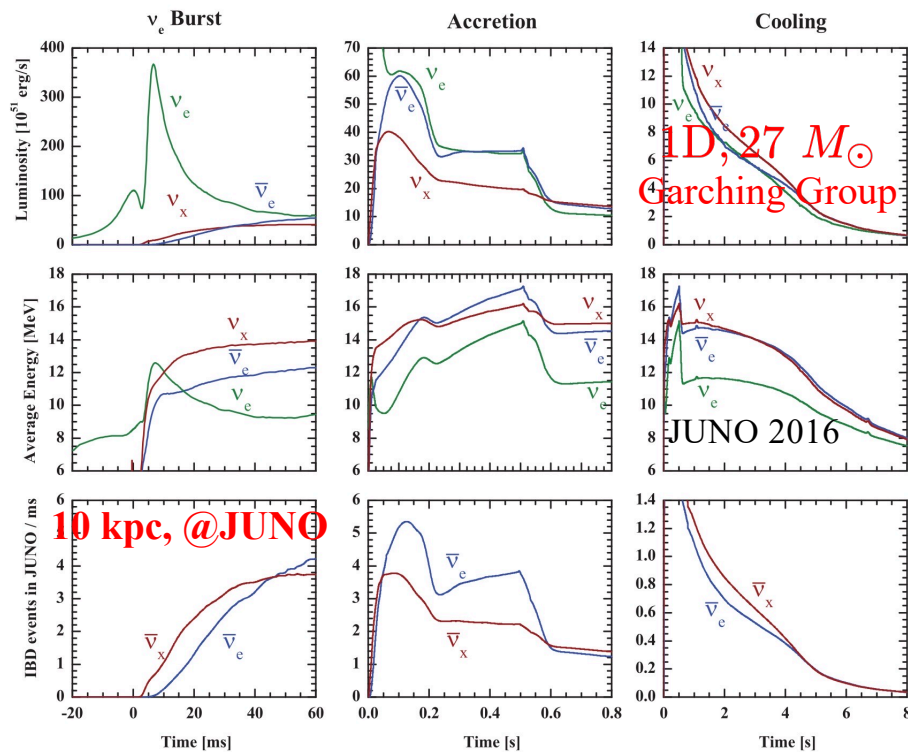
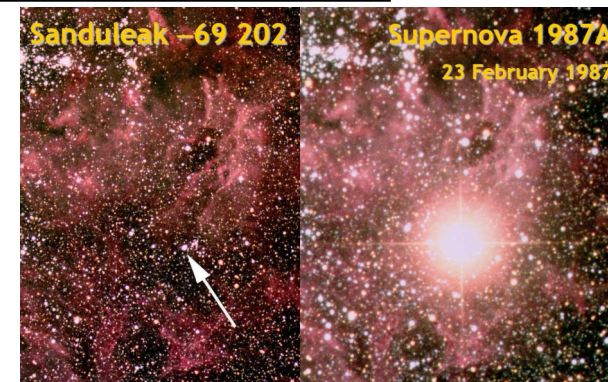
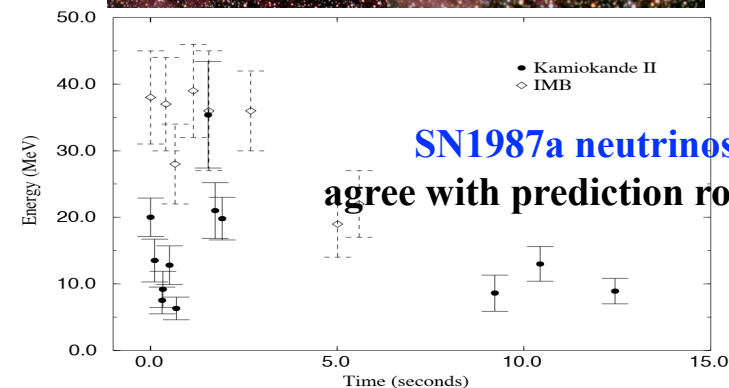
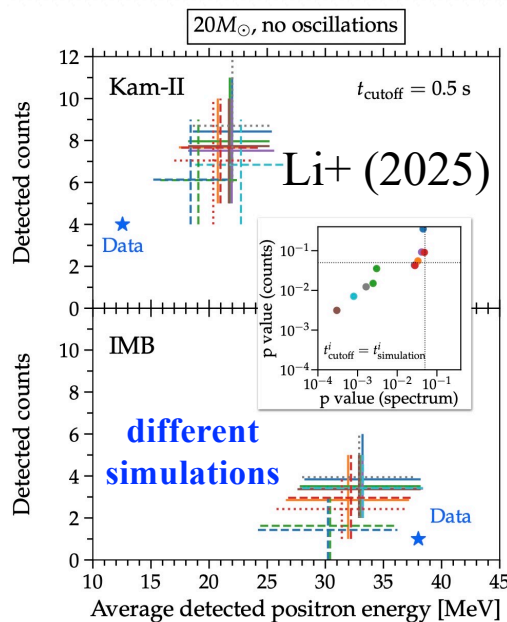
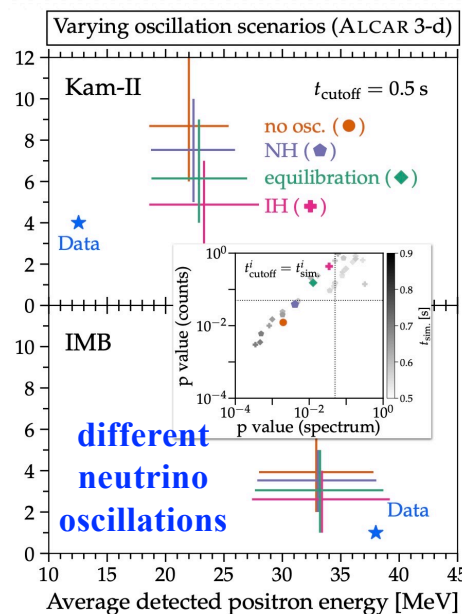
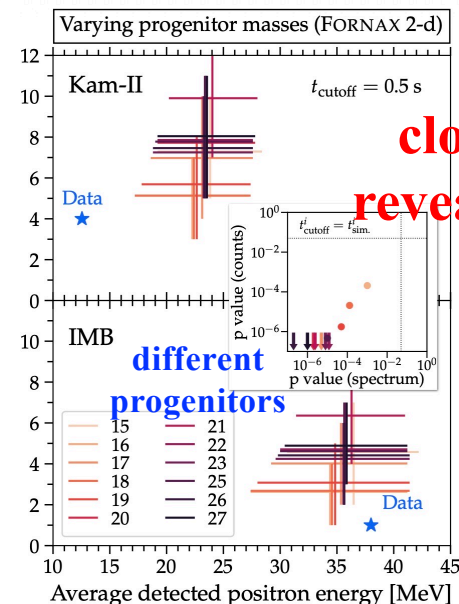
Burrows & Sawyer (1998, 1999), Duan & Urban (2023) with N3LO

- Virial expansion, Horowitz+ (2006, 2017); Bedaque+ (2018)
- Statistical approach, Guo+ (2024) PRC
- Unitary gas approximation, Lin+ (2017)
- Lattice Formulation, Alexandru+ (2020, 2021); Ma+ (2024) with N3LO
- Molecular dynamics simulation
Horowitz+ (2004), Li+ (2017)

Key effect on explodability !!!

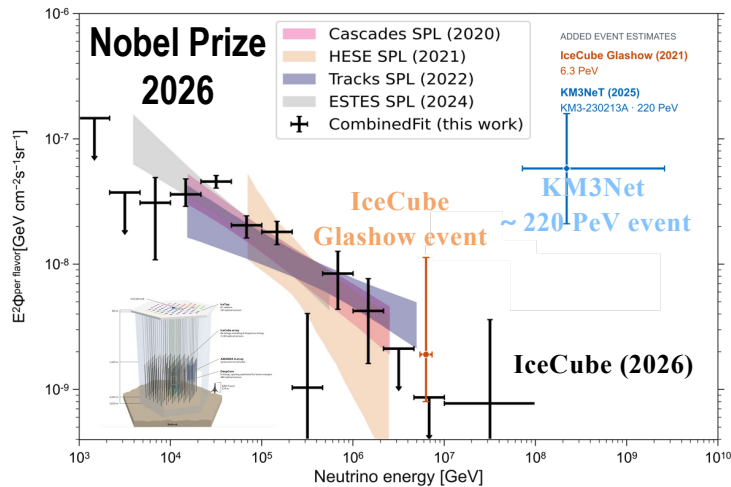
- ❑ The resulting SN neutrino signals exhibit only **modest sensitivities** to the variations in the above neutrino rates as well as nuclear EoS.
- ❑ However, **the inclusion of additional d.o.f.**, such as **muons** and **pions**, populated by neutrino reactions, can modify the EoS and the SN dynamics, and may introduce new features in SN neutrino signals. Fischer+ (2020) PRD, Bollig+ (2017), Fore+ (2019)
- ❑ **Nucleon correlation** in neutrino-nucleon scattering affects greatly the SN dynamics and explodability. Burrows+ (2018,2020)

A glimpse of CCSN neutrino signals



closer inspection reveals some tension

high-energy neutrinos ν s stellar explosions



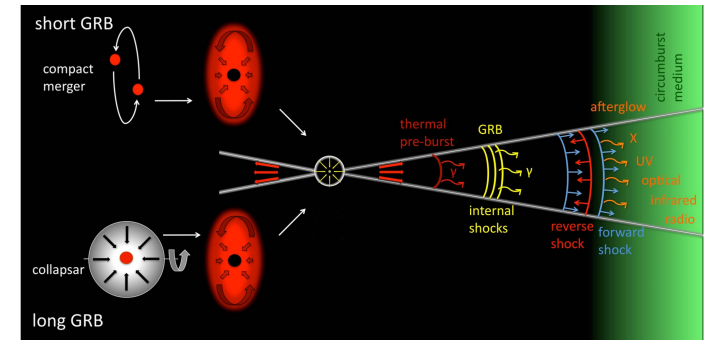
IceCube: thousands of HE neutrino events above 10 TeV are accumulated

- ✓ AGNs (TXS 0506+056 and NGC 1068) have been identified as HE neutrino sources;
- ✓ The Milky way has emerged as an extended Galactic neutrino source;
- ✓ Tidal disruptive events (TDEs) and other X-ray bright AGNs are shown to be associated with IceCube neutrinos (though not fully confirmed);
- ✓ The origins of most neutrino events, including the KM3Net 220 PeV event, remain unclear;

✓ *****Standard GRBs are tightly constrained as HE neutrino sources**

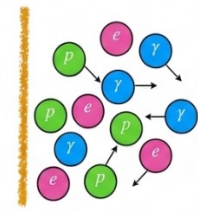
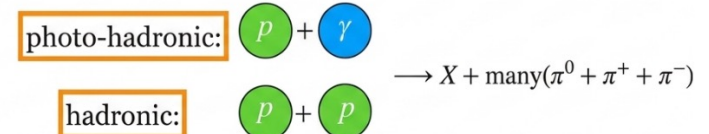
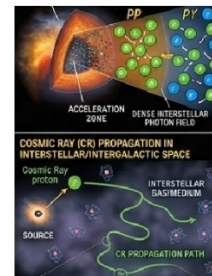
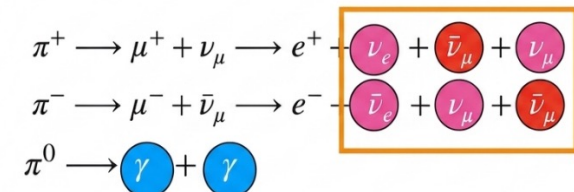


Gamma-ray bursts (GRBs)



- Mergers of binary neutron stars
- Collapsars (or magnetars)

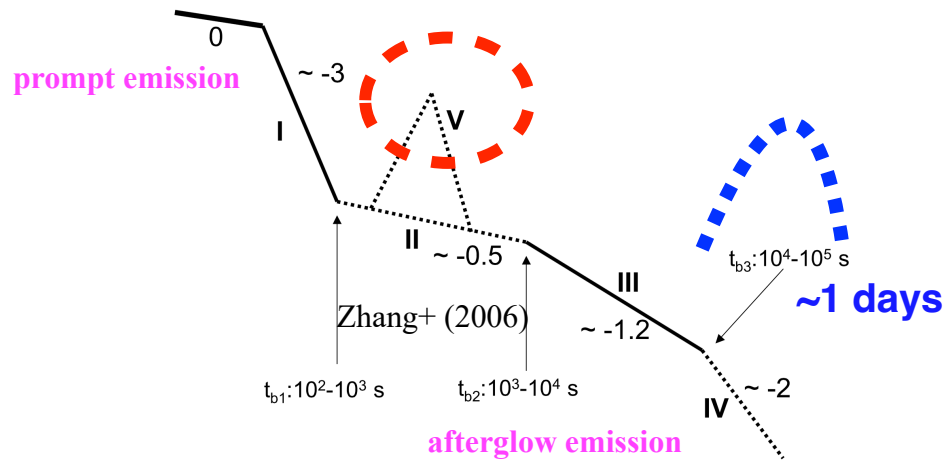
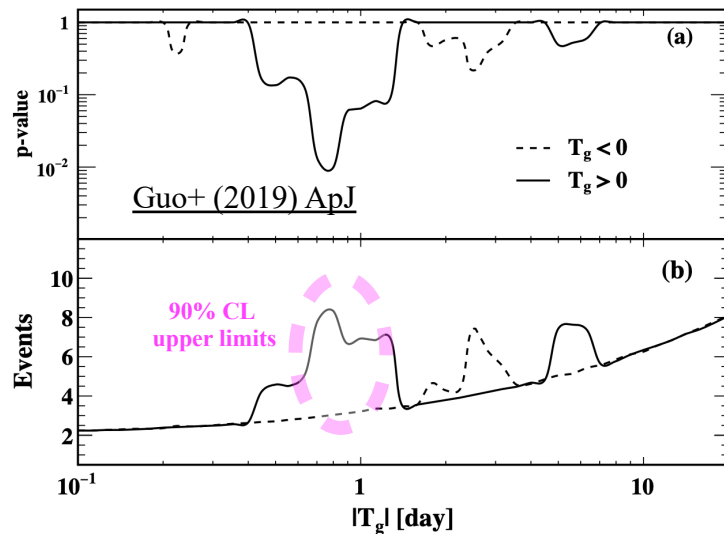
Shocks induced by relativistic jets are promising sites for proton acceleration



Are stellar explosions still interesting sources ???

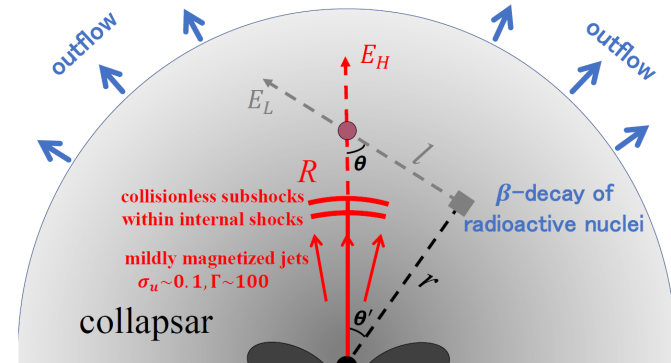
high-energy neutrinos ν s gamma-ray bursts

HE neutrino from late GRB optical bumps

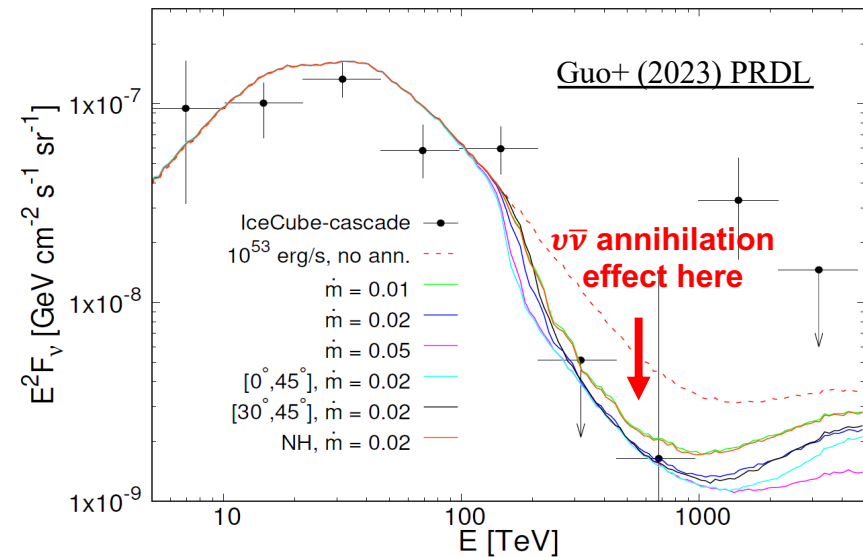


- ❑ Late bumps may contribute $\sim 10\%$ of IceCube events
- ❑ If true, driven by non- or mildly relativistic jets
- ❑ More data are needed to test this scenario

HE neutrino produced inside stars

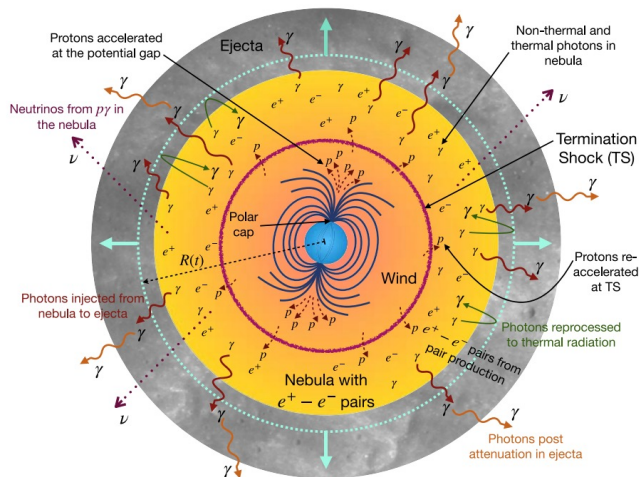


dark or weak in γ -rays, but 'bright' in HE neutrinos
not directly constrained by correlated searches



- ❑ Fast & mildly magnetized jets inside star
- ❑ Annihilation with low-energy neutrinos from β -decay of synthesized r -process
- ❑ Annihilation with thermal neutrinos from accretion disk, Guo+ (2024) PRD

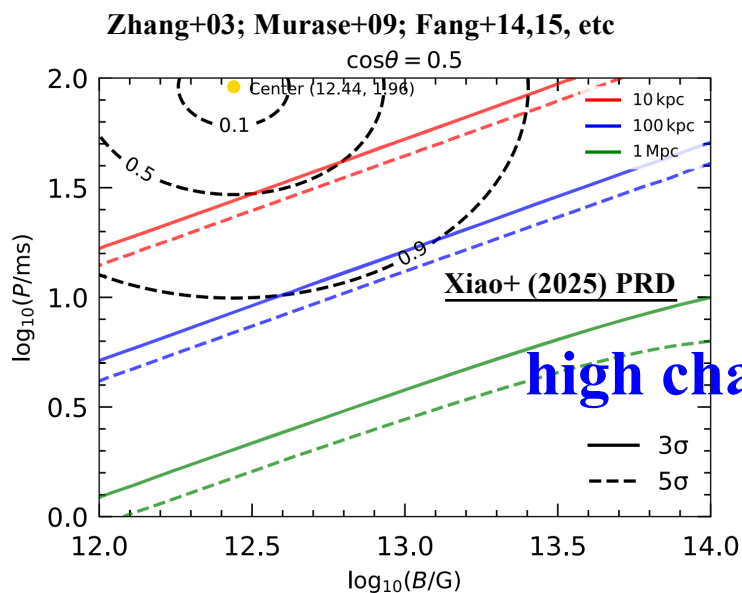
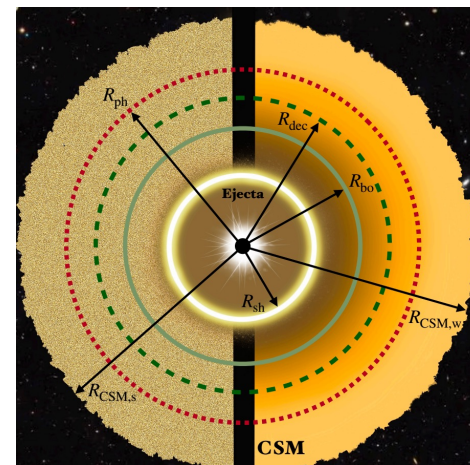
HE neutrinos from regular explosions



newborn pulsars with strong surface B-field (10^{12-14} G)
and rapid rotation (1 – 100 ms)



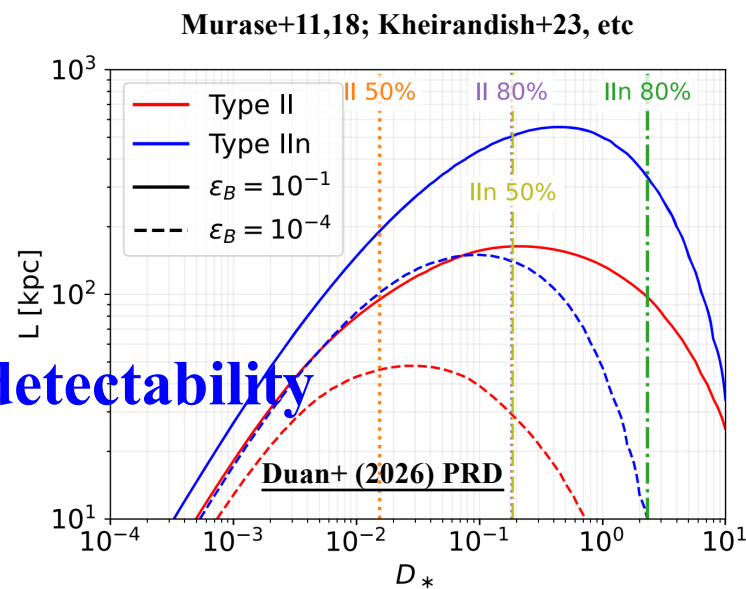
rotating magnetic fields induced electric field
(newborn pulsar scenario)



strong stellar winds prior core-collapse
leads to dense circumstellar material (CSM)



shocks produced from SN ejecta-CSM interaction
(interacting supernova scenario)



Summary & outlook

- Stars are profuse sources of neutrinos; **pre-SN neutrinos** from nearby sources within 1-2 kpc are detectable at JUNO.
- Neutrino rates can significantly affect the SN dynamics and explodability, and potential the resulting neutrino signals; more accurate theoretical calculations of the nuclear medium effects are demanding (using ab initio methods with **chiral EFT interactions**).
- Gamma-ray bursts with low luminosity, or at late emission phase, could still contribute to the observed IceCube events; **dense LE neutrinos** (from hot NS, accretion disks, and β -decay of heavy nuclei) in GRBs & CCSNe may affect the emerging HE neutrino spectra and the flavor content.
- HE neutrinos are detectable from future **galactic newborn pulsars** and **the interacting SNe** (ejecta + dense CSM), providing probes of their physical conditions and properties.
- BSM physics can be well probed in stellar evolution and explosion.