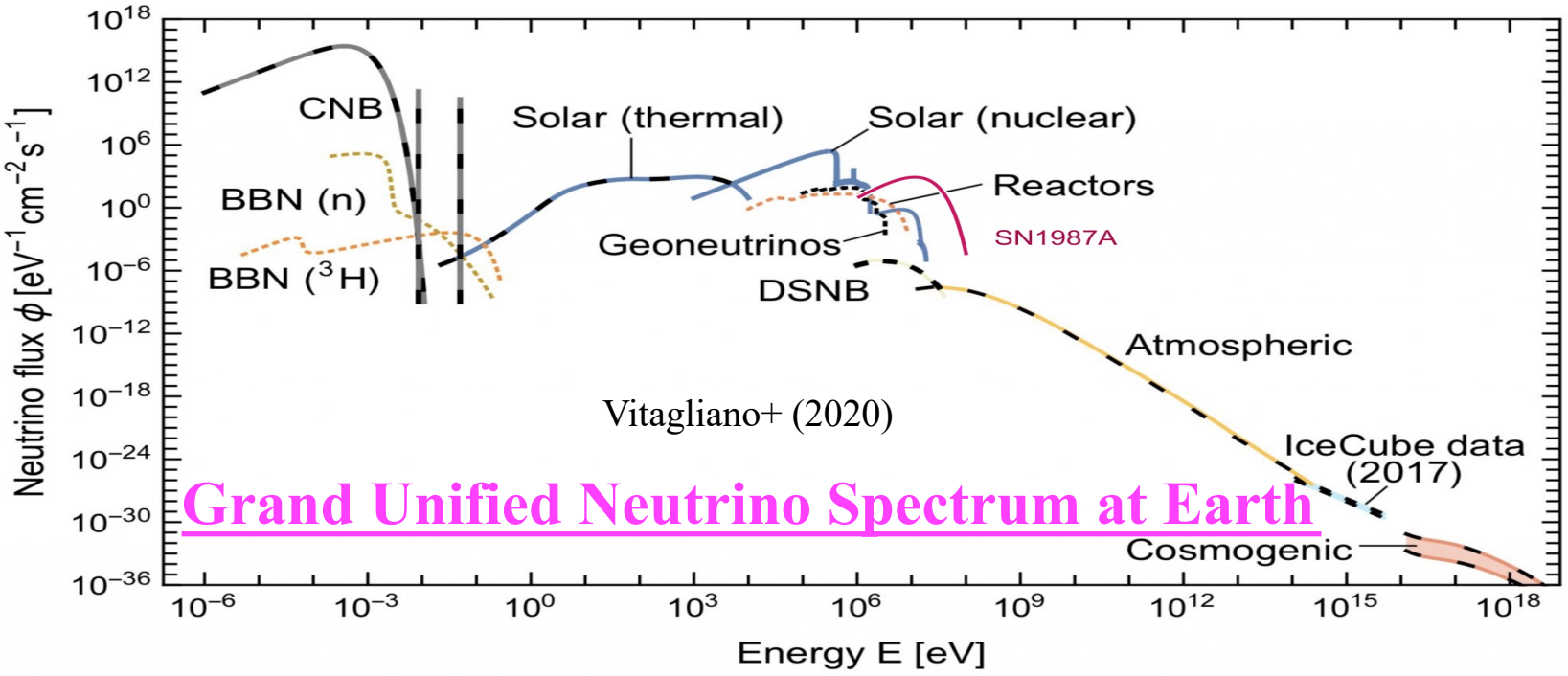
Neutrinos in Stellar Evolution and Explosions

An overview from microphysics to neutrino signatures

Gang Guo
China University of Geosciences (Wuhan)

Origin of Elements & Cosmic Evolution 2026,
Nov. 5-6, 2026, Beijing

Major collaborators: Yong-Zhong Qian, Gabriel Martinez-Pinedo, Meng-Ru Wu, Tobias Fischer



Vitagliano+ (2020)

Grand Unified Neutrino Spectrum at Earth

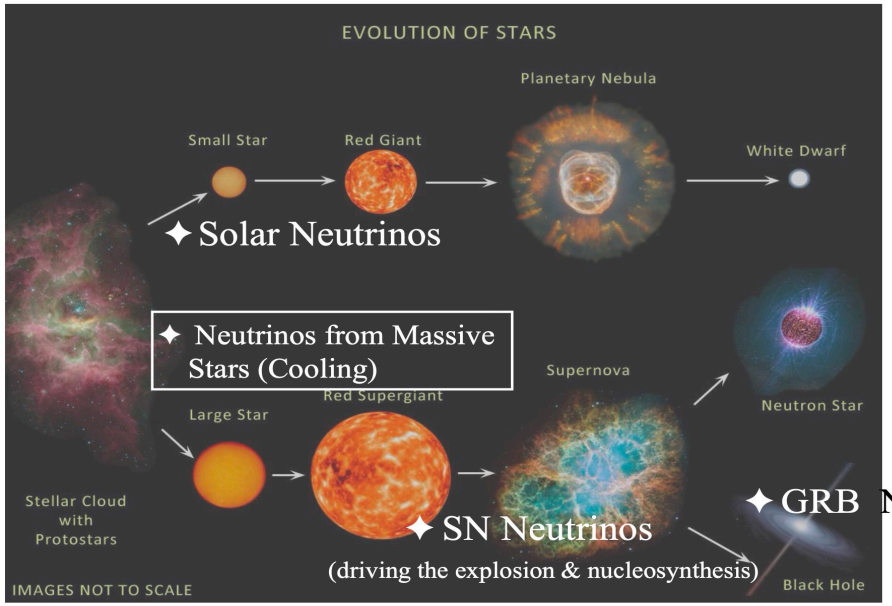
Three topics in this talk

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



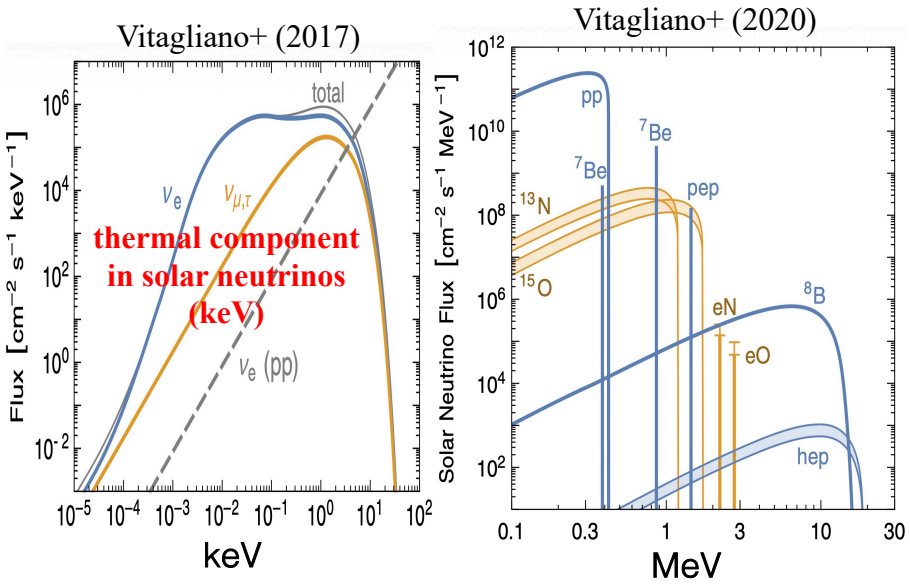
Supernova (SN)

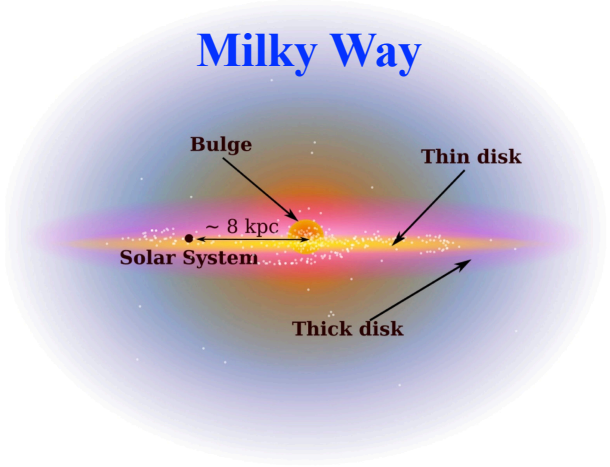
gamma-ray burst (GRB)

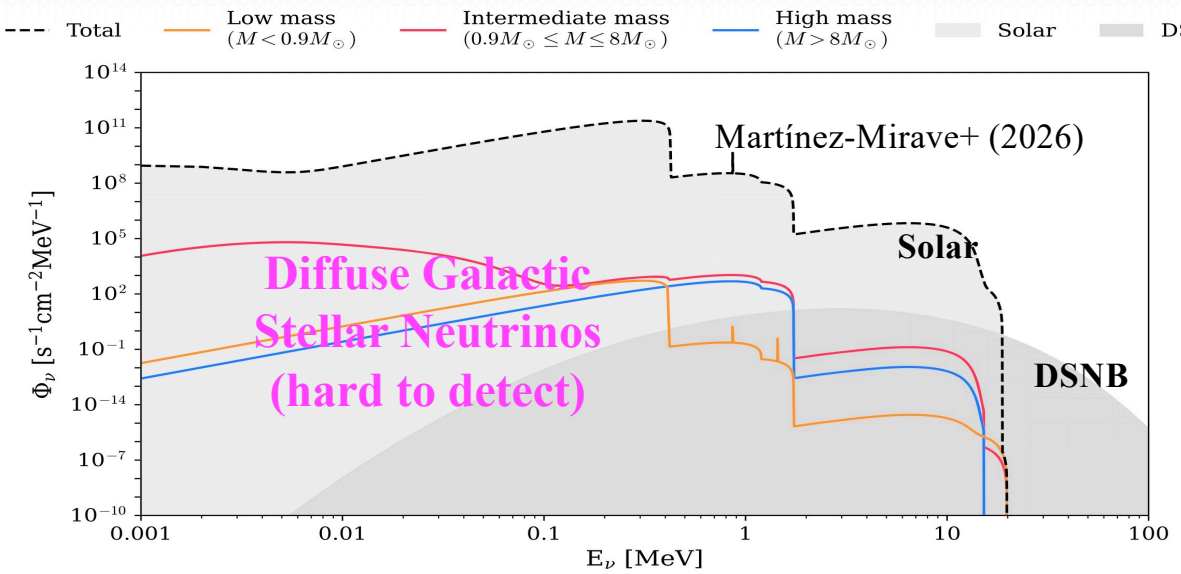
neutrino emission in stars

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

Solar neutrinos

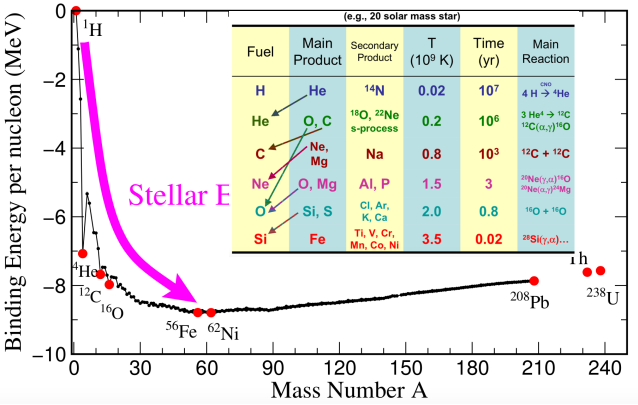




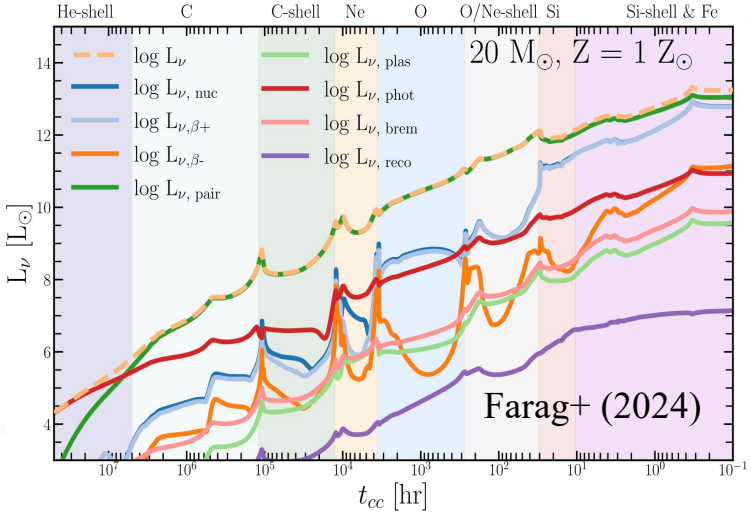


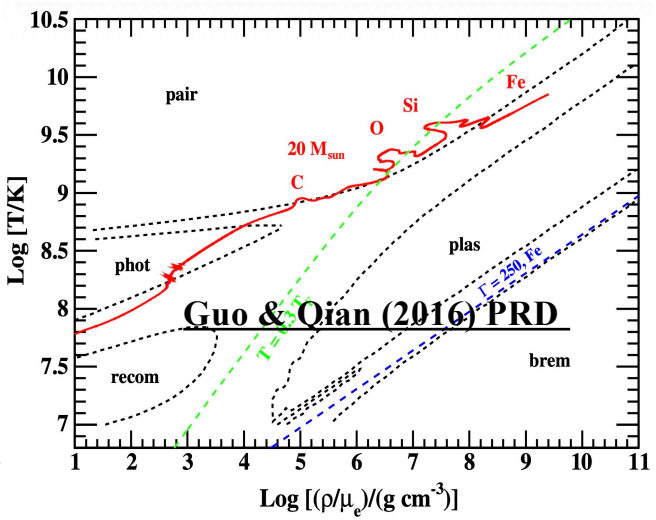
Steady stellar neutrinos, apart from solar nuclear neutrinos, remain beyond the reach of current detectors !

neutrinos during late stages of massive stars ($\gtrsim 10 M_\odot$)



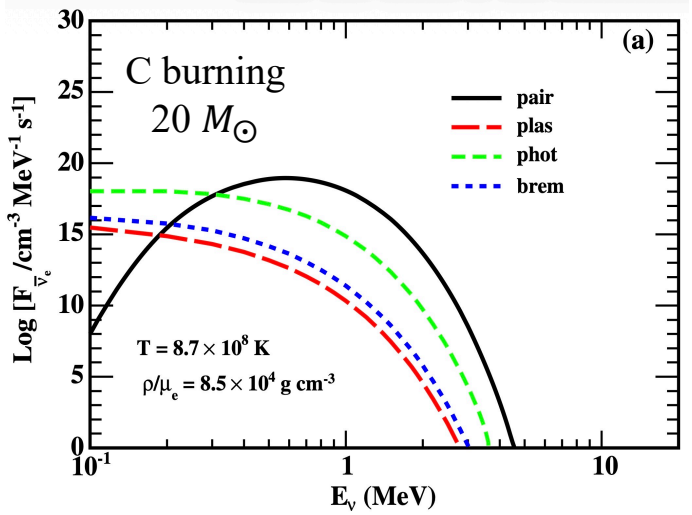
photon star → neutrino star
after core C burning

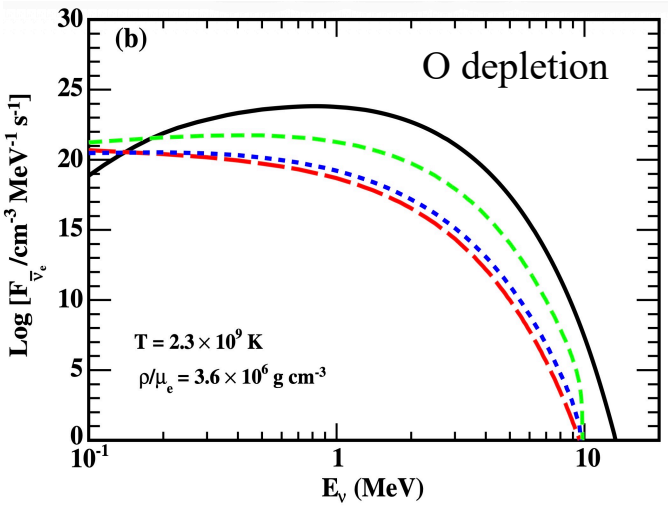


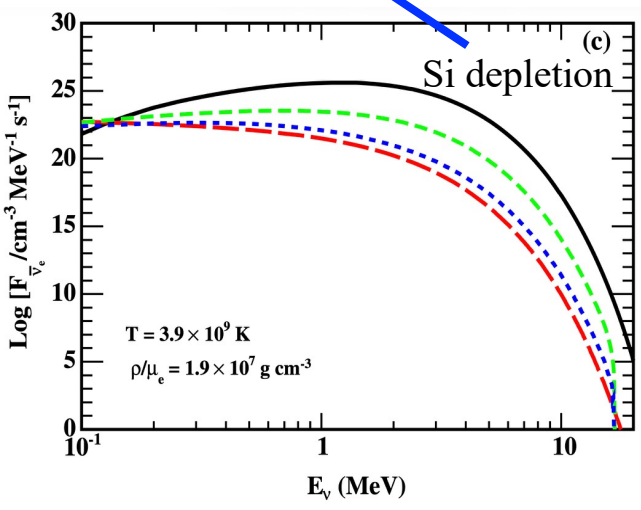


$e^\pm$ pair annihilation dominating

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

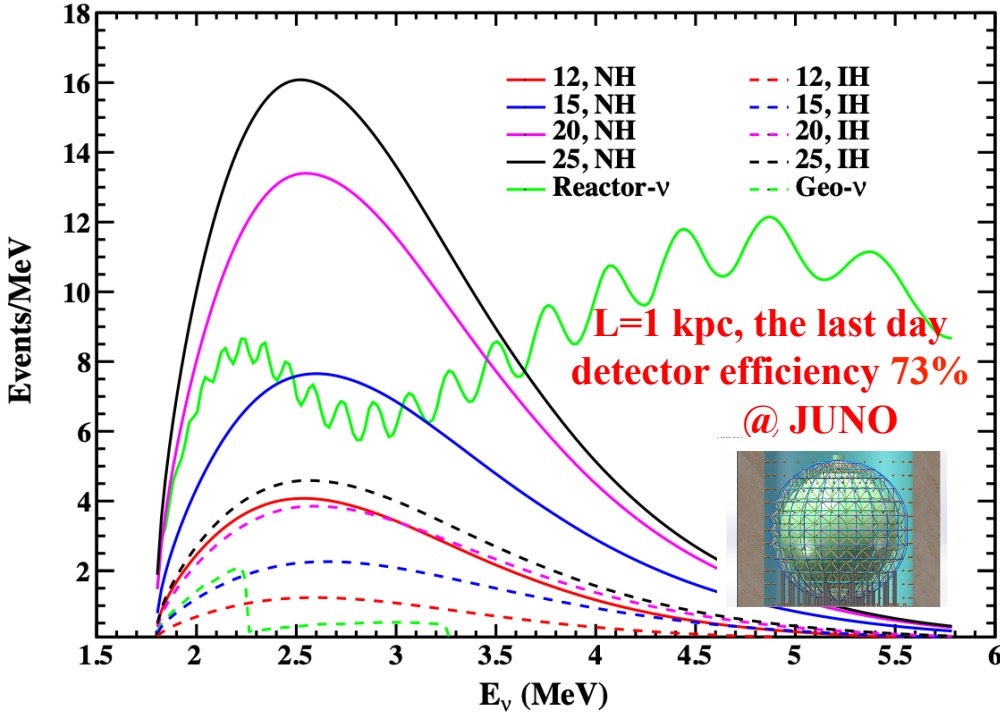


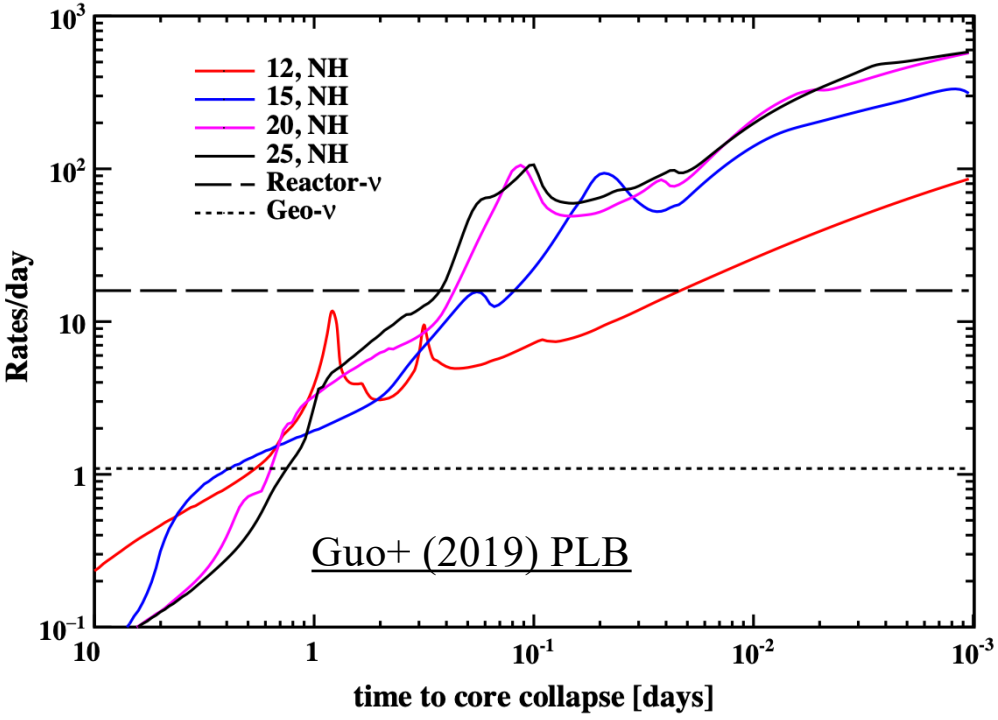




Guo & Qian (2016) PRD

Pre-SN neutrino events expected at JUNO





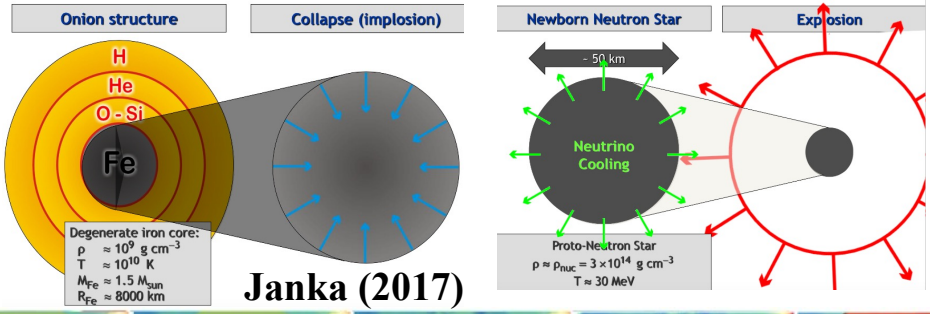
~6.2, 12.3, 21.0 and 25.0 IBD events for normal hierarchy;
~16 and 1 background events from reactor and geo-neutrinos.

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

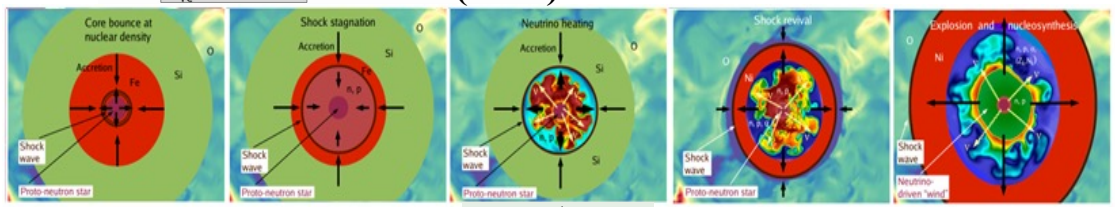
Potential lessons from future pre-SN neutrino observations, see Kato+ (2020)

- **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



Janka (2017)



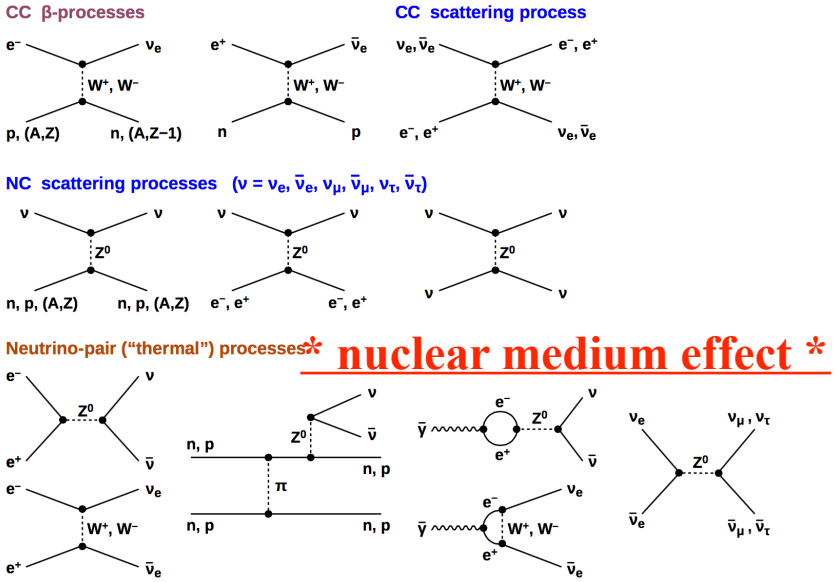
core-collapse & bounce shock | **shock stagnation** | **shock revival** | **explosion**

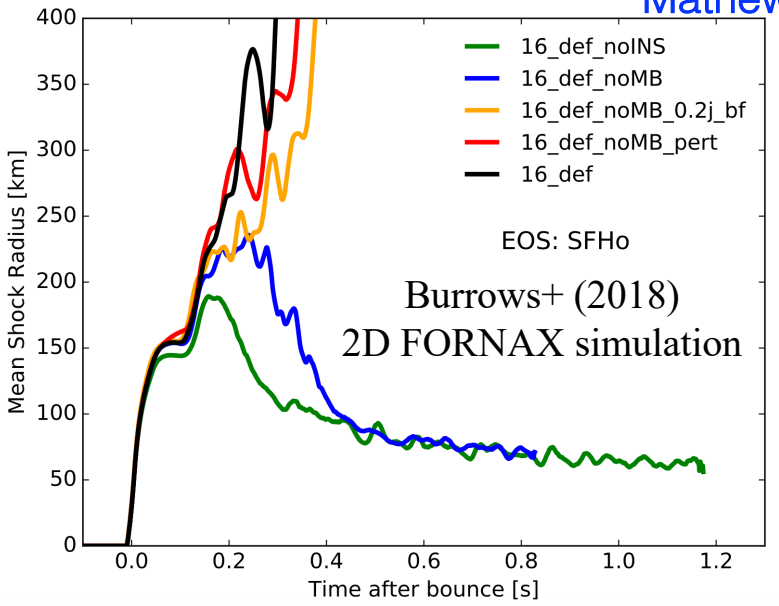
$\nu_e + n \rightleftarrows p + e^-$

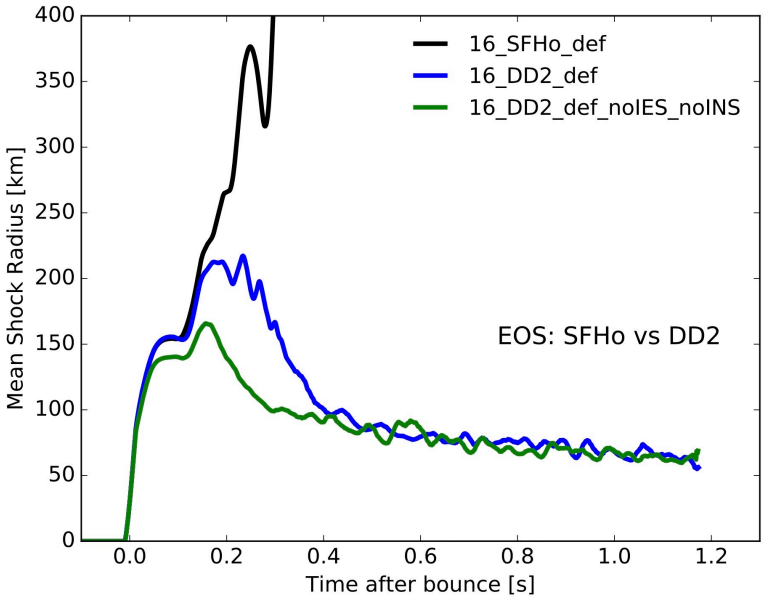
$\bar{\nu}_e + p \rightleftarrows n + e^+$

neutrino heating

See also Grant Mathews's talk







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

Theoretical calculation of neutrino-nucleon rates

See Zidu Lin's talk

Neutrino-nucleon scattering or absorption rates at mean field level

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

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

Depending on EoS

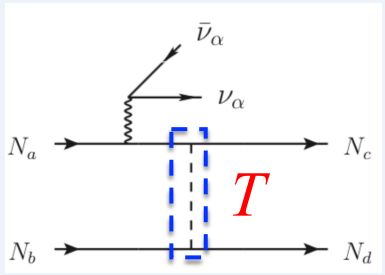
$$\bar{\psi}_4 \left\{ \gamma^\mu [G_V(q^2) - G_A(q^2)\gamma^5] + \frac{iF_2(q^2)}{2M_N}\sigma^{\mu\nu}q^*_\nu - \frac{G_P(q^2)}{M_N}\gamma^5 q^{*\mu} \right\} \psi_2$$

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 from the chiral effective field theory potential**

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

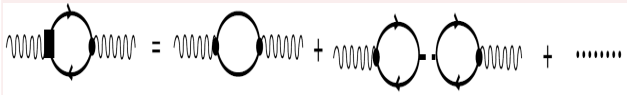
Generally minor effects on SN dynamics & neutrino signals

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

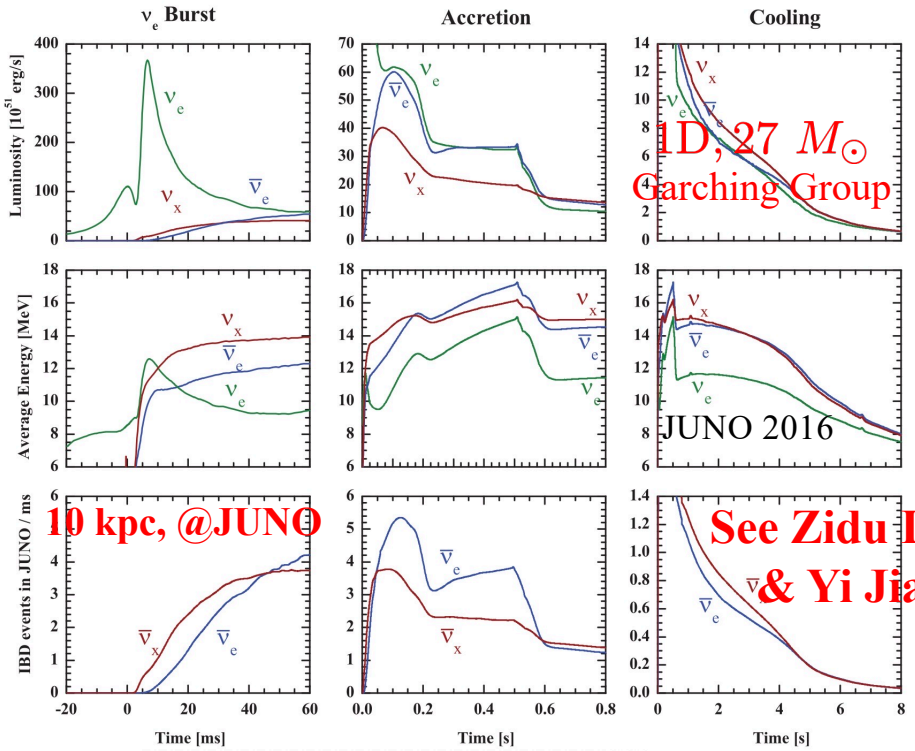


- Virial expansion, Horowitz+ (2006, 2017); Bedaque+ (2018)
- Statistical approach, Guo+ (2024) PRC
- Unitary gas approximation, Lin+ (2017)
- Lattice Formulation, Alexandru+ (2020, 2021); Ma+ (2024) with N3LO
- Molecular dynamics simulation
  Horowitz+ (2004), Li+ (2017)

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

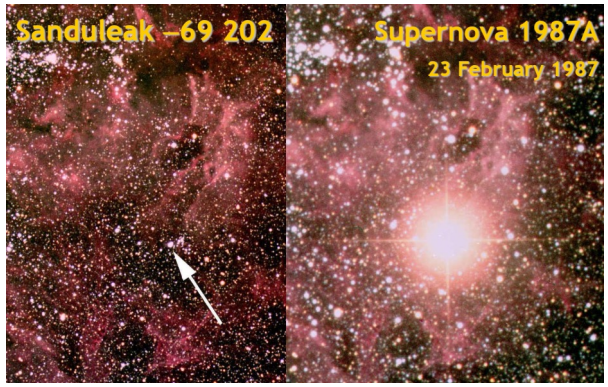


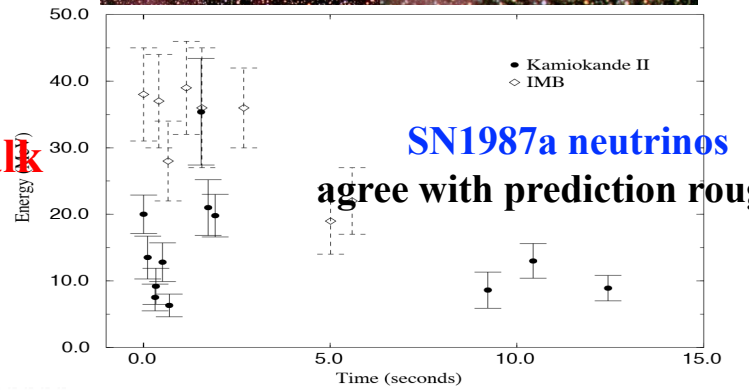
1D, 27 $M_\odot$
Garching Group

JUNO 2016

10 kpc, @JUNO

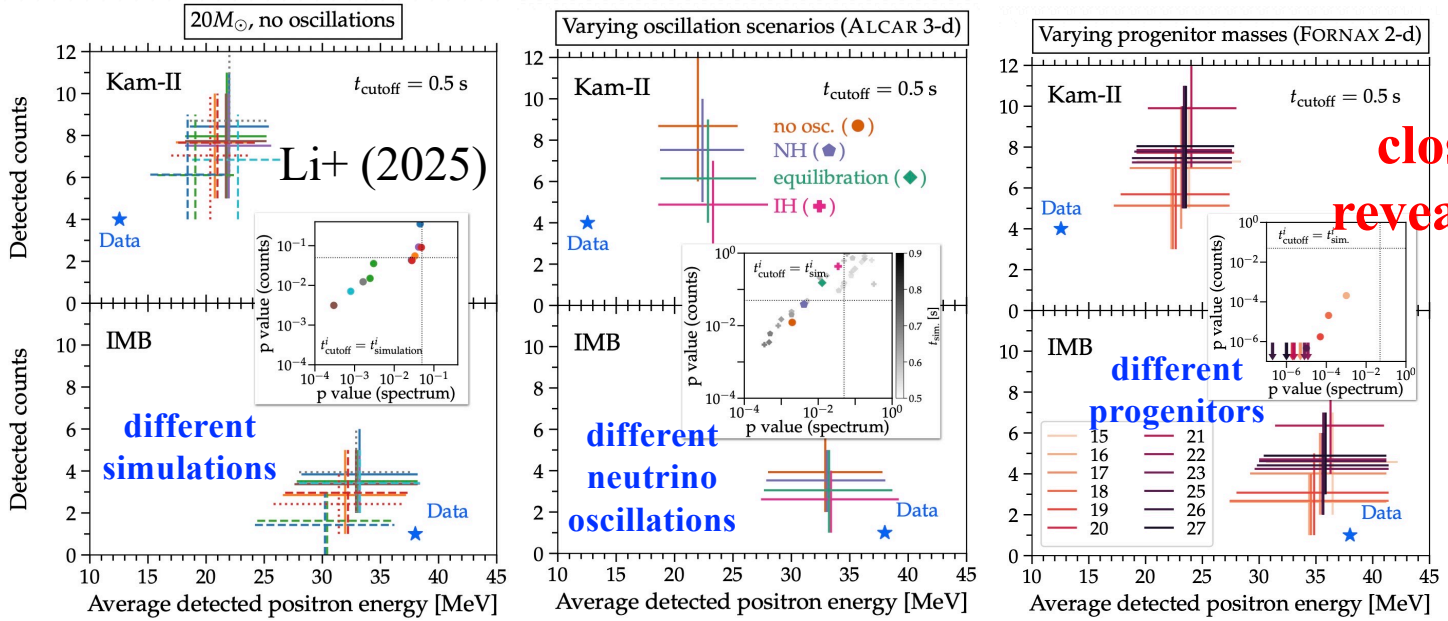
See Zidu Lin's talk
& Yi Jia's talk



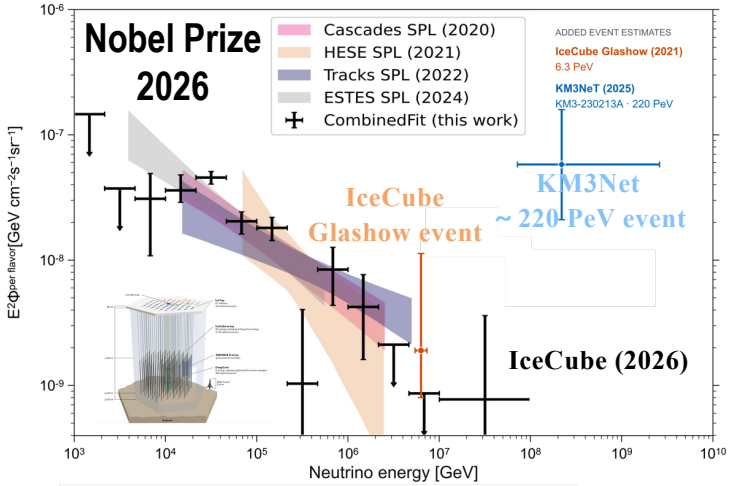


SN1987a neutrinos agree with prediction roughly

closer inspection reveals some tension



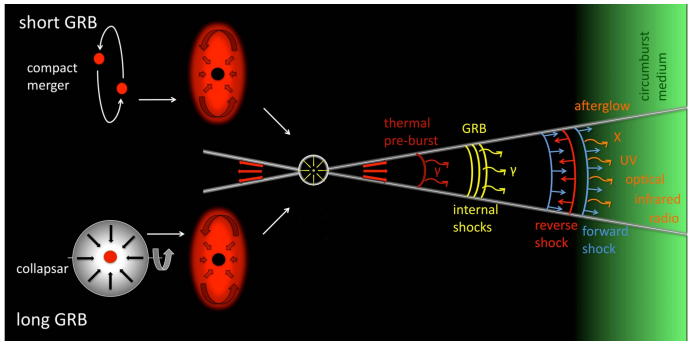
high-energy neutrinos νs stellar explosions



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



Gamma-ray bursts (GRBs)



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

Shocks induced by relativistic jets are promising sites for proton acceleration

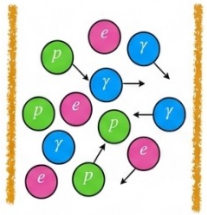
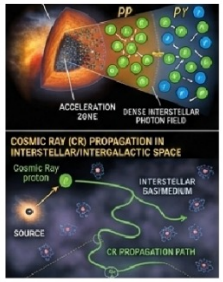


photo-hadronic: $p + \gamma \longrightarrow X + \text{many}(\pi^0 + \pi^+ + \pi^-)$

hadronic: $p + p$



$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu \longrightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$

$\pi^0 \longrightarrow \gamma + \gamma$

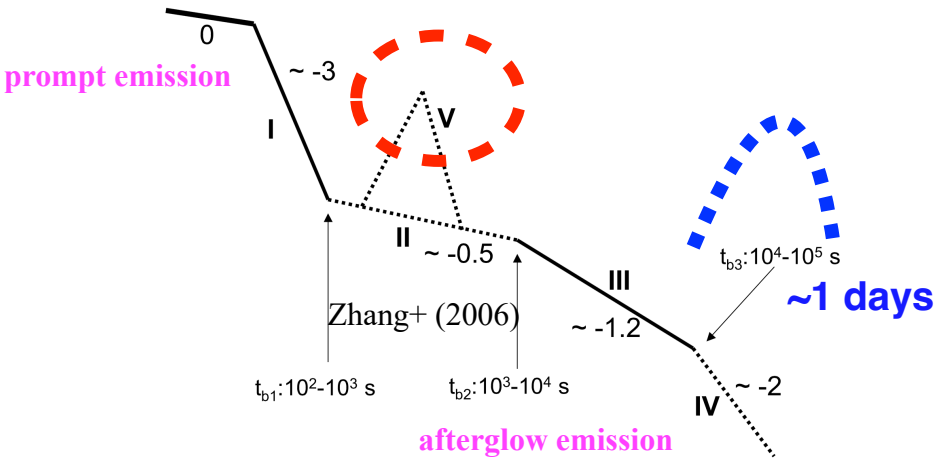
- ✓ AGNs (TXS 0506+056 and NGC 1068) have been identified as HE neutrino sources;
- ✓ The Milky way has emerged as an extended Galactic neutrino source;
- ✓ Tidal disruptive events (TDEs) and other X-ray bright AGNs are shown to be associated with IceCube neutrinos (though not fully confirmed);
- ✓ The origins of most neutrino events, including the KM3NeT 220 PeV event, remain unclear;

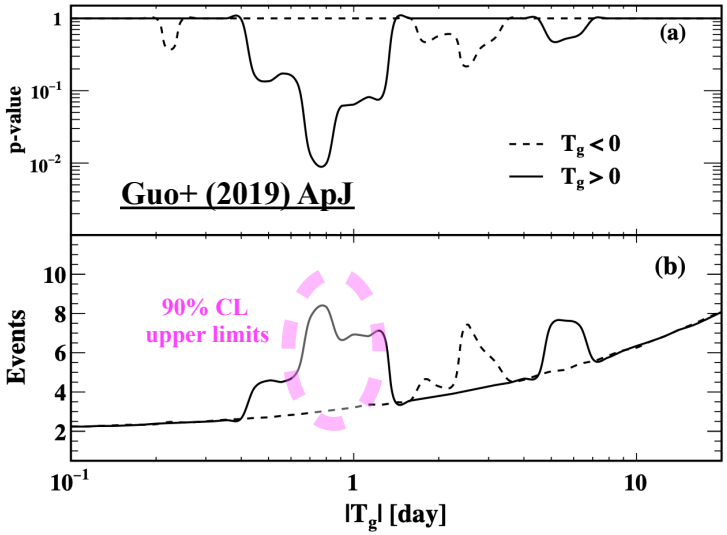
✓ ***Standard GRBs are tightly constrained as HE neutrino sources

Are stellar explosions still interesting sources ???

high-energy neutrinos Vs gamma-ray bursts

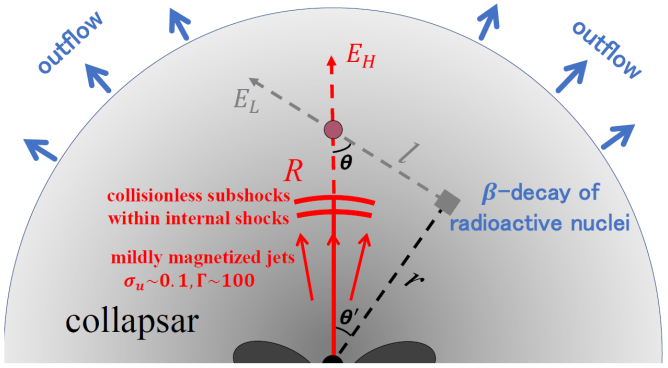
HE neutrino from late GRB optical bumps



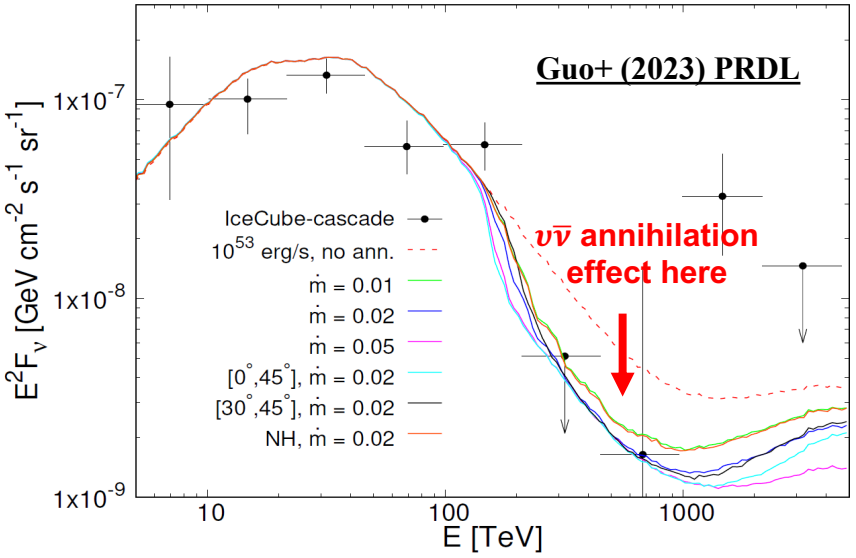


- Late bumps may contribute ~10% of IceCube events
- If true, driven by non- or mildly relativistic jets
- More data are needed to test this scenario

HE neutrino produced inside stars

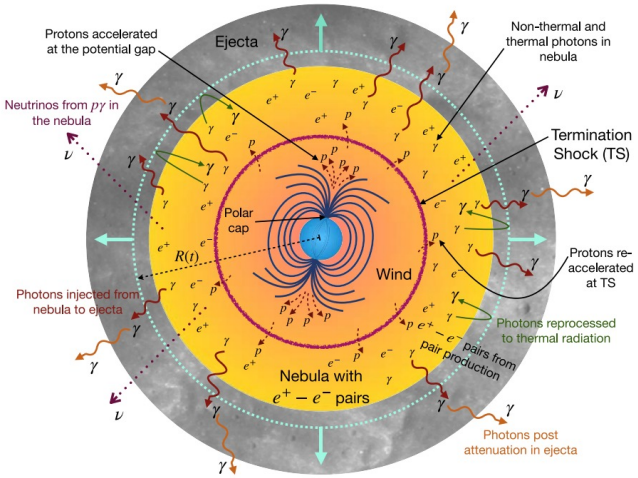


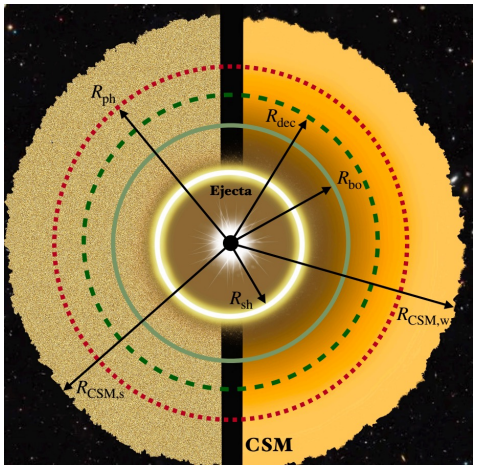
dark or weak in γ-rays, but 'bright' in HE neutrinos
not directly constrained by correlated searches



- 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





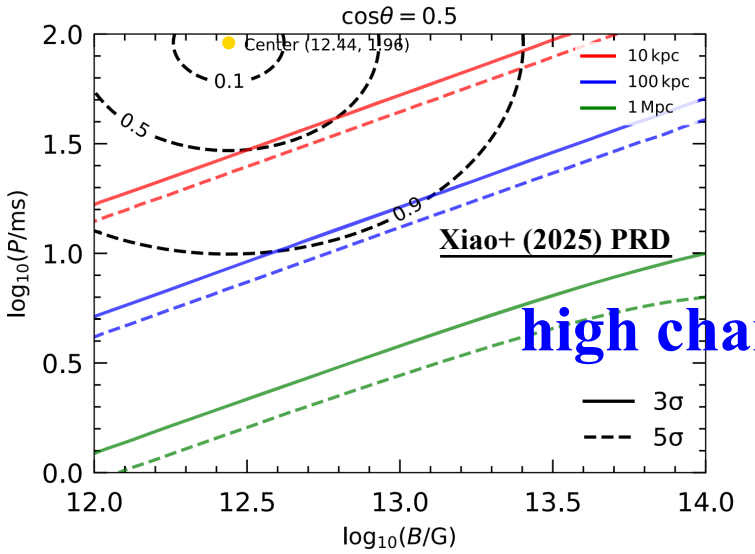
newborn pulsars with strong surface B-field (10^{12-14} G) and rapid rotation ($1-100$ ms)

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

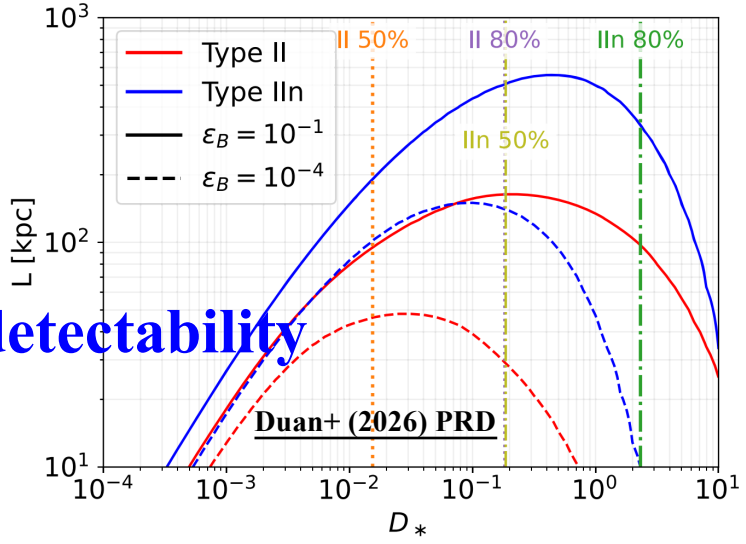
rotating magnetic fields induced electric field
(newborn pulsar scenario)

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

Zhang+03; Murase+09; Fang+14,15, etc



Murase+11,18; Kheirandish+23, etc



high chance of detectability

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 potentially 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.