Presupernova and Supernova Neutrinos

Yong-Zhong Qian
University of Minnesota

32nd Texas Symposium on Relativistic Astrophysics
Shanghai, China
December 11, 2023

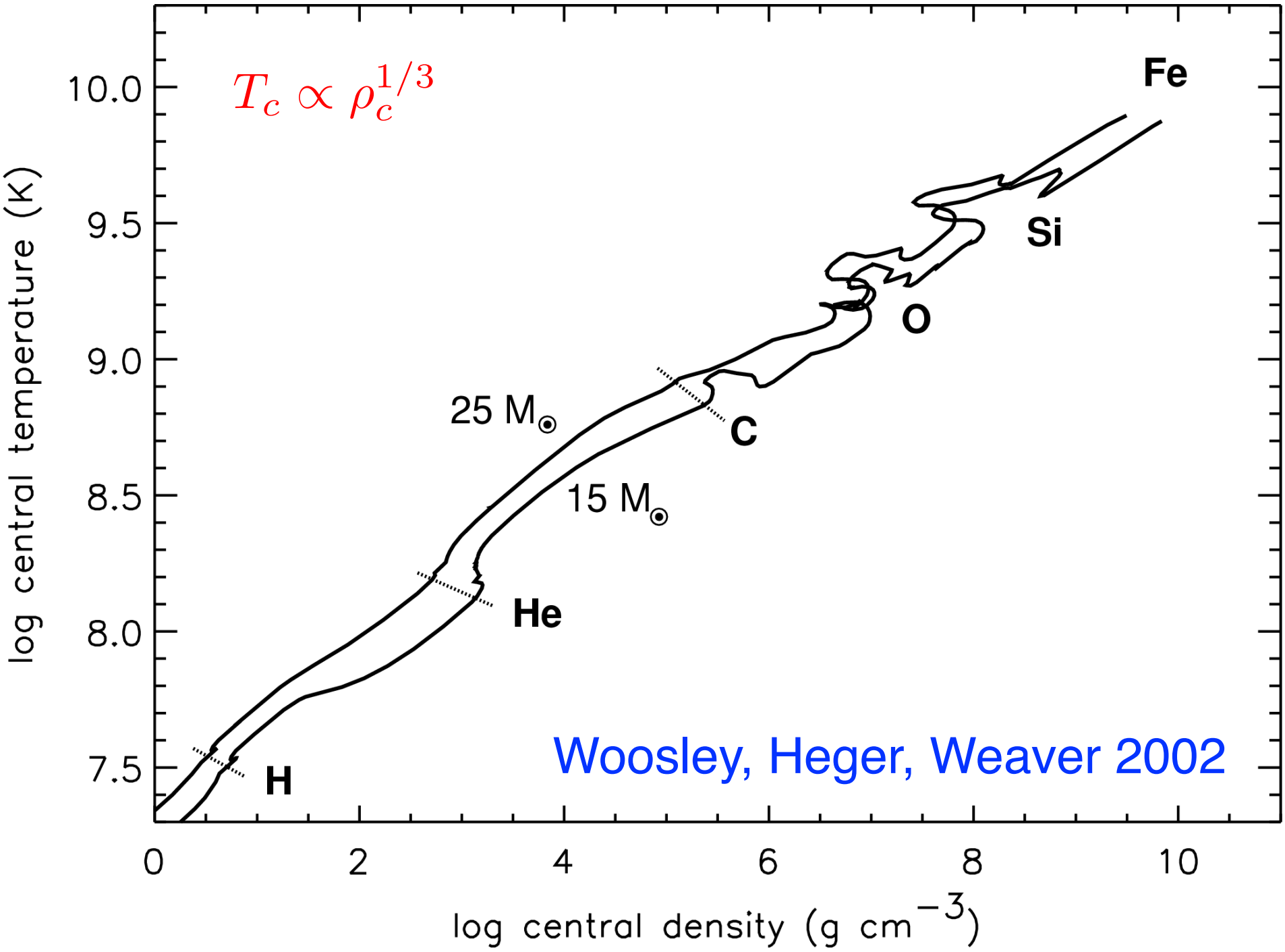
Summary

Pre-SN MeV neutrinos provide advance warning for nearby SNe within ~1 day & may tell neutrino mass ordering

Next Galactic SN will induce ~10^4 events of ~10 MeV neutrinos in terrestrial detectors & provide diagnostics of SN processes

Collapsars could be a source for r-process nuclei and high-energy neutrinos of ~100 TeV

Annihilation of HE neutrinos by LE antineutrinos from decay of r-process nuclei leaves distinct signatures on the spectrum and flavor composition of HE neutrinos, which can be tested by precise measurements at IceCube-Gen2

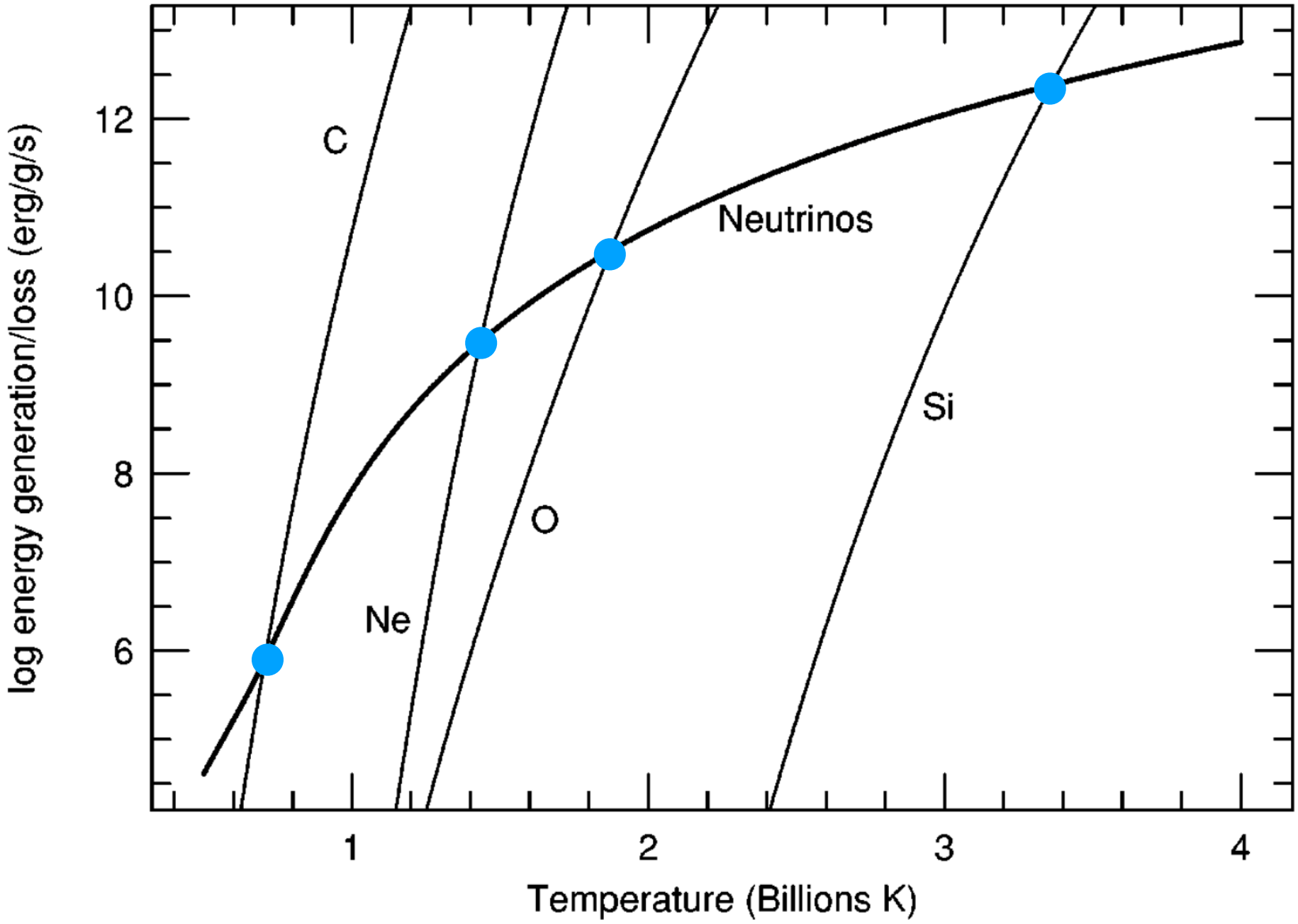

$T_c \propto \rho_c^{1/3}$
Fe
Si
O
C
He
H
25 M⊙
15 M⊙
Woosley, Heger, Weaver 2002
log central temperature (K)
log central density (g cm^{-3})
10.0
9.5
9.0
8.5
8.0
7.5
0
2
4
6
8
10

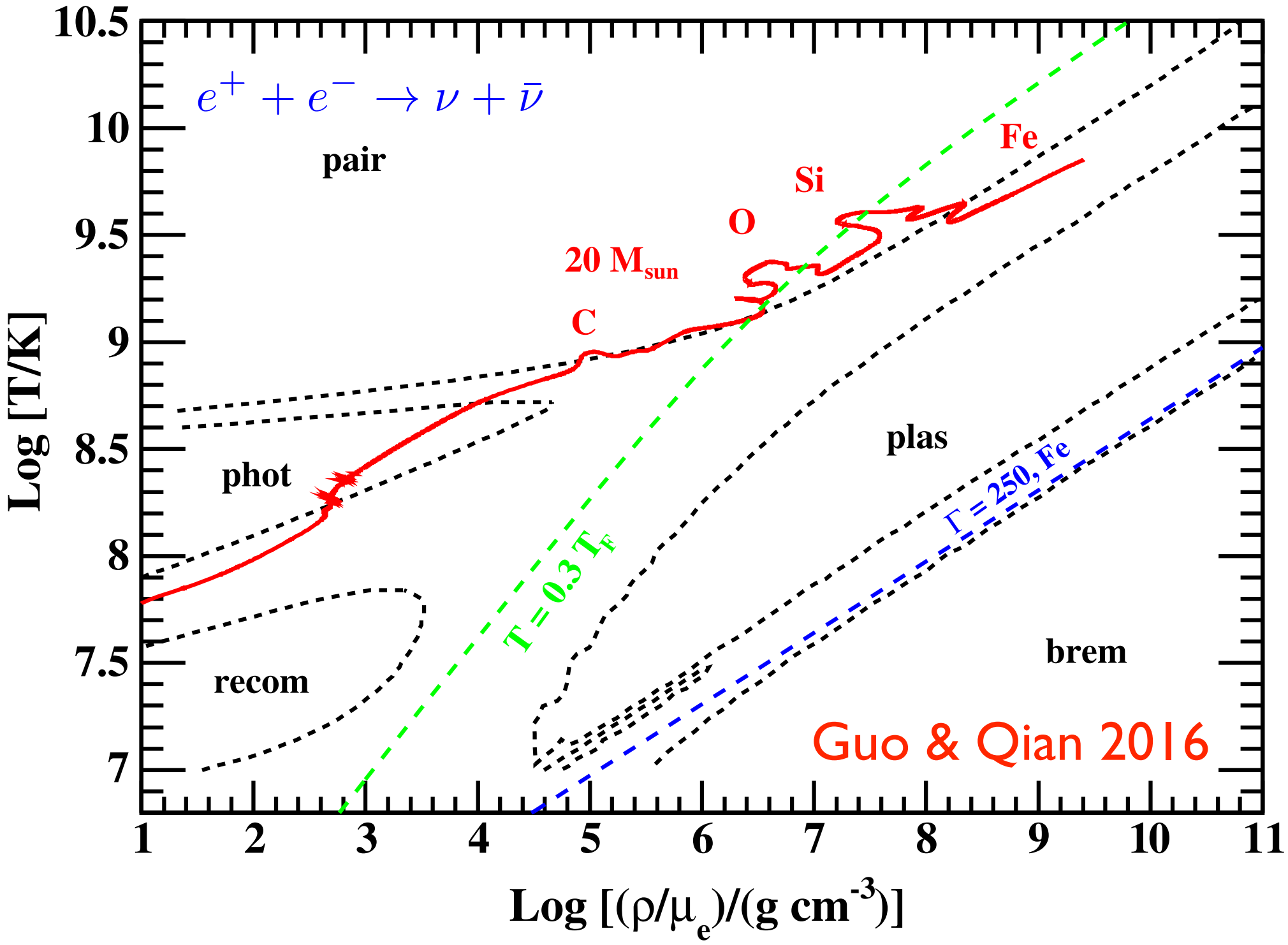
Nuclear burning stages

(20 $M_\odot$ stars)

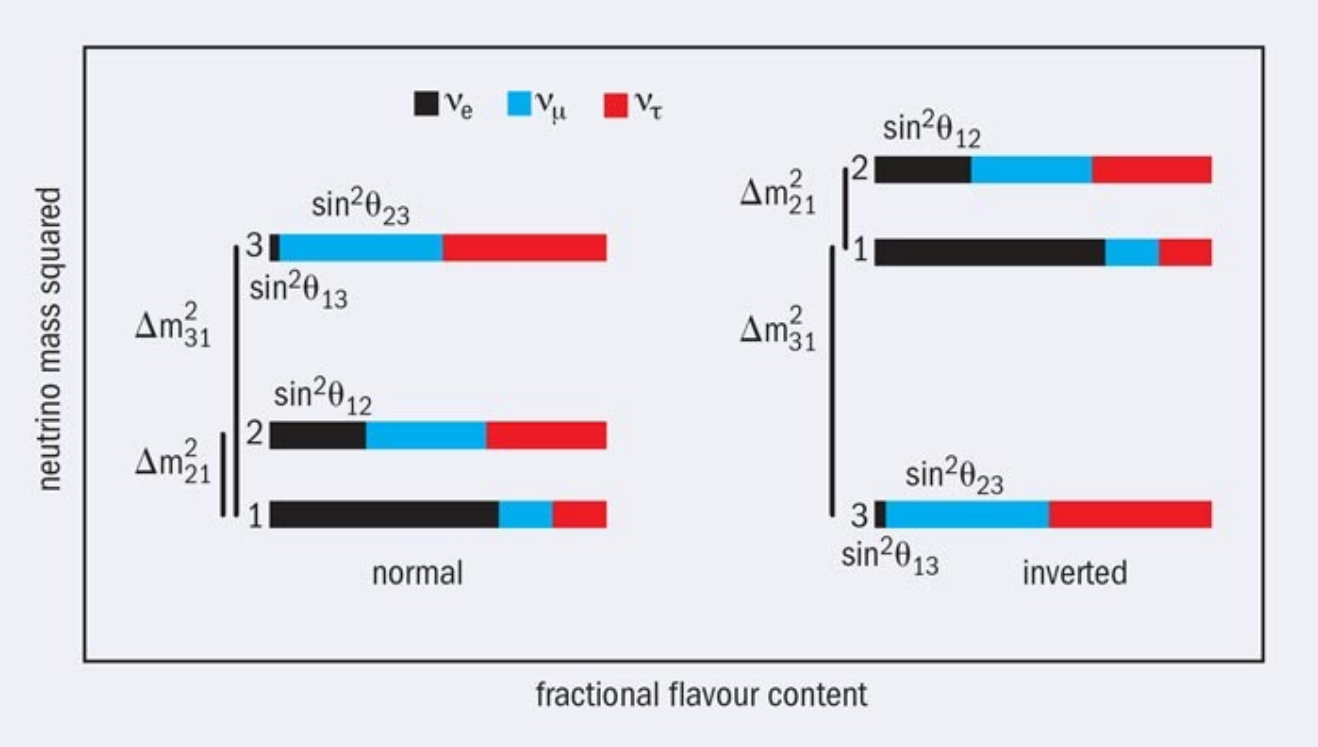
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$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

Energy Generation vs. Loss




$e^+ + e^- \rightarrow \nu + \bar{\nu}$
pair
phot
recom
plas
brem
20 M_{sun}
C
O
Si
Fe
$T = 0.3\ T_F$
$\Gamma = 250$, Fe
Guo & Qian 2016
Log [T/K]
Log [(ρ/μ_e)/(g cm^{-3})]
10.5
10
9.5
9
8.5
8
7.5
7
1
2
3
4
5
6
7
8
9
10
11

matter effect $\Rightarrow \bar{\nu}_e$ is the lightest eigenstate at high density



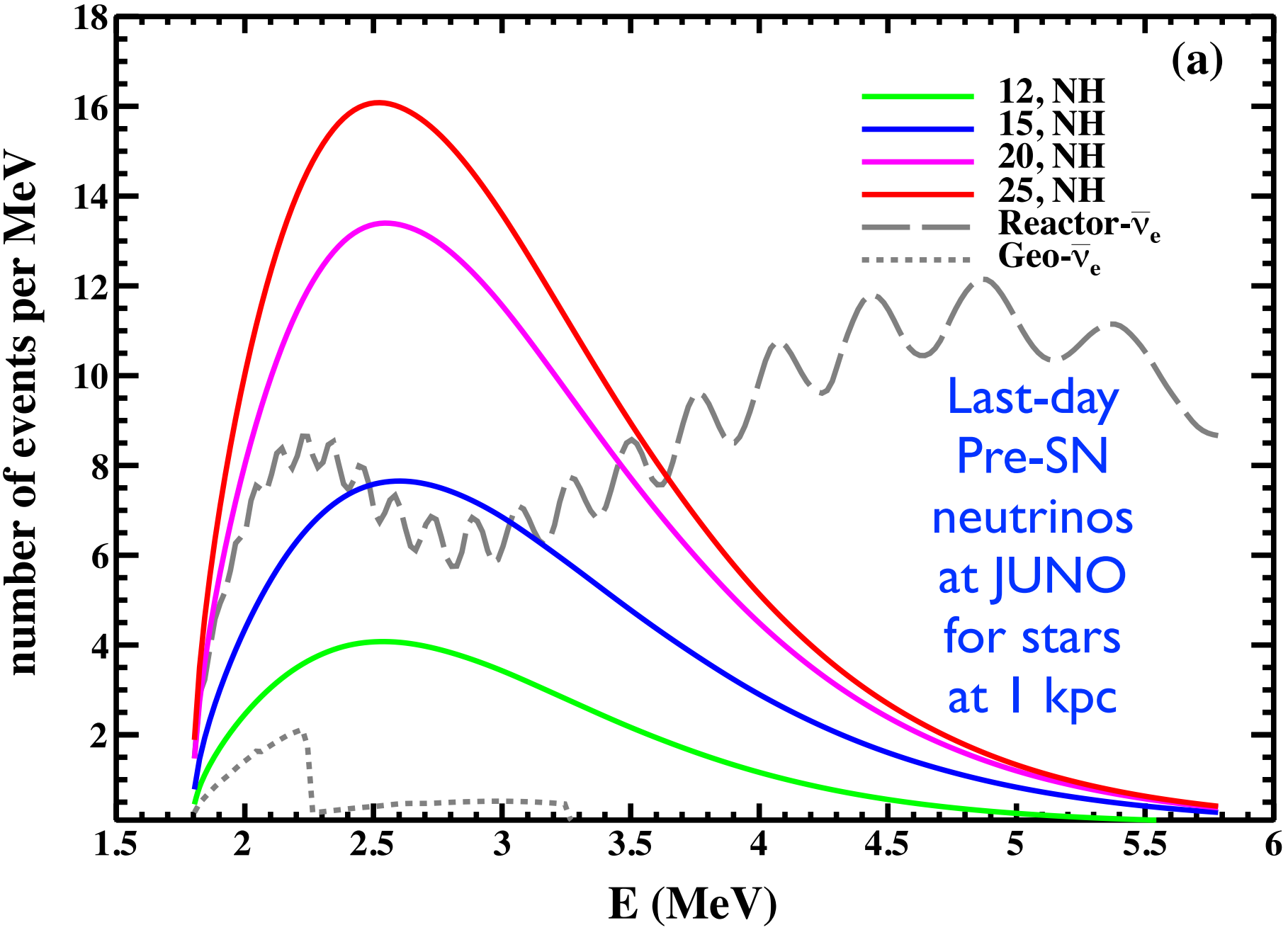
$\bar{P} \approx 0.681$ (NH) vs. 0.022 (IH)

$$F_{\bar{\nu}_e} = \bar{P} F^{(0)}_{\bar{\nu}_e} + (1 - \bar{P}) F^{(0)}_{\bar{\nu}_x}$$

$$F^{(0)}_{\bar{\nu}_x} \approx 0.2 F^{(0)}_{\bar{\nu}_e}$$

$F_{\bar{\nu}_e}/F^{(0)}_{\bar{\nu}_e} \approx 0.74$ (NH) vs. 0.22 (IH)

Guo, Qian, & Heger 2019



What Can Pre-SN Neutrinos Tell Us ?

Advance warning of supernovae

Last-day events of 1.8 to 4 MeV for 1 kpc & 20 kton

$\bar{\nu}_e + p \rightarrow n + e^+$ (IBD @ JUNO)

12 M_{sun}	15 M_{sun}	20 M_{sun}	25 M_{sun}
6.1	12.0	20.5	24.5
1.9	3.6	5.9	7.0

Probe of neutrino mass ordering: NH/IH ~ 3.4

Test of stellar models: progenitor mass

Model-Indepdent Determination (Guo, Qian, & Heger 2019)

Elastic Scattering (ES): $\nu + e \rightarrow \nu + e$

For 0.8 < T_e < 2.5 MeV: $\frac{N_{\rm ES}^{\rm IH}}{N_{\rm ES}^{\rm NH}} \approx 1.23$

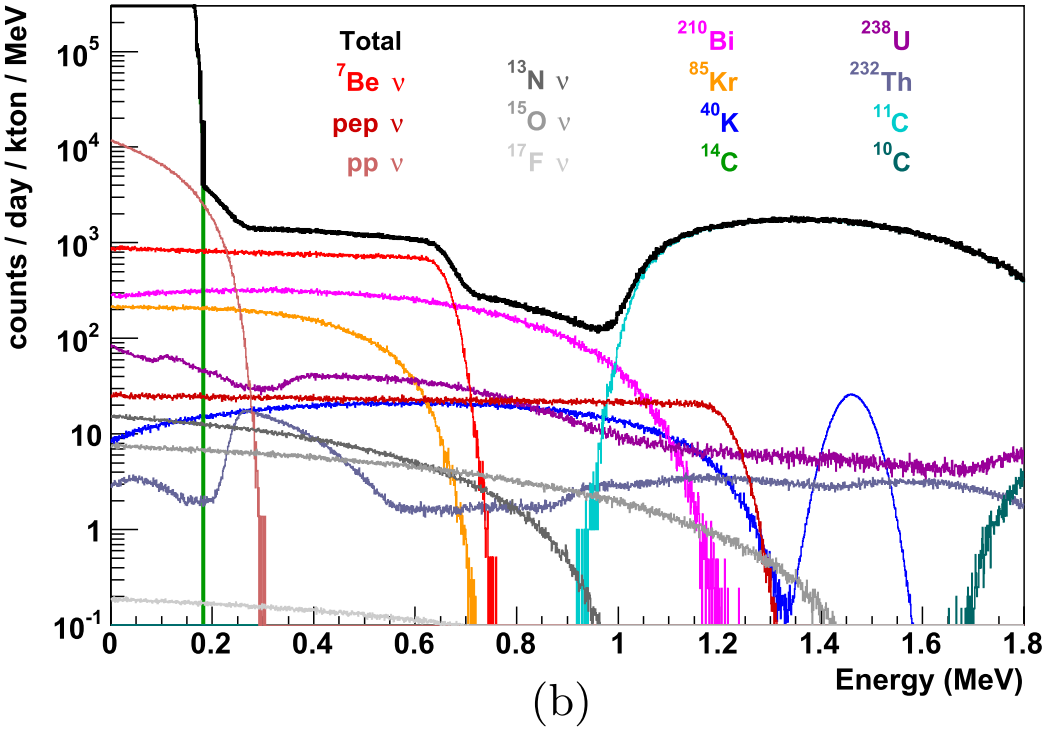
Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow n + e^+$

For 1.8 < E < 4 MeV: $\frac{N_{\rm IBD}^{\rm NH}}{N_{\rm IBD}^{\rm IH}} \approx 3.42$

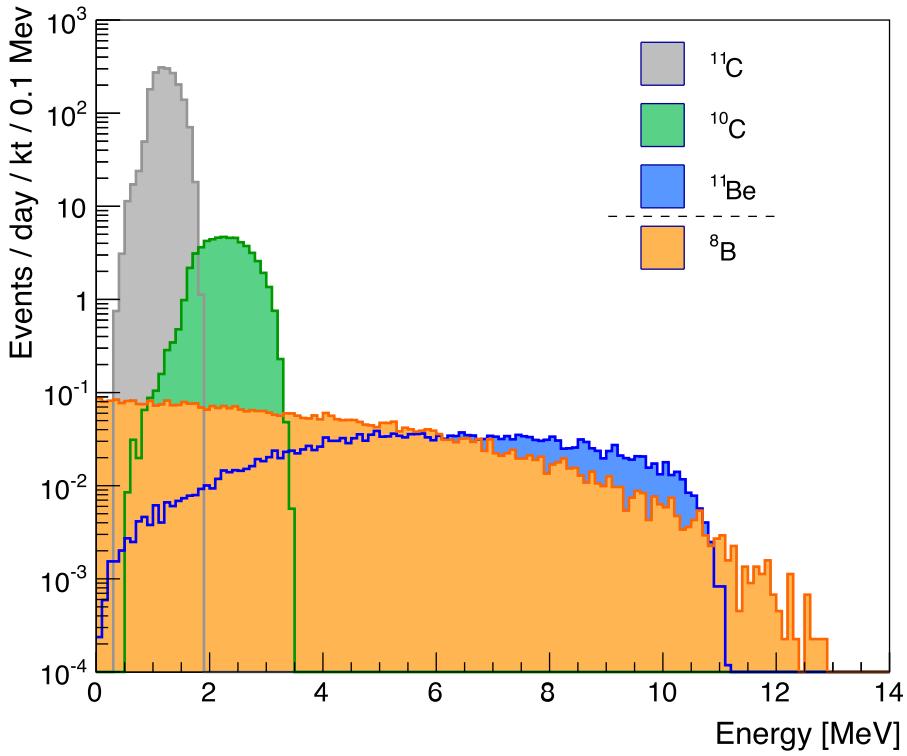
$\boxed{\frac{N_{\rm ES}^{\rm NH}}{N_{\rm IBD}^{\rm NH}} \approx 0.91}$ vs. $\boxed{\frac{N_{\rm ES}^{\rm IH}}{N_{\rm IBD}^{\rm IH}} \approx 3.8}$

Background for ES events

For 0.8 < T_e < 2.5 MeV, cosmogenic background dominates



(b)



signals from Betelgeuse (222 pc): ~100 to 500 during last day

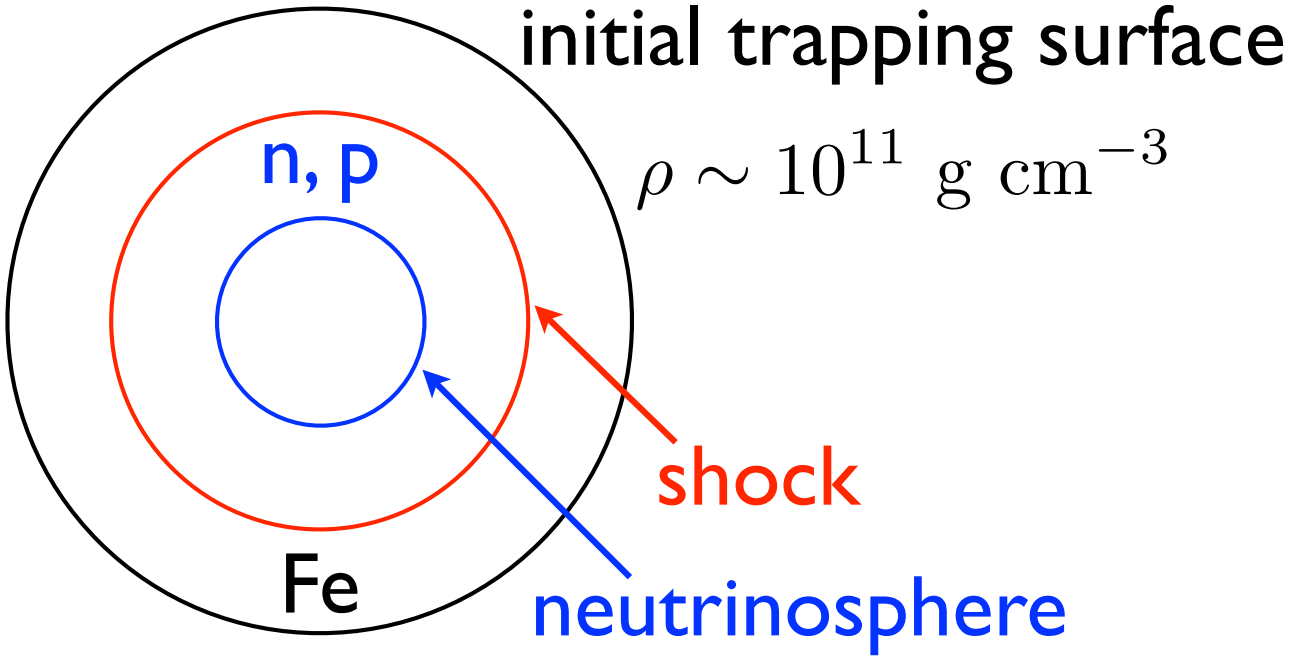
currently-estimated background: ~20000

$$\mu \text{ shower} \Rightarrow {}^{12}\mathrm{C}(\gamma, n)^{11}\mathrm{C}(e^{+}\nu_e)^{11}\mathrm{B}$$

potential background reduction by coincidence!

"neutronization" pulse at shock breakout

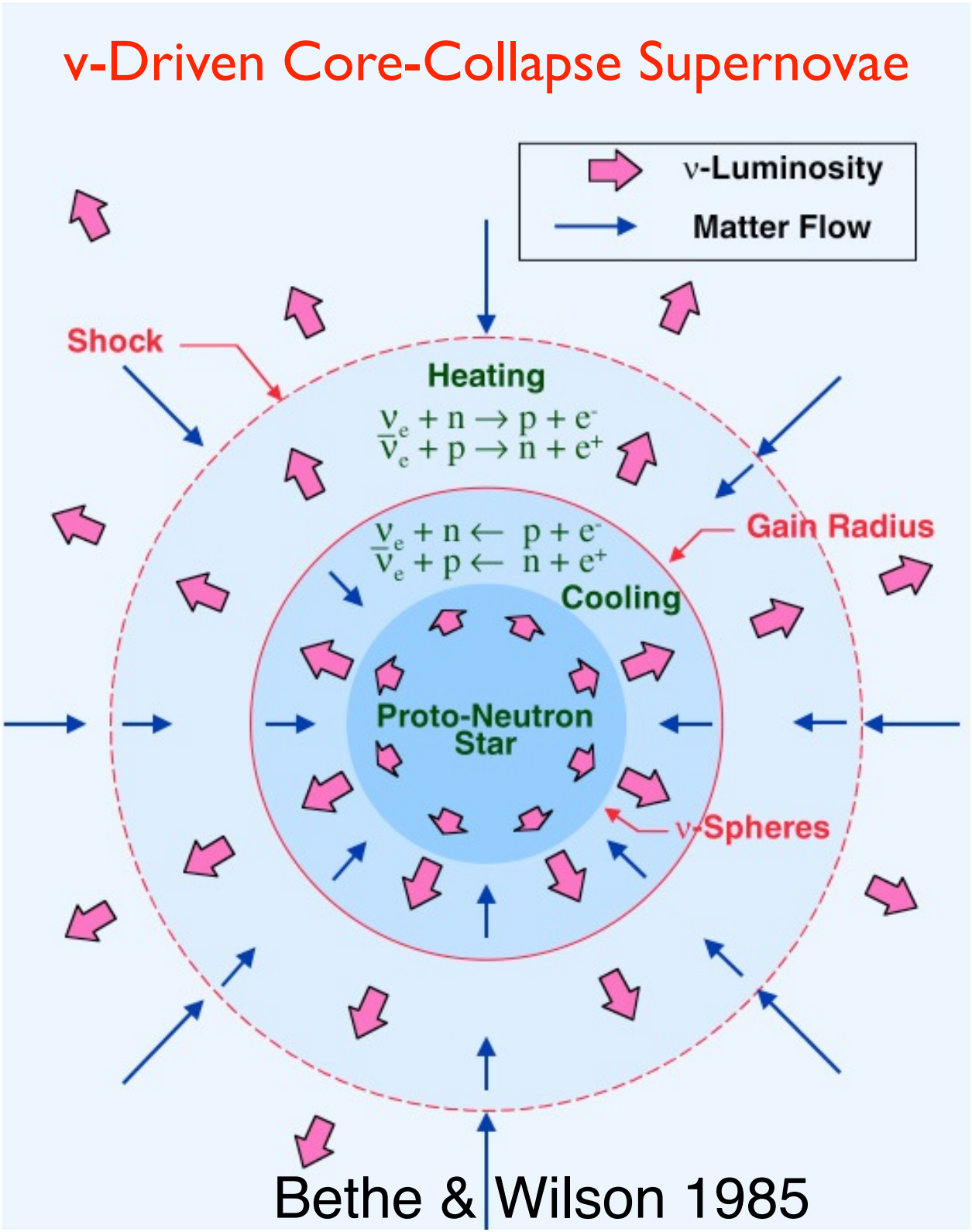
$$e^- + p \rightarrow n + \nu_e \Rightarrow \text{predominantly } \nu_e$$



DUNE $\quad \nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

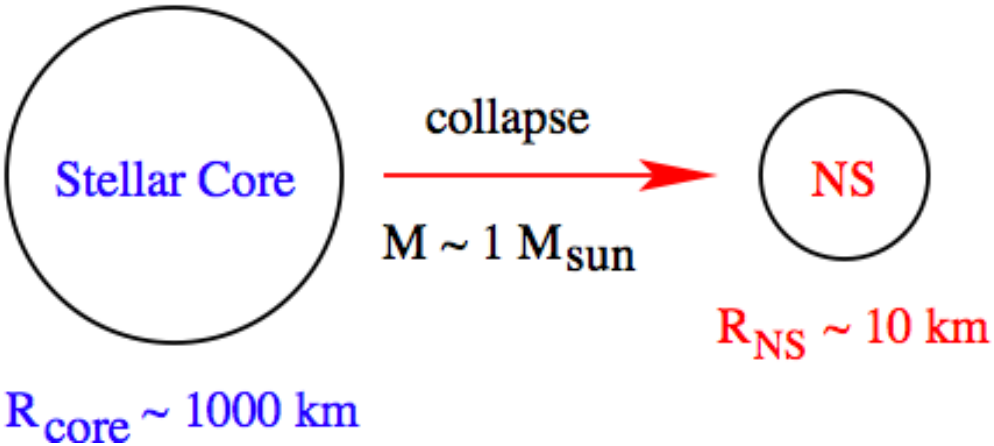
event rate sensitive to neutrino mass ordering

ν-Driven Core-Collapse Supernovae



Bethe & Wilson 1985

Neutrino Emission from NS Formation



$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$

$$N + N \rightarrow N + N + \nu + \bar{\nu}$$

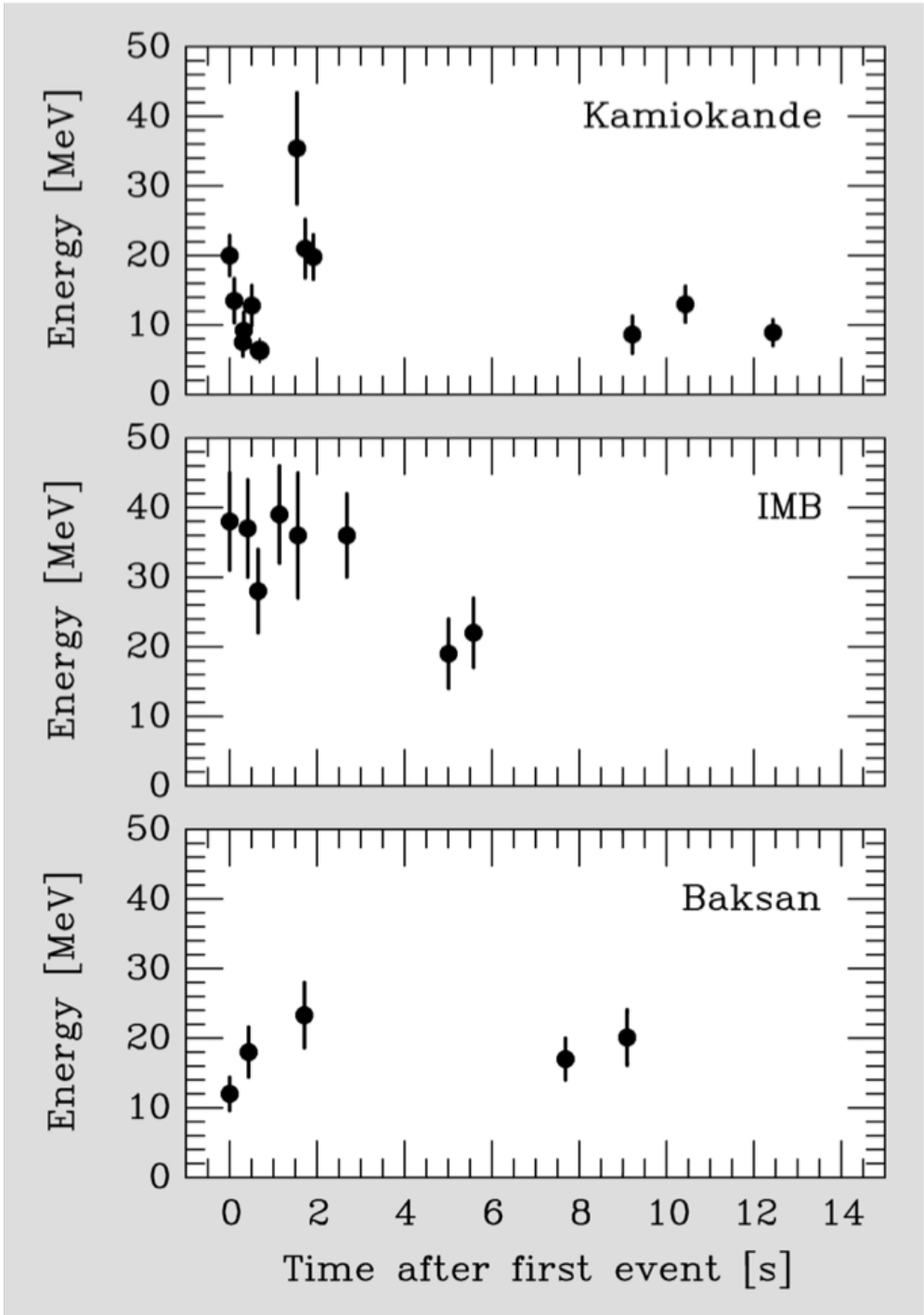
$$\frac{GM^2}{R_{\rm NS}} \sim 3 \times 10^{53}\ {\rm erg}$$

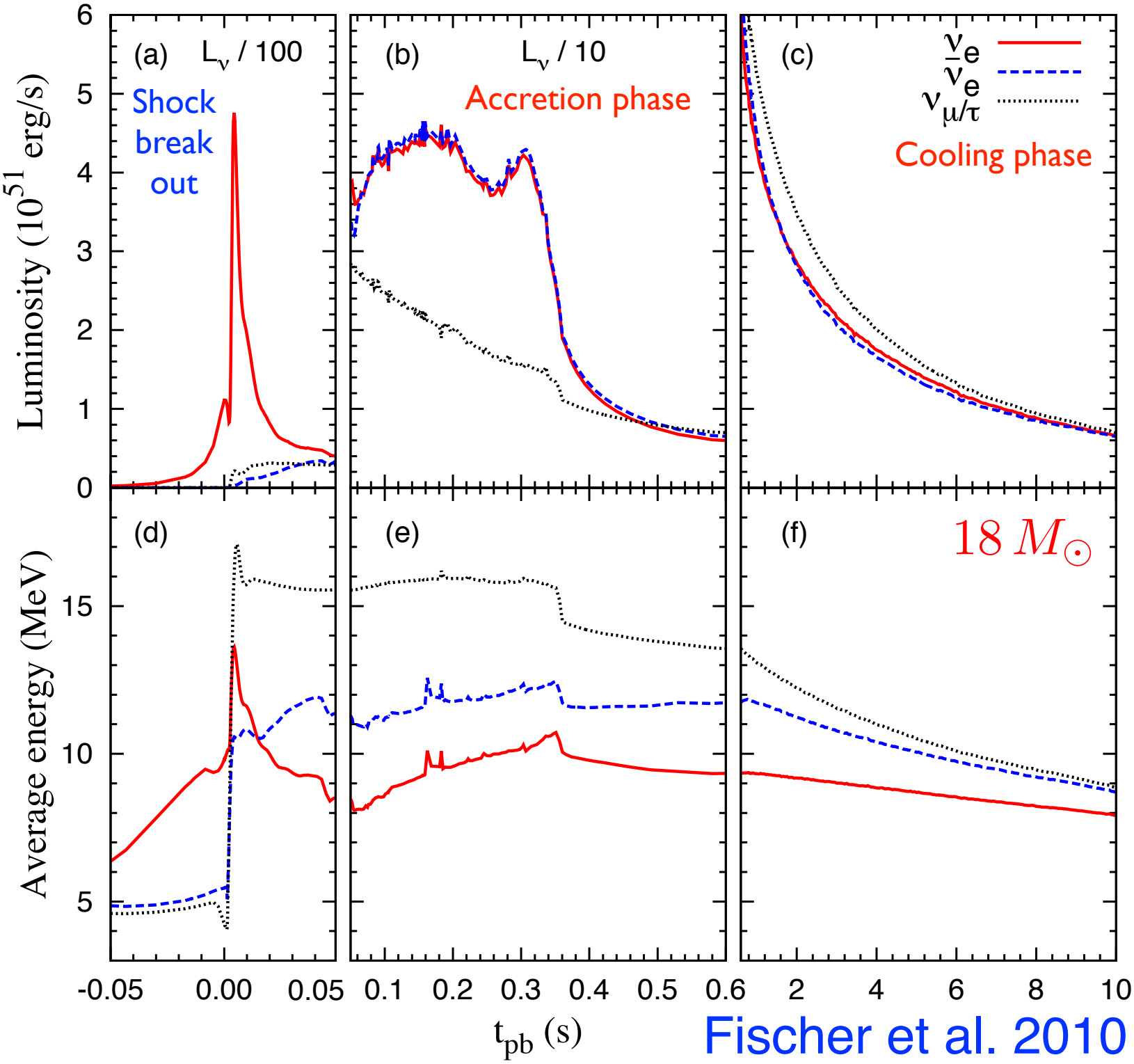
$$\Rightarrow \nu_e,\ \bar{\nu}_e,\ \nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau,\ \bar{\nu}_\tau$$

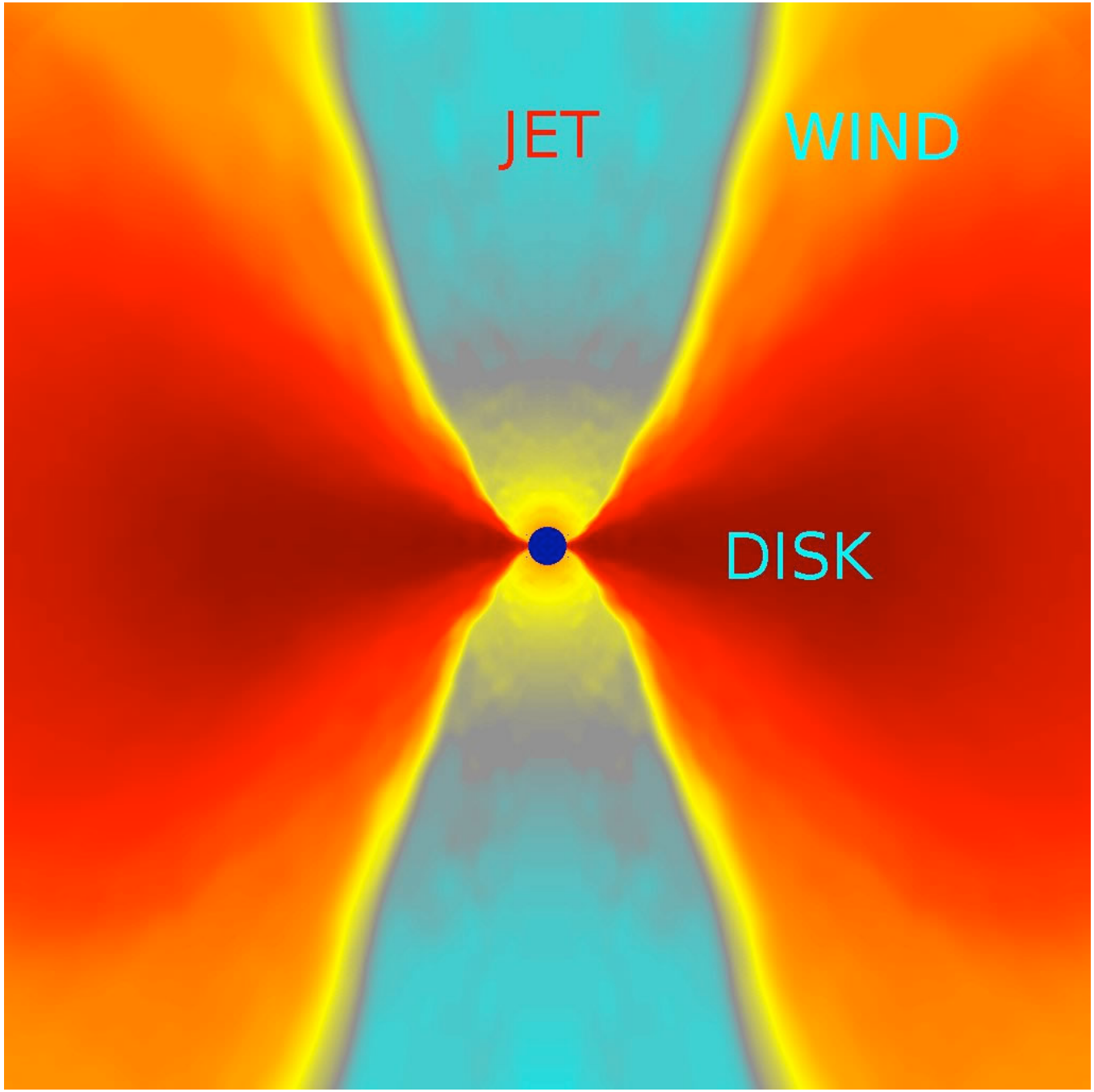
for a Galactic SN at ~10 kpc

~10^4 events due to

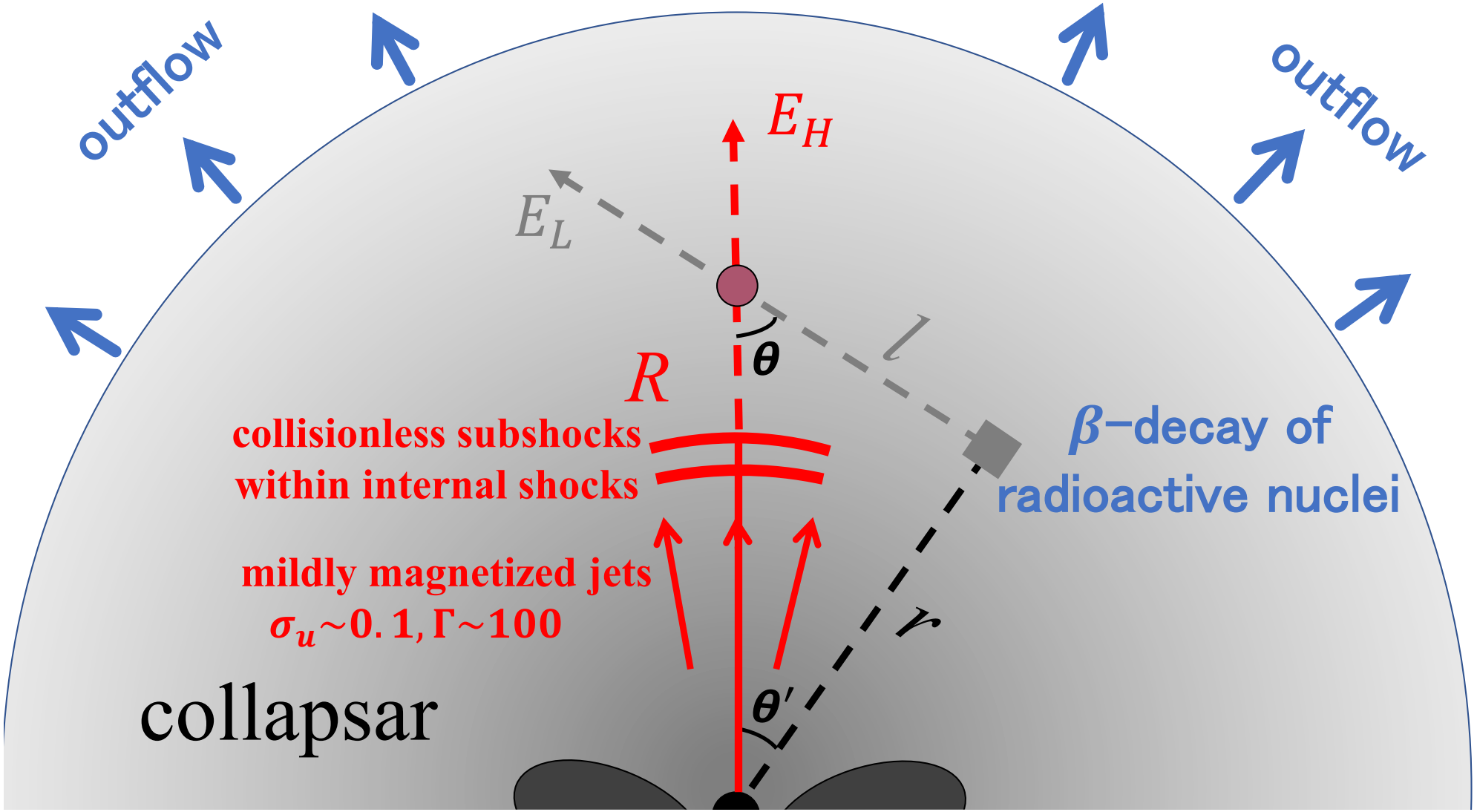
$$\bar{\nu}_e + p \rightarrow n + e^+$$




(a) L_ν / 100
(b) L_ν / 10
(c)
$\bar{\nu}_e$
ν_e
$\nu_{\mu/\tau}$
Shock break out
Accretion phase
Cooling phase
(d)
(e)
(f)
18 $M_\odot$
Luminosity (10^{51} erg/s)
Average energy (MeV)
t_{pb} (s)
Fischer et al. 2010


JET
WIND
DISK

Guo, Qian, & Wu 2023



r-process in collapsars (Siegel, Barnes, & Metzger 2019)

High-Energy Neutrino Production

collision of slow and rapid jets with $\Gamma \sim 250$–500

⟶ mildly relativistic shock

shock acceleration of protons up to 10^6 GeV

$pp,\ p\gamma$ reactions produce $\pi^{\pm},\ K^{\pm}$

$$\pi^+ \to \mu^+ + \nu_\mu,\ \pi^- \to \mu^- + \bar{\nu}_\mu$$

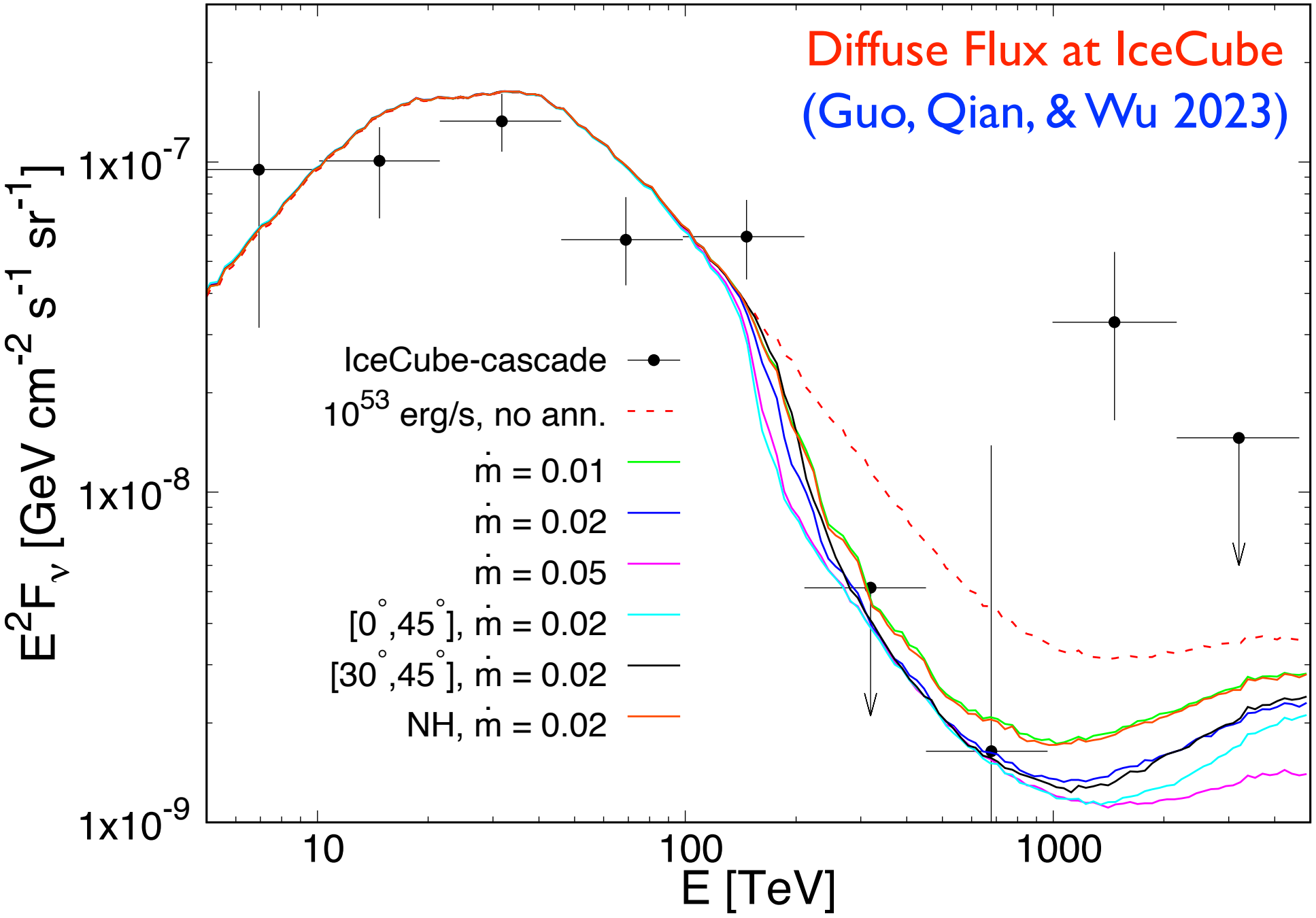
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu,\ \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

$$E_\nu \sim 0.05 \Gamma E_p$$

Annihilation of HE ν_μ by LE $\bar{\nu}_\mu$ Converted from β-Decay $\bar{\nu}_e$

$$2E_L E_H (1 - \cos\theta) = M_Z^2$$

$$\Rightarrow E_{H,\min} = \frac{M_Z^2}{4E_{L,\max}} \approx 260 \text{ TeV}$$


Diffuse Flux at IceCube
(Guo, Qian, & Wu 2023)
IceCube-cascade
10^53 erg/s, no ann.
ṁ = 0.01
ṁ = 0.02
ṁ = 0.05
[0°,45°], ṁ = 0.02
[30°,45°], ṁ = 0.02
NH, ṁ = 0.02
E^2F_ν [GeV cm^-2 s^-1 sr^-1]
1x10^-7
1x10^-8
1x10^-9
10
100
1000
E [TeV]

Summary

Pre-SN MeV neutrinos provide advance warning for nearby SNe within ~1 day & may tell neutrino mass ordering

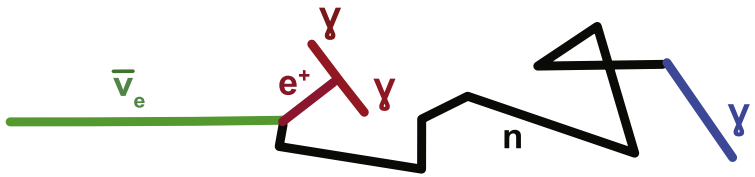
Next Galactic SN will induce ~10^4 events of ~10 MeV neutrinos in terrestrial detectors & provide diagnostics of SN processes

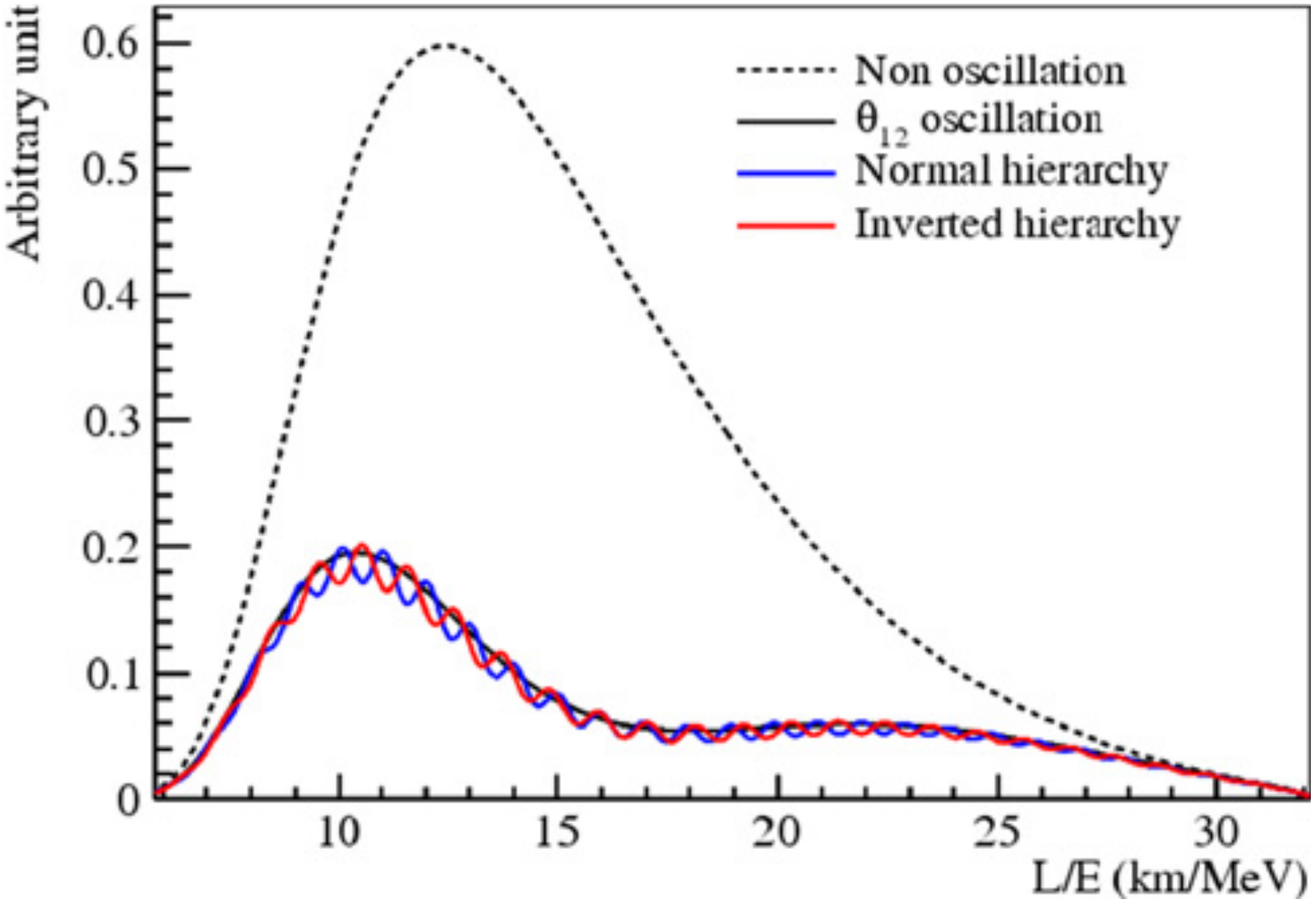
Collapsars could be a source for r-process nuclei and high-energy neutrinos of ~100 TeV

Annihilation of HE neutrinos by LE antineutrinos from decay of r-process nuclei leaves distinct signatures on the spectrum and flavor composition of HE neutrinos, which can be tested by precise measurements at IceCube-Gen2

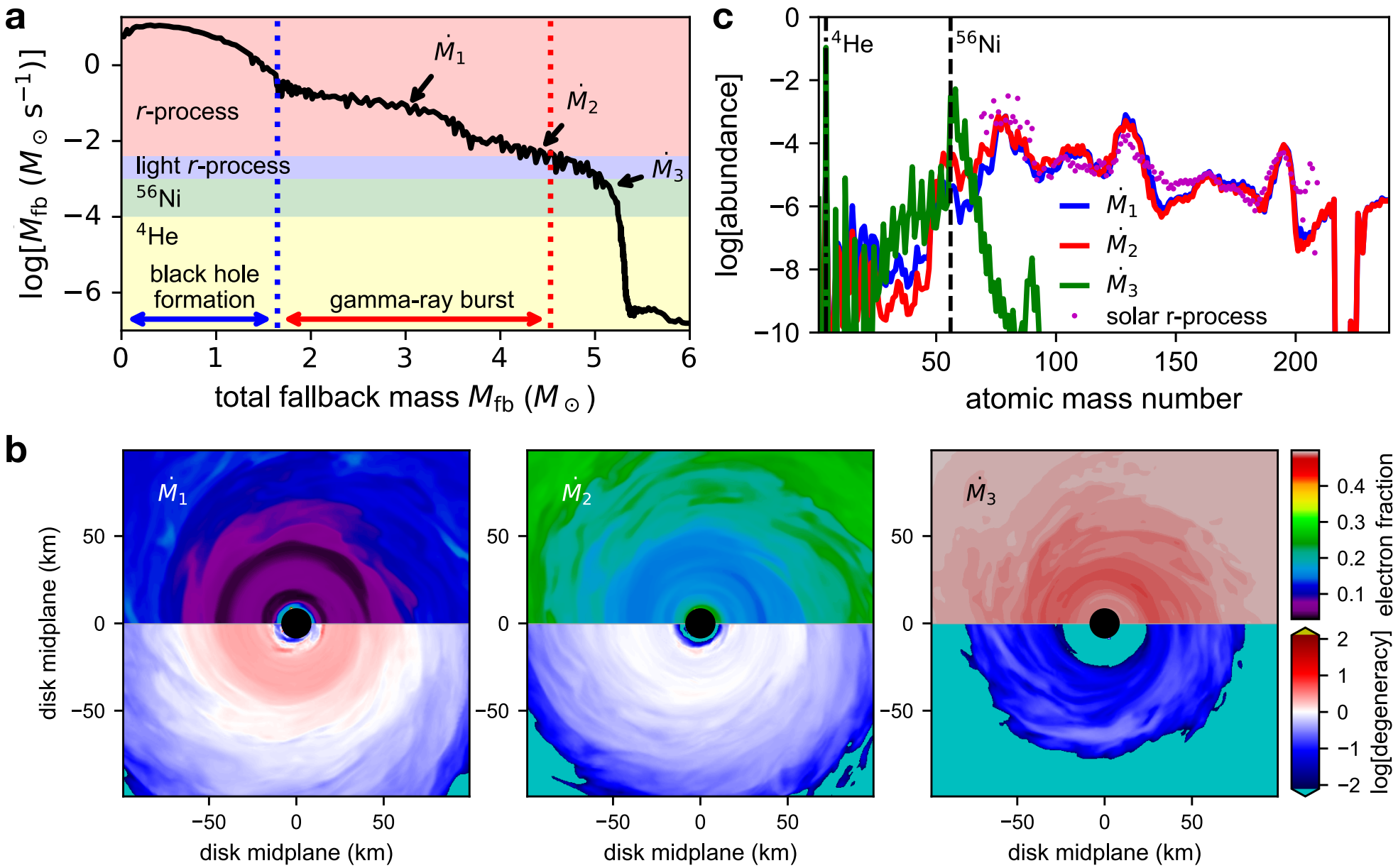
Jiangmen Underground Neutrino Observatory (JUNO)

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

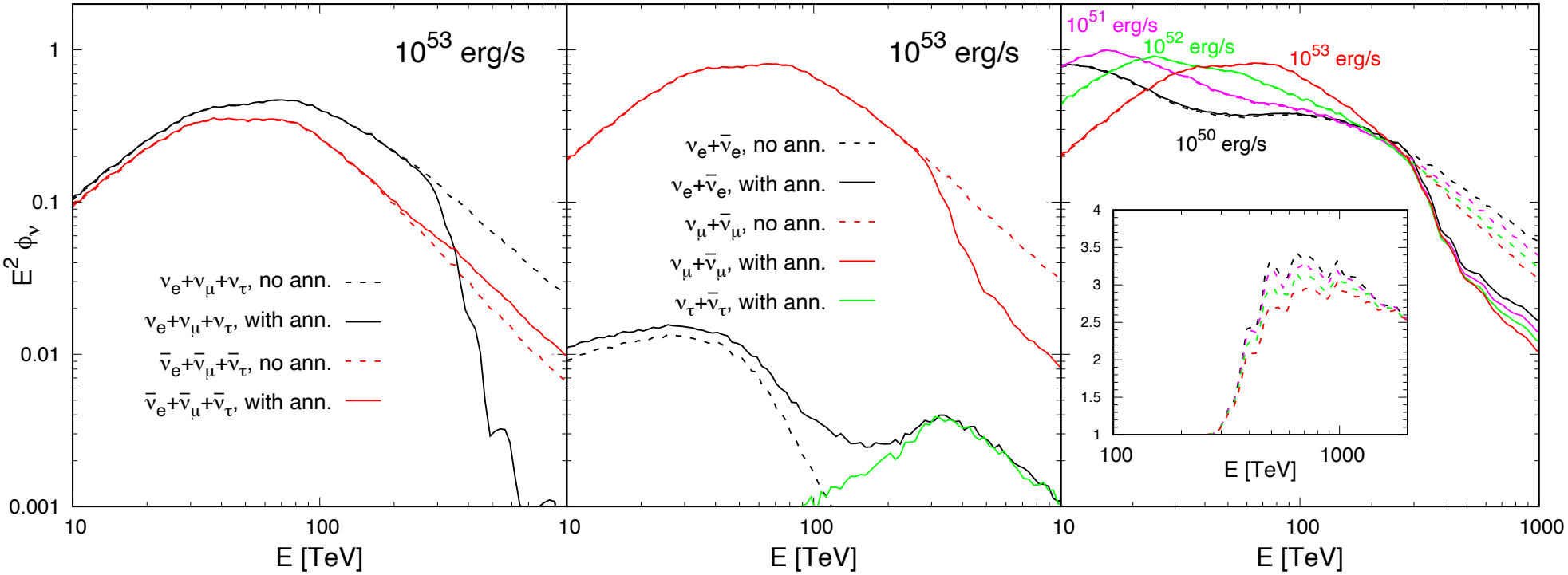




Collapsars as an r-process source (Siegel, Barnes, & Metzger 2019)



Guo, Qian, & Wu 2023



initial proton spectrum $E_p^{-2}\exp(-E_p/E_{p,\max})$

cooling of $\pi^\pm, K^\pm$ by synchrotron radiation

and $\pi^\pm/K^\pm + \gamma \to \pi^\pm/K^\pm + e^+ + e^-$

annihilation of HE ν_μ by LE $\bar{\nu}_\mu$ converted from β-decay $\bar{\nu}_e$