Probing Neutrino Physics with Stellar Evolution

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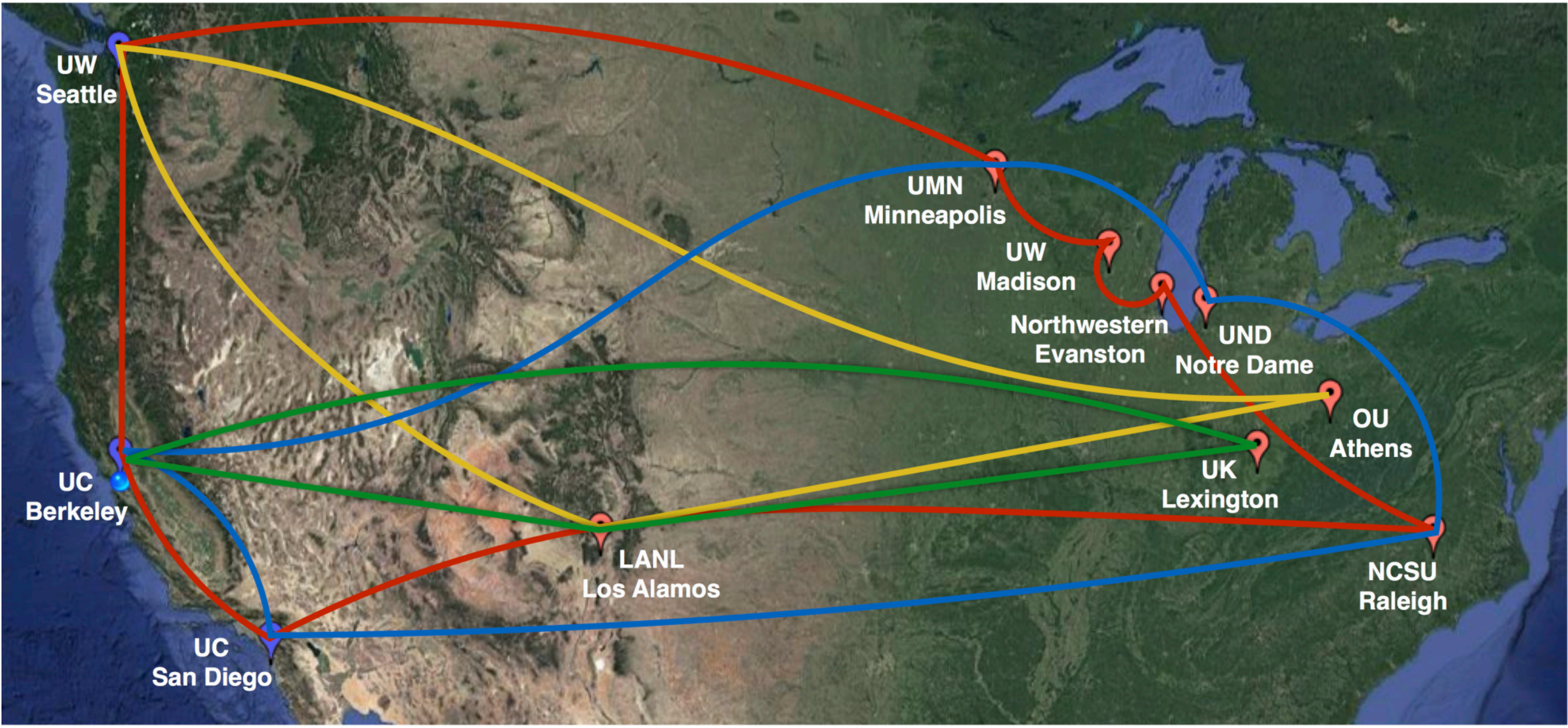
N3AS: Network in Neutrinos, Nuclear Astrophysics, and Symmetries

Neutrino Astrophysics — Nucleosynthesis

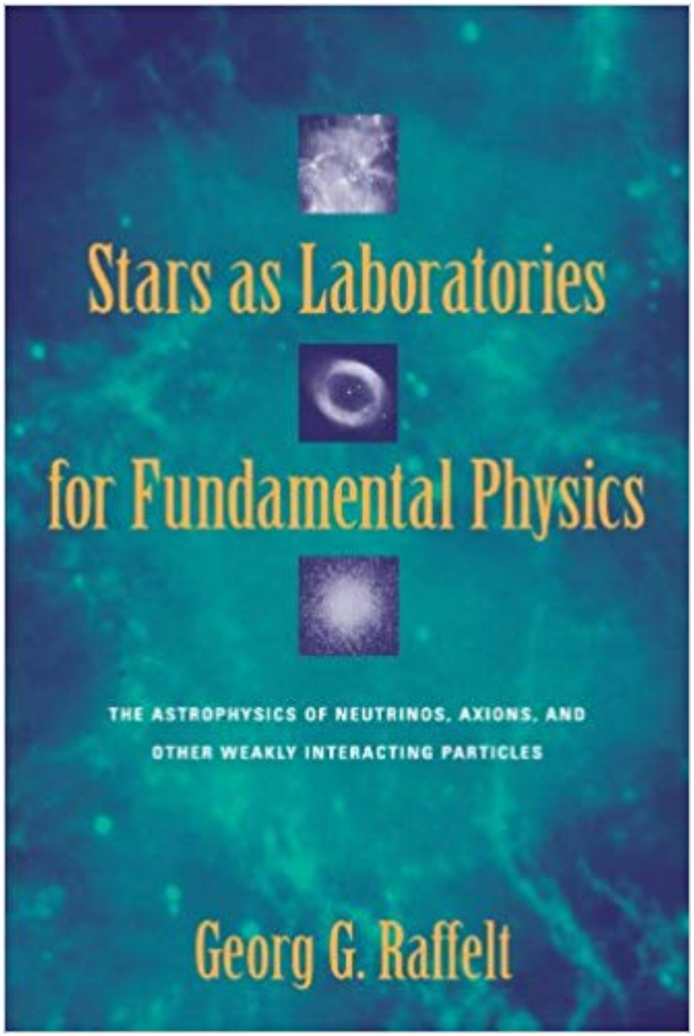


Dense Matter — Dark Matter

https://n3as.wordpress.com

HEISING-SIMONS FOUNDATION

micro-processes transfer energy and/or change composition, thereby affecting stellar evolution, explosion, and nucleosynthesis



Outline of this talk

Neutrino cooling is the standard energy loss mechanism governing evolution of massive stars

JUNO might be able to distinguish the neutrino mass ordering by detecting presupernova neutrinos

Dark photons complicate stellar evolution but might be constrained by detection of such neutrinos

How to Become a Star

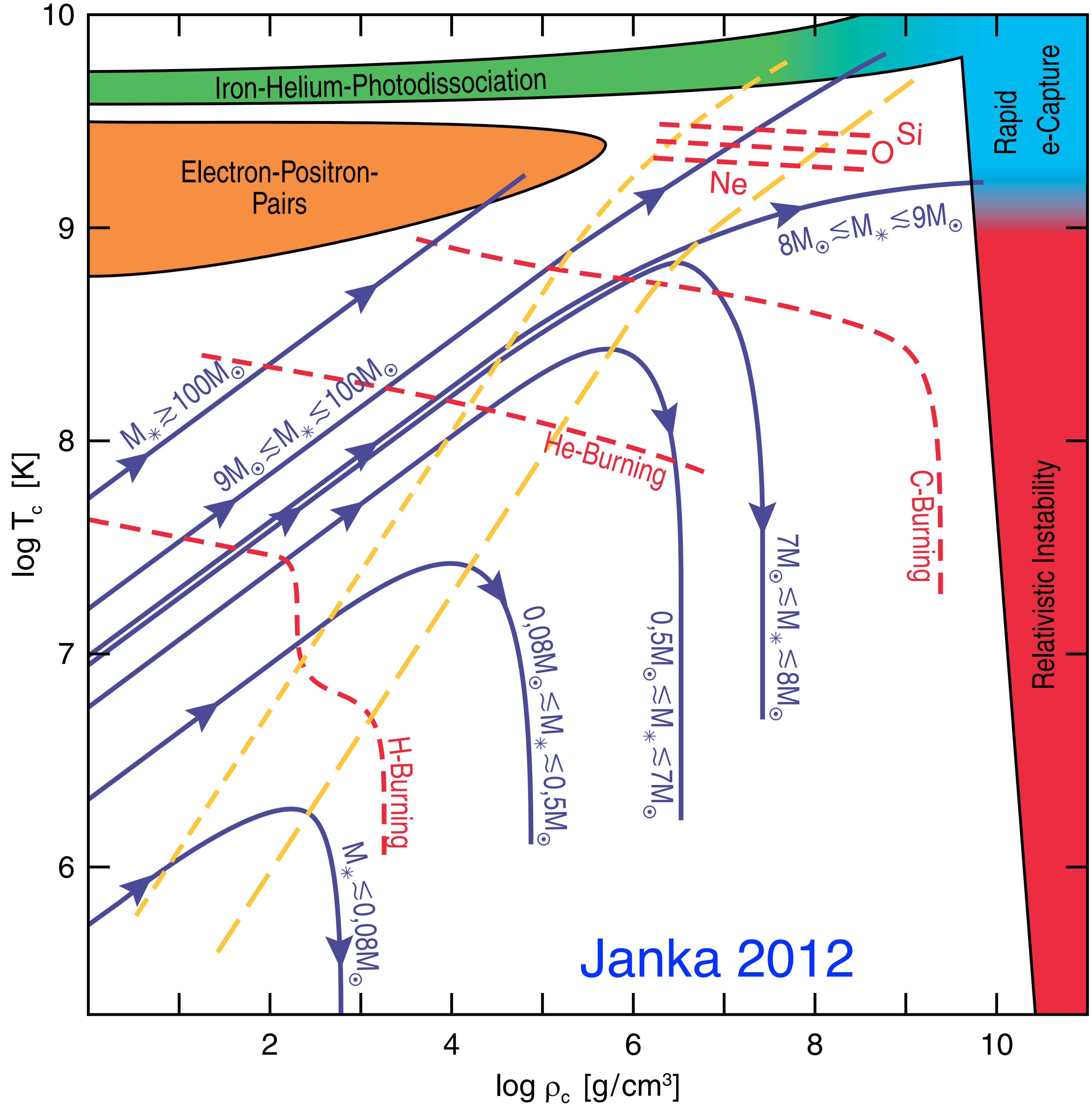
Virial theorem for a contracting gas cloud

$$T_c + \frac{\hbar^2}{2m_e d^2} \sim \frac{GMm_p}{R}$$

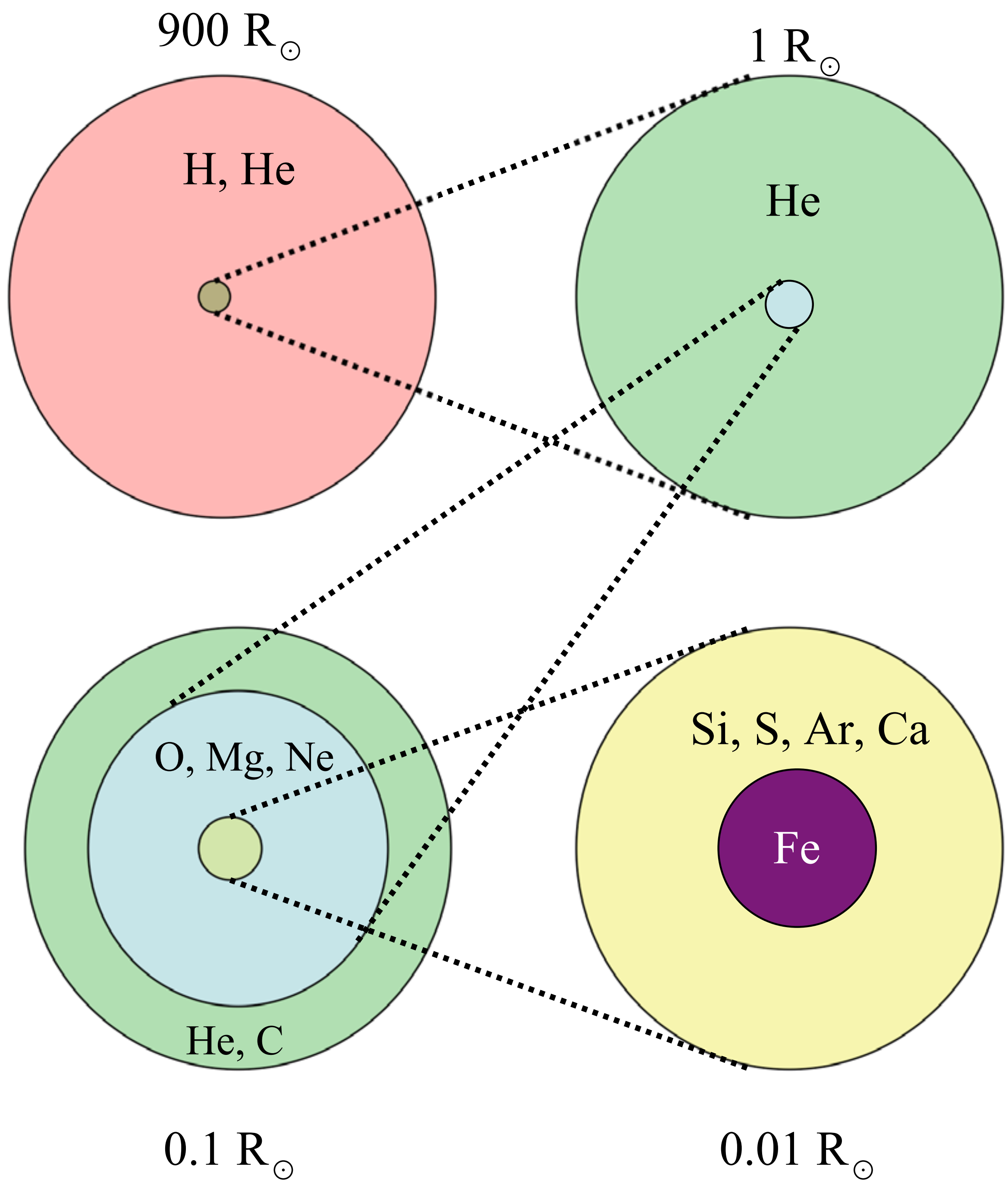
$$\left(\frac{M}{m_p}\right) d^3 \sim R^3 \Rightarrow$$

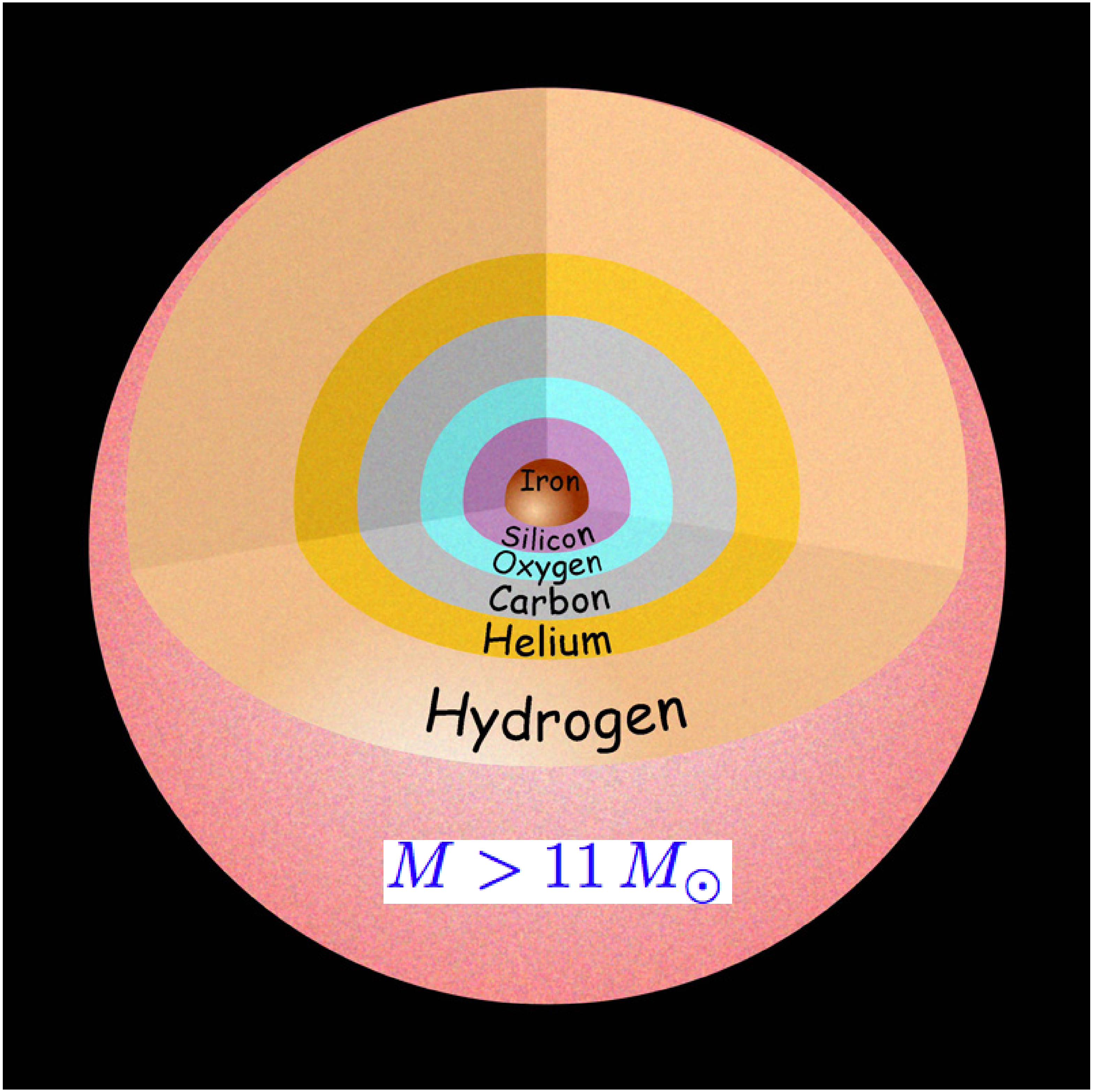
$$T_c \sim \frac{GMm_p}{R} - \frac{\hbar^2}{2m_e}\left(\frac{M}{m_p}\right)^{2/3}\frac{1}{R^2}$$

$$\Rightarrow T_{c,\mathrm{max}} \propto M^{4/3}$$


Iron-Helium-Photodissociation
Electron-Positron-
Pairs
Rapid
e-Capture
Relativistic Instability
Si
O
Ne
He-Burning
C-Burning
H-Burning
$M_* \gtrsim 100M_\odot$
$9M_\odot \lesssim M_* \lesssim 100M_\odot$
$8M_\odot \lesssim M_* \lesssim 9M_\odot$
$7M_\odot \leq M_* \leq 8M_\odot$
$0,5M_\odot \lesssim M_* \lesssim 7M_\odot$
$0,08M_\odot \lesssim M_* \lesssim 0,5M_\odot$
$M_* \lesssim 0,08M_\odot$
Janka 2012
log T_c [K]
log ρ_c [g/cm³]
10
9
8
7
6
2
4
6
8
10

25 $M_\odot$ Presupernova Star



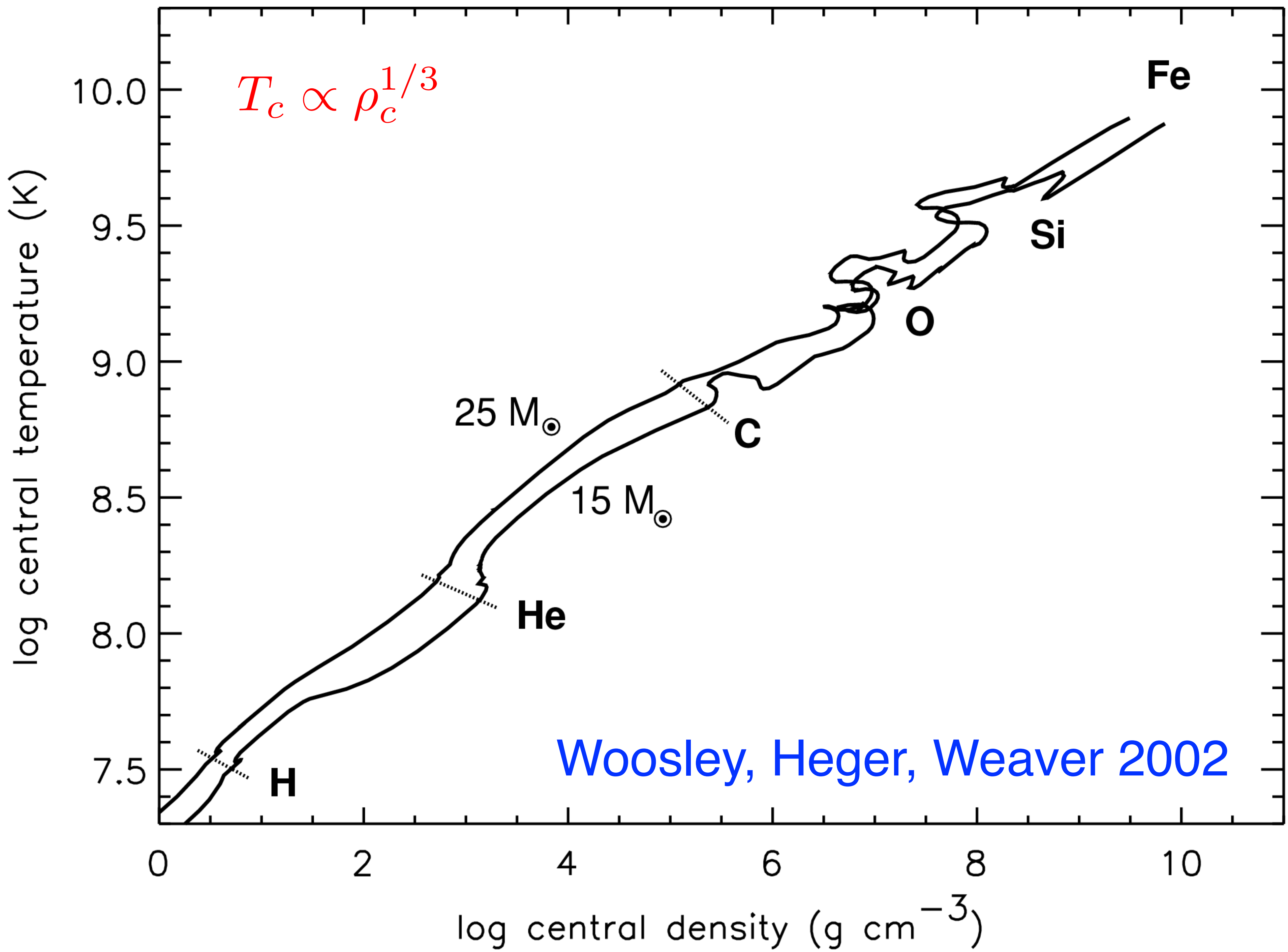

Iron
Silicon
Oxygen
Carbon
Helium
Hydrogen
$M > 11\,M_{\odot}$

Massive stars are radiation dominated !

$$\frac{T_c^4}{\rho_c/m_p} \sim \frac{GMm_p}{R}, \quad \rho_c \sim \frac{M}{R^3}$$

$$\Rightarrow T_c \propto \frac{M^{1/2}}{R}$$

$$\Rightarrow \frac{T_c^3}{\rho_c} \propto M^{1/2}$$



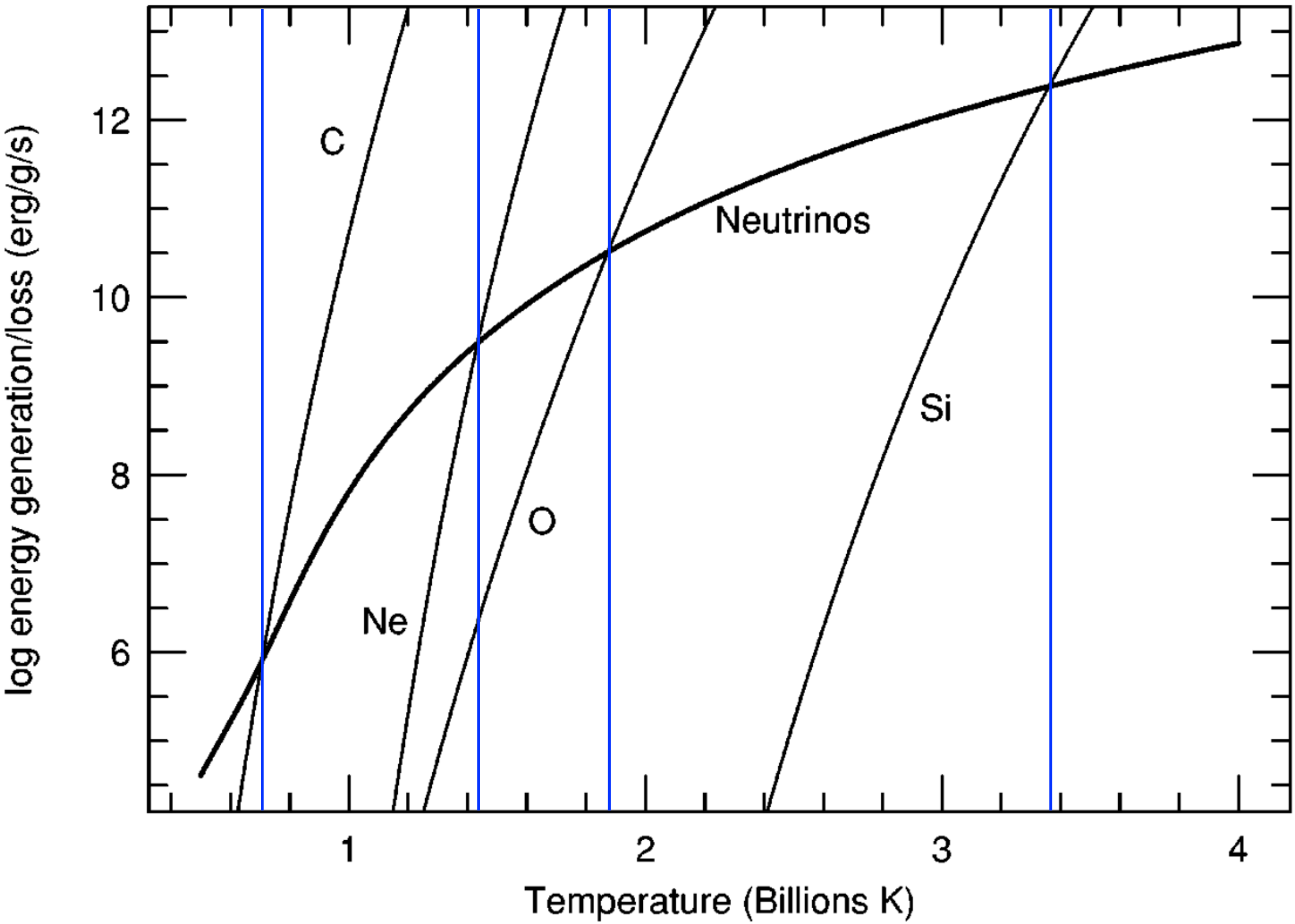
$T_c \propto \rho_c^{1/3}$
Fe
Si
O
C
He
H
25 M$_\odot$
15 M$_\odot$
Woosley, Heger, Weaver 2002
log central temperature (K)
log central density (g cm^{-3})
10.0
9.5
9.0
8.5
8.0
7.5
0
2
4
6
8
10

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	$4\,H \xrightarrow{CNO} {}^{4}He$
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



Processes of Thermal Neutrino Emission

Pair annihilation

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

Plasmon decay

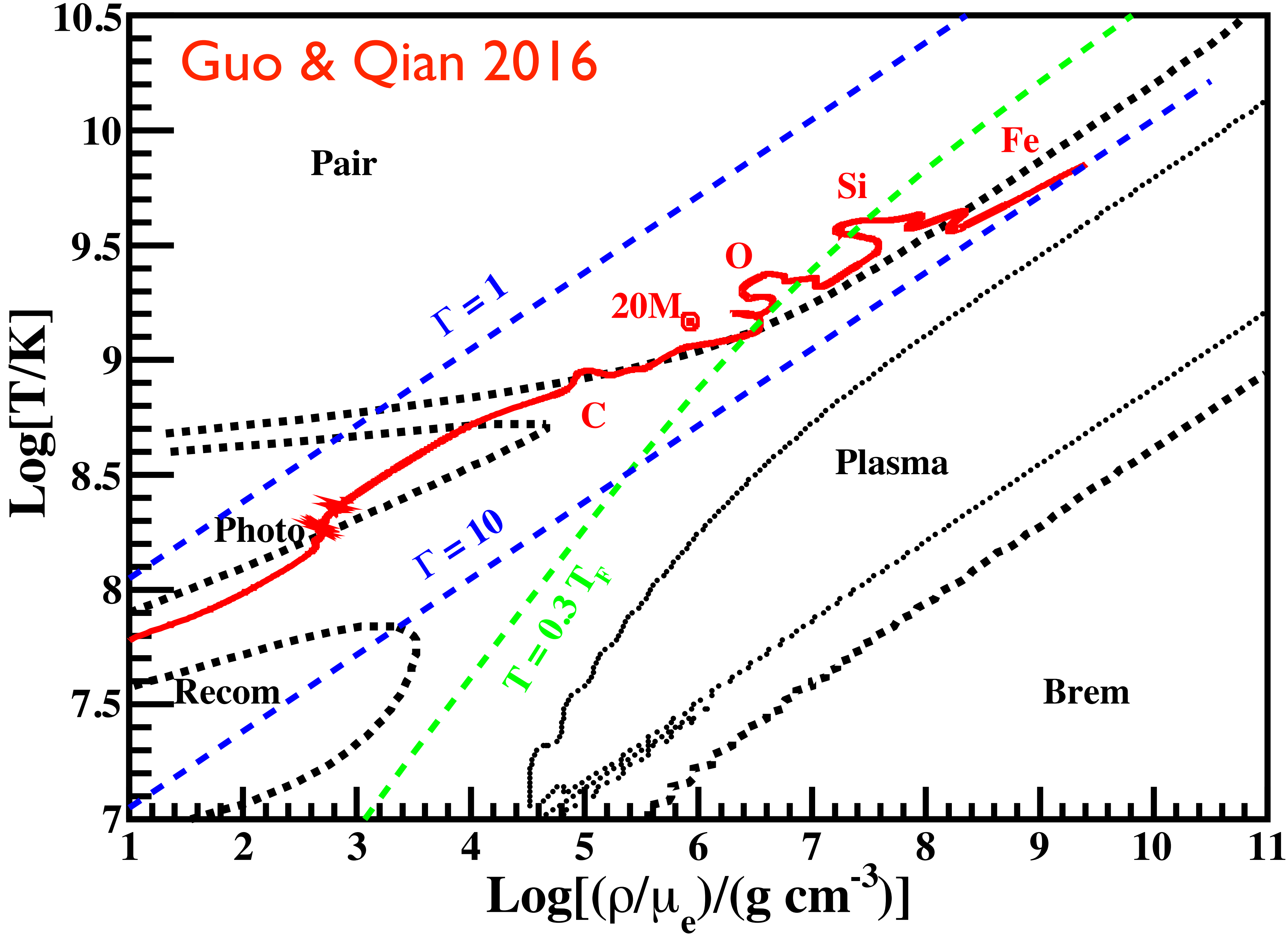
$$\gamma_{\rm pl} \to \nu + \bar{\nu}$$

Photo-neutrino emission

$$\gamma + e^- \to e^- + \nu + \bar{\nu}$$

Bremsstrahlung

$$(Z, A) + e^- \to (Z, A) + e^- + \nu + \bar{\nu}$$



Guo & Qian 2016
Pair
Photo
Recom
Plasma
Brem
Γ = 1
Γ = 10
T = 0.3 T_F
20M⊙
C
O
Si
Fe
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

Additional neutrino cooling processes

$\beta^{\pm}$ decay, $e^{\pm}$ capture

Patton, Lunardini, & Farmer 2017;
Patton, Lunardini, Farmer, & Timmes 2017;

detailed nuclear physics, including excited states & neutral-current neutrino pair emission

Misch, Brown, & Fuller 2013;
Misch, Fuller, & Brown 2014;
Misch & Fuller 2016;
Misch, Sun, & Fuller 2017

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

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

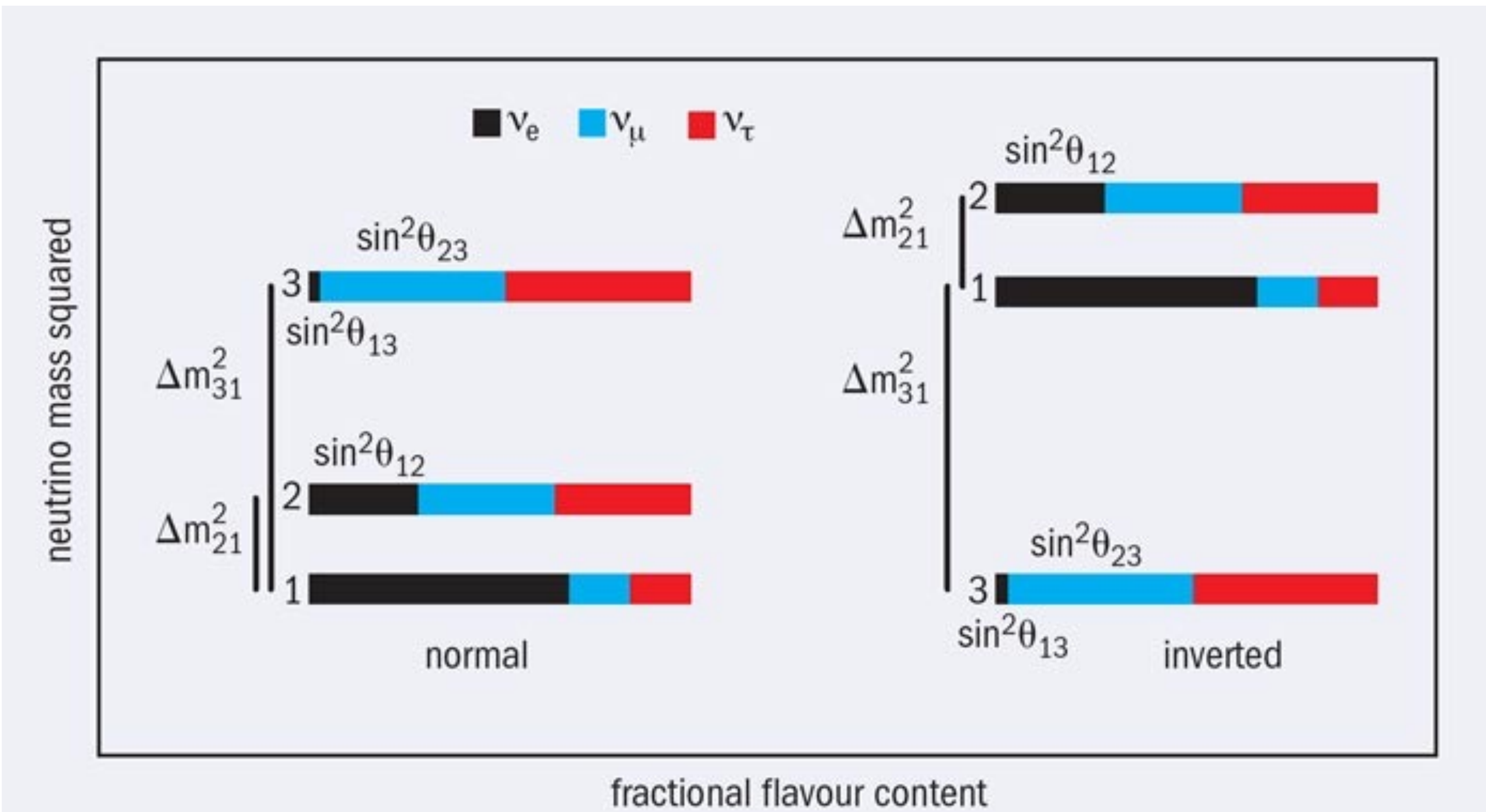
Probe of neutrino mass ordering: NH/IH ~ 3.4

Test of stellar models: progenitor mass

Three Neutrino Mixing

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle, \;\; |\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle$$

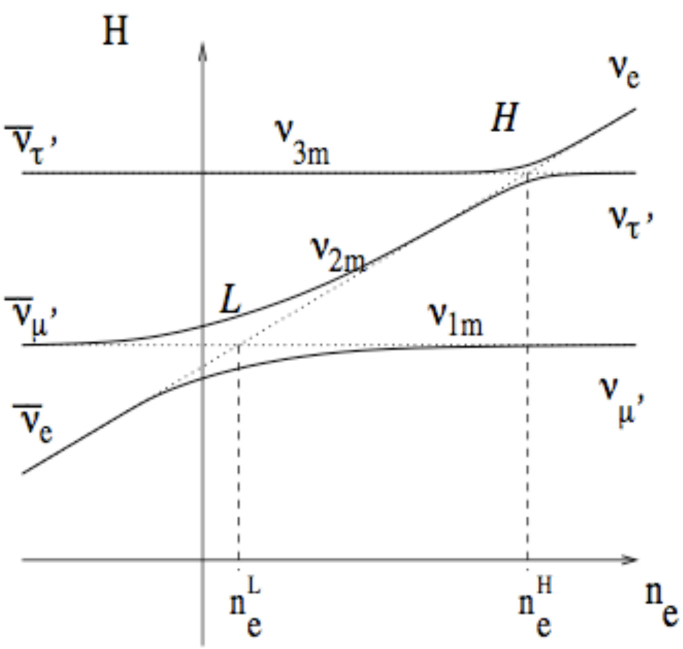
$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

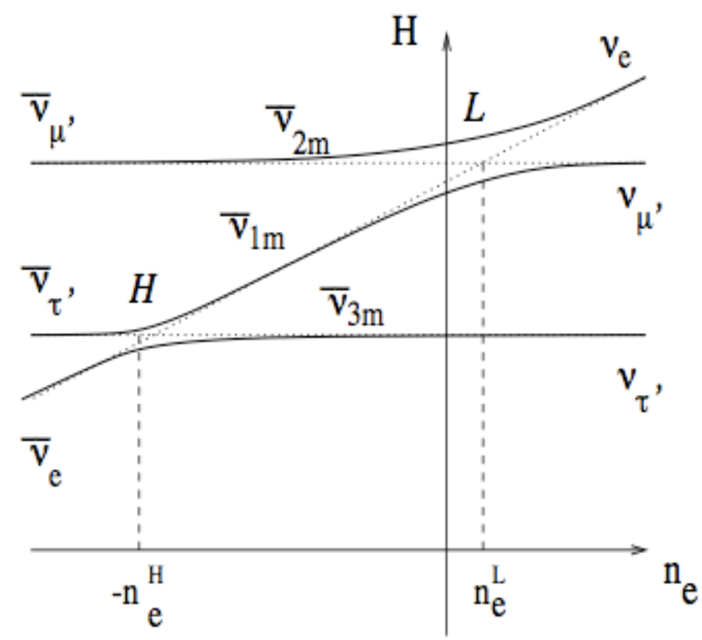


Neutrino Mixing in Vacuum

$$U_{\alpha i} = \langle \nu_\alpha | \nu_i \rangle, \ \bar{U}_{\alpha i} = \langle \bar{\nu}_\alpha | \bar{\nu}_i \rangle$$

Neutrino Flavor Evolution in Matter (MSW only)



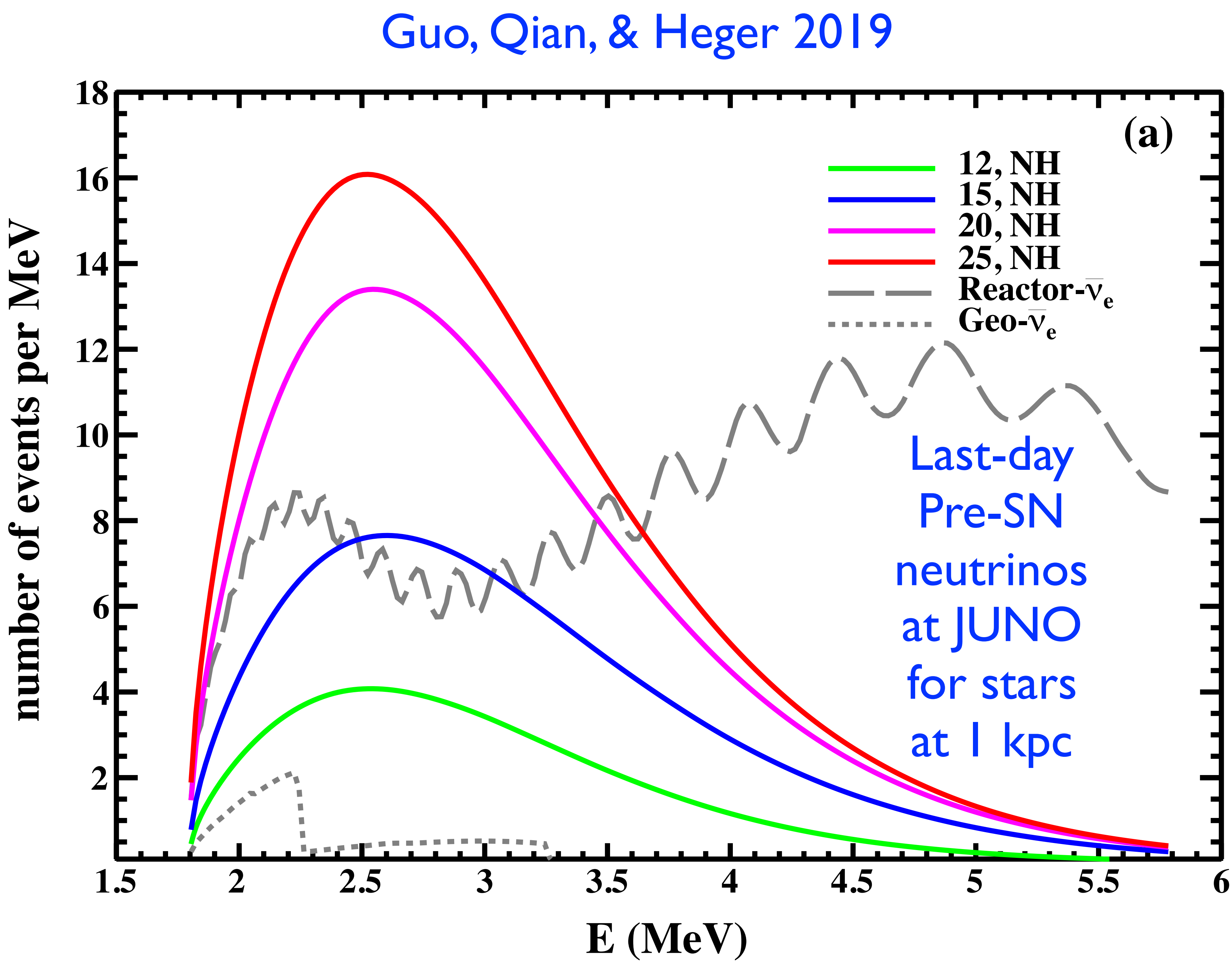


normal mass hierarchy

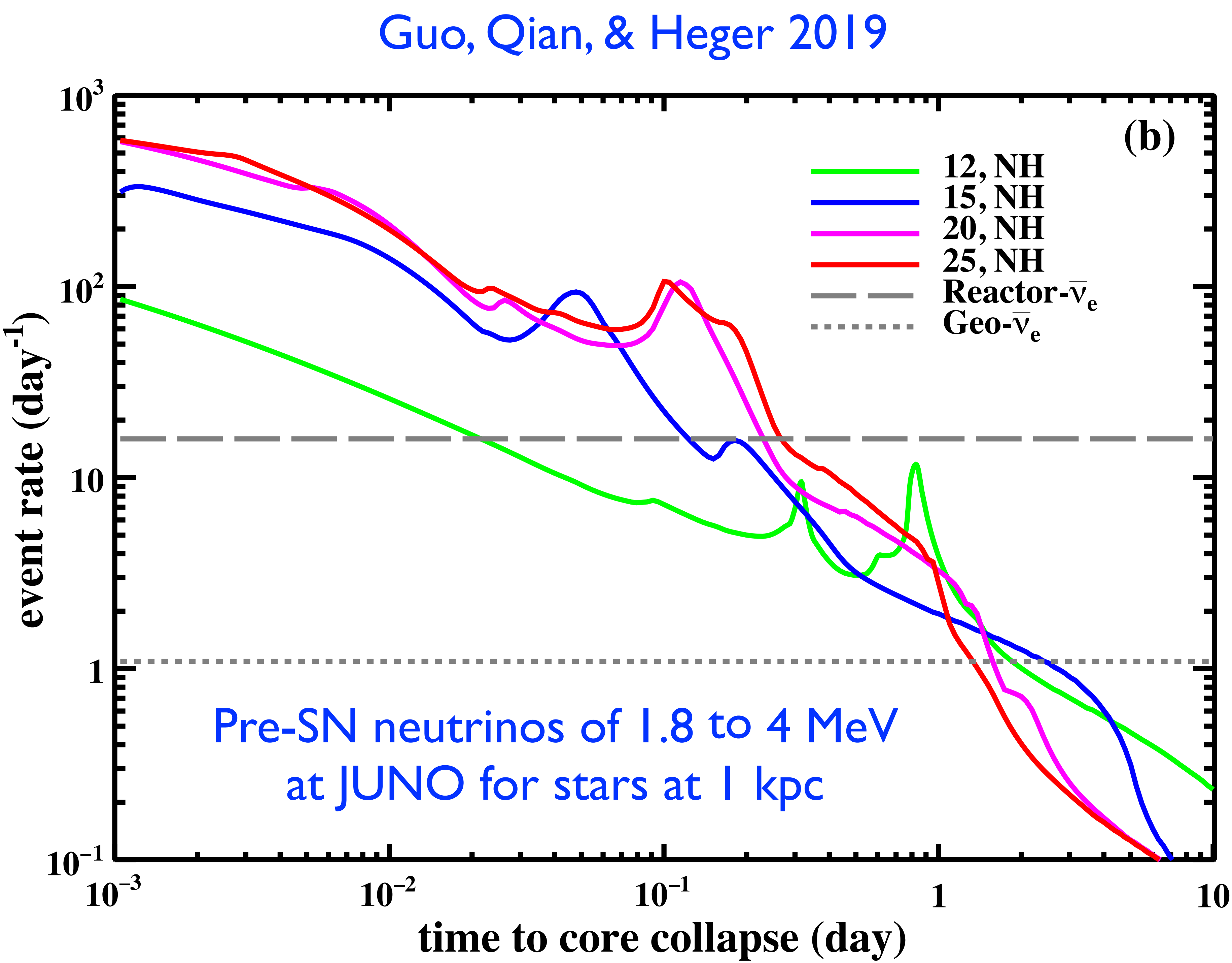
$$N_{\bar{\nu}_e}/N^0_{\bar{\nu}_e} \approx 0.74$$

inverted mass hierarchy

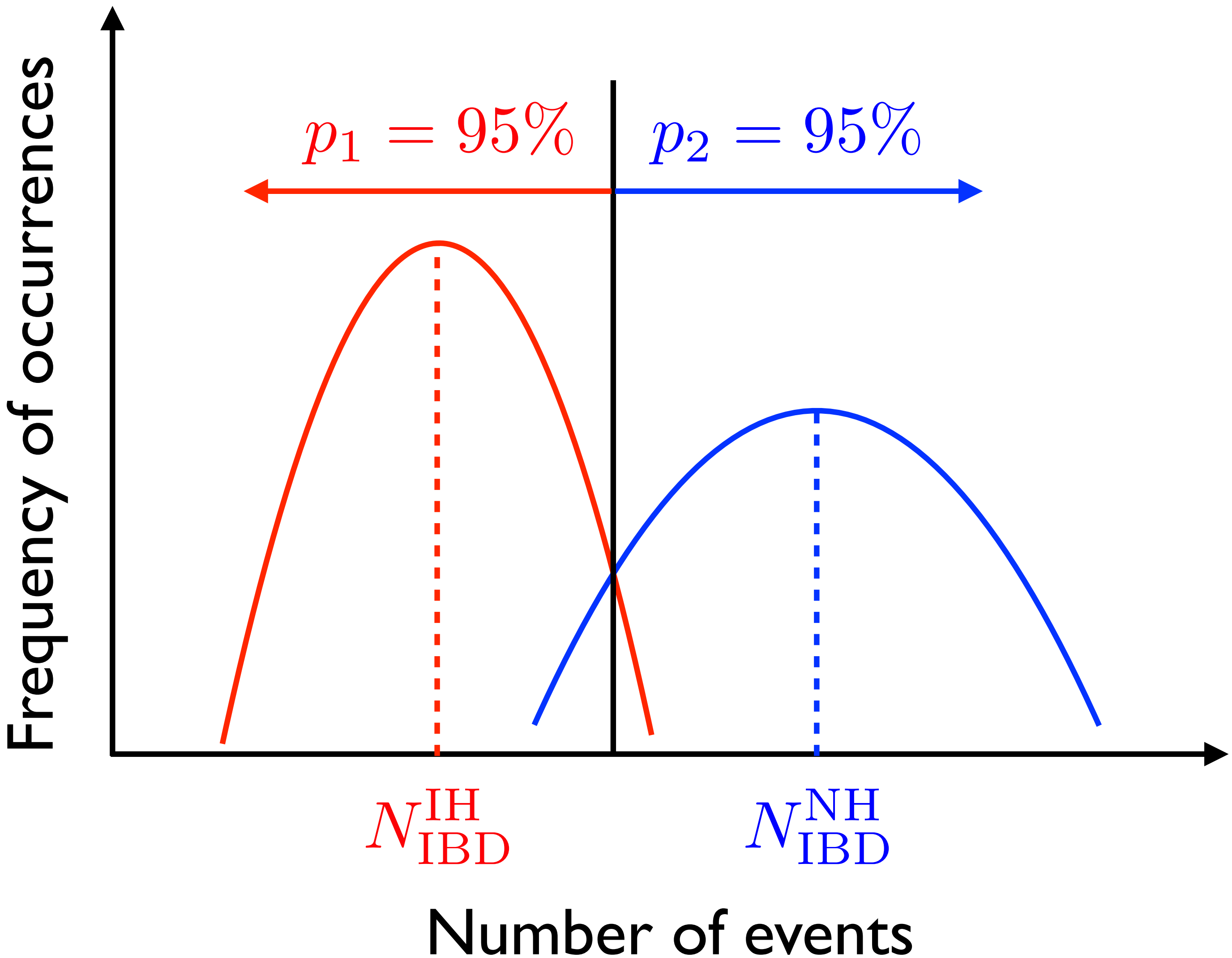
$$N_{\bar{\nu}_e}/N^0_{\bar{\nu}_e} \approx 0.22$$



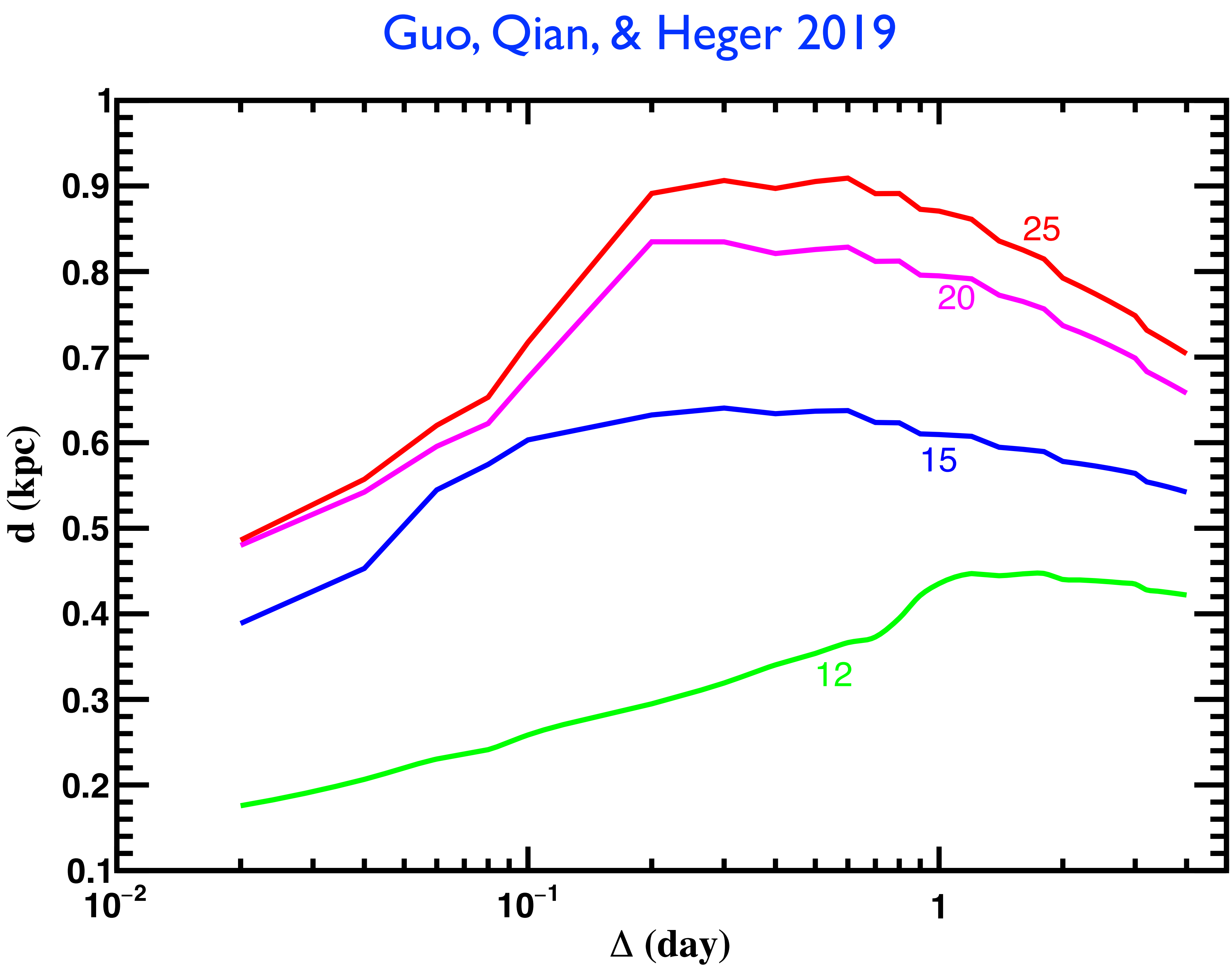
Guo, Qian, & Heger 2019
(a)
12, NH
15, NH
20, NH
25, NH
Reactor-$\bar{\nu}_e$
Geo-$\bar{\nu}_e$
Last-day
Pre-SN
neutrinos
at JUNO
for stars
at 1 kpc
number of events per MeV
E (MeV)
0
2
4
6
8
10
12
14
16
18
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6



Guo, Qian, & Heger 2019
(b)
12, NH
15, NH
20, NH
25, NH
Reactor-$\bar{\nu}_e$
Geo-$\bar{\nu}_e$
event rate (day^{-1})
time to core collapse (day)
Pre-SN neutrinos of 1.8 to 4 MeV
at JUNO for stars at 1 kpc
10^3
10^2
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
10

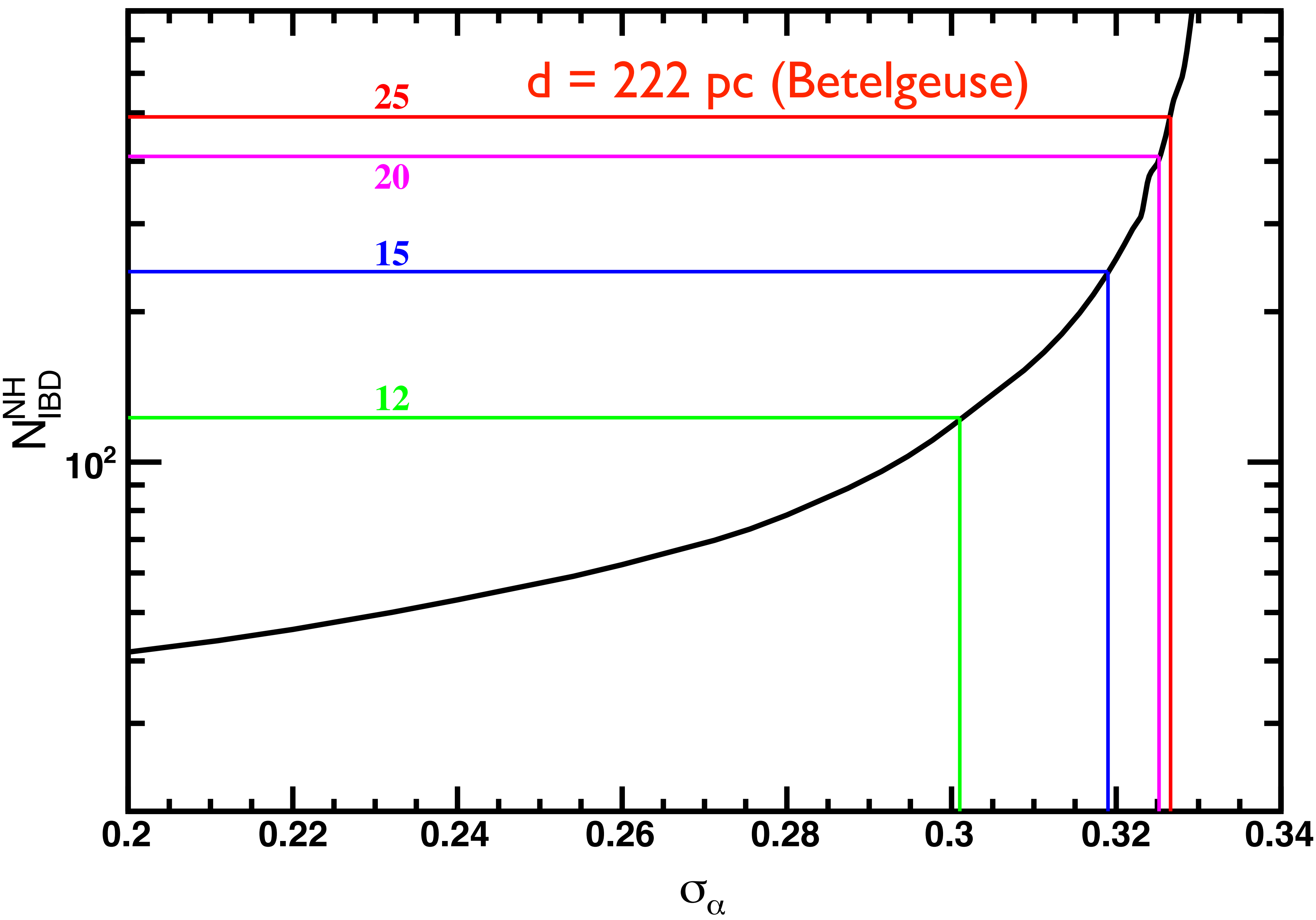


Frequency of occurrences
$p_1 = 95\%$
$p_2 = 95\%$
$N_{\rm IBD}^{\rm IH}$
$N_{\rm IBD}^{\rm NH}$
Number of events



Guo, Qian, & Heger 2019
d (kpc)
Δ (day)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10−2
10−1
1
25
20
15
12

Guo, Qian, & Heger 2019



Model-Indepdent Determination

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

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): $\bar{\nu}_e + p \to n + e^+$

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

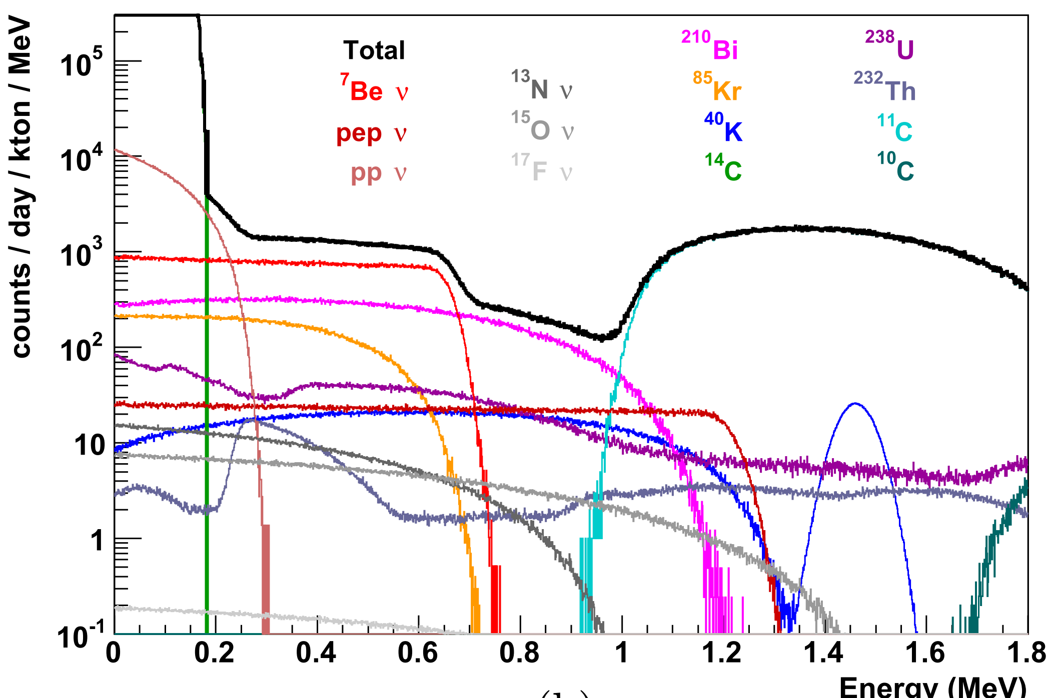
$$\frac{N_{\rm ES}^{\rm NH}}{N_{\rm IBD}^{\rm NH}} \approx 0.91$$

vs.

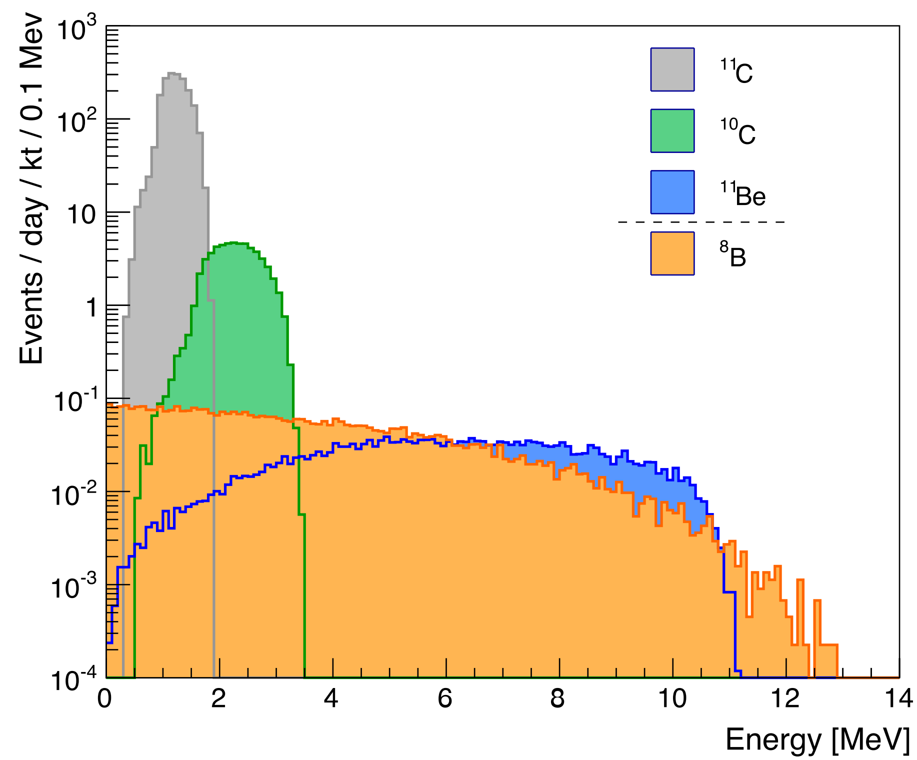
$$\frac{N_{\rm ES}^{\rm IH}}{N_{\rm IBD}^{\rm IH}} \approx 3.8$$

Background for ES events

For 0.8 < T_e < 2.5 MeV, cosmogenic background dominates



(b)

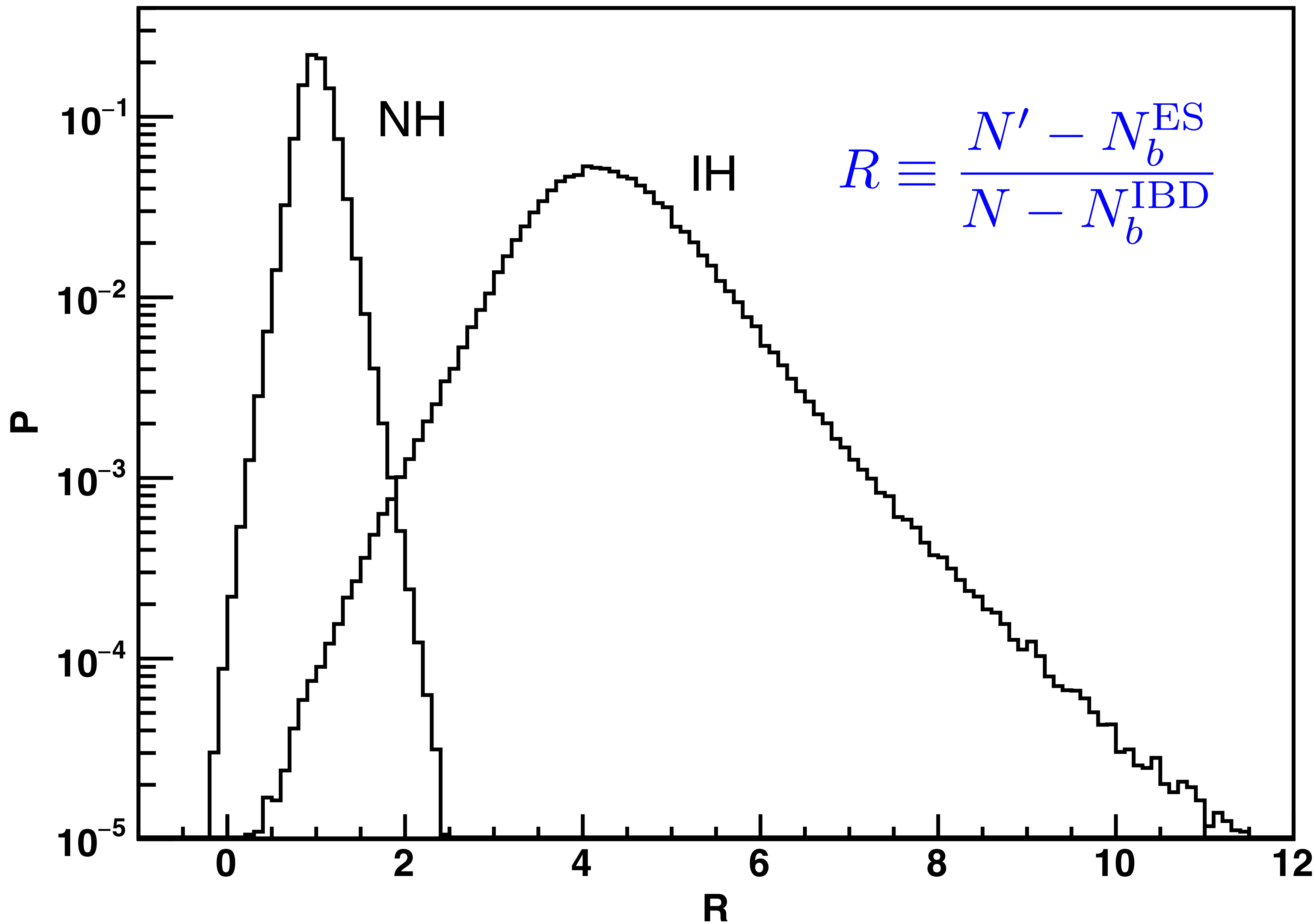


signals from Betelgeuse: ~100 to 500 during last day

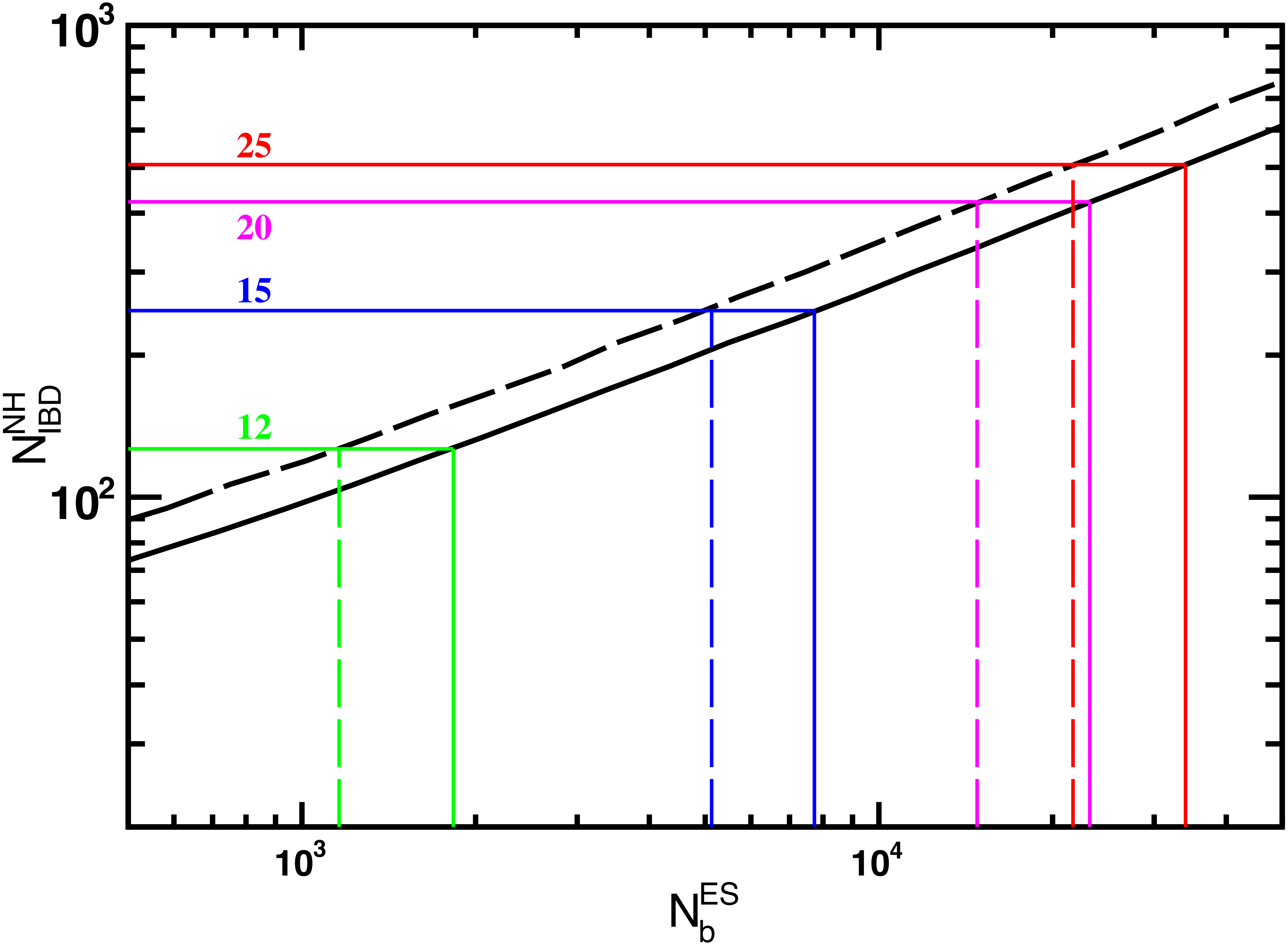
currently-estimated background: ~20000

potential background reduction by coincidence!

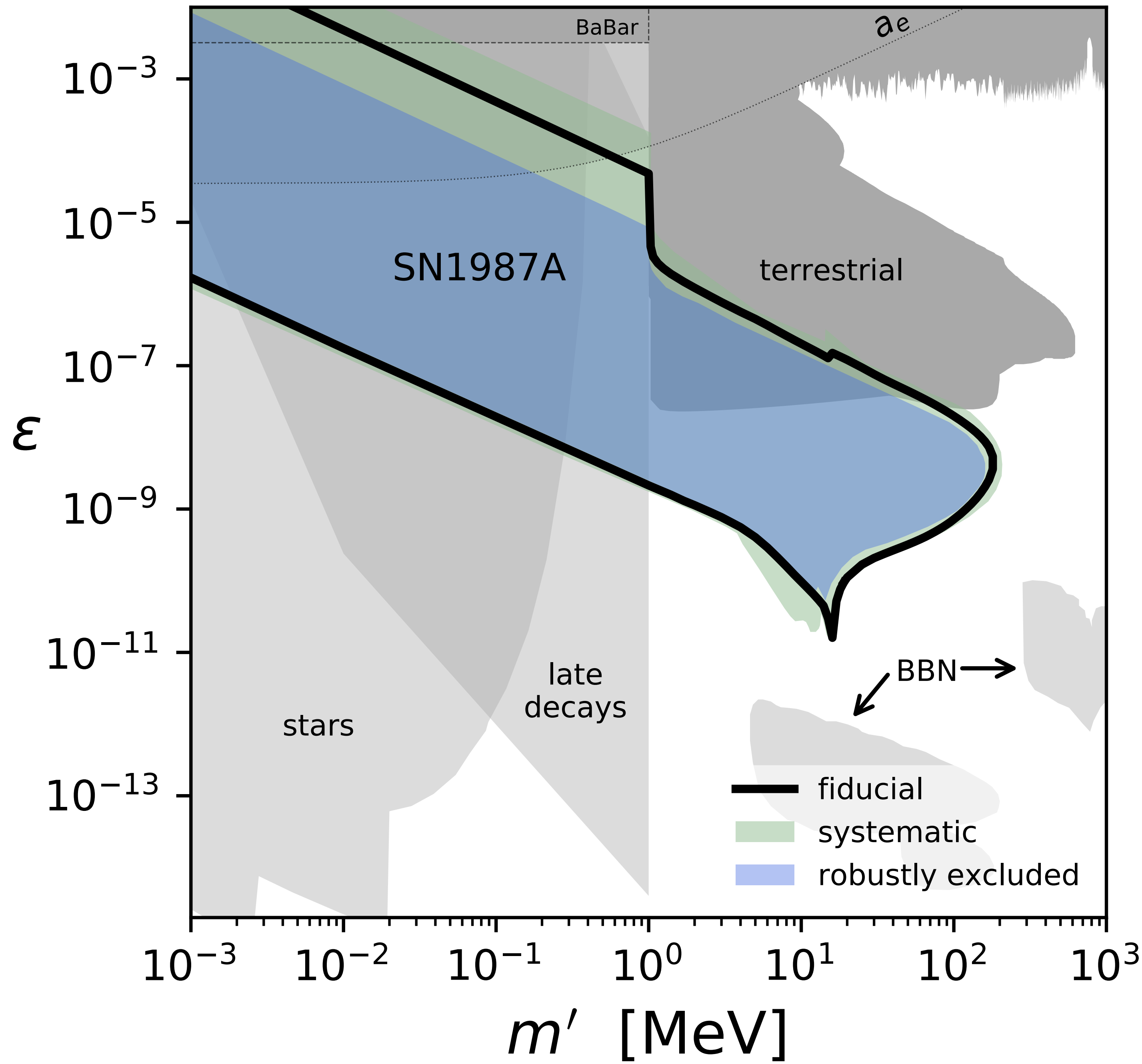
Example for 15 M_{sun}



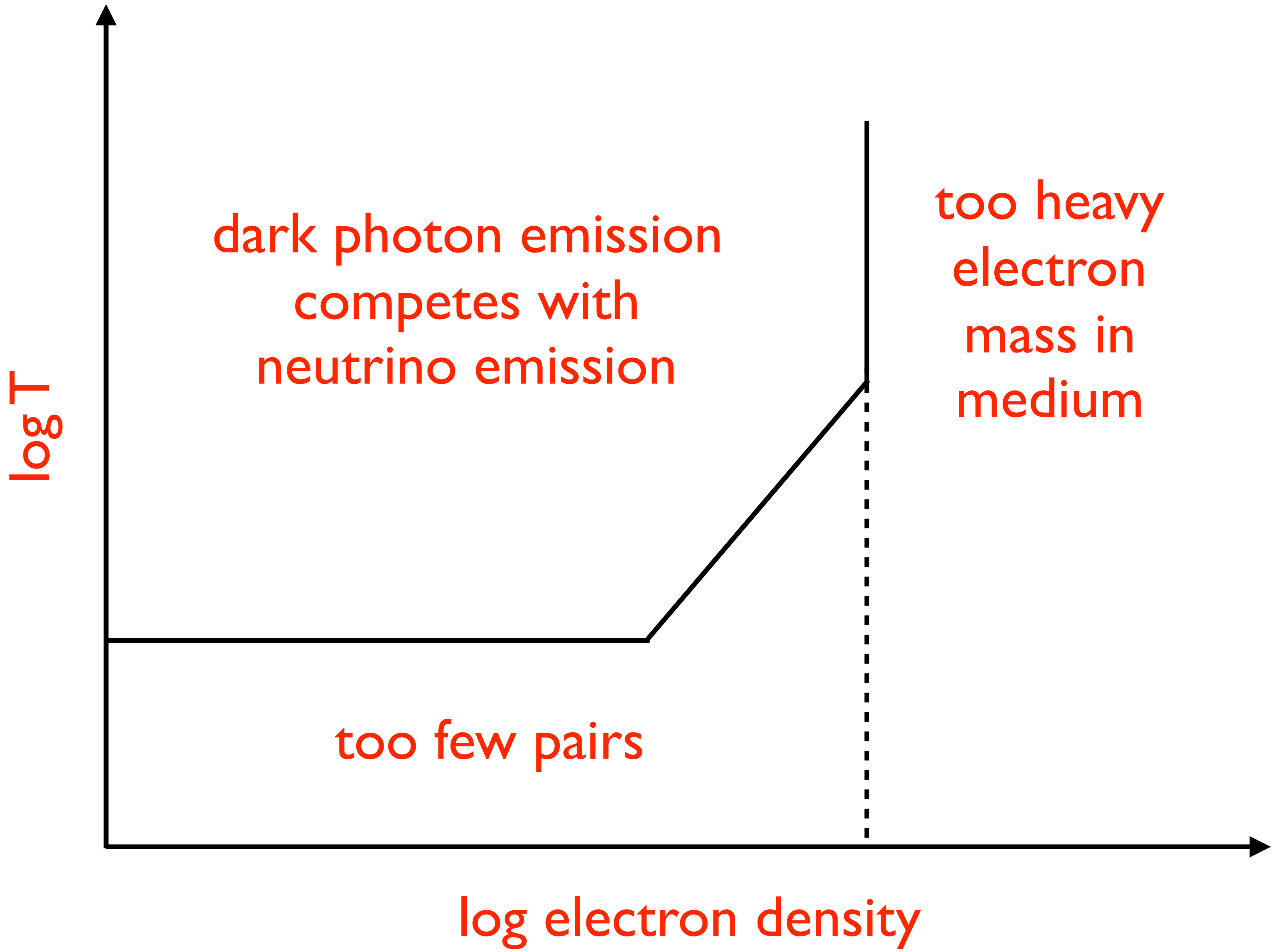
Guo, Qian, & Heger 2019



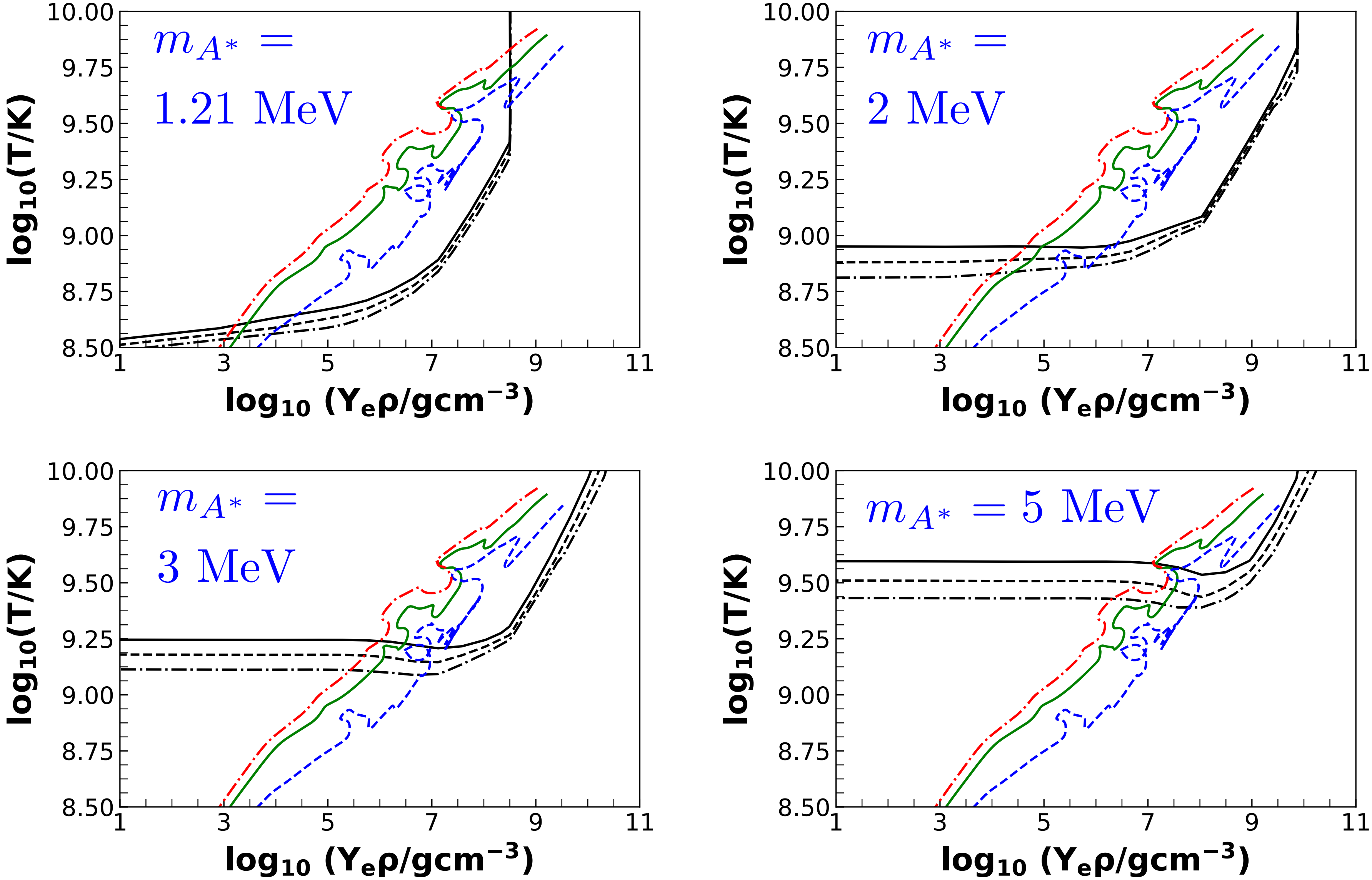
Chang, Essig, & McDermott 2017



$$e^- + e^+ \to A^* \quad \text{vs.} \quad e^- + e^+ \to \nu + \bar{\nu}$$



$\dot{Q}_{A^*}$ vs. $\dot{Q}_{\nu\bar{\nu}}$ (Rrapaj, Sieverding, & Qian 2019)



Summary

Neutrino cooling is the standard energy loss mechanism governing evolution of massive stars

Pre-SN neutrinos provide advance warning for nearby supernovae within ~1 day

JUNO might be able to distinguish the neutrino mass ordering by detecting pre-SN neutrinos

Dark photons complicate stellar evolution but might be constrained by detection of these neutrinos