Did a Low-Mass Supernova Trigger the Formation of the Solar System?

Clues from Stable Isotopes and ^{10}Be

Yong-Zhong Qian
University of Minnesota

Banerjee, YZQ, Heger, & Haxton 2016, Nat. Commun.

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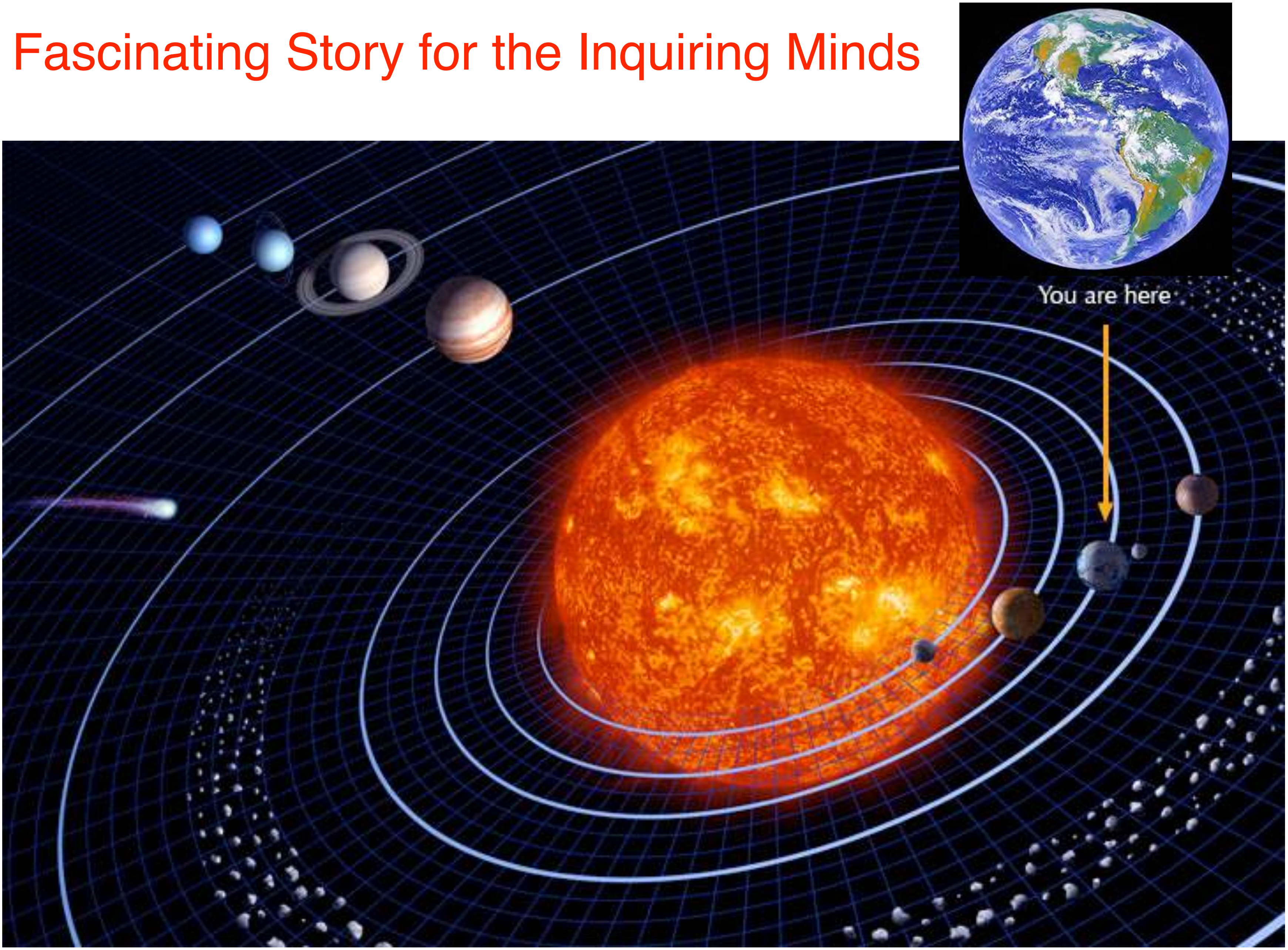
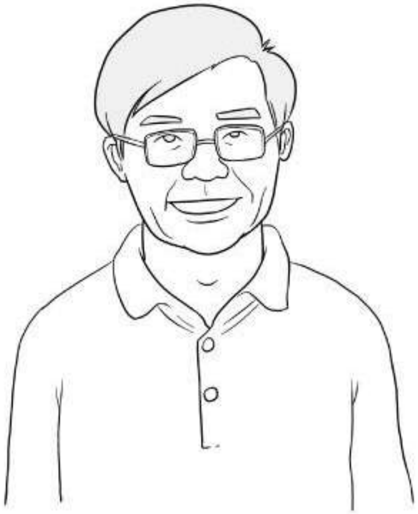
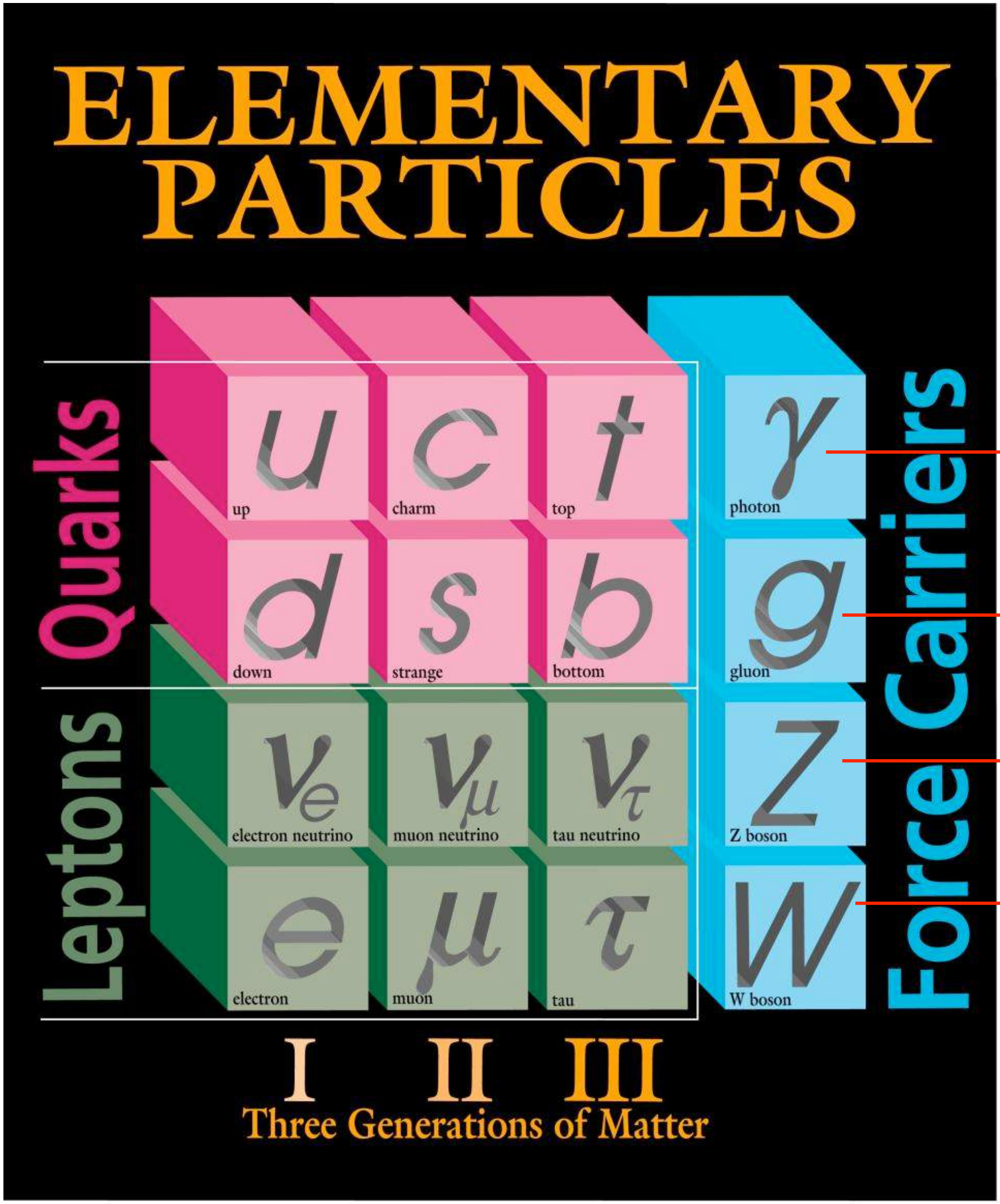
What Triggered the Formation of Our Solar System?

A Fascinating Story for the Inquiring Minds



You arose from the death of stars (01/10/2017)





Fermilab 95-759

Fundamental Interactions

Electromagnetic

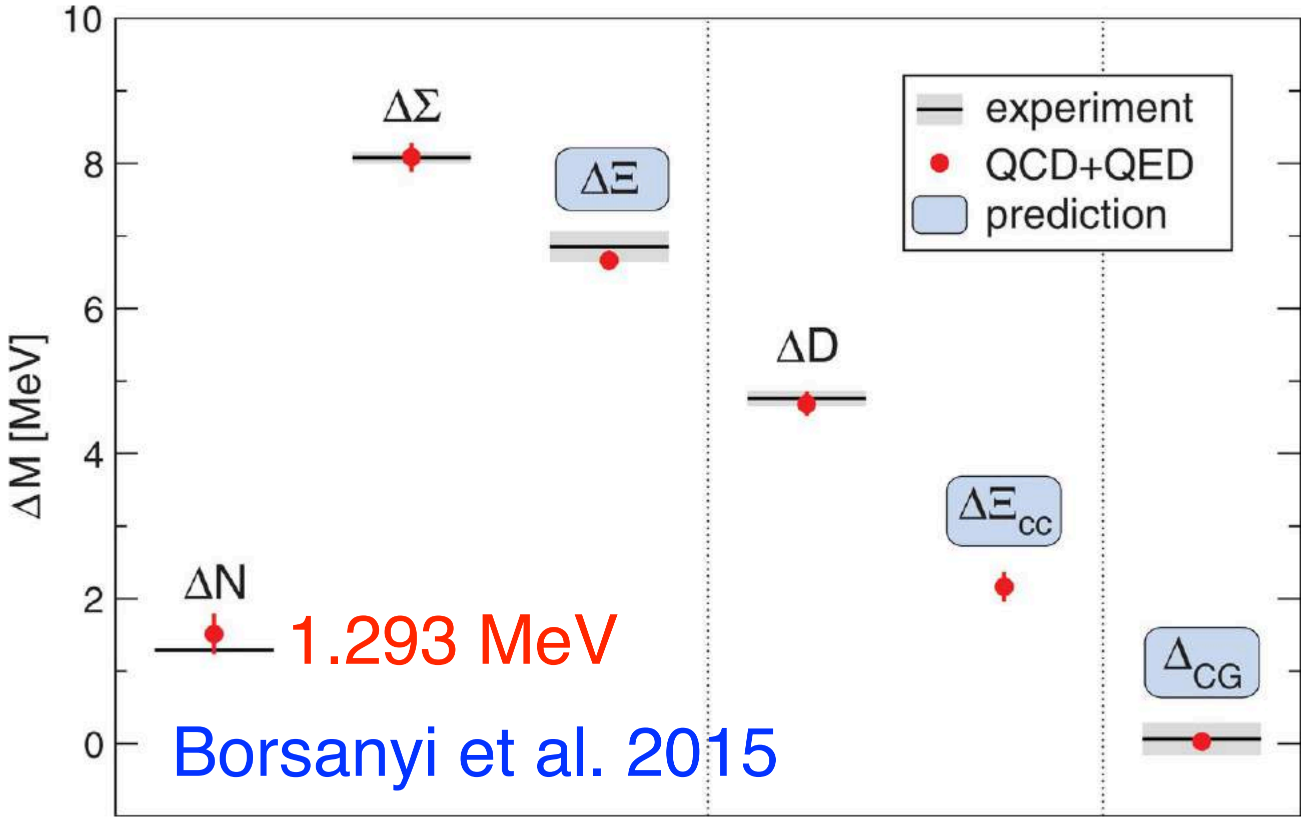
Strong

Weak (NC)

Weak (CC)

Gravitational

Standard Model of Particle Physics & Life of a Baryon: Big Bang Nucleosynthesis



1.293 MeV

Borsanyi et al. 2015

$$\frac{n}{p} = \exp\left(-\frac{M_n - M_p}{T}\right) < 1$$

Big Bang:

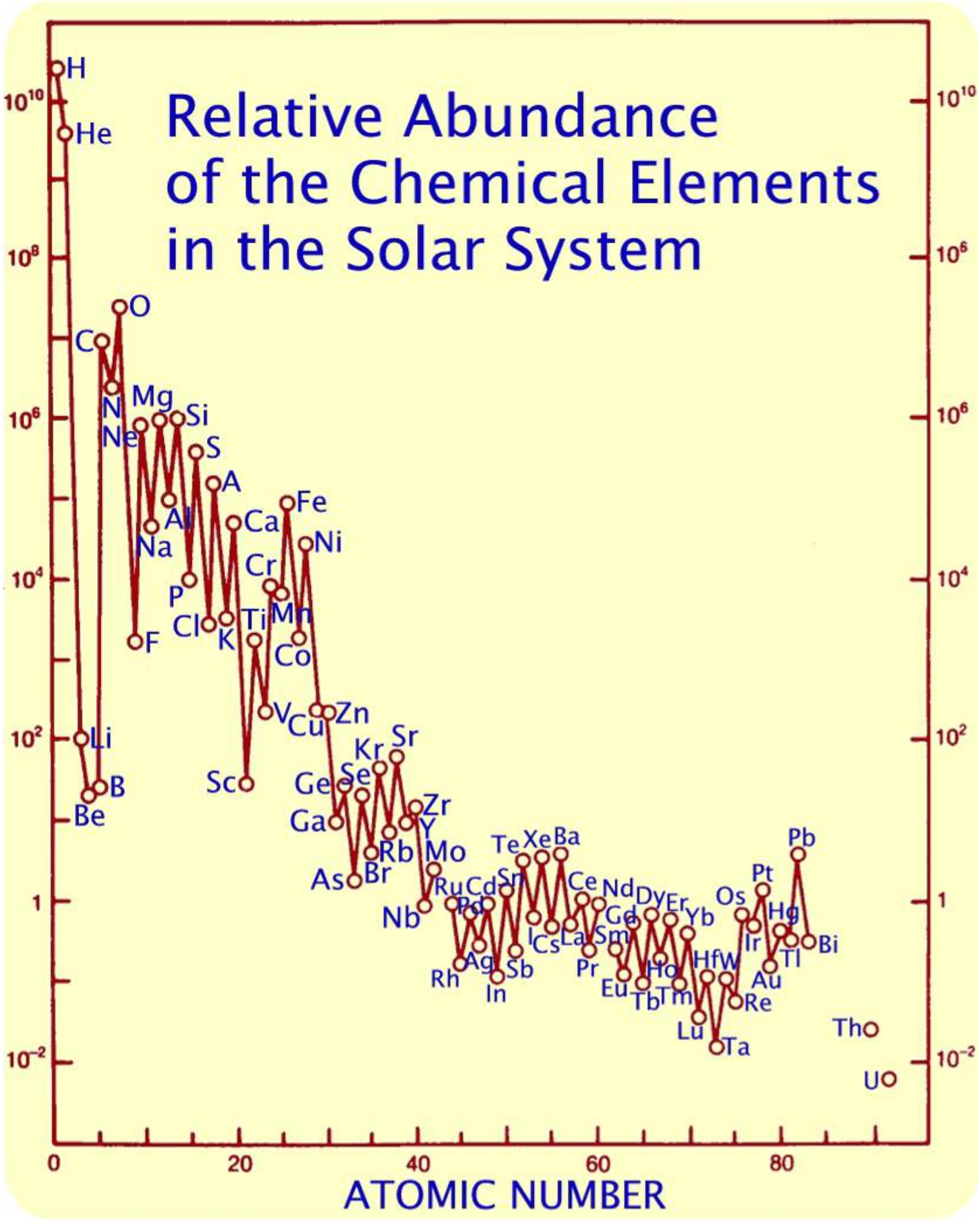
75% H + 25% He
(by mass)

Sun:

71.1% H + 27.4% He
+1.5% “Metals”

$$“p” \rightarrow “n” + e^+ + \nu_e$$

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



How to Become a Star

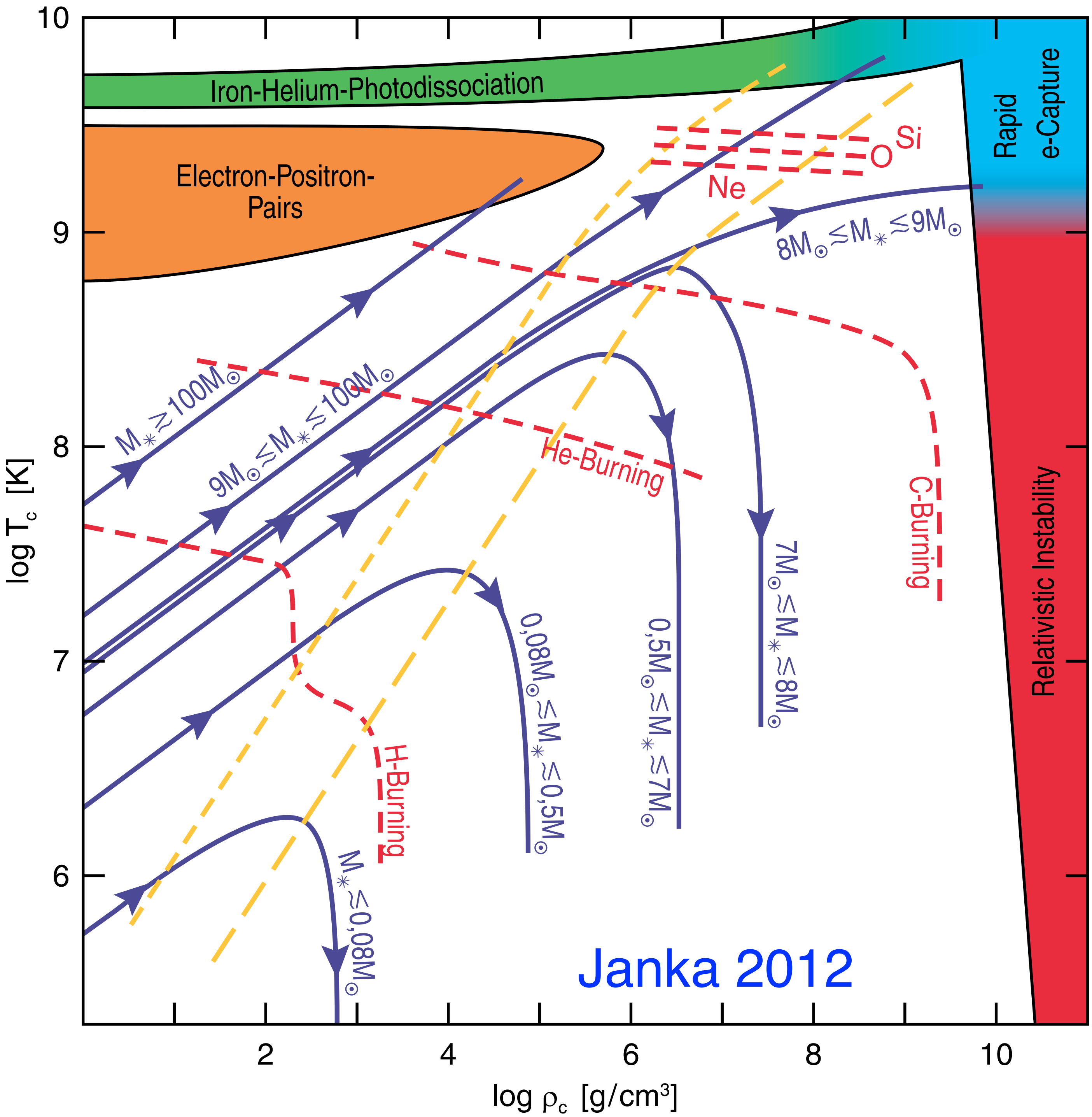
Virial theorem for a contracting gas cloud

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

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

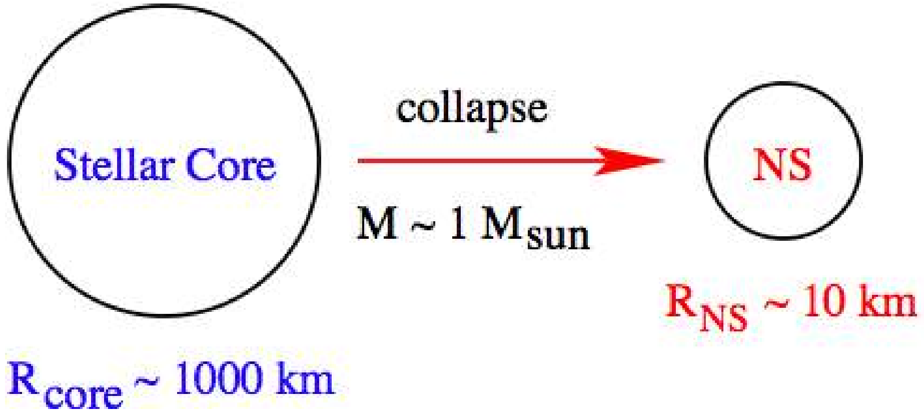
$$T_c \sim \frac{GMm_p}{R} - \frac{\hbar^2}{2m_e}\left(\frac{M}{m_p}\right)^{2/3}\frac{1}{R^2}$$

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


10
9
8
7
6
2
4
6
8
10
log T_c [K]
log ρ_c [g/cm^3]
Iron-Helium-Photodissociation
Electron-Positron-Pairs
Rapid e-Capture
Relativistic Instability
Si
O
Ne
He-Burning
C-Burning
H-Burning
$M_\ast \gtrsim 100M_\odot$
$9M_\odot \lesssim M_\ast \lesssim 100M_\odot$
$8M_\odot \lesssim M_\ast \lesssim 9M_\odot$
$7M_\odot \lesssim M_\ast \lesssim 8M_\odot$
$0{,}5M_\odot \lesssim M_\ast \lesssim 7M_\odot$
$0{,}08M_\odot \lesssim M_\ast \lesssim 0{,}5M_\odot$
$M_\ast \lesssim 0{,}08M_\odot$

Janka 2012

Neutrino Emission from NS Formation



Stellar Core

collapse

$M \sim 1\, M_{\rm sun}$

NS

$R_{\rm NS} \sim 10$ km

$R_{\rm core} \sim 1000$ km

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

$$N + N \to N + N + \nu + \bar\nu$$

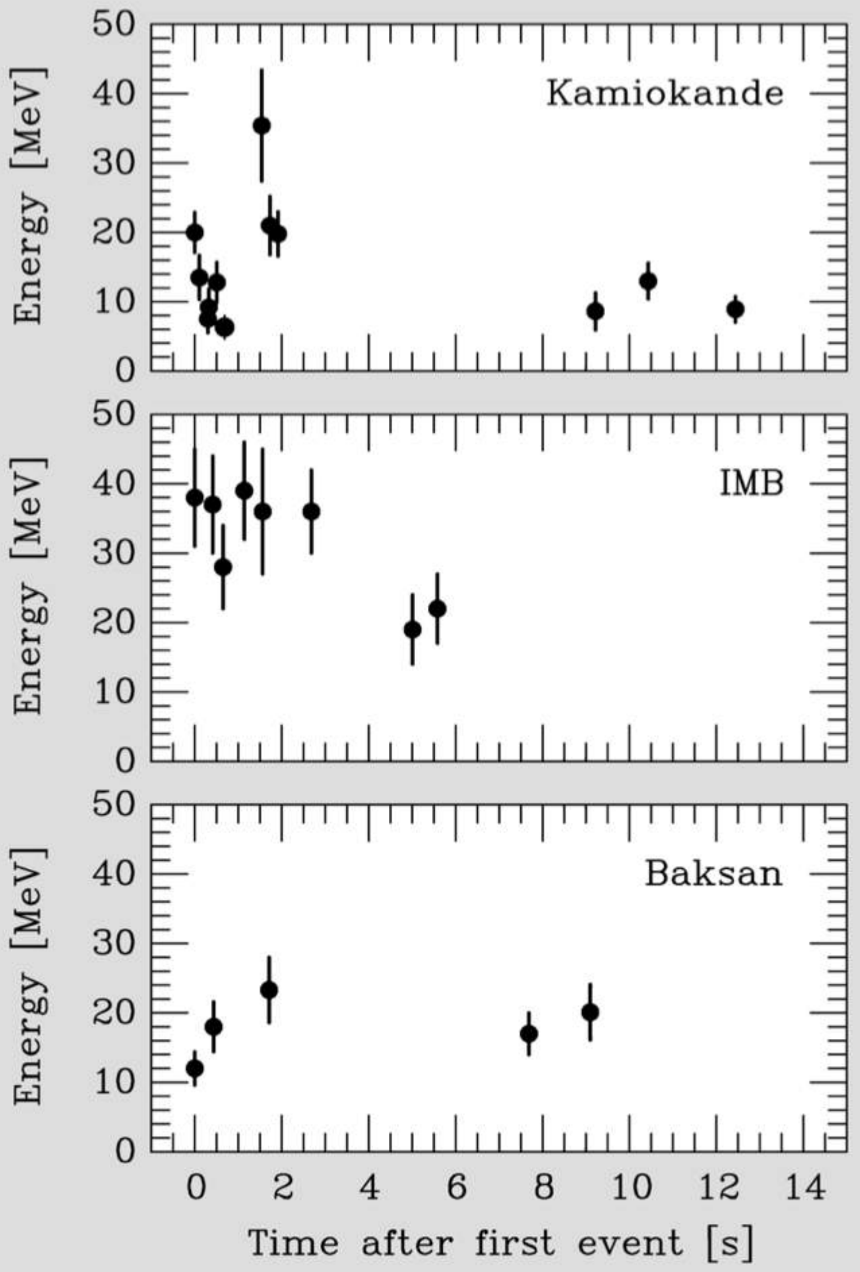
$$\frac{GM^2}{R_{\rm NS}} \sim 3 \times 10^{53}\ \text{erg}$$

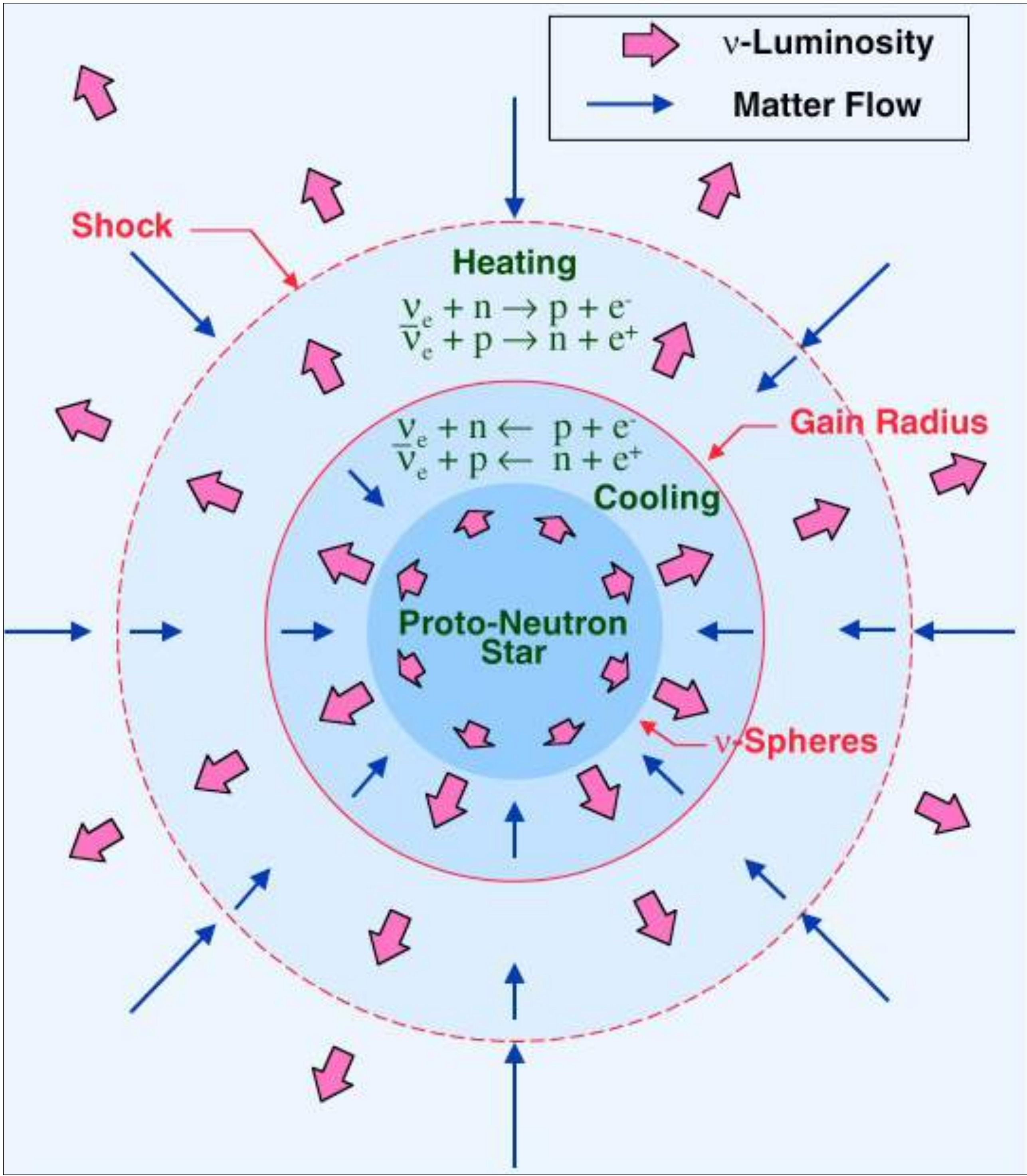
$$\Rightarrow \nu_e,\ \bar\nu_e,\ \nu_\mu,\ \bar\nu_\mu,\ \nu_\tau,\ \bar\nu_\tau$$

for a Galactic SN at ~10 kpc

~10^4 events due to

$$\bar\nu_e + p \to n + e^+$$





$$\dot{q}_{\nu N} \propto \frac{L_\nu}{\langle E_\nu \rangle} \frac{\langle E_\nu \sigma_{\nu N} \rangle}{r^2}$$

$$\dot{q}_{eN} \propto n_e \langle E_e \sigma_{eN} \rangle$$

$$\propto T^6$$

gain radius r_g

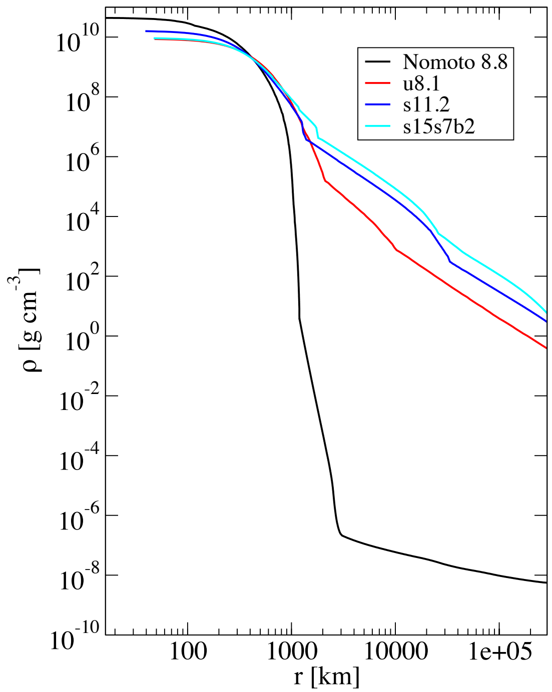
$$\dot{q}_{\nu N}(r_g) = \dot{q}_{eN}(r_g)$$

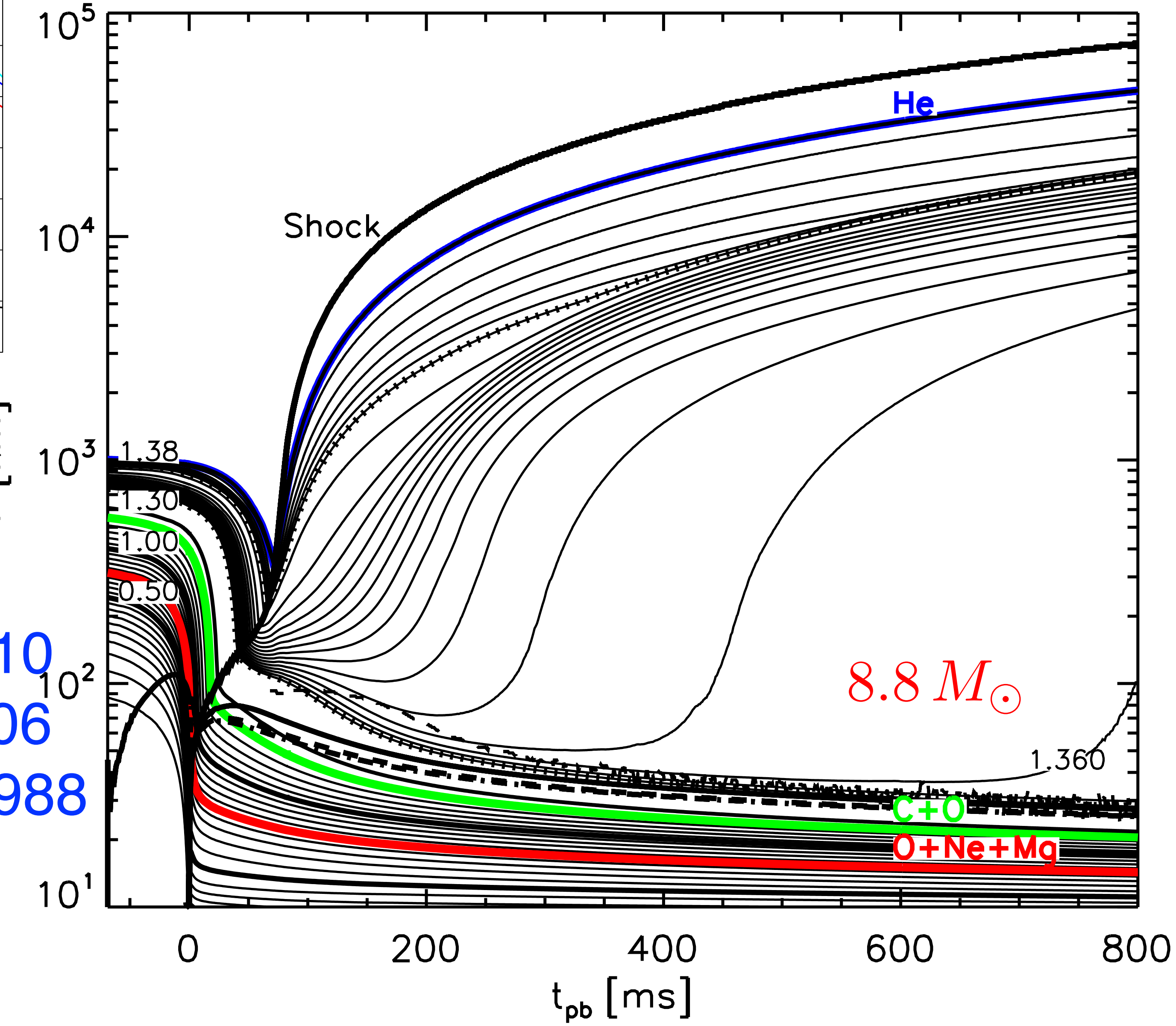
outside gain radius

$$\dot{q}_{\nu N}(r) > \dot{q}_{eN}(r)$$

Bethe & Wilson 1985

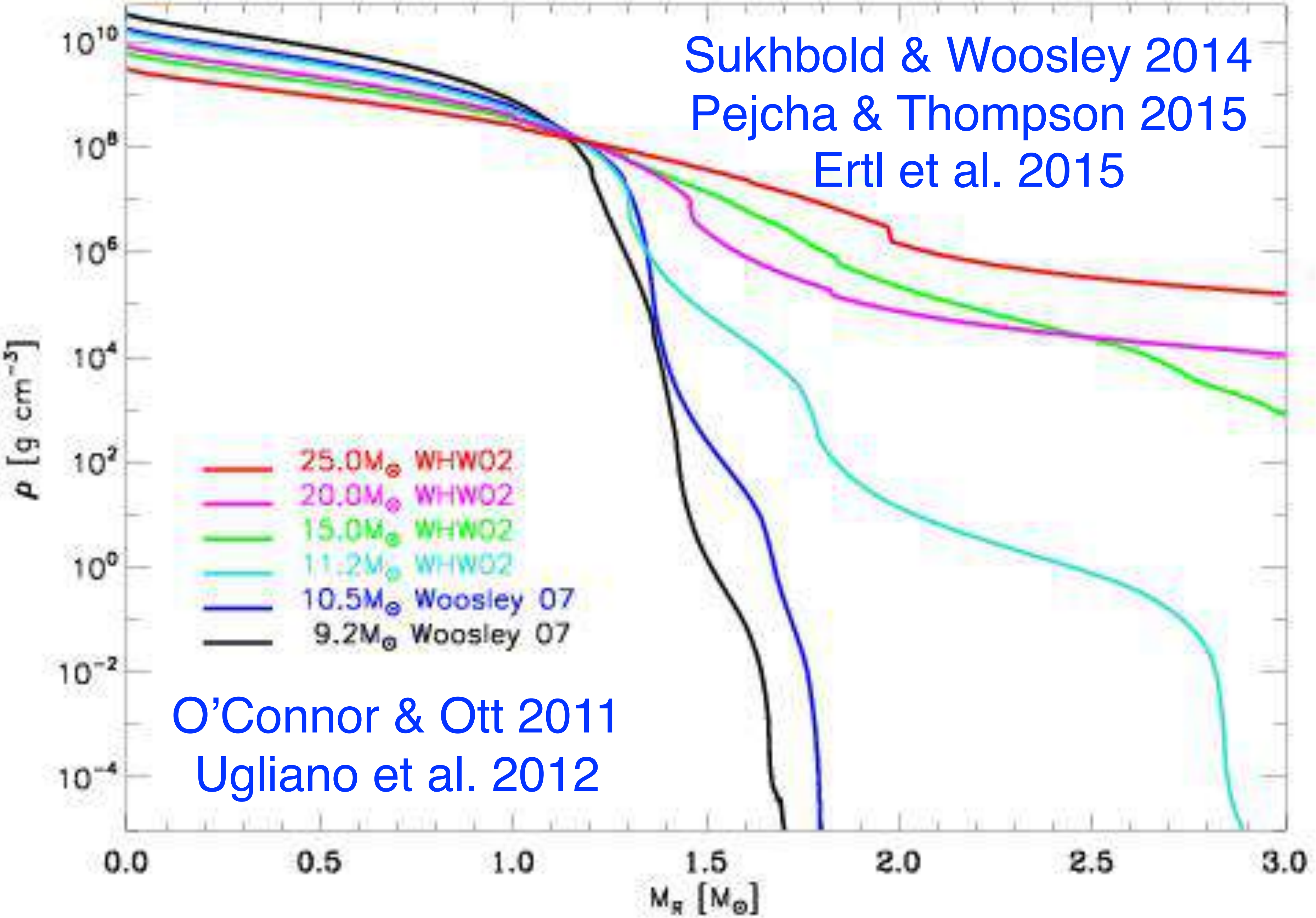
Neutrino-Driven Explosion of a Low-Mass SN





Janka 2012
Fischer et al. 2010
Kitaura et al. 2006
Mayle & Wilson 1988

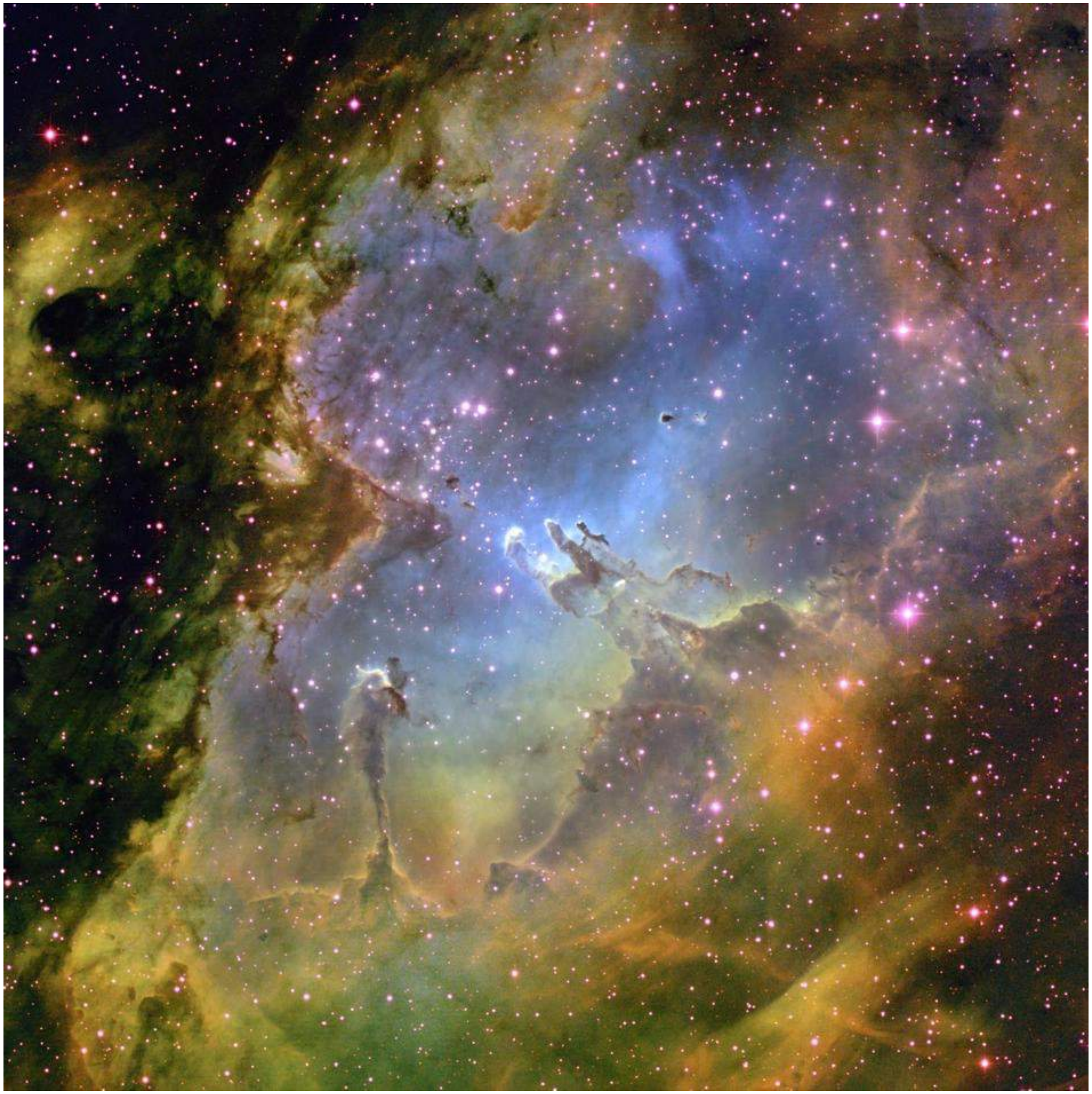
Compactness & Explodability



Sukhbold & Woosley 2014
Pejcha & Thompson 2015
Ertl et al. 2015

O'Connor & Ott 2011
Ugliano et al. 2012

Giant Molecular Cloud: Stellar Nursery



Lifetime of Giant Molecular Clouds ~ 15-39 Myr (Murray 2011)

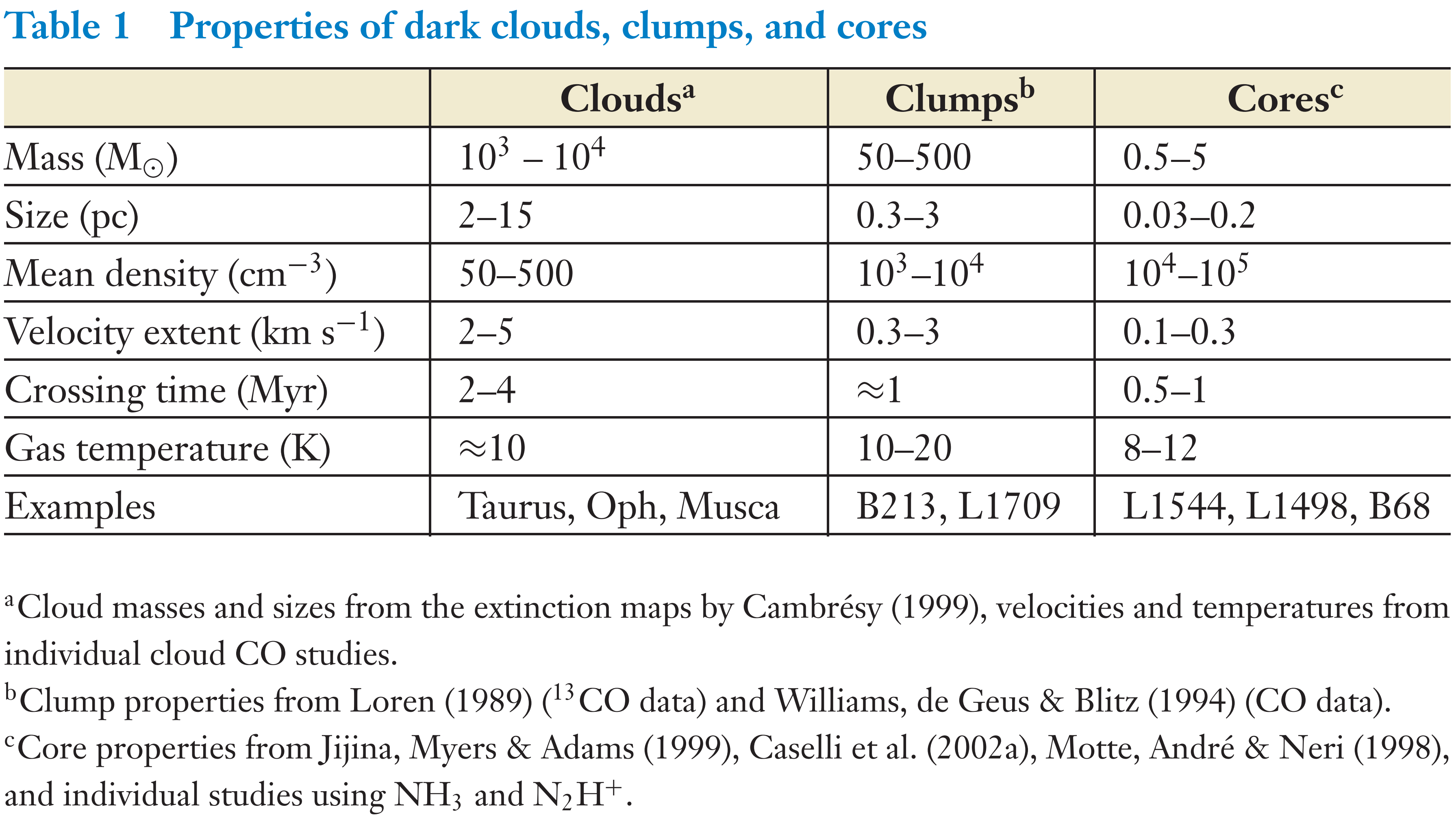


Table 1 Properties of dark clouds, clumps, and cores

	Clouds[a]	Clumps[b]	Cores[c]
Mass ($M_\odot$)	$10^3 - 10^4$	50–500	0.5–5
Size (pc)	2–15	0.3–3	0.03–0.2
Mean density (cm^{-3})	50–500	10^3–10^4	10^4–10^5
Velocity extent ($km\ s^{-1}$)	2–5	0.3–3	0.1–0.3
Crossing time (Myr)	2–4	≈1	0.5–1
Gas temperature (K)	≈10	10–20	8–12
Examples	Taurus, Oph, Musca	B213, L1709	L1544, L1498, B68

[a] Cloud masses and sizes from the extinction maps by Cambrésy (1999), velocities and temperatures from individual cloud CO studies.

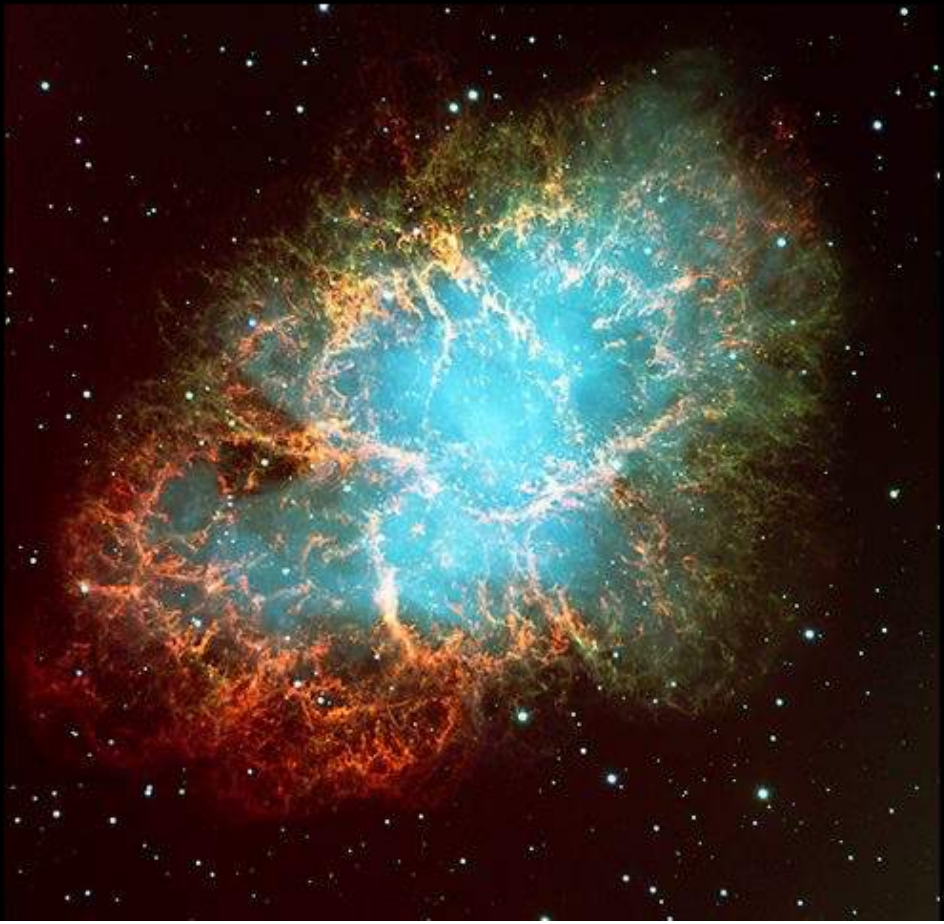
[b] Clump properties from Loren (1989) (^{13}CO data) and Williams, de Geus & Blitz (1994) (CO data).

[c] Core properties from Jijina, Myers & Adams (1999), Caselli et al. (2002a), Motte, André & Neri (1998), and individual studies using NH_3 and N_2H^+.

Bergin & Tafalla 2007

Sources of Shock Waves Triggering Star Formation

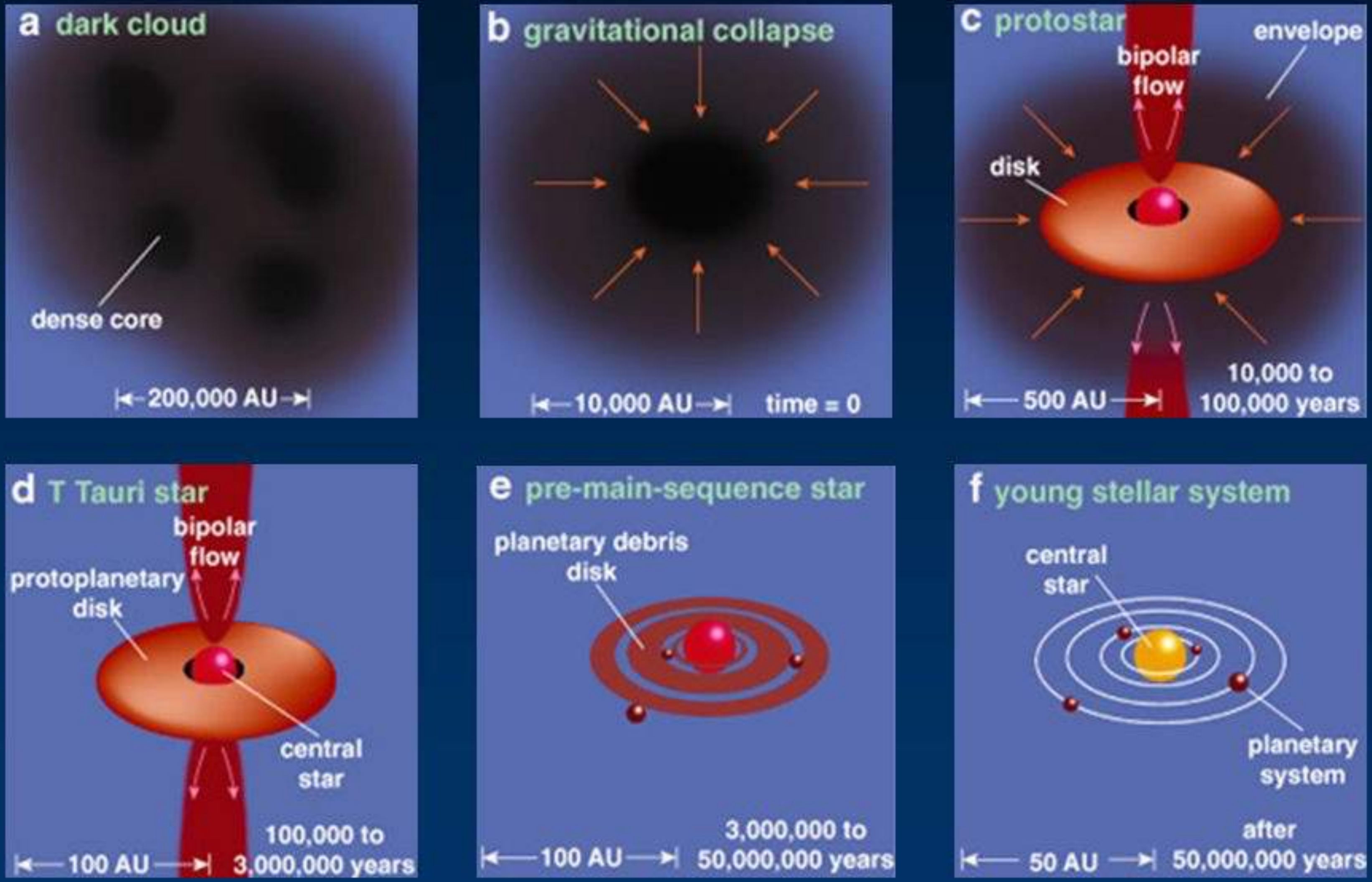
Previous star formation can trigger further star formation through:

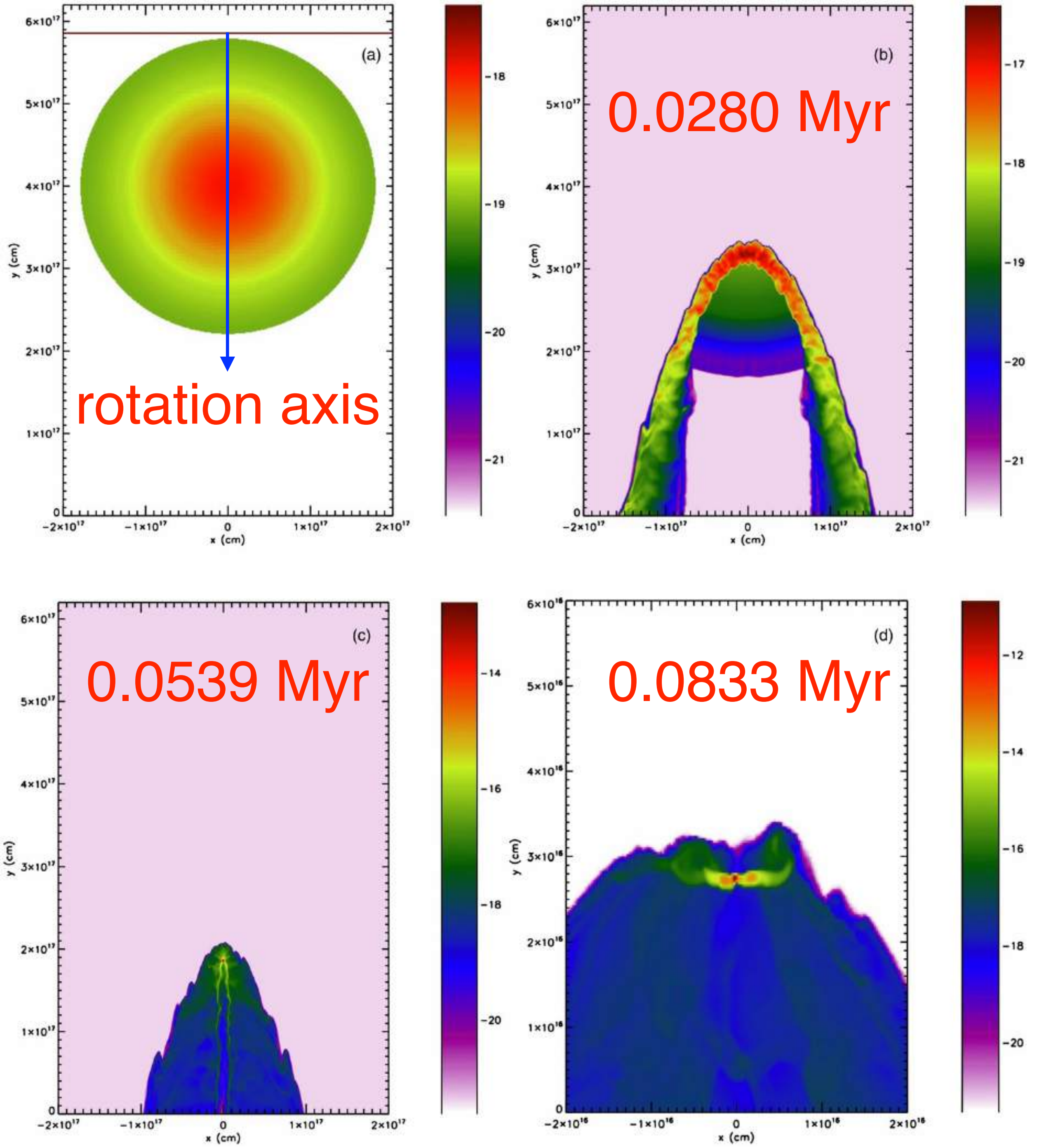


a) Shocks from supernovae (explosions of massive stars):

Massive (O, B) stars die young => Supernovae tend to happen near sites of recent star formation

Obligatory star & planet formation slide





rotation axis

0.0280 Myr

0.0539 Myr

0.0833 Myr

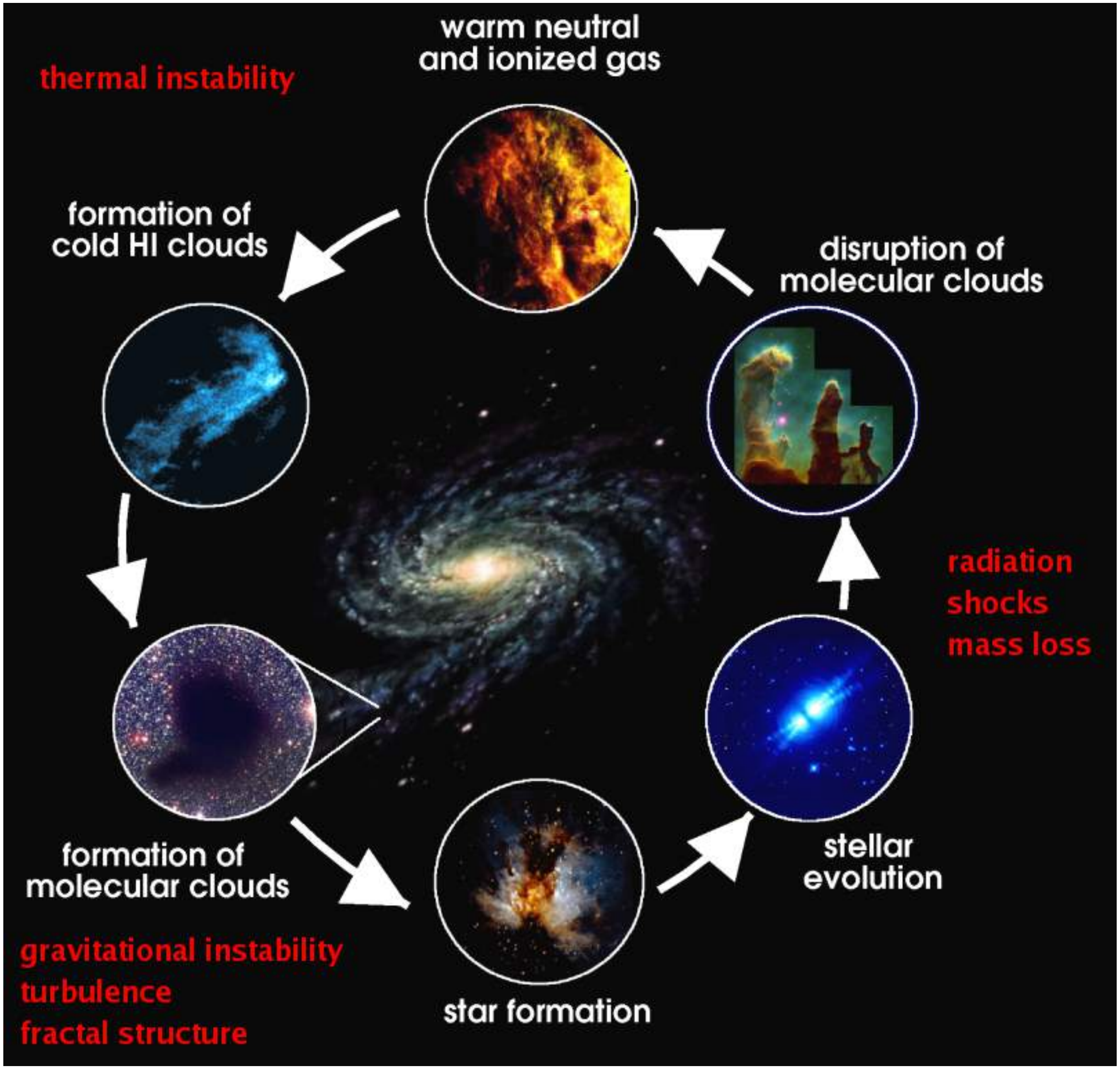
Boss & Keiser
2014, 2015

shock velocity
~ 20-40 km/s

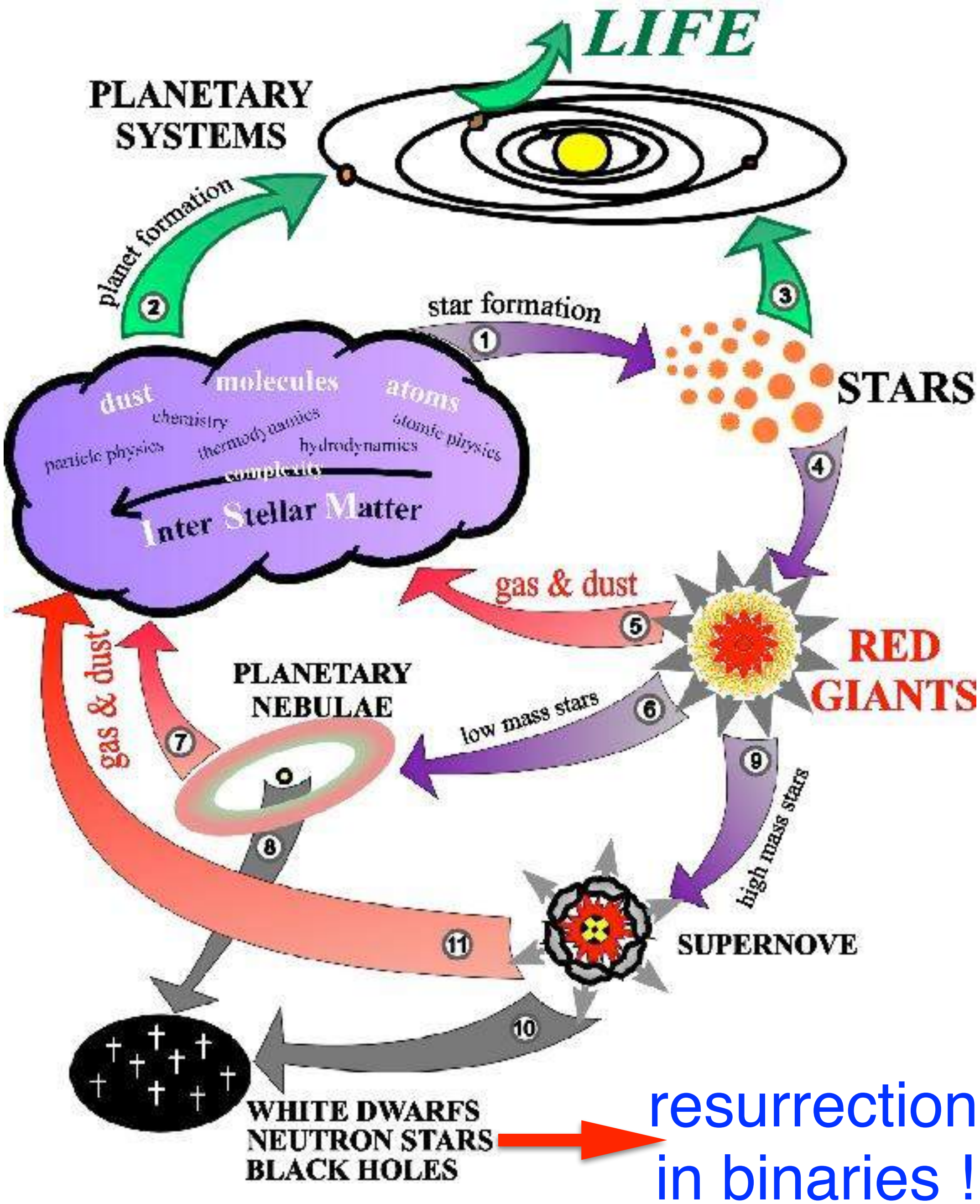
injection of shock
material via
Rayleigh-Taylor
fingers

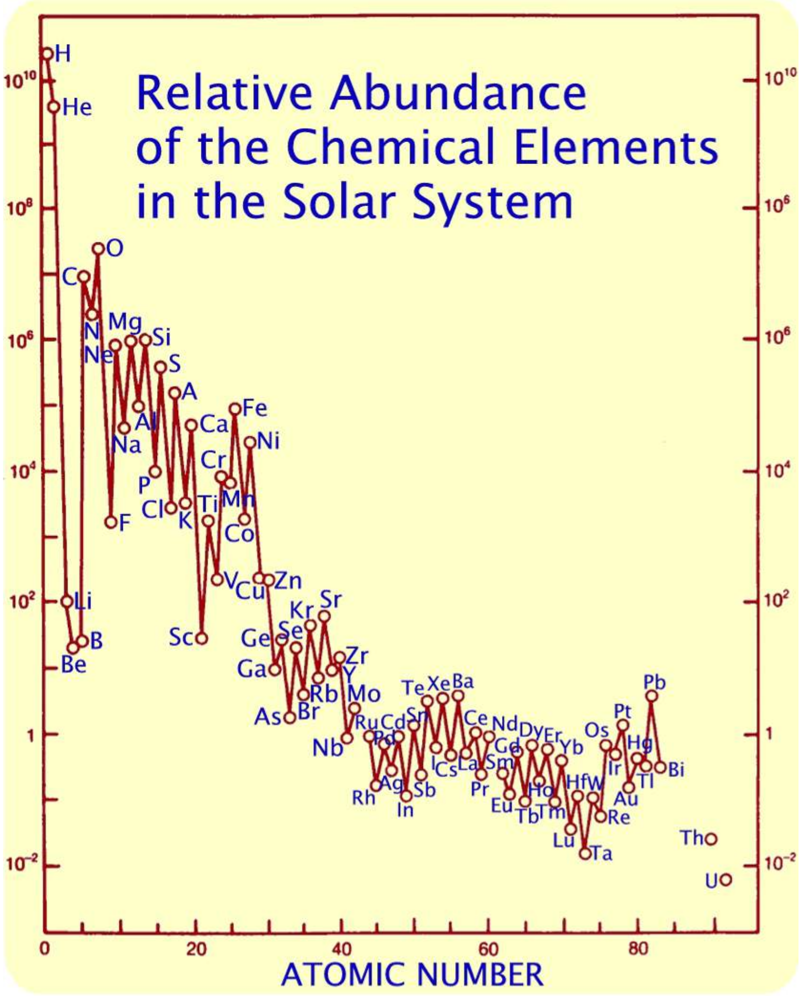
injection efficiency
~ 3-10%

Life Cycle of Interstellar Medium



Arise from the Ashes





→ resurrection in binaries !

Contributing CCSNe prior to Solar System Formation

$$R_{\rm CCSN} \sim (30\ {\rm yr})^{-1}$$

$$M_g \sim 10^{10}\ M_\odot$$

$$M_{\rm mix} \sim 3 \times 10^4\ M_\odot$$

$$\begin{aligned} R_{\rm mix} &\sim R_{\rm CCSN}\left(\frac{M_{\rm mix}}{M_g}\right) \\ &\sim \frac{1}{10^7\ {\rm yr}}\left[\frac{R_{\rm CCSN}}{(30\ {\rm yr})^{-1}}\right]\left(\frac{M_{\rm mix}}{3 \times 10^4\ M_\odot}\right)\left(\frac{10^{10}\ M_\odot}{M_g}\right) \end{aligned}$$

$$t \sim 9\ {\rm Gyr} \Rightarrow N_{\rm CCSN} \sim R_{\rm mix} t \sim 900$$

Constraints on a CCSN Trigger for Solar System Formation

Do No Evil !

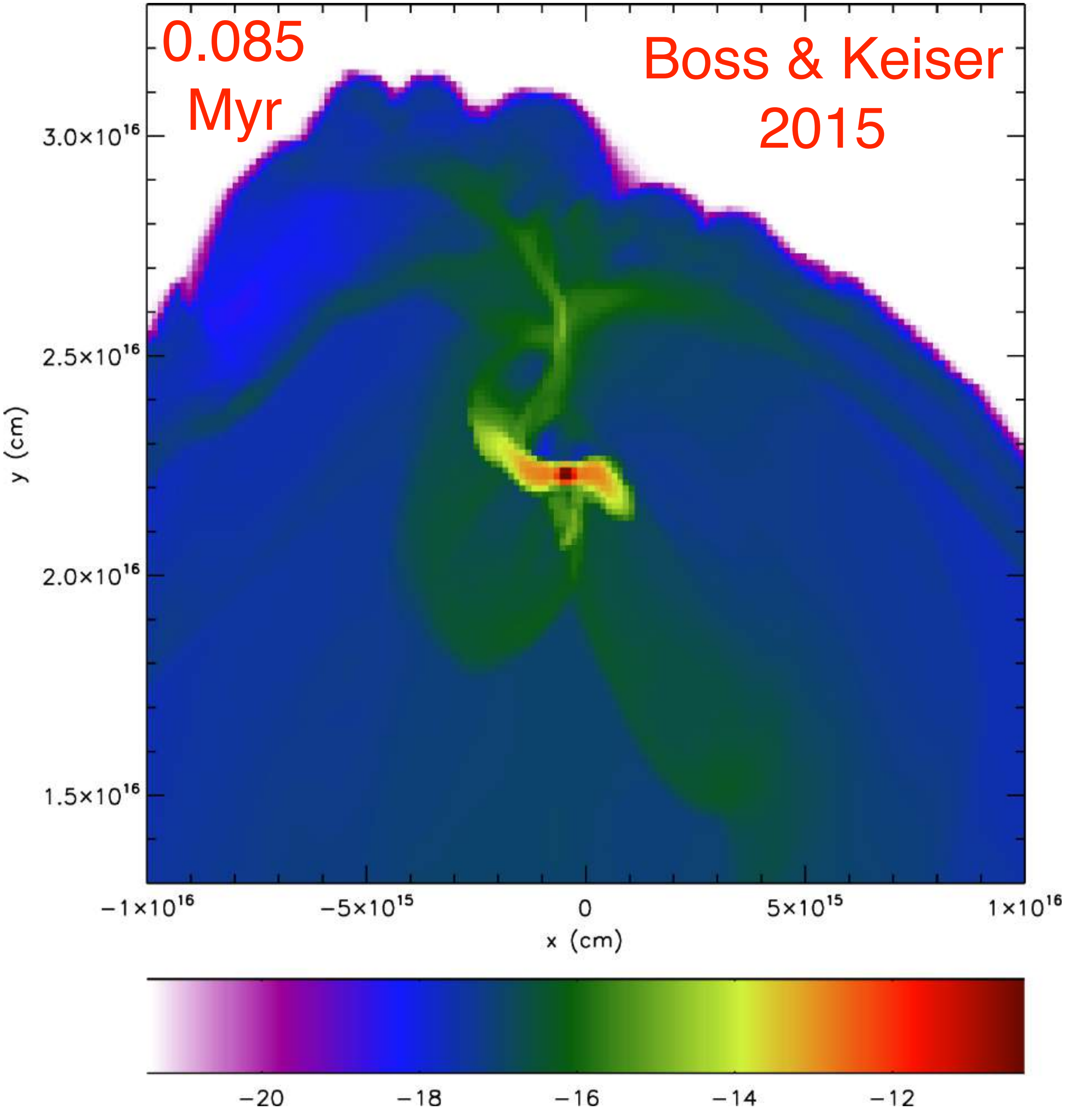
$$\delta({}^{i}\mathrm{E}/{}^{j}\mathrm{E}) \equiv \frac{({}^{i}\mathrm{E}/{}^{j}\mathrm{E}) - ({}^{i}\mathrm{E}/{}^{j}\mathrm{E})_{\odot}}{({}^{i}\mathrm{E}/{}^{j}\mathrm{E})_{\odot}}$$

for stable isotopes of major elements, e.g., Mg, Si, Ca, Fe

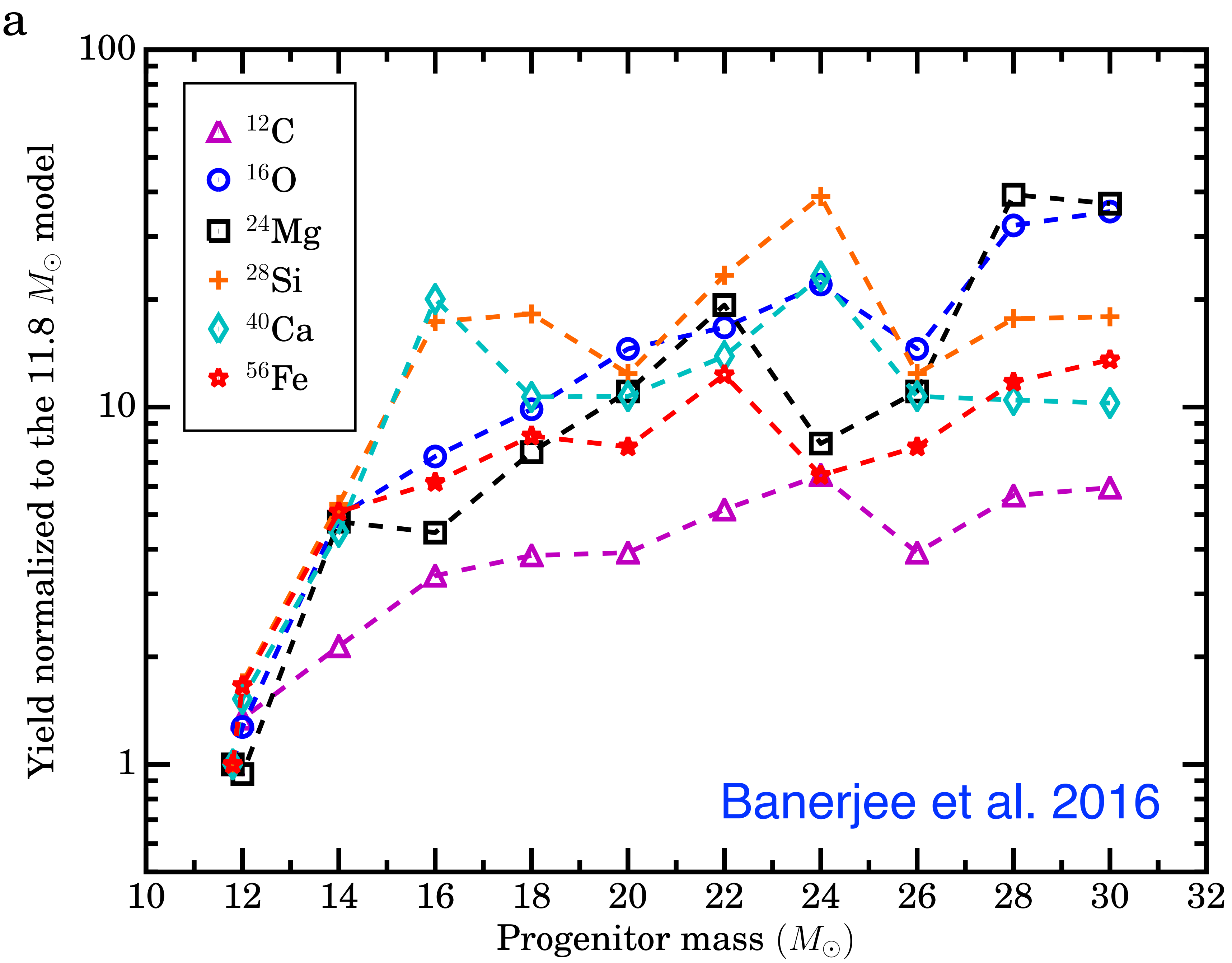
$|\delta({}^{i}\mathrm{E}/{}^{j}\mathrm{E})| \lesssim 1\%$ →

high-mass CCSNe problematic !

Wasserburg et al. 2006



if SN trigger
had provided
too much of
any stable
isotope,
incomplete
mixing with
proto-solar
cloud would
have produced
large isotopic
anomalies

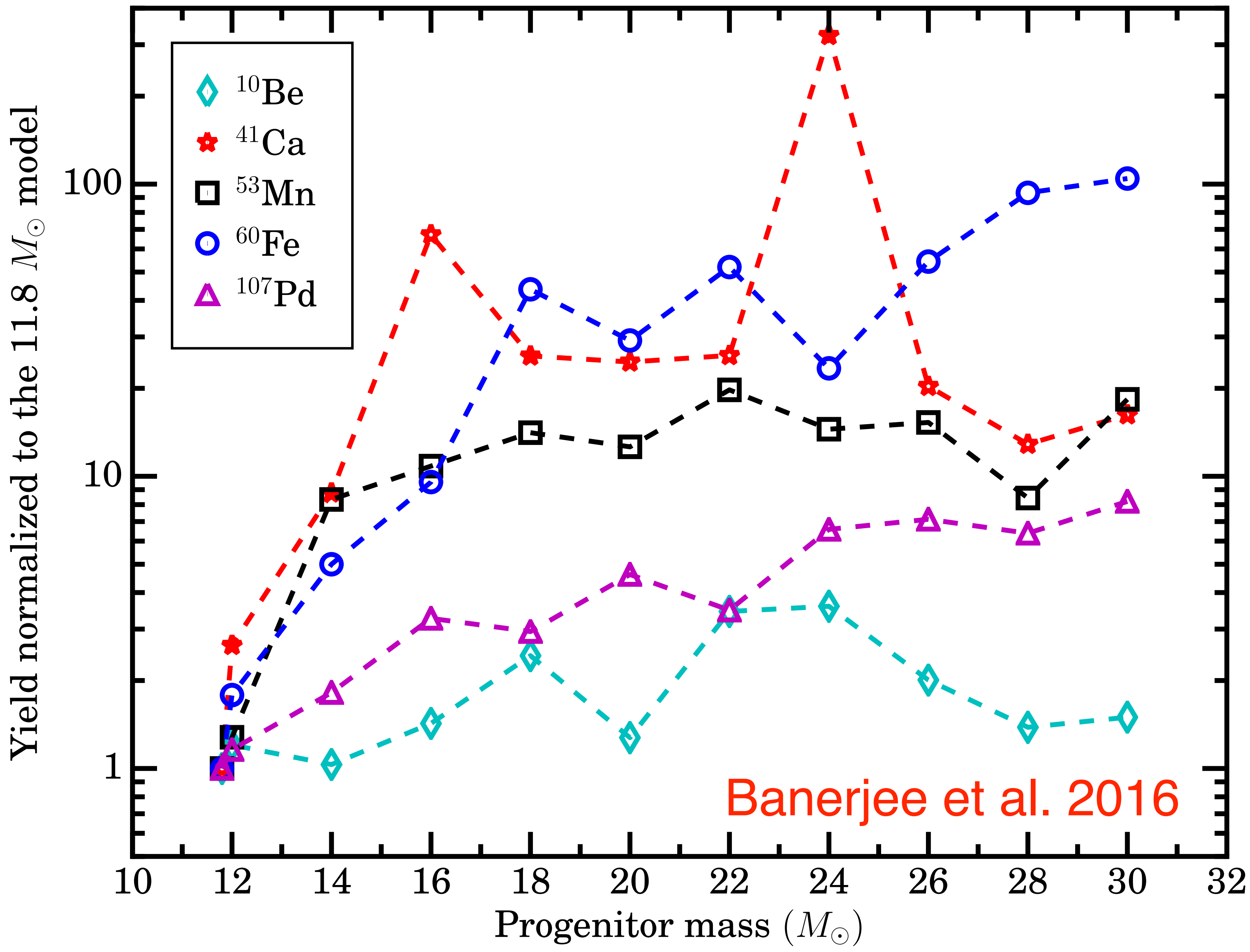

a
100
10
1
Yield normalized to the 11.8 $M_\odot$ model
^{12}C
^{16}O
^{24}Mg
^{28}Si
^{40}Ca
^{56}Fe
Banerjee et al. 2016
10
12
14
16
18
20
22
24
26
28
30
32
Progenitor mass ($M_\odot$)

Short-Lived Radionuclides in the Early Solar System

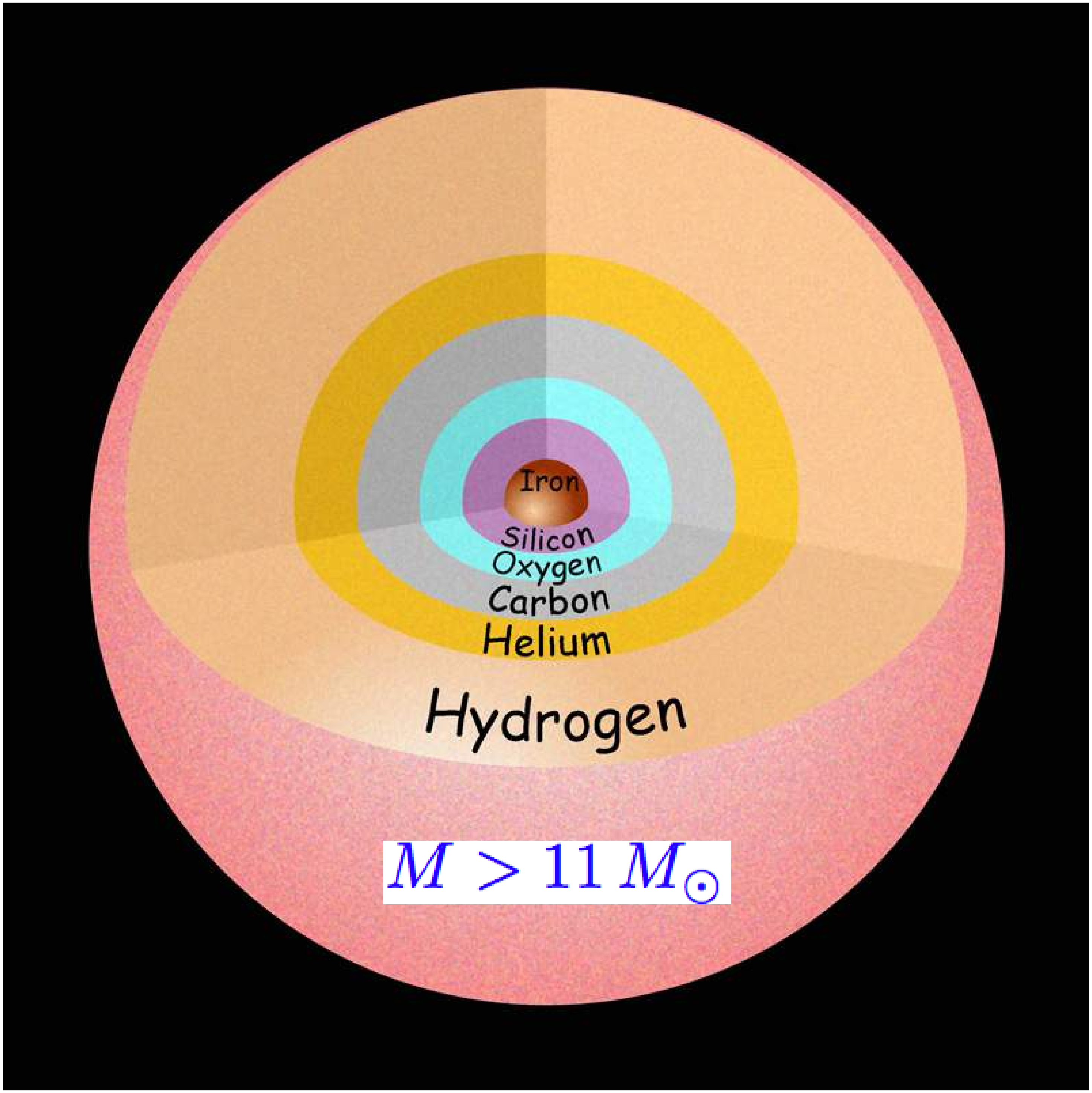
SLR	$^{41}\mathrm{Ca}$	$^{36}\mathrm{Cl}$	$^{26}\mathrm{Al}$	$^{10}\mathrm{Be}$	$^{135}\mathrm{Cs}$
Lifetime (Myr)	0.147	0.434	1.03	2.00	3.32
SLR	$^{60}\mathrm{Fe}$	$^{53}\mathrm{Mn}$	$^{107}\mathrm{Pd}$	$^{182}\mathrm{Hf}$	$^{247}\mathrm{Cm}$
Lifetime (Myr)	3.78	5.40	9.38	12.8	22.5
SLR	$^{129}\mathrm{I}$	$^{205}\mathrm{Pb}$	$^{92}\mathrm{Nb}$	$^{146}\mathrm{Sm}$	$^{244}\mathrm{Pu}$
Lifetime (Myr)	22.7	25.0	50.1	98.1	115

Constraints from Short-Lived Radionuclides (SLRs)

b



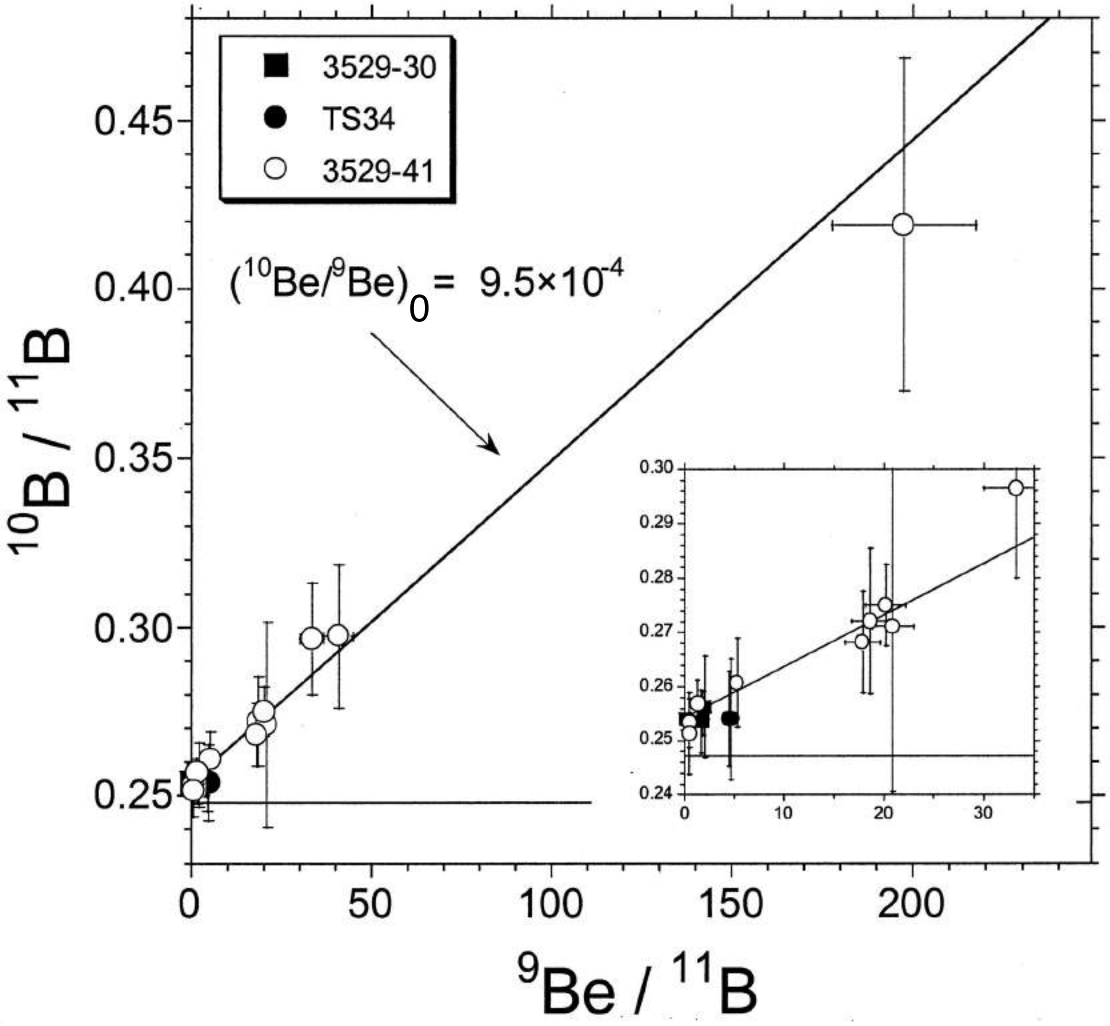
Banerjee et al. 2016



$M > 11\,M_{\odot}$

Neutrino-Induced Production of ^{10}Be (Banerjee et al. 2016)

$$\nu + {}^{12}\mathrm{C} \rightarrow {}^{10}\mathrm{Be} + 2p + \nu'$$



McKeegan et al. 2000

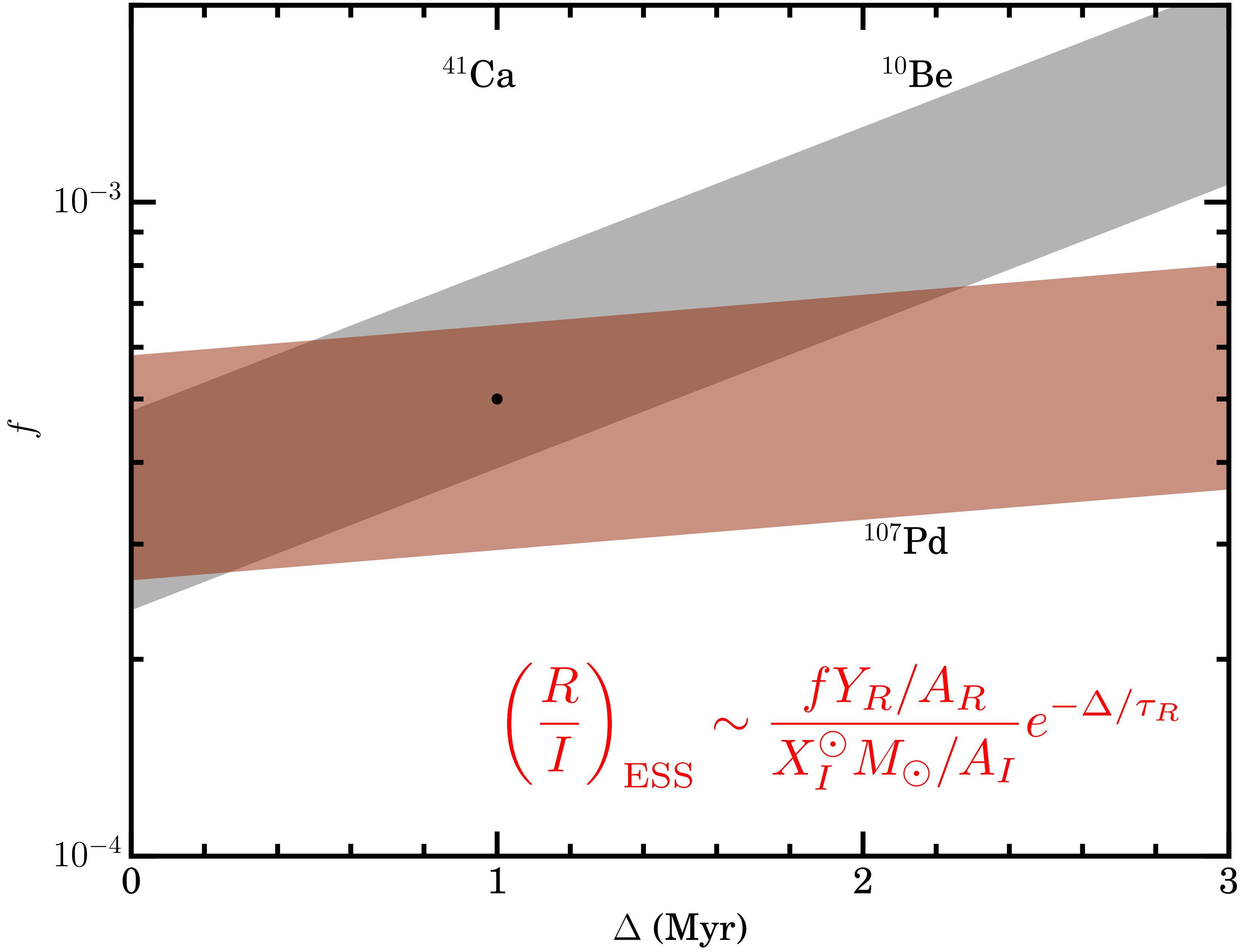
number of ^{12}C targets increases with progenitor mass

\+

neutrino flux in C shell decreases with progenitor mass

approximately constant production of ^{10}Be by CCSNe

Banerjee et al. 2016

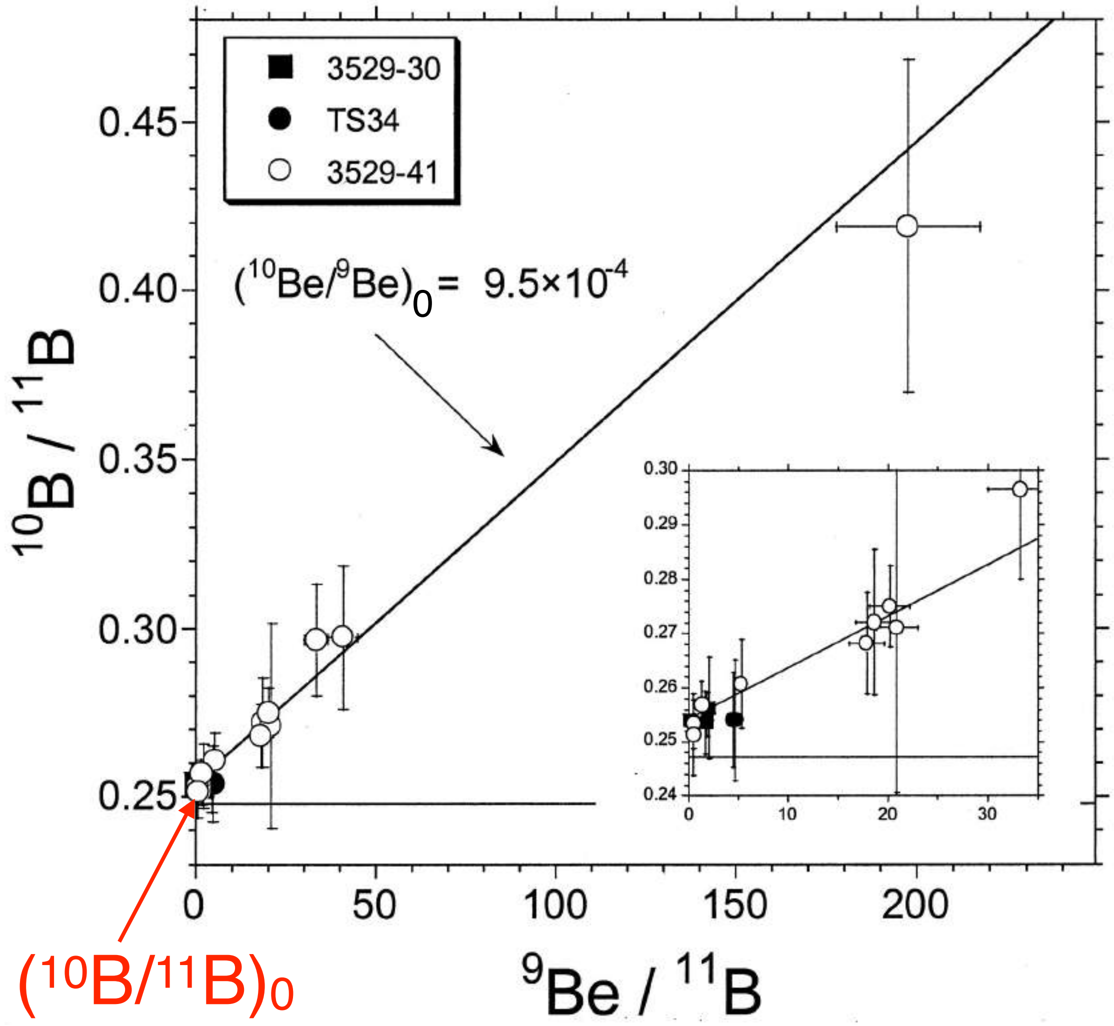


$$\left(\frac{R}{I}\right)_{\mathrm{ESS}} \sim \frac{fY_R/A_R}{X_I^{\odot}M_{\odot}/A_I}e^{-\Delta/\tau_R}$$

Forensic Evidence for a Low-Mass CCSN Trigger

R/I	τ_R	Y_R	$X_I^{\odot}$	$(N_R/N_I)_{\rm ESS}$			
	(Myr)	$(M_{\odot})$		Data	Case 1	Case 2	Case 3
$^{\mathbf{10}}\mathbf{Be}/^{\mathbf{9}}\mathbf{Be}$	2.00	$3.26(-10)$	$1.40(-10)$	$(\mathbf{7.5}\pm\mathbf{2.5})(-\mathbf{4})$	$6.35(-4)$	$6.35(-4)$	$5.20(-4)$
$^{26}\mathrm{Al}/^{27}\mathrm{Al}$	1.03	$2.91(-6)$	$5.65(-5)$	$(5.23\pm0.13)(-5)$	$1.02(-5)$	$9.90(-6)$	$5.77(-6)$
$^{36}\mathrm{Cl}/^{35}\mathrm{Cl}$	0.434	$1.44(-7)$	$3.50(-6)$	$\sim(3\text{–}20)(-6)$	$2.00(-6)$	$1.45(-6)$	$6.15(-7)$
$^{\mathbf{41}}\mathbf{Ca}/^{\mathbf{40}}\mathbf{Ca}$	0.147	$3.66(-7)$	$5.88(-5)$	$(\mathbf{4.1}\pm\mathbf{2.0})(-\mathbf{9})$	$3.40(-9)$	$2.74(-9)$	$2.26(-9)$
$^{53}\mathrm{Mn}/^{55}\mathrm{Mn}$	5.40	$1.22(-5)$	$1.29(-5)$	$(6.28\pm0.66)(-6)$	$4.04(-4)$	$6.39(-6)$	$6.16(-6)$
$^{60}\mathrm{Fe}/^{56}\mathrm{Fe}$	3.78	$3.08(-6)$	$1.12(-3)$	$\sim1(-8);(5\text{–}10)(-7)$	$9.80(-7)$	$9.80(-7)$	$1.10(-7)$
$^{\mathbf{107}}\mathbf{Pd}/^{\mathbf{108}}\mathbf{Pd}$	9.38	$1.37(-10)$	$9.92(-10)$	$(\mathbf{5.9}\pm\mathbf{2.2})(-\mathbf{5})$	$6.27(-5)$	$6.27(-5)$	$5.72(-5)$
$^{135}\mathrm{Cs}/^{133}\mathrm{Cs}$	3.32	$2.56(-10)$	$1.24(-9)$	$\sim5(-4)$	$7.51(-5)$	$7.51(-5)$	$3.18(-5)$
$^{182}\mathrm{Hf}/^{180}\mathrm{Hf}$	12.84	$4.04(-11)$	$2.52(-10)$	$(9.72\pm0.44)(-5)$	$7.36(-5)$	$7.36(-5)$	$6.34(-6)$
		$8.84(-12)$			$1.60(-5)$	$1.60(-5)$	$2.37(-6)$
$^{205}\mathrm{Pb}/^{204}\mathrm{Pb}$	24.96	$9.20(-11)$	$3.47(-10)$	$\sim1(-4);1(-3)$	$1.27(-4)$	$1.27(-4)$	$7.78(-5)$

Test of a Low-Mass CCSN Trigger for Solar System Formation



(^{10}B/^{11}B)$_0$

neutrino-induced
co-production of
^{7}Li and ^{11}B

higher (^{10}Be/^{9}Be)$_0$
correlates with
higher (^{7}Li/^{6}Li)$_0$ &
lower (^{10}B/^{11}B)$_0$

Summary

Constraints on shifts in ratios of stable isotopes
of major elements, e.g., Mg, Si, Ca, Fe, and
on contributions to SLRs, especially ^{53}Mn & ^{60}Fe,
strongly favor a low-mass CCSN trigger
for solar system formation

Such a CCSN can account for the SLR ^{10}Be
by neutrino-induced production, and ^{41}Ca & ^{107}Pd,
possibly also ^{53}Mn & ^{60}Fe, by other mechanisms

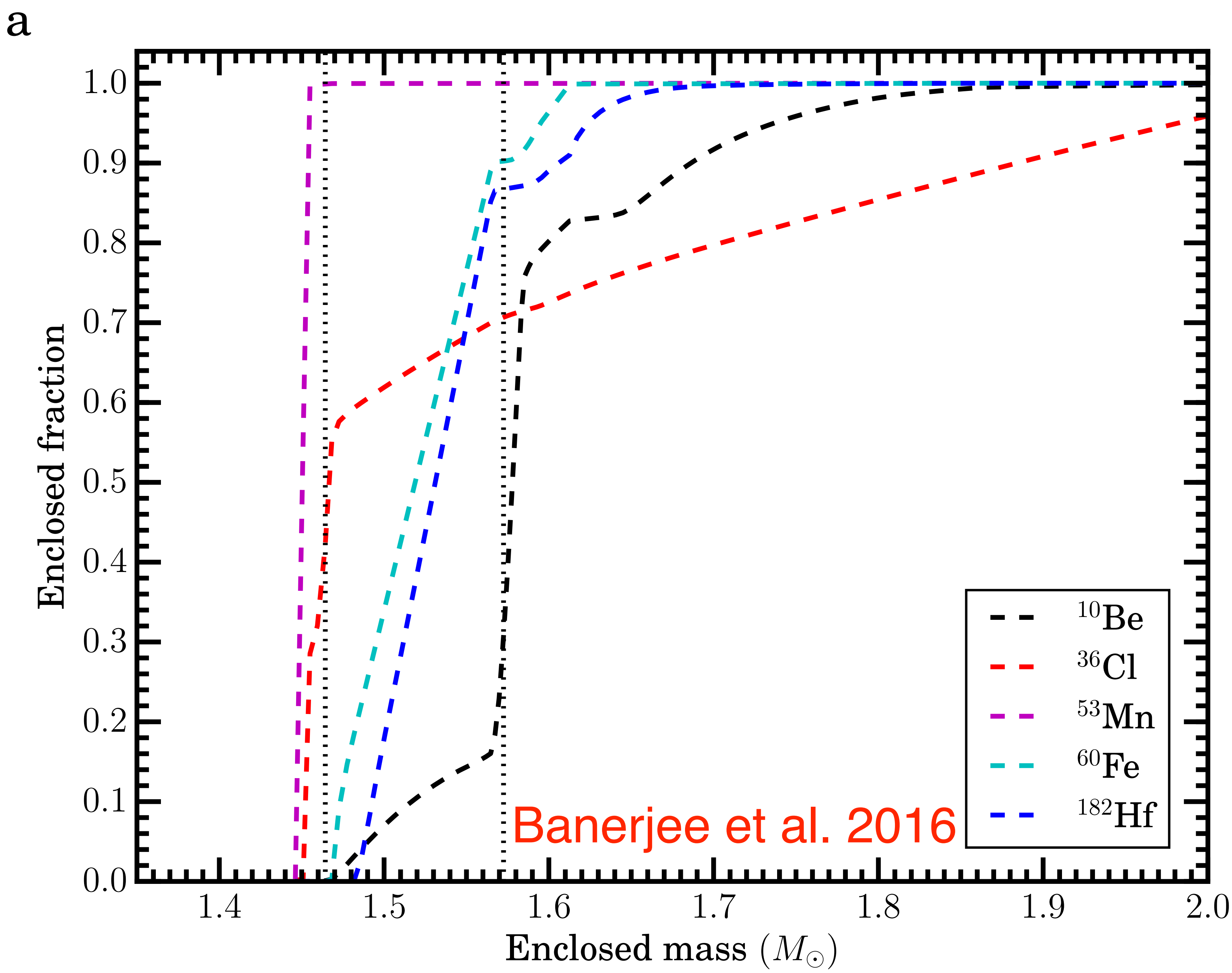
The neutrino-induced co-production of ^{7}Li & ^{11}B
provides a test for this CCSN trigger

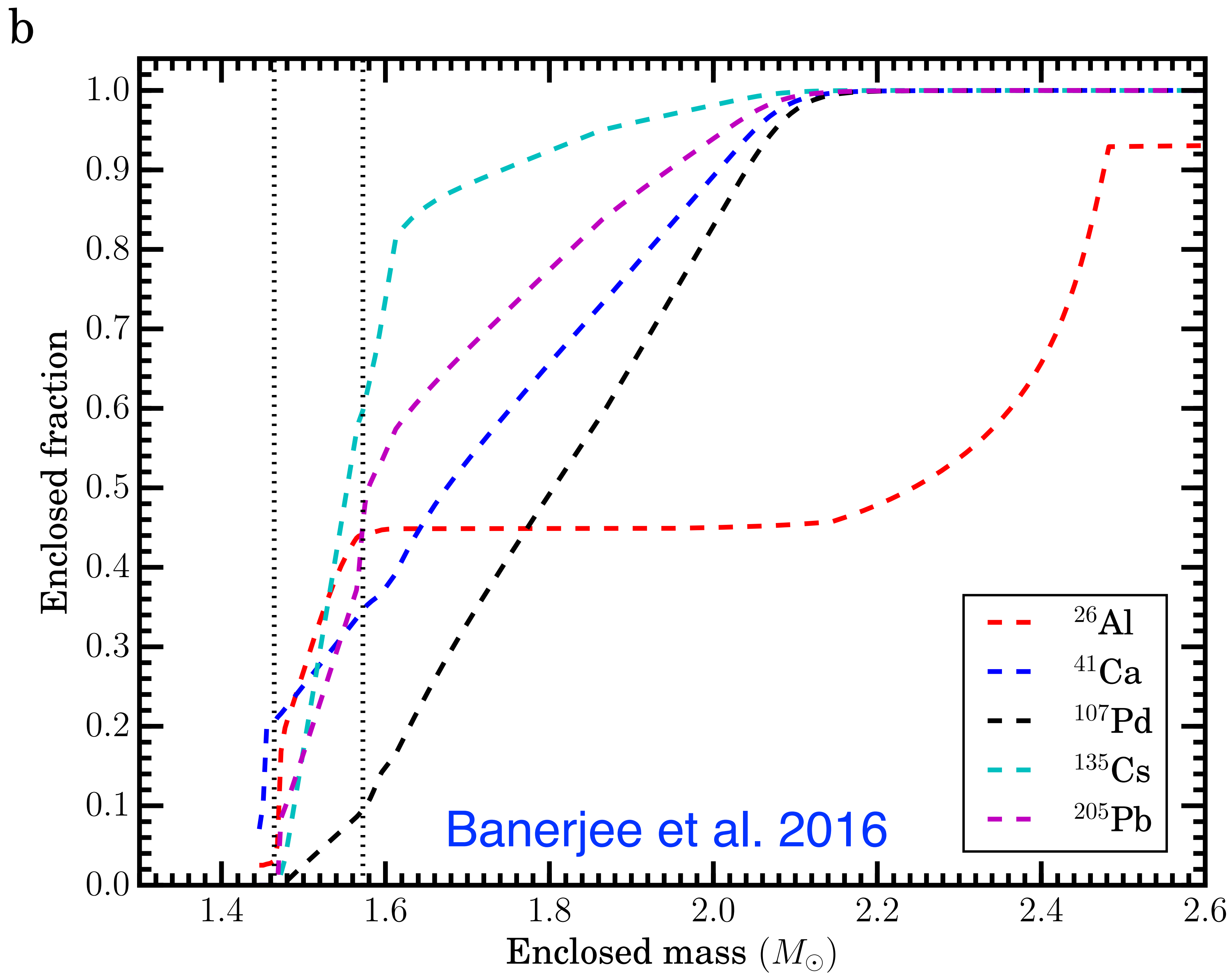
Future Studies

3D modeling of low-mass SN explosion & associated nucleosynthesis, especially production of ^{53}Mn & ^{60}Fe

simulations of low-mass SN remnant evolution in a giant molecular cloud to quantify the triggering scenario of solar system formation

explanations of other SLRs, especially ^{26}Al, in the early solar system


a
Enclosed fraction
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Enclosed mass ($M_\odot$)
^{10}Be
^{36}Cl
^{53}Mn
^{60}Fe
^{182}Hf
Banerjee et al. 2016


b
Enclosed fraction
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.4
1.6
1.8
2.0
2.2
2.4
2.6
Enclosed mass ($M_\odot$)
^{26}Al
^{41}Ca
^{107}Pd
^{135}Cs
^{205}Pb
Banerjee et al. 2016