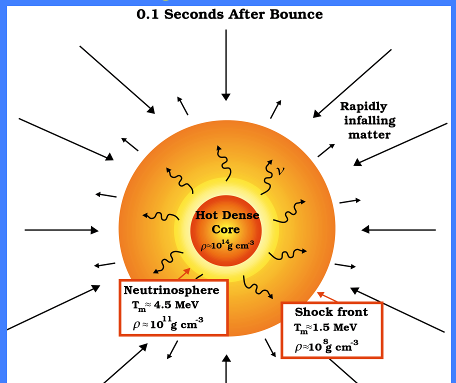
New Frontiers in Supernova Neutrino Physics: Collapsar MHD Jets and the *r* Process; the ν Process and the Neutrino Mass Hierarchy

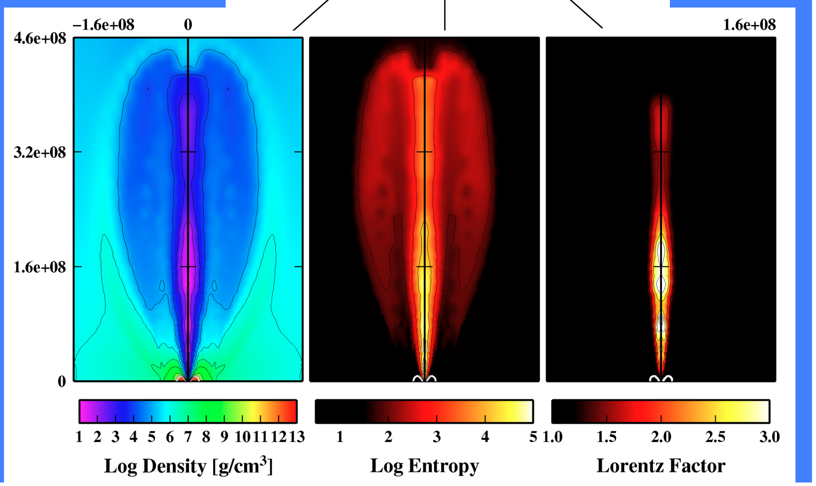
G. J. Mathews – University of Notre Dame



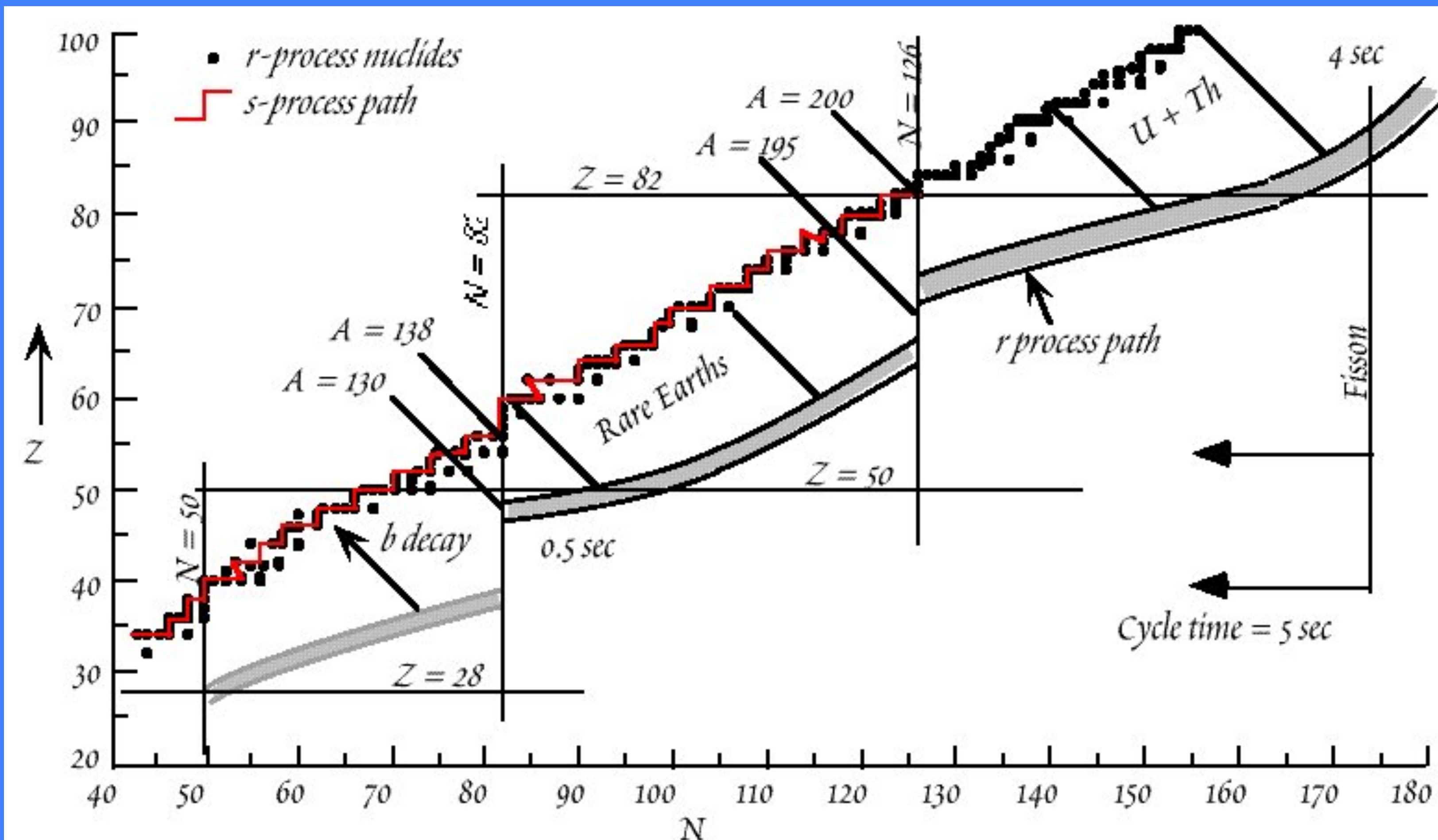
International Workshop on "Element Genesis and Cosmic Chemical Evolution: the r-process perspective"

Oct. 17, 2012

RIKEN, Wako, Japan



The r-process perspective



What we know?

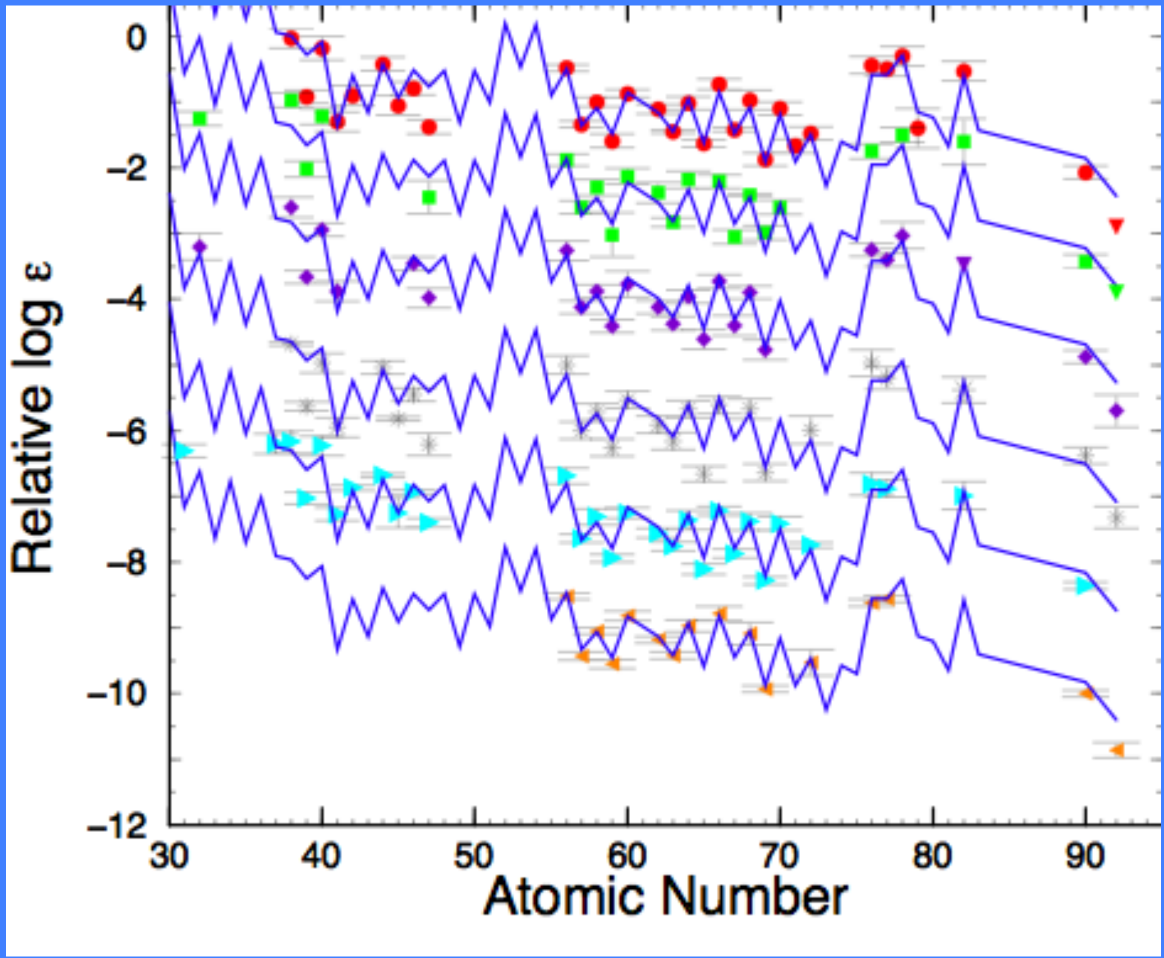
Observations

Models for the r-process

Nuclear physics

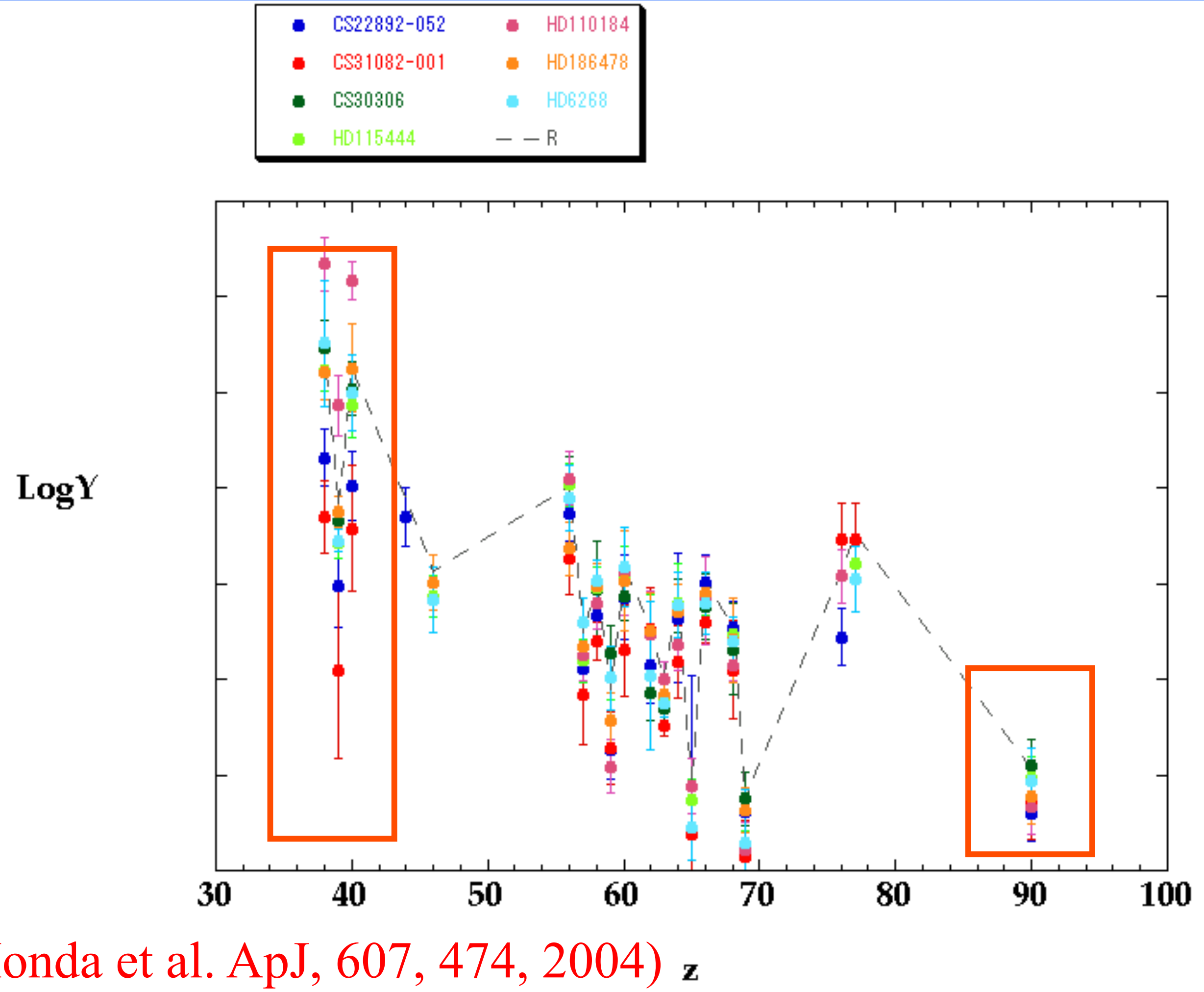
Observations

Universality



Cowan et al. (2007)

Deviations from universality for light and heavy elements



(Honda et al. ApJ, 607, 474, 2004)

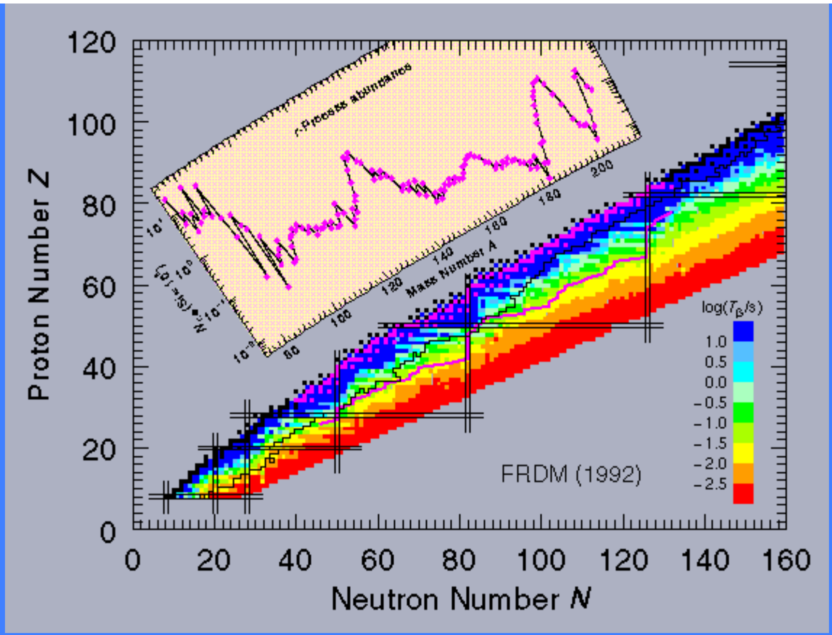
What we need to find out

– Is there one r-process or many?

– Were there different conditions in the same site?

– Another Nucleosynthesis process?

Nuclear Physics Issues for the *r*-process



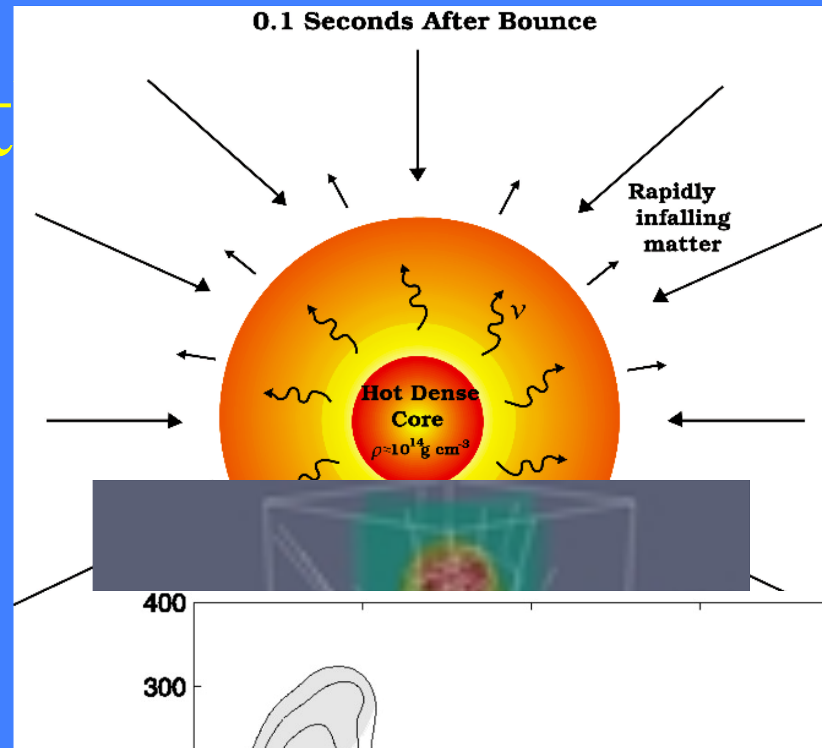
Beta half lives τ_β and beta-delayed neutron emission $\tau_{\beta,n1,n2,n3,n4}$
Nuclear masses, M(Z,A), S_n, Q_β
$\sigma(n,\gamma)$, $\sigma(\gamma,n)$
Partion functions, j^π, $E_{j,}$

Beta-delayed fission, Neutron-induced fission, fission yields

Neutrino nucleus scattering/absorption :
Light-element reactions to produce seed nuclei

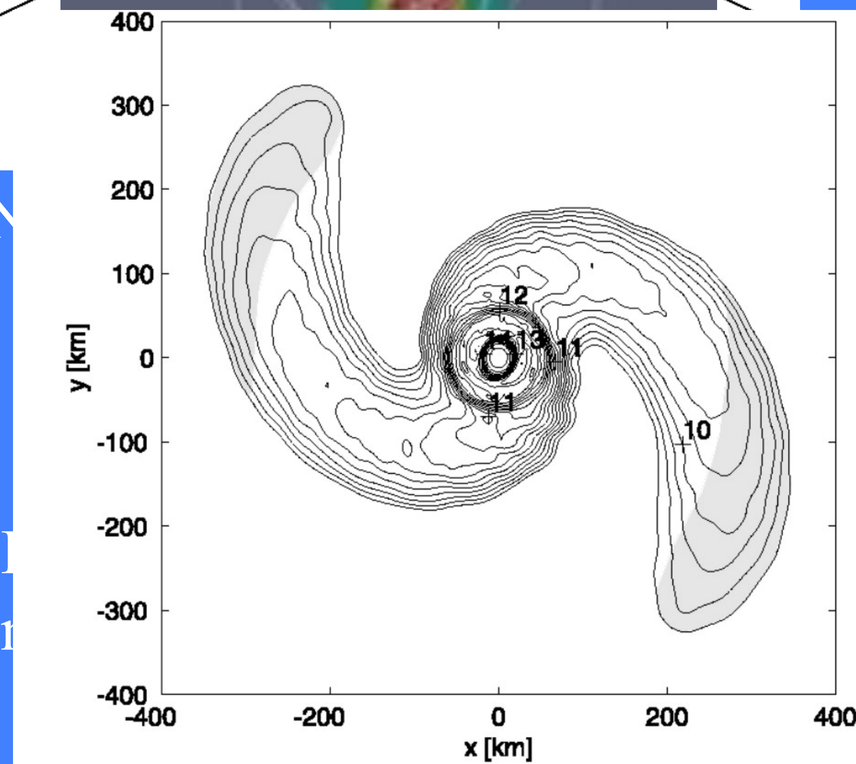
Models for t

Neutrino Driven Winds in the High Entropy Supernova Bubble



Ejection of neutronized core material in a low-mass supernovae or MHD jets

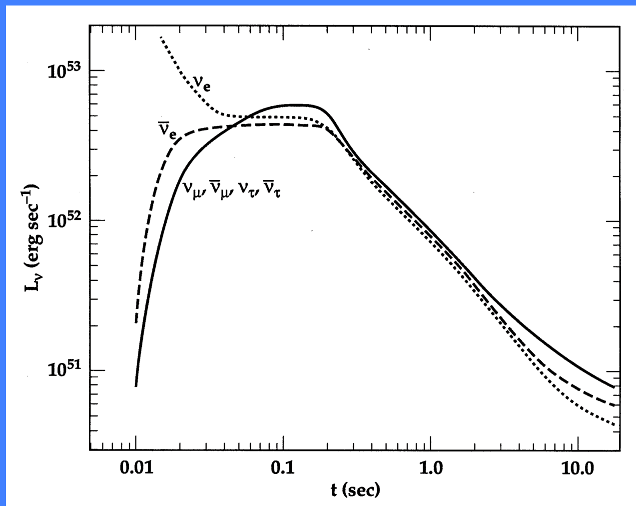
Neutron star mergers



Frontiers of neutrino physics in supernovae
Part I

Crisis in the Neutrino Driven Wind r-Process

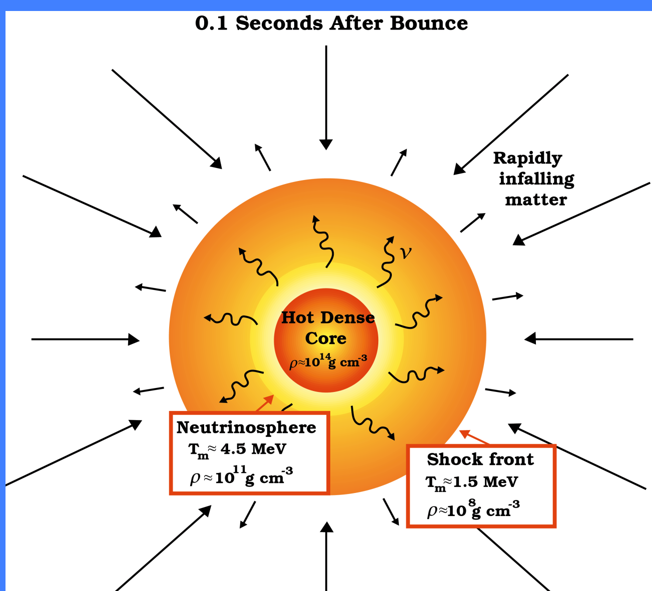
Neutrino Heated Wind r-Process

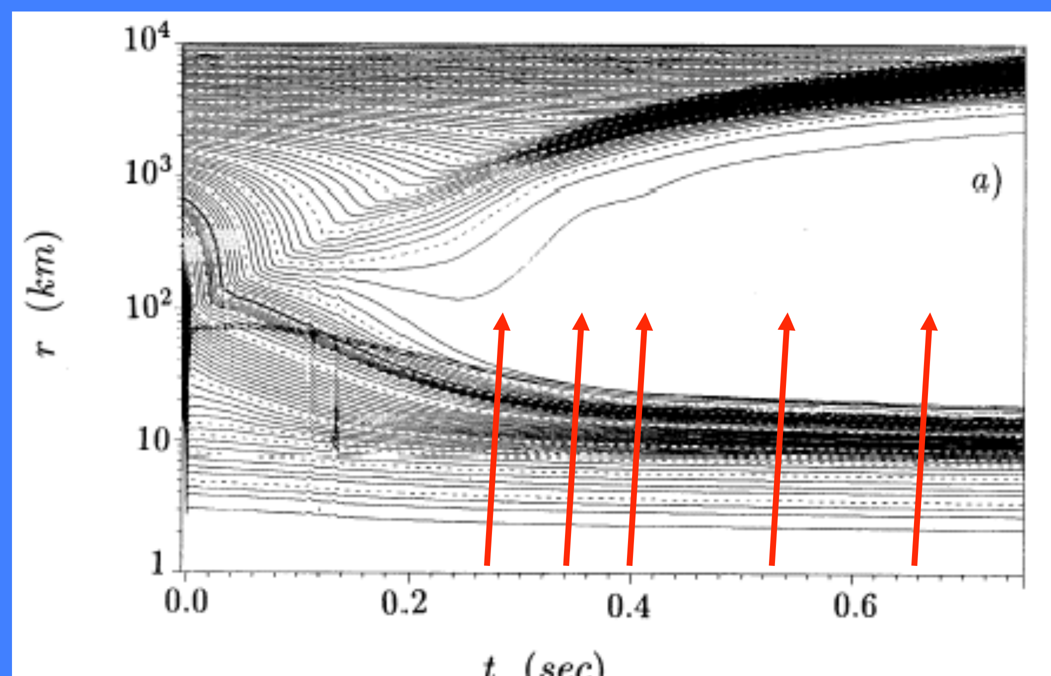


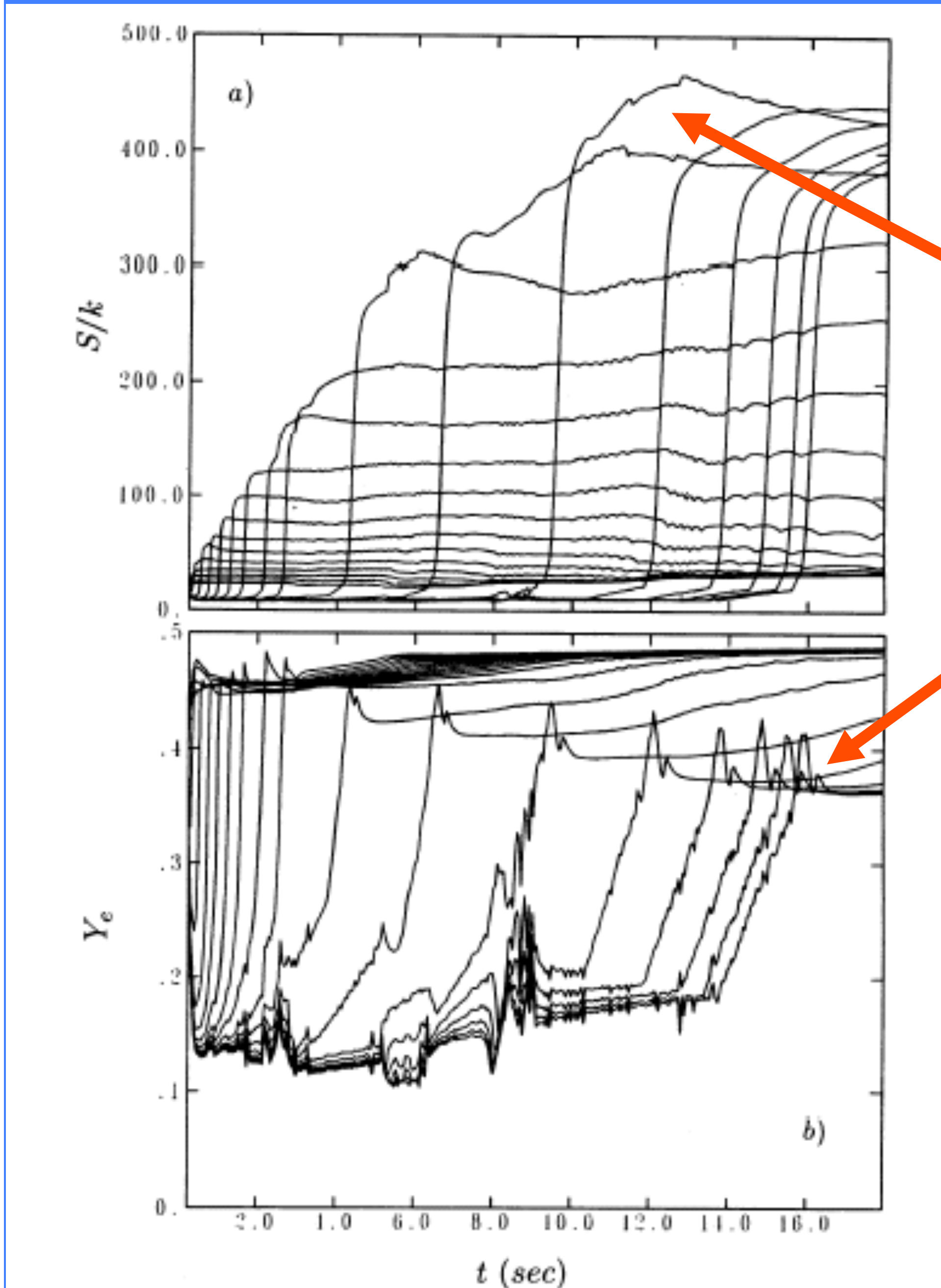
Neutrino Luminosity ~10^{53} erg/sec

Neutrino Heating Produces a high entropy bubble

$S = \int dt\,(dQ/dt)/T$



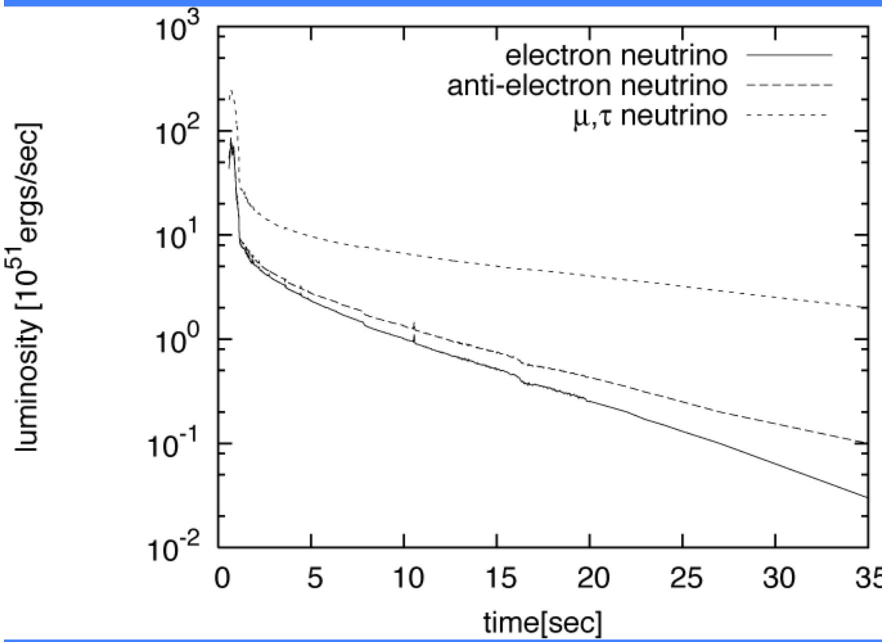


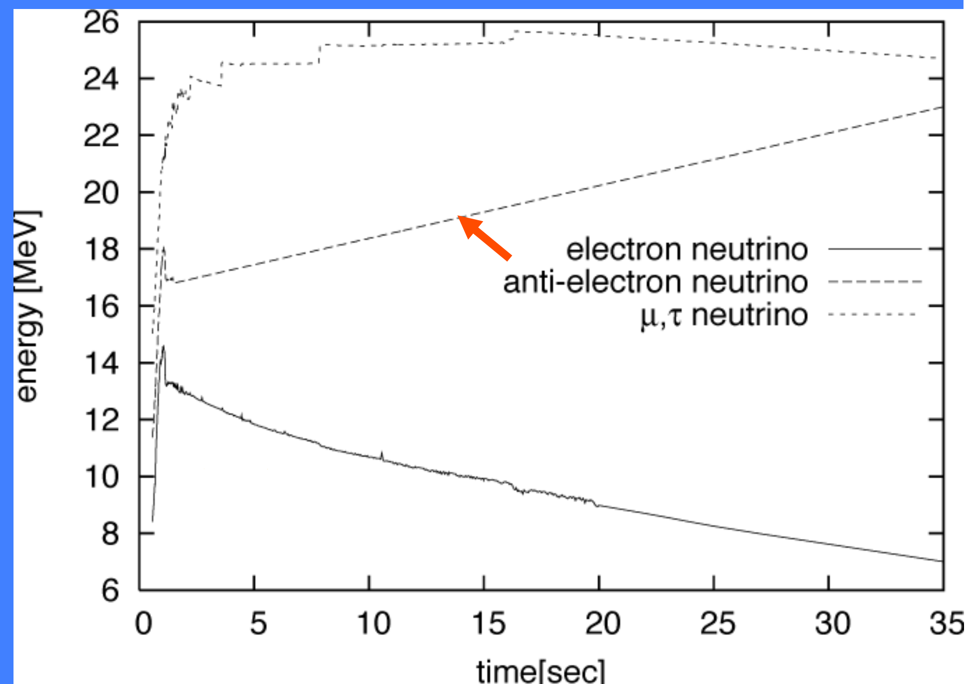


Requires material moving through the bubble to achieve very high entropy and be slightly neutron rich.

Woosley et al (1994)

Ye < 0.5 requires distinct neutrino luminosities and energies





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

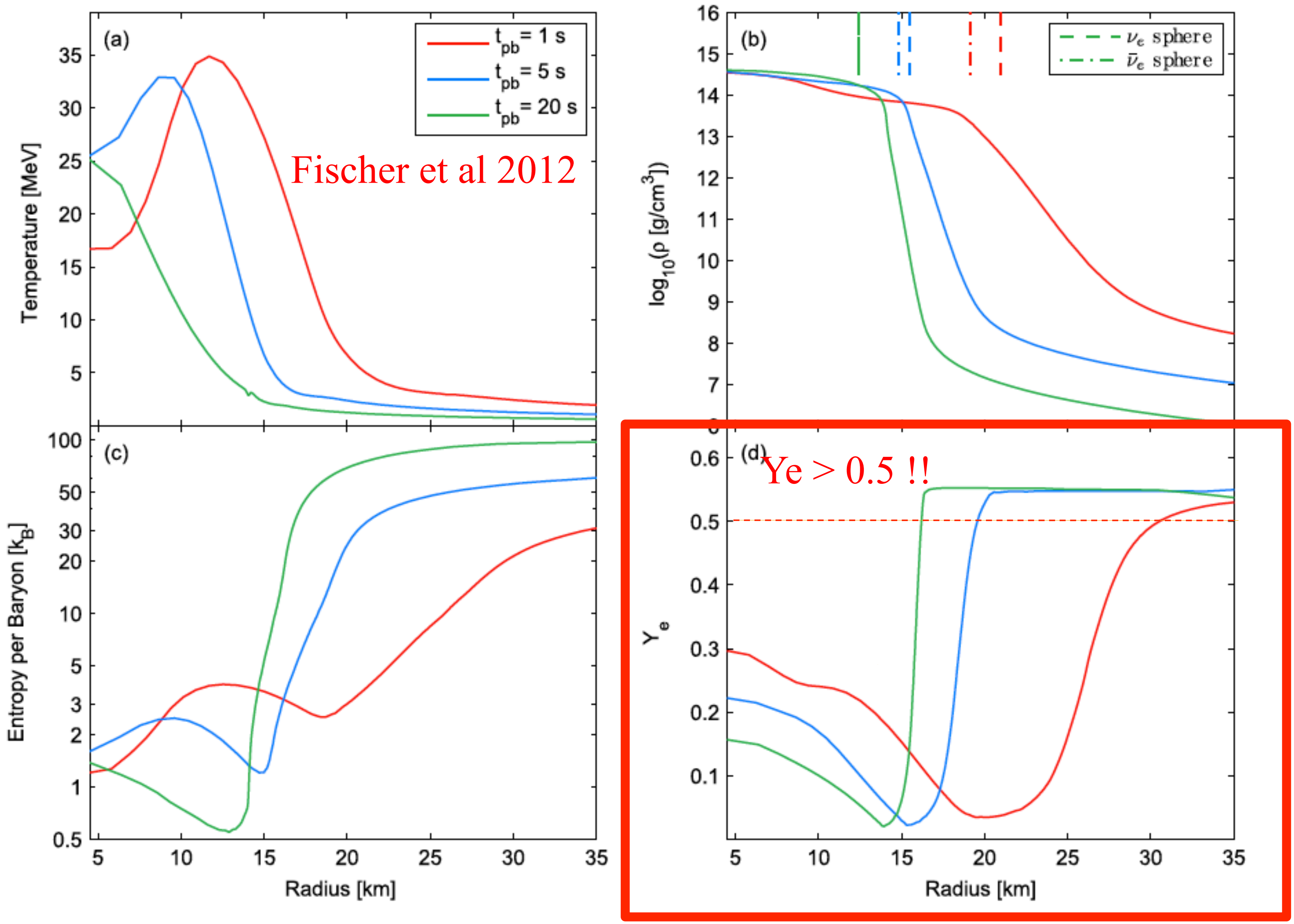
$$n + \nu_e \rightarrow p + e^-$$

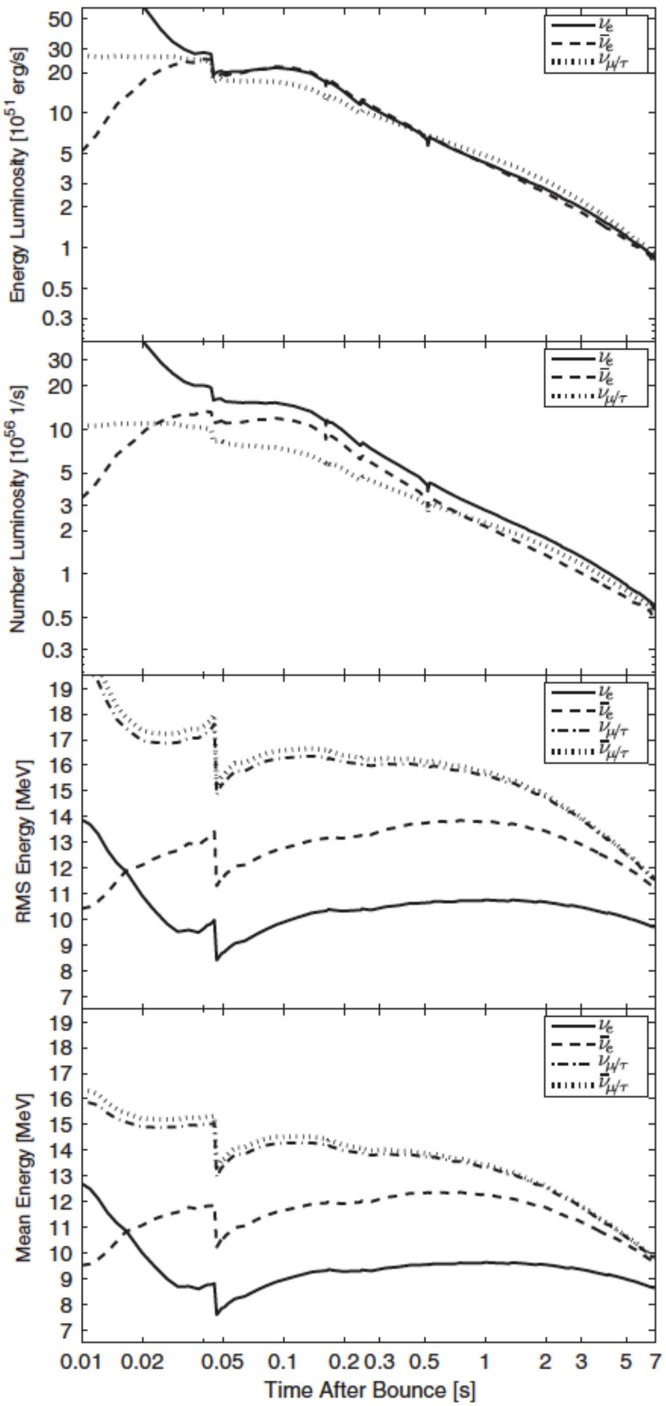
$$\Delta = m_n - m_p = 1.2935 \text{ MeV}$$

$$\varepsilon_{\overline{\nu e}} - \varepsilon_{\nu e} > 4\Delta$$

$$Y_{e,\mathrm{NDW}} \approx \left[1 + \frac{\dot{N}_{\bar{\nu}_e} \langle \sigma(\epsilon)_{p,\bar{\nu}_e} \rangle}{\dot{N}_{\nu_e} \langle \sigma(\epsilon)_{n,\nu_e} \rangle}\right]^{-1}$$

Crisis in the Neutrino Driven Wind r-Process





Why is Ye> 0.5??

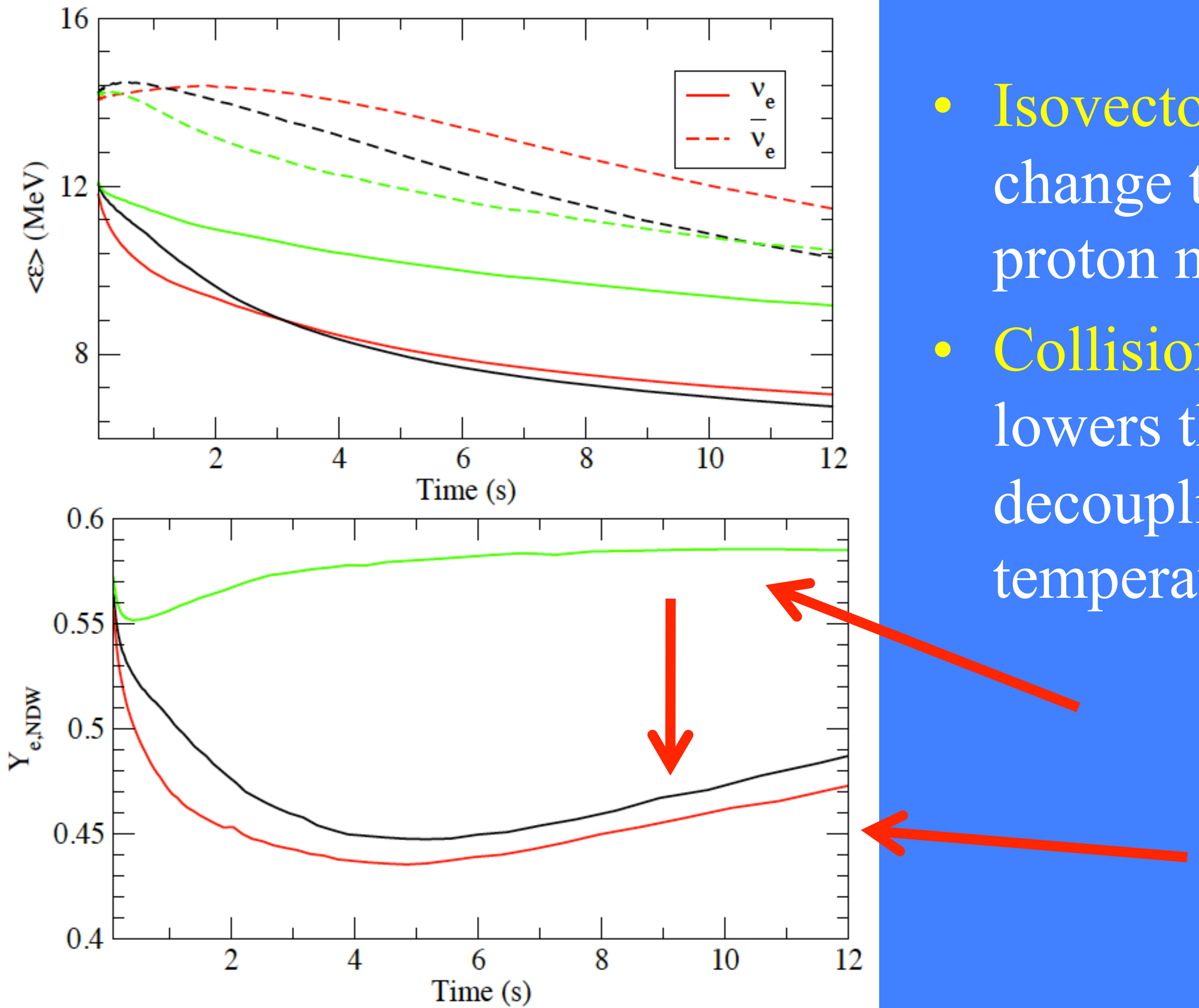
- Charged Current $\overline{\nu}_e$ reactions suppressed by Pauli blocking of neutrons
- Neutrino energies and luminosities converge at late times

$$p + \overline{\nu}_e \rightarrow n + e^+$$
$$n + \nu_e \rightarrow p + e^-$$

$$Y_{e,\mathrm{NDW}} \approx \left[1 + \frac{\dot{N}_{\bar{\nu}_e} \langle \sigma(\epsilon)_{p,\bar{\nu}_e} \rangle}{\dot{N}_{\nu_e} \langle \sigma(\epsilon)_{n,\nu_e} \rangle}\right]^{-1}$$

Fischer et al. 2012 PRD, 85, 083003

Saving the Wind Driven r-Process
Roberts & Reddy Archive:1205.4066v2 (2012)



- Isovector interactions change the neutron and proton mass difference
- Collisional broadening lowers the neutrino decoupling temperature

Lesson:

Detailed neutrino physics and nuclear physics in hot neutron star matter above and below the proto-neutron star surface is crucial to understanding the r-process in the neutrino driven wind

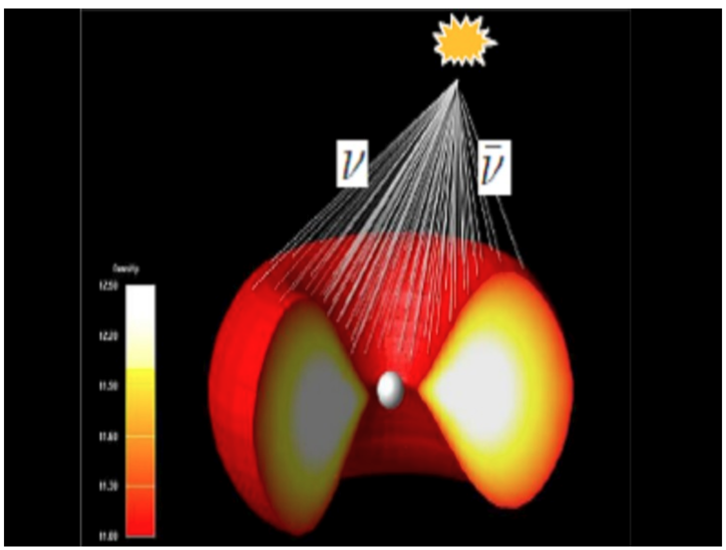
What about other models?

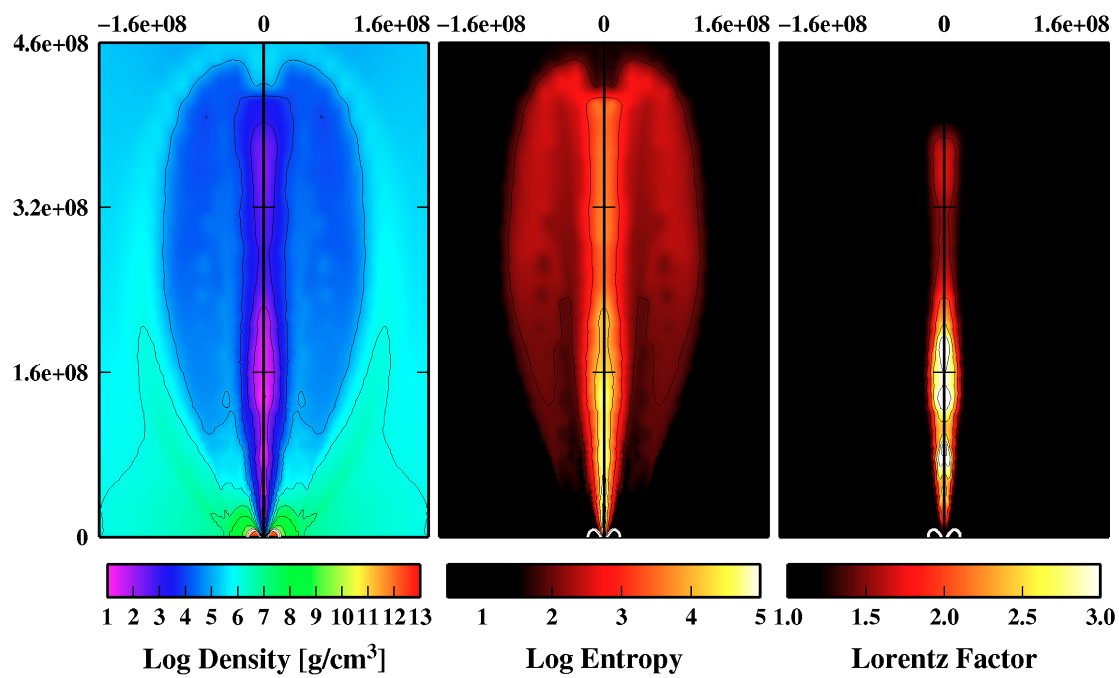
Frontiers of neutrino physics in supernovae
Part II

The Collapsar *r* Process

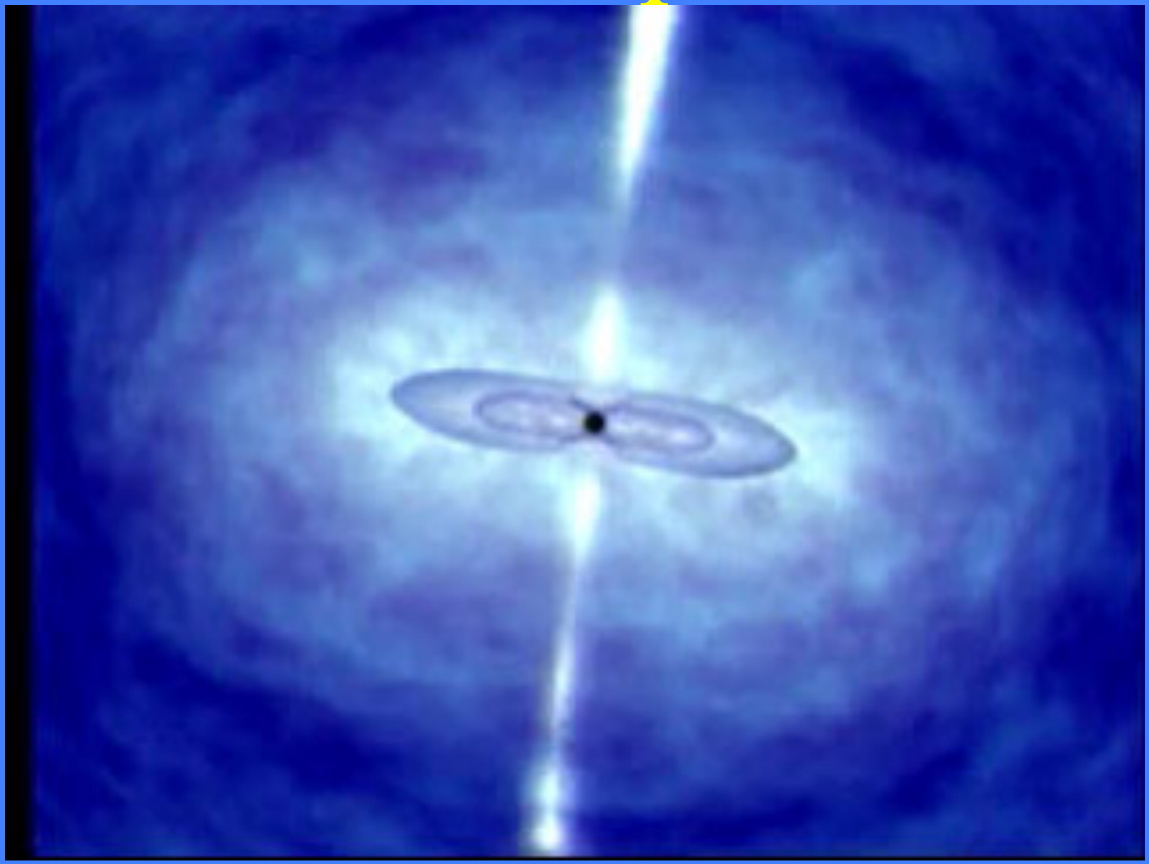
R-PROCESS NUCLEOSYNTHESIS IN THE MHD+NEUTRINO-PAIR HEATED COLLAPSAR JET

K. Nakamura, S. Sato, S Harikae, T. Kajino,1,2 and GJM, ApJ Submitted (2012)





What is a collapsar?

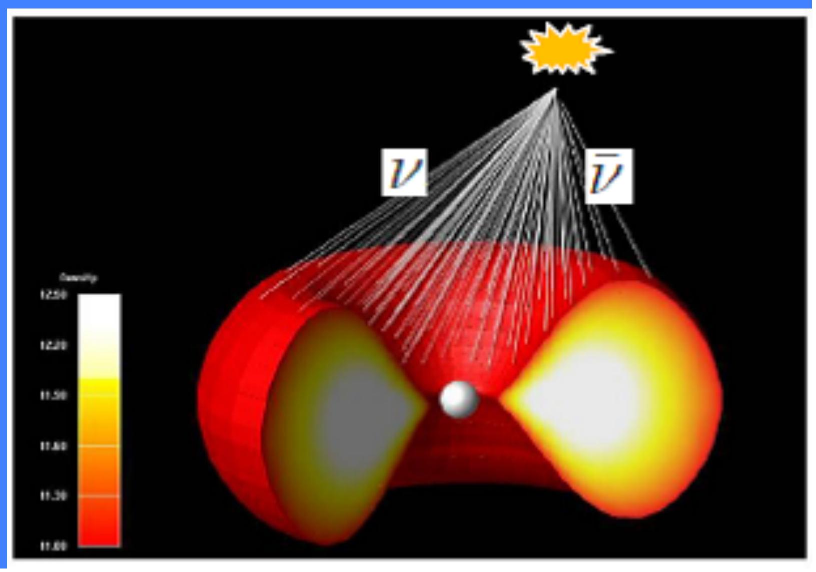


- Model for long duration gamma-ray bursts (GRB)
- A failed supernova
- Produces a black hole and a high temperature accretion disk
- MHD + neutrino heating produces an energetic jet

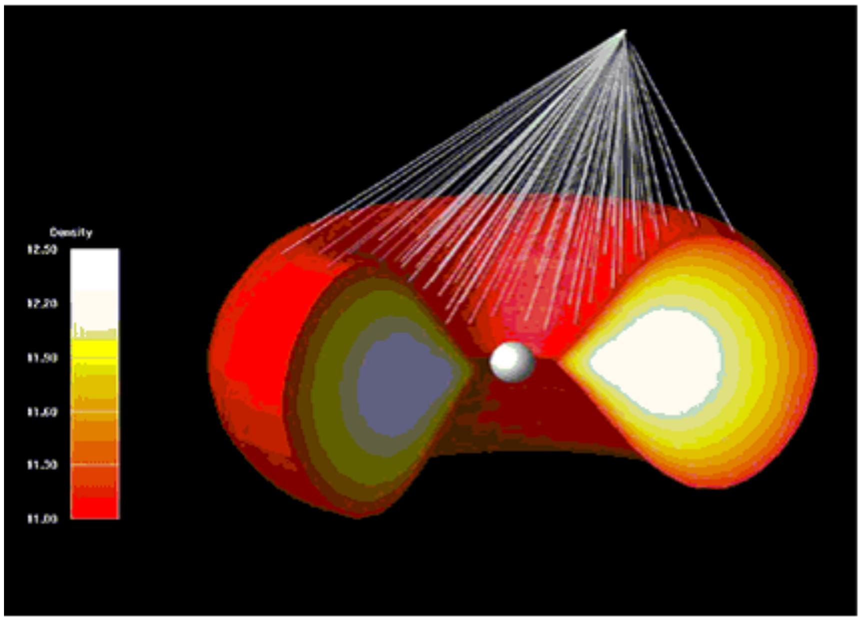
Stages of a collapsar

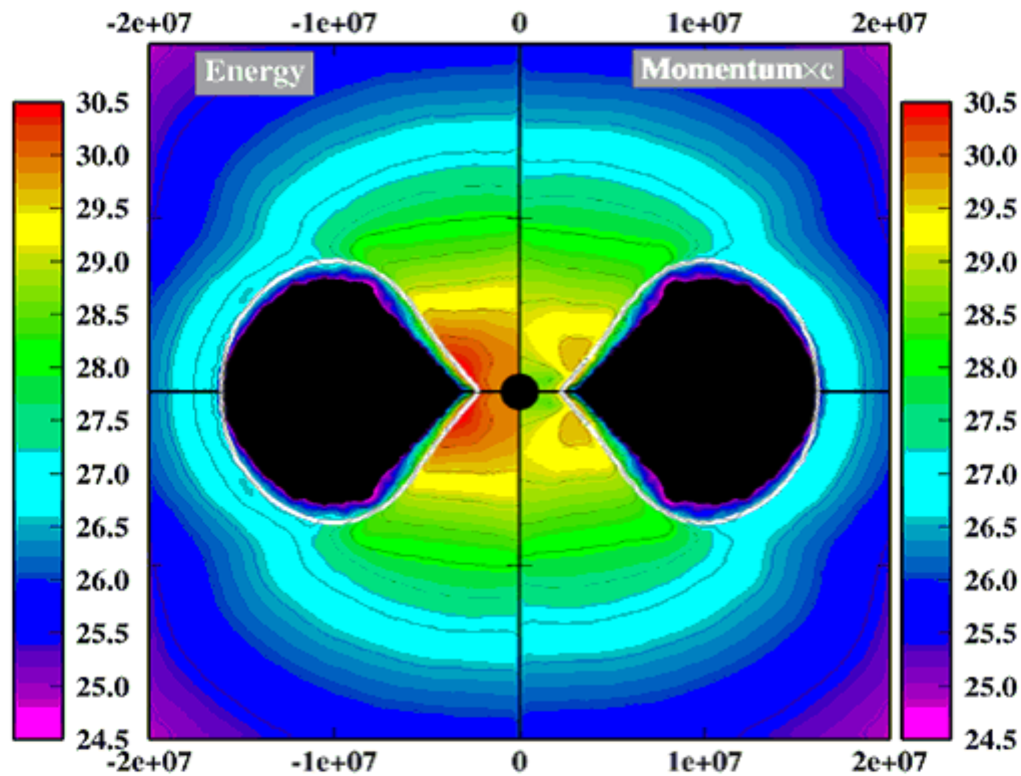
1. Initial Collapse of 35-40 $M_{\odot}$ progenitor
2. Accretion disk heats up and a funnel region above the black hole is heated by neutrinos and magnetic fields

3. Causes launch of a relativistic jet

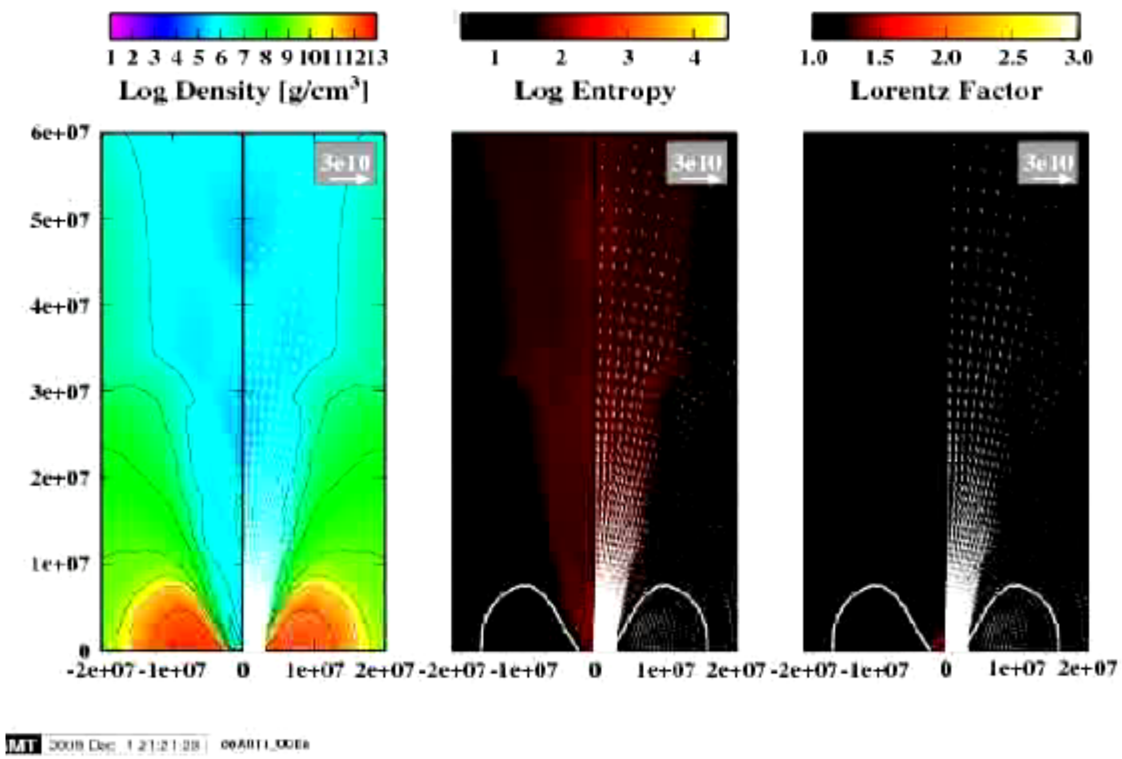


Harikae, et al. 2010





Harikae, et al. 2009; 2010



A robust jet forms when neutrino heating is included, but could only evolve for 200 ms

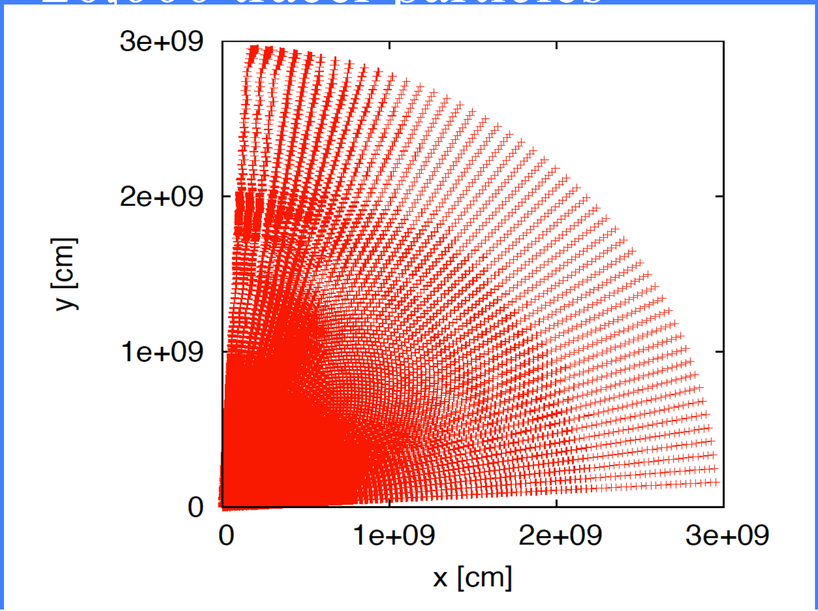
Need to extend to later times and greater distance.

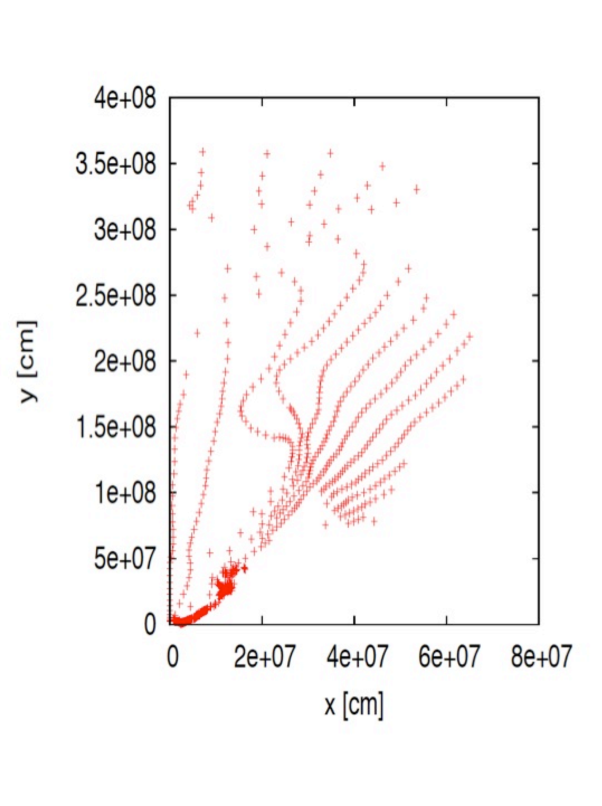
Modeling the r-process

K. Nakamura, et al (2012)

- Extend the jet beyond the MHD+neutrino pair heating using 2D hydo
- Attach tracer particles to evolve the flow of material into the accretion disk and out into the jet

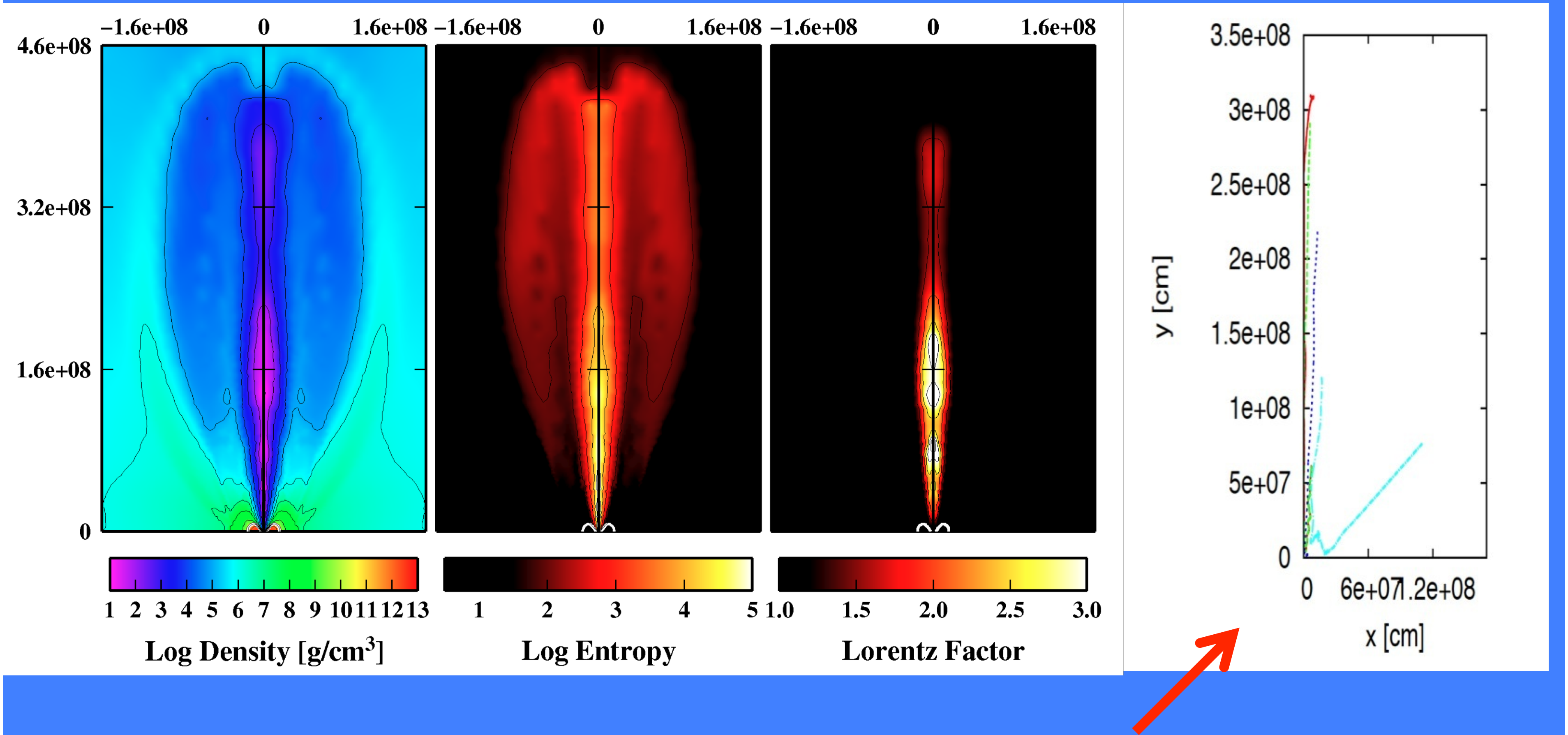
20,000 tracer particles





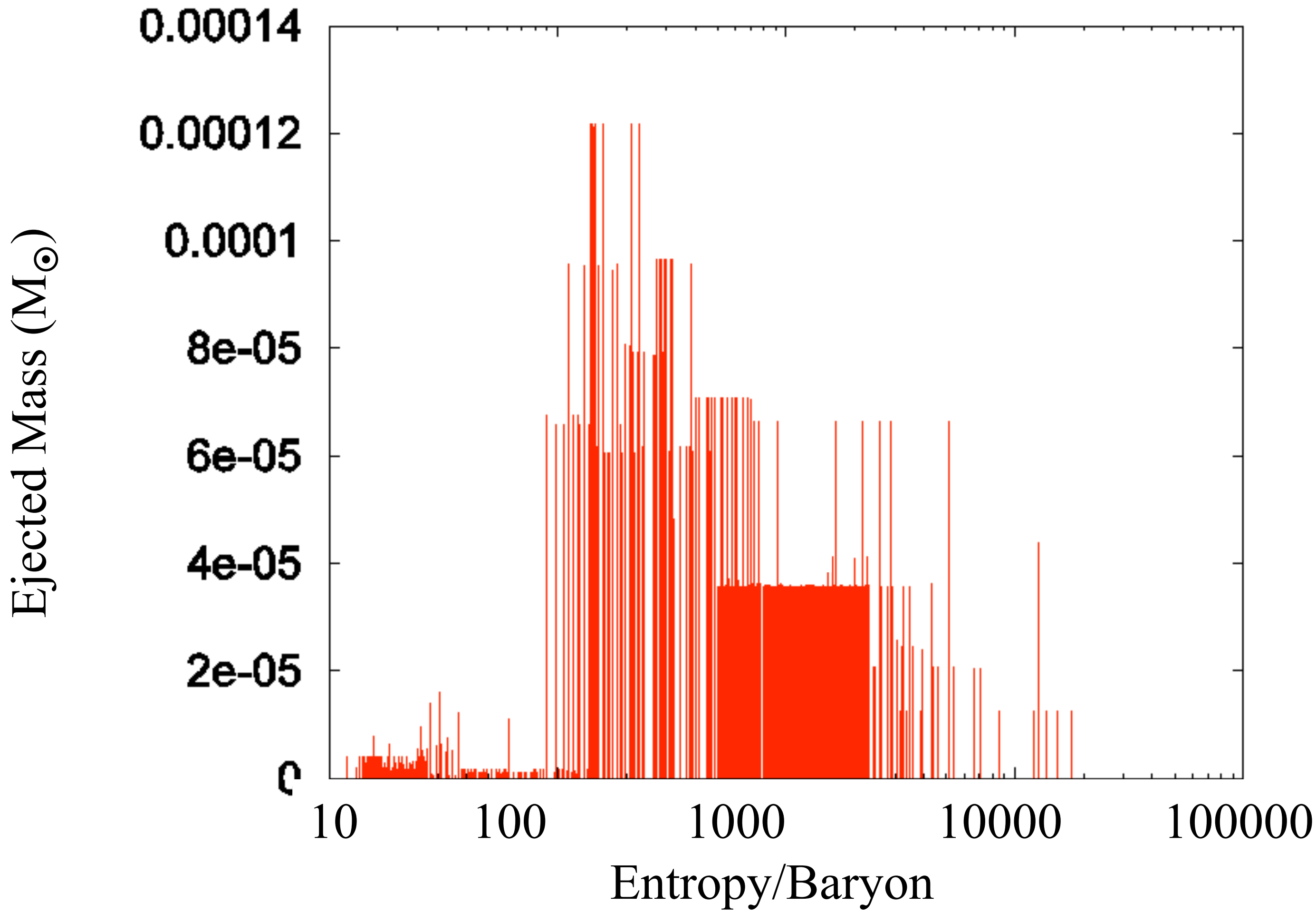
1208 trajectories with positive energy

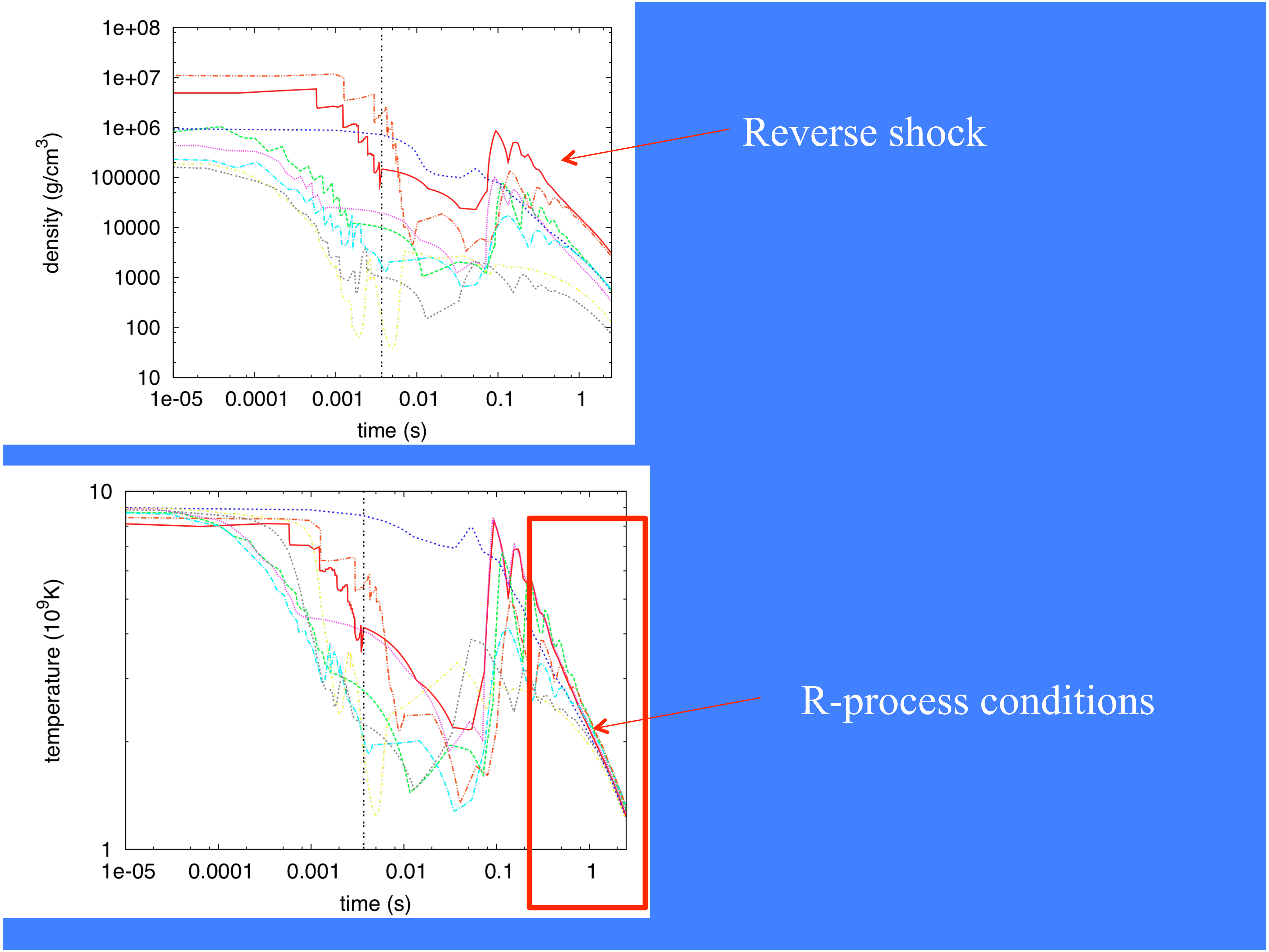
Tracer particles ejected with the jet



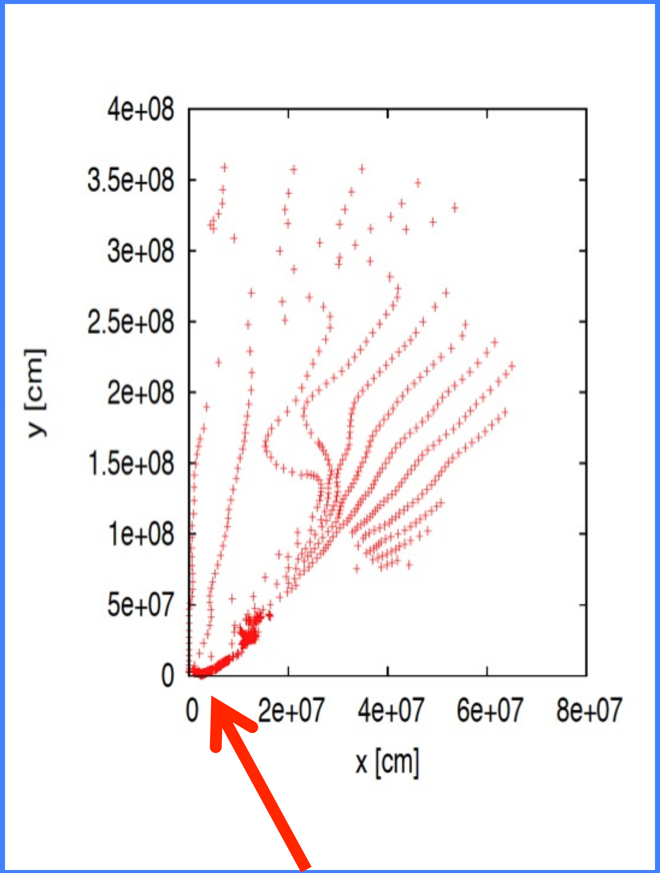
Tracer particles experience a high entropy r-process

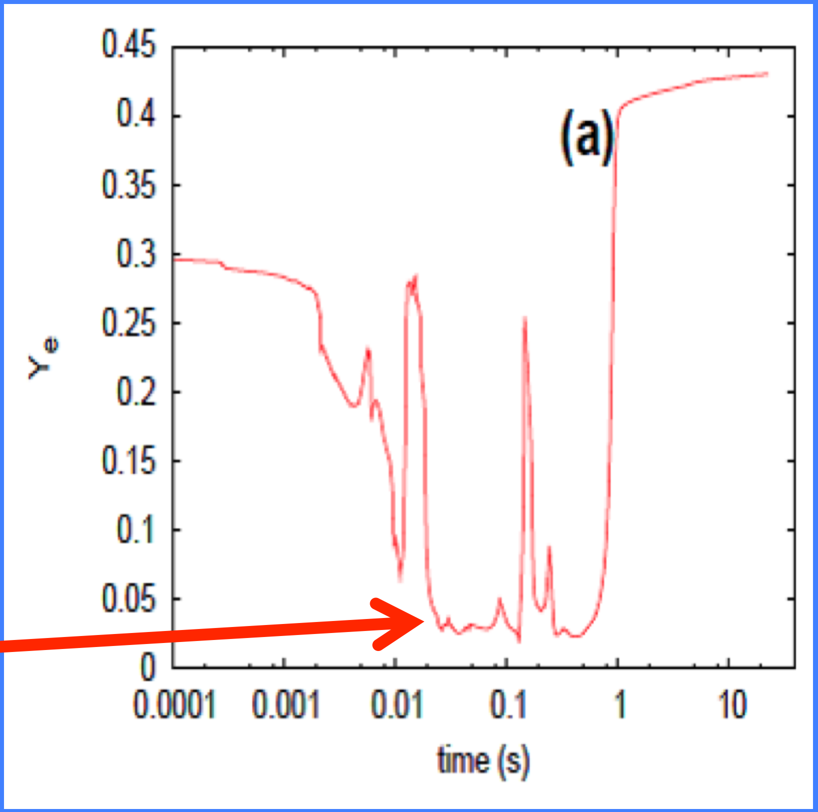
Entropy in the jet



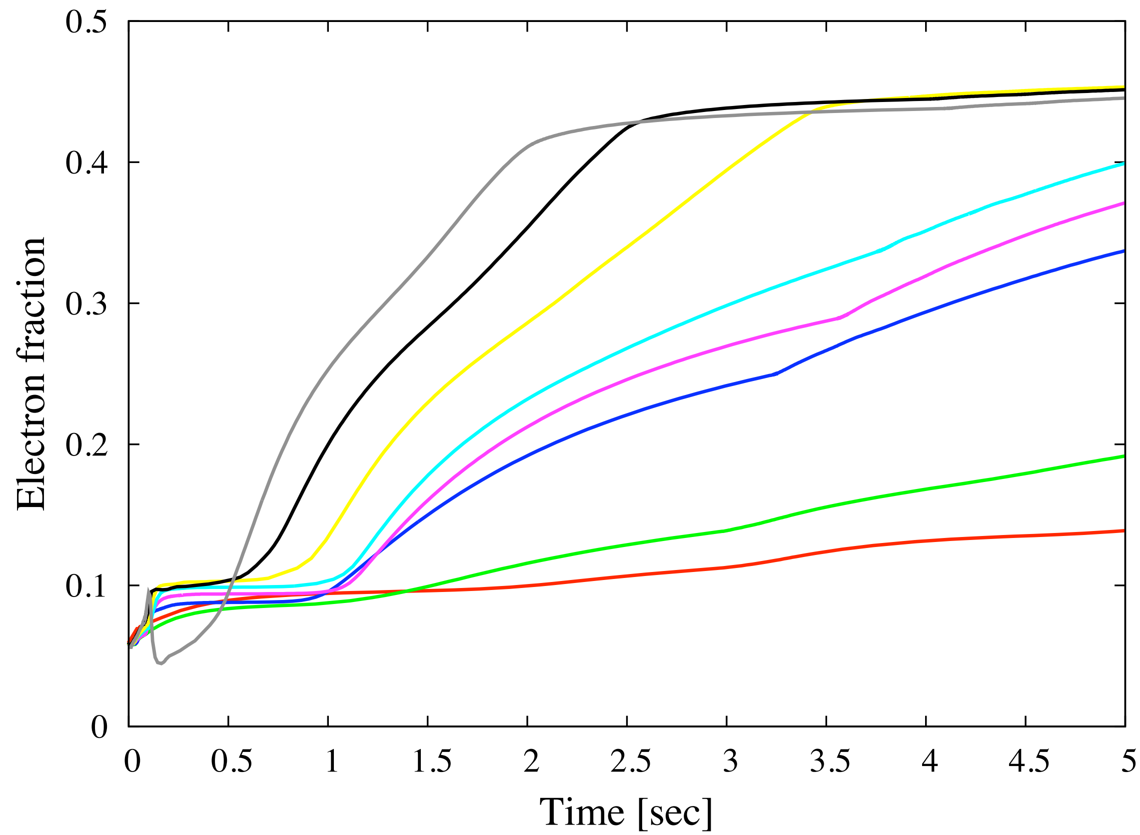

Reverse shock
R-process conditions
density (g/cm³)
1e+08
1e+07
1e+06
100000
10000
1000
100
10
1e-05
0.0001
0.001
0.01
0.1
1
time (s)
temperature (10⁹K)
10
1
1e-05
0.0001
0.001
0.01
0.1
1
time (s)

Evolution of Y_e



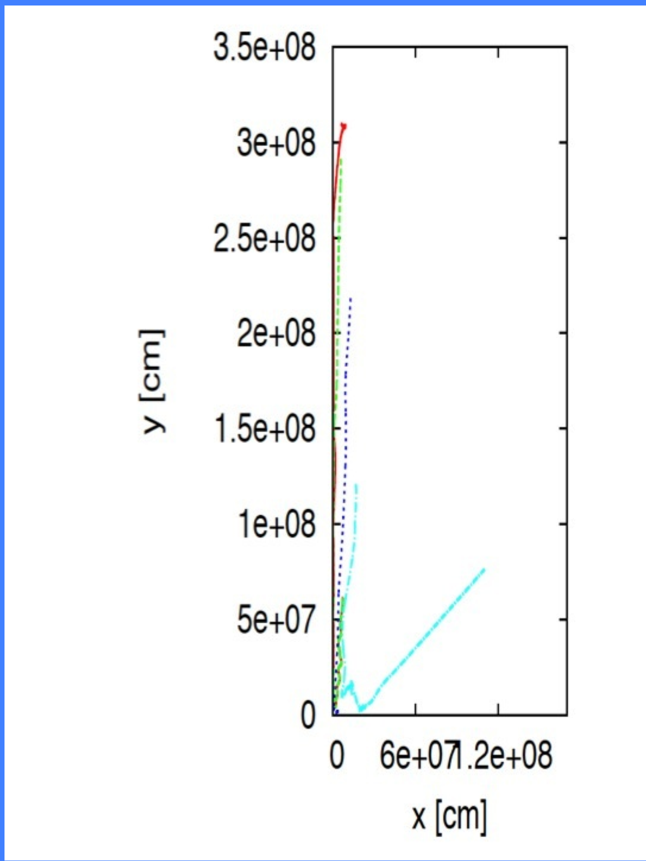


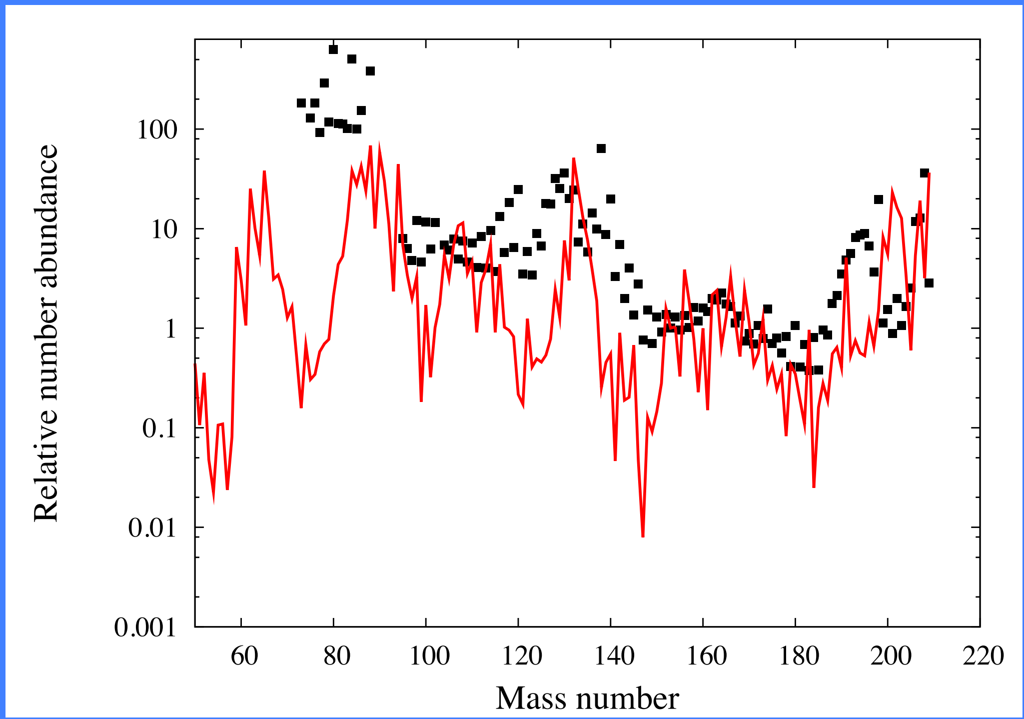
Neutronized accretion-disk material



Ye stays low close to the jet

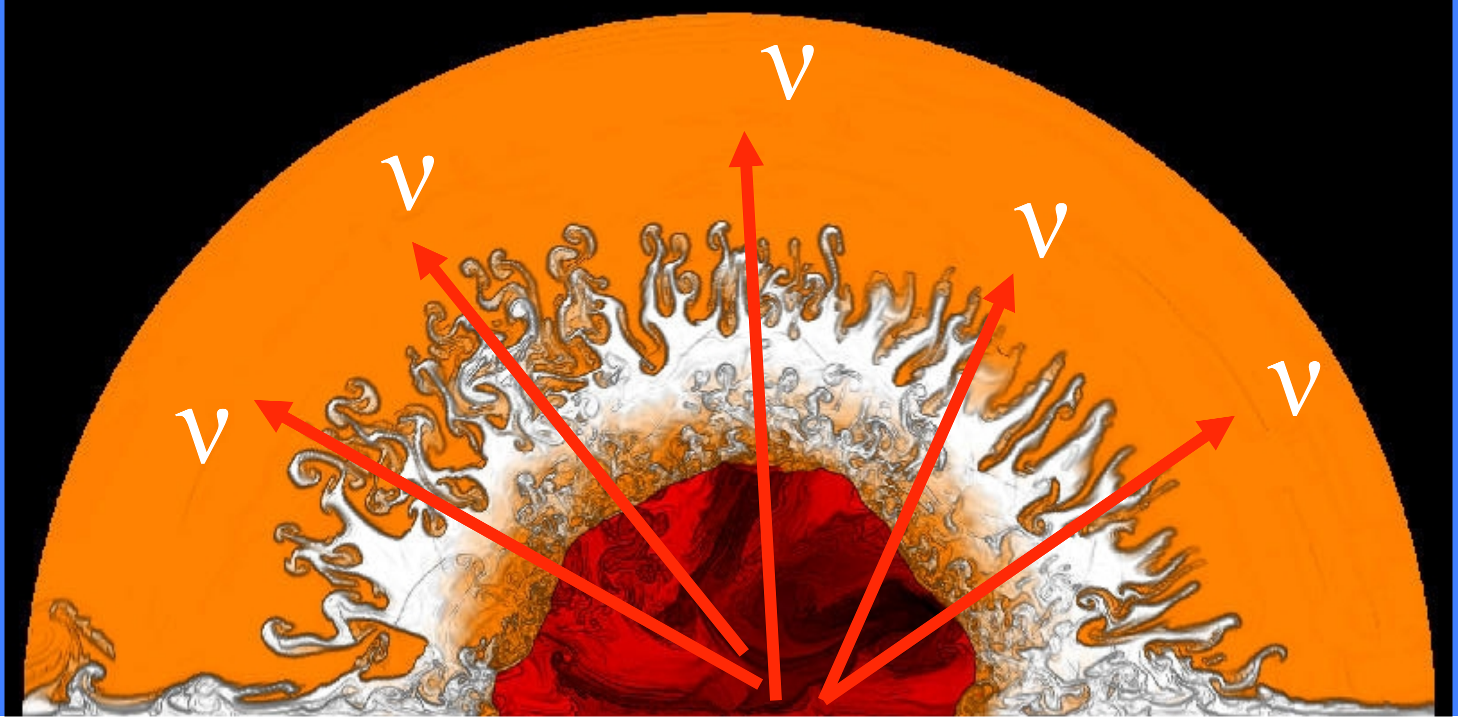
R-Process in the jet?



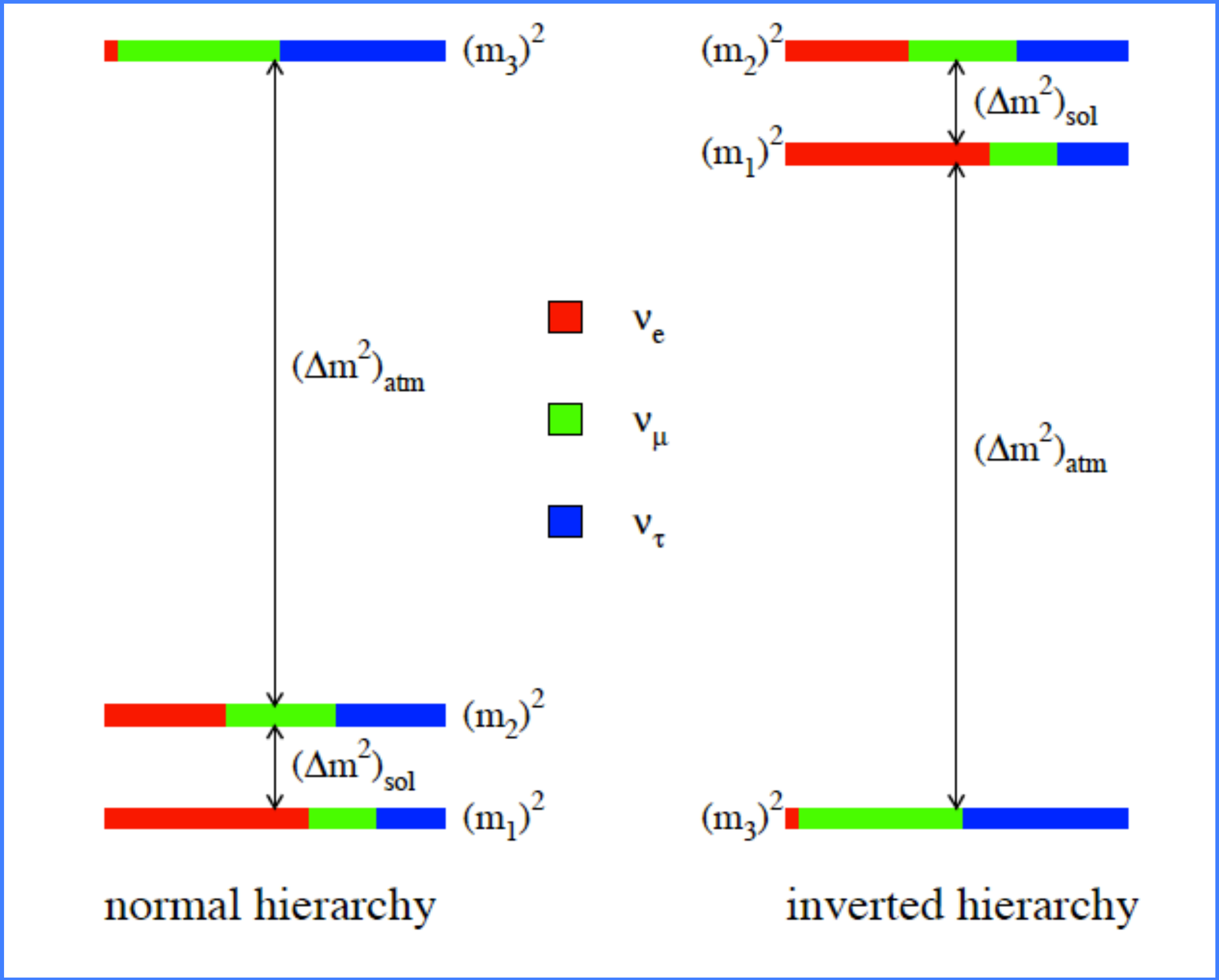


Final abundances sum of 1208 ejected tracer particles

Frontiers of neutrino physics in supernovae
Part III
Neutrino Nucleosynthesis and the Neutrino Mass Hierarchy

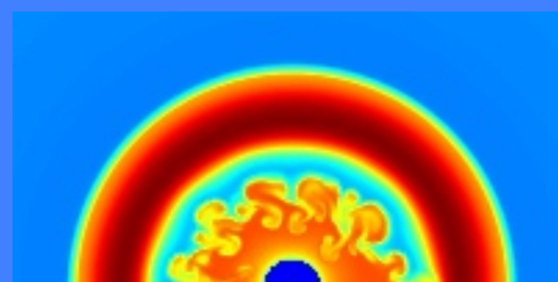


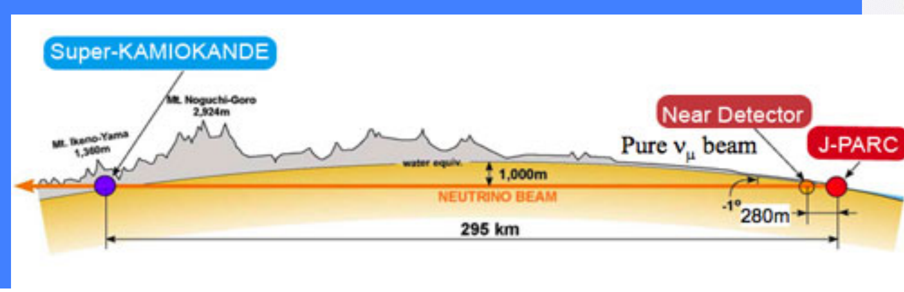
Mass Hierarchy?



Evidence for an ***inverted neutrino hierarchy*** from ***neutrino nucleosynthesis*** in core collapse supernovae, ***meteorites*** and new measurements of the ***θ_{13} neutrino mixing angle***

G JM, Kajino, Aoki, Fujiya, Pitts, PRD 85, 105023 (2012)





Neutrino reactions to produce ^{7}Li and ^{11}B

- ^{7}Li, ^{7}Be

^{11}B

$^{4}\mathrm{He}(\nu,\nu' n)^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$

$^{4}\mathrm{He}(\nu_e,e^{-} p)^{3}\mathrm{He}$

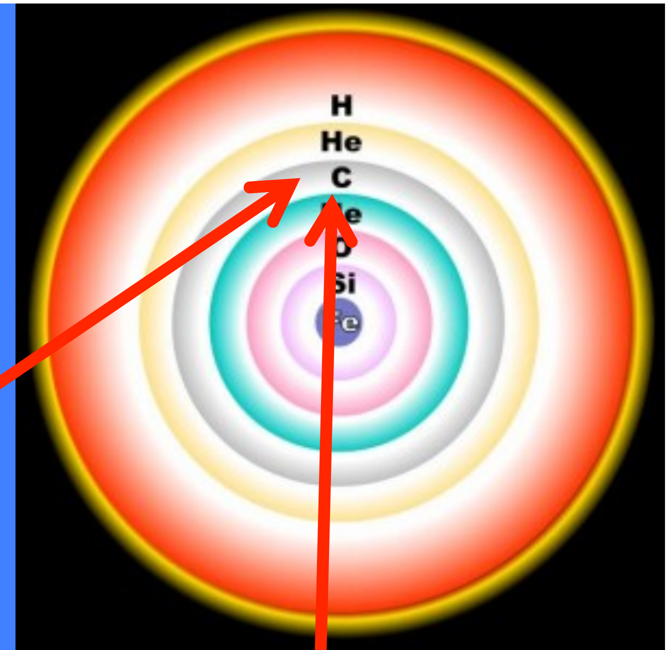
$^{4}\mathrm{He}(\nu,\nu' p)^{3}\mathrm{H}(\alpha,\gamma)^{7}\mathrm{Li}$

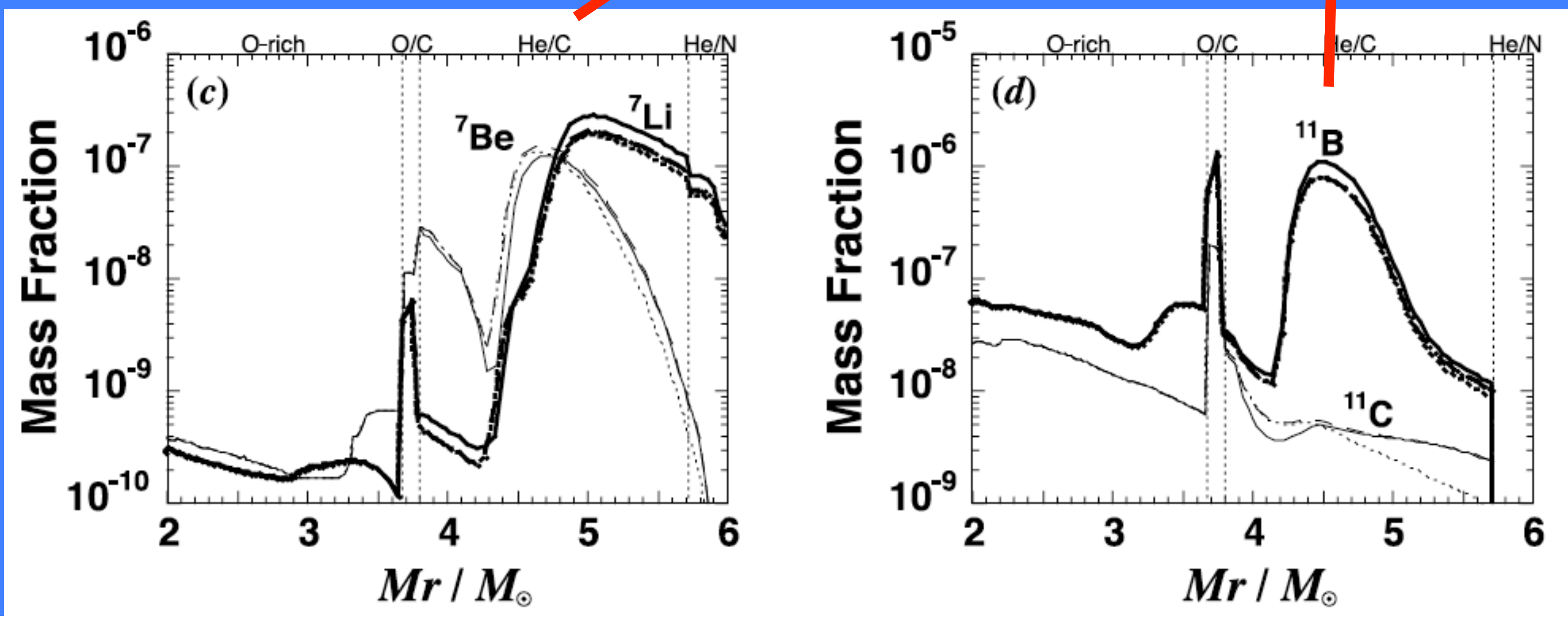
$^{4}\mathrm{He}(\nu,\nu' p)^{3}\mathrm{H}(\alpha,\gamma)^{7}\mathrm{Li}(\alpha,\gamma)^{11}\mathrm{B}$

$^{4}\mathrm{He}(\bar{\nu}_e,e^{+} n)^{3}\mathrm{H}$

$^{12}\mathrm{C}(\bar{\nu}_e,e^{+} n)^{11}\mathrm{B}$

^{7}Li and ^{11}B are produced in the He/C Shell





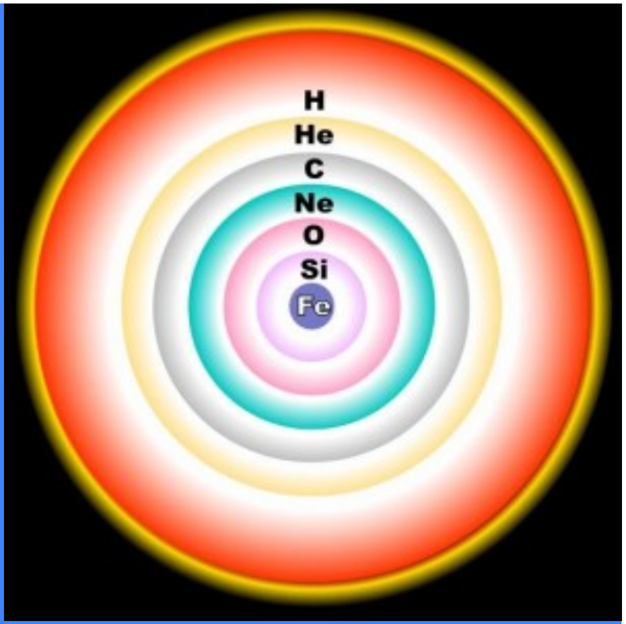
As Neutrinos Pass through the Supernova they can Oscillate

$$i\hbar c \frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2 c^4}{2\varepsilon_\nu} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2 c^4}{2\varepsilon_\nu} \end{pmatrix} U^\dagger + \begin{pmatrix} \pm\sqrt{2} G_{\mathrm{F}} (\hbar c)^3 \frac{\rho Y_e}{m_u} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}, \tag{1}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}, \tag{2}$$

Resonance Density

- => neutrinos convert in O shell



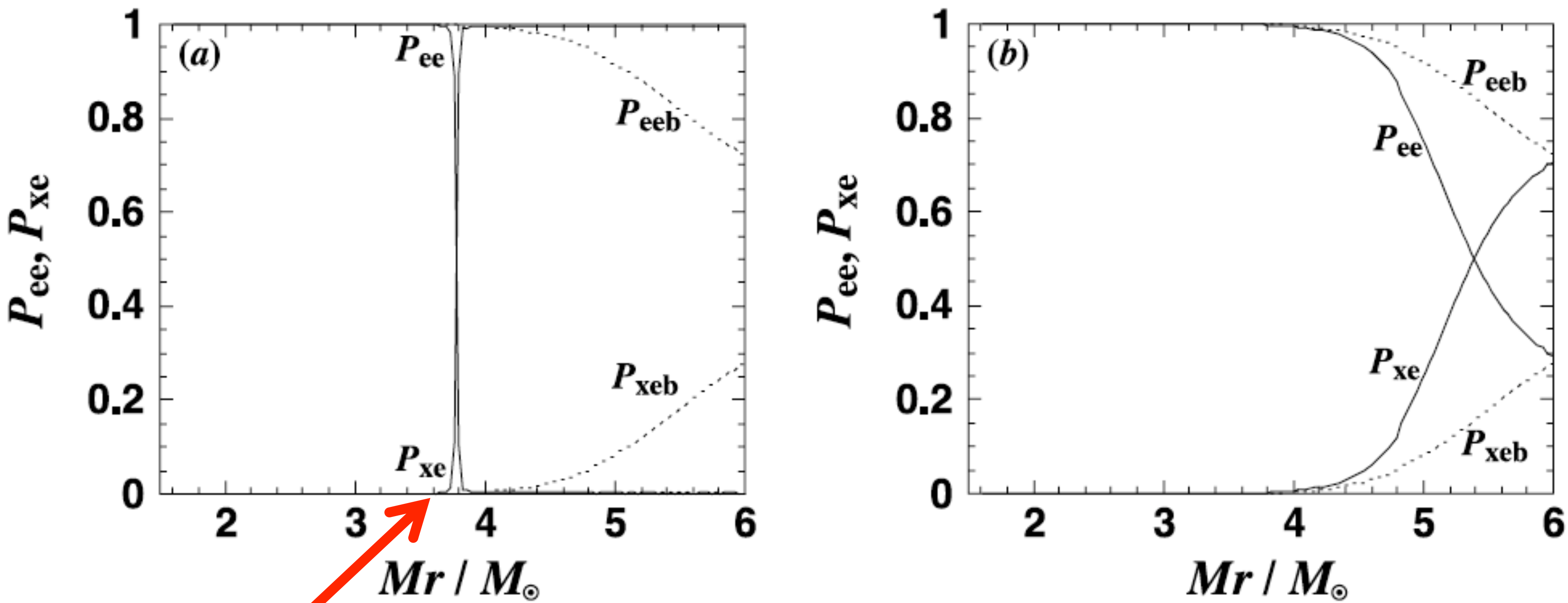
$$\rho_{\rm res} Y_e = \frac{m_u \Delta m_{ji}^2 c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_{\rm F} (\hbar c)^3 \varepsilon_\nu}$$

$$= 6.55 \times 10^6 \left(\frac{\Delta m_{ji}^2}{1\ {\rm eV}^2}\right) \left(\frac{1\ {\rm MeV}}{\varepsilon_\nu}\right) \cos 2\theta_{ij}\ {\rm g\ cm}^{-3}.$$

$$P_{\mu e} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{13}^2 L}{4E}\right)$$

Transition probabilities

Normal | Inverted



Strong $\nu_{\mu\tau}$ => ν_e mixing in O shell

Effects of neutrino mixing

- Neutrino mixing in O shell affects neutrino spectrum in outer He/C shell
- => ^{7}Li, ^{11}B affected
  - (^{138}La, ^{180}Ta unaffected)

Normal hierarchy -

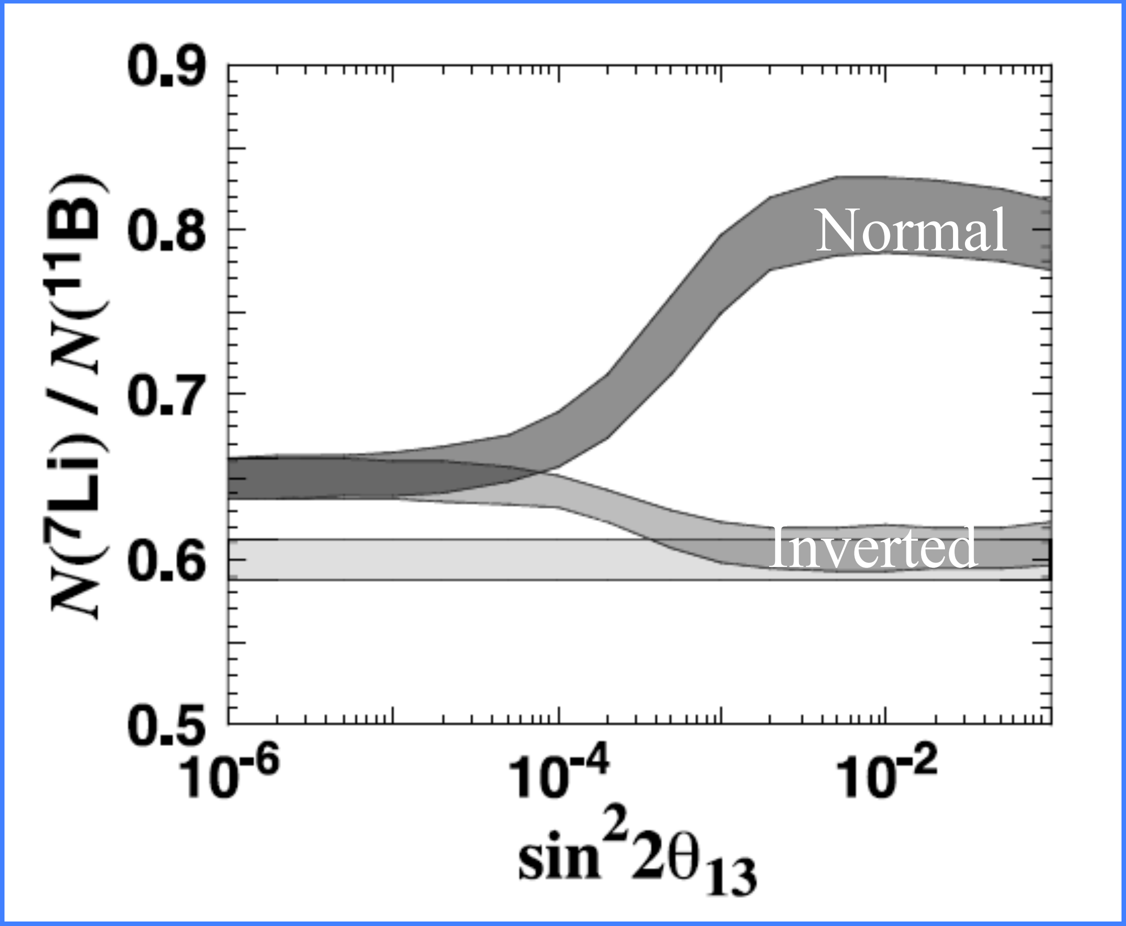
$$^{4}\mathrm{He}(\nu,\nu' n)^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$$

$$^{4}\mathrm{He}(\nu_e,e^- p)^{3}\mathrm{He}$$

Inverted hierarchy -

$$^{12}\mathrm{C}(\bar{\nu}_e,e^+ n)^{11}\mathrm{B}$$

Sensitivity of $^{7}Li/^{11}/B$ ratio to θ_{13}

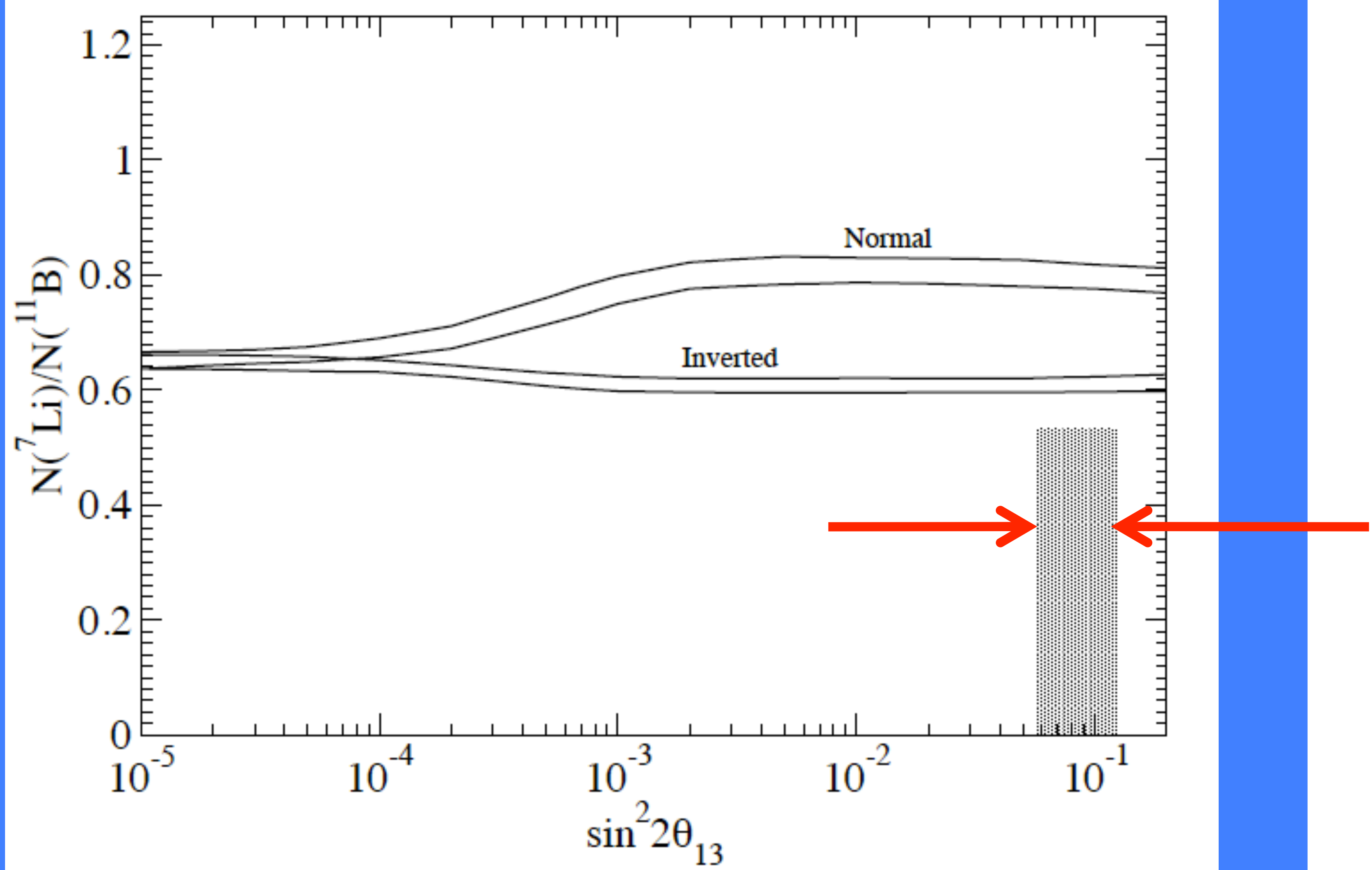


- requirement $\sin^2(2\theta_{13}) > 10^{-3}$

Yoshida et al. 2006; 2008

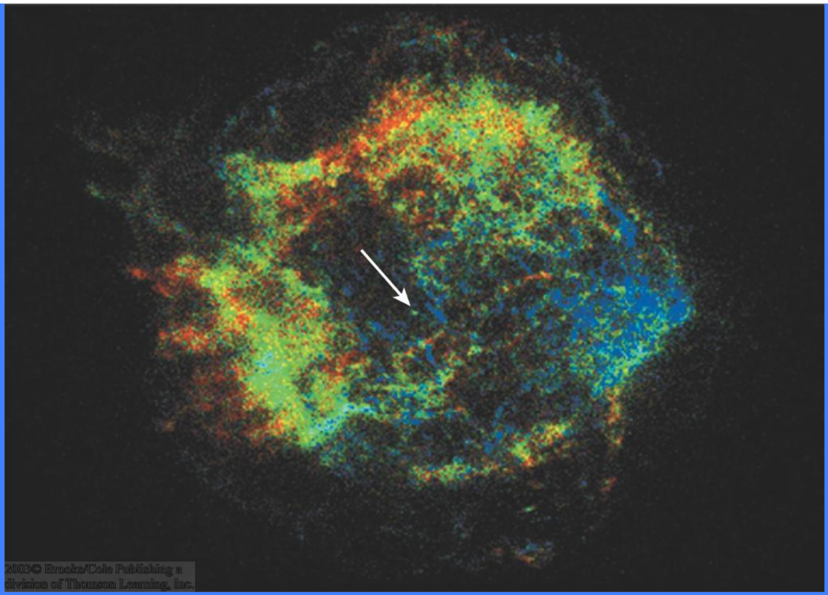
Measurements of $sin^2(2\theta_{13})$

$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$	Daya Bay 2012
$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\mathrm{stat.}) \pm 0.019(\mathrm{syst.})$	Rino (2012)
$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\mathrm{stat.}) \pm 0.030(\mathrm{syst.})$	Double Chooz (2012)
$\sin^2 2\theta_{13} < 0.12(0.20)$	Minos (2011)
$0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$	T2K (2012)



1.2
1
0.8
0.6
0.4
0.2
0
N(7Li)/N(11B)
Normal
Inverted
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\sin^2 2\theta_{13}$

Problem

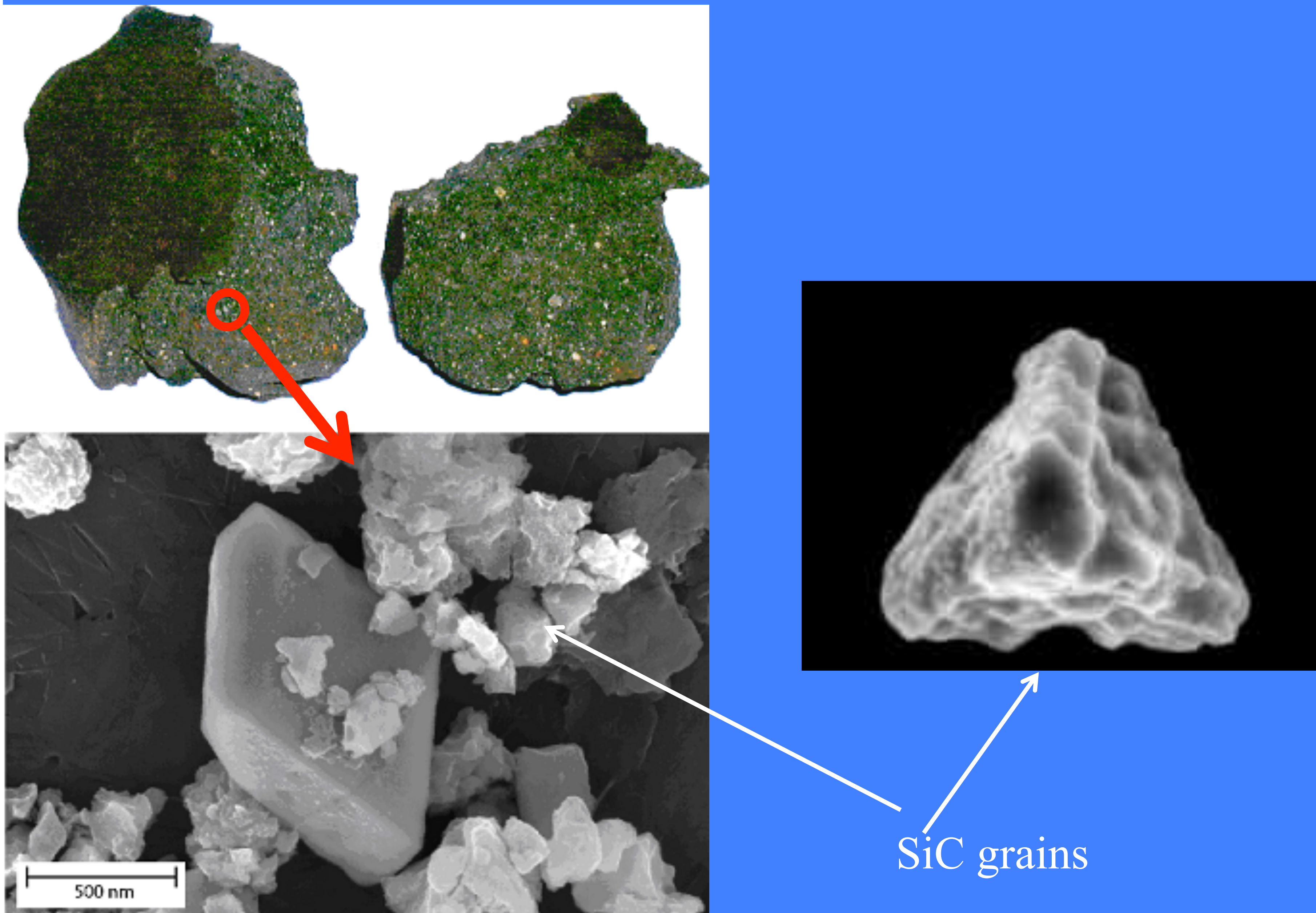


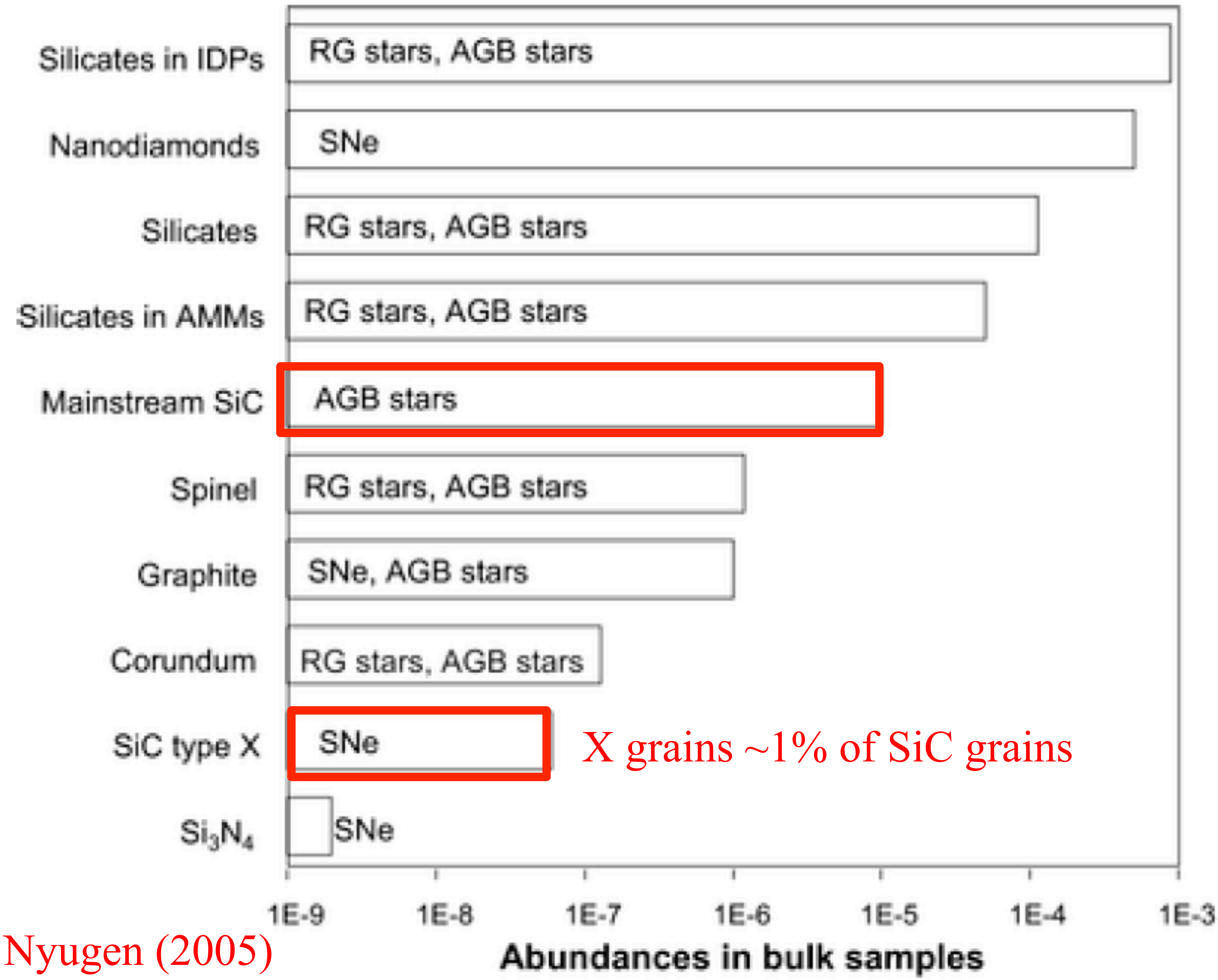
- Isotopic Li/B exceedingly difficult to measure in a SN remnant
- Even if measured, would be difficult to distinguish the ν-process contribution from surface contamination
- Need a sample direct from ejected He/C shell

Murchison Meteorite

Ca-Al rich Inclusions

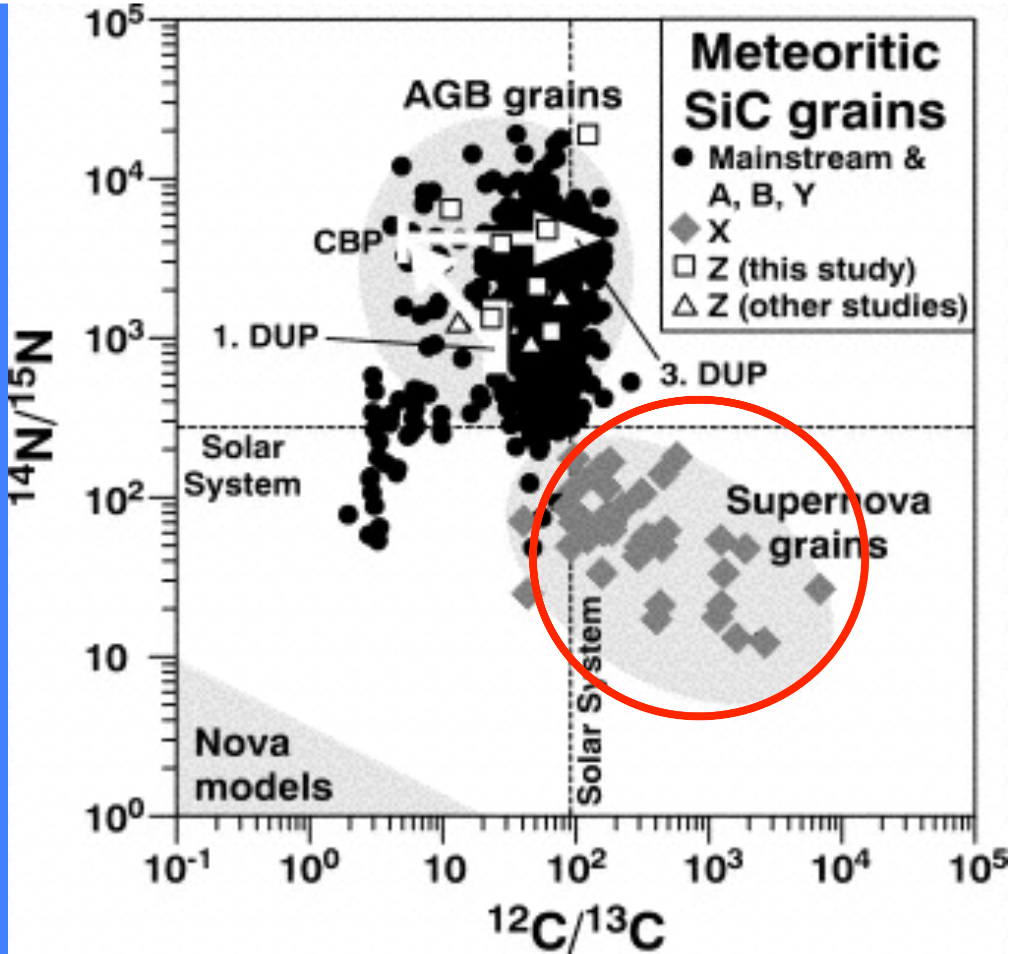
Primitive Solar System Material


500 nm
SiC grains


Silicates in IDPs
RG stars, AGB stars
Nanodiamonds
SNe
Silicates
RG stars, AGB stars
Silicates in AMMs
RG stars, AGB stars
Mainstream SiC
AGB stars
Spinel
RG stars, AGB stars
Graphite
SNe, AGB stars
Corundum
RG stars, AGB stars
SiC type X
SNe
X grains ~1% of SiC grains
Si_3N_4
SNe
1E-9
1E-8
1E-7
1E-6
1E-5
1E-4
1E-3
Abundances in bulk samples

Nyugen (2005)

Composition of SiC grains



SiC X grains exhibit

$^{12}C/^{13}C$ > Solar, $^{14}N/^{15}N$ < Solar,

Enhanced ^{28}Si,

Decay of ^{26}Al ($t_{1/2} = 7x10^5$ yr) and ^{44}Ti ($t_{1/2} = 60$ yr)

=> origin in **Core Collapse Supernovae**

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HINTS FOR NEUTRINO-PROCESS BORON IN PRESOLAR SILICON CARBIDE GRAINS FROM SUPERNOVAE

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- Out of 1000 SiC grains from a 30 g sample of the Murchison CM2 chondrite,
- 7 X grains show resolvable anomalies in Li and/or B.
- => ^{7}Li/^{11}B > upper limit

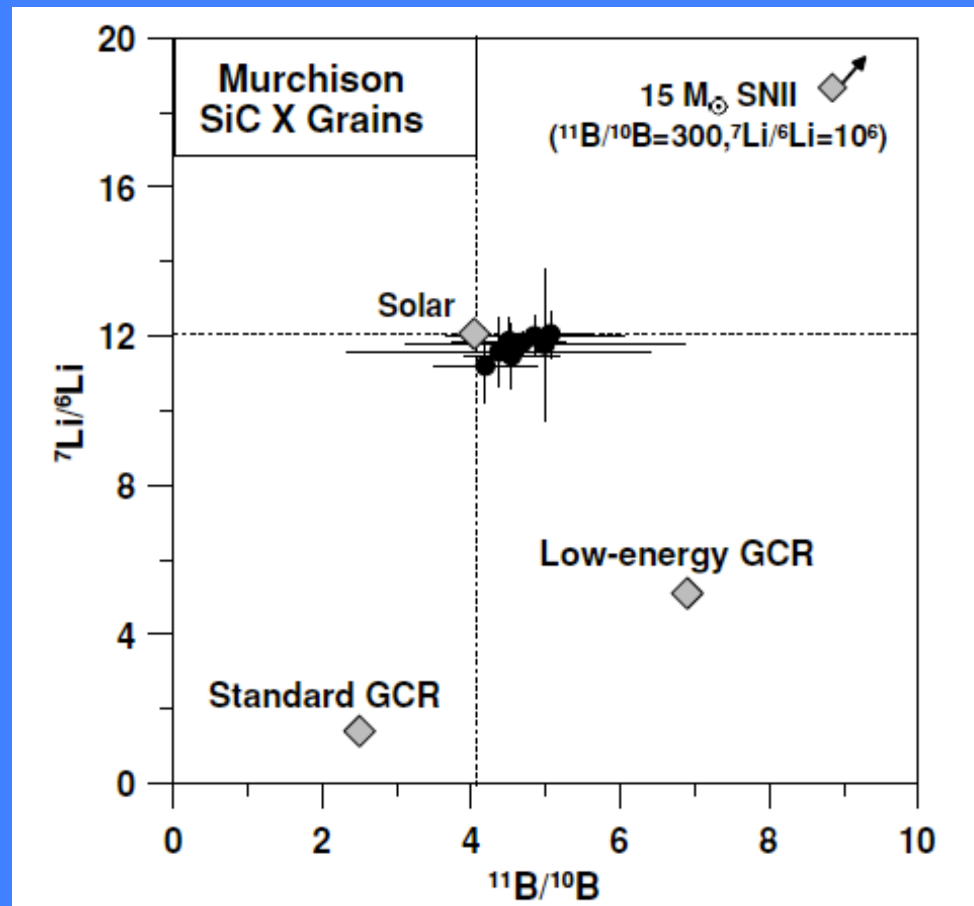


Table 1

C-, Si-, Li-, and B-isotopic Compositions of SiC X Grains from the Murchison Meteorite

Grain	Size (μm)	$^{12}C/^{13}C$	$\delta^{29}Si^a$ (‰)	$\delta^{30}Si^a$ (‰)	$^7Li/^6Li$	$^{11}B/^{10}B$	Li/Si (10^{-5})	B/Si (10^{-5})
Single X grains								
X1	0.6	114 ± 2	−178 ± 11	−265 ± 9	11.87 ± 0.63	4.51 ± 0.77	9.69	3.33
X2	1.2	128 ± 2	−377 ± 11	−261 ± 10	12.06 ± 0.62	5.06 ± 0.58	23.8	18.8
X3	1.5	244 ± 5	−205 ± 10	−297 ± 7	11.48 ± 0.86	4.54 ± 0.63	1.76	1.92
X4	1.0	241 ± 6	−556 ± 10	−245 ± 9	12.00 ± 0.56	4.85 ± 1.19	24.8	3.31
X9	0.6	38 ± 1	−361 ± 10	−394 ± 8	11.20 ± 1.01	4.19 ± 0.70	10.8	11.4
X11	0.8	326 ± 14	−358 ± 12	−432 ± 11	11.78 ± 2.03	4.99 ± 1.88	3.66	3.00
X13	0.7	345 ± 6	−261 ± 10	−424 ± 7	11.59 ± 0.93	4.37 ± 2.04	10.7	1.14
Average					11.83 ± 0.29	4.68 ± 0.31		
X grains + other nearby/attached SiC grains								
X5		34 ± 1	−226 ± 11	−120 ± 10	12.21 ± 0.41	4.36 ± 0.40	40.2	18.8
X6		88 ± 1	−236 ± 11	−189 ± 9	13.06 ± 1.36	3.83 ± 0.27	2.15	14.2
X7		78 ± 1	−281 ± 11	−208 ± 10	11.20 ± 2.40	11.47 ± 6.36	8.28	9.48
X8		76 ± 1	−223 ± 10	−266 ± 8	11.29 ± 0.64	4.27 ± 0.29	4.80	12.4
X12		83 ± 1	−271 ± 11	−242 ± 10	11.54 ± 0.52	4.13 ± 0.46	24.3	14.2
Average					11.90 ± 0.28	4.16 ± 0.17		
Solar		89	0	0	12.06	4.03	5.6	1.9

Note. $^a\delta^iSi = [(^iSi/^{28}Si)/(^iSi/^{28}Si)_\odot - 1] \times 1000$.

$$\frac{^7\mathrm{Li}}{^6\mathrm{Li}} = \frac{^7\mathrm{Li}_\odot + ^7\mathrm{Li}_\nu}{^6\mathrm{Li}_\odot} \qquad \frac{^{11}\mathrm{B}}{^{10}\mathrm{B}} = 4.03 + \frac{^{11}\mathrm{B}_\nu}{^{10}\mathrm{B}_\odot} = 4.68 \pm 0.31$$

$$= 12.06 + \frac{^7\mathrm{Li}_\nu}{^6\mathrm{Li}_\odot} = 11.83 \pm 0.29$$

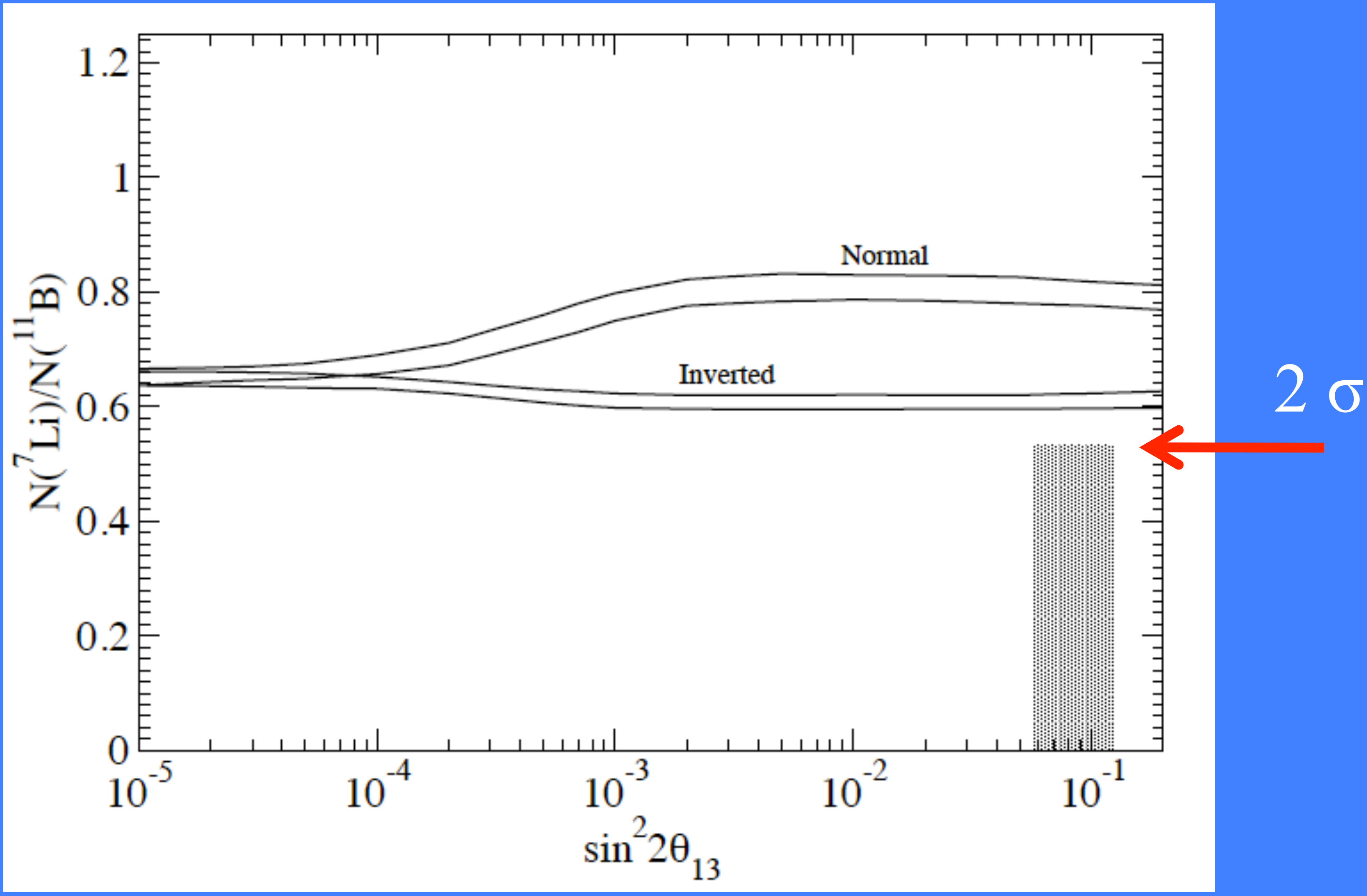
$$\frac{^7\mathrm{Li}_\nu}{^{11}\mathrm{B}_\nu}\left(\frac{^{10}\mathrm{B}_\odot}{^6\mathrm{Li}_\odot}\right)_X = -0.35 \pm 0.48$$

$$\left[\frac{(^7\mathrm{Li}_\odot + ^7\mathrm{Li}_\nu)/^6\mathrm{Li}_\odot + 1}{(^{11}\mathrm{B}_\odot + ^{11}\mathrm{B}_\nu)/^{10}\mathrm{B}_\odot + 1}\right]_X = 2.00 \pm 0.04\left(\frac{^{10}\mathrm{B}_\odot}{^6\mathrm{Li}_\odot}\right)_\mathrm{X}$$

$$^7\mathrm{Li}_\nu/^{11}\mathrm{B}_\nu = -0.31 \pm 0.42$$

$$\frac{^7\mathrm{Li}_\nu}{^{11}\mathrm{B}_\nu} < 0.53(2\sigma\ 95\%\ \mathrm{C.L.})$$

Preference for inverted hierarchy



One needs a proper statistical analysis that takes into account the meteoritic uncertainties along with the uncertainties in the supernova models, reaction rates, progenitor mass, etc. ….

- Bayesian Statistics

Bayesian Analysis

$$P(M_i|D) = \frac{P(D|M_i)P(M_i)}{\sum_j P(D|M_j)P(M_j)}$$

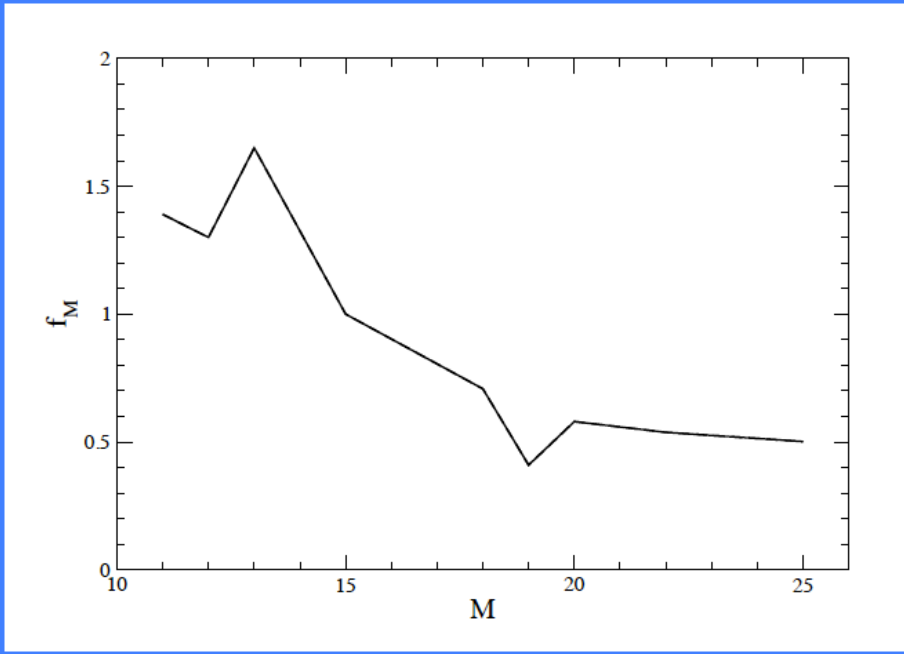
$$P(D|M_i) = \int dEdZda_k P(E,Z,D|M_i,a_k)P(a_k|M_i)$$

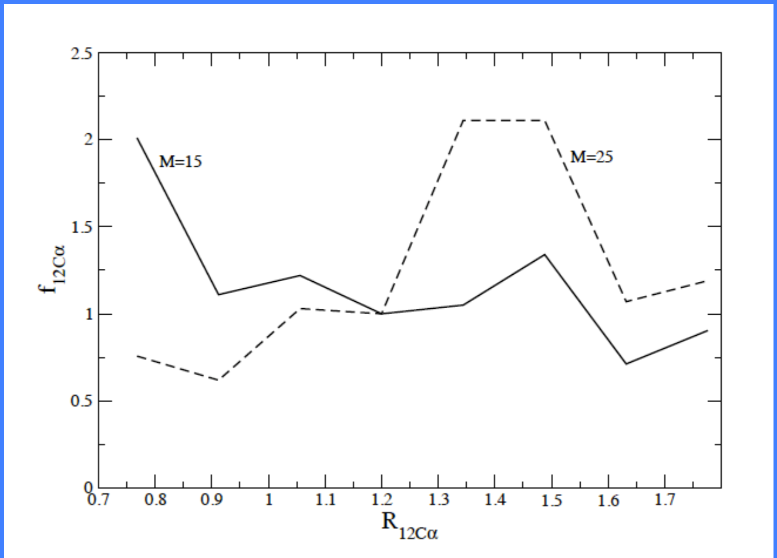
$$= \int dEdZda_k P(D|M_i,a_k,E,Z)P(Z,E|M_i,a_k)P(a|M_i)$$

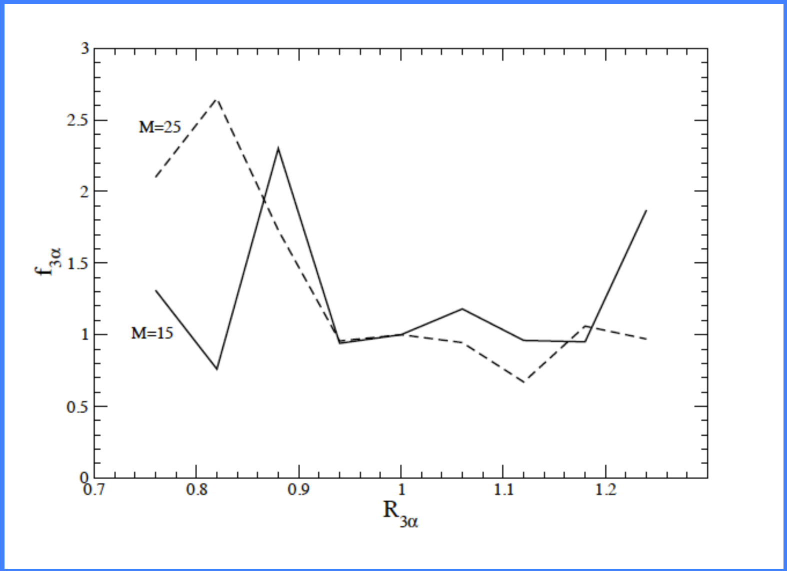
TABLE I: Parameter likelihood functions $P(a_k|M_i)$.

Parameter a_k	prior			reference
$\sin^2 2\theta_{13}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 0.92$	$\sigma_x = 0.017$	[7]
$R_{3\alpha}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 1.0$	$\sigma_x = 0.12$	[35]
$R_{12C\alpha}$	$e^{-(x-x_0)/2\sigma_x^2}$	$x_0 = 1.2$	$\sigma_x = 0.25$	[36]
$M_{prog}(\mathrm{M}_\odot)$	$m^{-2.65}$	$m_{min} = 10$	$m_{max} = 25$	[37]
T_ν(MeV)	Top hat	$T_\nu = 3.2 - 6.5$	(see text)	[15]

Astrophysical Model Dependence







Probability normal vs inverted mass hierarchy

$$P(M_i|D) = \frac{P(D|M_i)P(M_i)}{\sum_j P(D|M_j)P(M_j)}$$

= 74% - Inverted mass hierarchy

= 26% - Normal mass hierarchy

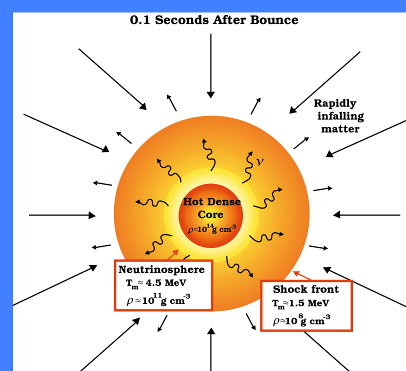
Conclusions

•Understanding the neutrino driven wind r-process requires very detailed understanding of the neutrino and nuclear physics above and below the neutron star surface

•The collapsar model for gamma-ray bursts has the potential to produce an r-process like abundance distribution in the early universe and warrants further investigation.

•SiC X grains enriched in ν-process material have the potential to solve the neutrino mass hierarchy problem for finite θ_{13}.

Evidence for an ***inverted neutrino hierarchy*** from ***neutrino nucleosynthesis*** in core collapse supernovae, ***meteorites*** and new measurements of the ***θ_{13} neutrino mixing angle***



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