MACROS, IAP, November 27–29th 2013

Jets, Nucleosynthesis, and Nuclei Survival

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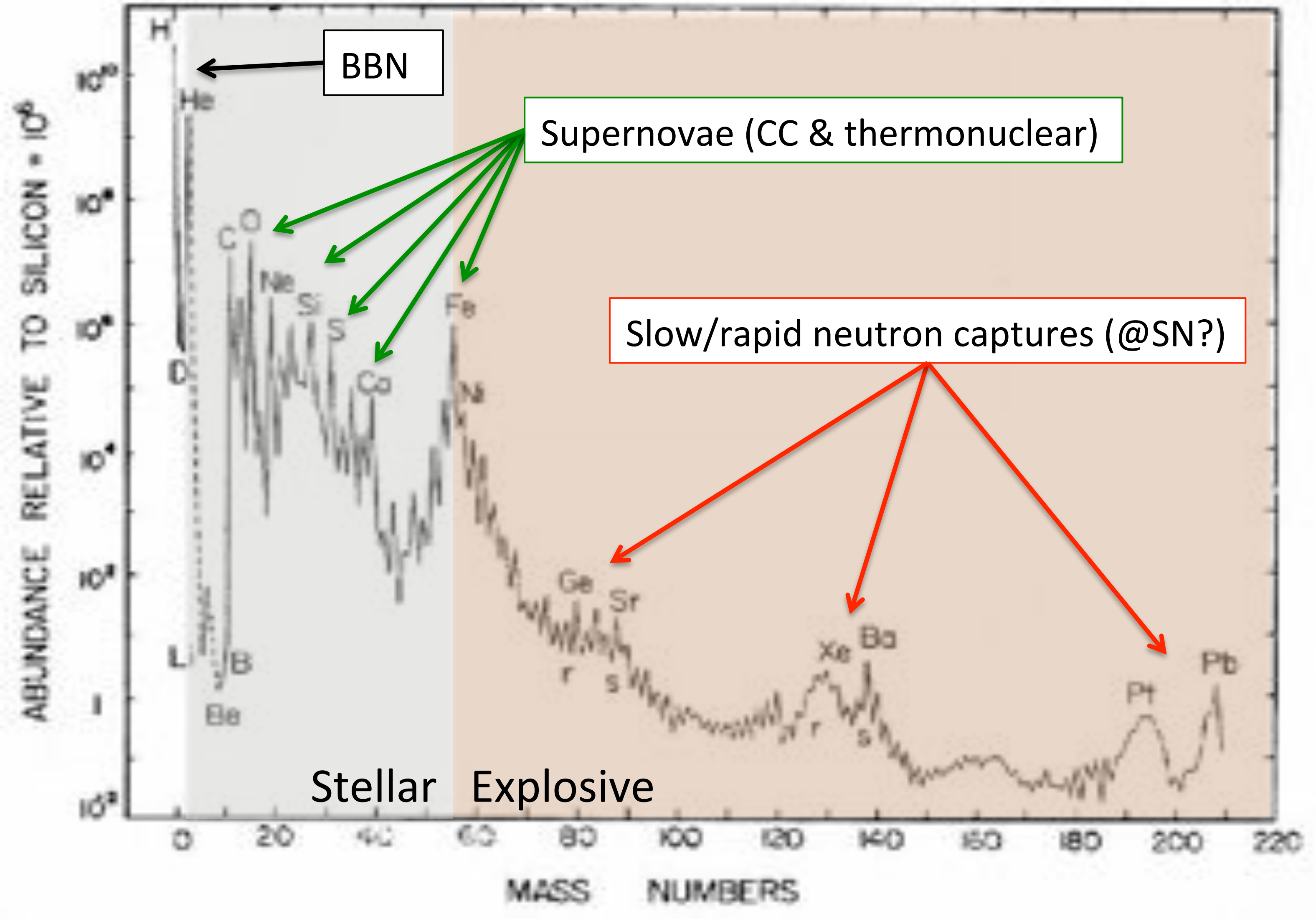
Image credit: NASA/ESA

Solar nuclei abundance

A large fraction of nuclei (likely) come from core collapse of massive stars

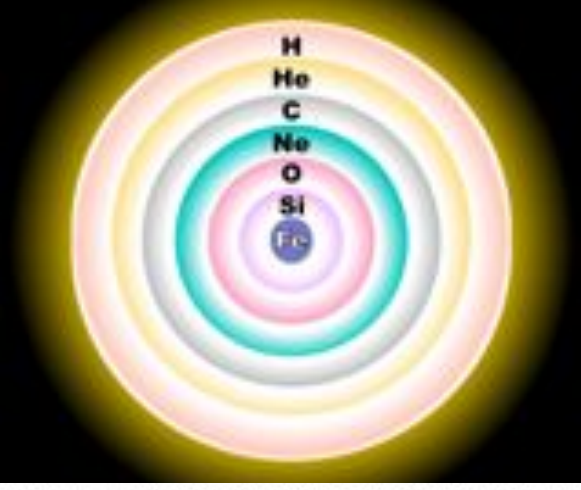


Contents

- Nuclei abundances in massive stars and their collapse
  - Stellar nucleosynthesis
  - Explosive nucleosynthesis
  - Nucleosynthesis in jets
- Nuclei destruction/survival
  - During initial loading
  - During entrainment
  - In the jet
- As sources of ultra-high energy cosmic rays
- Summary

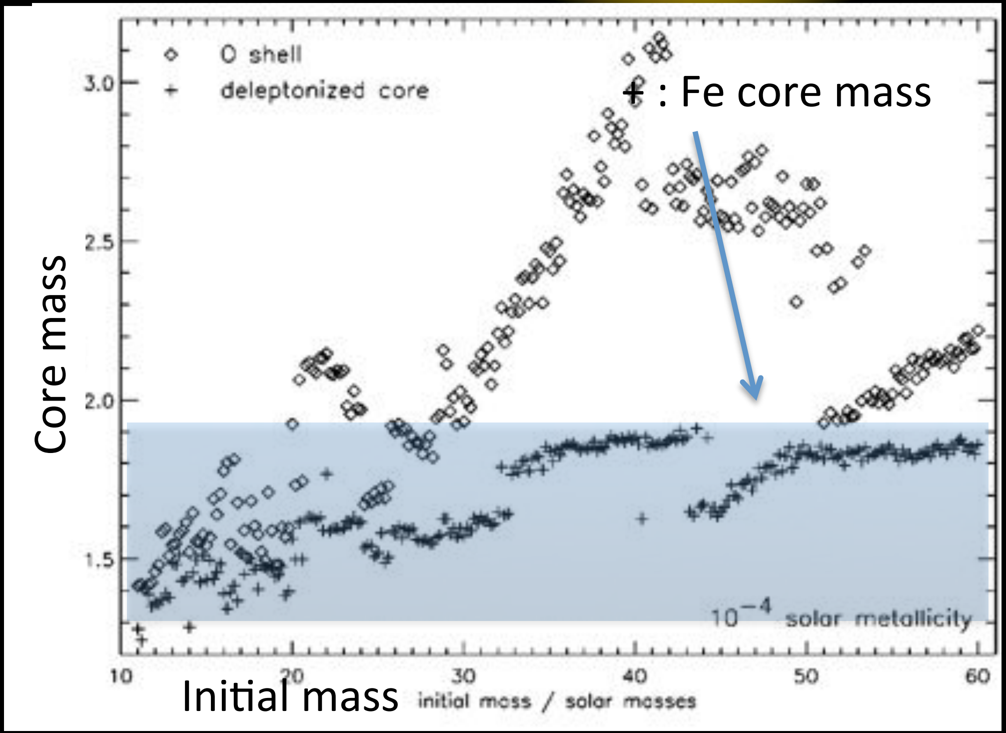
Stellar Nucleosynthesis

Massive star nucleosynthesis results in the famous onion-shell structure:



Stellar modeling requires knowledge of extended nuclear networks, and depend on metallicity, rotation, magnetic fields, convection, mass loss, binaries, etc…

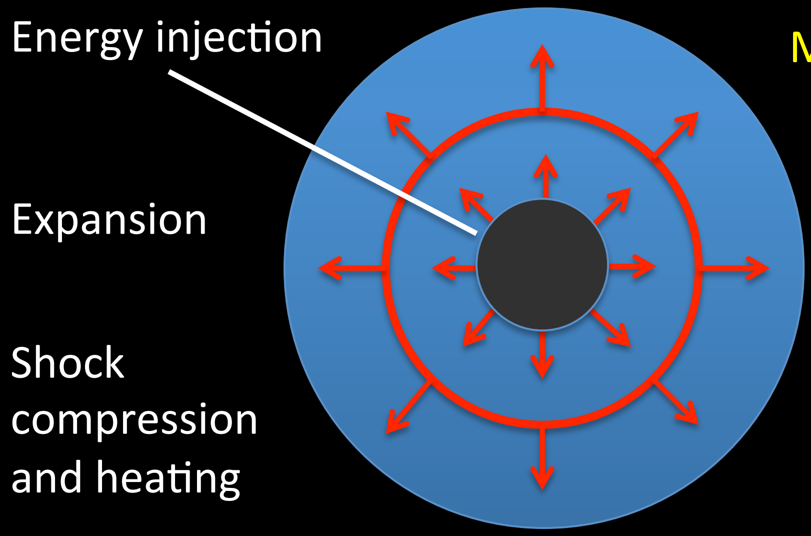
Nevertheless, the final Fe core mass does not vary too much (and neutron star masses are fairly narrowly scattered)

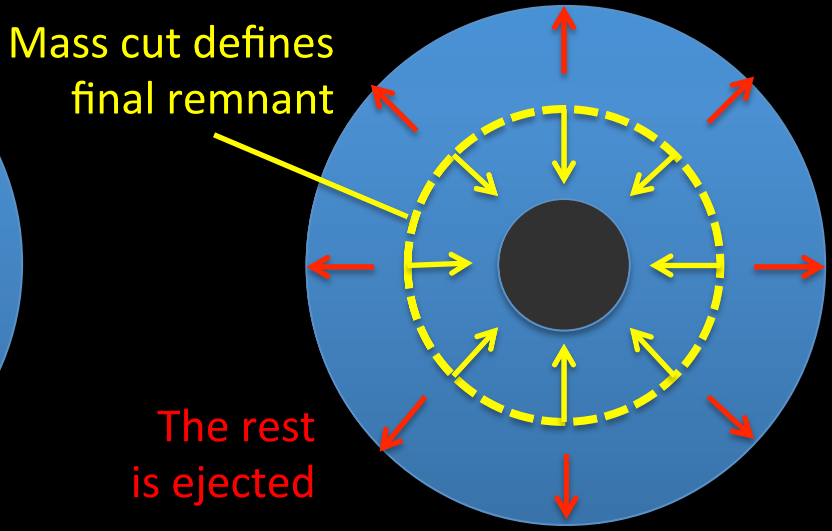


Woosley et al (2002)

Explosive Nucleosynthesis

Propagation of shock wave through the core & envelope → Compression and heating → Explosive nucleosynthesis





However, how much heavy nuclei is made is quite uncertain:

1. An arbitrary amount of energy injection
2. At an arbitrary location
3. With an arbitrary mass cut

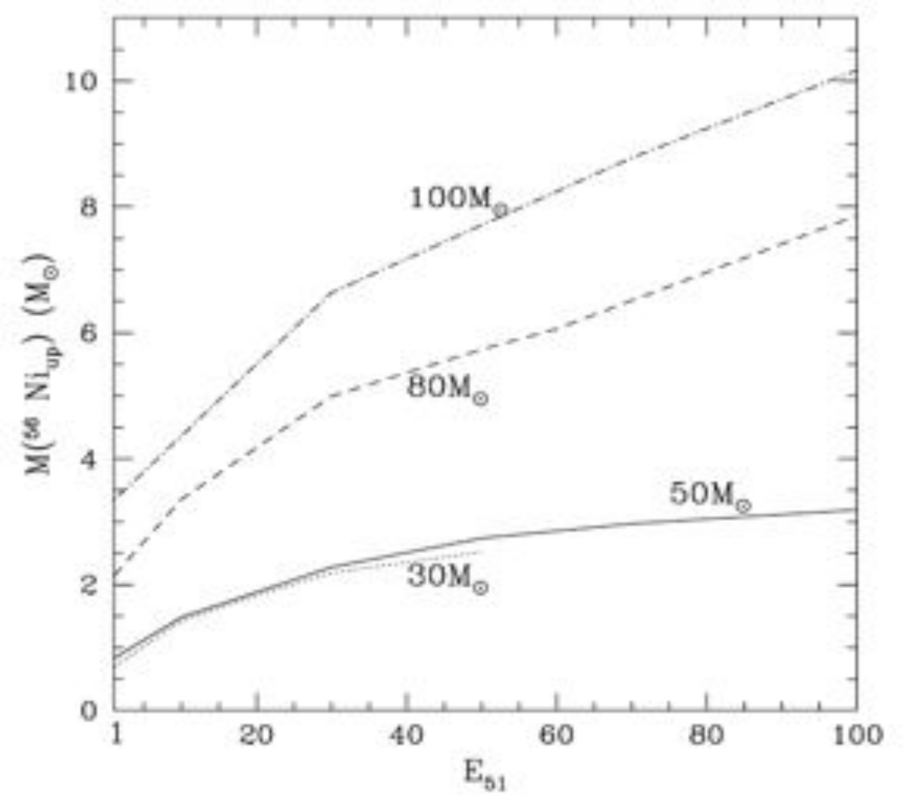
Much nucleosynthesis is possible

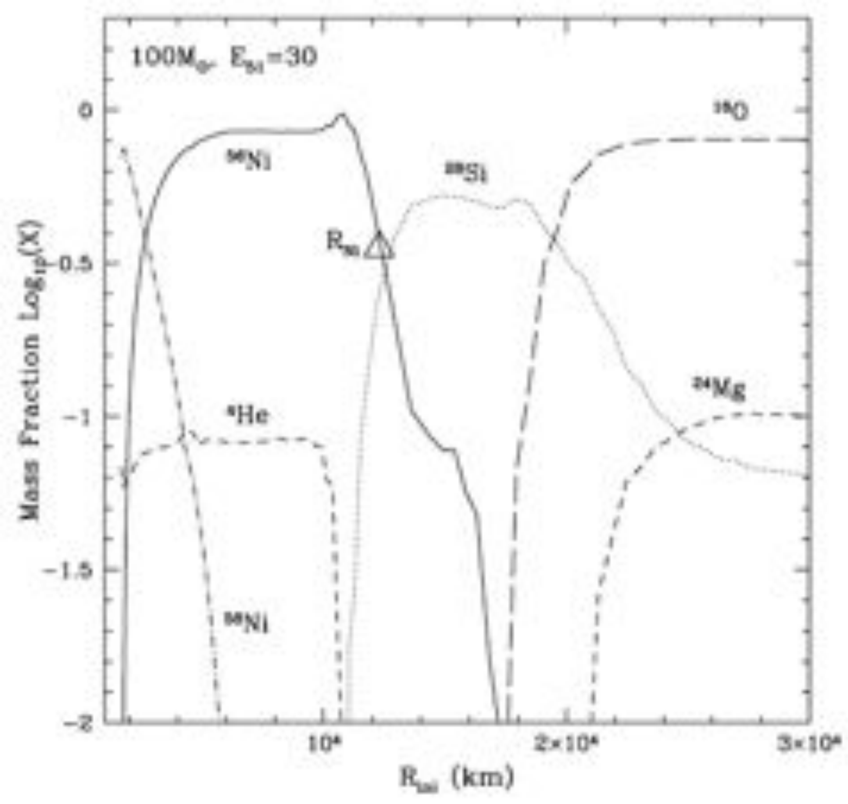
Super-luminous supernova (e.g., SN2006gy) have been discovered:

- CSM interaction, pair-instability supernova, magnetic power, higher ^{56}Ni ???
- Late-time bolometric LC consistent with ~7 Msun of ^{56}Ni (x100 usual SN)

Ofek et al. (2007), Smith et al. (2007), Gal-yam et al (2009) Agnoletto et al. (2009), Kawabata et al. (2009)

How to get so much ^{56}Ni ? E.g., increase energy, reduce mass cut

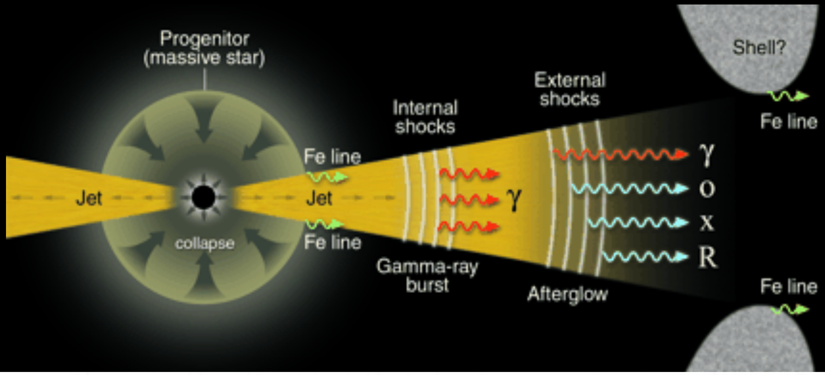




Umeda & Nomoto (2008)

Nucleosynthesis in GRB fireballs

Some fraction of supernovae have jet-like ejecta (e.g., GRBs)



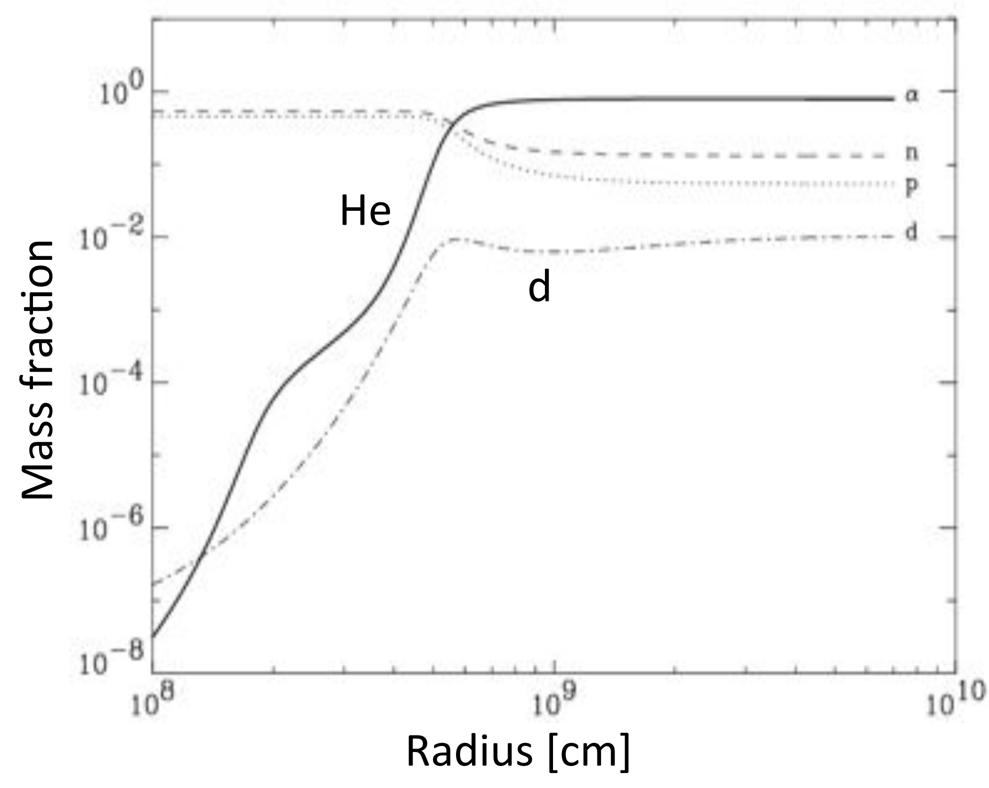
GRB fireball nucleosynthesis:

- Initial temperatures of ~ a few MeV → all nuclei are dissociated at jet launch
- Huge entropy ($n_\gamma/n_p = 10^5$) and rapid expansion time (~0.1 ms)
- Electron fraction typically < 0.5

- Not much C made, and freeze out composition has only trace amounts of heavy nuclei

c.f. BBN

Pruet et al (2002)
Lemoine (2002)
Beloborodov (2003)



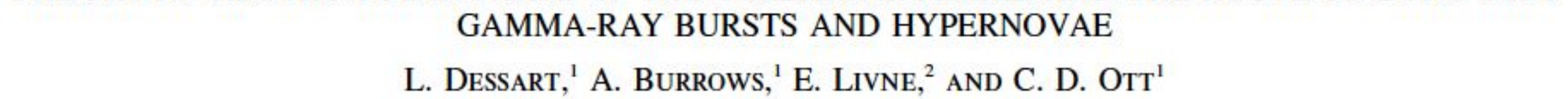
Magnetic-dominated GRB models

Situation changes if jet is magnetic-energy dominated: e.g., the magnetar model

A rapidly rotating proto-neutron star has sufficient energy to power a GRB if it can be tapped:

$$\dot{E} \approx 10^{49} \left(\frac{P}{1\,\mathrm{ms}}\right)^{-4} \left(\frac{B}{10^{15}\,\mathrm{G}}\right)^{2} \mathrm{ergs/s}$$

e.g., Bisonaty-Kogan 1971, Usov (1992), Thompson (1994), Akiyama et al (2003)

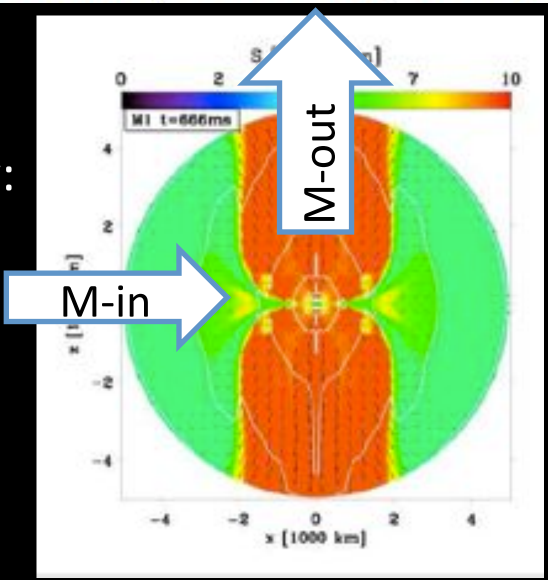


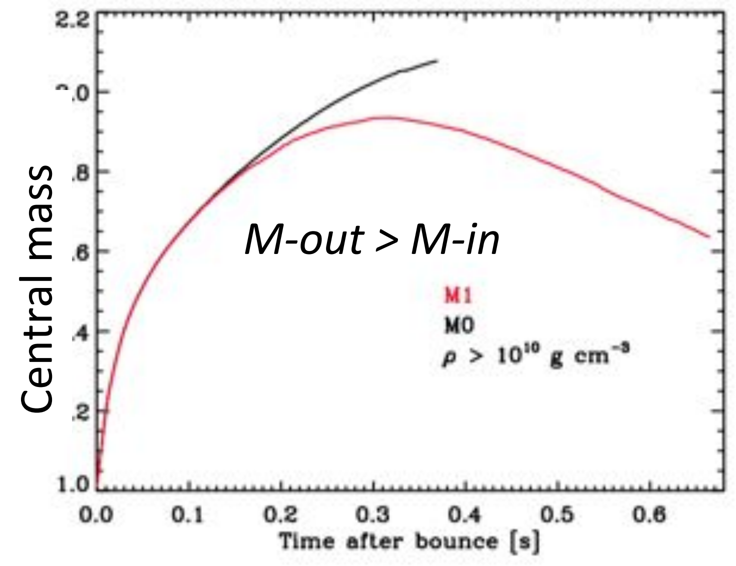
THE PROTO–NEUTRON STAR PHASE OF THE COLLAPSAR MODEL AND THE ROUTE TO LONG-SOFT GAMMA-RAY BURSTS AND HYPERNOVAE

L. Dessart,[1] A. Burrows,[1] E. Livne,[2] and C. D. Ott[1]

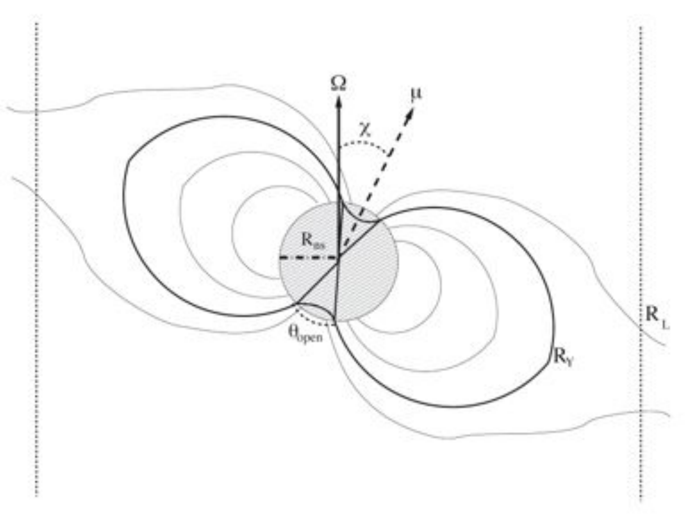
Having the right angular momentum distribution is the key:

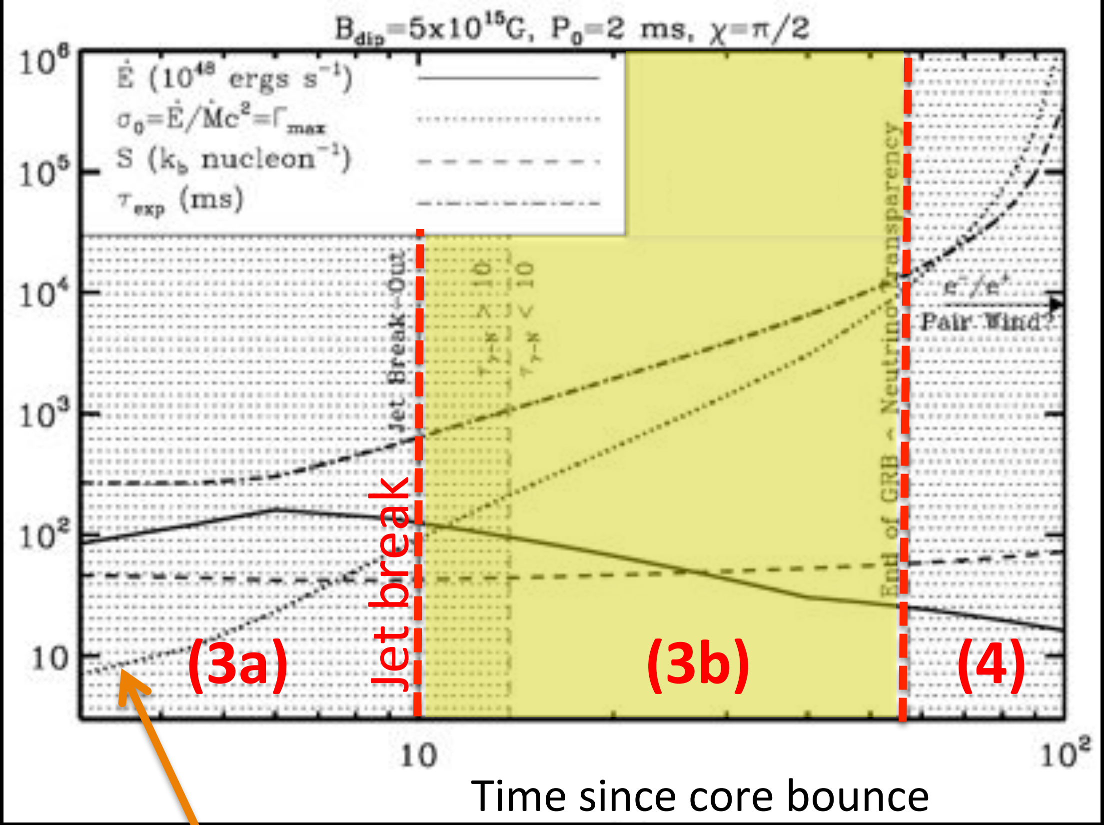
Fast rotating core
→ B-field generation
→ Rapid mass-loss
→ Evades BH formation





Magnetic-dominated GRB models





Metzger et al 2011

The proto-magnetar model:

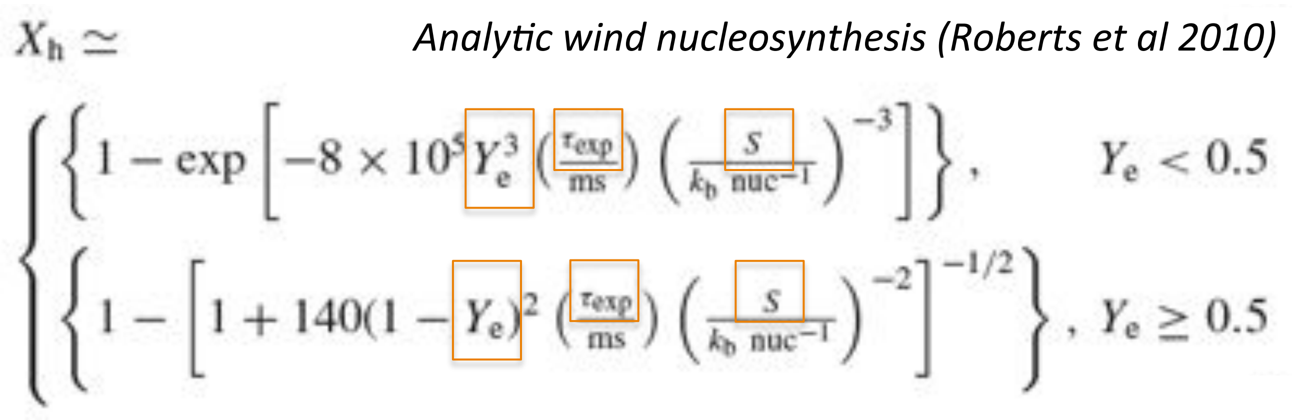
1. Thermally-driven wind
2. Non-relativistic magnetic driven wind
3. Relativistic magnetic driven wind
    a) Pre-break out
    b) GRB phase
4. Pair wind phase

"magnetization" or terminal Lorentz factor

$$\sigma_0 = \frac{\dot{E}}{\dot{M}c^2}$$

Nucleosynthesis yields

The mass fraction of heavy nuclei (A≥56):



Analytic wind nucleosynthesis (Roberts et al 2010)

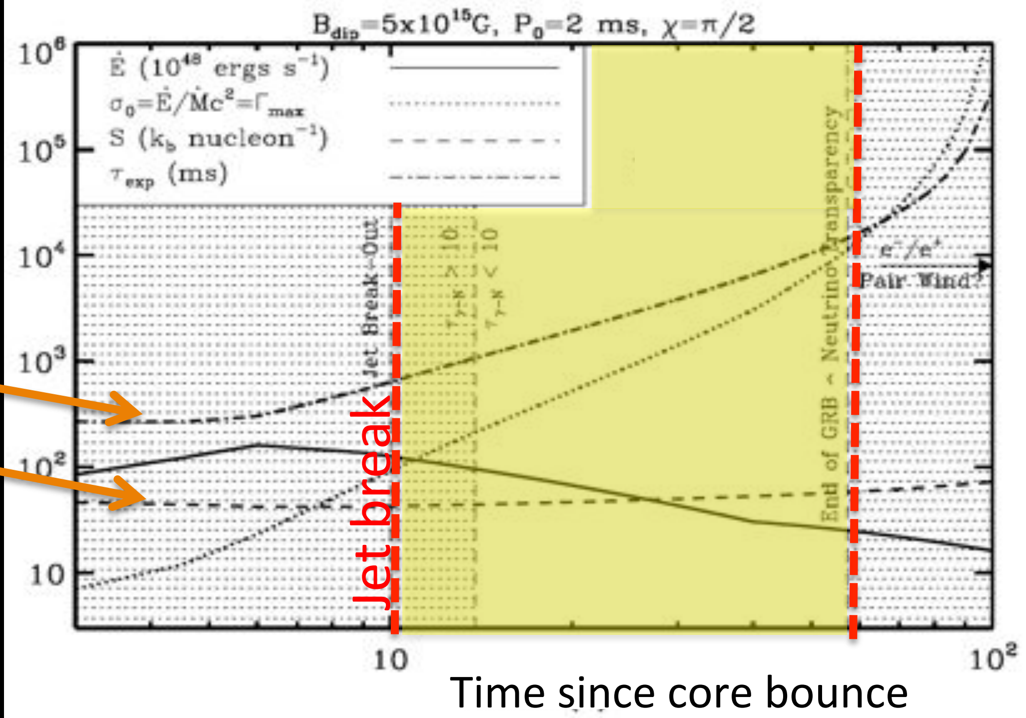
$$X_h \simeq \begin{cases} \left\{1 - \exp\left[-8 \times 10^5 \boxed{Y_e^3} \left(\frac{\boxed{\tau_{\rm exp}}}{\rm ms}\right)\left(\frac{\boxed{s}}{k_b\ {\rm nuc}^{-1}}\right)^{-3}\right]\right\}, & Y_e < 0.5 \\ \left\{1 - \left[1 + 140(1 - \boxed{Y_e})^2 \left(\frac{\boxed{\tau_{\rm exp}}}{\rm ms}\right)\left(\frac{\boxed{s}}{k_b\ {\rm nuc}^{-1}}\right)^{-2}\right]^{-1/2}\right\}, & Y_e \geq 0.5 \end{cases}$$

Where:
Y_e: electron fraction
τ_{exp}: expansion timescale
s: entropy

For an oblique* rotator:

- Expansion time-scale [ms]
- Entropy [k_B/baryon]

*Important since obliquity affects ν-heating through centrifugal force



Metzger, Giannios, Horiuchi (2011)

Nucleosynthesis yields

Y_e: PNS is n-rich ($Y_e \sim 0.1$), but evolves by neutrino irradiation to 0.4 – 0.6

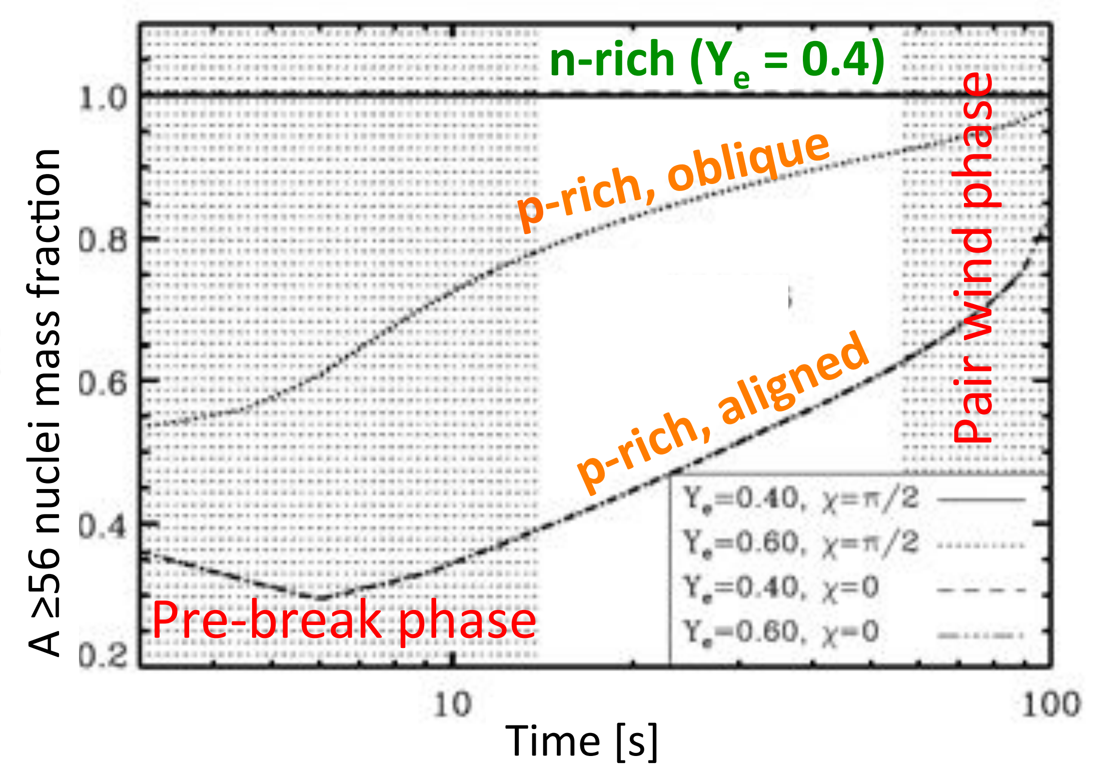
$$\begin{array}{c} \nu_e + n \rightarrow e^- + p \\ \bar{\nu}_e + p \rightarrow e^+ + n \end{array} \quad \Rightarrow \quad \frac{n}{p} \rightarrow \frac{\dot{N}_{\bar{\nu}_e}\sigma_{\bar{\nu}_e}}{\dot{N}_{\nu_e}\sigma_{\nu_e}} \sim \frac{L_{\bar{\nu}_e}\langle E_{\bar{\nu}_e}\rangle}{L_{\nu_e}\langle E_{\nu_e}\rangle}$$

Nucleosynthesis: with the reduced entropy, the freeze out composition can be heavy-dominated, especially for:

- Initially n-rich matter
- Oblique rotators what receive less n-heating and hence have lower entropies

c.f. baryon-rich jets

Inoue et al (2003)

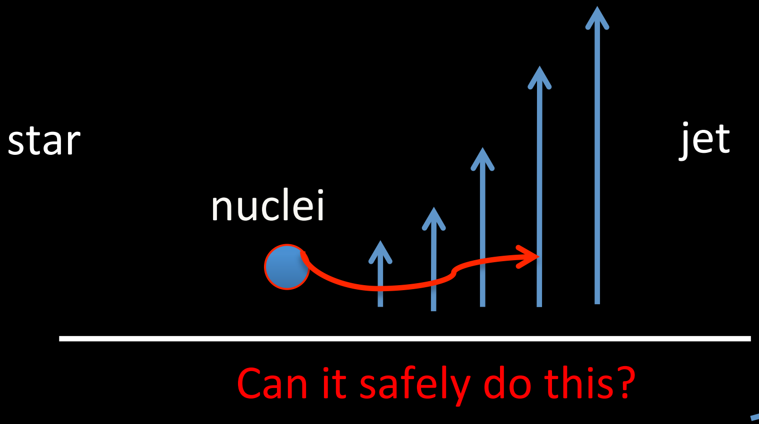


Metzger, Giannios, Horiuchi (2011)

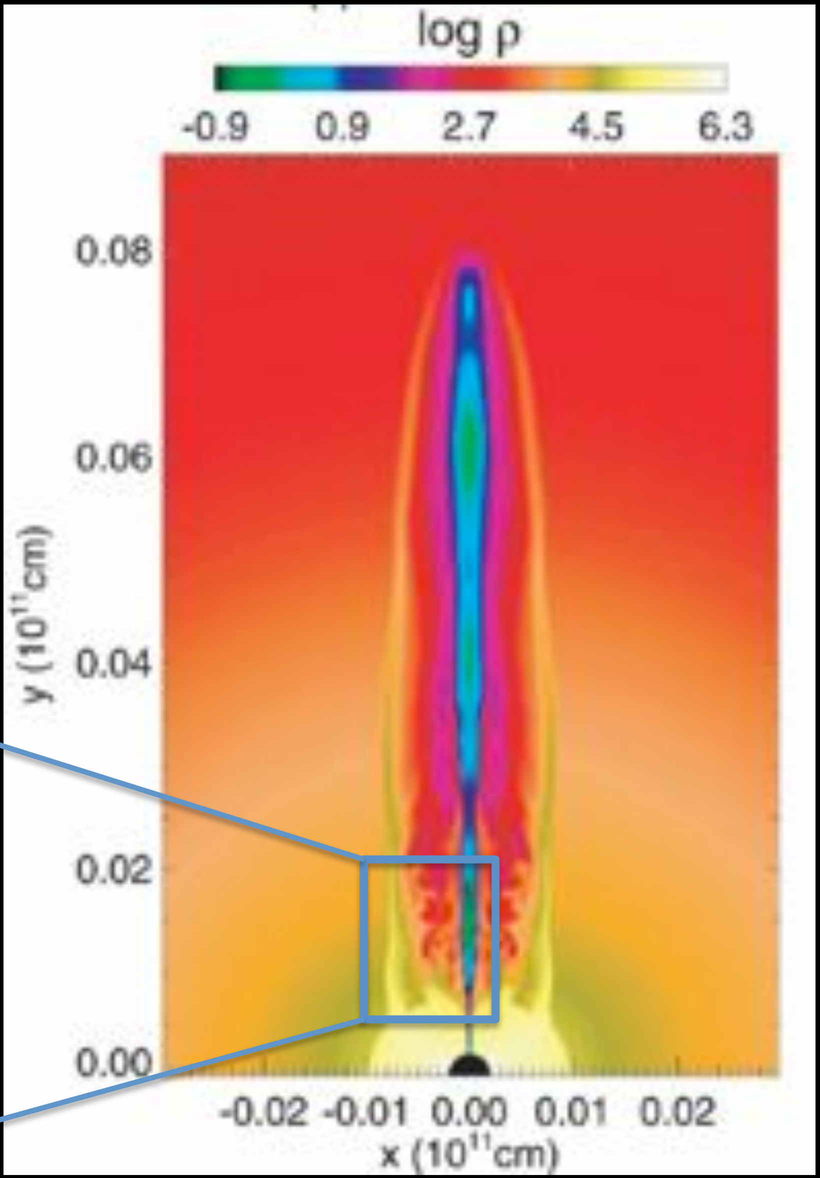
NUCLEI DESTRUCTION / SURVIVAL

Survival in nuclei entrainment

Jet baryon loading is an unanswered question. But we can explore nuclei destruction/survival during mixing.



Can it safely do this?



Zhang et al. (2003)

Nuclei entrainment

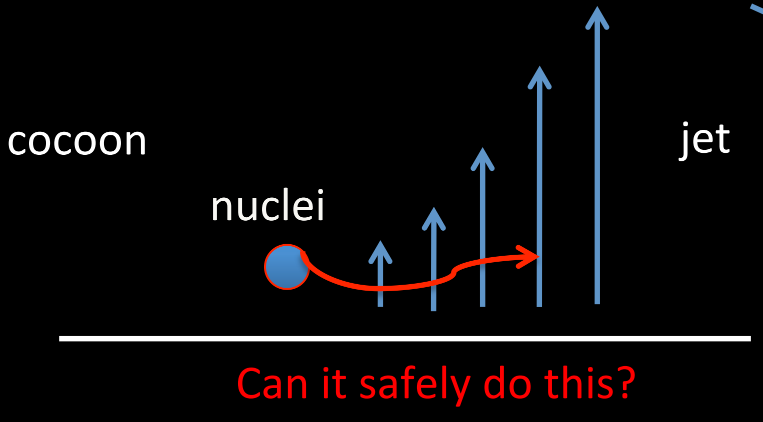
Jet baryon loading is an unanswered question. But we can explore nuclei destruction/survival during mixing.

We need to model the cocoon:

Cocoon: made up of shocked stellar and jet material; Fe-rich

Jet: mostly nucleons, $e^{\pm}$, and γ

Mixing can occurs by e.g., Kelvin-Helmholtz instability [e.g., Aloy 2002]



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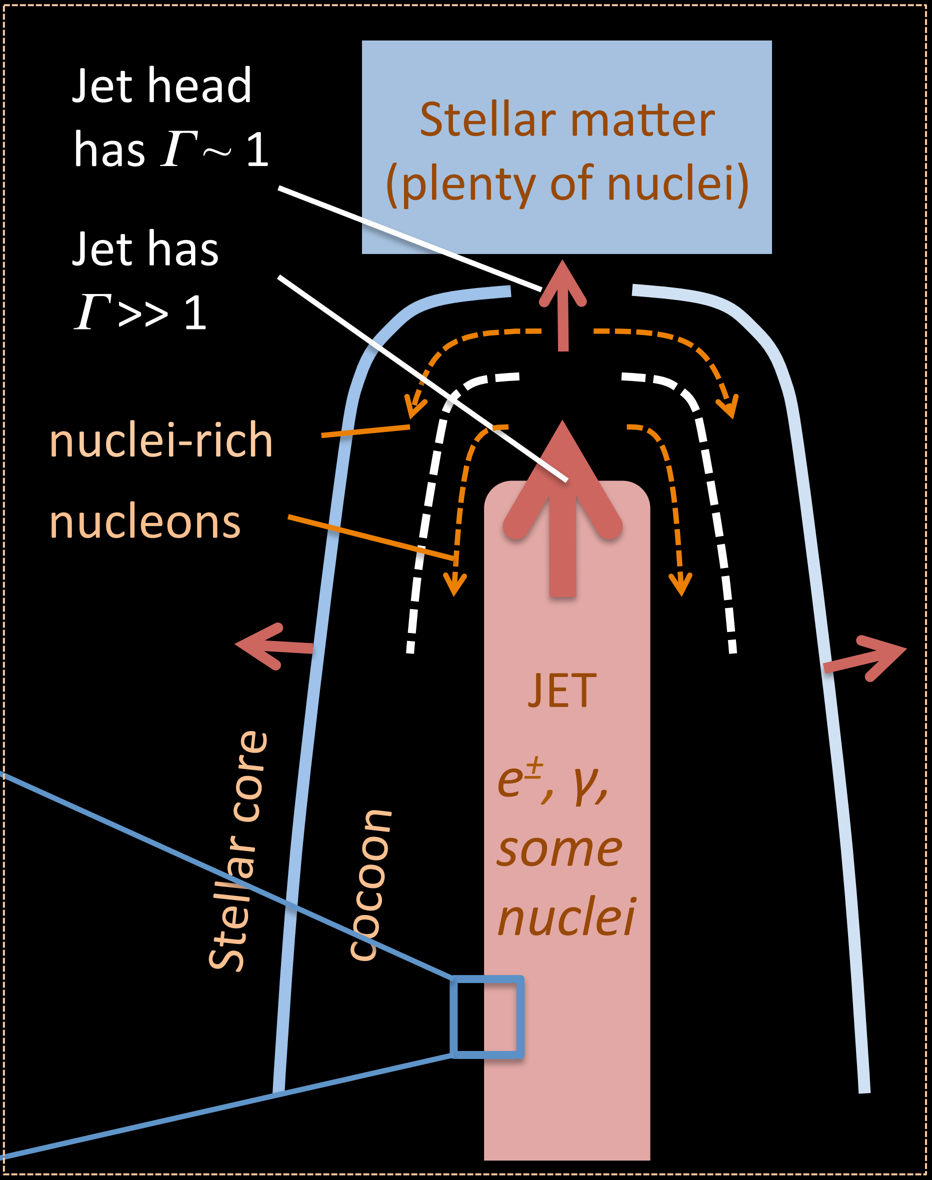
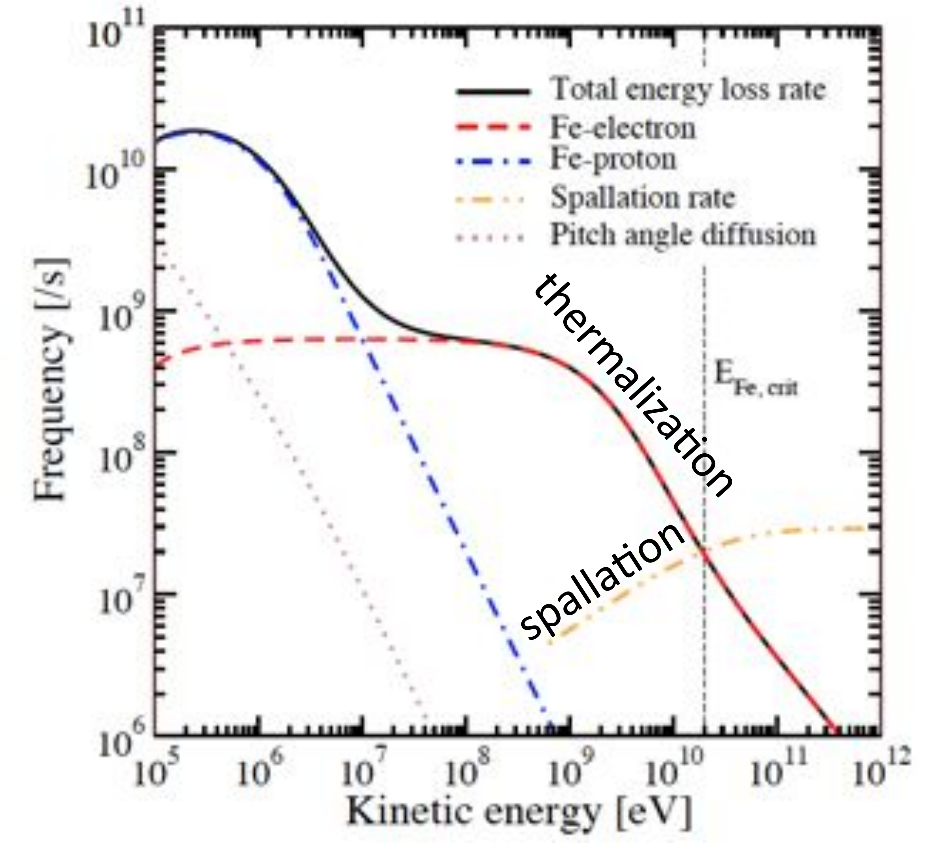
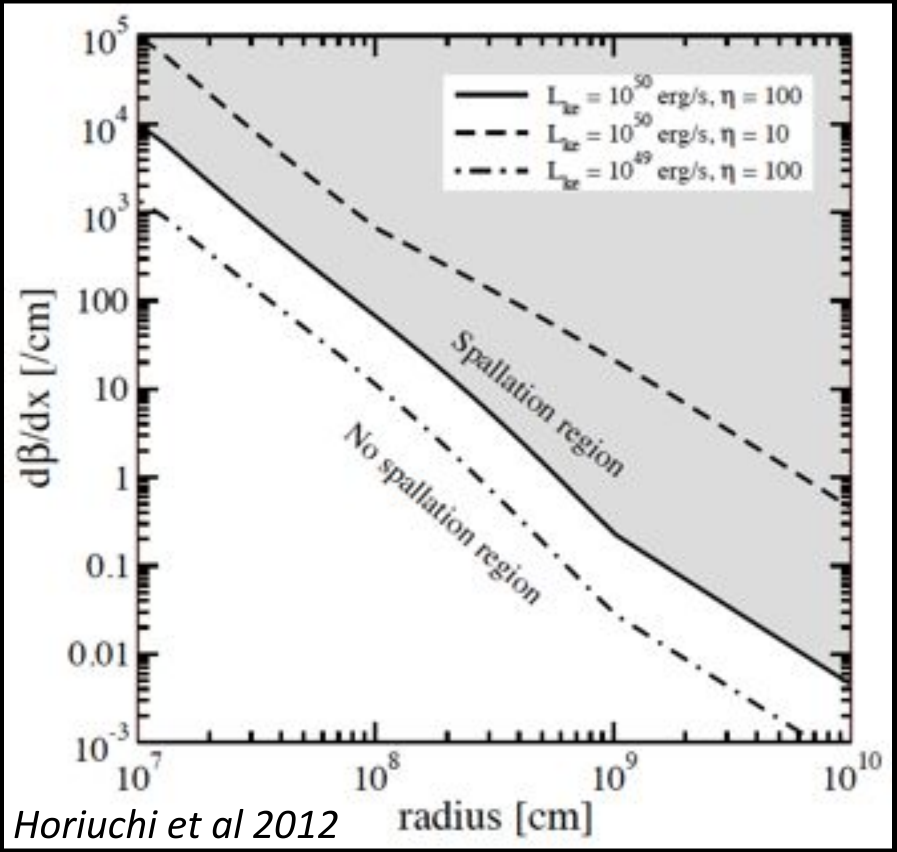


Survival in nuclei entrainment

For nuclei survival: demand that in the jet frame, the nuclei velocity is below the spallation threshold → requires the nuclei to be thermalized FASTER than it takes to move up the velocity gradient where its speed becomes too fast



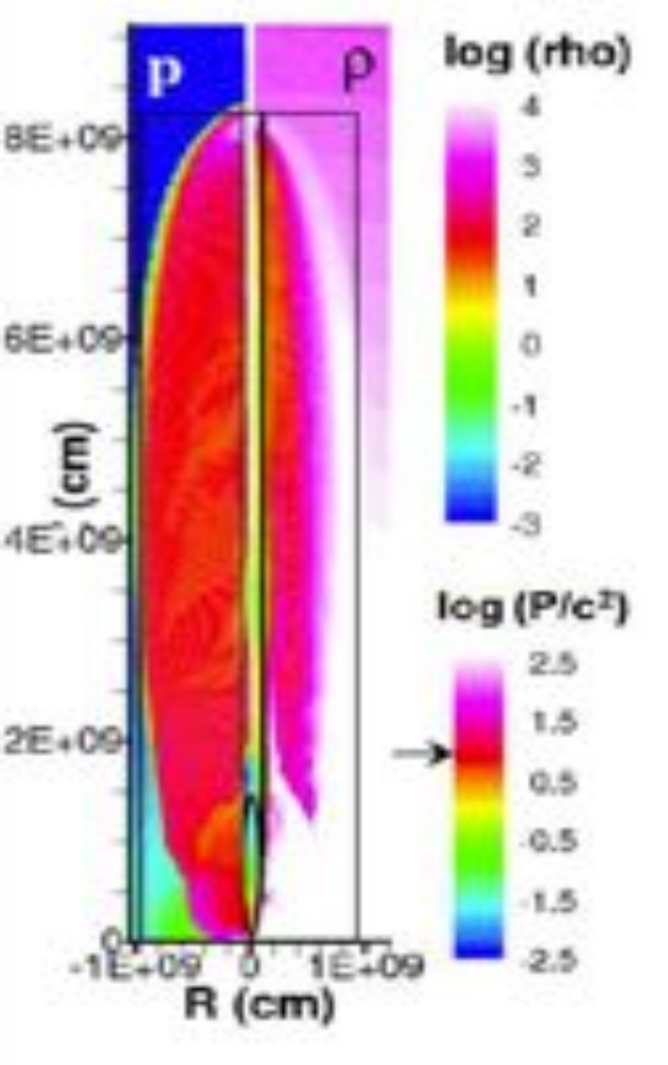
Rapid thermalization possible for KE < 20 GeV



Horiuchi et al 2012

Spallation region depends on velocity gradient

Survival in jets: recollimation shocks



Mizuta & Aloy (2009)

Jet collimated by cocoon pressure → becomes shock and the jet moves at *Bromberg et al (2011)*

$$\Gamma_s \sim 1/\theta_j \sim 8$$

The relative Lorentz factor can hence be large

$$\sim \Gamma_j/2\Gamma_s \sim 10$$

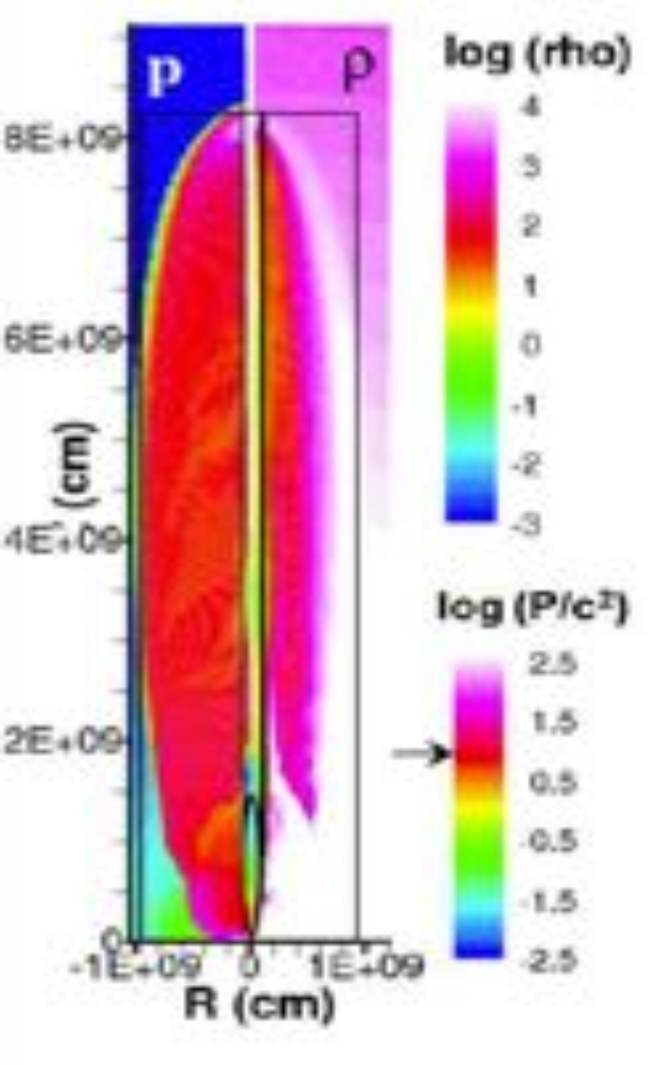
→ Nuclei destroyed!

But the temperature is high

$$T_j \sim 100 L_{50}^{1/4} r_9^{-1} \mathrm{keV}$$

Which is conducive to pair-creation → creates more target to thermalize with

Survival in jets: recollimation shocks



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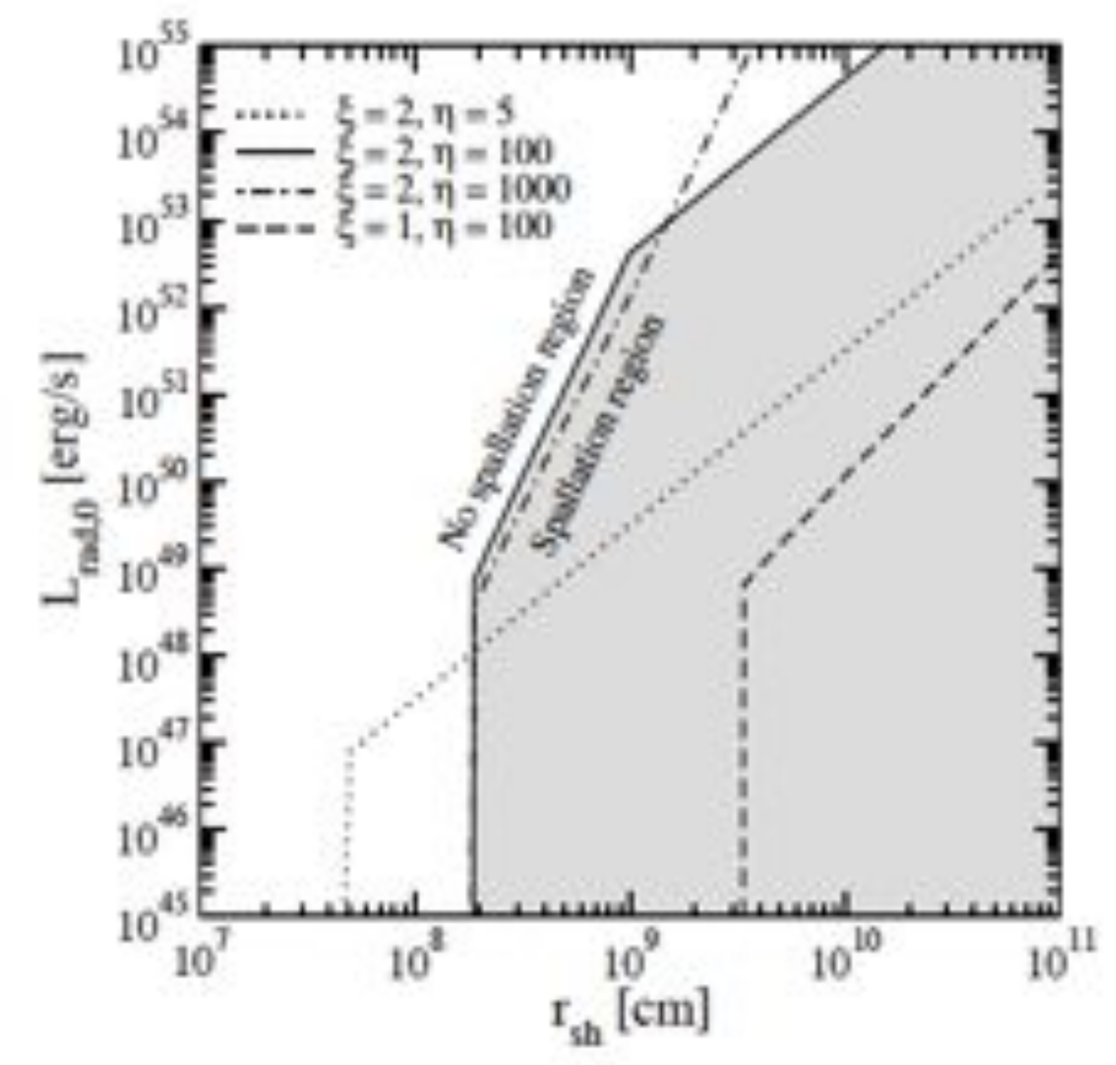


Horiuchi et al 2012

Survival in jets: collisions with neutrons

Neutrons are collisionally coupled to the accelerating plasma:

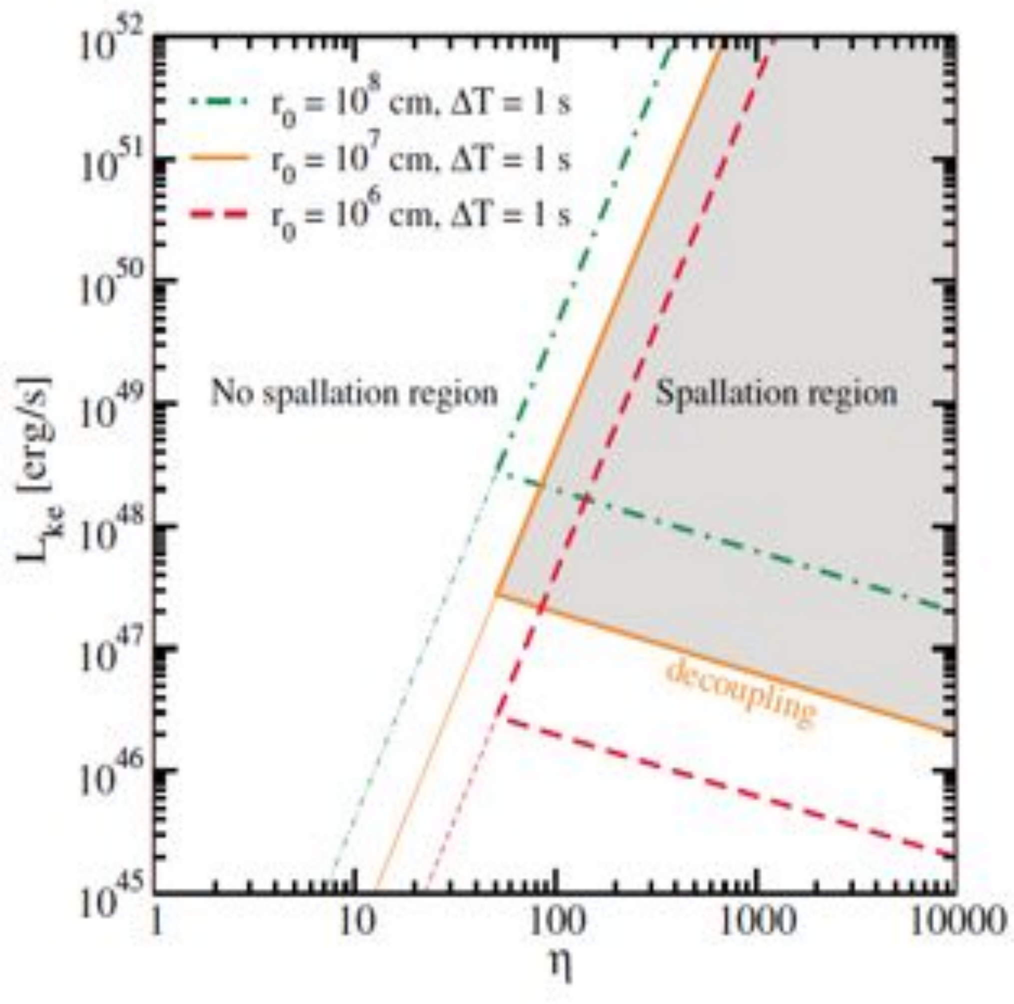
$$\overset{\text{EM}}{\gamma \leftrightarrow e} \overset{\text{coulomb}}{\leftrightarrow p} \overset{\text{strong}}{\leftrightarrow n}$$

But they can lag behind and even decouple. Requiring the relative velocity:

$$\tilde{\beta} \sim \frac{\tau_{\rm coll}}{\tau_{\rm acc}} \propto L^{-1} r^3 \eta$$

to be less than the spallation threshold gives survival & destruction regions:

$$\eta < 200(L_j/10^{50}\mathrm{erg/s})^{1/4}$$



Horiuchi et al 2012

Short summary

	Fireball GRB	**Magnetic GRB**	**Sub-luminous GRB**
Source: stellar nucleosynthesis	Y	Y	Y
Source: jet nucleosynthesis	N	Y	Y
Survives: initial loading?	N	Y/N	Y
Survives: entrainment?	vel gradient	vel gradient	vel gradient
Survives n-collisions?	Y	Y	Y
Survives: oblique shocks?	Initially Y	Y/N	harder

"N" means not possible;
"Y" means possible for canonical parameters;

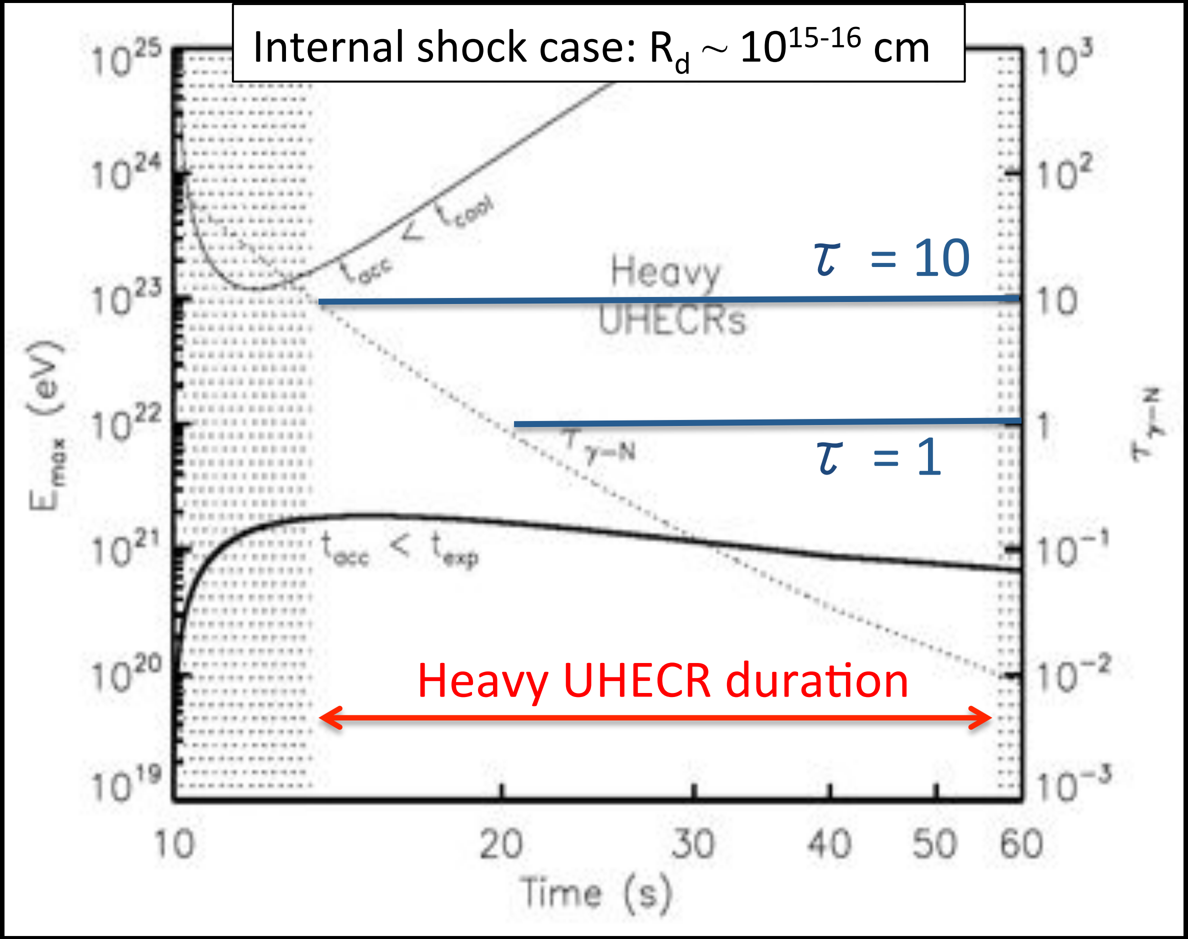
As sources of UHECRs

Acceleration:
Demand that the timescale for acceleration is shorter than both the cooling and expansion timescales:

→ Expansion limited

Survival:
Adopt the standard Band function photon spectrum and demand that the optical depth of photodisintegration is

- t = 1 [conservative]
- t = 10 [a few is ok]



Metzger, Giannios, Horiuchi (2011)

General discussions in: *Murase et al (2008), Wang et al (2008), Horiuchi et al (2012)*

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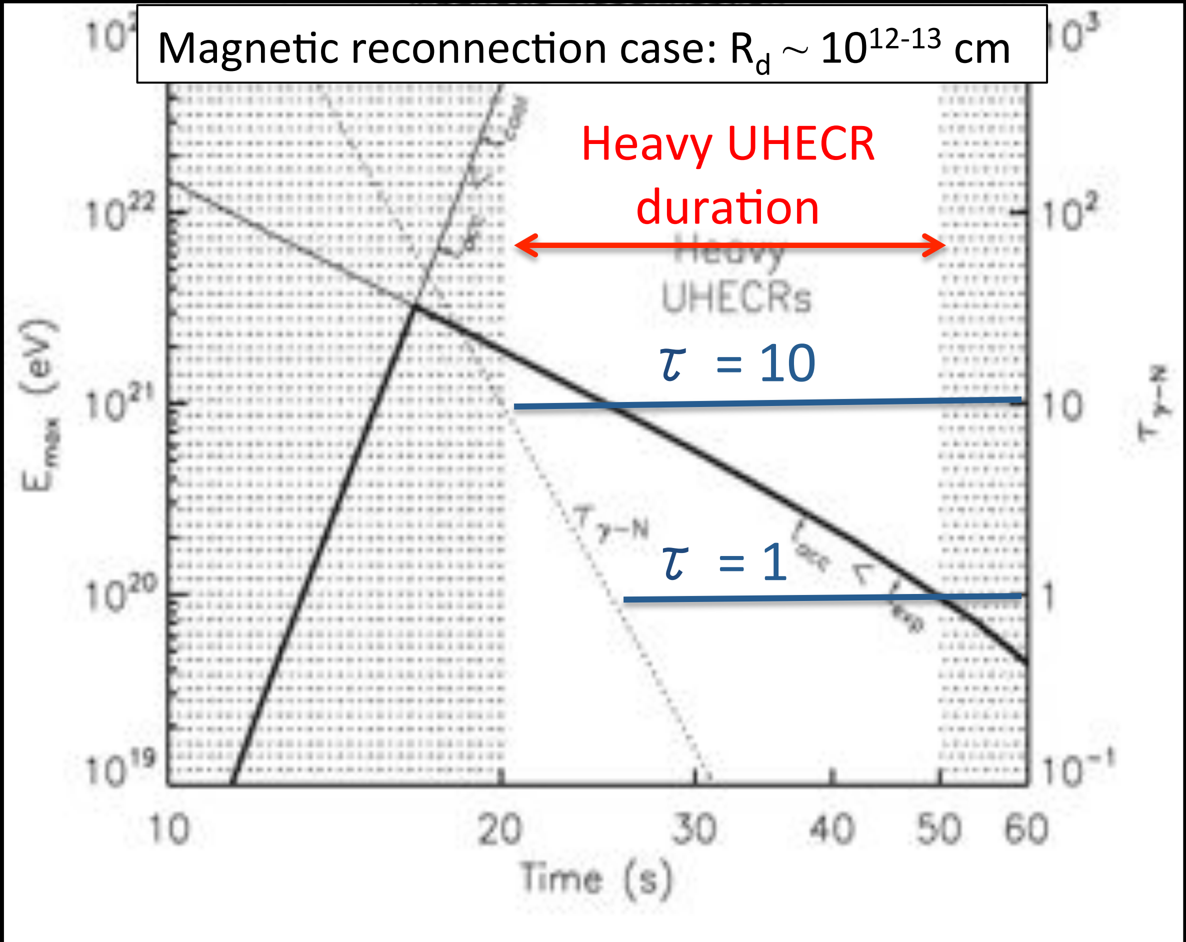


Metzger, Giannios, Horiuchi (2011)

General discussions in: *Murase et al (2008), Wang et al (2008), Horiuchi et al (2012)*

Summary

- Massive stars are stores of heavy nuclei: through stellar nucleosynthesis, explosive nucleosynthesis, and jet nucleosynthesis

- Nuclei in jets:
  - Magnetar models for GRBs, low-luminosity GRBs, and baryon-rich jets are especially conducive to heavy nuclei synthesis
  - Nuclei may safely enter the jet medium through entrainment

- Nuclei survival: concerns at recollimation shocks, collisions with neutrons, and destruction at the dissipation radius
  - Recollimation shocks are problematic, but not for small radii and entrainment post-shock
  - Other concerns easier to avoid in magnetic GRB models and low-luminosity GRBs, and larger dissipation radii

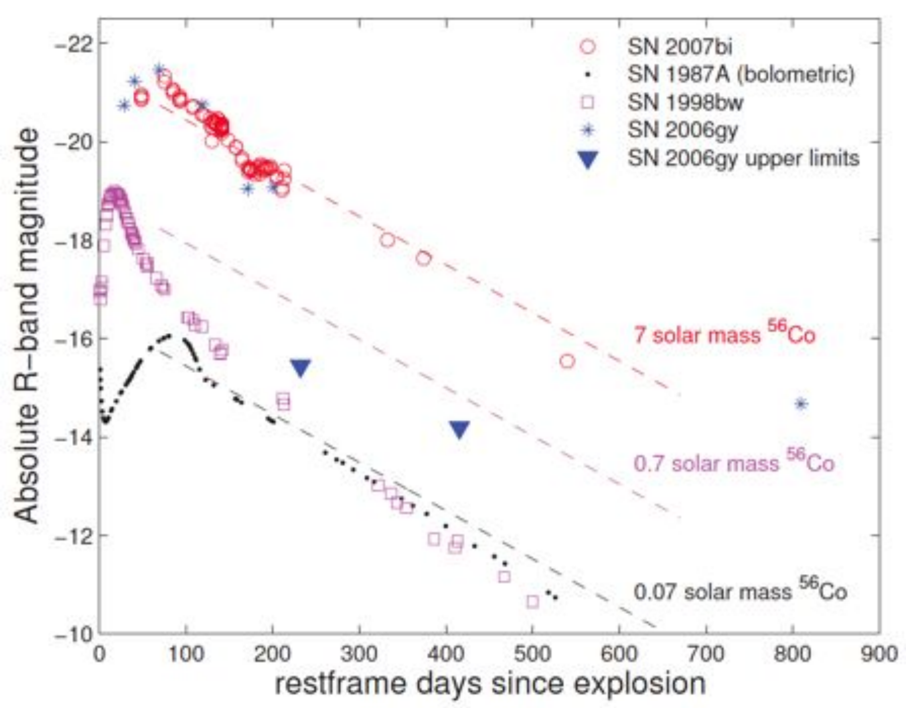
BACKUP SLIDES

SNSN: Hypernovae

- SN2006gy was ~100 times brighter than usual CCSNe, even brighter than 98bw
  - Integrated light >~ 10^{51} erg

Ofek et al. (2007), Smith et al. (2007), Agnoletto et al. (2009), Kawabata et al. (2009)

- CSM interaction, higher ^{56}Ni, or both? Many fascinating models proposed (pair-instability, pulsational, η-Carina-like, magnetar power)
  - <u>CSM interaction</u>: clear Type IIn-like spectral features seem, but only weak soft X-ray detected and no radio
  - <u>High ^{56}Ni</u>: late bolometric LC consistent with > 7 Msun (also SN2007bi), which is also consistent with [FeII] spectra, but may not exactly be ^{56}Co slope, and how to get so much ^{56}Ni



- Several other SNe like this
  - Estimated rate:

Also SN2005ap

$\sim 10^{-7} - 10^{-6}$ /yr /Mpc^3

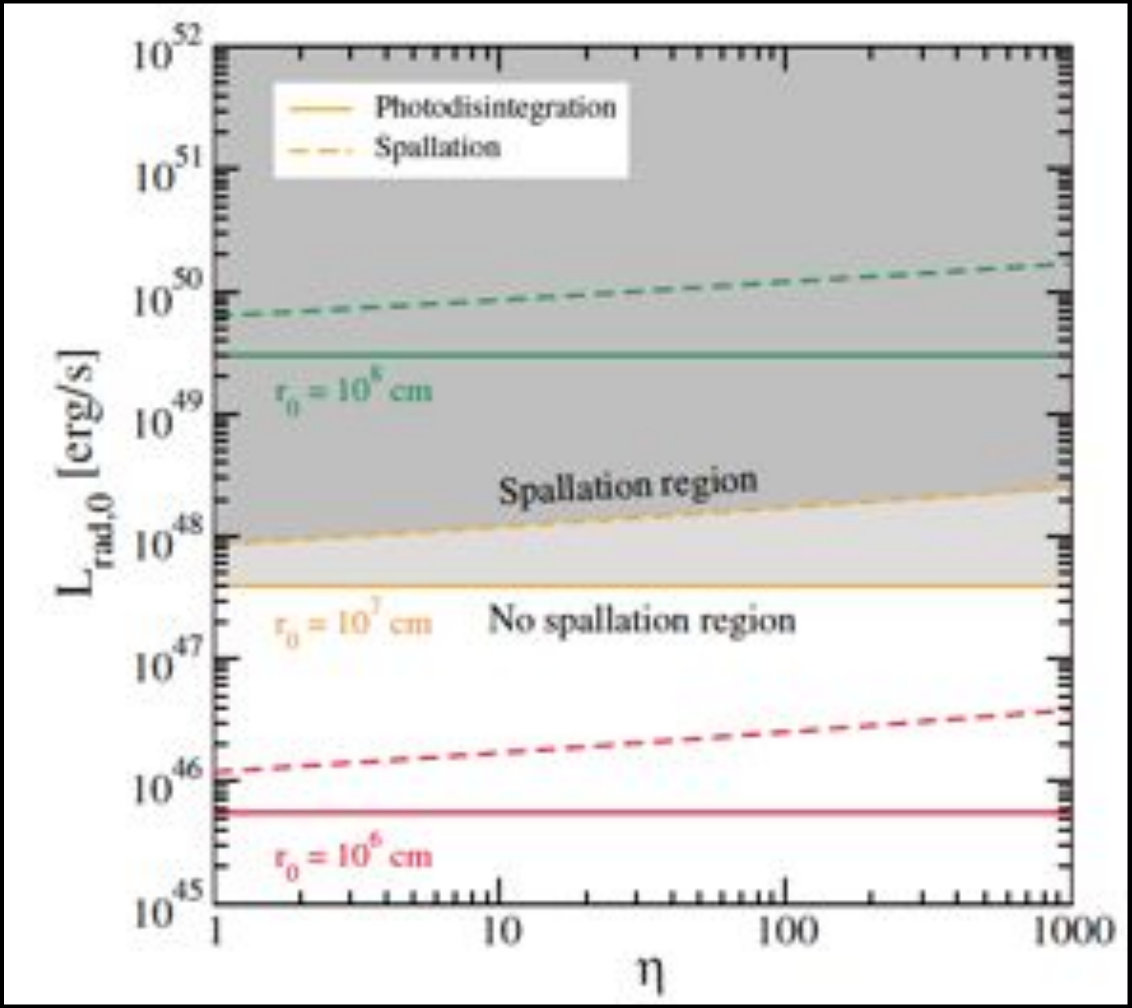
(one every 1000 – 100 CCSNe)

Survival in initial loading

Baryon loading: remains uncertain (where and how), but any baryons must come from the immediate environment.

Stellar matter: natural to expect it to be dominated by heavy nuclei

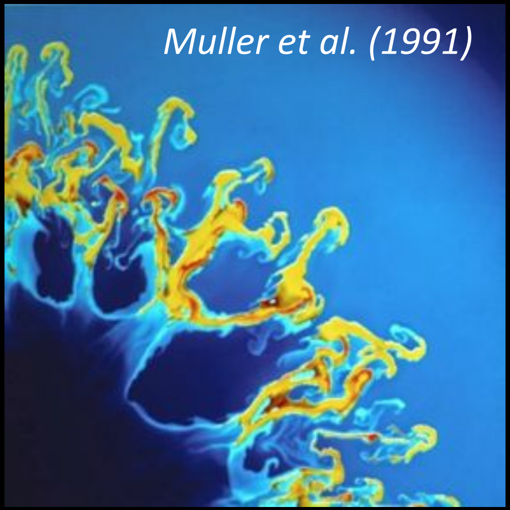
Define survival region: by requiring that the optical depth to spallation and photodisintegration is <1. [Depends on *T* and ρ
→ larger r and lower L better]



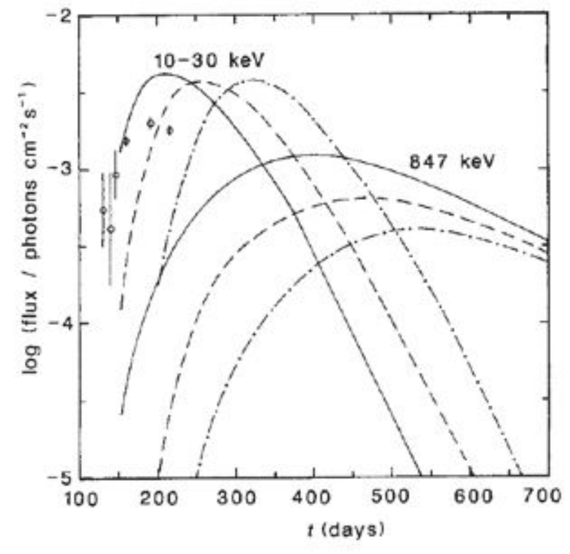
Horiuchi et al 2012

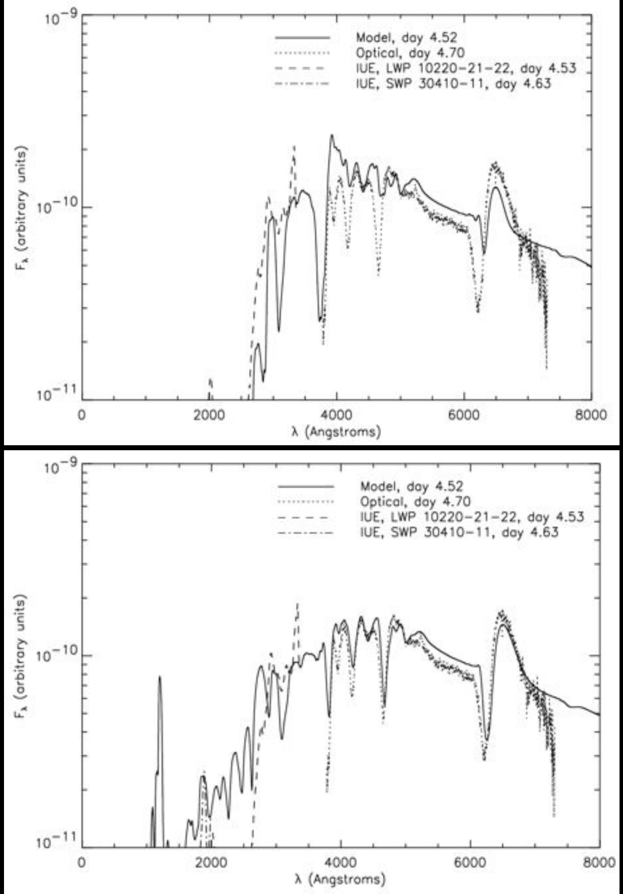
Transport in CCSNe

- Nuclei transport: instabilities are important
- Even in normal CCSNe, some Ni56 likely transported to near the surface by, e.g., Rayleigh-Taylor instability
- Tested by various observables
  - X rays
  - Opt spectra
  - Light curve
  - γ-ray lines

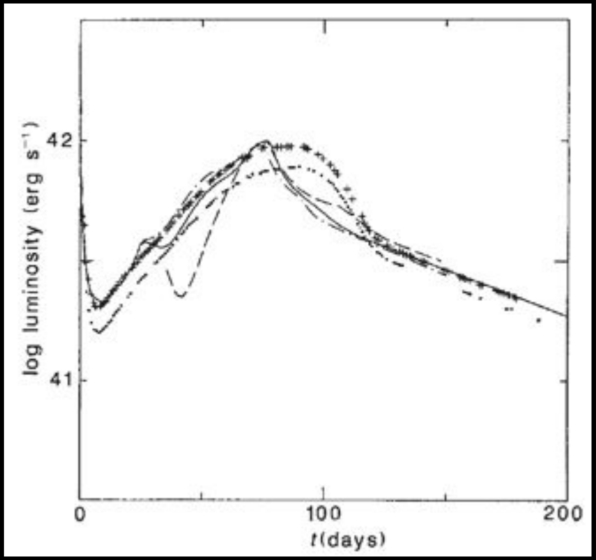

Muller et al. (1991)

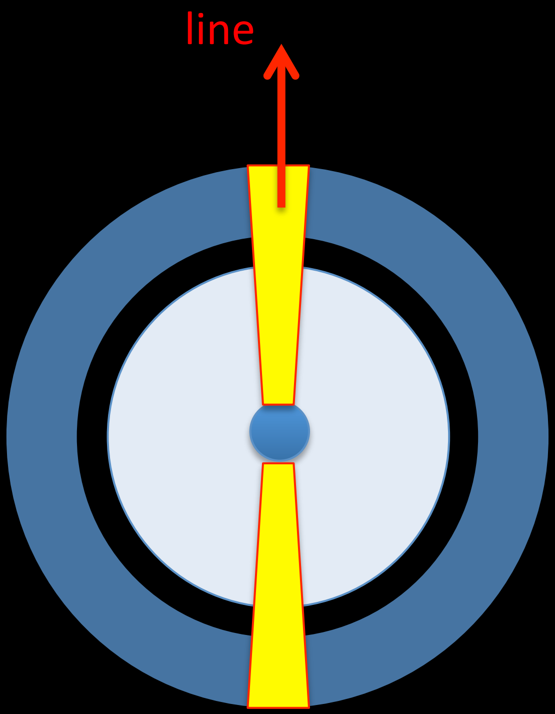
Itoh et al (1987)



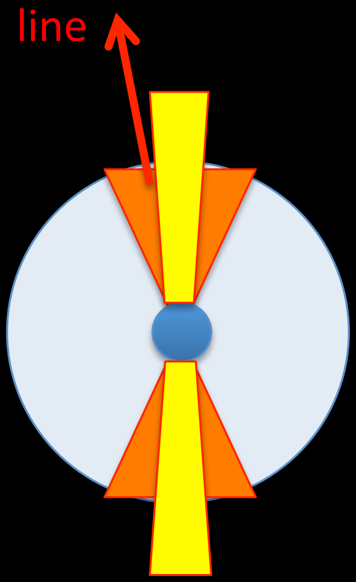


Woosley (1988)

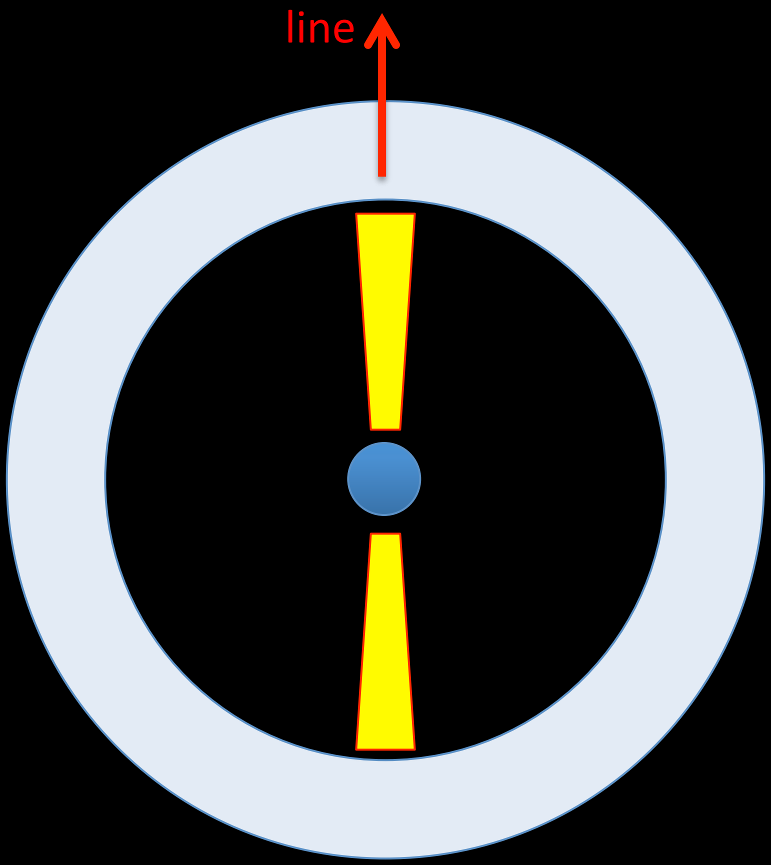




At break out if there's previous mass loss or dense dust layers?

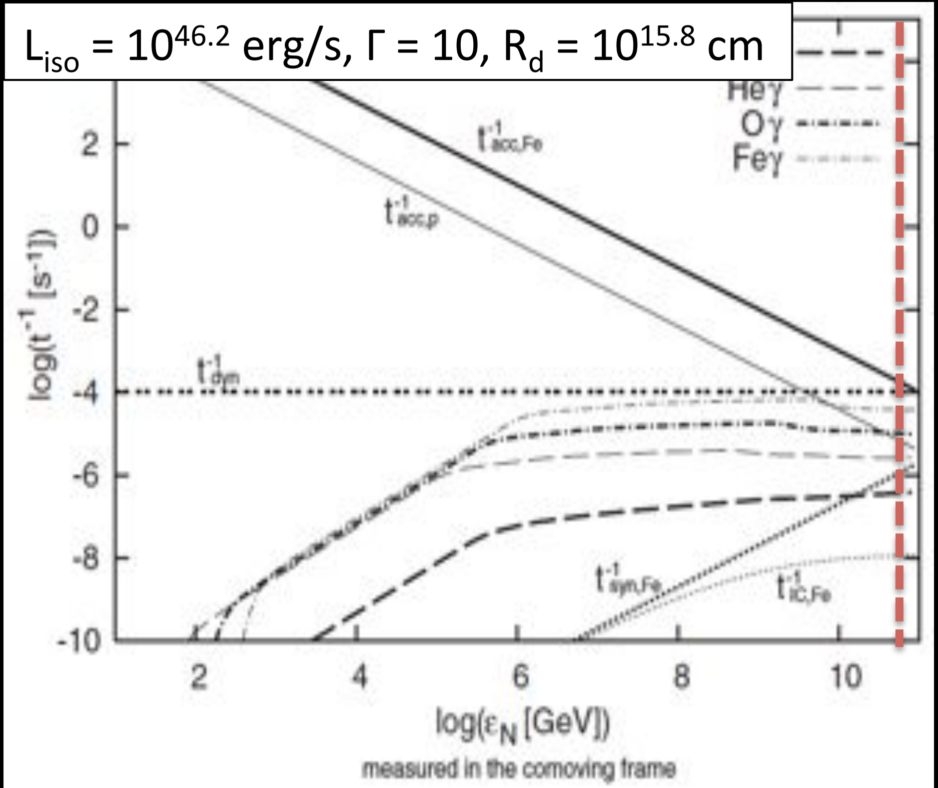


At cocoon break out?
e.g., Meszaros & Rees (2001)

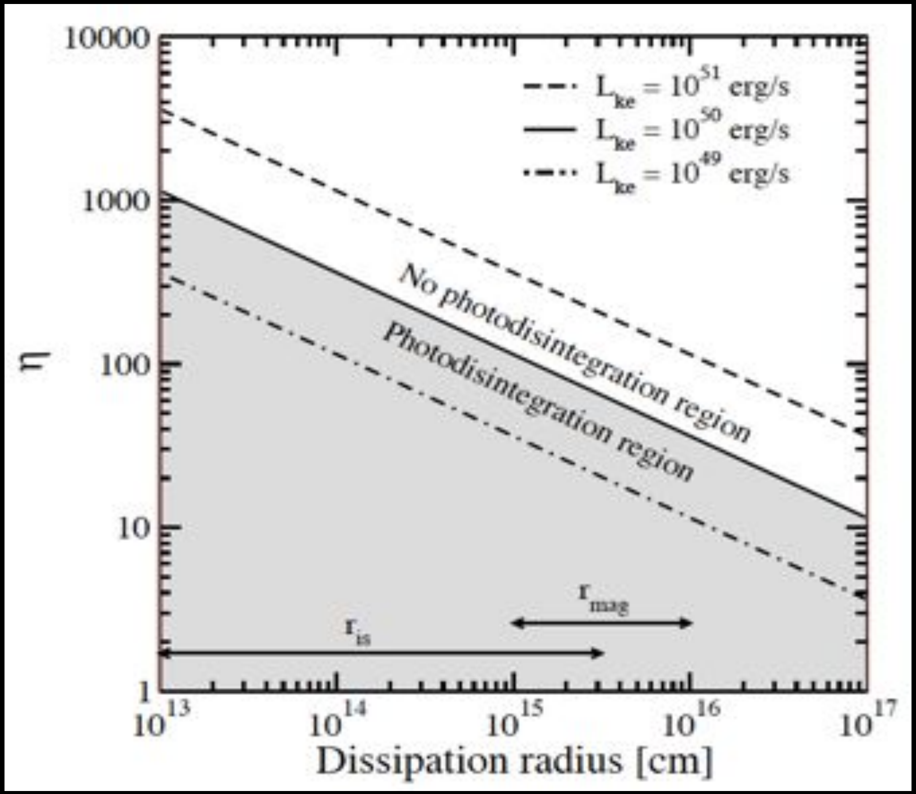


After the supernova, illumination by central engine?
e.g. Rees & Meszaros (2000)

As sources of UHECRs



$L_{iso} = 10^{46.2}$ erg/s, $\Gamma = 10$, $R_d = 10^{15.8}$ cm



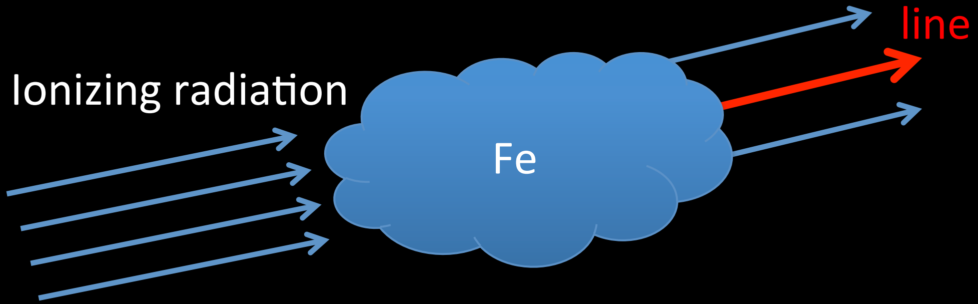
Wang et al (2008), Murase et al (2008), Anchordoqu et al (2008), Horiuchi et al (2012)

Future detection prospects?

Look for a line? Ionization timescale usually << recombination timescale

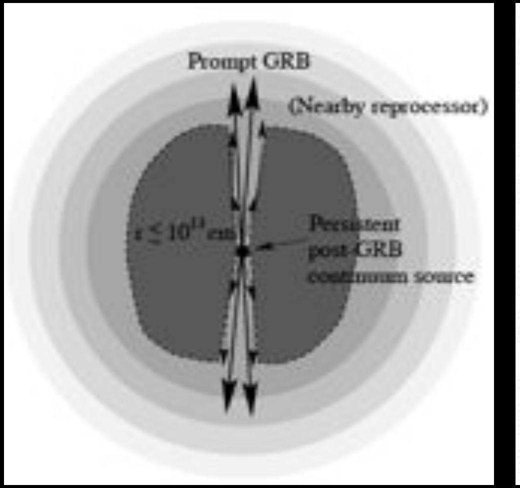
$$t_{\rm PI} \approx 2 \times 10^{-7} L_{47}^{-1} r_{13}^{2}$$

$$t_{\rm rec} \approx 60 T_8^{1/2} n_{10}^{-1} Z_{\rm Fe}^{-2}$$

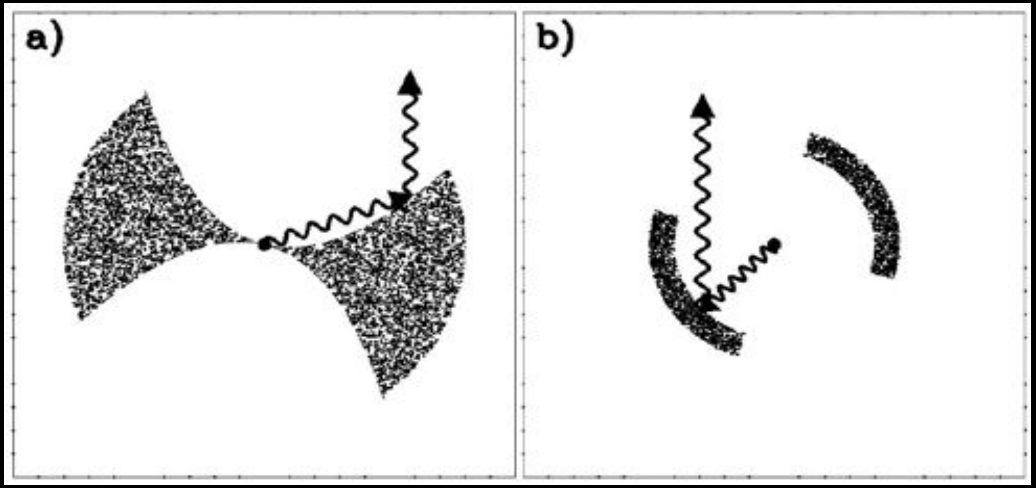


Various geometries are possible:

Near and far models depending on the target matter location wrt radiation source



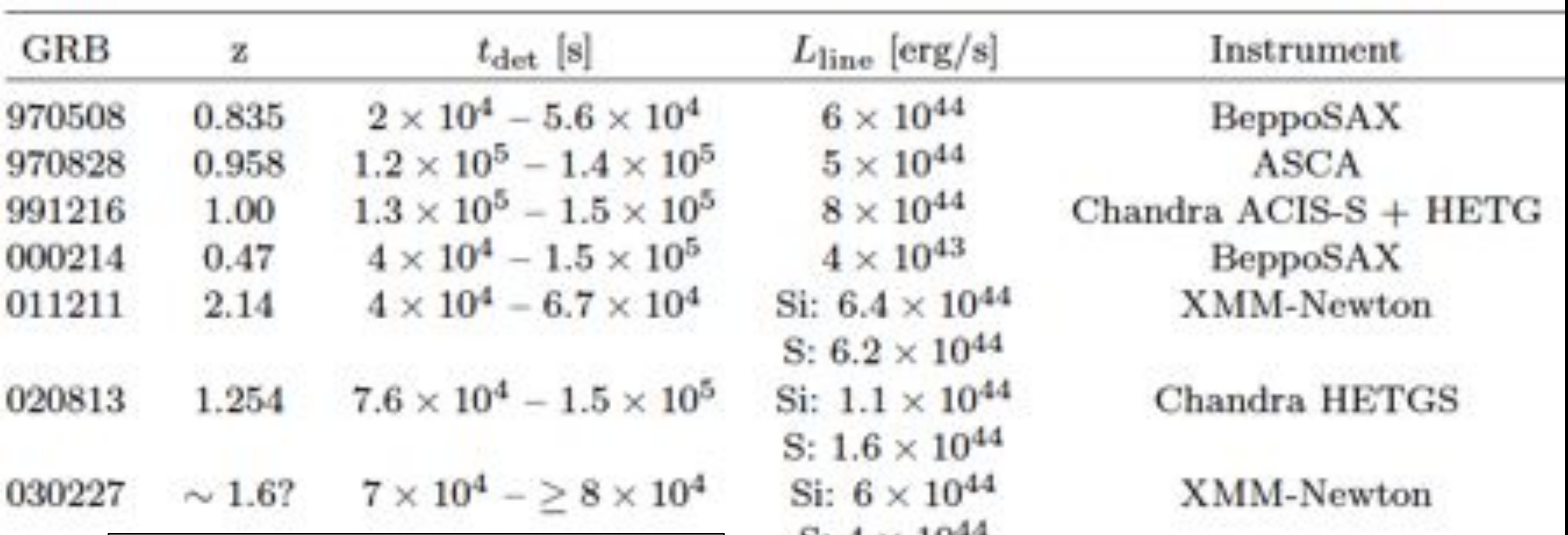
Rees & Meszaros (2000)
Meszaros & Rees (2001)



Lazzati et al. (1999, 2000, 2002), Weth et al. (2000), Bottcher (2000), Vietri et al. (2000), Bottcher & Fryer (2001), Ballantyne & Ramirez-Ruiz (2001), …

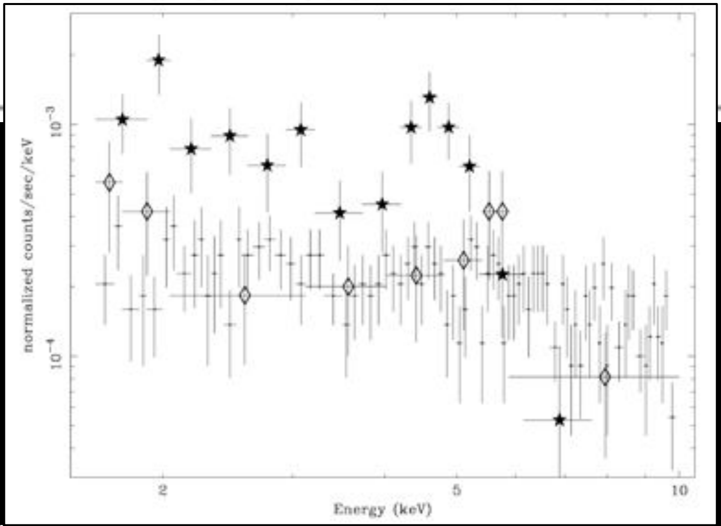
Some past line detection @GRB

Tentative hints: in early GRB and afterglow phase, high L, duration ~day



GRB	z	$t_{\rm det}$ [s]	$L_{\rm line}$ [erg/s]	Instrument
970508	0.835	$2 \times 10^4 - 5.6 \times 10^4$	6×10^{44}	BeppoSAX
970828	0.958	$1.2 \times 10^5 - 1.4 \times 10^5$	5×10^{44}	ASCA
991216	1.00	$1.3 \times 10^5 - 1.5 \times 10^5$	8×10^{44}	Chandra ACIS-S + HETG
000214	0.47	$4 \times 10^4 - 1.5 \times 10^5$	4×10^{43}	BeppoSAX
011211	2.14	$4 \times 10^4 - 6.7 \times 10^4$	Si: 6.4×10^{44} S: 6.2×10^{44}	XMM-Newton
020813	1.254	$7.6 \times 10^4 - 1.5 \times 10^5$	Si: 1.1×10^{44} S: 1.6×10^{44}	Chandra HETGS
030227	$\sim 1.6?$	$7 \times 10^4 - \geq 8 \times 10^4$	Si: 6×10^{44} S: 4×10^{44}	XMM-Newton

Piro (1999, 2000), Yonetoku (2001), Reeves (2002), Watson (2003), etc



GRB000214: line broadening of ~0.5 keV

Antonelli et al. (2000)