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Nuclear composition of GRB jets: sources and survival

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Image credit: NASA/ESA

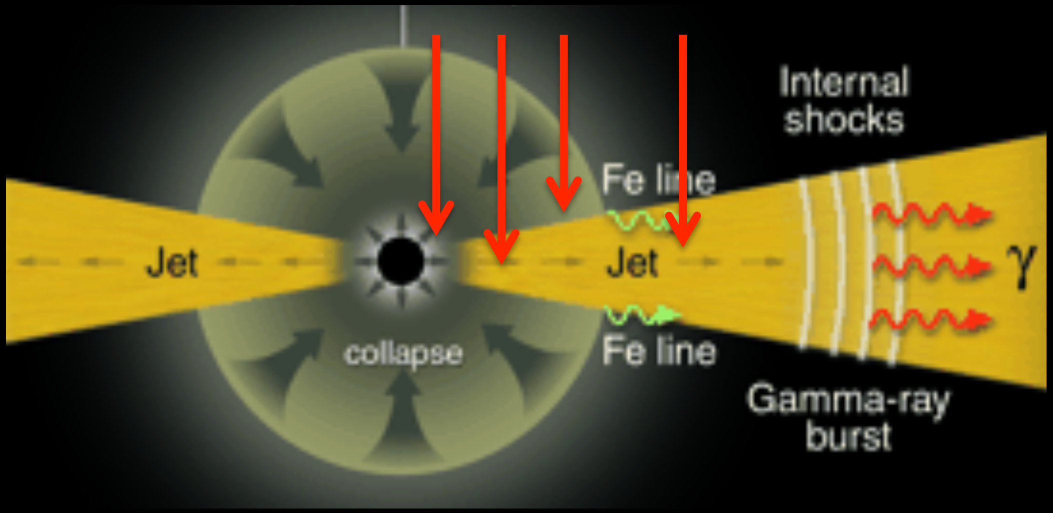
Contents

A. Heavy nuclei in massive stars
   - Stellar nucleosynthesis
   - Explosive nucleosynthesis

B. The nuclei composition of jets
   - Initial loading
   - Entrainment
   - In-situ jet nucleosynthesis
   - Destruction processes

C. Acceleration to UHECR

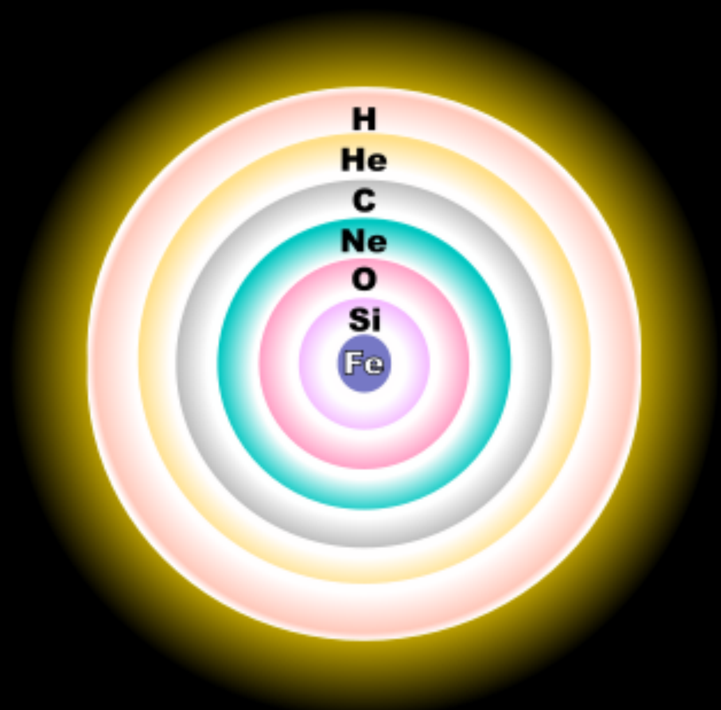
D. Conclusion



Stellar Nucleosynthesis

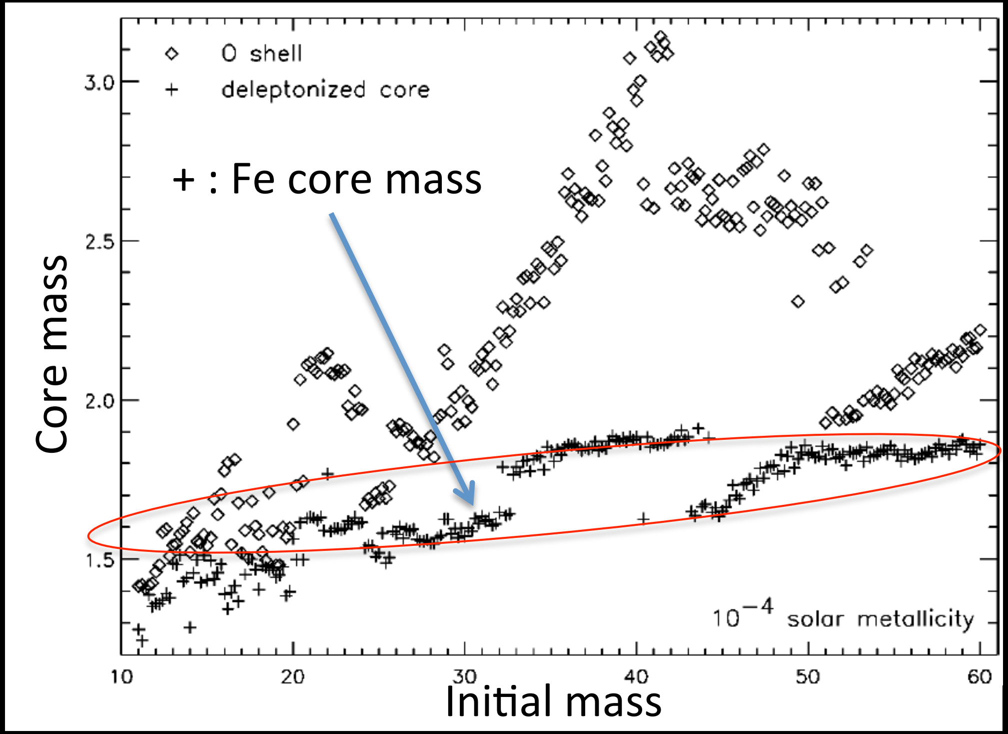
Nucleosynthesis

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



Iron nuclei abundance

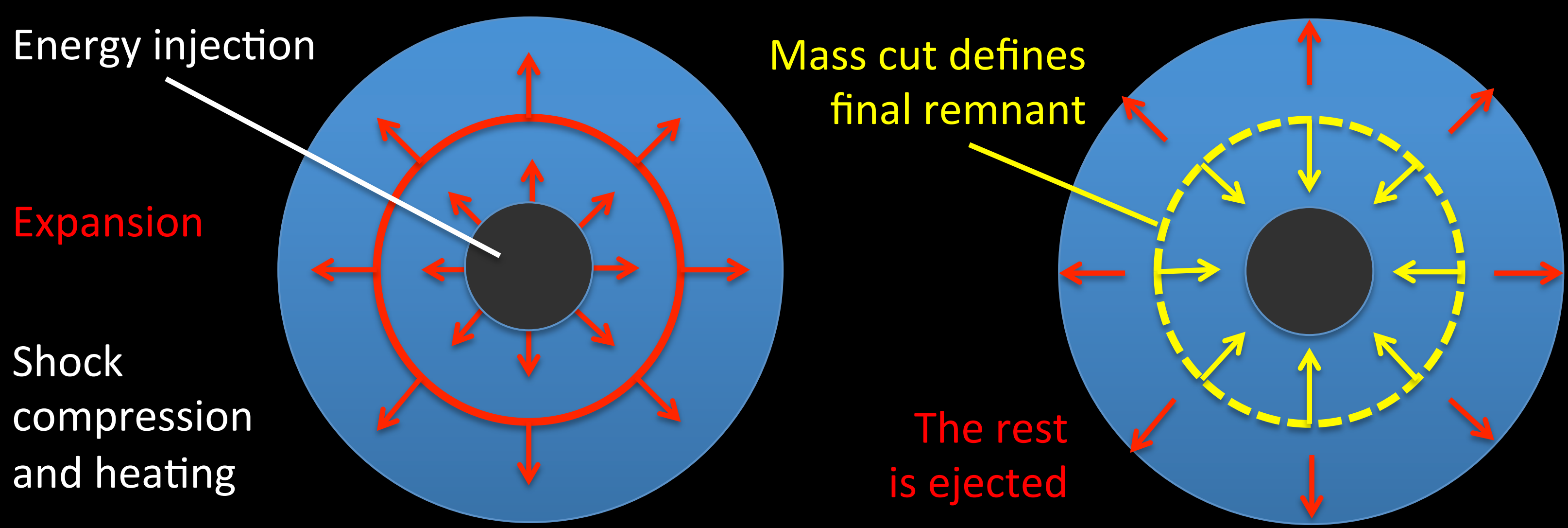
The final Fe core mass is typically some 1.5 Msun with radius of 10^8 cm or so



Woosley et al (2002)

Explosive Nucleosynthesis

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



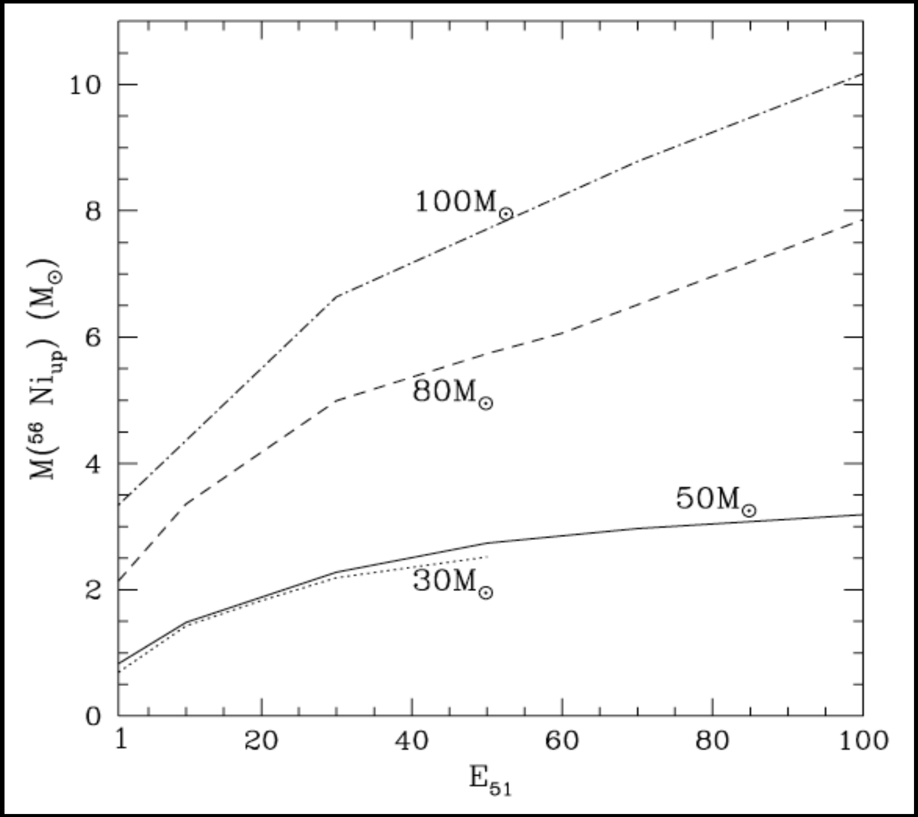
However, how much heavy nuclei is released is model dependent:

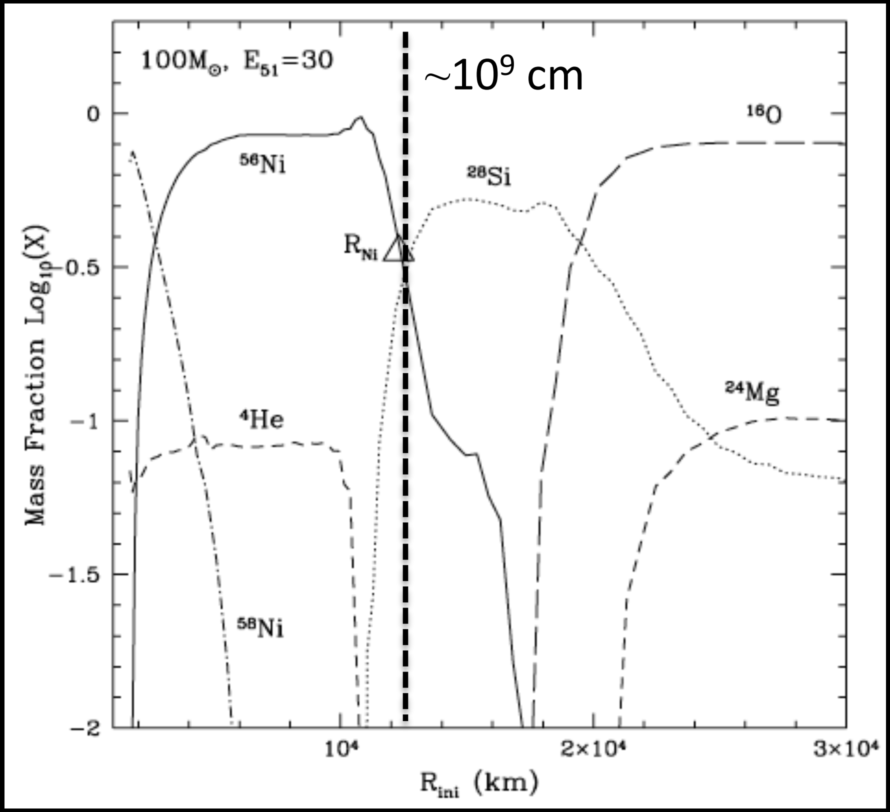
1. Some amount of energy injection
2. At some location
3. With some mass cut

How much is possible?

A lot of 56Ni (potentially)

With large CO core, large explosion energies, and small mass cut, up to ~10 Msun





Umeda & Nomoto (2008)

Core collapses typically observed ~0.1 Msun of ^{56}Ni.

(some may have more, e.g., hypernovae, superluminous supernovae; x100 needed if ^{56}Ni)

1. Initial loading
2. Entrainment
3. In-situ nucleosynthesis
4. Destruction processes

COMPOSITION OF JETS

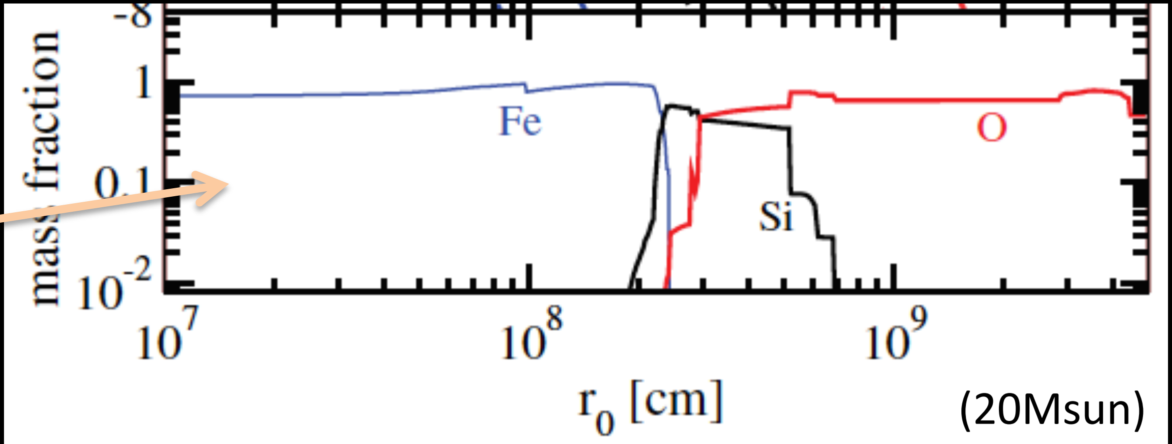
1. Initial loading

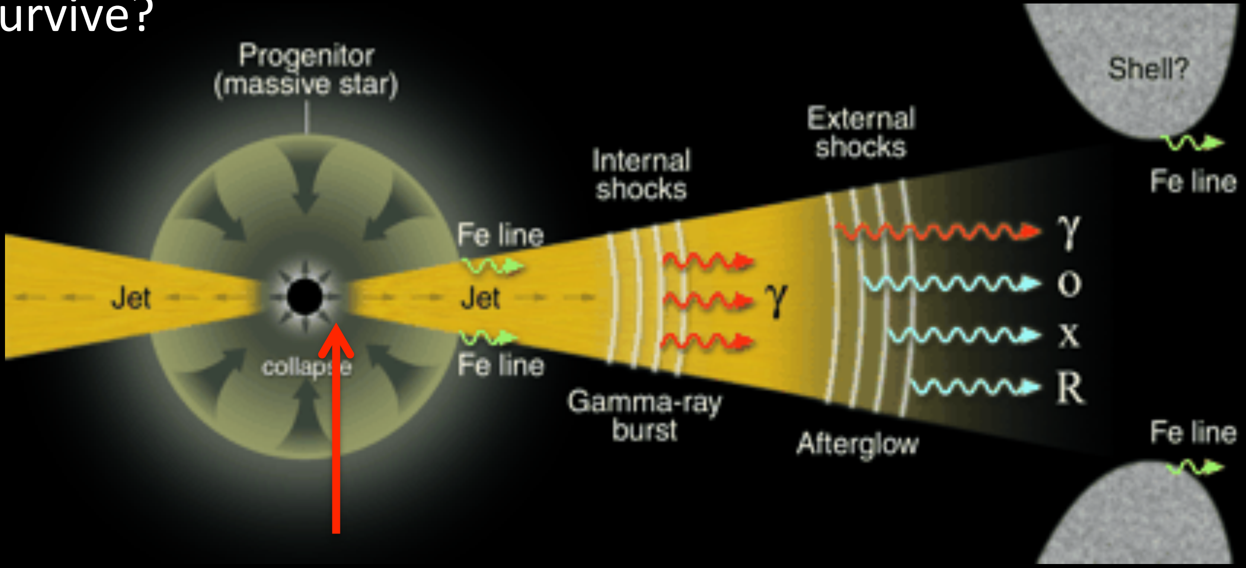
External composition

Depends on jet model and launch timing, e.g.,

- Original stellar nuclei if launched prior to supernova shock revival
- More nuclei if after explosive nucleosynthesis

Can nuclei survive?





Survival in initial loading

Photodisintegration
Thermal photons with T_0 as:

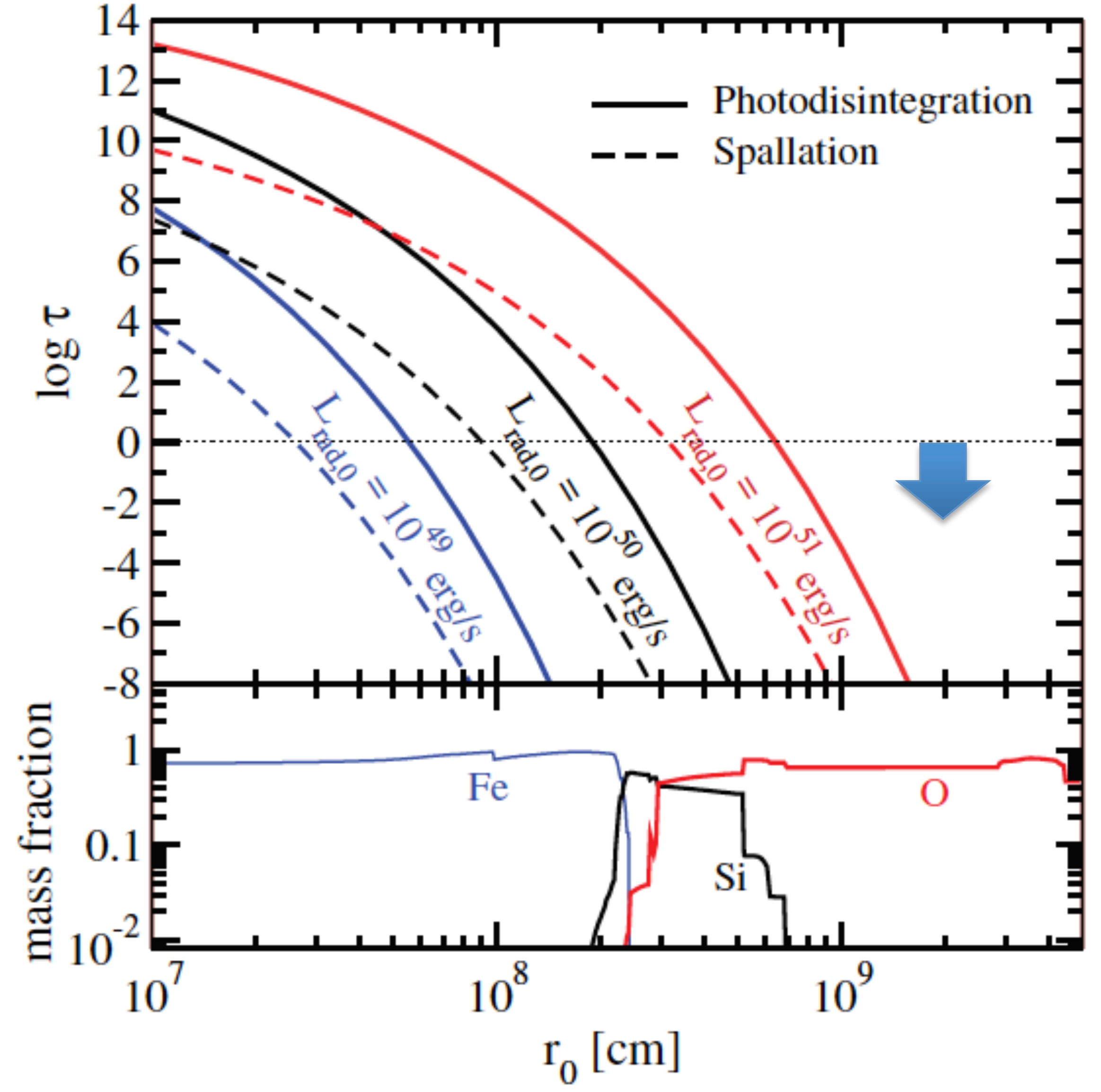
$$aT_0^4 = \frac{L_{\mathrm{rad},0}}{\Sigma_0 \Gamma_0^2 c},$$

Spallation
Target ion/nucleons thermalized to T_0

Nuclei survival
Optical depths of destructive processes must be small

→ Needs large $r_0 > 10^8$ cm or low $L_{rad} < 10^{49\text{-}50}$ erg/s

→ **Low-luminosity or magnetic models better for survival than fireball**



Horiuchi, Murase, et al (2012)

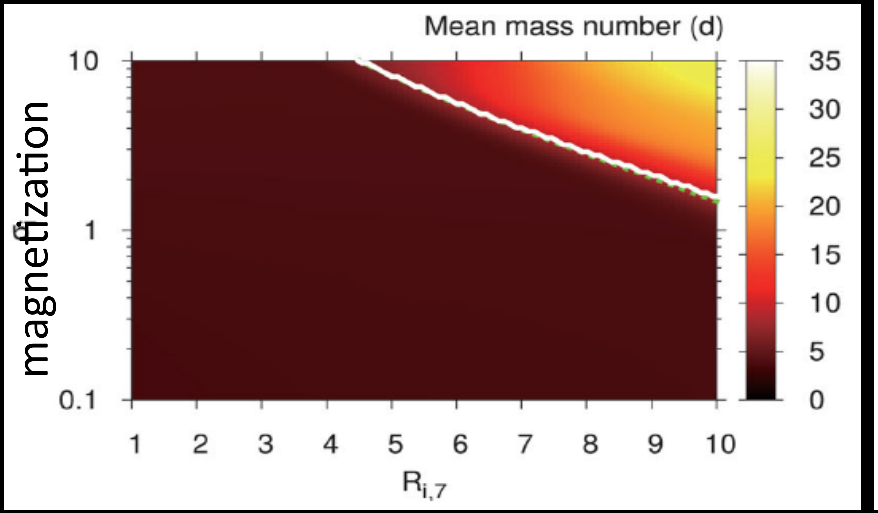
Simulations

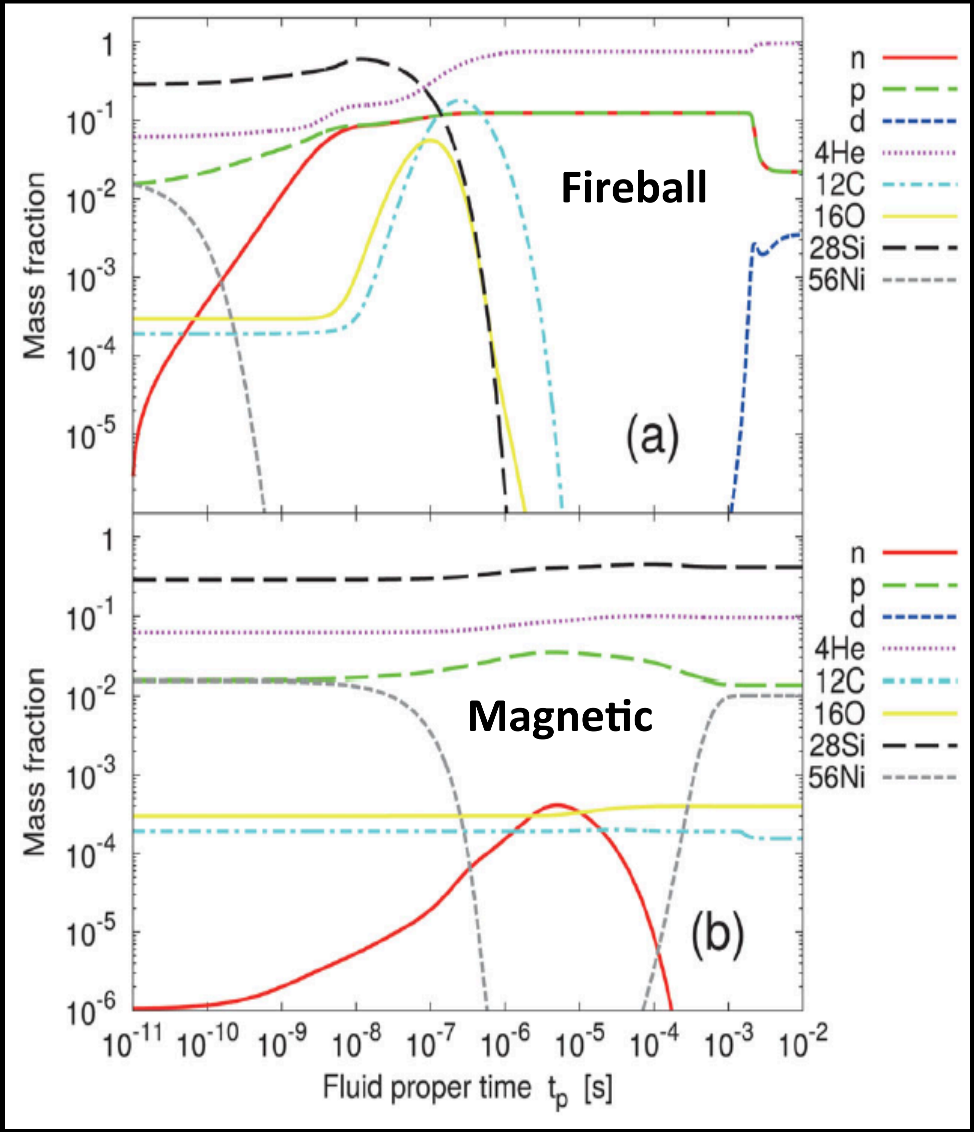
Loading simulations

2D relativistic MHD simulation of jet induced collapse, mass fall back, and jet bulk acceleration.

- Fireball: heavy nuclei dissociated
- Magnetic (partially): partial dissociation of nuclei

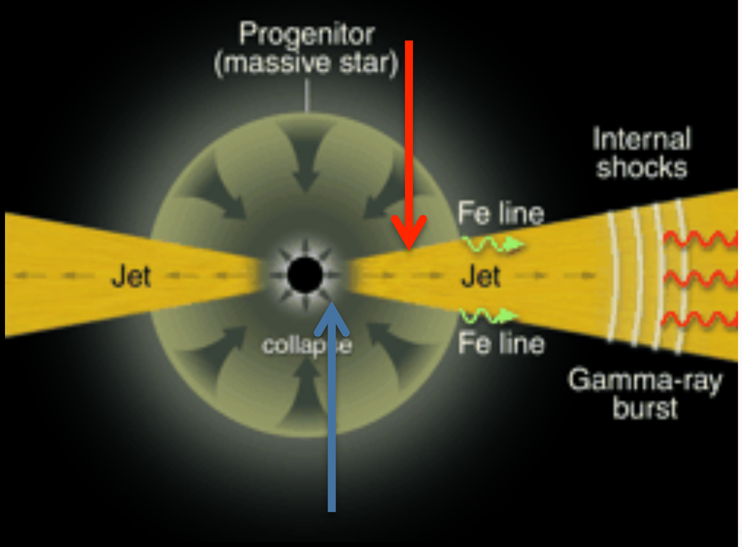
→ **Magnetic models (and low-L_{rad}) better for nuclei composition**



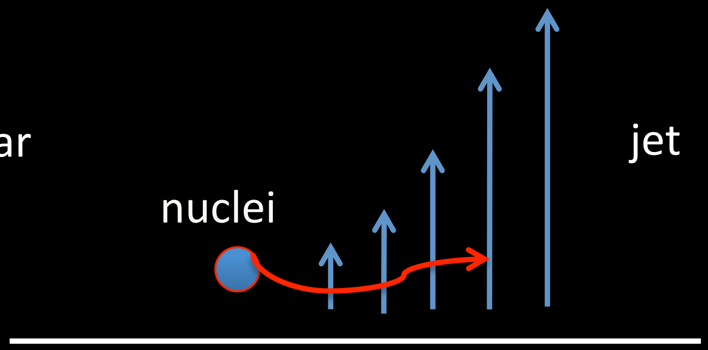


Shibata & Tominaga (2015)

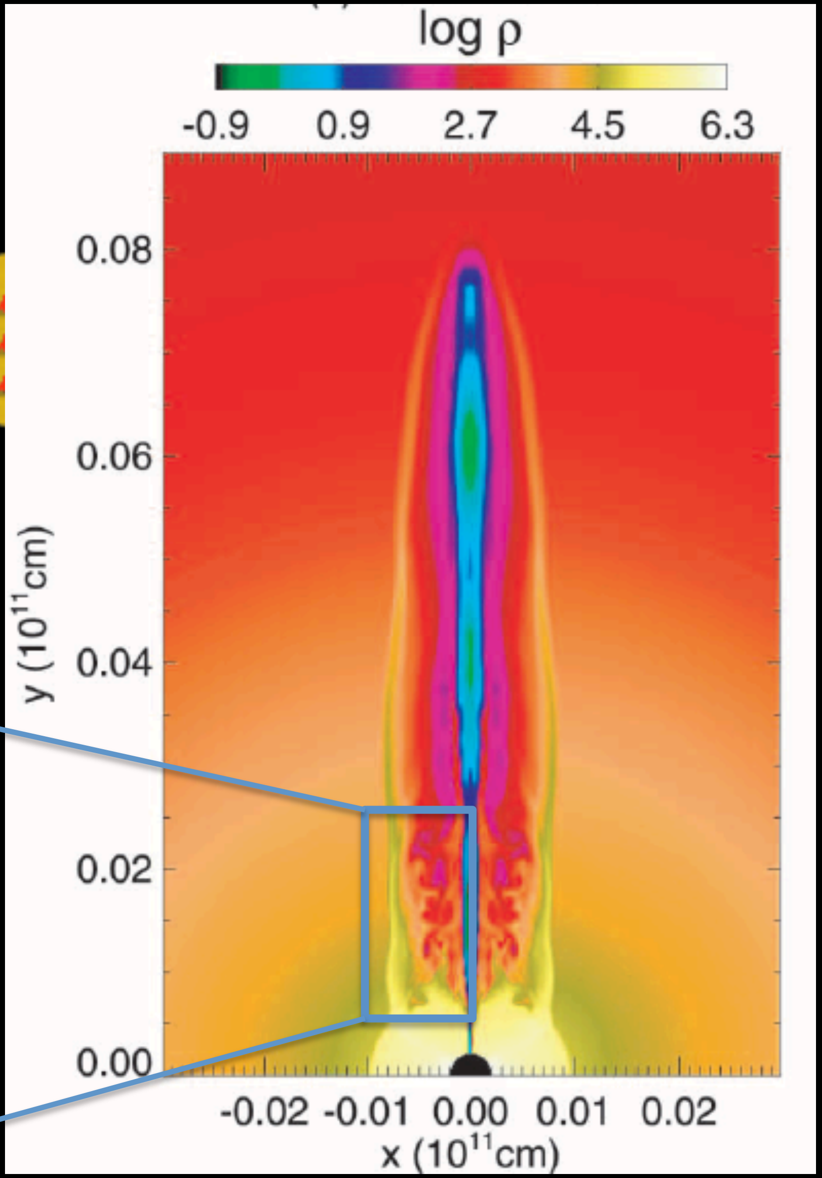
2. Entrainment



Entrainment of external nuclei into the jet medium: do nuclei survive?



Can it safely do this?



Zhang et al. (2003)

Survival in entrainment

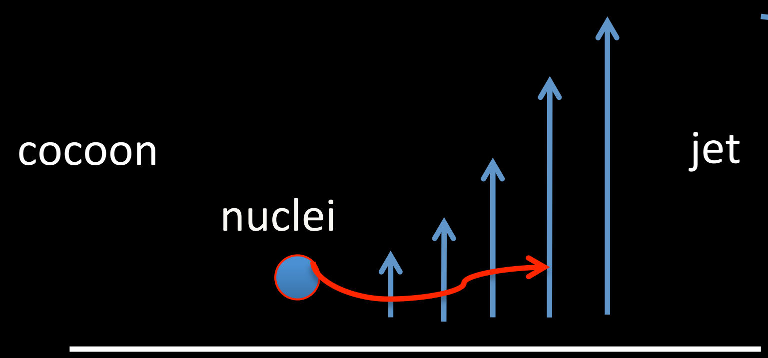
Cocoon

The cocoon is made up of shocked stellar and shocked jet material and expands non-relativistically into the stellar material.

$$\beta_c^{(1)} \sim 0.01 L_{\mathrm{ke},50}^{3/8} r_9^{1/2}$$

$$T_c^{(1)} \sim 100 L_{\mathrm{ke},50}^{3/16} r_9^{-1/2}\,\mathrm{keV}$$

→ Cocoon can be nuclei rich (mixing aided by instabilities) *e.g., Aloy (2002)*



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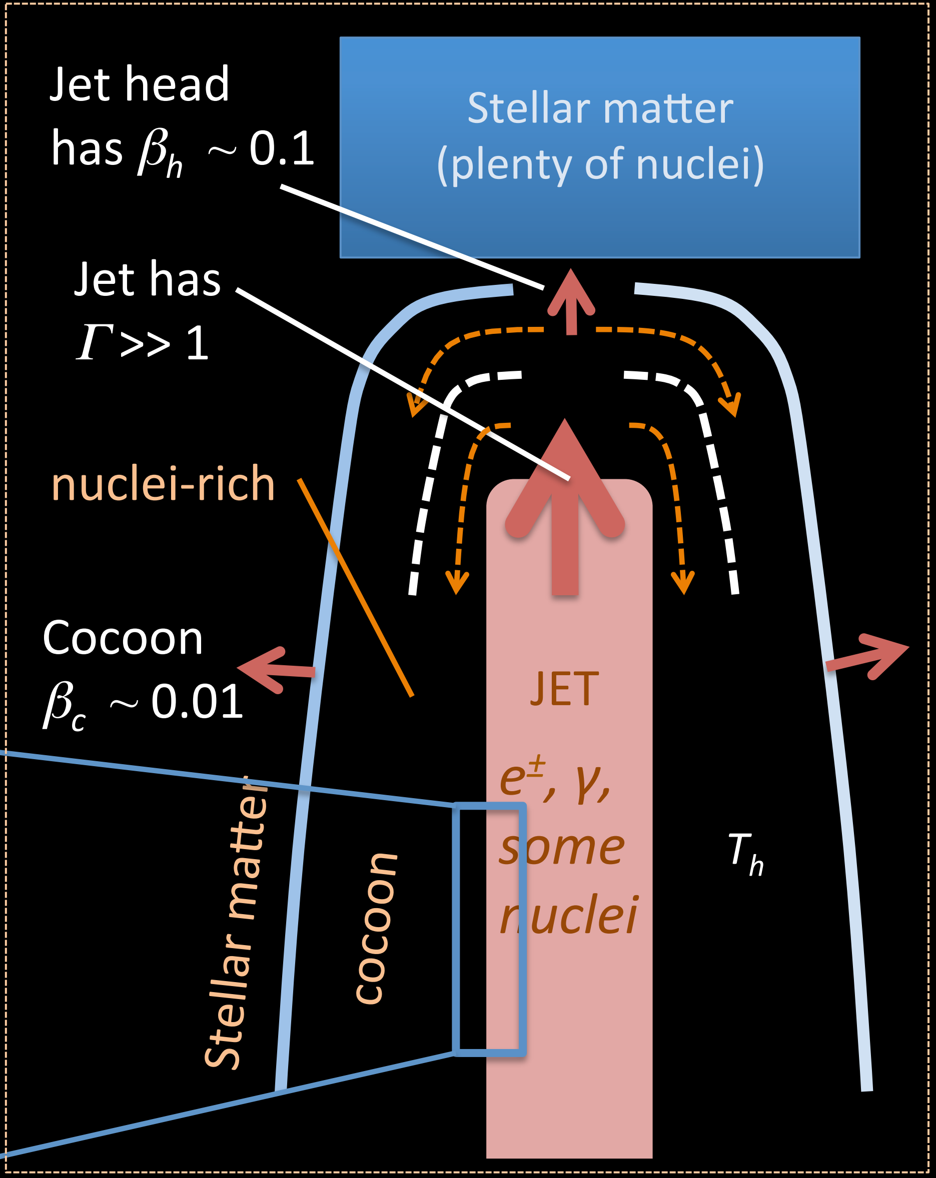


Survival in entrainment

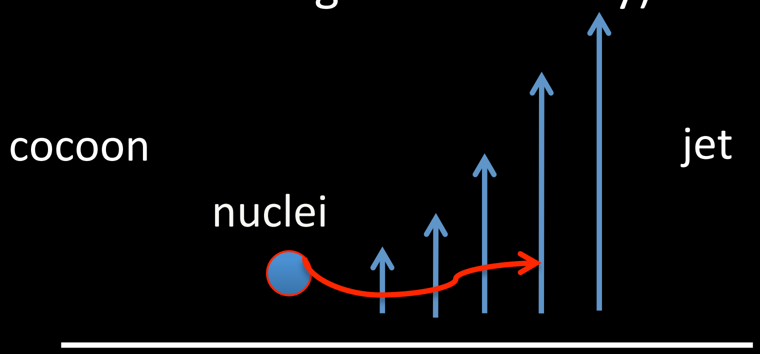
Survival

Demand the nuclei velocity is always below the spallation threshold
→ requires the nuclei to be thermalized FASTER than it takes to move up the velocity gradient and its speed becomes too fast

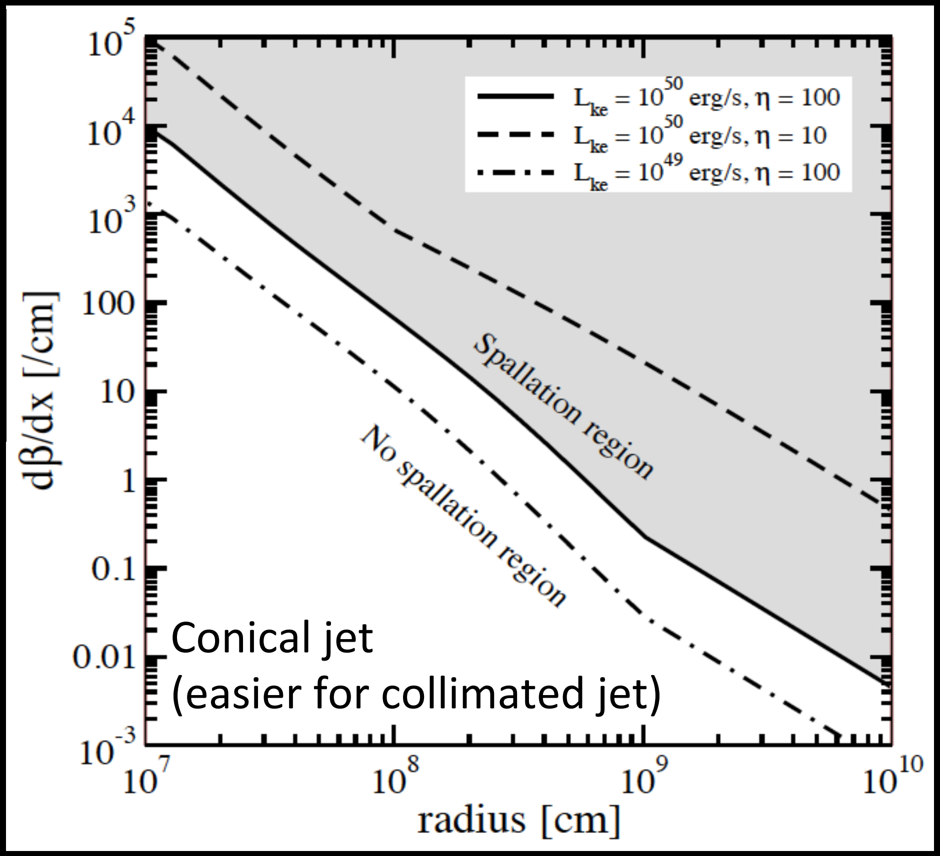
Survival

→ If velocity gradient is small, nuclei thermalize before reaching the spallation threshold

(Collimated jets can tolerate a higher gradient due to higher e- density)

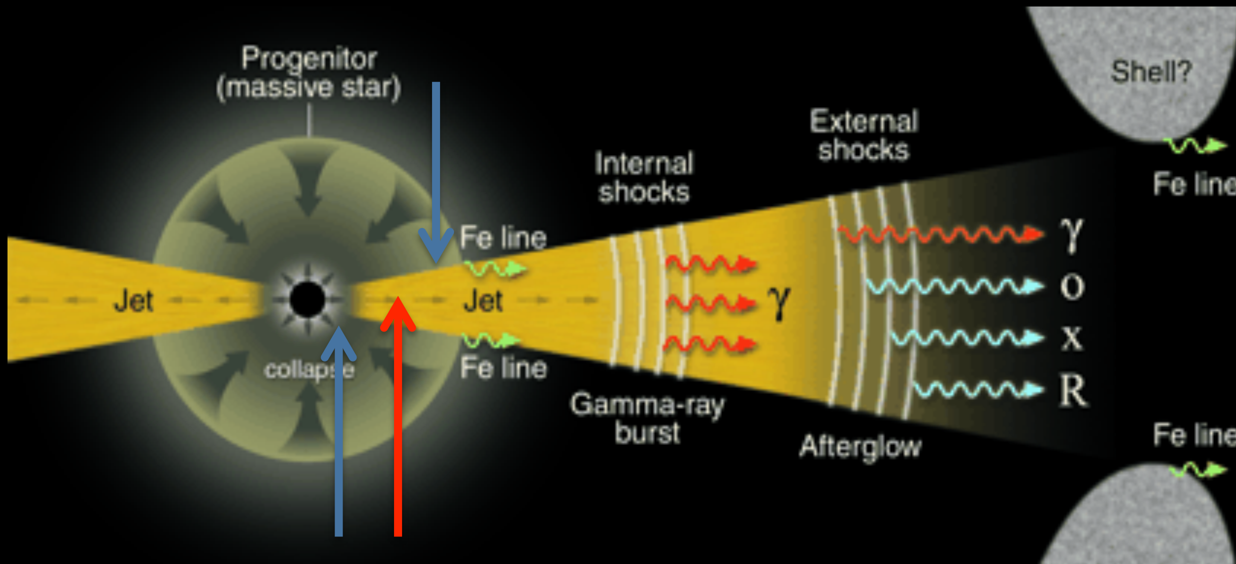


Can it safely do this?



Horiuchi et al (2012)

3. In-situ jet nucleosynthesis



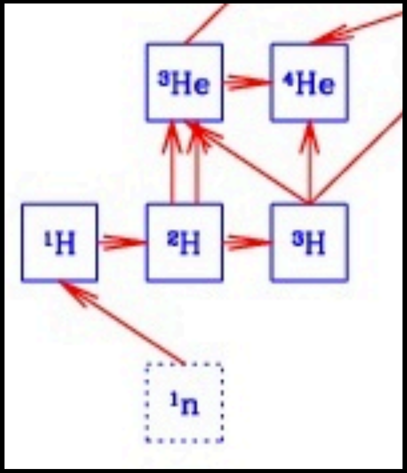
GRB fireball:

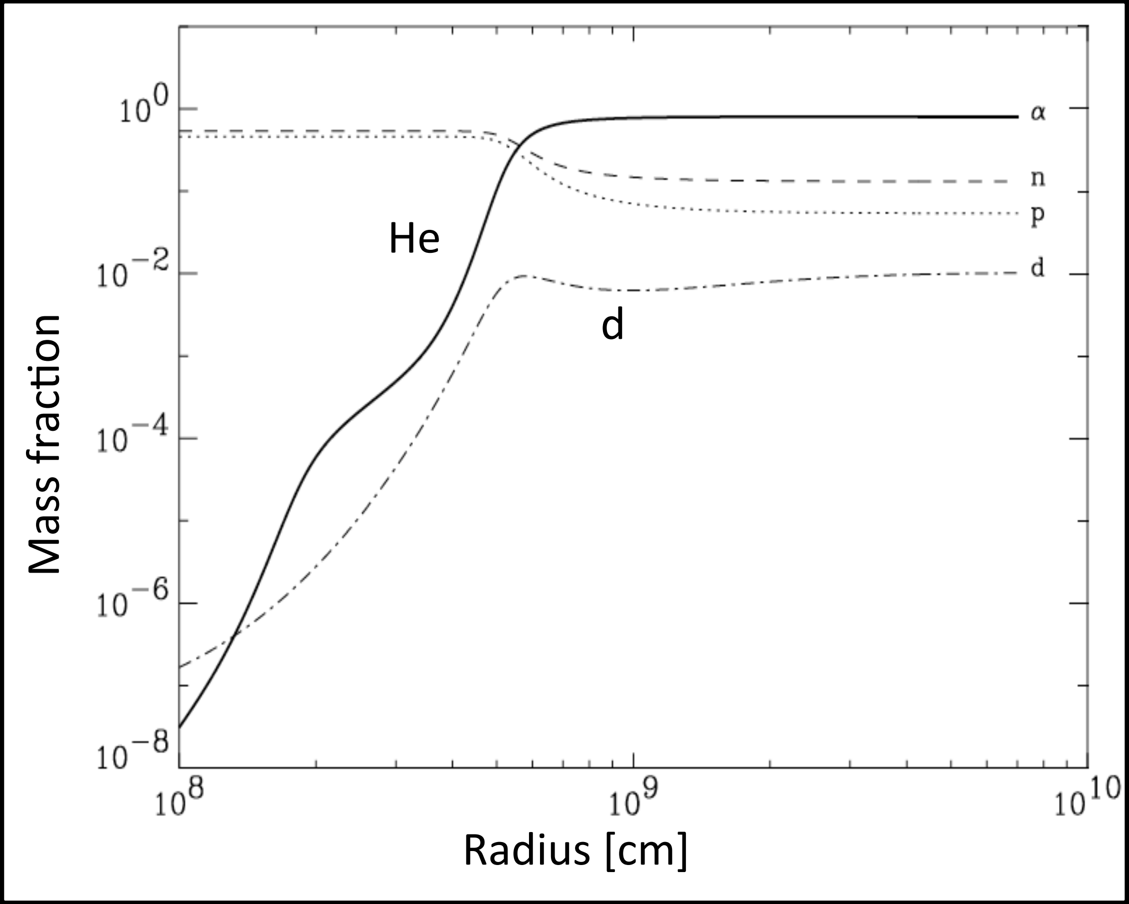
- Initial radiation temperatures of a few MeV
  → nuclei are dissociated (NSE)
- Large entropy ($n_\gamma/n_p \sim 10^5$)
  - needed for saturation Lorentz factor $\eta > 100$
- Rapid expansion time scales (~0.1 ms)
- Electron fraction probably close to 0.5
  - but uncertain

In-situ jet nucleosynthesis: fireball

Nucleosynthesis

Bottleneck to heavy nuclei synthesis due to easily destroyed deuterium.





When *T* is low enough for the bottleneck to be broken, the jet is too dilute for tripe-alpha to be fast enough.

Freeze-out composition

→ Very few heavy nuclei are made

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

Alternatives

Importance of entropy and expansion timescale

Lower entropy and larger timescale are conducive to nucleosynthesis

→ Deuterium production is more efficient and deuterium bottleneck is broken earlier while densities are still high.

1. Magnetic scenario

L_{rad} can be low if the GRB can be powered magnetically, e.g., for rapidly rotating proto-magnetar model

$$\dot{E} \sim 10^{49} P_{\rm ms}^{-4} B_{15}^2 R_6^6 \,{\rm erg\,s^{-1}}$$

e.g., Usov (1992) Thompson (1994)

Other models, e.g., magnetized disk winds or BH powered

e.g., Blandford & Znajek (1977)

2. Low-luminosity GRB and dirty (baryon) jets

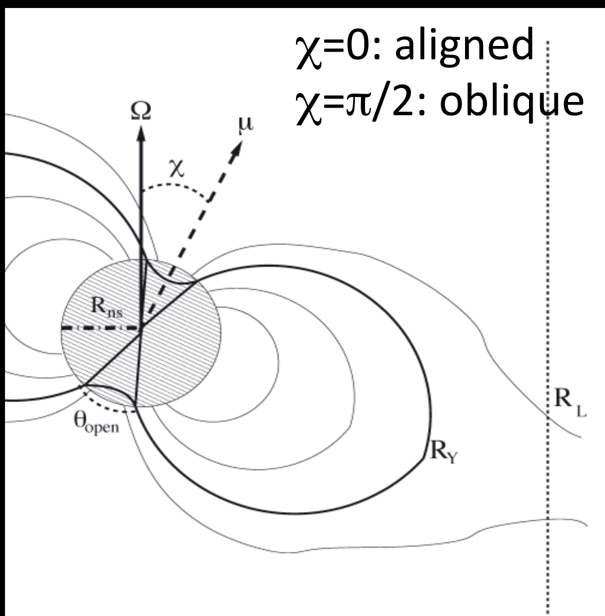
With lower L_{rad} by default (but enough for initial dissociation).

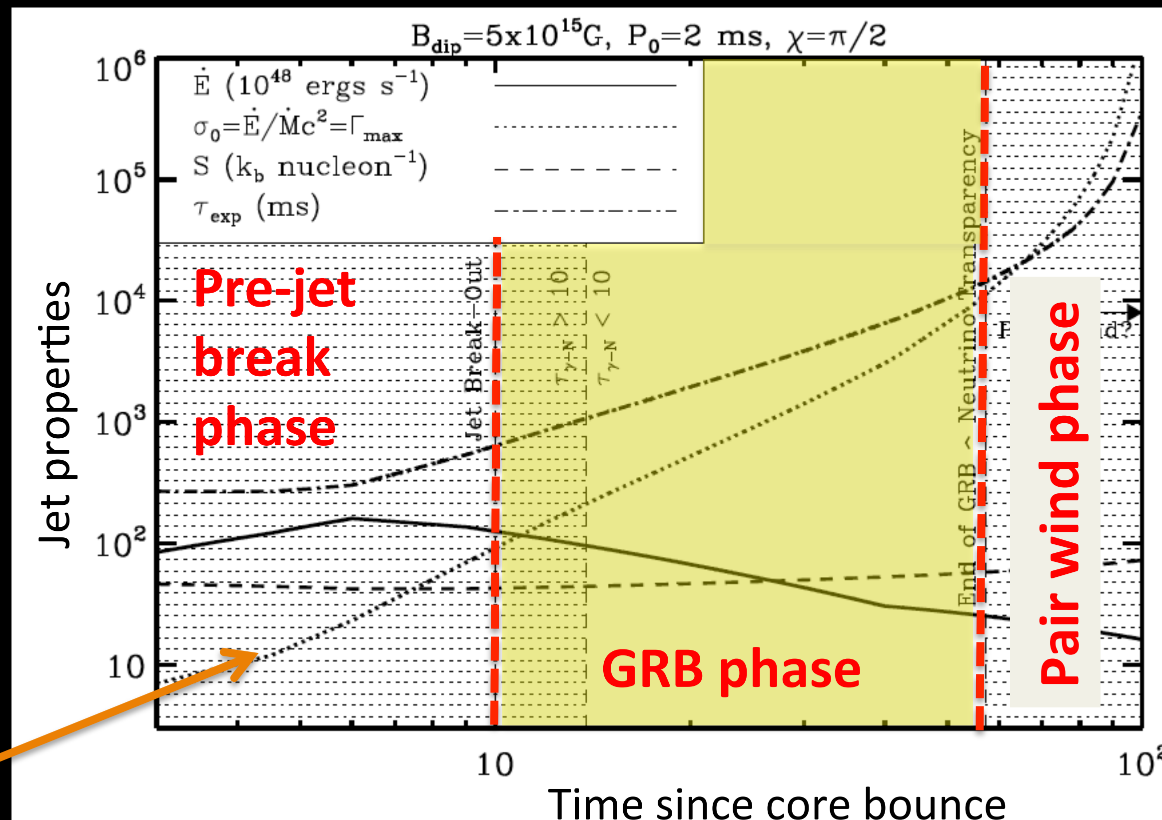
With large baryon loading by default

Example: proto-magnetar scenario

Proto-magnetar model:
Neutrino-driven wind + magnetic driven outflow

The GRB jet fills a sweet spot; later, it becomes a pair-wind as the neutrino-driven wind subsides





Metzger et al (2011)

"magnetization"

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

(=η if fully converted to KE)

Nucleosynthesis yields

Freezeout yield

Estimate the mass fraction of A≥56 (X_h) with analytic wind nucleosynthesis

- τ_{exp}: timescale
- s: entropy
- Y_e: electron fraction

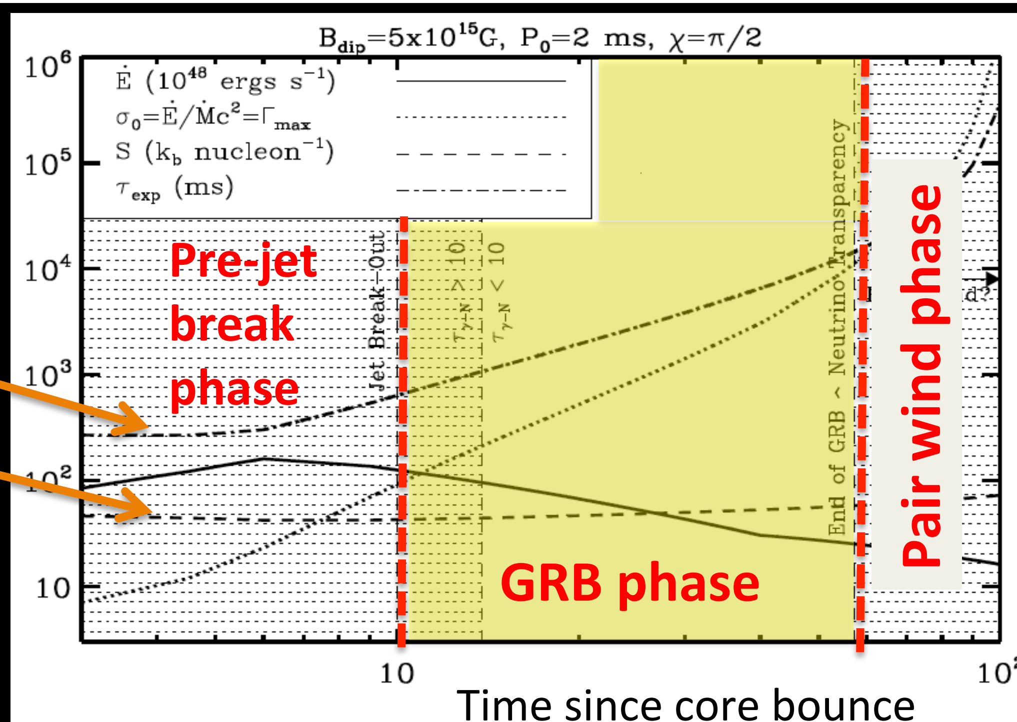
$$X_h \simeq \begin{cases} \left\{1 - \exp\left[-8\times10^5 Y_e^3 \left(\frac{\tau_{exp}}{\mathrm{ms}}\right)\left(\frac{S}{k_b\ \mathrm{nuc}^{-1}}\right)^{-3}\right]\right\}, & Y_e < 0.5 \\ \left\{1 - \left[1 + 140(1-Y_e)^2 \left(\frac{\tau_{exp}}{\mathrm{ms}}\right)\left(\frac{S}{k_b\ \mathrm{nuc}^{-1}}\right)^{-2}\right]^{-1/2}\right\}, & Y_e \geq 0.5 \end{cases}$$

Roberts et al (2010)

For an oblique* rotator:

- Expansion time-scale [ms]
- Entropy [k_B/baryon]
- Electron fraction?

*Obliquity reduces ν-heating by centrifugal force



Metzger, Giannios, Horiuchi (2011)

Nucleosynthesis yields

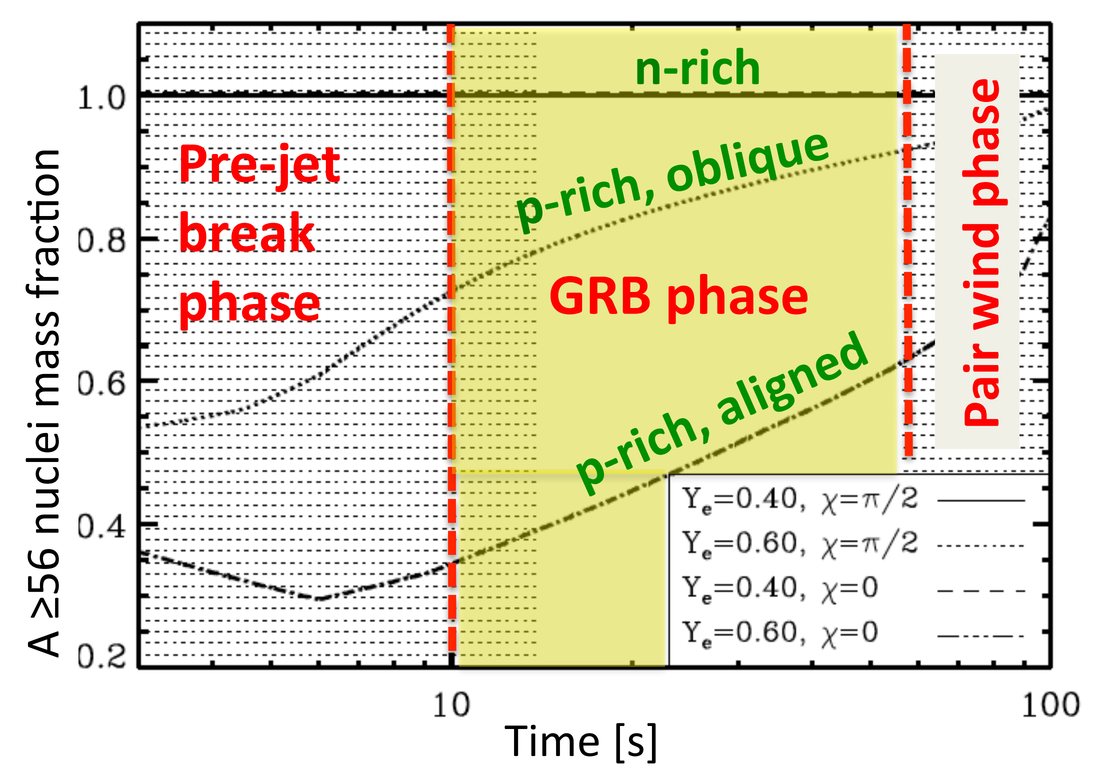
Electron fraction: evolves by neutrino irradiation to 0.4 – 0.6, but may be different due to B field alignment

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

Nucleosynthesis
→ **Freezeout composition can be heavy-dominated during the GRB phase**

Especially for:

- Initially *n*-rich matter
- Oblique rotators (receive less ν-heating and hence have lower entropies)



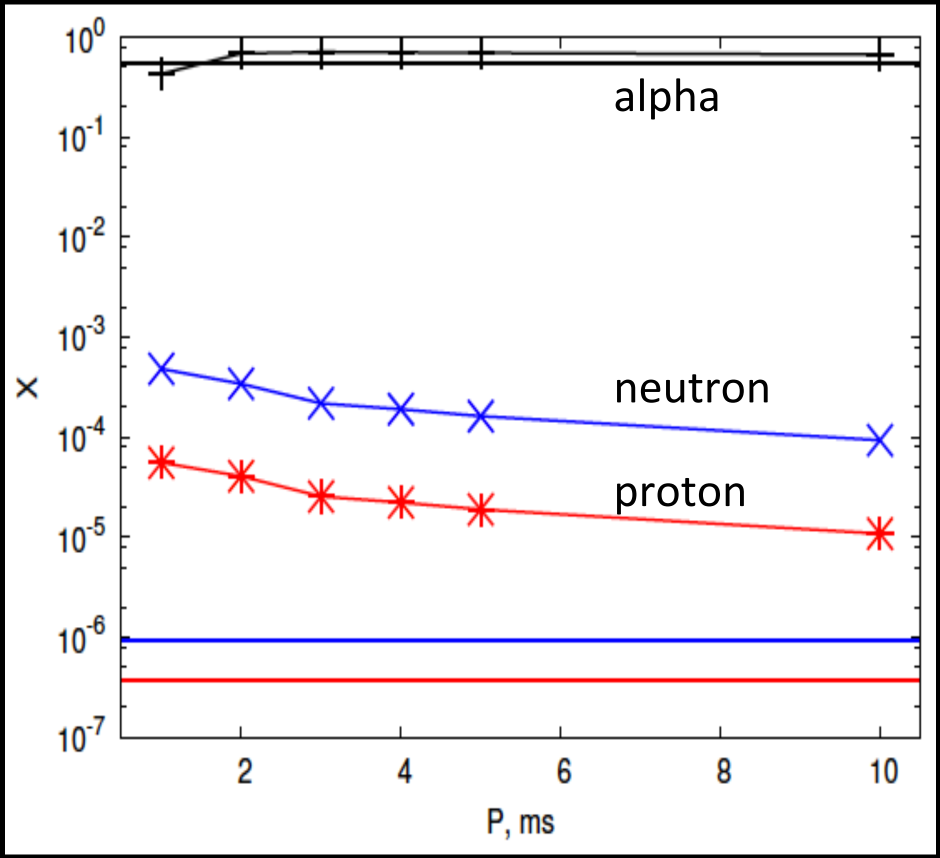
Metzger, Giannios, Horiuchi (2011)

Simulations

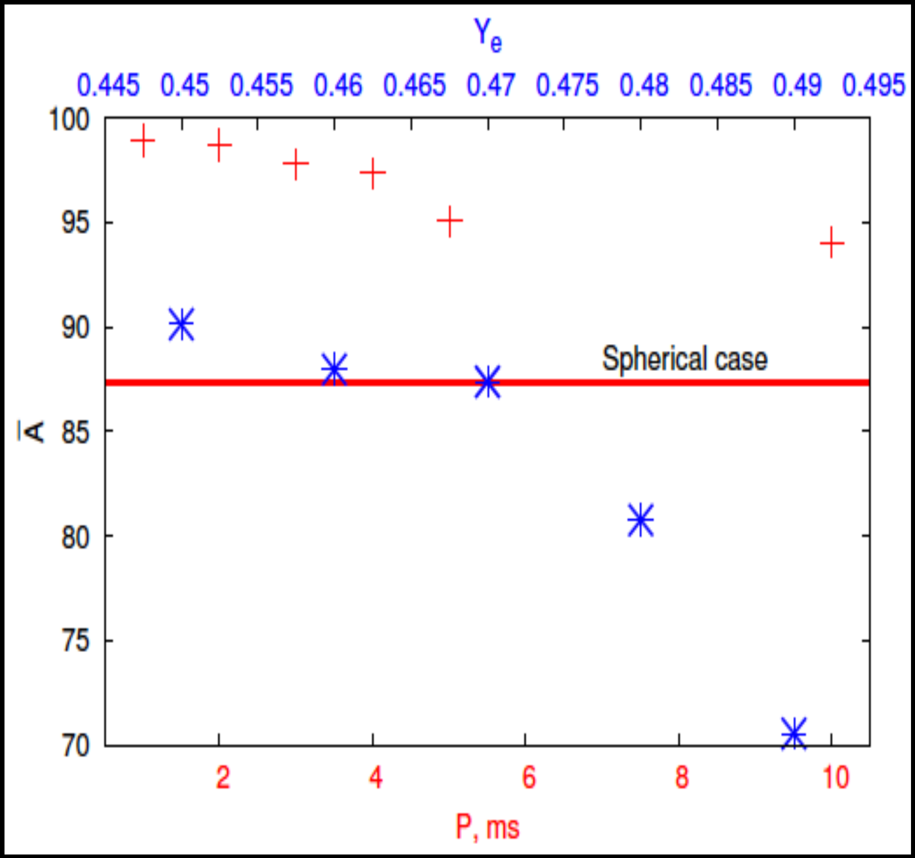
Aligned rotator simulations

Force-free approximation, aligned dipole field $10^{14\text{-}15}$ G, SkyNet nuclear reaction network. Shows r-process nucleosynthesis across a range of rotation periods

Approximately 40% He, trace *n* and *p*



The rest: abundance-weighed mean A



 Vlasov et al (2017)

4. Collisions with neutrons

Neutrons are collisionally coupled to the accelerating plasma:

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

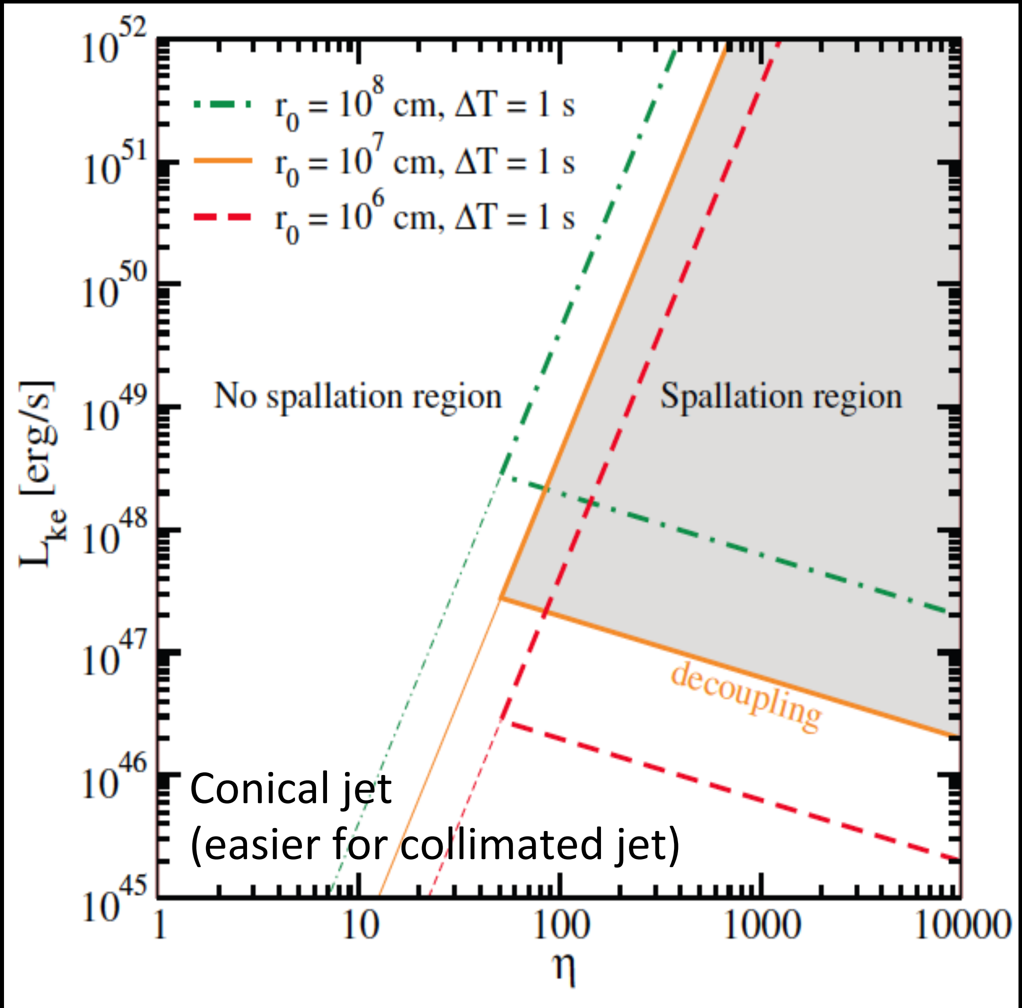
But they lag behind if $\tau_{collision} > \tau_{acc}$

- Make sure the relative velocity

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

  does not exceed the spallation threshold

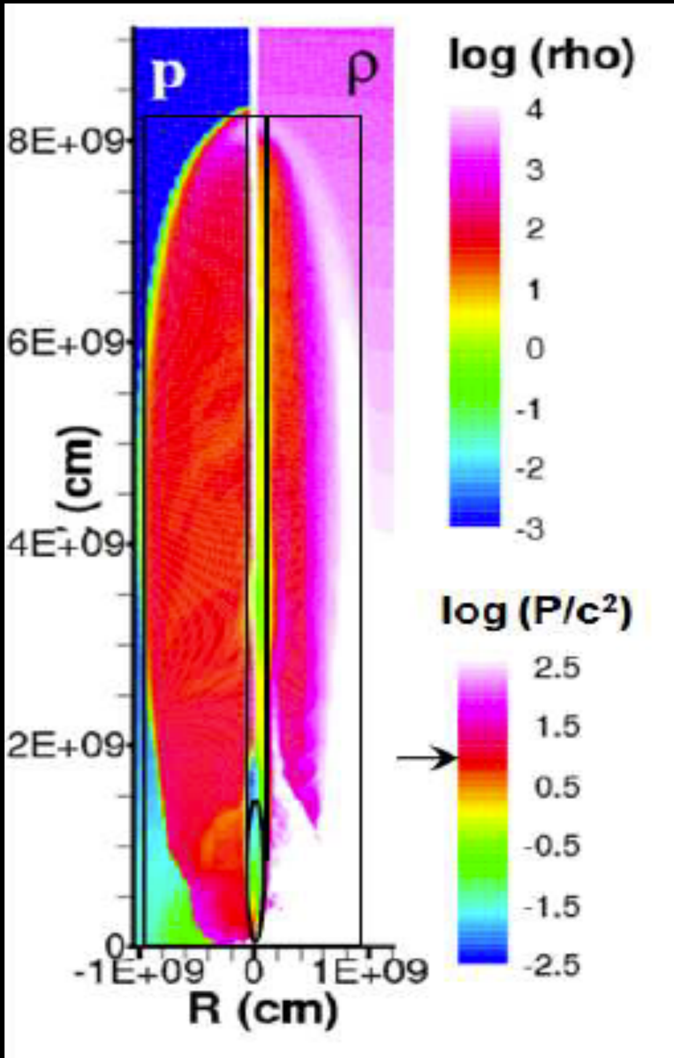
- Or, the neutrons decouple before the spallation threshold is reached



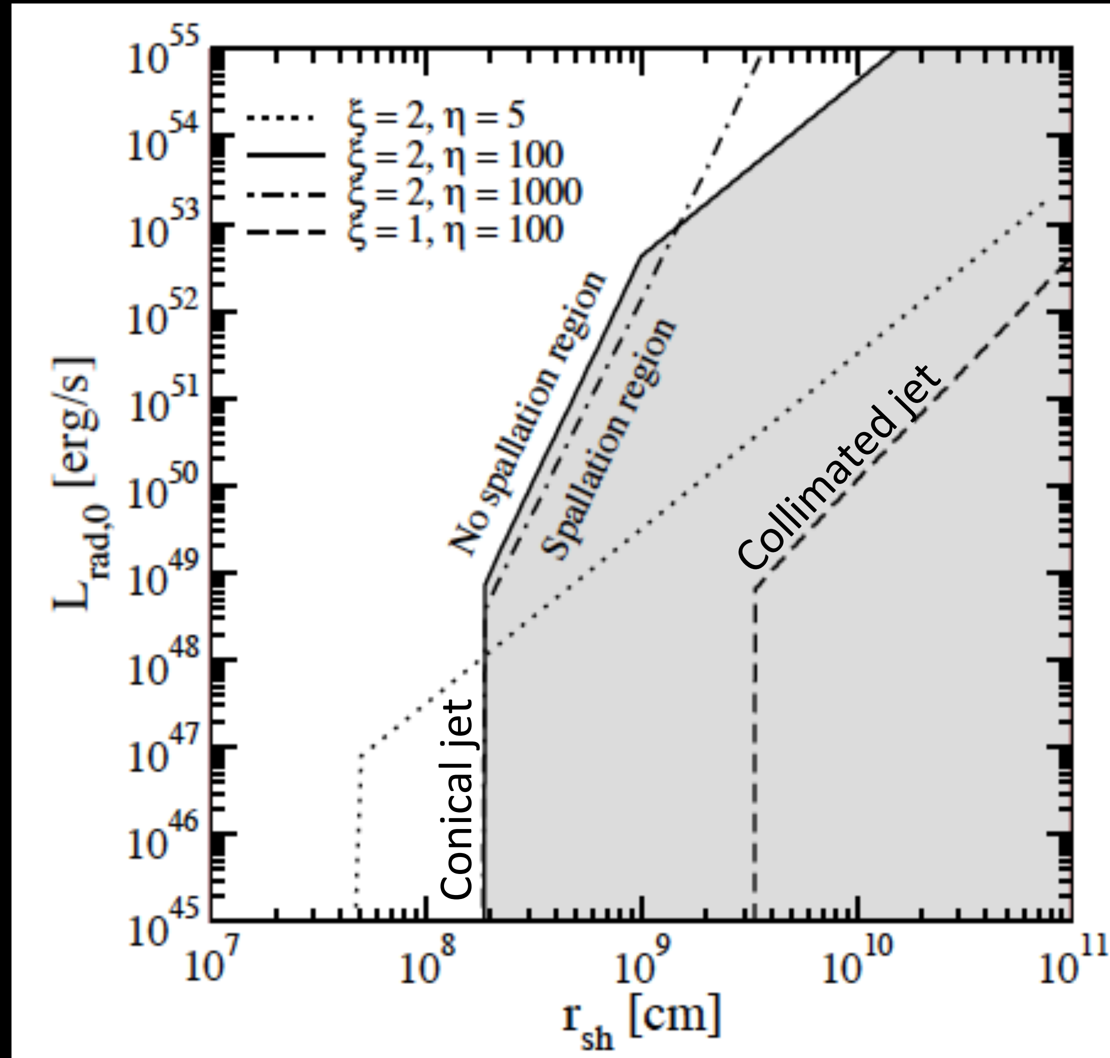
Horiuchi, Murase, et al (2012)

→ Nuclei survive unless η is very large

5. Recollimation shocks



Mizuta & Aloy (2009)



Horiuchi, Murase et al (2012)

→ Will be a problem once shock grows

Brief Summary

	Fireball GRB	Magnetic GRB	Low-luminosity GRB
Source: stellar nucleosynthesis	**Y**	**Y**	**Y**
Survives: initial loading?	N	**Y**	**Y**
Survives: entrainment?	gradient	gradient	gradient
Source: jet nucleosynthesis	N	**Y**	maybe
Survives: *n*-collisions?	**Y**	**Y**	**Y**
Survives: oblique shocks?	Only early	If collimation magnetic	Only early

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

- ➔ In Fireball GRB, nuclei must be entrained beyond recollimation shock radii
- ➔ In magnetic GRB, multiple options
- ➔ In LL GRB, multiple options

ACCELERATION & SURVIVAL

Proto-magnetar model

Acceleration:

Demand acceleration is faster than cooling & expansion timescales:

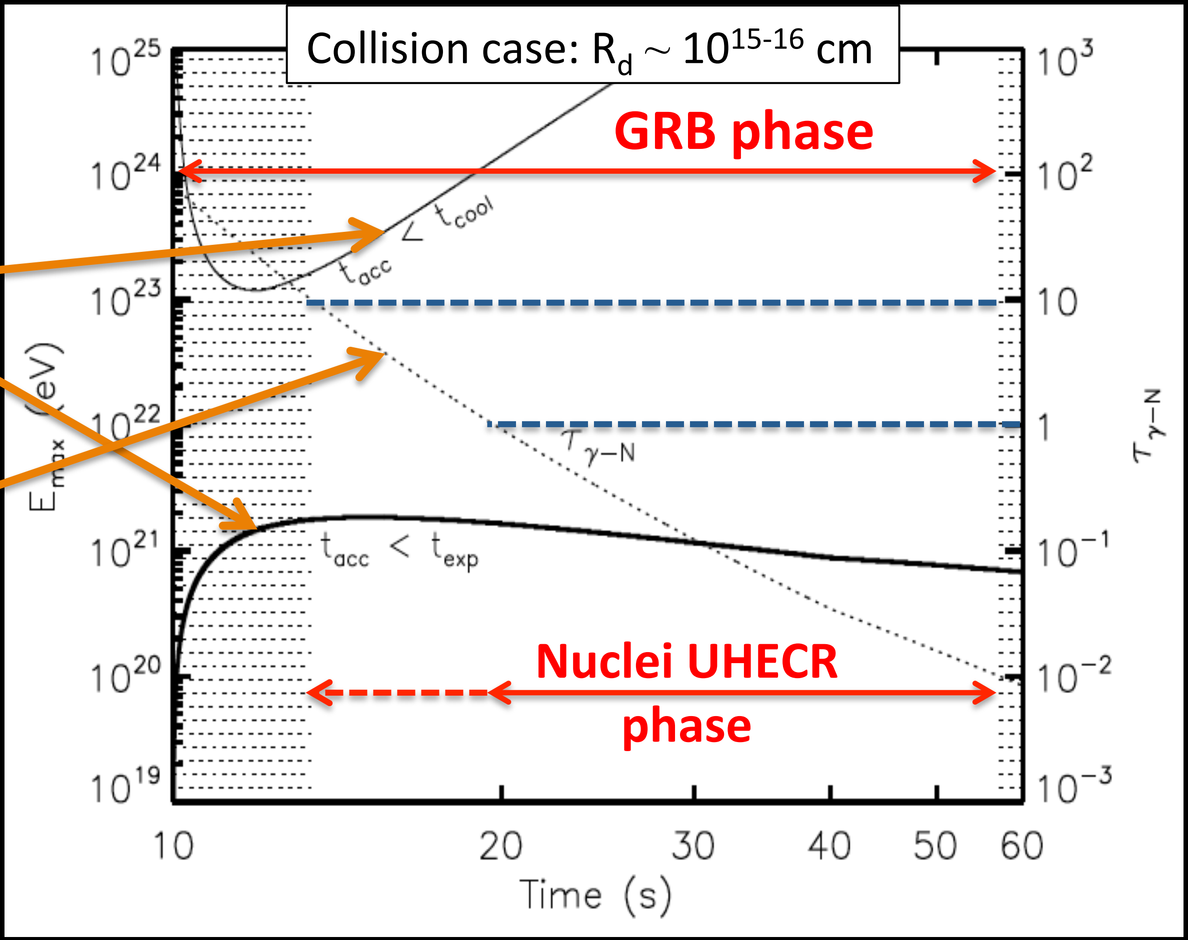
Cooling limit

Expansion limited

Survival:

Calculate the optical depth of photodisintegration based on the Band function for the photon spectrum

Demanding this is = 1 (or a few, allowing for a few destructions) defines the UHECR phase



Metzger, Giannios, Horiuchi (2011)

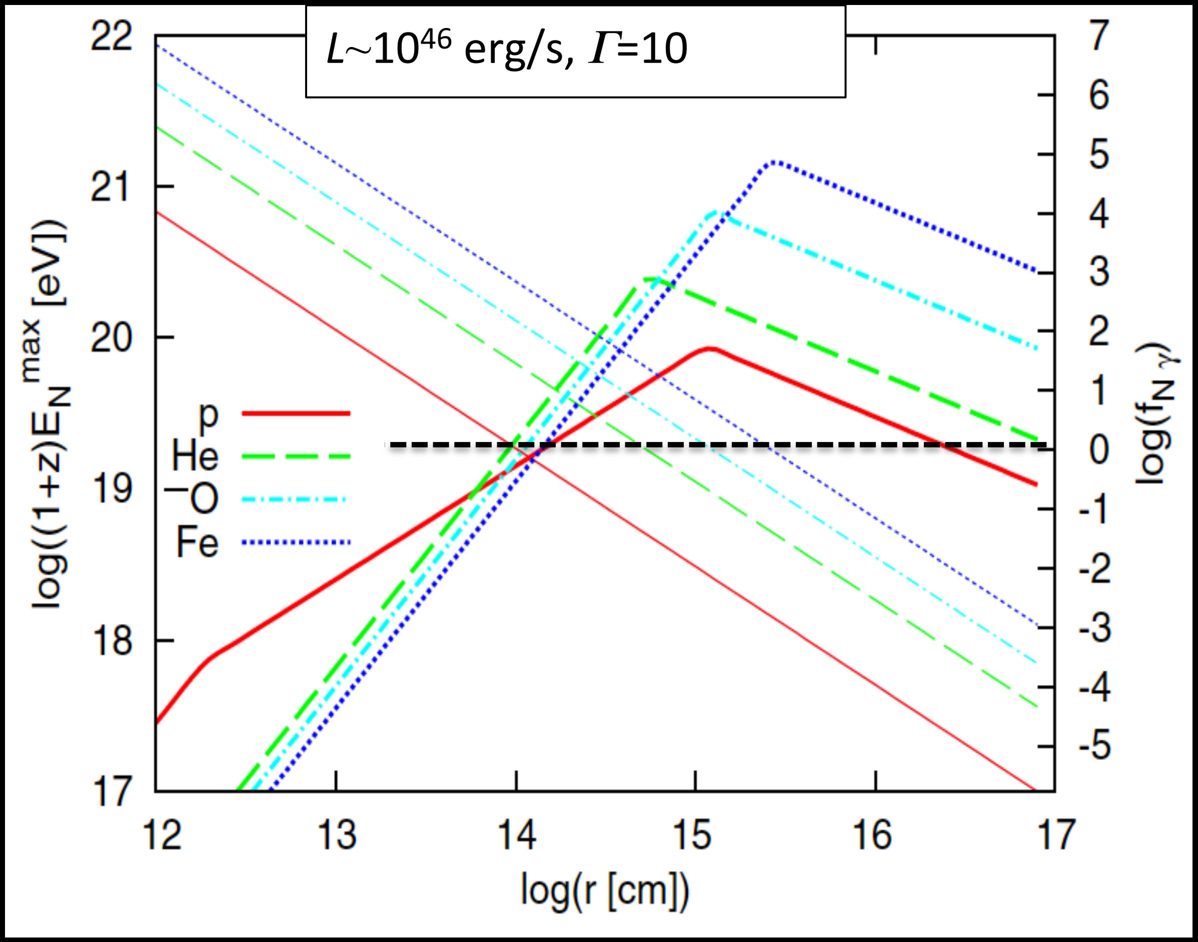
→ There remains a window for UHECR nuclei generation

Low-luminosity GRB

Nuclei UHECR in LL GRB

Nuclei can reach UHECR energies and maintain their composition for large enough dissipation radii

Murase et al (2008)



see also
Wang et al (2008)
Anchordoqu et al (2008)

Summary

- GRBs are stores of heavy nuclei:
  - Through stellar nucleosynthesis, explosive nucleosynthesis, and in-situ jet nucleosynthesis
- Composition of jets:
  - Magnetar models for GRBs, low-luminosity GRBs, and baryon-rich jets are especially conducive to heavy nuclei composition
- Nuclei survival:
  - Neutron collisions and destruction during acceleration appear avoidable depending on parameters
  - Recollimation shocks may be more problematic, but safe while its size is small (=early epochs)
- Want self-consistent composition predictions!

Example: proto-magnetar scenario

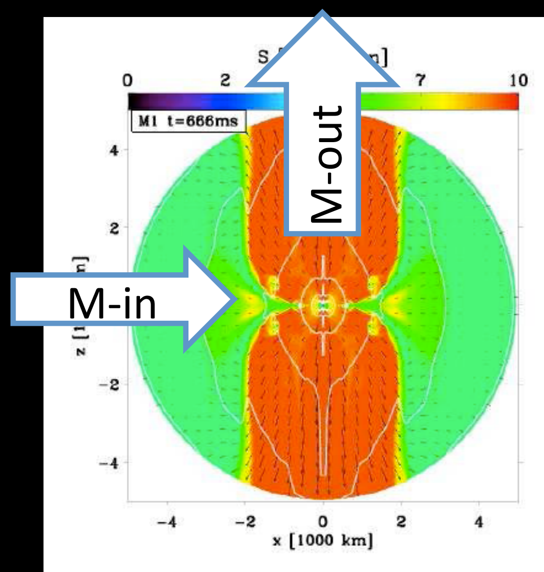
Need a neutron star remnant:

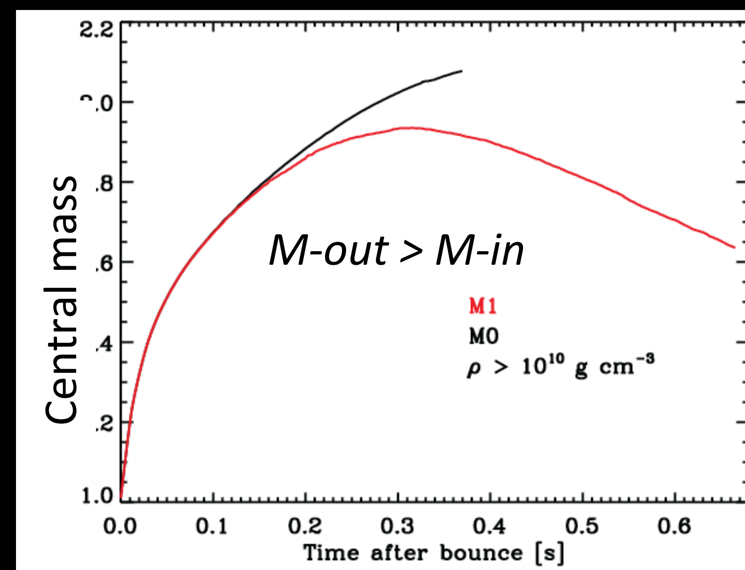
THE PROTO–NEUTRON STAR PHASE OF THE COLLAPSAR MODEL AND THE ROUTE TO LONG-SOFT GAMMA-RAY BURSTS AND HYPERNOVAE

L. DESSART,[1] A. BURROWS,[1] E. LIVNE,[2] AND C. D. OTT[1]

Having the right angular momentum distribution is key:

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





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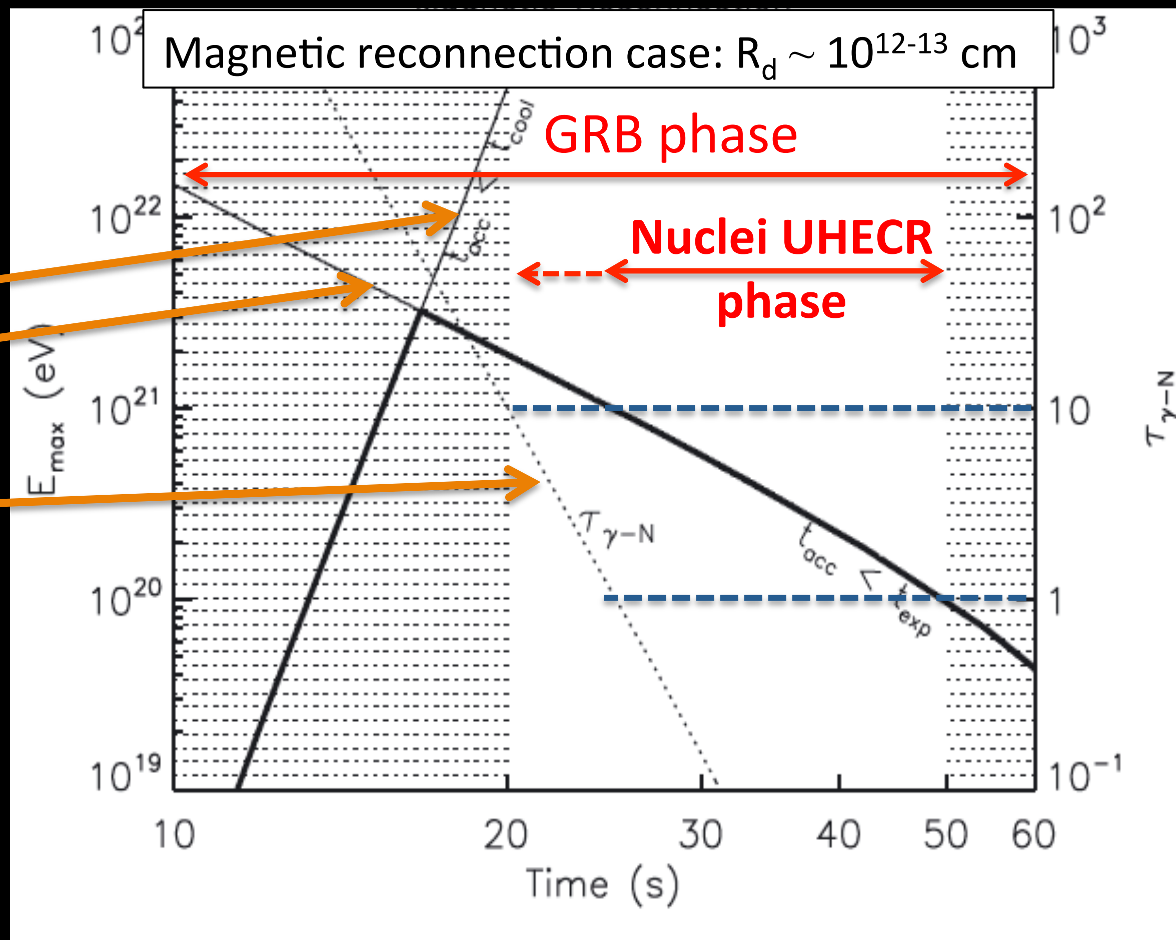

Metzger, Giannios, Horiuchi (2011)

→ **There remains a window for UHECR nuclei generation**