ICEHAP Seminar, Chiba University, ~~Jan 19th 2022~~

~~March 4th 2022~~

April 6th 2022

Source models of UHECR nuclei

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KAVLI IPMU · WPI · VIRGINIA TECH · The Center for Neutrino Physics

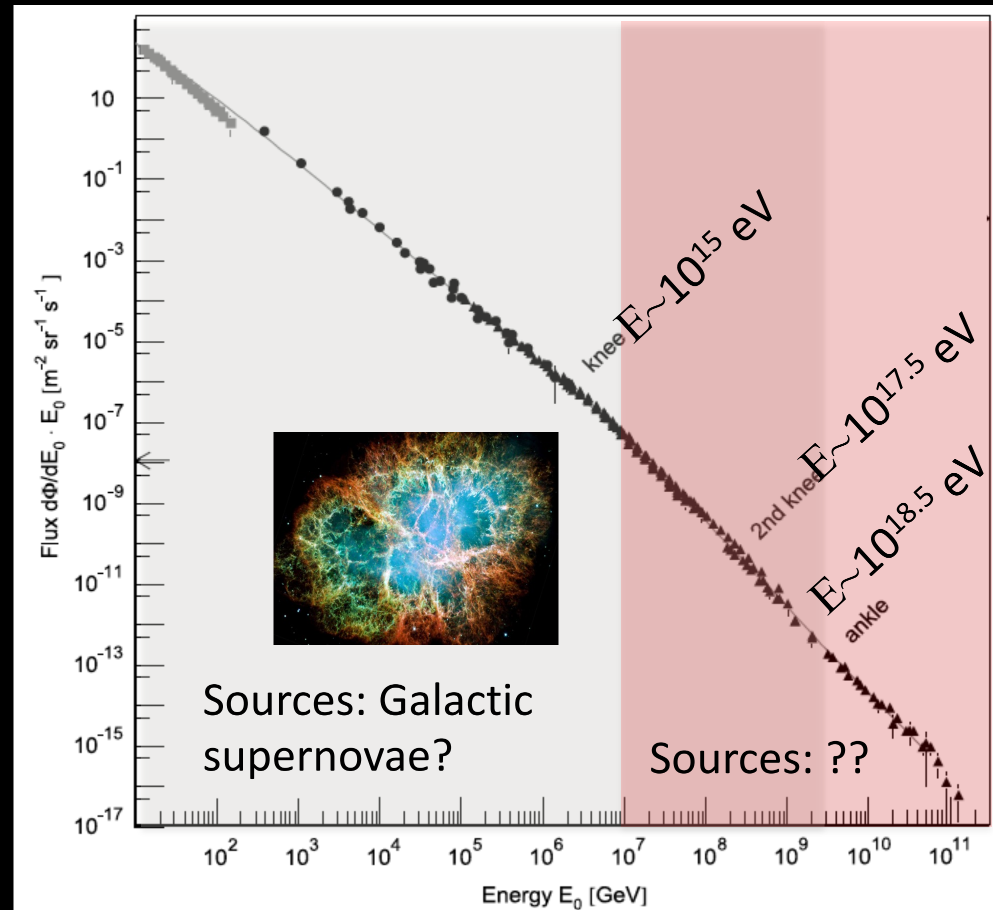
U.S. DEPARTMENT OF ENERGY Office of Science · NSF

Image credit: NASA/ESA

Today's contents

- Introduction to ultra-high energy cosmic rays (UHECR)
  - Observations
  - Mass composition
- Origins of nuclei
  - Nucleosynthesis in massive stars
- Source models for UHECR nuclei: gamma-ray bursts
  - Initial loading
  - In-situ nucleosynthesis
  - Entrainment (time allowing)
- Concluding remarks

Cosmic rays



Blumer et al 2009

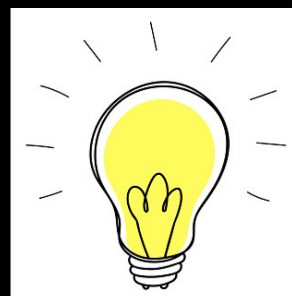
Much history:
100+ years since Victor Hess's first discovery. Millikan coined the name cosmic rays.

Much progress:
Since those times, we have much data. *But we still are grappling with fundamental questions: what is (are) their source(s)?*

The most extreme energies

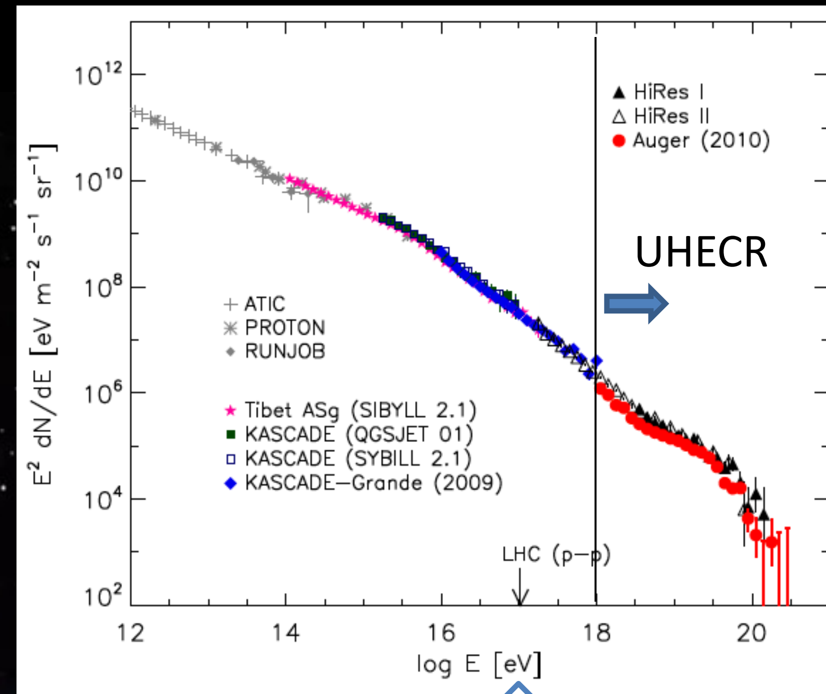
Ultra-high energy cosmic rays (UHECR)

- The most energetic (known) particles in the Universe



Macroscopic energies in microscopic particles…!

- Energy frontier, extreme sources, very interesting



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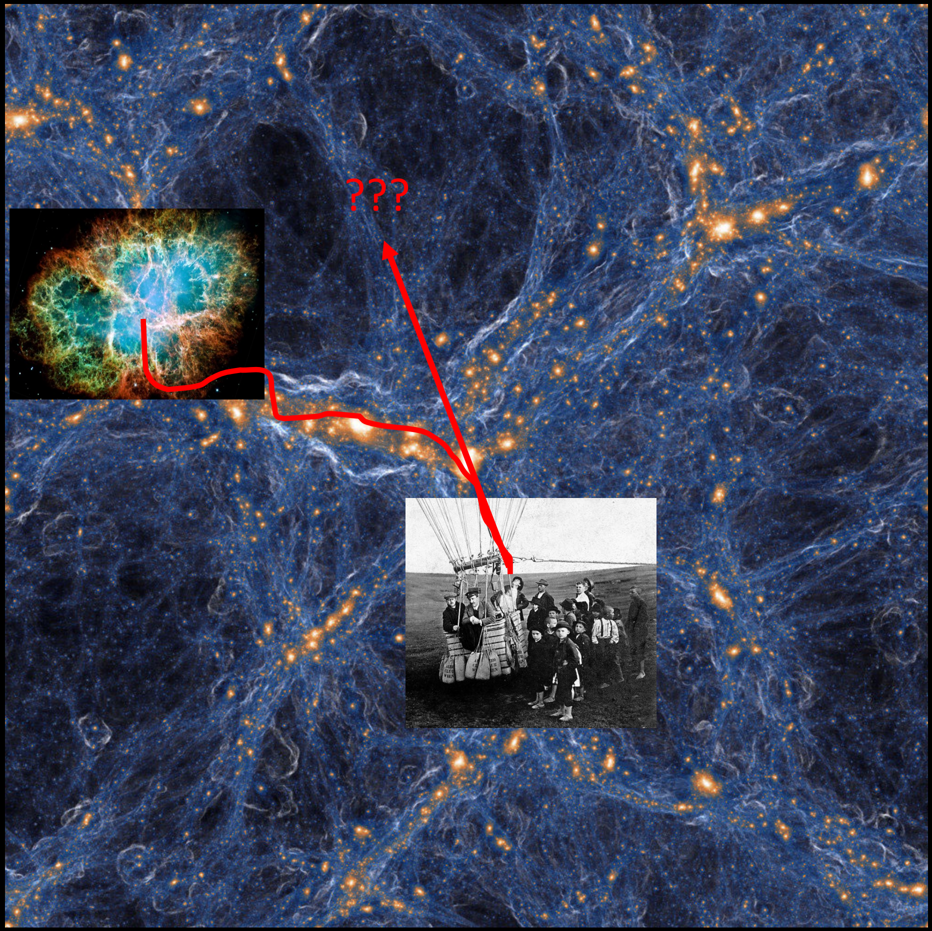
Why is it so difficult?

Charged particles bend in magnetic fields

- Magnetic field is ubiquitous in the Universe

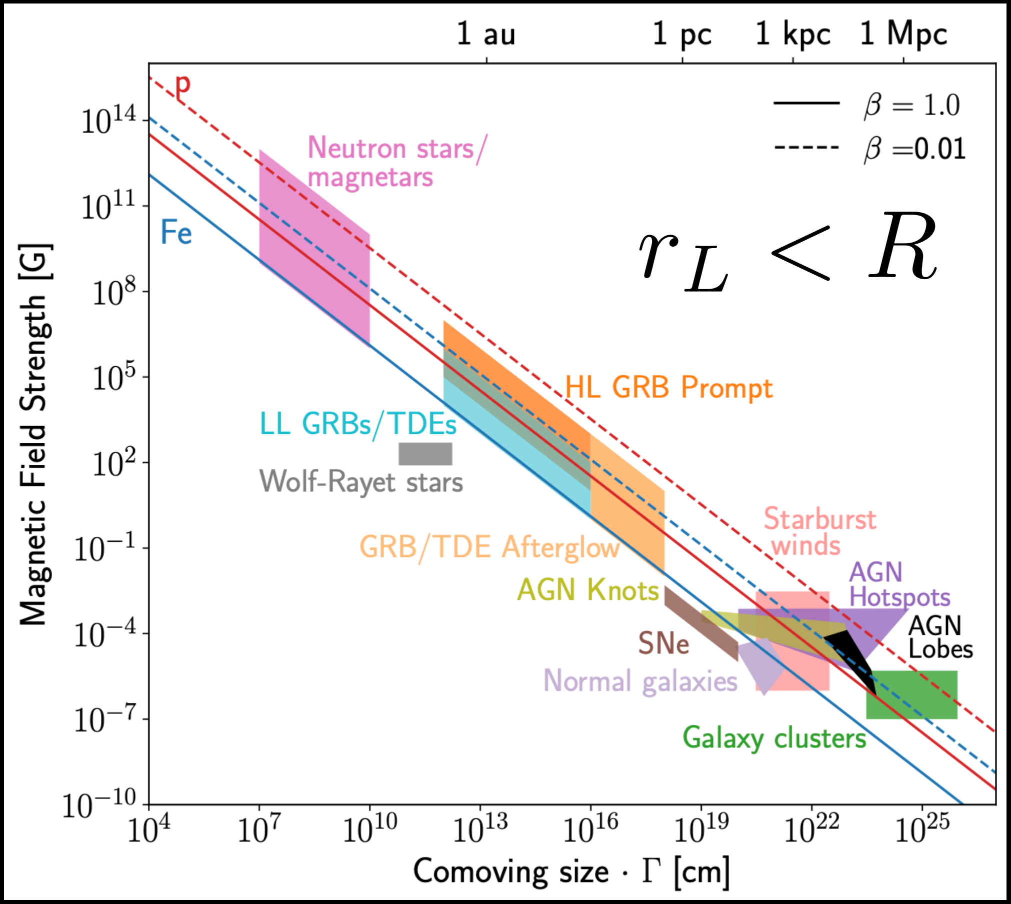
Difficult to model

- Requires some of the most extreme astrophysics and particle physics

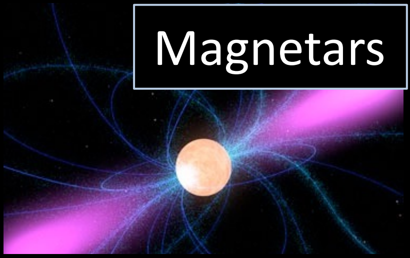


The most extreme sources

Only the most extreme objects can accelerate to UHECR energies

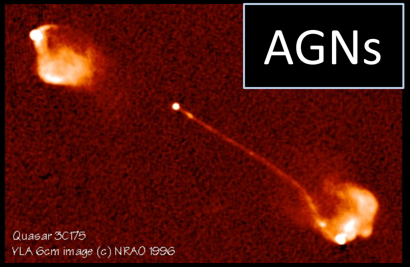


Hillas plot: required, but not sufficient, condition for UHECR sources



The strongest B-fields

The most luminous explosions



The most massive black holes

Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

The largest bound objects

Which of these are the source(s) ???

Why is it so difficult?

Charged particles bend in magnetic fields

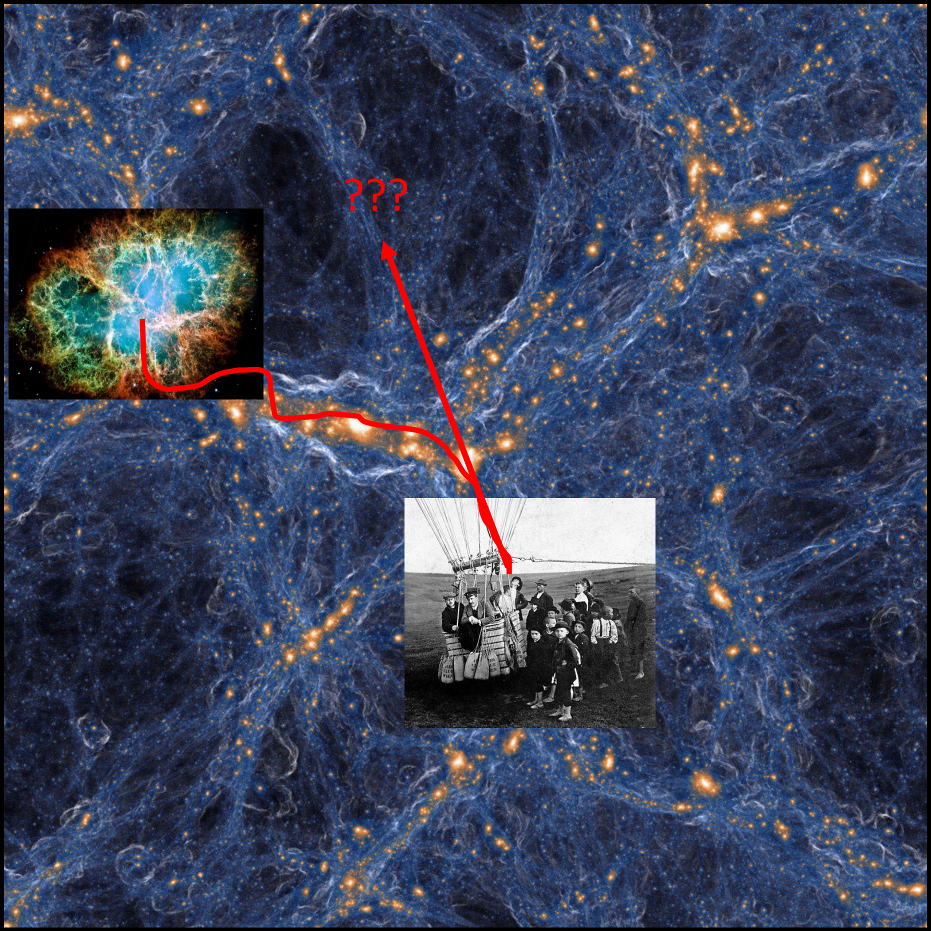
- Magnetic field is ubiquitous in the Universe

Difficult to model

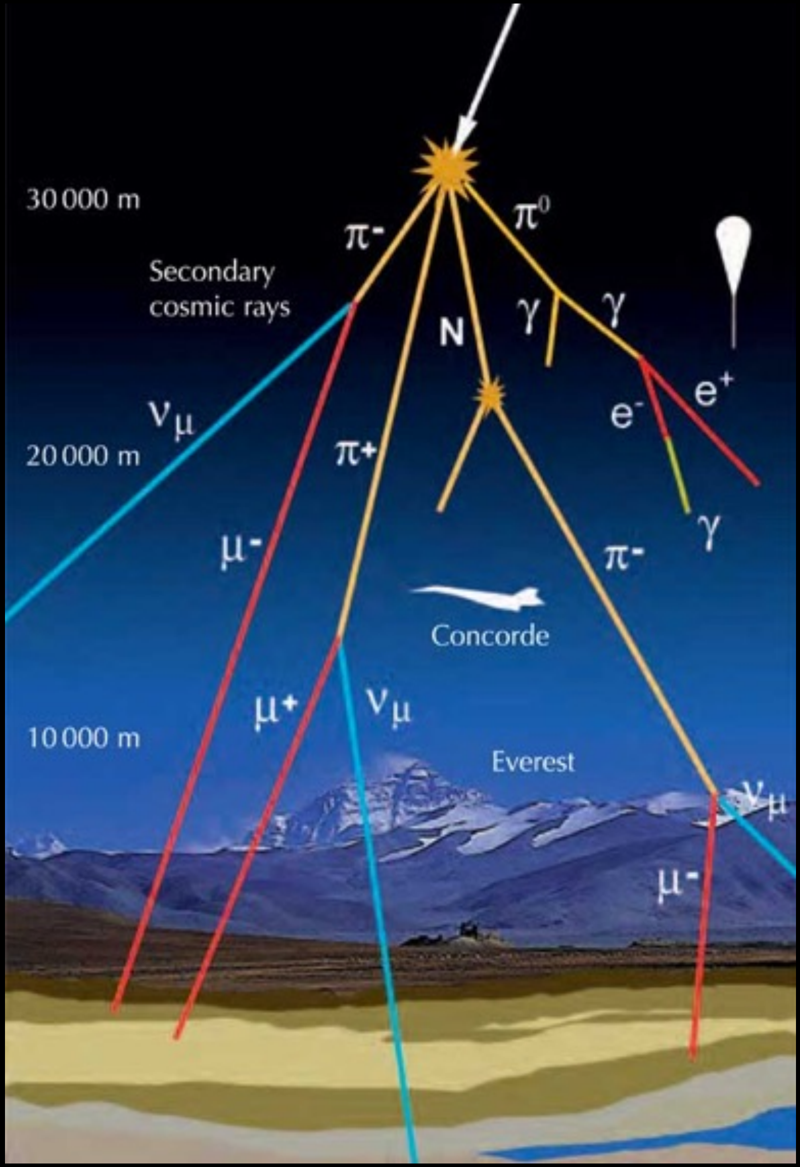
- Requires some of the most extreme astrophysics and particle physics

Difficult to measure & interpret

- UHECR are extremely rare
  $\sim$ 1 /m^2/Myr $\sim$ 1 /km^2/yr
- Beyond terrestrial probes



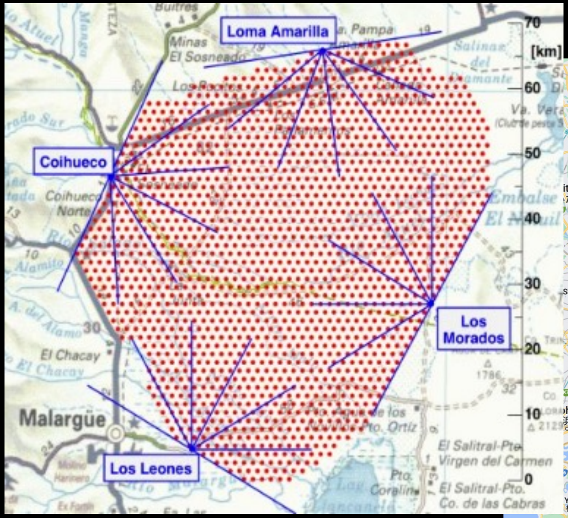
Extensive air showers

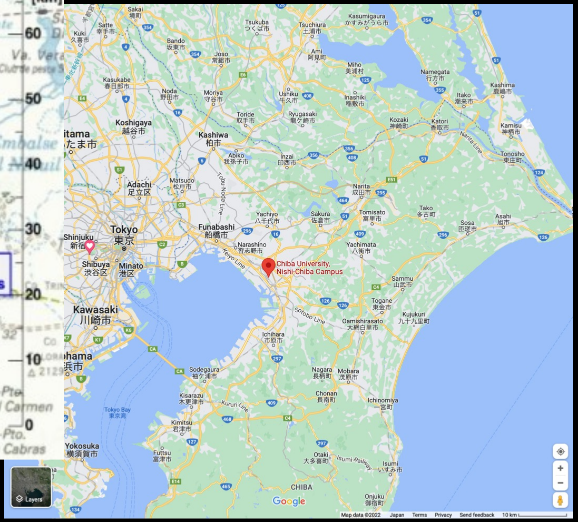


Detect UHECR through extensive air showers.

Giant detectors!

- Pierre Auger Observatory: ~3,000 km^2 @Argentina
- Telescope Array (TA): ~680 km^2 @Utah → TA x4





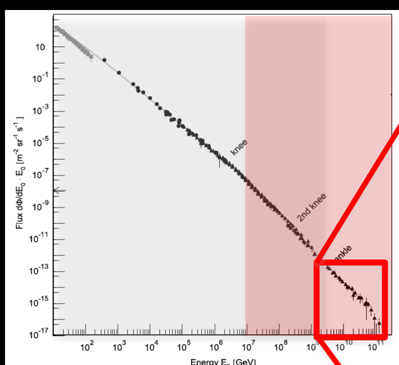
→ Three observables:

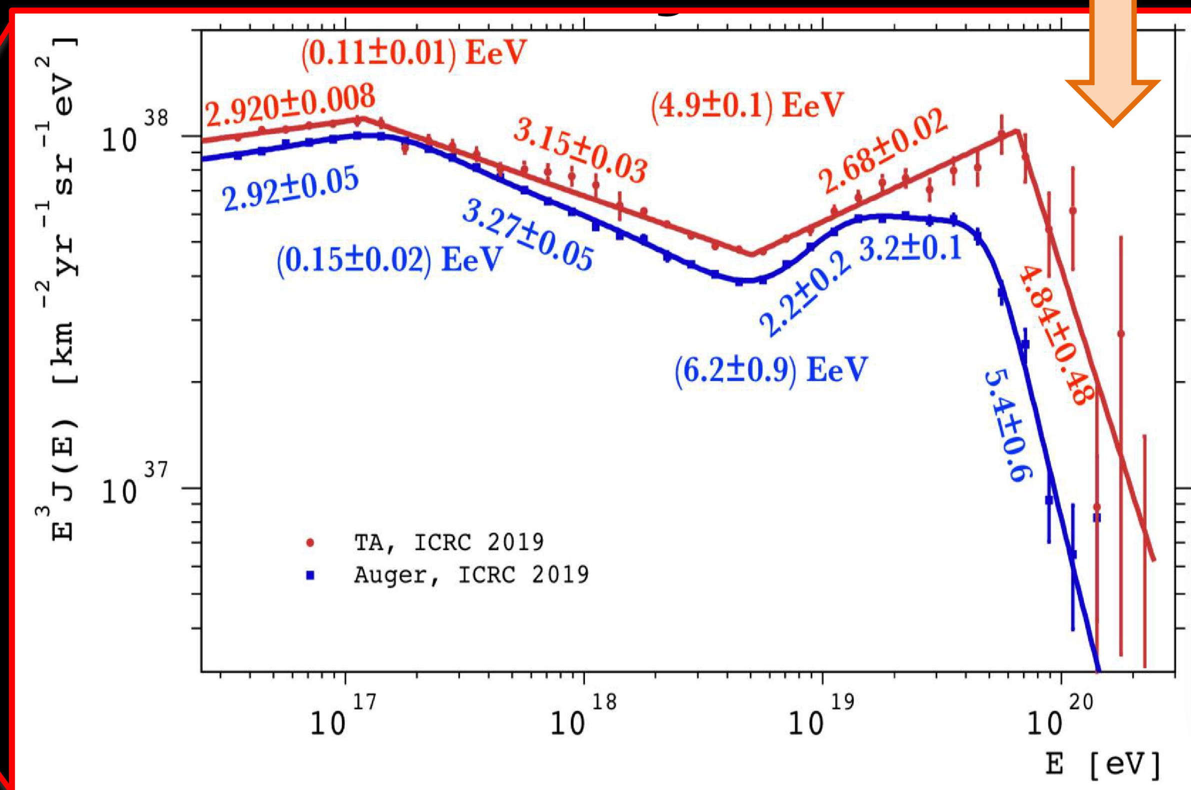
Energy, arrival direction, mass composition

Hints from energy spectrum

- After consideration for detector systematics, mostly in agreement
- Cut-off seen just before 1e20 eV

Maximum acceleration energy or GZK cutoff?





ICRC (2019)

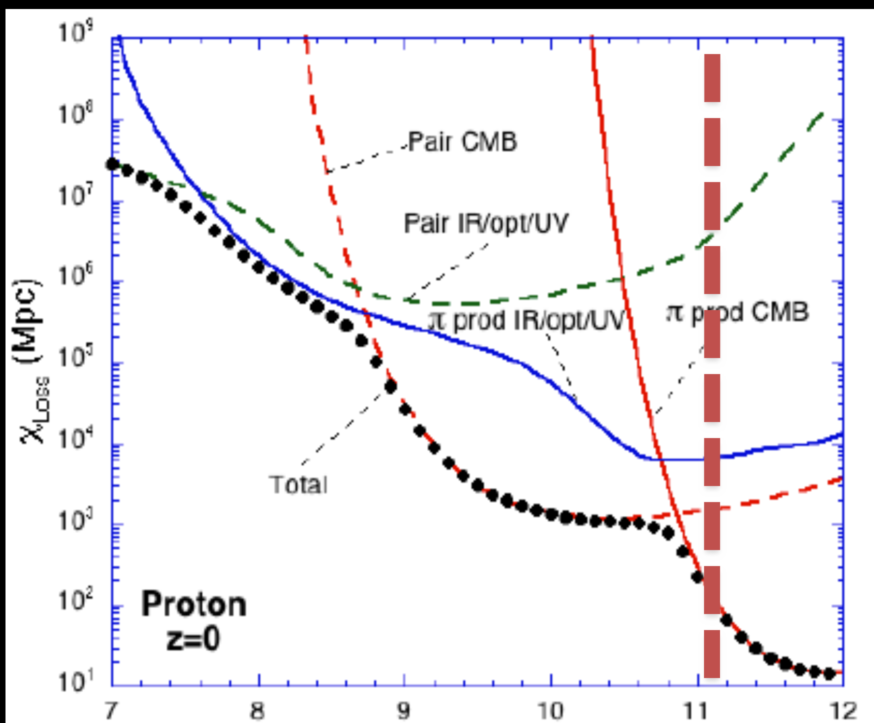
GZK cutoff

CR with E > ~10^{18} eV suffer energy losses during propagation, aka "GZK"

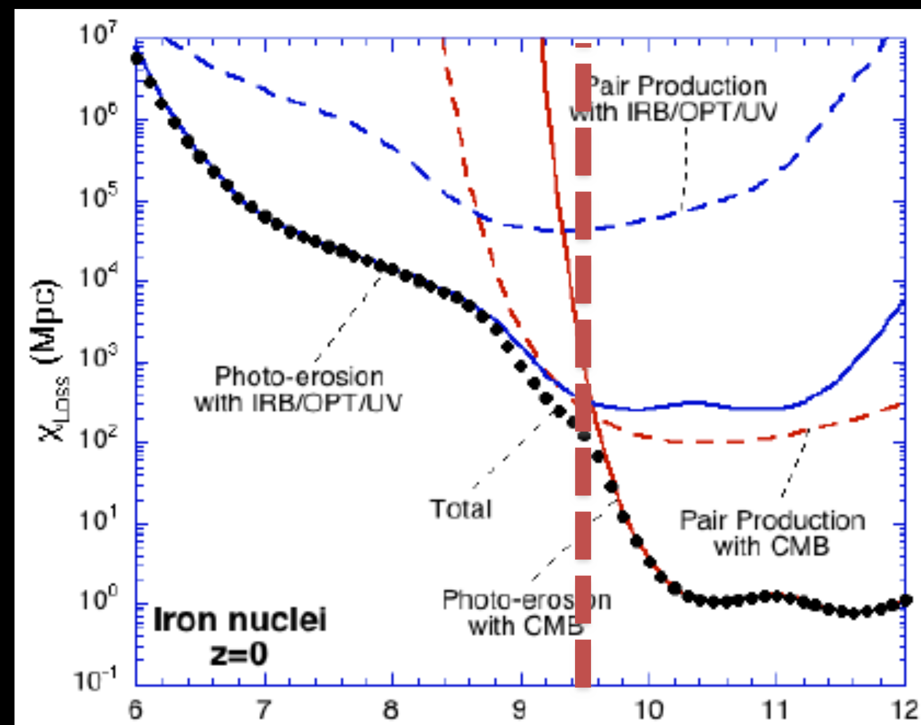
$$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$N + \gamma_{\rm CMB} \rightarrow (N-1) + p/n$$

Greisen (1966)
Zatsepin and Kuz'min (1966)



Allard et al. (2006)



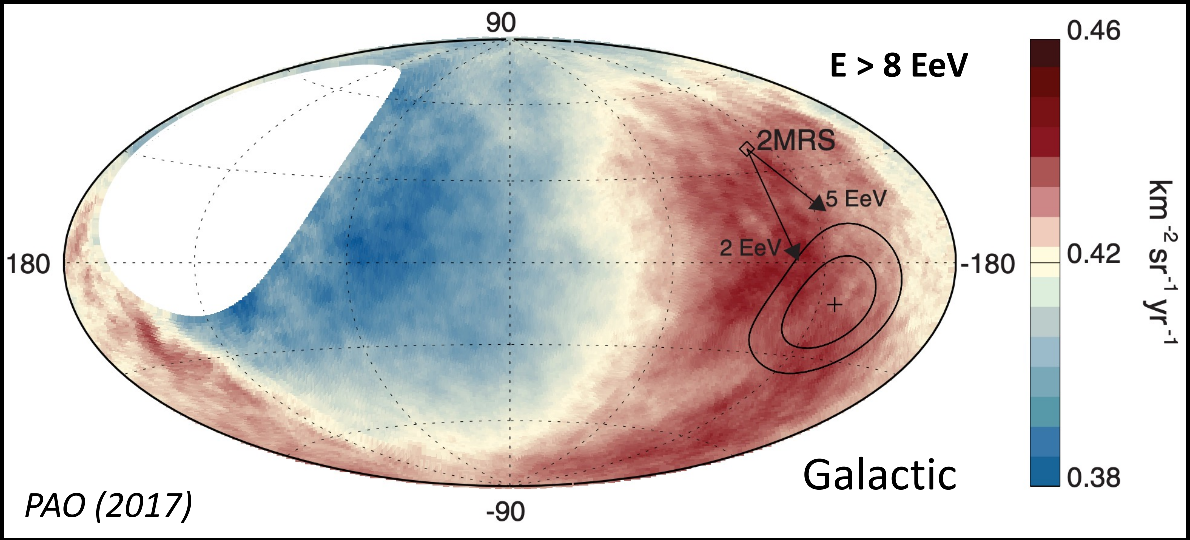
Allard et al. (2006)

- Energy loss during propagation limits the UHECR horizon to ~100 Mpc
- Ongoing debate on GZK effect vs maximum energy

Hints from anisotropies

Large scale

Dipole anisotropy shows extragalactic origin, not Galactic

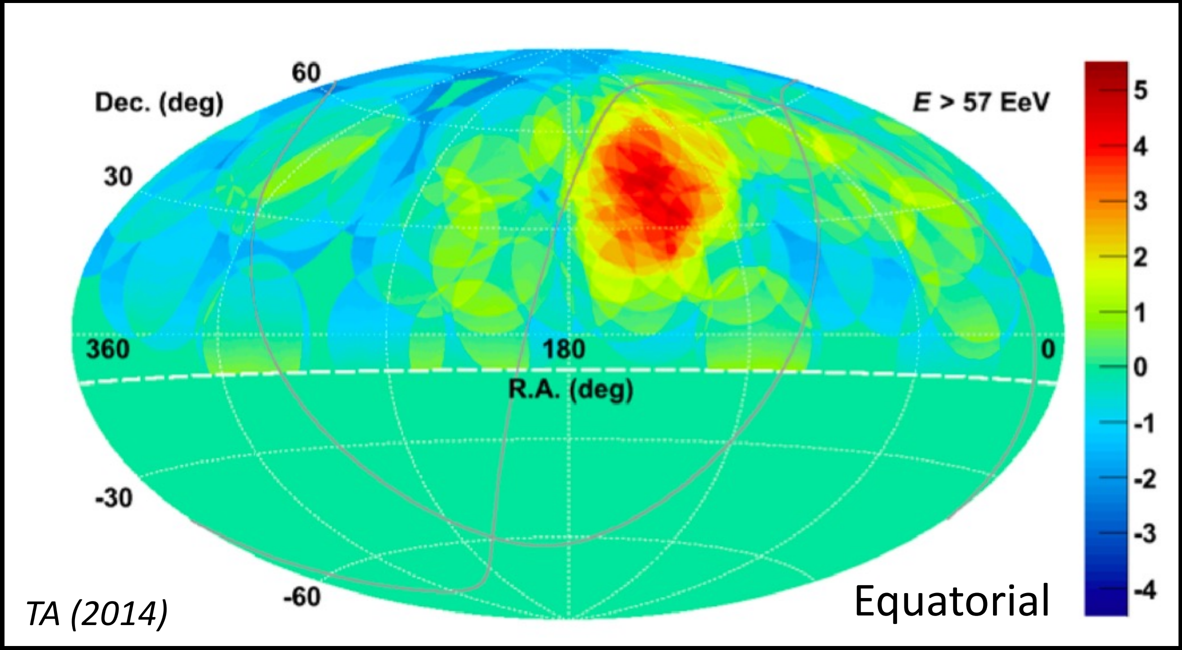


Hotspots

Growing hints, eg the TA hotspot.

Coverage includes eg M82, Mrk 180, 421.

However still unclear.



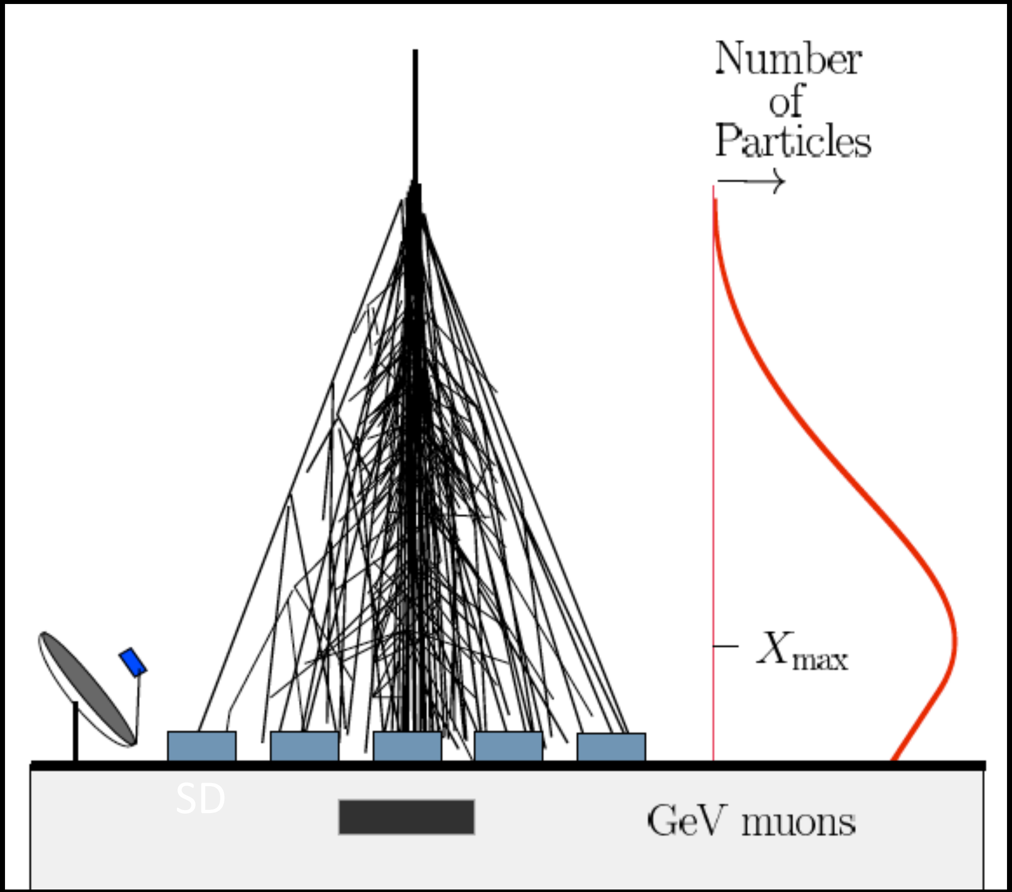
Hints from mass composition

Shower development is composition dependent

Some observables to probe the composition:

1. $\langle X_{max} \rangle$: mean maximum of the shower longitudinal profile smaller for nuclei

1. rms$\langle X_{max} \rangle$: the shower to shower variance is smaller for nuclei

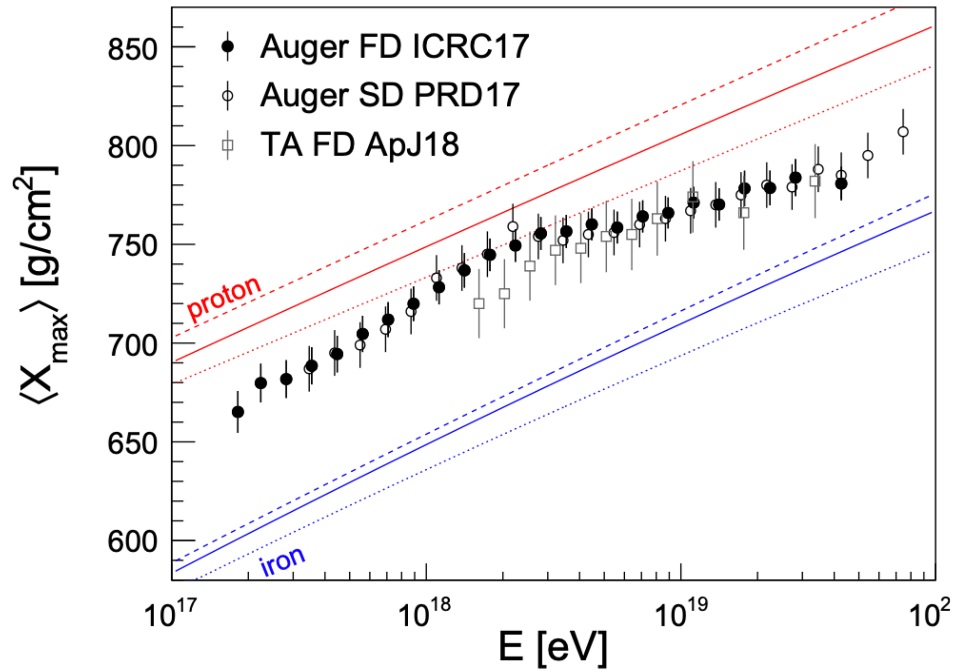


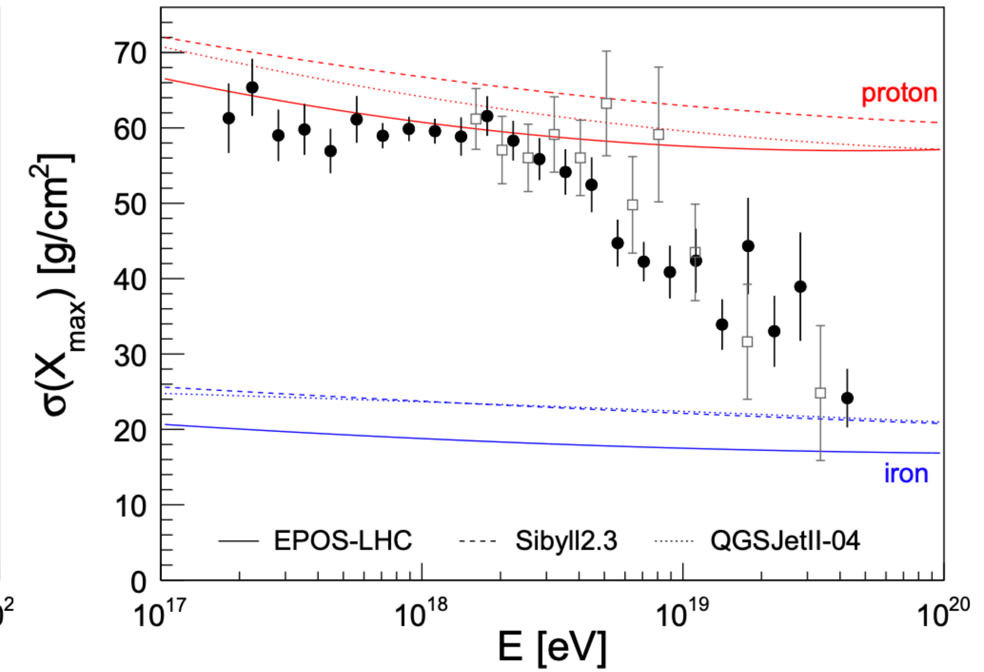
From Anchordoqui 2011

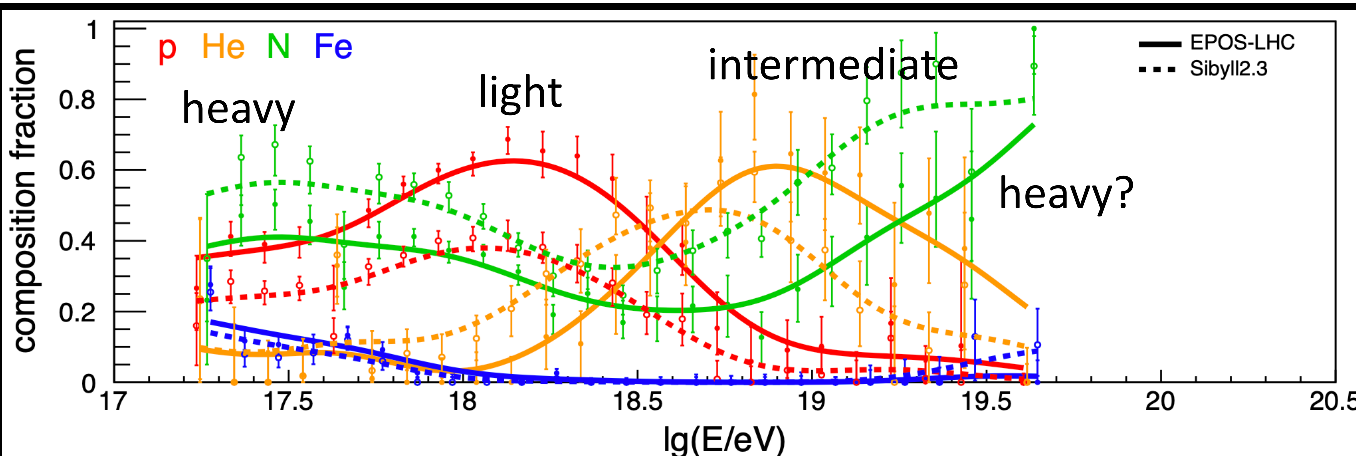
Heavy composition

Gradually transitions to heavier composition above ~ankle

Batista et al (2019)







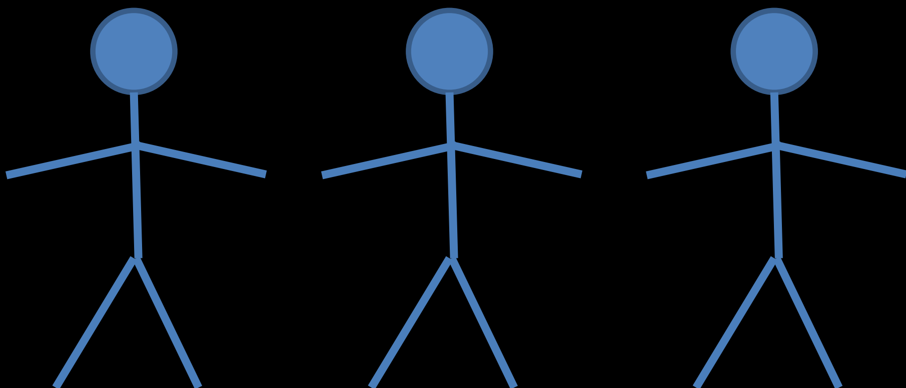
Interpretation uncertainties, from hadronic shower models that need to be extrapolated

PAO (2019)

- UHECR are extragalactic, but we haven't revealed the source(s) yet.
- More data is needed! But spectrum is generic and many sources follow the matter distribution.
- Interesting possibility for nuclei UHECR. Quantitatively still unknow, but it leads us to ask: *what does composition imply for sources?*

The check list

1. **Source must be able to accelerate UHECR**
2. **Source must be energetic & common enough**
3. **<u>Source must have a nuclei origin story</u>**

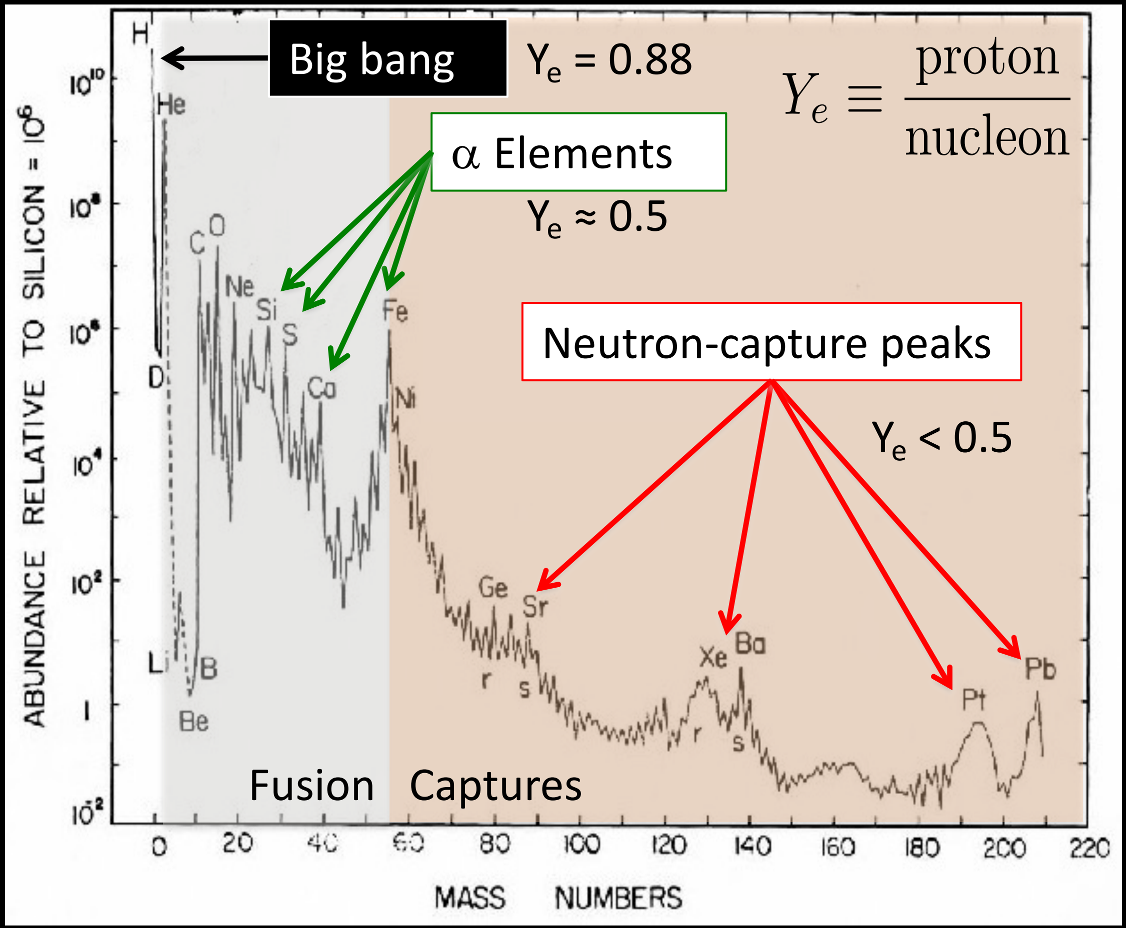


Origins of nuclei

Q: where are nuclei?

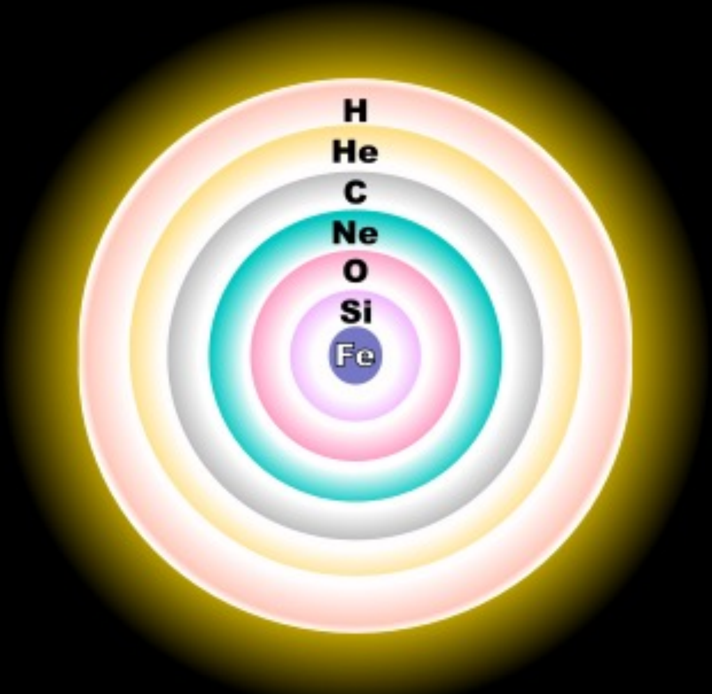
- Nucleosynthesis in stars
- Explosive nucleosynthesis in supernovae:
  - Up to Fe elements via α captures
  - Heavier nuclei via fast nucleon captures
- Rapid neutron captures in NS-NS mergers

➔ **i.e., massive stars**

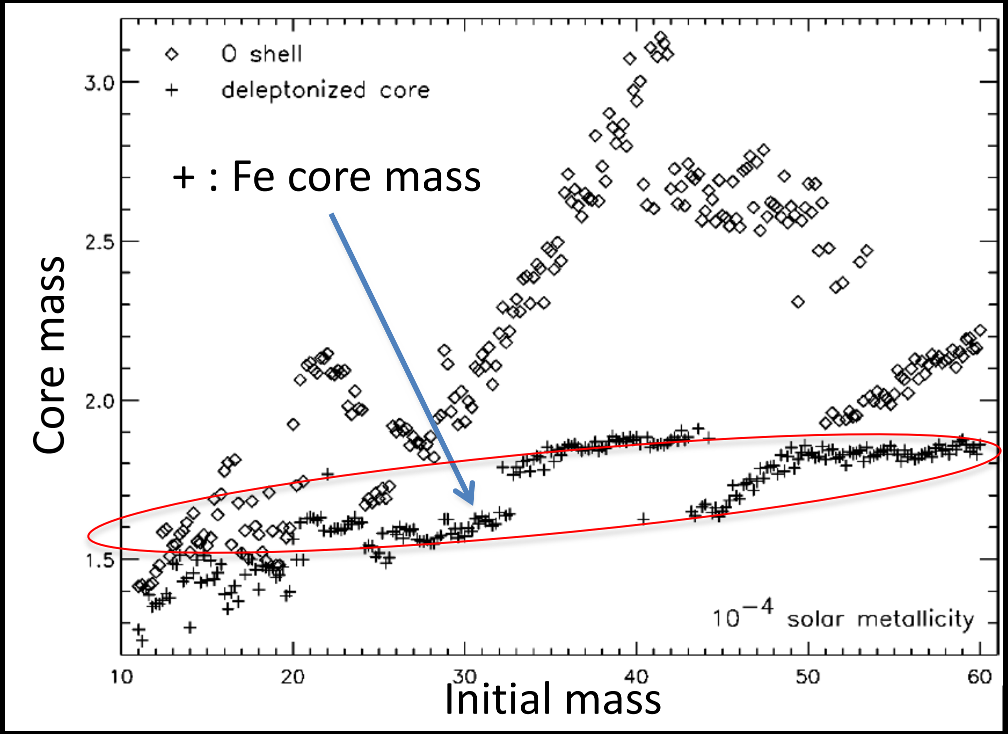


Stellar Nucleosynthesis

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



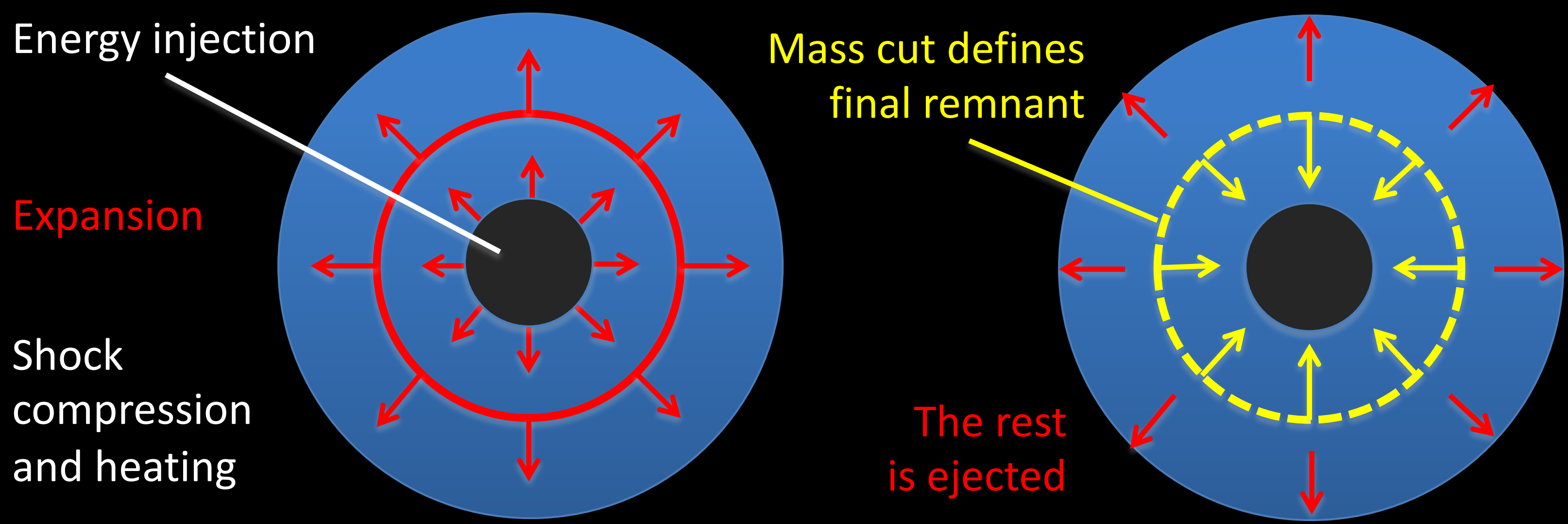
Iron nuclei abundance
The final Fe core mass is ~1.5 Msun with radius of 10^8 cm or so



Woosley et al (2002)

Explosive Nucleosynthesis

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



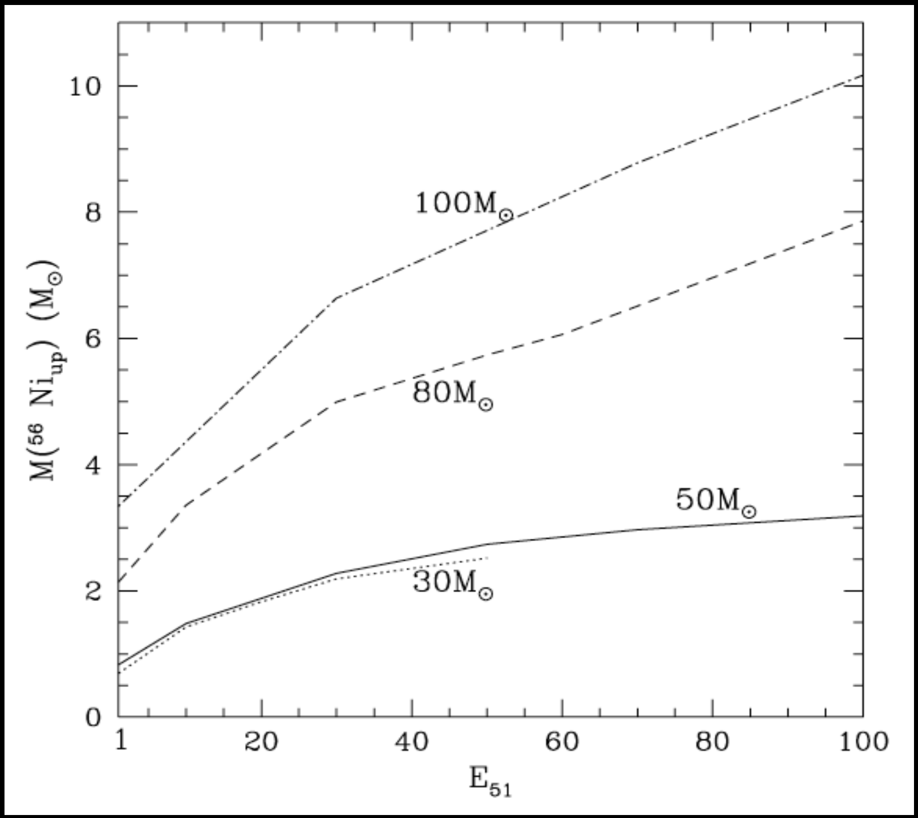
However, how much heavy nuclei is released is model dependent:

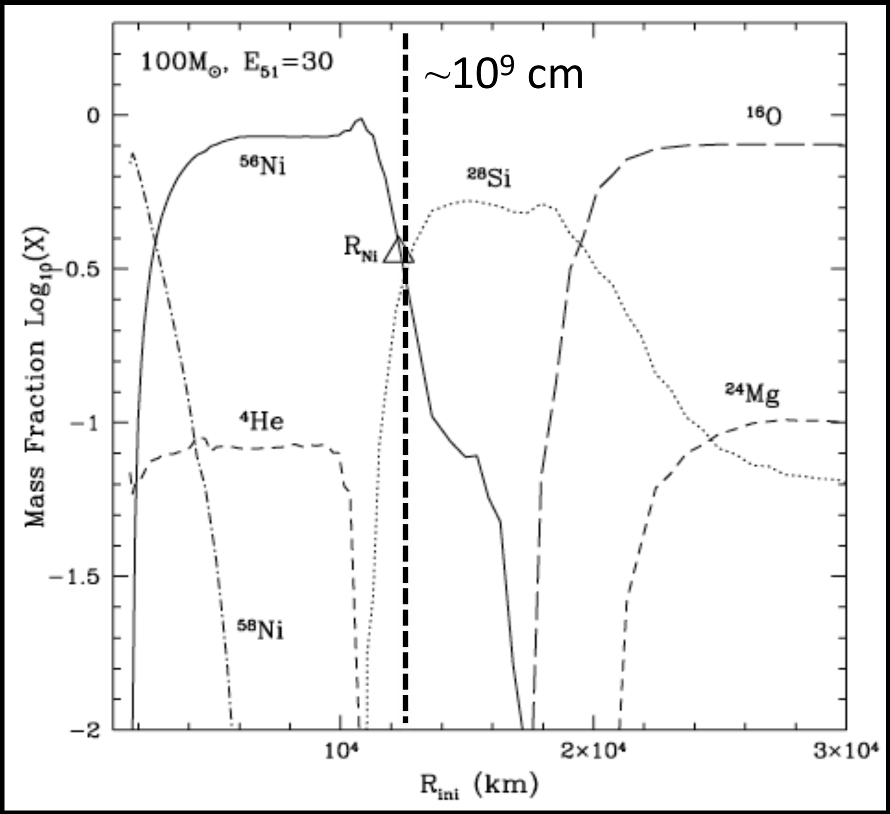
1. Some amount of energy injection
2. At some location
3. With some mass cut

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

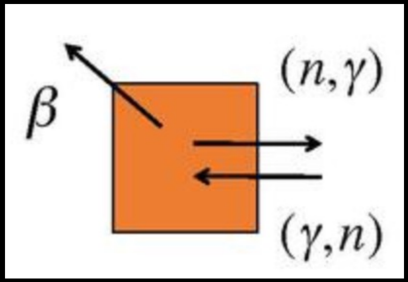
But can be more, e.g., hypernovae, superluminous supernovae (x100 ^{56}Ni needed*)

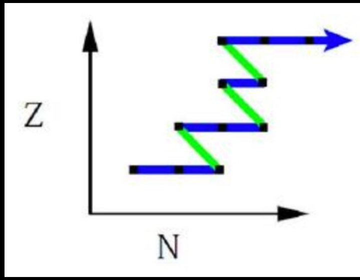
*if powered by nickel decay

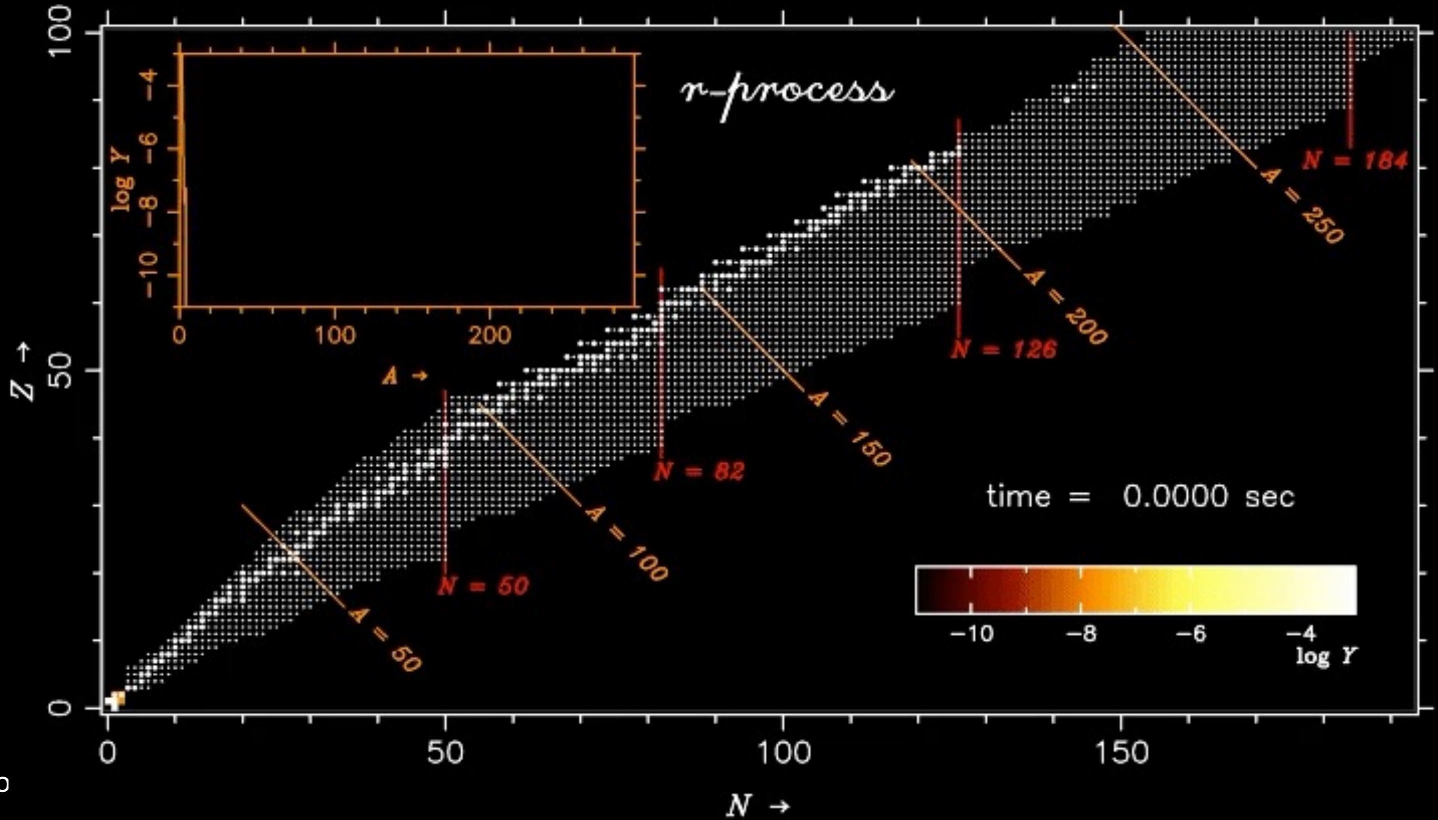
r-process nucleosynthesis

Generates neutron-rich nuclei

R-process network
- Neutron captures
- Photo-disintegrations
- Decays (weak, fission)



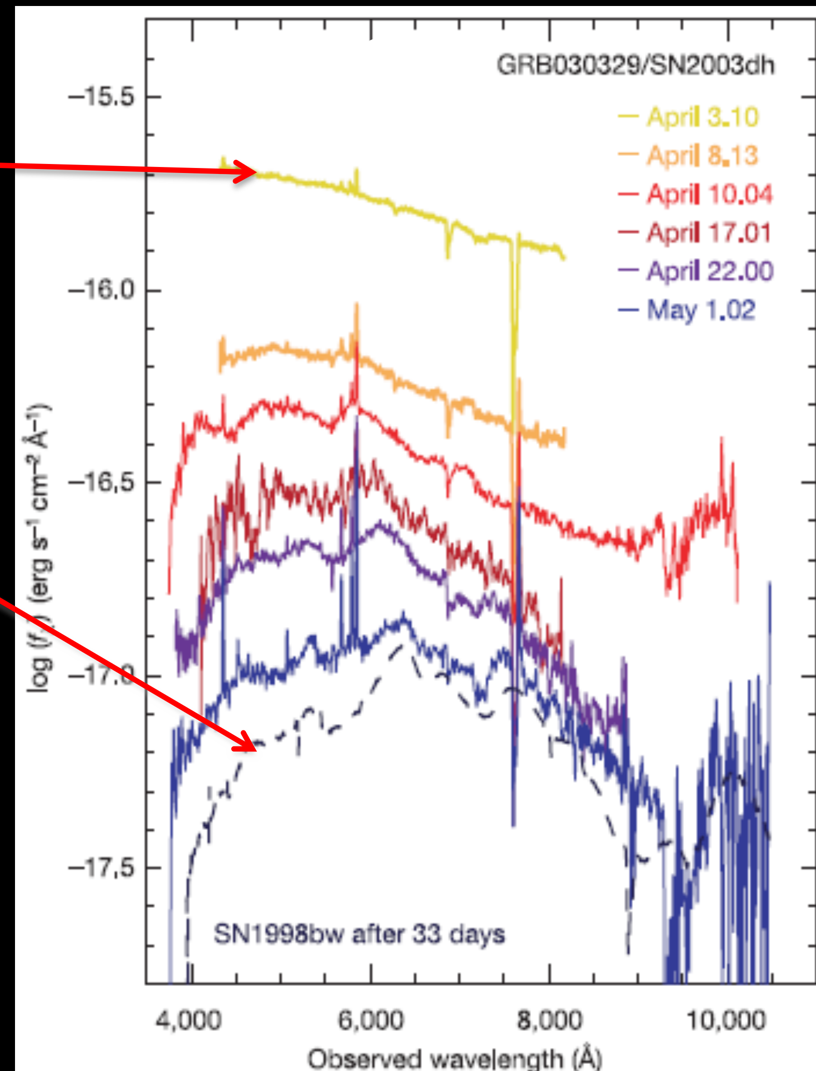




Massive stars collapse spectacularly

GRB (long)

Supernova



Stanek et al (2003)

GRBs are rare: $\frac{GRB}{SN} \sim 10^{-3}$

Inside a gamma-ray burst

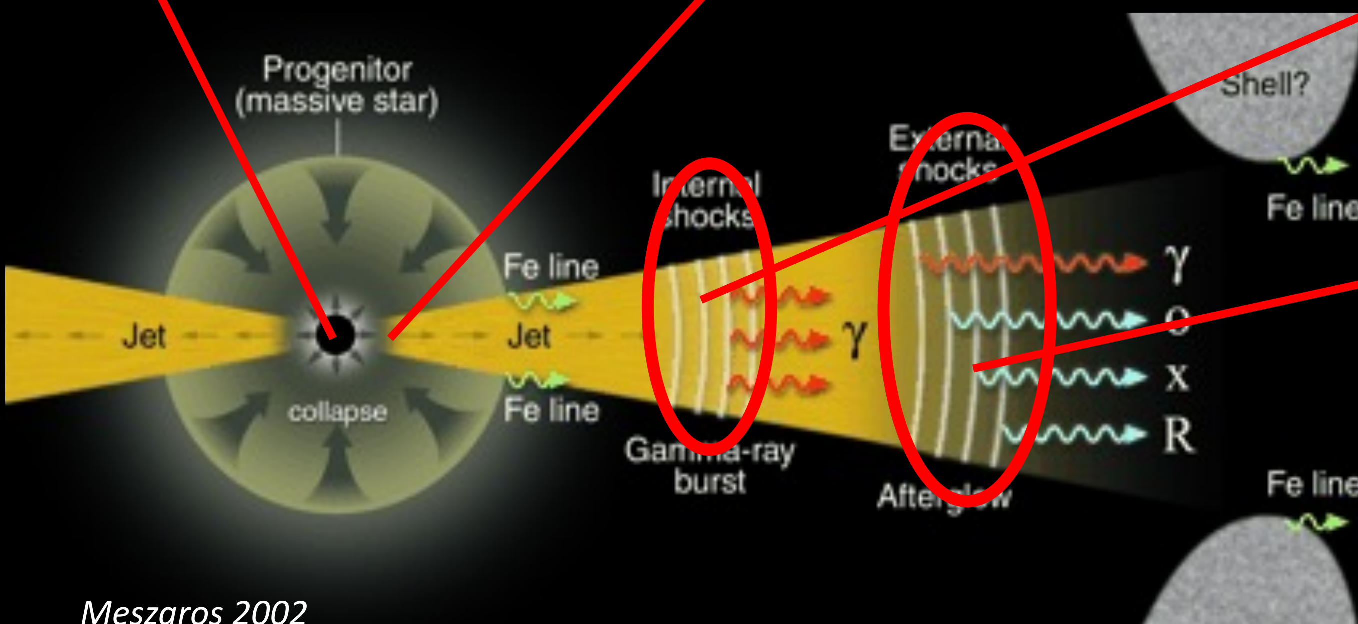
GRBs, Low-luminosity GRB

Massive stars launching relativistic outflow (jets) upon gravitational collapse

Collapse to a BH or NS

Energy deposited as some combination of radiation and magnetic energy

GRB: internal dissipation of jet energy (KE or mag -> heat)



Afterglow: more dissipation of jet energy by interaction with ambient medium (cf SNR)

Meszaros 2002

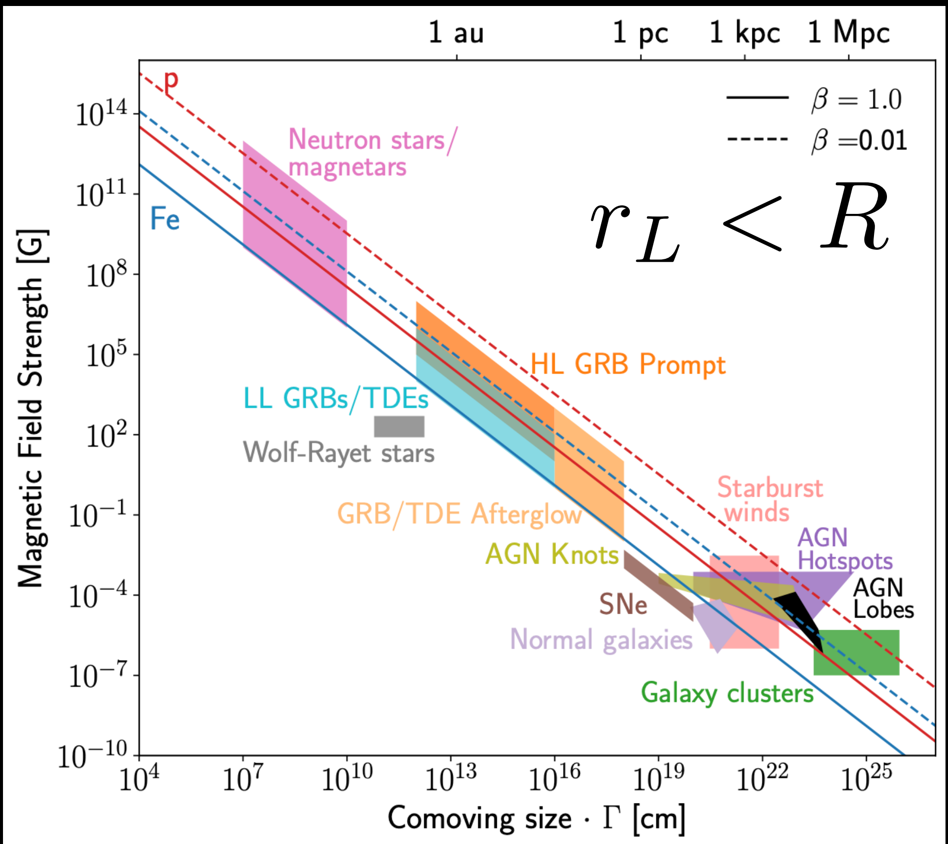
UHECR source candidate

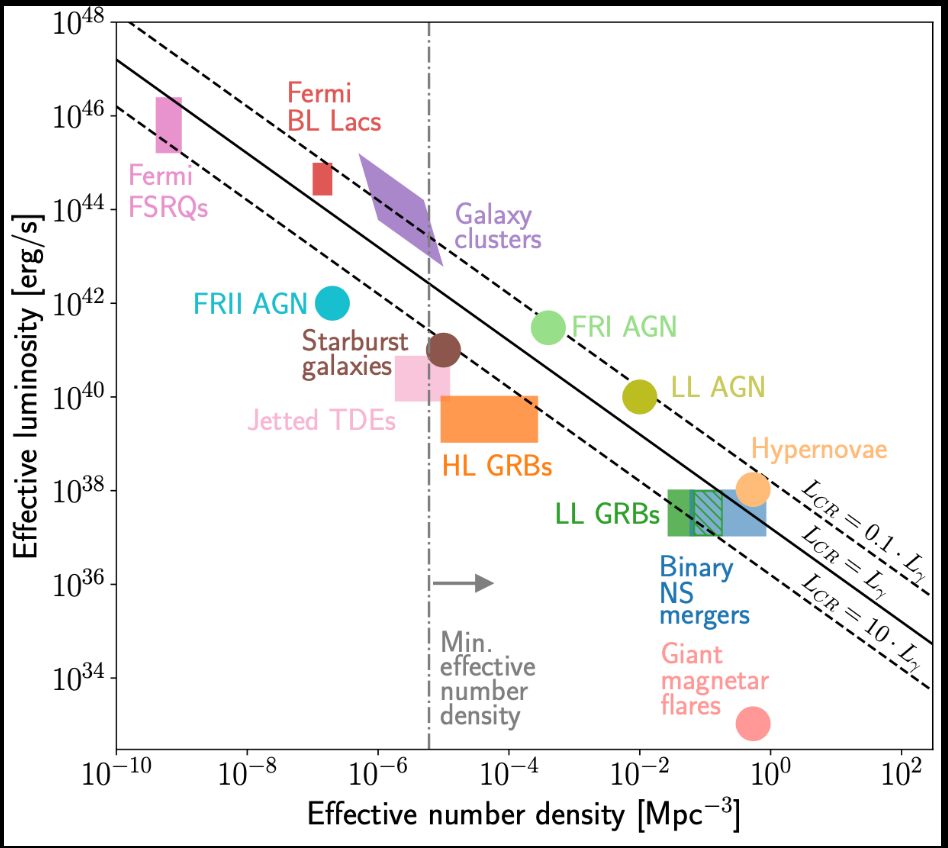
1. UHECR energy can be reached

- Acceleration by shocks and/or magnetic reconnection.
- Energy loss by photodisintegration typically most important for nuclei

2. Energetics can be explained

- Satisfied if CR luminosity > photon luminosity
- Depends on CR spectral index and minimum CR energy

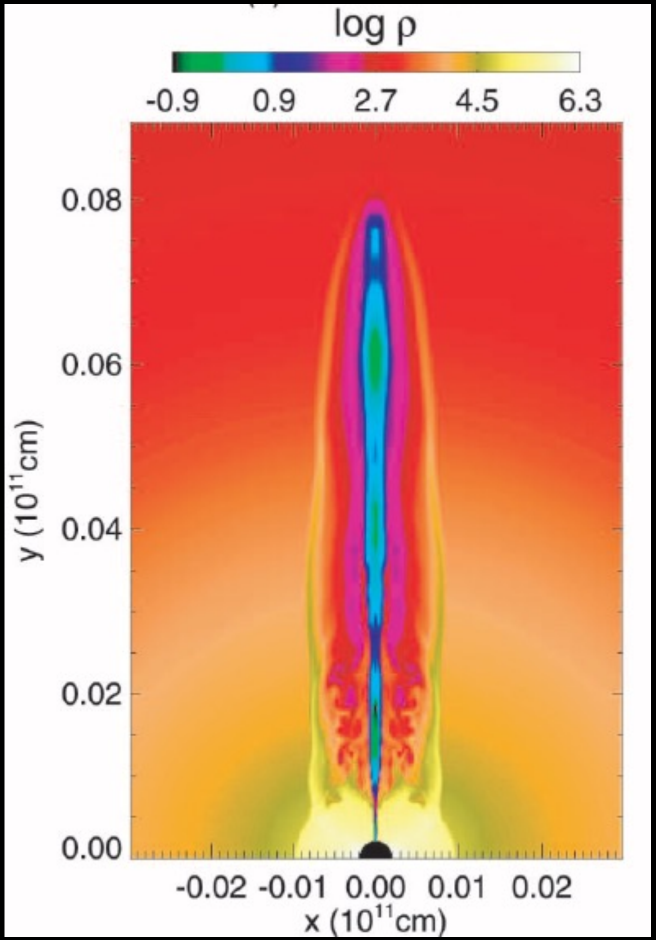




Batista et al (2019)

1. Initial loading
2. In-situ nucleosynthesis
3. (Entrainment – if time)

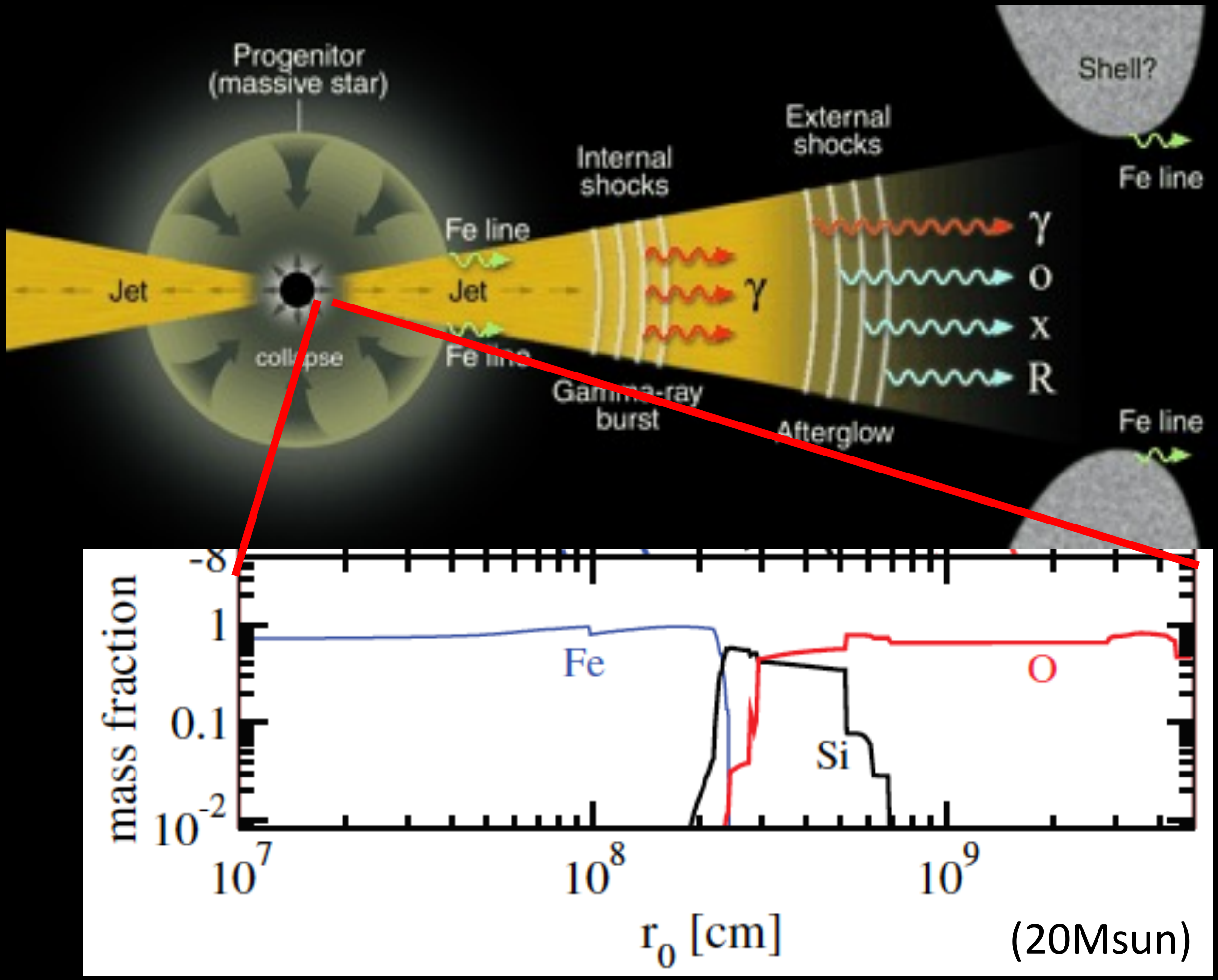
COMPOSITION OF JETS



1. Initial loading

External composition

- Radial dependence: stellar nuclei distribution
- Time dependence: supernova shock, explosive nucleosynthesis



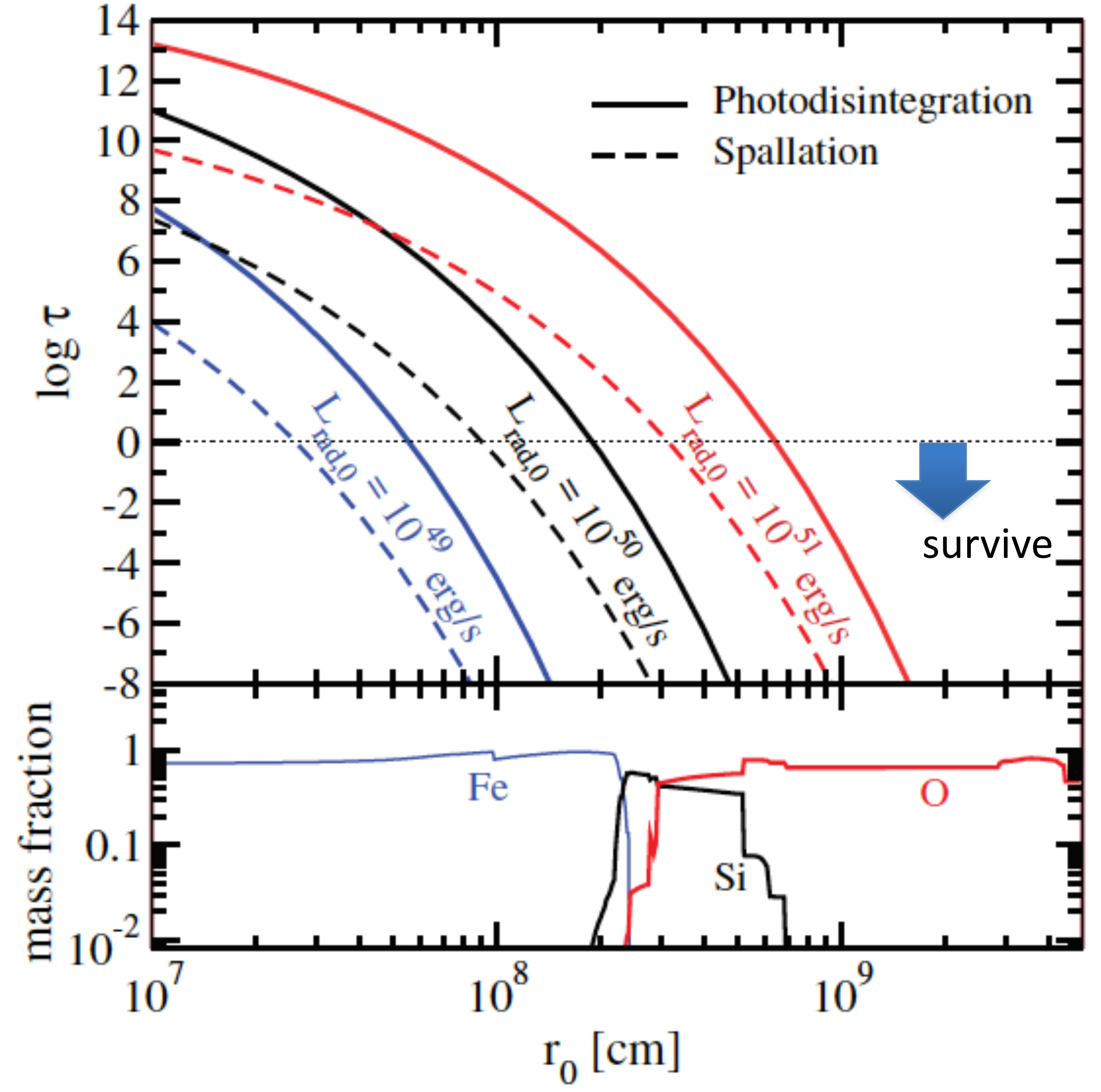
Can initial nuclei survive?

Nuclei survival
Optical depths of destructive processes must be small

Photodisintegration
Thermal temperatures T_0
Spallation
Target ion/nucleons thermalized to T_0

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

→ **Low-luminosity better for survival. Another scenario is magnetic-dominated outflows.**



Horiuchi et al (2012)

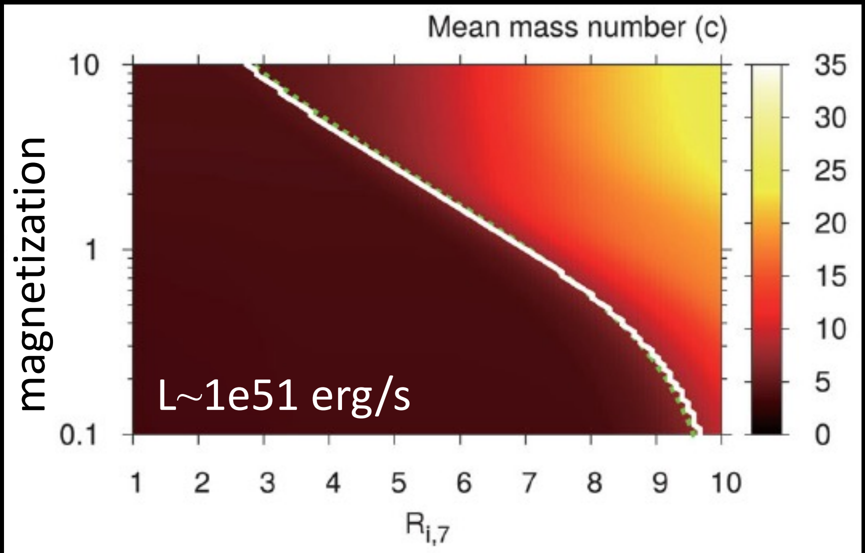
Simulations

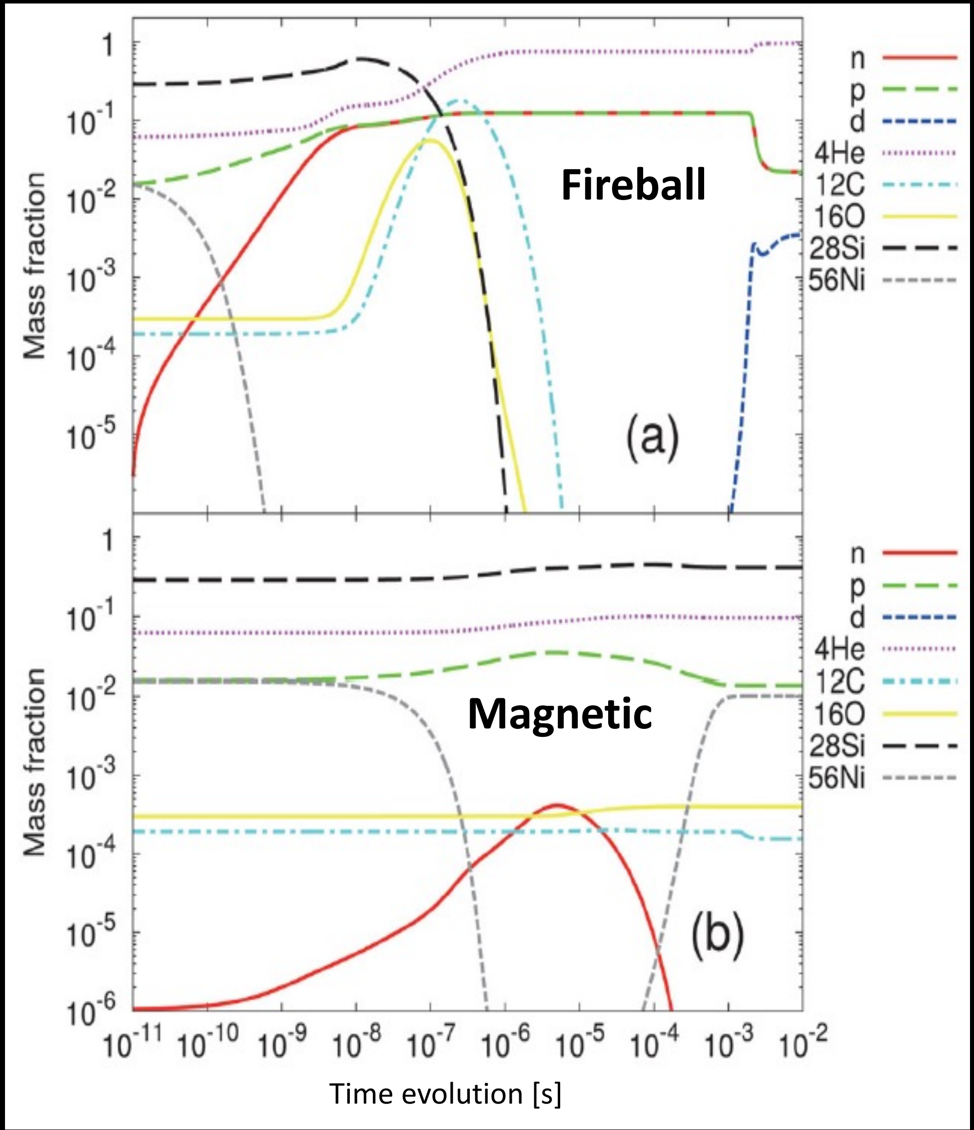
Initial loading simulations

2D relativistic MHD simulation of jet induced collapse and jet acceleration

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

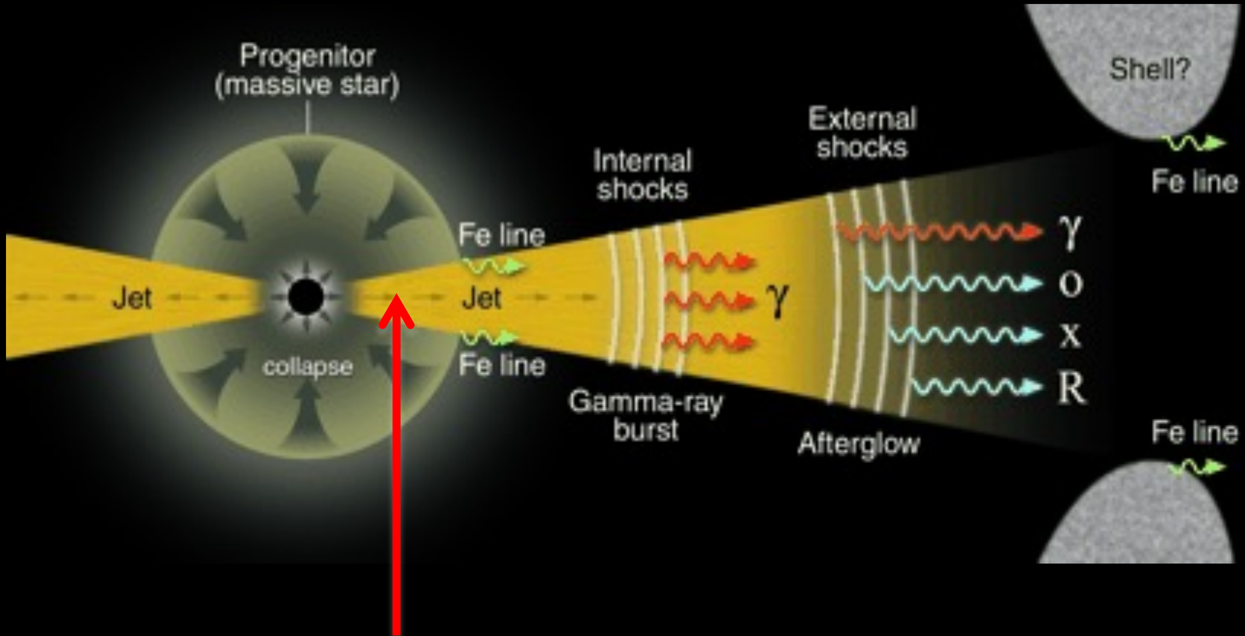
→ **Magnetic models (and low-L_{rad}) better for nuclei composition**





Shibata & Tominaga (2015)

2. In-situ jet nucleosynthesis



Nucleosynthesis inside the jet

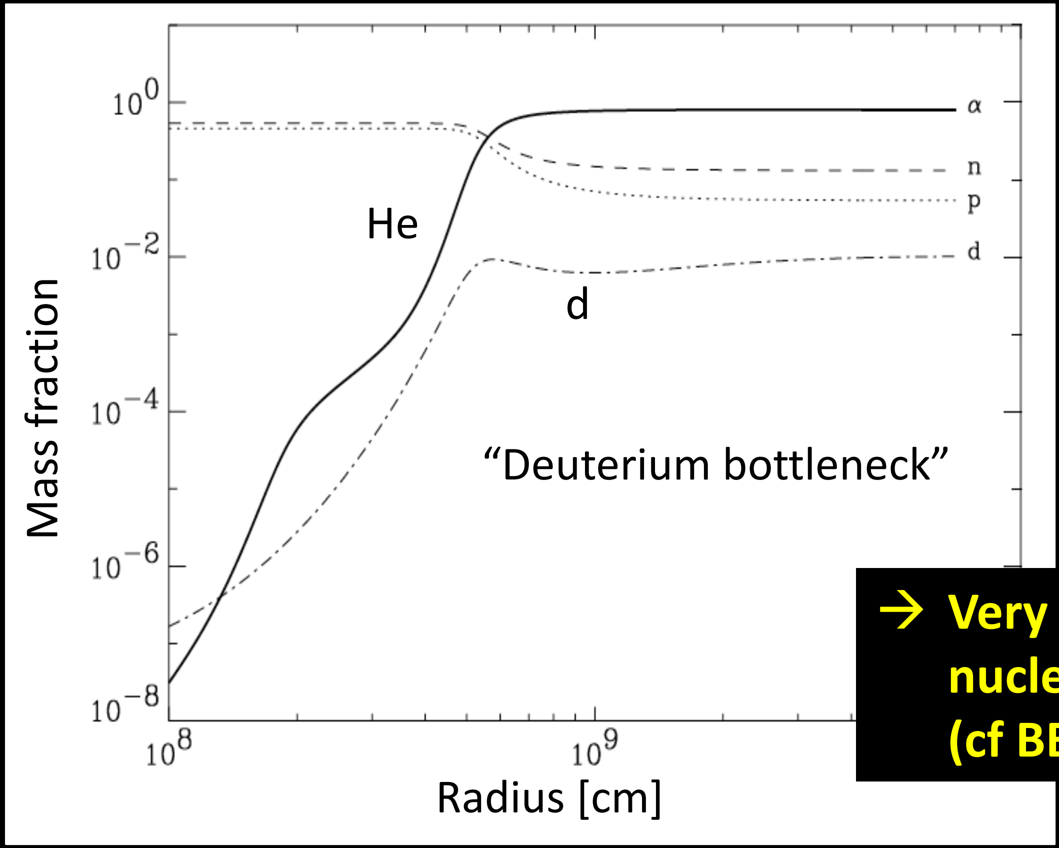
- Protected
- Critically depends on thermodynamic conditions

Personally, a very interesting possibility

Fireball scenario

Composition of GRB fireball:

- Initial radiation temperatures of a few MeV
  → *nuclei are dissociated*
- Large entropy ($n_\gamma/n_p \sim 10^5$)
- Rapid expansion time scales (~0.1 ms)
- n/p fraction probably close to equal (but uncertain)



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

→ Very few heavy nuclei are made (cf BBN)

Alternative scenarios

Importance of entropy and expansion timescale
Lower entropy and larger timescale are conducive to nucleosynthesis
→ Deuterium bottleneck can be prevented

1. Magnetic scenario
L_{rad} can be low if the GRB is powered magnetically, e.g., for rapidly rotating neutron stars:

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

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, or with large baryon loading by default

Proto-magnetar

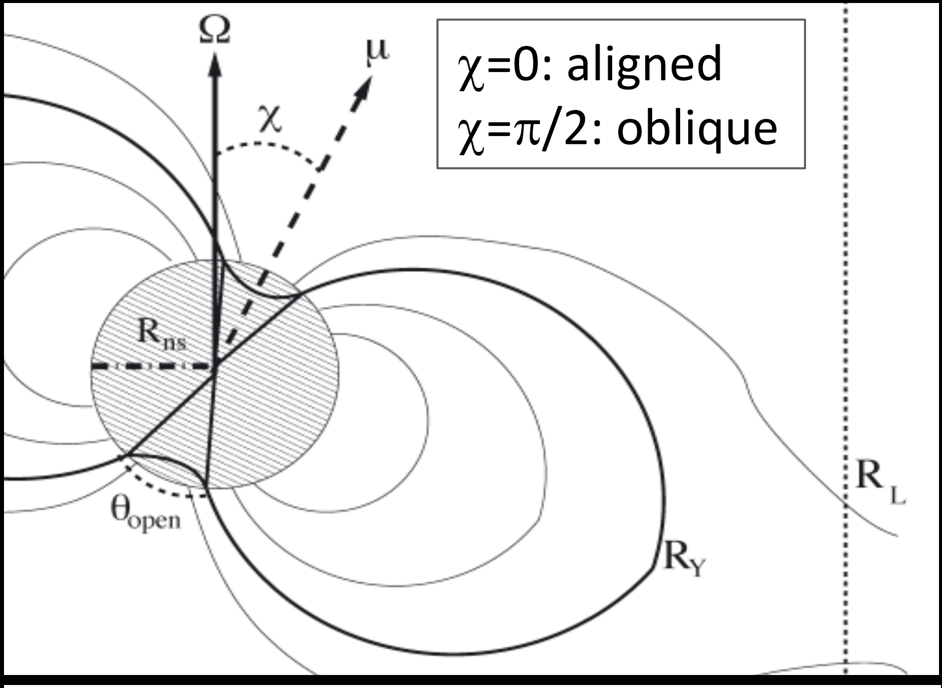
Proto-magnetar model:
The birth of magnetars. Consider a two-component model:

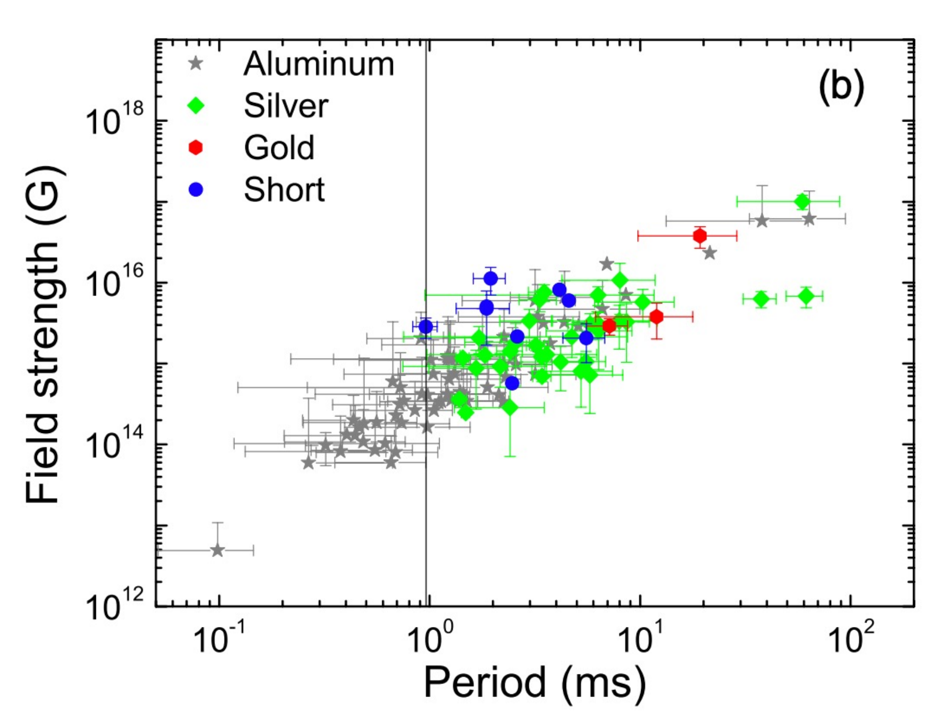
1. Neutrino-driven wind
2. magnetic outflow

The ratio sets the magnetization of the outflow

$$\sigma_0(B,P) = \frac{\dot{E}(B,P)}{\dot{M}c^2}$$

Interpretations of X-ray light curves of GRBs, suggests certain ranges of (B,P) are likely to be causing GRBs





Shunsaku Horiuchi

Lu & Zhang (2014)

Analytic study: nucleosynthesis

Freezeout yields

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

Roberts et al (2010)

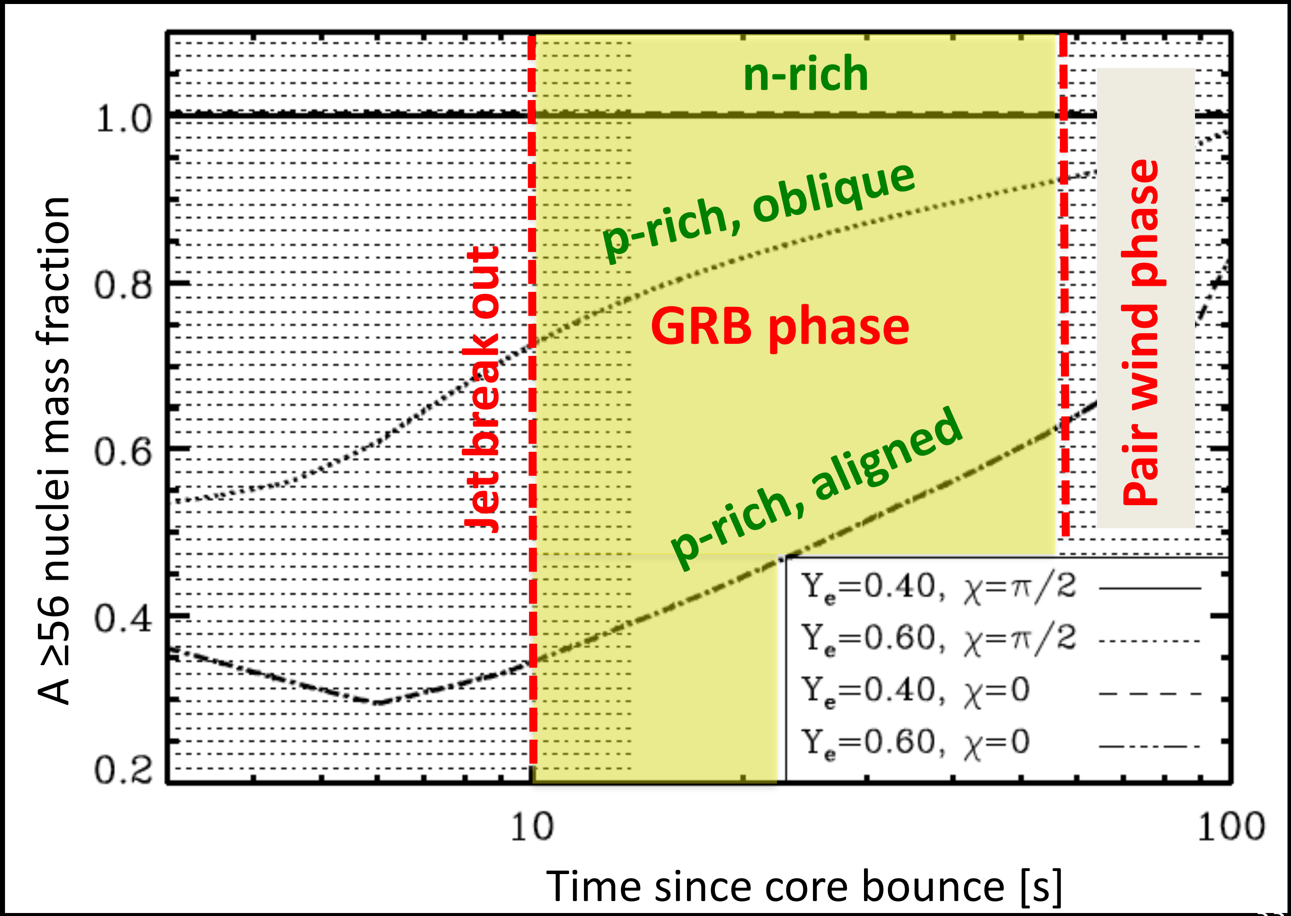
→ Freezeout composition can be heavy-dominated during the GRB phase

Especially for:

- Initially *n*-rich matter
- Oblique rotators (receive less ν-heating, thus has lower entropies)

(B=5e15G,P=2ms)

Metzger, Giannios, Horiuchi (2011)



Analytic study: acceleration

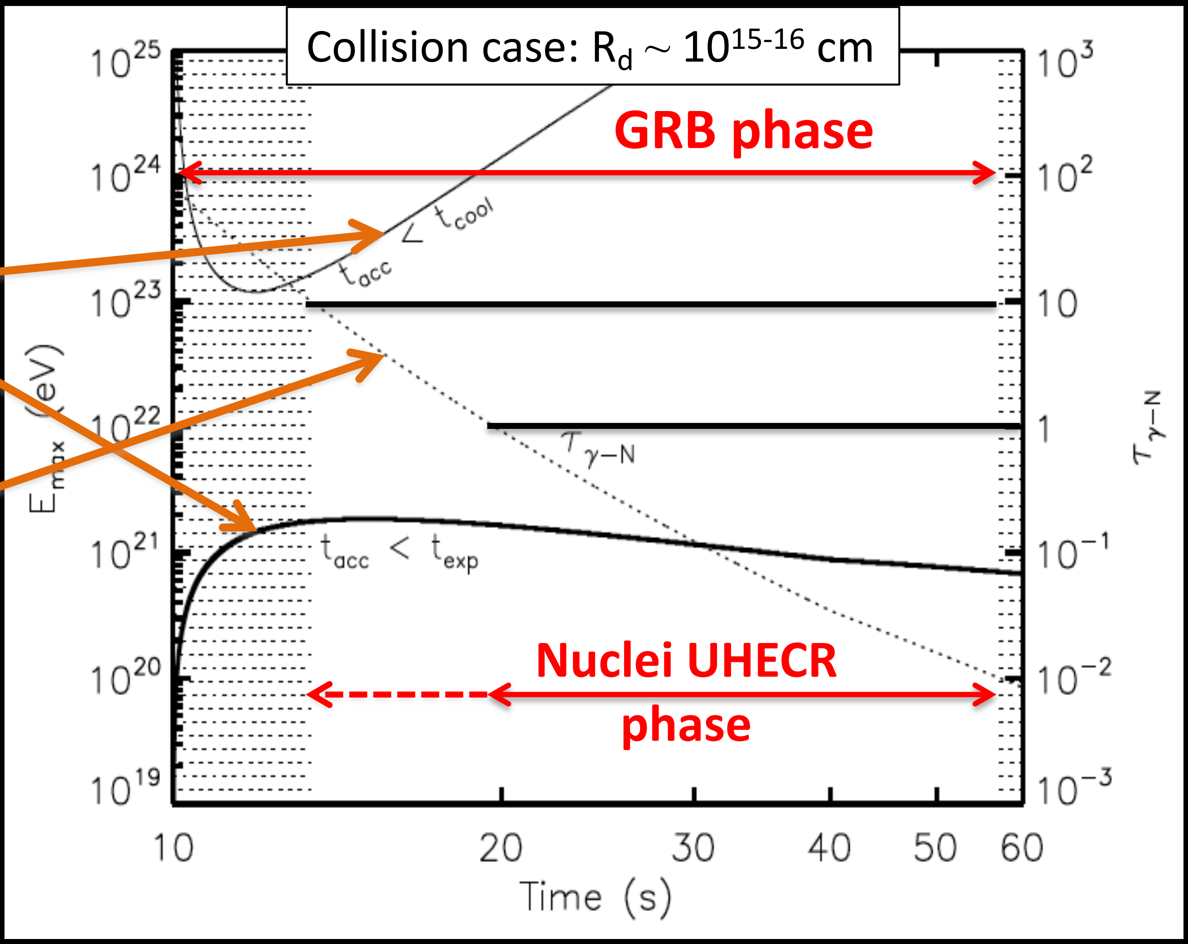
(B=5e15G,P=2ms)

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

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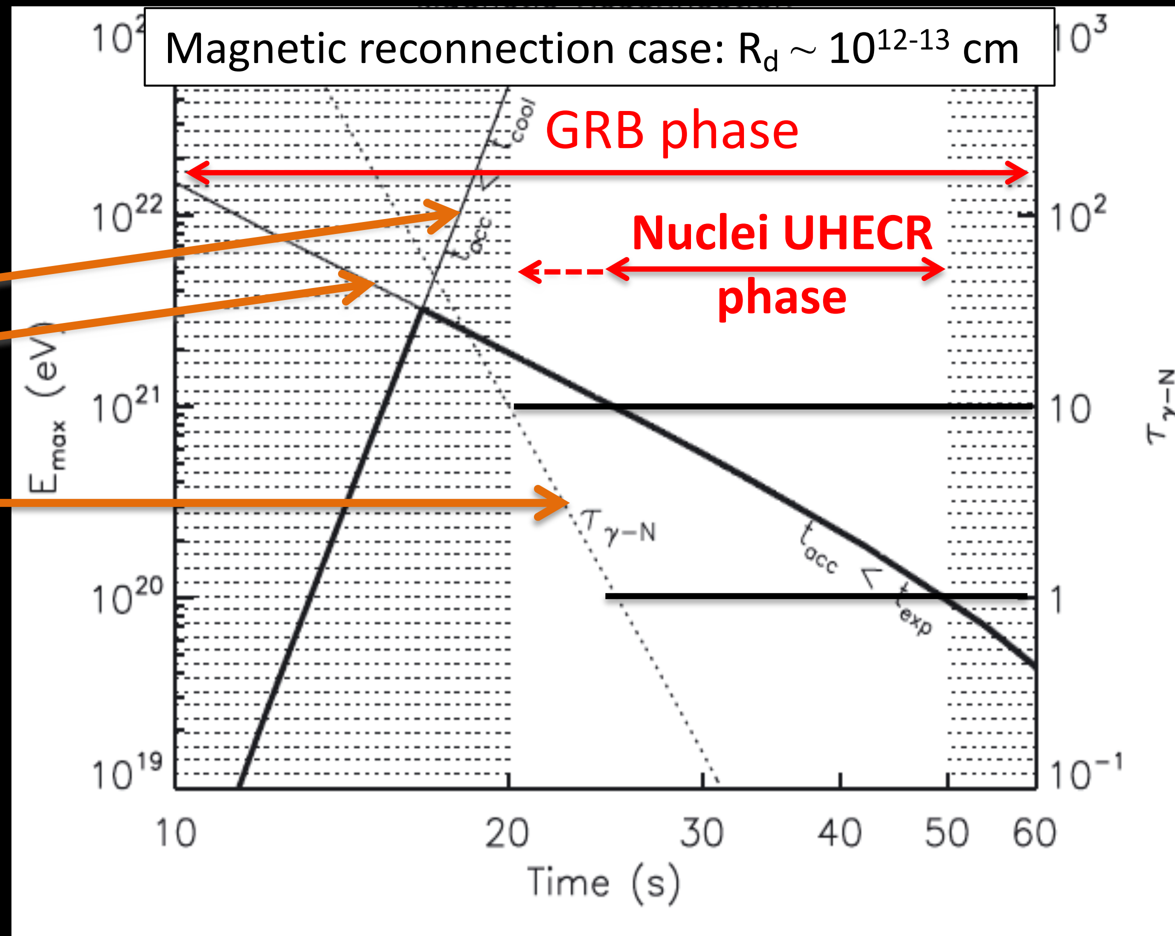


Metzger, Giannios, Horiuchi (2011)

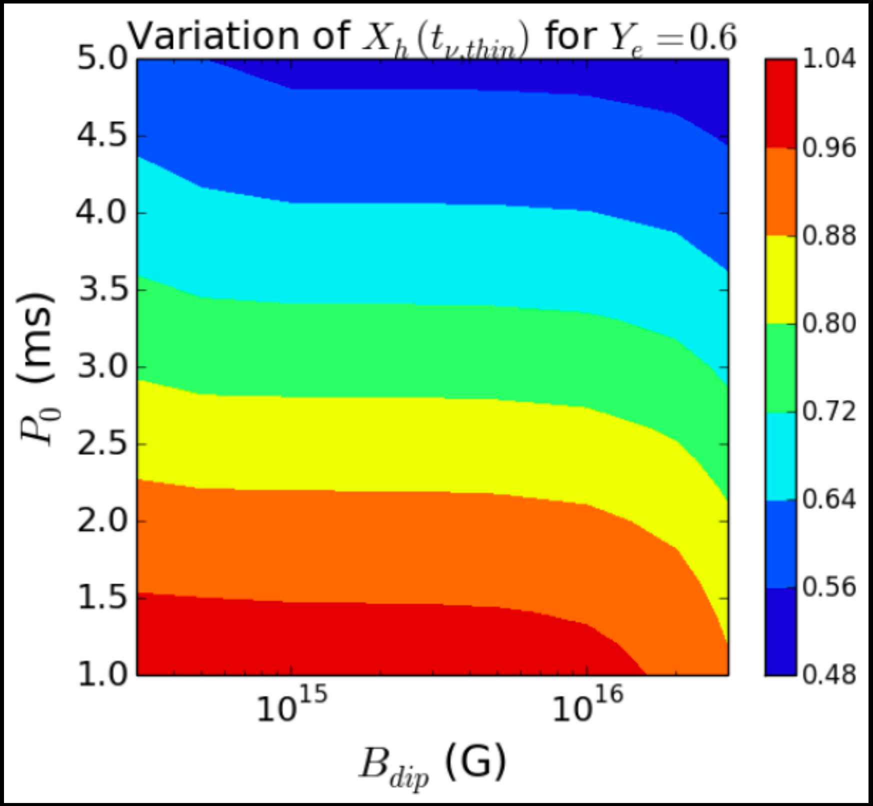
→ There remains a window for UHECR nuclei generation

Dependence on model parameters

Vary magnetic field (B) and rotation period (P): $\sigma_0(B,P) = \frac{\dot{E}(B,P)}{\dot{M}c^2}$

Nucleosynthesis

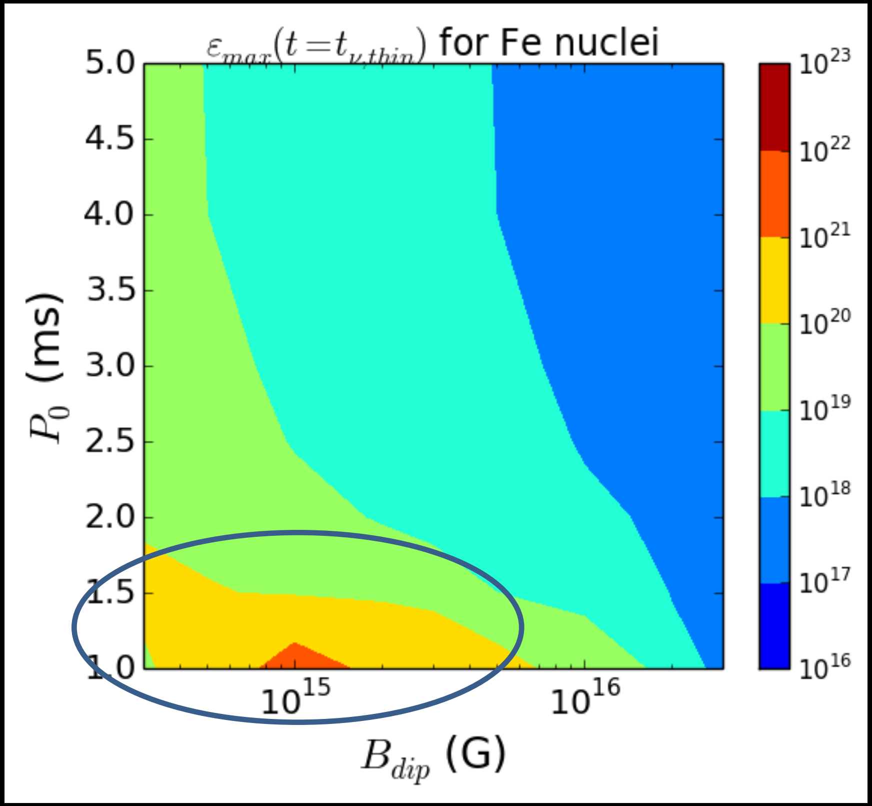
Better for faster rotator, which impacts outflow size & entropy



Emax

Assuming Fe composition:

At breakout At end of GRB phase



Bhattacharya et al (2021)

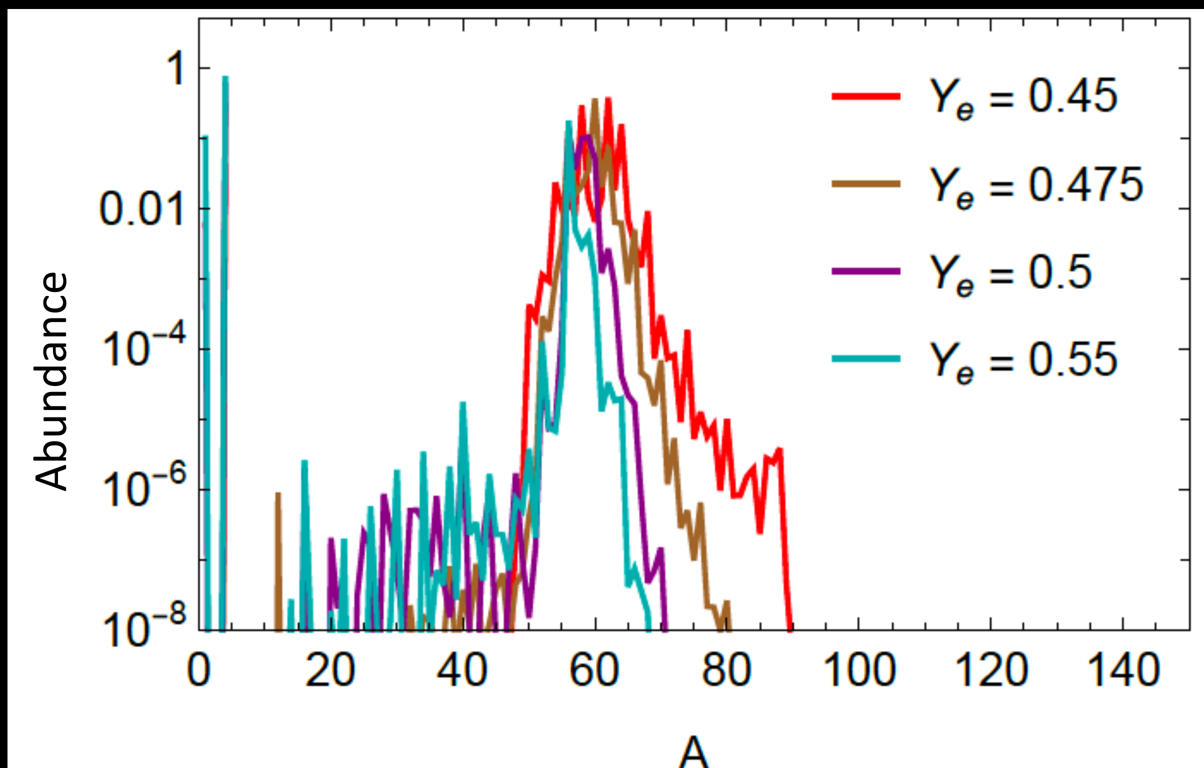
Numerical treatment: nucleosynthesis

(B,P) → Semi-analytic neutrino-driven wind model → (entropy, timescale) → Nucleo-synthesis → (abundances)

Electron fraction ↗ Nucleo-synthesis

Lippuner et al (2017)

(B=4e15G,P=1.5ms)



(NB: when maximum particle acceleration takes place) *Ekanger et al (2022)*

Epochs of the jet

Consider four epochs (or locations) along the jet

1. Initial launch
2. Breakout from progenitor (assumed Wolf-Rayet)
3. Beginning of when photodisintegration optical depth < 1
4. Last moment when maximum CR energy is > 10^{20} eV

} Epoch which can have nuclei UHECR

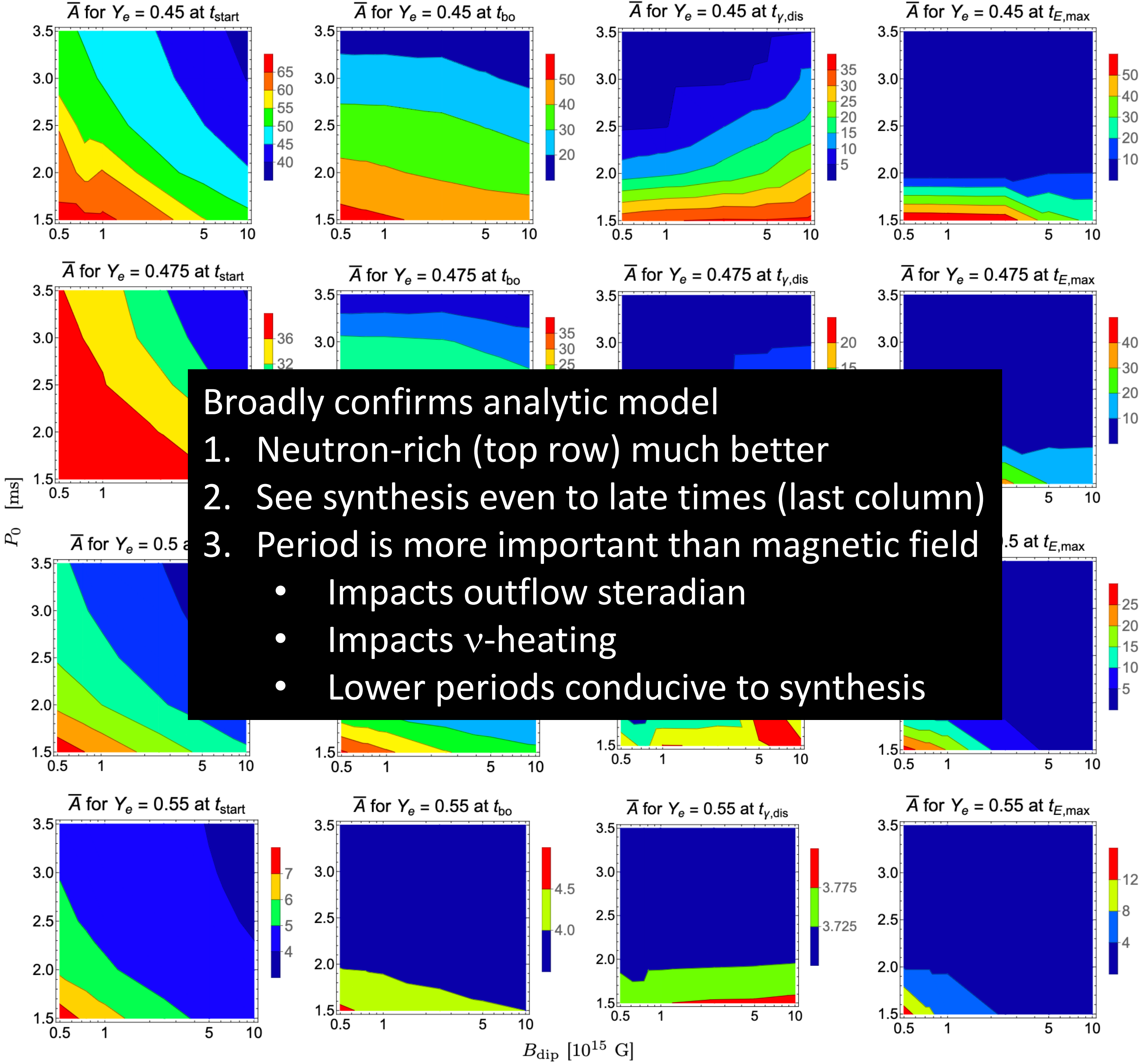
Mean

Ye = 0.

Ye = 0

Ye = 0

Ye = 0



Broadly confirms analytic model

1. Neutron-rich (top row) much better
2. See synthesis even to late times (last column)
3. Period is more important than magnetic field
   - Impacts outflow steradian
   - Impacts ν-heating
   - Lower periods conducive to synthesis

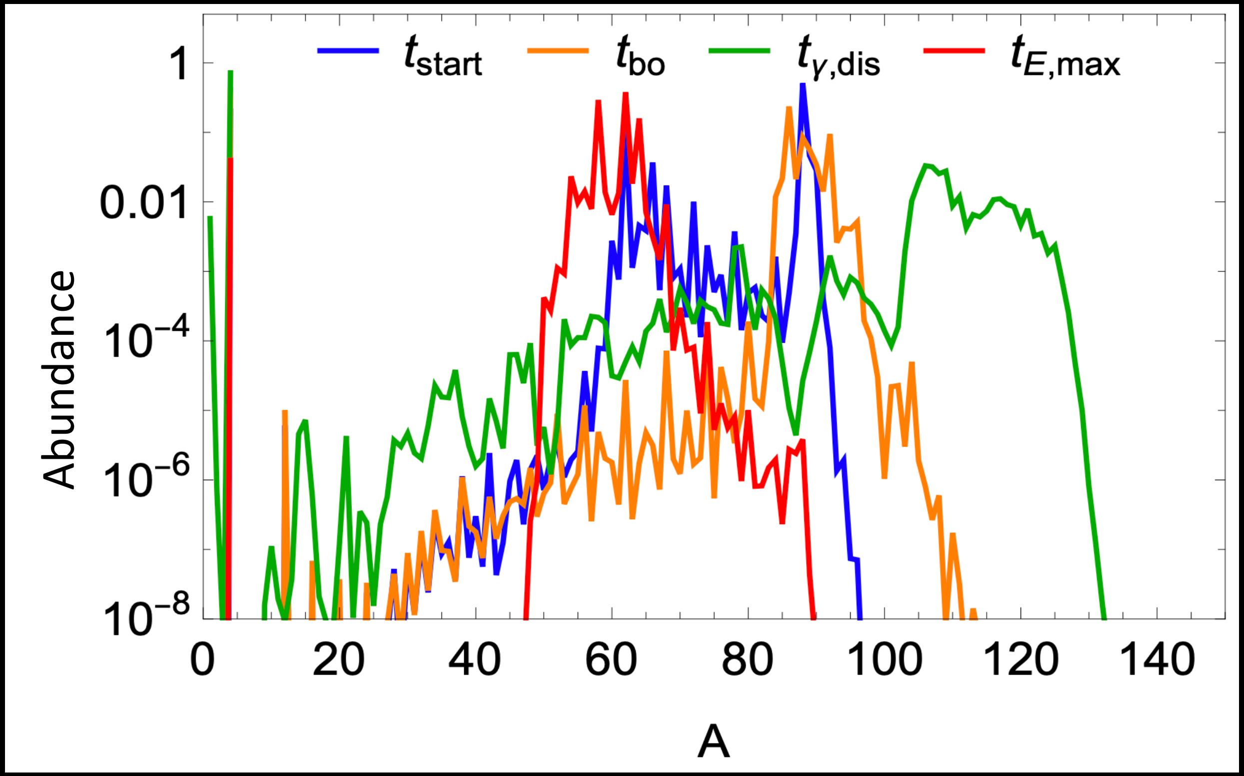
Gaining detailed picture

Consider four epochs (or locations) along the jet

1. Initial launch
2. Breakout from progenitor (assumed Wolf-Rayet)
3. Beginning of when photodisintegration optical depth < 1
4. Last moment when maximum CR energy is > 10^{20} eV

Epoch which can have nuclei UHECR (epochs 3 and 4)

(B=4e15G,P=1.5ms)



Ekanger et al (2022)

Ongoing studies

UHECR from population
- (B,P) distributions, others

Detailed nuclei survival
- Consideration of jet propagation in stars and collimation effects

Estimate time-integrated UHECR
- Nucleosynthesis between our 4 time epochs
- Changes in the intermediate photo-disintegration regime
- Mass-weighted integral

Detailed synthesis
- Dependence on model parameters

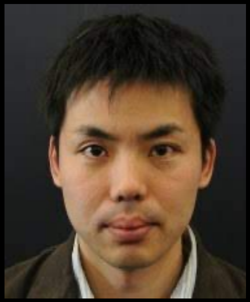
ν & γ-ray signatures of accelerated nuclei

UHECR propagation

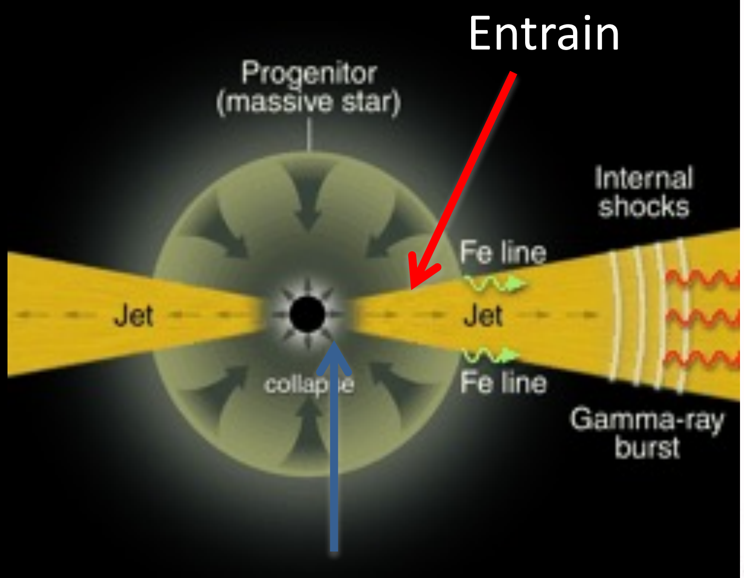

Nick Ekanger

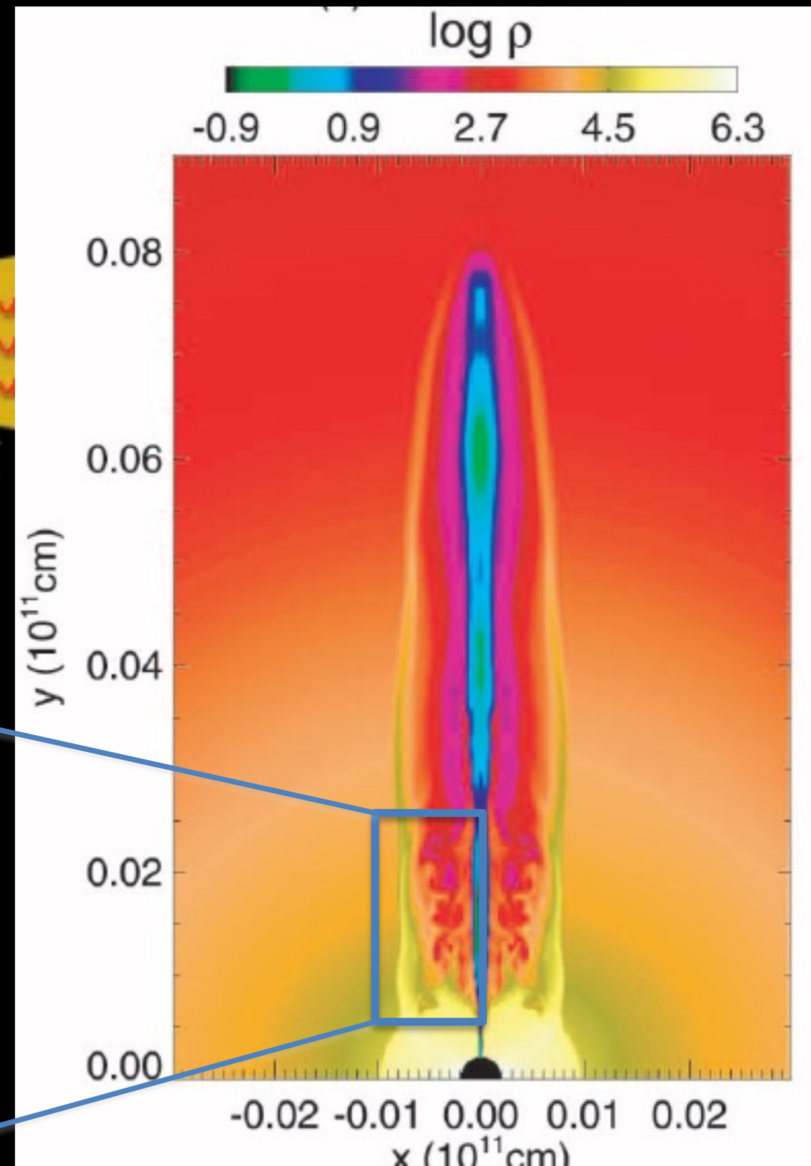

Jose Carpi


Mukul Bhattacharya


Kohta Murase

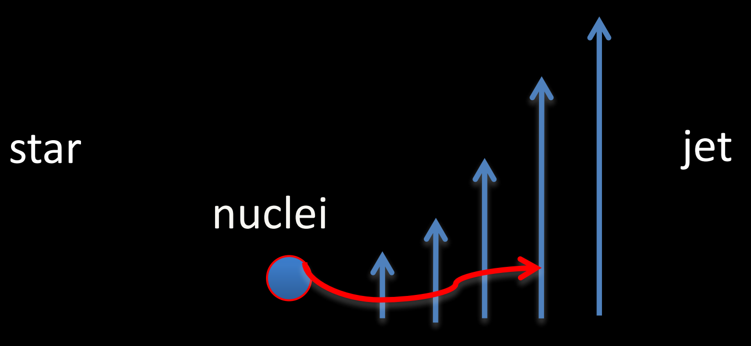
3. Entrainment





Zhang et al. (2003)

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



Can it safely do this?

Survival in entrainment

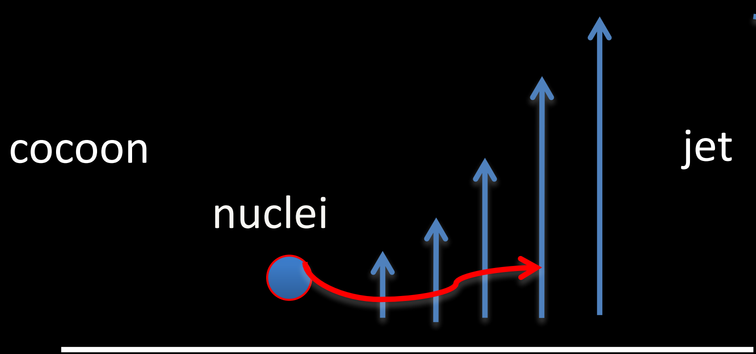
Cocoon

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

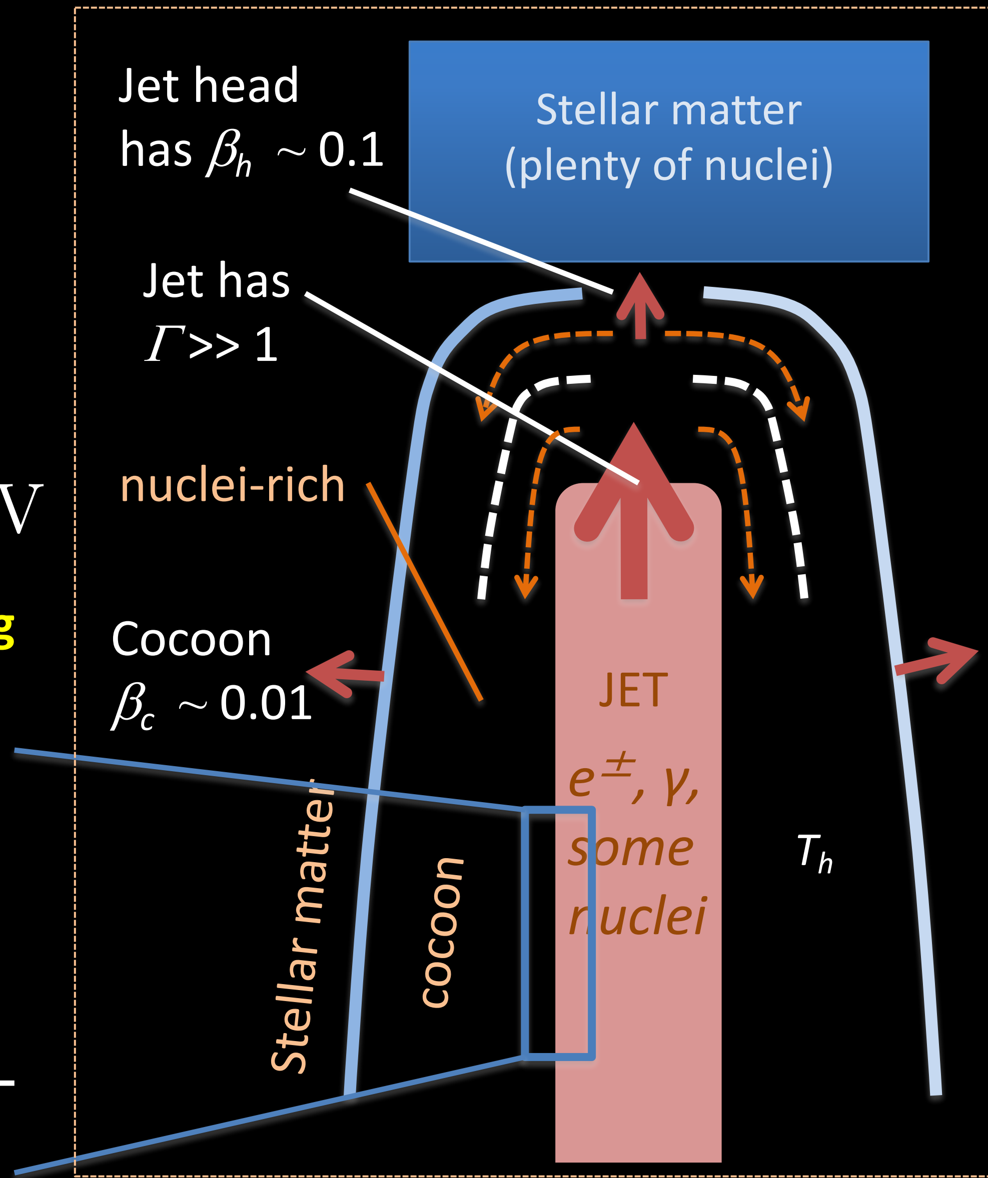
$$\beta_c^{(1)} \sim 0.01 L_{\mathrm{ke},50}^{3/8} r_9^{1/2}$$

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

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



Can it safely do this?



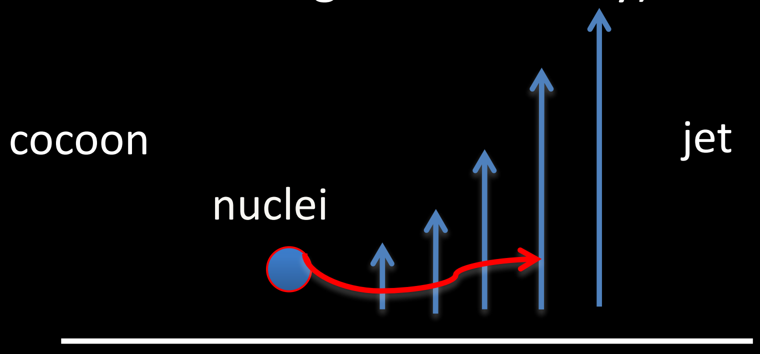
Survival in entrainment

Survival

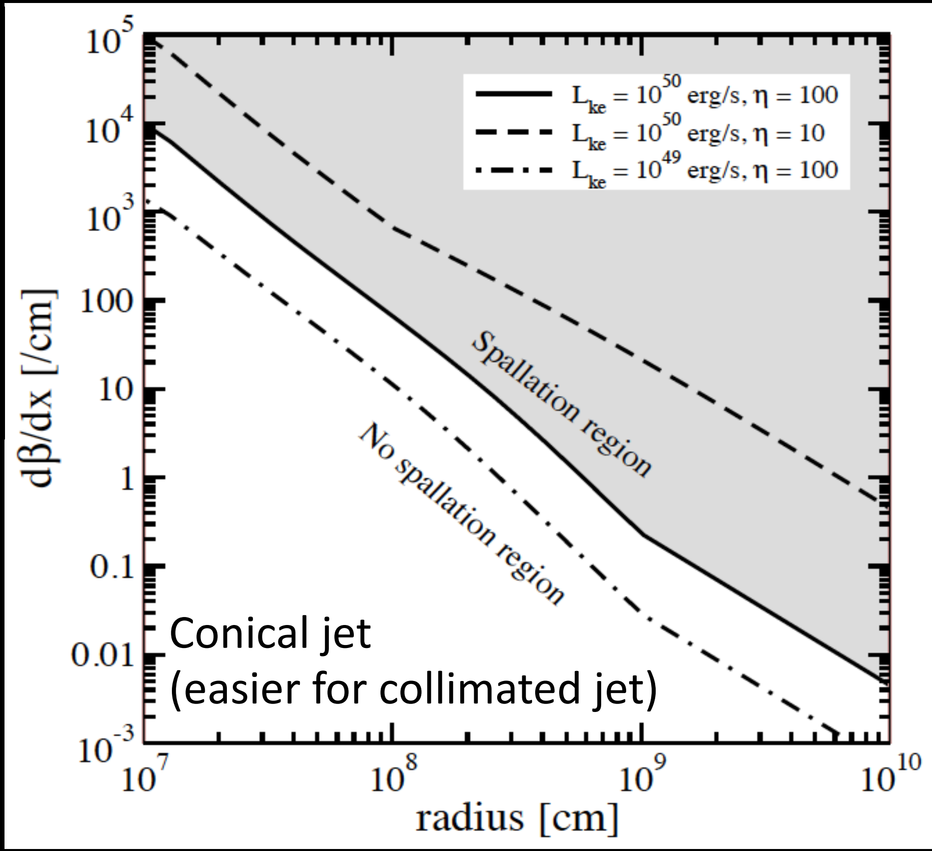
Demand the nuclei velocity is always below the spallation threshold
→ requires the nuclei to be thermalized FASTER than it takes to move up the velocity gradient and its speed becomes too fast

→ 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)

Summary table

→ In Fireball GRB, only entrainment remains (but likely is difficult)
→ In magnetic or low-luminosity GRB, multiple options exist

	Fireball GRB	Magnetic GRB	Low-luminosity GRB
Survives: initial loading?	N	**Y**	**Y**
Source: jet nucleosynthesis	N	**Y**	Maybe
Survives: entrainment?	gradient	gradient	gradient
Survives: *n*-collisions?	**Y**	**Y**	**Y**

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

Concluding remarks

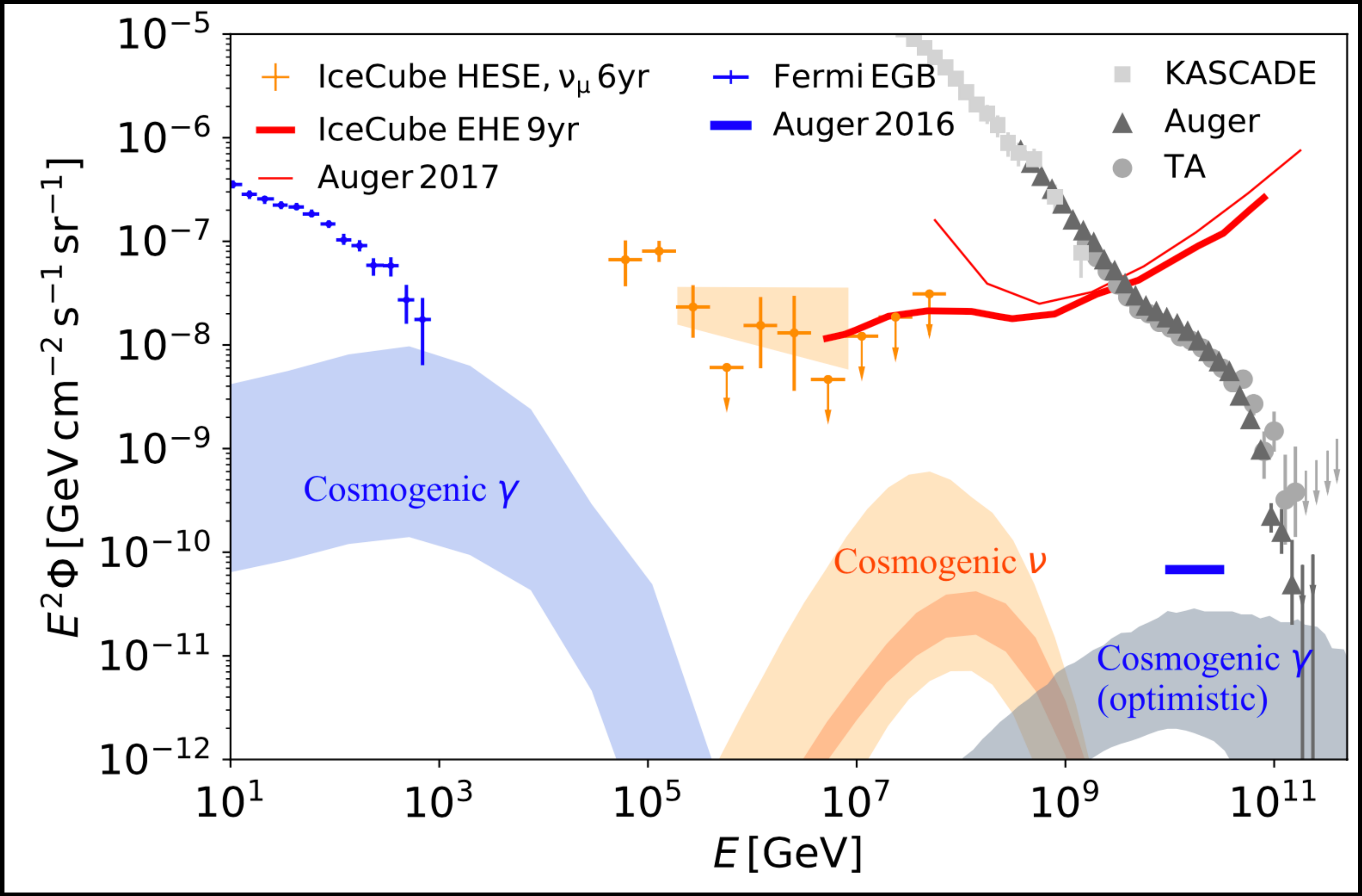
- **UHECR origins remain a mystery**
- **Supernova/related explosions are stores of heavy nuclei**
  - Through stellar nucleosynthesis, explosive nucleosynthesis, and in-situ jet nucleosynthesis
- **Models for UHECR nuclei**
  - Magnetar models for GRBs, low-luminosity GRBs, and baryon-rich jets are especially conducive to heavy nuclei UHECR
- **Future works**
  - Ongoing studies of the impacts of jet propagation inside progenitors, regime of partial photo-disintegration, UHECR propagation and connections to multi-messenger astronomy
- **Aiming to create self-consistent composition predictions!**

Thank you for your attention!

BACKUP SLIDES

Multi-messenger considerations

At a minimum, UHECR propagation creates multi-messenger signatures (additional signals possible from sources themselves)



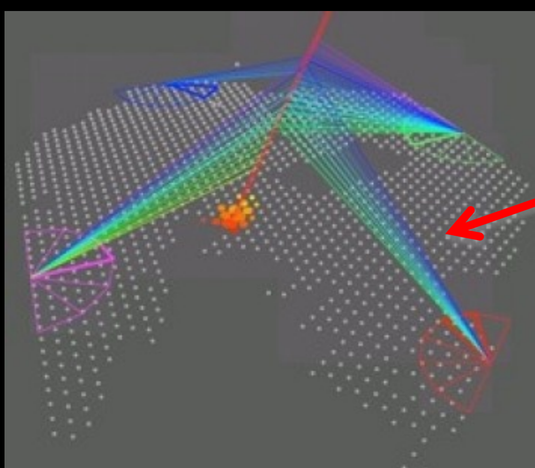
Batista et al (2018)

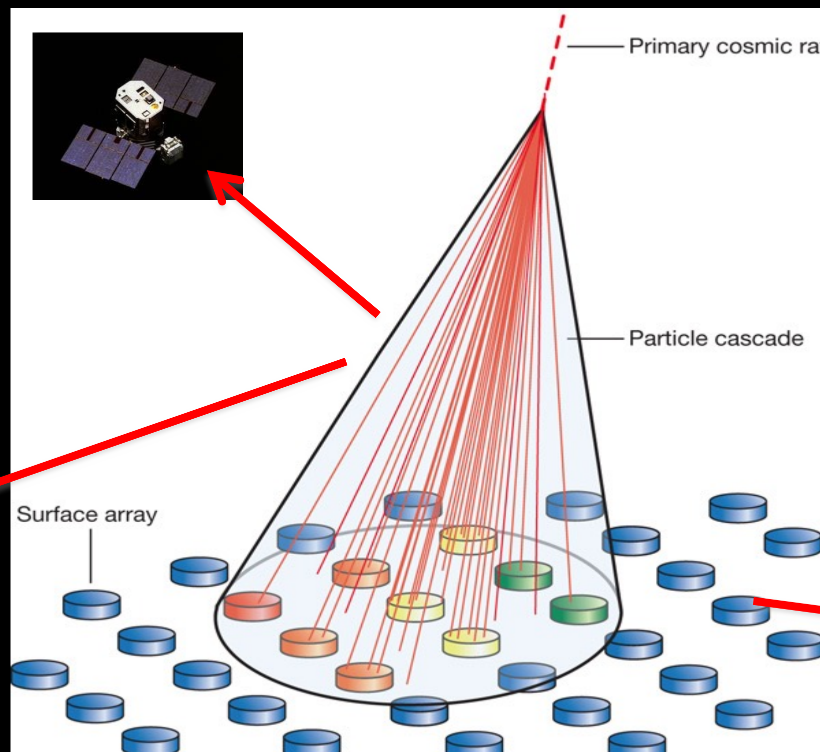
Various observatories

Hybrids:
- Pierre Auger Observatory ('04 ~)
- Telescope Array ('09 ~)

Fluorescence from space:
- EUSO balloon ('13)
- JEM-EUSO (proposed)

Fluorescence from ground:
- Fly's eye
- HiRes





Surface array of particle detectors, eg plastic scintillator, Cerenkov detector
- AGASA
- Yakutsk
- …many more

➔ **Three observables:**

Energy, arrival direction, mass composition

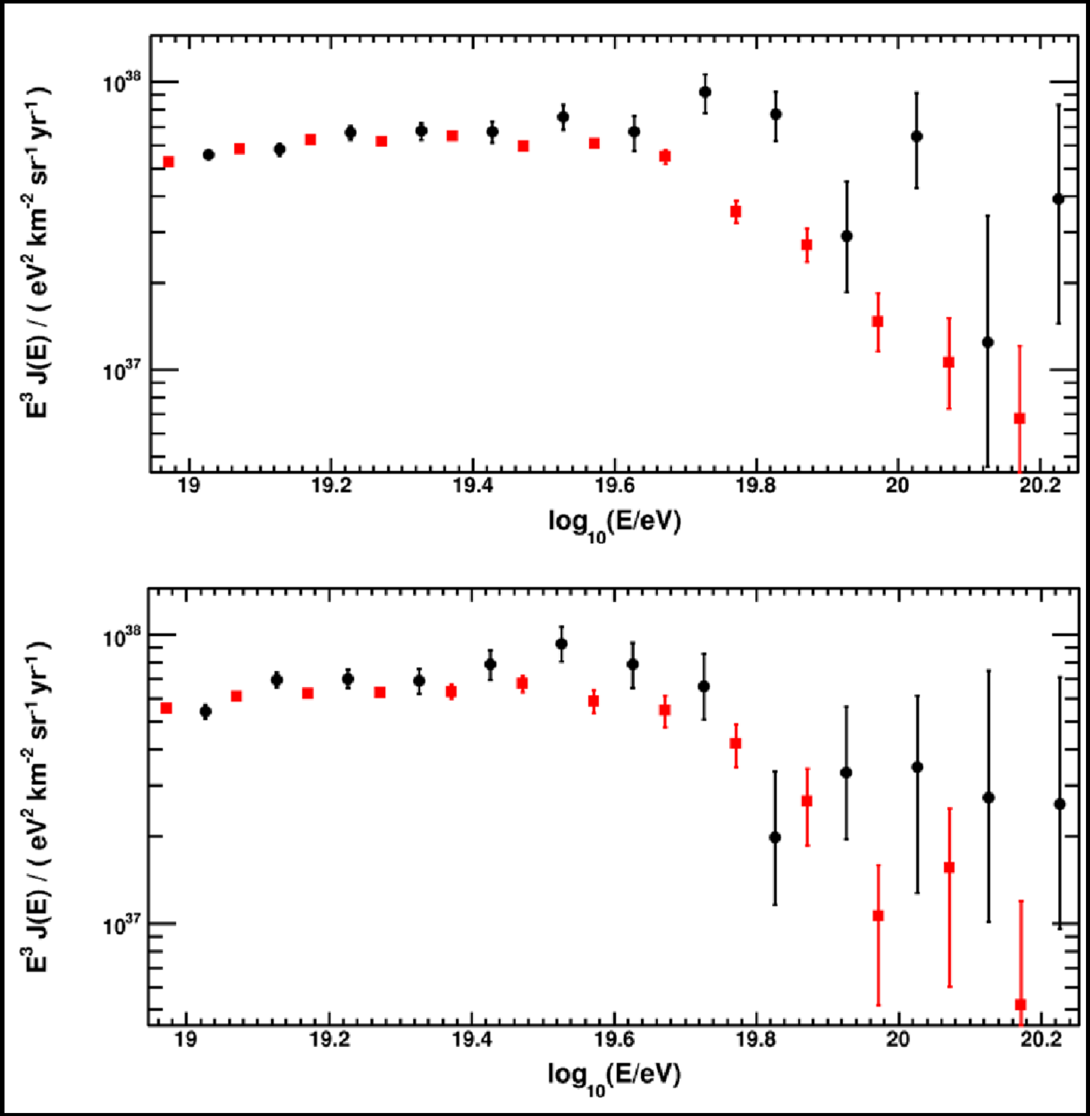
Cutoff in more detail

Allowing for systematics brings datasets in agreement, but only below ~1e19.7 eV

Systematics only at highest energies or source physics?

Eg focusing only on overlapping region of the sky shows better agreement (at cost of statistics).

- TA shows declination dependence.
- TA coverage includes eg M82, Mrk 180, 421.



PAO (2018)

Example: proto-magnetar scenario

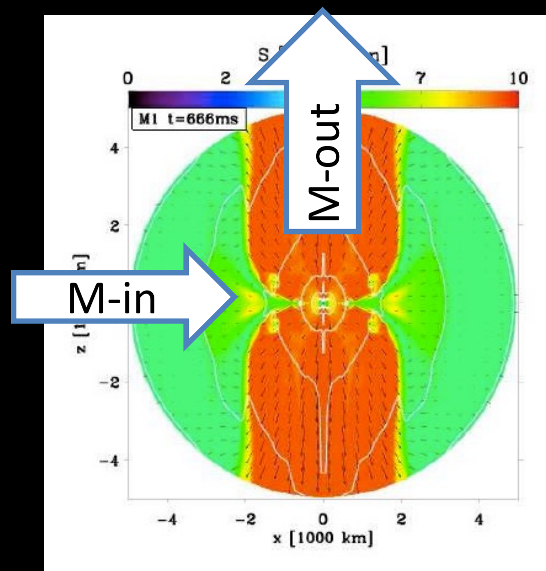
Need a neutron star remnant:

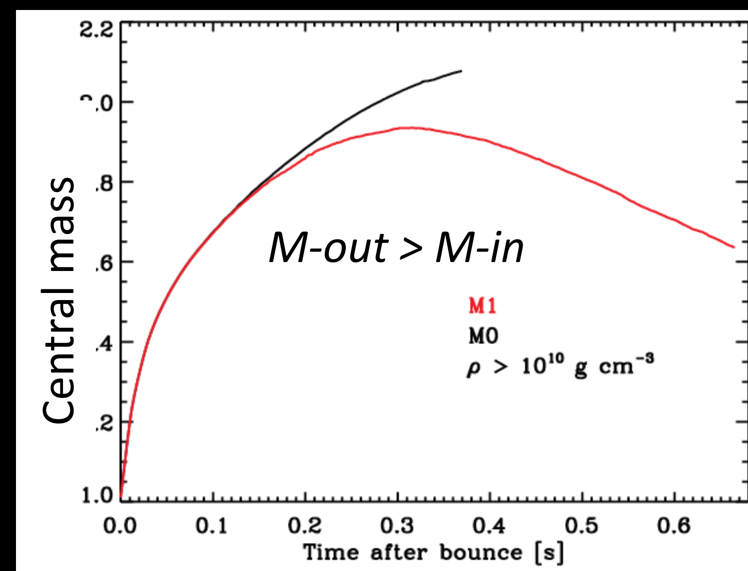
THE PROTO–NEUTRON STAR PHASE OF THE COLLAPSAR MODEL AND THE ROUTE TO LONG-SOFT GAMMA-RAY BURSTS AND HYPERNOVAE

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

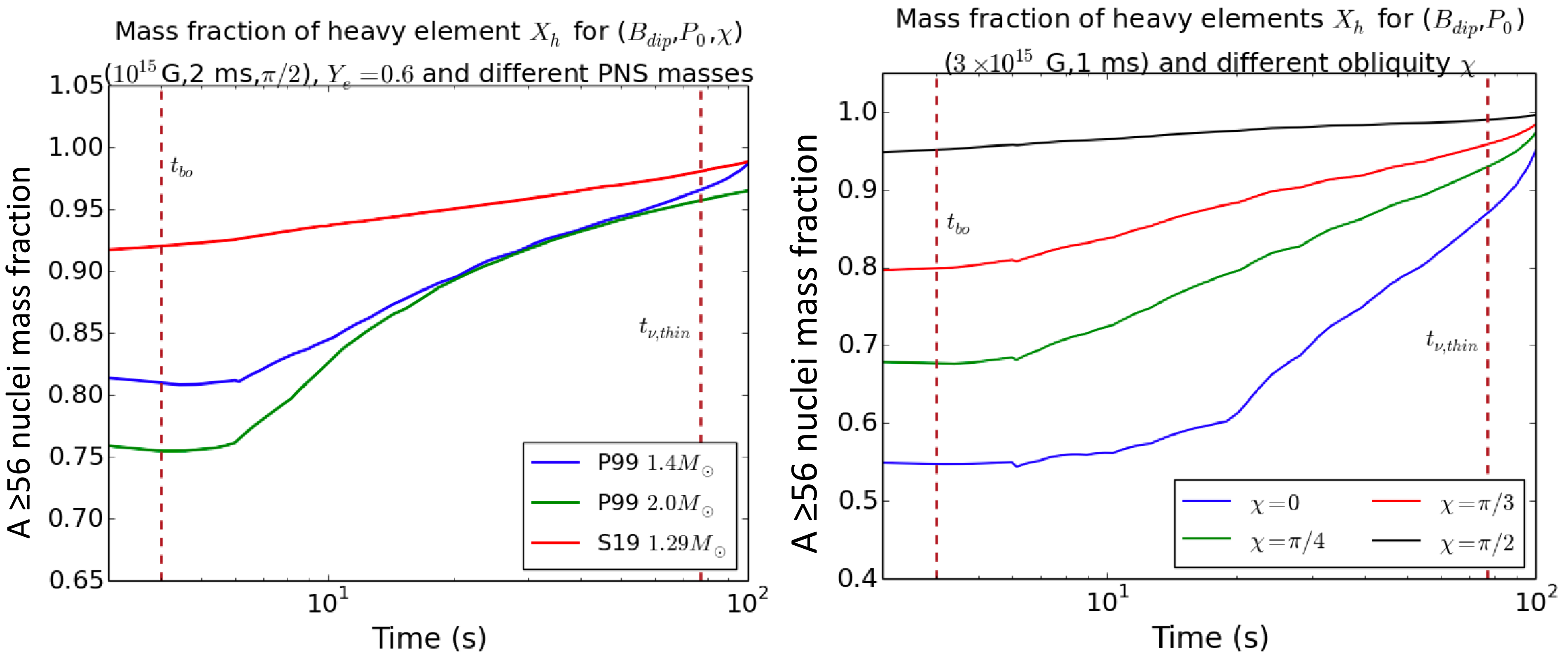
Having the right angular momentum distribution is key:

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





Other model dependences

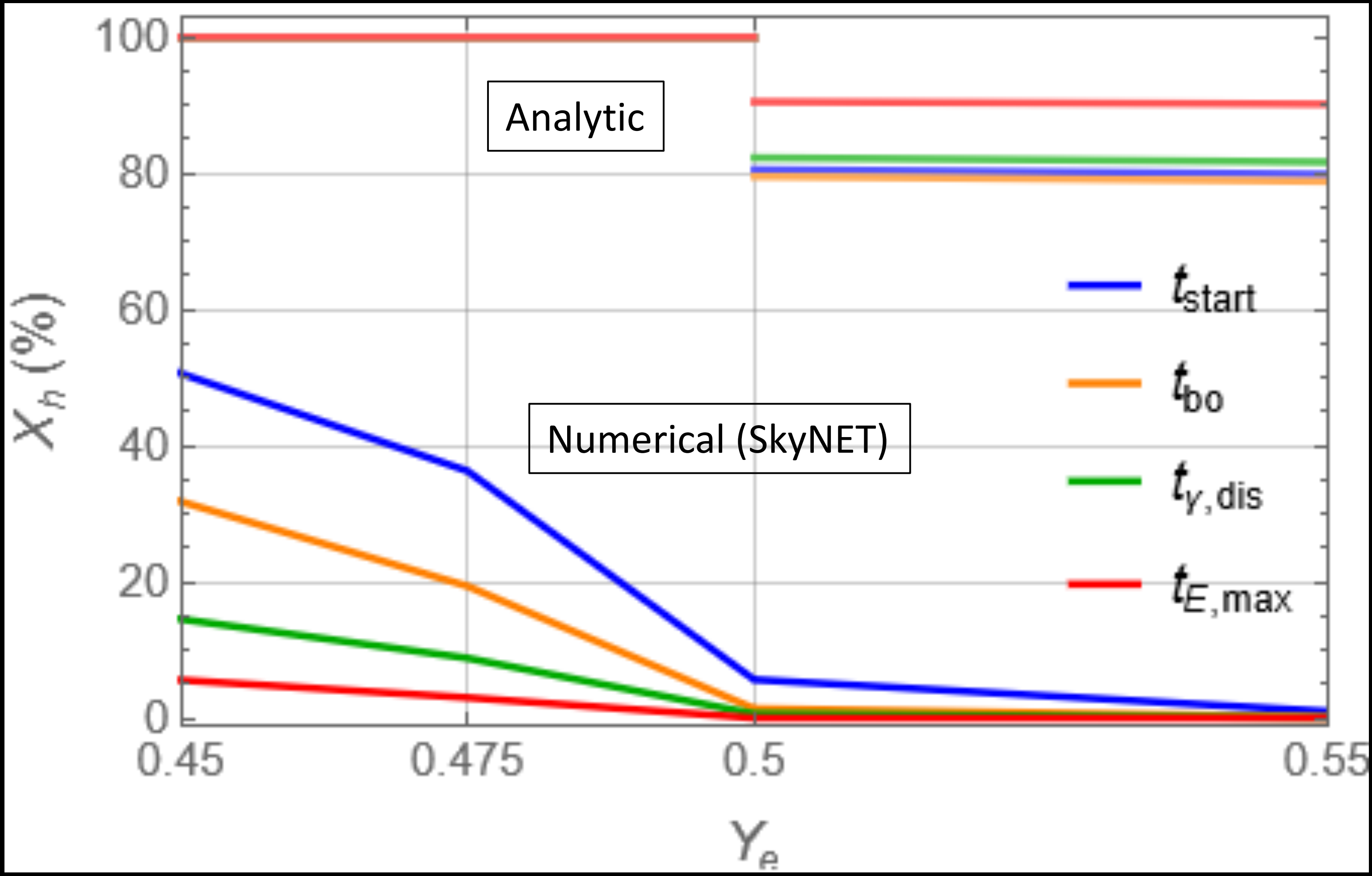


Bhattacharyna et al (2021)

Comparison

Fraction of heavy (Fe and above) nuclei:

Quantitative predictions require numerical treatment



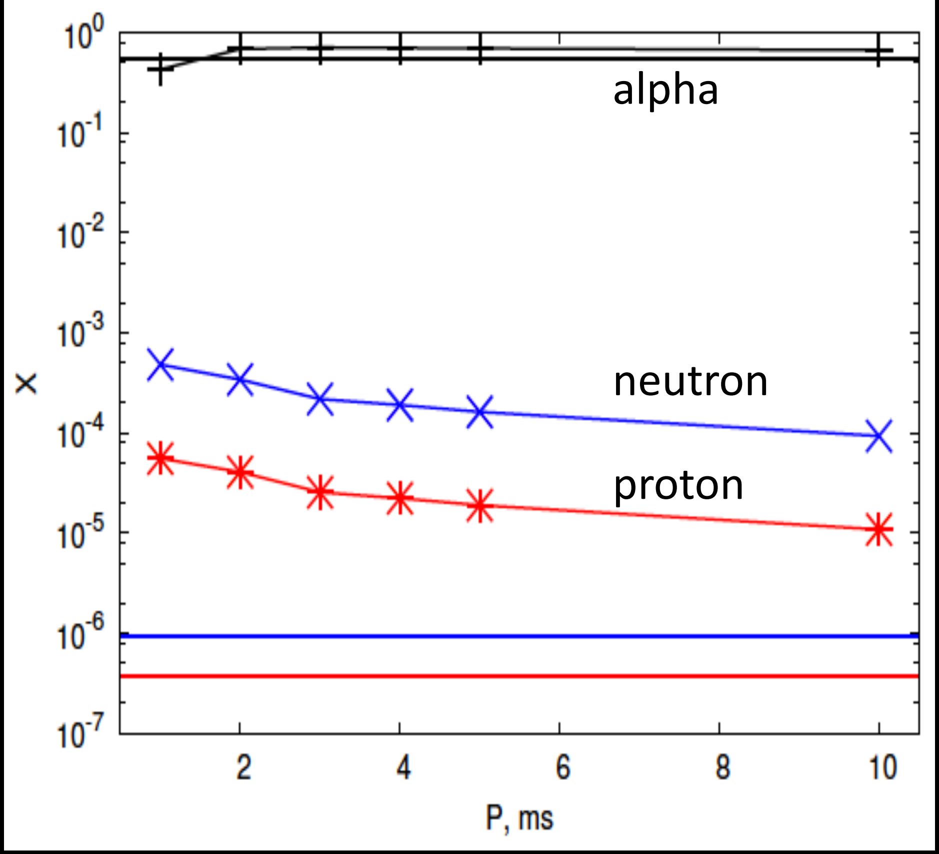
Ekanger et al (2022)

More simulations

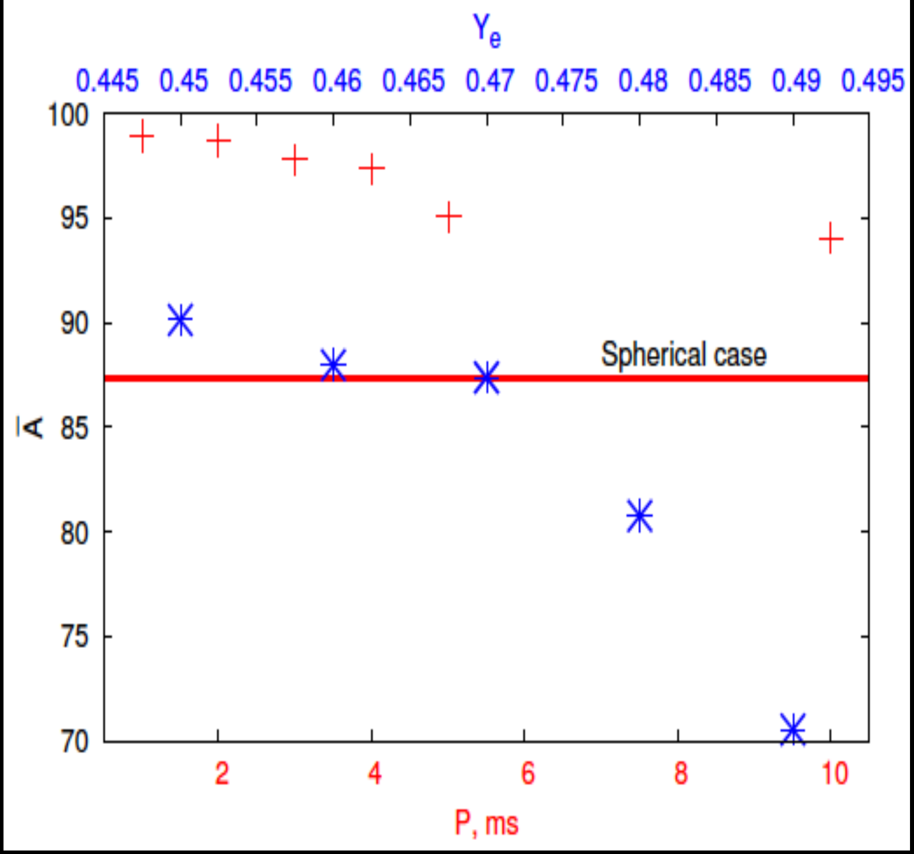
Aligned rotator simulations

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:

EM *coulomb* *strong*

$$\gamma \leftrightarrow e \leftrightarrow p \leftrightarrow n$$

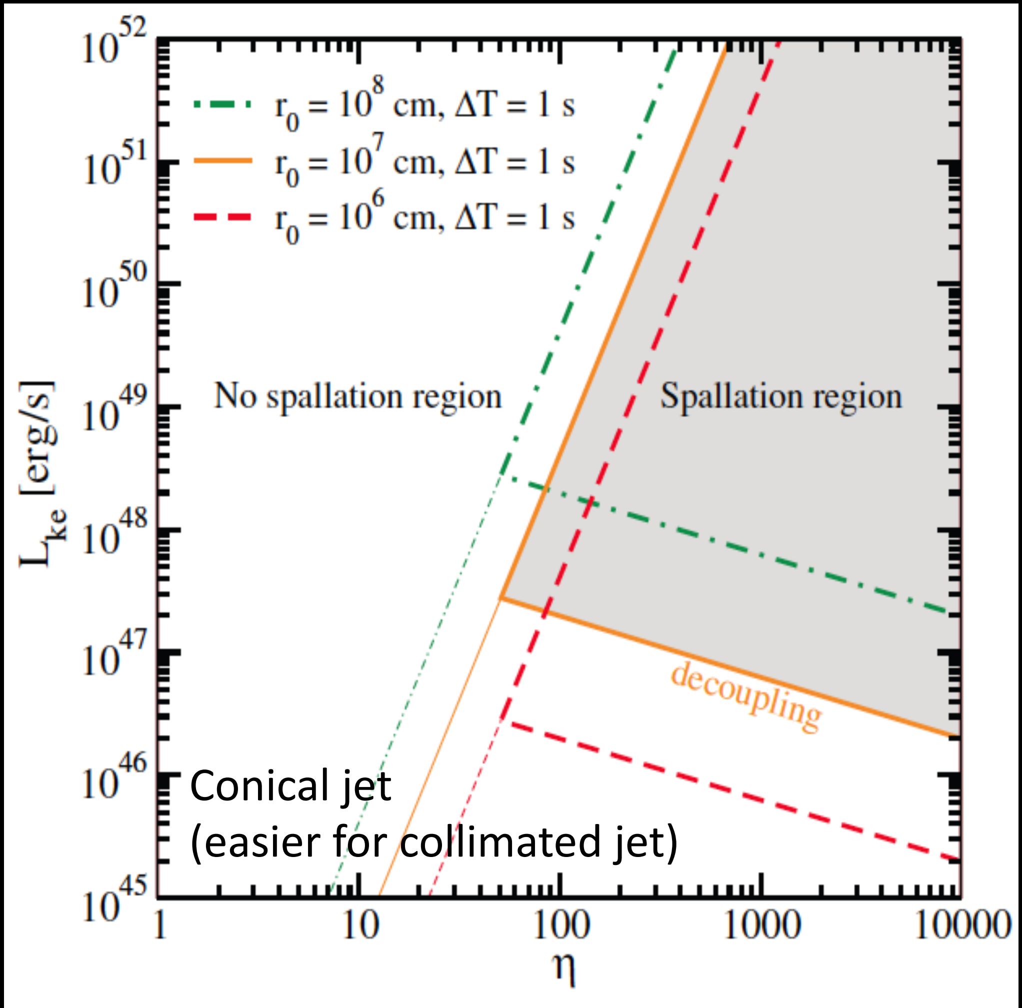
But they lag behind if $\tau_{collision} > \tau_{acc}$

- 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