Ultra-high-energy emission from an evolving gamma-ray burst: neutrinos, cosmic rays, and gamma rays

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THE OHIO STATE UNIVERSITY

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Reminder – why GRBs might be UHE CR & ν sources

- radiated gamma-ray energy of $\sim 10^{52} - 10^{54}$ erg
- intense magnetic fields of up to $\sim 10^{5}$ G
- magnetically-confined p's shock-accelerated to $\sim 10^{12}$ GeV
- TeV-PeV neutrinos created via $p\gamma$ interactions with source photons
- plus: low backgrounds (for ν's) due to small time window

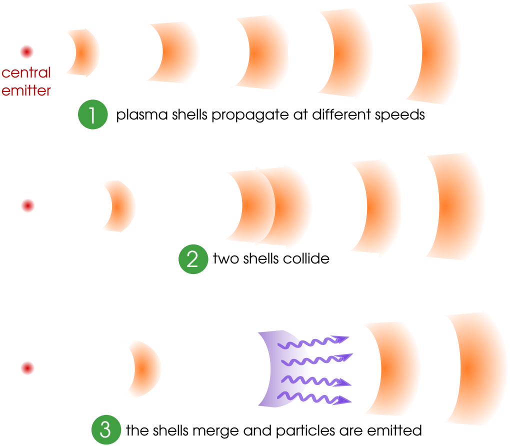
Current status: experiments (IceCube, ANTARES) are starting to strongly constrain the emission models

IceCube, *Nature* **484**, 351 (2012); IceCube, 1412.6510; ANTARES, *JCAP* **1303**, 006 (2013)

Therefore: it is time to take a more detailed look at the models

The fireball model – internal collisions

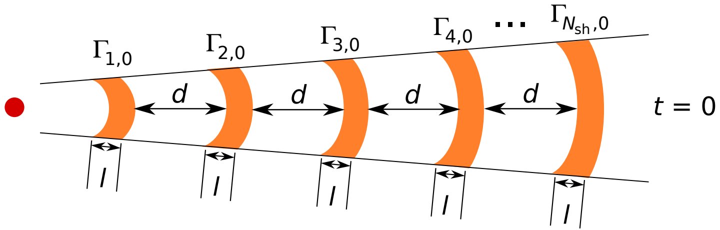
Fireball model: blobs, or shells, of plasma, at relativistic speeds, collide with each other, merge, and emit UHE particles



- We have simulated individual collisions
- Computed the UHE ν, CR, γ-ray emission from each
- Spoiler: we found a minimal GRB diffuse neutrino flux, only weakly dependent on burst parameters

Initialising the burst simulation

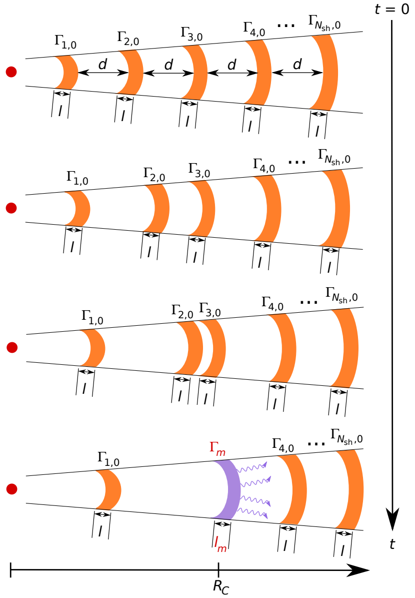
Initial number of plasma shells in the jet: $\gtrsim 1000$



Initial values of shell parameters:

- Width of shells and separation between them: $l = d$
- Equal kinetic energy for all shells ($\sim 10^{52}$ erg)
- Shell speeds $\Gamma_{k,0}$ follow a distribution (log-normal or other)

Propagating and colliding the shells



During propagation:

- speeds, masses, widths do not change (only in collisions)
- the new, merged shells continue propagating and can collide again

Evolution stops when either:

- a single shell is left; or
- all remaining shells have reached the circumburst medium ($\gtrsim 6 \times 10^{11}$ km)

final number of collisions

$\approx$

number of initial shells ($\gtrsim 1000$)

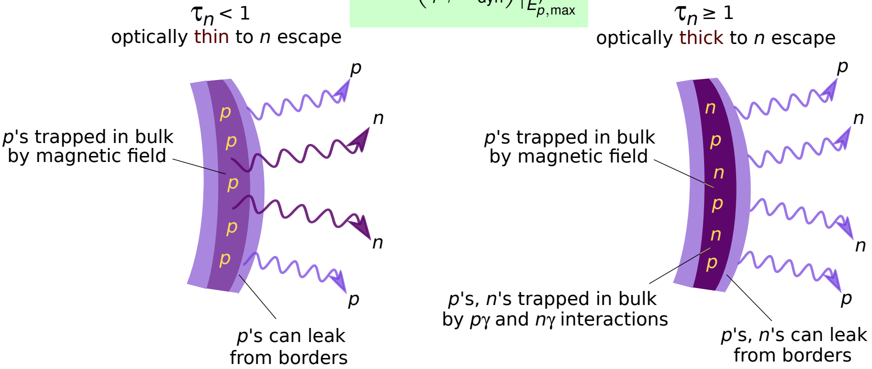
S. Kobayashi, T. Piran, and R. Sari, *ApJ* **490**, 92 (1997)
F. Daigne and R. Mochkovitch, *MNRAS* **296**, 275 (1998)

Particle emission from a collision

In each collision, UHECRs escape as either:

- neutrons: created in $p\gamma$ interactions, accompanied by ν's; or
- protons: they leak out of the shell without creating ν's

$$\tau_n \equiv \left(t_{p\gamma}^{-1} / t_{\rm dyn}^{-1} \right) \Big|_{E'_{p,\max}}$$



▲ high neutrino emission

low neutrino emission ▲

P. Baerwald, MB, and W. Winter, *ApJ* **768**, 186 (2013)

Producing the UHE ν's, CRs, γ rays

Joint production via $p\gamma$ interactions at the source, *e.g.*,

$$p\gamma \to \Delta^+(1232) \to \begin{cases} n\pi^+ \\ p\pi^0 \end{cases}$$

$$\pi^+ \to \mu^+\nu_\mu \to \bar{\nu}_\mu e^+ \nu_e \nu_\mu$$

$$\pi^0 \to \gamma\gamma$$

$$n \to p e^- \bar{\nu}_e$$

- **proton spectrum:** $\sim E^{-2}$ with cut-off
- **photon spectrum:** broken power law (normalised to observed gamma-ray emission of 10^{53} erg)

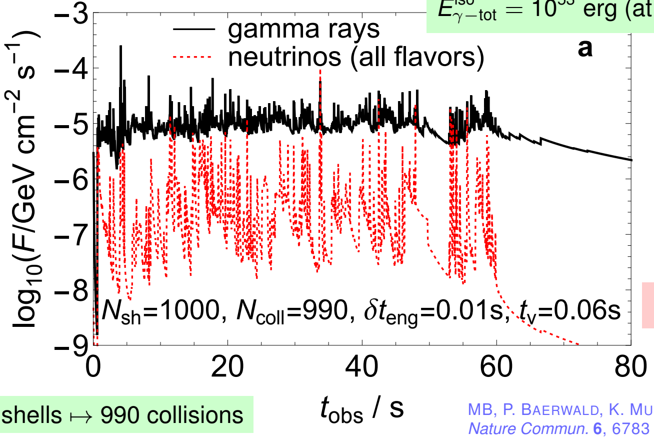
Numerical ν flux calculation via NeuCosmA

- $p\gamma \to \Delta^+(1232) \to \pi^0, \pi^+, \ldots$
- extra K, n, π^-, multi-π production modes
- synchrotron losses of secondaries
- adiabatic cooling
- full photon spectrum
- neutrino flavour transitions

S. Hümmer, P. Baerwald, and W. Winter, *PRL* **108**, 231101 (2012); see also H. He *et al.*, *ApJ* **752**, 29 (2012)

An emission pulse is assigned to each collision
– their superposition yields a synthetic light curve:

Total energy in gamma-rays:
$E^{\text{iso}}_{\gamma-\text{tot}} = 10^{53}$ erg (at source)



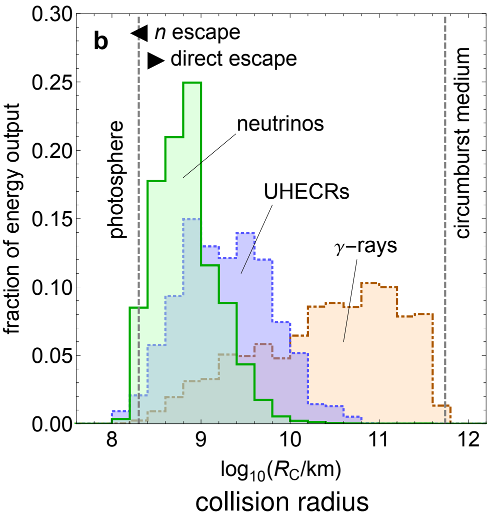
$T_{90} \approx 59$ s

1000 initial shells $\mapsto$ 990 collisions

MB, P. Baerwald, K. Murase, W. Winter
Nature Commun. **6**, 6783 (2015)

Different particles come from different jet regions

Emission of different species peaks at different collision radii –



Why?

As the fireball expands, photon and proton densities fall (as R_C^{-2})
$\Rightarrow \nu$ production decreases

Why does it matter?

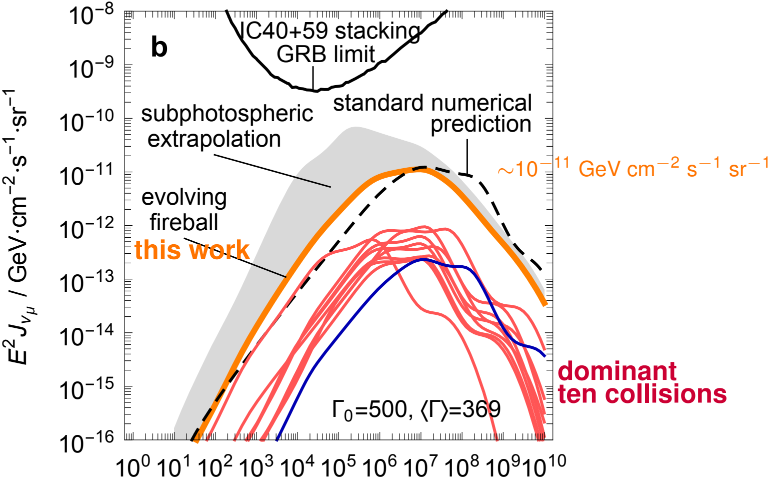
GRB parameters derived from gamma-ray observations might not be adequate to (directly) describe ν and UHECR emission

MB, P. Baerwald, K. Murase, and W. Winter
Nature Commun. **6**, 6783 (2015)

See also Globus *et al.* 1409.1271

A robust minimal diffuse ν flux from GRBs

- Take the simulated burst as stereotypical
- Quasi-diffuse neutrino flux, assuming 667 identical GRBs per year:



MB, P. BAERWALD, K. MURASE, AND W. WINTER
Nature Commun. **6**, 6783 (2015)

How is the new prediction different?

- The top-contributing collisions are at the photosphere
- Pion production efficiency there is independent of Γ:

$$f_{p\gamma}^{\text{ph}} \sim 5 \cdot \frac{\varepsilon}{0.25} \cdot \frac{\epsilon_e}{0.1} \cdot \frac{1\ \text{keV}}{\epsilon'_{\gamma,\text{break}}}$$

ε: energy dissipation efficiency
ϵ_e: fraction of dissipated energy as e.m. output (photons)

- $\Rightarrow$ Time-integrated neutrino fluence dominated is independent of Γ:

$$\mathcal{F}_\nu \propto \frac{N_{\text{coll}}\left(f_{p\gamma} \gtrsim 1\right)}{N_{\text{coll}}^{\text{tot}}} \times \min\left[1, f_{p\gamma}^{\text{ph}}\right] \times \frac{\epsilon_p}{\epsilon_e} \times E_{\gamma-\text{tot}}^{\text{iso}}$$

- Compare to standard predictions, which have a $\langle\Gamma\rangle^{-4}$ dependence
- Raising ϵ_p automatically decreases ϵ_e, so the photosphere grows, but still ~ 10 photospheric collisions dominate

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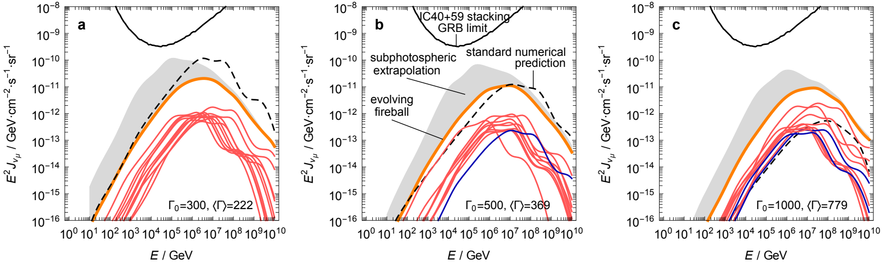
$$\mathcal{F}_\nu \propto \frac{\overbrace{N_{\rm coll}\left(f_{p\gamma} \gtrsim 1\right)}^{\sim 10}}{\underbrace{N_{\rm coll}^{\rm tot}}_{\sim 1000}} \times \min\left[1, f_{p\gamma}^{\rm ph}\right] \times \overbrace{\frac{\epsilon_p}{\epsilon_e}}^{10} \times \overbrace{E_{\gamma-\rm tot}^{\rm iso}}^{10^{53}~\text{erg}}$$

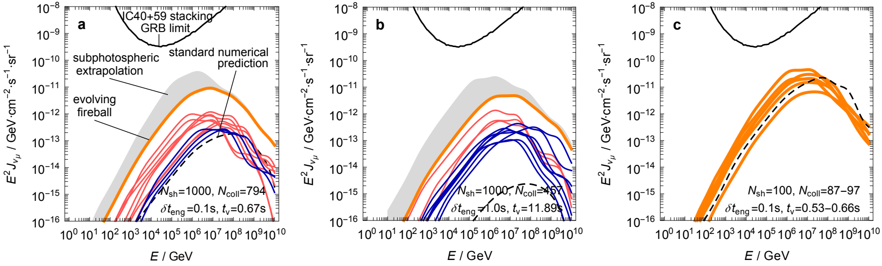
- Compare to standard predictions, which have a $\langle\Gamma\rangle^{-4}$ dependence
- Raising ϵ_p automatically decreases ϵ_e, so the photosphere grows, but still ~ 10 photospheric collisions dominate

The prediction *is* robust

Simulations show only weak dependence of the **flux** on the boost Γ . . .



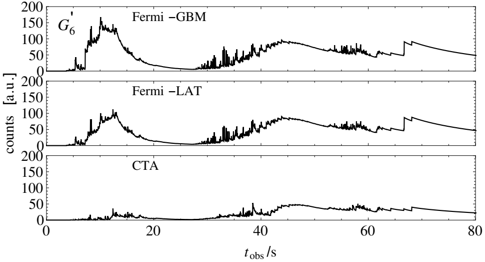
. . . and on the GRB engine variability time δt_{eng}



Conclusions . . . and the future

- GRBs *are* good UHECR and ν source candidates
- Simulating multiple internal collisions reveals where different particles come from
- We have derived a minimal GRB ν flux from superphotospheric internal collisions
- The prediction is only weakly dependent on burst parameters
- We need next-gen neutrino telescopes (IceCube-Gen2, KM3NeT)

More to come (in preparation):

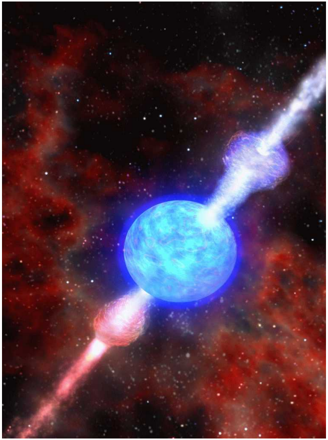


Backup slides

GRBs – what are they?

GRBs: the most luminous explosions in the Universe

- **brief** flashes of gamma rays: from 0.1 s to few 100's s
- isotropically distributed in the sky
- they are **far**: most occur at $\sim$ 1 Gpc from us ($z \approx 2$)
- they are **rare**: ~ 0.3 Gpc^{-3} yr^{-1}
- two populations:
  - **short-duration ($<$ 2 s):** neutron star-neutron star or NS-black hole mergers
  - **long-duration ($>$ 2 s):** associated to hypernovae
- powered by matter accretion onto a black hole



NeuCosmA: (revised) GRB particle emission – I

In a collision, UHE protons, photons, and neutrinos are emitted:

$$\underbrace{N'_p\left(E'_p\right)}_{\text{proton density at the source [GeV}^{-1}\text{ cm}^{-3}]} \overset{\text{NeuCosmA}}{\otimes} \underbrace{N'_\gamma\left(E'_\gamma\right)}_{\text{photon density at the source}}$$

$$= \underbrace{Q'_\nu\left(E'_\nu\right)}_{\text{ejected neutrino spectrum [GeV}^{-1}\text{ cm}^{-3}\text{ s}^{-1}]}$$

- From Fermi shock acceleration: $N'_p\left(E'_p\right) \propto E_p'^{-\alpha_p} e^{-E'_p/E'_{p,\text{max}}}$
- Photon density at source has same shape as observed:

$$N'_\gamma\left(E'_\gamma\right) = \begin{cases} \left(E'_\gamma/E'_{\gamma,\text{break}}\right)^{-\alpha_\gamma} & , E'_{\gamma,\text{min}} \leq E'_\gamma < E'_{\gamma,\text{break}} \\ \left(E'_\gamma/E'_{\gamma,\text{break}}\right)^{-\beta_\gamma} & , E'_\gamma \geq E'_{\gamma,\text{break}} \\ 0 & , \text{otherwise} \end{cases}$$

$$\alpha_\gamma = 1,\ \beta_\gamma = 2.2,\ E'_{\gamma,\text{min}} = 0.2 \text{ eV},\ E'_{\gamma,\text{break}} = 1 \text{ keV}$$

NeuCosmA: (revised) GRB particle emission – II

Normalise the densities at the source – for one collision:

- Photons:

$$\underbrace{\int E'_\gamma \, N'_\gamma \left(E'_\gamma\right) \, dE'_\gamma}_{\text{total energy density in photons}} = \frac{E'^{\text{iso}}_{\gamma-\text{sh}}}{V'_{\text{iso}}}$$

- Protons:

baryonic loading (energy in p's / energy in e's + γ's), *e.g.*, 10

$$\underbrace{\int E'_p \, N'_p \left(E'_p\right) \, dE'_p}_{\text{total energy density in protons}} = \frac{1}{f_e} \frac{E'^{\text{iso}}_{\gamma-\text{sh}}}{V'_{\text{iso}}}$$

NeuCosmA: (revised) GRB particle emission – III

NeuCosmA calculates the injected/ejected spectrum of secondaries (π, K, n, ν, etc.):

$x \equiv E'/E'_p$

$y \equiv E'_p E'_\gamma / \left(m_p c^2\right)$

$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p\left(E'_p\right) \int_0^{\infty} c\, dE'_\gamma\, N'_\gamma\left(E'_\gamma\right) R\left(x, y\right)$$

response function

R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

- $p\gamma \to \Delta^+(1232) \to \pi^0, \pi^+, \ldots$
- extra K, n, π^-, multi-π production modes
- synchrotron losses of secondaries
- adiabatic cooling
- full photon spectrum
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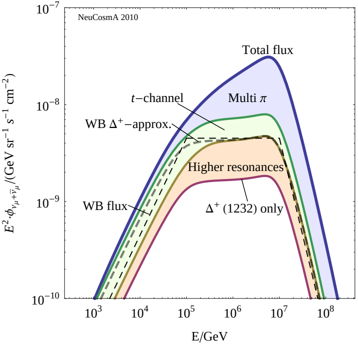
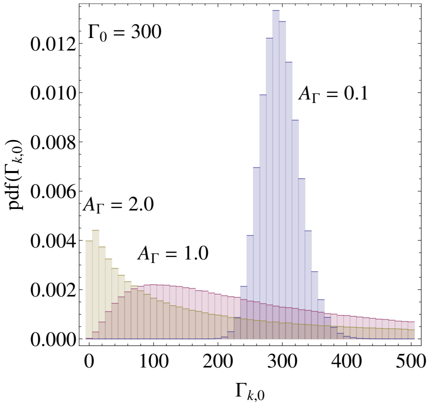


Initial distribution of shell speeds

Distribution of initial shell speeds (Lorentz factors):

$$\ln\left(\frac{\Gamma_{k,0}-1}{\Gamma_0-1}\right) = A_\Gamma x$$

x follows a Gaussian distribution, $P(x)\,dx = dx\; e^{-x^2/2}/\sqrt{2\pi}$



$A_\Gamma < 1$

speeds too similar, collisions only at large radii

$A_\Gamma \gg 1$

spread too large, too many collisions at low radii

$A_\Gamma \approx 1$

just right, burst has high efficiency of conversion of kinetic to radiated energy

A two-component model of CR emission – I

Two important points:

1. $E'_{p,\text{max}}$ is determined by energy-loss processes:
   $t'_{\text{acc}}\left(E'_{p,\text{max}}\right) = \min\left[t'_{\text{dyn}}, t'_{\text{syn}}\left(E'_{p,\text{max}}\right), t'_{p\gamma}\left(E'_{p,\text{max}}\right)\right]$

2. Photons can be trapped in the source by pair production:

$$\gamma + \gamma \rightarrow e^+ + e^-$$

   Photosphere: radius where $\tau_{\gamma\gamma}\left(E'_\gamma\right) = 1$ for all E'_γ

A two-component model of CR emission – II

Optical depth:

$$\tau_n = \left. \frac{t_{p\gamma}^{-1}}{t_{\text{dyn}}^{-1}} \right|_{E_{p,\max}} = \begin{cases} \lesssim 1 \, , & \text{optically } \textbf{thin} \text{ source} \\ > 1 \, , & \text{optically } \textbf{thick} \text{ source} \end{cases}$$

Particles can escape from within a shell of thickness λ'_{mfp}:

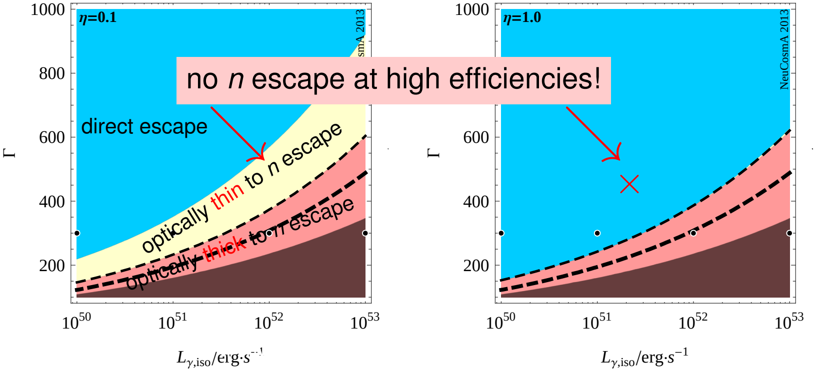
$$\left.\begin{aligned} \lambda'_{p,\text{mfp}}\left(E'\right) &= \min\left[\Delta r', R'_L\left(E'\right), ct'_{p\gamma}\left(E'\right)\right] \\ \lambda'_{n,\text{mfp}}\left(E'\right) &= \min\left[\Delta r', ct'_{p\gamma}\left(E'\right)\right] \end{aligned}\right\} f_{\text{esc}} = \frac{\lambda'_{\text{mfp}}}{\Delta r'}$$

fraction of escaping particles

We *need* direct proton escape

Scan of the GRB emission parameter space –

acceleration efficiency $\longrightarrow$ $\eta = 0.1$ $\eta = 1.0$

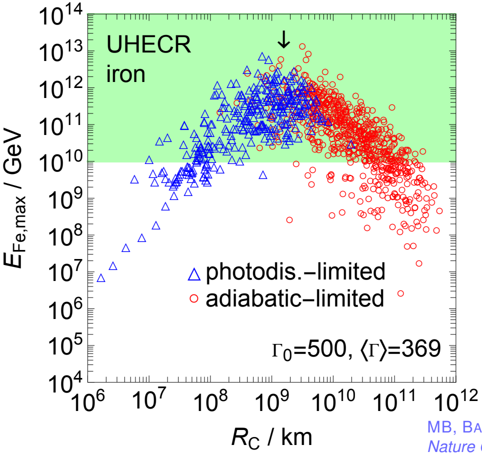


P. Baerwald, MB, and W. Winter, *ApJ* **768**, 186 (2013)

we need high efficiencies $\Rightarrow$ direct proton escape *is* required

Accelerating iron

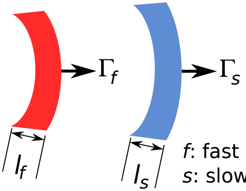
- Photodisintegration destroys nuclei close to the center ($\sim 10^8$ km)
  e.g., ANCHORDOQUI *et al.*, *Astropart. Phys.* **29**, 1 (2008)
- However, they can survive at large radii:



MB, BAERWALD, MURASE, WINTER
Nature Commun. **6**, 6783 (2015)

Anatomy of an internal collision

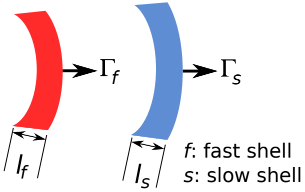
1. Propagation



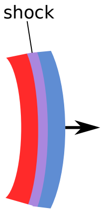
f: fast shell
s: slow shell

Anatomy of an internal collision

1 Propagation

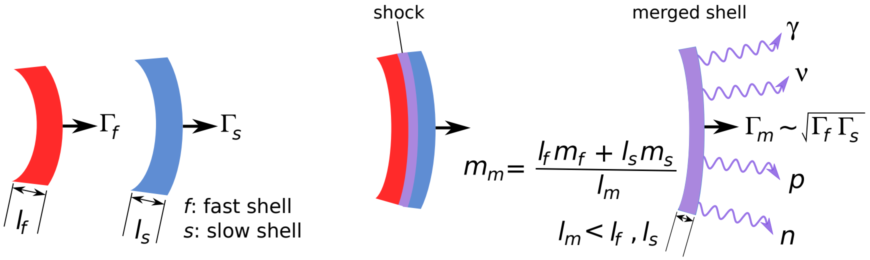


2 Collision



Anatomy of an internal collision

1 Propagation — 2 Collision — 3 Radiation



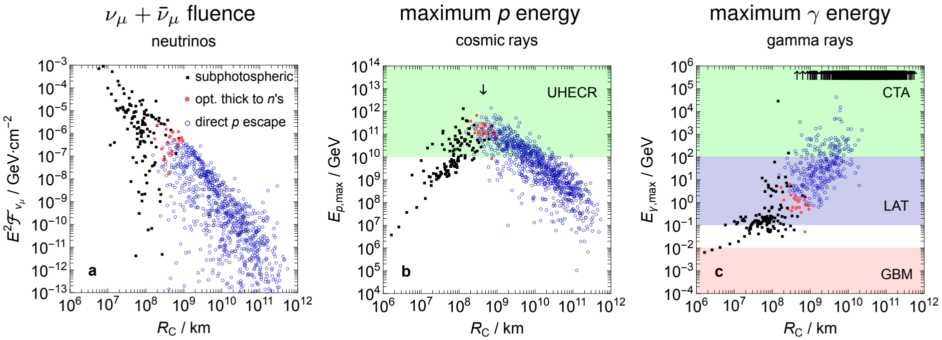
Part of the initial kinetic energy radiated as γ's, ν's, p's, and n's:

$$E_{\rm coll}^{\rm iso} = \left(E_{{\rm kin},f}^{\rm iso} - E_{{\rm kin},m}^{\rm iso} \right) + \left(E_{{\rm kin},m}^{\rm iso} - E_{{\rm kin},s}^{\rm iso} \right)$$

1/12	1/12	5/6
$\underbrace{\epsilon_e E_{\rm coll}^{\rm iso}}$	$\underbrace{\epsilon_B E_{\rm coll}^{\rm iso}}$	$\underbrace{\epsilon_p E_{\rm coll}^{\rm iso}}$
energy in photons	energy in magnetic fields	energy in baryons

Tracking each collision individually

Each collision occurs in a different emission regime –
(R_C: collision radius)



(observer's frame) (source frame)

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