Gamma-Ray Bursts, Cosmic-Rays and Neutrinos

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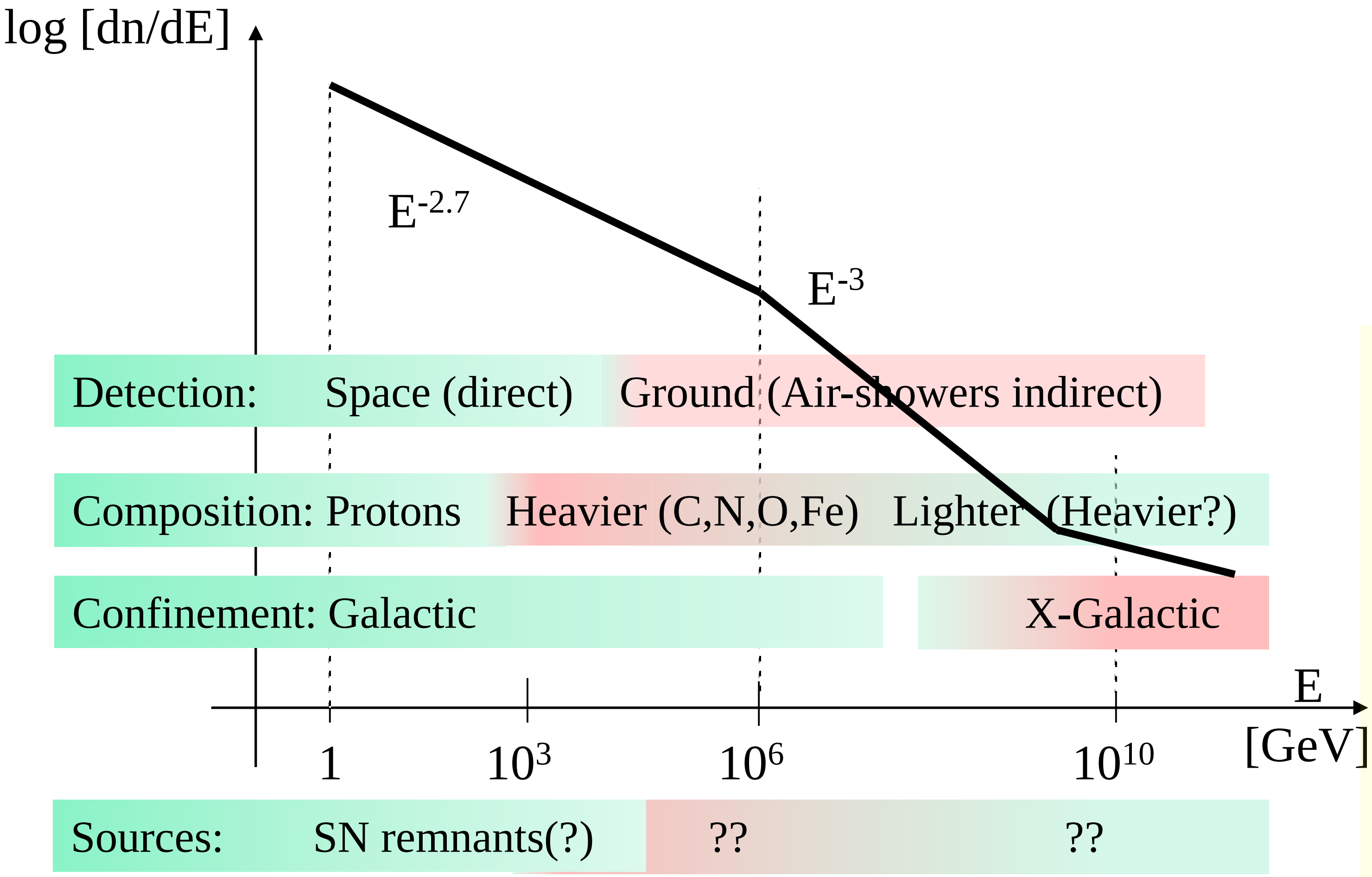
CDY initiative, “NYC”, Sep. 2021

The origin of Cosmic Rays:
Long standing open questions



Detection: Space (direct) Ground (Air-showers indirect)

Composition: Protons Heavier (C,N,O,Fe) Lighter (Heavier?)

Confinement: Galactic X-Galactic

Sources: SN remnants(?) ?? ??

Open Q’s

Composition?

G/XG transition?

Sources?

Acceleration?

[Reviews: Helder, et al. 12; Lemoine 13]

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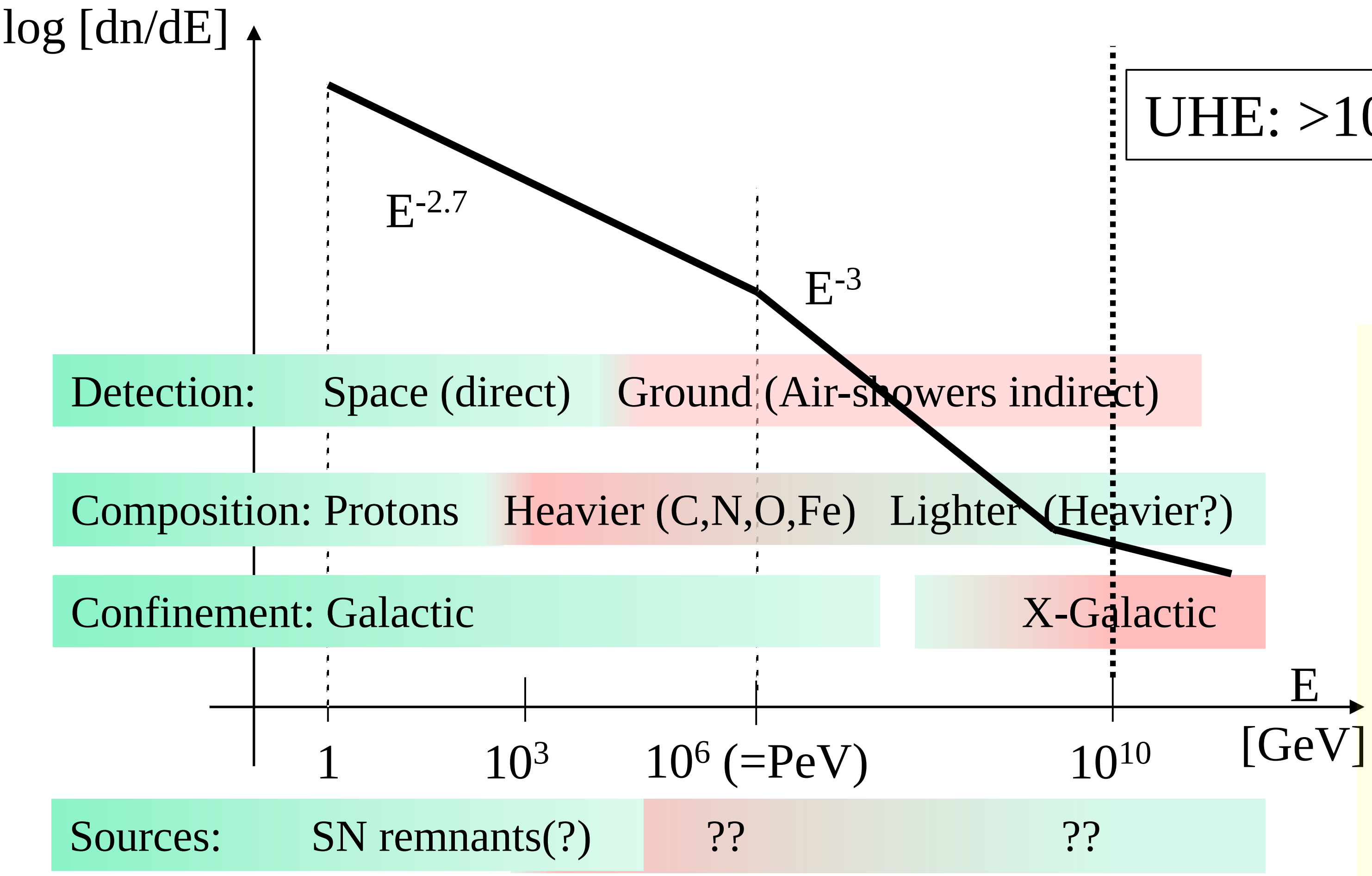

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This talk

- Why UHECR are interesting
- Why GRBs are likely candidate sources
- What we know and don't know about UHECRs
- What the experimental status of testing the GRB-CR association is
- What the prospects are for more conclusive experimental tests in the near future

UHECR: The acceleration challenge

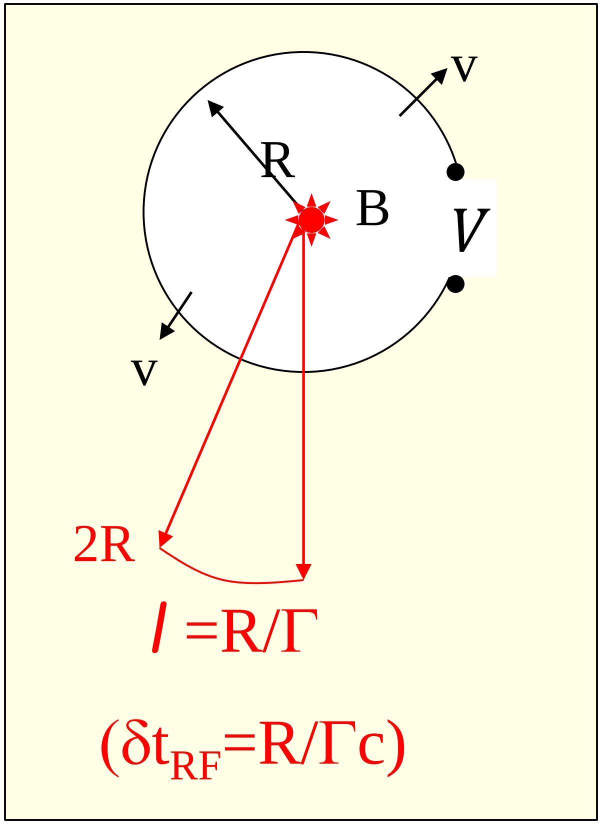
- A lower limit to the power required:

$$V = \frac{1}{c}\dot{\Phi} \approx \frac{1}{c}\frac{BR^2}{\frac{R}{v}} = \frac{v}{c}BR \quad \Rightarrow \quad E < \frac{\beta ZeBR}{\Gamma},$$

$$L > 4\pi R^2\Gamma^2 \frac{B^2}{8\pi}\beta c > \frac{\Gamma^2}{\beta}\left(\frac{E/Z}{10^{11}\mathrm{GeV}}\right)^2 10^{12} L_{\mathrm{Sun}}.$$

[Lovelace 76; EW 95; Norman et al. 95; Lemoine & EW 09]

- Few candidate sources.
  A challenge to theory:
  Constructing an acceleration mechanism,
  that efficiently utilizes the full potential.



UHECR: Candidate sources

- EM acceleration: $L > 10^{12}\,\frac{\Gamma^2}{v/c}\left(\frac{E/Z}{10^{11}\mathrm{GeV}}\right)^2 L_{\mathrm{sun}}$.

  [Lovelace 76; EW 95; Norman et al. 95; Lemoine & EW 09]

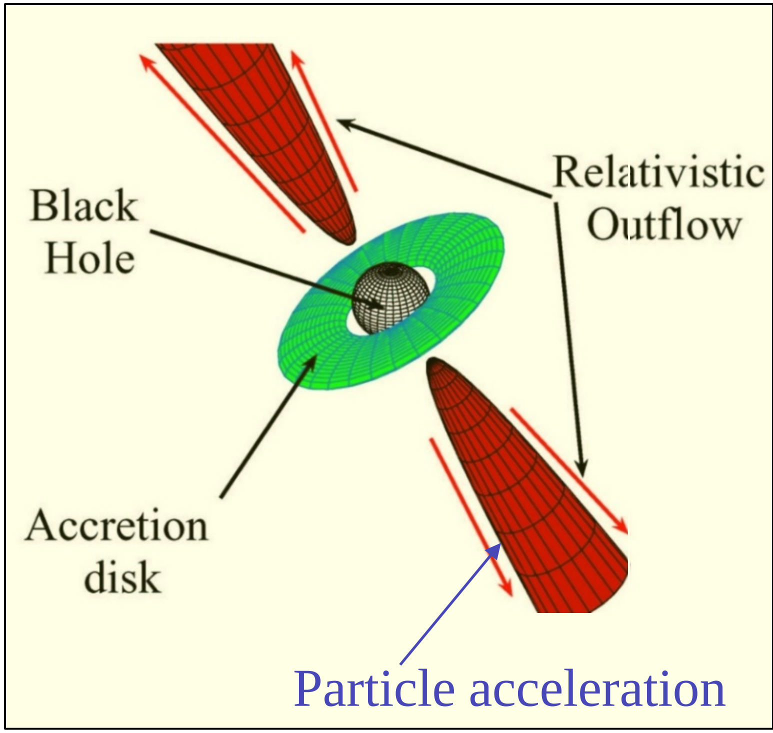
- $Z > 10$ - a handful of candidates.

- Protons at UHE:
  2 candidate transient sources,
  Rapid mass accretion onto BHs.
  - Gamma-ray bursts (GRB), newly formed solar mass BHs;

    [Vietri 95; Milgrom & Usov 95; EW 95]

  - Tidal disruption of stars (TDE) by massive BHs at galaxy centers, may produce "GRB-like" jets.

    [Gruzinov & Farrar 09; Wang & Liu 16]



(- Young, ms, 10^{13}G Neutron Stars? If they exist… [Arons 03;… Lemoine et al. 15].)

UHECR: Key observational constraints

- Flux & Spectrum:

$$\frac{dn}{dE} = \frac{d\dot{n}}{dE} \times t_{\mathrm{eff}}\,(E, \{A, Z\})$$

Observed

Source

Composition dependent
Life time

→ Combined constraints on sources' energy production rate, spectrum and composition (degenerate)

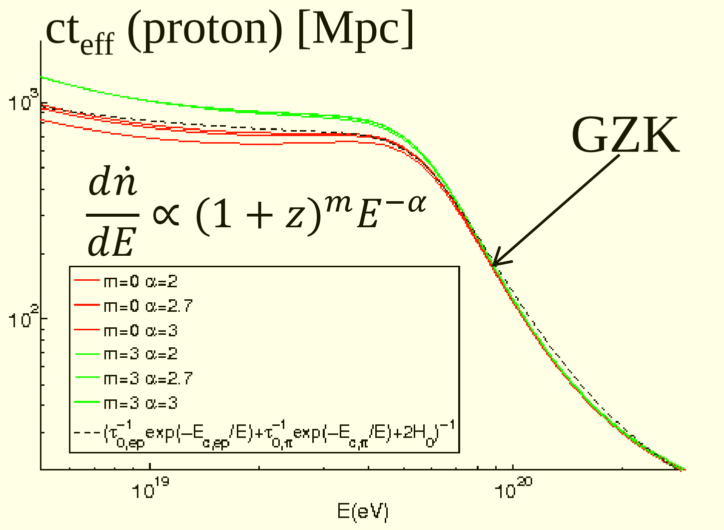
- Composition at Earth:
  A (more) direct constraint on source composition

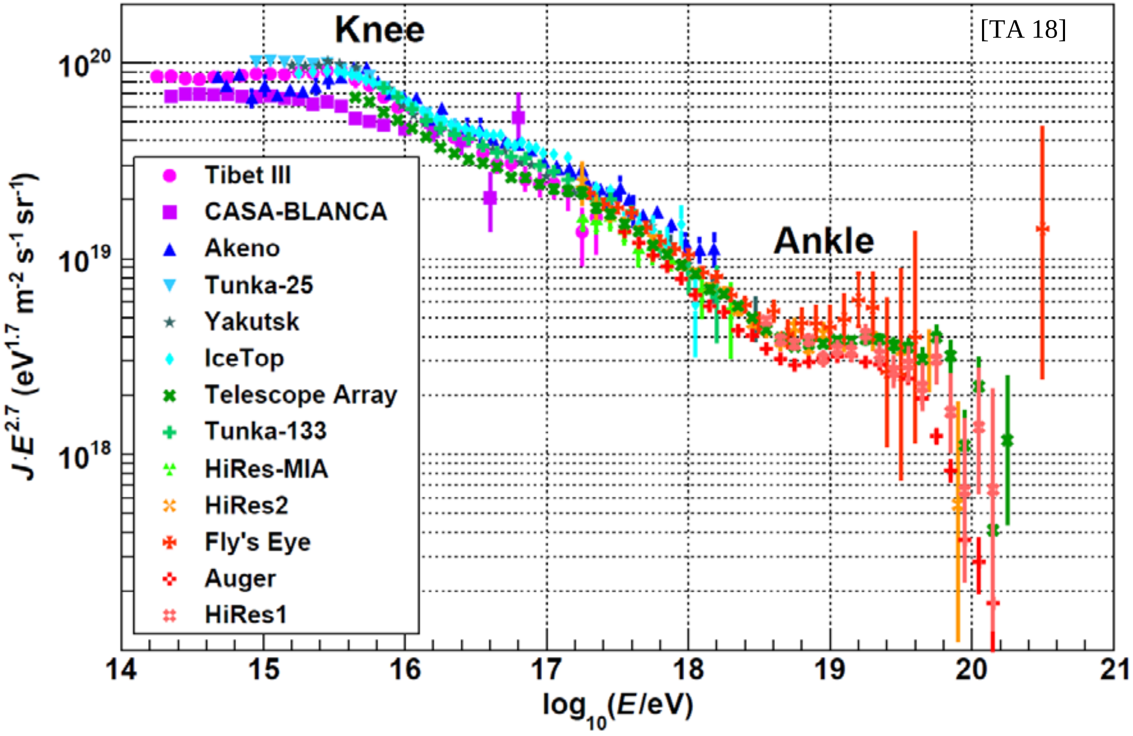
- (Angular distribution- no strong anisotropy/source association)

>10^{10}GeV flux & spectrum

- Protons: strong (GZK) suppression expected above $5\text{x}10^{19}\text{eV}$, due to $p + \gamma[\text{CMB}] \rightarrow N + \pi$.
- Suppression observed, consistent with GZK.

$$\left.\frac{dn}{dE}\right|_{\text{Obs.}} = \left.\frac{d\dot{n}}{dE}\right|_{\text{Source}} t_{\text{eff}}(E)$$





$>10^{10}$GeV flux & spectrum

- Protons: strong (GZK) suppression expected above 5×10^{19}eV, due to $p + \gamma[\mathrm{CMB}] \rightarrow N + \pi$.
- Suppression observed, consistent with GZK.

<u>Alternative explanations</u>

- Proton sources with a flat spectrum,

$$E^2\frac{d\dot{n}}{dE} = Const = (5 \pm 2)10^{43}\,\frac{\mathrm{erg}}{\mathrm{Mpc^3yr}}\,.$$

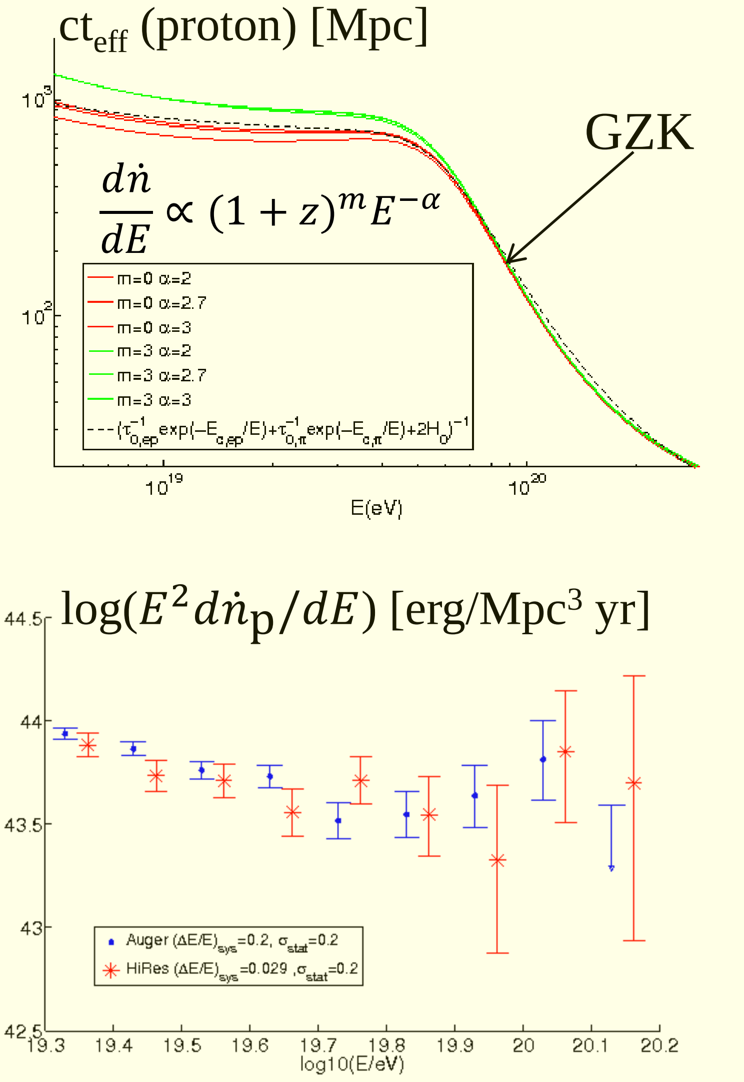
[EW 95; Bahcall & EW 03; Katz & EW 09]

(Flat spectra observed at a wide range of systems, commonly attributed to Fermi shock acceleration).

- Z>>1 sources with Acceleration cutoff at $E=5\times10^{19}$eV,

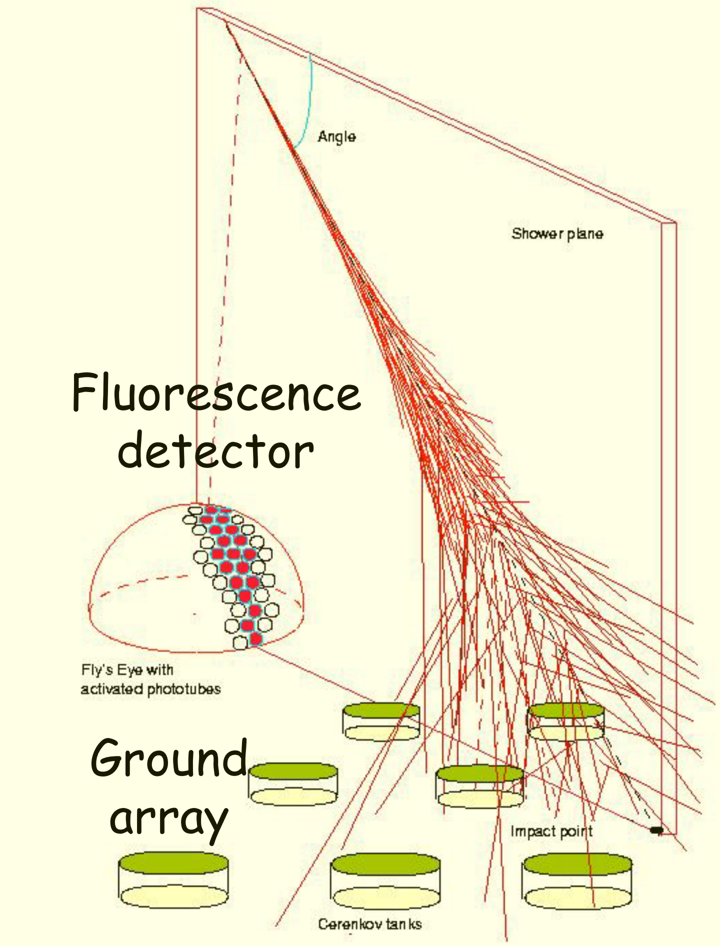
$$Q(>10^{19}\mathrm{eV}) \approx 10^{44}\,\frac{\mathrm{erg}}{\mathrm{Mpc^3yr}}\,.$$

$$\left.\frac{dn}{dE}\right|_{\mathrm{Obs.}} = \left.\frac{d\dot{n}}{dE}\right|_{\mathrm{Source}} t_{\mathrm{eff}}(E)$$



$>10^{10}$GeV composition- X_{max}

- Main handle:
  $X_{\max}$ =Atmospheric Depth (g/cm^2) of max # of rel. shower particles.
  $<X_{\max}>, Var(X_{\max})$ decrease with atomic mass A (at fixed E).

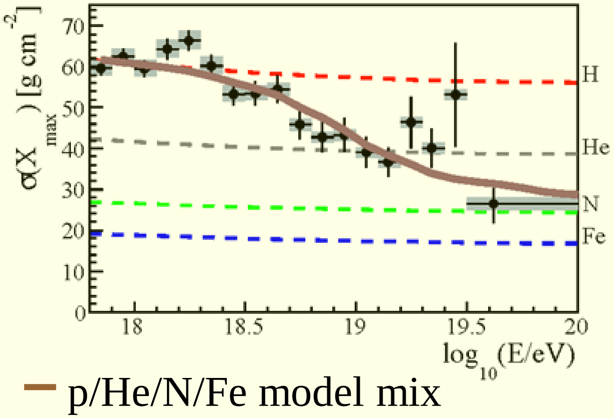


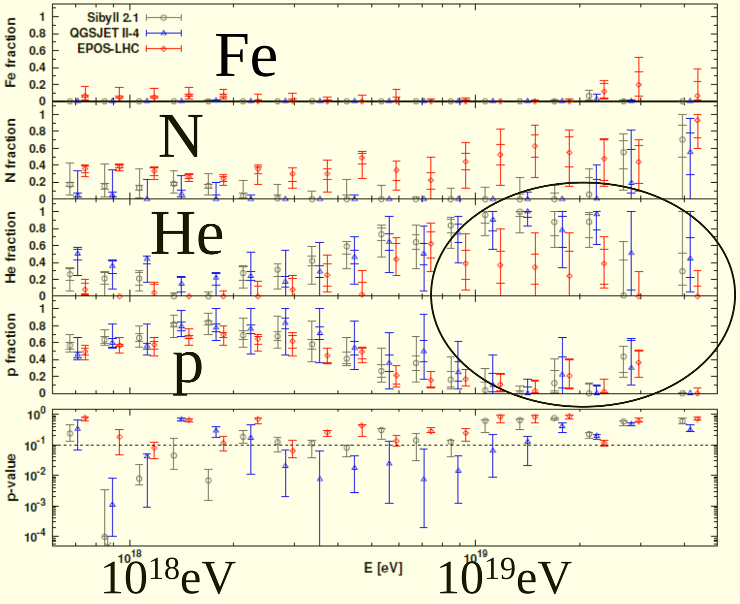
J($>10^{11}$GeV)~1 / 100 km^2 year 2π sr
Auger- 3000 km^2

>10^{10}GeV Air shower composition constraints

- Auger data commonly interpreted as Transition to heavy (N) at high E, Dominant p/He component to $10^{19.5}$eV.

Auger 2015: p/He/N

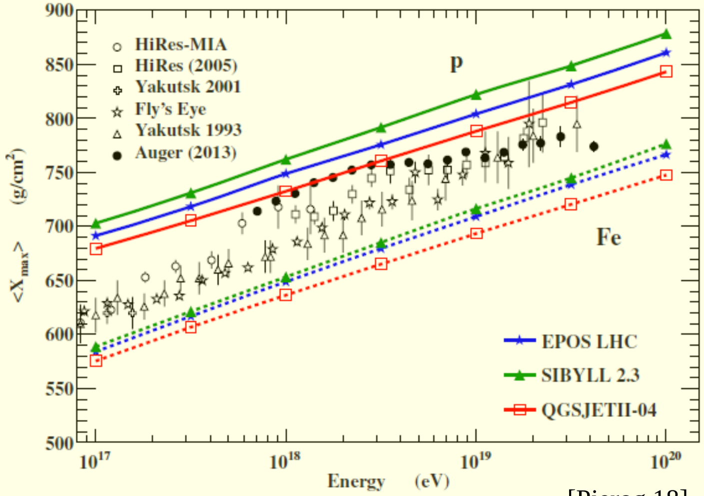




>10^{10}GeV Air shower composition constraints

- Auger data commonly interpreted as Transition to heavy (N) at high E, Dominant p/He component to $10^{19.5}$eV.
- Large uncertainties
  - HiRes/Auger/TA discrepancies.

Experimental discrepancies



[Pierog 18]

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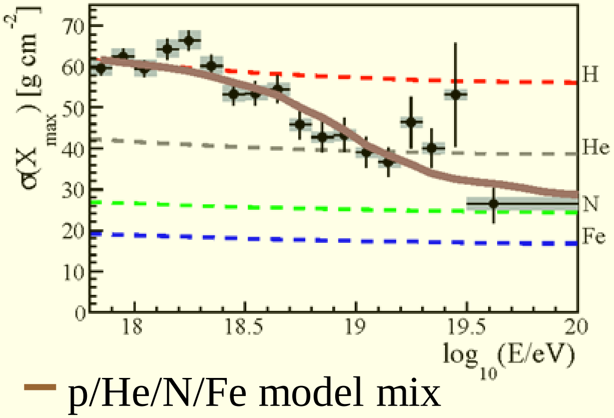
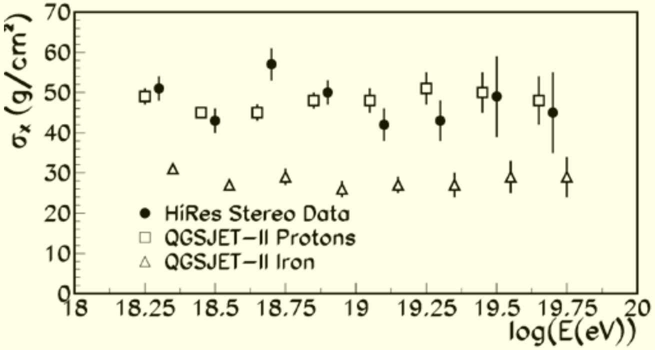


HiRes Stereo 2010: p



$>10^{10}$GeV Air shower composition constraints

- Auger data commonly interpreted as Transition to heavy (N) at high E, Dominant p/He component to $10^{19.5}$eV.

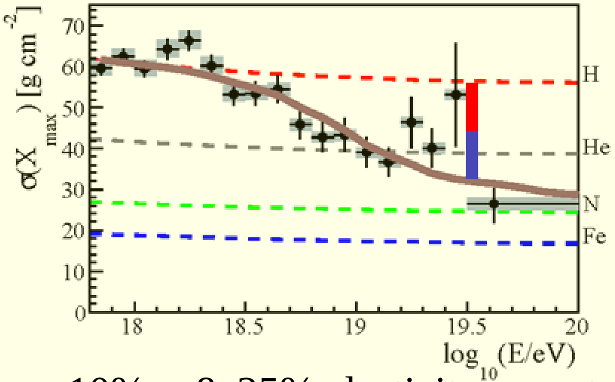
- Large uncertainties
  - HiRes/Auger/TA discrepancies.

  - Sys + Interaction model uncertainties.
  - Data inconsistent with (all) models, implies unaccounted for systematics (experimental and/or theoretical).
  - Is the model uncertainty spanned by the 'generator' span (QGSJET, EPOS, SIBYLL)?

- Composition constraints- Inconclusive.
- Progress requires:
  - <10% exp. sys. uncertainty. <10% uncertainty (σ, elasticity,…) at ~300TeV, forward scattering.

[e.g. Pierog 17]

Auger 2015: p/He/N

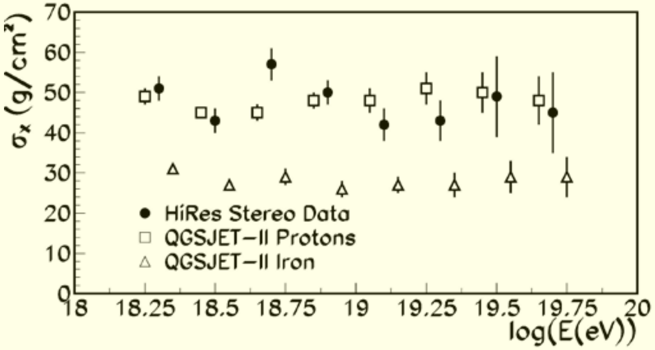


🟥 10% σ & 25% elasticity uncertainty

🟦 exp. sys. uncertainty

🟫 p/He/N/Fe model mix

HiRes Stereo 2010: p

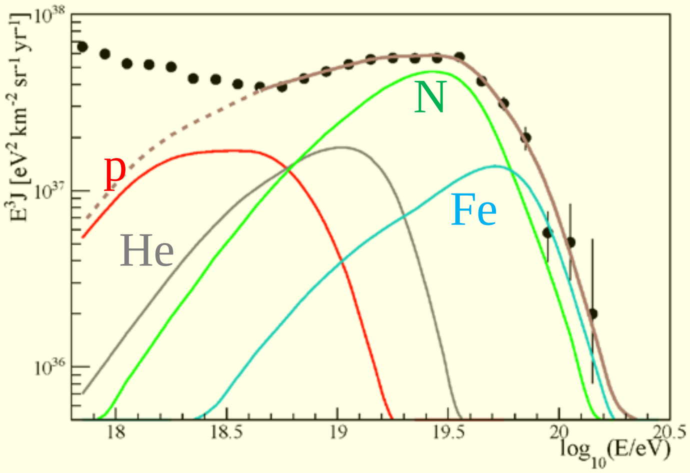


Mixed composition models- Challenges

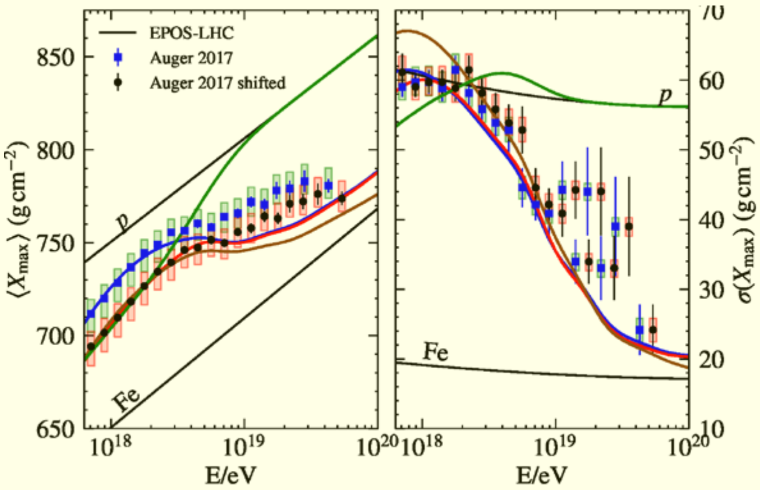
- Ad hoc assumptions
  * Acceleration
  - Cutoff at $E = Z \times 10^{9.2}\text{GeV}$ -
    A chance coincidence with p-GZK.
  - $E^2 \frac{d\dot{n}}{dE} \propto E$ -
    Unknown acceleration process.
  * Composition @ source
  H : He : N = 10% : 60% : 30% -
  Unique environment.

- Do not reproduce large $\sigma(X_{max})$ above 10^{19}eV.
- A proton fraction $f_p \cong 0.1$ above 10^{19}eV significantly improves (5σ) the fit.

[e.g. Muzio, Unger & Farrar 19]



[Auger Dec 16]



[Muzio, Unger & Farrar 19]

UHECR: Key observational constraints

- Flux & Spectrum:
  Proton sources with a flat spectrum,
  $$E^2 \frac{d\dot{n}}{dE} = Const = (5 \pm 2)10^{43} \frac{\text{erg}}{\text{Mpc}^3\text{yr}} .$$
  OR
  Z>>1 sources with
  Acceleration cutoff at E=5x10^{19}eV,
  $$Q(> 10^{19}\text{eV}) \approx 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{yr}} .$$

- Composition: A robust conclusion cannot be drawn.
  Auger data commonly interpreted as transition to heavy (N) at high E; A significant proton fraction, $f_p \cong 0.1$, preferred.

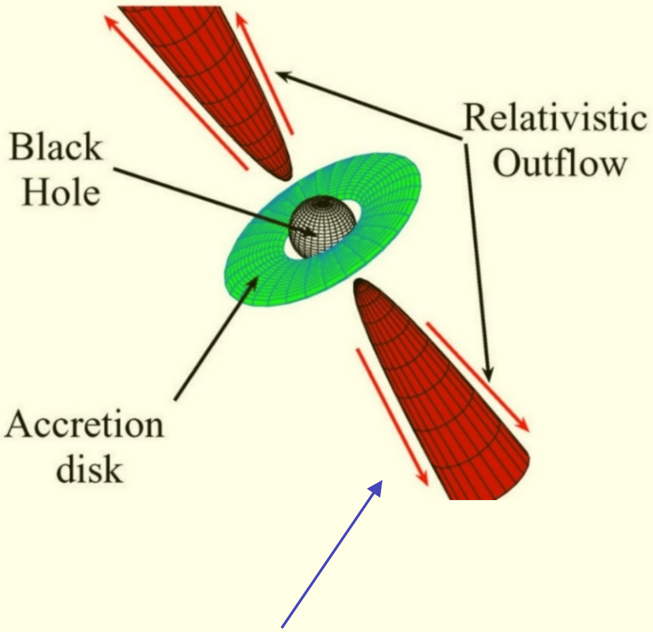
Widely considered GRB models

- GRBS are the brightest known objects
  $L(\sim 1\mathrm{MeV}) \approx 10^{52}\mathrm{erg/s}$,
  $T \sim 10\ \mathrm{s}$,
  $\Delta t \sim 10\ \mathrm{ms}$ observed in a significant fraction,
  100 MeV photons observed in some.

- Most models: radiation produced by internal energy dissipation in a highly relativistic jet, driven by rapid mass accretion onto a compact object (BH/NS).
  γ>100 based on 100 MeV photons' escape.

- 2 model classes
  - e-p jet, dissipation and particle acceleration via internal collisionless shocks [partial understanding of micro-physics].
  - EM jet, dissipation and particle acceleration via magnetic reconnection [limited understanding of micro-physics].

Relativistic flows driven by BH accretion.



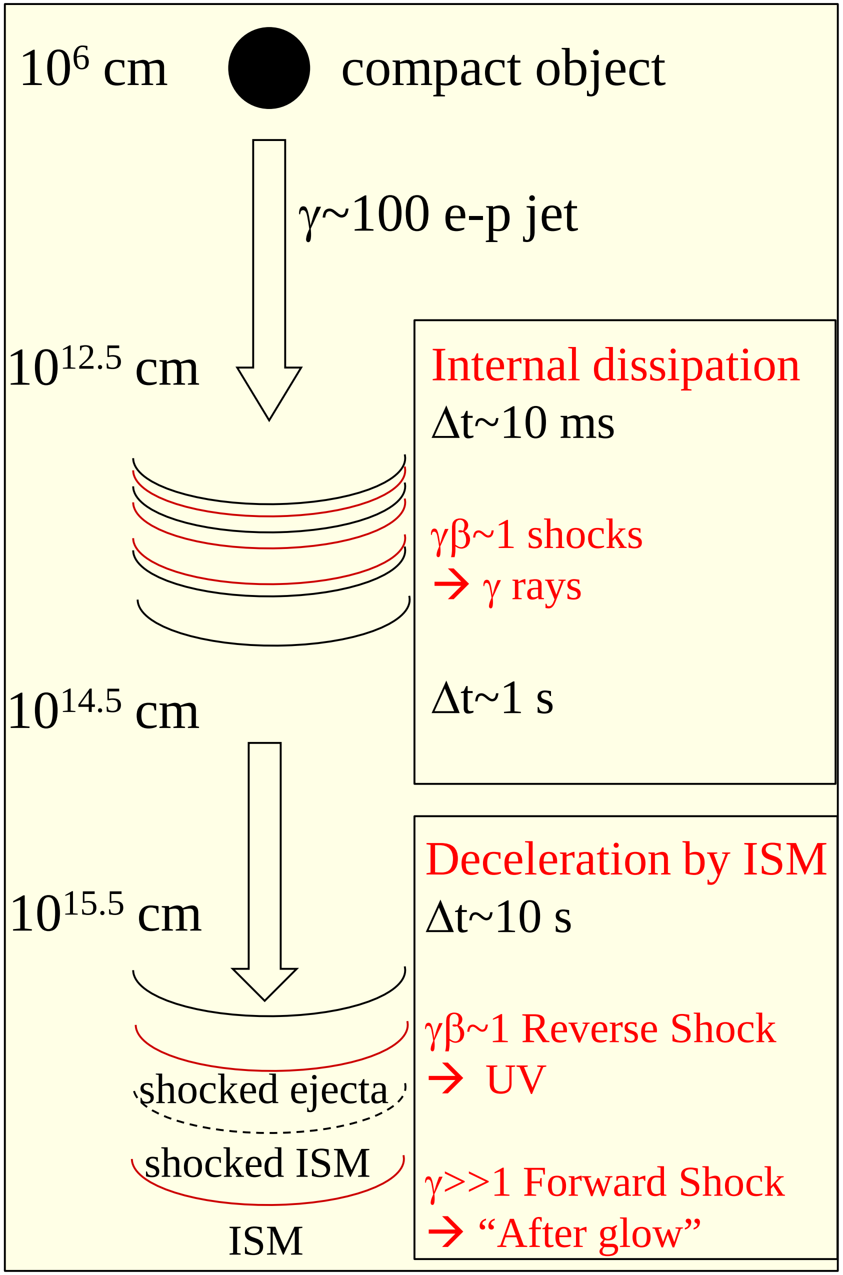
Particle acceleration

Common e-p jet models

- Electrons accelerated by collisionless shocks.

- In the jet frame, the internal & reverse shocks are mildly relativistic.
  - $E^2 \frac{d\dot{n}}{dE} = \mathrm{Const.}$ e^- spectrum.
  - Magnetic field near equipartition.

- Radiation produced by synchrotron and IC emission.
  - Some challenges in explaining the γ-ray spectra (“photospheric models”)
  - “Afterglow” emission well accounted for with $E^2 \frac{d\dot{n}}{dE} = \mathrm{Const}$ and near equipartition B.



10^6 cm compact object

γ~100 e-p jet

$10^{12.5}$ cm

$10^{14.5}$ cm

$10^{15.5}$ cm

shocked ejecta

shocked ISM

ISM

Internal dissipation

Δt~10 ms

γβ~1 shocks

→ γ rays

Δt~1 s

Deceleration by ISM

Δt~10 s

γβ~1 Reverse Shock

→ UV

γ>>1 Forward Shock

→ “After glow”

p acceleration in GRBs

- In the region where e^- are accelerated, p would also be.
- Max p energy independent of r, Internal & Reverse shocks,

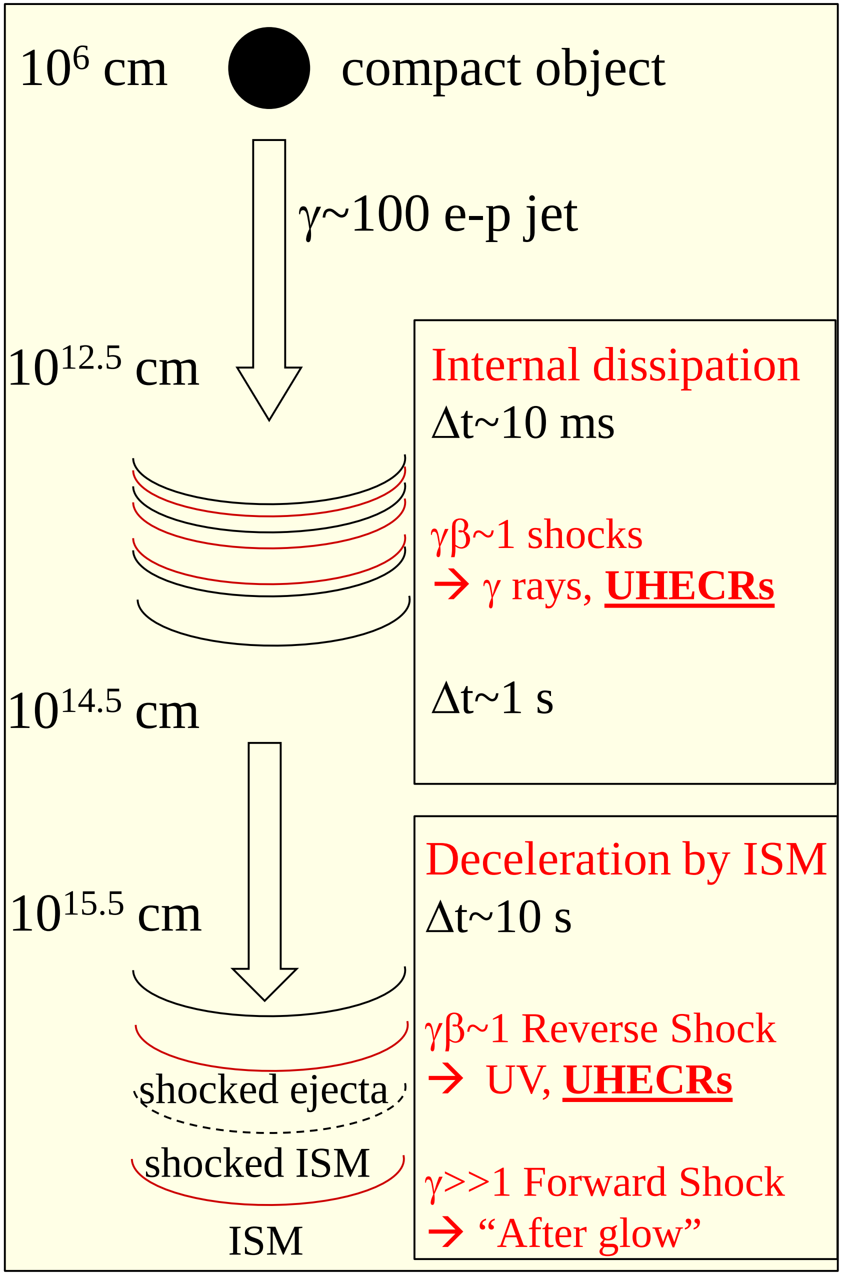
$$E < 10^{21}\left(\frac{100}{\gamma}\right)\left(\frac{L}{10^{52}\mathrm{erg/s}}\right)^{1/2}\ \mathrm{eV}\ .$$

[EW 95]

- Reverse shock:
Most of the kinetic energy dissipated, Accelerated p escape downstream to the ISM.

→ Escaping UHECRs carry a significant fraction of the energy.

- Heavy nuclei dissociated by radiation field.



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$\gamma\sim100$ e-p jet

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$\Delta t\sim10$ ms

$\gamma\beta\sim1$ shocks
→ γ rays, **UHECRs**

$10^{14.5}$ cm

$\Delta t\sim1$ s

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Deceleration by ISM
$\Delta t\sim10$ s

$\gamma\beta\sim1$ Reverse Shock
→ UV, **UHECRs**

$\gamma>>1$ Forward Shock
→ “After glow”

Extra-Galactic flux of GRB UHE p's

- Energy production rate

$$\gamma:\ R_{z=0}\overline{E_\gamma}=\frac{10^{52.3\pm0.7}\,\mathrm{erg}}{\mathrm{Gpc^3yr}}=10^{43.3\pm0.7}\frac{\mathrm{erg}}{\mathrm{Mpc^3yr}}$$

p:

$$E^2\frac{d\dot{n}}{dE}\approx\frac{Q_p}{Q_e}\frac{Q_e}{\ln 10^8}\approx\frac{Q_p}{Q_e}10^{42.3\pm0.7}\frac{\mathrm{erg}}{\mathrm{Mpc^3yr}}$$

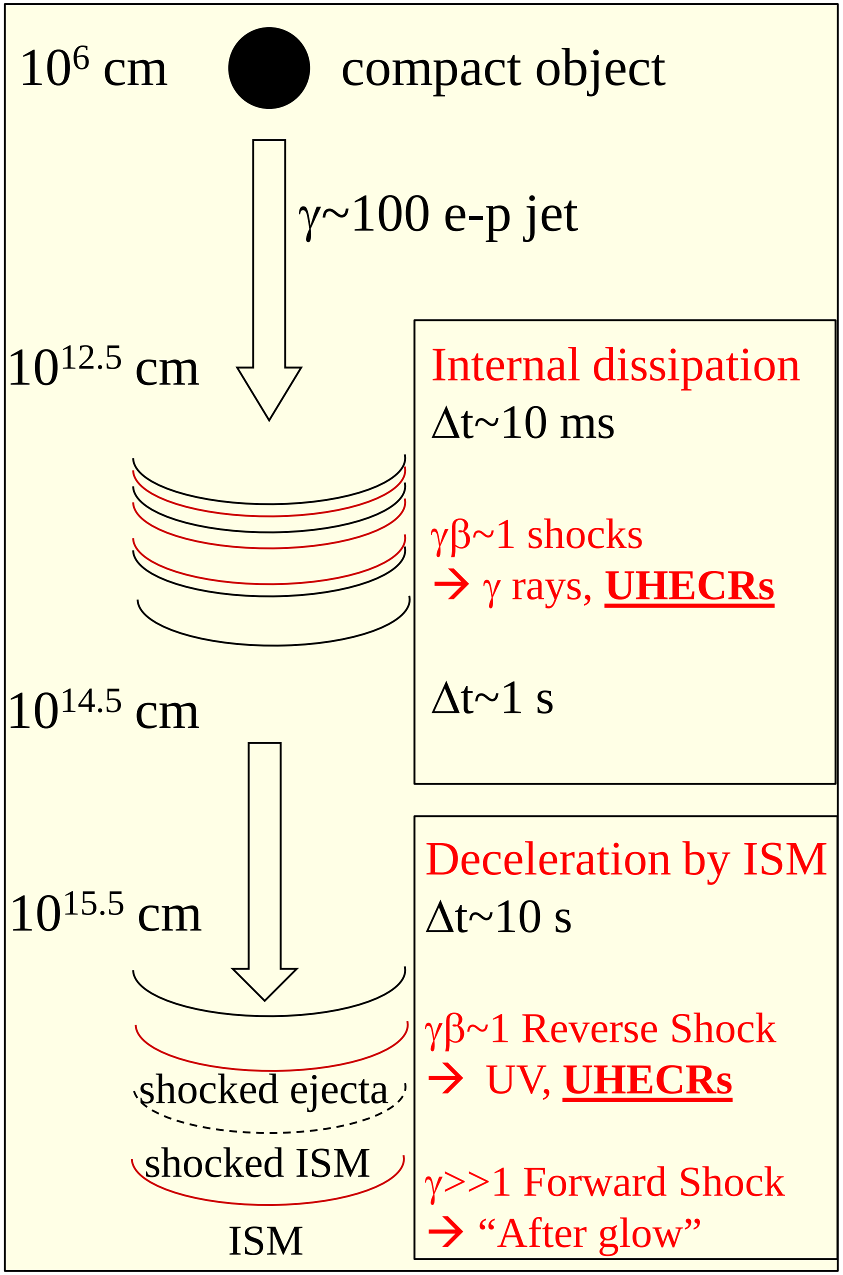
- The proton generation rate required to produced the full >10^{19}eV CR flux:

$$E^2\frac{d\dot{n}}{dE}=10^{43.7\pm0.2}\frac{\mathrm{erg}}{\mathrm{Mpc^3yr}}$$

- The fraction of >10^{19}eV CR flux contributed by GRB protons:

$$f_{p,\mathrm{grb}}\approx 0.1\frac{Q_p}{Q_e}=1\frac{Q_p}{10Q_e}.$$

If GRBs are produced by e-p jets, they are likely to produce a p-flux, which is a significant fraction of the > 10^{19}eV CR flux (and a small fraction at lower energy). [EW 95]



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γ>>1 Forward Shock

→ "After glow"

Identifying a GRB-UHECR association

- Direct p-γ association impossible,
  Large delay in arrival time of charged p's compared to γ's,
  Due to magnetic deflections.

- A possible signature- VHE ν's from
  p(A)-p/p(A)-γ → charged pions → ν's,
  $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \overline{\nu_\mu}$,
  $E_\nu/(E_A/A) \sim 0.05$.

The expected VHE ν flux

- For cosmological proton sources,

$$E^2\frac{d\dot{n}}{dE}=Const.=(0.5\pm0.2)10^{44}\,\frac{\mathrm{erg}}{\mathrm{Mpc^3yr}}\ ,$$

- An upper bound to the ν intensity (all p→π):

$$E^2\frac{dj_\nu}{dE}\le E^2\Phi_{\mathrm{WB}}=\frac{3}{8}\frac{ct_H}{4\pi}\zeta\left(E^2\frac{d\dot{n}}{dE}\right)=10^{-8}\zeta\,\frac{\mathrm{GeV}}{\mathrm{cm^2s\ sr}},$$

$$\zeta=0.6{,}3\ \text{for}\ f(z)=1,(1+z)^3.$$

[EW & Bahcall 99; Bahcall & EW 01]

- Saturation of the bound expected at
  - ~10^{10}GeV – GZK ν's IF UHECR dominated by p's. [Berezinsky & Zatsepin 69]
  - <~10^6GeV – IF CR production follows star-formation activity.
    Most stars formed in rapidly star-forming galaxies,
    which are CR "calorimeters" for E/Z <~ 10^6 GeV=1 PeV -
    All E/Z <~ 1 PeV CR energy lost to π production in ISM. [Loeb & EW 06]

GRB ν's

- Neutrinos are produced efficiently only at the smallest collision radii :

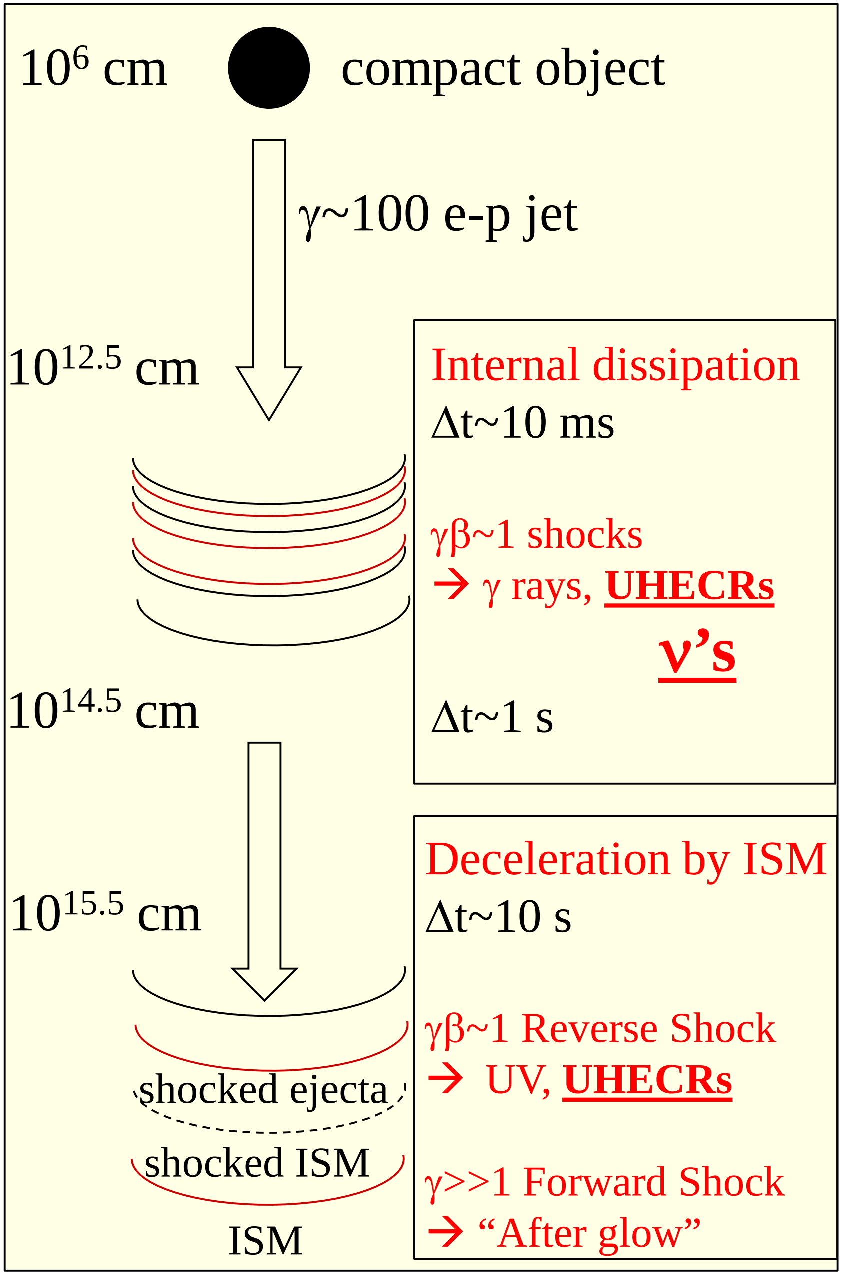
$$\tau_{\gamma p} = 1\,\frac{L_{52}}{\gamma_{300}^{4}\Delta t_{10\mathrm{ms}}}\begin{cases}1 & E > E_b\\ E/E_b & E < E_b\end{cases}$$

$$= 1\tau_{\gamma\gamma}(100\mathrm{MeV})\begin{cases}1 & E > E_b\\ E/E_b & E < E_b\end{cases}$$

$$E_b = 10^{7}(\gamma/300)^{2}\ \mathrm{GeV}$$

[EW & Bahcall 97]

p's lose ≈10% of their energy to π's,
At ~10ms Internal Shocks.
Prompt ν's:
$\Phi_{\mathrm{grb}} \approx 0.1\, f_{p,\mathrm{grb}}\, \Phi_{\mathrm{WB}}$ (at $E>E_b/20$).



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→ γ rays, **UHECRs**
ν's

Δt~1 s

Deceleration by ISM
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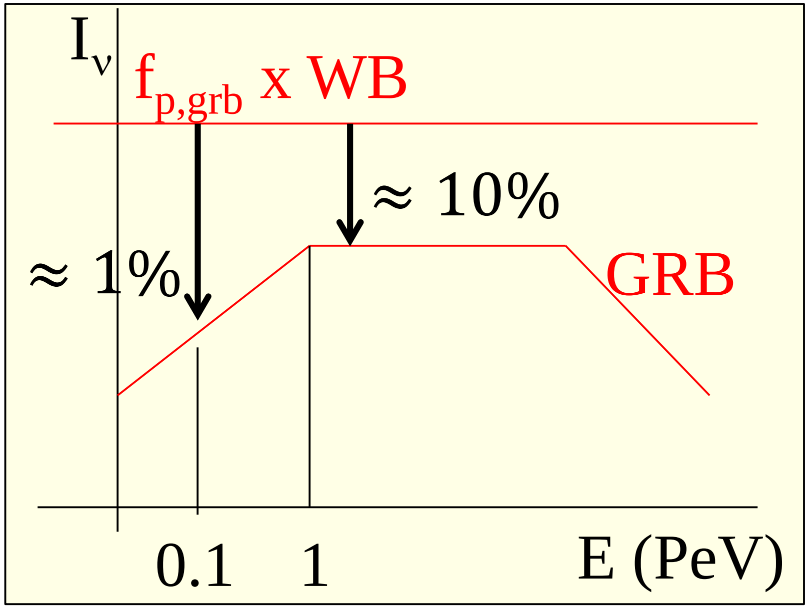
→ UV, **UHECRs**

γ>>1 Forward Shock
→ "After glow"

GRB ν's: Predictions vs Observations

- IceCube & ANTARES limits (90% CL) at 0.1 PeV:
  ANTARES $\Phi_{grb} < 10\% \; \Phi_{WB}$
  IceCube $\Phi_{grb} < 0.4\% \; \Phi_{WB}$
  (5 expected, none detected)
- Imply $f_{p,grb} < 1$ or $\tau_{\gamma\gamma}(100\mathrm{MeV}) < 1$, or both.
- Limited implications to common GRB models.

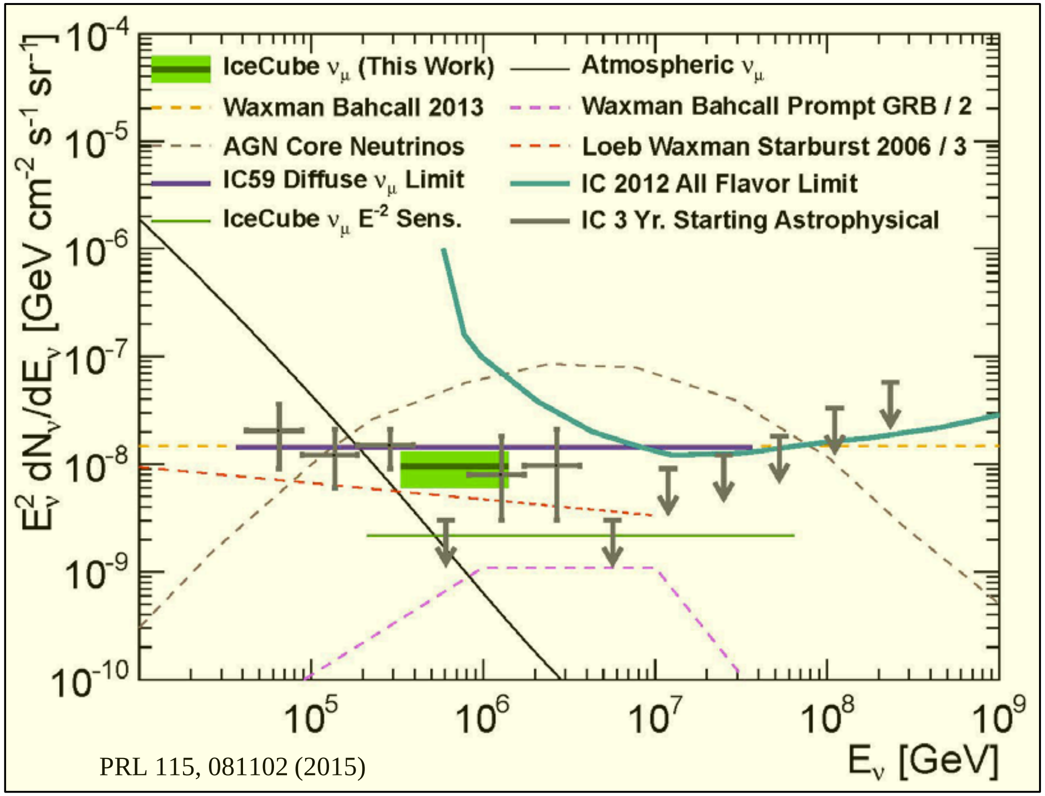


[EW & Bahcall 97; Ahlers et al. 11; Hummer, Baerwald, and Winter 12; Li 12; He et al 12 …Tamborra & Ando 15, Bustamante et al. 17]

Significantly larger detectors are required for detection/ more stringent constraints.

Identifying the UHECR sources

- IceCube detects $\Phi_\nu \approx \Phi_{WB}$ at 50 TeV < E_ν < few PeV.
- The saturation of the bound suggests an association with UHECR sources, Consistent with the expected saturation for CR sources residing in star-forming galaxies ("PeV calorimeters"). [e.g. Murase & EW 16]



PRL 115, 081102 (2015)

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- The saturation of the bound suggests an association with UHECR sources, Consistent with the expected saturation for CR sources residing in star-forming galaxies ("PeV calorimeters").

- $\Phi_\nu \ll \Phi_{WB}$ is expected for "Prompt ν emission", associated with transient photon production at the source, for all candidate sources.
- Identifying the sources is, and will remain, challenging.

  No significant ν association with EM sources in current IceCube data.

  [arXiv:2109.05818]

- Temporal prompt ν–γ association

  is the most promising way to source identification.

  Requires:

  Wide field EM sky monitoring,

  Real time alerts for follow-up of HE ν events,

  and

  Significant [x10] increase of the ν detector mass at ~100TeV.

GRBs & heavy nuclei

- Heavy nuclei in HL (10^{52}erg/s) GRBs
  - May be entrained (for a jet propagating through a pre-SN star) or formed in cold (<<1MeV) outflows, and
  - May survive disintegration if accelerated at r~10^{15}cm.

[e.g. Lemoine 02, Beloborodov 03, Metzger et al. 11, Murase et al. 12, Globus et al. 15, Winter et al. 15, Murase et al 18]

- Heavy nuclei survival is more likely in LL, L<10^{49}erg/s, GRB jets. Have been suggested as high Z UHECR sources,

[e.g. Murase et al. 08, Horiuchi et al. 12, S. Shibata & Tominaga 15, Zhang et al. 18]

and as IceCube neutrino sources.

[e.g. Murase et al. 06, Gupta & Zhang 07, Murase & Ioka 13, Liu & Wang 13]

** Requires: UHECR energy > 100 e^- energy.

** Not clear that LL GRBs are produced by relativistic jets. They are likely produced by "shock breakout" in supernovae with compact progenitors- no UHE CRs and ν's.

Summary & Outlook

- HL, 10^{52}erg/s, GRB jets are capable of accelerating p's to 10^{20}eV.
  - $E^2 \frac{d\dot{n}}{dE} \approx Const.$, $f_p \geq 10\%$ at $E > 10^{19}\mathrm{eV}$ (for e-p dominated jets),
  - $\Phi_{\nu,\mathrm{grb}} \approx 0.01(0.1) f_p \Phi_{\mathrm{WB}}$ at $0.1(1)$ PeV (for common γ production models).

- Current experimental constraints
  - UHECRs: Heavy composition at $E > 10^{19}\mathrm{eV}$, $f_p \approx 10\%$ allowed & preferred.

    Experimental & HE interaction model uncertainties (inconsistencies)

    → Large composition uncertainty, f_p may be $\gg 10\%$.
  - HE ν's: $\Phi_{\nu,\mathrm{grb}} < 0.01\ \Phi_{\mathrm{WB}}$ at 0.1 PeV.

- What is required for a conclusive test of the model/ UHECR source identification?
  - * A (reliable) measurement of the p-fraction at UHE.
  - * Prompt γ-ν coincidence.
- Can be addressed by next generation CR, ν & γ telescopes.
  - * UHECRs: Auger', TA.
  - * ν's: $0.1\Phi_{WB} = 10^{-9}\mathrm{GeV/cm^2 s\ sr}$ @ $10^8 - 10^{10}\mathrm{GeV}$ (Radio).
  - * ν's: M_{eff}~10 Gton @ $10^5 - 10^8\mathrm{GeV}$ (IceCube Gen 2, KM3NeT, GVD-2).
  - * Wide field EM monitoring, X/γ telescopes (real time alerts).