High energy neutrinos (and cosmic rays) from Gamma-Ray Bursts

Status of the WB model

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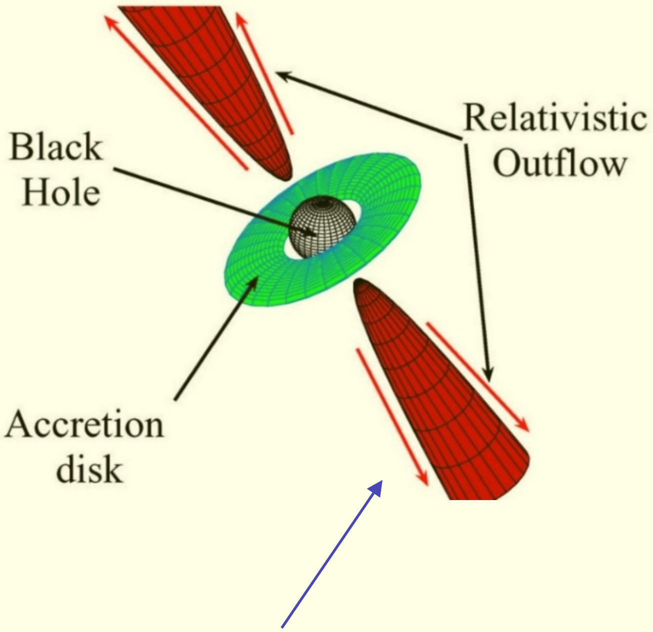
Widely considered GRB models

- 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).
  $\gamma > 100$ based on 100 MeV photons' escape.

- 2 scenarios
  - 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.



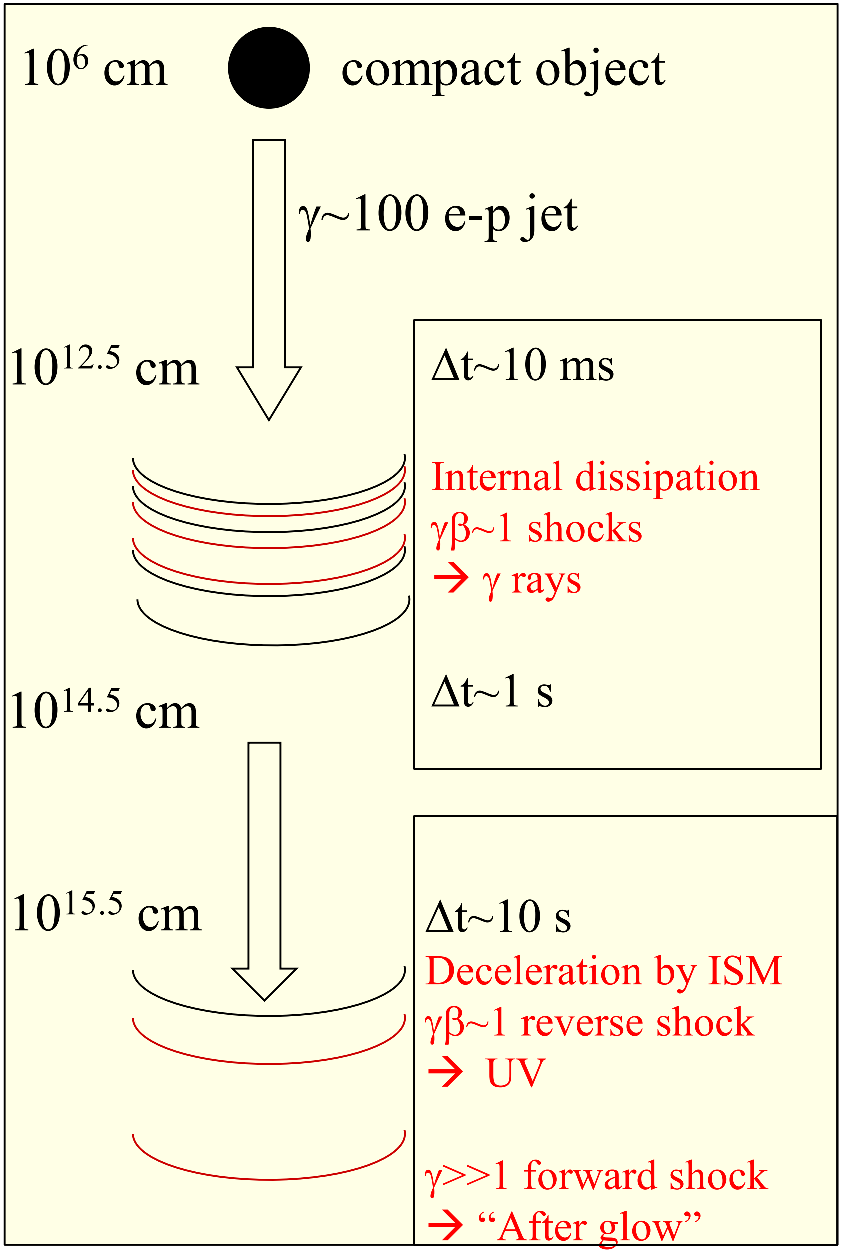
Particle acceleration

Common e-p jet models

- Electrons accelerated by collisionless shocks.

- In the jet frame, the internal (& reverse) shocks are mildly relativistic.
  - $E^2 \frac{d\dot{n}}{dE} = \text{Const.}$ 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 $E^2 \frac{d\dot{n}}{dE} = \text{Const}$ and near equipartition B.



10^6 cm

compact object

$\gamma \sim 100$ e-p jet

$10^{12.5}$ cm

$\Delta t \sim 10$ ms

Internal dissipation
$\gamma\beta \sim 1$ shocks
→ γ rays

$\Delta t \sim 1$ s

$10^{14.5}$ cm

$10^{15.5}$ cm

$\Delta t \sim 10$ s
Deceleration by ISM
$\gamma\beta \sim 1$ reverse shock
→ UV

$\gamma >> 1$ forward shock
→ "After glow"

p acceleration in GRBs

- In the region where e^- are accelerated, p would also be.

  - Max p energy

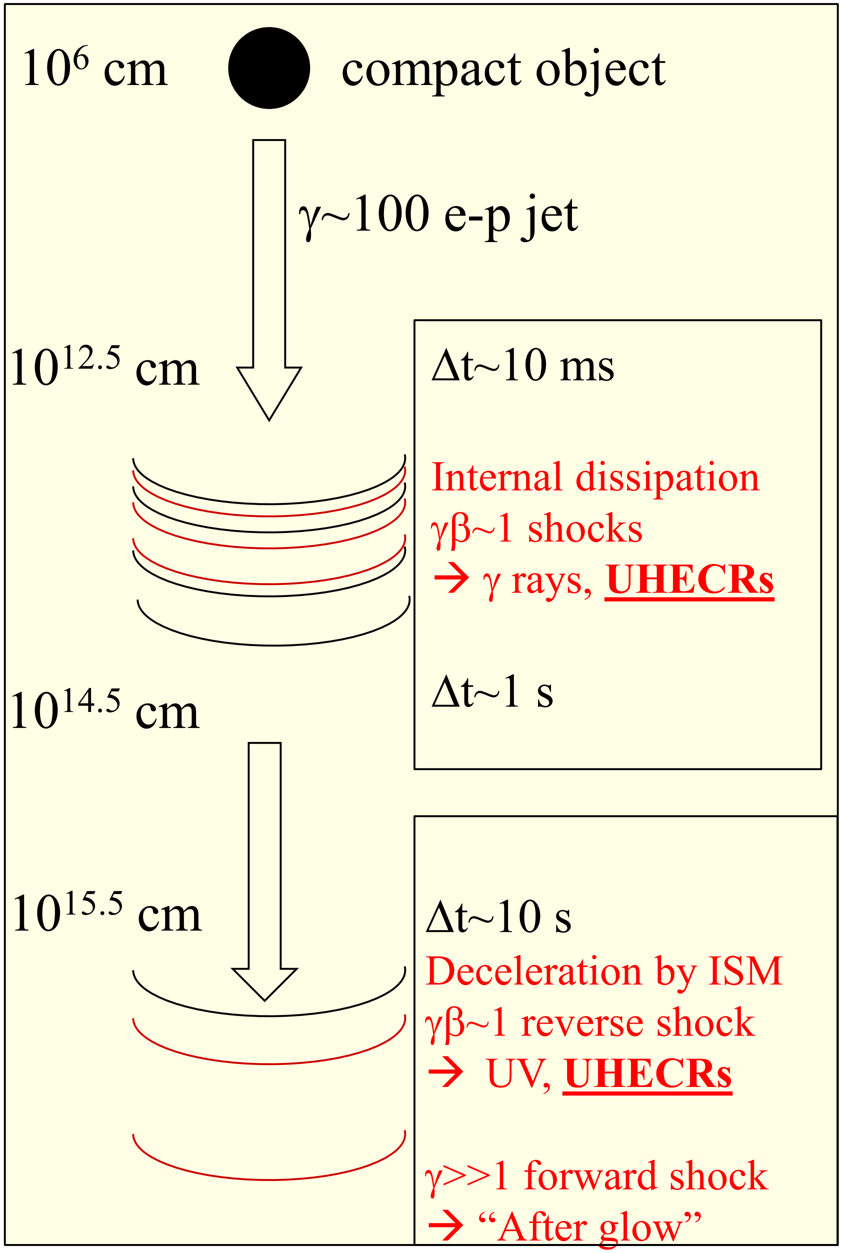
$$E < 10^{21}\left(\frac{100}{\gamma}\right)\left(\frac{L}{10^{52}\mathrm{erg/s}}\right)^{1/2}\ \mathrm{eV}\ .$$

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

  - Min γ to avoid acceleration suppression by radiation losses: $\gamma > 100$.
    Consistent with γ inferred from escape of 100 MeV photons.

[EW 95]

(Heavy nuclei dissociated by radiation field.)



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Extra-Galactic flux of GRB UHE p's

- Energy production rate

$$\gamma:\ R_{z=0}\overline{E_\gamma} = \frac{10^{52.3\pm0.7}\,\mathrm{erg}}{1\,\mathrm{Gpc^3yr}} = 10^{43.3\pm0.7}\,\frac{\mathrm{erg}}{\mathrm{Mpc^3yr}}$$

p:

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

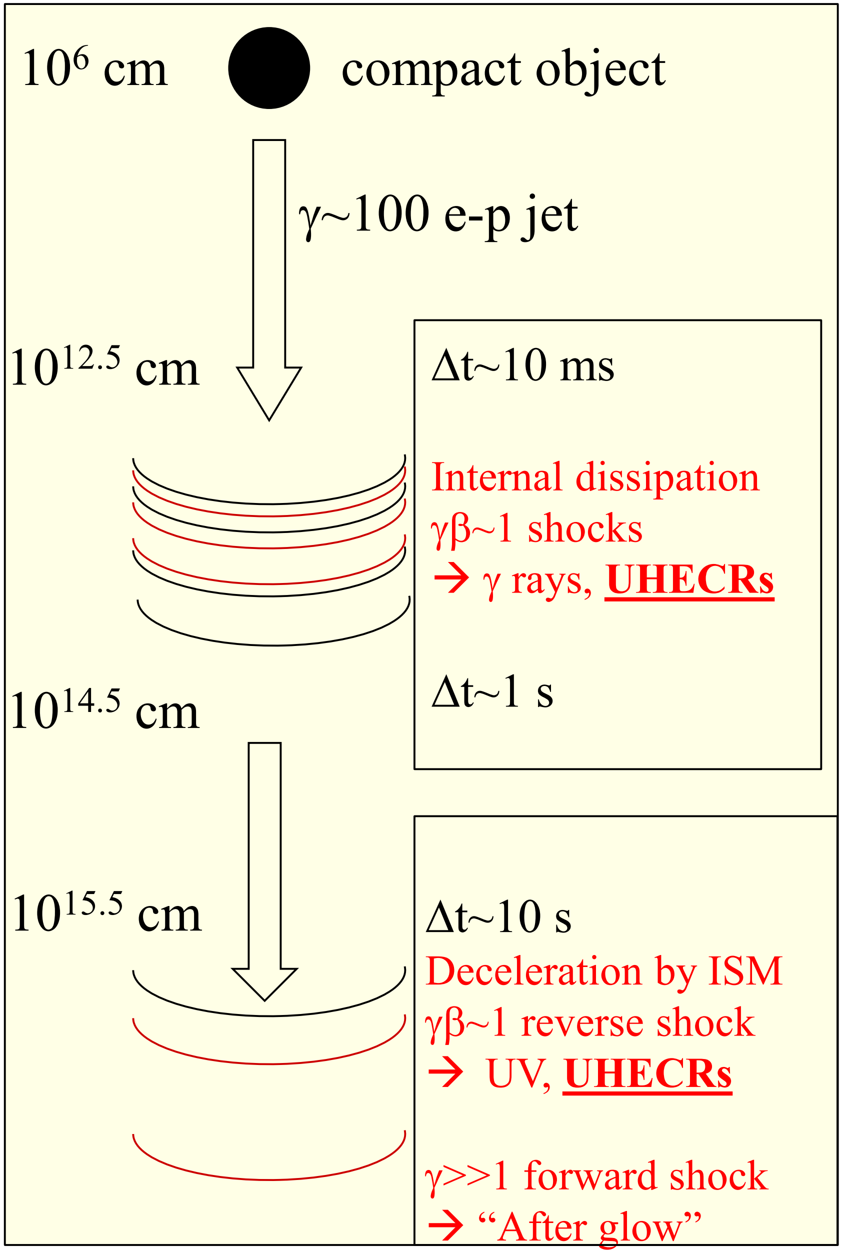
- The proton generation rate required to produced the full >10^{19}eV CR flux:

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

- 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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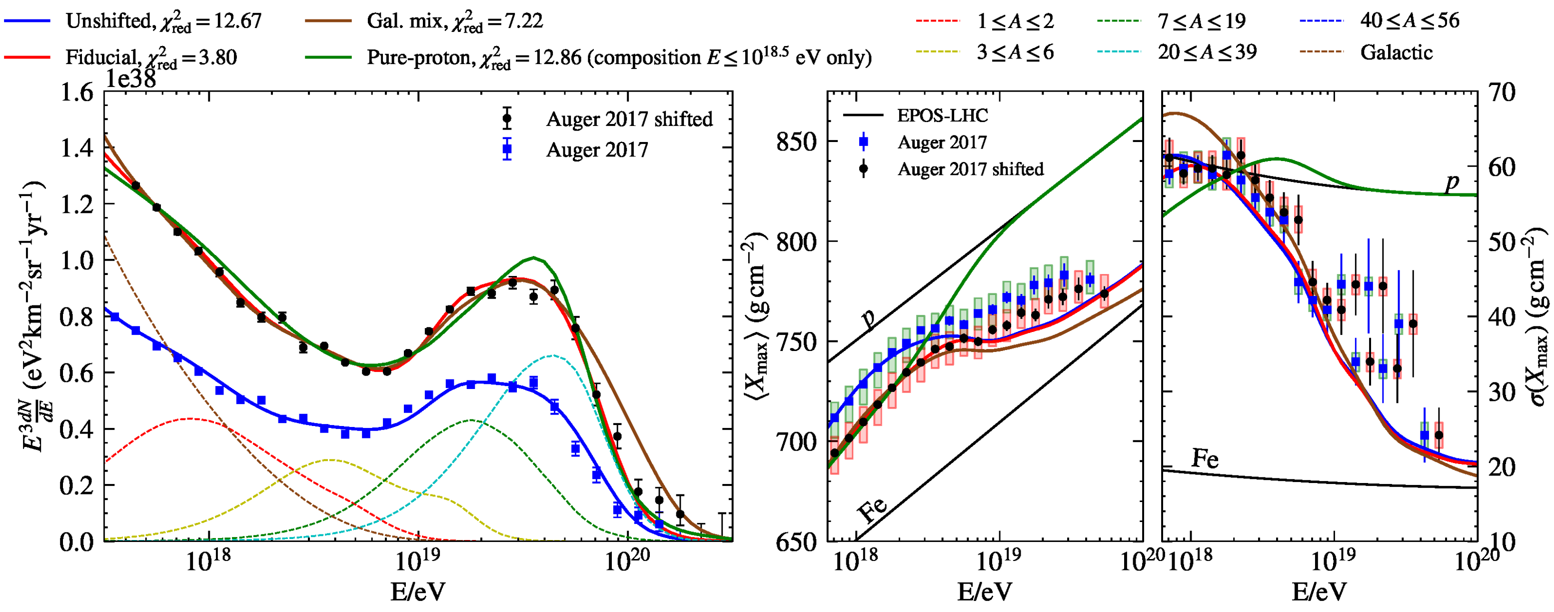
PAO/TA composition constraints

- PAO X_{max} data commonly interpreted as a heavy mix.
- Model X_{max} variance inconsistent (smaller than) measured at >10^{19}eV.



[Muzio, Unger & Farrar 19]

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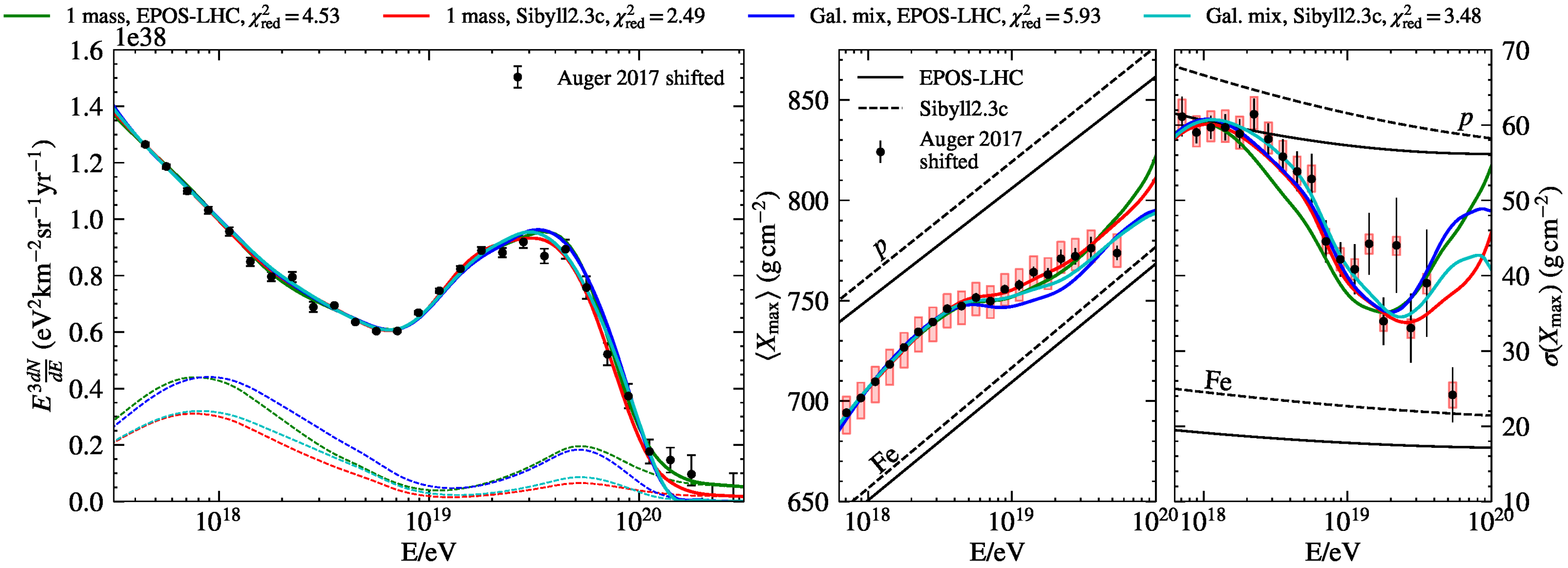

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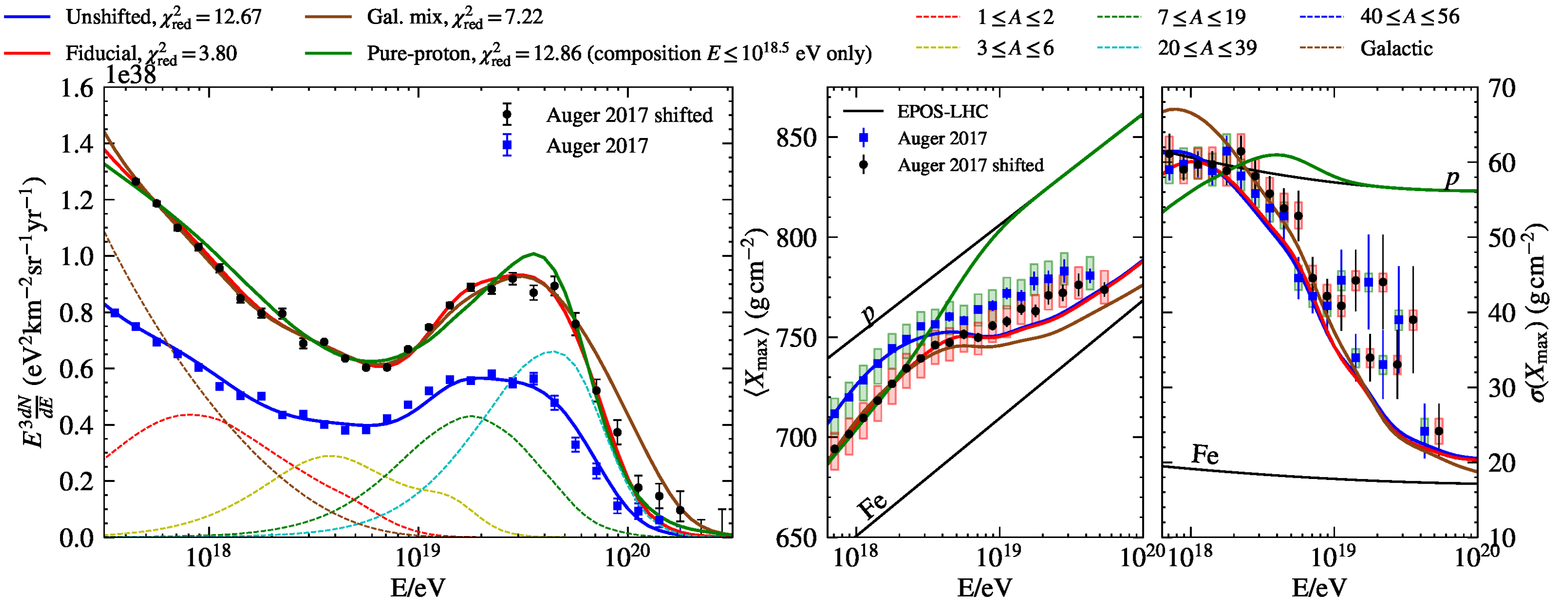
- Some questionable ad-hoc model choices:
  - Generation spectrum $E^2 \frac{d\dot{n}}{dE} \propto E$,
  - Acceleration “cutoff” at $10^{19.5}$eV- a chance coincidence with p-GZK,
  - Composition @ source H : He : Heavier = 1 : 1 : 1,
  no known astrophysical system.



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- Major uncertainties due to interaction models' uncertainties.
  - Model uncertainty may be larger than spanned by the 'generator' span (QGSJET, EPOS, SIBYLL)?
  - Data inconsistent with models (see e.g. Sergey Ostapchenko's talk): PAO data inconsistent with QGSJET, consistent with EPOS that probably underestimates the X_{max} variance; X^{μ}_{max} - X_{max} .

- Experimental discrepancies- e.g.
  - PAO/TA spectra.
  - TA consistent with QGSJET & implies a very light composition.

A robust conclusion RE composition cannot be drawn.
$f_p \geq 0.1$ cannot be ruled out, may be required.

The significance of UHECR composition

- EM acceleration:

$$L > 10^{46}\,\frac{\Gamma^2}{\mathrm{v}/c}\left(\frac{E/Z}{10^{20}\mathrm{eV}}\right)^2 \mathrm{erg/s}\ .$$

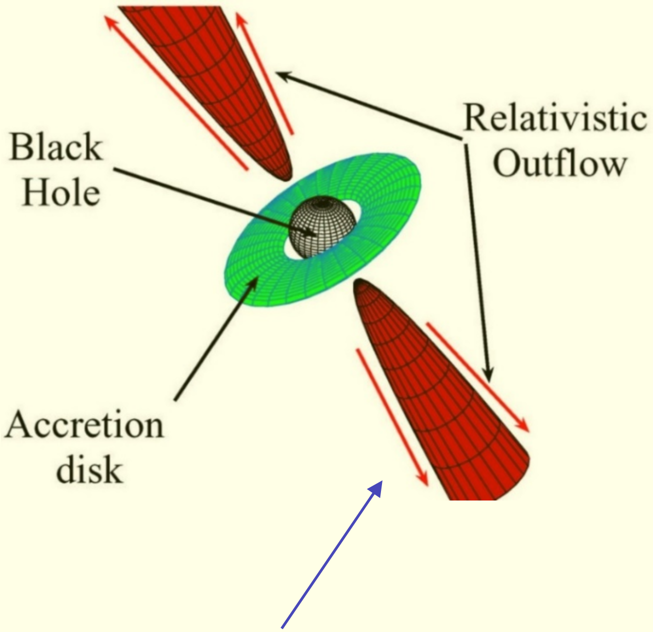
- Z>10 - Several candidate sources.

Z=1, p – 2 candidate transient sources,
Rapid mass accretion onto BHs.

- Gamma-ray bursts (GRB), newly formed solar mass BHs;
- Tidal disruption of stars (TDE) by massive BHs at galaxy centers, MAY produce "GRB-like" jets.

(- Young, ms, 10^{13}G Neutron Stars? If they exist…)

Relativistic flows driven by BH accretion.



Particle acceleration

GRB prompt ν's

- p-γ interaction at the internal/reverse shocks will produce neutrinos.
- p acceleration occurs with similar efficiency and max E at all radii (up to deceleration).
- Neutrinos are produced efficiently at the smallest collision radii only:

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

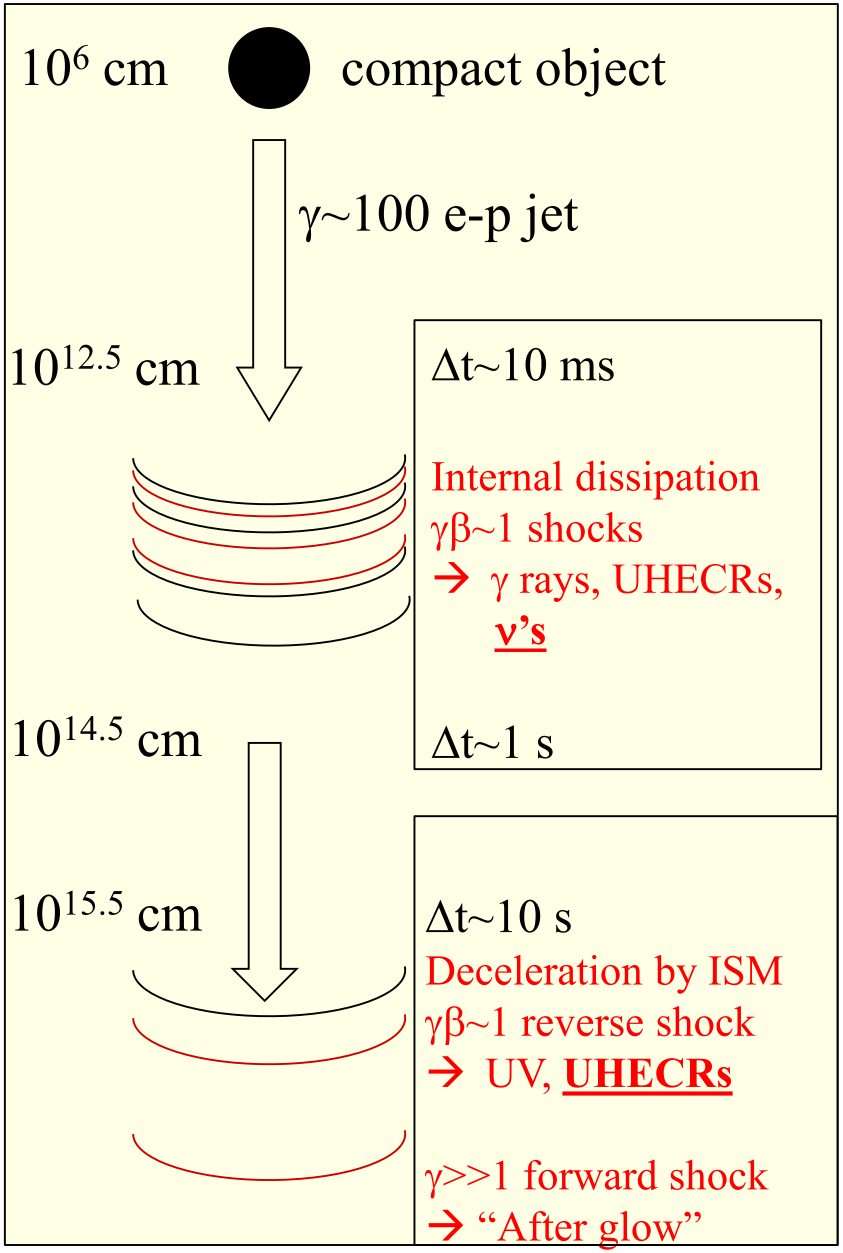
$$= 1 \tau_{\gamma\gamma}(100\mathrm{MeV}) \begin{cases} 1 & E > E_b \\ E/E_b & E < E_b \end{cases}$$

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

p's lose ≤10% of their energy to π's.
Prompt ν's:
$\Phi_{grb} = 0.06 \, f_{p,grb} \, \Phi_{WB}$ (at $E > E_b/20$)

[EW & Bahcall 97]

$$\Phi_{WB} \approx 10^{-8} \frac{\mathrm{GeV}}{\mathrm{cm}^2 \mathrm{s\ sr}} \quad \text{per flavor}$$



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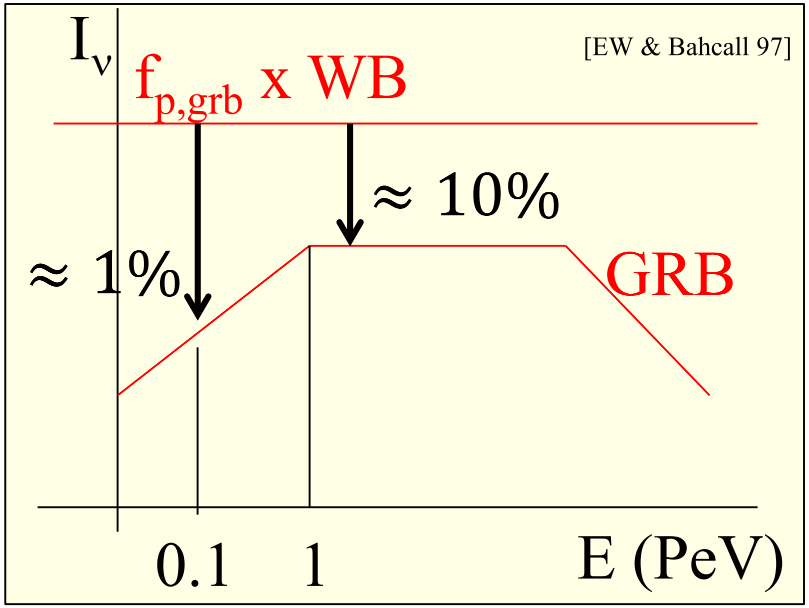
GRB Prompt ν's: Predictions vs Observations

- 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.
- *A* positive detection would be highly significant, e.g.
  - Identify UHECR p sources,
  - Support e-p dominated jets.
- Due to limited statistics and existing model uncertainties, the current negative result does not have major 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 CR sources

- IC's ν's are likely produced by the "calorimeters" surrounding the sources.
  Prompt emission from the source, $\Phi \ll \Phi_{WB}$.
  Identifying the sources is, and will remain, challenging.

- UHECRs are likely produced by transient "bursting" sources.
  Temporal (prompt) $\nu-\gamma$ 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: ν-γ timing (10s over Hubble distance)
  → LI to $1:10^{16}$; WEP to $1:10^{6}$.

[EW & Bahcall 97; Amelino-Camelia,et al.98;
Coleman &.Glashow 99; Jacob & Piran 07, Wei et al 16]

GRBs & heavy nuclei

- Heavy nuclei in (10^{52}erg/s) GRBs
  - May be entrained (for a jet propagating through a 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]

  Enhances model's flexibility, difficult to rule out…

- heavy nuclei survival more easily in LL, L<10^{49}erg/s.
  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]

  ** Not clear that LL GRBs are produced by relativistic jets,
  If produced by "shock breakout"- no UHE CRs and ν's.

- "Chocked" GRB jets have also been suggested to dominate IceCube's ν signal.

[e.g. Meszaros & EW 01, Senno, Murase, and Mészáros 16]

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.

    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).