A holistic view of UHECR sources

populations, energetics, and observational constraints

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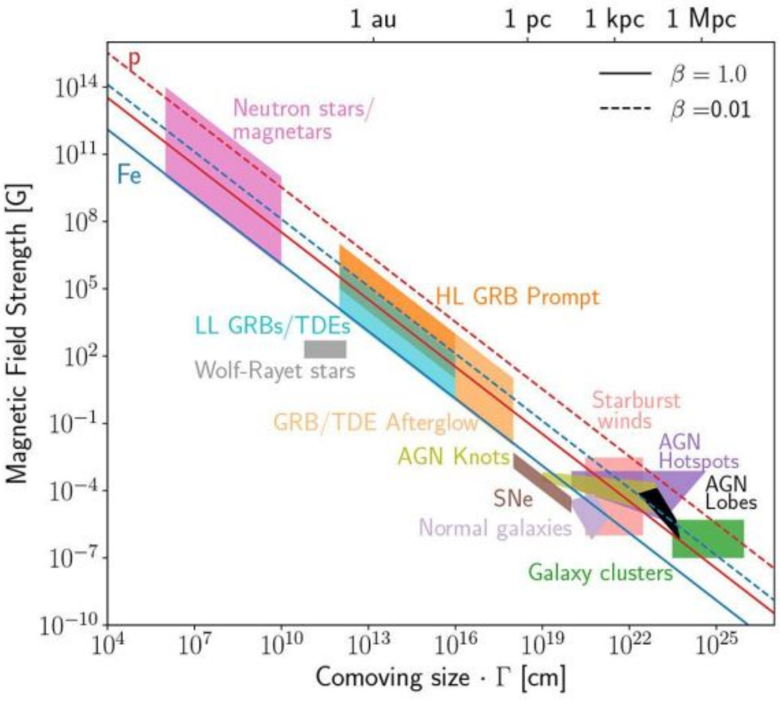
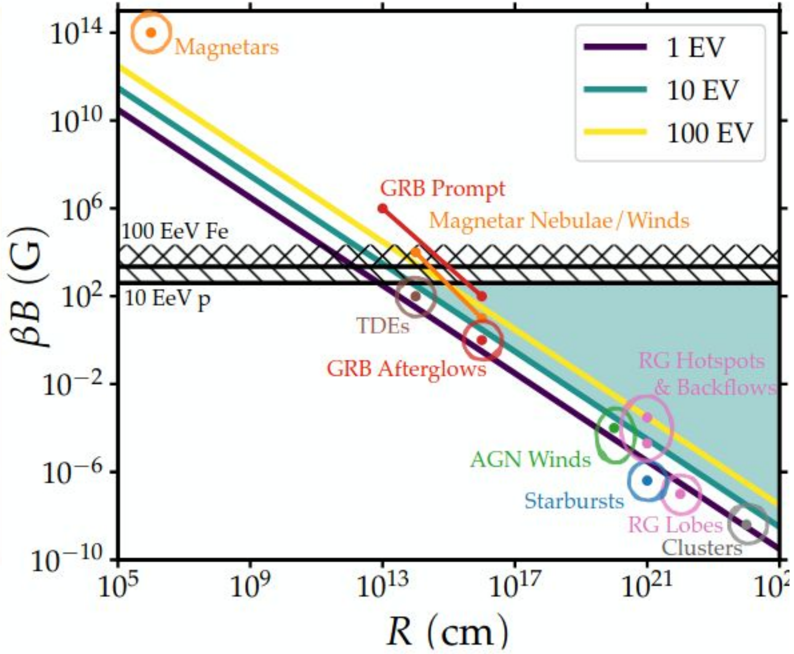
Potential sources of UHECR



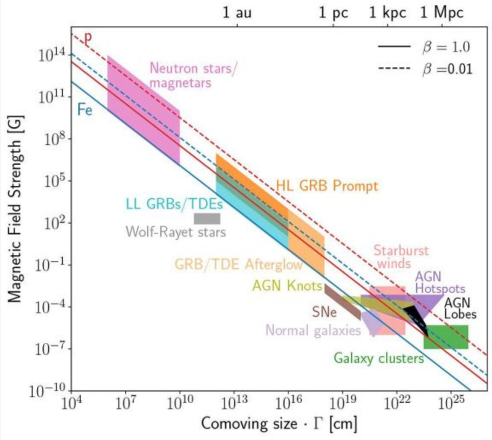
Alves Batista et al.,FSPAS,2019

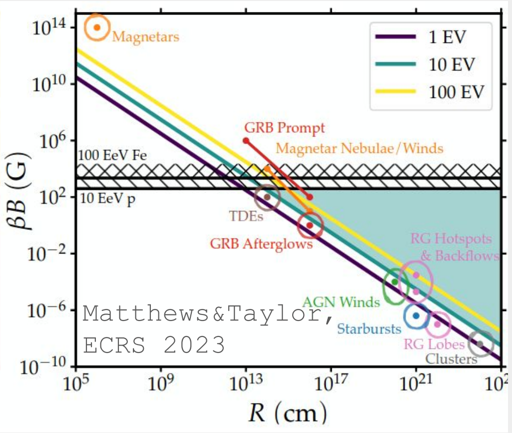


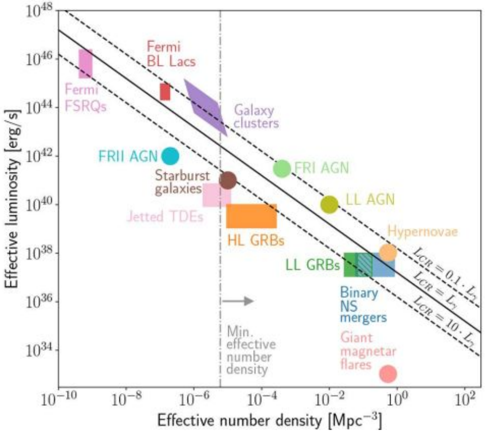
Matthews&Taylor, ECRS 2023

Potential sources of UHECR

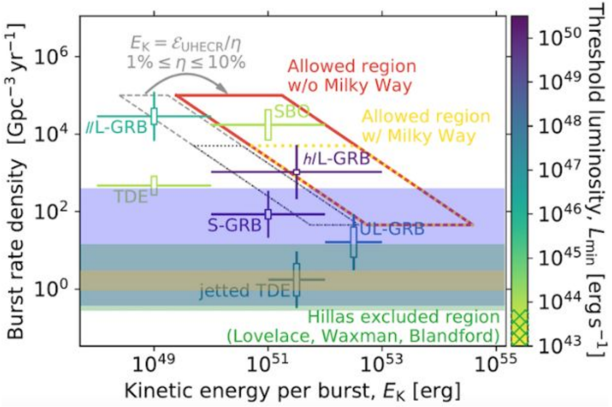
Alves Batista et al.,FSPAS,2019



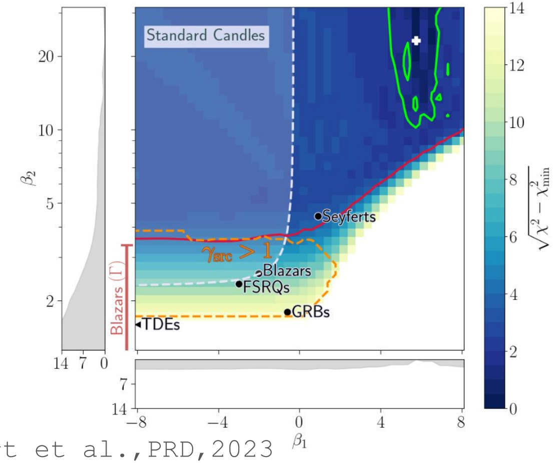




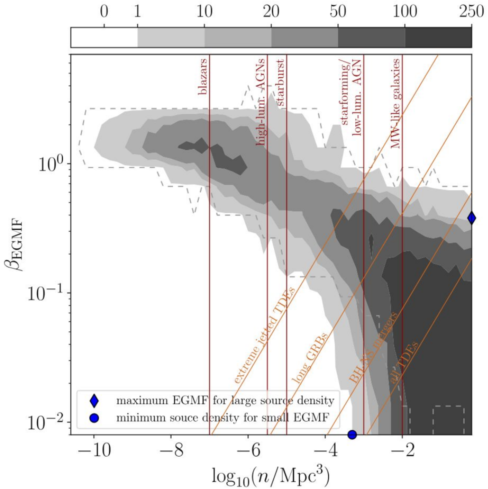
Alves Batista et al.,FSPAS,2019



Marafico et al.,ApJ,2024



Ehlert et al.,PRD,2023



Bister&Farrar,ApJ,2024

In this work

- Study the constraints of UHECR in a unified scenario
- Populations: Radio Galaxies: FRI & FRII

  Blazars: FSRQ & BL Lac

  Tidal Disruption Events: All

  Gamma-Ray Bursts: Long & Short

- Verify astrophysical consequences for sources

- Initially most ideal assumptions as possible/reasonable

- Populations can be characterized by Luminosity Functions

$$\frac{dN_{\rm src}}{dV\,d\log L} = \rho_0 \left[\left(\frac{L}{L_*} \right)^{\gamma_1} + \left(\frac{L}{L_*} \right)^{\gamma_2} \right]^{-1} e(z, L)$$

- Overall UHECR injection is associated with “total energy injection”
  - Continuous: Kinetic Power (Q_{kin})
  - Bursts: Kinetic Energy (E_{kin})

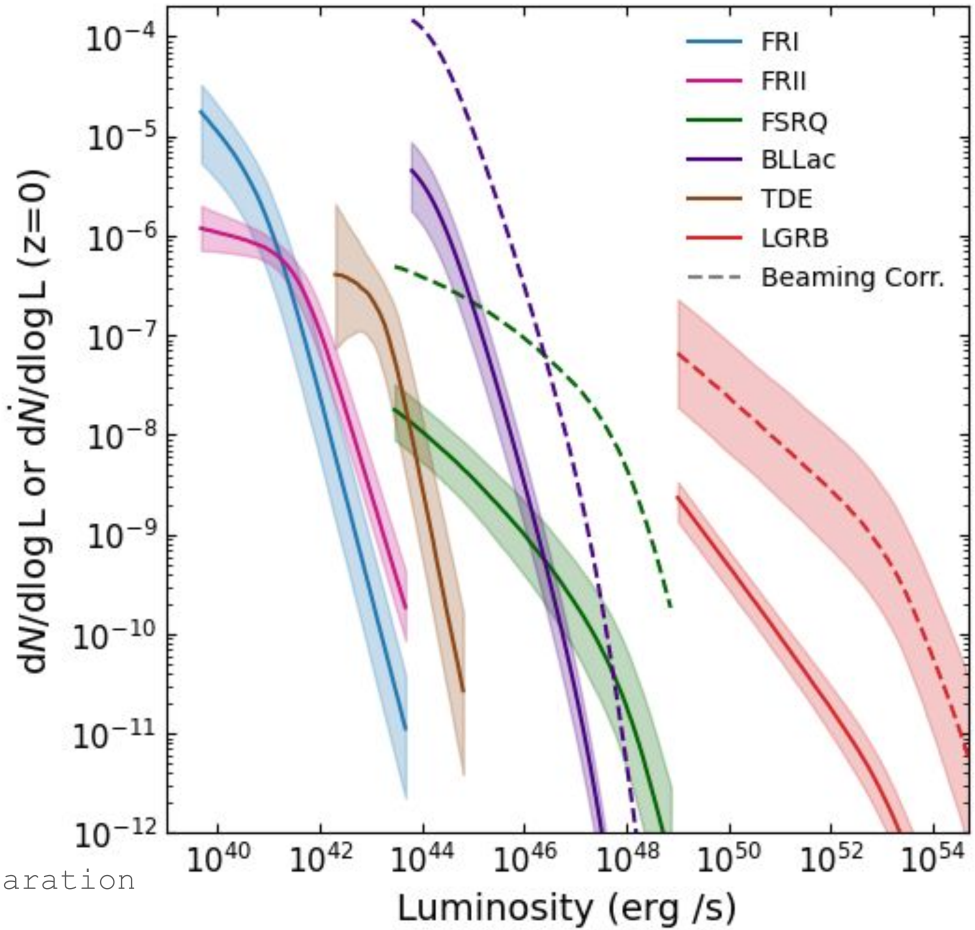
- Kinetic power/energy can be associated with Luminosity

Luminosity Functions

$$\frac{dN_{\rm src}}{dV\,d\log L} = \rho_0\left[\left(\frac{L}{L_*}\right)^{\gamma_1} + \left(\frac{L}{L_*}\right)^{\gamma_2}\right]^{-1} e(z,L)$$

FRI & FRII: de Jong et al. A&A 683 2024
BL Lacs: Ajello et al. ApJ 780 2014
FSRQ: Rajguru et al. ApJ 994 2025
TDE: Yao et al. ApJL 955 2023
LGRB: Lan et al. MNRAS 488 2019

Beaming Factors
BL Lac/FSRQ: Chen et al. MNRAS 519 2023
LGRB: Nemmen et al. Science 338 2012



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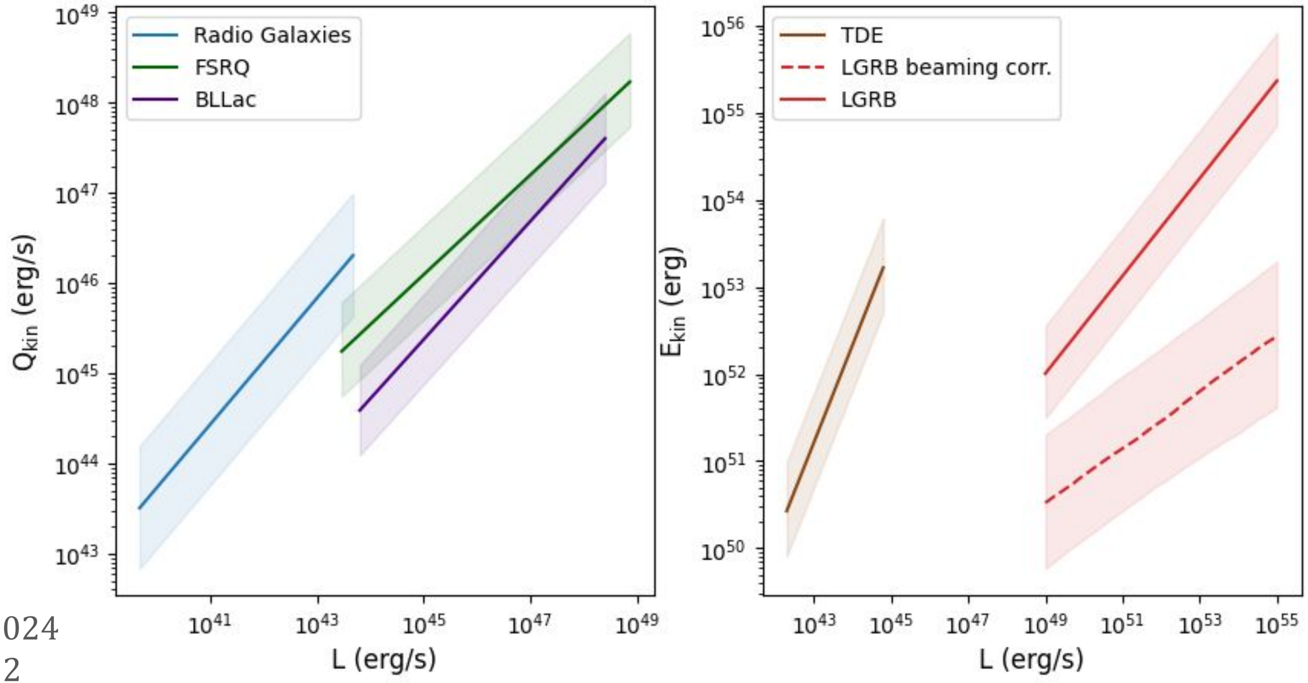
Intrinsic Energetics: Scaling Relationships

For Continuous injection

$$Q_{\rm kin} = Q_0 \left(\frac{L}{L_0} \right)^q$$

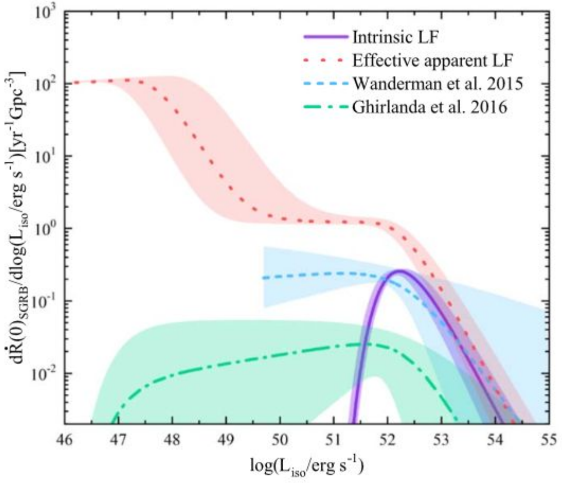
For Bursts

$$E_{\rm kin} = E_0 \left(\frac{L}{L_0} \right)^q$$



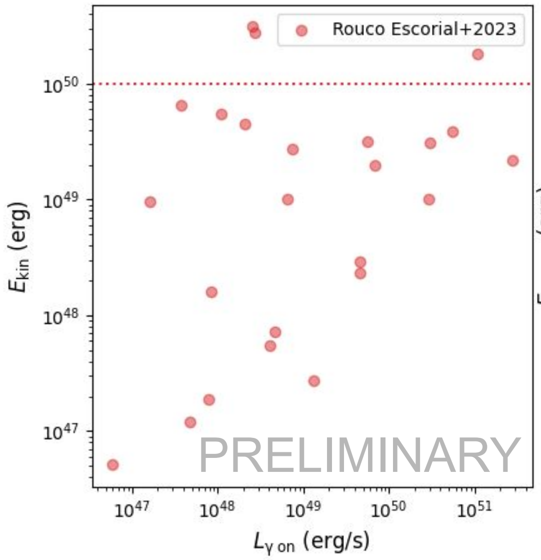
RG: Cavagnolo et al ApJ 720 2010
Blazars: Chen et al. MNRAS 519 2023
TDE: Ledd + Mummery et al MNRAS 2024
LGRB: Nemmen et al. Science 338 2012

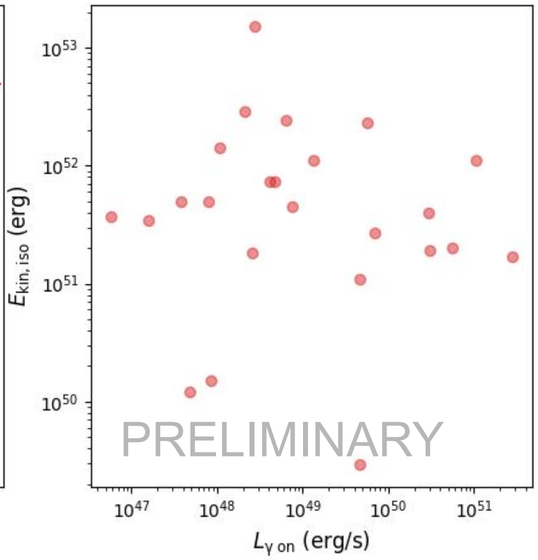
Luminosity Function?



Tan & Yu, **ApJ**, 2020

Scaling Relationship?





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- Alternative: “Universal” scenario SGRB/BNS

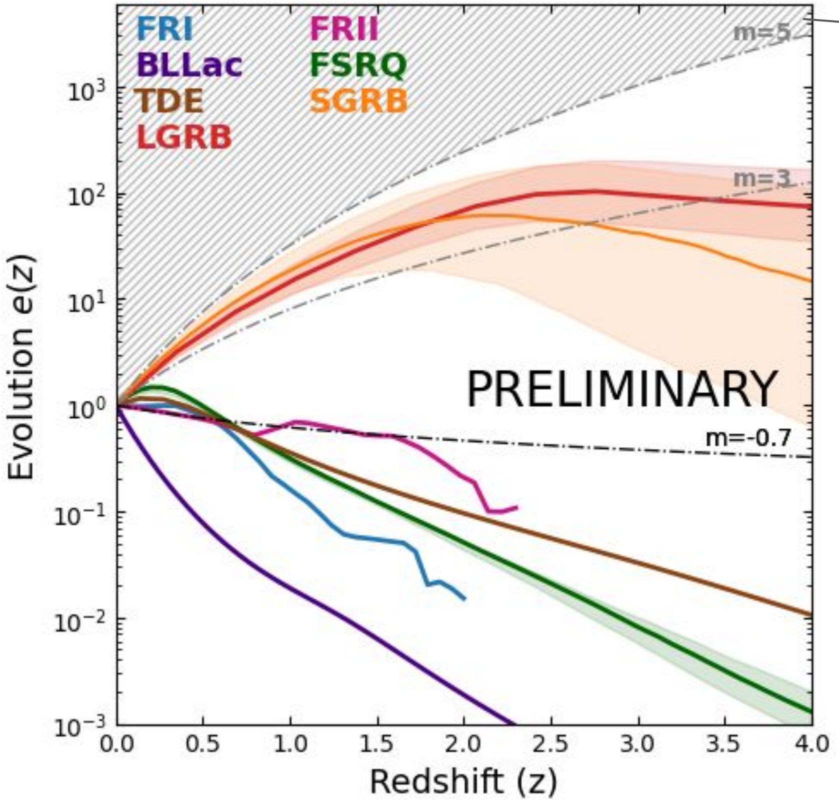
$$\dot{\rho}_{\rm BNS} = 110^{+192}_{-82}\ {\rm Gpc^{-3}\ yr^{-1}} \qquad E_{\rm kin} \sim 10^{49} - 10^{50}\ {\rm erg}$$

$$E^{\rm up}_{\rm kin} \lesssim 1 \times 10^{51}\ {\rm erg}$$

(GW 170817A)

A. Evolution with Redshift: e(z)

Typically assumed $e(z) \sim (1+z)^m$



e.g. Abdul Halim *et al.* JCAP05 2023 024

Alves Batista *et al*. JCAP01(2019)002

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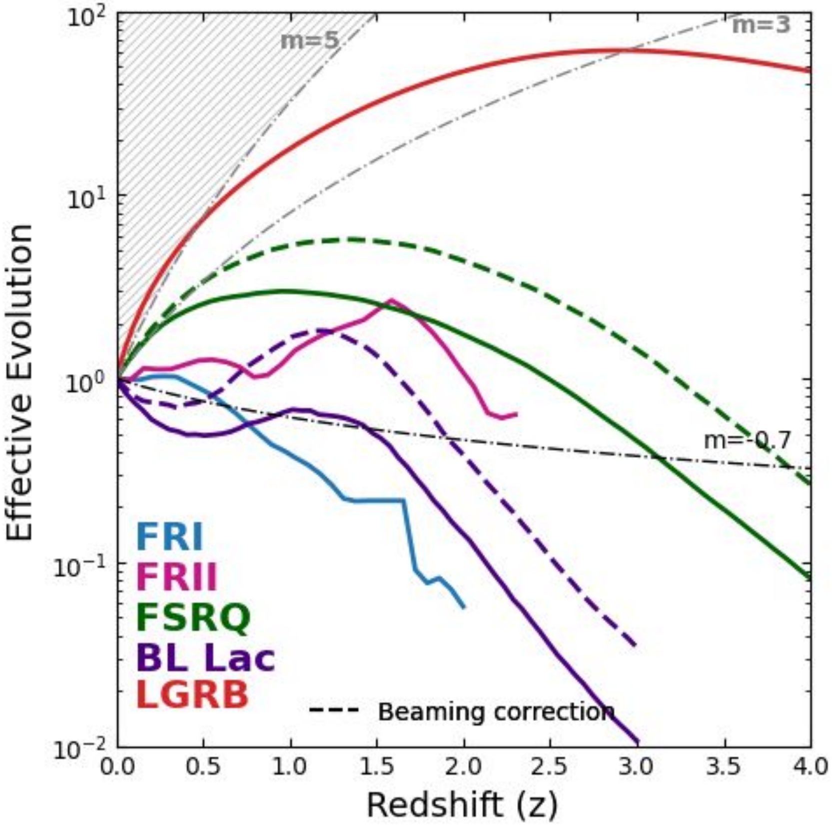
B. Evolution with Redshift: weighted by injection (Qkin or Ekin)

$$e_{\rm eff}(z) = \frac{\int dL\, Q(L)\, e(z,L)}{\int dL\, Q(L)}$$

- TDE and SGRB:
  Largely unknown evolution
  (even less if e = e(L))



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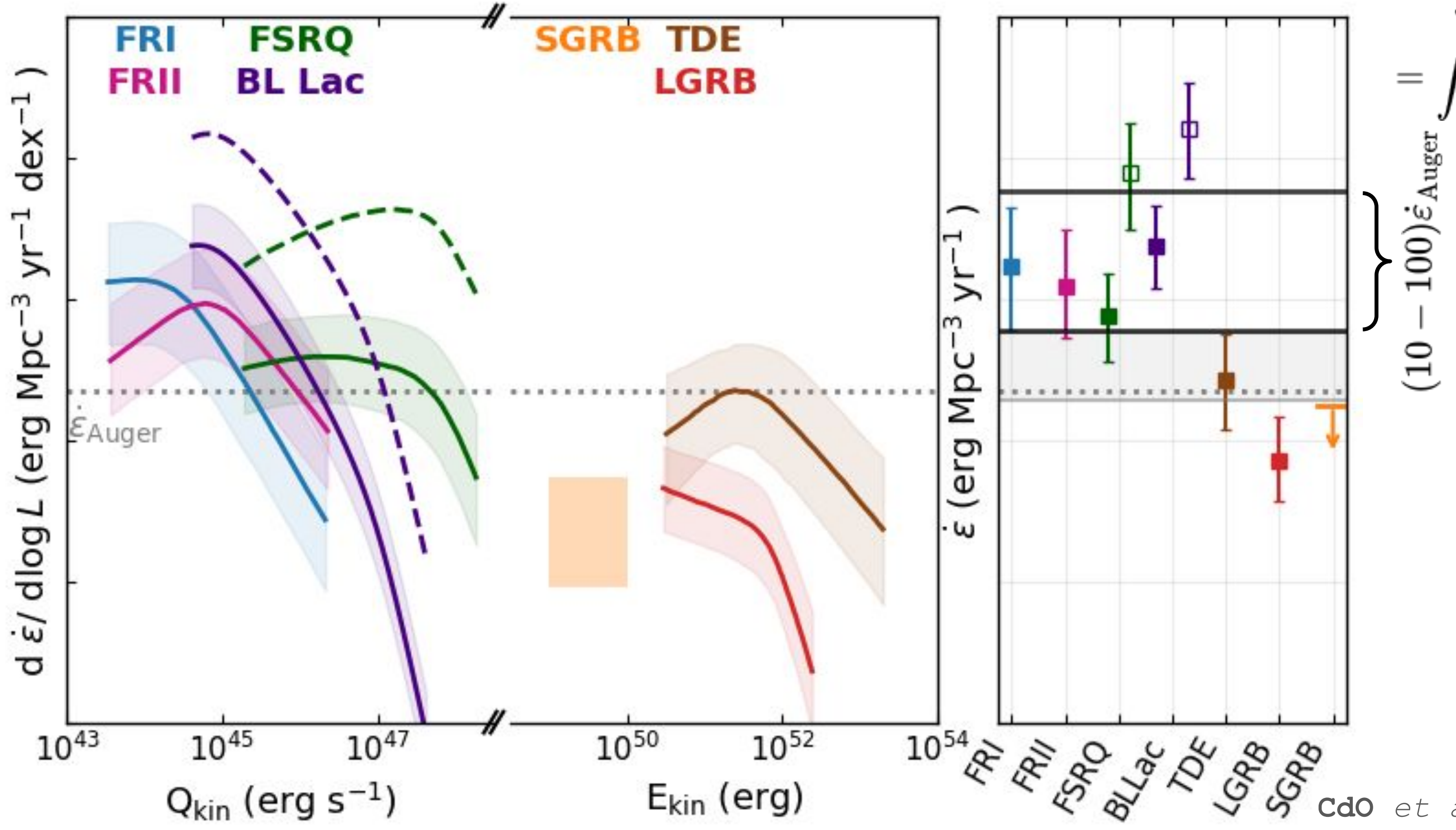
C. Energy Budget (at z=0)

$$\dot{\varepsilon}_{\rm cont} = \int d\log L \, \rho(L) \, Q_{\rm kin}(L)$$

$$\dot{\varepsilon}_{\rm burst} = \int d\log L \, \dot{\rho}(L) \, E_{\rm kin}(L)$$

$$= \int d\log L \, \dot{\rho}_{\rm iso}(L) \, E^{\rm iso}_{\rm kin}(L)$$



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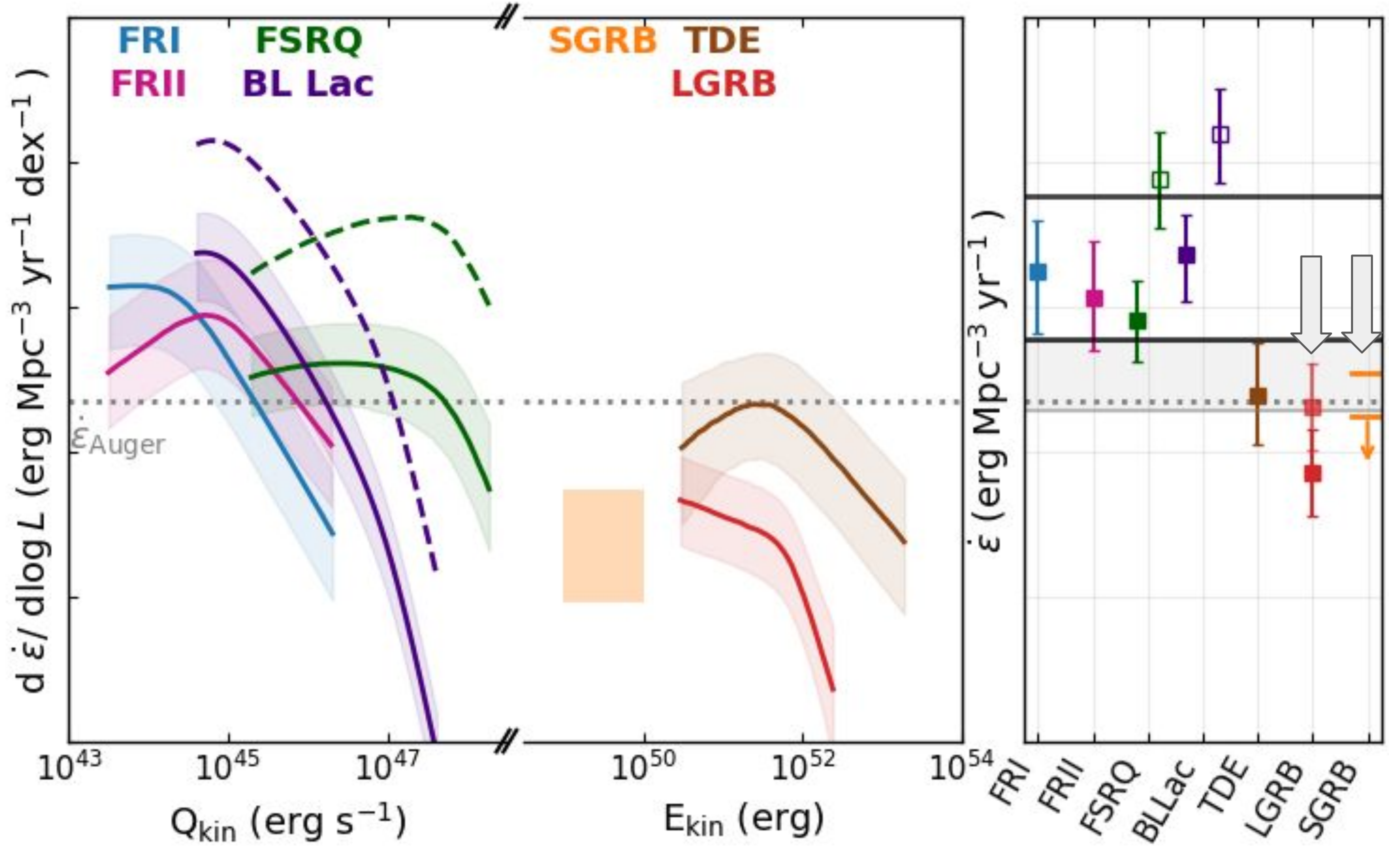
C. Energy Budget – Volumetric Correction?

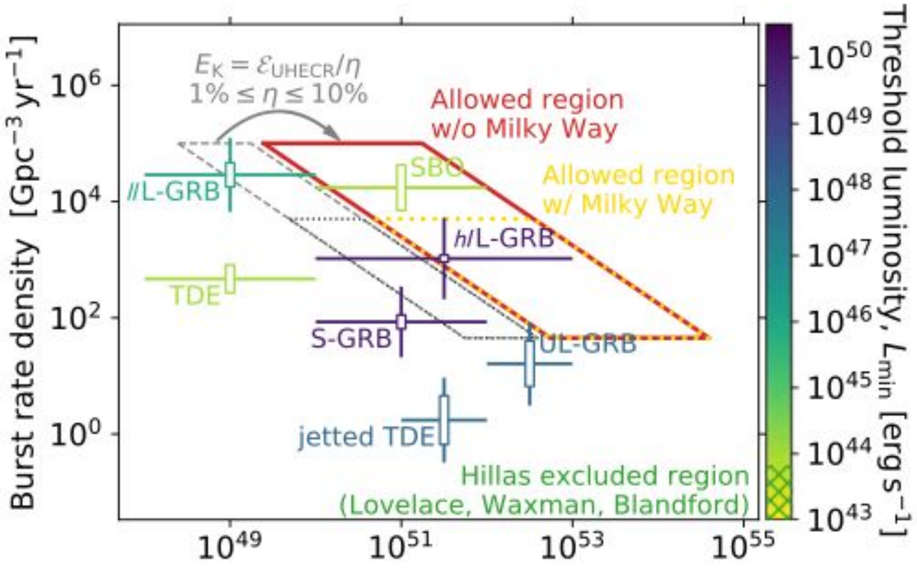
- Since $E \geq 10^{17.8}$ eV and $z_{max} \sim 1$



$$\mathcal{K} \sim \frac{\int dV e(z)}{\int dV}$$

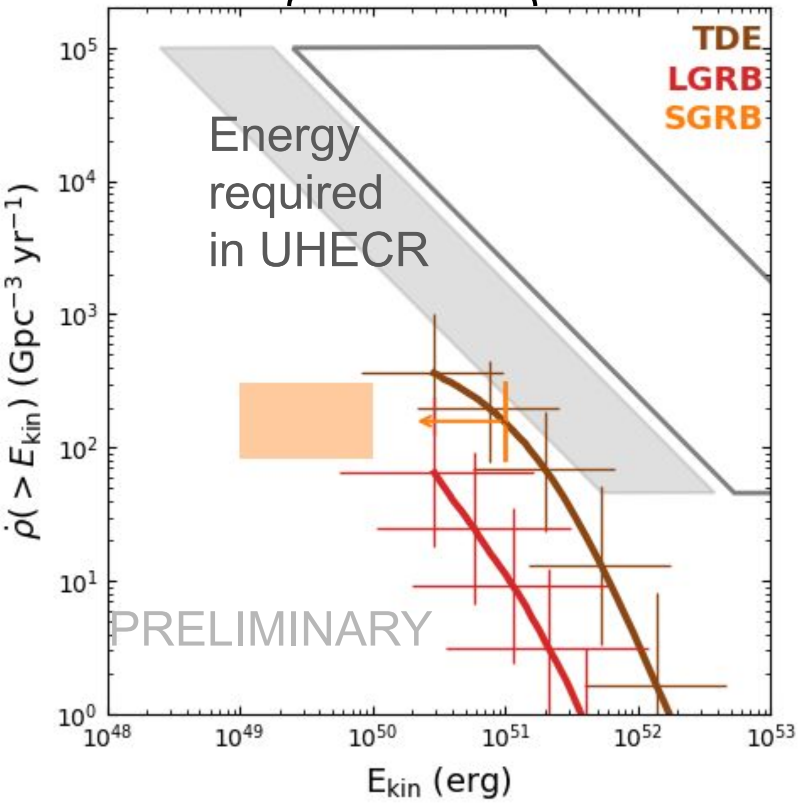
SGRB	2.8 – 4
LGRB	~8
For m ~ 5	K_{max} ~ 9

D. Energy injection vs Burst rate



Marafico et al.,ApJ,2024

$(10-100)\dot{\varepsilon}_{\rm Auger}$



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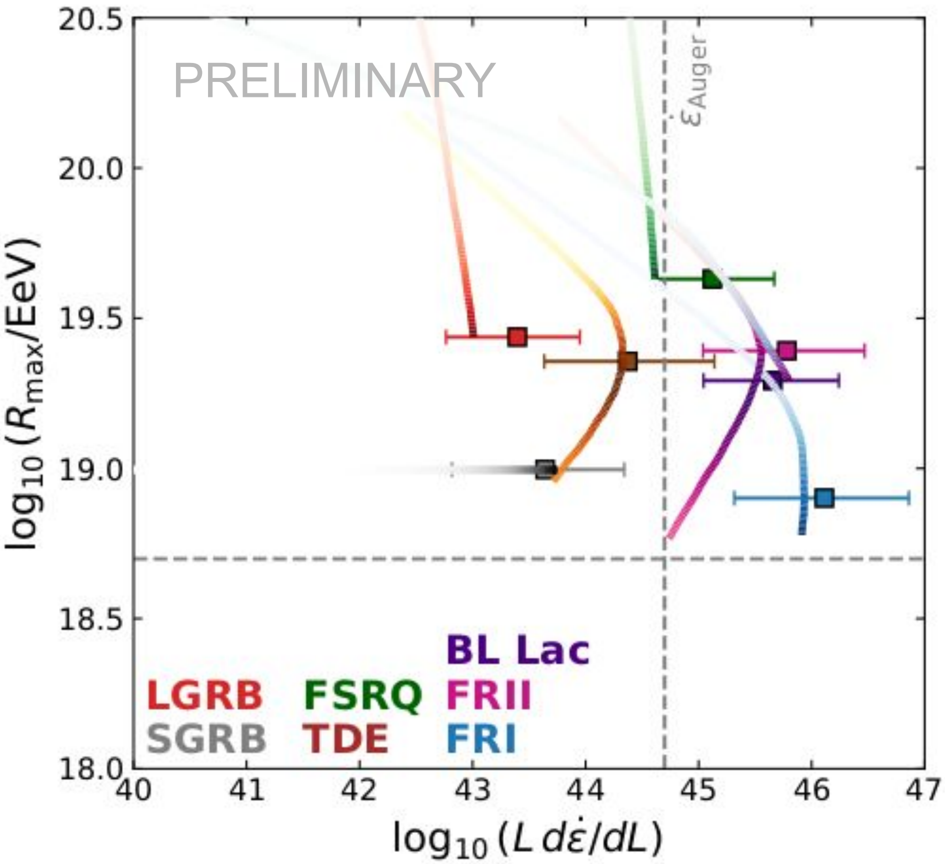
Maximum Rigidity

Radio Galaxy (FRI & FRII)	**Hillas-Lovelace-Waxman-Blandford Limit**	$R_{\rm max} = \eta_{\rm acc} \left(\frac{Q_{\rm jet}}{10^{42}} \right)^{1/2}$
Gamma AGN (FSRQ & BL Lac)		
TDE		$R_{\rm max} = \eta_{\rm acc} \left(\frac{L_{\rm edd}}{10^{42}} \right)^{1/2}$
LGRB	**S. Razzaque, PRD, 2013** Liso $\rightarrow \Gamma_0$ Ghirlanda et al,A&A,2018	$R_{\rm max}^{\rm homog} = \eta_{\rm acc} 120 \left(\frac{\Gamma_0 E_{\rm kin}^{\rm iso}}{10^{55}} \right)^{1/3}$
SGRB	**G. Farrar, ApJ L, 2025**	R_{max} ~ 10 EeV

F. Emax distribution



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Implication: Narrow Rigidity

Ehlert et al.,PRD,2023

$$\rho = \begin{cases} L^{-y_1} & : L < 0 \\ L^{-y_2} & : L \geq L_0 \end{cases}$$

$$\beta_i = 2y_i - 3$$

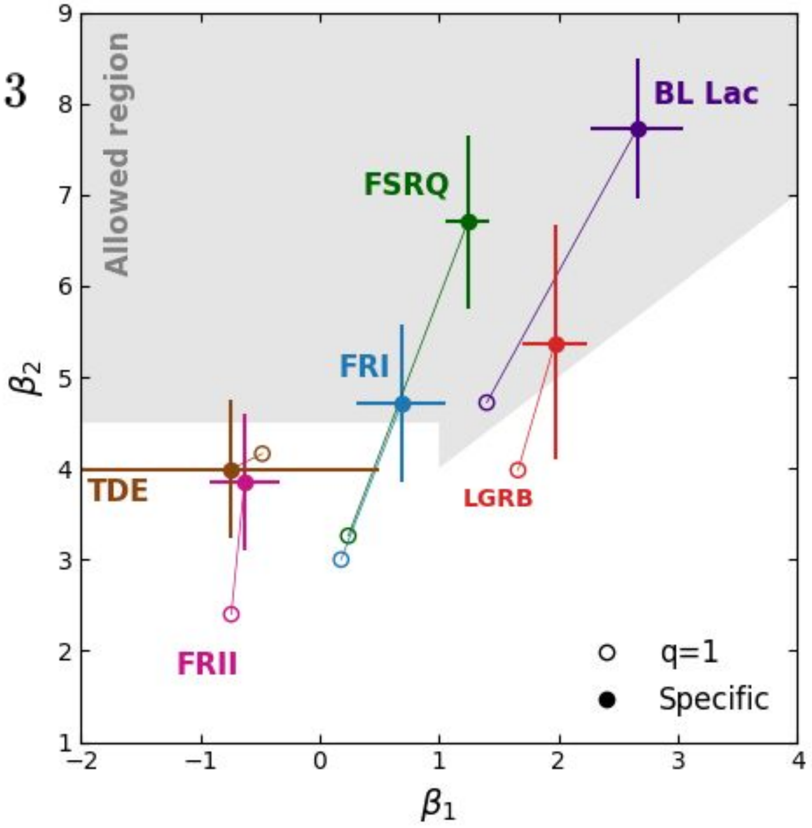
$$E_{\max} \propto L^{1/2}$$

- Example: continuous injection case

$$\beta_i = 1 - (1/r) + \gamma_i/q \cdot r$$

$$\beta(r = 1/2, q = 1) = 2y - 3, \quad y = \gamma + 1$$

$$E_{\max} \propto Q^r \quad \rho \propto L^{-\gamma_i} \quad Q \propto L^q$$



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A holistic view of UHECR sources I: populations, energetics, and observational constraints

TABLE IV. Holistic view for proposed populations of UHECR sources.

	$R_{\rm max}$	$\dot{\varepsilon}$	Narrow	Evol.	Rate
FRI	✓	✓	✓	✓	
FRII	✓	✓	✗?	✓	
FSRQ	✓	✓	✓	✓	
BL Lac	✓	✓	✓	✓	
TDE	✓	✓?	✗?	✓?	✗?
LGRB	✓	✗	✓	✗?	✗
SGRB/BNS	✓	✗	✓	✓?	✗

Symbols followed by "?" indicate *unfavoured*/*favoured* despite the data cannot totally rule out/confirm the population.

Preliminary Conclusions + Open Questions to be answered in Part II

- Further Astrophysical information required to constraint the sources

- AGN dominance, open questions:
  - effects of evolution of luminosity with redshift?
  - if excluded: important constraint on efficiency parameters

- What it **does not prove**: subdominant source are not accelerators of UHECR $\rightarrow$ consequences of subdominant sources?

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