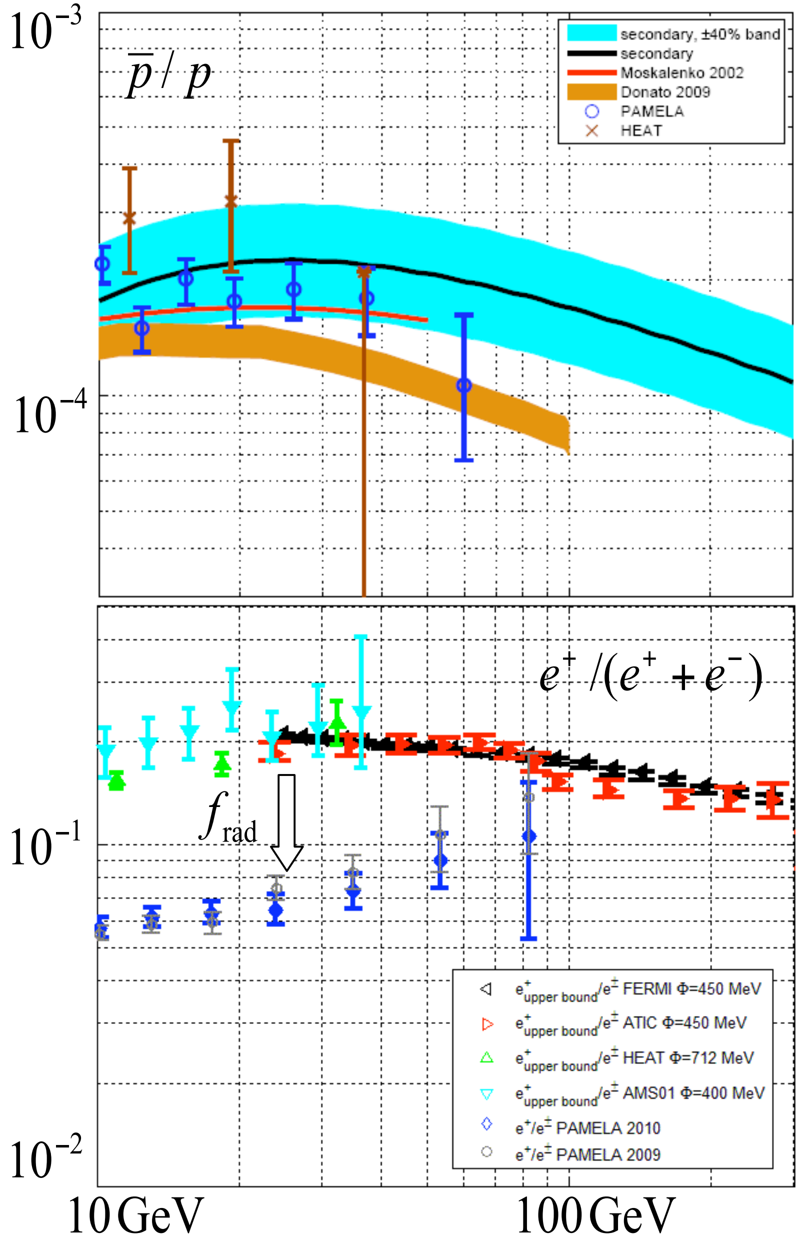
PAMELA: New e⁺ sources?



- For all secondaries (e.g. anti-p)

$$n_i(\varepsilon) = \left[\sum_{j\neq i} n_j \frac{\sigma_{j\to i}}{m_p} - \frac{n_i\sigma_i}{m_p}\right] X_{\rm sec}(\varepsilon/Z)$$

$$X_{\rm sec} \approx 8.7\left(\frac{\varepsilon}{10Z\ {\rm GeV}}\right)^{-0.5} {\rm g/cm^2}$$

- Radiative e⁺ losses- depend on propagation in Galaxy (poorly understood)

$$n_+(\varepsilon) = Q_+\ X_{\rm sec}(\varepsilon/Z)\ f_{\rm rad}$$

* At ~20GeV: f_{rad}~0.3~f_{10Be}

→ e⁺ consistent with 2ⁿᵈary origin

* Above 20GeV:

If PAMELA correct

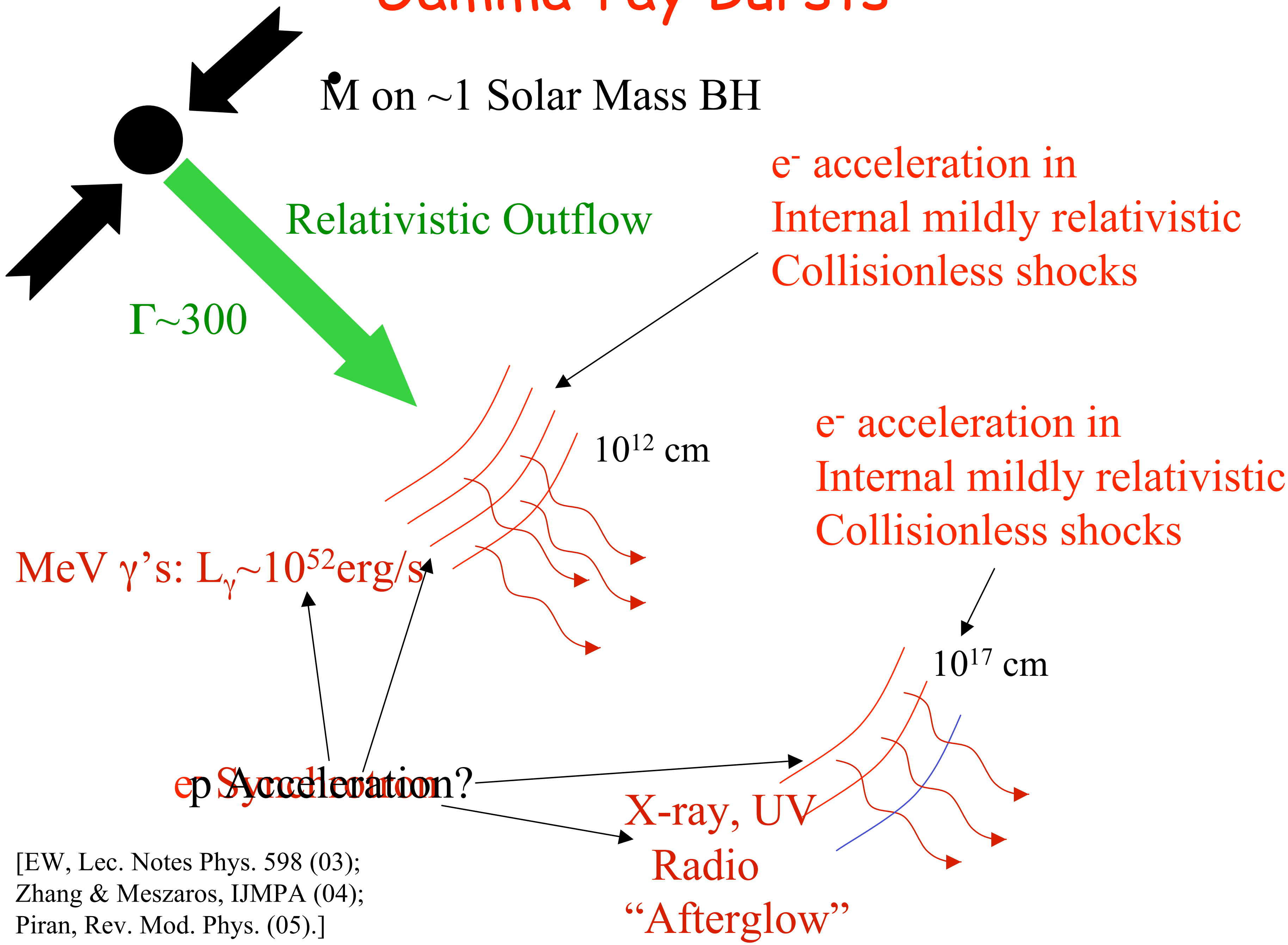
→ energy independent $f_{rad}(\varepsilon)$

[Katz, Blum & EW 10, MNRAS 405, 1458]

Gamma-ray bursts,
Collisionless shocks
and
Ultra-high energy comsic-rays

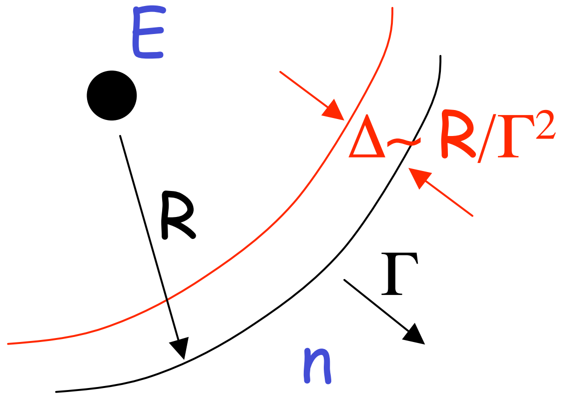
E. Waxman
Weizmann Inst., Israel

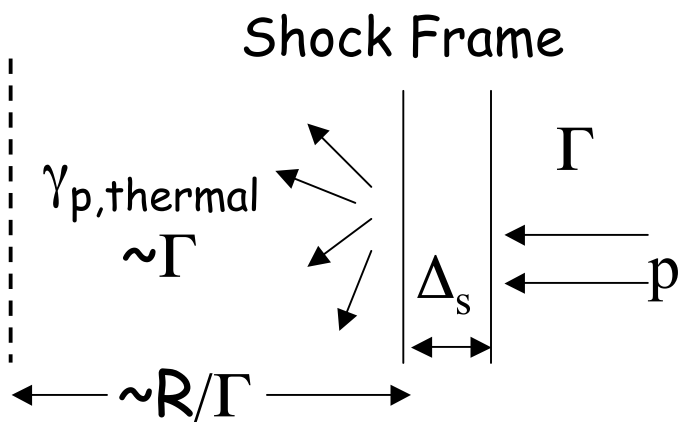
Gamma-ray Bursts



[EW, Lec. Notes Phys. 598 (03);
Zhang & Meszaros, IJMPA (04);
Piran, Rev. Mod. Phys. (05).]

Afterglow: I. Dynamics
Relativistic "point explosion"





- $E \sim \Gamma^2 M(R,n)c^2 \quad \rightarrow \quad \Gamma \sim (E/nm_pR^3)^{1/2}$

  Γ {1min, 1day, 1yr} ~{100, 10, 1 }

[Blandford & McKee 76]

- Why collisionless shock?

$$\text{Coulomb}: \Gamma m_p c^2 = \frac{e^2}{d} \Rightarrow \quad \Delta_s \sim \lambda_{Coul.} \approx \frac{1}{\Gamma n \pi d^2} = 10^{31}\Gamma n_0^{-1}\ \text{cm}$$

$$\text{Plasma}: \omega_p = \sqrt{\frac{4\pi\Gamma n e^2}{\Gamma m_p}} \Rightarrow \quad \Delta_s \sim \lambda_{sd} = \frac{c}{\omega_p} \approx 10^7 n_0^{-1/2}\ \text{cm}$$

Afterglow: II. Radiation
A phenomenological model

- Collisionless: B generation, non-thermal particles
  → synchrotron emission

- Open questions:
  1. B generation: $B^2_{\text{down}} / 8\pi = \varepsilon_B u_{thermal,\text{down}}$
  2. Non-thermal e^-: $\gamma_{e,thermal} = \varepsilon_e \frac{m_p}{m_e} \Gamma$

$$\gamma_e > \gamma_{e,thermal} : \quad \frac{dn_e}{d\gamma_e} \propto \gamma_e^{-p} ; p \approx 2$$

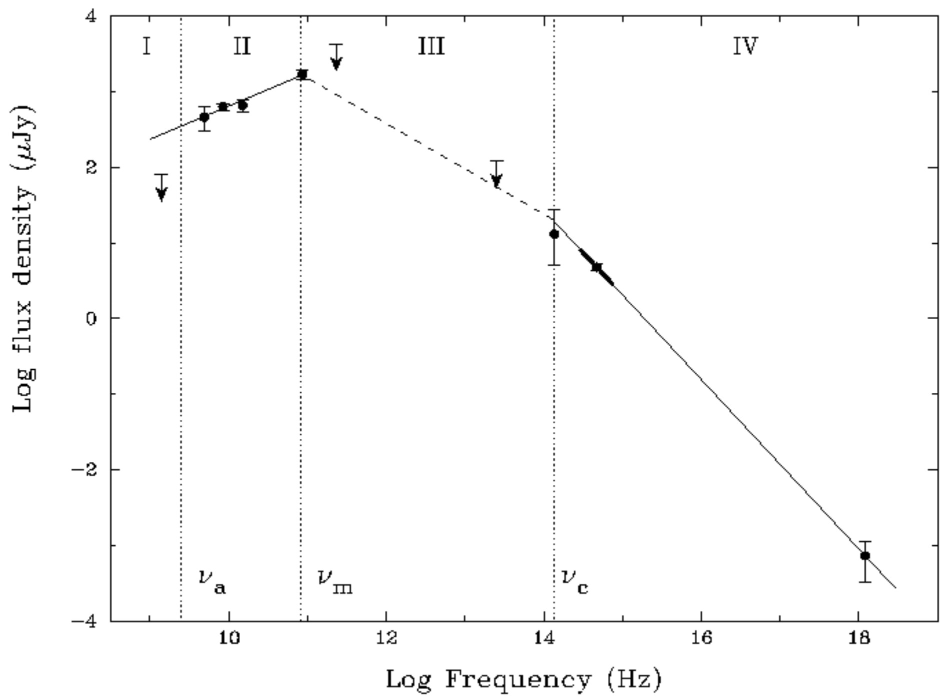
Observations: Phenomenological success

- Model parameters
  $\{E, n, p, \varepsilon_e, \varepsilon_B\}$

- Qualitative agreement (t>10hr)
  $f(t,\nu)=A\ t^{\alpha(p)}\ \nu^{\beta(p)}$

- Observables
  $\{f_m, \nu_m, \nu_c, \nu_a\}$

- Typical values:
  $\{E\sim10^{52}$erg, $n\sim1/cm^3$, $p=2.2\pm0.1$, $\varepsilon_e\sim\varepsilon_B\sim0.1\}$
  No Γ dependence ($\Gamma<30$)



[Wijers & Galama 98]

[EW 97;
Freedman & EW 01]

The challenges

- Highly non magnetized: $U_{B,up} \sim 10^{-9}\ nm_pc^2$
  [$\omega_L = e\Gamma B_{up}/\Gamma m_p c$, $\omega_L^2/\omega_p^2 = B_{up}^2/4\pi n m_p c^2 \sim 10^{-9}$]

- $\varepsilon_B \sim 0.1$

- EM instabilities (ala Weibel) may give $\varepsilon_B \sim 0.1$

  [Gruzinov & EW 99;
  Medvedev & Loeb 99]

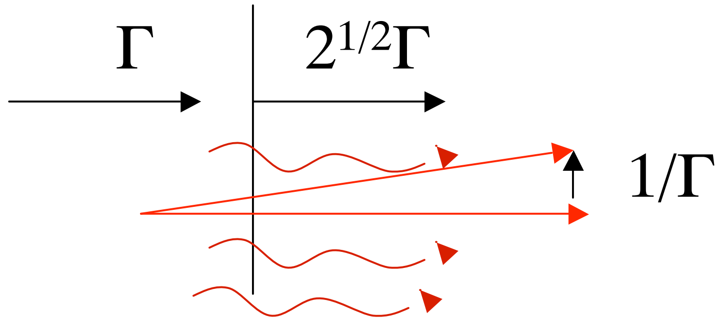
  But: $\Delta' \sim R/\Gamma \sim \Gamma ct \sim 10^{17}$cm >> $c/\omega_p \sim 10^7$cm

  λ_B must increase by orders of mag. @ downstream?

  [Gruzinov & EW 99;
  Gruzinov 01]

- Particle acceleration:
  e^- coupling ($\varepsilon_e \sim 0.1$); $dn/d\gamma \sim \gamma^{-2}$
  p acceleration to UHE?

A note on upstream field



- t(acceleration) < t(inverse-Compton)

  X-ray (@10hr) → $B_{up} > 0.2\ n_0^{5/8}$ mG >> ~3μG [Li & EW 06]

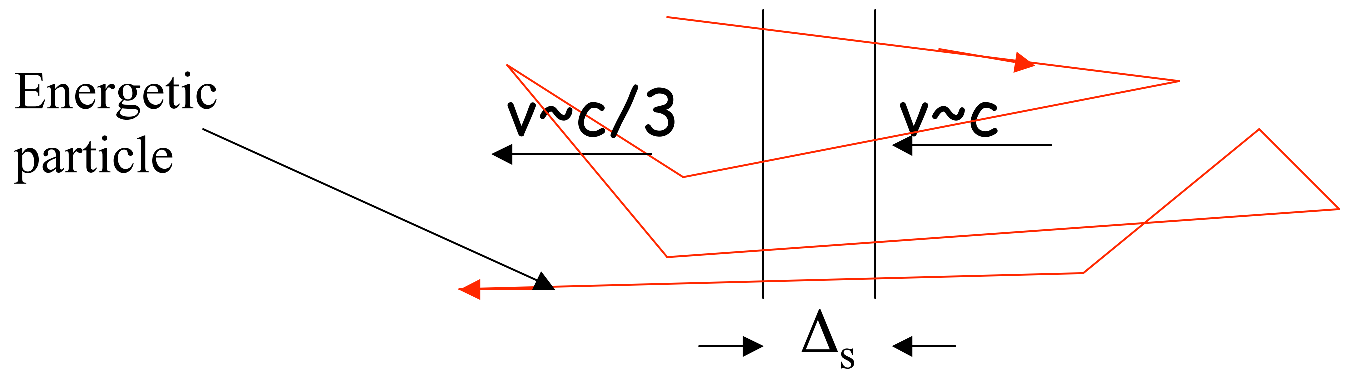
  100MeV (@100s) → $B_{up} > 1\ n_0^{5/8}$ mG >> ~3μG [Li 10]

  (confinement only → B_{up}>0.1mG [Piran & Nakar 10])

→ Upstream field generation

(Inconsistent with [Barniol & Kumar 10])

Fermi shock acceleration



- Test particle, elastic scattering, small momentum change: "diffusion"

- v/c<<1: p=2 (strong shock)

[Krimsky 77; Axford, Leer & Skadron 78; Blandford & Eichler 78]

- v/c~1, Assuming Isotropic diffusion
  - Simulations: $p(\Gamma \gg 1)=2.2\pm 0.2$
  - Analytic approximation: $p(\Gamma \gg 1)=20/9$

[Bednarz & Ostrowski 98; Kirk et al. 00; Ellison 05; Meli & Quenby 06]

[Keshet & EW 05, Keshet 06]

- Open Q's:

  p depends on diffusion form

  Self-consistent (particles + EM fields) theory

Plasma simulations: I. Homogeneous

- 1D, 2D applicability??

[e.g. Wallace 91; Kato 05; Dieckmann 06]

- Homogeneous (anisotropic) plasma

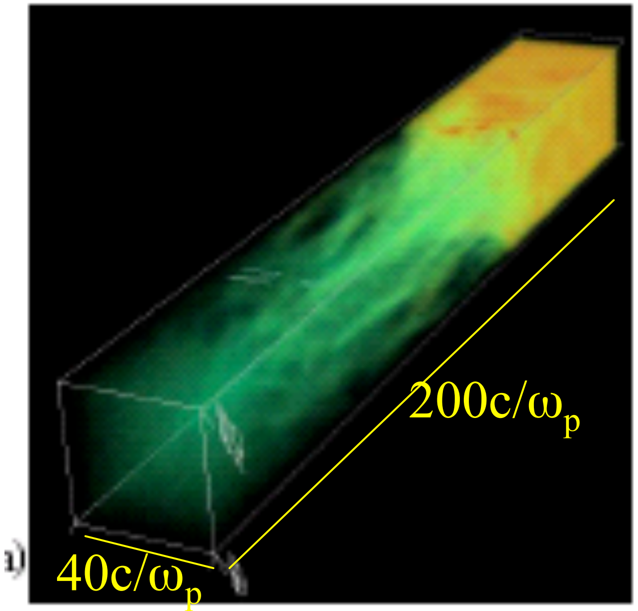
Study linear growth & saturation of EM instabilities,
Reach ε_B~0.01,
But:

Does the field decay on long (>>1/ω_p) time scale?
No particle acceleration
Relevance for non-homogeneous shock flow?

[e.g. Silva et al. 03; Jaroschek et al. 04]

Plasma simulations II: 3D

- 3D $e^+ e^-$ plasma, Γ=15 "piston"
  Shock forms, width ~10 c/ω_p ,
  Reach ε_B~0.01,
  But:
  >>$1/\omega_p$ field decay?
  Particle acceleration?
  Relevance for e/p plasma?



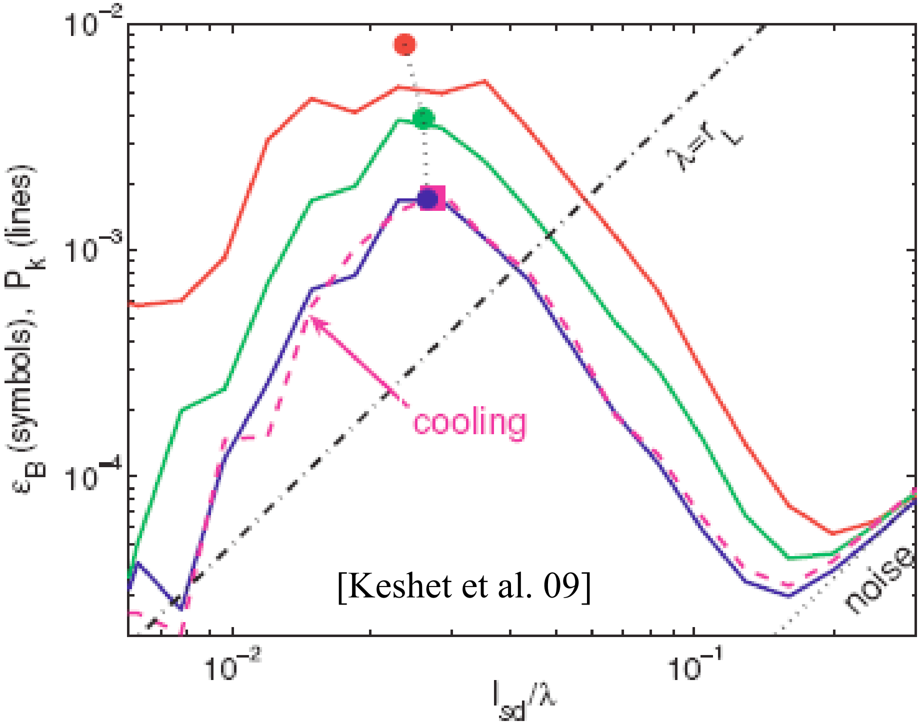
[Spitkovsky 06]

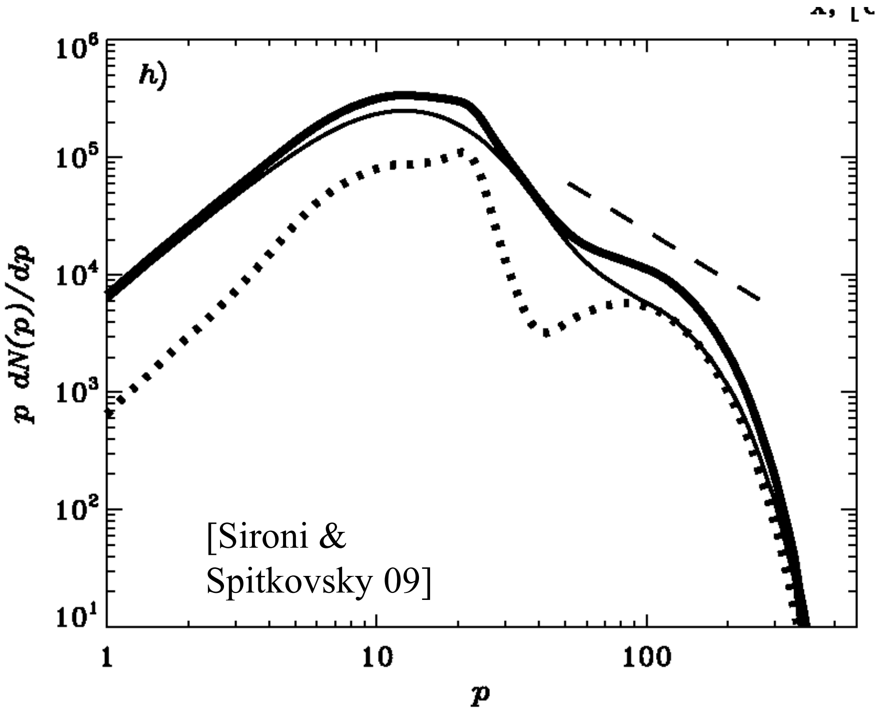
- e/p (m_p/m_e=16) plasma simulations:
  Study physical process, but
  Do not reach shock formation.

[Nishikawa et al. 03;
Fredriksen et al. 04;
Hededal et al. 04]

Plasma simulations: III. Large 2D $e^+ e^-$

Γ=15 "piston", transverse ~100 c/ω_p, $\omega_p t$~10^4





B

$\omega_p t/10^3$=2,5,13

B scale grows, ε_B grows to 0.01

Cooling = no γ>80

No steady state @ $\omega_p t$~10^4

Particles

Non-thermal (Γ>>15) tail

However: Note Γ^2!

Simulations: What have we learned?

- 2D $e^+ e^-$ plasma, Γ=15 "piston":
  Shock forms, width ~10 c/ω_p
  B scale grows, ε_B grows to 0.01
  Growth associated with non-thermal particles
  No steady state @ $\omega_p t \sim 10^4$

- Open:
  Does B survive to $\omega_p t \sim 10^9$?
  Particle acceleration to $>\Gamma^2$?
  $e^+ e^-$ = e-p plasma?
  2D=3D?

→ Numerics unlikely to directly resolve open Qs.
Provides input/tests for analytic studies.

Some analytic beginnings

- B amplifications by instabilities

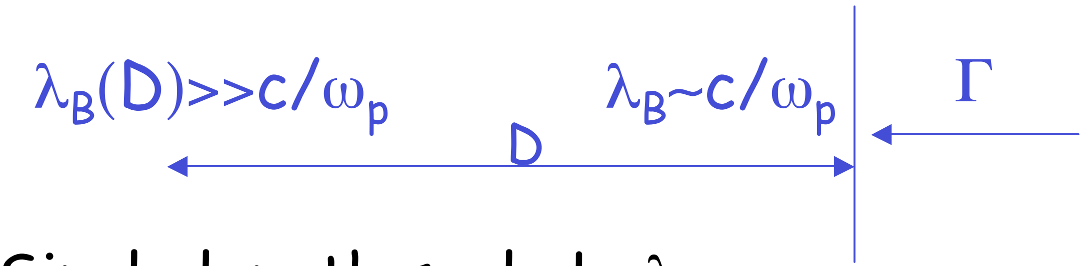
[Medvedev et al. 05; Milosavljevic & Nakar 05; Lyubarsky & Eichler 06; Achterberg & Wiersma 2007; Bret 2009; Lemoine & Pelletier 2009; Lazar, Schlickeiser & Poedts 10 ...]

- Long wave-length modes in upstream

  - may deflect $\gamma<\Gamma^2$ in e^+e^- plasma
  - suppressed for $\Gamma<(m_p/m_e)^{1/2}$ in e-p plasma

[Rabinak, Katz & EW 09]

- Self-similarity



As λ_B diverges → Single length scale $L\sim\lambda_B$

→ Self-similar (scaleable) solutions

e.g.

$$-1 < s_B < 0: \quad B \propto D^{s_B}, \quad dn/d\gamma \propto \gamma^{-2/(s_B+1)}$$

Infinite conductivity → $s_B=0$ (p=2).

[Katz, Keshet & EW 06]

UHE, $>10^{19}$eV, CRs & GRBs

- Constraints:
  - Confinement → $L>10^{12} (\Gamma^2/\beta) L_{sun}$
  - Synch. Losses → $\Gamma > 10^{2.5} (L_{52})^{1/10} (\delta t/10ms)^{-1/5}$ [EW 95]
  - Production rate: $\varepsilon^2(dQ/d\varepsilon) \sim 10^{43.5}$ erg/Mpc^3 yr
  - Source distance: $d(10^{20}eV)<d_{GZK}\sim 100$Mpc

  !! No $L>10^{12} L_{sun}$ at $d<d_{GZK}$ → Transient Sources

- Gamma-ray Bursts (GRBs) [EW 95, Vietri 95, Milgrom & Usov 95]

  √ $L_\gamma \sim 10^{19} L_{Sun} > 10^{17} (\Gamma/10^{2.5})^2 L_{sun}$

  √ $\Gamma \sim 10^{2.5}$ (pair production)

  √ $\varepsilon^2(dQ/d\varepsilon)_\gamma \sim 10^{52.5}erg*10^{-9.5}$/Mpc^3 yr = 10^{43} erg/Mpc^3 yr

  √ Transient: $\Delta T_\gamma \sim 10$s << $\Delta T_{p\gamma} \sim 10^5$ yr [EW 95, 04]

* Acceleration @ Internal mildly relativistic shocks

Or: External highly relativistic shocks provided B_{up} amplified

A comment on production rates

- "$Q_{\gamma,MeV,GRB} \sim 10^{-2} Q_{UHECR}$"

[e.g. Wick et al. 04 ; Berezinsky 08; Eichler et al 2010]

- Discrepancy due mainly to
  Assuming UHECRs X-Galactic above $\sim 10^{18}$eV
  (instead of $\sim 10^{19}$eV)

- Requires:
  Fine tuning
  $(dQ/d\varepsilon)_{XG} \sim \varepsilon^{-2.7}$ -- Inconsistent with > 10^{19}eV data

GRBs & UHECRs: Predictions

- CR experiments:
  - Few narrow spectrum sources above $3x10^{20}$eV

    [Miralda-Escude & EW 96]
  - Difficult to check, even with Auger

- HE ν experiments
  - Internal shocks: ~10 (100TeV events)/Gton/yr
    Accessible to IceCube, Km3Net [EW & Bahcall 97, 99; Rachen & Meszaros 98; Guetta et al. 01; Murase & Nagataki 06]
  - External shocks: 10^{18}eV ν's, difficult to detect

Summary: Collisionless shocks

- GRB afterglows- likely e^- acceleration in Collisionless, Relativistic (Γ=100→1), Un-magnetized ($U_{B,up}$~10^{-9} nm_pc^2) shocks

- Challenges:
  - $U_{B,down}$ near equipartition (x10^9), survive to $\omega_p t$~10^9
    (Evidence for $U_{B,up}$ amplification x10^4 – 10^6)
  - e^- coupling (ε_e~0.1) and acceleration, $dn/d\gamma \sim \gamma^{-2}$

- Current status
  - Test particle understanding of particle acceleration
  - 2D $e^+ e^-$ simulations:
    Shock forms @ ~10 c/ω_p, — No steady state @ $\omega_p t$~10^4
    ε_B grows to 0.01, — Survive to $\omega_p t$~10^9?
    Non-thermal particles — Acceleration to >Γ^2?
    B scale grows, associated with non-thermal particles
    $e^+ e^-$ = e-p? 2D=3D?

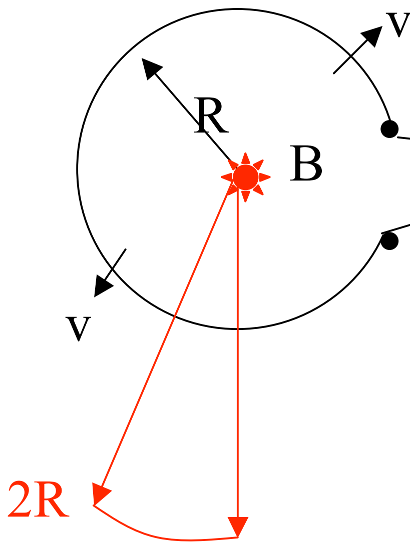
Summary: UHECRs

- $>10^{19}$eV particles: Origin, Acceleration not known.

- GRBs- only known sources satisfying all constraints.
  May produce observed flux if accelerate e^- and p with similar efficiency.

- Predictions
  - CR experiments:
    Few narrow spectrum sources above 3×10^{20}eV,
    Difficult to check, even with Auger.
  - HE ν experiments:
    Internal shocks→ ~10 (100TeV events)/Gton/yr,
    Accessible to IceCube, Km3Net.

UHECRs: The 10^{20}eV challenge



$l = R/\Gamma$

$(\delta t_{RF} = R/\Gamma c)$

$$V = \frac{1}{c}\dot{\Phi} \sim \frac{1}{c}\frac{BR^2}{R/\mathrm{v}} = \beta BR \quad \Rightarrow \quad \varepsilon_p < \beta eBR/\Gamma$$

$$L > 4\pi R^2 \Gamma^2 \frac{B^2}{8\pi}\mathrm{v} > \frac{1}{2\beta}\left(\frac{\varepsilon_p}{e}\right)^2 c\,\Gamma^2$$

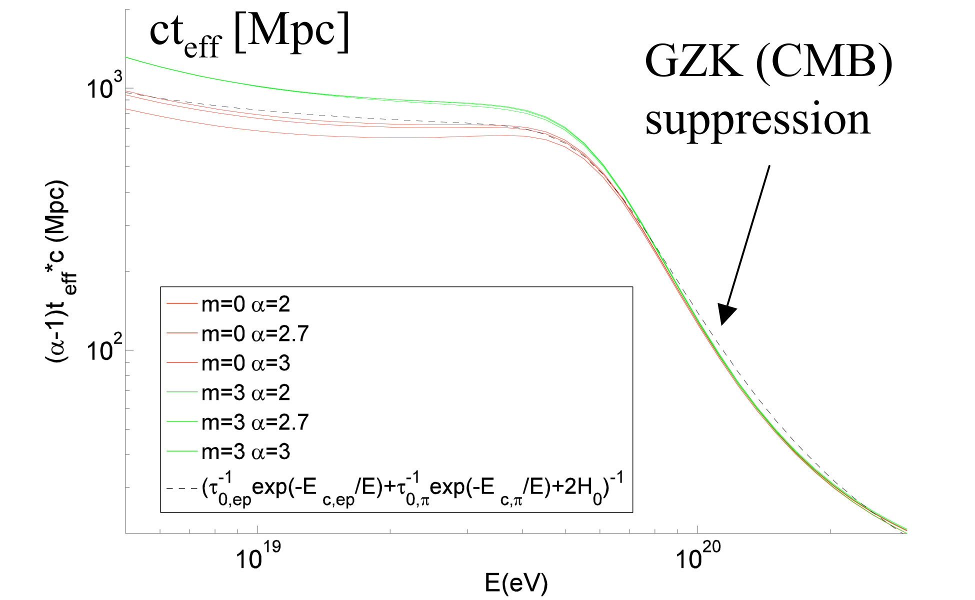
$$L > \frac{\Gamma^2}{\beta}\varepsilon_{p,20}^2 \times 10^{46}\ \mathrm{erg/s}$$

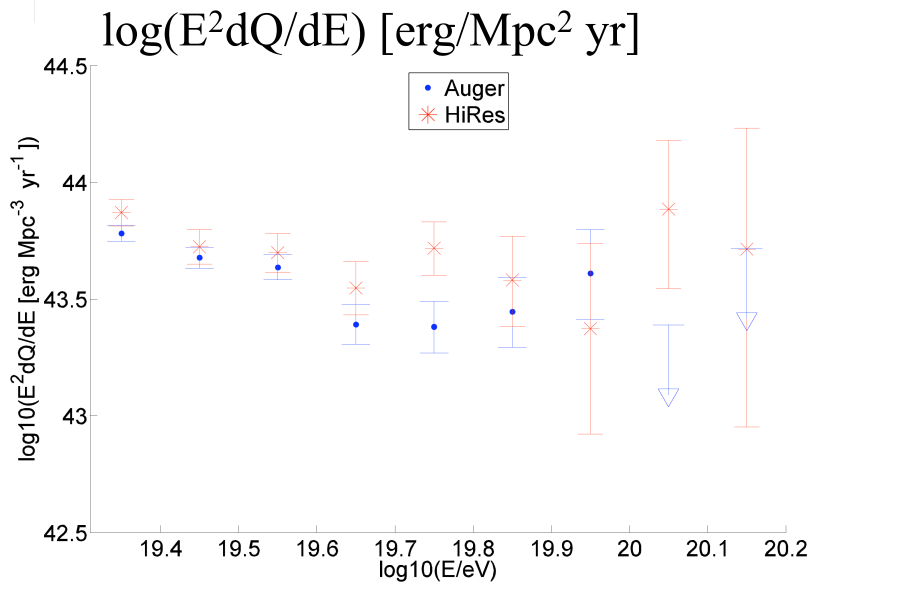
- AGN: $\Gamma \sim$ few → $L > 10^{47}$ erg/s
- GRB: $\Gamma \sim 300$ → $L > 10^{51}$ erg/s

[EW 95, 04]

Flux & Spectrum

- $E^2(dN/dE)=E^2(dQ/dE)\, t_{eff.}$ $(t_{eff.}: p + \gamma_{CMB} \rightarrow N + \pi)$





[Katz, Budnik & EW 09]

- >$10^{19.3}$eV: consistent with protons, $E^2(dQ/dE) \sim 10^{43.5}$ erg/Mpc^3 yr + GZK

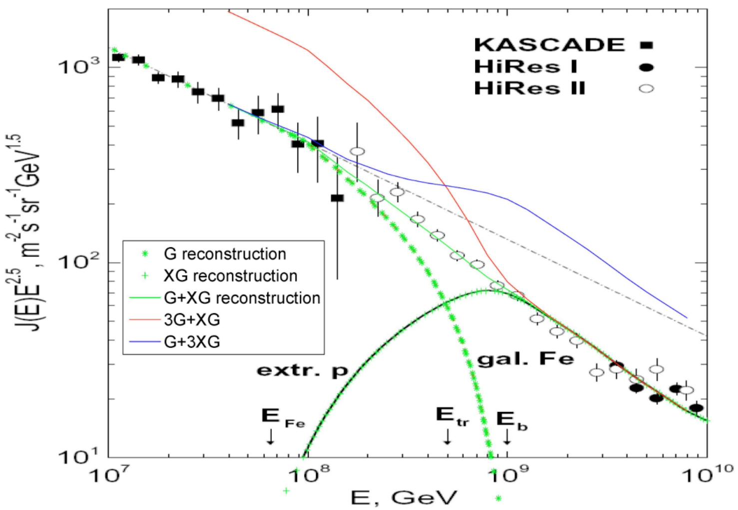
[EW 1995; Bahcall & EW 03]

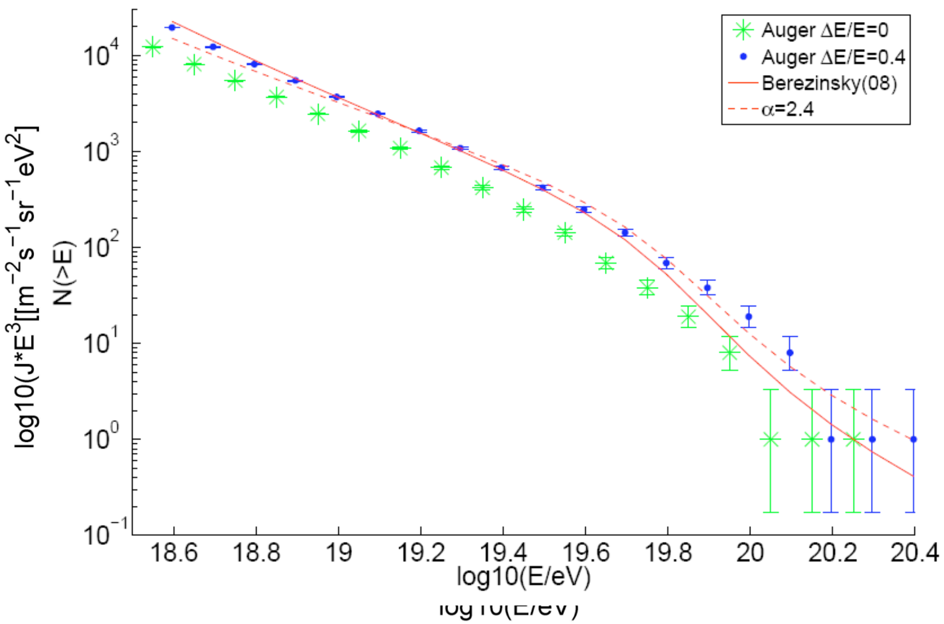
- $E^2(dQ/dE)$ ~Const.: Consistent with shock acceleration

[Krimsky 77; Bednarz & Ostrowski 98; Keshet & EW 05

cf. Lemoine & Revenu 06]

Galactic-ex. Galactic





Transition @ ~10^{18}eV

Fine tuning

$(dQ/d\varepsilon)_{XG} \sim \varepsilon^{-2.7}$

Inconsistent spectrum

Transition @ ~10^{19}eV

Inconsistent spectrum

[Katz, Budnik & EW 09]