Some new (old) ideas about particle acceleration and other topics

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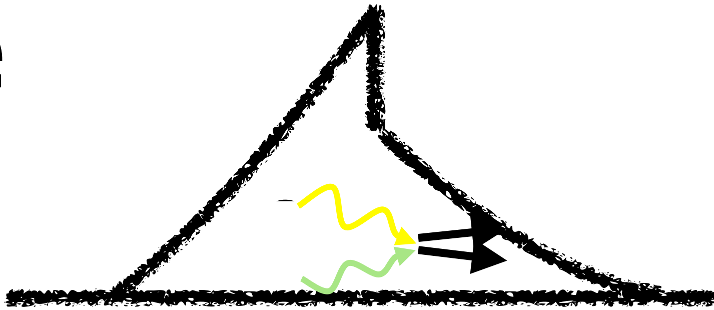
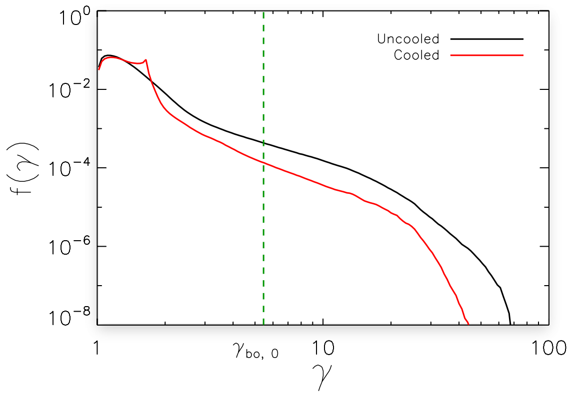
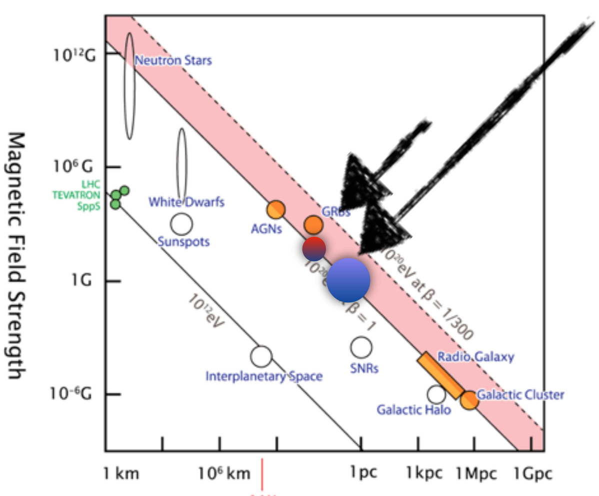
Outline

- Shock Acceleration (Derishev & TP, MNRAS, 460, 2036, 2016)
- Reconnection (Kagan, Nakar & TP, ApJ, 826,221, 2016; Kagan, Nakar & TP, submitted)
- UHECRs from TDEs (Farrar & TP, 2014, arXiv1411.0704)







1. Particle Acceleration in Relativistic Shocks

(Derishev and TP, 2016; Garasev & Derishev 2016)

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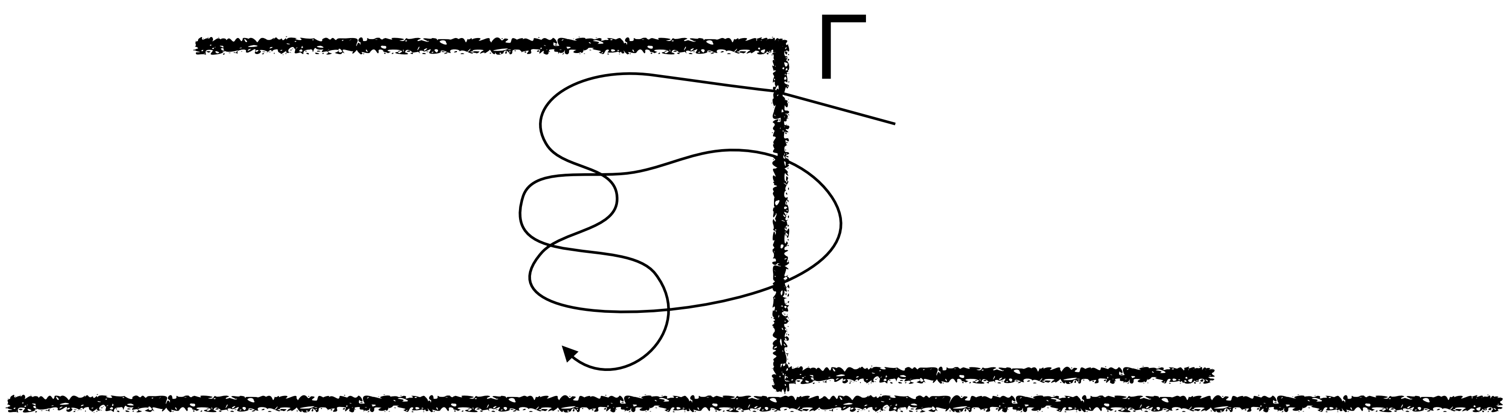
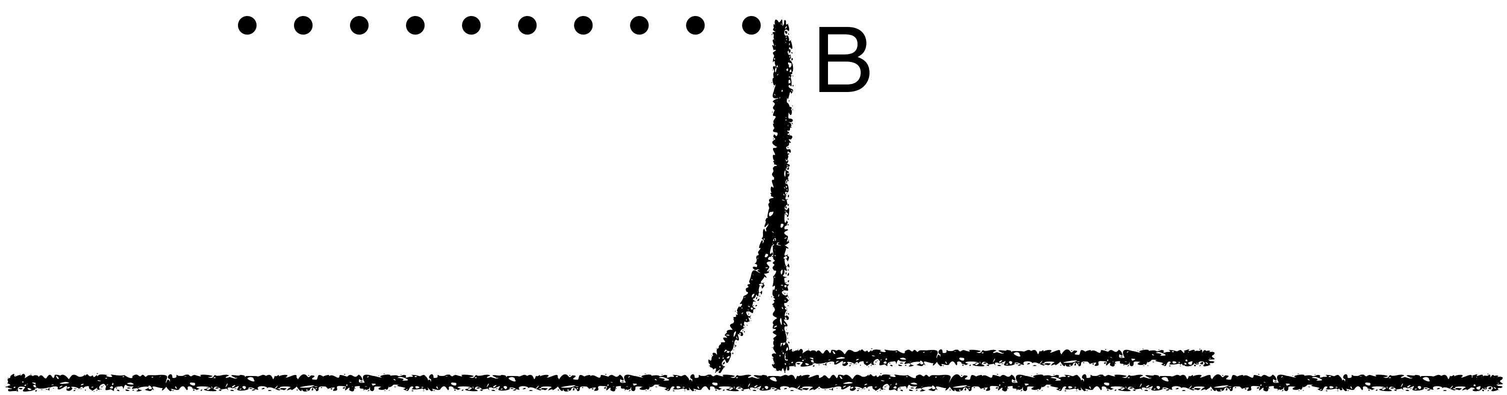
"An idea for an idea"
John Wheeler

Diffusive shock Acceleration



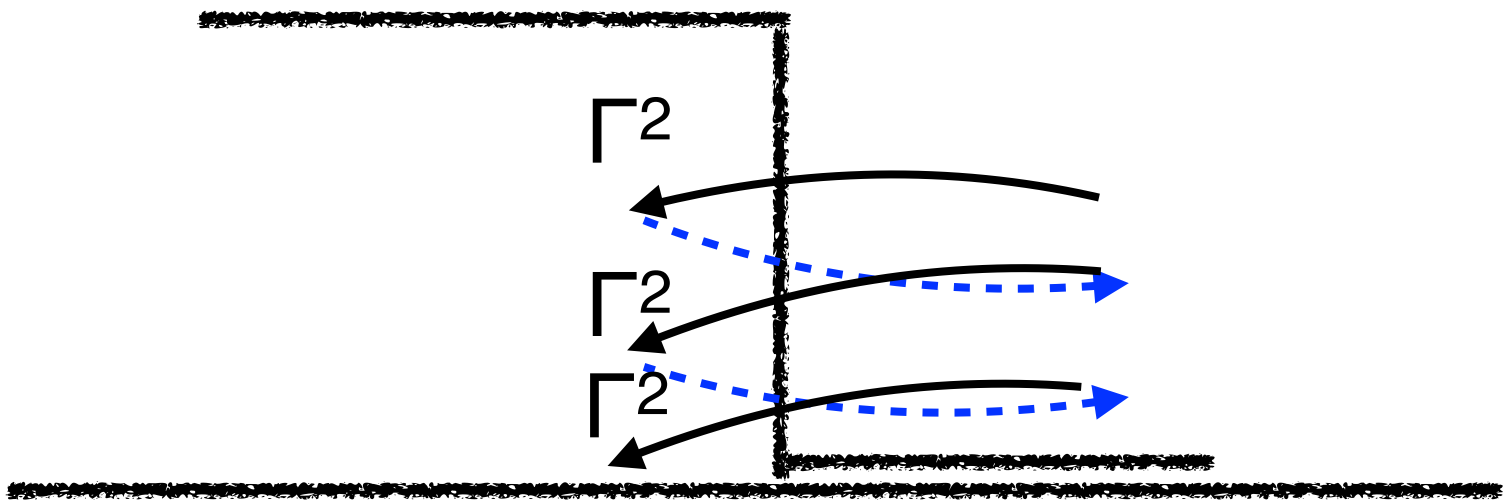
Magnetic Field Generation and Decay

(Gruzinog, 99, Lemoine, 2013)

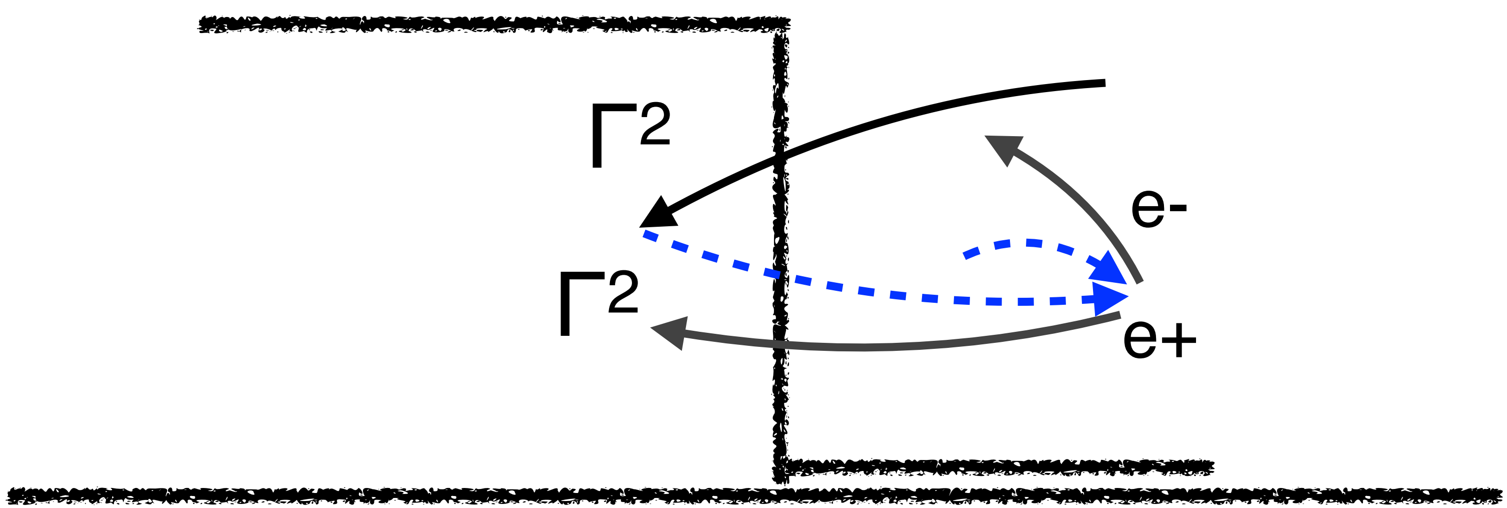


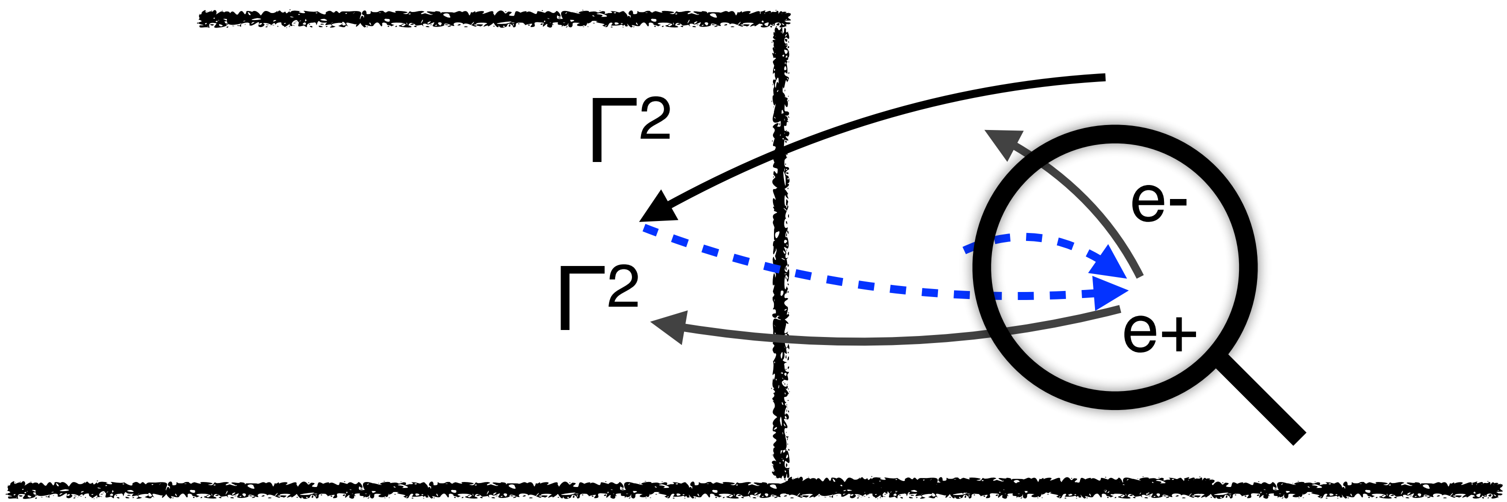
Converter acceleration

Derishev et al. (2003); Stern (2003)



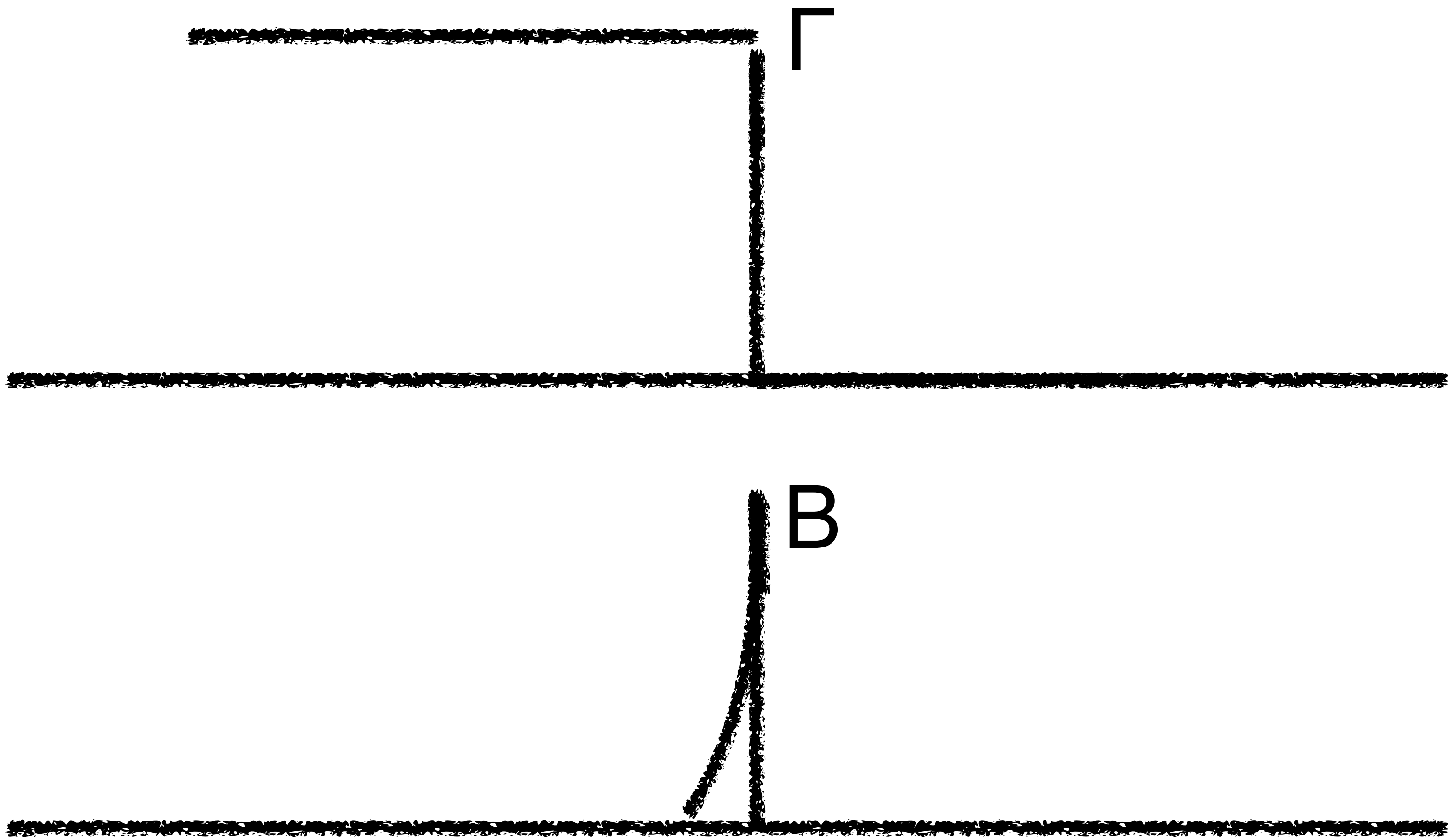
Converter acceleration via high energy (IC) photons





1) Accelerate the flow
2) Produce magnetic field via Weibel Instability

Modified structure



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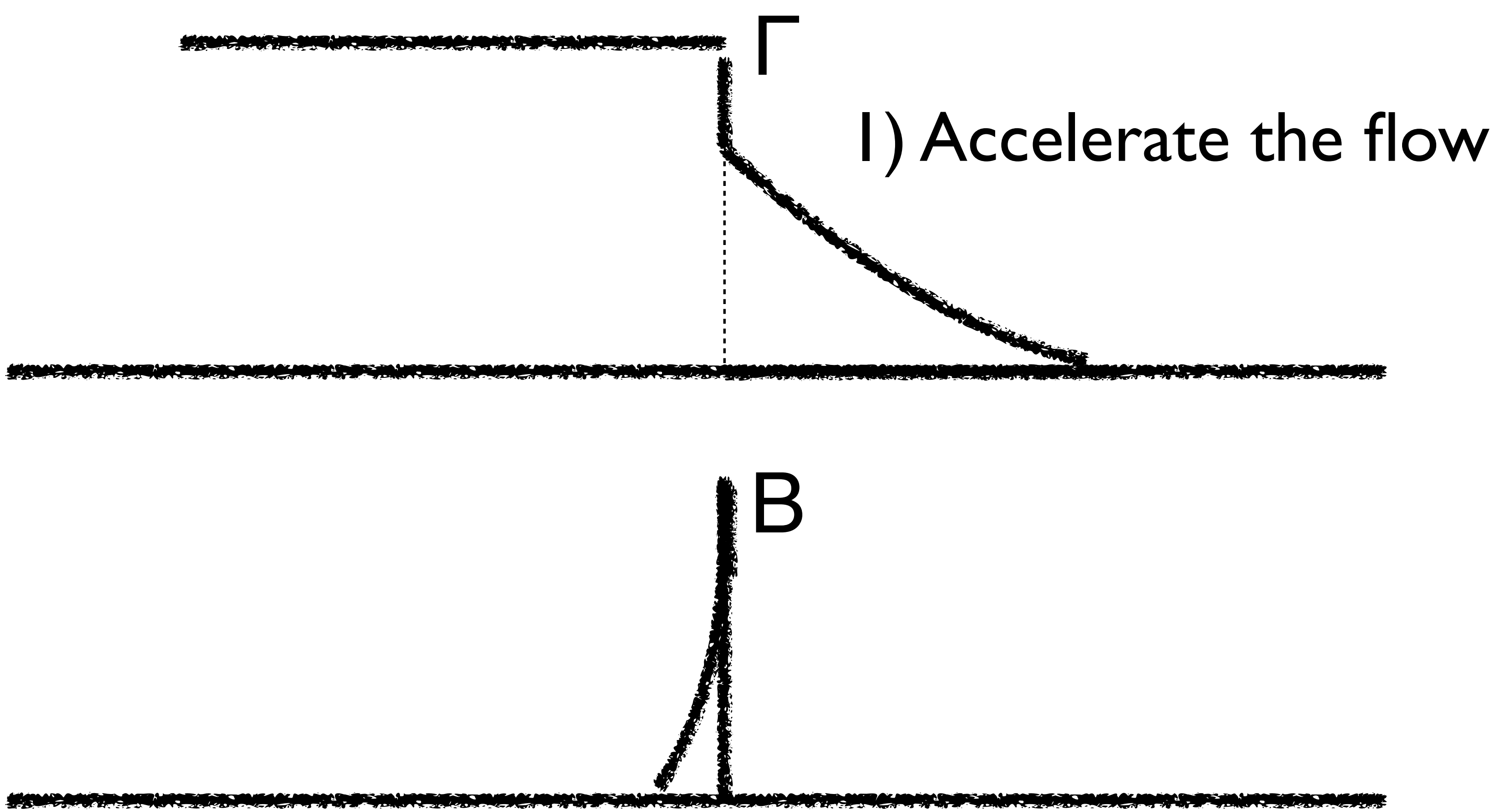

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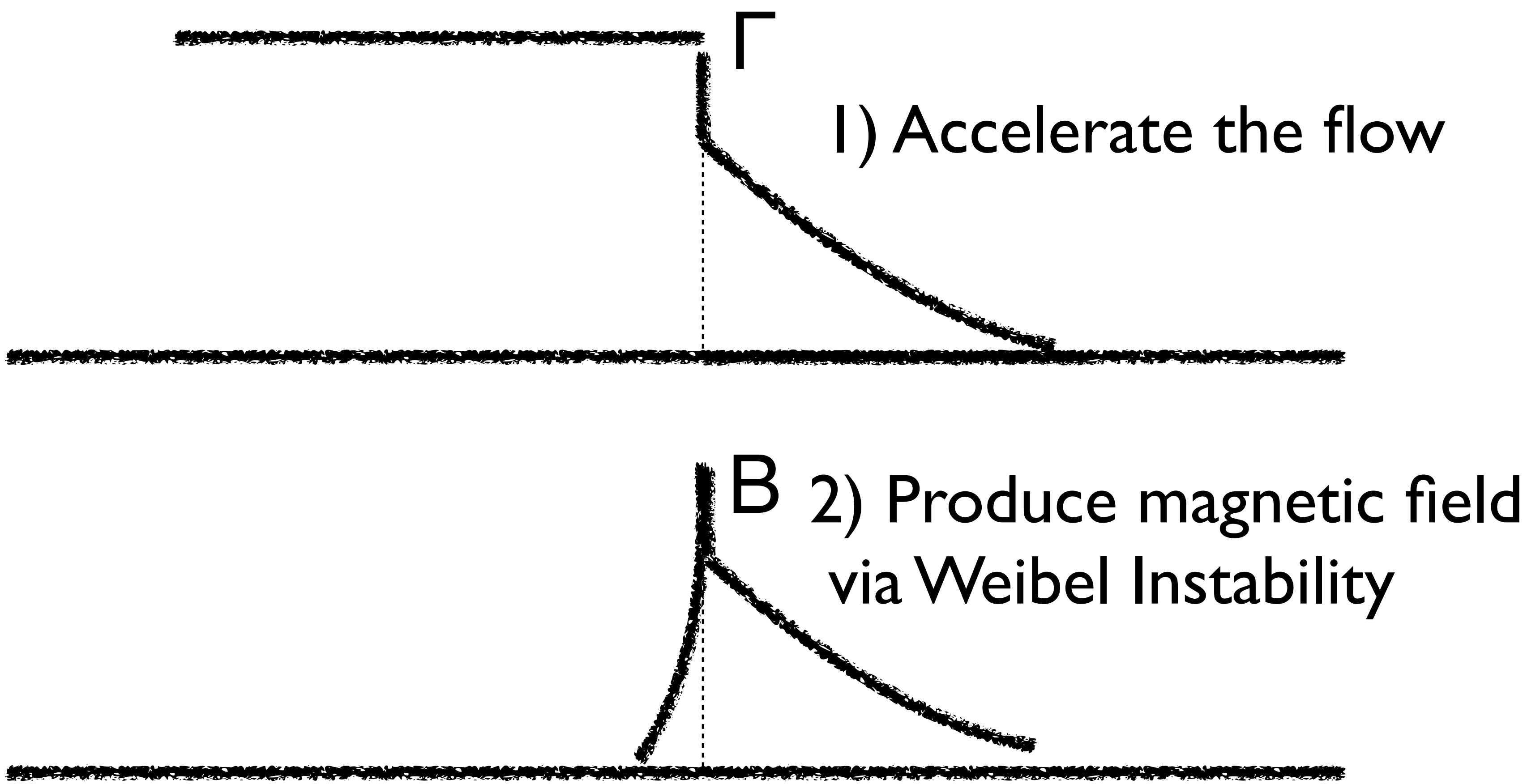

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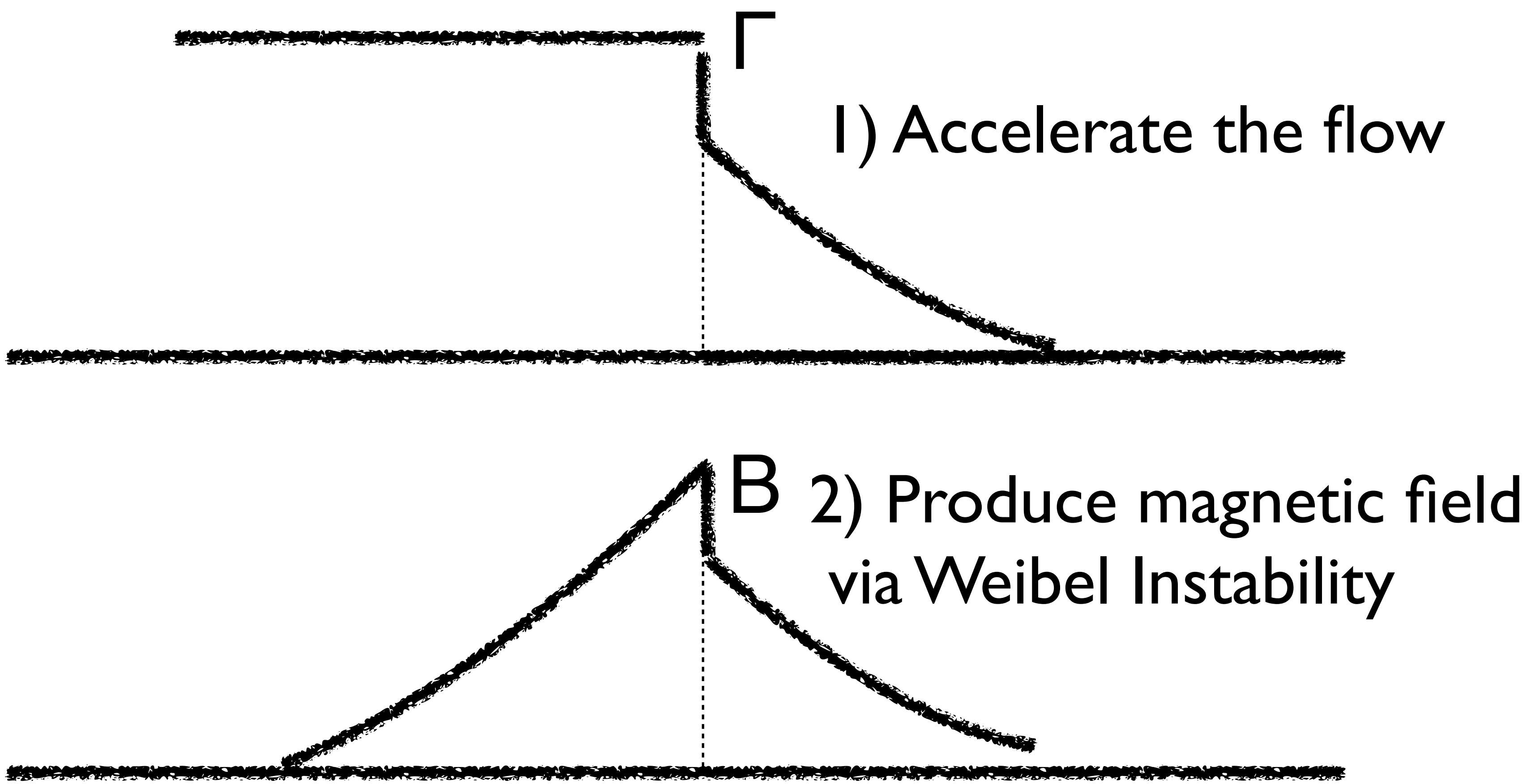

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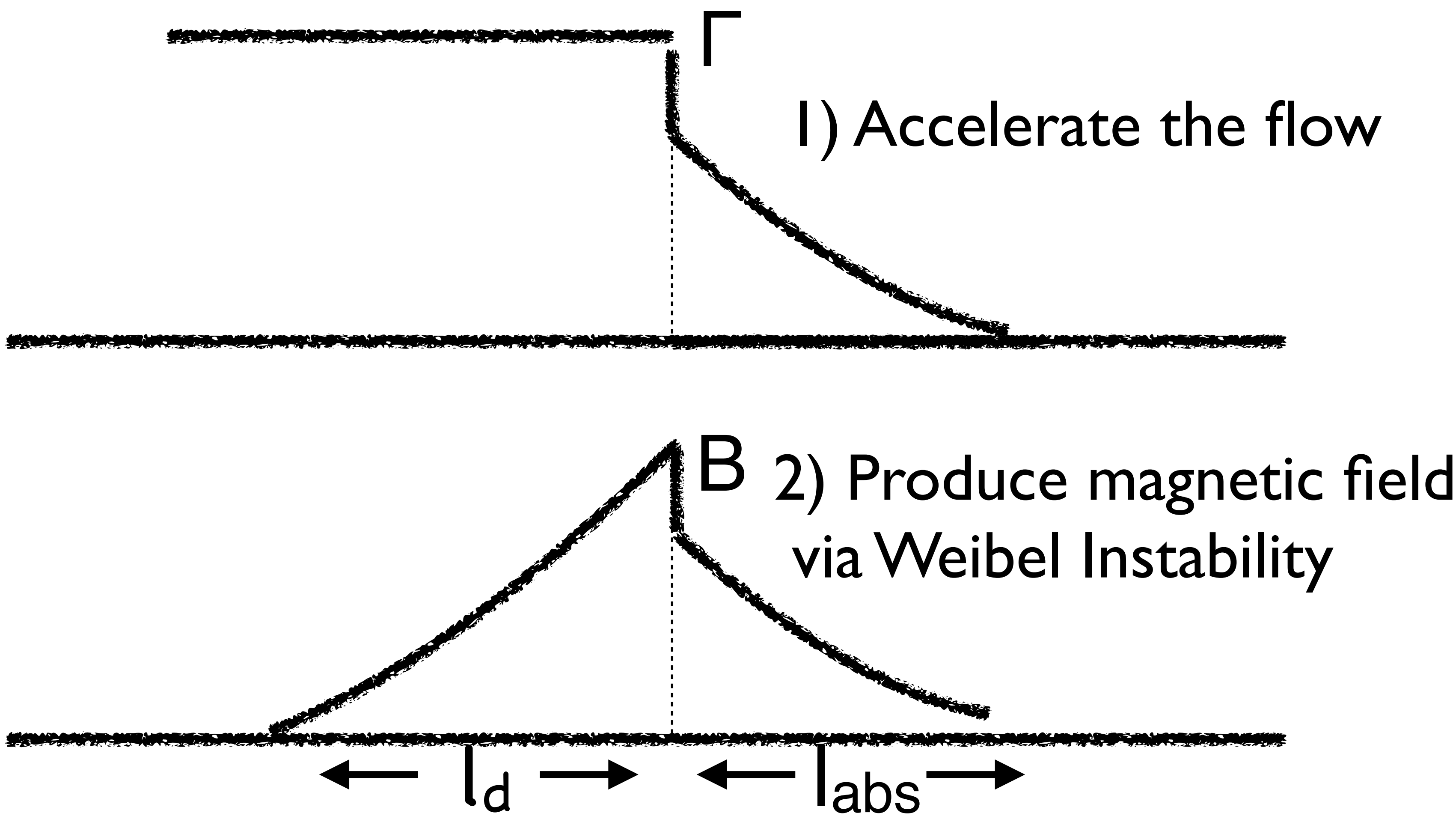
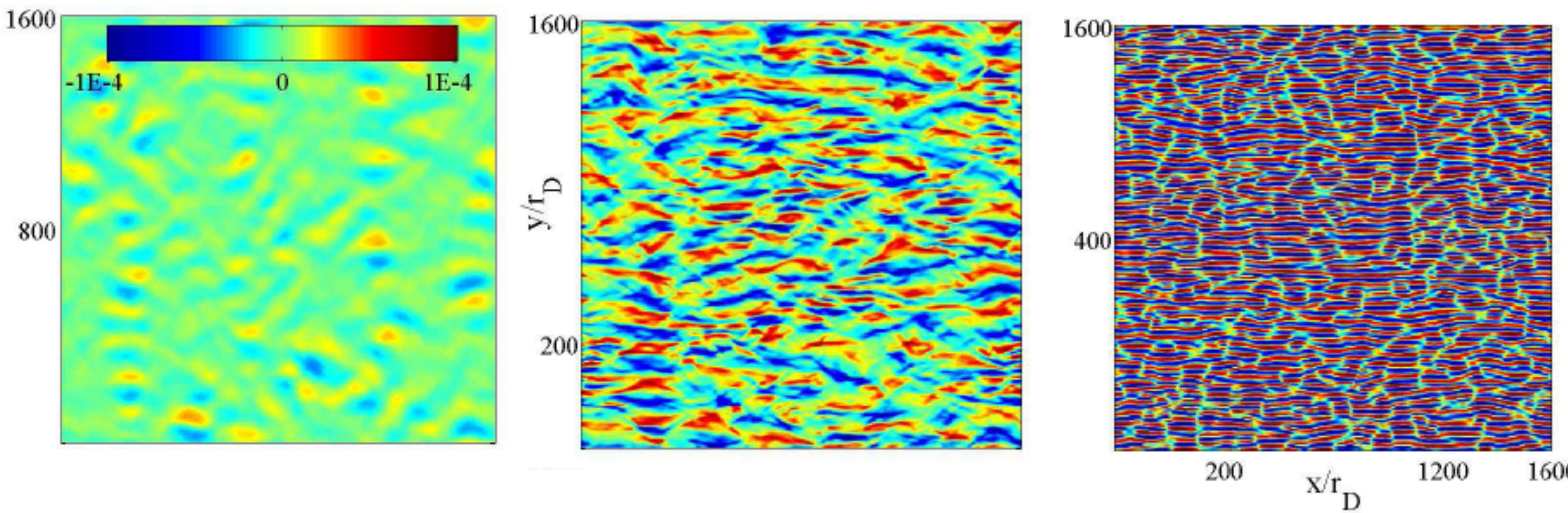
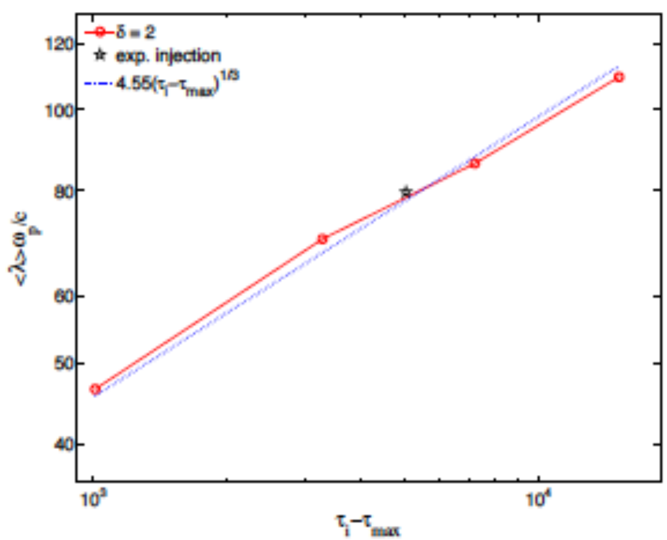
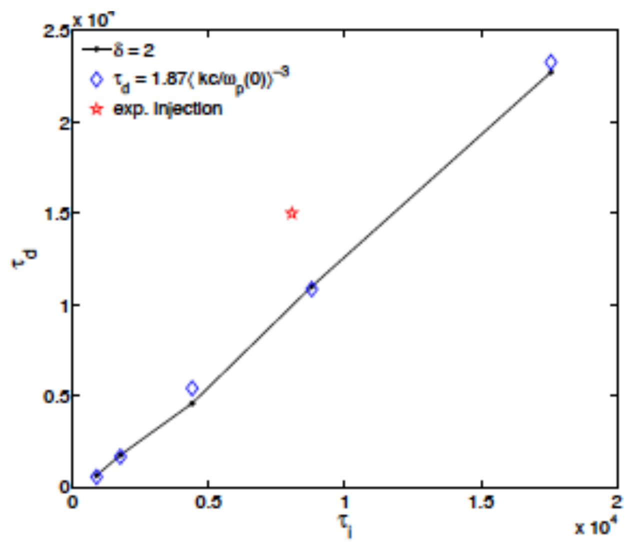


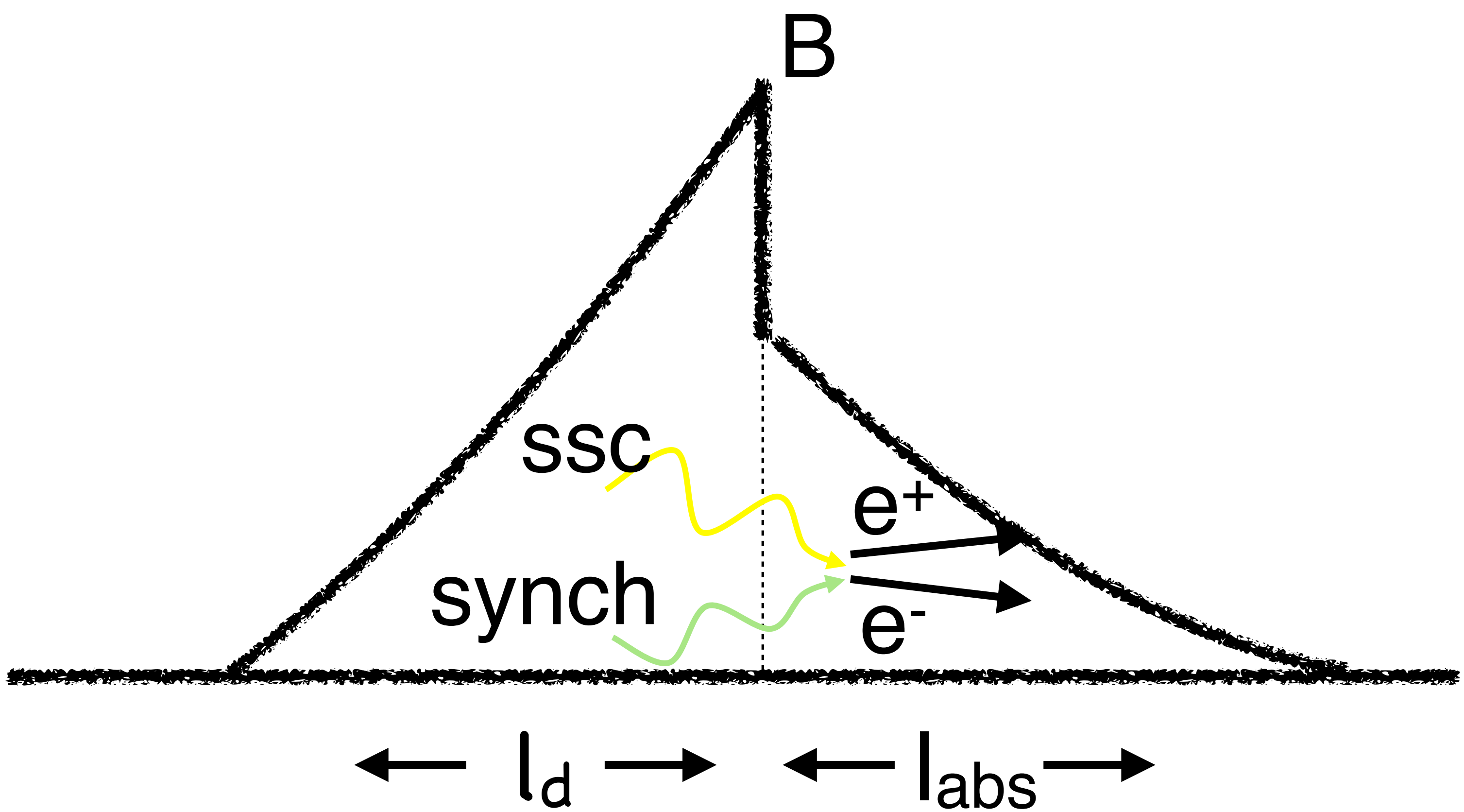
Generation and decay of B

(Garasev & Derishev 16)

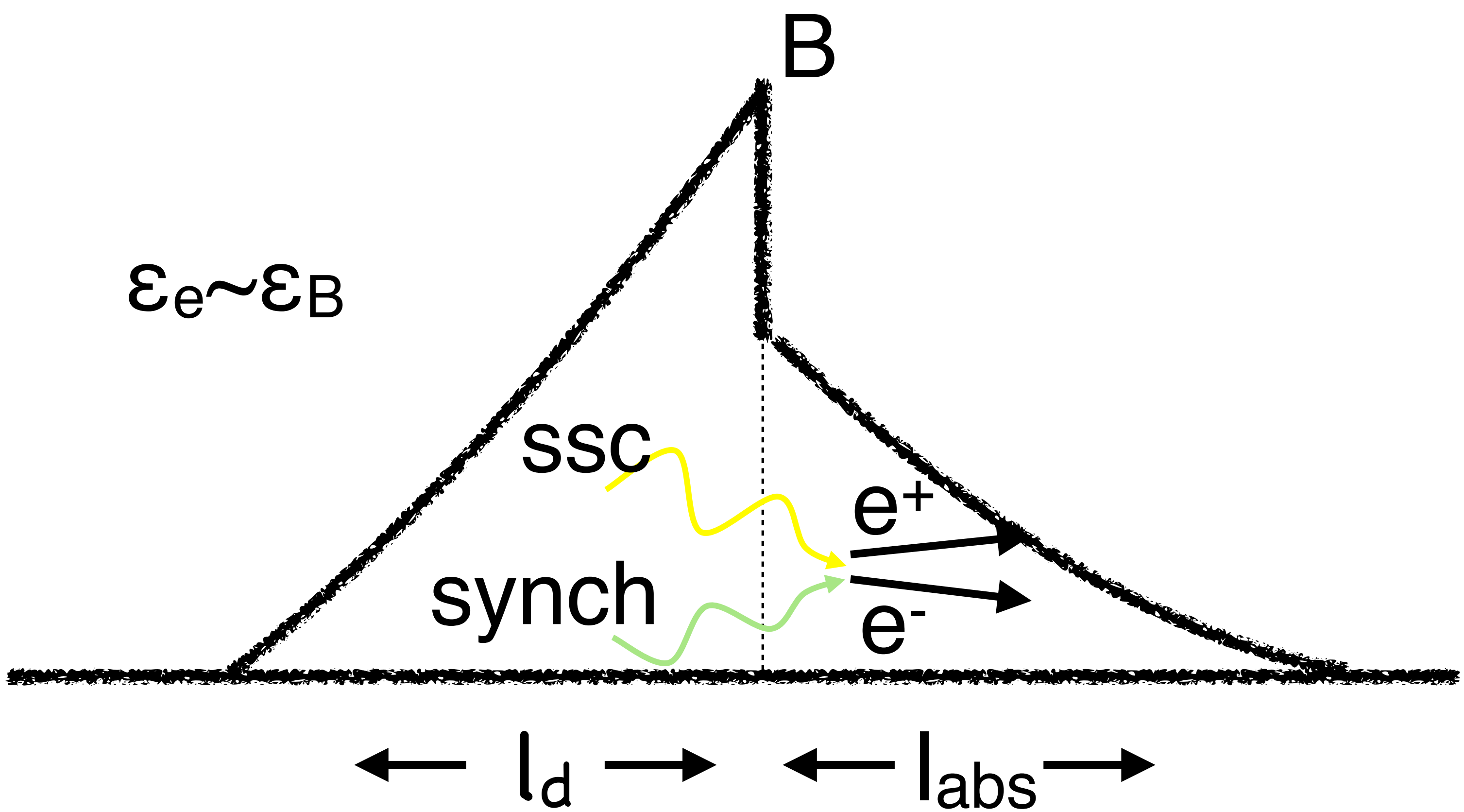








Decaying magnetic field, in the downstream, accelerates particles



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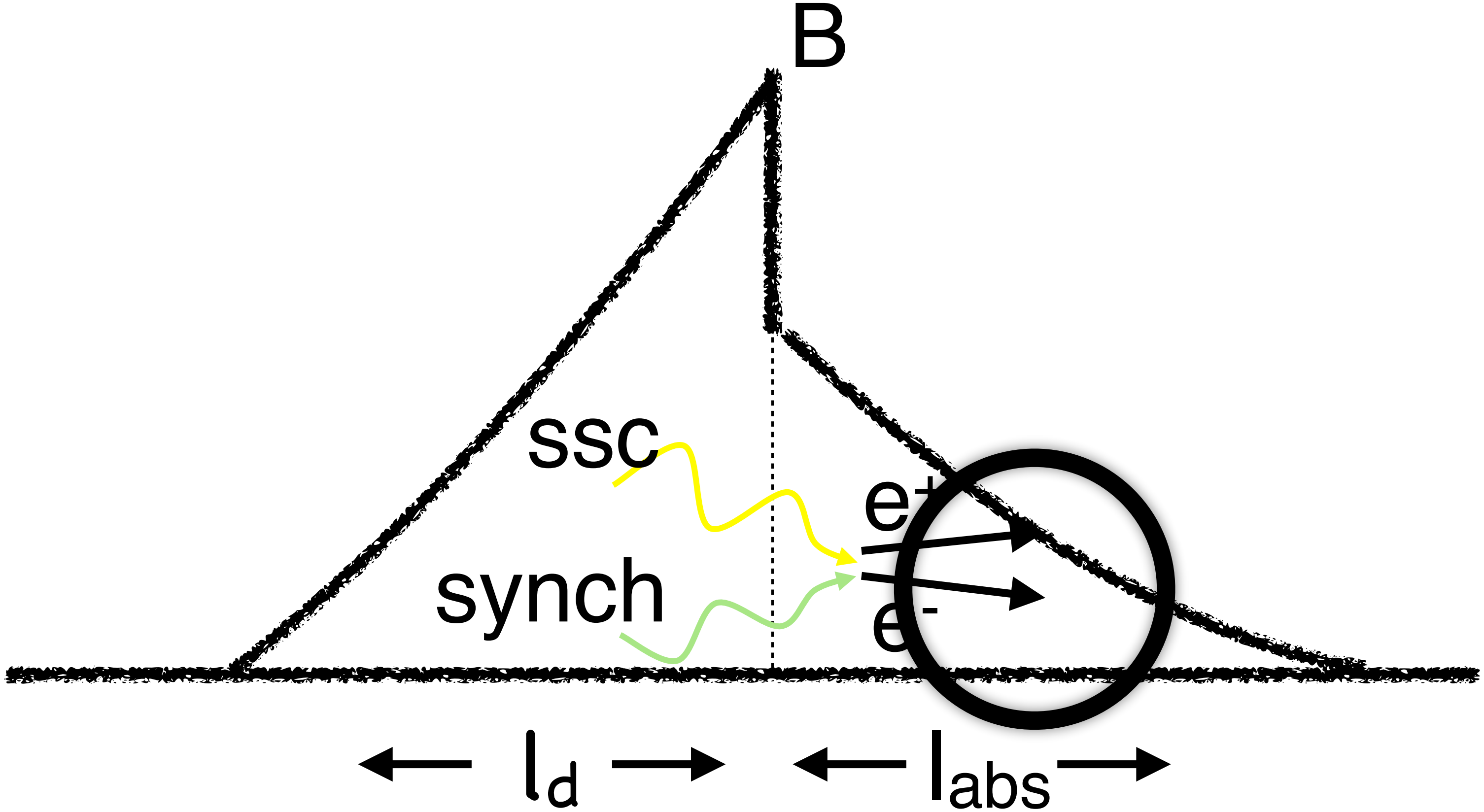
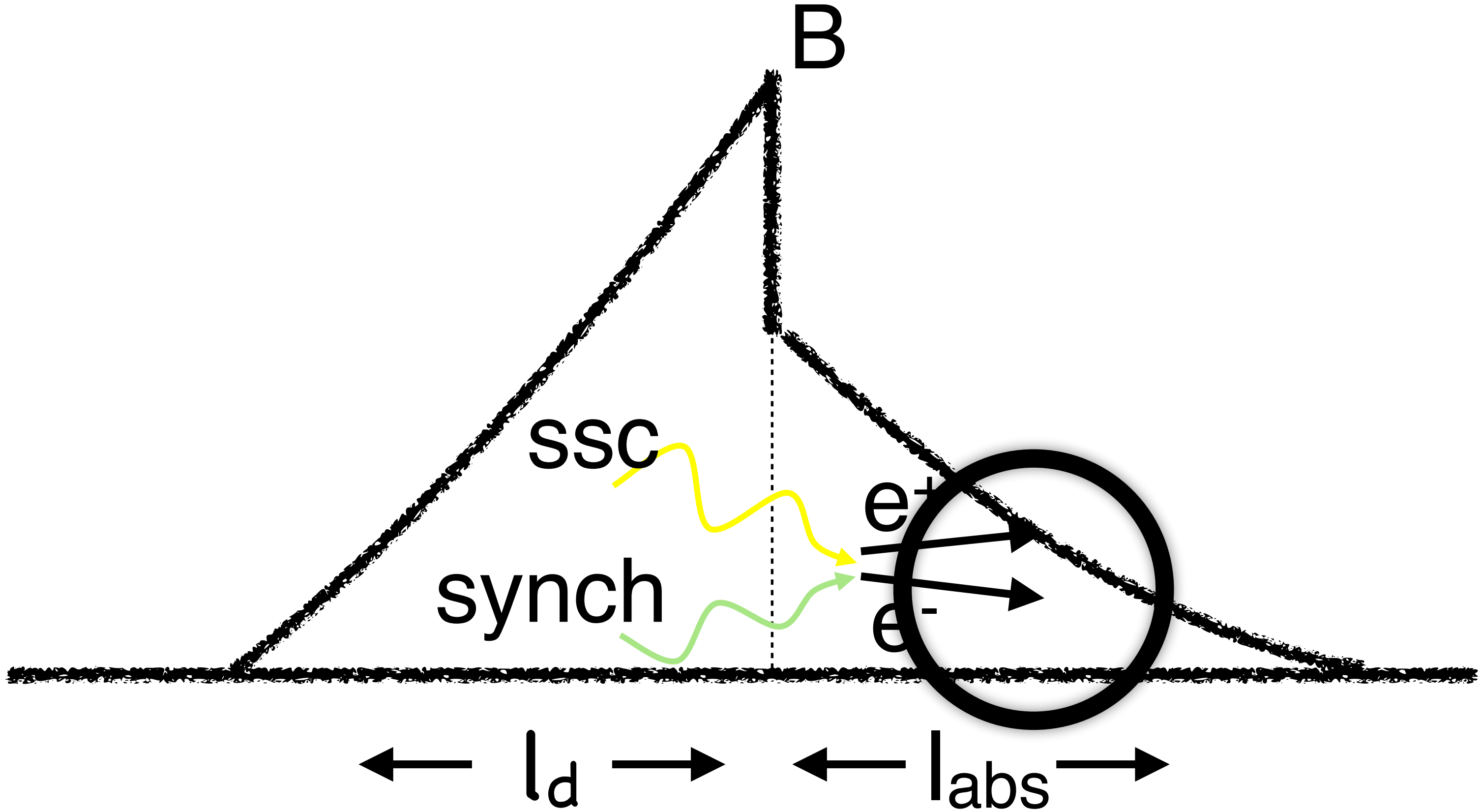


Pairs from the upstream increase the multiplicity of the downstream



Pairs from the upstream increase the multiplicity of the downstream

Length Scales

Skin Depth

$$l_s = \left(\frac{\Gamma m_p c^2}{4\pi e^2 n_p} \right)^{1/2} \simeq \frac{4 \times 10^5 \text{ cm}}{n_3^{1/2}}$$

Decay≈
Absorption

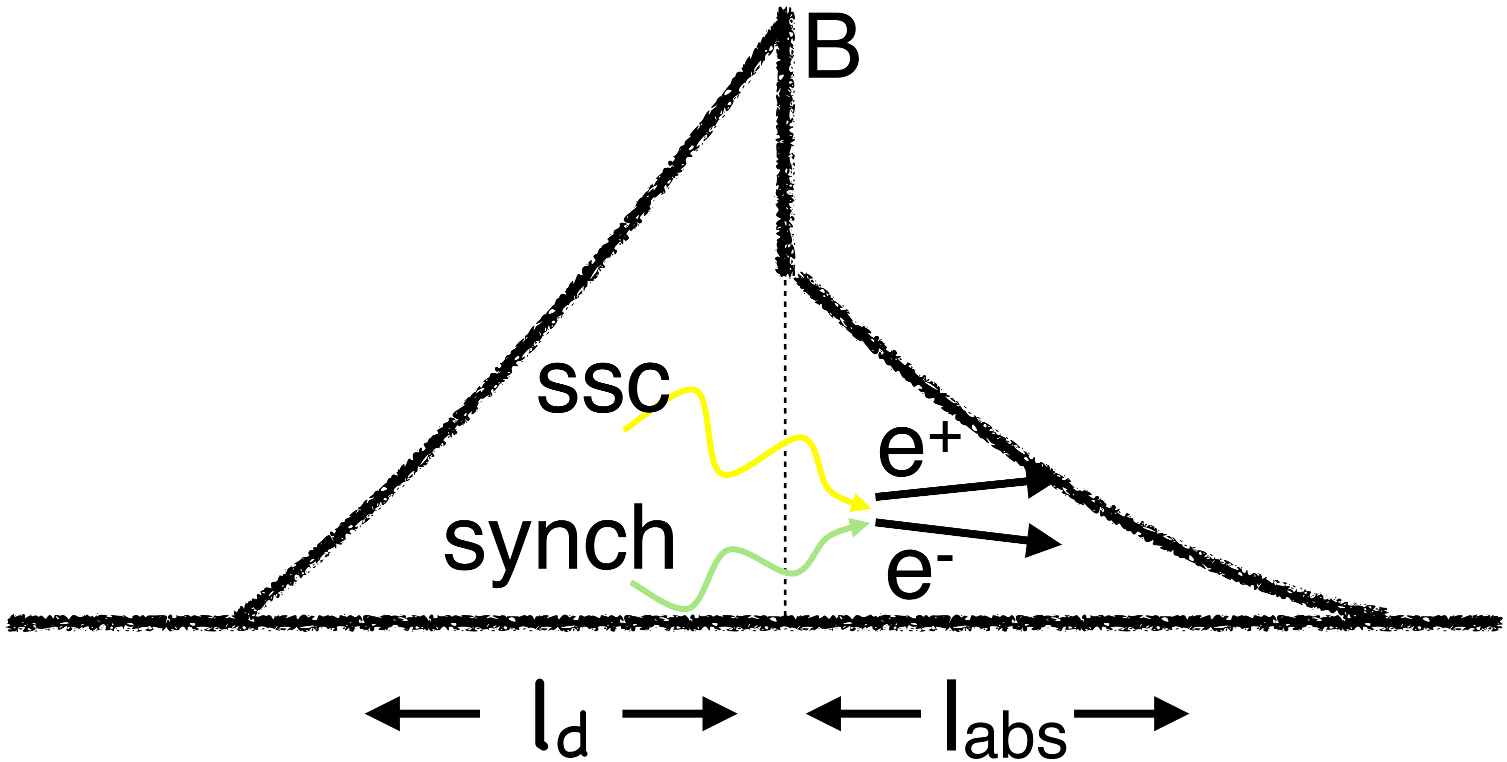
$$l_d = \lambda l_s \approx l_{abs} = R/\Gamma/\tau_c$$

$$\tau_c \simeq 50\, \sigma_{\gamma\gamma,-25}\, \epsilon_B R_{16} \Gamma_2^2 n_3 \frac{m_e c^2}{E_{p,lab}}$$

Cooling
(downstream)

$$l_c = \frac{3\beta_d m_e c^2}{4\sigma_T \gamma (1+y) e_B} \simeq \frac{5 \times 10^9}{\gamma_3 \Gamma_2^2 n_3 \epsilon_B} \text{ cm}$$

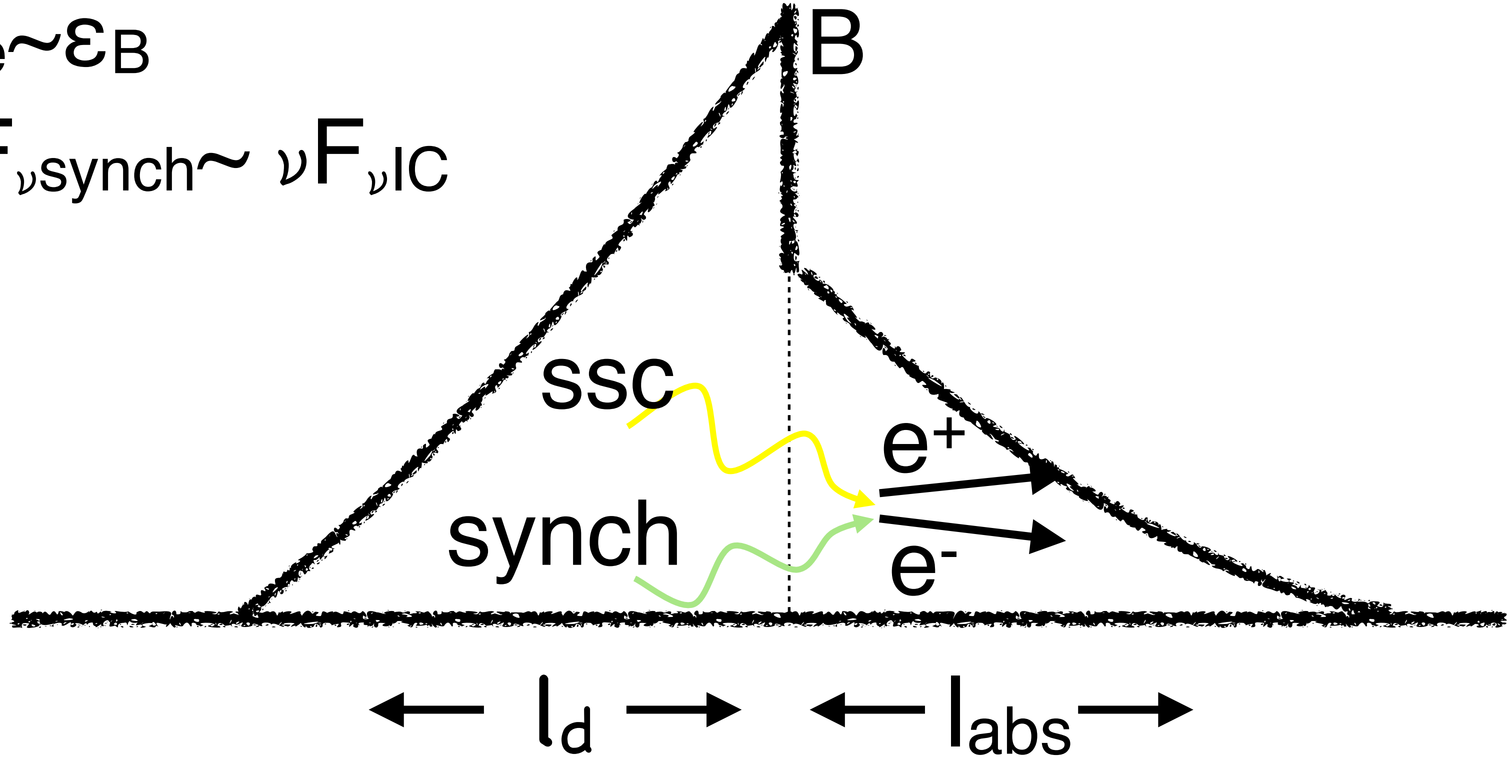
$$l_s \ll l_c \ll l_d \leq R/\Gamma,$$



$$\gamma_{cr} E_p = \gamma_{cr}^3 \hbar \omega_B = m_e c^2.$$

$\varepsilon_e \sim \varepsilon_B$

$\nu F_{\nu \mathrm{synch}} \sim \nu F_{\nu \mathrm{IC}}$



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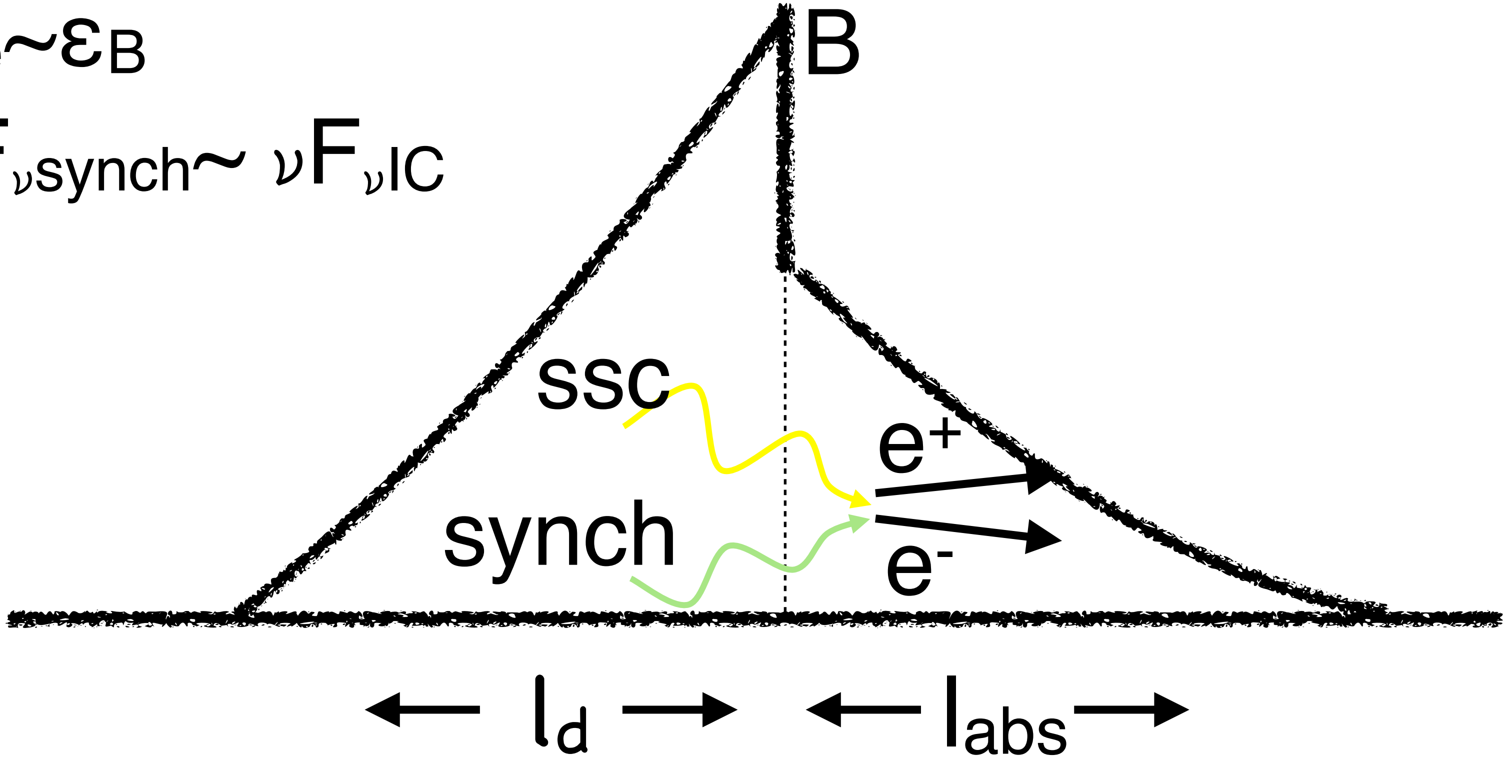
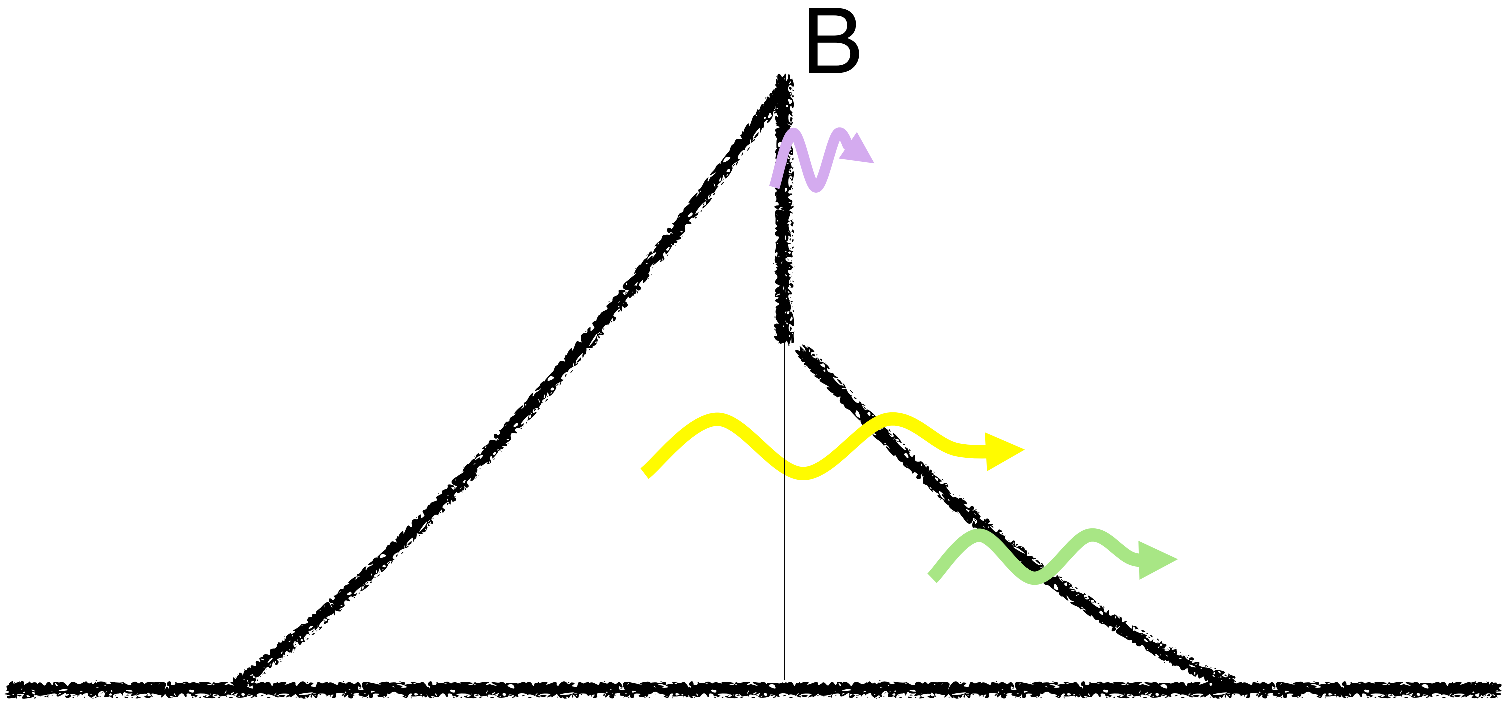


Self-regulation

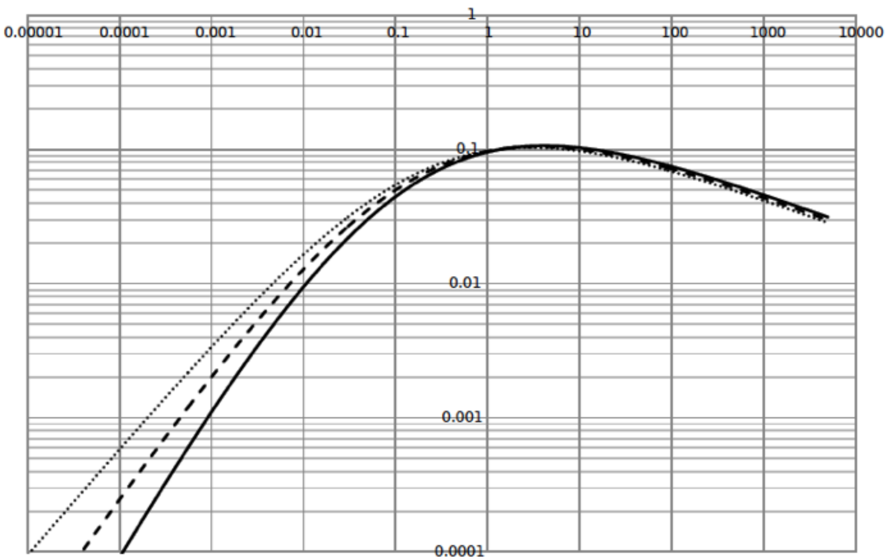
The process stops at $\nu_{IC} \simeq \nu_{KN}$

$$\gamma_{cr} E_p = \gamma_{cr}^3 \hbar \omega_B = m_e c^2$$

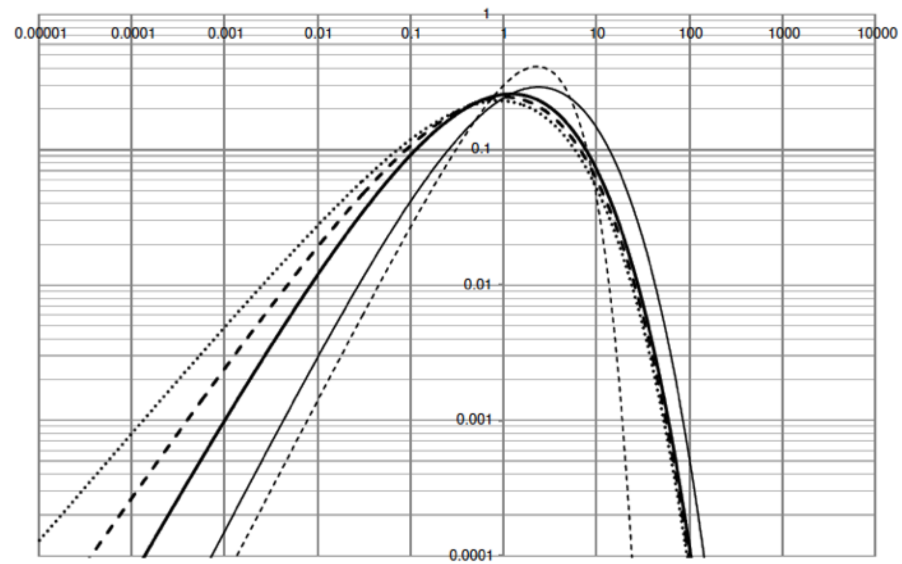
Three emission components



Downstream synch SED



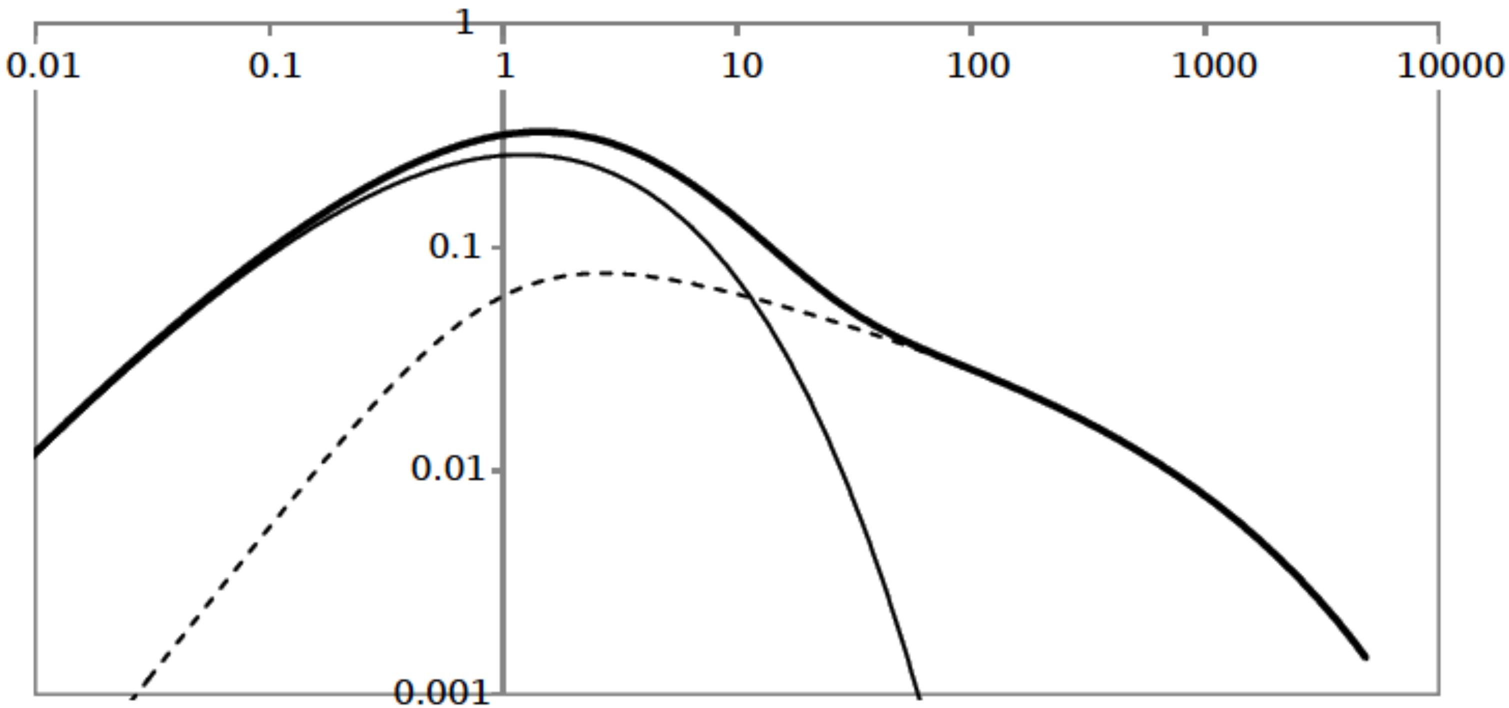
Power law elns



Thermal elns

$$E_{p,lab} = \Gamma E_p \sim 400\,\mathrm{keV} \times \frac{\Gamma_3^{2/3} L_{iso}{}_{,51}^{1/6}}{R_{13}^{1/3}}$$

SED thermal Downstream + Shock

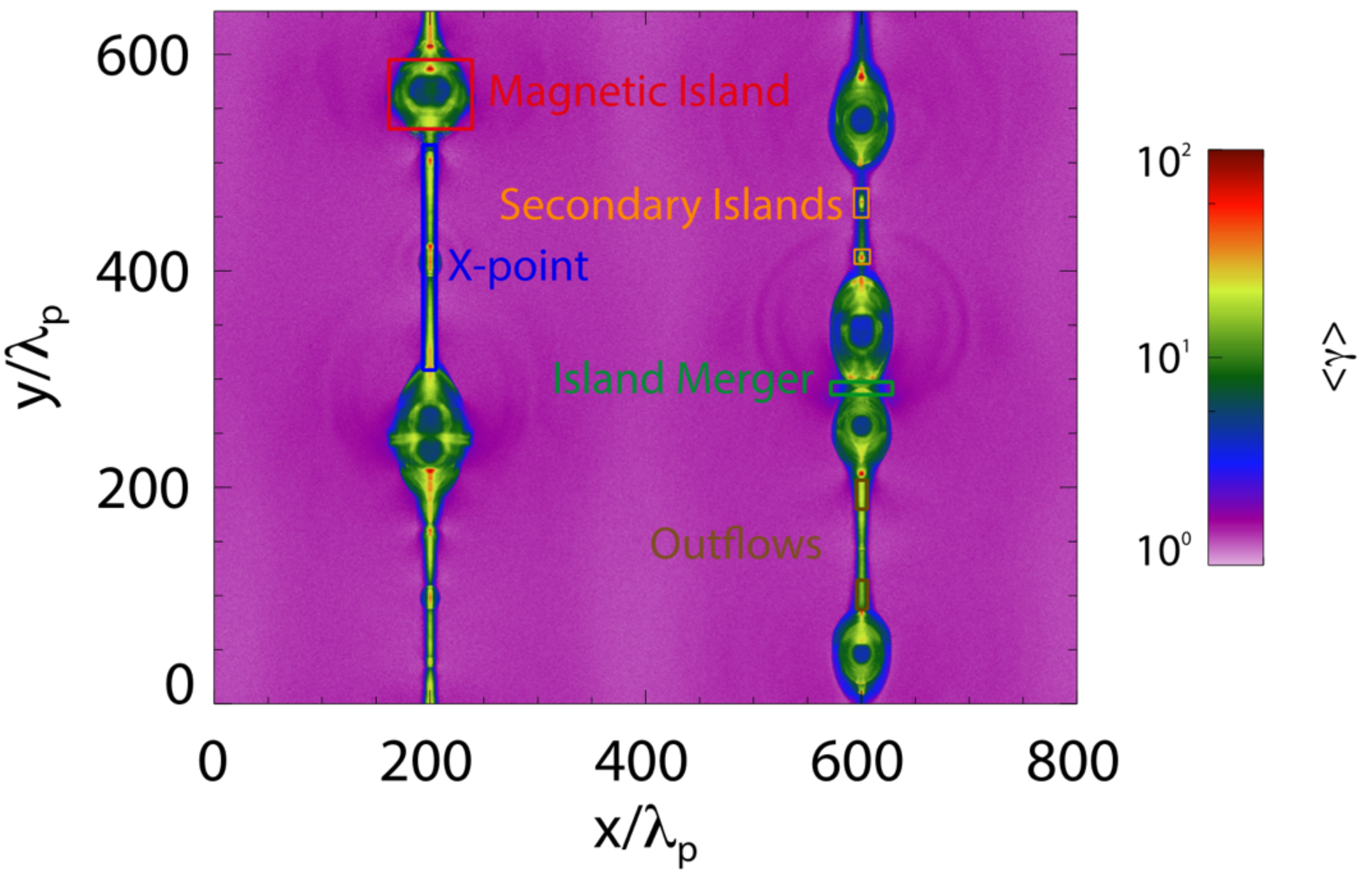


1. Summary

- With classical parameters the peak flux (at the self regulation point) is consistent with both prompt and afterglow
- Three emission components - flexibility in the spectrum (Different Fermi components?)
- But - high energy component ~1 GeV?

2. PIC simulations of Reconnection

(Kagan, Nakar Piran, 2016a, b)



Questions

- Beaming of particles and synchrotron radiation?
- The effects of the burnoff limit and the resulting synchrotron spectrum

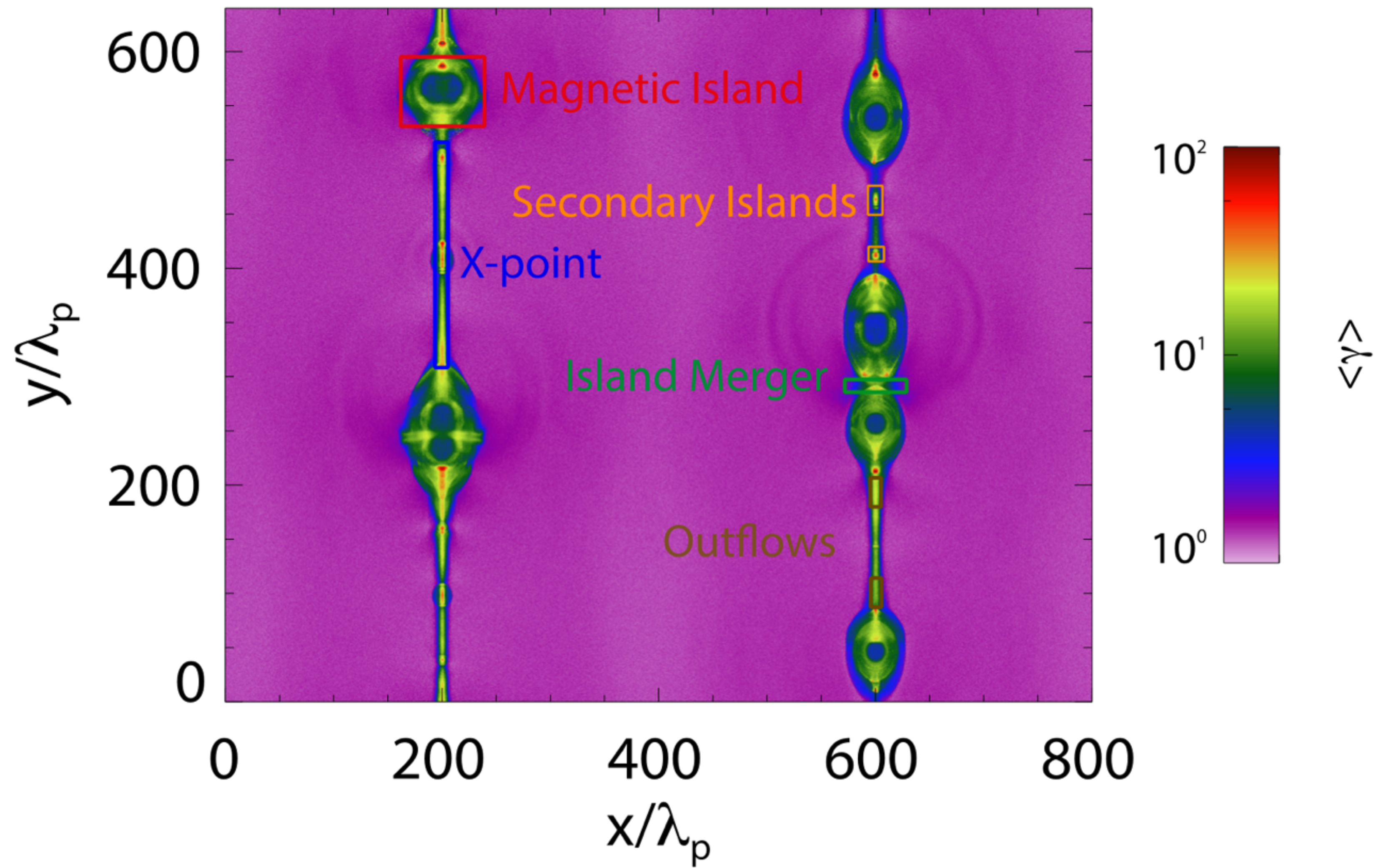
Methods

- PIC
- Cooling without cooling

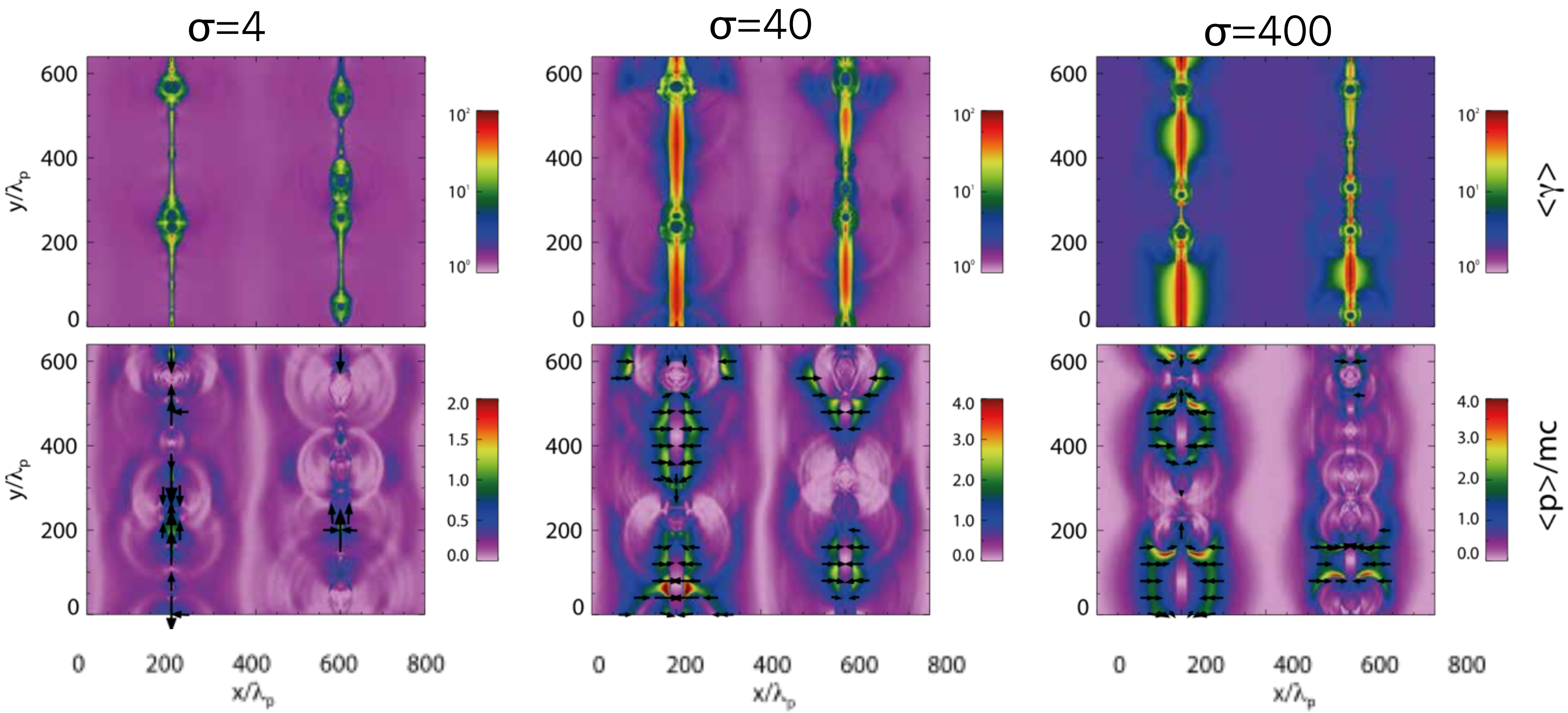
2D PIC simulations

- Tristan-MP particle-in-cell code (Spitkovsky 2008) with current density filtering algorithm that reduces particle noise
  - 16 particles per cell (similar results for up to 50 particles per cell)
  - Skin depth is set to $\lambda_p = 8\Delta$ (similar results for up to 20Δ)
- Simulation setup:
  - Pair plasma
  - Use Harris current sheet with sheet width $\delta = 3\lambda_p$
  - 2D simulations with $L_x \times L_y = 800\lambda_p \times 640\lambda_p$ ($6400\Delta \times 5120\Delta$)
  - Periodic boundary conditions
- Set background magnetizations of $\sigma = 4$, 40, and 400

Schematic of Reconnection



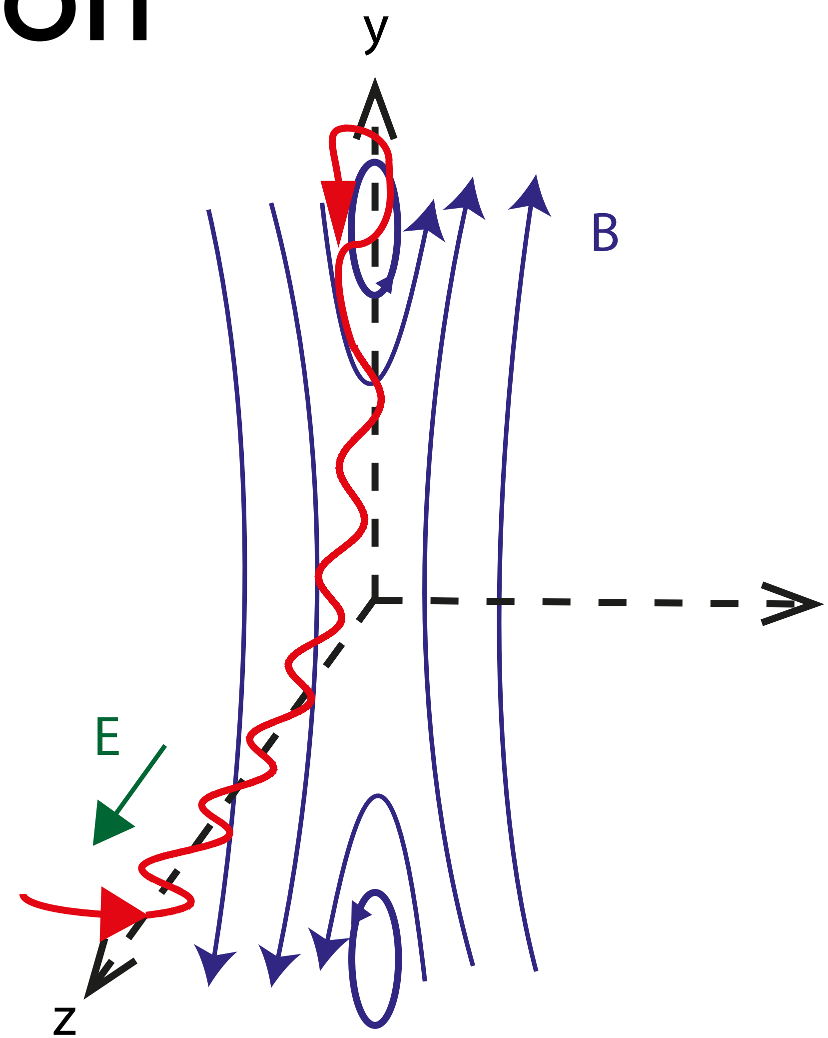
Results during nonlinear reconnection



- X-points and outskirts of islands contain the highest-energy particles
- Outflow velocities are small, typically <p>/mc ≤2
  - Agrees with Guo+14,15 but not with Sironi+14:a system size, initial values or boundary condition issue?
- Fast inflows and thick current sheets found for σ=40, 400
  - Consistent with previous work (e.g. Bessho and Bhattacharjee 2012)

Schematic motion of an electron

- Particle enters X-point, and is accelerated by electric field (initial acceleration occurs here)
- Deflected towards the magnetic island by the reconnected field
- Then it is isotropized in the island
- Acceleration in the islands can be important, but it won't produce beaming
- Unclear that Fermi acceleration happens at high energy when cooling present



Synchrotron Radiation Calculations

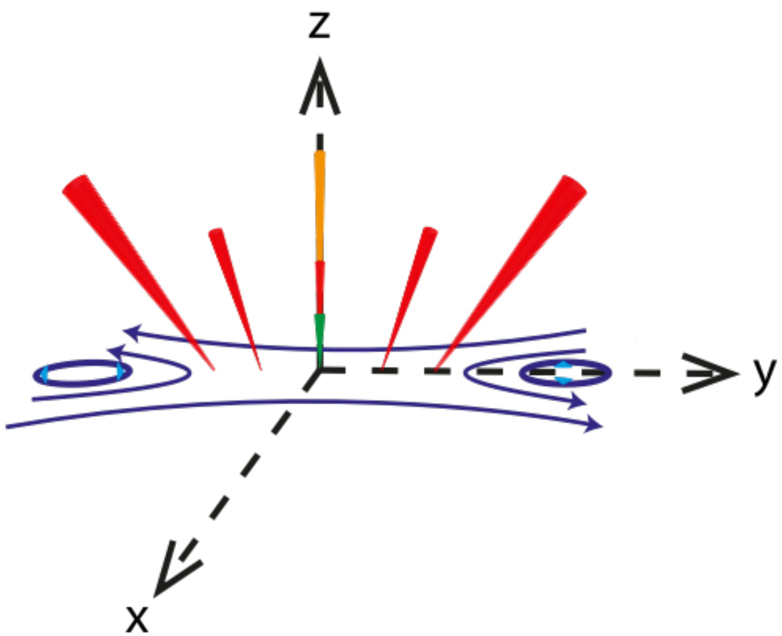
- Particles are accelerated mostly in the X-points, so
  - Fast cooling corresponds to X-point emission
  - Slow cooling corresponds to island emission
- Effective magnetic field from the curvature of particle trajectories (Wallin et al 2015)

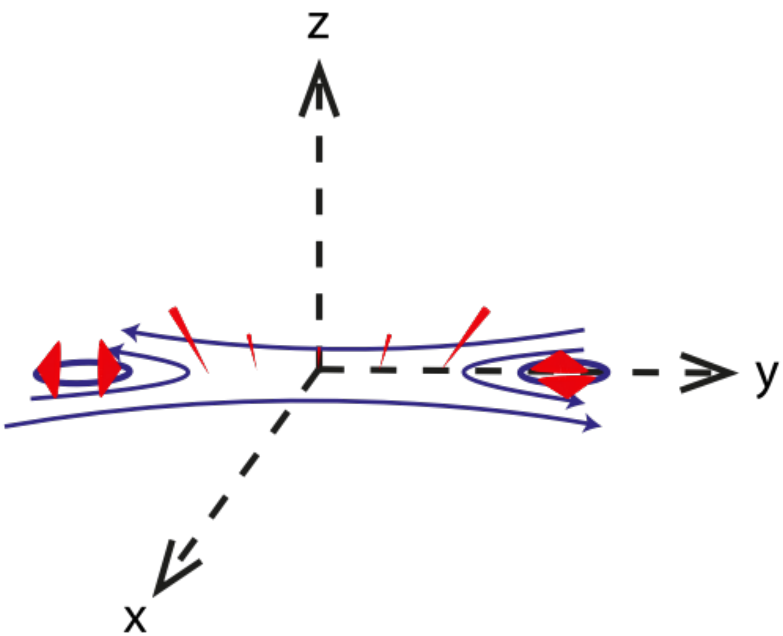
$$B_{\rm eff} = \frac{mc\gamma}{q} \frac{\sqrt{p^2 F_L^2 - (\mathbf{p} \cdot \mathbf{F}_L)^2}}{p^2}$$

- Synchrotron formula to calculate radiation

$$\frac{dF_\omega}{d\omega} = \frac{\sqrt{3} q^3 B_{\rm eff}}{2\pi mc^2} F\left(\frac{\omega}{\omega_c}\right) \qquad \omega_c = \frac{3qB_{\rm eff}\gamma^2}{2mc}$$

Schematic Radiation Beaming





Fast cooling- strong beaming

Slow cooling- no beaming

Fast cooling and the synchrotron burnoff limit

$$mc^2 \left(\frac{d\gamma}{dt}\right)_{\text{accel}} = qEc, \qquad mc^2 \left(\frac{d\gamma}{dt}\right)_{\text{rad}} = -\frac{2q^4B^2\gamma^2}{3m^2c^3}.$$

- For fast cooling, particles must have X-point beaming
- Fast cooling only occurs if

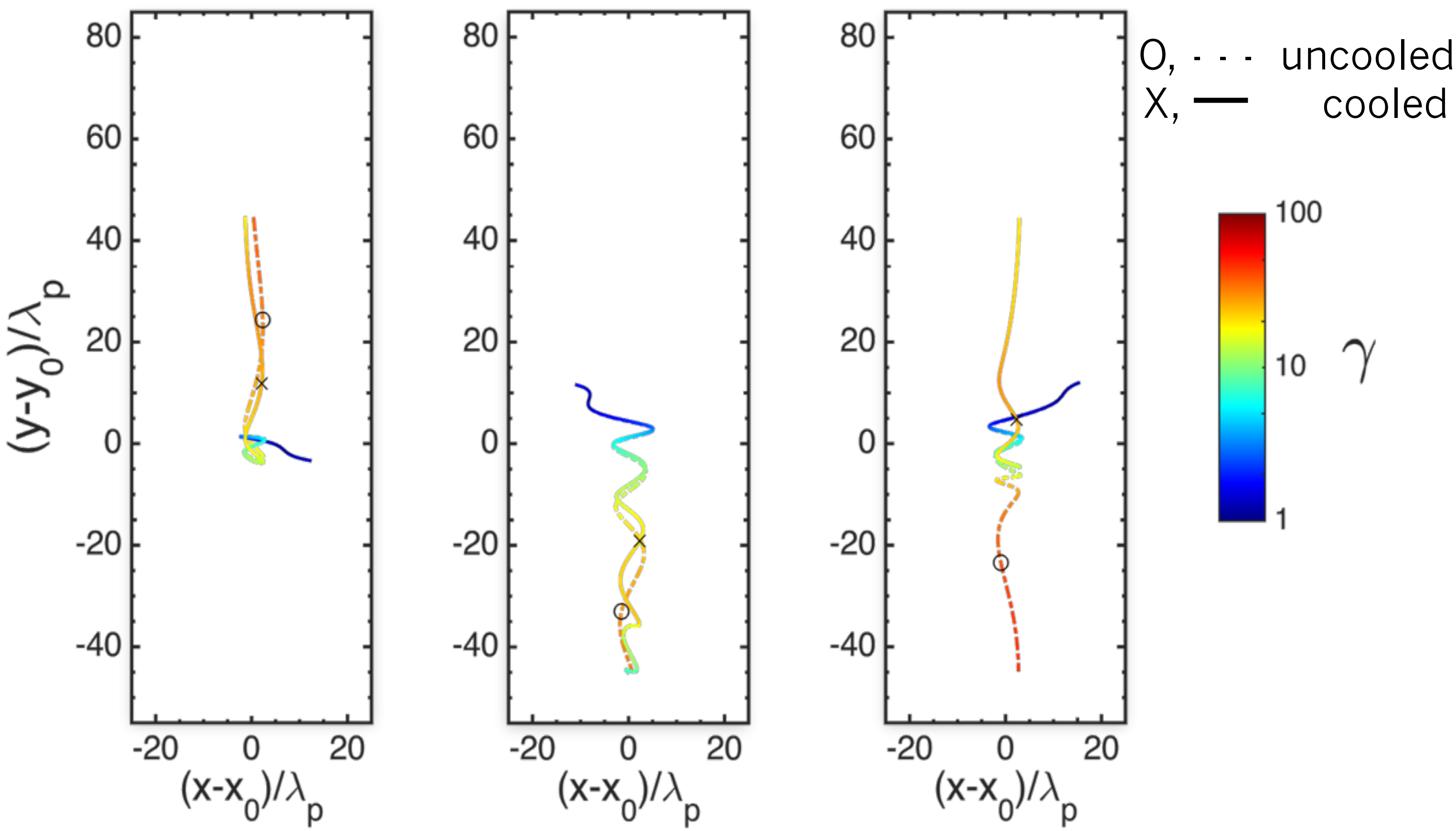
$$\gamma > \sqrt{\frac{B}{E}}\gamma_{\text{bo}} \qquad \gamma_{\text{bo}} = \sqrt{\frac{3m^2c^4E}{2q^3B^2}}.$$

- Peak emission energy ε is from fast cooling particles only if it's above the synchrotron burnoff limit

$$\epsilon > \frac{9mc^3h}{4q^2} \sim 100 \text{ MeV},$$

This is way above the energy of GRBs and (most) AGNs!

Particle Trajectories



- Trajectories are Speiser orbits
- Cooled and uncooled trajectories similar in 99% of cases

The effective burnoff limit - cooling with no cooling

Particles are limited by an effective burnoff limit determined by the average fields they experience.

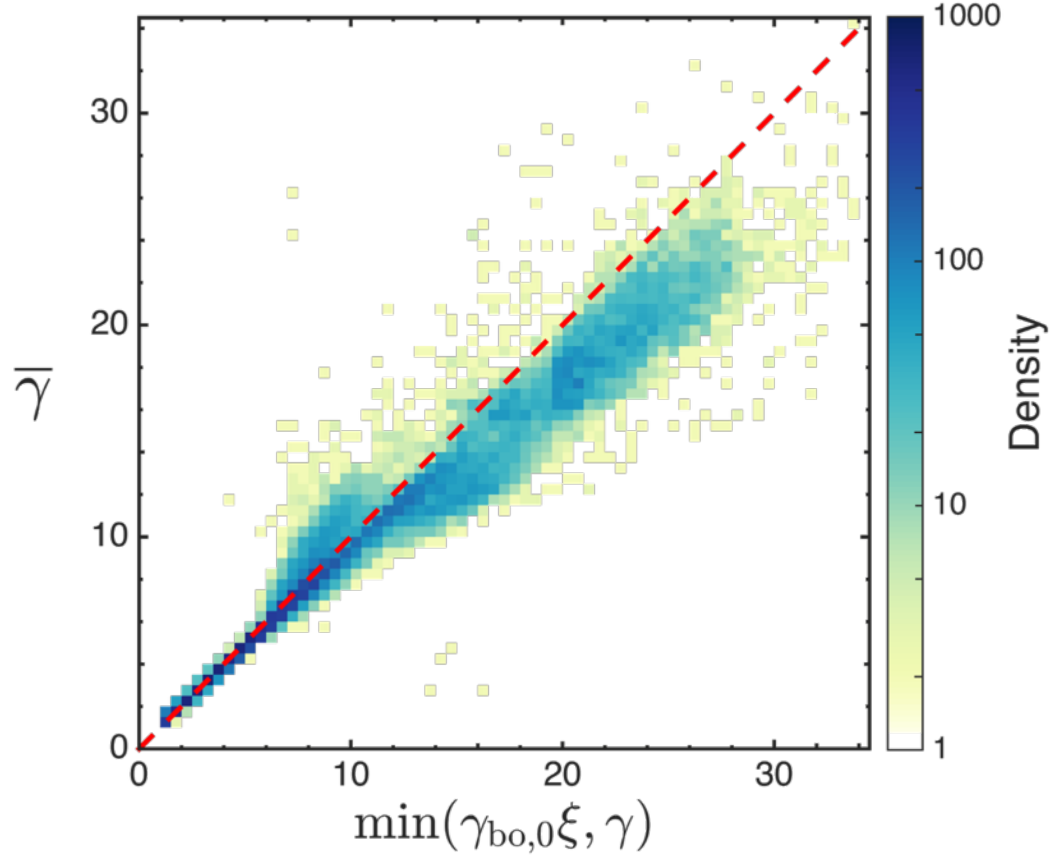
$$\gamma_{\rm bo} = \xi \gamma_{\rm bo,0} \qquad \xi = \sqrt{\left\langle \frac{E B_0^2}{E_0 B^2} \right\rangle} \qquad \gamma_{\rm bo,0} = \sqrt{\frac{3 m^2 c^4 E_0}{2 q^3 B_0^2}}$$

ξ is the burrowing parameter of the particle.

The cooled Lorentz factor is given by

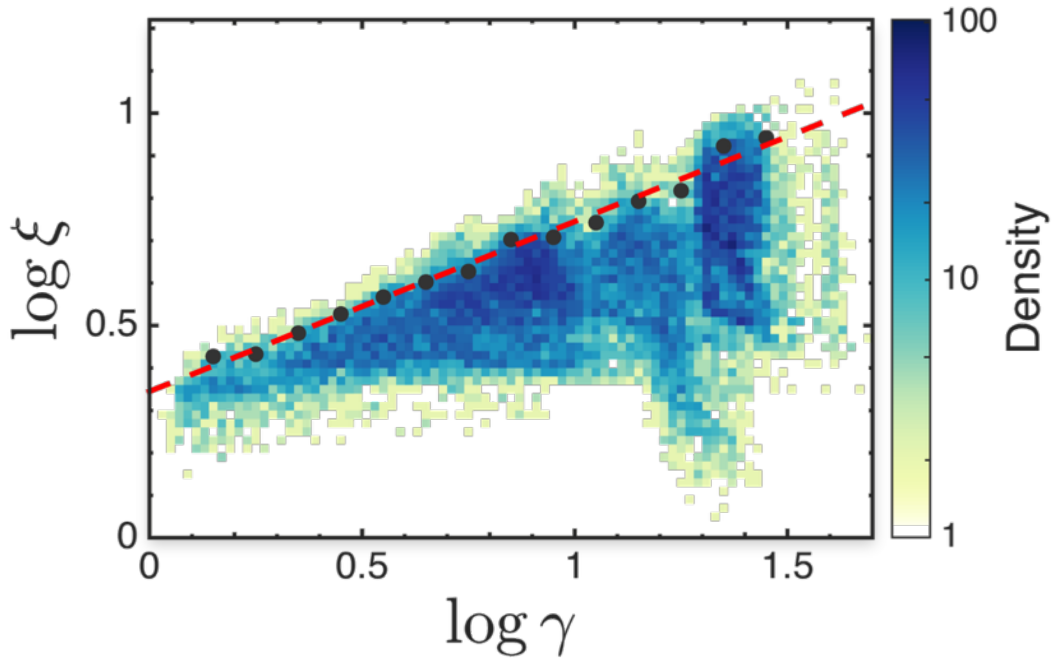
$$\bar{\gamma} = \min(\gamma, \xi \gamma_{\rm bo,0})$$

Comparison of predicted and observed cooling



The prediction (red-dashed line) works quite well (within 20%) for the vast majority of particles

Relationship between ξ and γ



Distribution at constant γ is uniform up to

$$\xi_{\max}(\gamma) = a\gamma^{\beta} \quad a = 2.2,\ \beta = 0.40$$

The maximum is consistent with analytical results for Speiser orbits without strong radiation [2], which predict β=0.5.

Effect of cooling on a power law distribution

For a power law distribution

$$N(\gamma) = \frac{p-1}{\gamma^p}$$

A joint probability distribution is approximately given by

$$N(\gamma, \xi) = (p-1)\frac{\gamma^{-p}}{\gamma^\beta - 1} \qquad 1 < \xi < \gamma^\beta$$

The distribution of $\bar{\gamma} = \min(\gamma, \xi\gamma_{\mathrm{bo},0})$ is then given by

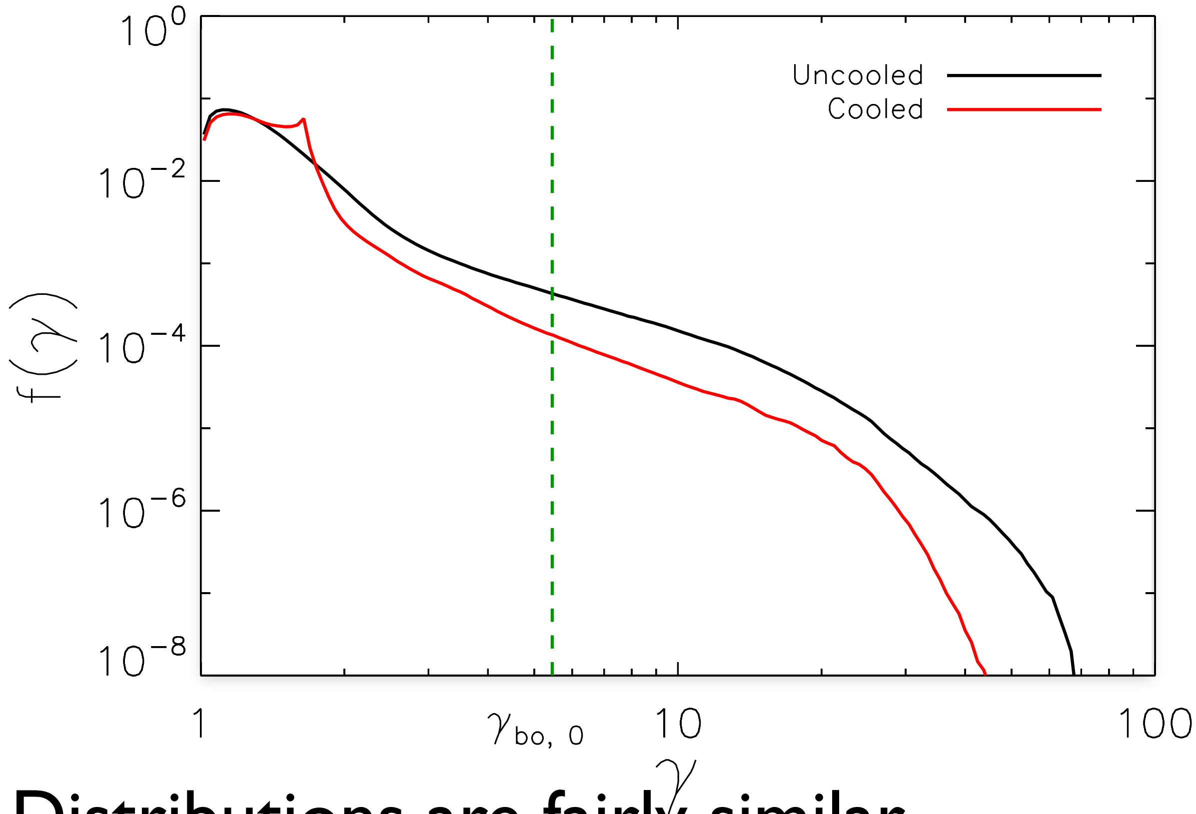
$$N(\bar{\gamma}) = N_0 \begin{cases} \bar{\gamma}^{-p} & \bar{\gamma} \le \gamma_{\mathrm{bo},0} \\ \bar{\gamma}^{-p}(1 + \kappa\bar{\gamma}^{-\beta}) & \gamma_{\mathrm{bo},0} < \bar{\gamma} \le \gamma_{\mathrm{br}} \\ \gamma_{\mathrm{br}}^{-p}(1 + \kappa\gamma_{\mathrm{br}}{}^{-\beta})(\frac{\bar{\gamma}}{\gamma_{\mathrm{br}}})^{-(p+\beta-1)/\beta} & \bar{\gamma} > \gamma_{\mathrm{br}} \end{cases}$$

$$\kappa = \frac{p - 1 + \beta^2 - \beta p + \beta}{\beta + p - 1} \qquad 0 < \kappa < 1 \qquad\qquad \gamma_{\mathrm{br}} = \gamma_{\mathrm{bo},0}^{\frac{1}{1-\beta}} \gg \gamma_{\mathrm{bo},0}$$

We expect no significant effect from cooling below the break- .
Even then, the break is not very sharp:

For $p = 1.7,\ \beta = 0.5,\ (p + \beta - 1)/\beta = 2.4$

Comparison of fully cooled vs. uncooled energy spectra



- Distributions are fairly similar
- No cutoff at the burnoff limit!

2. Summary

- The trajectories of accelerating particles are weakly affected by cooling.

- The acceleration of a particle in a cooled simulation may be derived from its acceleration in the uncooled simulation and its burrowing parameter by using the prescription:

$$\bar{\gamma} = \min(\gamma, \xi\gamma_{\mathrm{bo},0})$$

- More highly accelerated particles have higher effective burnoff limits, consistent with analytical Speiser orbit calculations.

- A power law distribution is not strongly affected by cooling until far above the burnoff limit at .

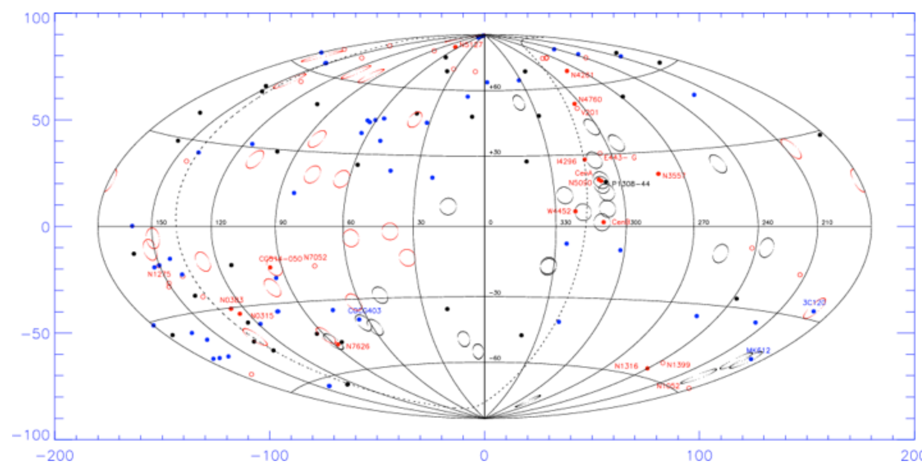
- The energy spectrum in simulations with cooling of all particles is similar to that in uncooled simulations, and has no cutoff at the synchrotron burnoff limit.

3. TDEs as UHECRs Sources

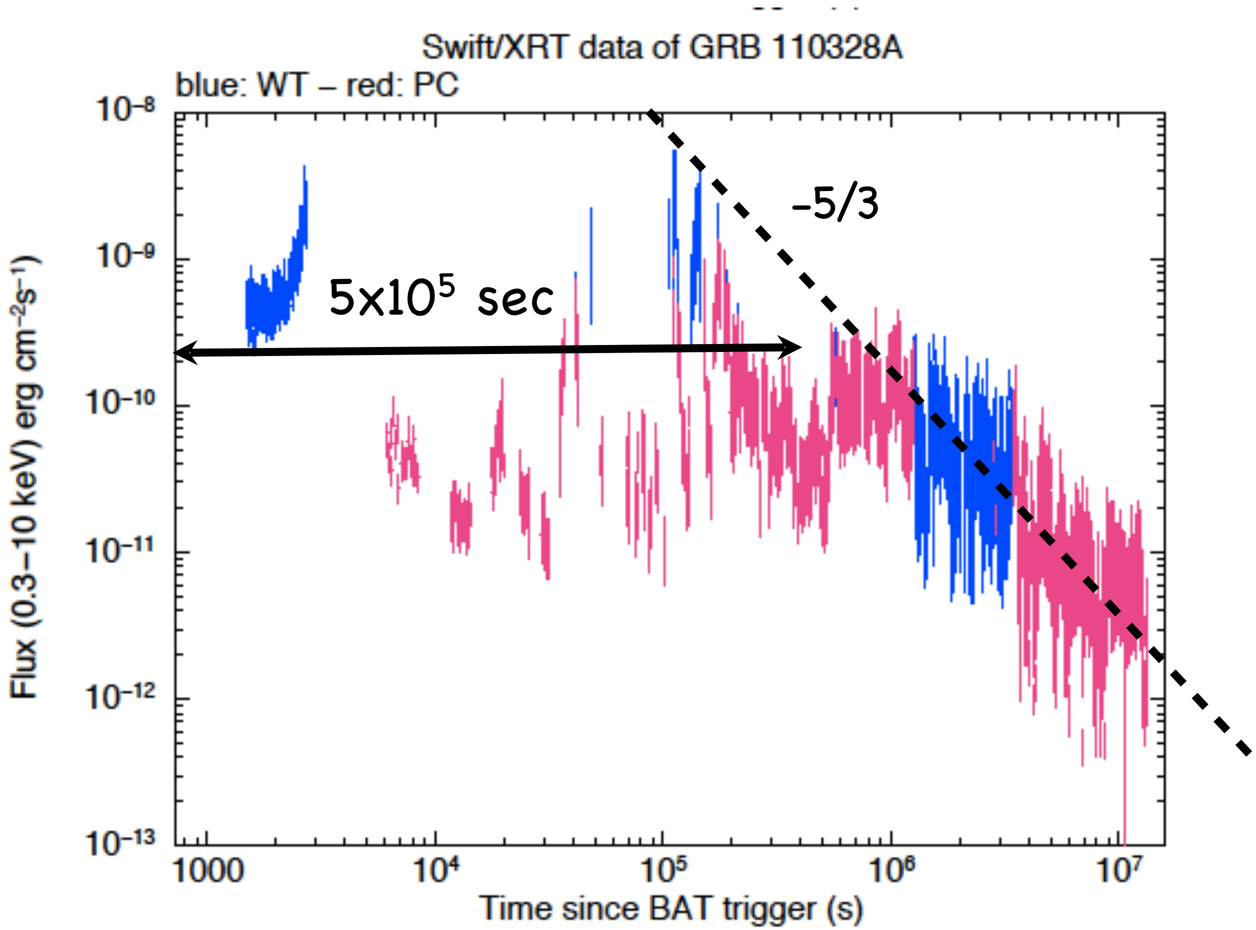
(Farrar & TP 14)

Transient Protonic UHECR sources (Waxman & Loeb 08)

- Hillas RB > 10^{17} Gauss cm =>
- $L_B \sim (RB)^2 > 10^{45}$ erg/sec =>
- One continuous source within the GZK distance (100 Mpc) produces all the observed UHECR flux.
- But angular distribution suggests many sources

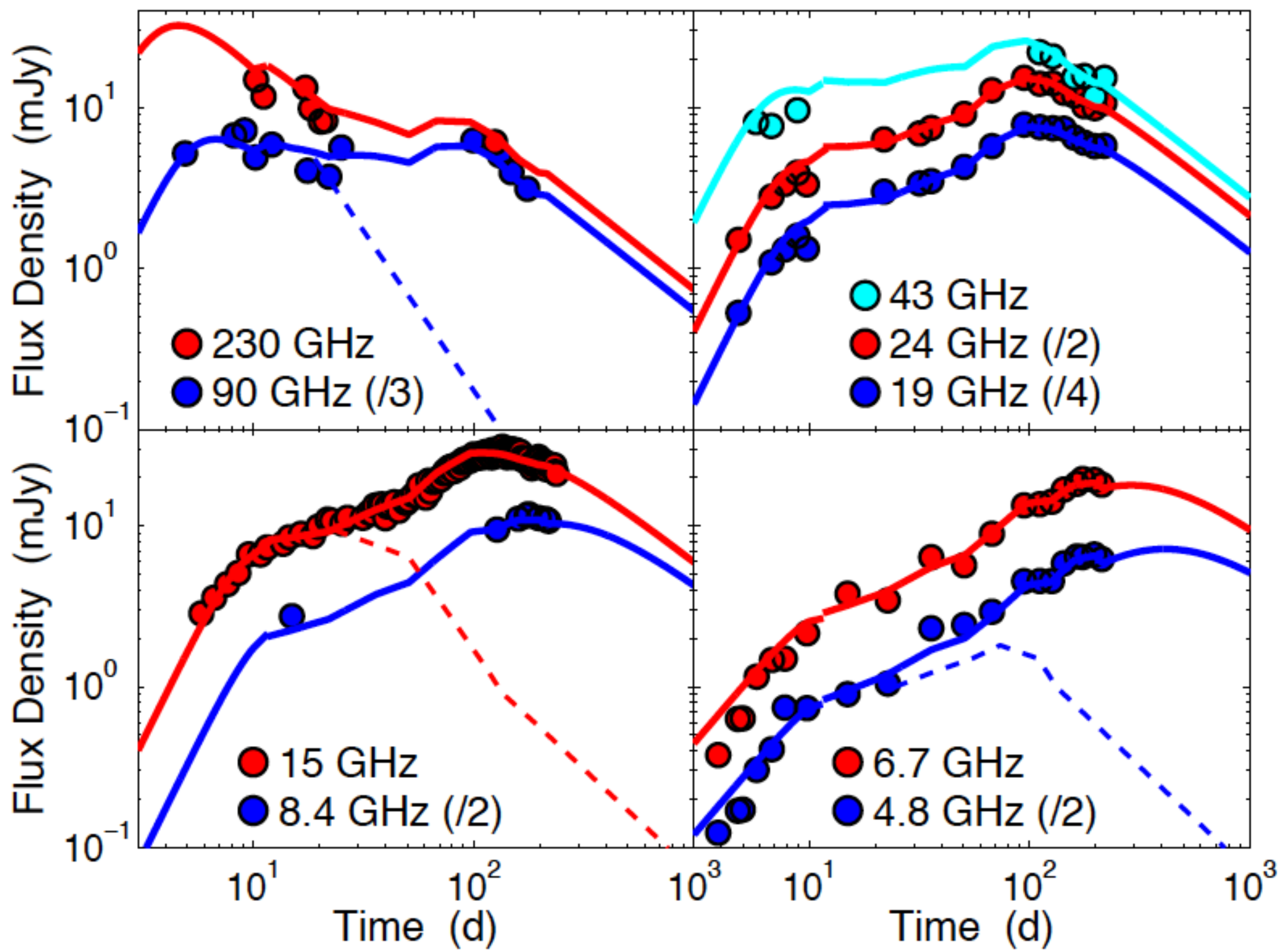


Swift J1644



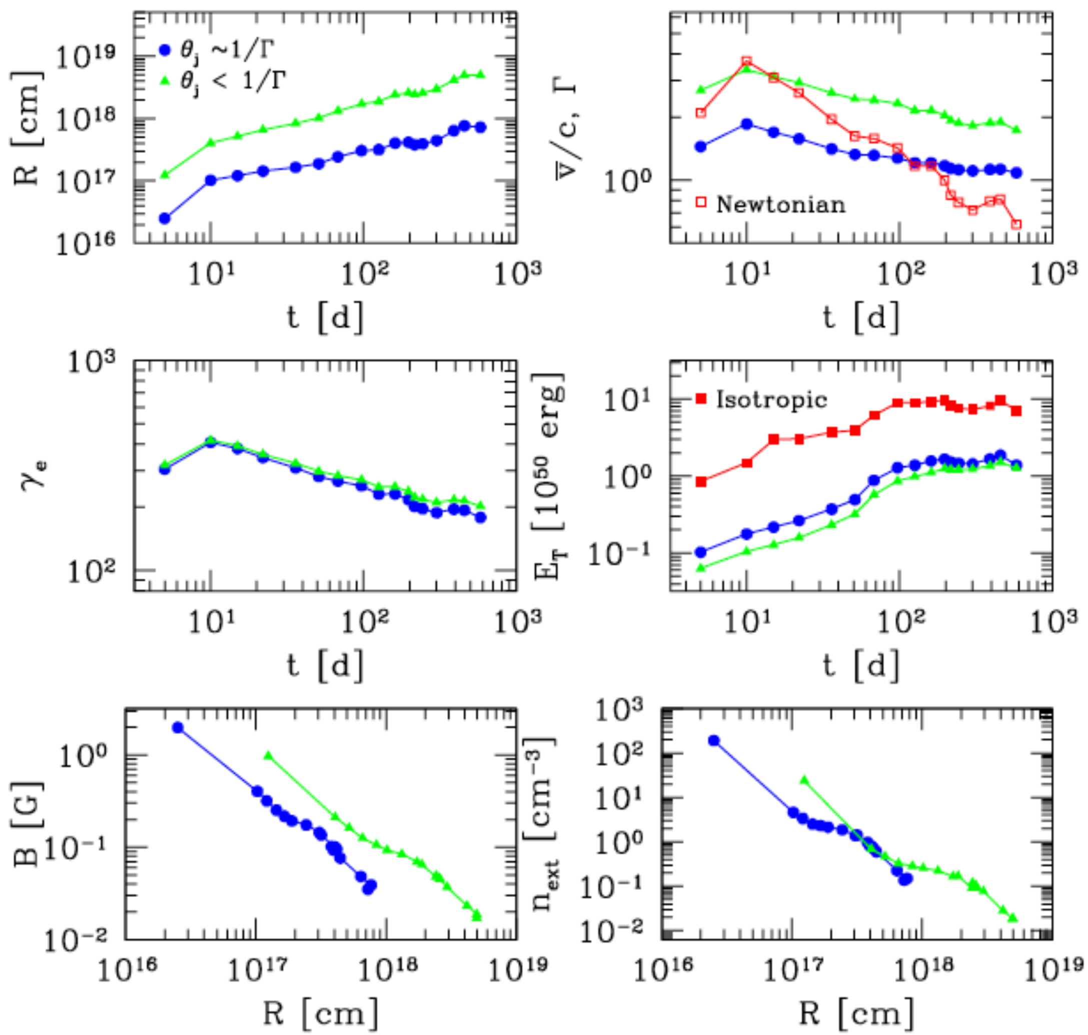
(Giannios & Metzger & 11 - jets in TDEs)

Radio observations
(Zuaderer+11, Berger +12)

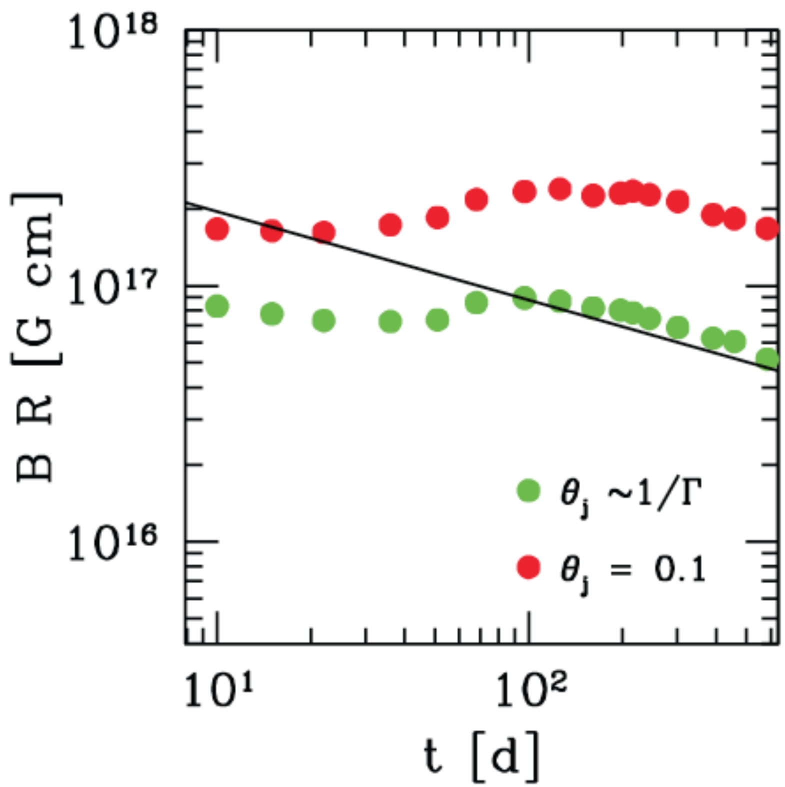


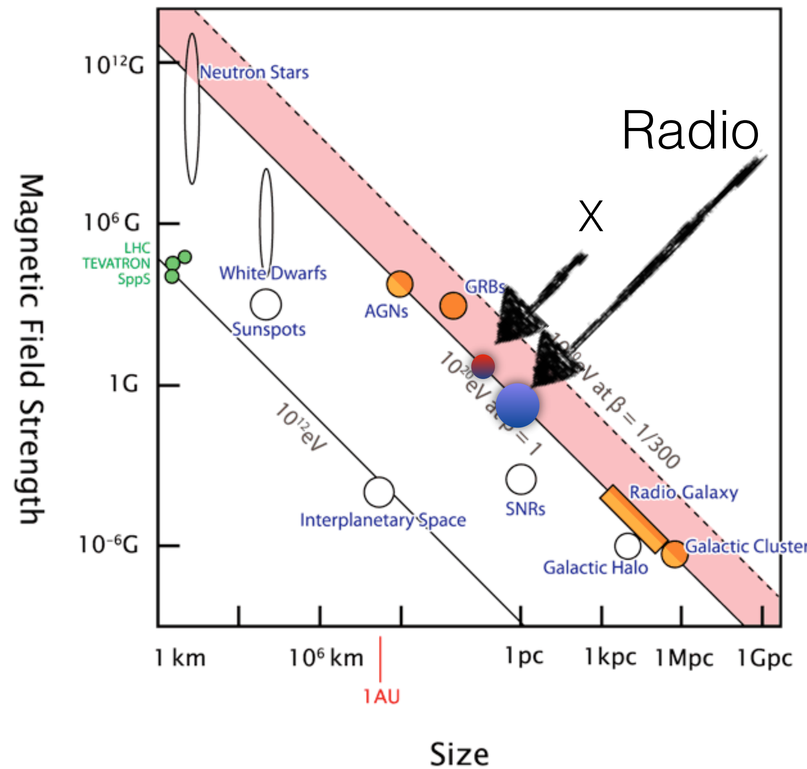
Equipartition analysis

(Barniol Duran & TP 12)



TDE 1644 in radio





(Barniol-Duran + TP; 13)

Energy input and Rates

$$\Gamma_{\rm TDE} = (0.4 - 0.8) \cdot 10^{-7\pm0.4}\,{\rm Mpc}^{-3}\,{\rm yr}^{-1},$$

- From Observations of 2 Swift TDEs
- From X-ray estimates

$$\approx 3 \times 10^{-11}\ \ {\rm Mpc}^{-3}\,{\rm yr}^{-1}$$
$$\approx 3\times10^{43}\,{\rm erg}\ \ {\rm Mpc}^{-3}\,{\rm yr}^{-1}$$

- With energy estimates from the radio and beaming estimate

$$2 \times 10^{44}(f_b/10^{-3})^{-1}{\rm erg}\,{\rm Mpc}^{-3}\,{\rm yr}^{-1}$$

3. Summary

- (Some) TDEs satisfy the Hillas conditions for acceleration of protonic UHECRs to 10^{20}ev
- The overall rate and energy available are compatible with the UHECRs flux
- Effective rate (and energy) of ``jetted'' TDEs might be too small. A comparable problem to GRBs (a factor of 10?)