Relativistic Accelerators: Gamma-Ray Bursts

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PASTO – Particle Acceleration in aSTrophysical Objects,
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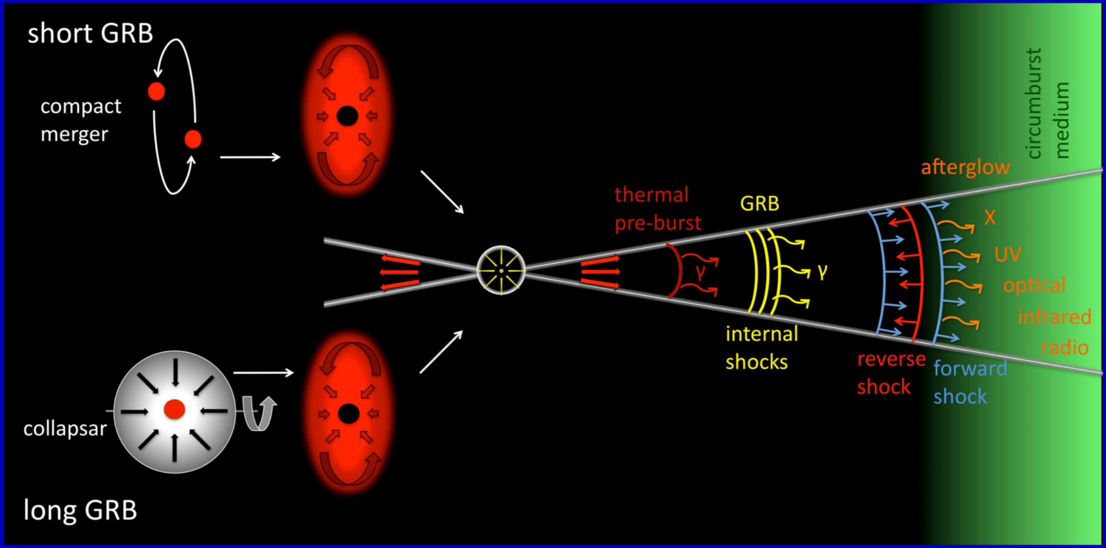
Outline of the Talk:

- Potential particle acceleration sites & mechanisms
- Observational constraints:
  - Spectral index ⇒ electron power-law index p ($dN_e/d\gamma_e \propto \gamma_e^{-p}$)
  - Spectral breaks ⇒ $\gamma_{e,\min}$ & $\gamma_{e,\max}$
  - Pulse onset time $t_{on}(E_\gamma)$ ⇒ acceleration time $t_{acc}\left(E_{e,p}\right)$ **(Ryde's talk)**
  - Signatures of anisotropic velocity distribution (local / global)
  - Polarization ⇒ B-field structure in shocks / GRB ejecta **(Gill's talk)**
- Observational puzzles:
  - Apparent violation of the $E_{\rm syn,max}$ limit (in GeV / TeV)
  - Lack of clear signs for a thermal electron component
  - Transition to a Newtonian shock; Evidence for ion acceleration?
- Conclusions

GRB Theoretical Framework:

- **Progenitors**:
  - Long: massive stars
  - Short: binary mergers
- **Acceleration**:
  fireball or magnetic?
- **Prompt γ-rays**:

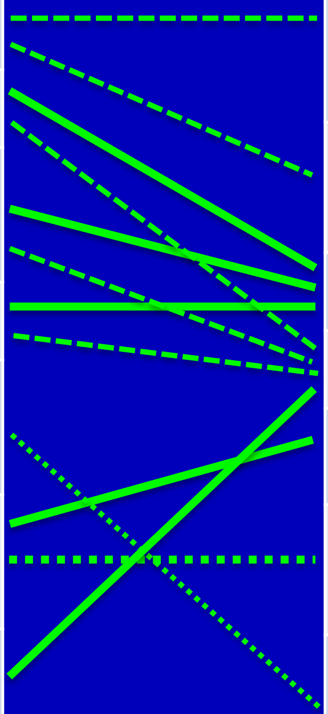


Dissipation: internal shocks or magnetic reconnection?
Emission mechanism?

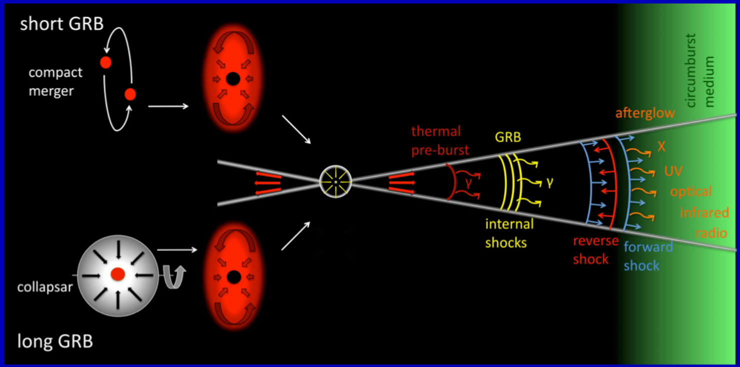
- **Deceleration**: the outflow decelerates (by a **reverse** shock for $\sigma \lesssim 1$) as it sweeps-up the external medium
- **Afterglow**: from the long lived **forward** shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray ➔ optical ➔ radio

Potential Particle Acceleration Sites & Mechanisms

Potential Sites	Medium	Emission
Mag. reconnection	Outflow	Prompt GRB
Internal Shocks	Outflow	Prompt GRB
Reverse Shock	Outflow	Optical Flash, Radio Flare
Forward Shock	External	Afterglow
Radiation Mediated Shocks	Outflow, progenitor	Prompt GRB? Shock breakout
Shear Layers	Near the boundary	Prompt GRB? Early Afterglow?
Turbulence	Outflow, External	Prompt GRB? Afterglow?



Pot. Mechanisms
Direct acceleration in electric fields;
Magnetic island dynamics
Fermi Type I
Fermi Type II
Shear acceleration
Neutral-charged conversion
A new mechanism and/or instability???



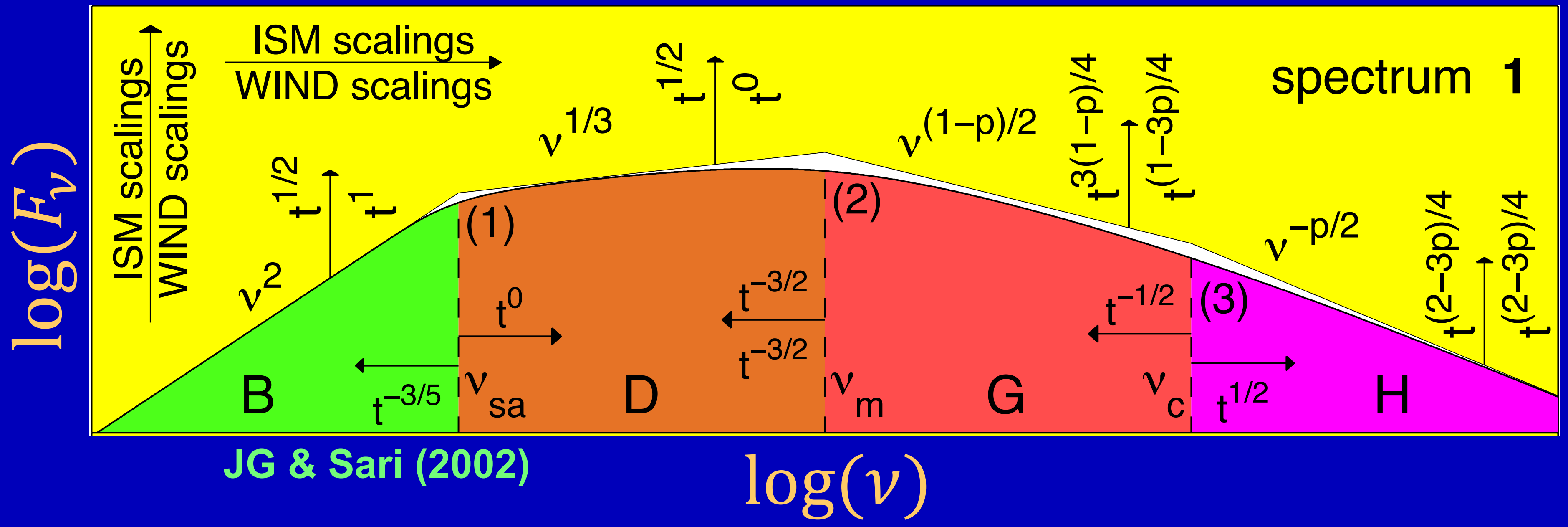
Observational constraints: Spectral index

◆ Spectral index ⇒ electron power-law index $p = -\frac{d\log N_e}{d\log \gamma_e}$)

- Power-law electron distribution: $\frac{dN_e}{d\gamma_e} \propto {\gamma_e}^{-p}$ $\gamma_m < \gamma_e < \gamma_M$
- $F_\nu \propto \nu^{-\alpha}$ with $\alpha = \frac{p-1}{2}$ $(p/2)$ for $\nu_m < \nu < \nu_c$ $(\nu > \nu_m, \nu_c)$

⇒ $p = 2\alpha + 1$ $(p = 2\alpha)$ (for synchrotron emission)

⇒ Afterglow: $2.1 \lesssim p \lesssim 2.5$ Prompt GRB: $2 \lesssim p \lesssim 4$ (?)



JG & Sari (2002)

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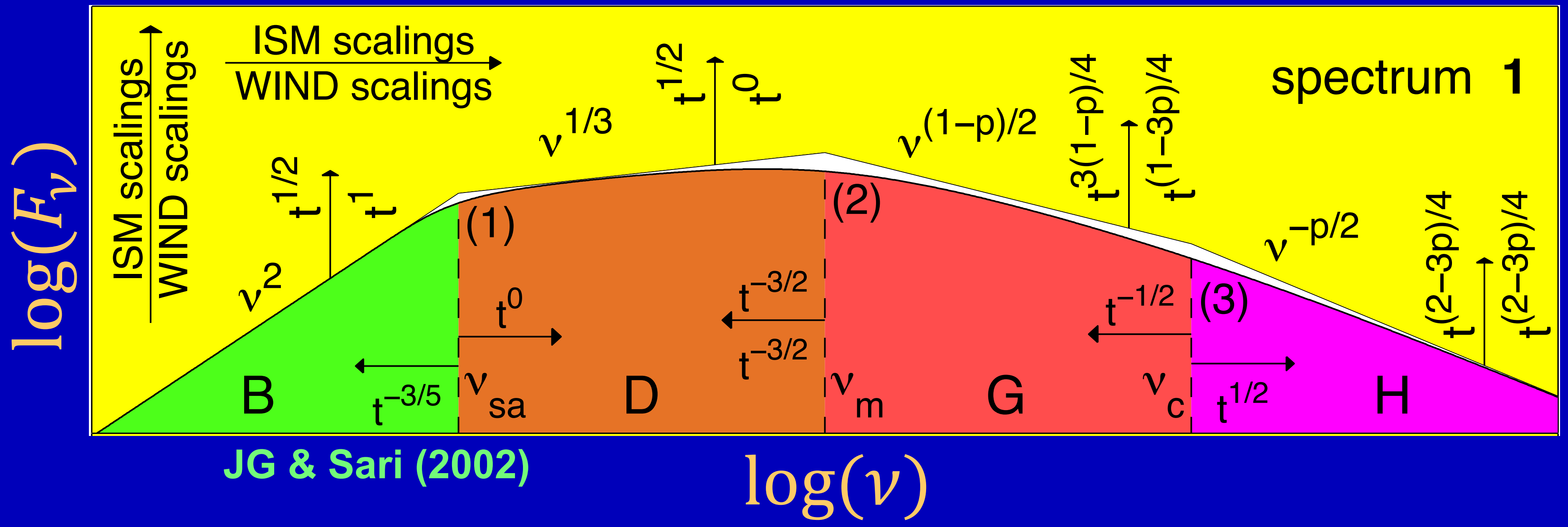
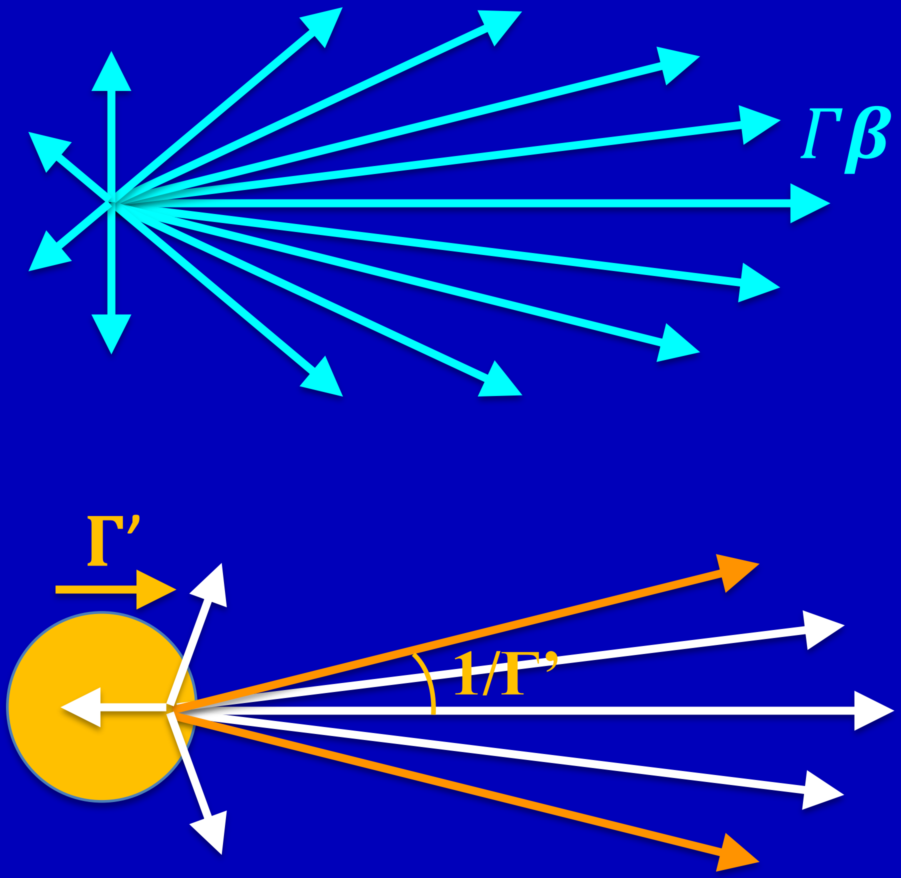
- Power-law electron distribution: $\frac{dN_e}{d\gamma_e} \propto \gamma_e^{-p}$ $\quad \gamma_m < \gamma_e < \gamma_M$
- $\nu_m \propto \Gamma B'\gamma_m^2$ with $\gamma_m = \frac{p-2}{p-1}\frac{\epsilon_e}{\xi_e}\frac{m_p}{m_e}(\Gamma_{sh}-1)$ $\;(\xi_{e,\gamma} \ll 1\,?)$
- $\nu_M \propto \Gamma B'\gamma_M^2$ with $\gamma_M = (6\pi\kappa e/\sigma_T B')^{1/2}$ ("burnoff limit")

  ⇒ $E_{syn,max} = 7.0\kappa(1+z)^{-1}\Gamma_2$ GeV



JG & Sari (2002)

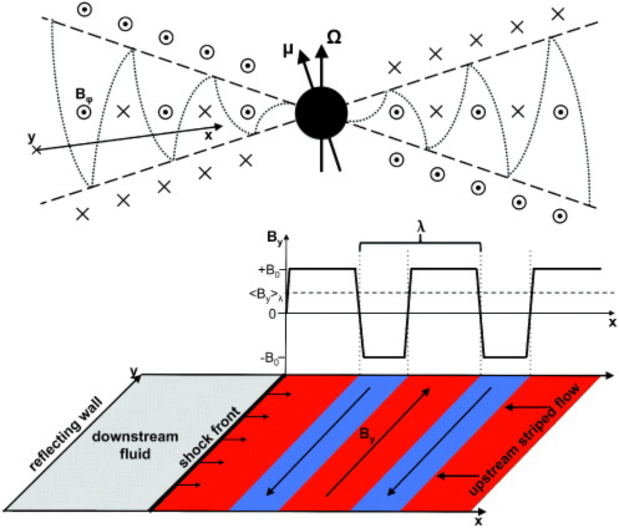
Signatures of an anisotropic velocity distribution or relativistic bulk motions in the jet comoving frame:

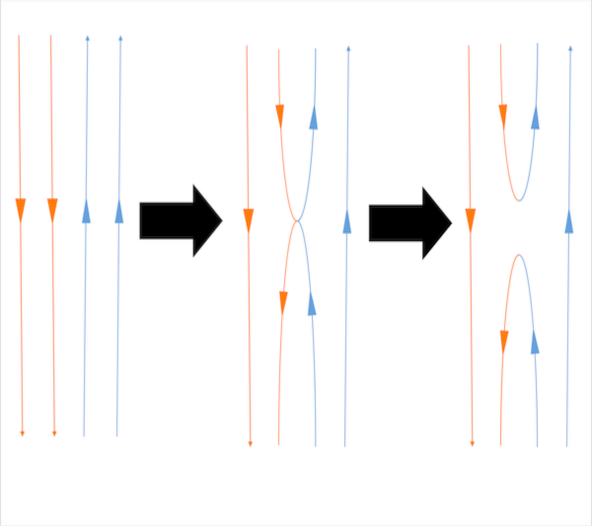


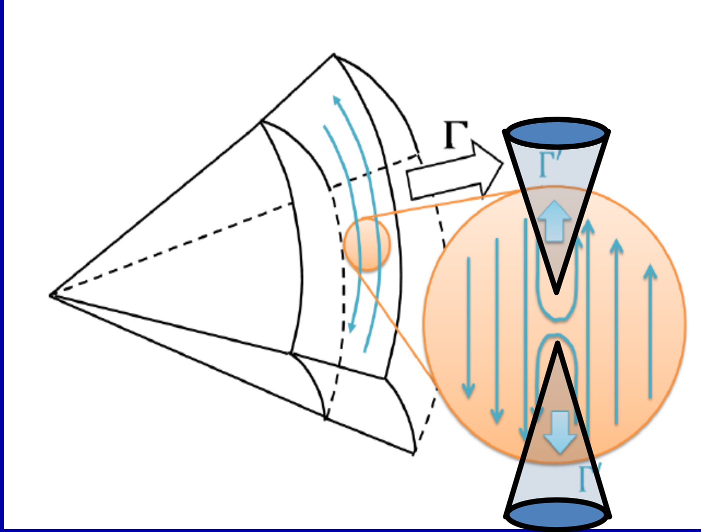
- **Local**: anisotropic w.r.t local **B**’ that is random globally (Comisso’s talk)
- **Global**: anisotropic w.r.t globally ordered **B**’ or reconnection layers

GRB Lightcurves from Magnetic Reconnection (Beniamini & JG 2016)

- Field reversals at the source can lead to reconnection at large distances
  millisecond-magnetar ➔ millisecond quasi-periodic variability (✖)
  accreting BH ➔ stochastic field-reversal & lightcurve variability (✔)







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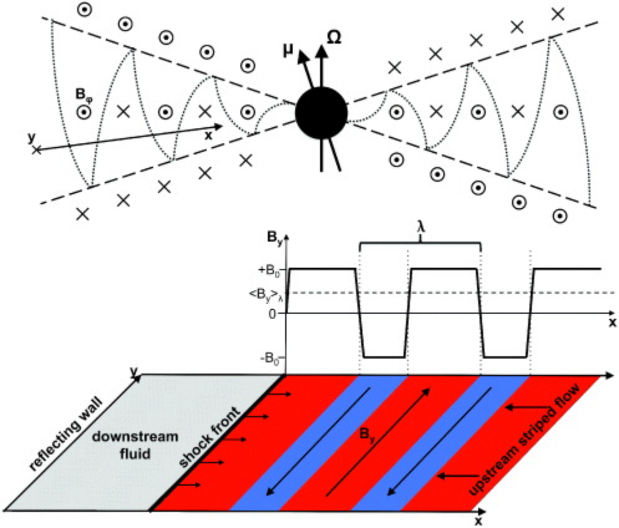

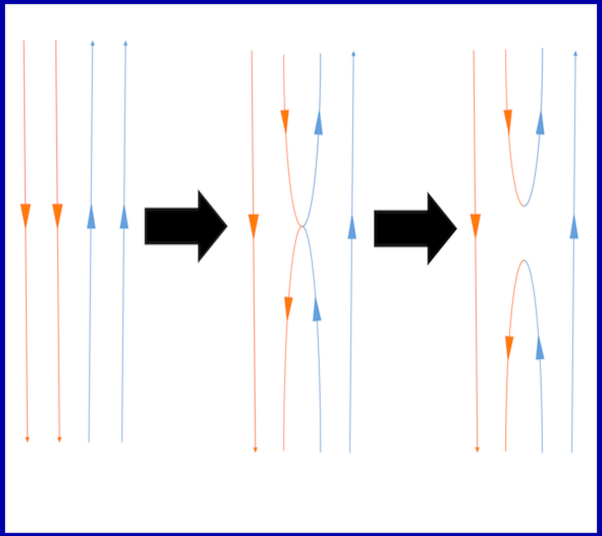

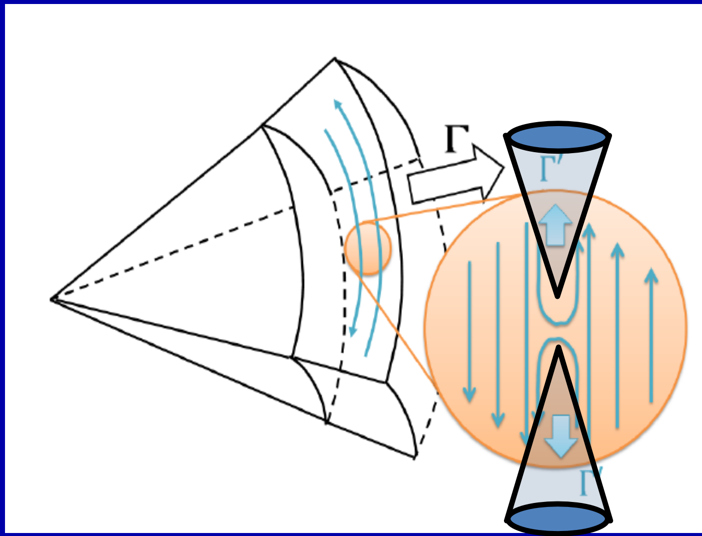

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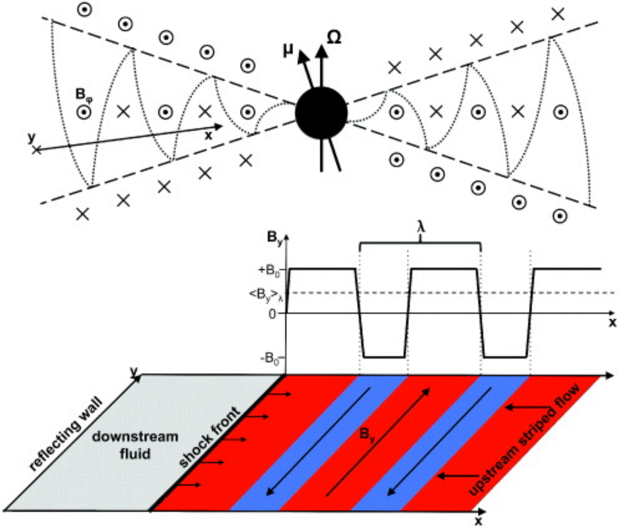
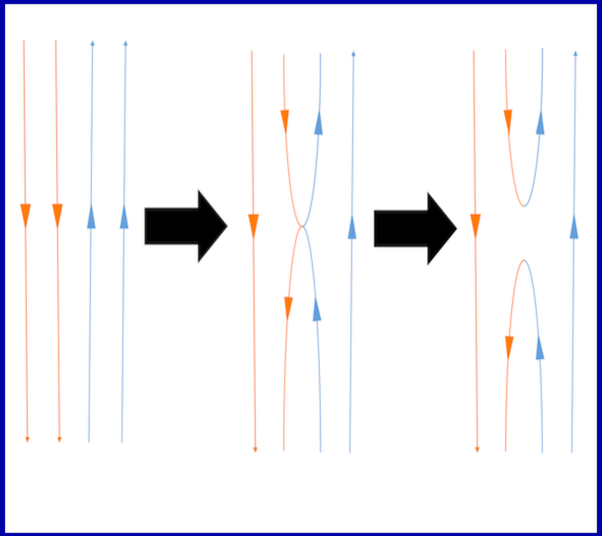
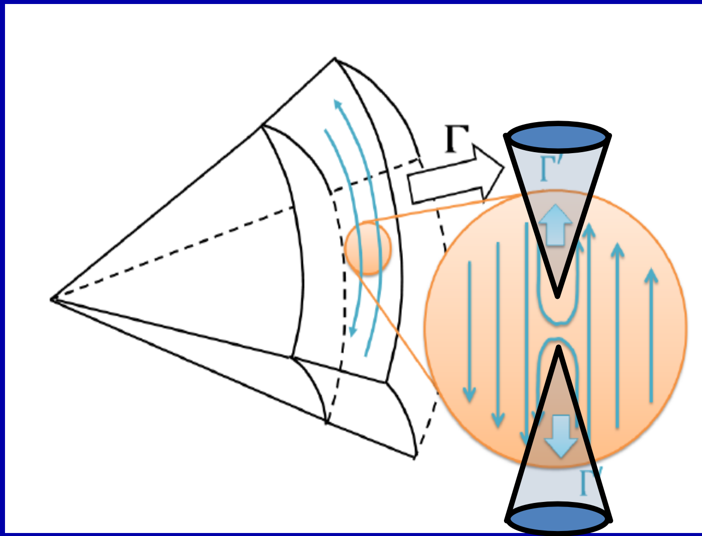
- For large ingoing σ reconnection leads to local relativistic outward bulk motion at Γ’ ~ few – several ⇒ anisotropic emission in jet’s bulk frame







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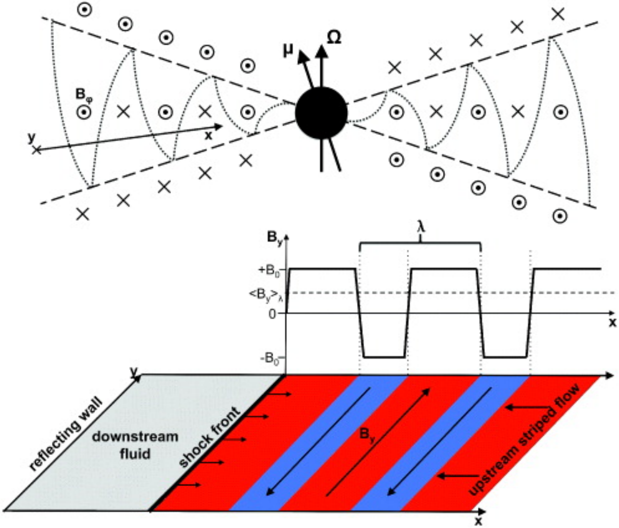
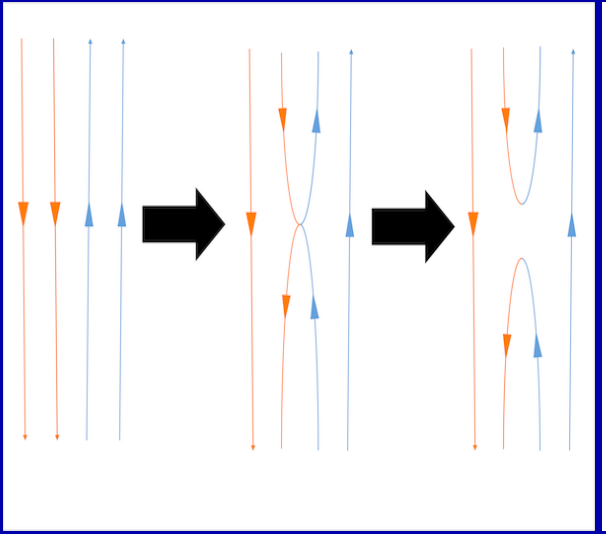
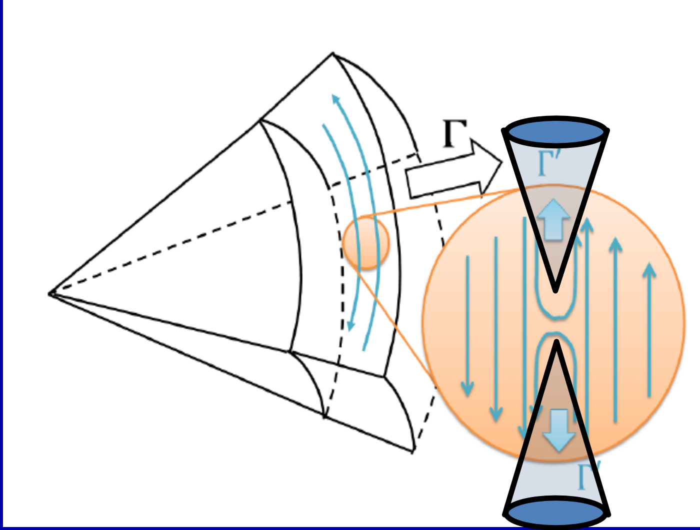
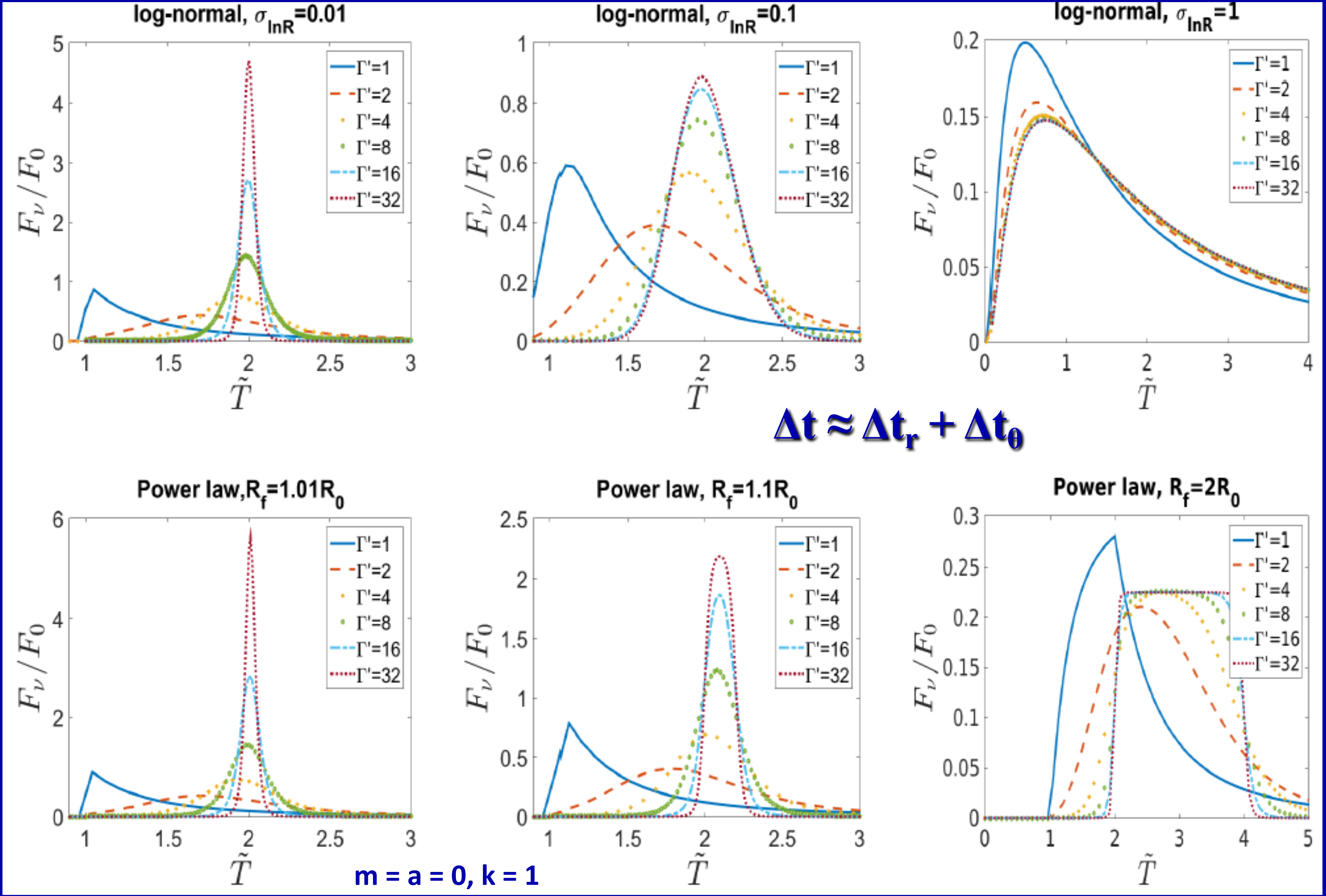
- Larger $\sigma \Rightarrow$ higher Γ', larger rec. rate (v_{in}/v_A), harder particle spectrum







The Shape of Pulses in the Lightcurves

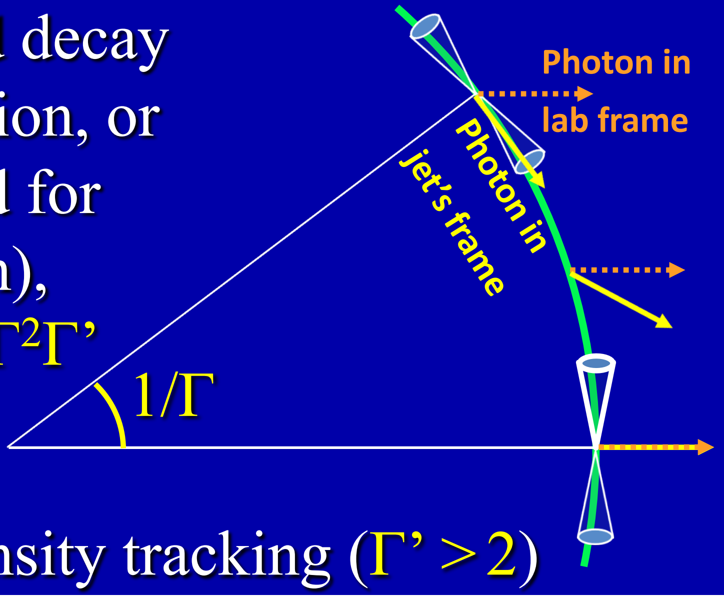


$$\Delta t \approx \Delta t_r + \Delta t_\theta$$

m = a = 0, k = 1

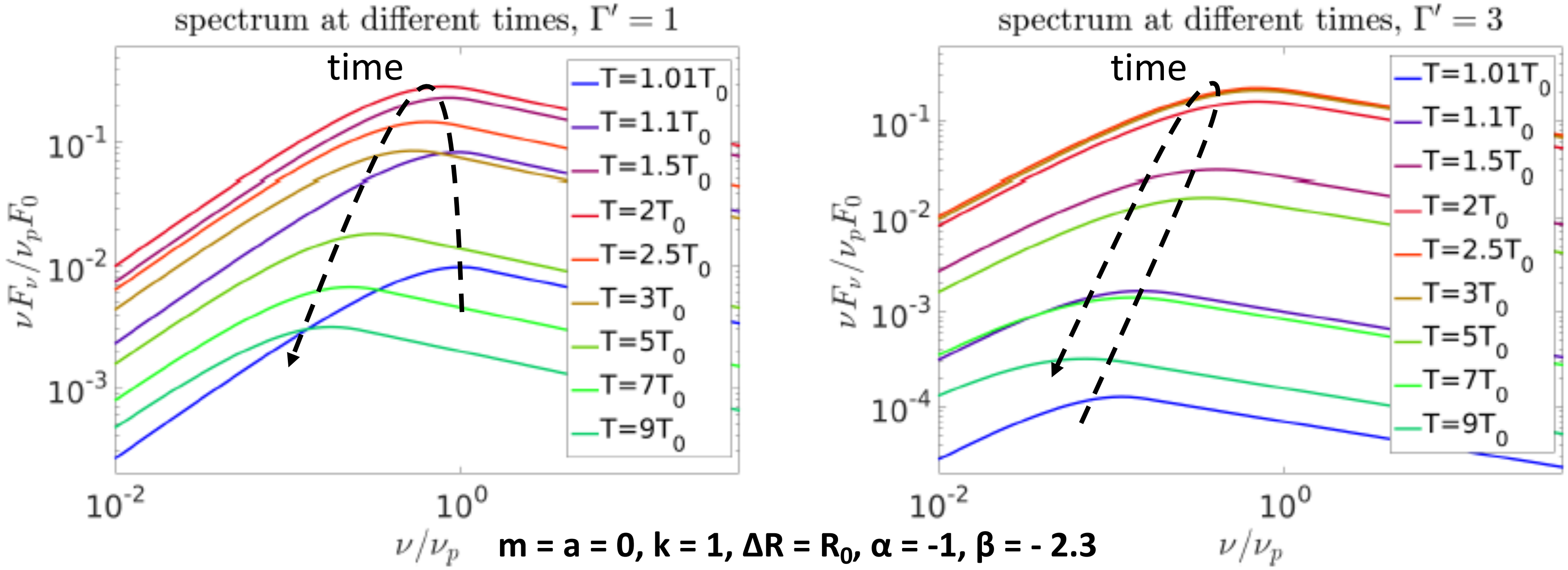
Some Other Pulse Properties

- Anisotropic emission can explain the "rapid decay phase" at the end of the GRB prompt emission, or X-ray pulses that decay faster than expected for isotropic emission ("high-latitude" emission), thanks to the shorter angular time $\Delta t_\theta \approx R/2\Gamma^2\Gamma'$



- Spectral evolution of pulses:

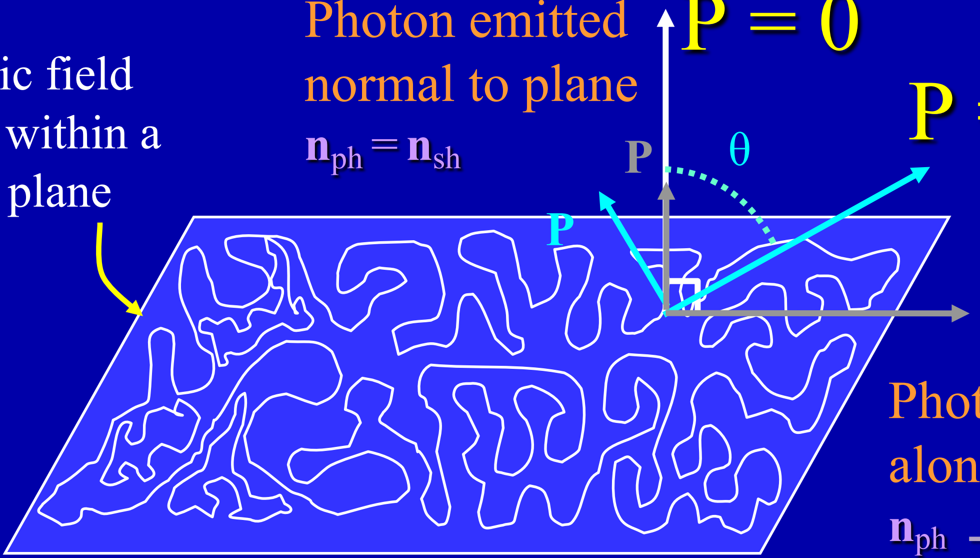
Hard to soft for ($\Gamma' < 2$) intensity tracking ($\Gamma' > 2$)



$m = a = 0$, $k = 1$, $\Delta R = R_0$, $\alpha = -1$, $\beta = -2.3$

Shock Produced Magnetic Field:

- A magnetic field produced at a relativistic collisionless shock, due to the two-stream instability, is **naively** expected to be **tangled within the plane of the shock** (Medvedev & Loeb 1999)



Magnetic field tangled within a (shock) plane

Photon emitted normal to plane

$\mathbf{n}_{ph} = \mathbf{n}_{sh}$

$P = 0$

$P = P_{max}\sin^2\theta/(1+\cos^2\theta)$

(Liang 1980)

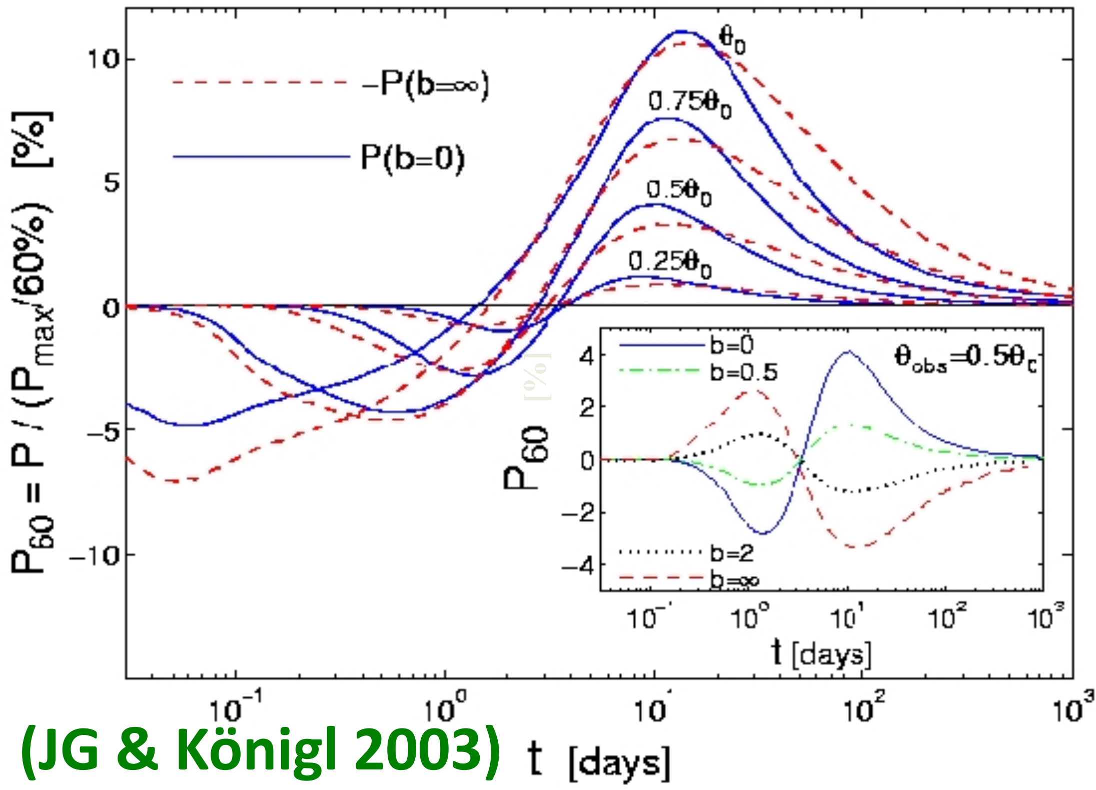
$P = P_{max}$

Photon emitted along the plane

$\mathbf{n}_{ph} \perp \mathbf{n}_{sh}$

The Random B-field's Degree of Anisotropy:

- $b = 2\langle B_{||}^2\rangle / \langle B_{perp}^2\rangle$ parameterizes the asymmetry of B_{rnd}
- Sign(b-1) determines θ_p ($P > 0$ is along the direction from the line of sight to the jet axis & $P < 0$ is rotated by 90°)
- For $b \approx 1$ the polarization is very low (field is almost isotropic)
- $P \lesssim 3\%$ in afterglows observations $\Rightarrow 0.5 \lesssim b \lesssim 2$



(JG & Königl 2003)

$$P = P_{max}/[1+2/(b-1)\sin^2\theta']$$

(valid for $j'_{\nu'} \propto [B' \sin\chi']^2$)

$\theta_0 = 5^o$

$E_{jet} = 3 \times 10^{51}$ erg

$n = 1\ cm^{-3}$

$z = 1$

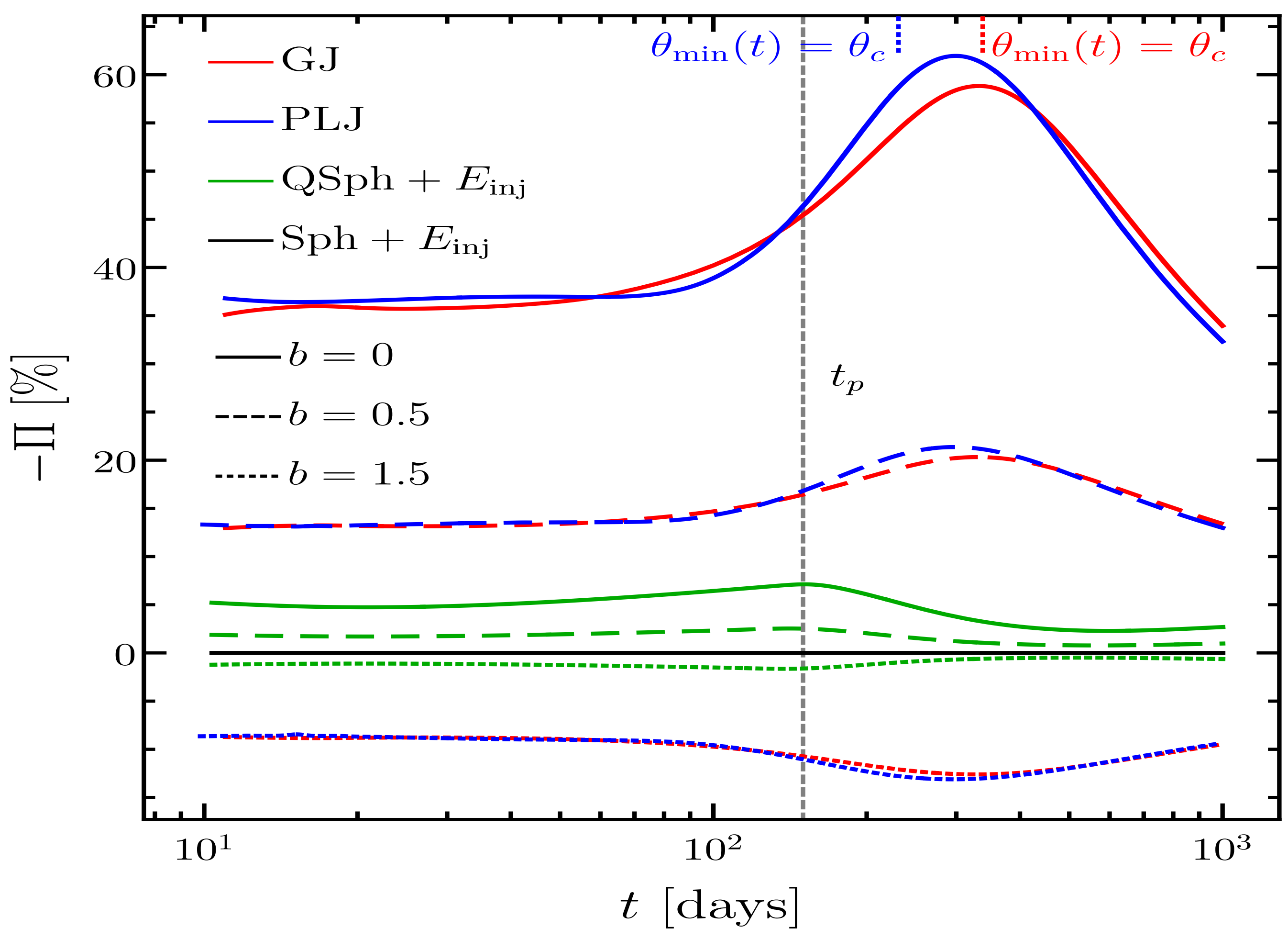
$p = 2.5$

$\varepsilon_e = 0.1$

$\varepsilon_B = 0.01$

GW170817/GRB170817A Afterglow (Gill & JG 18)

- Assuming a shock-produce B-field with $b \equiv 2\langle B_{\parallel}^2 \rangle / \langle B_{\perp}^2 \rangle$
- Data favor two core-dominated jet models with similar P(t)



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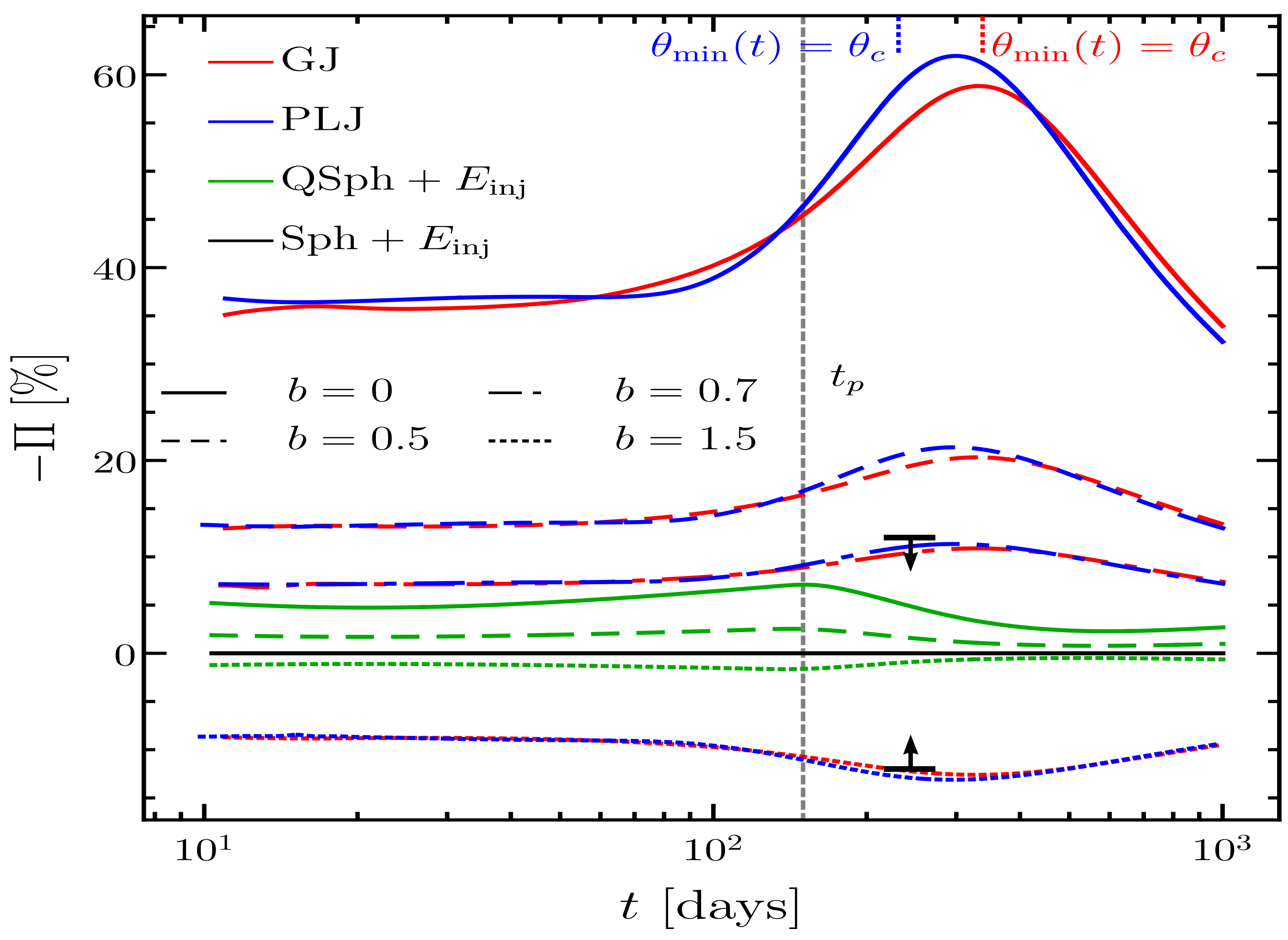

$0.66 \lesssim b \lesssim 1.49$ for jet models

New: upper limit $P_{\rm lin} < 12\%$ @ $\nu = 2.8$ GHz, $t = 244$ days (Corsi + 2018)

GW170817/GRB170817A Afterglow (Gill & JG 20)

More realistic assumptions ⇒ B-field in collisionless shocks:

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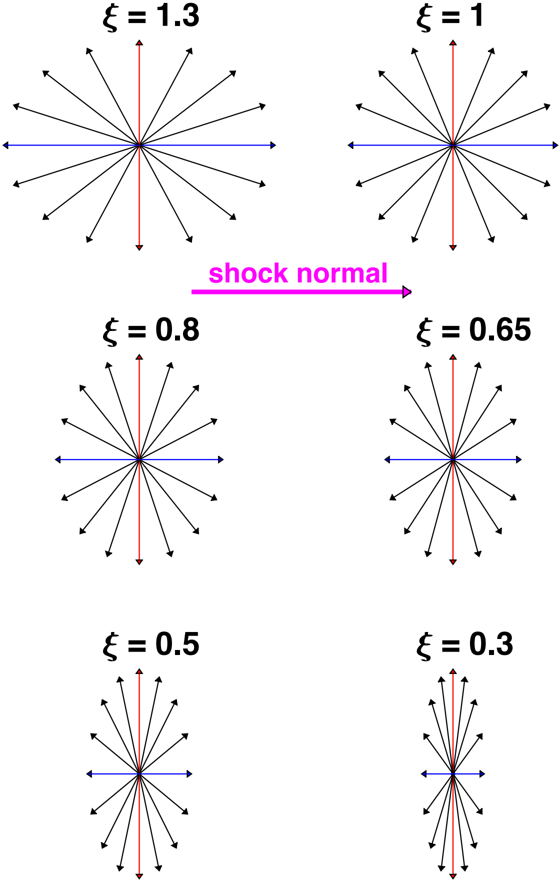
- B-field evolution by faster radial expansion: $L'_r / L'_{\theta,\varphi} \propto \chi^{(7-2k)/(8-2k)}$
  B-field isotropic in 3D with $B'_r \rightarrow \xi B'_r$ (Sari 1999); $\xi = \xi_f \chi^{(7-2k)/(8-2k)}$



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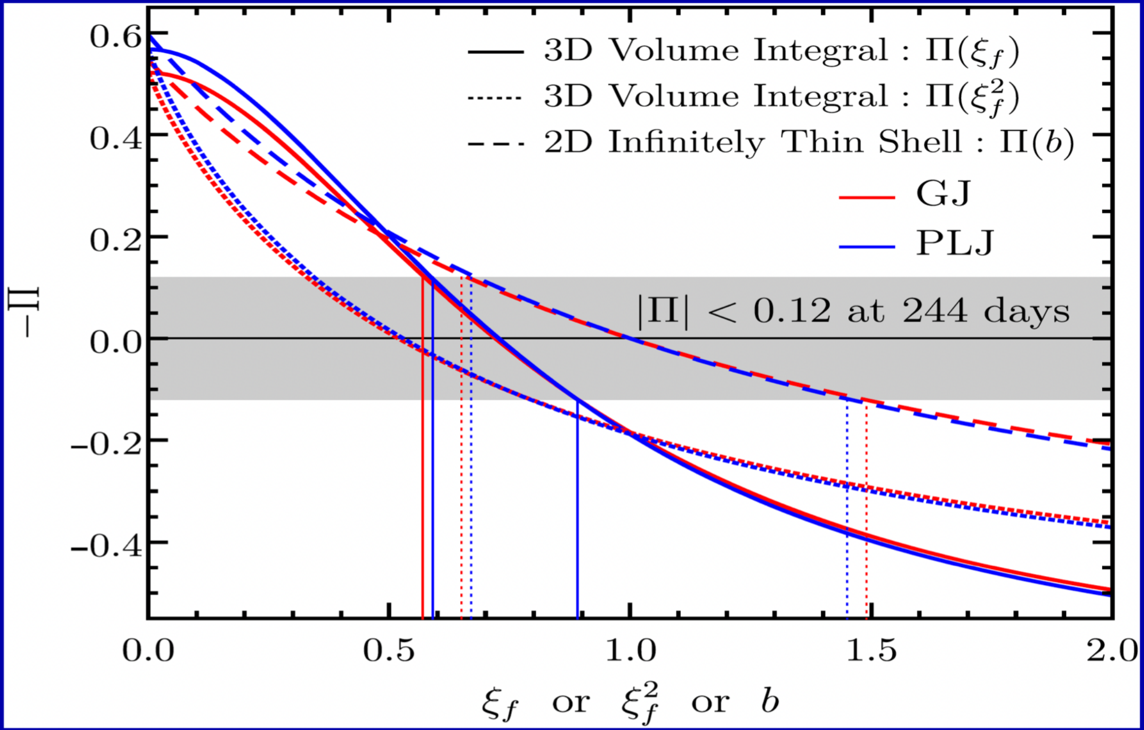
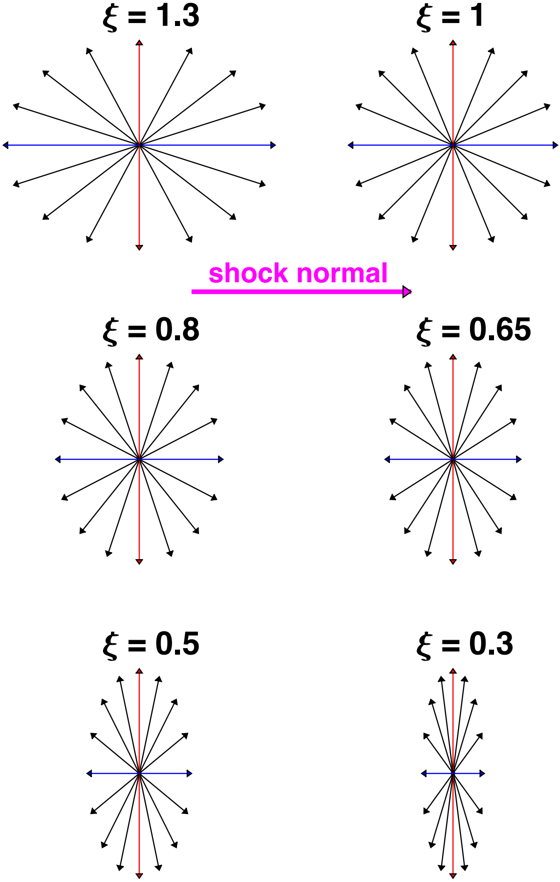


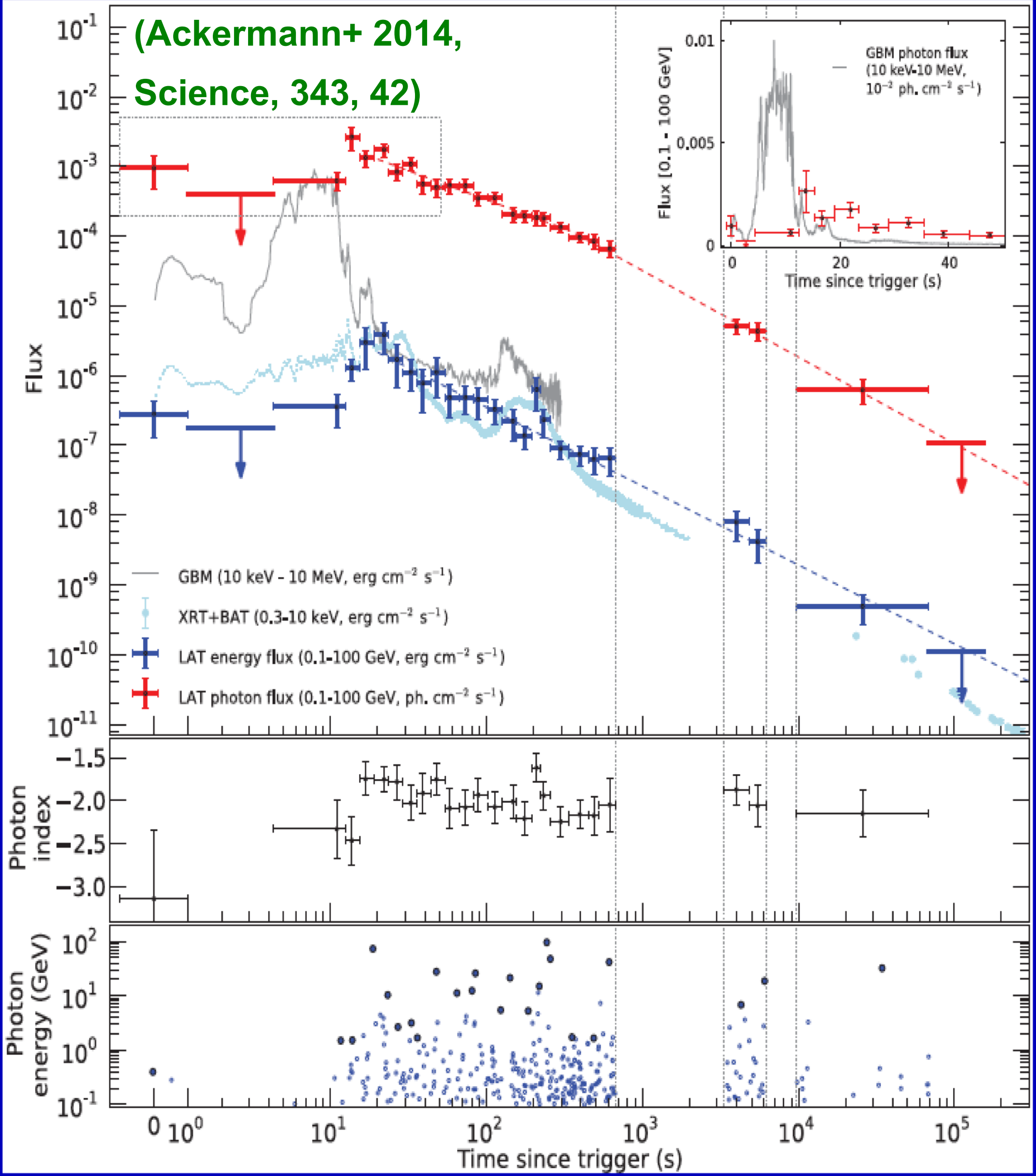


$0.57 \lesssim \xi_f \lesssim 0.89$

Observational Puzzles: 1. $E_{syn,max}$ Violation

High-Energy Afterglow: GRB130427A

- LAT detected emission up to ~ 20 hr after GRB
- >10 GeV γ's observed up to hours after GRB
- May arise at least partly from the prompt γ-ray emission up to few 10^2 s
- At later times there is no prompt emission, only a simple power-law decay: afterglow


(Ackermann+ 2014, Science, 343, 42)

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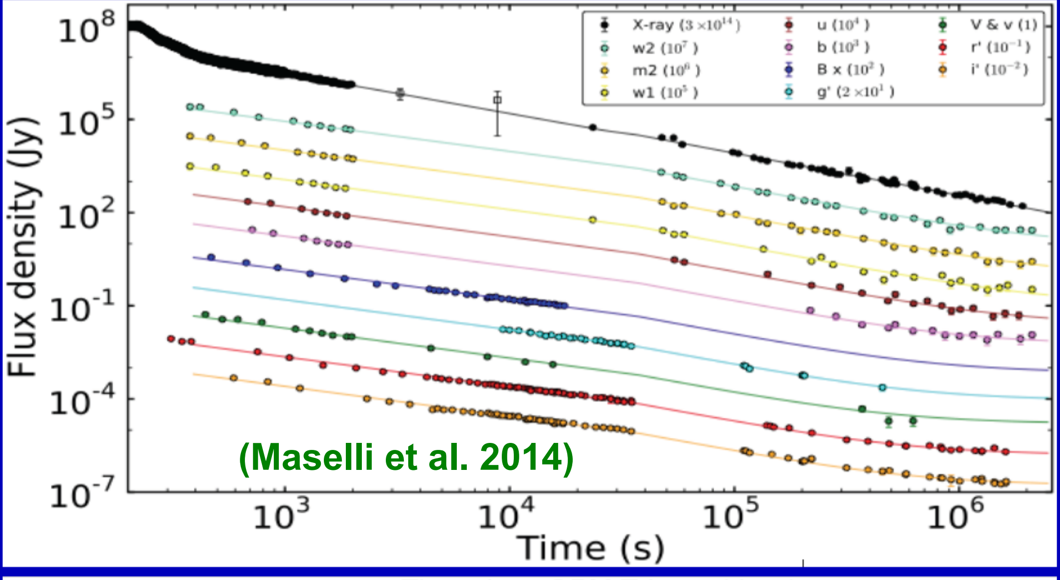
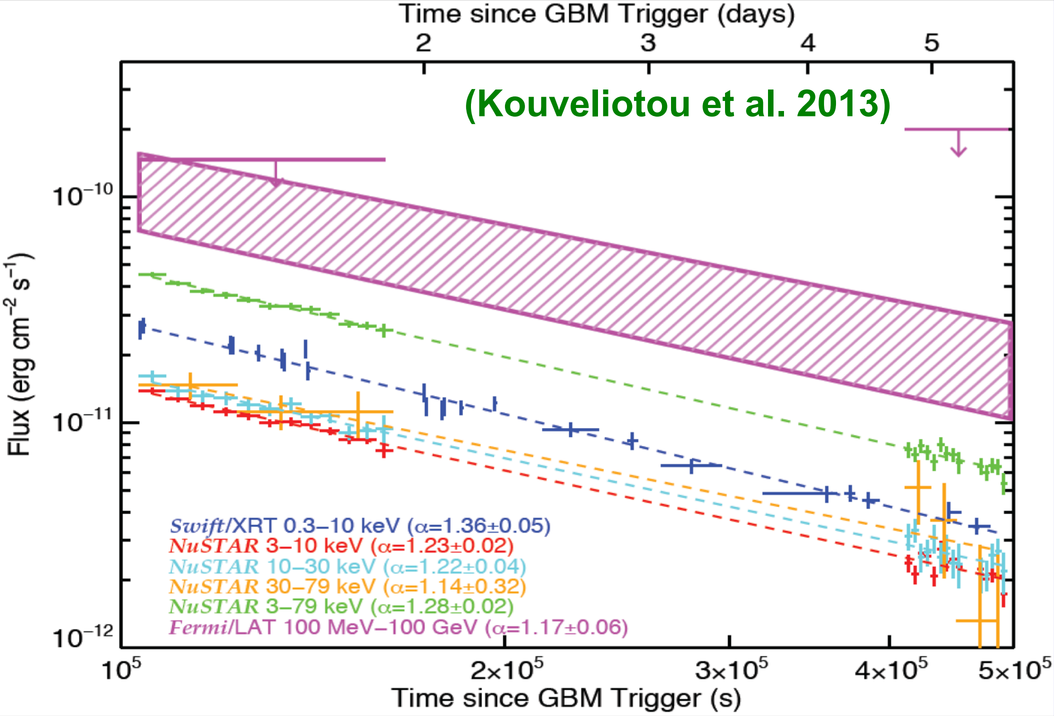


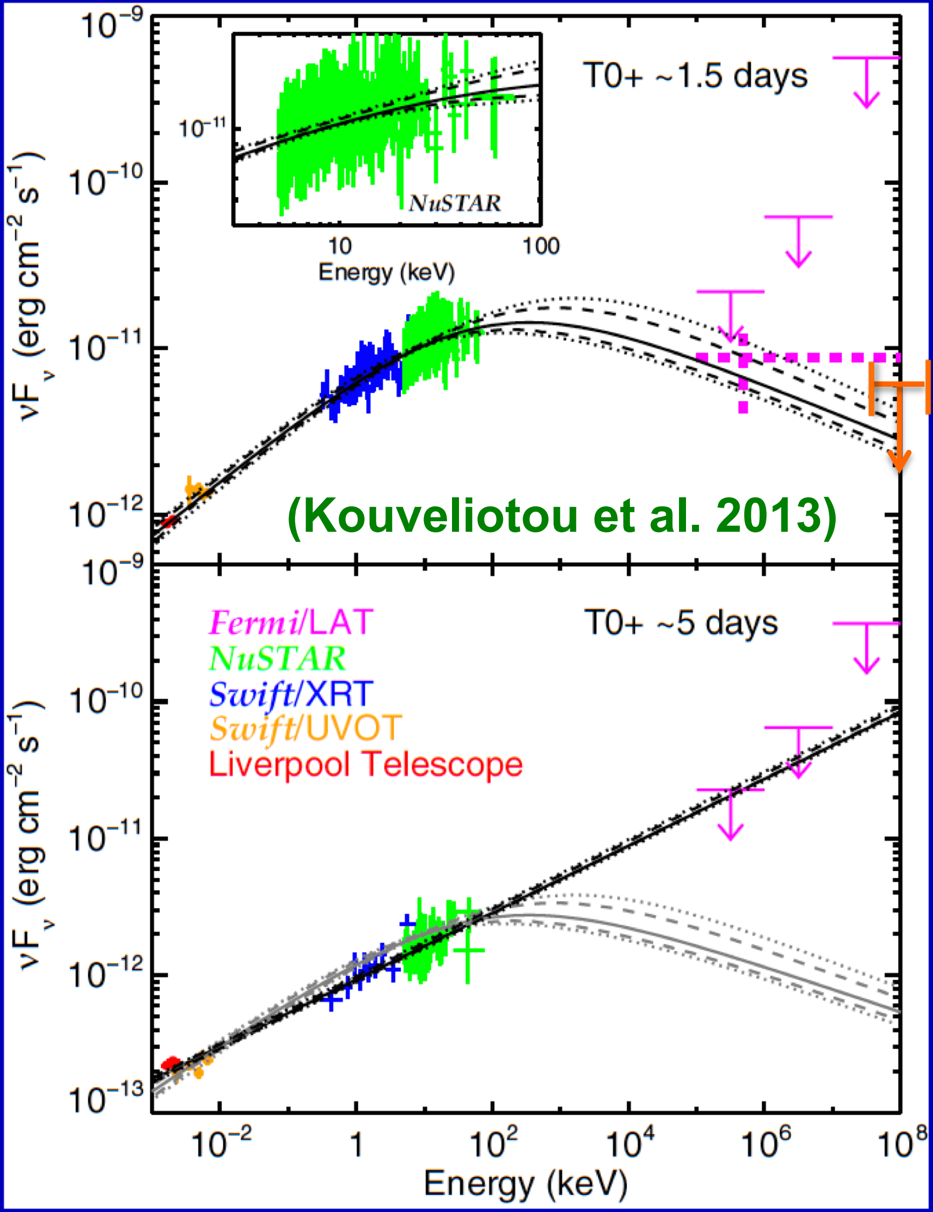
(Maselli et al. 2014)

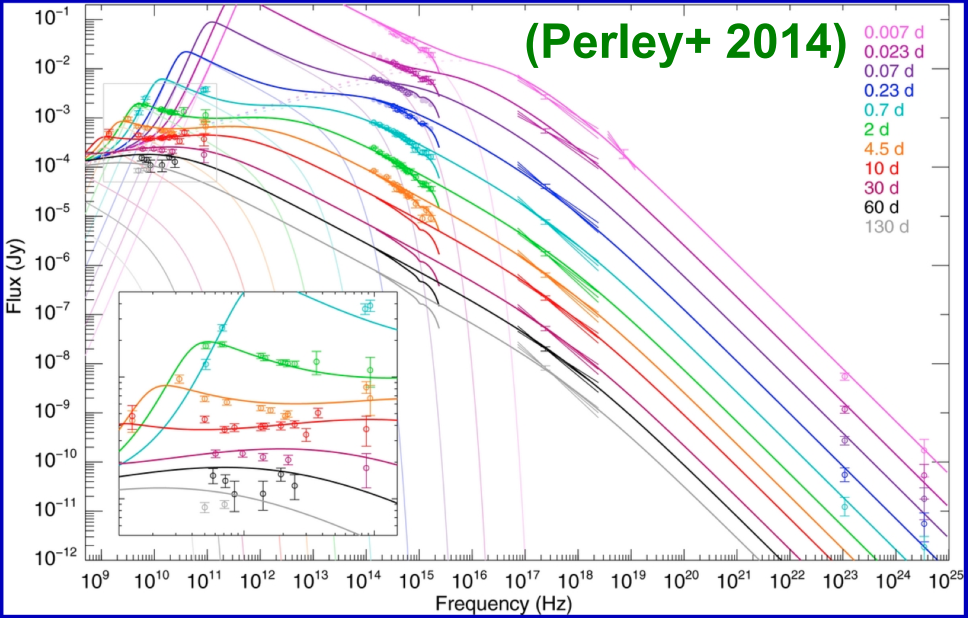


(Kouveliotou et al. 2013)

High-Energy Afterglow: GRB130427A

- **NuSTAR**: 1st late-time GRB afterglow detection at 3-79 keV
- A single-component synchrotron spectrum nicely fits all energies
- No need or much room for SSC
- Also supported by VERITAS observations (Aliu et al. 2014)





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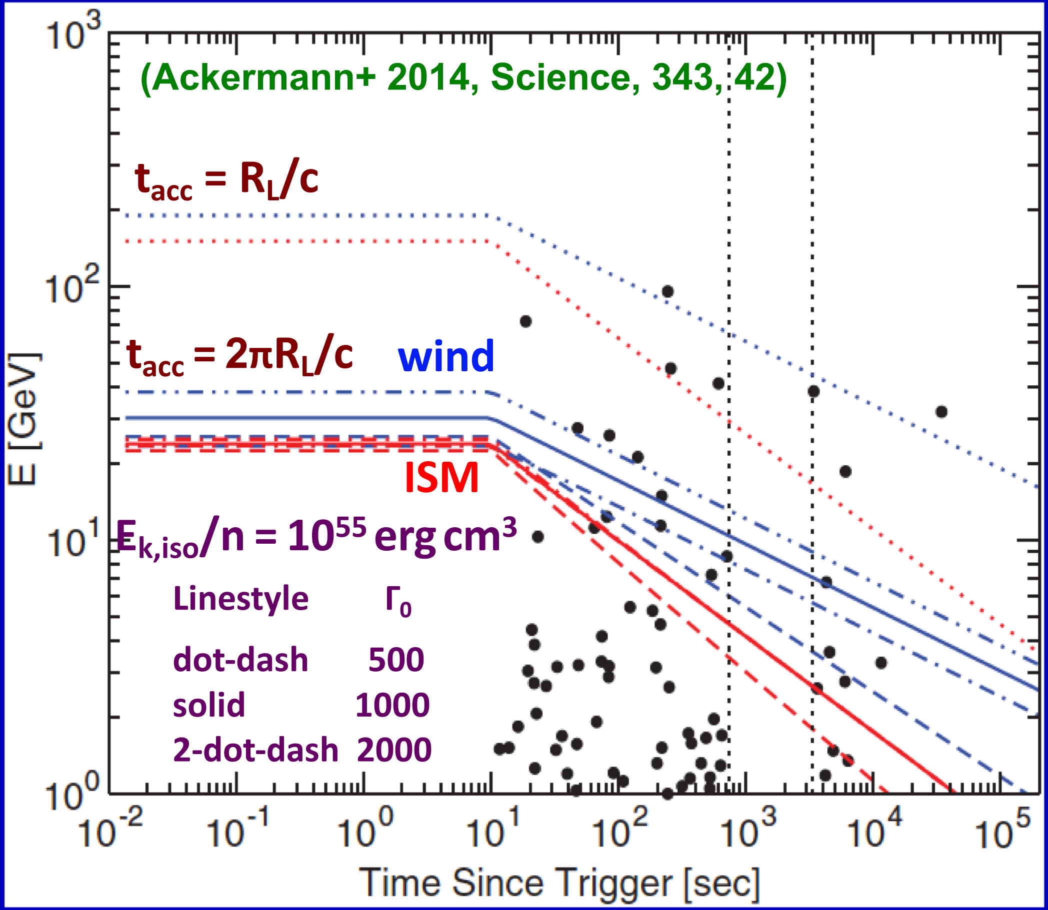
- LAT HE photons violate:

$$E_{\mathrm{syn,max}} \sim \frac{\Gamma}{(1+z)}\frac{m_e c^2}{\alpha} \approx 5\left(\frac{\Gamma}{100}\right)\ \mathrm{GeV}$$

- Based on a one-zone model balancing electron energy gains and losses: $t_{\mathrm{acc}} \sim t_{\mathrm{syn}}$



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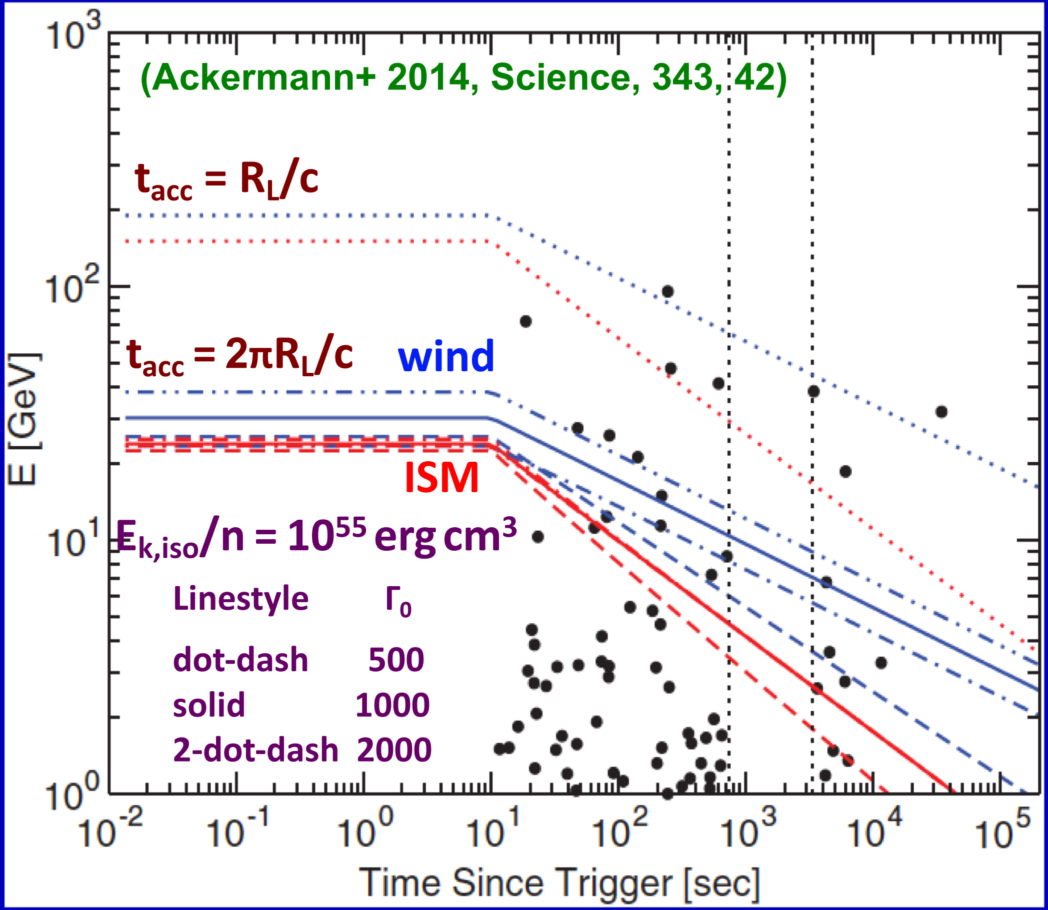

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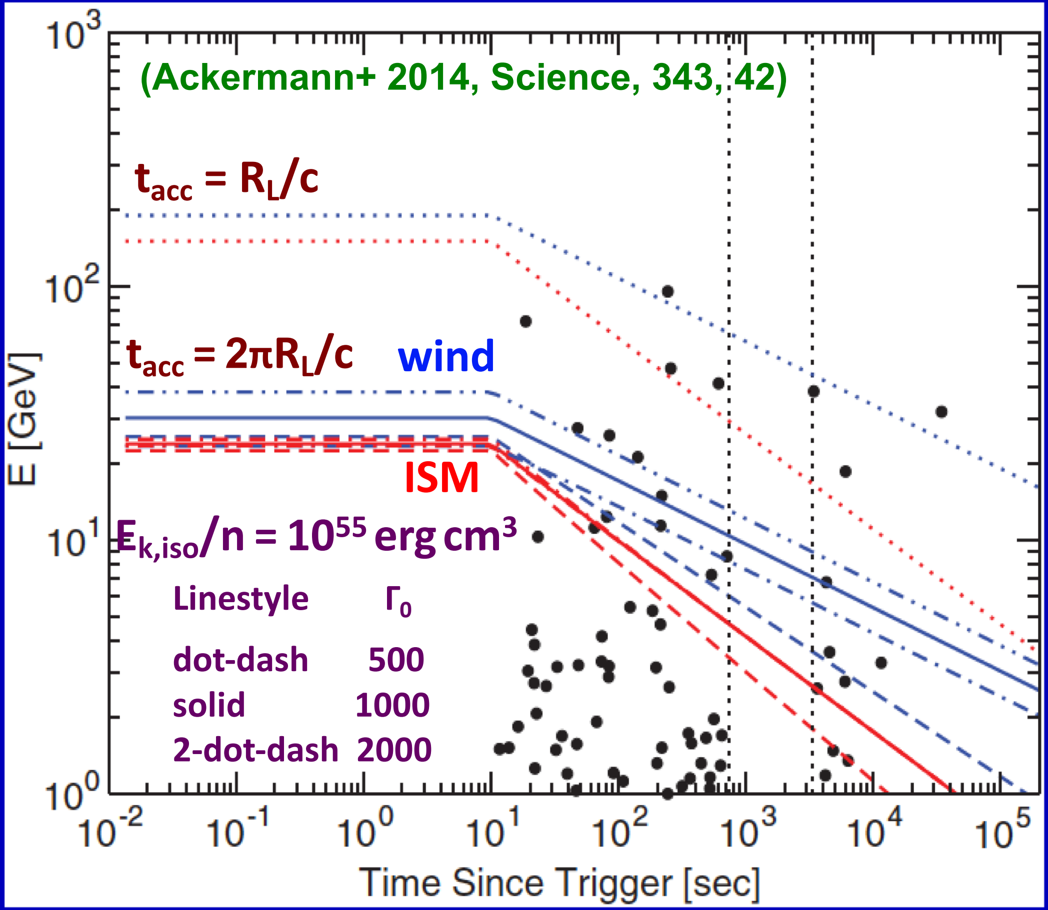
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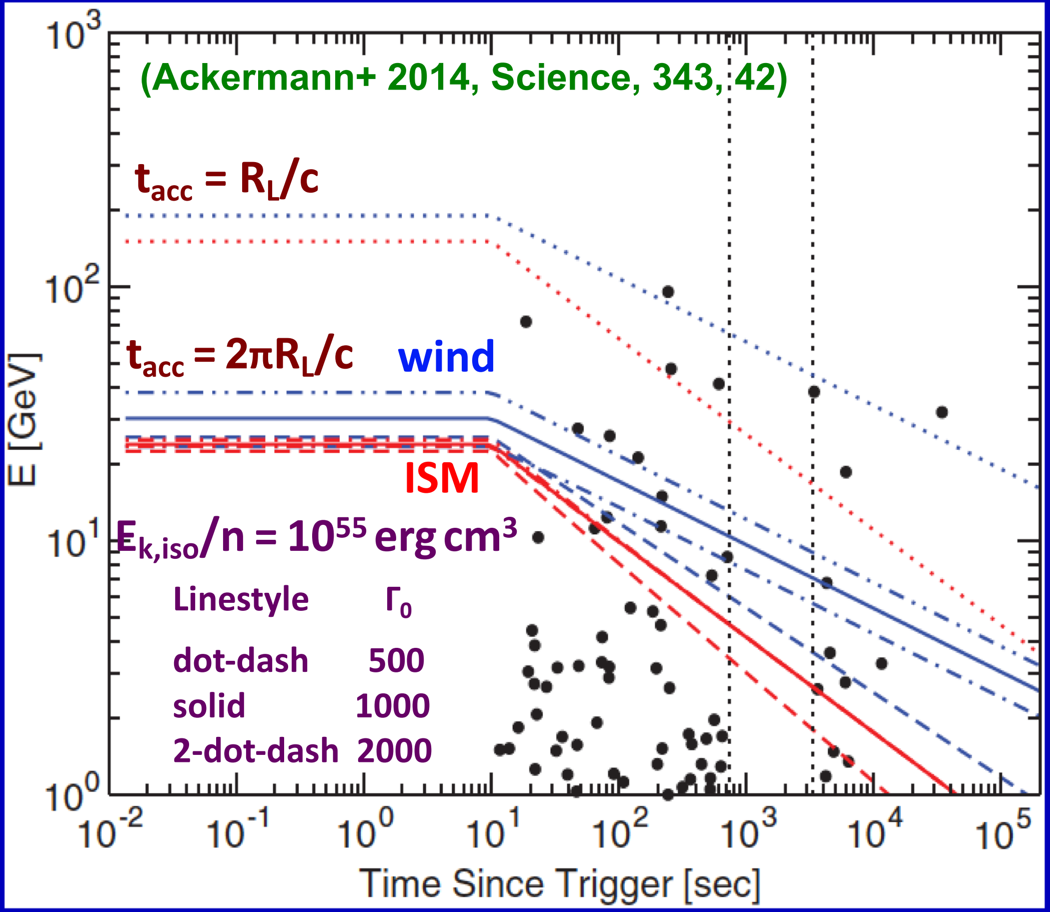

- ⇒ $E_{\rm syn,max}$ appears to be truly violated ⇒ ≥ 1 assumption must break

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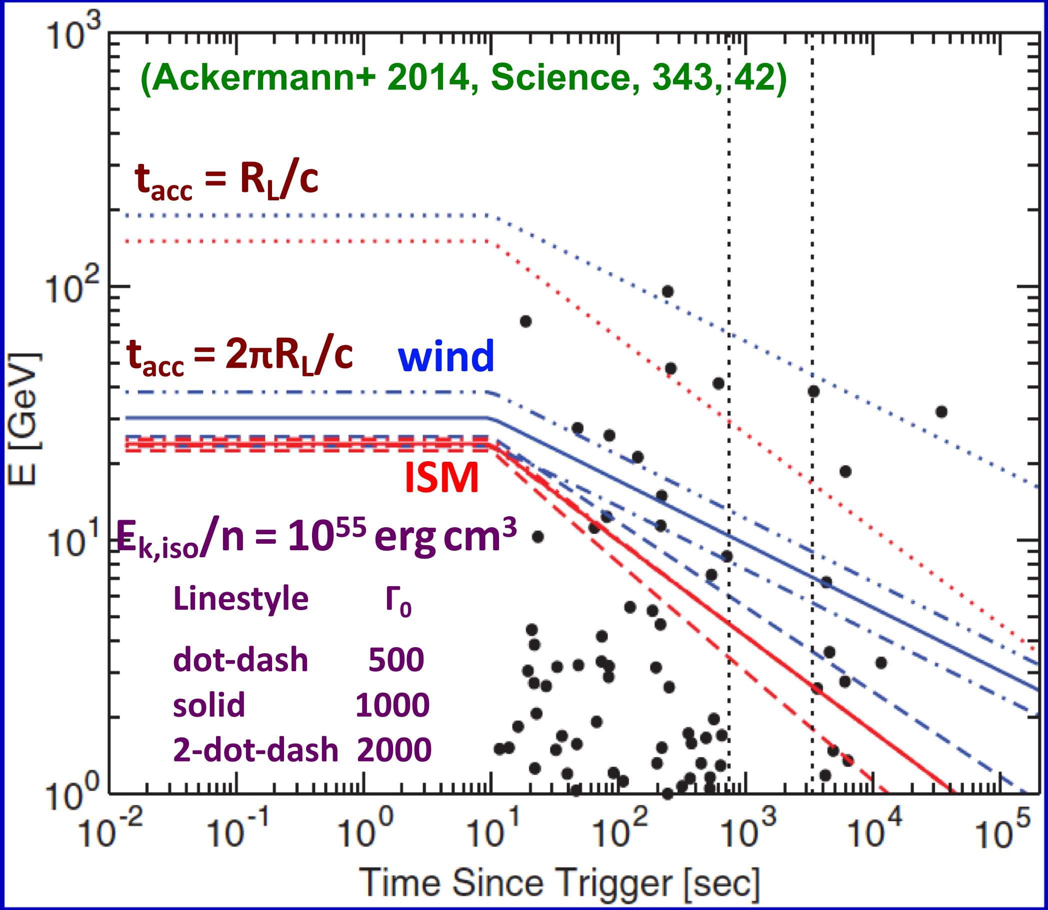
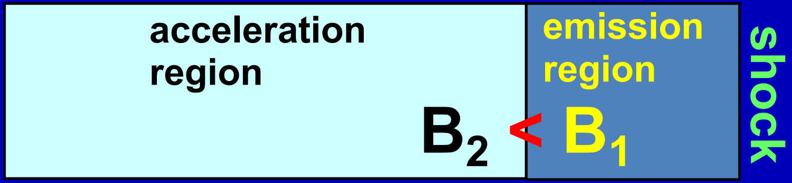

(Ackermann+ 2014, Science, 343, 42)

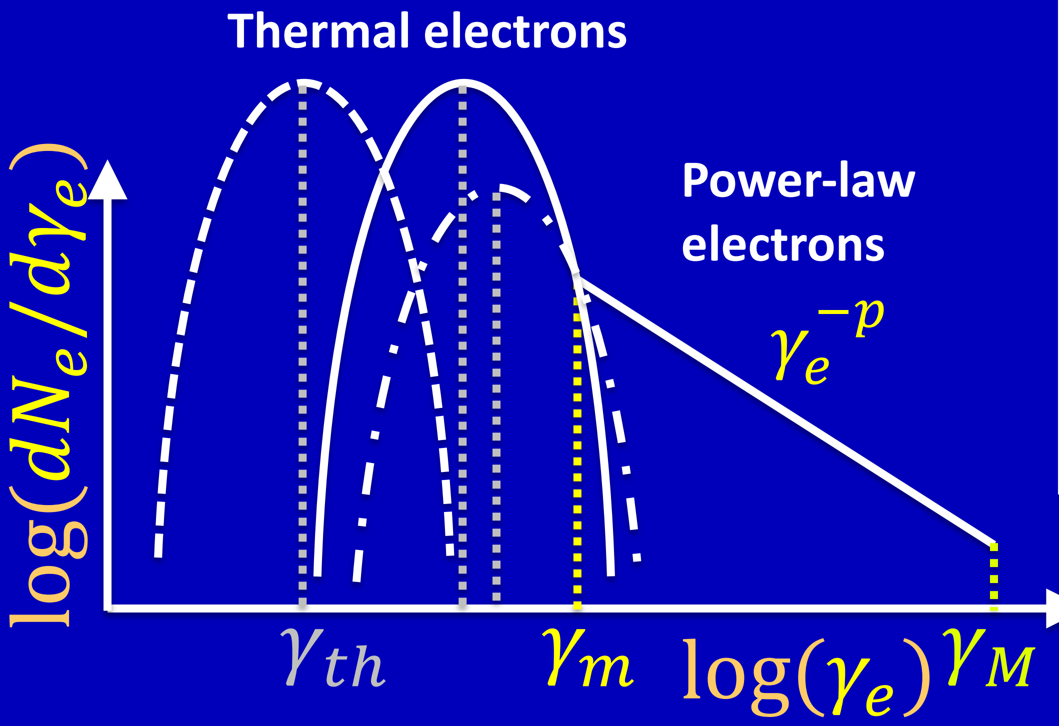
- ⇒ $E_{\rm syn,max}$ appears to be truly violated ⇒ ≥ 1 assumption must break
- Non-uniform magnetic field?

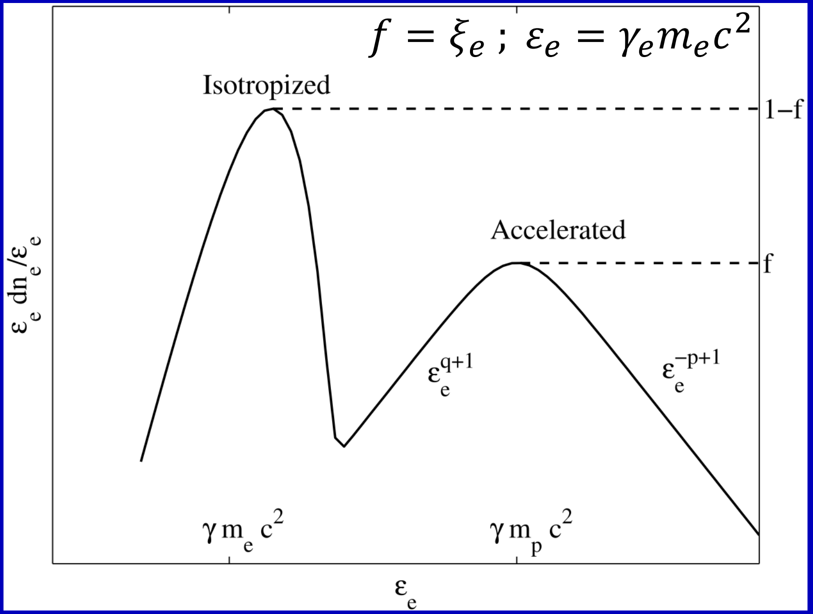
$E_{\rm syn,max}$ grows by a factor of B_1/B_2



Puzzle 2: Where are the thermal electrons?

- PL electron emission **degeneracy** (Eichler & Waxman 2005): $(\epsilon_e, \epsilon_B, n, E) \rightarrow (\xi_e\epsilon_e, \xi_e\epsilon_B, n/\xi_e, E/\xi_e)$ for $\frac{m_e}{m_p} < \xi_e \leq 1$
- How can the thermal electrons still affect the observations?





(Eichler & Waxman 2005)

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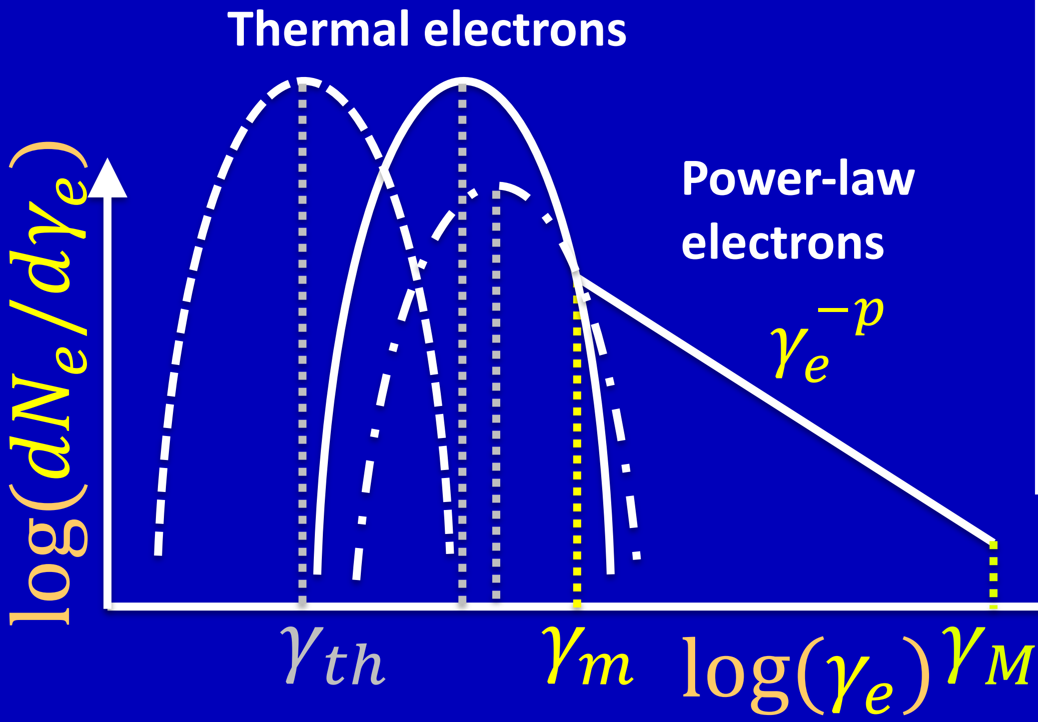

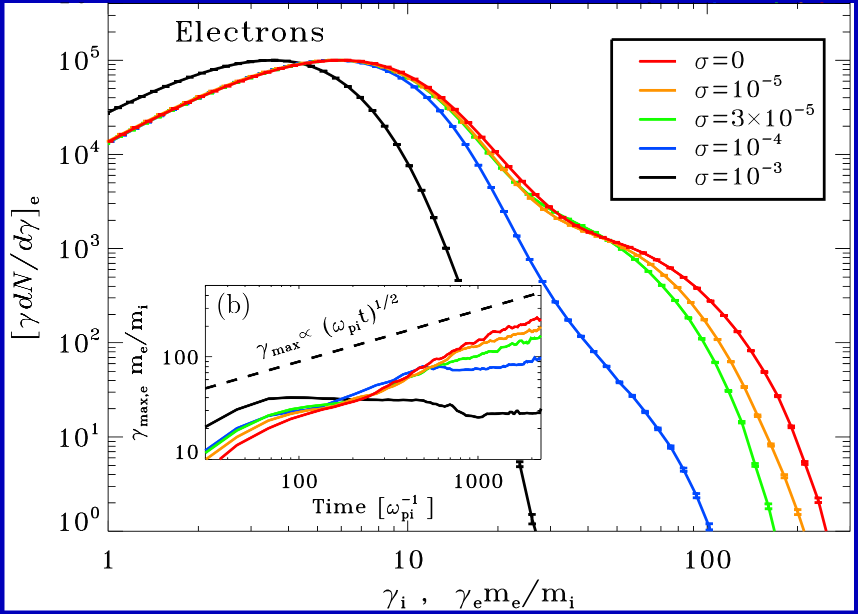

(Sironi et al. 2013)

PIC simulations

Puzzle 2: Where are the thermal electrons?

- A. Plasma propagation effects in the source (radio, mm, NIR):
  - May reduce the linear polarization & partly convert it to circular polarization (Matsumiya & Ioka 03; Sagiv et al. 04;…)
  - May cause Faraday depolarization due to the finite $\Delta\nu/\nu$

Puzzle 2: Where are the thermal electrons?

- **B**. Thermal electron emission / synchrotron self-absorption:
  - May produce unique features in the afterglow spectrum and lightcurve (Eichler & Waxman 05; Giannios & Spitkovsky 09)
  - Self-absorption by thermal electrons may be important in radio / mm (Eichler & Waxman 2005; Ressler & Laskar 2017)
  - SSC radiation by thermal electrons may also be detectable (Warren et al. 2022)

Puzzle 3: Transition to a Newtonian Shock

- The phenomenological assumption of $\epsilon_e, \xi_e = \text{const.}$ must break once $\gamma_m = \frac{p-2}{p-1}\frac{\epsilon_e}{\xi_e}\frac{m_p}{m_e}(\Gamma_{sh} - 1) \sim 1$ or $\beta_{sh} = \beta_{dn} \approx 0.22\sqrt{\frac{(p-1)}{3(p-2)}\frac{\xi_e}{\epsilon_{e,-1}}}$ – onset of the **deep Newtonian regime**

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- Can shock acceleration models reproduce this behavior?

Puzzle 4: Evidence for accelerated protons?

- While protons / ions are expected to be accelerated together with electrons, there is **no clear evidence** for this!!!
  - Some **prompt GRB emission models** involve accelerated protons (synchrotron by protons or secondary pairs, pion production + decay, pair cascades; Böttcher's talk) but are generally less radiatively efficient and not preferred over competing leptonic models
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  - A smoking gun will be high-energy neutrinos (some correlate w. blazars)
  - If protons are accelerated, then what are: $\epsilon_p, \xi_e, \gamma_{m,p}, p_p$

Conclusions:

- **Many** potential acceleration sites & mechanisms
- Observational constraints:
  - Electron PL index: afterglow: $2.1 \lesssim p \lesssim 2.5$ prompt: $2 \lesssim p \lesssim 4$ (?)
  - Spectral breaks: $\nu_m \Rightarrow \gamma_{e,\min} \frac{\epsilon_e}{\xi_e}(\Gamma_{sh} - 1)$ $(\xi_{e,\gamma} \ll 1\ ?)$
  - Signatures of anisotropic velocity distribution: spectral, temporal
  - Polarization ⇒ B-field structure in shocks: $0.57 \lesssim \xi_f \lesssim 0.89$
- Observational puzzles:
  - Apparent violation of the $E_{\text{syn,max}}$ limit ⇒ some assumnption breaks
  - Transition to a Newtonian shock
  - Lack of clear signs for a thermal electron component
  - No clear evidence for proton / ion acceleration