GRB Prompt Emission Physics

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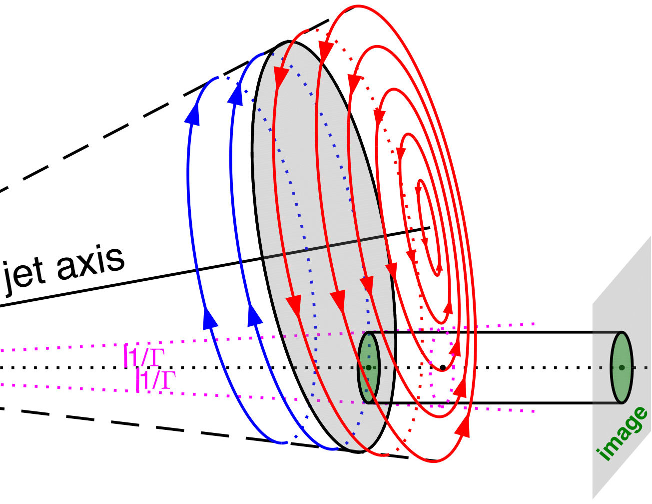
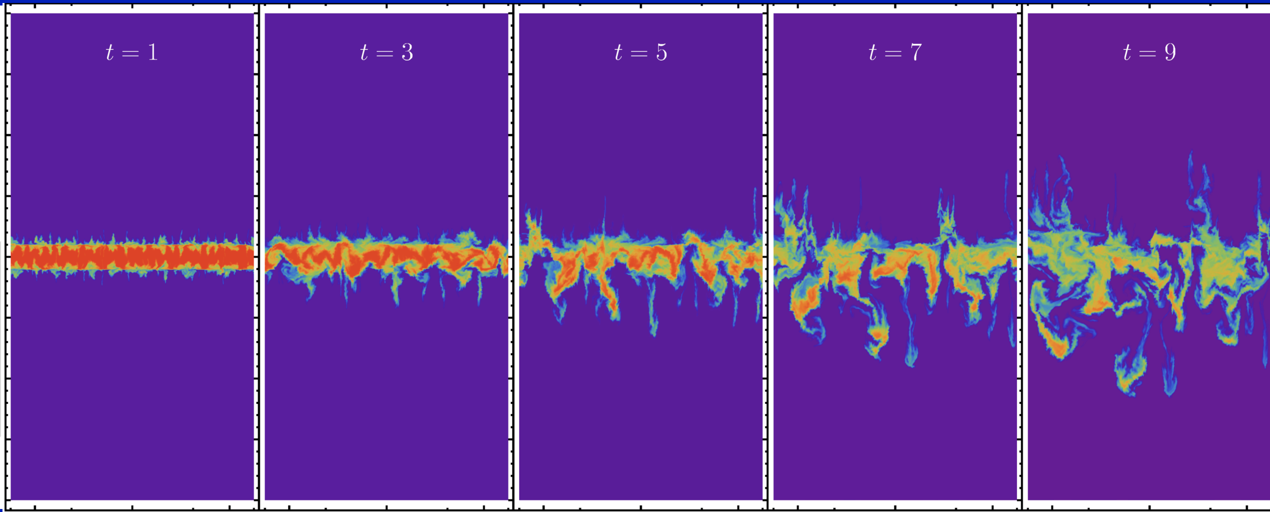




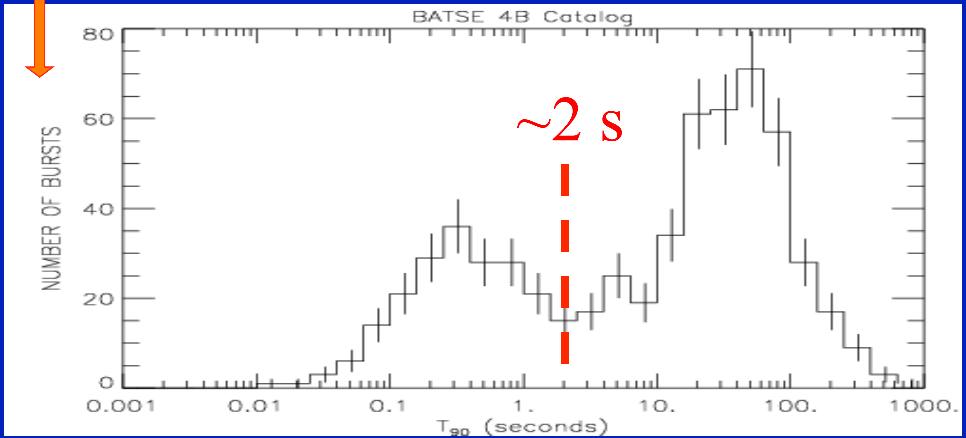
Workshop on Gamma-Ray Bursts: Prompt to Afterglow
NCRA-TIFR, Pune, India, 4 July 2017

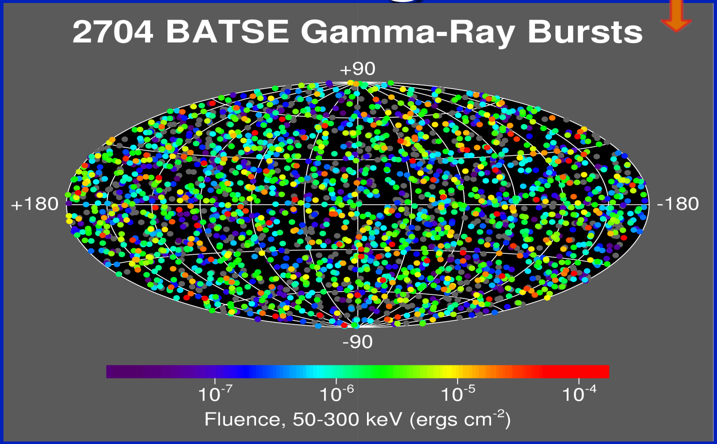
Outline of the Talk:

- GRBs: brief historical overview, prompt GRB obs.
- Theoretical framework, prompt emission processes
- **Acceleration & Dissipation**: Fireball vs. Magnetic
- Magnetic acceleration: steady vs. impulsive, effect of external medium & multiple sub-shells
- GRB lightcurves from magnetic reconnection
- Reconnection+acceleration through K-S instability
- Prompt GRB spectrum: a phenomenological model

GRBs: Brief Historical Overview

- 1967: 1st detection of a GRB (published in 1973)
- In the early years there were many theories, most of which invoked a Galactic (neutron star) origin
- 1991: the launch of CGRO with BATSE lead to significant progress in our understanding of GRBs
  - **Isotropic dist. on sky**: favors a cosmological origin
  - **Bimodal duration** distribution: **short** vs. **long** GRBs





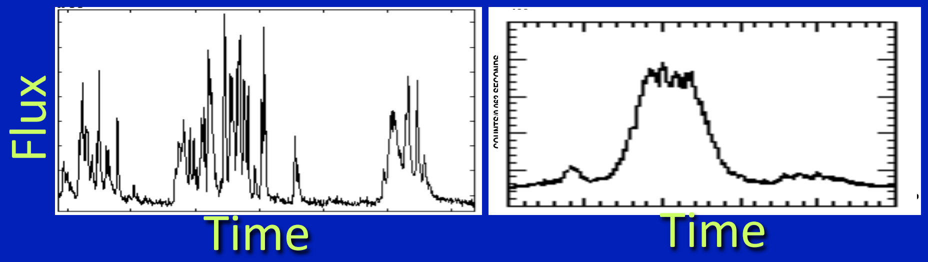
- **BeppoSAX** (1996–2002): led to **afterglow** discovery (1997) in X-rays, optical, radio (for long GRBs)

- This led to **redshift** measurements: clear determination of **distance/energy** scale (long GRBs) $E_{\gamma,\rm iso} \sim 10^{52}$ - 10^{54} erg
- Afterglow observations provided information on beaming (narrow jets: $E_\gamma \sim 10^{51}$ erg), event rate, external density, supernova connection (⇒ long GRB progenitors)

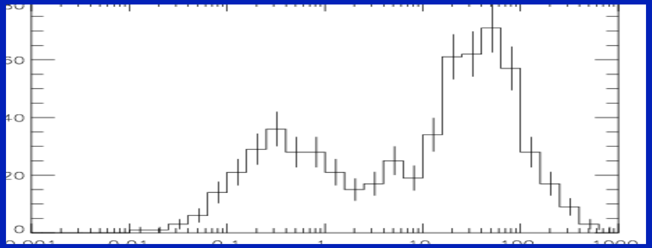
- **Swift** (2004-?): autonomously localizes GRBs, slews (in ~1-2 min) and observes in X-ray + optical/UV
  - Discovered unexpected behavior of early afterglow: rapid decay phase, plateaus, flares, chromatic breaks
  - Led to the discovery of **afterglow** from **short** GRBs → **host galaxies**, redshifts, energy, rate, clues for progenitors
- **Fermi** (2008-?): high-energy emission – delayed onset, long lived emission, distinct high-energy component*, high $\Gamma_{\rm min}$, short GRBs show smaller delay + harder spectrum

Prompt GRB Observations ($\lesssim$ MeV)

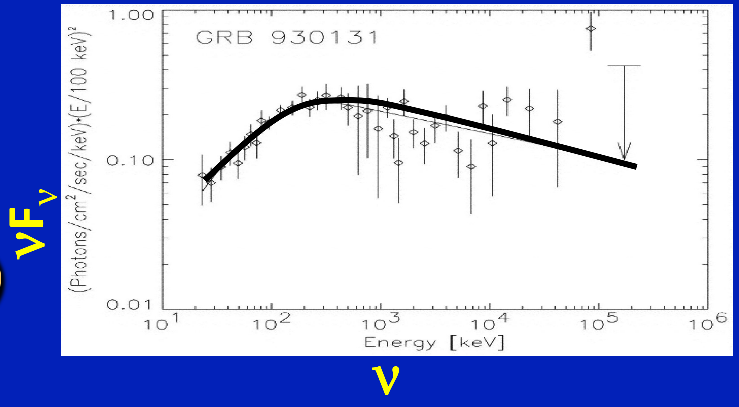
- Variable light curve



- Duration: $\sim 10^{-2} - 10^{3}$ sec



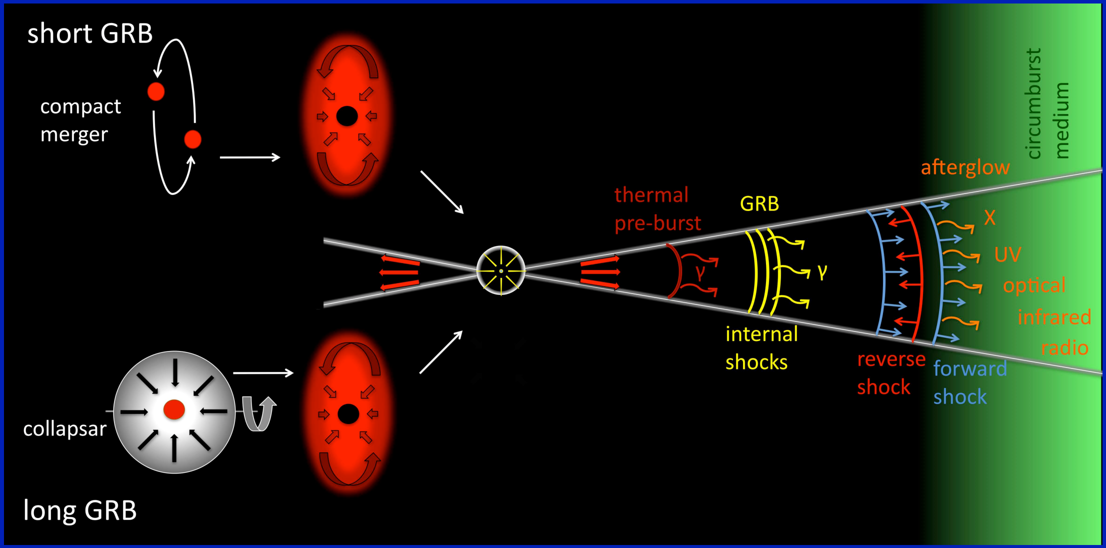
- Spectrum: non-thermal
  νF_ν peaks at ~ 0.1-1 MeV
  (well fit by a Band function*)



- Rapid variability, non thermal spectrum & $z \sim 1$
  $\Rightarrow$ relativistic source ($\Gamma \gtrsim 100$) (compactness problem: Schmidt 1978; Fenimore et al. 1993; Woods & Loeb 1995;…)

GRB Theoretical Framework:

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

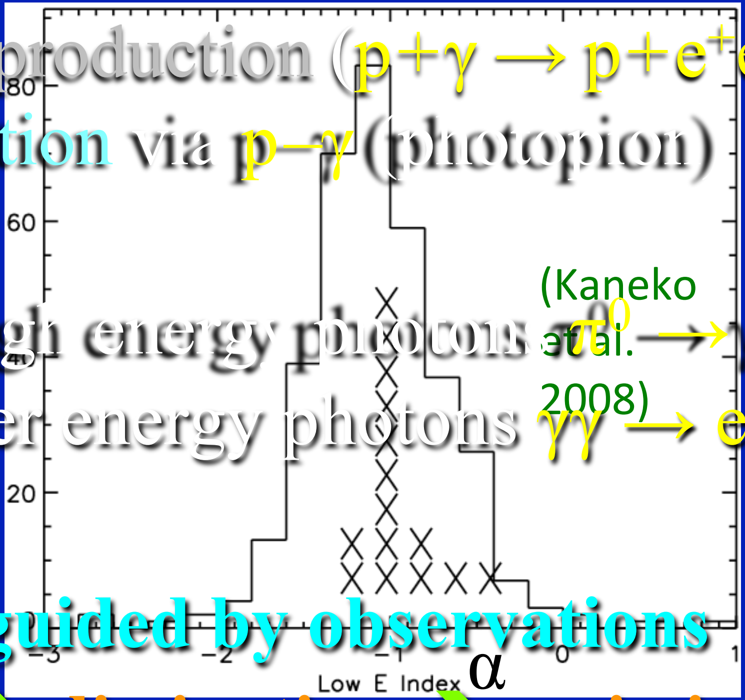


Dissipation: internal shocks or magnetic reconnection? Emission mechanism?

- **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

Candidate Prompt Emission Processes

- **Leptonic:** (dN/dE $\propto E^{\alpha}$ below E_{peak})
  - Synchrotron (optically thin: $\alpha \leq -2/3$; fast cooling: $\alpha \leq -3/2$)
  - Jitter (similar to synchrotron but from tangled B-field; $\alpha \leq 0$)
  - Inverse-Compton or Synchrotron-Self Compton (HE?)
  - Photospheric (not always BB, $-1 \lesssim \alpha \lesssim 1$; also from high-$\sigma$)
- **Hadronic** processes: photopair production ($p+\gamma \rightarrow p+e^+e^-$), proton synchrotron, pion production via $p-\gamma$ (photopion) interaction or p-p collisions
  - The neutral pions decay into high energy photons $\pi^0 \rightarrow \gamma\gamma$ that can pair produce with lower energy photons $\gamma\gamma \rightarrow e^+e^-$ producing a pair cascade



(Kaneko et al. 2008)

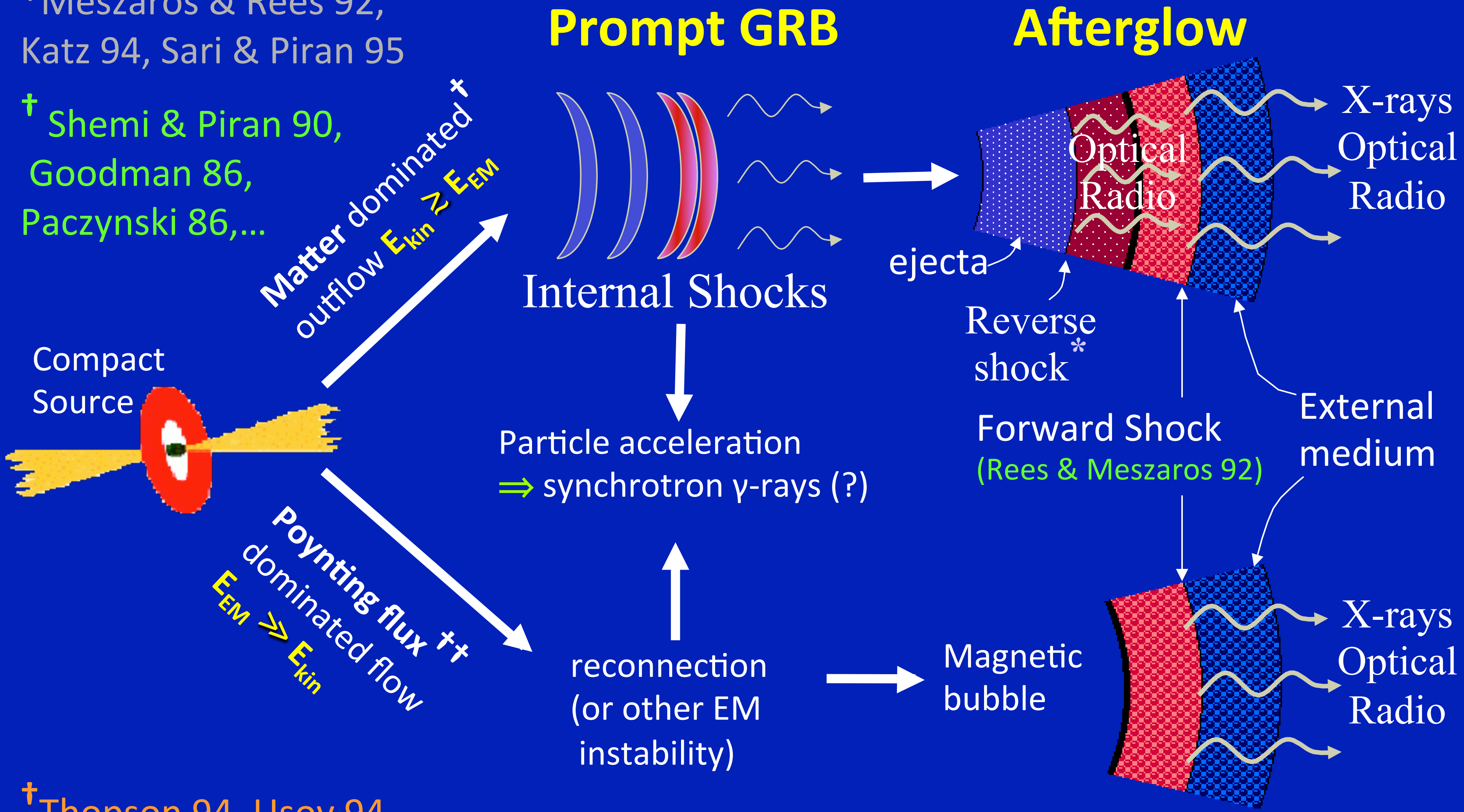
- **Still unclear − we are largely guided by observations**

composition ➔ acceleration ➔ dissipation ➔ emission

Theory: Fireball vs. Poynting Flux

*Meszaros & Rees 92,
Katz 94, Sari & Piran 95

† Shemi & Piran 90,
Goodman 86,
Paczynski 86,...



Prompt GRB

Afterglow

Matter dominated outflow $E_{kin} \gtrsim E_{EM}$ †

Internal Shocks

X-rays
Optical
Radio

Optical
Radio

ejecta

Reverse shock*

Forward Shock
(Rees & Meszaros 92)

External medium

Compact Source

Particle acceleration
⇒ synchrotron γ-rays (?)

Poynting flux ††
dominated flow
$E_{EM} \gg E_{kin}$

reconnection
(or other EM
instability)

Magnetic
bubble

X-rays
Optical
Radio

††Thopson 94, Usov 94,
Meszaros & Rees 97,
Katz 97,...

Lyutikov & Blandford 02,03

Outflow Acceleration & Dissipation:

- **Fireball**: thermal acceleration (by radiation pressure)
  - Fast ($\Gamma \propto R$), robust, allows efficient internal dissipation
  - Baryon kinetic energy eventually dominates
  - Requires a small baryon loading ($\sim 10^{-5}\,M_\odot$)
  - Naturally produces internal shocks (dissipate $\lesssim 10\%$ of energy)
  - n-p collisions in a neutron rich outflow
- **Magnetic** acceleration: Poynting flux dominated jets
  - Steady, axisymmetric, ideal-MHD: slow, not robust or efficient
  - Can naturally produce a small baryon loading
  - Gradual dissipation (of alternating fields or instability induced) can enhance the acceleration & contribute to the radiation
  - Strong time dependence: enhances acceleration & dissipation
  - Fast **reconnection** can accelerate particles, produce relativistic turbulence, spikes in lightcurve & high radiative efficiencies

Composition: Fireball vs. Poynting flux

- **Fireball**: $E_{\mathrm{thermal}} \rightarrow \mathbf{E}_{\mathbf{kinetic}} \rightarrow \mathbf{E}_{\mathbf{thermal}} + \mathbf{E}_{\mathbf{radiation}}$
  (thermal acceleration ; dissipation in internal shocks)
- Relatively well studied

- **Poynting flux dominated outflows:**
  - If no B-field reversal: $E_{\mathbf{magnetic}} \rightarrow E_{\mathbf{kinetic}} \rightarrow \mathbf{E}_{\mathbf{thermal}} + \mathbf{E}_{\mathbf{radiation}}$
    (steady + impulsive magnetic acceleration; internal shocks)
  - Field reversals/striped wind: $E_{\mathbf{magnetic}} \rightarrow E_{\mathbf{kinetic}} + \mathbf{E}_{\mathbf{thermal}} + \mathbf{E}_{\mathbf{radiation}}$
    (magnetic reconnection + acceleration)
- Generally less studied

The "σ-problem": for a "standard" steady ideal MHD axisymmetric flow

- In spherical flows $\Gamma_\infty \sim \sigma_0^{1/3}$ & $\sigma_\infty \sim \sigma_0^{2/3} \gg 1$ ($\sigma_0 = B_0^2/4\pi\rho_0 c^2$) but PWN obs. imply $\sigma \ll 1$ after the wind termination shock
  - In PWN the solution is dissipation of the striped wind
  - However, this doesn't work well in relativistic jet sources, where a broadly similar σ problem persists
- Jet **collimation** helps, but not enough: $\Gamma_\infty \sim \sigma_0^{1/3}\theta_{jet}^{-2/3}$, $\sigma_\infty \sim (\sigma_0\theta_{jet})^{2/3}$ & $\Gamma\theta_{jet} \lesssim \sigma^{1/2}$ (~1 for $\Gamma_\infty \sim \Gamma_{max} \sim \sigma_0$)
- Still $\sigma_\infty \gtrsim 1$ ⇒ inefficient internal shocks, $\Gamma_\infty\theta_{jet} \gg 1$ in GRBs
- Sudden drop in external pressure can give $\Gamma_\infty\theta_{jet} \gg 1$ but still $\sigma_\infty \gtrsim 1$ **(Tchekhovskoy et al. 2009)** ⇒ inefficient internal socks

Alternatives to the "standard" picture

- ~~Axisymmetry~~: non-axisymmetric instabilities (e.g. the current-driven kink instability) can tangle-up the magnetic field & lead to significant dissipation (Begelman; Spruit; Eichler; Lyubarsky; Giannios;…)

◆ If $\langle B_r^2\rangle = \alpha\langle B_\phi^2\rangle = \beta\langle B_z^2\rangle\ ;\ \ \alpha,\beta = \mathrm{const}$ then the magnetic field behaves as an ultra-relativistic gas: $p_{\mathrm{mag}} \propto V^{-4/3}$ $\Rightarrow$ magnetic acceleration as efficient as thermal

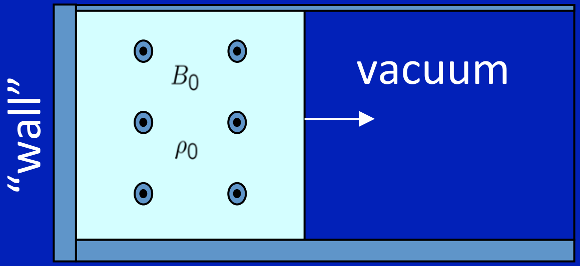
- ~~Ideal~~ MHD: a tangled magnetic field can reconnect (Drenkham 2002; Drenkham & Spruit 2002)
  magnetic energy $\Rightarrow$ heat (+radiation) $\Rightarrow$ kinetic energy

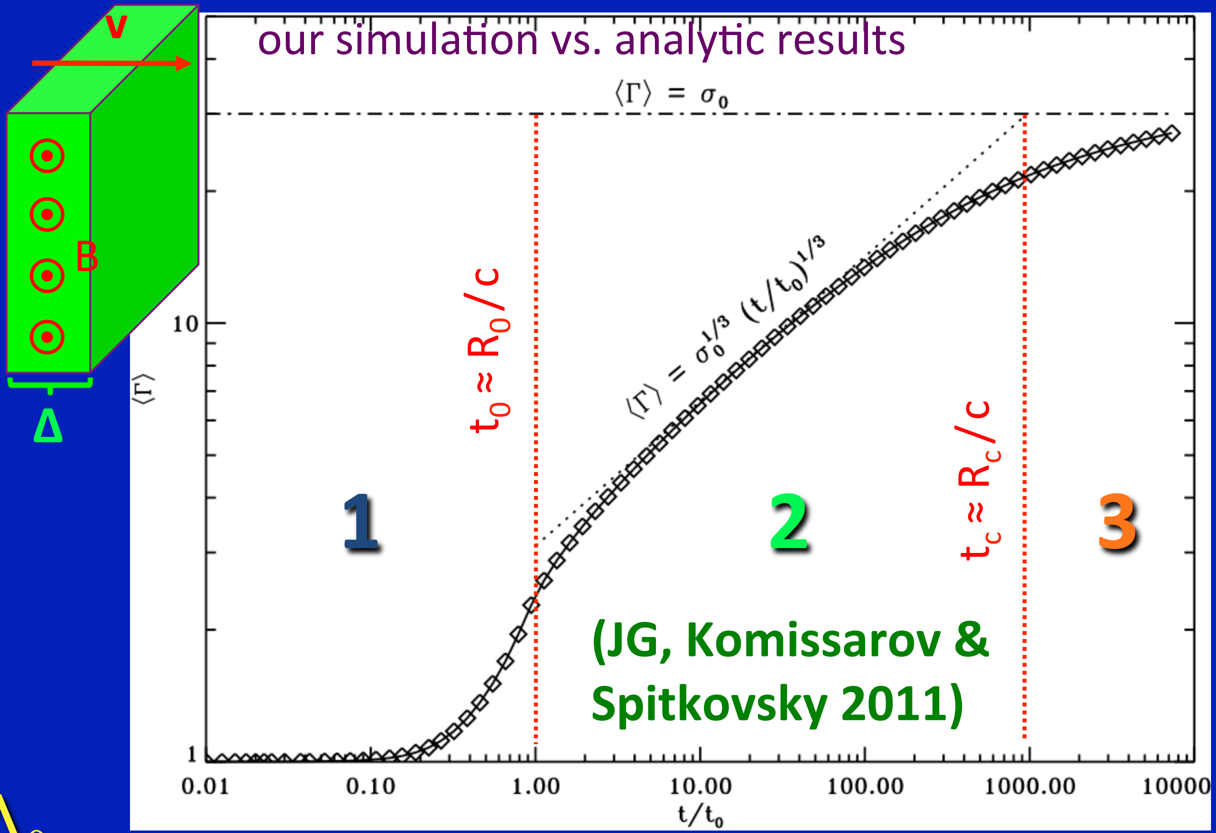
- ~~Steady-state~~: **effects of strong time dependence** (JG, Komissarov & Spitkovsky 2011; JG 2012a, 2012b)

Impulsive Magnetic Acceleration: $\Gamma \propto R^{1/3}$

Useful **case study**:

Initial value of magnetization parameter: $\sigma_0 = \dfrac{B_0^2}{4\pi\rho_0 c^2} >> 1$





(JG, Komissarov & Spitkovsky 2011)

1. $\langle\Gamma\rangle_E \approx \sigma_0^{1/3}$ by $R_0 \sim \Delta_0$
2. $\langle\Gamma\rangle_E \propto R^{1/3}$ between $R_0 \sim \Delta_0$ & $R_c \sim \sigma_0^2 R_0$ and then $\langle\Gamma\rangle_E \approx \sigma_0$
3. At $R > R_c$ the sell spreads as $\Delta \propto R$ & $\sigma \sim R_c/R$ rapidly drops

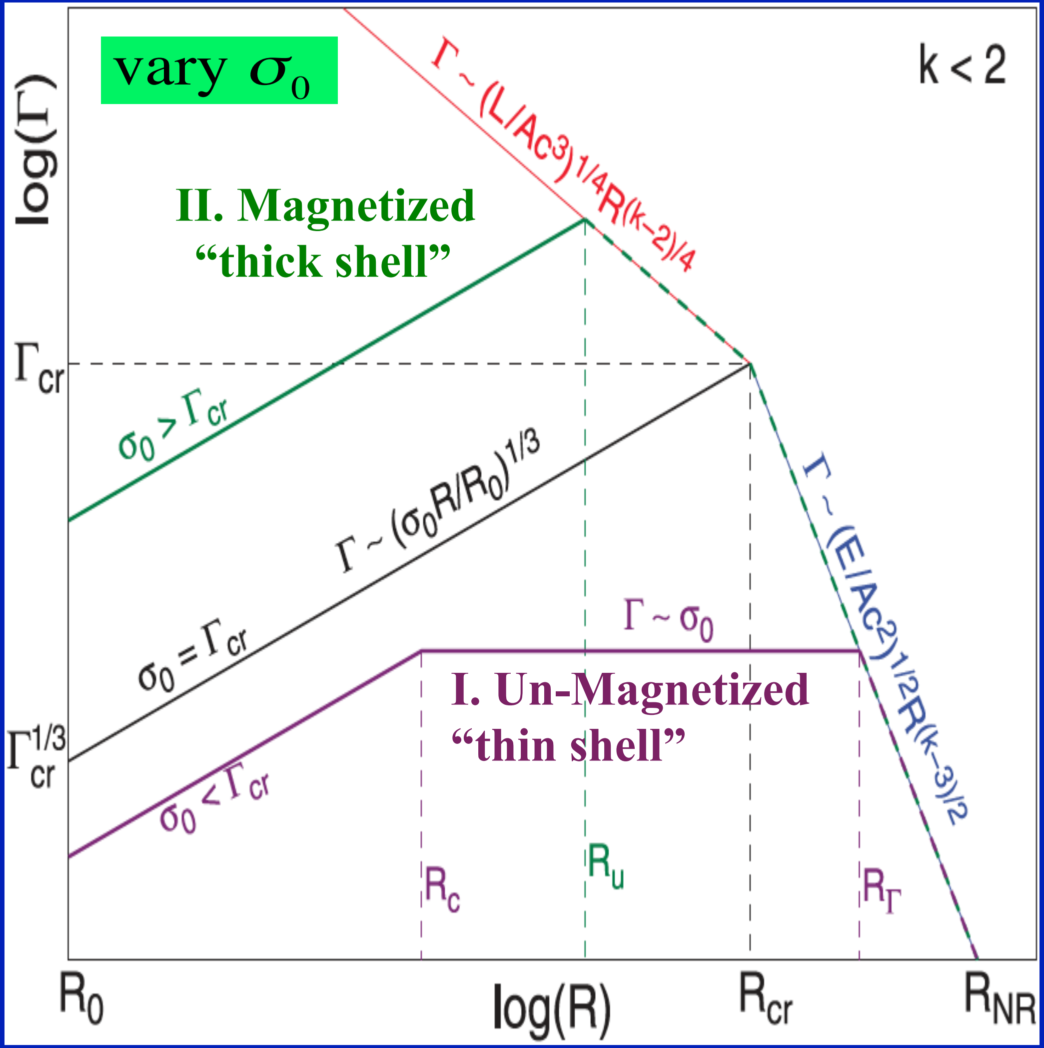
- **Complete conversion of magnetic to kinetic energy!**
- **This allows efficient dissipation by shocks at large radii**

1^{st} Steady then Impulsive Acceleration

- Our test case problem has no central engine: it may be, e.g., directly applicable for giant flares in SGRs; however:
- In most astrophysical relativistic (jet) sources (GRBs, AGN, μ-quasars) the variability timescale ($t_v \approx R_0/c$) is long enough ($>R_{ms}/c$) that steady acceleration operates & saturates (at R_s)
- Then the impulsive acceleration kicks in & leads to $\sigma < 1$

Impulsive Magnetic Acceleration: single shell propagating in an external medium

acceleration & deceleration are tightly coupled (JG 2012)



$$\rho_{\rm ext} = AR^{-k}$$

$$R_{\rm cr} \sim R_0\Gamma_{\rm cr}^2 \sim \left(\frac{ER_0}{Ac^2}\right)^{\frac{1}{4-k}}$$

I. “Thin shell”, low-σ : strong reverse shock, peaks at ≫ $T_{\rm GRB}$

II. “Thick shell”, high-σ: weak or no reverse shock, $T_{\rm dec} \sim T_{\rm GRB}$

III. like II, but the flow becomes independent of σ_0

IV. a Newtonian flow (if $\rho_{\rm ext}$ is very high, e.g. inside a star)

II*. if $\rho_{\rm ext}$ drops very sharply

Sub-shells: acceleration, collisions (JG 2012b)

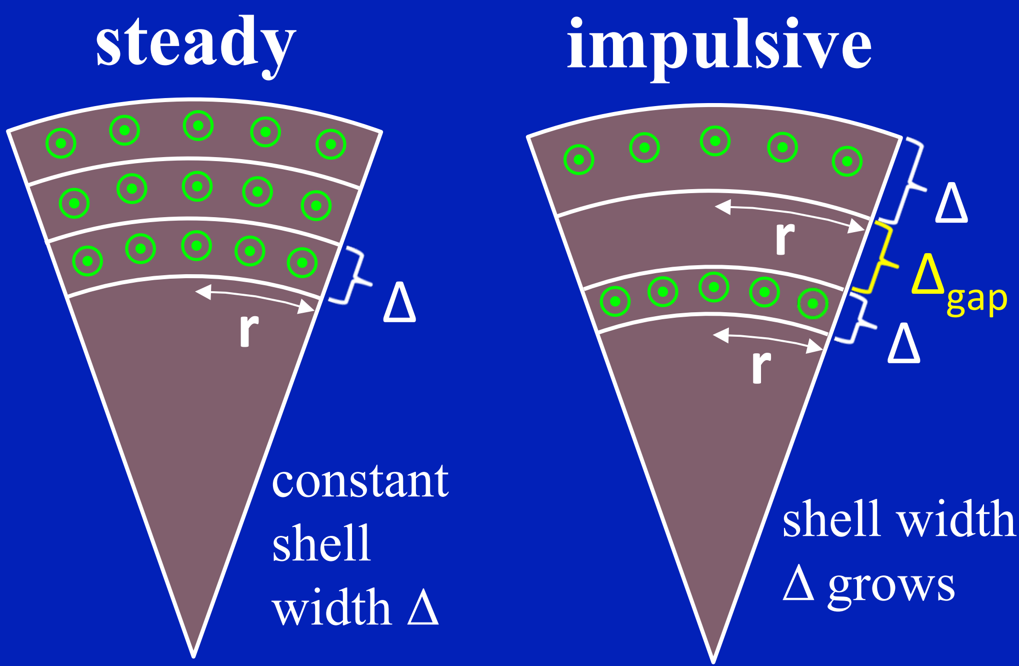
Flux freezing (ideal MHD):

$\Phi \sim B\,r\,\Delta = \textbf{constant}$

$E_{EM} \sim B^2\,r^2\,\Delta \propto 1/\Delta$

$$\frac{\text{total energy}}{\text{rest energy}} = (1+\sigma)\Gamma$$

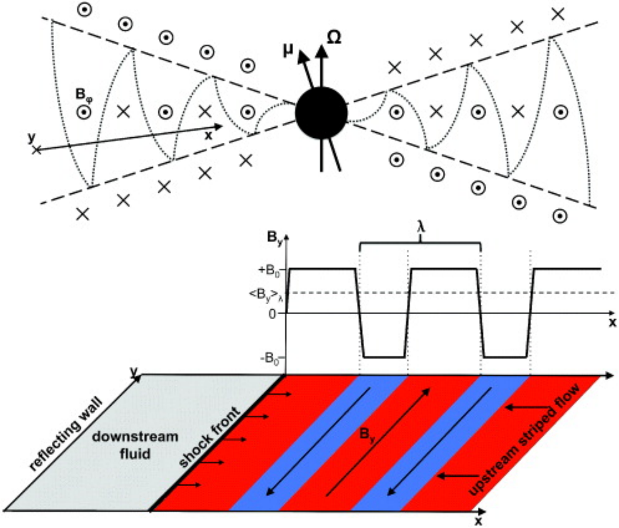
acceleration $(\Gamma\uparrow) \;\Leftrightarrow\; \sigma\downarrow$

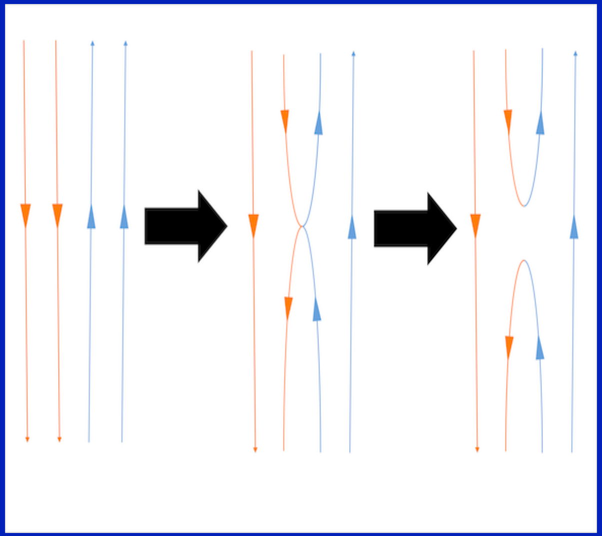


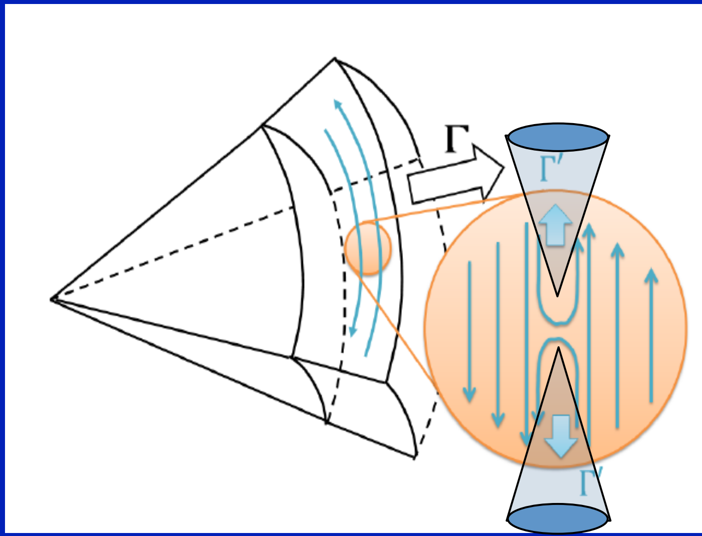
- For a long lived variable source (e.g. AGN), each sub shell can expand by $1+\Delta_{gap}/\Delta_0 \Rightarrow \sigma_\infty = (E_{total}/E_{EM,\infty} - 1)^{-1} \sim \Delta_0/\Delta_{gap}$
- For a finite # of sub-shells the merged shell can still expand
- Sub-shells in GRBs can lead to a low-magnetization thick shell & enable the outflow to reach higher Lorentz factors
- $\sigma < 1$ shocks: magnetic energy ➔ kinetic ➔ thermal (+radiation)
- $\sigma \gg 1$ shocks: magnetic ➔ thermal ➔ kinetic (Komissarov 2012)

GRB Lightcurves from Magnetic Reconnection (Beniamini & JG 2015; 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 (✔)
- Reconnection far from the source has a natural preferred direction
- For large ingoing σ reconnection leads to local relativistic outward bulk motion at $\Gamma' \sim$ few – several $\Rightarrow$ anisotropic emission in jet's bulk frame
- Larger $\sigma \Rightarrow$ higher Γ', larger rec. rate (v_{in}/v_A), harder particle spectrum

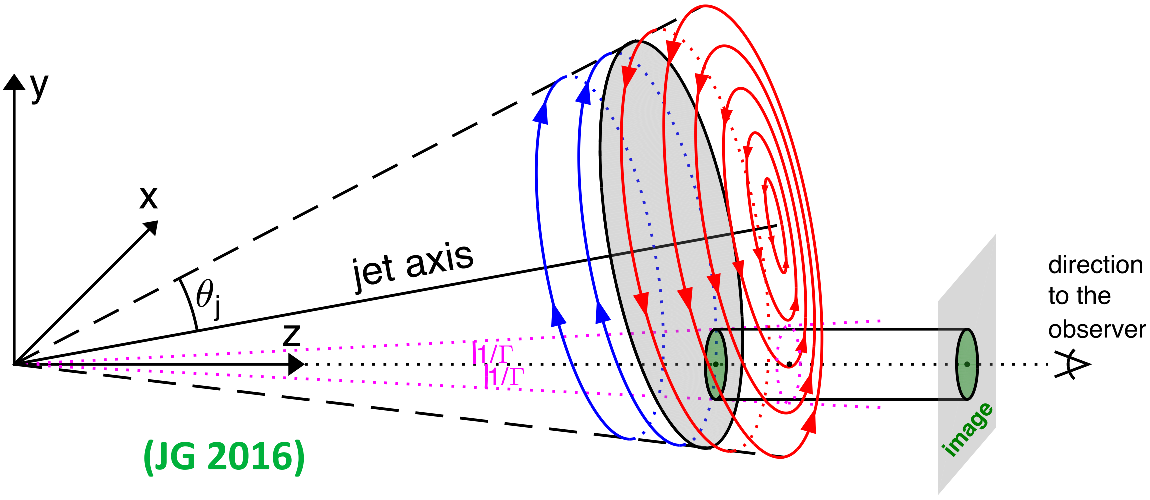




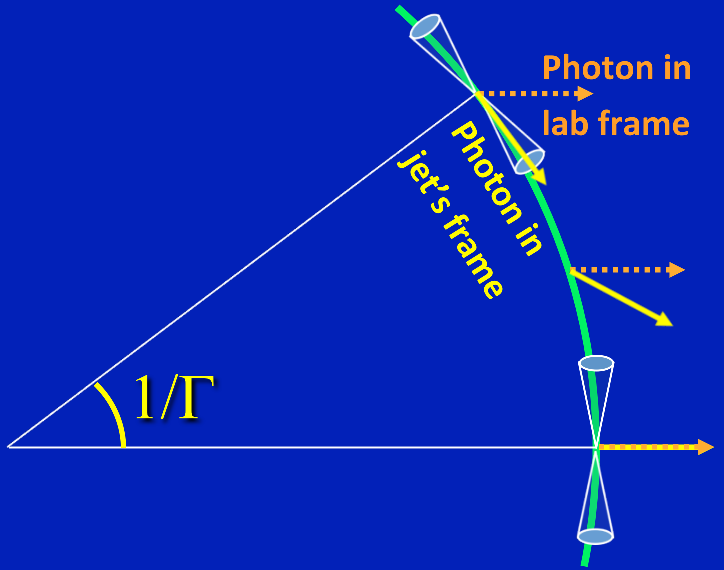


Model for GRB Lightcurves (Beniamini & JG 2015)

- Emission from thin locally quasi-spherical reconnection layers / shells
- Each shell moves at $\Gamma \gg 1$ & produces one pulse in the GRB lightcurve
- The emitting plasma moves in two opposite directions in the jet's bulk frame along the initial **B** direction (assumed uniform in visible region)
- Emission is either continuous (steady in the jet's frame), or blob-like
- Emitted spectrum: either a power-law or a Band function
- $\Gamma^2 \propto R^{-m}$, Luminosity L evolves with R as a power-law or log-normal

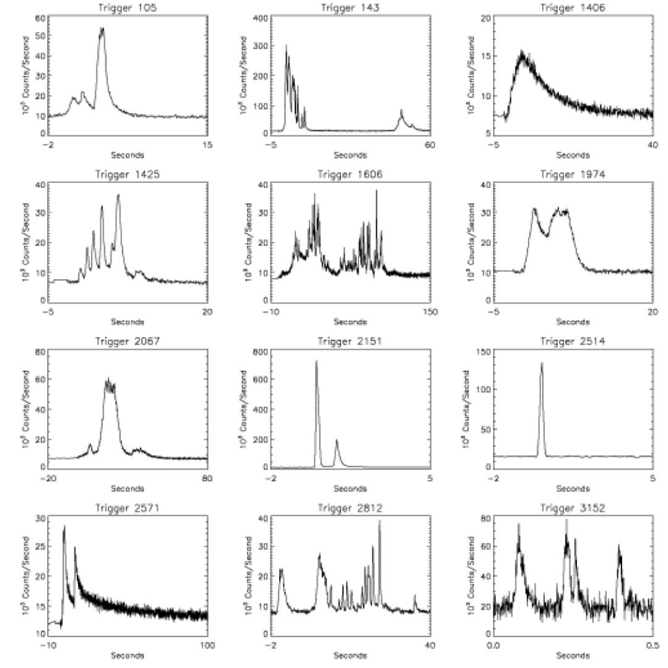


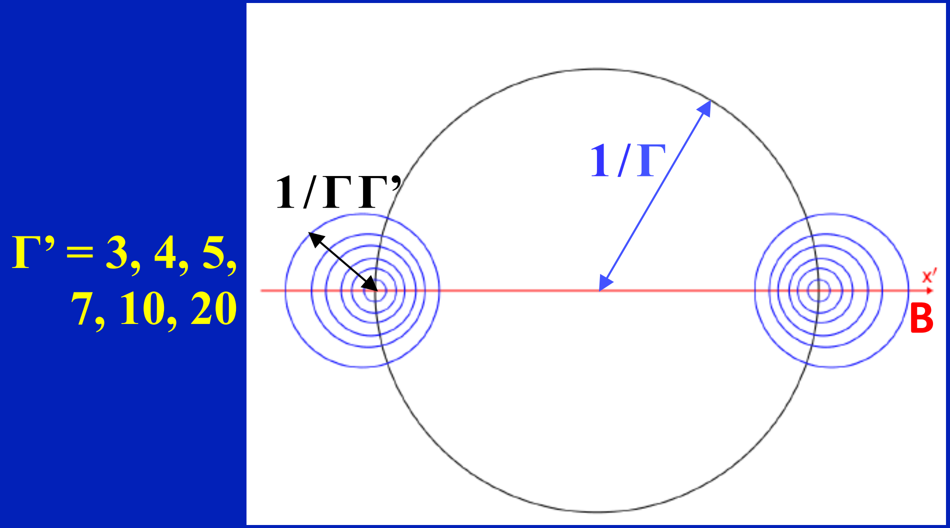
(JG 2016)

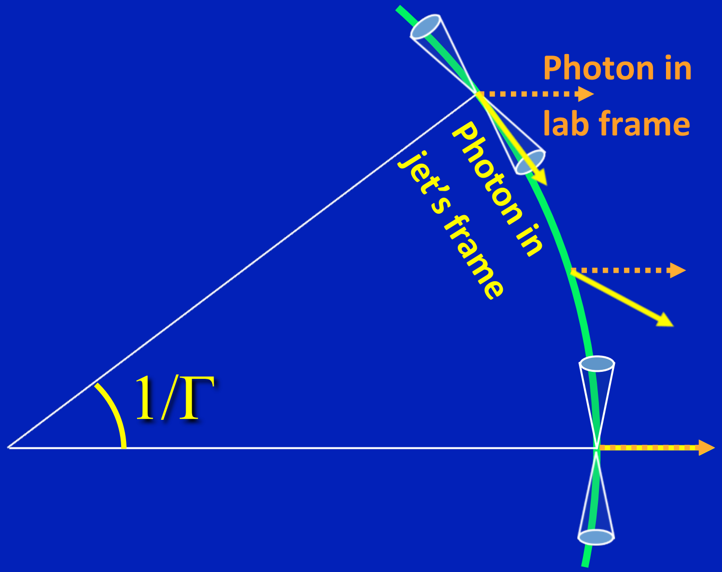


Model for GRB Lightcurves (Beniamini & JG 2015)

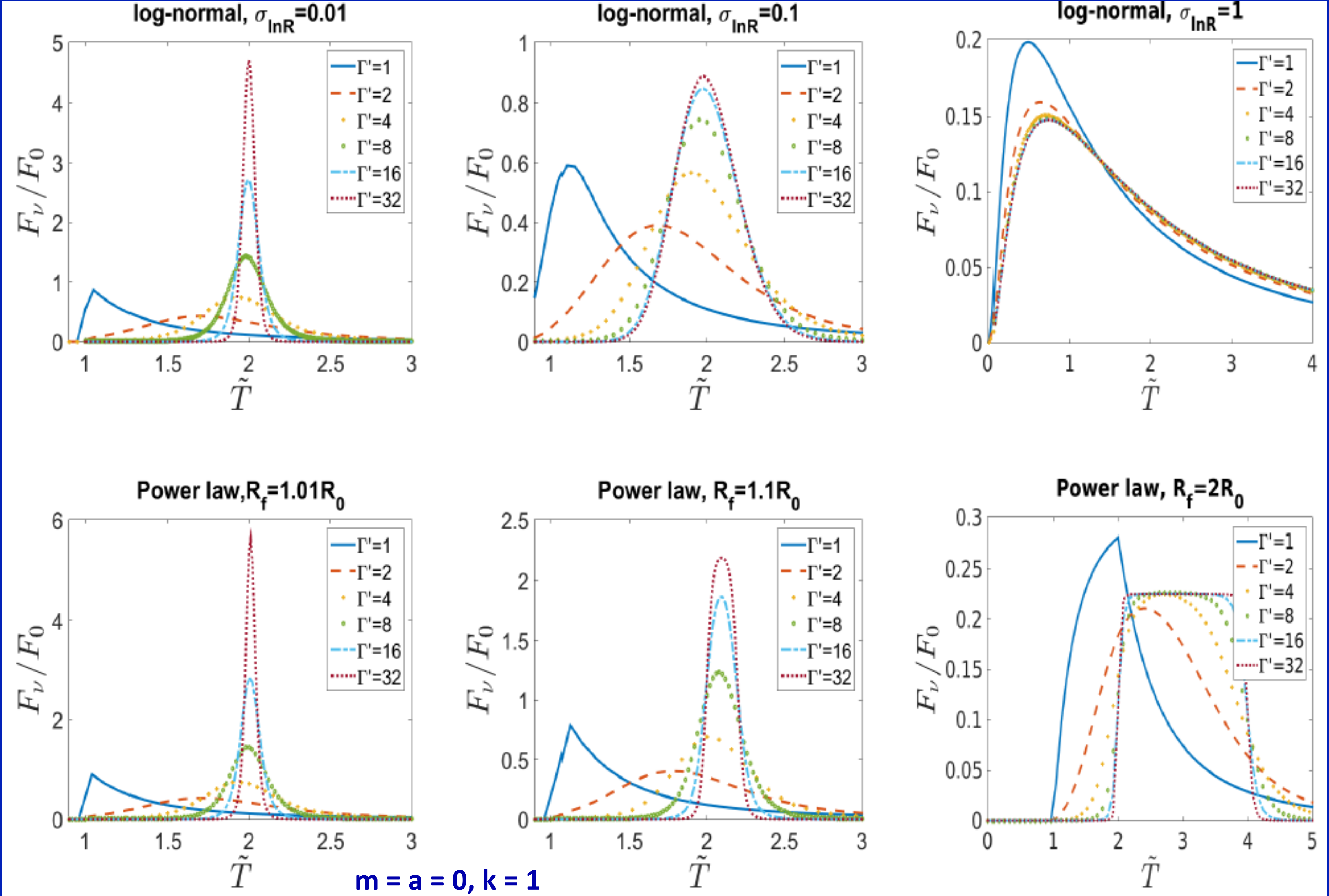
- Pulse width: $\Delta t \approx \Delta t_r + \Delta t_\theta$ & the angular time is reduced by a factor of Γ', to $\Delta t_\theta \approx R/2\Gamma^2\Gamma'$
- $\Rightarrow$ Fast variability is possible, limited by Δt_r
- For isotropic emission pulses tend to be asymmetric: $\Lambda = T_{rise} / T_{decay} < 1$
- While a fast rise & slower decay is typically observed, some pulses as rather symmetric







The Shape of Pulses in the Lightcurves

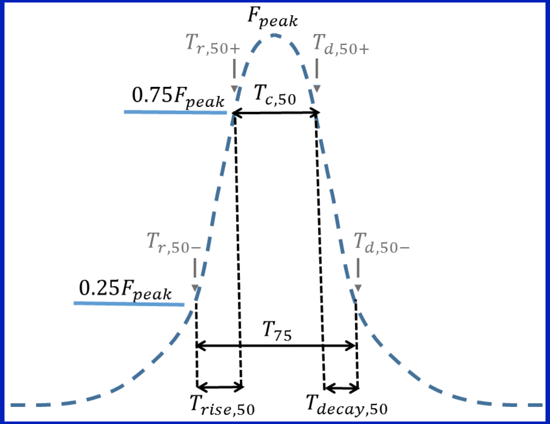


m = a = 0, k = 1

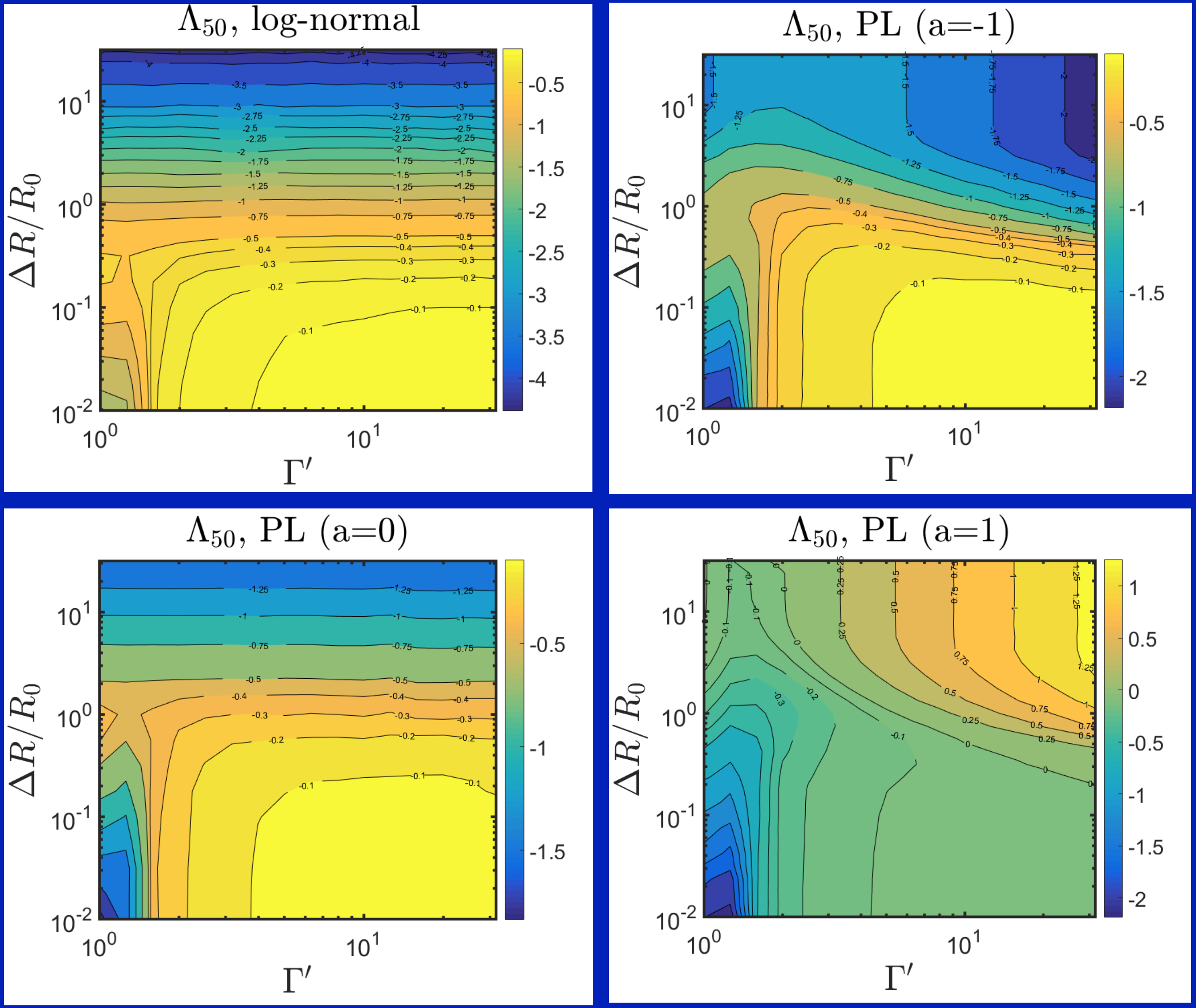
The Shape of Pulses in the Lightcurves

$\Lambda_{50} = T_{rise,50} \,/\, T_{decay,50}$

($\Lambda_{50} = 1$ for symmetric pulses)



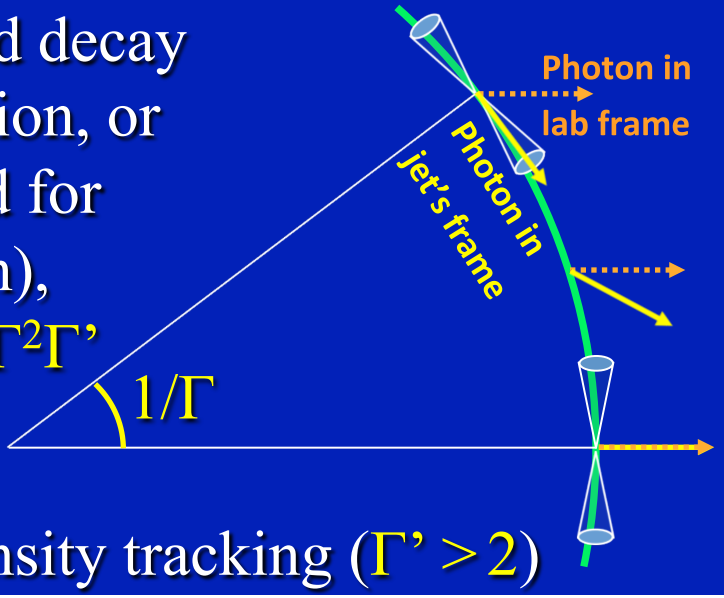
$\log_{10}(\Lambda_{50})$



m = 0 (Γ = const)
k = 1 ("steady state" in jet's bulk frame)

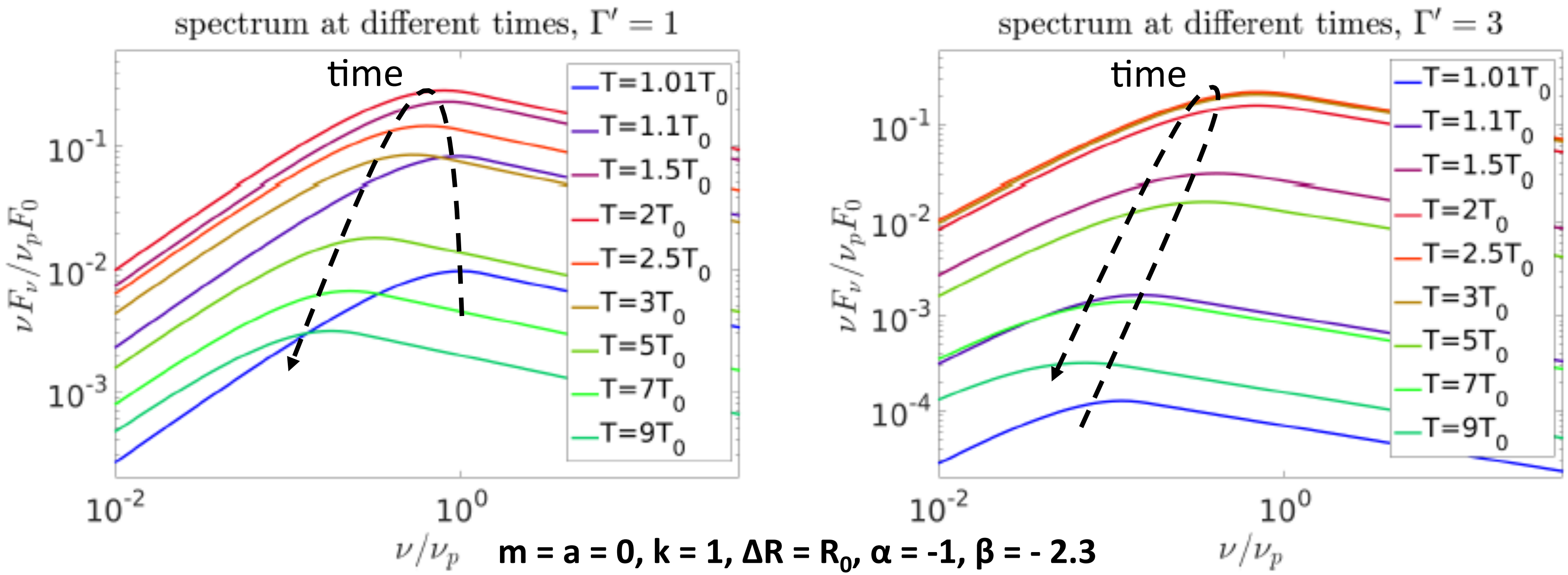
Some Other Pulse Properties

- An isotropic 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 ($\Gamma' > 2$)

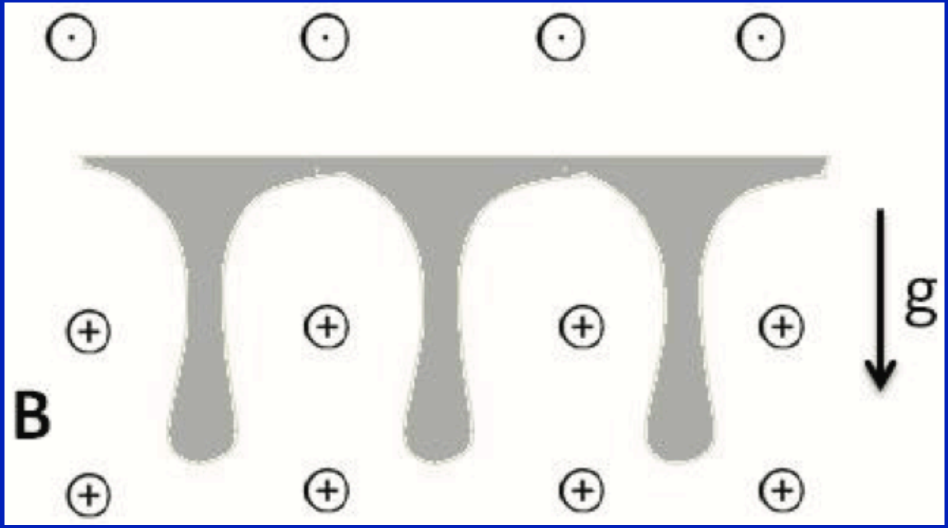

spectrum at different times, $\Gamma' = 1$

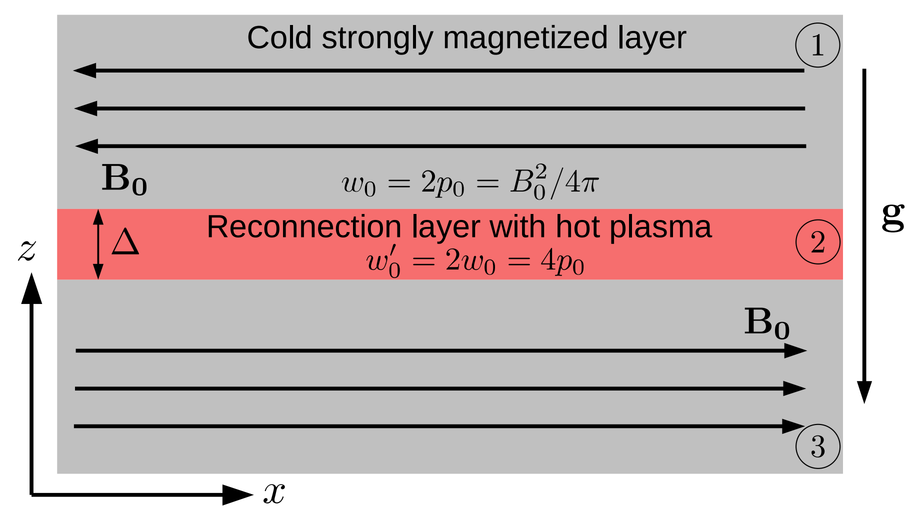
spectrum at different times, $\Gamma' = 3$

m = a = 0, k = 1, ΔR = R_0, α = -1, β = - 2.3

Kruskal–Schwarzchild Instability:

(Lyubarsky 2010 ; Gill, JG & Lyubarsky 2017)

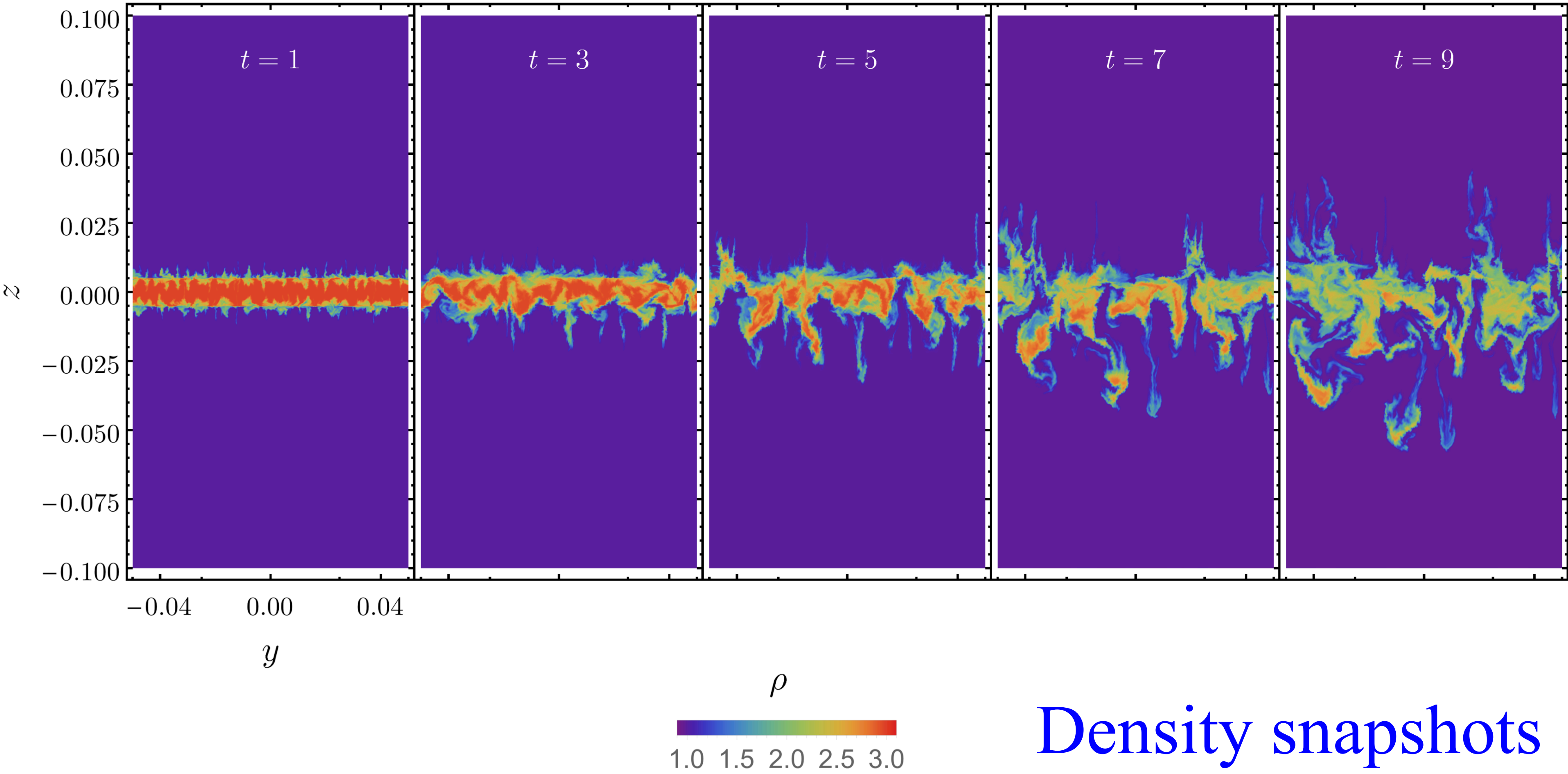




- The Magnetized analog of the Rayleigh-Taylor instability
- Hot plasma accumulates in the reconnection layer, and can prevent further reconnection
- The heavier hot plasma is unstable in the effective gravity due to the outflow’s acceleration & it drips out of the layer
- ⇒ enhances reconnection rate ⇒ increases the acceleration & effective gravity ⇒ creates a positive feedback loop

Kruskal–Schwarzchild Instability:

(Gill, JG & Lyubarsky 2017)



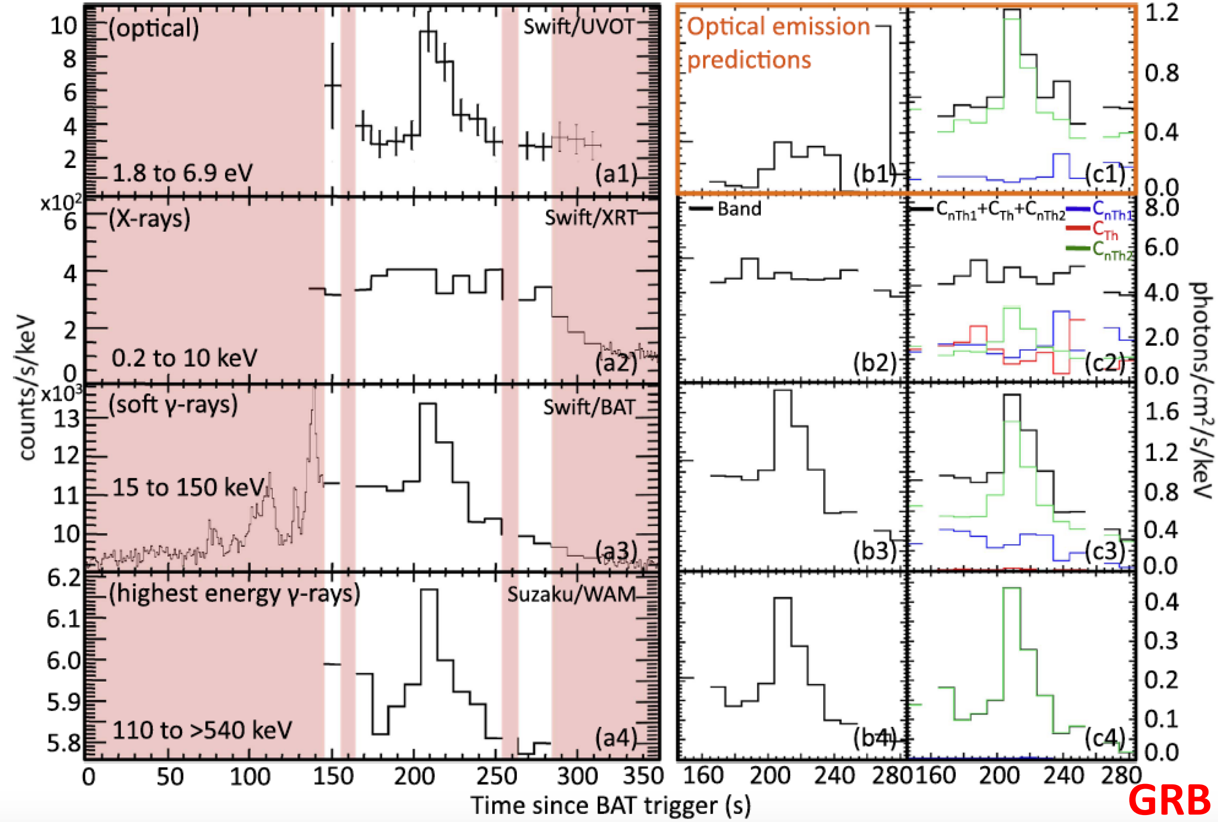
Density snapshots

Initial results of 2D RMHD simulations

GRB Spectrum: Phenomenological Model

(Guiriec, Kouveliotou, Hartmann, JG, Asano, Meszaros, Gill, Gehrels & McEnery 2016)

- Some GRBs have correlated prompt optical+γ-ray emission
- Spectrum well fit by phenomenological 3-component model
- Optical−γ-ray lightcurves correlated ⇒ same emission region



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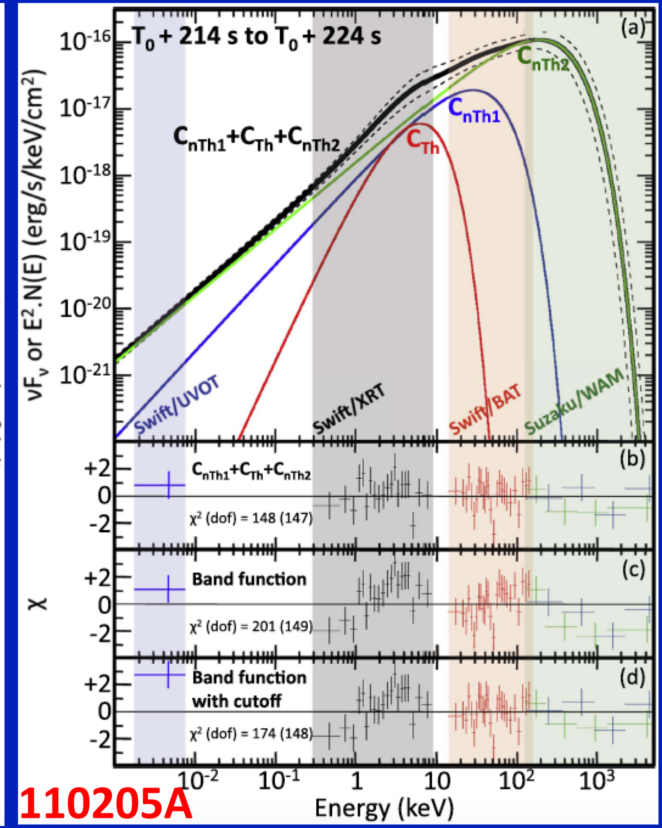
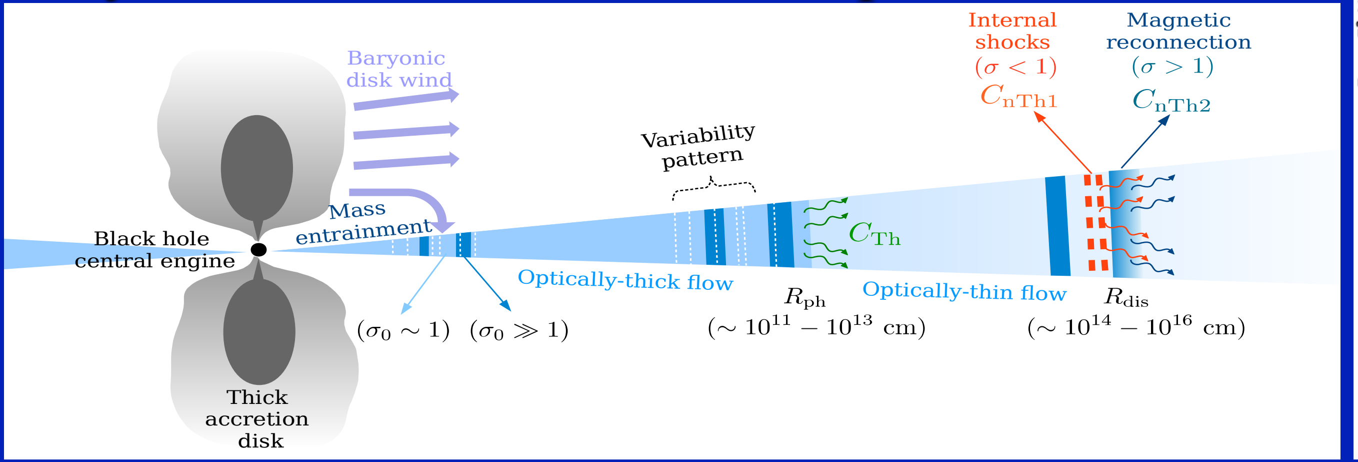
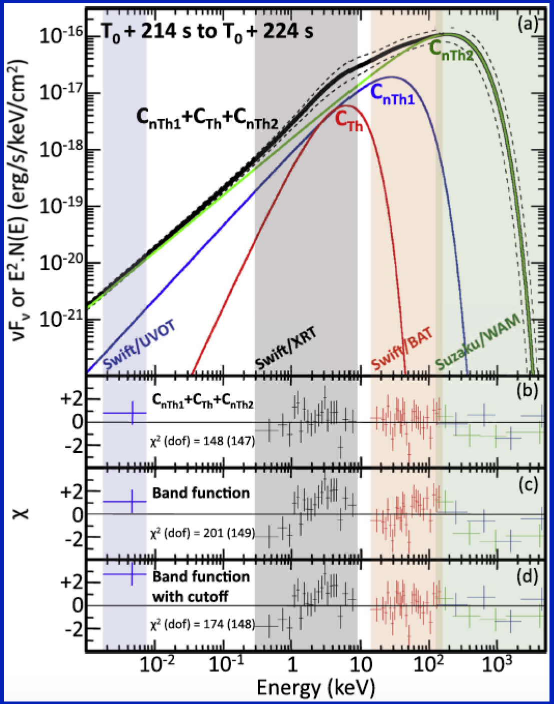


GRB Spectrum: Phenomenological Model

(Guiriec, Kouveliotou, Hartmann, JG, Asano, Meszaros, Gill, Gehrels & McEnery 2016)

- C_{Th}: likely photospheric; $\alpha \approx 0.6$ slightly softer than thermal ($\alpha = 1$ where $dN/dE \propto E^{\alpha}$) perhaps sum over BB with $T(\theta)$.
- C_{nTh1}: partial correlation+slight delay w.r.t C_{Th} is natural for internal shocks at larger radius, $R_{IS} > R_{ph}$; $\alpha \approx -0.7$ suggests synchrotron from quasi-thermal electron dist. ($10^{-3} < \sigma < 1$ strong shocks+suppressed DSA, or heating-cooling balance)
- C_{nTh1}: strong variability ⇒ ~~external shock~~ uncorrelated w. C_{Th}, C_{nTh1} ⇒ different region maybe reconnection at $\sigma > 1$ parts of outflow





Thank You