Magnetic Fields in GRBs

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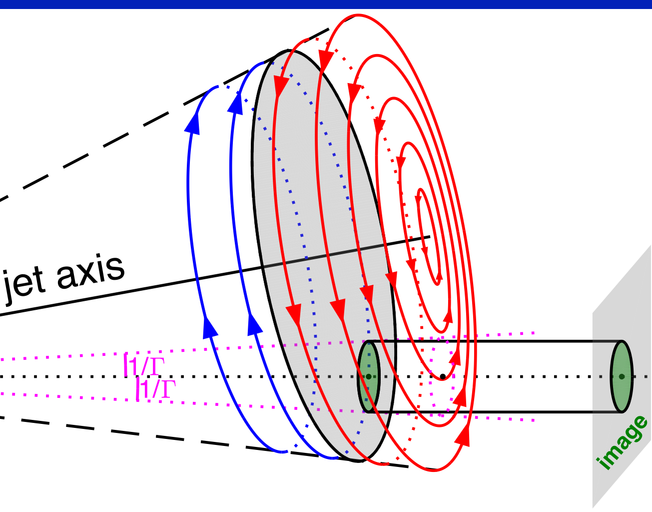
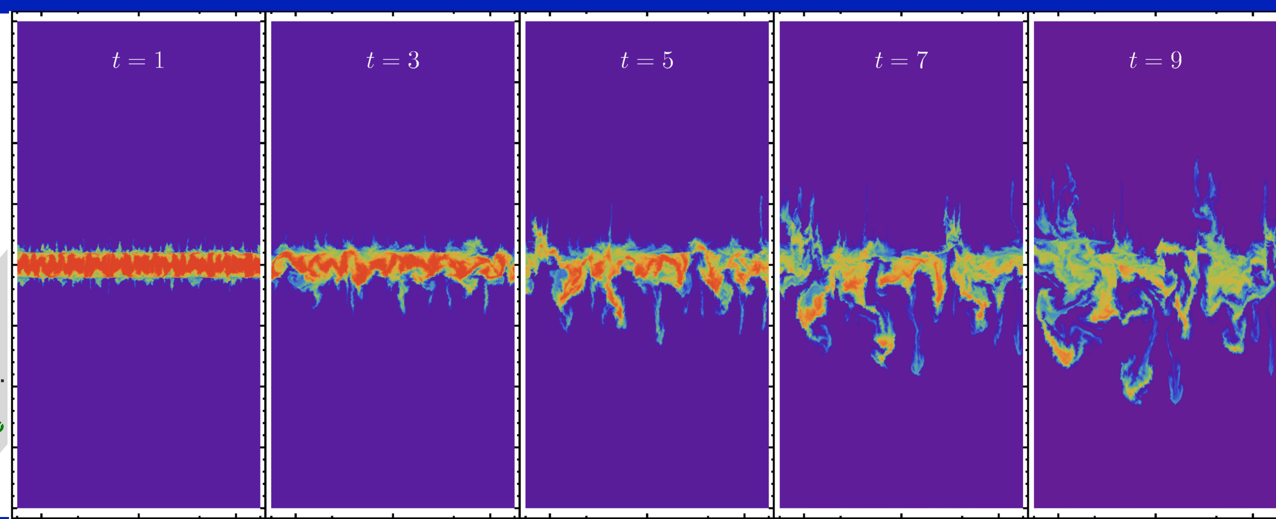
Collaborators: R. Gill, P. Beniamini, Y. Lyubarsky, T. Piran, S. Komissarov, A. Spitkovsky, C. Kouveiotou,…





Deciphering the Violent Universe

Playa del Carmen, Mexico, 14 December 2017

B-fields play many key roles in GRBs

- **Accretion**: instabilities (e.g. MRI), facilitate angular momentum transport, can inhibit accretion,…
- **Jet launching**: Blandford-Payne, Blandford-Znajek,…
  - **a magnetar central engine?** (see next talk by P. Beniamini)
- Magnetic **acceleration**:
  - Gradual dissipation of magnetic energy
  - Ideal MHD: steady vs. impulsive acceleration, effect of external medium & multiple sub-shells
- Jet dynamics: inside a star (also stability & dissipation) (Bromberg et al. 2014, 2015, 2016; talk by E. Sobbachi)

B-fields play many key roles in GRBs

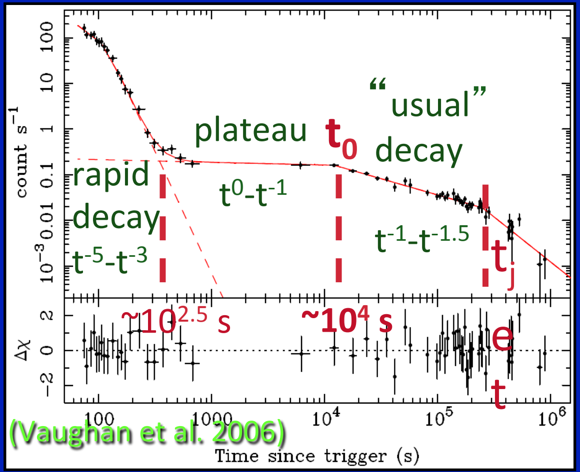
- Reconnection + acceleration: K-S instability
- Particle acceleration (shocks or reconnection; talk by G. Kowal)
- Prompt GRB emission:
  - lightcurves from magnetic reconnection
- Polarization: prompt GRB, reverse shock, afterglow
- Afterglow: GRB130427A – clear violation of $E_{syn,max}$

Millisecond-Magnetar GRB Central Engine?

- Initial rotational energy & spin-down time:

$$E_0 \approx 2\times10^{52} I_{45}\left(\frac{P_0}{1\text{ ms}}\right)^{-2}\ \text{erg}$$

$$t_0 \approx 1.4\times10^{3} I_{45}\left(\frac{P_0}{1\text{ ms}}\right)^{2}\left(\frac{B_p}{10^{15}\text{ G}}\right)^{-2}\left(\frac{R_{NS}}{10\text{ km}}\right)^{-6}\ \text{s}$$



- Strict upper limit E_0 on total GRB energy (Cenko et al. 2010)
- Spin-down luminosity was argued to explain plateaus:

$$L_{sd} = \frac{L_0}{(1+t/t_0)^2} \approx L_0 \times \begin{cases} 1 & t<t_0 \\ (t/t_0)^{-2} & t>t_0 \end{cases}, \qquad L_0 = \frac{E_0}{t_0}$$

- Requires $t_0 \sim 10^4$ s, but what powers a ~30 s GRB?
- Differential rotation dissipation (Kluzniac & Ruderman 98')?

Millisecond-Magnetar GRB Central Engine?

- Rapid B-field decay, over $\sim T_{GRB}$, tapping similar energies before and after the decay: fine tuning + unclear mechanism
- During first ~10-100 s a strong ν-driven wind causes large baryon loading & small σ_0 ⇒ opens field lines & increases L_{sd} by $\sim(R_L/R_{NS})^2 \sim 10^{1.5}$ but low-σ_0 wind can't make a GRB
- SMNS has larger initial energy: $E_{rot,0} \approx 1.2\times10^{53}\left(\frac{M}{2.5M_\odot}\right)^2\left(\frac{P_0}{1\text{ ms}}\right)^{-1}$ erg
- "time reversal" (Kumar & Rezzolla 15'): SMNS ➔BH➔GRB but the collapse can't form an accretion disc (Margalit+ 15')
- Short GRBs: $\sim10^2$ s extended emission? $\lesssim 1$ s accretion but $\sigma_0 \lesssim 1$ ⇒ hard to produce a GRB; $\gtrsim 10^{52.5}$ erg into afterglow (lessons from GRB170817A/GW170817: talk by R. Gill)

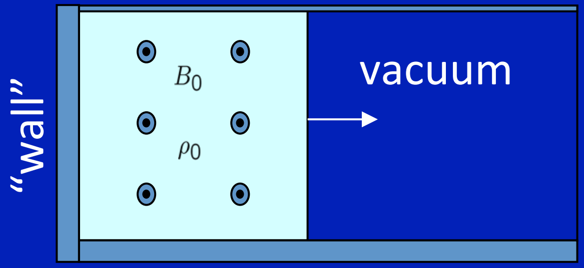
Outflow Acceleration & Dissipation:

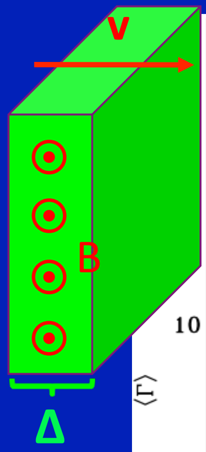
- **Fireball**: thermal acceleration (by radiation pressure)
  - Fast ($\Gamma \propto R$), robust, allows efficient internal dissipation
  - Baryon kinetic energy eventually dominates
  - Requires a small baryon loading ($\sim 10^{-5}\ M_\odot$)
  - Naturally produces internal shocks (dissipate $\lesssim 10\%$ 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

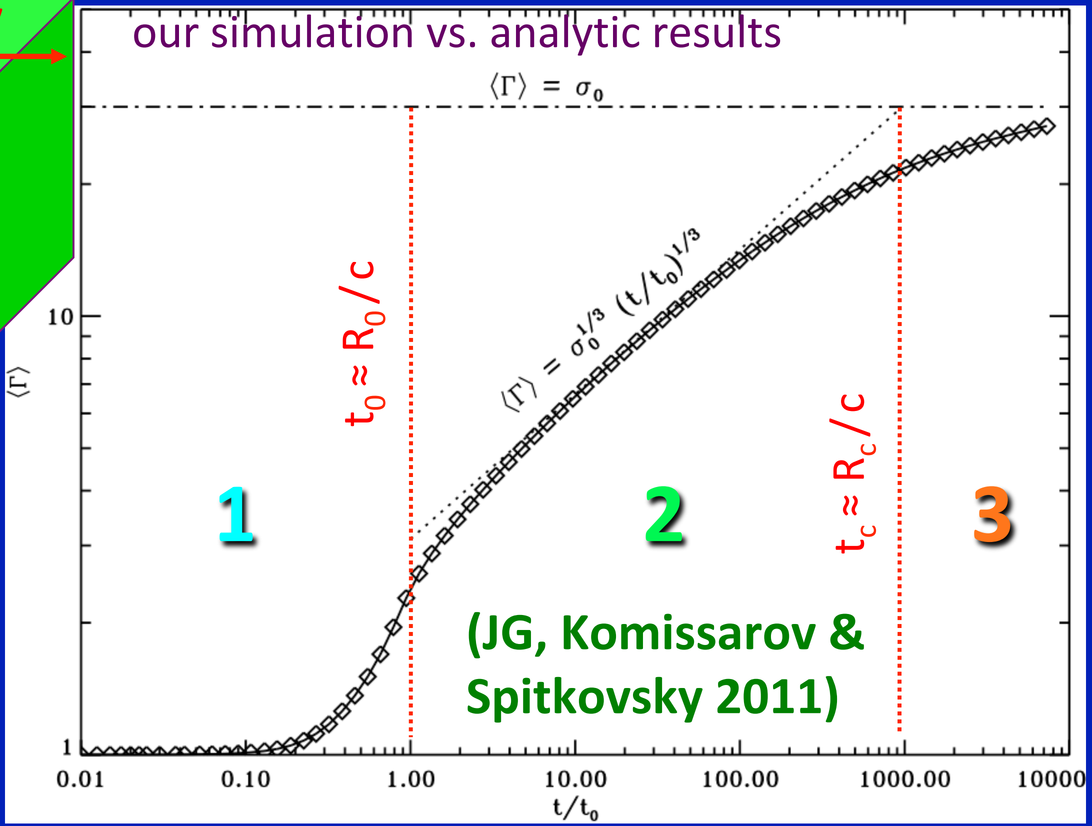
Impulsive Magnetic Acceleration: $\Gamma \propto R^{1/3}$

Useful **case study**:

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





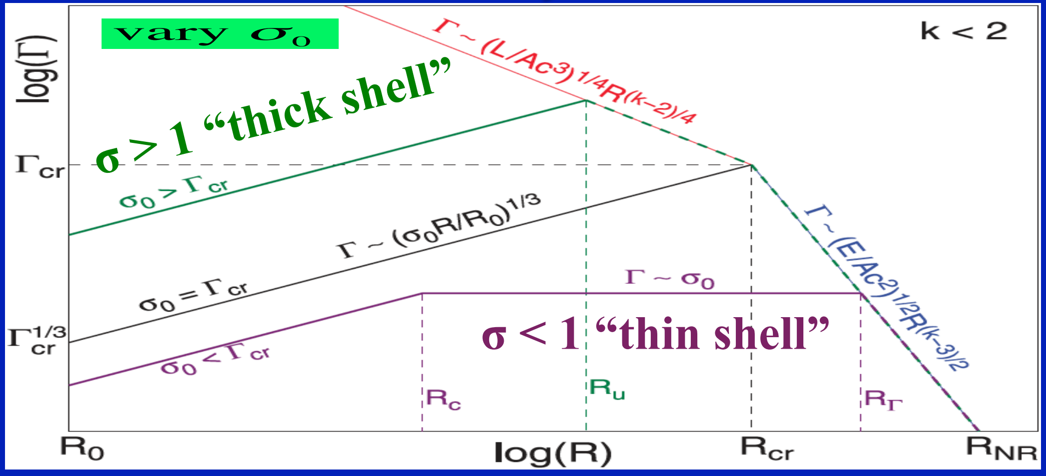


1. $\langle\Gamma\rangle_E \approx \sigma_0^{1/3}$ by $R_0 \sim \Delta_0$
2. $\langle\Gamma\rangle_E \propto R^{1/3}$ between $R_0 \sim \Delta_0$ & $R_c \sim \sigma_0^2 R_0$ and then $\langle\Gamma\rangle_E \approx \sigma_0$
3. At $R > R_c$ the sell spreads as $\Delta \propto R$ & $\sigma \sim R_c/R$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

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

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

- Our test case problem has no central engine! 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, and then the impulsive acceleration kicks in & leads to $\sigma < 1$
- Interaction with the **external medium**: two main regimes
  - "Thin shell", $\sigma < 1$: strong reverse shock, peaks at $\gg T_{GRB}$
  - "Thick shell", $\sigma > 1$: weak or no reverse shock, $T_{dec} \sim T_{GRB}$



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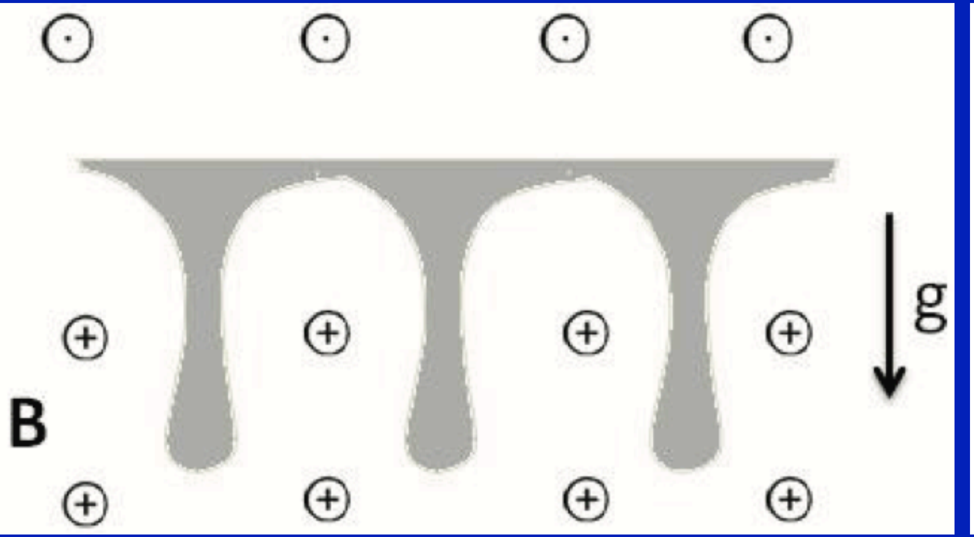
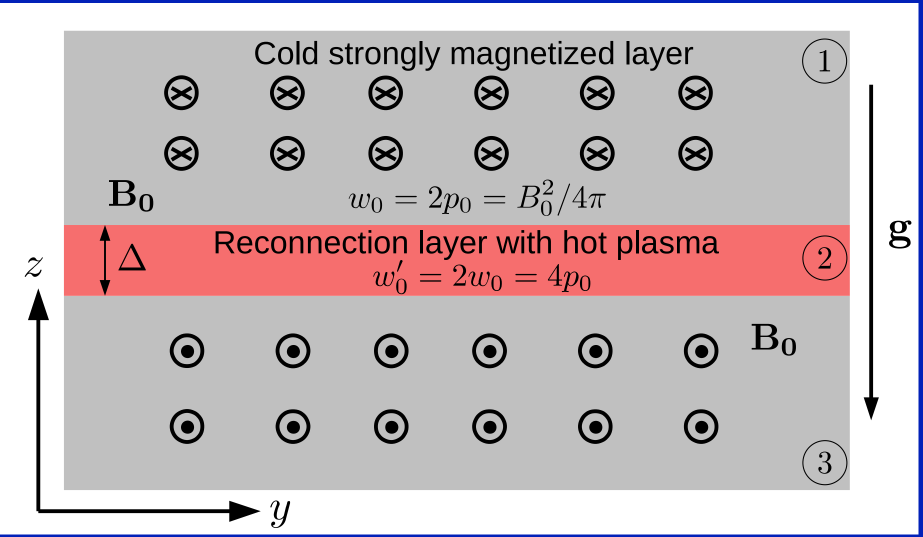
- Sub-shells in GRBs can lead to a low-σ thick shell & enable the outflow to reach higher Lorentz factors
  - $\sigma < 1$ shocks: magnetic → kinetic → thermal (+radiation)
  - $\sigma \gg 1$ shocks: magnetic → thermal → kinetic **(Komissarov 12')**

Kruskal–Schwarzchild Instability:

(Lyubarsky 2010 ; Gill, JG & Lyubarsky 2017)



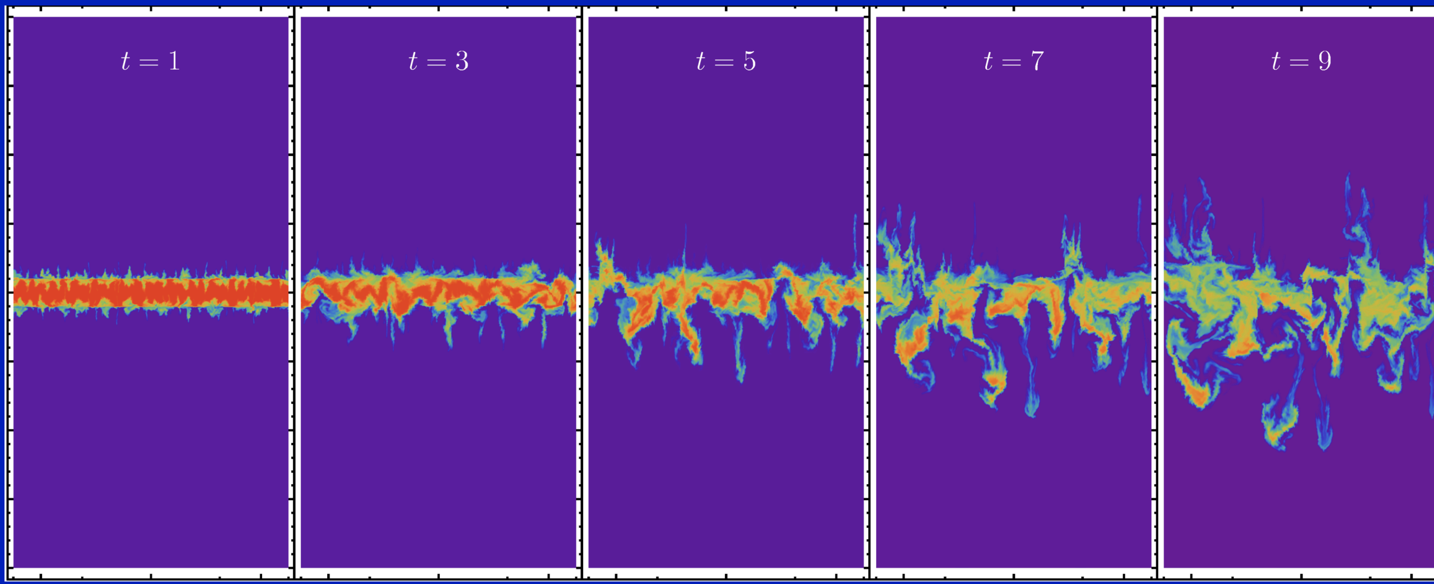


- The Magnetized analog of the Rayleigh-Taylor instability
- Hot plasma accumulates in the reconnection layer, and can prevent further reconnection
- The heavier hot plasma is unstable in the effective gravity due to the outflow's acceleration & it drips out of the layer
- ⇒ enhances reconnection rate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

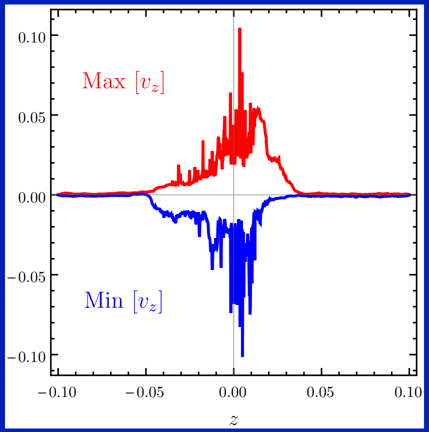
Kruskal–Schwarzchild Instability:

(Gill, JG & Lyubarsky 2017)

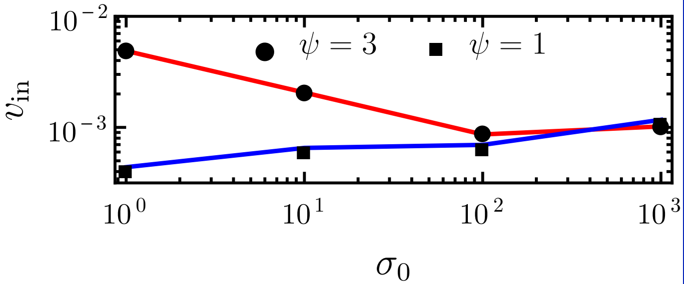
2D RMHD simulation

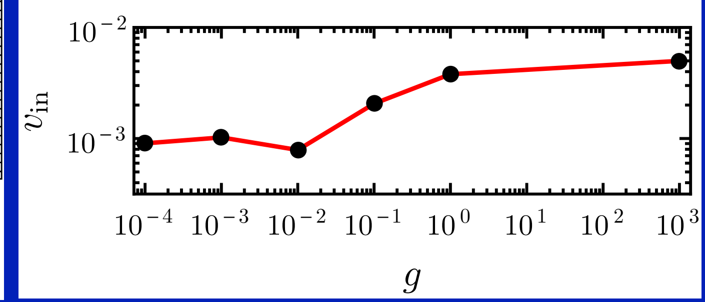


Vertical velocity range

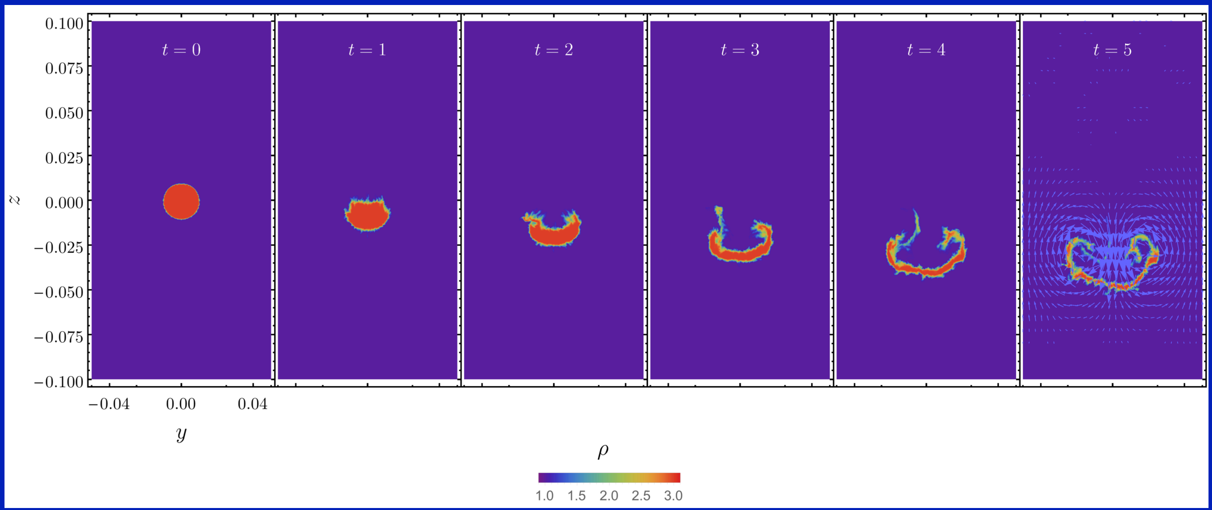


Effective reconnection speed; $\Psi = \rho_{hot} / \rho_{cold}$



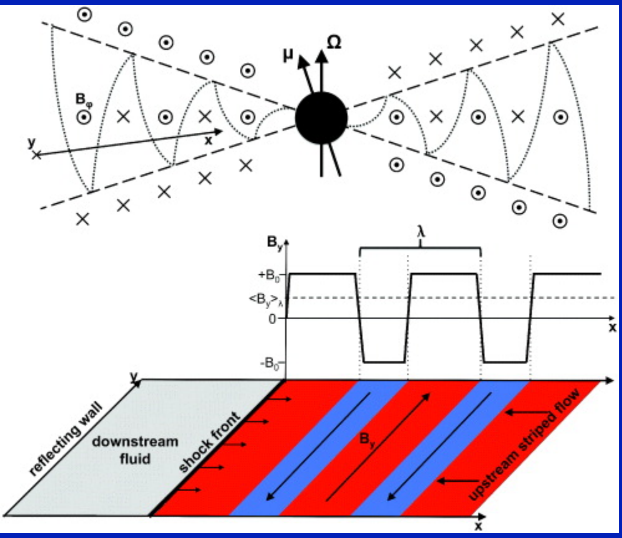


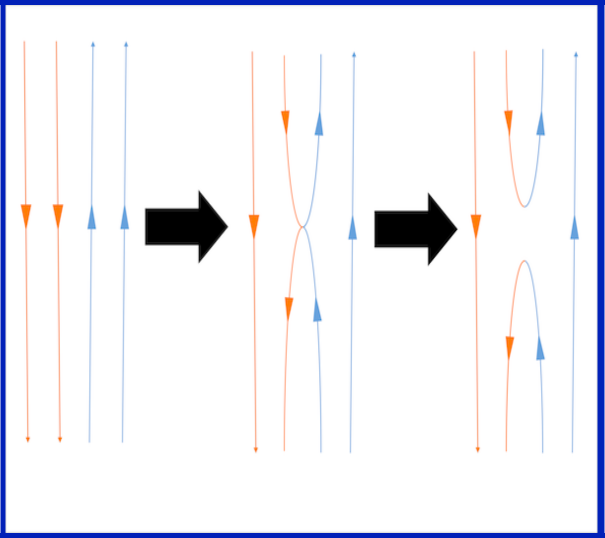
Effective drag on sinking blob due to vorticity limits its velocity

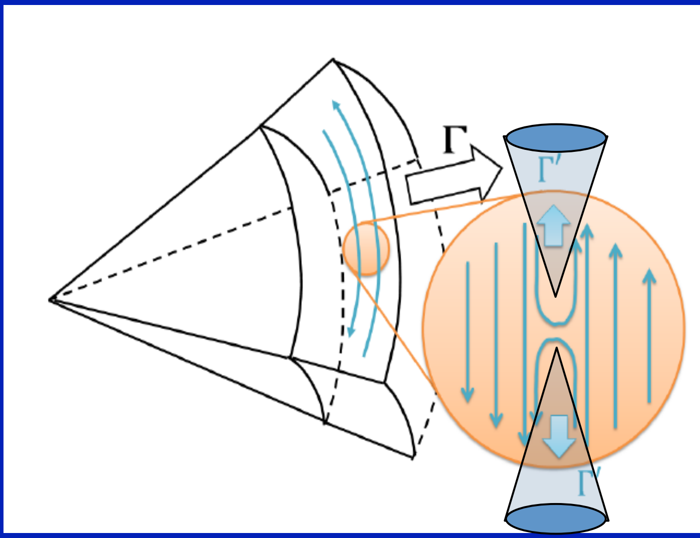


GRB Lightcurves from Magnetic Reconnection (Beniamini & JG 2016)

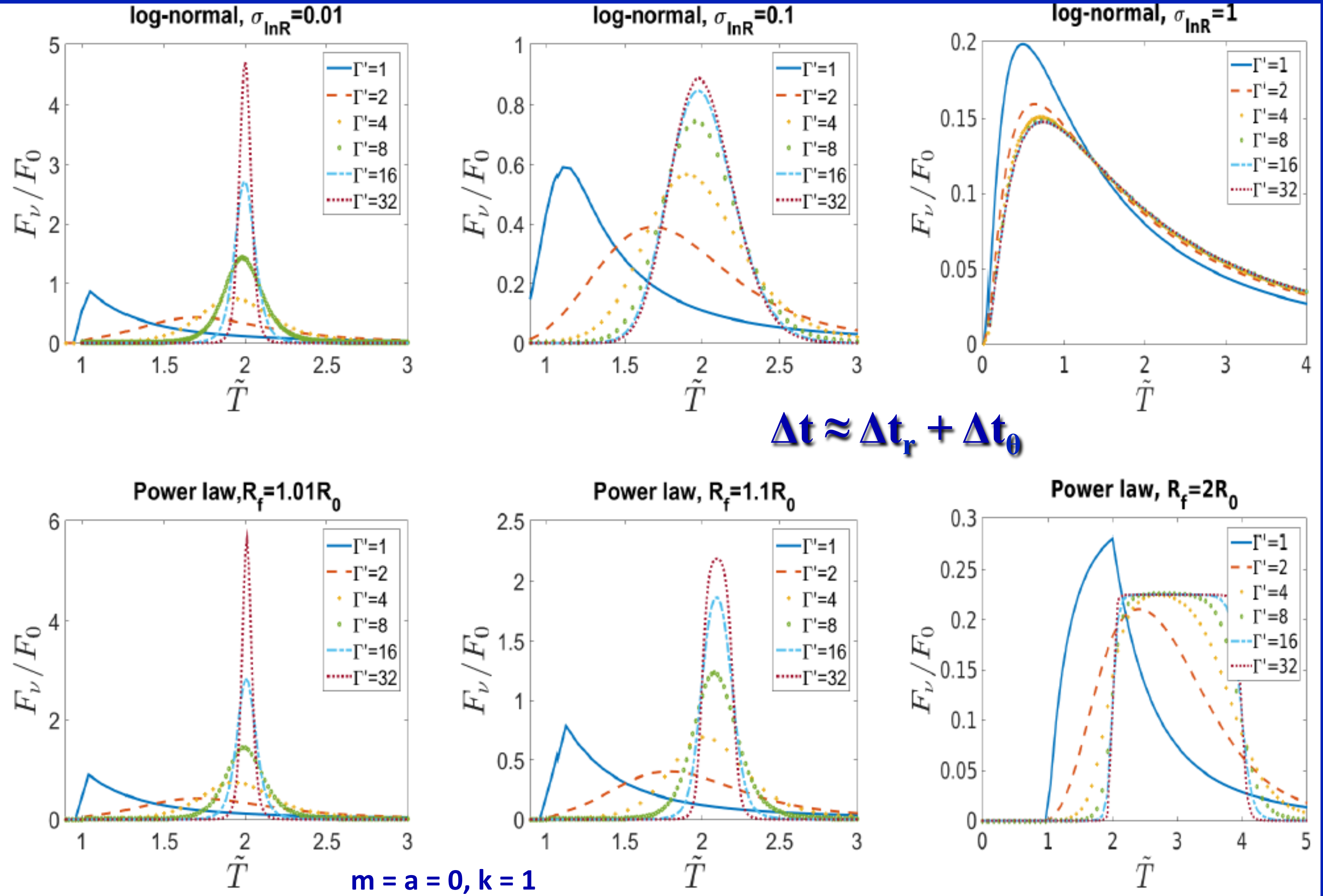
- Field reversals at the source can lead to reconnection at large distances
  millisecond-magnetar ➔ millisecond quasi-periodic variability (✖)
  accreting BH ➔ stochastic field-reversal & lightcurve variability (✔)
- Reconnection far from the source has a natural preferred direction
- For large ingoing 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







The Shape of Pulses in the Lightcurves

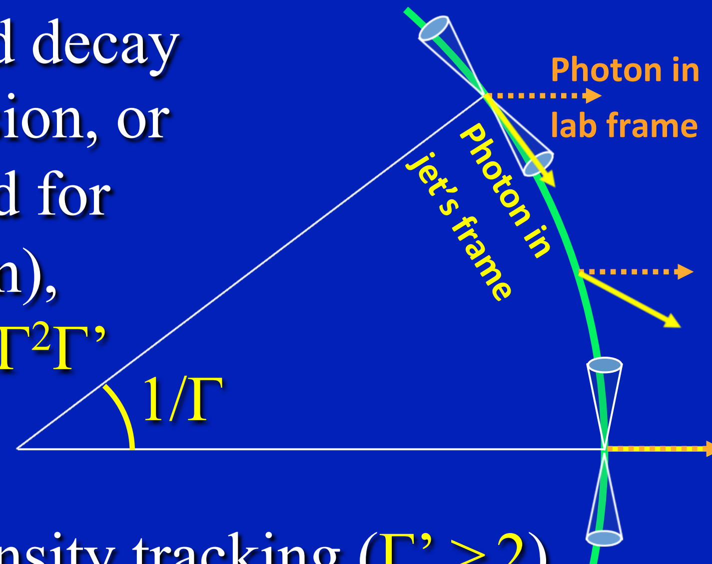


$$\Delta t \approx \Delta t_r + \Delta t_\theta$$

m = a = 0, k = 1

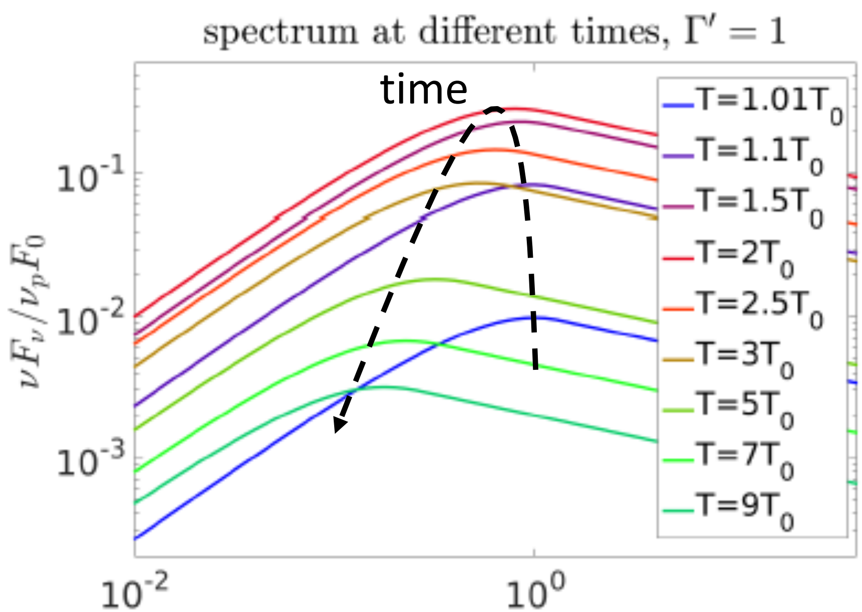
Some Other Pulse Properties

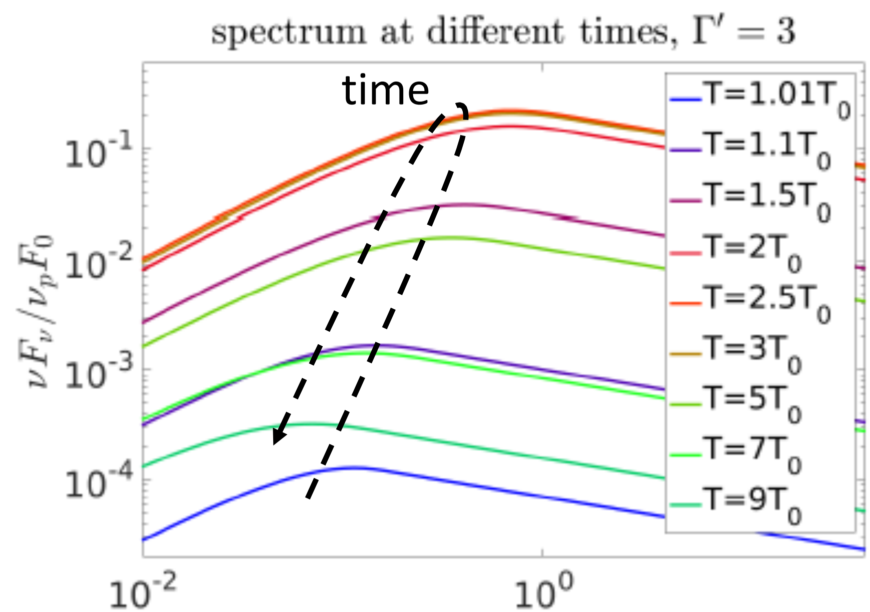
- Anisotropic emission can explain the "rapid decay phase" at the end of the GRB prompt emission, or X-ray pulses that decay faster than expected for isotropic emission ("high-latitude" emission), thanks to the shorter angular time $\Delta t_\theta \approx R/2\Gamma^2\Gamma'$



- Spectral evolution of pulses:

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

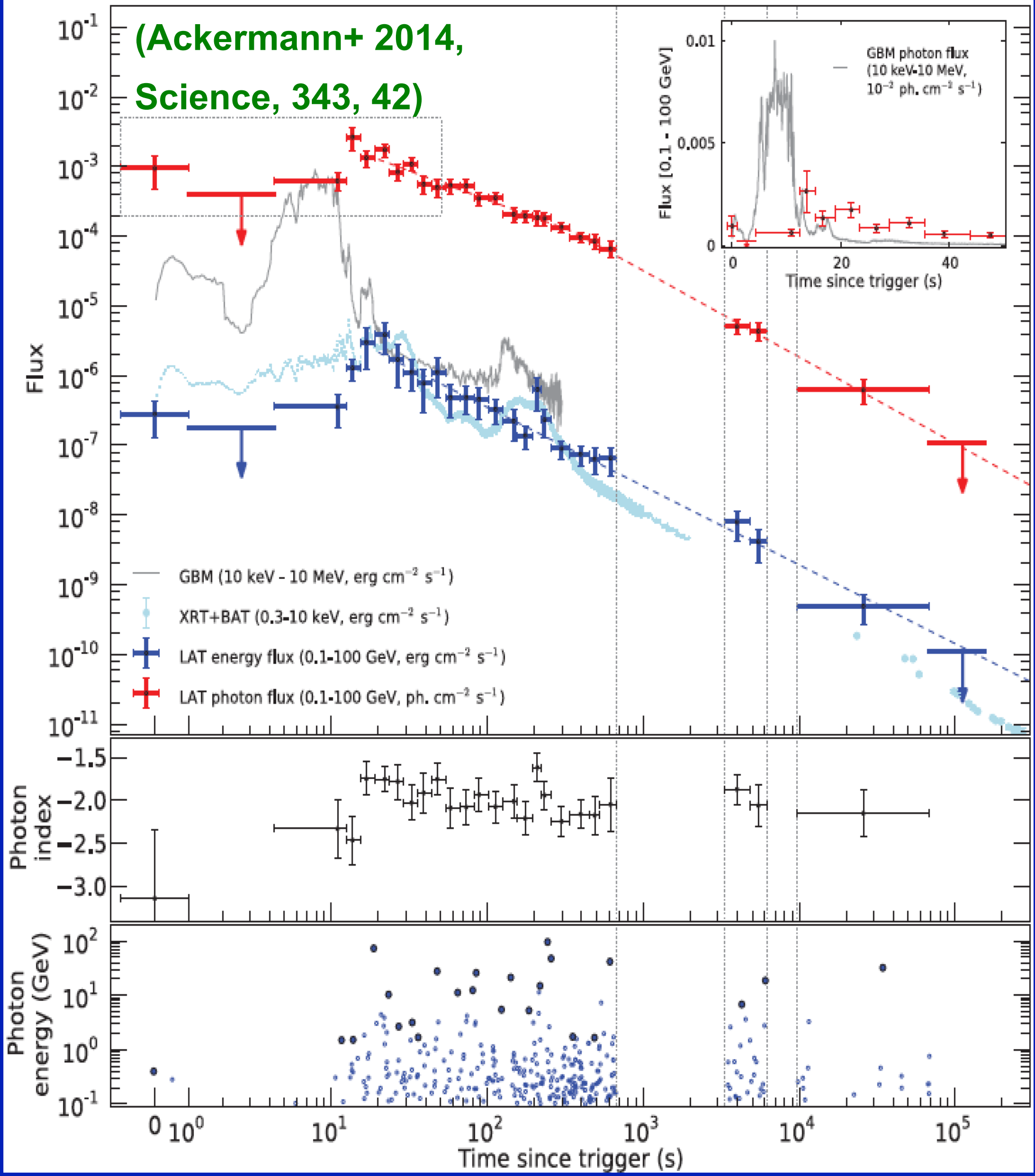




$m = a = 0$, $k = 1$, $\Delta R = R_0$, $\alpha = -1$, $\beta = -2.3$

High-Energy Afterglow: GRB130427A

- Fermi/LAT detection up to ~ 20 hr after the 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



High-Energy Afterglow: GRB130427A

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- >10 GeV γ's observed up to hours after GRB
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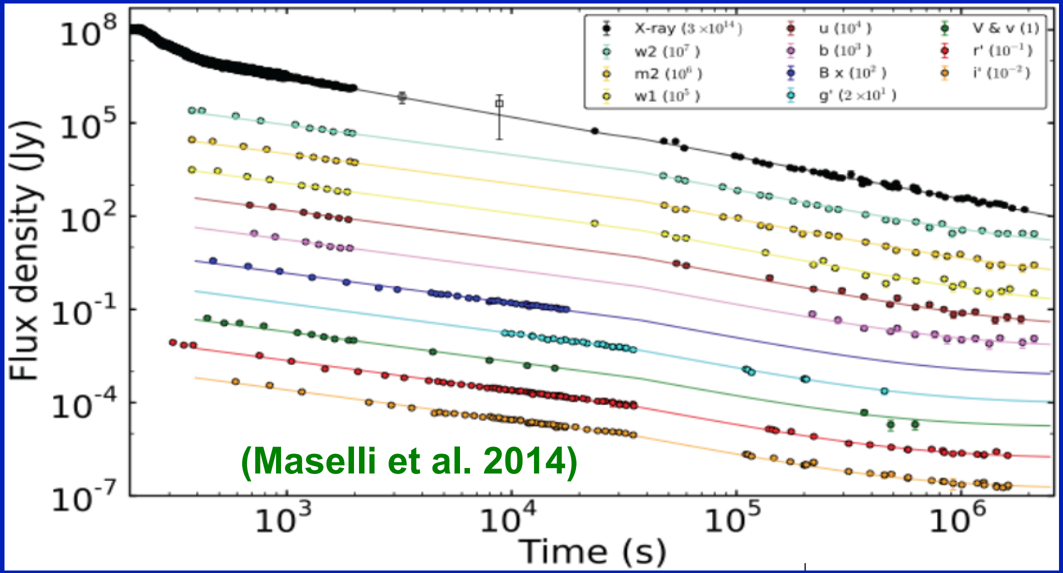
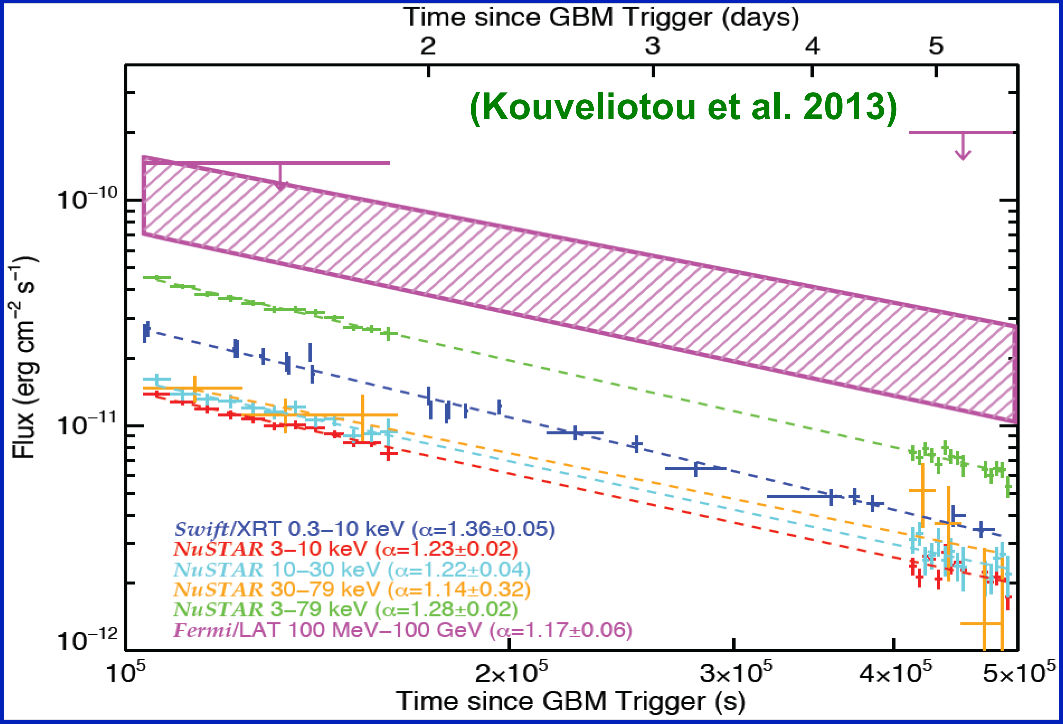
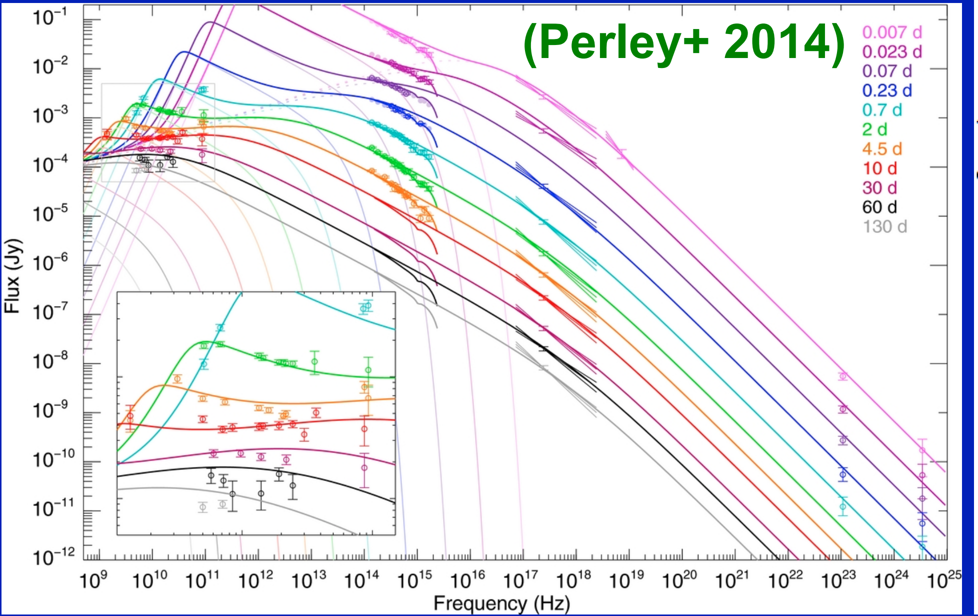
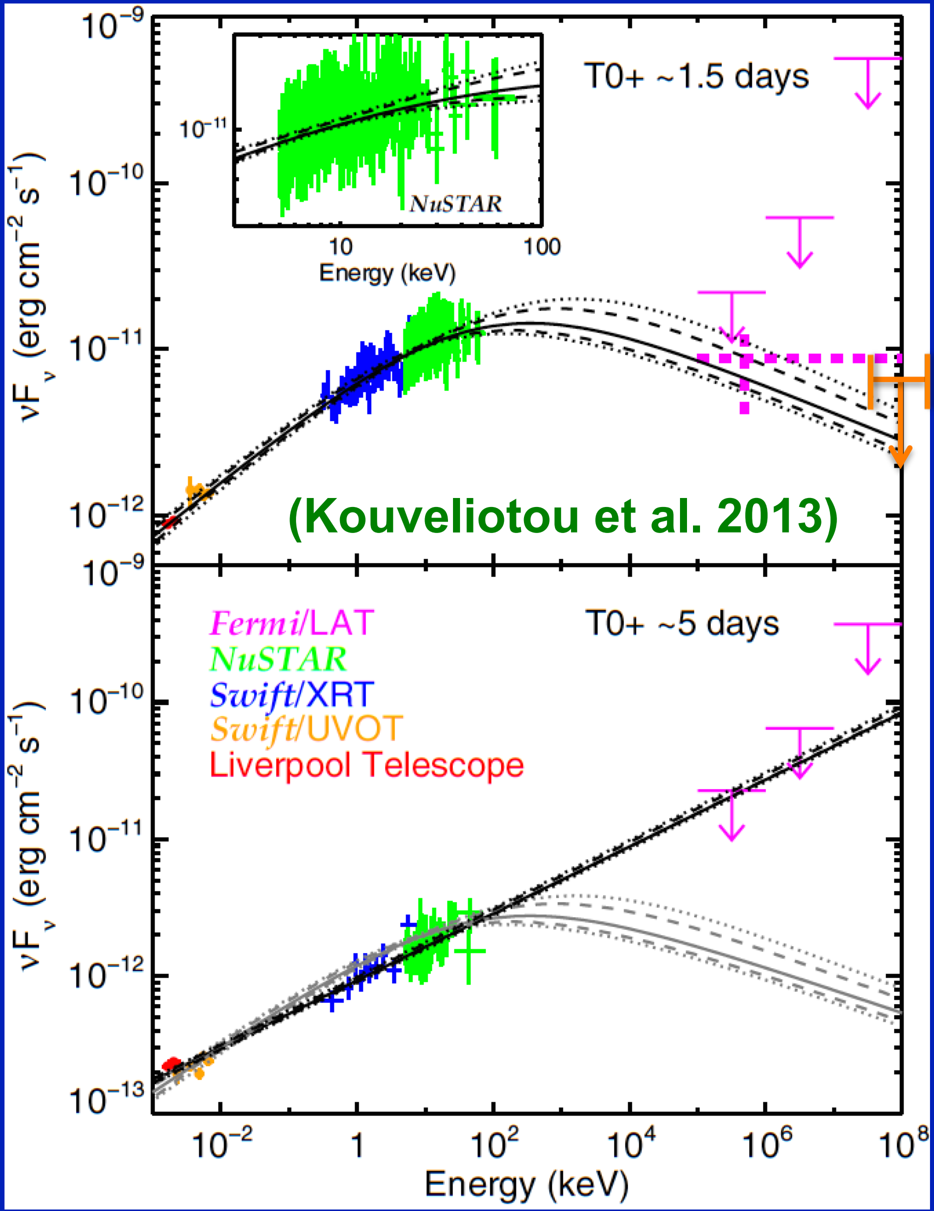




High-Energy Afterglow: GRB130427A

- **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 obs. (Aliu et al. 2014)



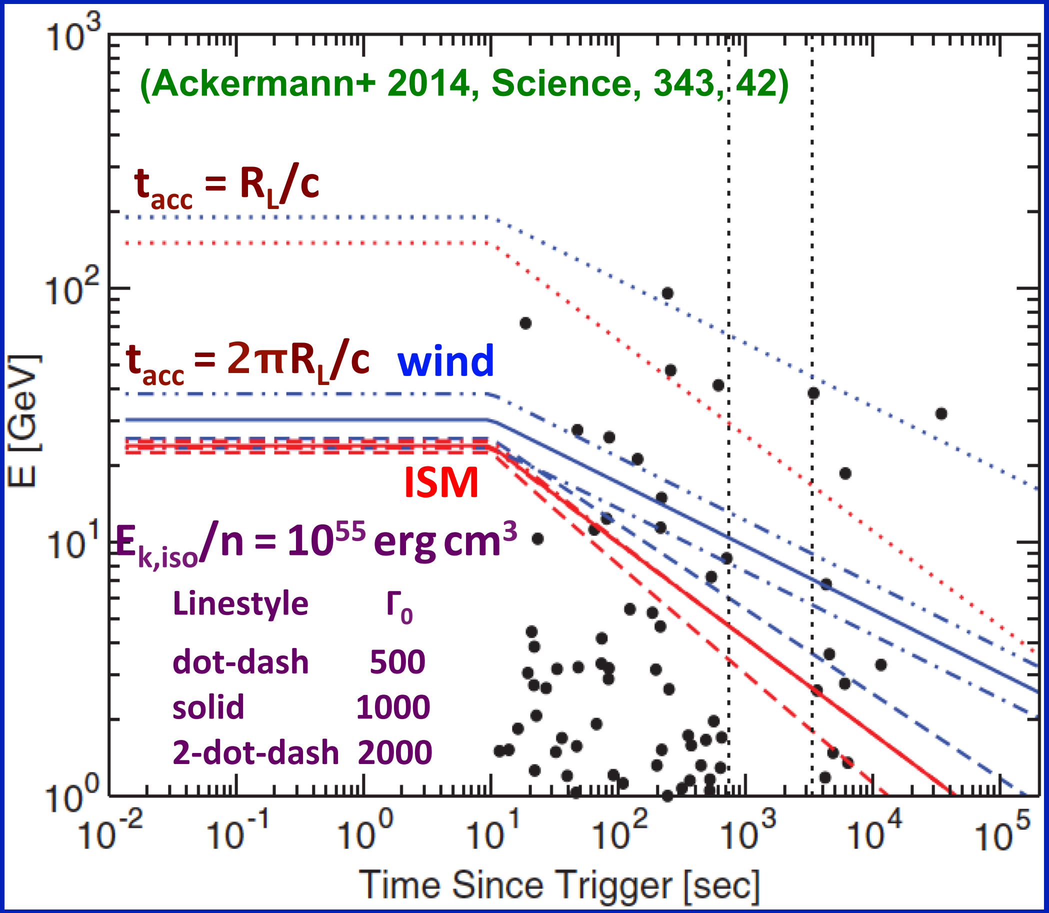


High-Energy Afterglow: GRB130427A

- **LAT HE photons violate:**

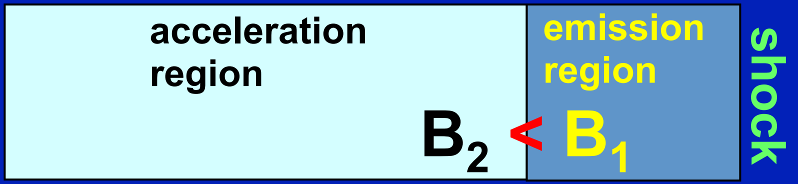
$$E_{\mathrm{syn,max}} \sim \frac{\Gamma}{(1+z)} \frac{m_e c^2}{\alpha} \approx 5 \left(\frac{\Gamma}{100} \right) \mathrm{GeV}$$

- Based on a one-zone model balancing electron energy gains and losses: $t_{acc} \sim t_{syn}$
- $t_{acc} \sim 1/\omega_L = R_L/c$ (extremely fast) or $P_L = 2\pi/\omega_L$ (still very fast but a bit more realistic)
- An "easy way out" would be if SSC emission dominated at highest LAT energies (Fan+ 2013; Liu+ 2013), but it doesn't work



- $\Rightarrow E_{\mathrm{syn,max}}$ appears to be truly violated $\Rightarrow \geq 1$ assumption must break
- Non-uniform B-field (Kumar+ 2012)?

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



Conclusions:

- B-fields play an important role almost anywhere in GRBs
- A GRB ms-magnetar central engine faces many challenges
- Magnetic jet acceleration may play an important role (steady to impulsive, sub-shells, interaction with CSM)
- K-S instability may play a role, but with slow reconnection
- Reconnection driven prompt GRB has testable predictions
- $E_{syn,max}$ seems to be genuinely violated in a GRB afterglow