Towards an understanding of Gamma Ray Burst prompt emission

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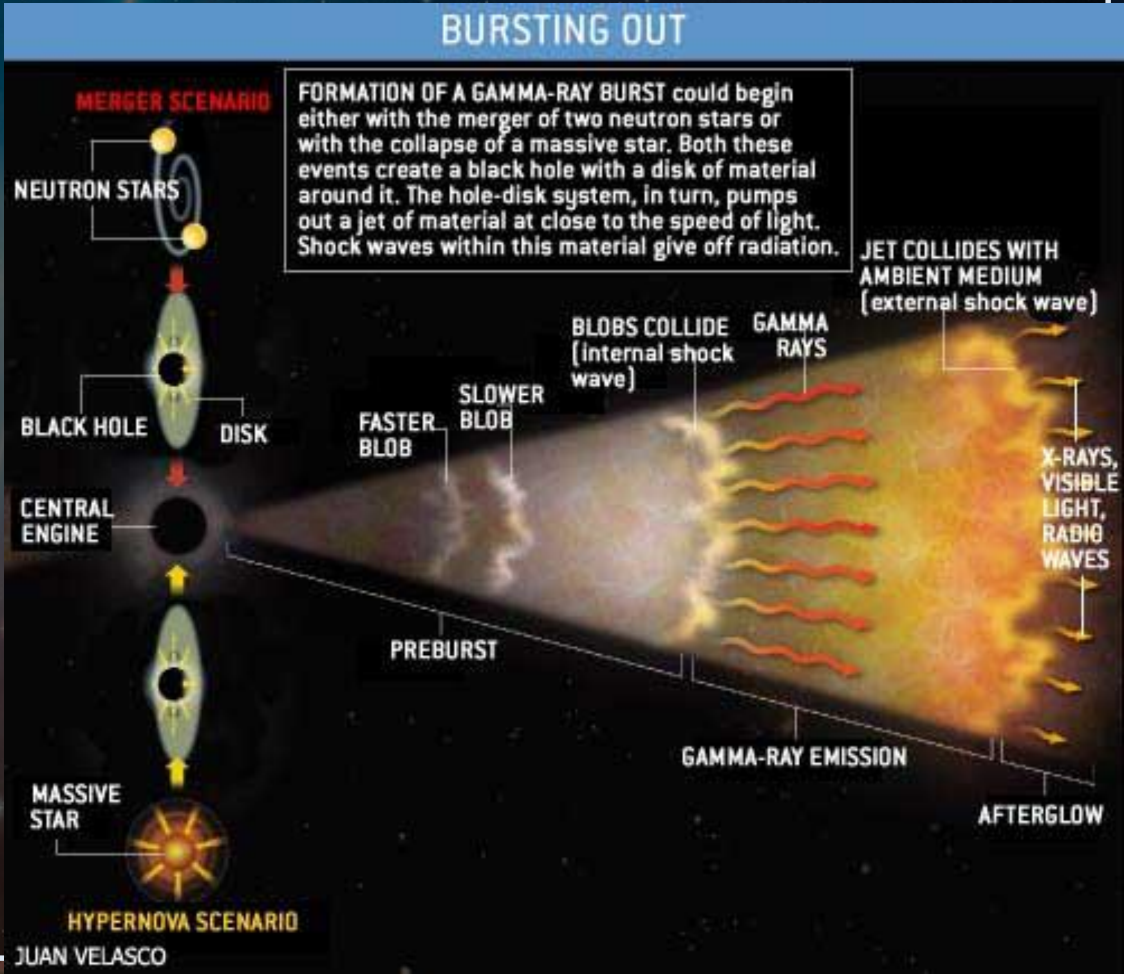
Gamma ray bursts (GRBs)

- most extreme explosions in nature (huge luminosities released during seconds)
- Formed by collapse of massive stars or NS-NS (NS-BH) merger
- "prompt" - extremely variable emission peaking at ~0.1MeV and typically lasting tens of seconds
- Followed by a longer and smoother "afterglow", gradually decreasing in frequency with time and observed up to years after the burst



Introduction

- (Late time) afterglow well modelled by synchrotron from a forward external shock
- What are we sure of regarding the prompt?

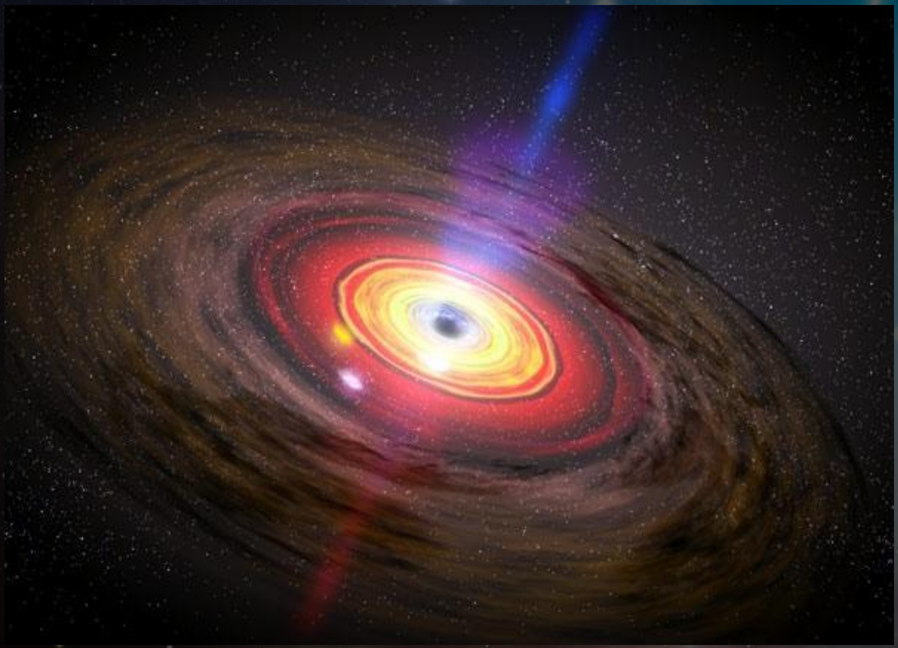
1. Spectra non-thermal
2. Produced by rapidly moving matter with $\Gamma \geq 100$
3. Huge amount of energy (of order $10^{51} - 10^{53}$ ergs) involved
4. Energy emitted at large distances $10^{13} - 10^{17}$ cm from the source

Introduction

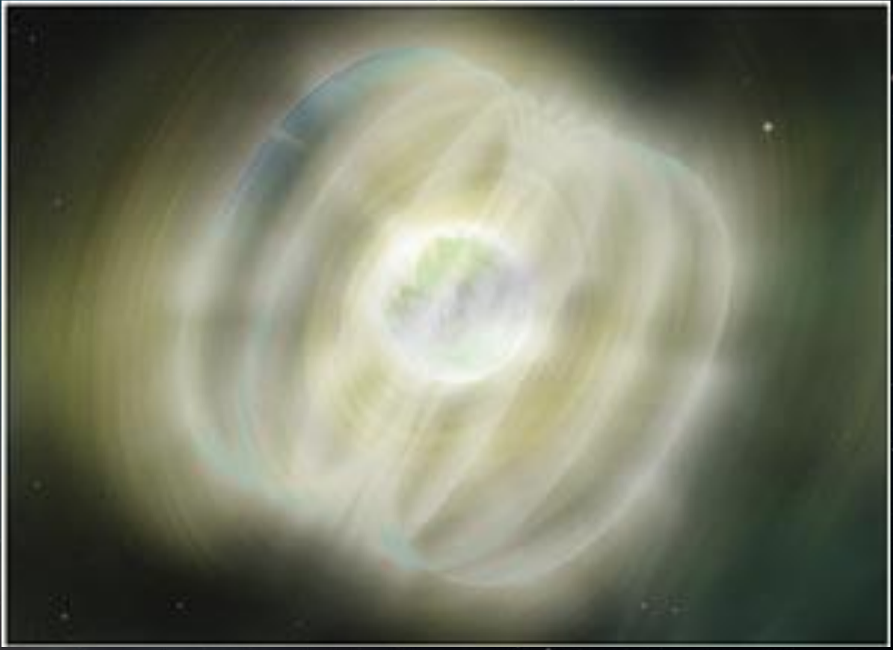
- Main open questions:

1. What is the progenitor?

Black hole



Rapidly rotating magnetar

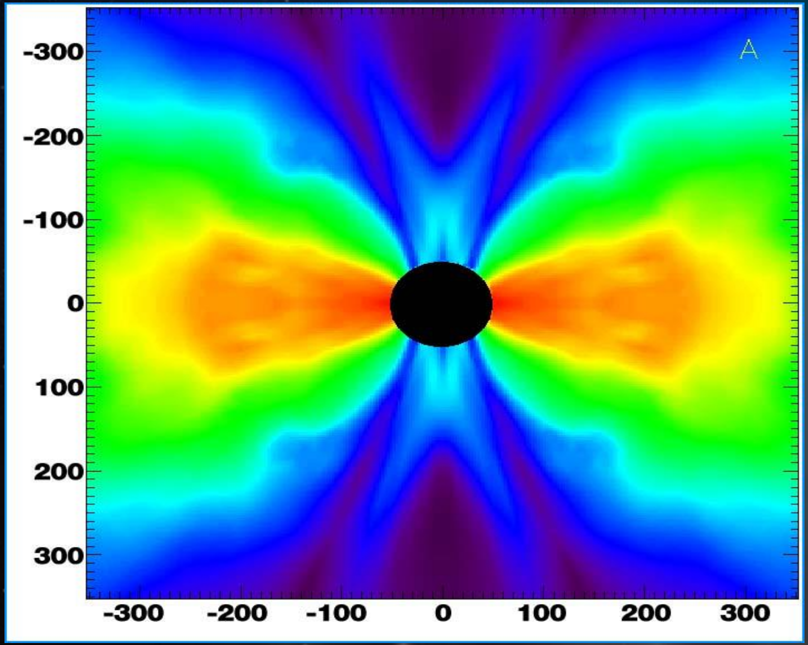


Introduction

- Main open questions:

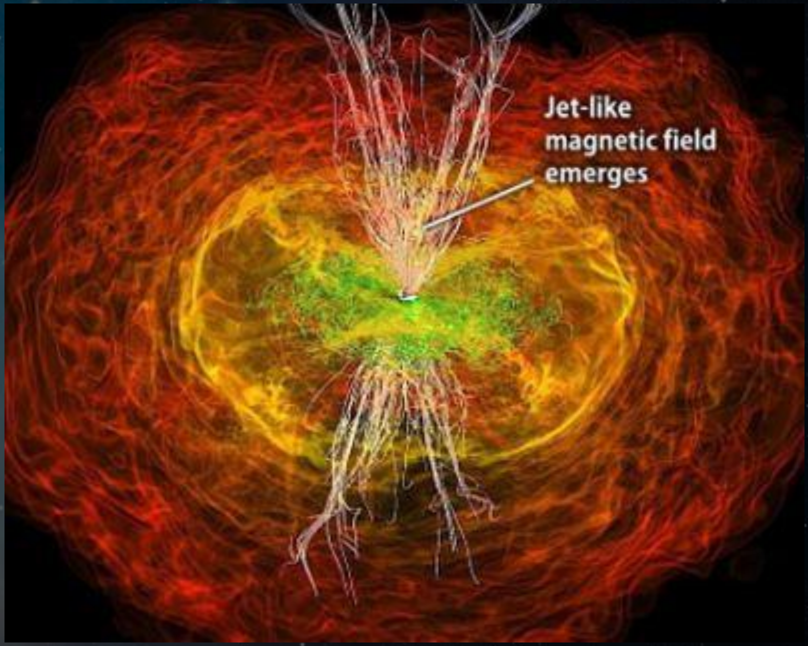
1. What is the composition of the jet?

Baryonic



Simulation: Woosley

Poynting flux (magnetic fields)



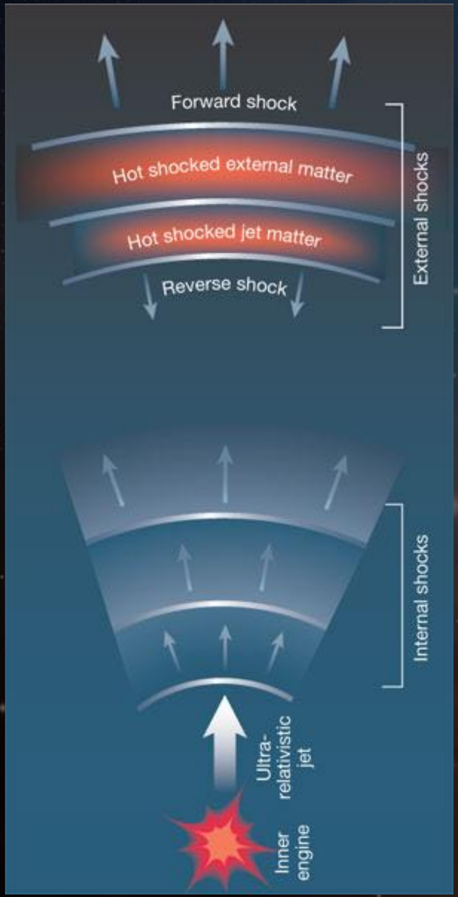
Simulation: Koppitz & Rezzolla

Introduction

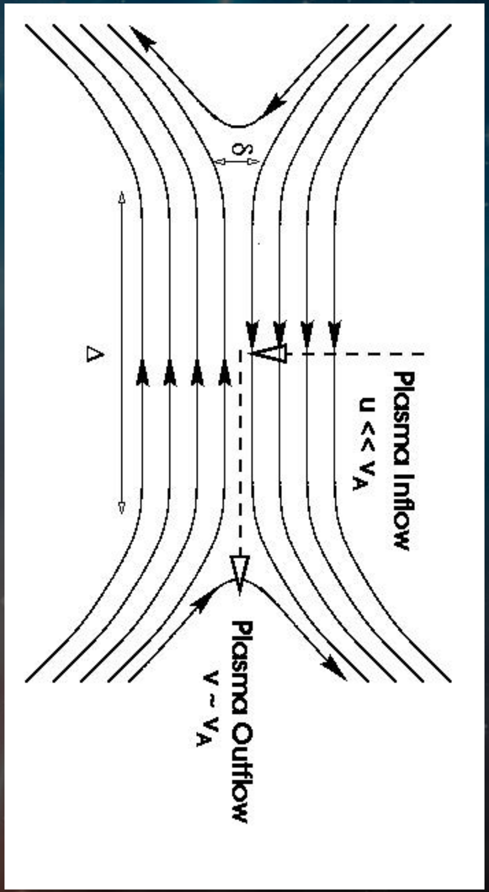
- Main open questions:

1. What is the dissipation mechanism?

Internal shocks



Reconnection



Other?

Neutron – Proton collisions

Nuclear collisions

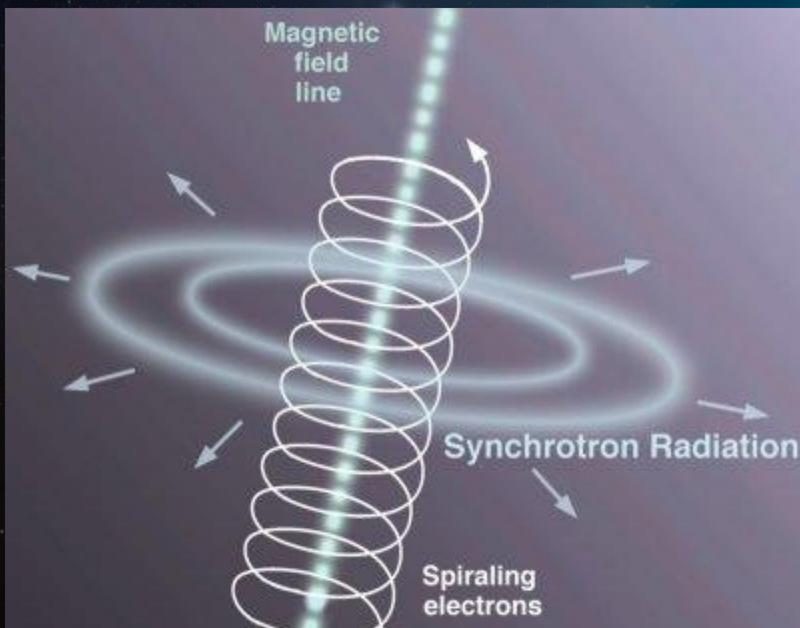
Etc.

Introduction

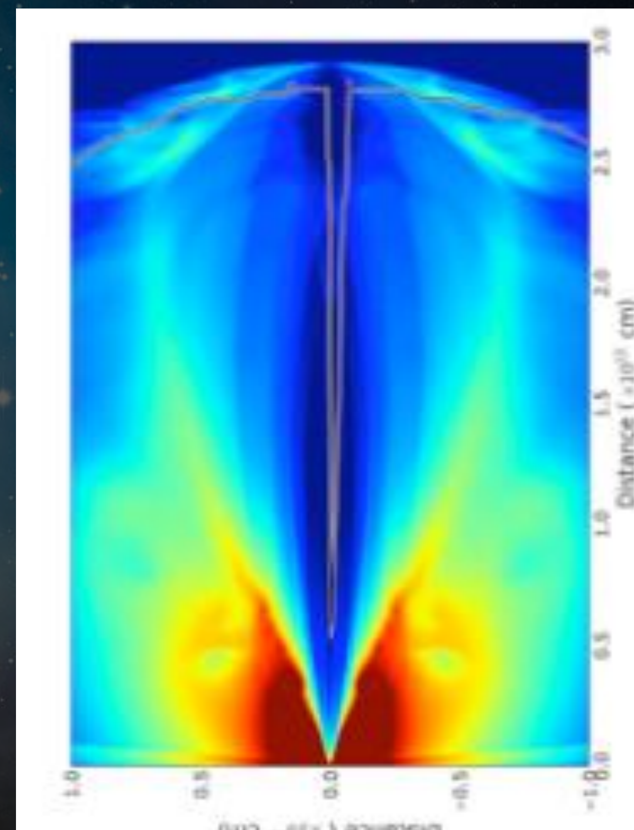
- Main open questions:

1. What is the radiation process?

Synchrotron



Photospheric



Simulation: Lazzati

The emission mechanism in magnetically dominated GRBs

2014, MNRAS, 445, 3892B

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Why magnetic jets?

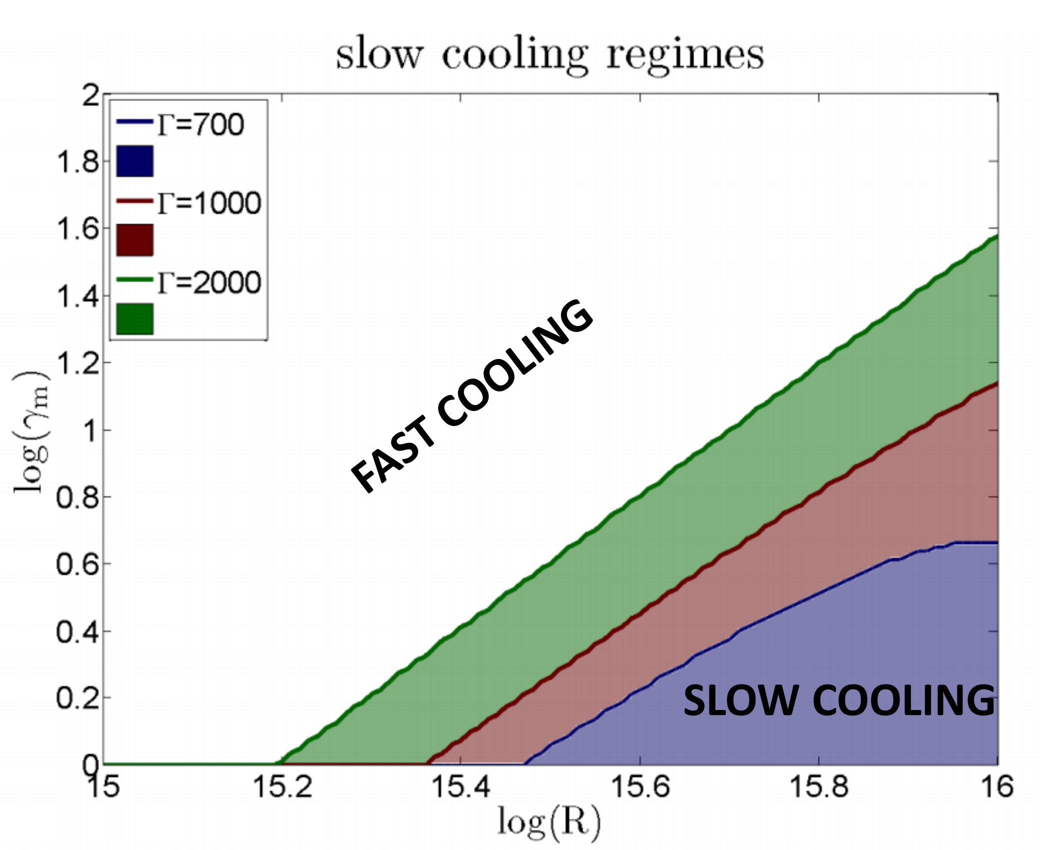
- AGNs produce relativistic jets but thermal pressure insufficient to support Baryonic outflows (however, strong IC component observed in AGNs suggests that a large fraction of magnetic energy dissipates before emission zone and transferred to a Baryonic component)
- Modeling of GRBs accretion disks suggest Poynting flux jet power much stronger than thermal driven outflow derived from neutrino annihilation (Kawanaka Piran & Krolik 13)
- No strong IC component in GRBs suggests jets are magnetically dominated near the emission zone

Synchrotron cooling in magnetic jets

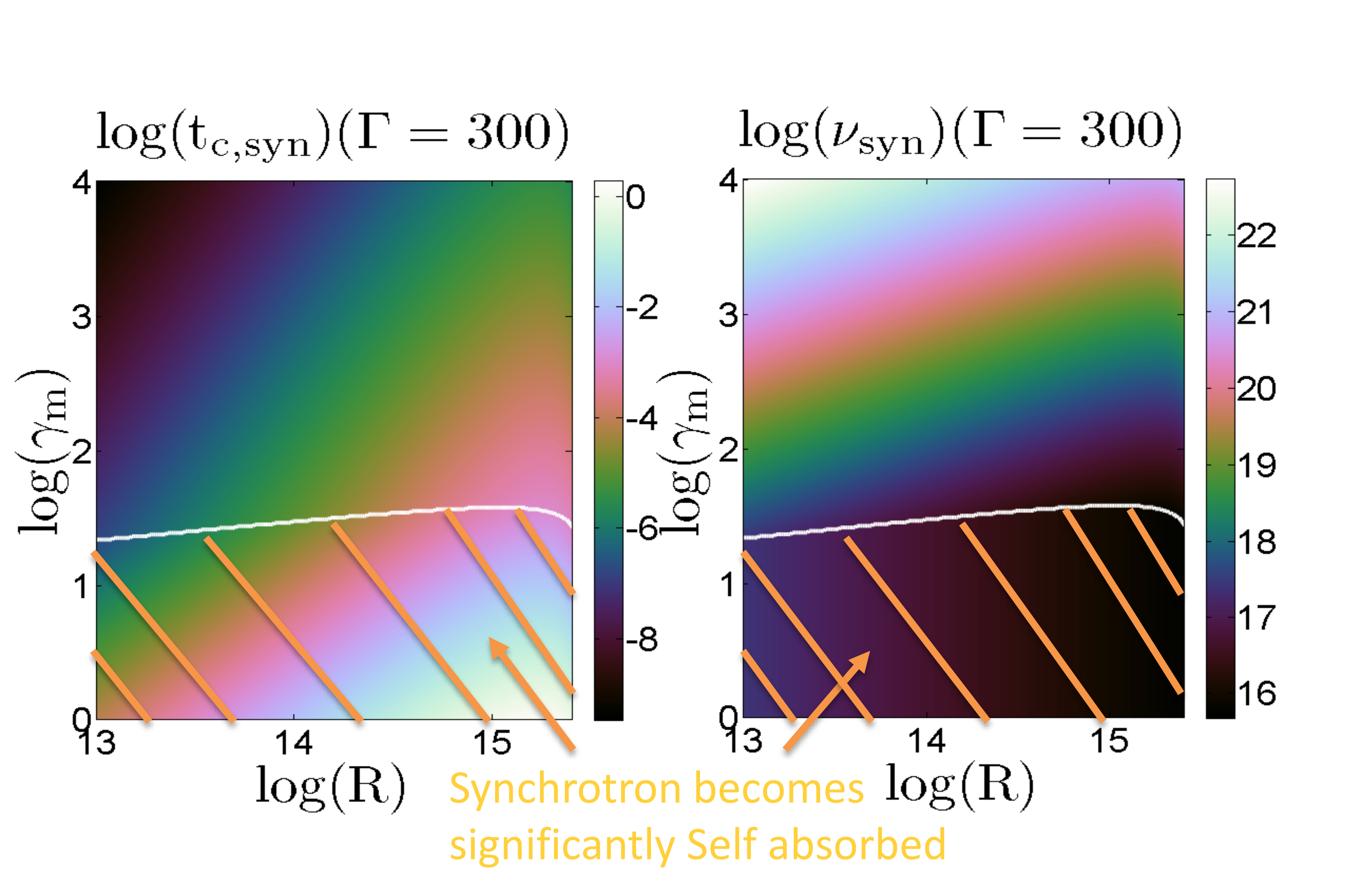
Efficient synchrotron emission regardless of the emission mechanism responsible for the prompt gamma rays

Fast cooling – Most of the electrons lose their energy by synchrotron in less than a dynamical time

For a magnetically dominated emission region and $\Gamma \leq 600$ synchrotron is fast cooling, independent of emission radius and electrons' Lorentz factors



Synchrotron cooling in magnetic jets

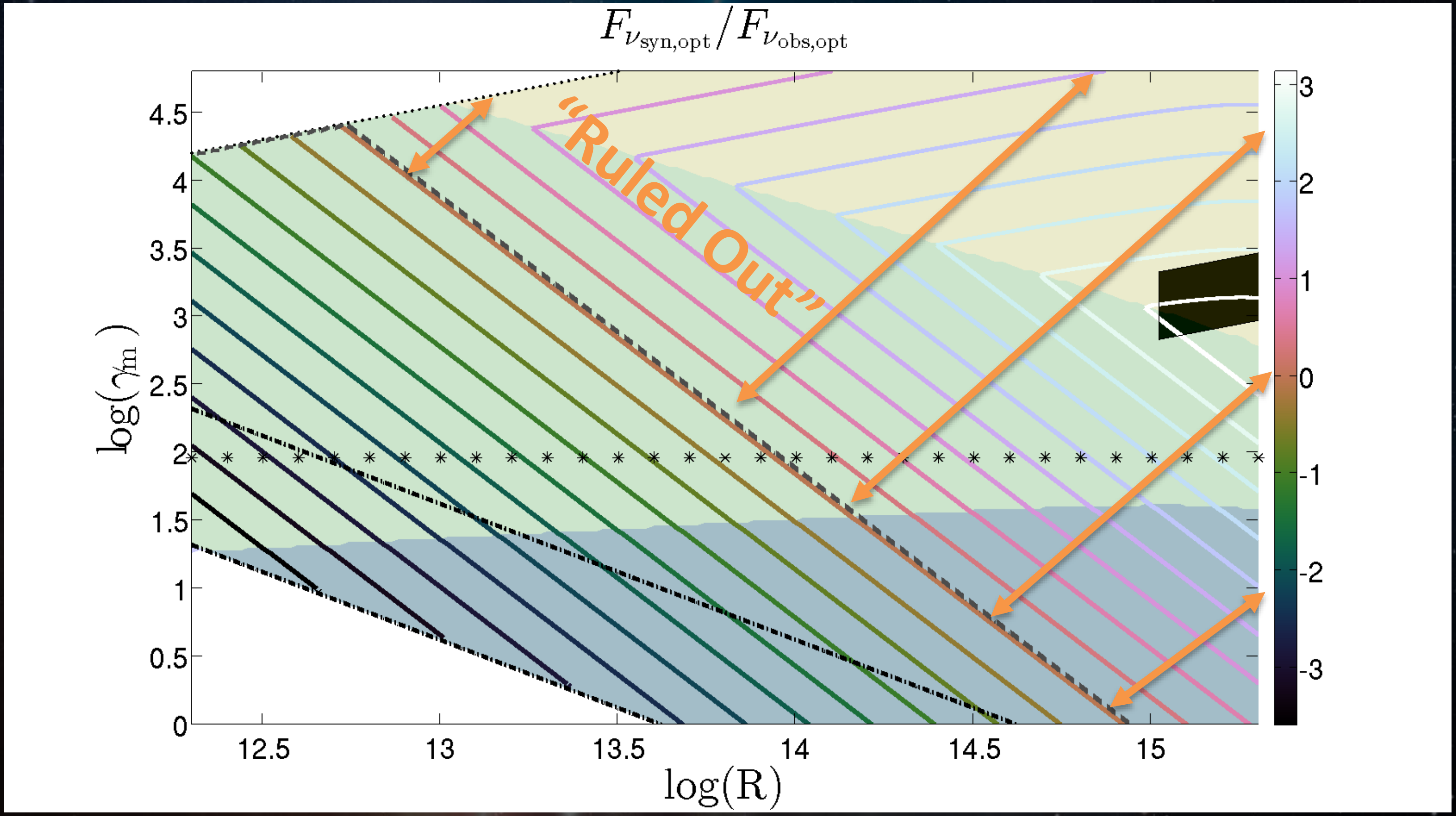


Cooling time by synchrotron very short

typical frequencies between EUV and high energy gamma rays

General cooling in magnetic jets

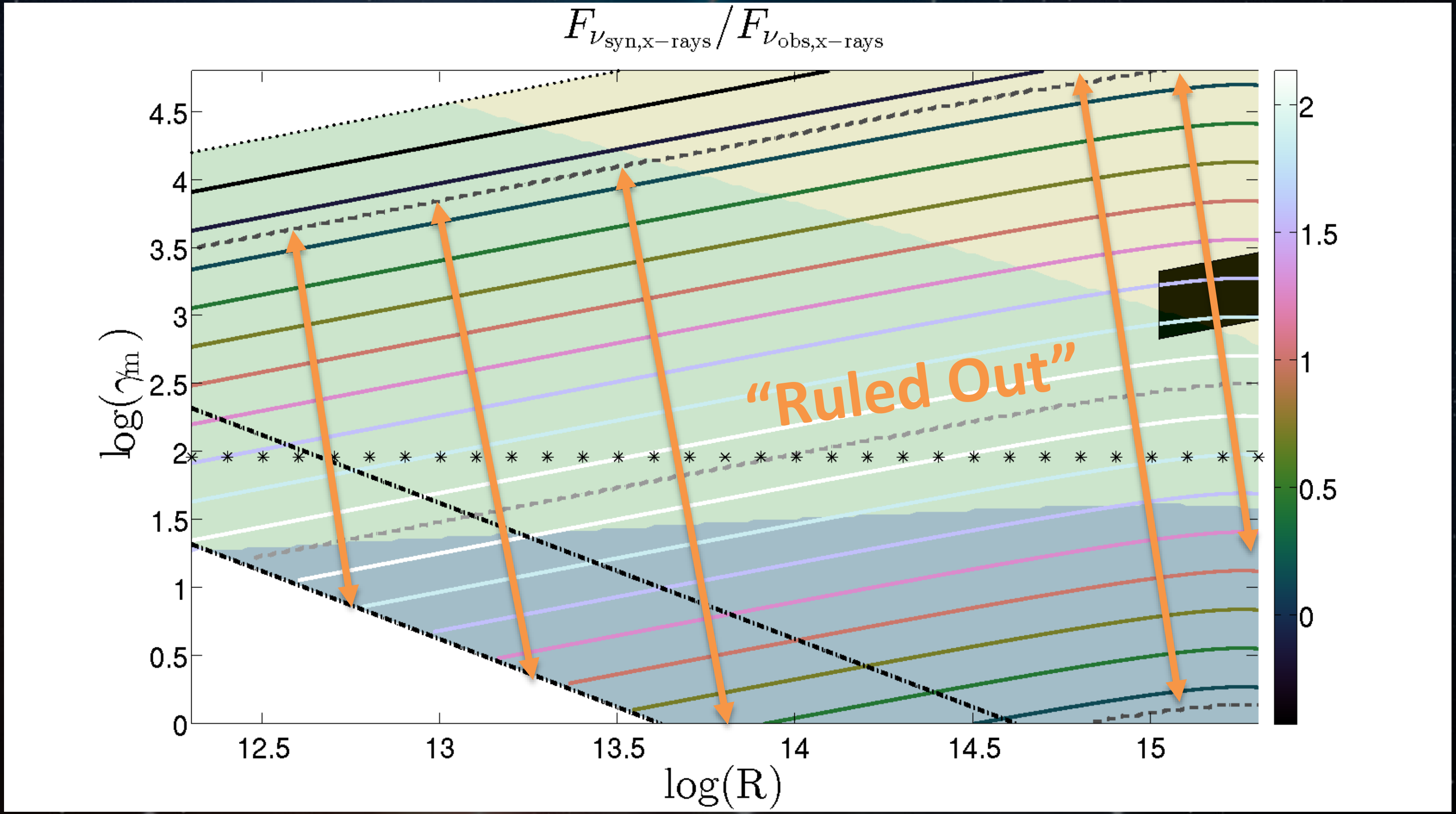
$$\frac{t_c}{t_{c,syn}} < \frac{F_{\nu,syn,opt}}{F_{\nu,obs,opt}}$$



Ratio of optical synchrotron flux to observed optical flux

General cooling in magnetic jets

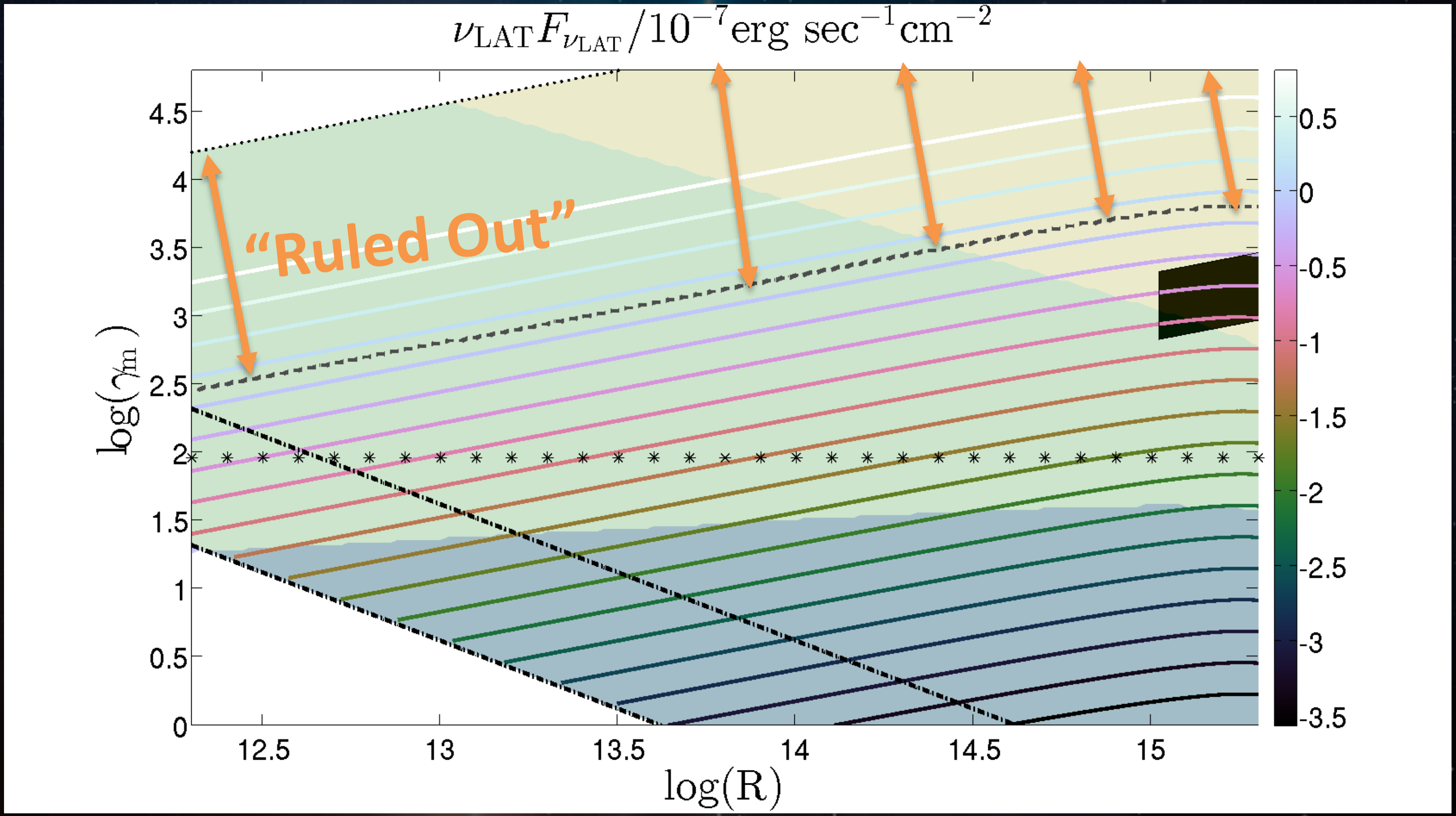
$$\frac{t_c}{t_{c,syn}} < \frac{F_{\nu,syn,X}}{F_{\nu,obs,X}}$$



Ratio of X-ray synchrotron flux to observed X-ray flux

General cooling in magnetic jets

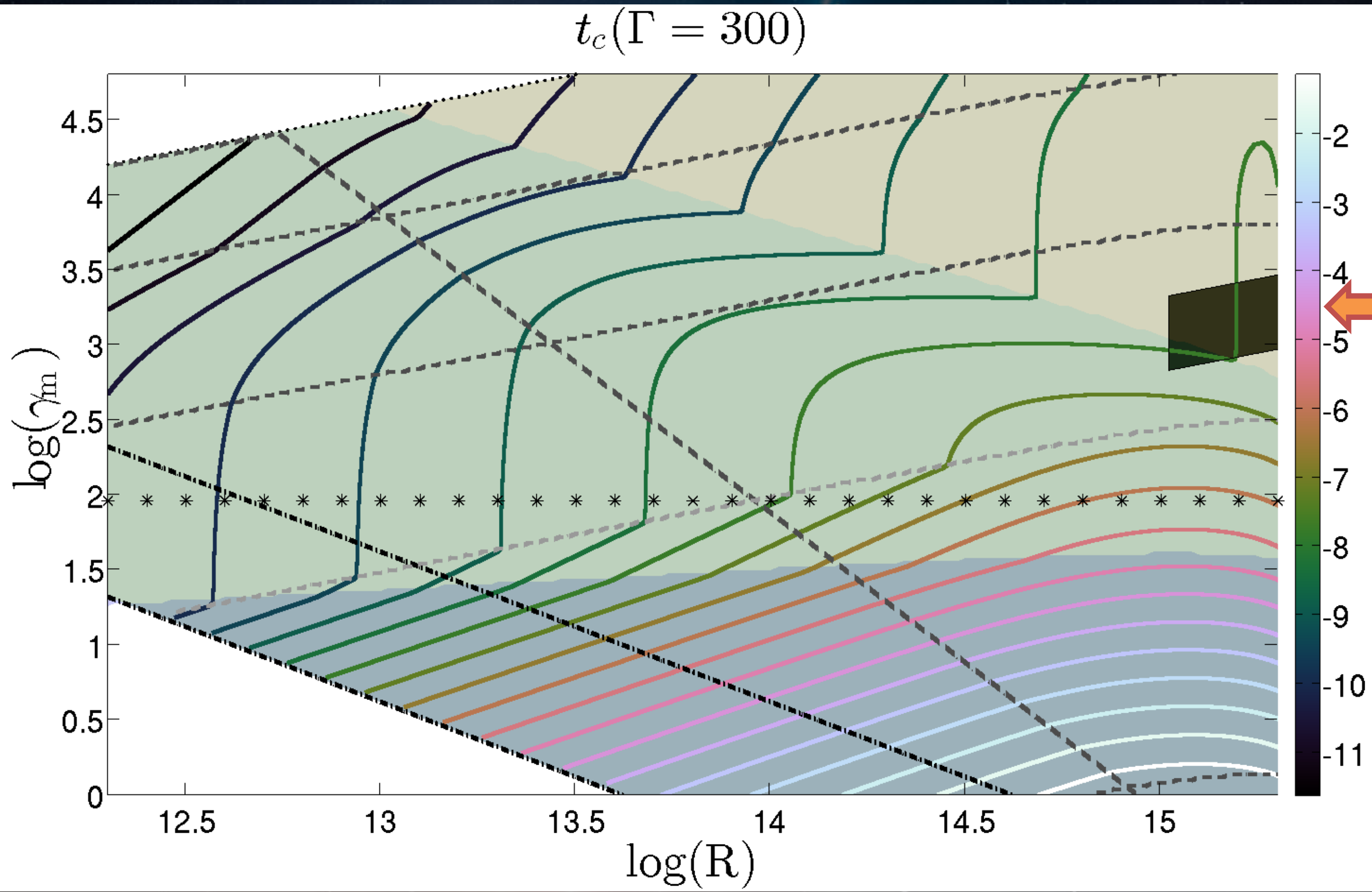
$$\frac{t_c}{t_{c,syn}} < \frac{F_{\nu,syn,GeV}}{F_{\nu,obs,GeV}}$$



Ratio of GeV synchrotron flux to observed GeV flux

General cooling in magnetic jets

Putting everything together:



gamma ray emission produced by synchrotron (Beniamini & Piran 2013)

Limits prompt mechanism cooling time-scale

Alternatives?

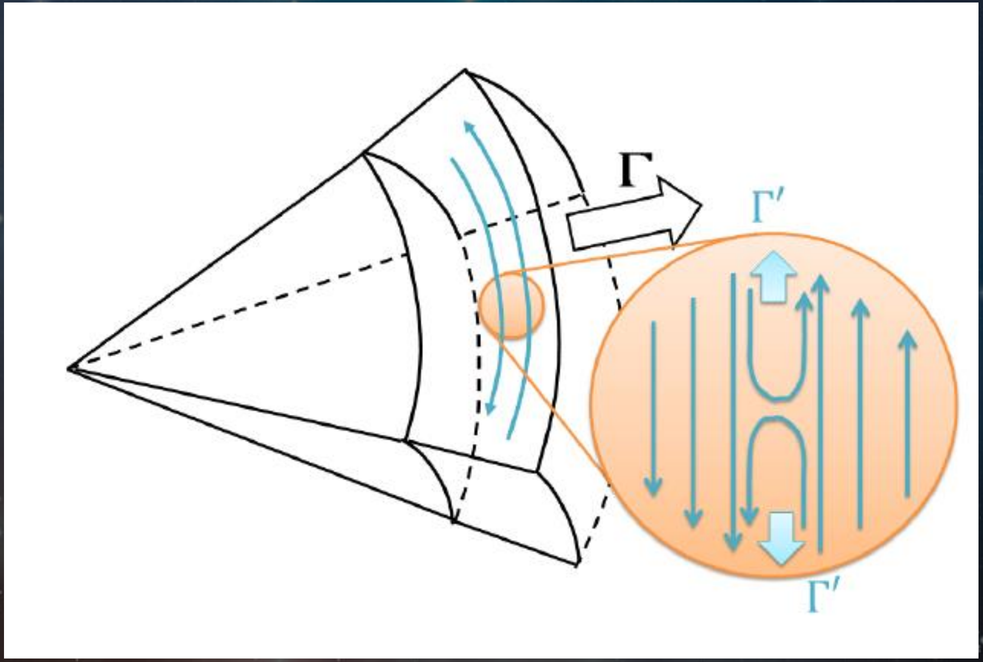
For synchrotron to produce the prompt we need at least ν_c>40keV

- Electrons re-accelerated before cooling down, stopping them from overproducing low frequency radiation
- Magnetic field could be highly inhomogeneous -> electrons emit for a short time in large B areas before escaping to background where they do not cool efficiently
- Electrons may remain confined in weak B sub-regions where they are accelerated, and then radiate less efficiently

Continuous acceleration possible, other scenarios ran into extreme theoretical difficulties

Properties of GRB light-curves from magnetic reconnection

arXiv:1509.02192



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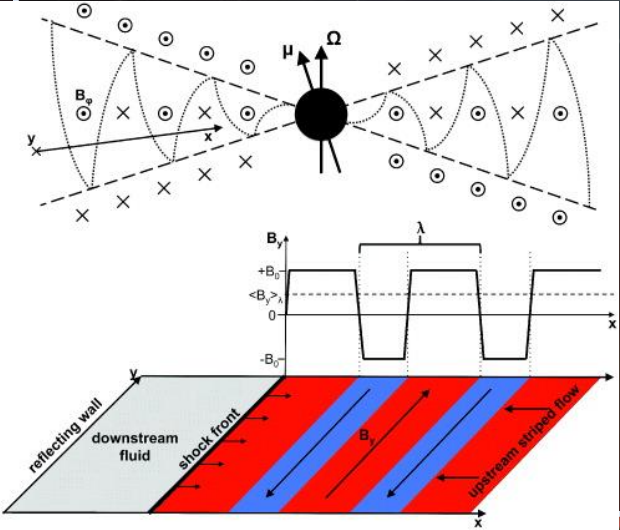
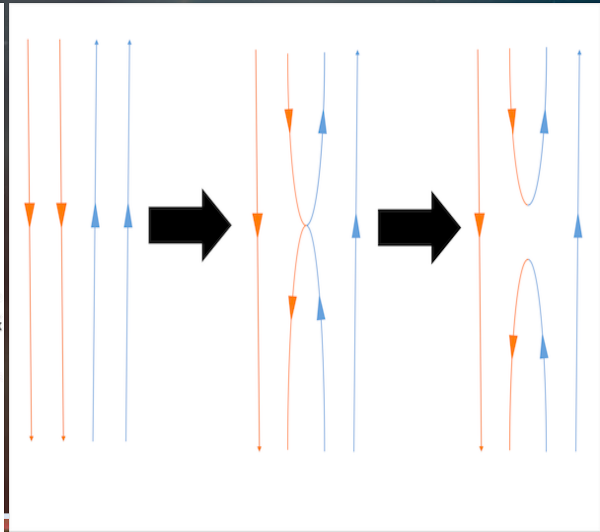
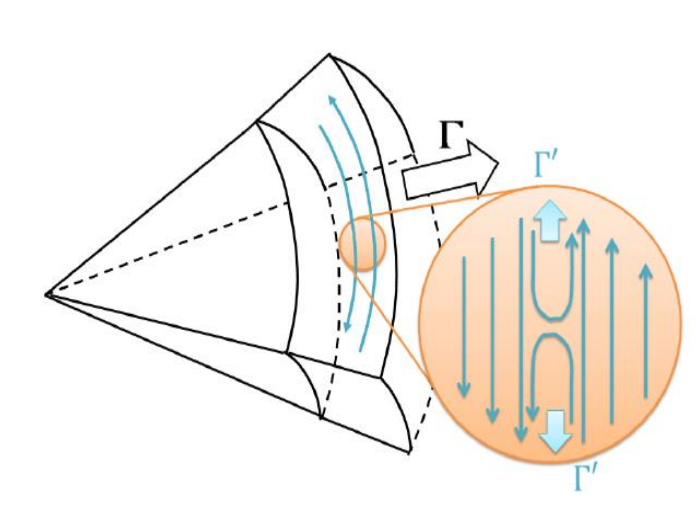
Magnetic Reconnection

- Highly magnetized jets may lead to reconnection
- In a striped wind field configuration, reconnection at large distances from the source has a naturally preferred direction
- For large σ just before the dissipation region, reconnection leads to local relativistic bulk motion away from the reconnection sites

We explore the effects of an-isotropic emission in jet's frame







The Model

- Each pulse due to emission from one "shell"
- Shell moves at a Lorentz factor Γ and emits from R_0 to $R_0+\Delta R$
- Emitters move in 2 opposite directions, parallel to shell front with Lorentz factors Γ' compared to bulk
- Emission from emitters is either continuous or blob-like
- Intrinsic spectrum power law or broken power law
- Luminosity and Γ may evolve as power laws of R

$$F_\nu(T) = \frac{2\Gamma_0 \Gamma' L''_{\nu''_0}}{4\pi D^2}\left(\frac{T}{T_0}\right)^{-\frac{m}{2(m+1)}} \int_{y_{\min}}^{y_{\max}} dy \left(\frac{m+1}{m+y^{-m-1}}\right)^2 y^{-1-\frac{m}{2}}\, f\left[y\left(\frac{T}{T_0}\right)^{\frac{1}{m+1}}\right] \times \frac{1}{2\pi\Gamma'^4}\int_0^{2\pi} d\phi\,(1-\beta'\sin\theta'\cos\phi)^{k-3}\, S[x(\phi,y)]$$

$$T_0 = \frac{(1+z)R_0}{2(m+1)c\Gamma_0^2}$$

Motivation for anisotropic Reconnection

1- Avoiding over-production of optical and X-rays and changing low energy spectral slope **(Beniamini & Piran 2014)**

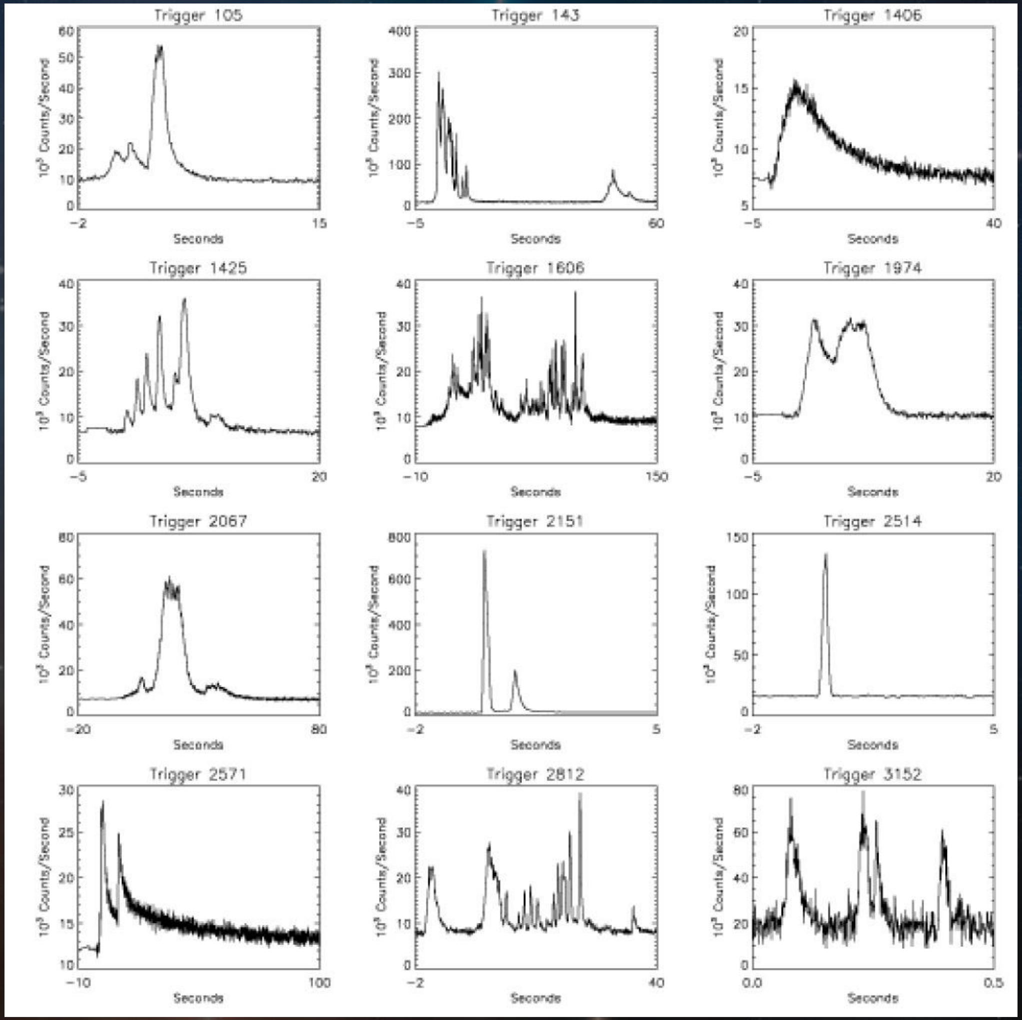
- Continuous heating more likely in reconnection than in shock heating - could allow for marginally slow cooling

- Radius larger by a factor Γ’ leading to weaker average magnetic fields. In addition, particles emit where the field is weaker than average -> slow cooling electrons for $\gamma \leq 10(\Gamma/100)^{5}$

Motivation for anisotropic Reconnection

2 – Reconciling the observed variability

- Examples of observed GRB light-curves:



Motivation for anisotropic Reconnection

characteristic times for radiation from a relativistic shell

- Consider a shell expanding relativistically while emitting
- What is the duration of the signal received by a distant observer?

1. If shell emits during $\Delta t' = \frac{\Delta t}{\Gamma}$ then last photon will be emitted at a distance $\Delta R' = c\Delta t'$ closer to observer. Difference in their observation times: $\Delta t_{r,obs} = \frac{\Delta R}{v} - \frac{\Delta R}{c} \approx \frac{\Delta R}{2c\Gamma^2}$
2. Photons emitted at large angles take longer to reach observer. Due to beaming the effective largest angle that can be observed is $\theta = \frac{1}{\Gamma}$. Difference in observation times between forward and θ directed photons is: $\Delta t_{\theta,obs} = \frac{R}{c}(1 - cos\ \theta) \approx \frac{R}{2c\Gamma^2}$

$$\Delta t_{pulse,obs} = \Delta t_{\theta,obs} + \Delta t_{r,obs}$$

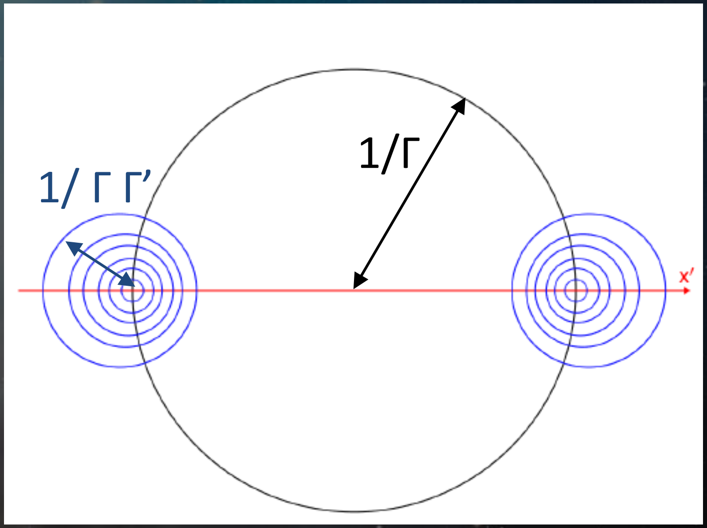
- For isotropic models:

$\Delta T_{pulse} \geq \Delta T_{\theta} \sim \frac{R}{2c\Gamma^2} \geq \frac{c\Delta t}{2c\Gamma^2} \sim \frac{L\prime}{\Gamma v_{in}'} > \frac{L}{c} \sim \Delta T_{ej}$ where L is the typical size of the region feeding the reconnection layer and $v_{in}{}' \sim 0.1c$ is the speed of matter flowing into the reconnection layer (Lyubarski 05)

Isotropic reconnection models predict pulses much broader than the time between them

- For anisotropic models ΔT_{θ} is reduced by Γ’. This enables variability on a shorter time-scale of the order of ΔT_{ej} as observed (see also Lazar et al. 2009)

Anisotropic reconnection naturally produces the observed variability



$$\mathbf{\Delta t_{\theta,obs} = \frac{R}{c}(\cos\theta_{-} - \cos\theta_{+}) \approx \frac{R}{2c\Gamma^2\Gamma\prime}}$$

The shape of the light-curves

Pulse asymmetry

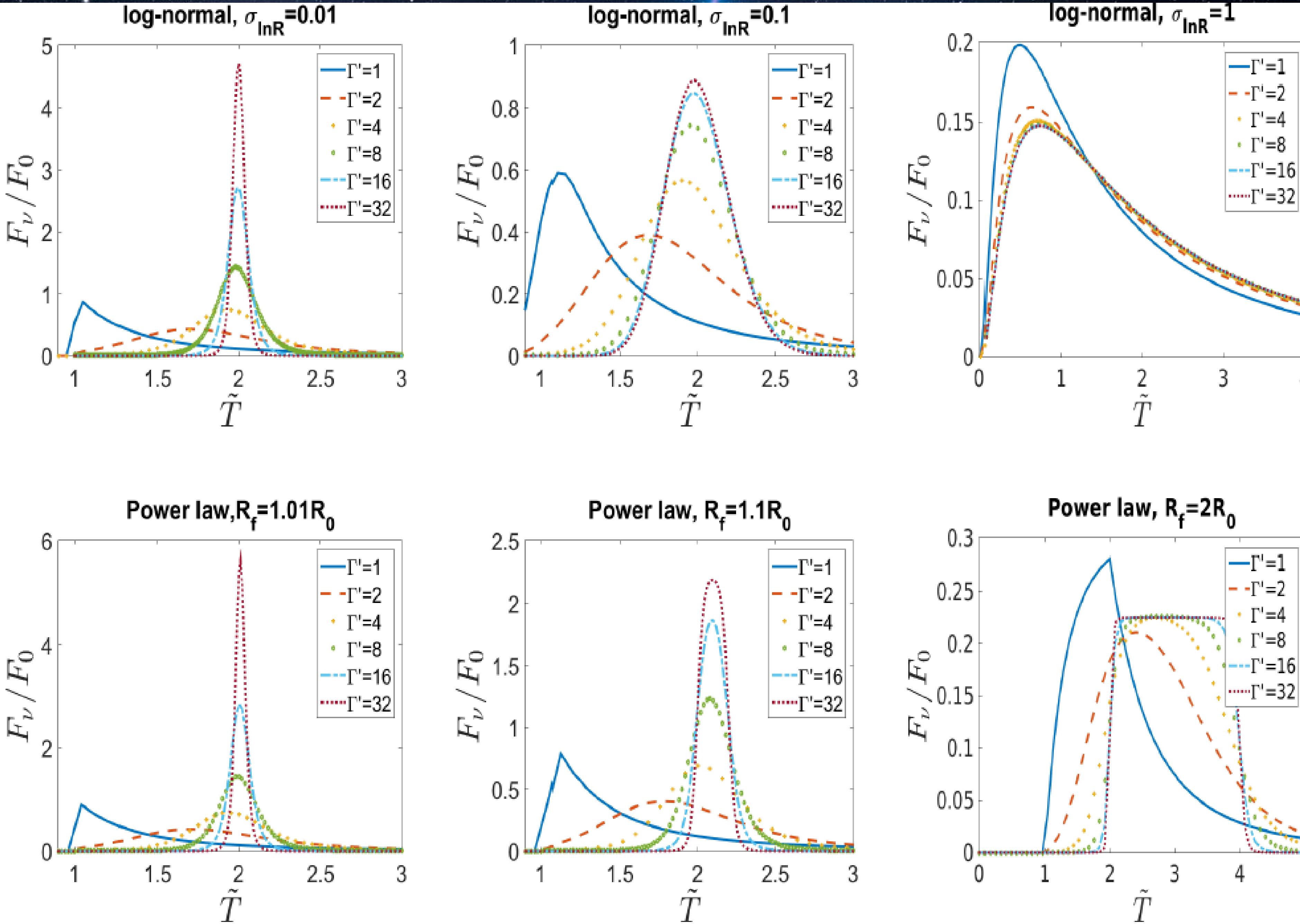
GRB pulses are asymmetric with average rise to decay ratio of 0.3-0.5
(Nemiroff 94, Fishman & Meegan 95, Norris 96, Quilligan 02, Hakkila & Preece 11)

- In Isotropic models, pulses tend to be very asymmetric:

$$\frac{T_{rise}}{T_{decay}} = \frac{\Delta R}{R_f} < \frac{1}{2} \quad \text{for} \quad \Delta R < R_0$$

- In anisotropic models, for $\frac{\Delta R}{R} > \frac{1}{\Gamma'}$ width determines the rise time and pulses are again asymmetric
- However, pulses become symmetric

for $\frac{\Delta R}{R} < \frac{1}{\Gamma'}$ and $\Gamma' \gg 1$



log-normal, $\sigma_{\ln R}$=0.01
log-normal, $\sigma_{\ln R}$=0.1
log-normal, $\sigma_{\ln R}$=1
Power law,R_f=1.01R_0
Power law, R_f=1.1R_0
Power law, R_f=2R_0
F_ν / F_0
$\tilde{T}$
Γ'=1
Γ'=2
Γ'=4
Γ'=8
Γ'=16
Γ'=32

Results and comparison to observations

$L_p - \upsilon_p$ correlation

Many studies claimed a correlation between peak luminosities and peak frequencies of GRBs (Yonetoku et al 04,10 Ghirlanda 05) and between pulses in a single burst (Guiriec 15)

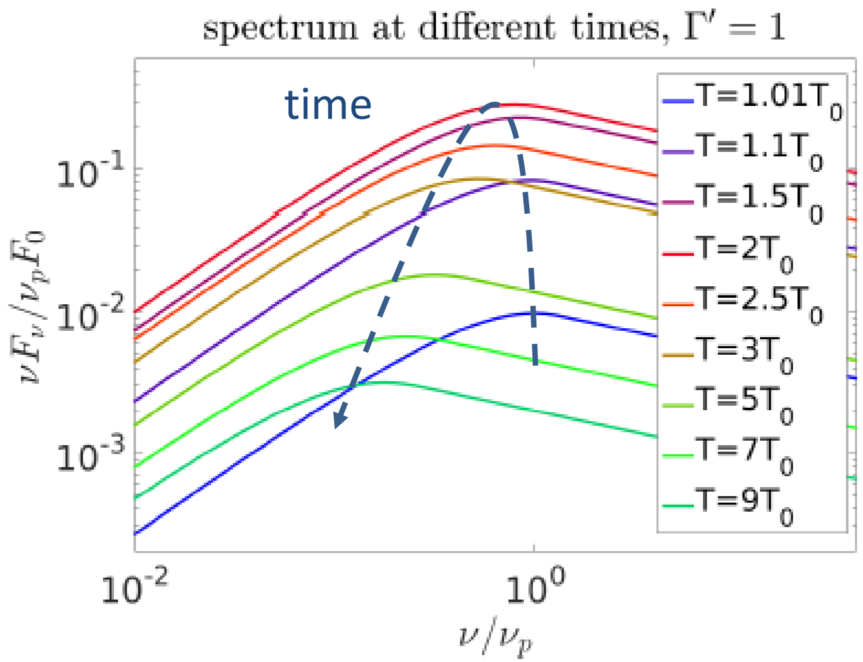
- In our model both peak frequency and luminosity are Doppler boosted from the emitters' frame leading to $\frac{L_p}{\nu_p^2} = \frac{L_p{}'}{\nu_p'^2}$ regardless of Γ
- A correlation in the co-moving frame would be reproduced in the observer frame

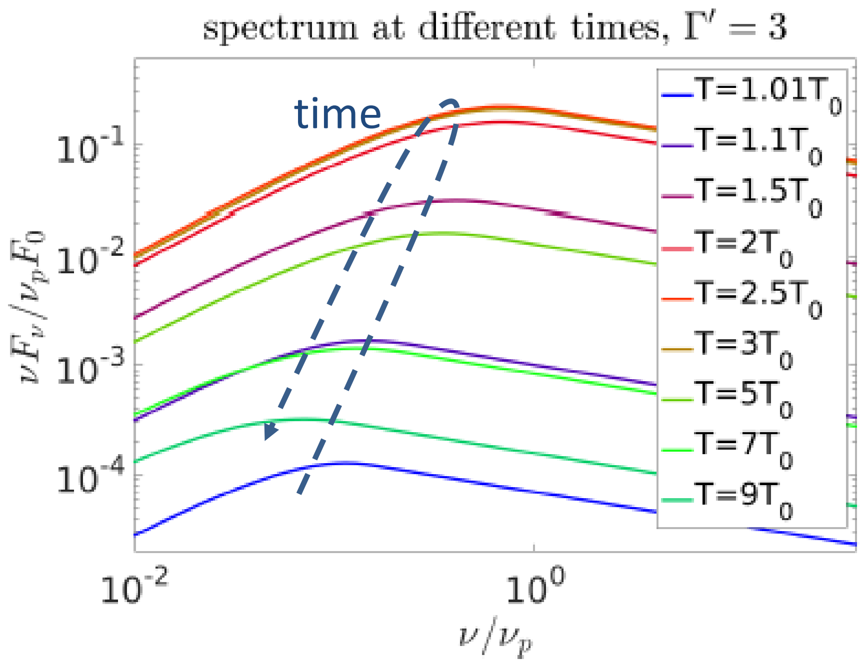
Results and comparison to observations

Peak and luminosity evolution during a pulse

Two typical behaviours are seen in GRB pulses: intensity tracking and hard to soft (Ford et al. 95, Preece 00, Kaneko 06, Lu 12, Hakkila 15)

- Both behaviours can be obtained in our model, depending on Γ’





Results and comparison to observations

Rapid decay phase

Observations of GRBs in early afterglow phase exhibit a "rapid decay" phase (Tagliaferri 05)

Observed flux often falls faster than predicted by high latitude emission

For anisotropic model, initial flux decay significantly more rapid than for isotropic case (see also Beloborodov et al. 11, Barniol Duran et al. 15)

A possible correlation between Γ' and γ_e

- We explore the implications of a relation $\Gamma' = K{\gamma_e}^{\eta}$ with $0 \leq \eta \leq 1$
- Electrons accelerated to larger energies, preferentially spend more time being accelerated in reconnection layer and their velocities tend to be more collimated
- Different energy electrons dominate flux at different bands
- Since emission from an emitter moving at Γ' can be seen up to an angle $\theta \sim \frac{1}{\Gamma'}$, a cut-off in the spectrum will be observed at different frequencies depending on the observation angle:

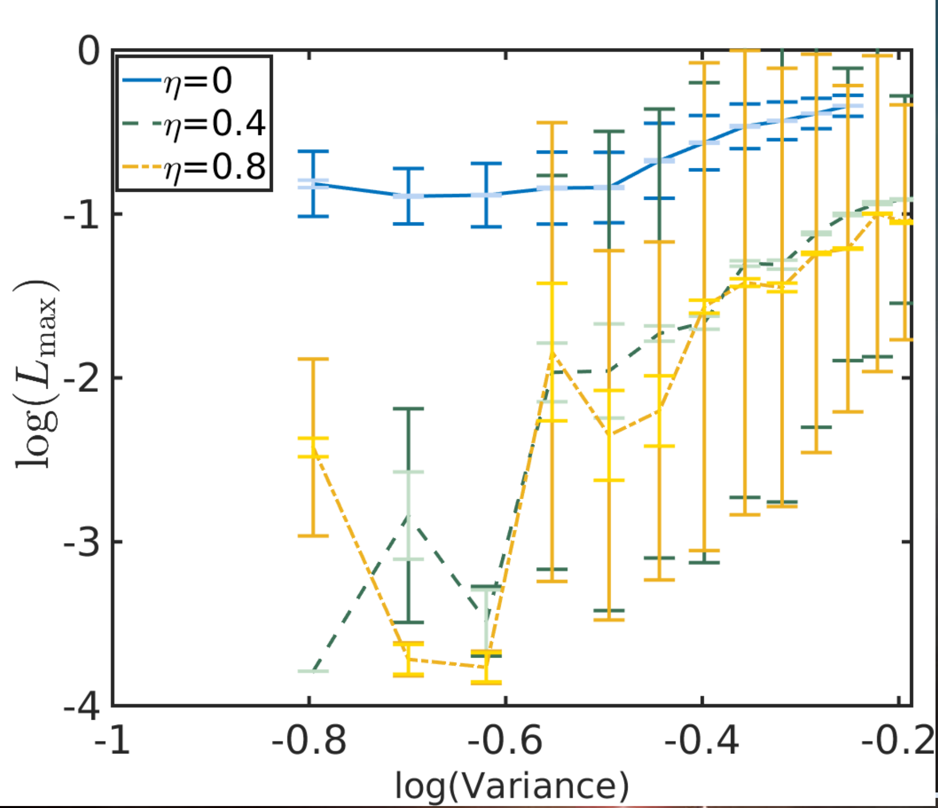
$$\nu_{\rm max}(\theta'_{\rm obs}) = \nu_{\rm obs}(\Gamma' = 1/\theta'_{\rm obs}) = \frac{\Gamma e B'}{2\pi m_e c}(K\theta'_{\rm obs})^{-2/\eta}$$

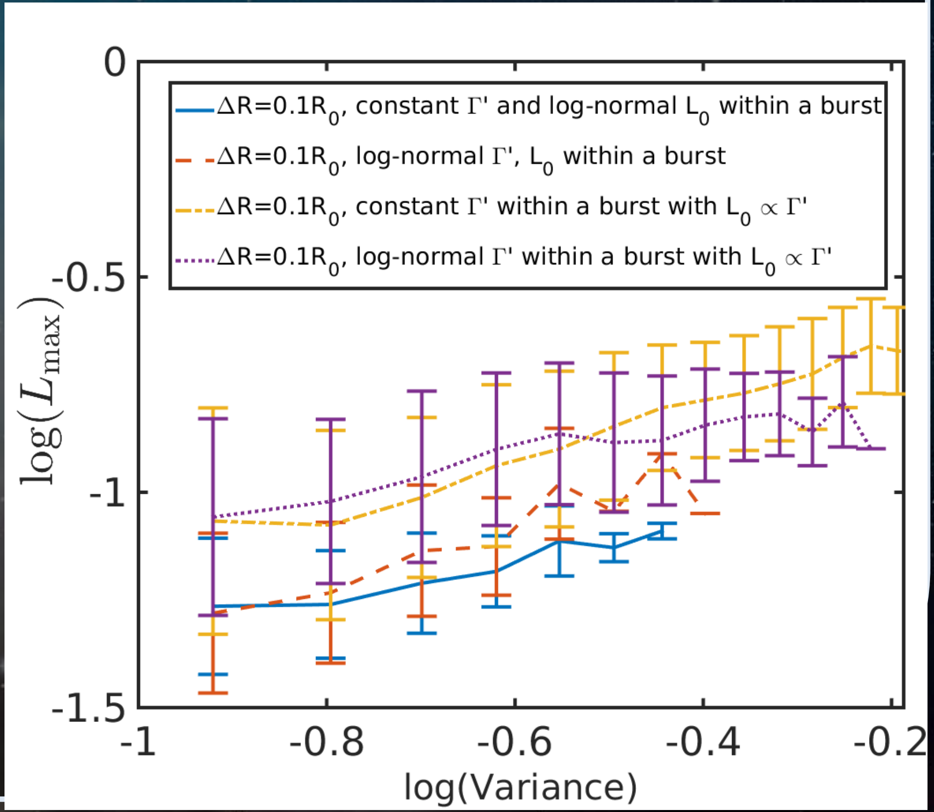
Results and comparison to observations

Luminosity-Variability correlation

Observations find more variable light-curves have larger luminosity
(Stern 99, Fenimore & Ramirez Ruiz 00, Reichart 01)

For $\frac{\Delta R}{R} < \frac{1}{\Gamma\prime}$ and Γ'>2 pulses become narrower and more luminous as Γ' increases and may reproduce the observed correlation





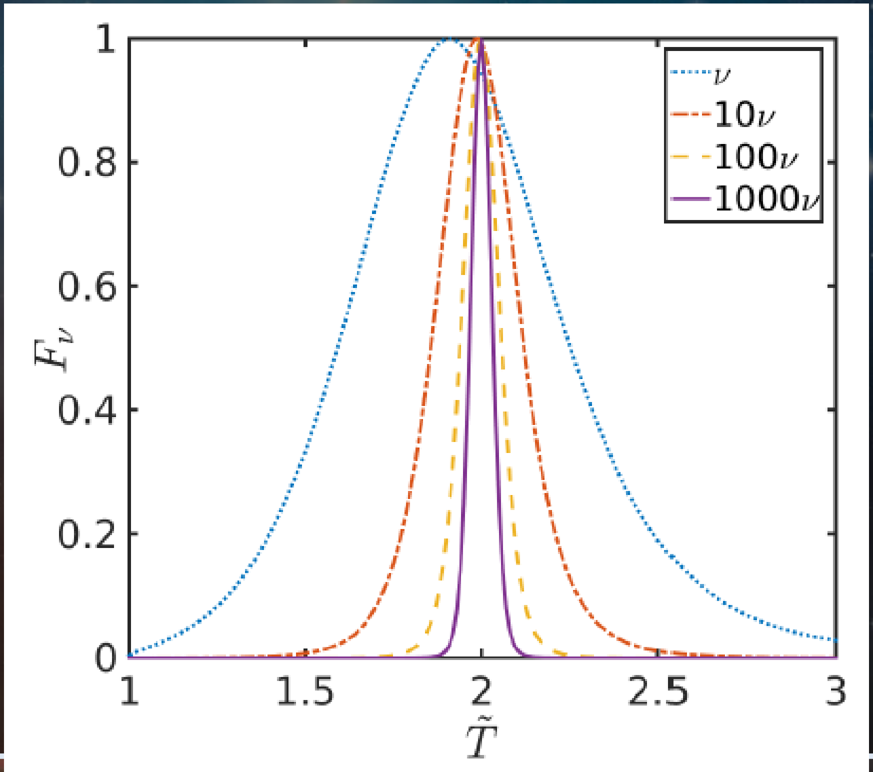
Results and comparison to observations

Pulse widths and spectral lags

Pulse widths tend to decrease with frequency as $\nu^{-0.4}$ (Fenimore et al 95, Norris et al 95,96, Bhat 12)

A related observation is that at larger frequencies pulses peak earlier

- Our model can reproduce this trend in case there is a correlation between Γ' and the electrons' Lorentz factors



Conclusions

- Anisotropic emission is relevant to a wide range of phenomena from "relativistic turbulence" to "mini jets" to astrophysical systems beyond GRBs such as AGNs and pulsar wind nebulae
- A broad range of behaviors can be obtained within this framework, possibly accounting for the variety of observed correlations
- In the future we will need to try and constrain the various parameters in the model as well as apply it in less "ideal" configurations

Thank You!