Particle acceleration in Gamma Ray Bursts

Paz Beniamini - IAP

Collaborators: Tsvi Piran, Jonathan Granot

Constraints on the Synchrotron emission mechanism in GRBs

2013, ApJ, 769, 69B.

Paz Beniamini, Tsvi Piran

- Examine a general synchrotron model for the prompt phase of GRBs
- Do not adopt specific energy dissipation or particle accelerations processes

Prompt emission from Synchrotron

Why Synchrotron?

- Naturally produces high frequency and non-thermal radiation (Katz 94 Rees and Meszaros 94, Sari et al. 96,98)
- Afterglow spectra are roughly described by synchrotron (Sari et al. 97)
- Polarization (Covino et al. 03, Yonetoku et al. 11)
- Difficult to avoid (Beniamini & Piran 14)

Why not?

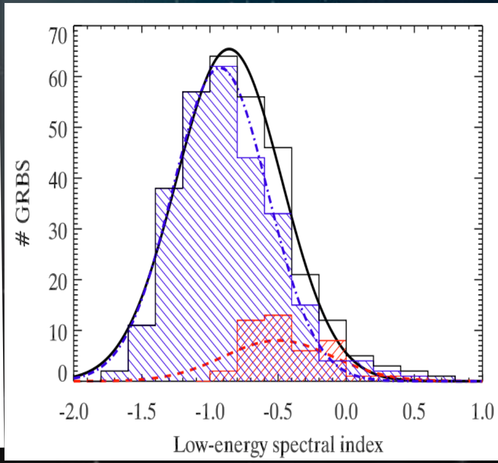
- Line of death (Crider et al. 97, Preece et al. 98,00)

$N_\nu \propto \nu^{-2/3}$ Slow cooling

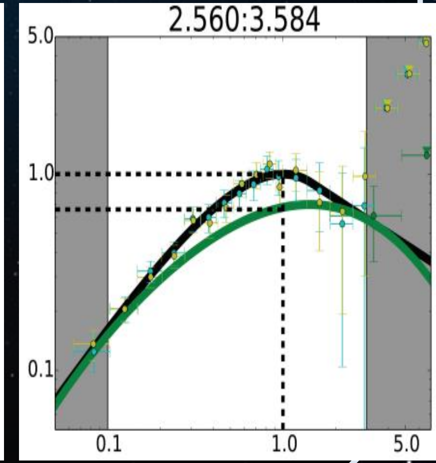
$N_\nu \propto \nu^{-3/2}$ Fast cooling

$N_\nu \propto \nu^{-1}$ Observed

- Narrowness of the "Band function" (Pelaez 94, Yu et al. 15)



Nava et al. 11



Yu et al. 15

Prompt emission from Synchrotron
What about alternatives?

- Photospheric models are the leading alternative

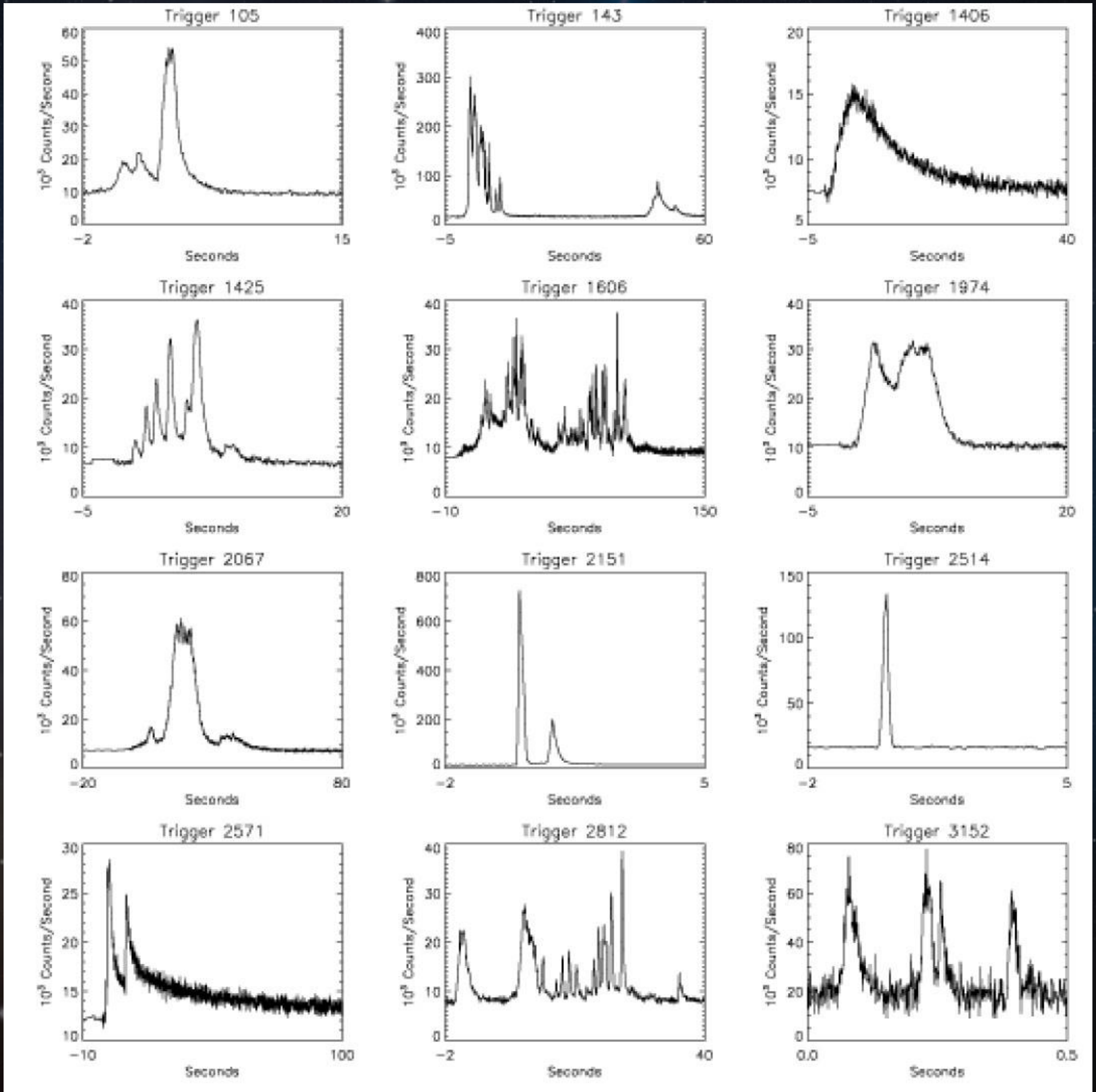
- However:

    1. How to lower Ep below MeV? (Vurm, Lyubarski, Piran 12)

2. How to create GeV emission from an optically thick medium? (Vurm, Granot, Piran 12) E.G. GRB 080916C – strong constraints on a thermal component (Zhang & Pe'er 09)

3. GRBs 100724B, 110721A, 120323A – Thermal component possibly detected but with small fraction (5-10%) of total energy in non-thermal component (Guiriec et al. 11,12; Axelsson et al. 12)

Overall bursts are very complex, simple pulses are better defined



Prompt emission from Synchrotron

- Build simple single zone model to describe one pulse
- Emitting region characterized by 6 numbers:

B (magnetic field)
N_e (number of emitting electrons)
ε (ratio between magnetic energy and energy in electrons)
Γ (bulk Lorentz factor)
γ_m (minimum electrons' Lorentz factor)
k (ratio between shell crossing time and angular time scale)

6D
B, N_e, ε,
Γ, γ_m, k

→

3D
ε, Γ, k

Three basic observations

Peak frequency

$$\nu_m = \Gamma\gamma_m^2 \frac{qB'}{2\pi m_e c(1+z)} = 6\times10^{19}\left(\frac{B'}{10^4 G}\right)\left(\frac{\gamma_m}{10^4}\right)^2\left(\frac{\Gamma}{100}\right) Hz = \nu_p \approx 6\times10^{19} Hz$$

Peak flux

$$F_\nu(\nu_m) = \frac{m_e c^2 \sigma_T \Gamma B' N_e (1+z)}{12 q_e \pi d_L^2}\left(\frac{\nu_c}{\nu_m}\right)^{1/2} = 8\left(\frac{10^4 G}{B'}\right)\left(\frac{10^4}{\gamma_m}\right)\left(\frac{N_e}{10^{53}}\right) mJy = F_p \approx 1.5 mJy$$

Pulse duration

$$\Delta t = \frac{R(1+z)(k+1)}{2c\Gamma^2} = t_p = 0.5 sec$$

For z=1 -> $E_{iso} = 2\times10^{51} erg = \eta E_{int}$

Some immediate results

- Magnetic energy: $\frac{B'^2}{8\pi}4\pi kR^3 = \varepsilon_B E_{int}$
- This immediately limits the particles' typical energies:

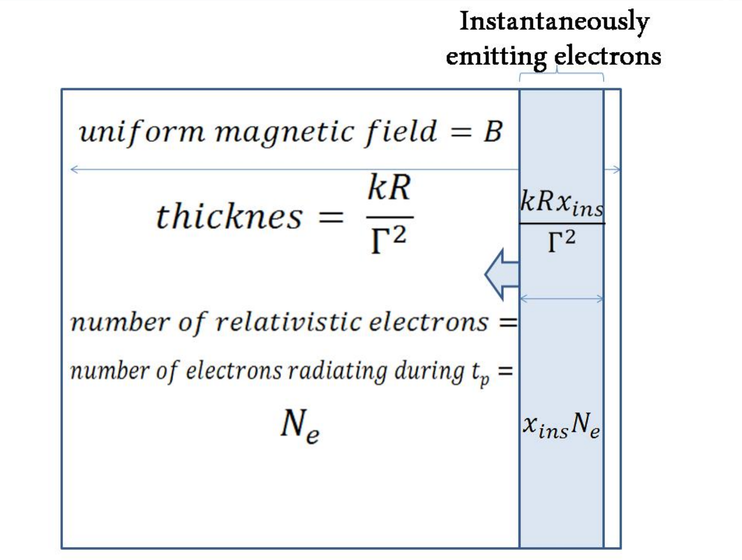
$$B' < 10^4\left(\frac{\Gamma}{100}\right)^{-3} G \Rightarrow \gamma_m > 10^4\left(\frac{\Gamma}{100}\right)$$

- Cooling frequency:

$$\nu_c = \frac{18\pi m_e q_e c(1+z)}{\sigma_T^2 B'^3 \Gamma t^2 (1+Y)^2} \approx 10^{11}\left(\frac{\Gamma}{100}\right)^8 \mathrm{Hz}$$

Typically $\nu_c \ll \nu_m \Rightarrow t_{cool} \ll t_{dyn} \Rightarrow$

1. Acceleration front propagates through shell – Small fraction of electrons emitting at any time
2. Continuous acceleration (Ghisellini and Celotti 99, Kumar & McMahon 08) – increase ν_c - marginally fast cooling



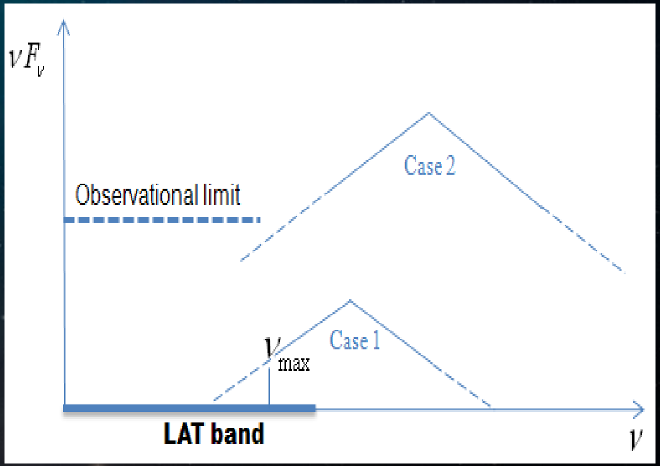
Prompt emission from Synchrotron

- 3 basic observations (source frame):

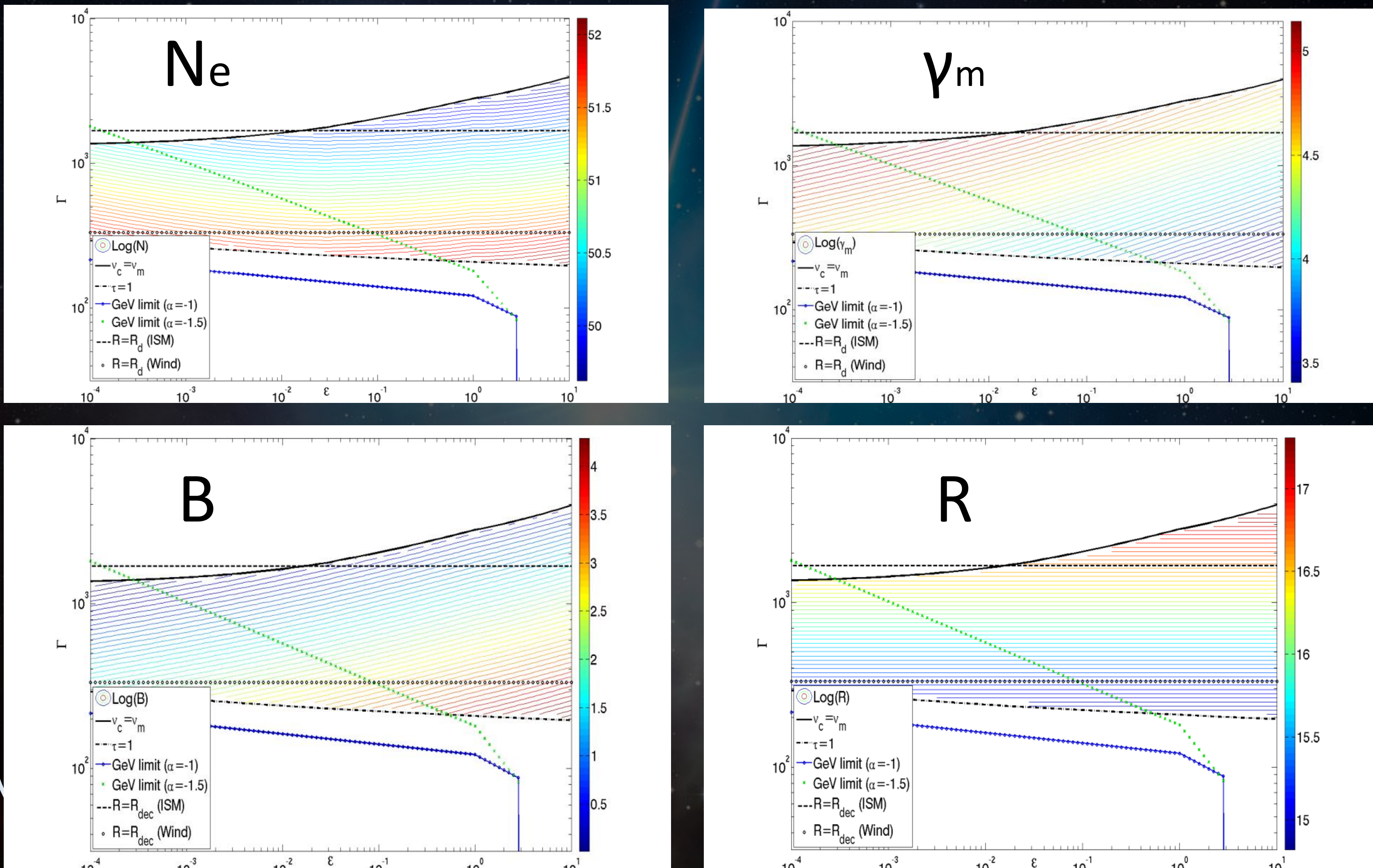
peak energy - E_p=300 KeV
Pulse duration - t=0.5 sec
Peak spectral flux – $F_p = 1.5 \times 10^{-26} \, {}^{erg}/_{cm^2 \, \sec \, Hz}$

- Additional limits:

1. Energy budget limits efficiency
2. Emission must be optically thin to Thomson scatterings
3. GeV component is significantly weaker in most GRBs than the MeV signal (Beniamini et al 11, Guetta et al 11, Ando et al 08)
4. Radius before deceleration radius



Results (k=1)


Ne
Log(N)
$\nu_c=\nu_m$
$\tau=1$
GeV limit (α=-1)
GeV limit (α=-1.5)
$R=R_d$ (ISM)
$R=R_d$ (Wind)
52
51.5
51
50.5
50
γ_m
Log(γ_m)
$\nu_c=\nu_m$
$\tau=1$
GeV limit (α=-1)
GeV limit (α=-1.5)
$R=R_d$ (ISM)
$R=R_d$ (Wind)
5
4.5
4
3.5
B
Log(B)
$\nu_c=\nu_m$
$\tau=1$
GeV limit (α=-1)
GeV limit (α=-1.5)
$R=R_{dec}$ (ISM)
$R=R_{dec}$ (Wind)
4
3.5
3
2.5
2
1.5
1
0.5
R
Log(R)
$\nu_c=\nu_m$
$\tau=1$
GeV limit (α=-1)
GeV limit (α=-1.5)
$R=R_{dec}$ (ISM)
$R=R_{dec}$ (Wind)
17
16.5
16
15.5
15
Γ
ε
10^4
10^3
10^2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1

Spectral shape

- High energy spectral slope: $\nu^{\beta} = \nu^{-\frac{p+2}{2}}$ for β≈-2.3 is roughly consistent with Fermi acceleration
- Low energy spectral slope - line of death
- A partial solution - "marginally fast synchrotron" (Derishev 03, Nakar et al. 09, Daign et al. 11):

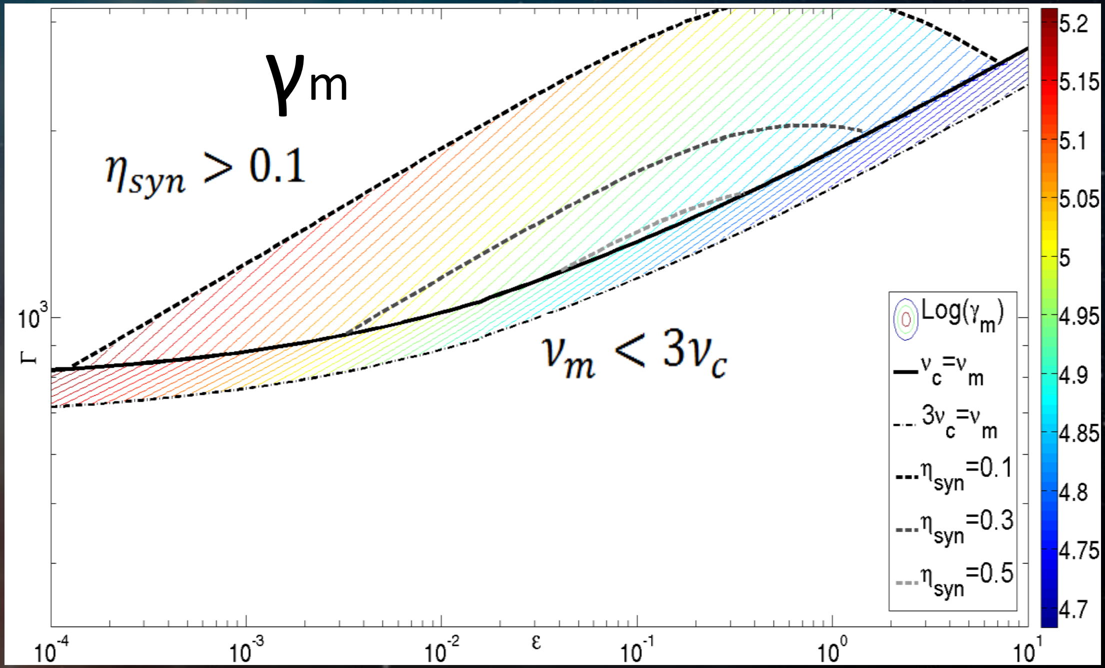
Γ>700

$\gamma_m \approx 10^5$

$N_e \approx 10^{50}$

$B \approx 10$ Gauss

$R \approx 10^{16}$ cm

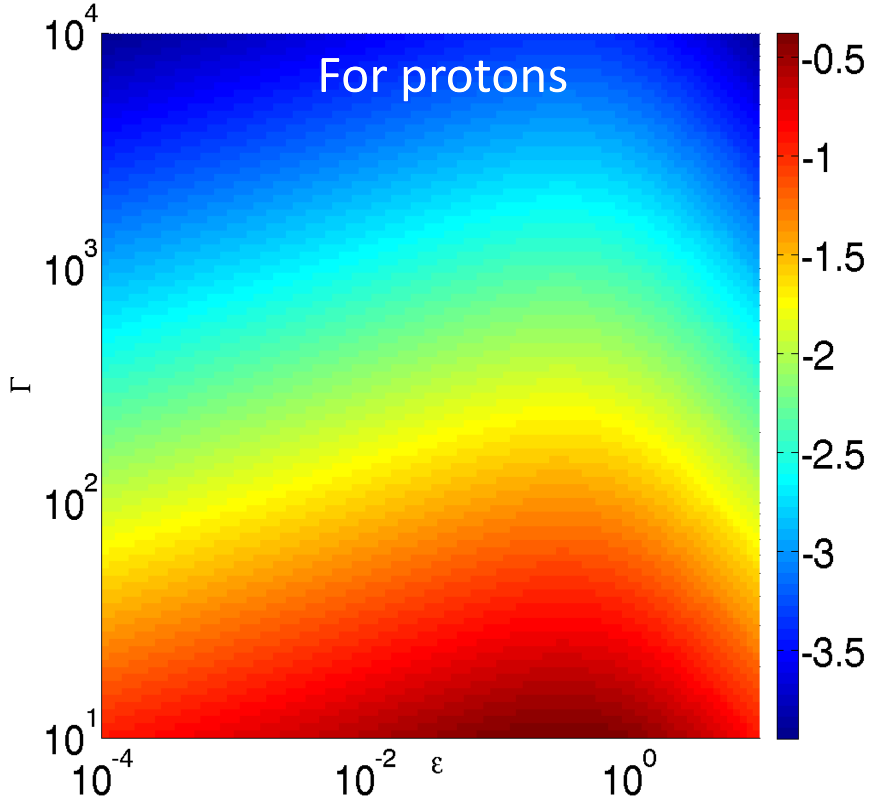


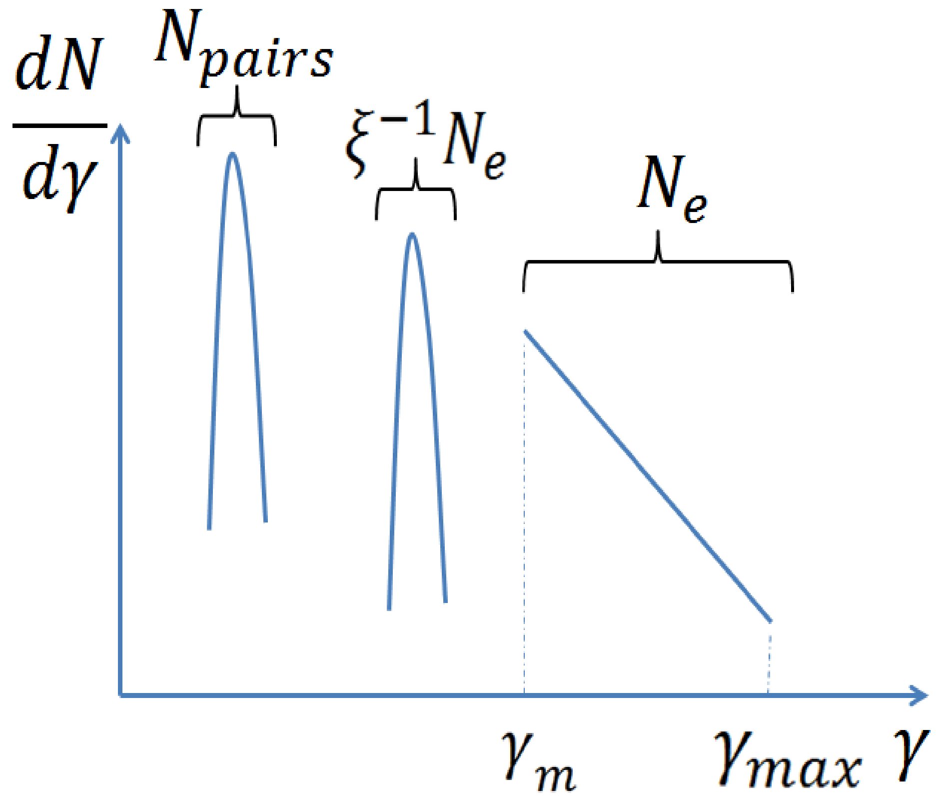
Internal Shocks

- Source of energy is kinetic: $E_{tot} = 2\Gamma N_{tot} m_p c^2$ (X $\frac{m_e}{m_p}$ for pairs)
- Radited energy is:

$$E_e = \varepsilon_e \eta_{int} E_{tot}$$

- $\xi N_{tot} \Gamma \gamma_m m_e c^2 = \varepsilon_e 2 N_{tot} \Gamma m_p c^2$ ⇨ $\xi = \varepsilon_e \frac{2}{\gamma_m} \frac{m_p}{m_e} = 0.04 \frac{\varepsilon_e}{0.1} \frac{10^4}{\gamma_m}$
- Ratio of relativistic to non relativistic electrons must be small (Daigne & Mochkovitch 98, Bosnjak et al 09):





The emission mechanism in magnetically dominated GRBs

2014, MNRAS, 445, 3892B

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Why magnetic jets?

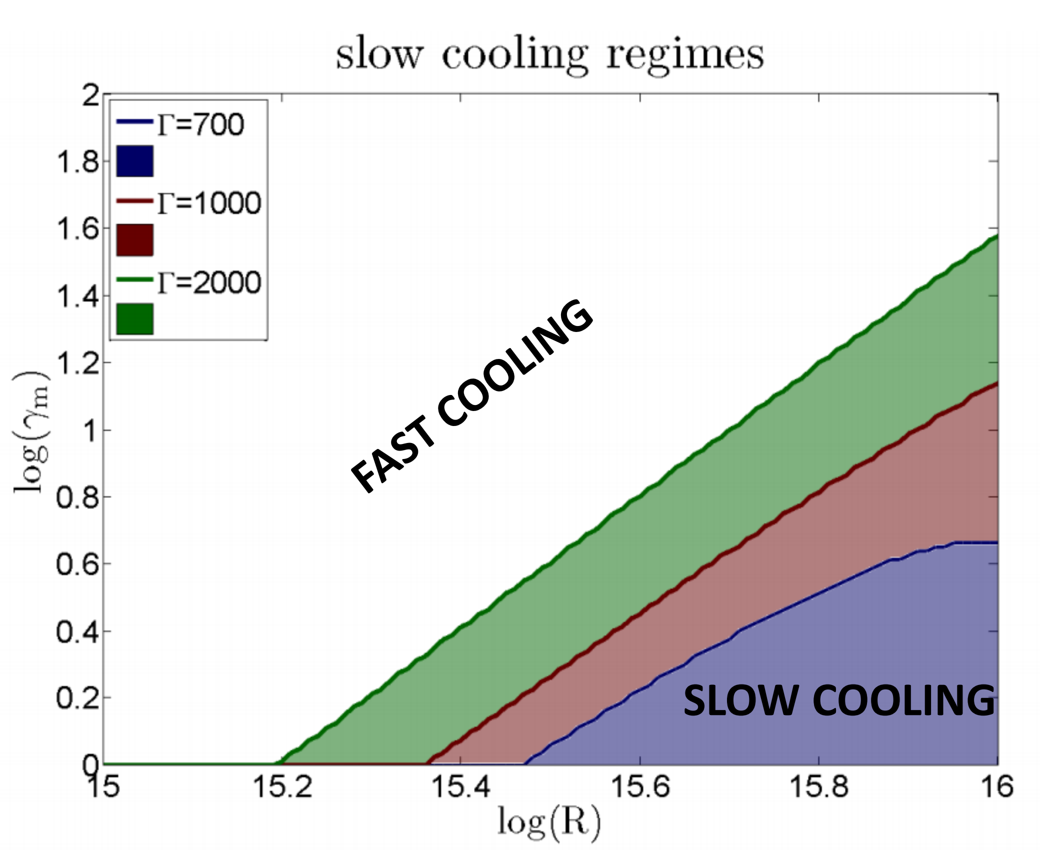
- AGNs produce relativistic jets but thermal pressure insufficient to support Baryonic outflows (however, strong IC component observed in AGNs suggests that a large fraction of magnetic energy dissipates before emission zone and transferred to a Baryonic component)
- Modeling of GRBs accretion disks 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

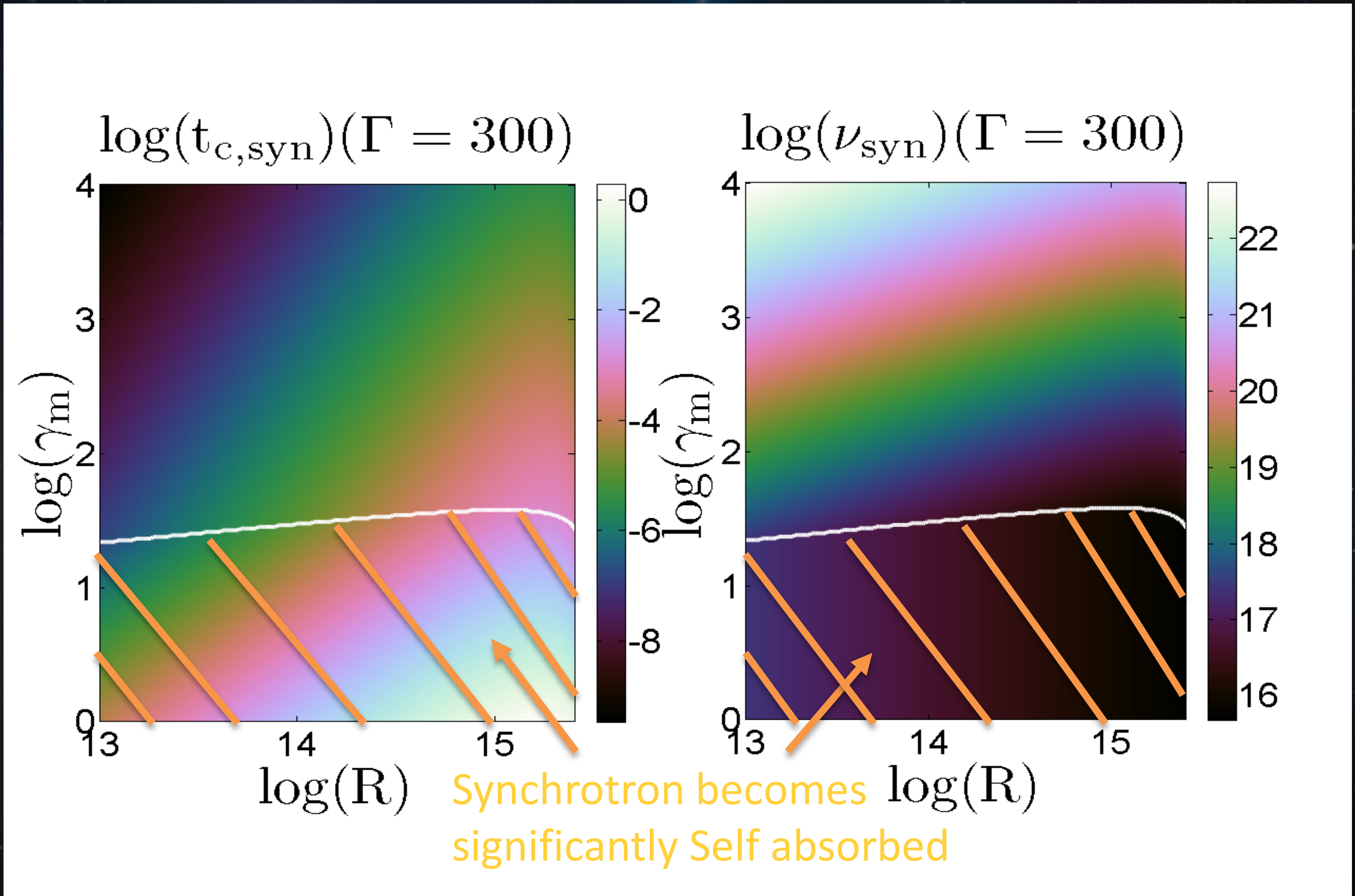
Efficient synchrotron emission regardless of the emission mechanism responsible for the prompt gamma rays

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

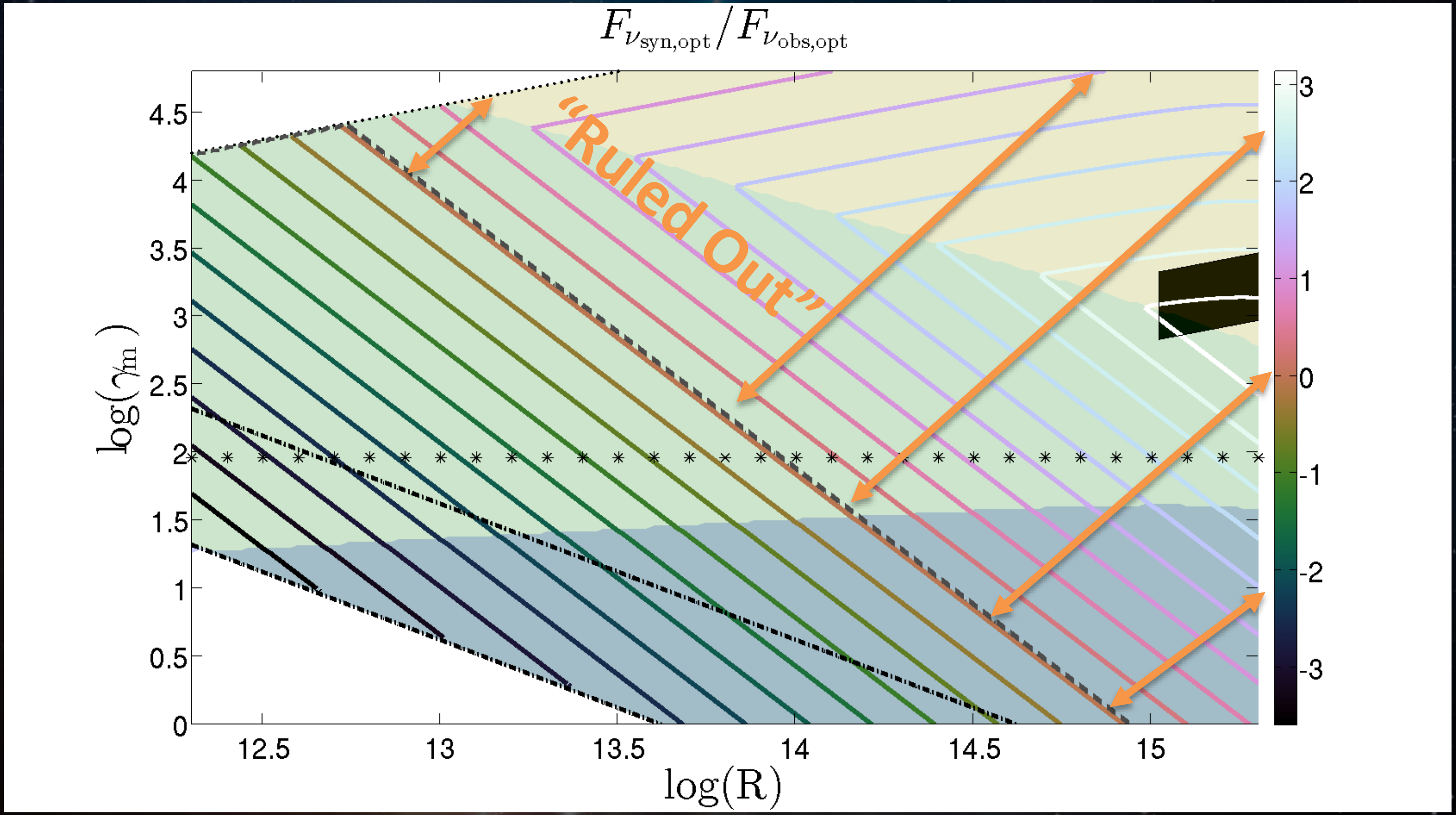


Cooling time by synchrotron very short

typical frequencies between EUV and high energy gamma rays

General cooling in magnetic jets

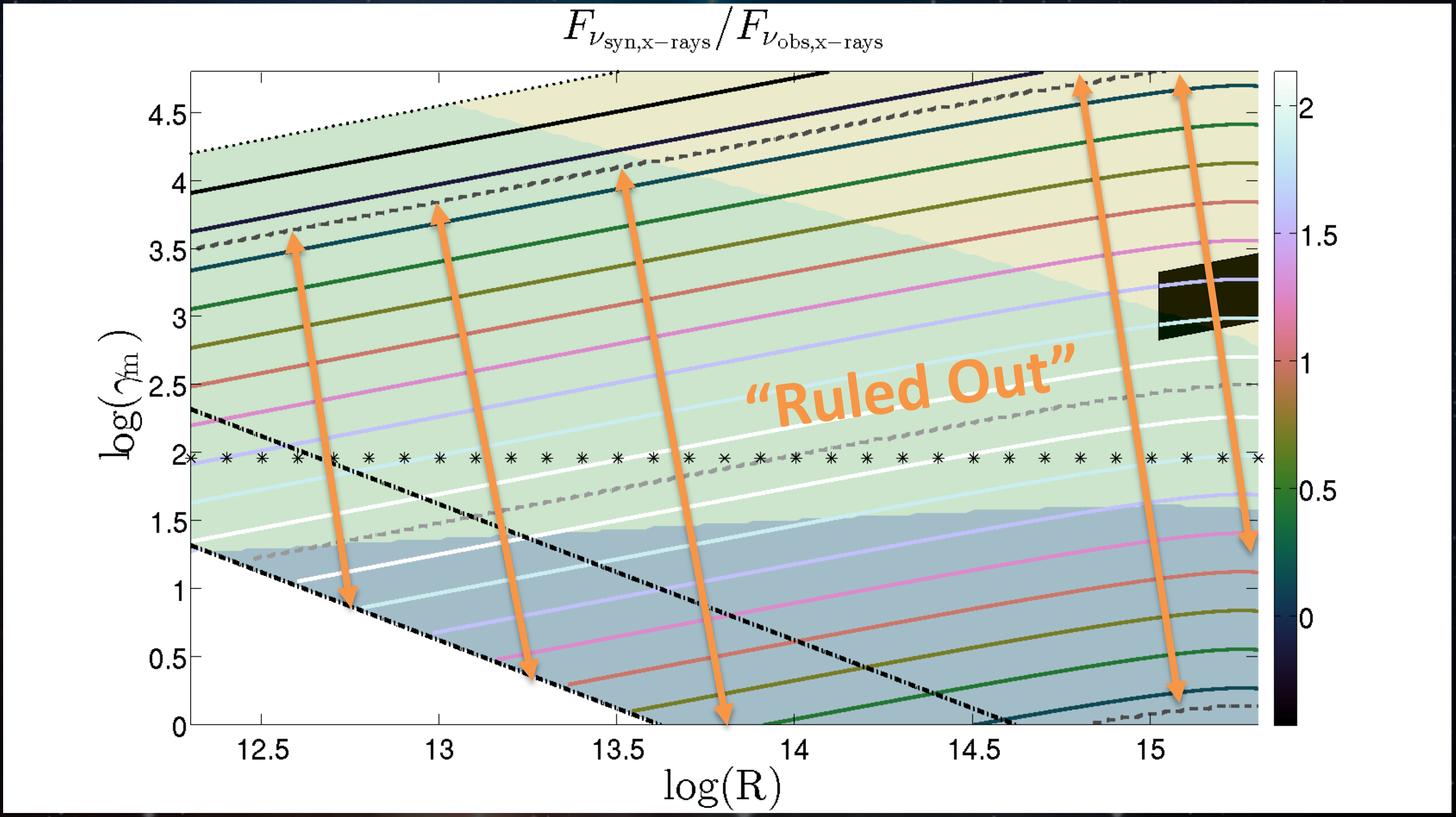
$$\frac{t_c}{t_{c,syn}} < \frac{F_{\nu,syn,opt}}{F_{\nu,obs,opt}}$$



Ratio of optical synchrotron flux to observed optical flux

General cooling in magnetic jets

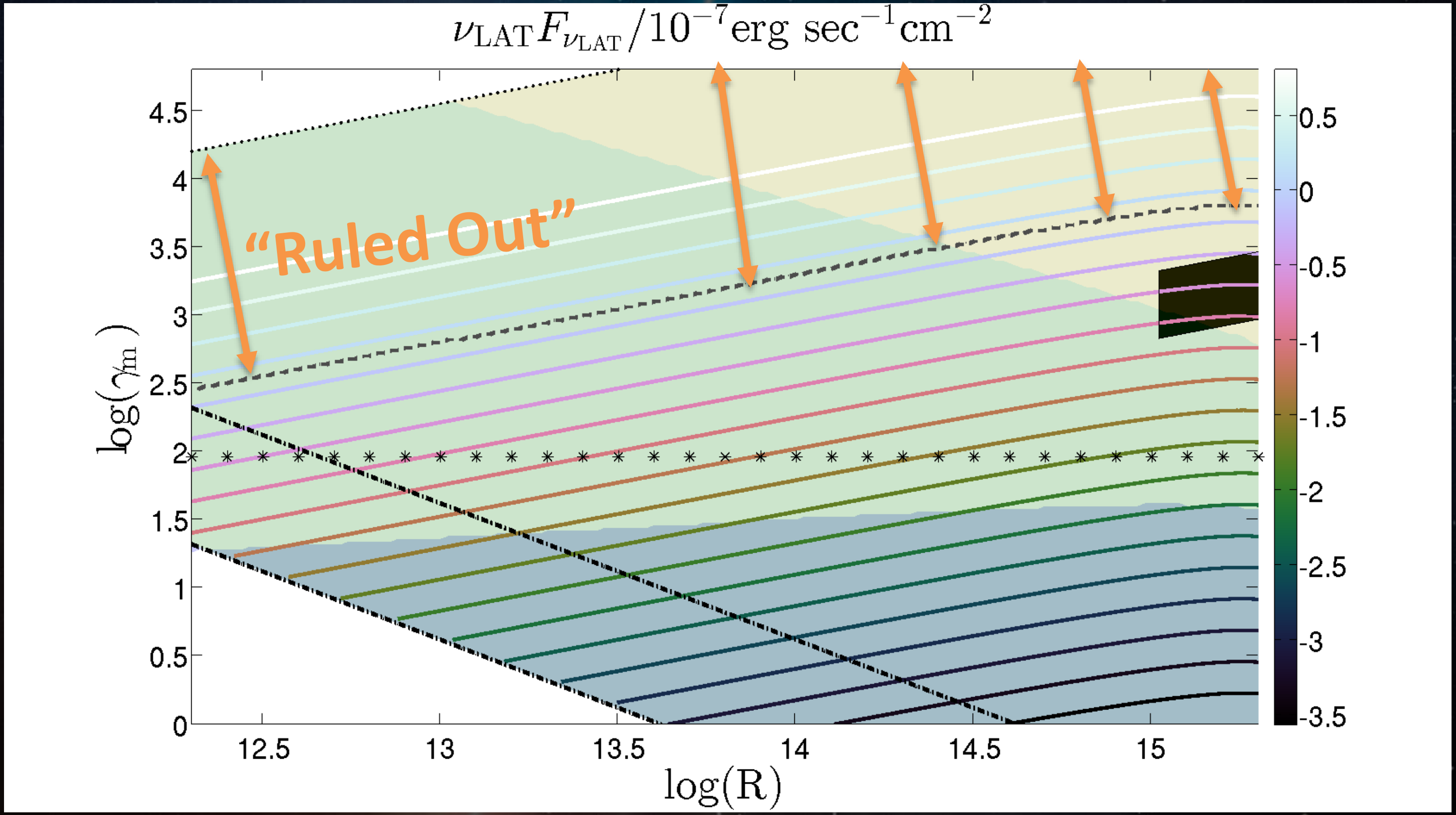
$$\frac{t_c}{t_{c,syn}} < \frac{F_{\nu,syn,X}}{F_{\nu,obs,X}}$$



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

General cooling in magnetic jets

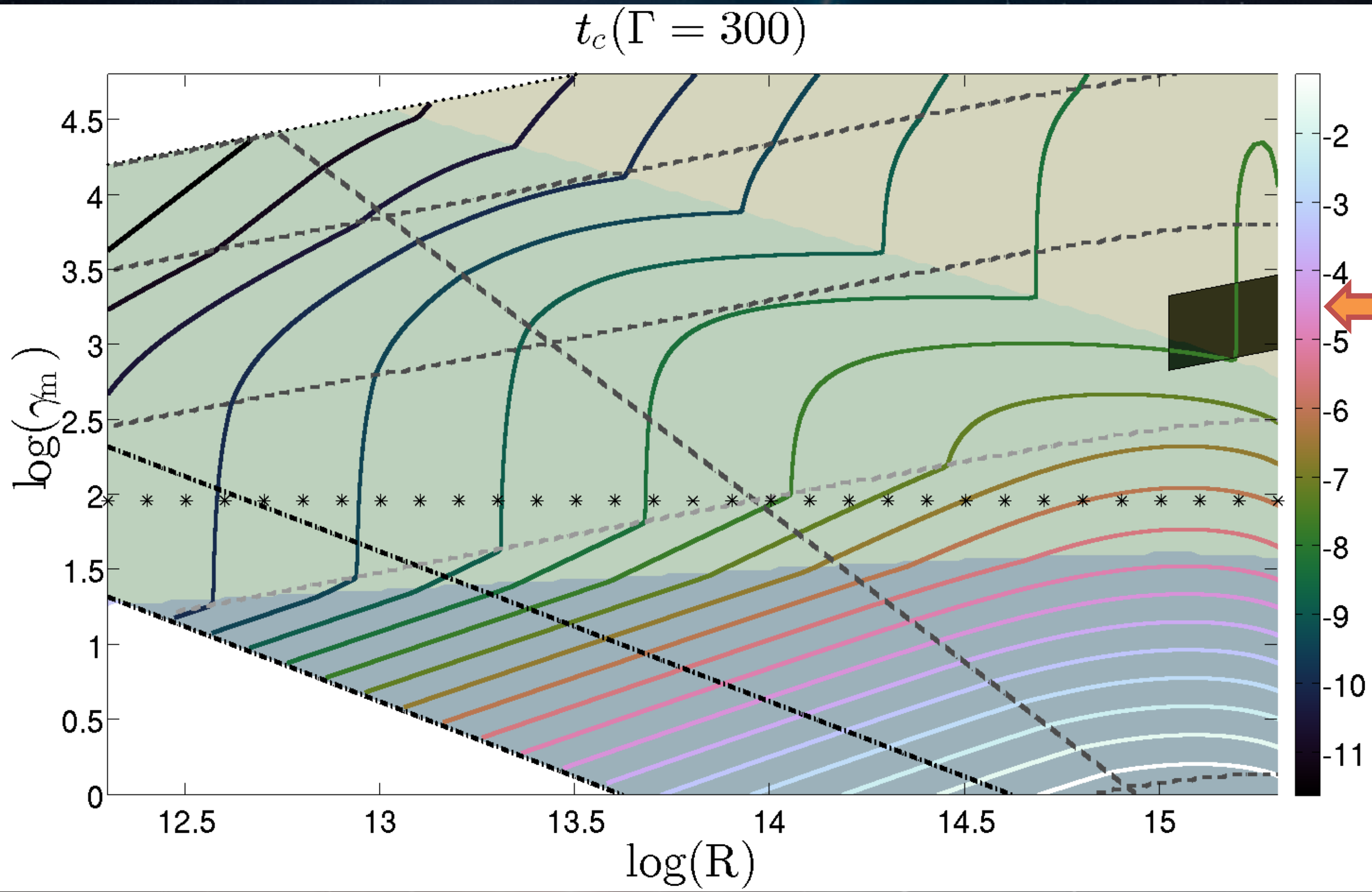
$$\frac{t_c}{t_{c,syn}} < \frac{F_{\nu,syn,GeV}}{F_{\nu,obs,GeV}}$$



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?

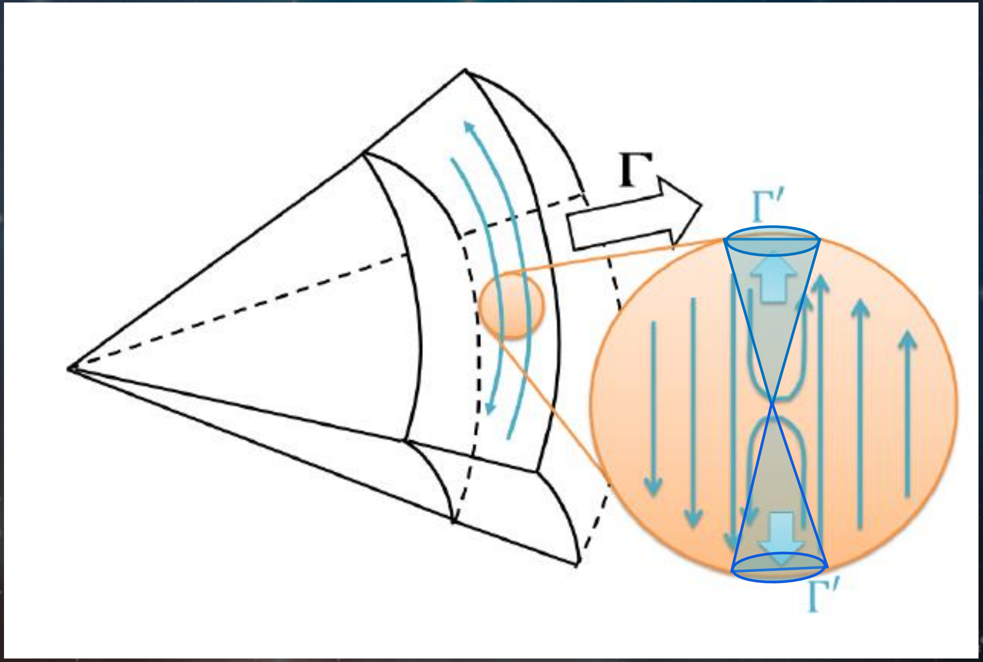
For synchrotron to produce the prompt we need at least ν_c>40keV

- 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

2016, MNRAS, 459, 3635B



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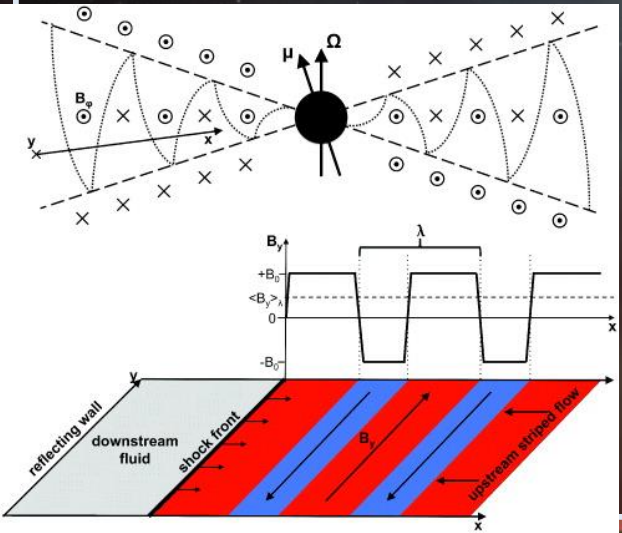
Magnetic Reconnection

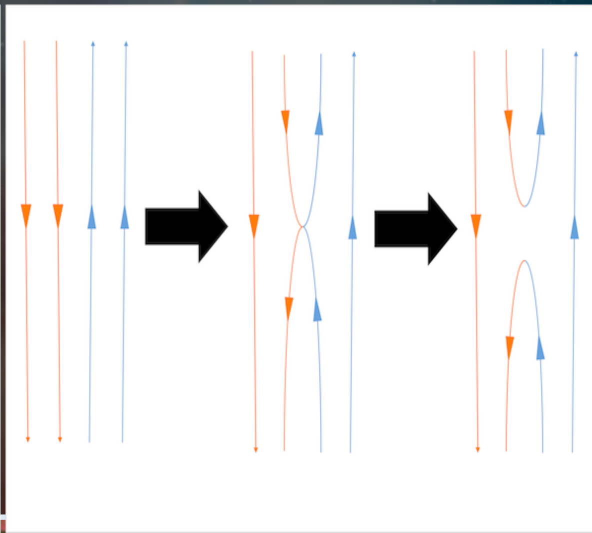
- Highly magnetized jets may lead to reconnection
- Field reversals at source -> reconnection at large distances with naturally preferred direction

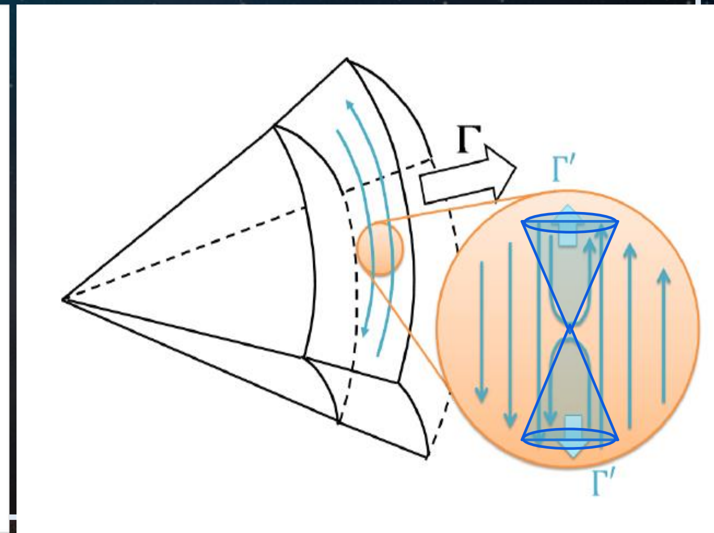
1. Millisecond Magnetar - millisecond quasi-periodic variability (❌)
2. Accreting BH – stochastic field reversal & lightcurve variability (✓)

- For large ingoing σ, reconnection leads to local relativistic bulk motion away from the reconnection sites at Γ'~few

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





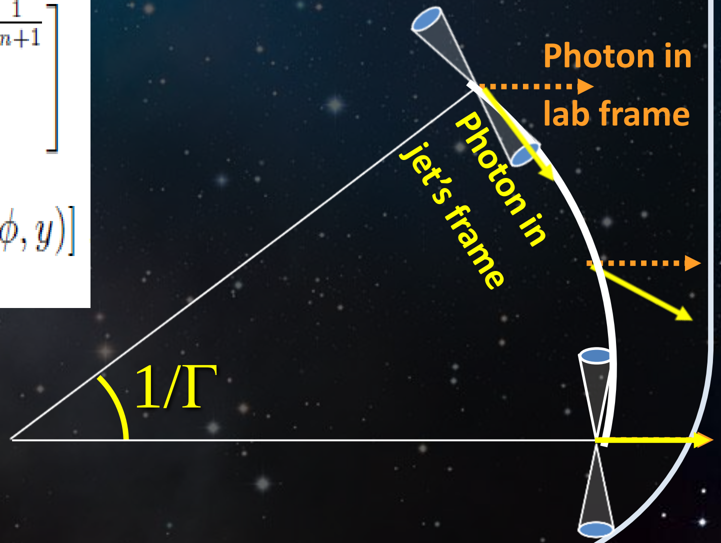


The Model

- 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

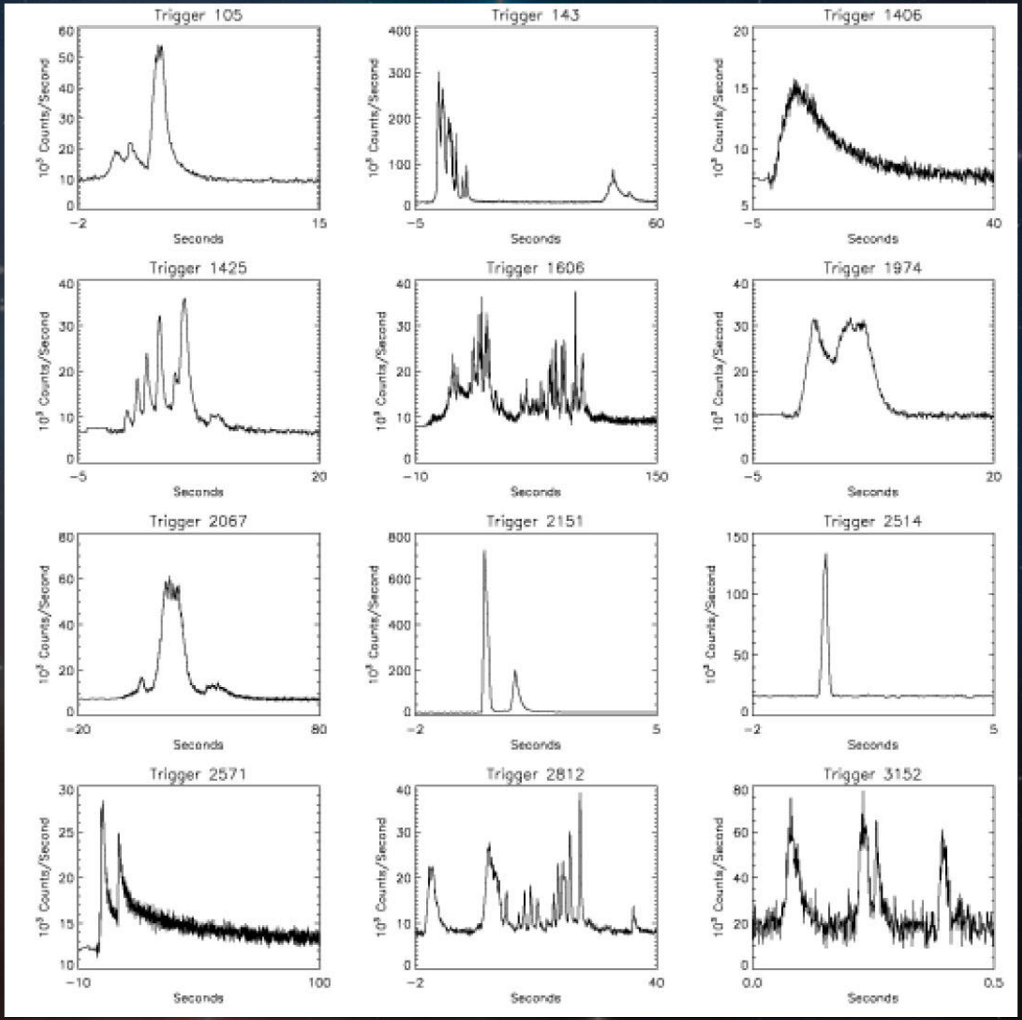
1- Avoiding over-production of optical and X-rays and changing low energy spectral slope (Beniamini & Piran 2014)

- 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:



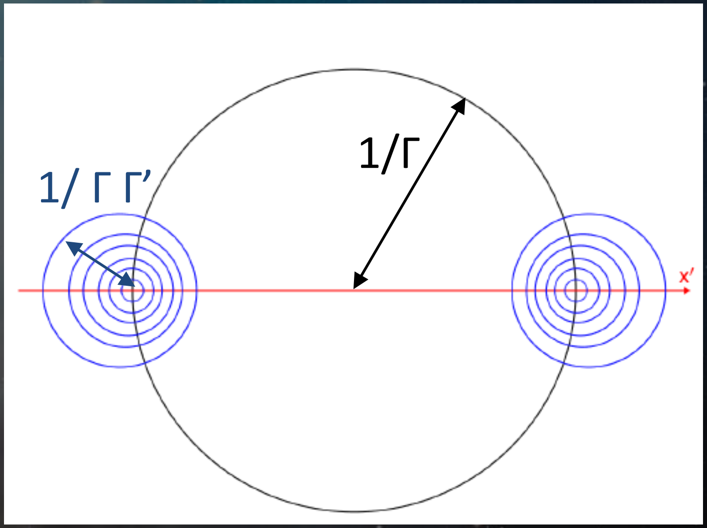
- For isotropic reconnection models:

$\Delta T_{pulse} \geq \Delta T_{\theta} \sim \frac{R}{2c\Gamma^2} \geq \frac{c\Delta t}{2c\Gamma^2} \sim \frac{L\prime}{\Gamma v_{in}'} > \frac{L}{c} \sim \Delta T_{ej}$ 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)

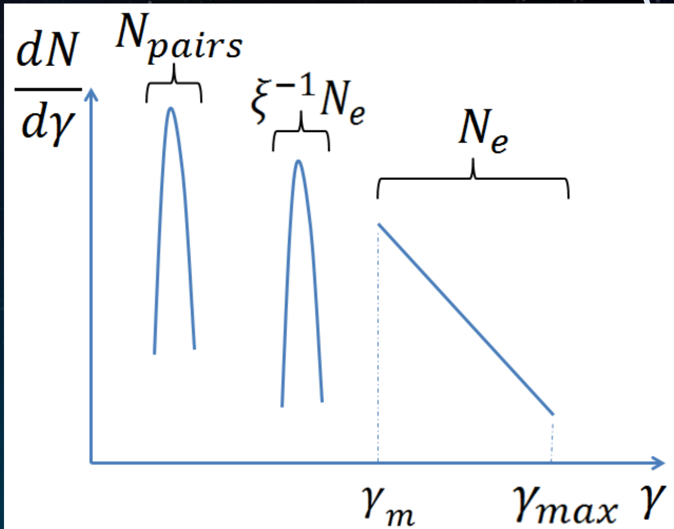
Anisotropic reconnection naturally produces the observed variability



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

Conclusions

- Available parameter space for synchrotron
- γ_m large due to radiation processes alone
- Electrons' energy distribution unlike that expected from PIC simulations
- CTA could strongly limit available parameter space and possibly solve for all parameters or rule out synchrotron



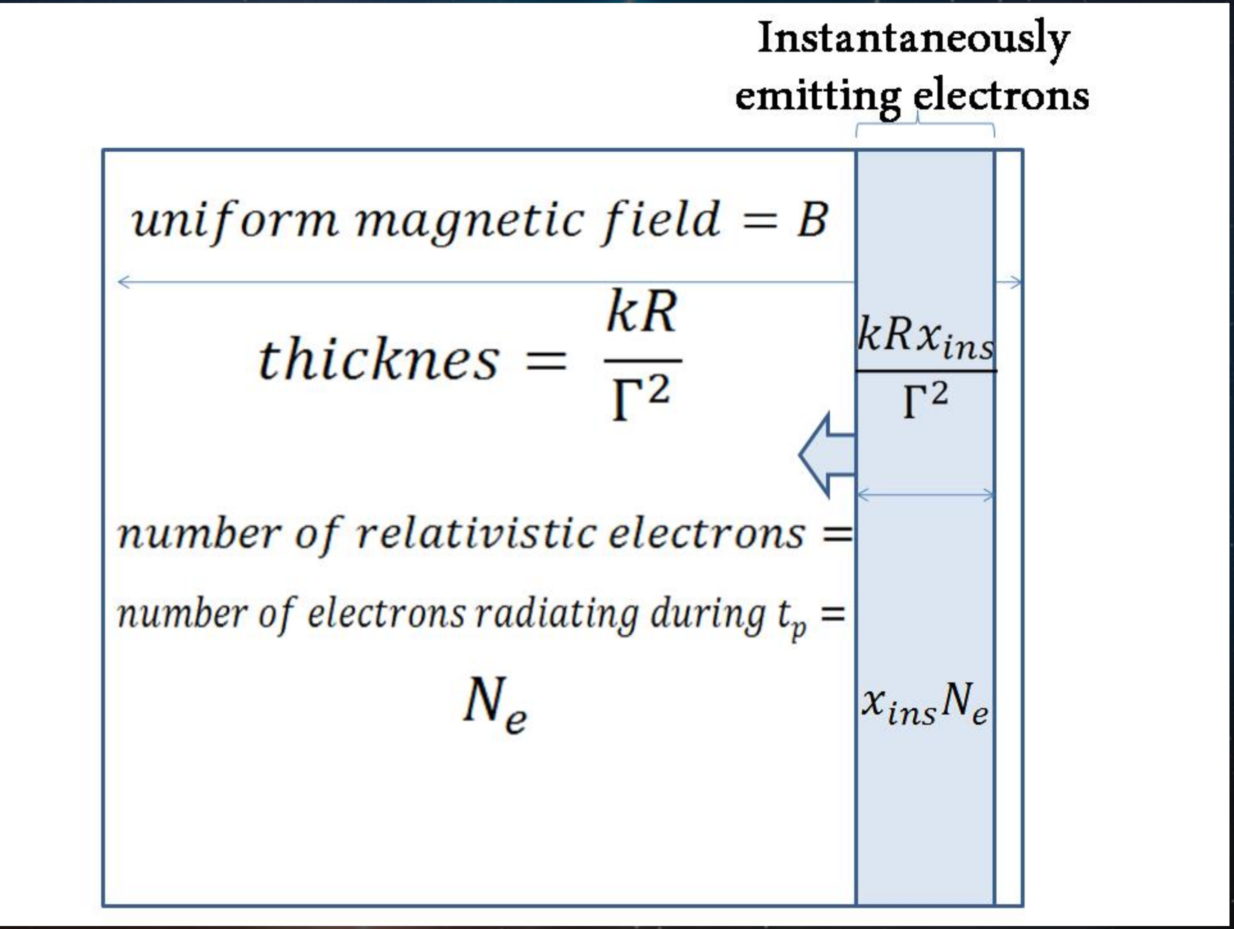
- Magnetically dominated outflows → strong observable yet undetected synchrotron signals → synchrotron dominates γ-ray emission in these environments
- Continuous acceleration is required to avoid overproducing optical and X-ray radiation - could arise naturally from reconnection
- A broad range of behaviors obtained with anisotropic emission, possibly accounting for variety of observed correlations


Thank you!

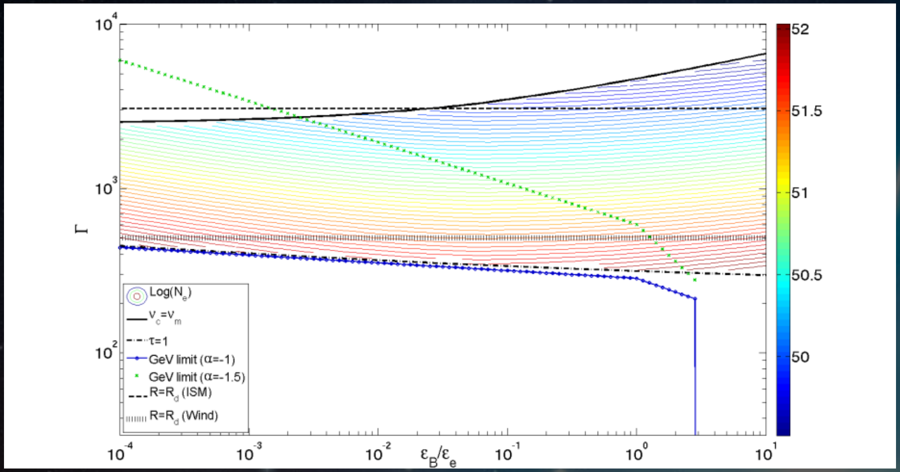
Backup slides

Single zone - Schematic figure

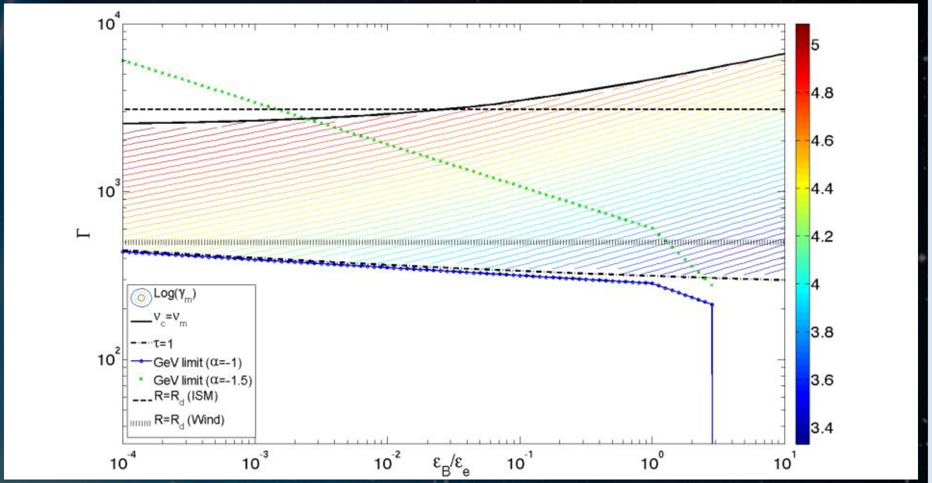
Instantaneously emitting electrons a small fraction of the overall population



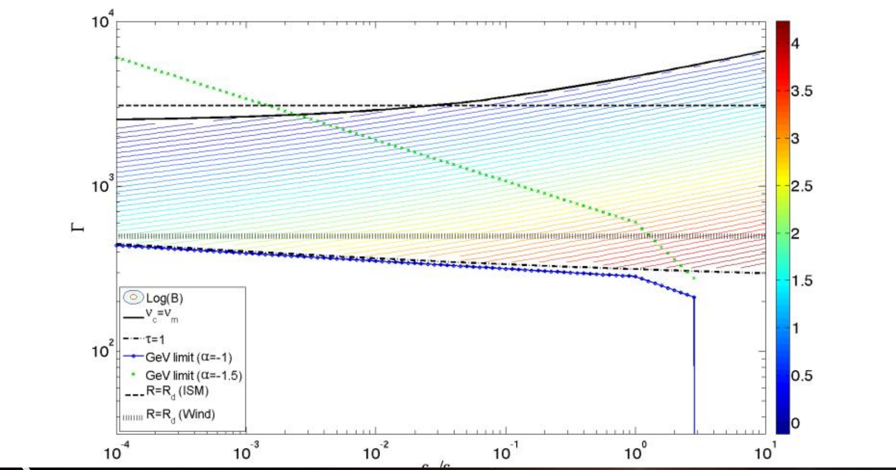
Results (k=10)



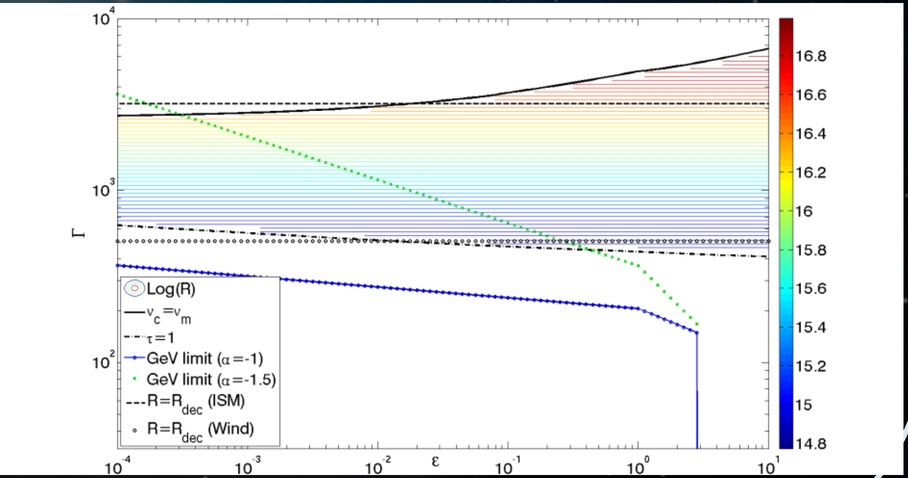
Γ
ϵ_B/ϵ_e
Log(N_e)
$\nu_c=\nu_m$
τ=1
GeV limit (α=-1)
GeV limit (α=-1.5)
R=R_d (ISM)
R=R_d (Wind)



Γ
ϵ_B/ϵ_e
Log(γ_m)
$\nu_c=\nu_m$
τ=1
GeV limit (α=-1)
GeV limit (α=-1.5)
R=R_d (ISM)
R=R_d (Wind)

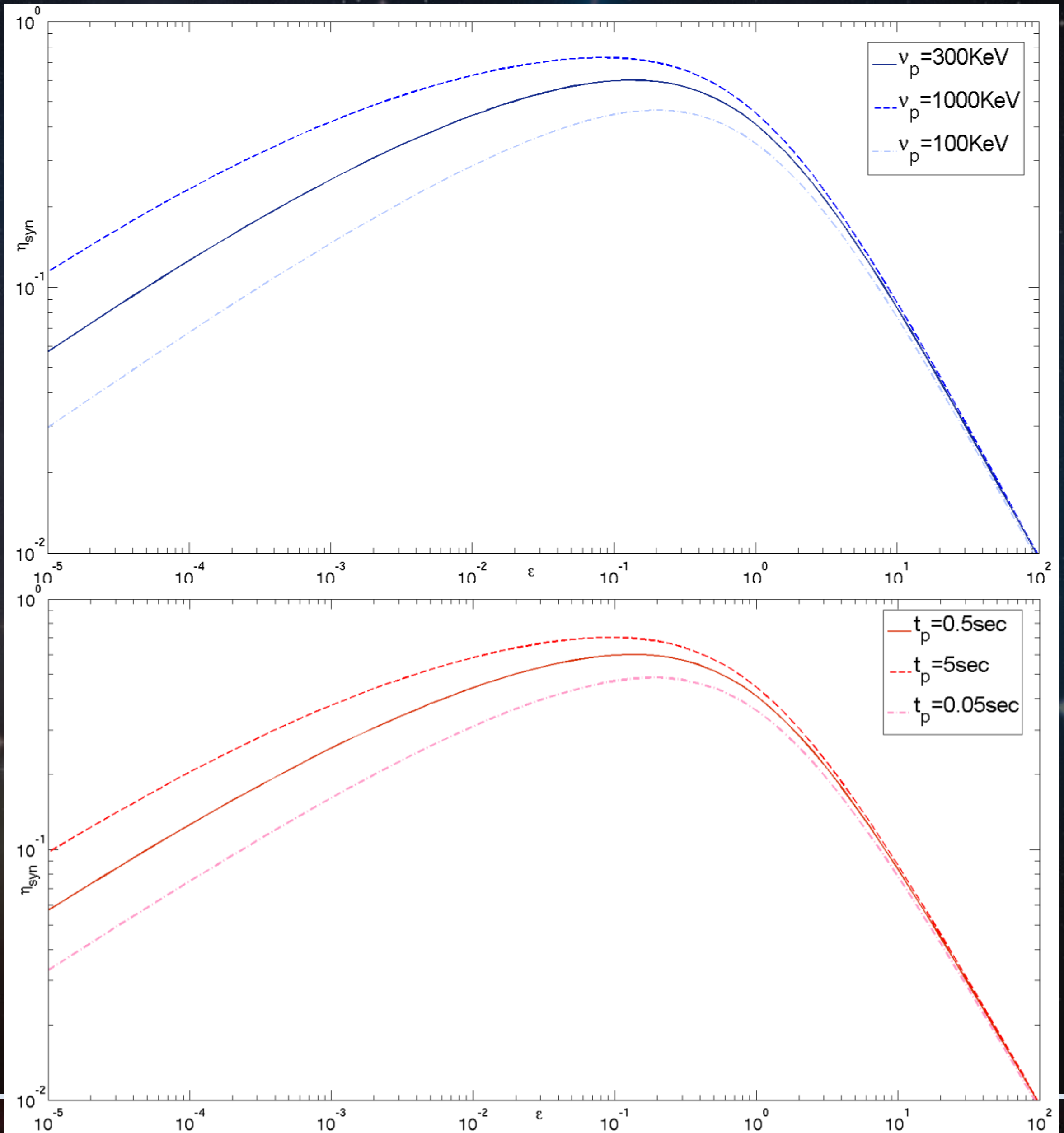


Γ
Log(B)
$\nu_c=\nu_m$
τ=1
GeV limit (α=-1)
GeV limit (α=-1.5)
R=R_d (ISM)
R=R_d (Wind)

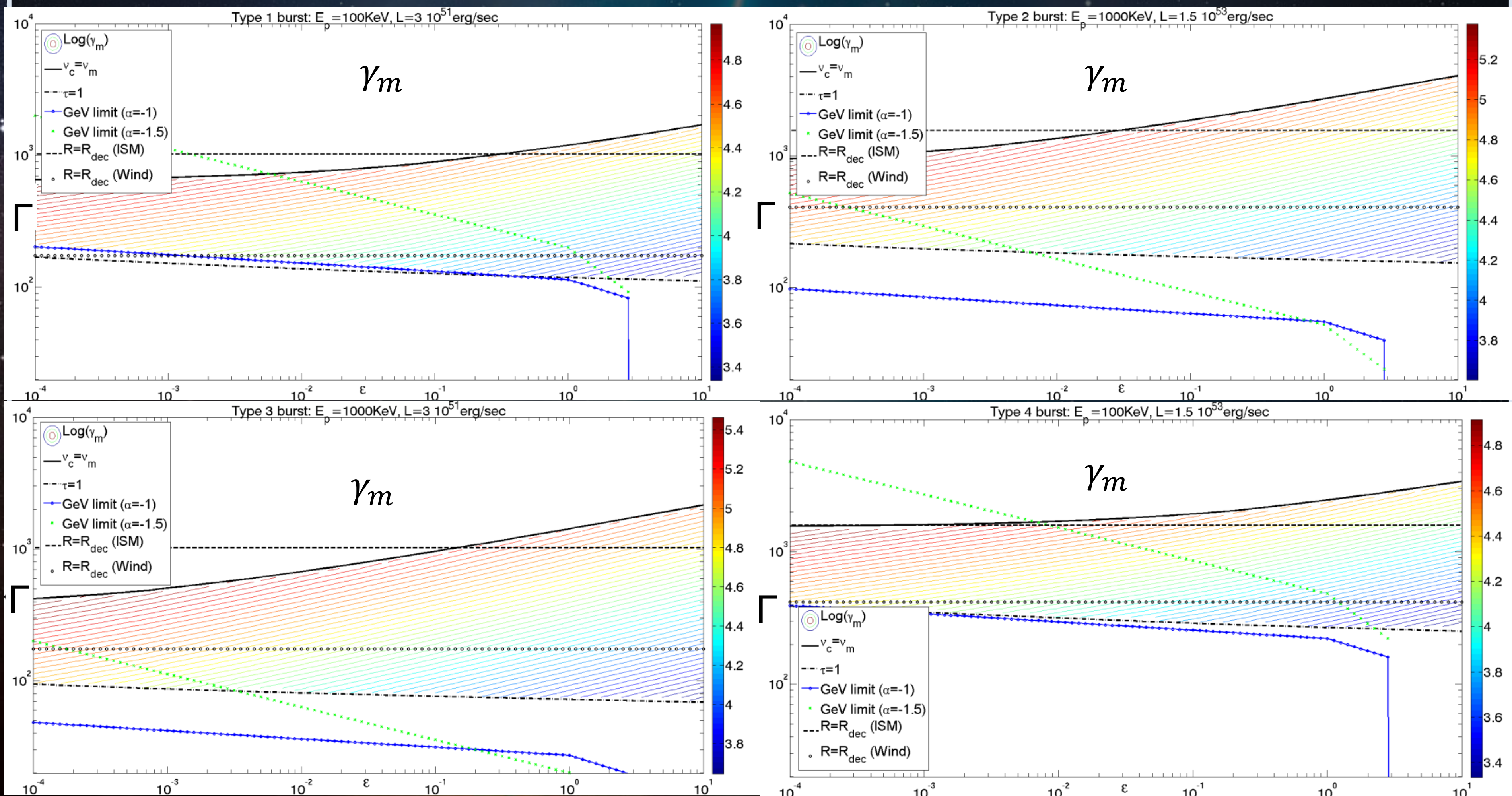


Γ
ε
Log(R)
$\nu_c=\nu_m$
τ=1
GeV limit (α=-1)
GeV limit (α=-1.5)
R=R_{dec} (ISM)
R=R_{dec} (Wind)

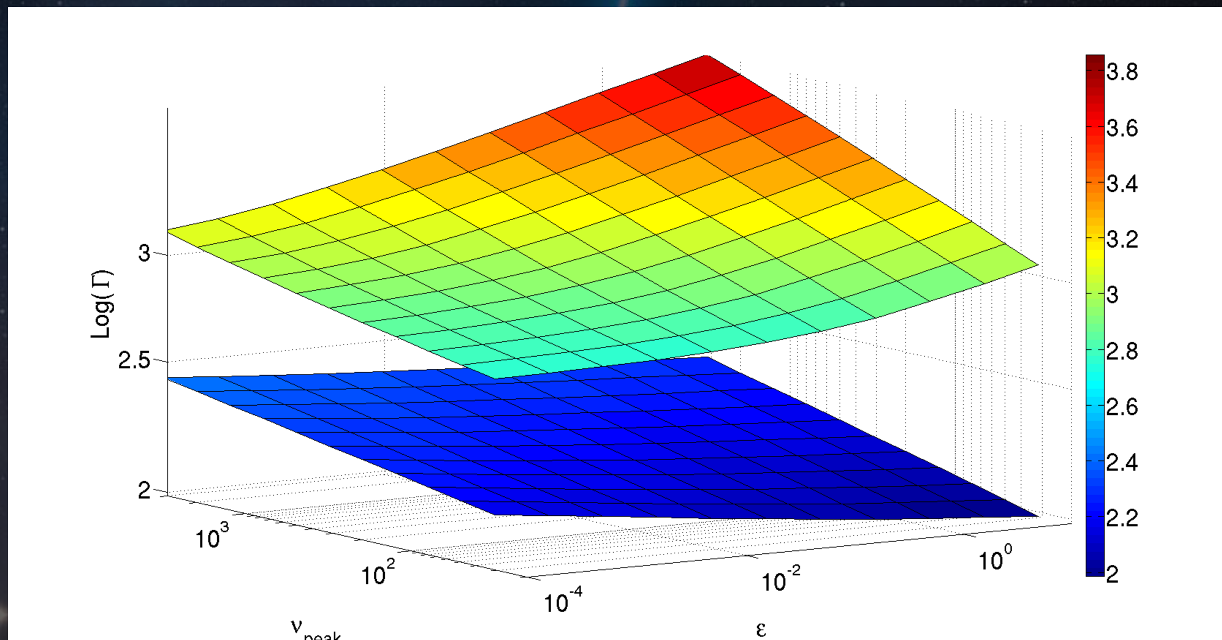
Synchrotron efficiency

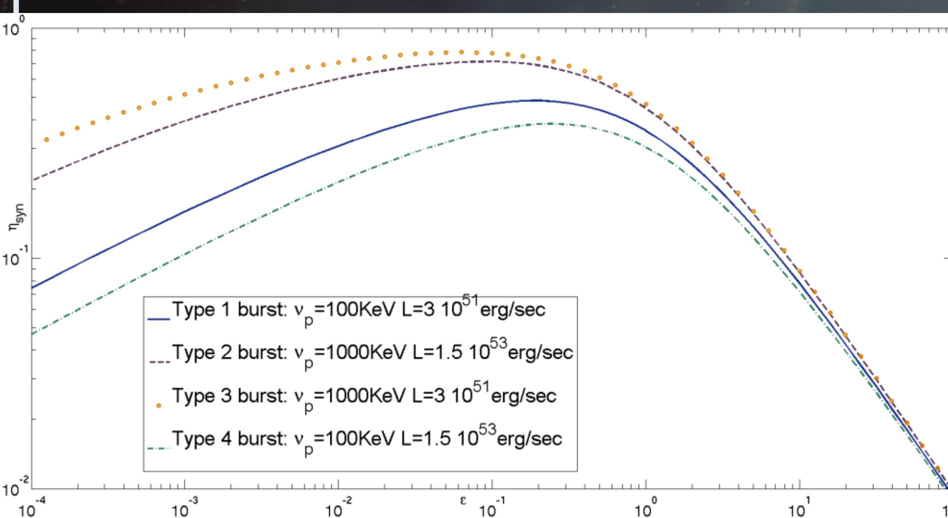


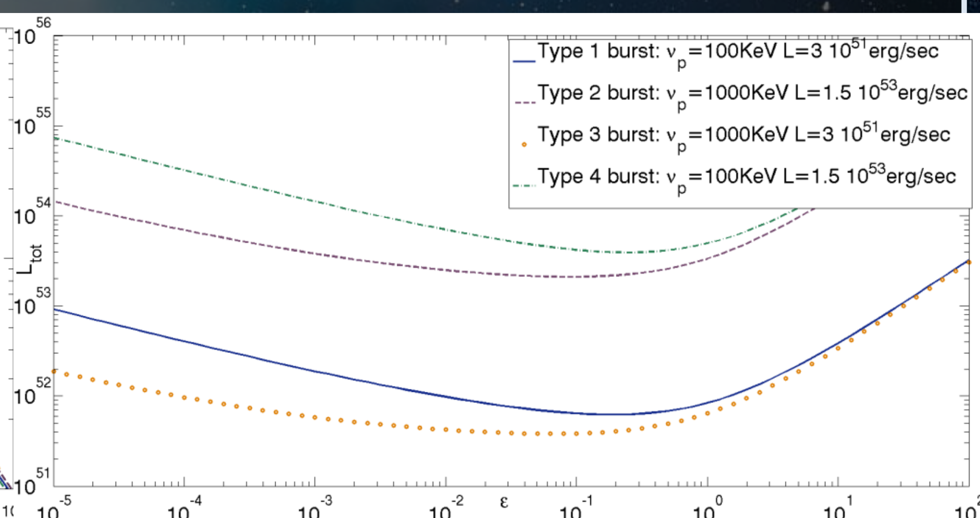
Changing observables and $E_p - L_p$ relation



Changing observables and $E_p - L_p$ relation







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: $\Delta t_{\theta,obs} = \frac{R}{c}(1 - cos\,\theta) \approx \frac{R}{2c\Gamma^2}$

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

The shape of the light-curves

Pulse asymmetry

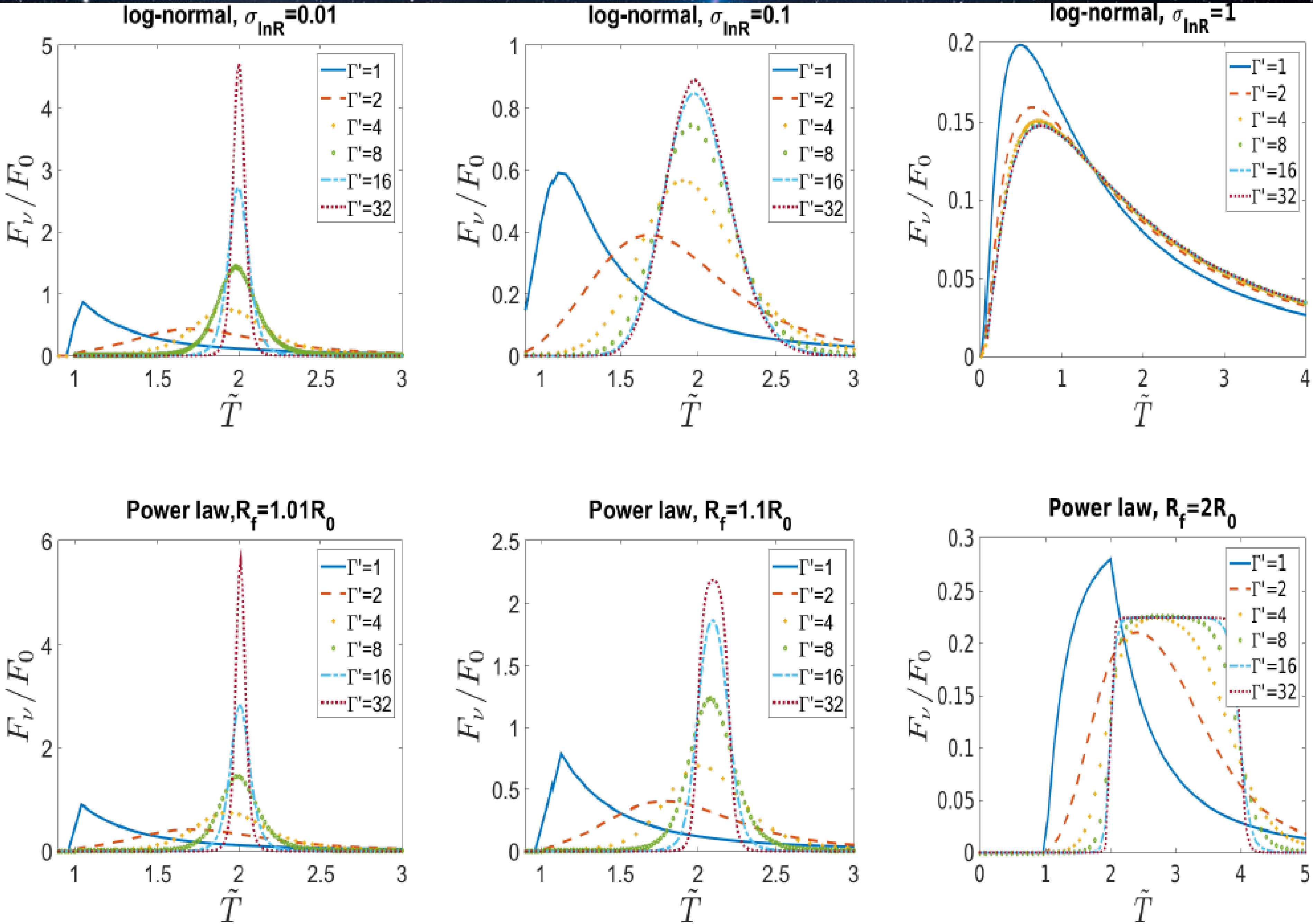
GRB pulses are asymmetric with average rise to decay ratio of 0.3-0.5
(Nemiroff 94, Fishman & Meegan 95, Norris 96, Quilligan 02, Hakkila & Preece 11)

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

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

- 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

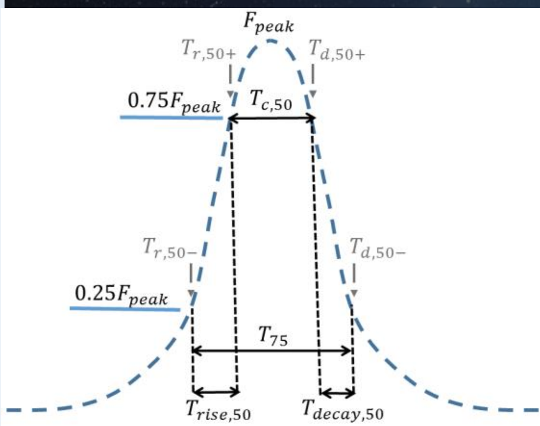
for $\frac{\Delta R}{R} < \frac{1}{\Gamma'}$ and $\Gamma' \gg 1$


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

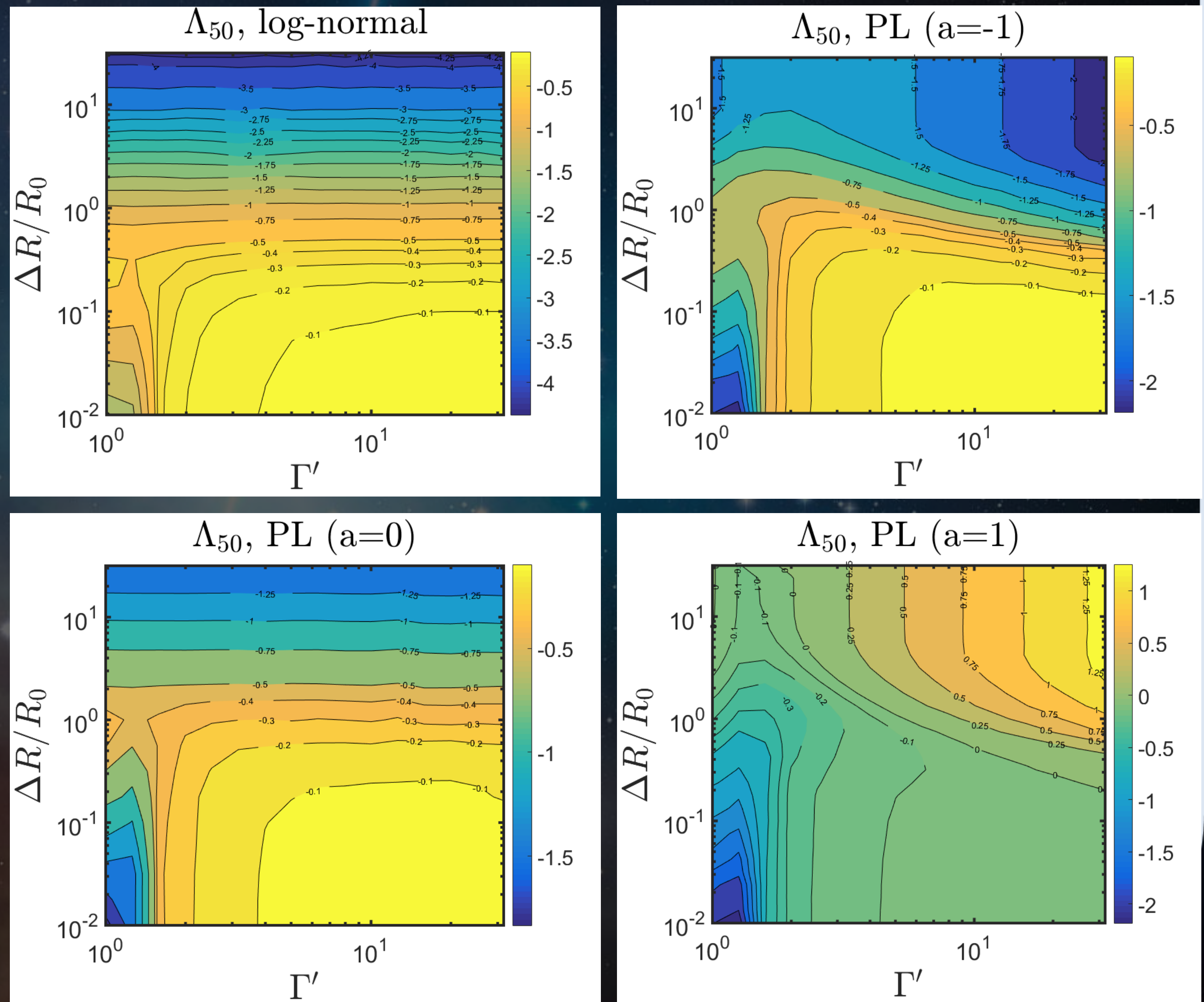
The shape of the light-curves

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

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



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



m = 0 (Γ = const)

k = 1 ("steady state" in jet's bulk frame)

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

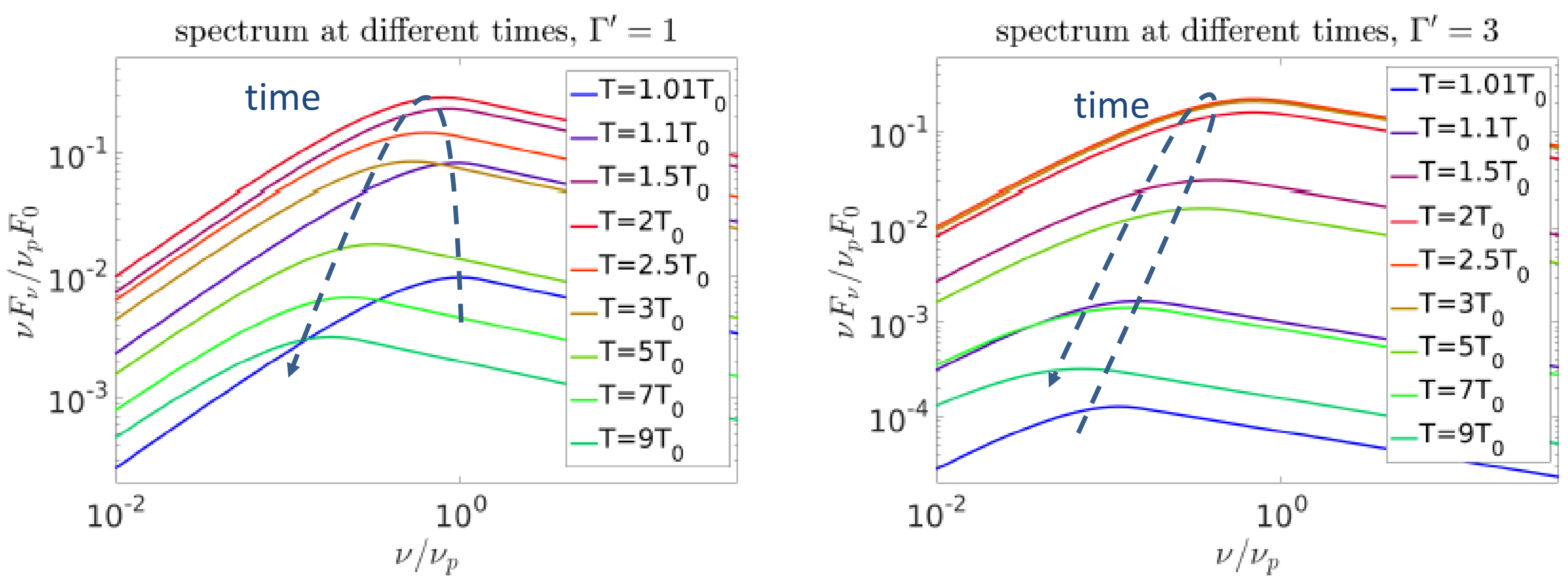
Results and comparison to observations

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)

- Spectral evolution of pulses:

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



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 thanks to the shorter angular time $\Delta t_\theta \approx R/2\Gamma^2\Gamma'$

(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:

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

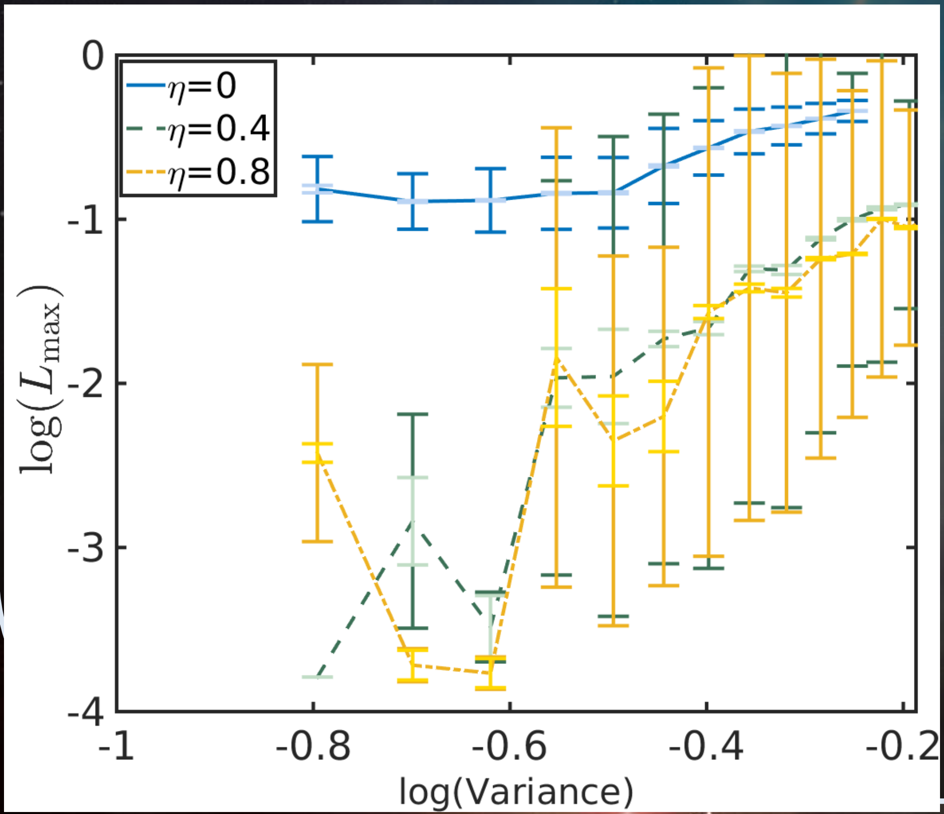
Results and comparison to observations

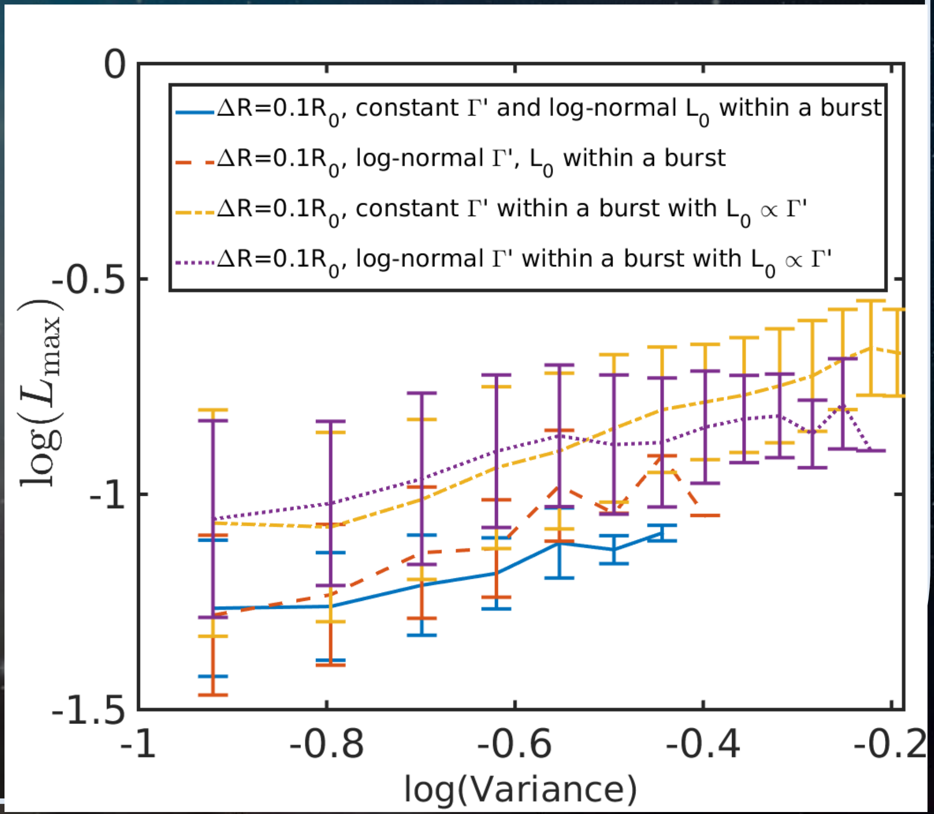
<u>Luminosity-Variability correlation</u>

Observations find more variable light-curves have larger luminosity

(Stern 99, Fenimore & Ramirez Ruiz 00, Reichart 01)

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





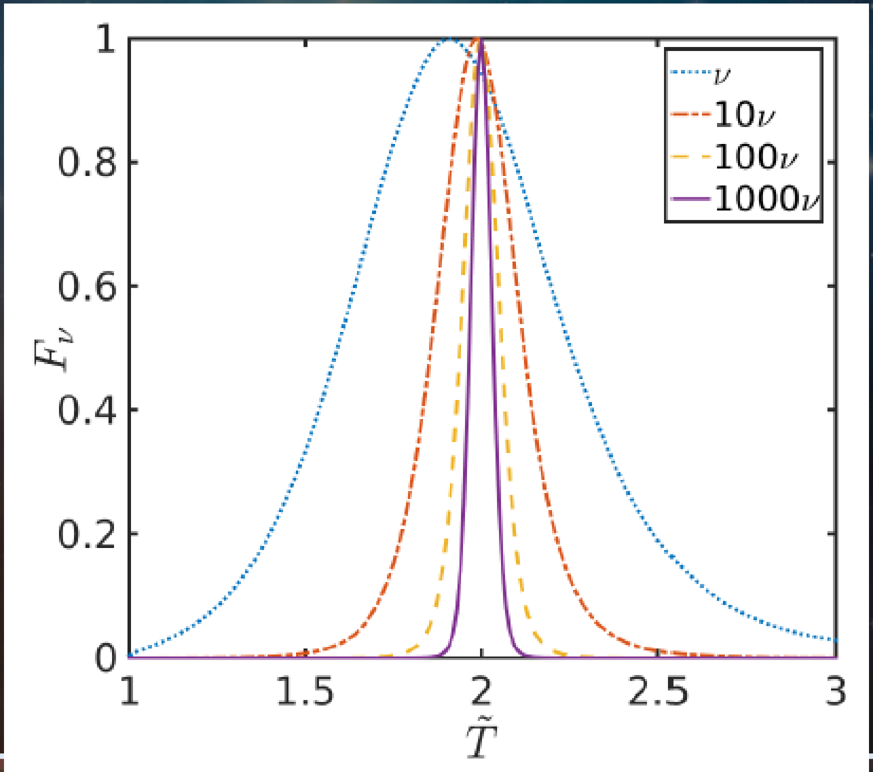
Results and comparison to observations

<u>Pulse widths and spectral lags</u>

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



Predicted Observed Images (JG 2016)

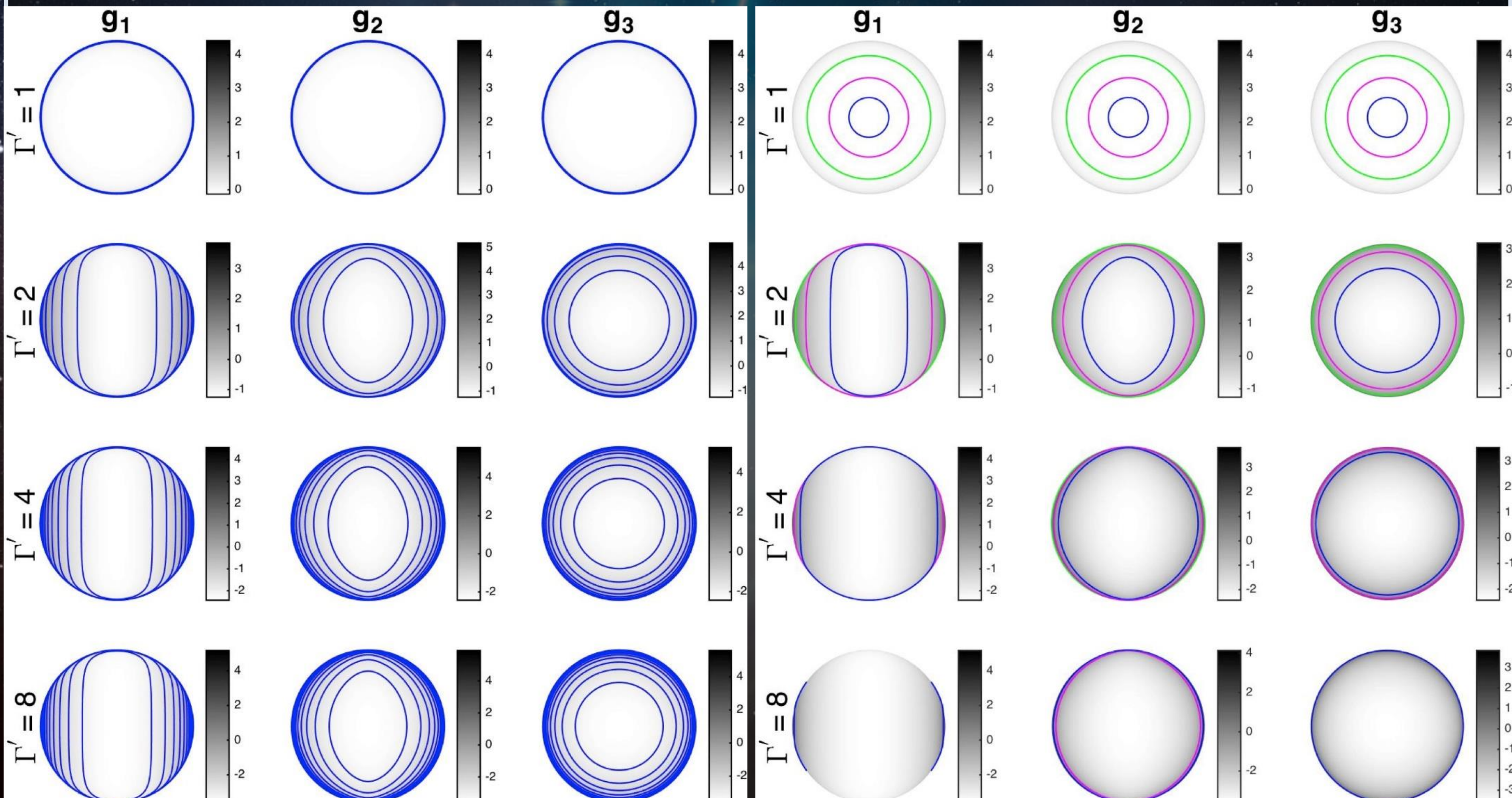
$m = a = 0$
$k = \alpha = 1$
$L_\nu \propto \nu^{-\alpha}$

$$g_1(\phi_v) = \frac{\delta(\phi_v) + \delta(\phi_v - \pi)}{2} \,,$$
$$g_2(\phi_v) = \frac{\cos^2\phi_v}{\pi} \,, \quad g_3(\phi_v) = \frac{1}{2\pi} \,,$$

Contours at:
$\log_{10}[I_\nu/\min(I_\nu)] =$ 0.5, 1, 1.5,…

Grayscale: $\log_{10}(I_\nu/\langle I_\nu \rangle)$

Contours bound regions with 50%, 80%, 95% of the total flux



Predicted Flux per Unit shell Area at a fixed R

Contours at:

$$\log_{10}\left(\frac{dF_n/dA}{\max(dF_n/dA)}\right) = 0.5, 1, 1.5, \ldots$$

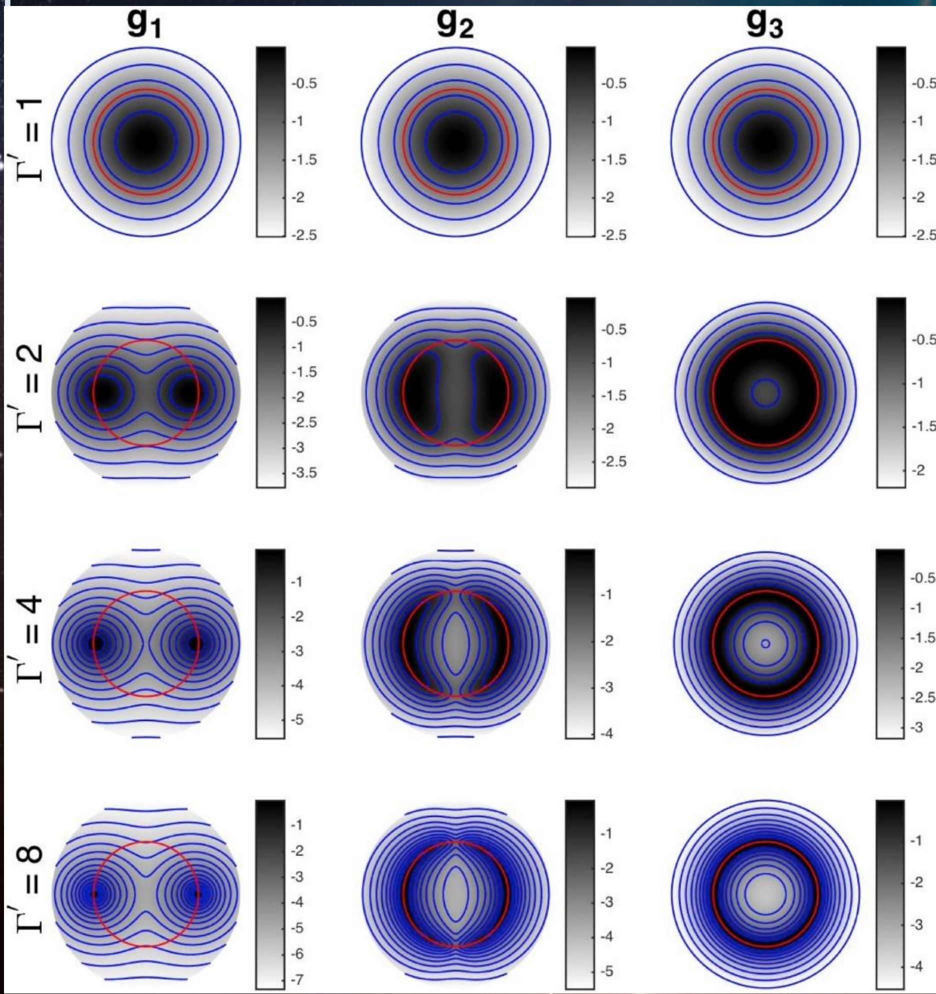
$$g_1(\phi_v) = \frac{\delta(\phi_v) + \delta(\phi_v - \pi)}{2} \, ,$$

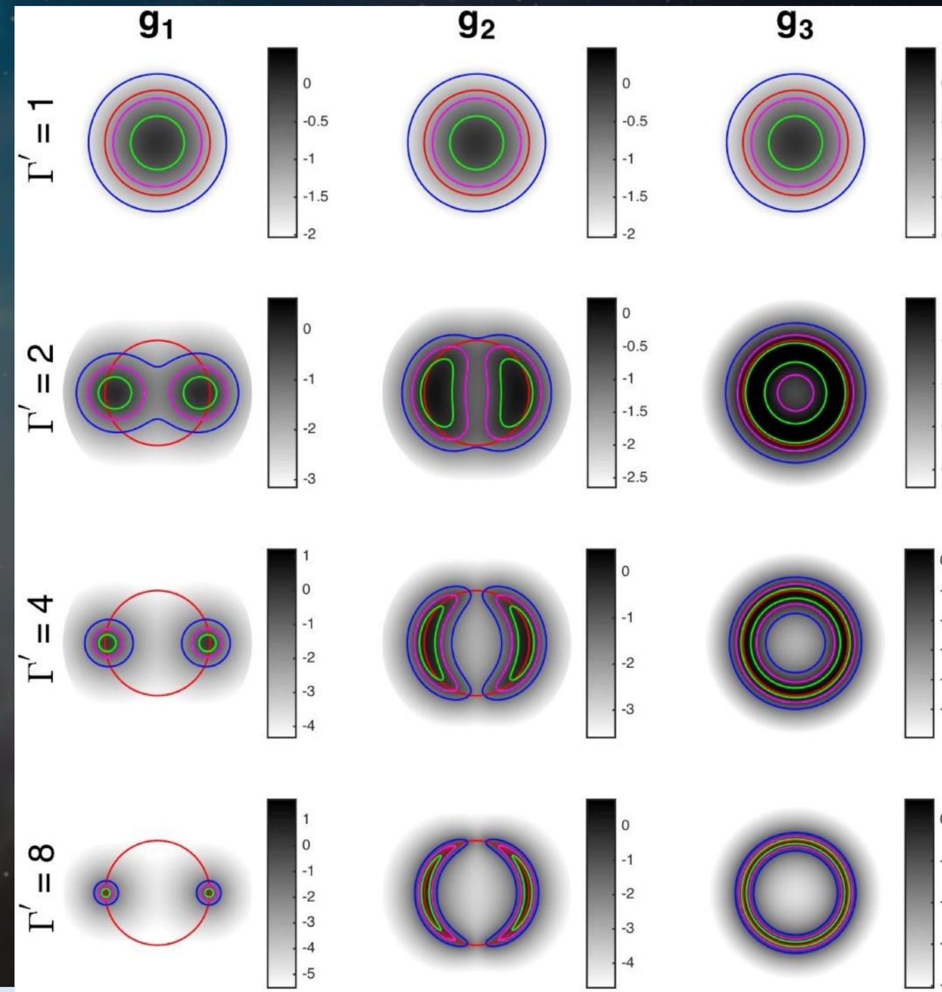
$$g_2(\phi_v) = \frac{\cos^2 \phi_v}{\pi} \, , \qquad g_3(\phi_v) = \frac{1}{2\pi} \, ,$$

Contours bound regions with 50%, 80%, 95% of the total flux

Grayscale: $\log_{10}\left[\left(dF_n/dA\right)/\max(dF_n/dA)\right]$

Red circle at θ = 1/Γ





Non-uniform emission: g-dependent variability

$$g_1(\phi_v) = \frac{\delta(\phi_v) + \delta(\phi_v - \pi)}{2}\,,$$
$$g_2(\phi_v) = \frac{\cos^2\phi_v}{\pi}\,, \quad g_3(\phi_v) = \frac{1}{2\pi}\,,$$

- For non-uniformly emitting shells this can induce variability
  - Γ = const: varying local emission
  - Γ ≠ const: also sweeps along jet
- Emission variation may reflect σ
  - Larger σ: higher Γ', larger rec. rate, harder particle spectrum
- Wider $g(\phi_v)$: larger "bright part" less variability (more averaging out of the non-uniform emission)
- Indirect information on $g(\phi_v)$ – uncertain reconnection physics

Red circle at θ = 1/Γ