Modelling the prompt and afterglow emission from Gamma-Ray Bursts

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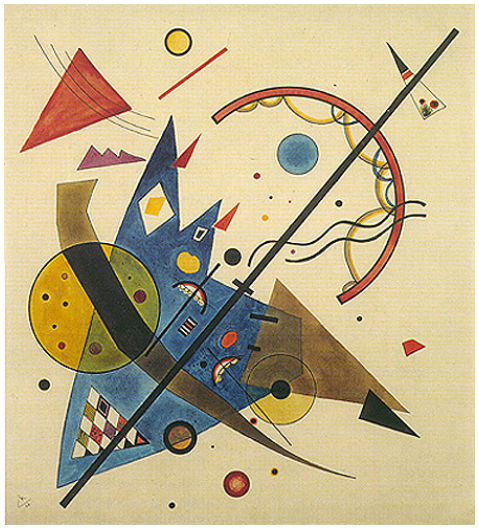


Les sursauts gamma avec Fermi, Swift et X-Shooter : situation et perspectives – Toulouse – September 23-34, 2010

Minimum requirements

- Cosmological distances (z = 0.01 → 8…) : Huge isotropic equivalent radiated energy E_{rad}
- Small timescales (t_{var} = ms → 100 s) : Small emitting region (< c t_{var})
- Non-thermal spectrum : Relativistic outflow (Γ_{min} > 100 ?)

General framework : *the different observed phases in gamma-ray bursts (prompt, afterglow) are associated to events in the life of a ultra-relativistic outflow produced by a newly formed compact source.*

Hopefully, the evolution of the relativistic jet can be understood without knowing the details of the central engine (central source + acceleration mechanism).

General framework : *the different observed phases in gamma-ray bursts (prompt, afterglow) are associated to events in the life of a ultra-relativistic outflow produced by a newly formed compact source.*

- Geometry and composition of the outflow ?

(e.g. spherical vs jet vs … ; cocoon … ;
neutron load … ;
matter vs Poyting flux vs …)

- Nature and role of the environment ?

(e.g. uniform density medium vs stellar wind vs plerion vs … ;
internal vs external mechanisms)

- Energy reservoir and extraction mechanism associated to each observed phase ?

(e.g. thermal vs kinetic vs magnetic vs … energy ;
photosphere vs internal shocks vs magnetic reconnection vs external shock vs …)

- Microphysics and radiative processes at work ?

(e.g. shock acceleration ; magnetic field amplification ; …
synchrotron radiation vs IC vs … ; leptonic vs baryonic contributions ; …)

- etc.

- Large similarities in the emission from short and long GRBs

Frequent assumption : *short and long GRBs are due to different progenitors leading to the same succession of events : formation of a compact object and ejection of a relativistic outflow. Differences in the two classes of bursts (prompt/afterglow) are then due to different initial/boundary conditions (energetics and lifetime of the central engine, circumburst environment, …*

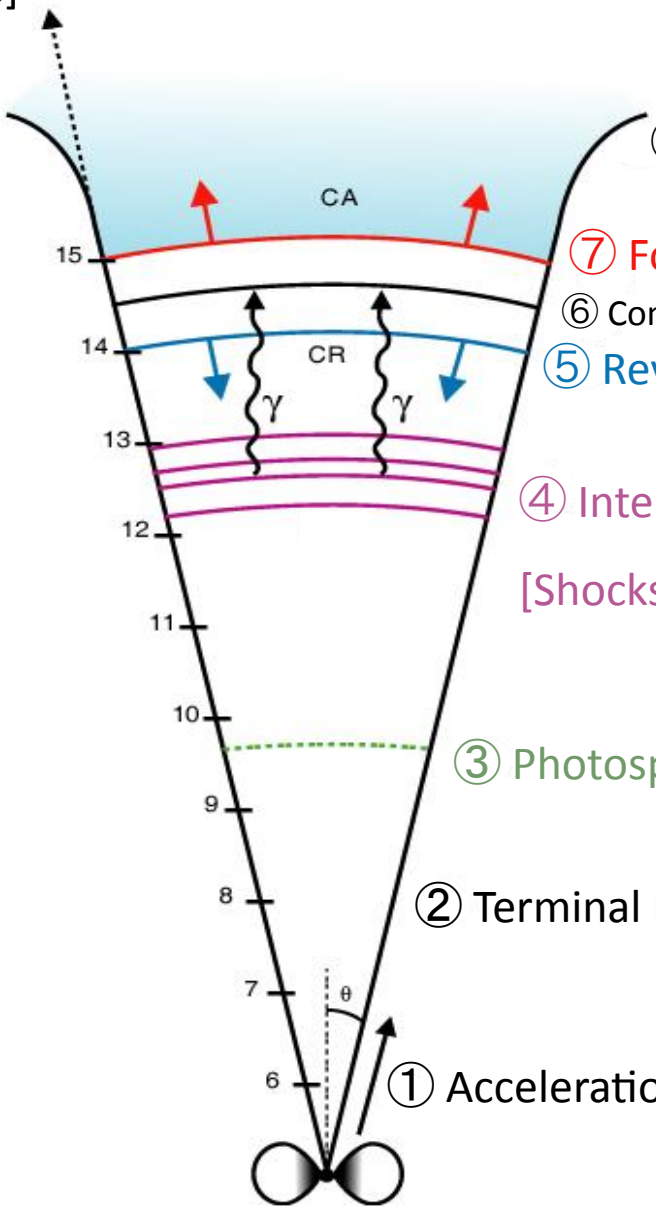
*The **afterglow** is usually interpreted as the signature of the deceleration of the relativistic outflow by the external medium.*

*As it is highly variable, the **prompt** emission has most probably an internal origin, i.e. is produced within the outflow at radii smaller than the deceleration radius.*

These ideas lead to the « standard scenario »…

(Paczynski, Rees, Meszaros, Piran, …)

« Standard » scenario



⑧ « jet-break » ? : $1/\Gamma > \theta$

⑦ Forward (external) shock → afterglow ?

⑥ Contact discontinuity

⑤ Reverse shock → optical flash ?

④ Internal dissipation → prompt emission ?

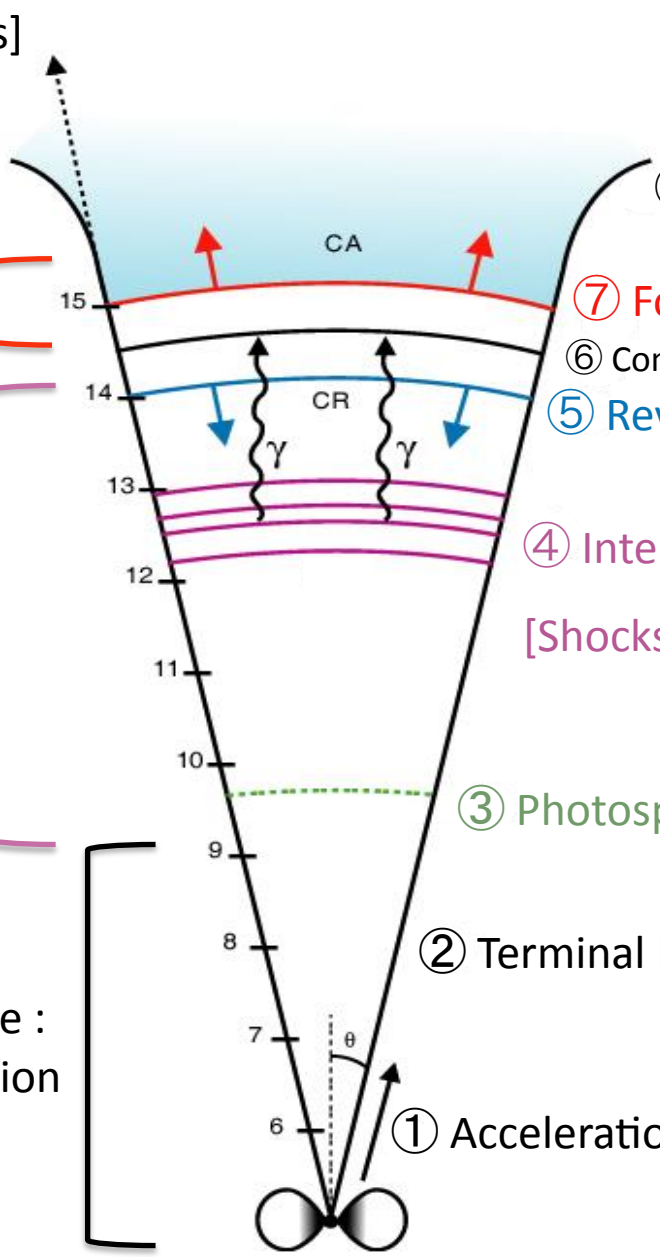
[Shocks or magnetic dissipation ?]

③ Photosphere → thermal emission ?

② Terminal Lorentz factor : $\Gamma > 100$

① Acceleration of the outflow

« Standard » scenario



Emission produced within the external medium

Emission produced within the outflow

Medium is opaque : no photonic emission

⑧ « jet-break » ? : $1/\Gamma > \theta$

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⑥ Contact discontinuity

⑤ Reverse shock → optical flash ?

④ Internal dissipation → prompt emission ?

[Shocks or magnetic dissipation ?]

③ Photosphere → thermal emission ?

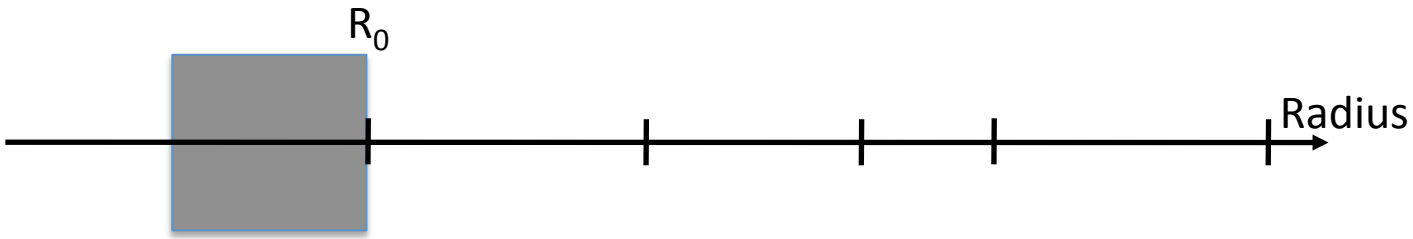
② Terminal Lorentz factor : $\Gamma > 100$

① Acceleration of the outflow

Energy reservoir ?

Extraction mechanism ?

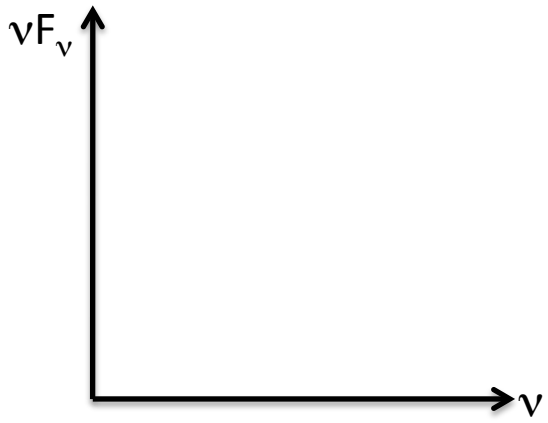
Prompt emission | Energy reservoir / extraction mechanism



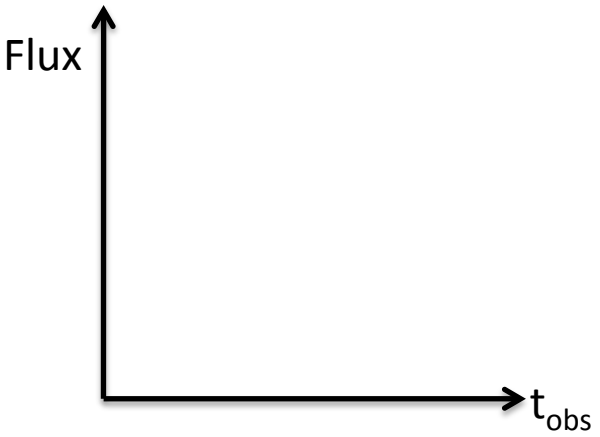
Ejection

[Central engine is active during Δt_{eng}]

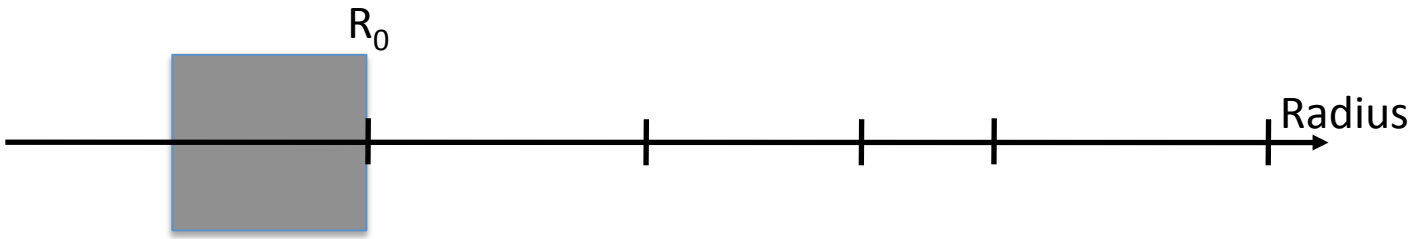
Obs. Spectrum



Obs. lightcurve



Prompt emission | Energy reservoir / extraction mechanism

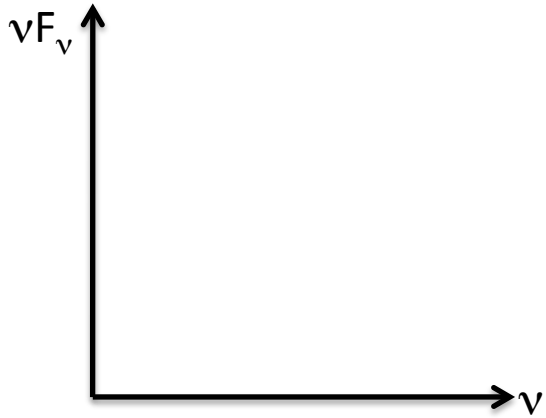


Ejection

[Central engine is active during Δt_{eng}]

Scenario (1) Magnetization is negligible

Obs. Spectrum



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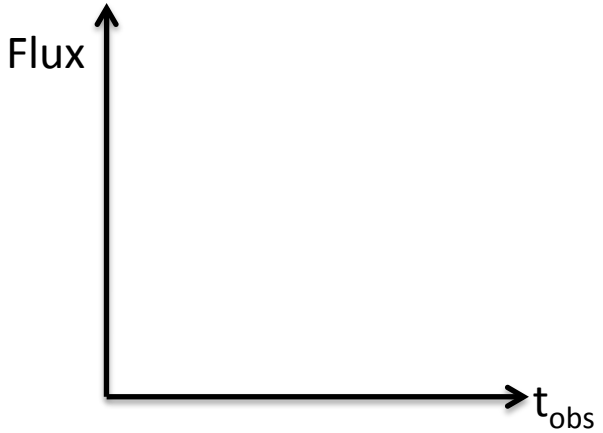
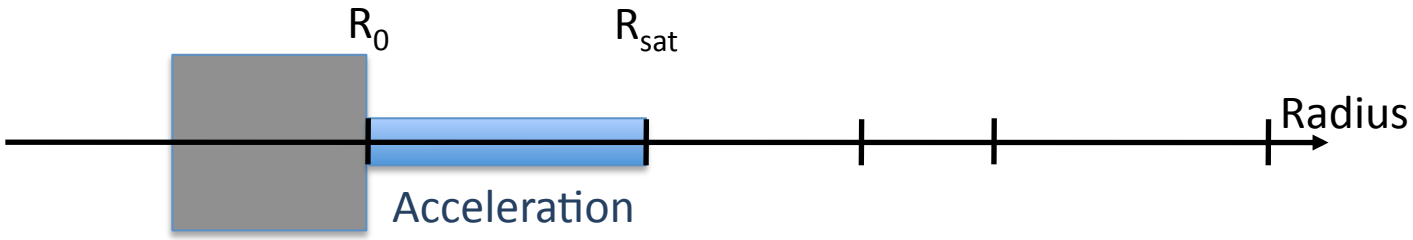


Prompt emission | Energy reservoir / extraction mechanism



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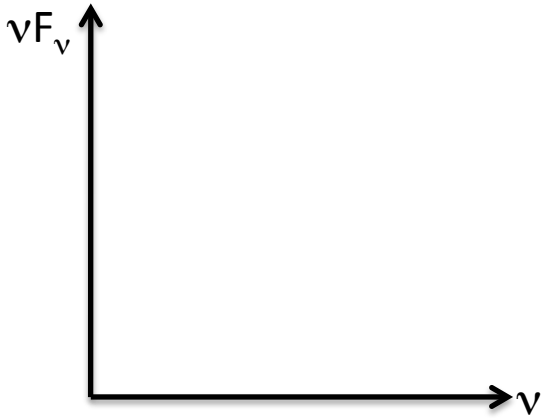

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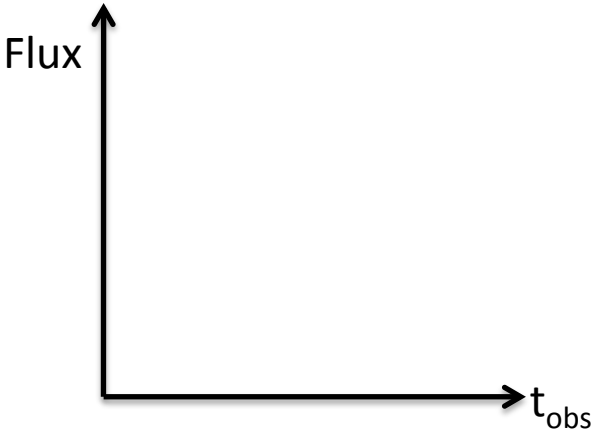

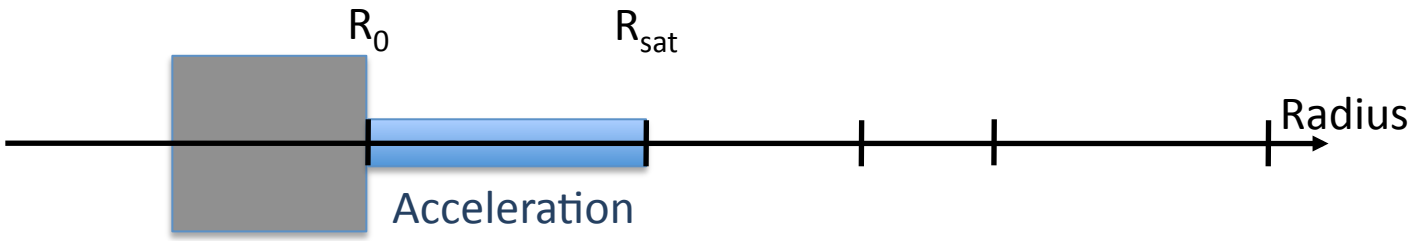

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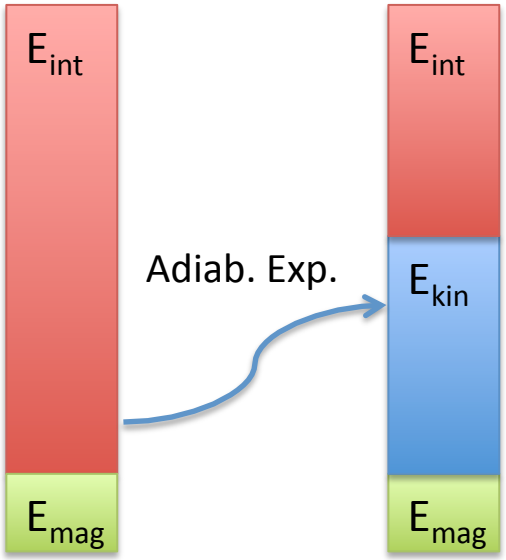
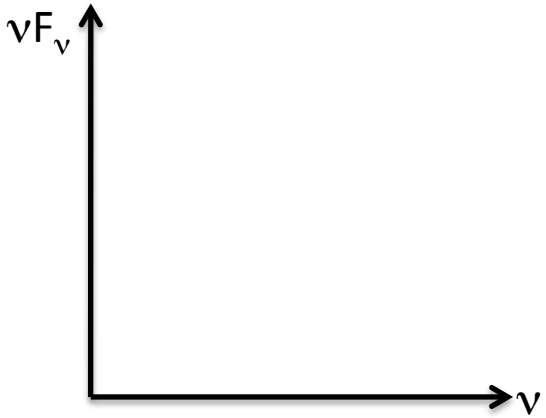


Obs. Spectrum



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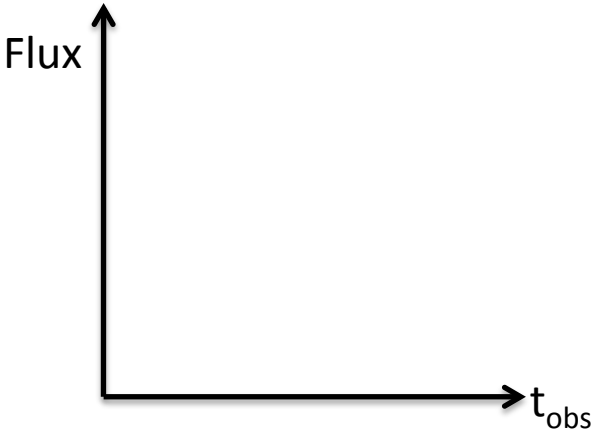

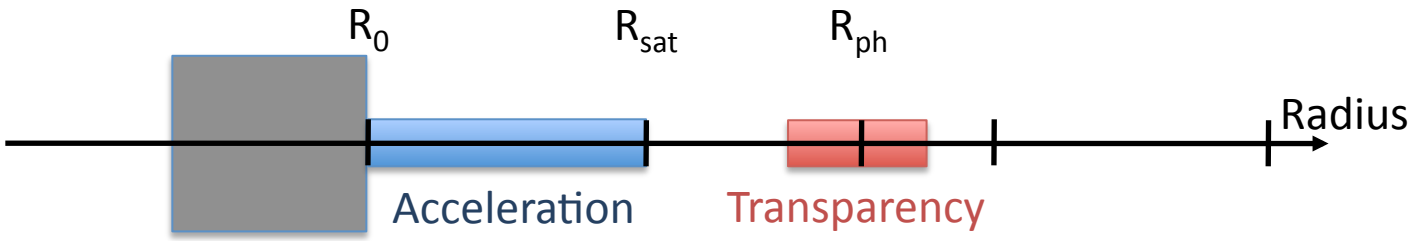

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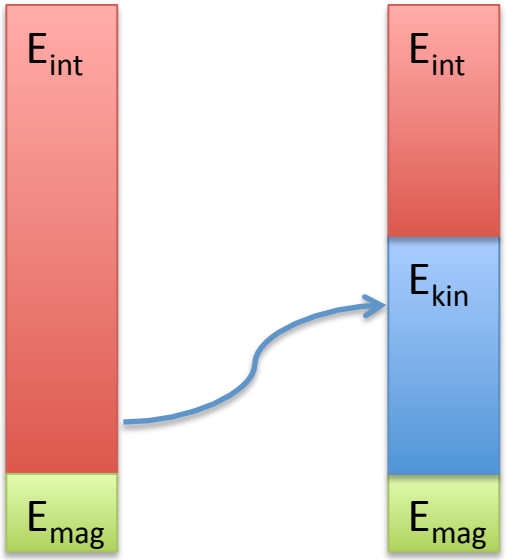

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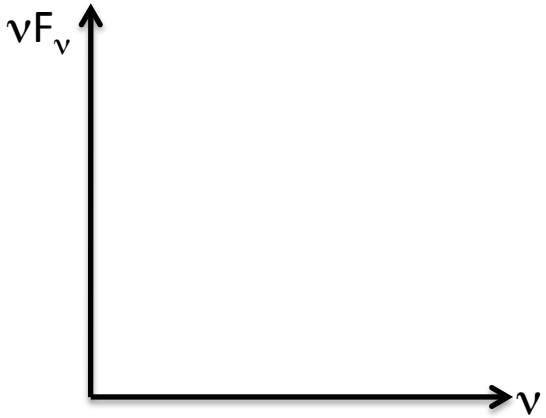

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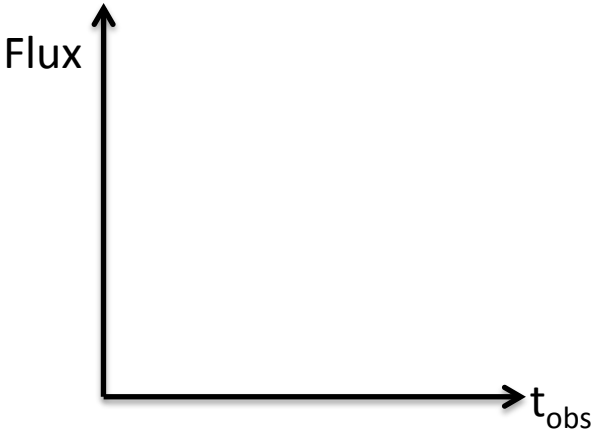
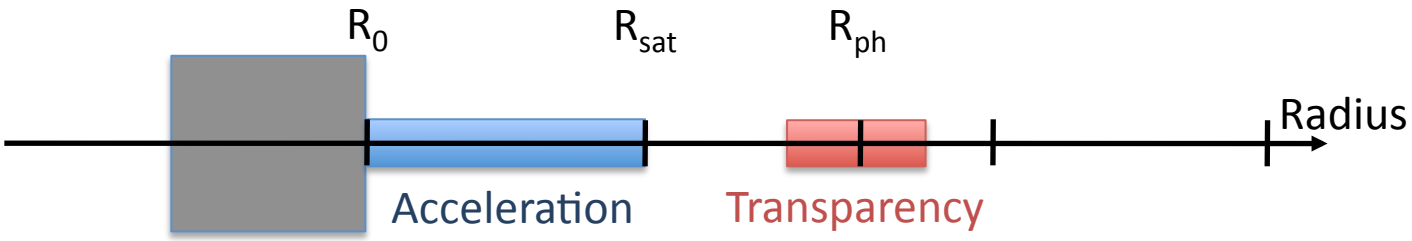


Prompt emission | Energy reservoir / extraction mechanism



Ejection

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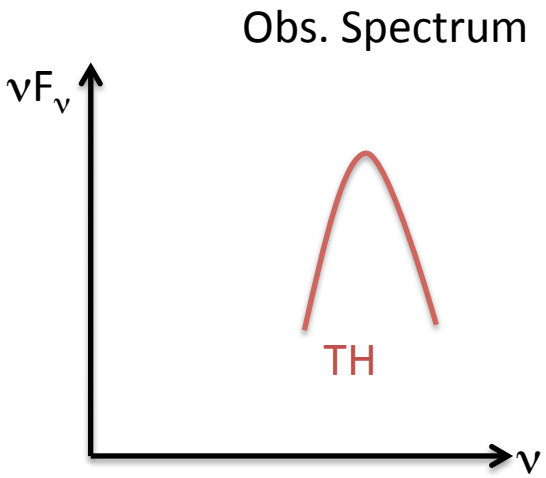
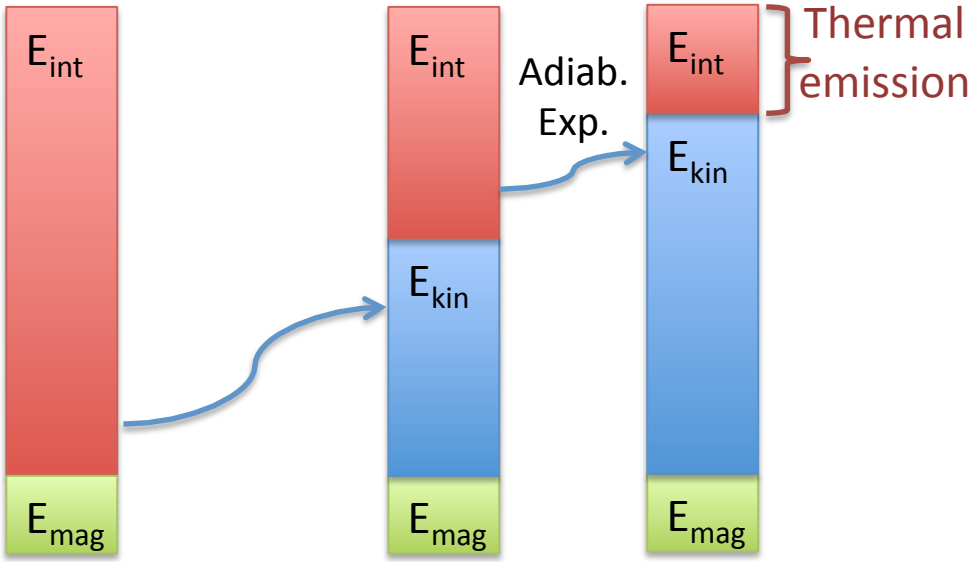
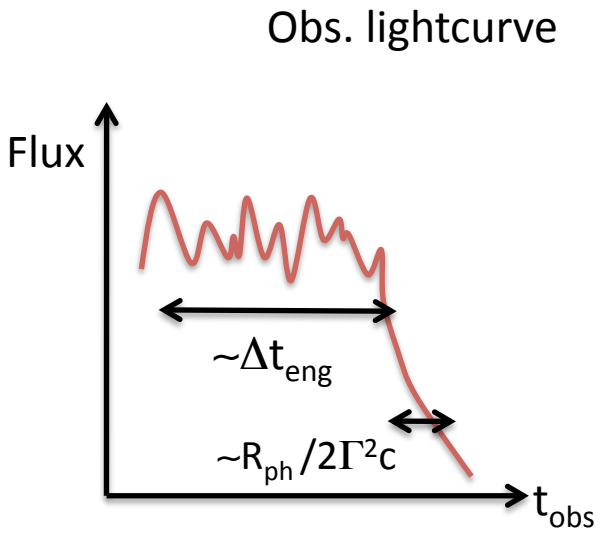
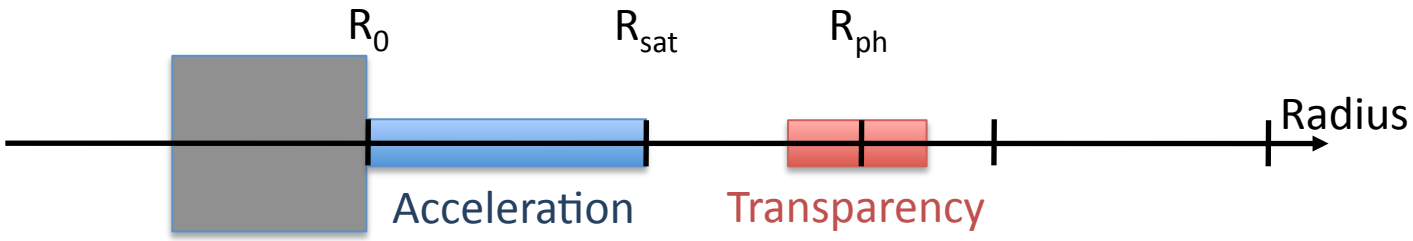


Scenario (1) Magnetization is negligible







Ejection

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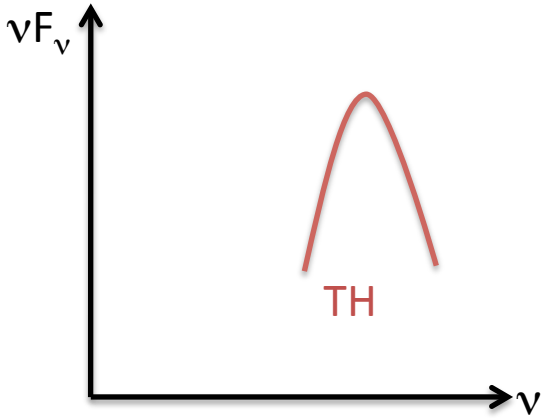
Obs. Spectrum



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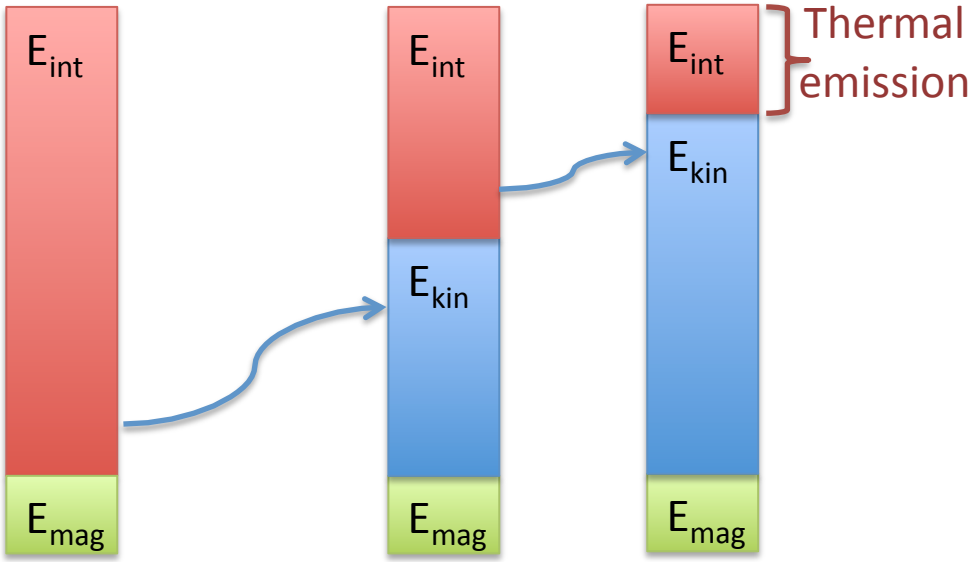
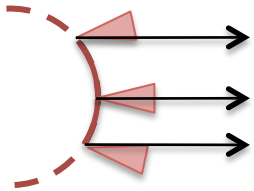
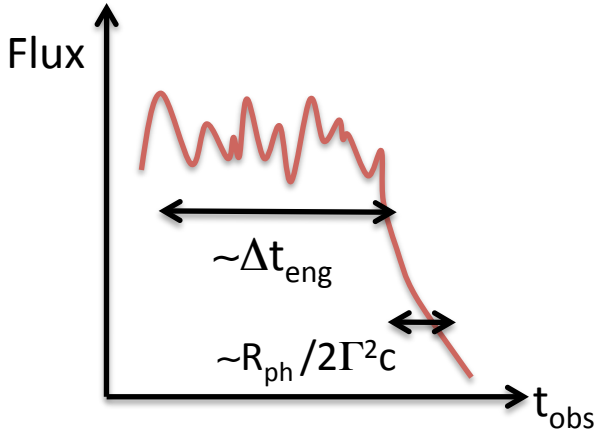
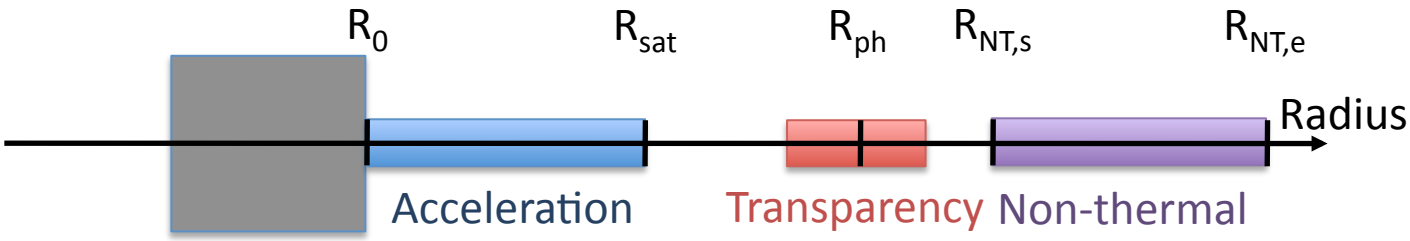




Tail due to high (co-)latitude emission

Obs. lightcurve





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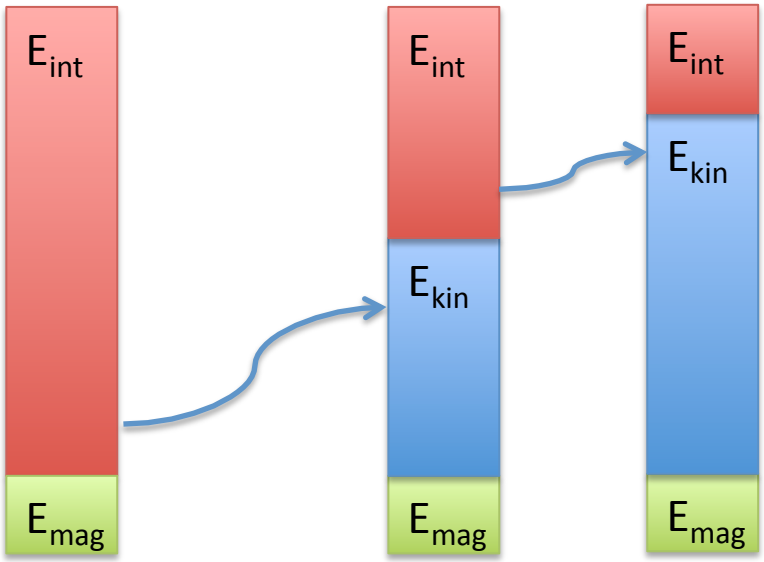
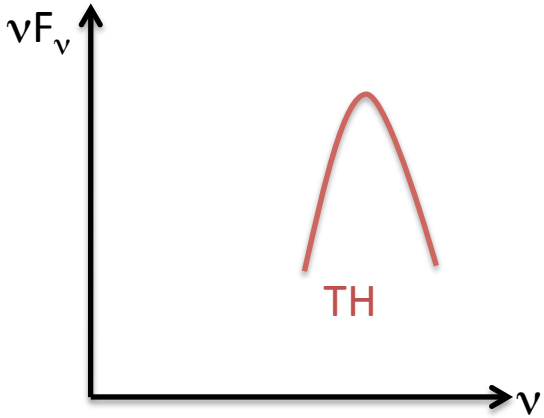


Obs. Spectrum



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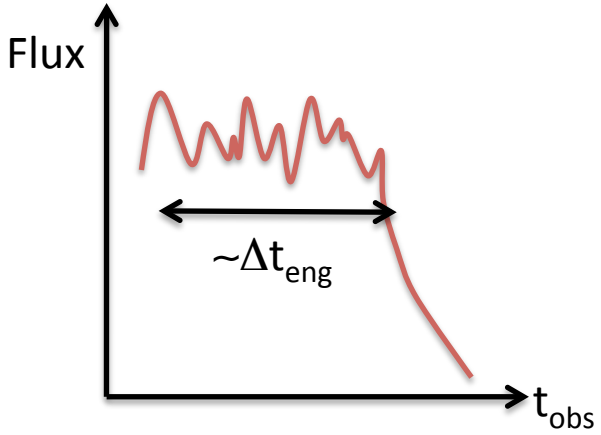
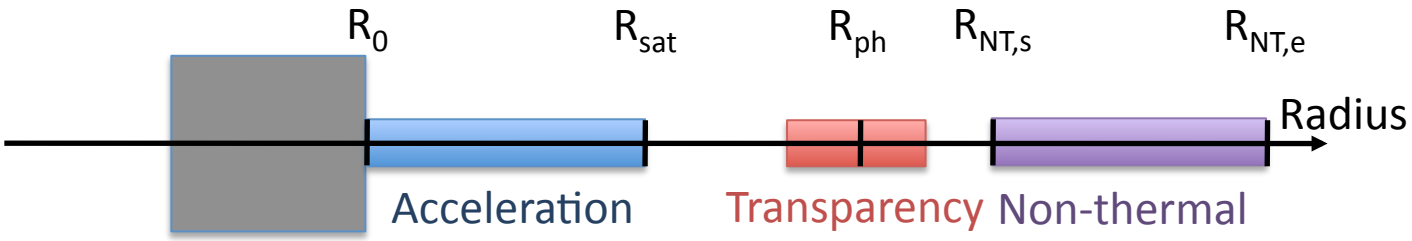


Prompt emission

Energy reservoir / extraction mechanism



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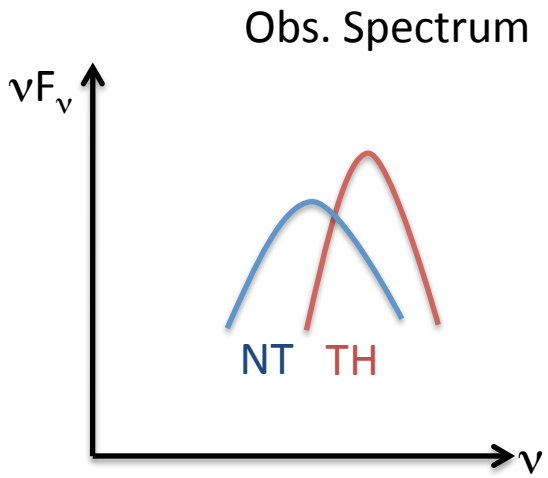
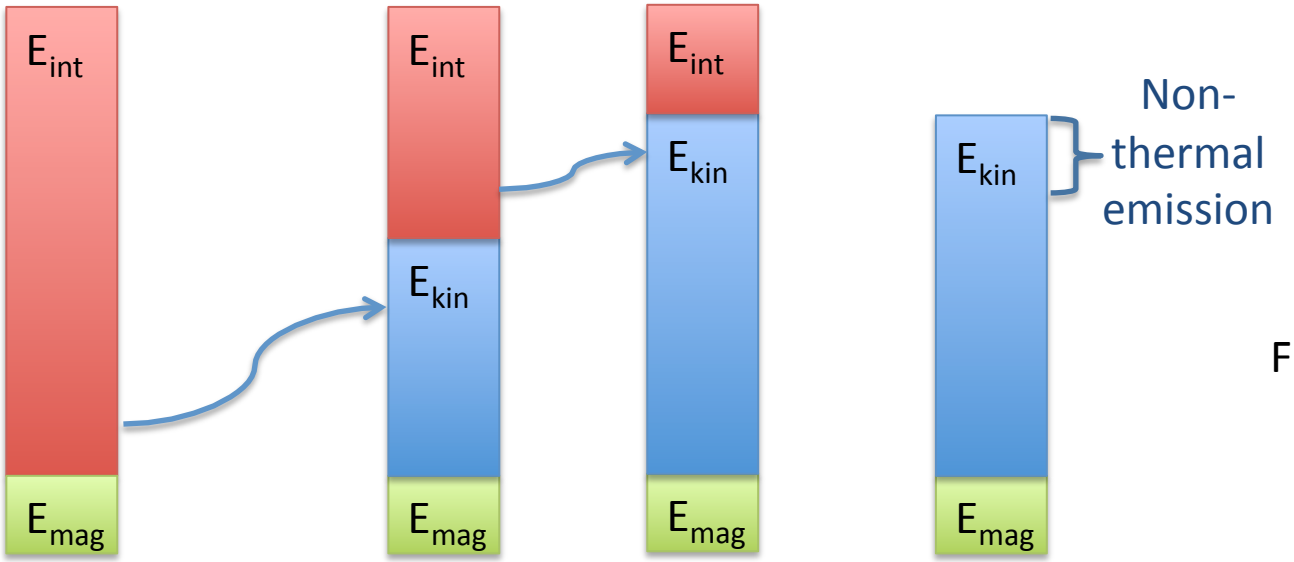
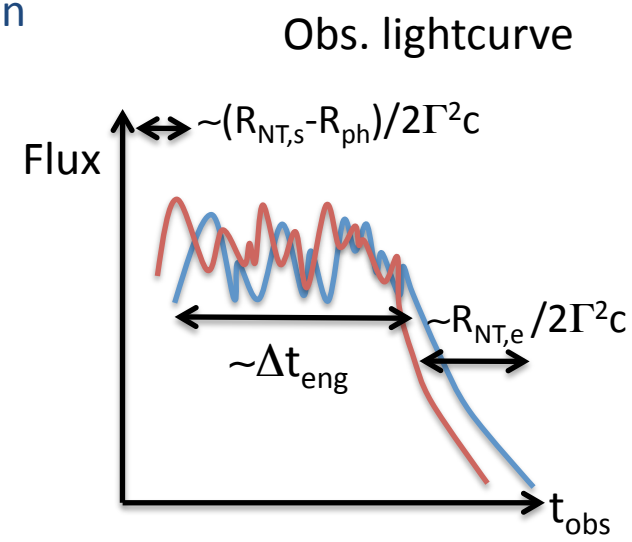
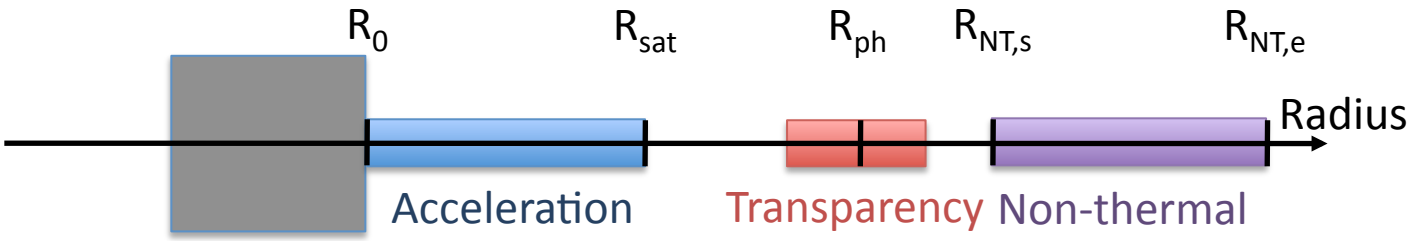


Scenario (1) Magnetization is negligible





Prompt emission | Energy reservoir / extraction mechanism



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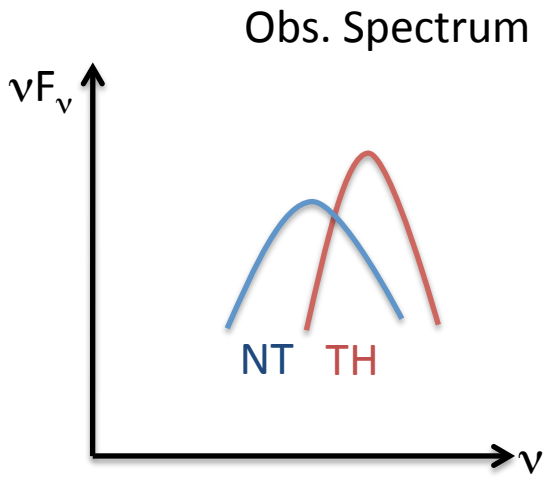

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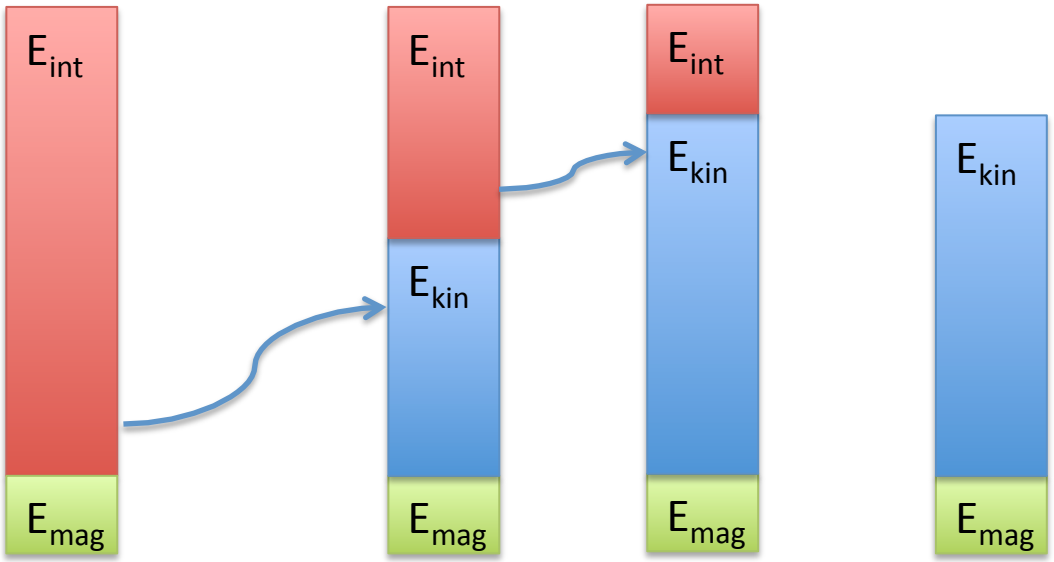
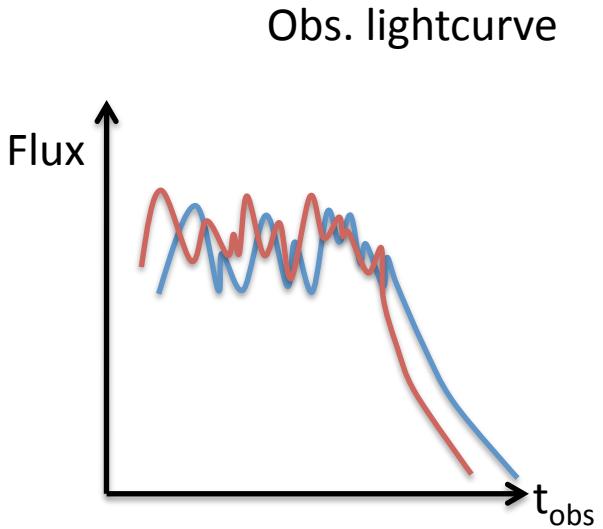


Internal shocks ?



Prediction : strong thermal components in the prompt spectrum except if (a) efficiency of internal shock is very high ; or (b) $R_{ph} >> R_{sat}$

Scenario (1) Magnetization is negligible : photosphere + internal shocks

- Photospheric emission : - can be computed (during the activity and the HLE tail)
  - spectrum may be more complicated than BB (multicolor BB ; comptonization ; etc…)

(Goodman 86, Meszaros et al. 02 ; Daigne & Mochkovitch 02 ; Pe'er et al. 07, 08, 10 ; Beloborodov 10 ; …)

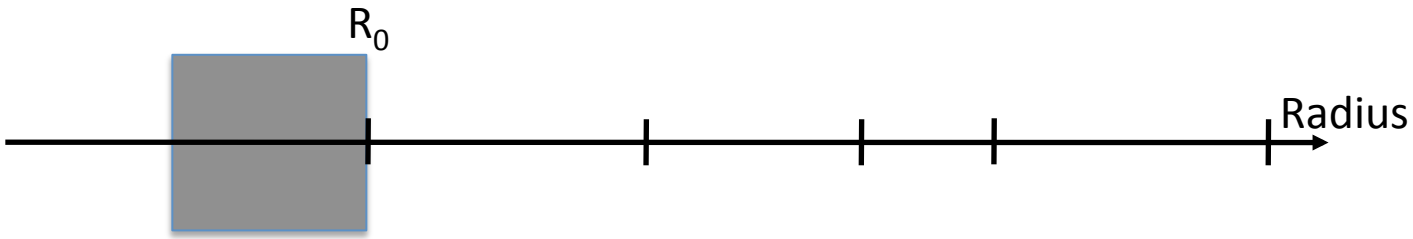
- Internal shocks : - dynamics can be computed (mildly relativistic shocks)
  - shock acceleration must be parametrized
  - radiative processes can be computed
  - spectrum may have several components
  - total efficiency can be estimated : less than 10 % ?

(Rees & Meszaros 94 ; Kobayashi et al. 97 ; Daigne & Mochkovitch 98, 00, 03 ; Bosnjak et al. 09 ; …)

- **In most cases, the photospheric emission should dominate : excluded by observations ?**

(BATSE spectroscopic catalog ; analysis of GRB 080916C by Zhang & Pe'er ; analysis of most Fermi-LAT GRBs that are well fitted by a Band function ; …)

- **Main uncertainties in this scenario** : - acceleration mechanism for the outflow
  - shock acceleration (B, electrons, protons ?)

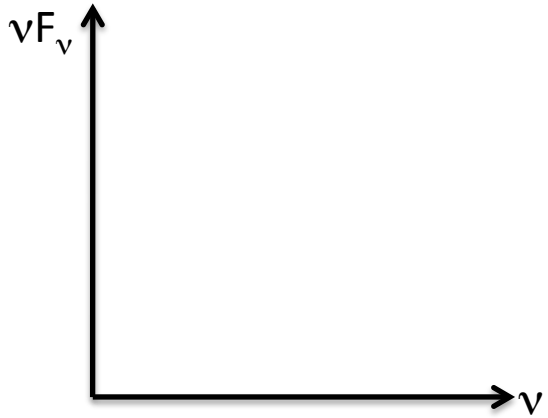


Ejection

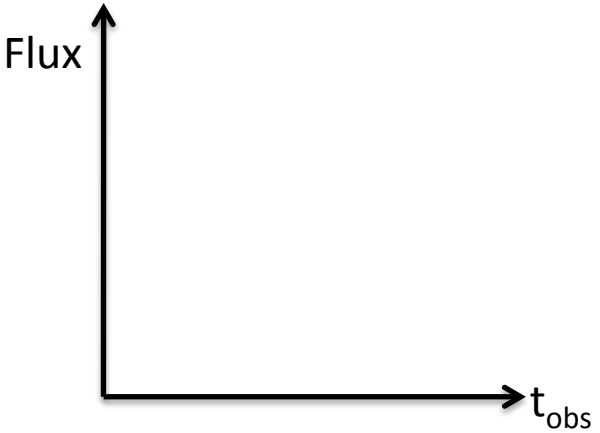
[Central engine is active during Δt_{eng}]

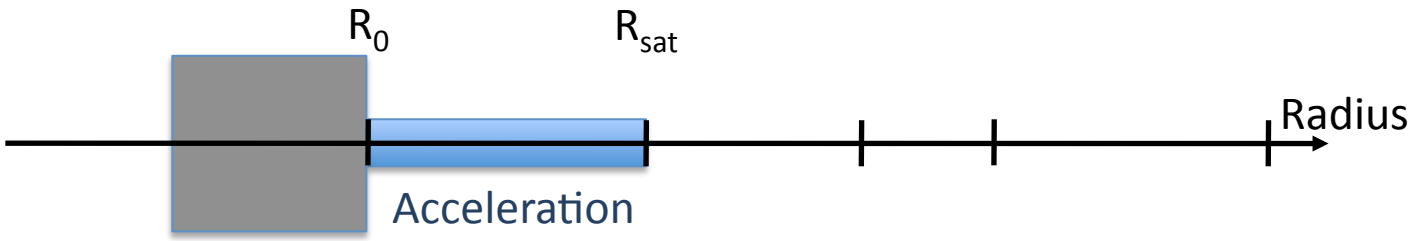
Scenario (2) Initial magnetization is high

Obs. Spectrum



Obs. lightcurve

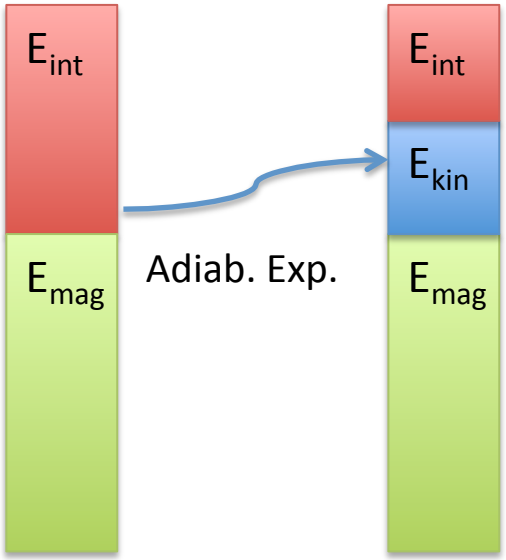




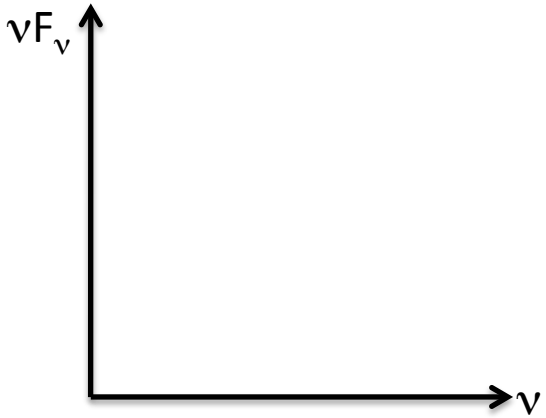
Ejection

[Central engine is active during Δt_{eng}]

Scenario (2A) Initial magnetization is high – No early dissipation



Obs. Spectrum



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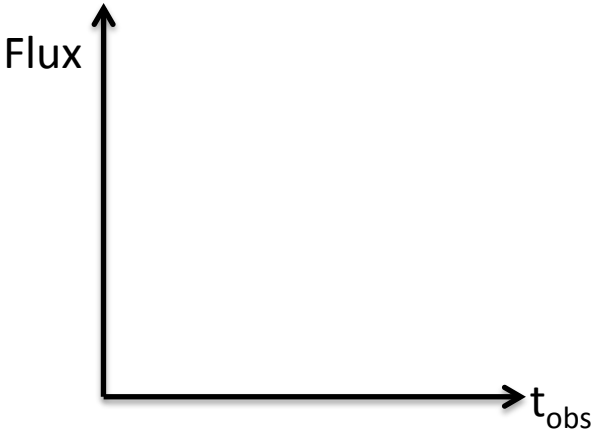
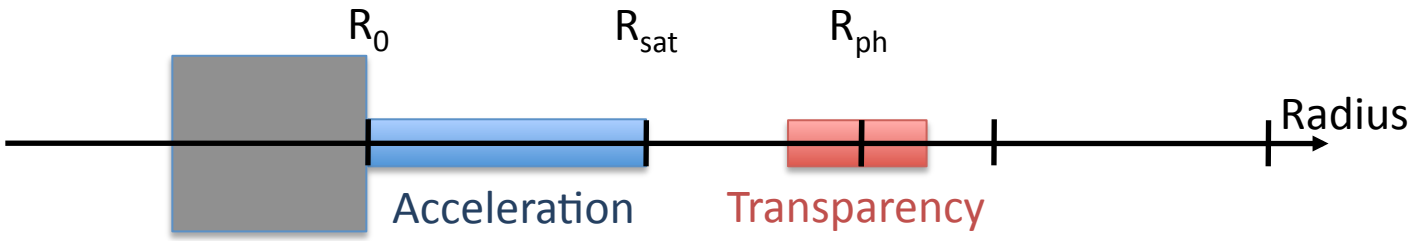
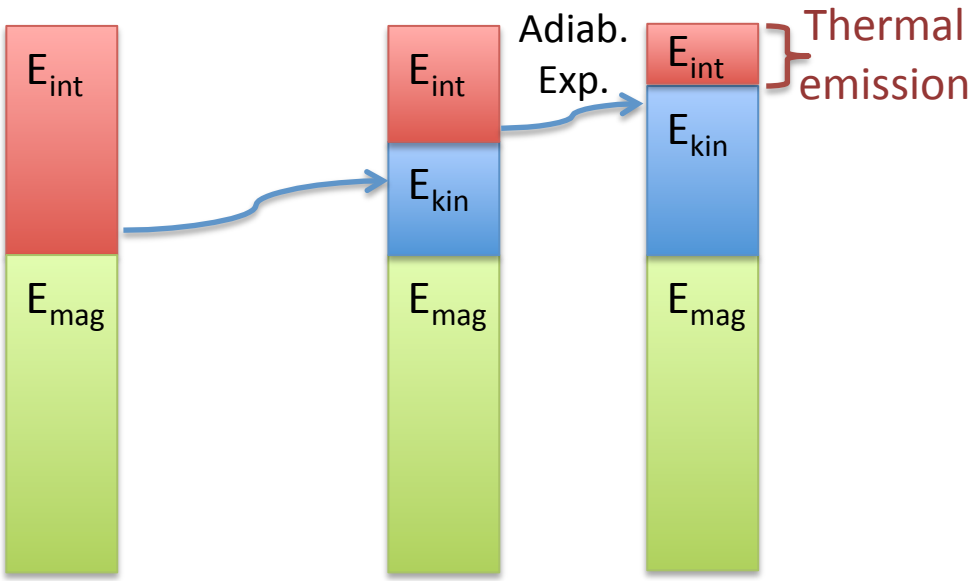




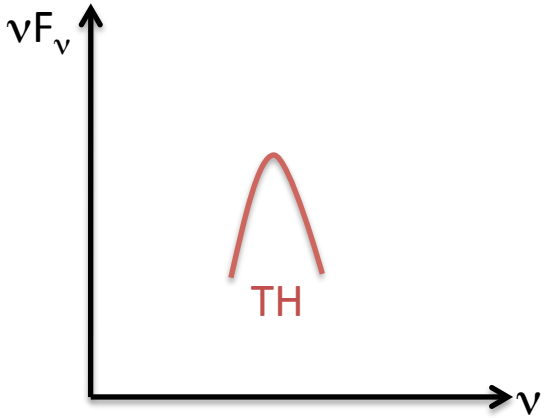
Ejection

[Central engine is active during Δt_{eng}]

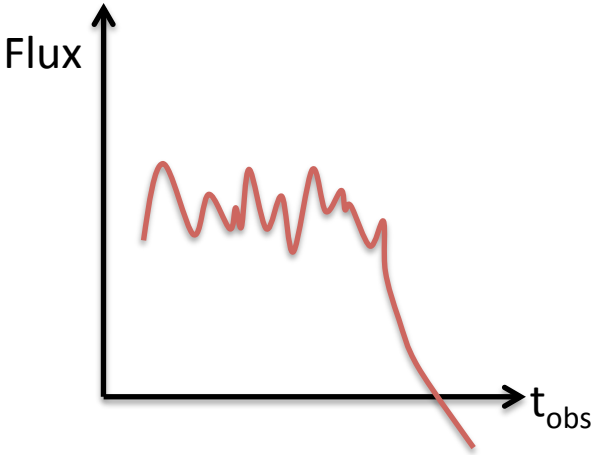
Scenario (2A) Initial magnetization is high – No early dissipation

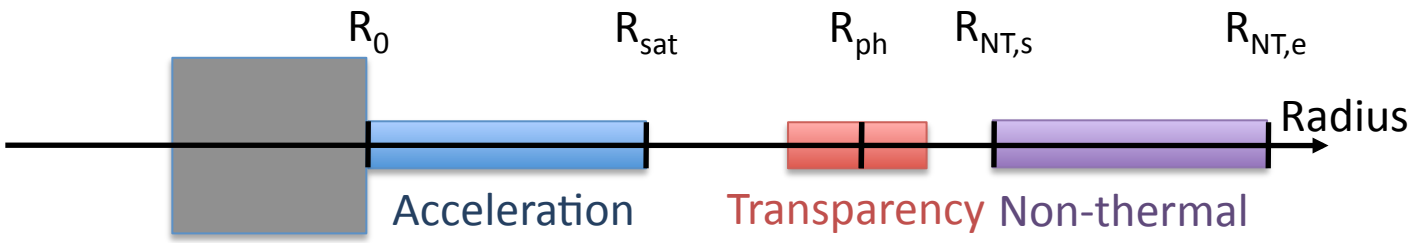


Obs. Spectrum

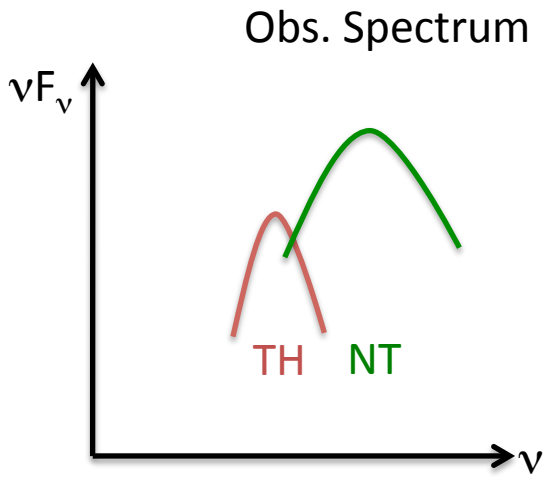


Obs. lightcurve

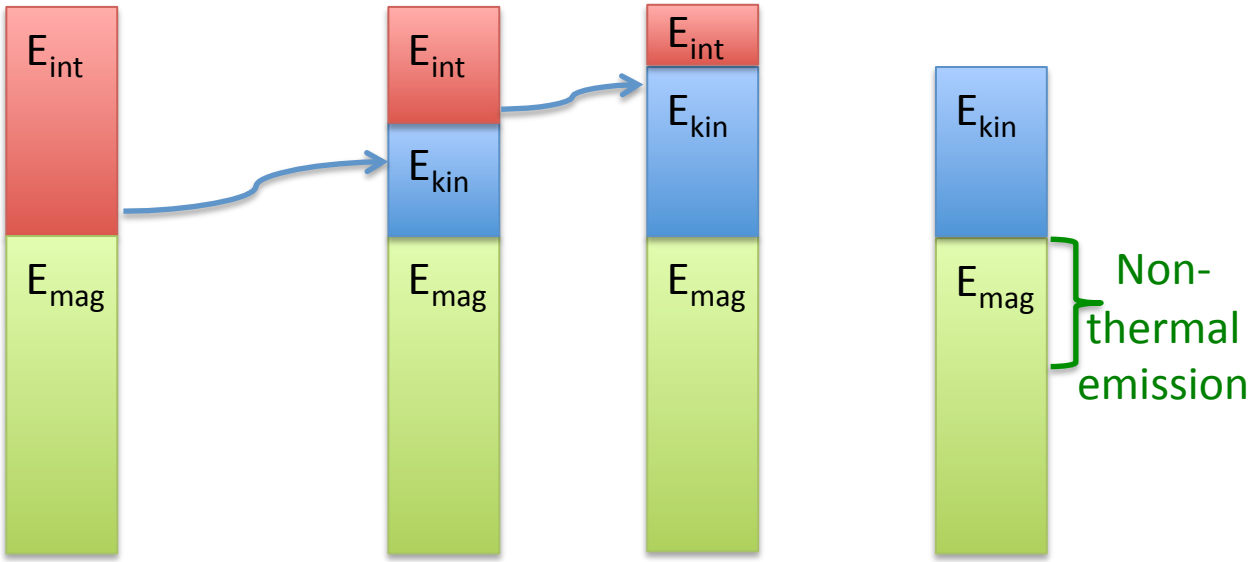


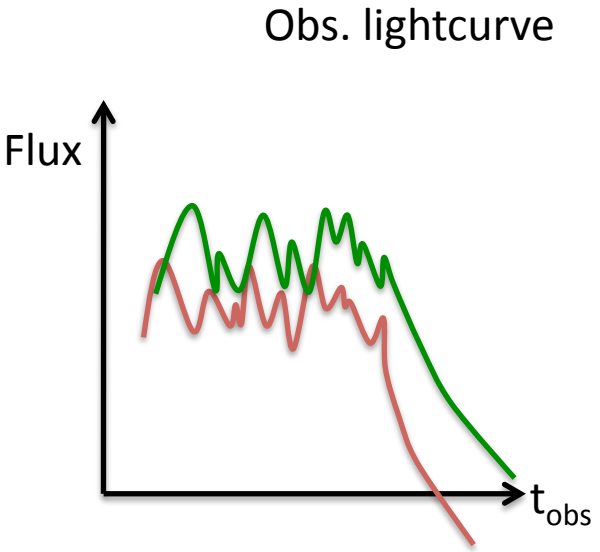


[Central engine is active during Δt_{eng}]



Scenario (2A) Initial magnetization is high – No early dissipation





Scenario (2A) Initial magnetization is high – No early dissipation

- Photospheric emission : - can be computed (during the activity and the HLE tail)
  - spectrum may be more complicated than BB (multicolor BB ; comptonization ; etc…)

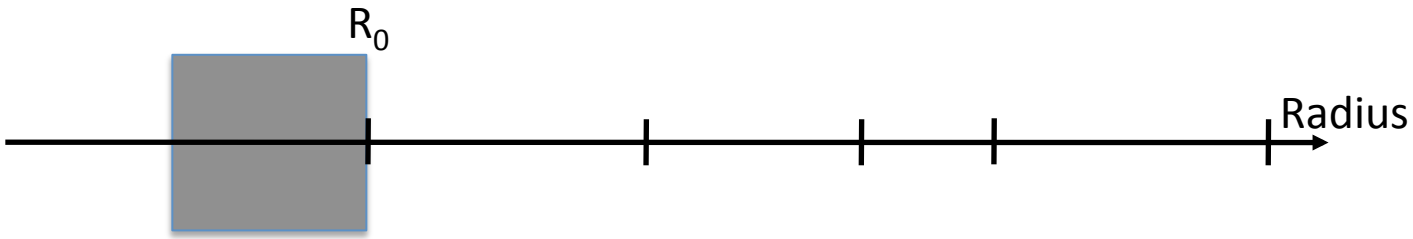
(Goodman 86, Meszaros et al. 02 ; Daigne & Mochkovitch 02 ; Pe'er et al. 07, 08, 10 ; Beloborodov 10 ; …)

- Magnetic dissipation : - dynamics not well understood (relativistic reconnection)
  - energy injection in particles must be parametrized
  - radiative processes can be computed
  - spectrum may have several components
  - total efficiency not well known : better than internal shocks ?

(Thomson 94 ; Spruit et al. 01 ; Giannios 08 ; …)

- **The non-thermal emission can easily dominate**

- **Main uncertainties in this scenario** : - acceleration mechanism for the outflow
  - physics of magnetic dissipation

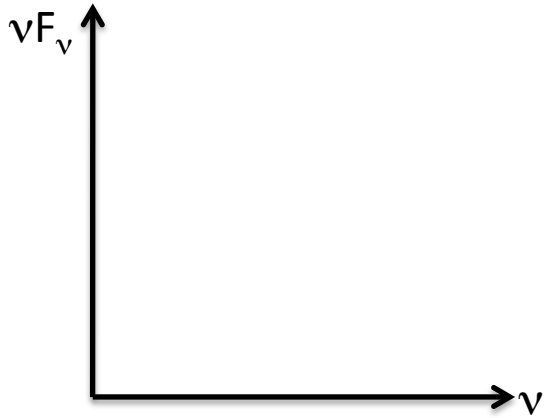


Ejection

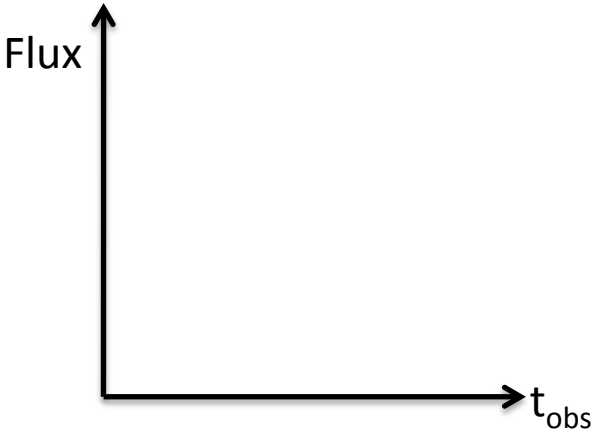
[Central engine is active during Δt_{eng}]

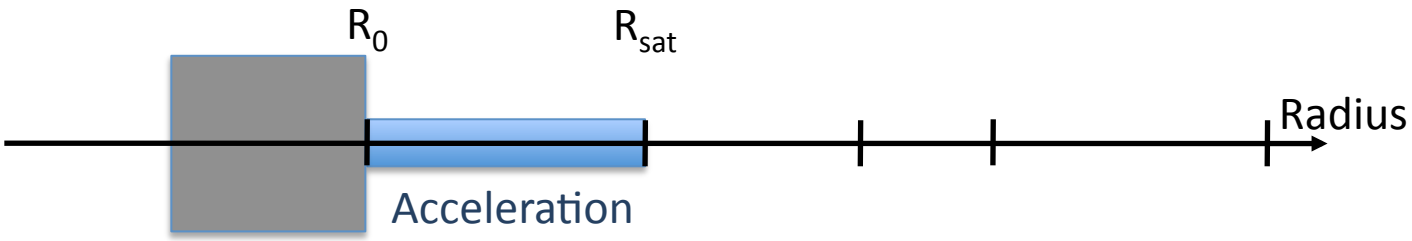
Scenario (2) Initial magnetization is high

Obs. Spectrum



Obs. lightcurve

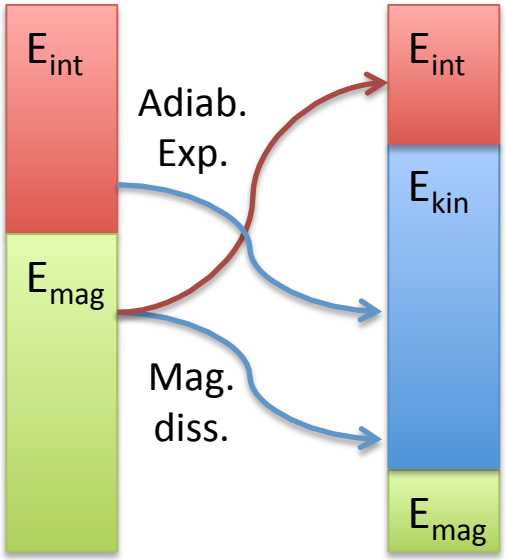




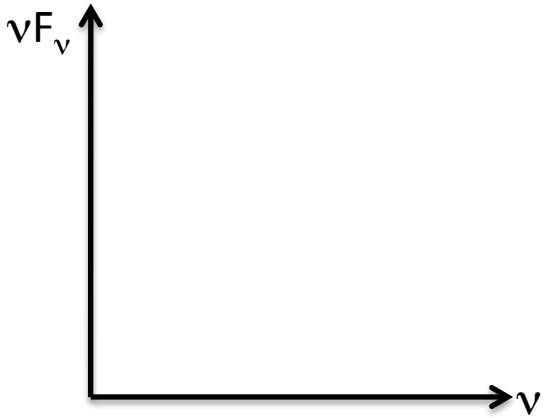
Ejection

[Central engine is active during Δt_{eng}]

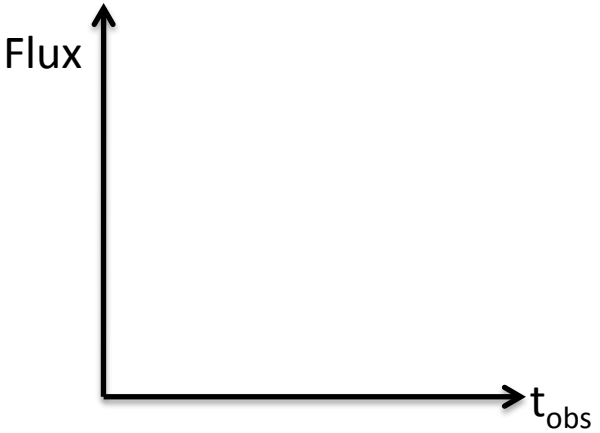
Scenario (2B) Initial magnetization is high – Early dissipation

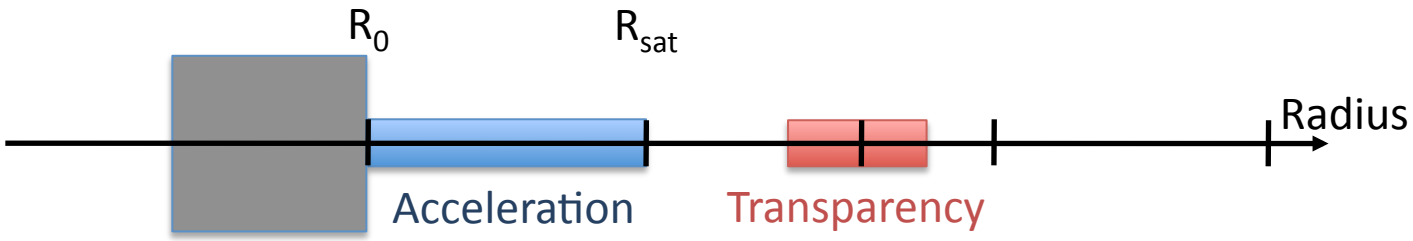


Obs. Spectrum



Obs. lightcurve

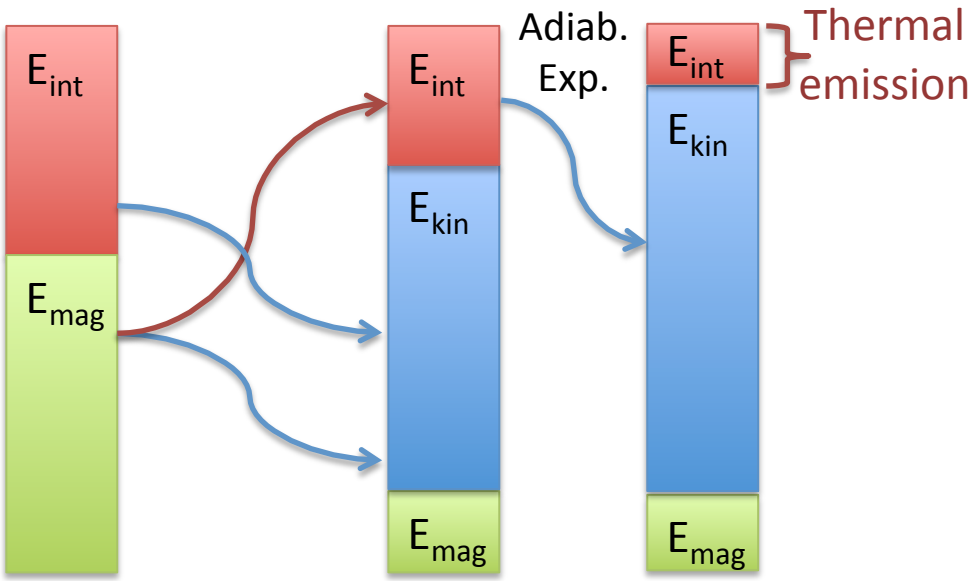


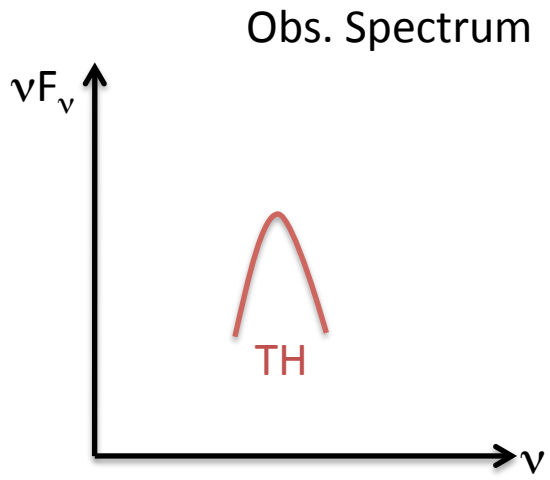


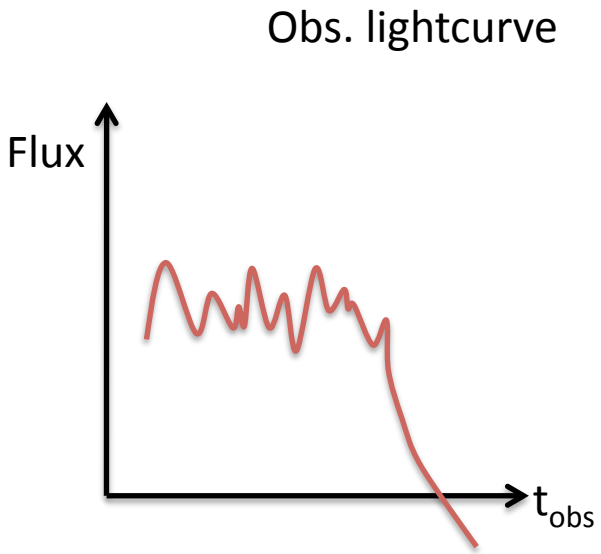
Ejection

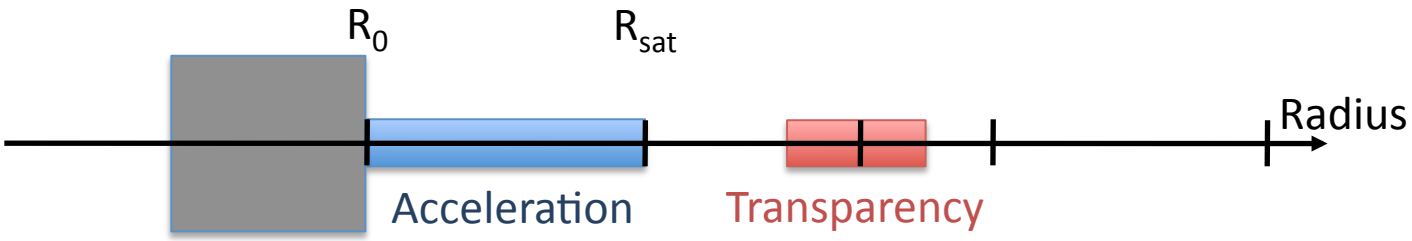
[Central engine is active during Δt_{eng}]

Scenario (2B) Initial magnetization is high – Early dissipation



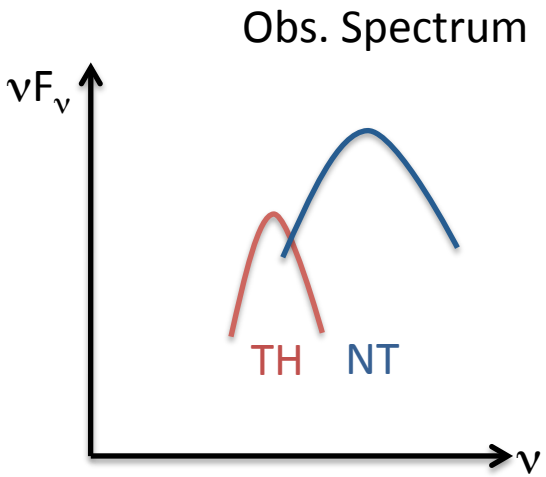




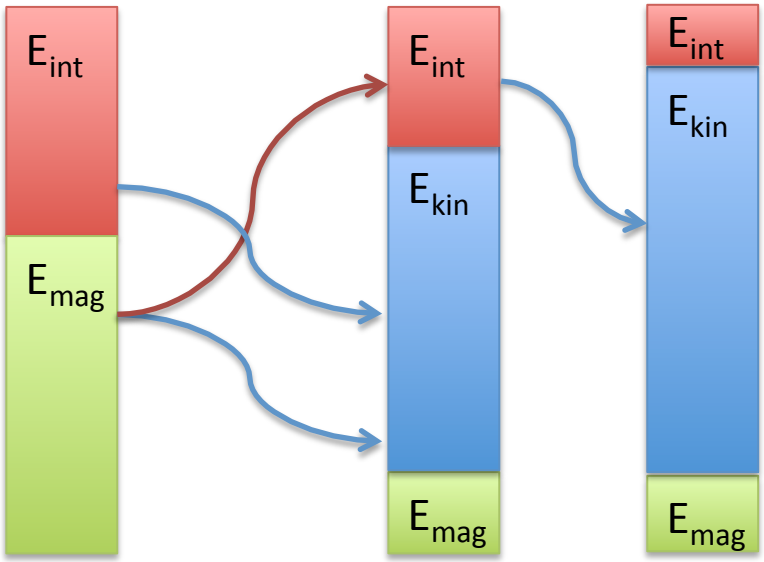


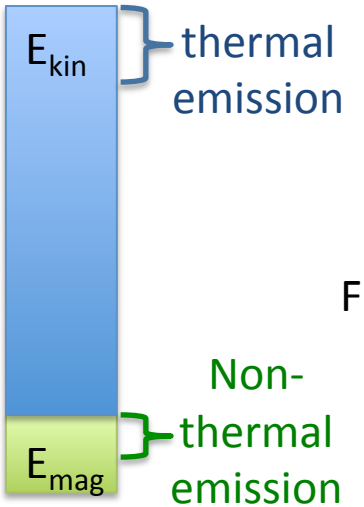
Ejection

[Central engine is active during Δt_{eng}]



Scenario (2B) Initial magnetization is high – Early dissipation





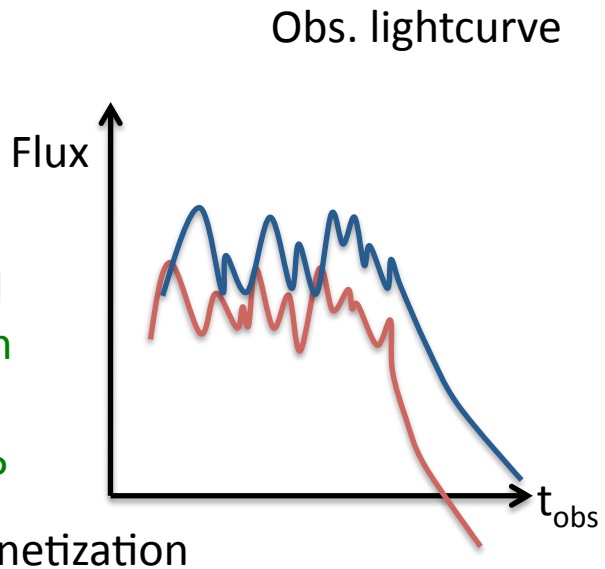
Non-thermal emission

Non-thermal emission

Internal shocks ?

Magnetic dissipation ?

Depends on final magnetization



Scenario (2B) Initial magnetization is high – Early dissipation

- **If the magnetic acceleration is efficient, the outflow above the photosphere is very similar to a standard (unmagnetized) fireball, except that the photosphere is less hot and luminous.**

- **Depending on the efficiency of the conversion of the magnetic energy, the non-thermal emission could be associated to shock waves or magnetic dissipation.**

- **Main uncertainties in this scenario** : - acceleration mechanism for the outflow
  (see e.g. « magnetic rockets » by Granot et al. 10)

  - shock acceleration
  or - physics of magnetic dissipation

Temporal properties

The bolometric lightcurve is shaped by

- the dynamics of the extraction mechanism
- the curvature of the emitting surface

● Pulse shape :

- is not due to the curvature effect : decay is too slow ;
- can be reproduced by internal shock (decay time scale = propagation time of the shock)
- is more difficult to test in magnetic dissipation model
  * mini-jets produce pulses which are too symmetric ;
  * calculations are possible with a parametrization of the reconnection speed

● Early steep decay detected in X-rays :

- can be explained by the high (co-)latitude emission of the non-thermal prompt emission
- this gives a constraint on $R_{NS,e} / 2\Gamma^2 c$ (large radius and/or low Lorentz factor)

- could probably also be explained by a gradual switch off of the central engine
[the no constraint on R, Γ ; why a power-law decay ?]

● Pulse shape at a given frequency / spectral evolution : more complicated to test
(need to include detailed microphysics)

Non-thermal emission :

Radiative processes ?

Internal shocks or magnetic dissipation leads to similar situations :
energetic particles + magnetic field.

● Possible radiative processes :
- synchrotron radiation ;
- inverse Compton scatterings (Thomson or Klein-Nishina) ;
- synchrotron self-absorption at low frequency (may be important for the prompt optical)
- gamma-gamma annihilation and pair creation (important at high energy)

● Possible radiative particles :
- accelerated electrons ;
- accelerated protons ;
- secondary leptons due to photon-photon annihilation ;
- electromagnetic cascades due to photomeson interactions ($p\gamma \rightarrow \ldots$) ;
- external photons …

Many possibilities exist to have a multi-component non-thermal spectrum.

● Many uncertainties due to the unknown microphysics
(shock acceleration or magnetic dissipation)
- distribution of particles (maxwell, PL ?)
- intensity and structure of B

Different approachs

- Single zone model : no assumption for the extraction mechanism / more d° of freedom

  - allows to test the general shape of the spectrum ;
  - relative intensity and position of the components depends on unknown microphysics parameters. Usually the contribution of protons is large if $\varepsilon_p >> \varepsilon_e$.

- Radiation coupled to dynamics : more complicated approach

  - this approach is more consistent but still needs a parametrization of the microphysics ;
  - it allows to predict and test the spectral evolution.

Synchrotron vs SSC ?

● SSC :

- predicts multiple bright components ;
- needs some fine tuning to have the soft gamma-ray component dominant ;
  usually predict a dominant component in the Fermi-LAT range.

This scenario seems unlikely as Fermi-LAT observations seem to indicate that the soft gamma-ray component is dominant in most cases.

(Piran et al. 09 ; Bosnjak et al. 09 ; …)

● Synchrotron :

- predicts components in better agreement with observations, especially if IC is limited by KN ;
- predicts a low-energy slope alpha which is not steep enough.

However :
- inverse Compton scatterings in KN regime allow to reach $-1 < \alpha < -3/2$ in fast cooling regime ;
- a marginally fast cooling regime allows to reach $\alpha \sim -2/3$

(Sari et al. 98 ; Derishev et al. 01 ; Bosnjak et al. 09 ; Nakar et al. 09 ; Daigne et al. 10 ; …)

The synchrotron process seems more promising but leads to strong constraints on microphysics parameters.

High-energy emission ?

- Origin of the different components
  - would be easier with brighter HE components … ;
  - possible correlations between low and high energy components could help ;

- Delayed onset / Delay ? / Long-lived emission :
  - opacity effect ?
  - complex spectral evolution ?
  - different emission regions ?
  - external shock contribution ?
  - reverse shock contribution ?

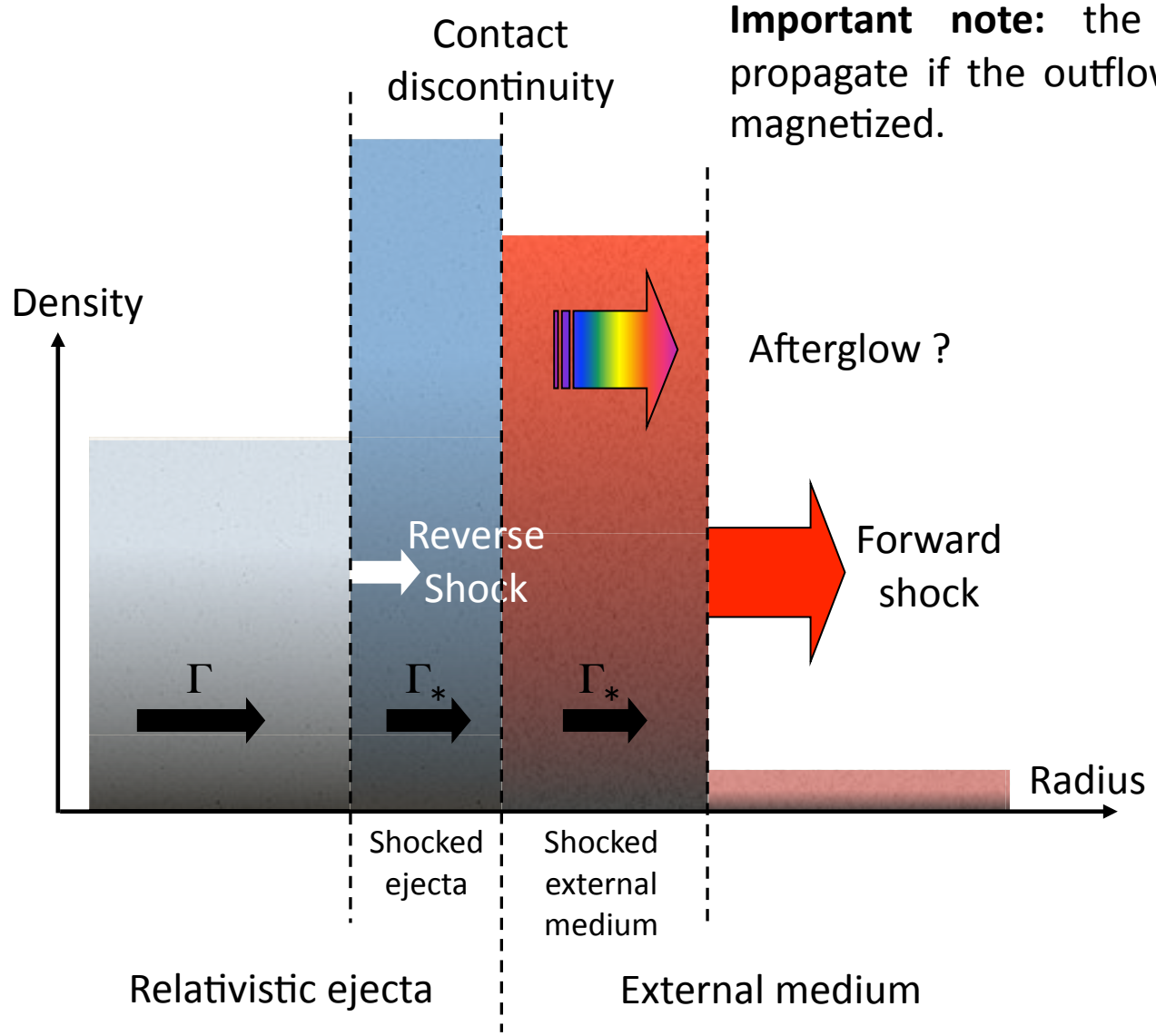
- Observations that would help :
  - variability timescale @ 1GeV ?
  - precise description of the components present in the spectrum
  - precise spectral shape at high energy ?
  - spectrum in the long-lived emission ?
  - simultaneous X-ray emission with long-lived emission ?
  - simultaneous optical emission with prompt / long-lived emission ?
  - …

Comparison between different scenarii

	Pros	Cons
Standard fireball (unmagnetized) Photosphere + internal shocks)	Simple model Rely on well understood physics (except for shock acceleration)	Predicts strong thermal components that are not observed.
Magnetized outflow with slow dissipation Photosphere + reconnection	Avoids strong thermal components Good efficiency ?	Rely on poorly understood physics Precise spectral shape ? Reverse shock ?
Magnetized outflow with rapid dissipation Photosphere + internal shocks (or reconnection)	Avoids strong thermal components Can reproduce the overall spectral shape (if syn + IC/KN) + observed spectral evolution	Rely on poorly understood μphysics Low efficiency

Do we understand the afterglow phase ?

*The **afterglow** is usually interpreted as the signature of the deceleration of the relativistic outflow by the external medium.*



Important note: the RS can't propagate if the outflow is highly magnetized.

● Forward shock :

The most simple version of the model is well described (only parametrization = shock accel.) and agreed well with pre-Swift observations (e.g. GRB 970728 : Wijers et al. 97).

Many possible additional effects : pair enrichment ; inhomogeneities in the external medium ; long-term activity of the central engine ; counter jet ; …)

● Reverse shock :

The most simple version of the model makes strong assumptions on the outflow (homogeneous).

Many additional effects can be related to the structure of the outflow (extreme version : long-lived reverse shock model).

● Main uncertainties :

- magnetization and structure of the outflow ;
- microphysics of relativistic shocks ;
- anisotropy of the radiative process ?

- Many problems with the standard forward shock model / no consensus on solutions …

  - observed lightcurves : plateaux , …
  - observed variability : flares, rebrightenings, …
  - spectral evolution : chromatic breaks …
  - radio observations : flares, temporal decay, late bumps, …
  - jet breaks ? geometry of the jet / energetics …

  Most proposed solutions have strong constraints
  - either on the central engine (energetics; long term activity; …) ;
  - and/or on the microphysics
  (efficiency of acceleration/magnetic field amplification in relativistic shocks).