Neutrinos emission in gamma-ray bursts

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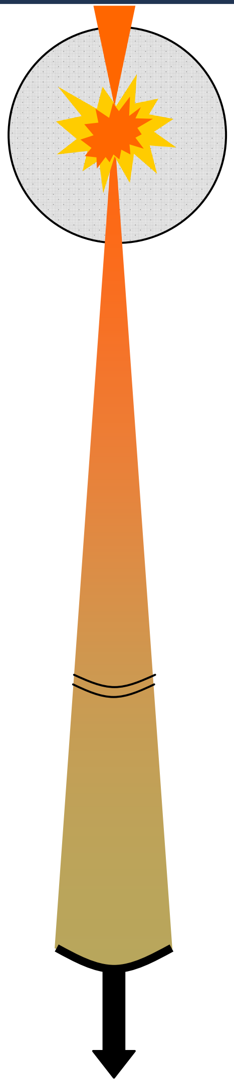
Outline



Gamma-ray bursts & neutrinos

Neutrino production in np collisions

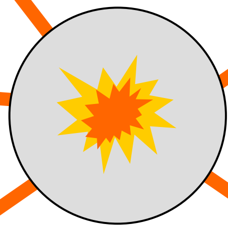
Conclusion

Motivation

Interesting for modelling due to extreme properties and unexpected observations

Probes of the universe up to z ~ 5

Candidate sources of cosmic rays



Candidate sources of neutrinos

Speculative ideas: constraining Lorentz invariance through photon arrival times, ...

Observations

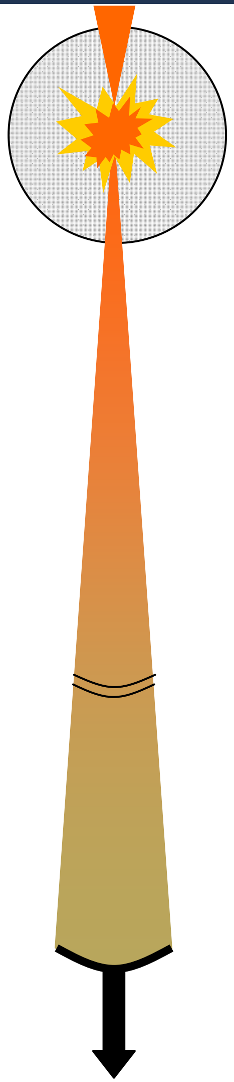
Prompt gamma-ray burst

- Extremely luminous
- Duration 10^{-3} s – 10^{3} s (long- and short-duration bursts)
- Rapid variability
- Non-thermal spectrum, peaking at ~100 keV

Afterglow

- Slowly declining (visible up to years)
- Broad spectrum from radio to X-ray (sub-eV – 10 keV)
- Typical break energies compatible with synchrotron emission of accelerated electrons

The fireball model



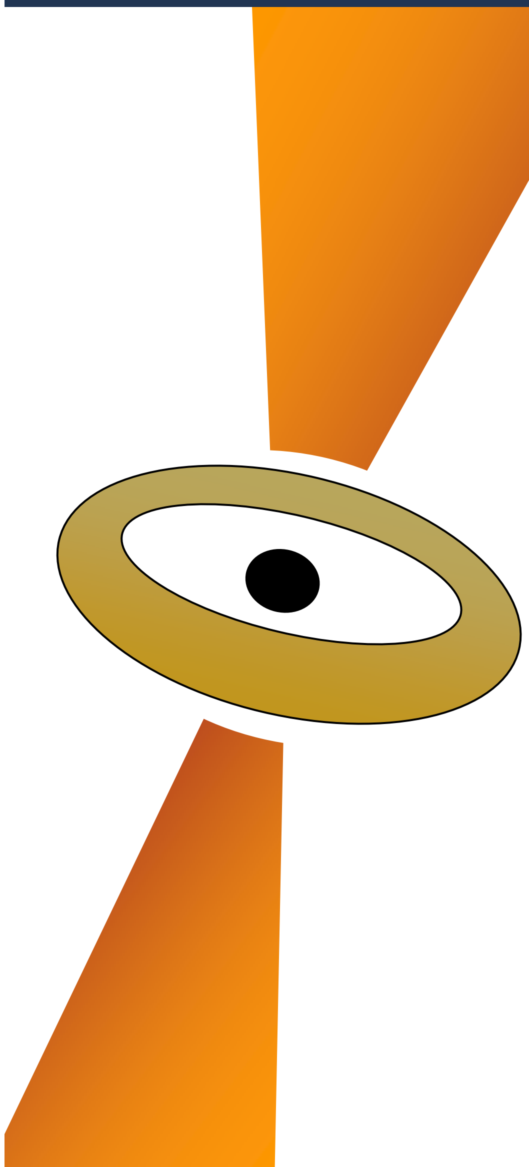
Initial phase ($10^{6.5}$ cm)	Catastrophic event: core-collapse of a massive star (long GRB): Formation of **black hole + accretion disk** system which launches a **fireball**
Accelerating phase (10^{8} cm)	Fireball accelerates to relativistic velocities **Γ ~ 300** by radiation pressure; stops due to energy constraints (**baryonic load**)
Coasting phase (10^{12} cm)	Energy dissipation (shock acceleration): **gamr**
Afterglow phase (10^{16} cm)	Intera

Key features

- Total energy ~ 10^{52} erg
- Lorentz factors ~ 300
- Collimation
- Small baryonic load

[Cavallo & Rees 1978; Paczynski 1986; Mészáros & Rees 1992, 1993]

Open questions



Important (partly) unsolved questions:

- How are the jets formed? And collimated?
- What is the nature of the outflow?
  Dominated by thermal energy (=fireball?)
  or by electromagnetic energy?
- How is shock-acceleration realized?

Neutrinos are expected to be very useful probes to gain insight in these issues!

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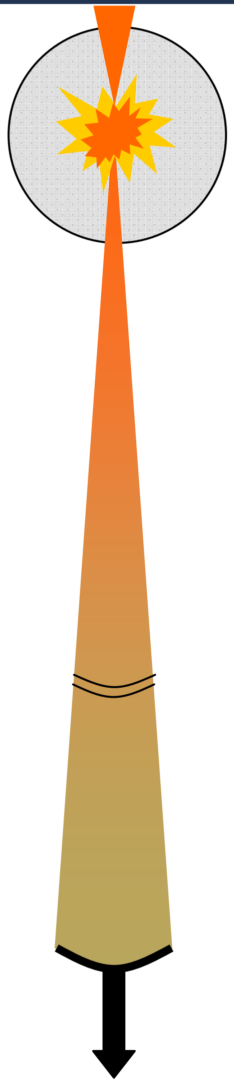
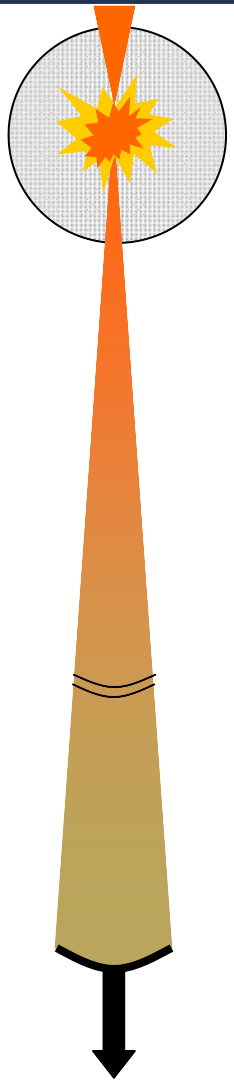
Neutrino production in the fireball model



	Neutrinos (fireball model)	Probing
Initial phase	(Quasi-)thermal ~60 MeV [Kumar 1999; HK & Wijers 2005]	Formation of outflow
Accelerating phase	Inelastic np collisions ~50 GeV [Derishev et al. 1997, Bahcall & Mészáros 1997, Mészáros & Rees 2000, HK & Giannios 2007]	Nature of the flow (protons, neutrons, energy/mass ratio)
Coasting phase	Internal shocks: 100 TeV [Waxman & Bahcall 1997]	Nature of the flow; shock acceleration
Afterglow phase	External shock 1 EeV [Waxman & Bahcall 1997]	External environment; shock acceleration

Neutrino production in np collisions



Gamma-ray bursts & neutrinos

Neutrino production in np collisions

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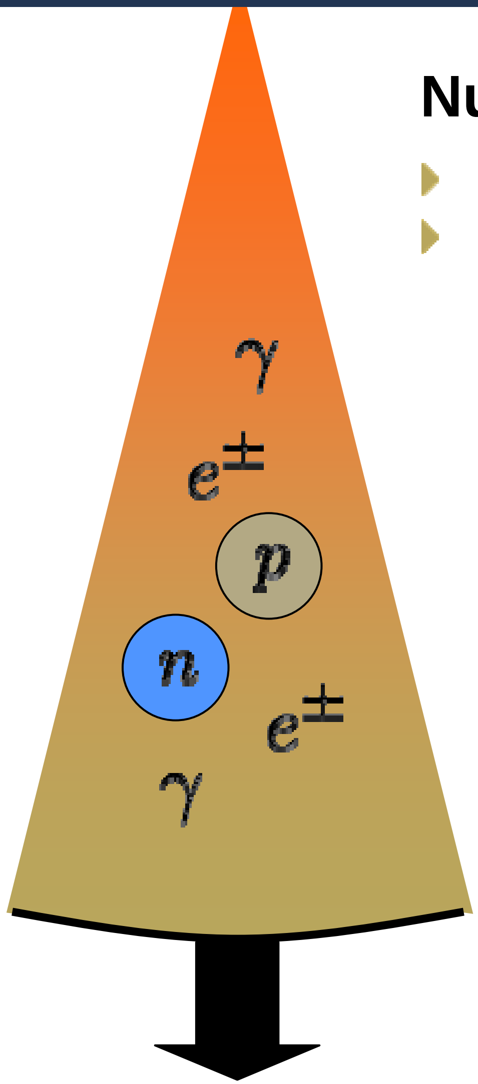
[Koers & Giannios, A&A, 471, 395, 2007]

Dynamics of the outflow



Nucleons in the flow:

- Protons are electromagnetically coupled to the plasma
- Neutrons are coupled through nuclear scattering with protons

Decoupling radius r_{np}

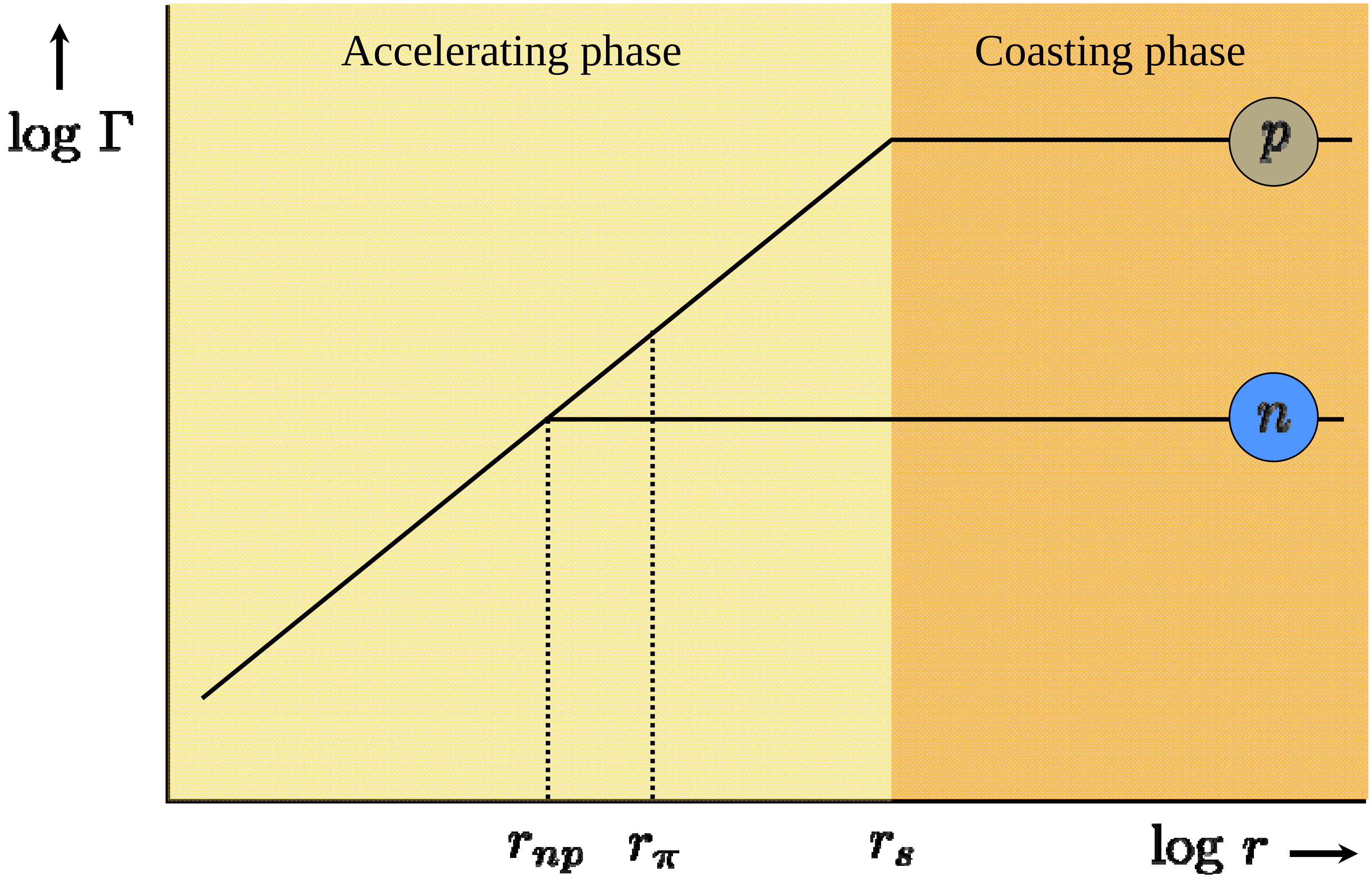
- Protons and neutrons decouple when interaction time ~ dynamical time
- This only happens when the flow is sufficiently pure (few baryons)

Pion production radius r_{π}

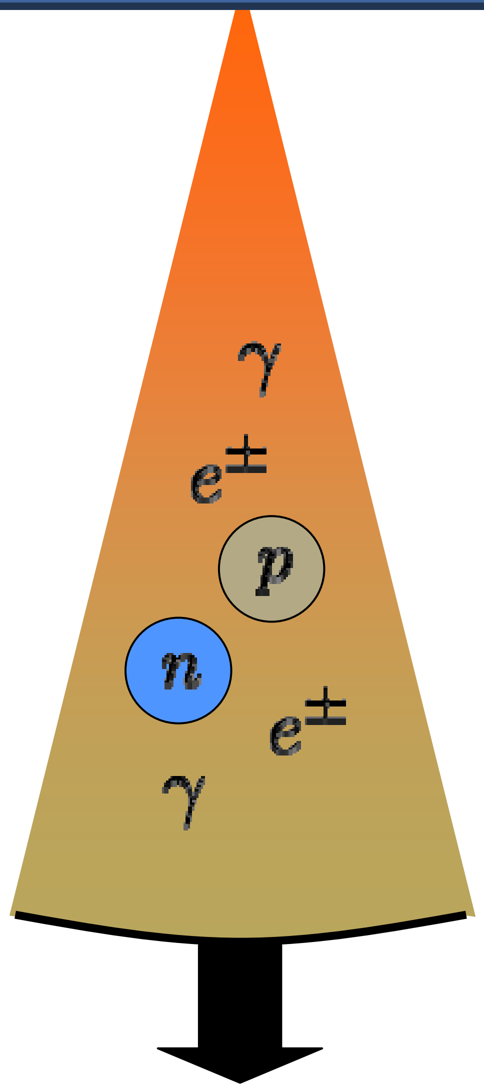
- Pions can be produced when COM energy is sufficient:

$$\Gamma_p/\Gamma_n > 2$$

Dynamics of the outflow



Dynamics of the outflow



Fireball model

- Dominated by **thermal energy**
- Acceleration due to **radiation pressure**
- Acceleration profile:

$$\Gamma \propto r$$

[Paczynski 1986]

VS

AC model

- Dominated by **electromagnetic energy**
- Acceleration due to **magnetic reconnection**
- Acceleration profile:

$$\Gamma \propto r^{1/3}$$

[Drenkhahn 2002]

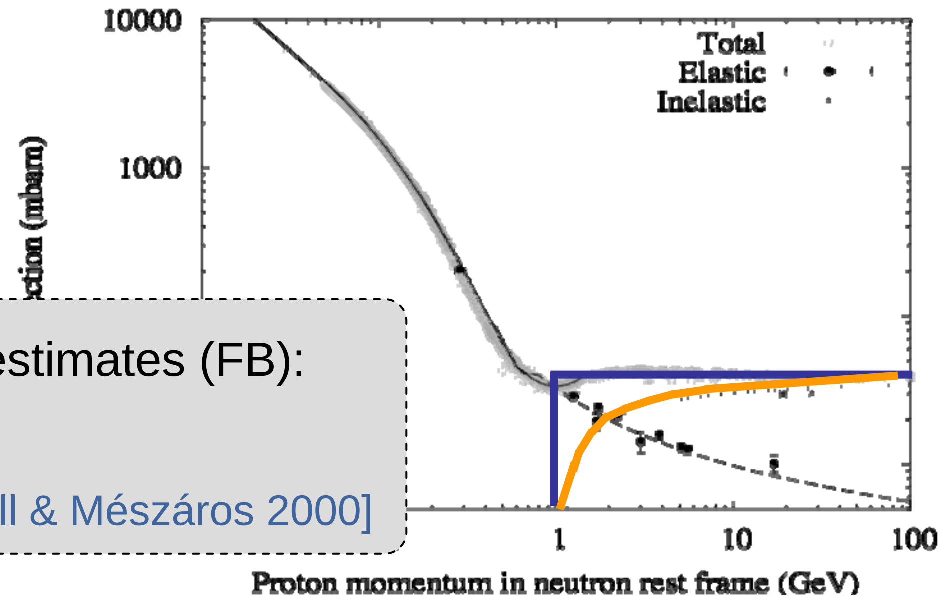
Neutrino emission

Optical depth (probability) for inelastic np interaction:

Fireball model: $\tau = 0.1$

AC model: $\tau = 0.01$ [HK & Giannios 2007]

(independent of model parameters as long as $\Gamma \propto r^p$)



Previous estimates (FB):
$\tau = 1$
[e.g. Bahcall & Mészáros 2000]

Neutrino emission: fluence

	Fireball (FB) model	AC model
fluence from burst at z=0.1	$\Phi \simeq 10^{-4}\ \mathrm{cm}^{-2}$	$\Phi \simeq 10^{-5}\ \mathrm{cm}^{-2}$
peak energy	$E_\nu \simeq 50\ \mathrm{GeV}$	$E_\nu \simeq 70\ \mathrm{GeV}$

Order of magnitude below IceCube sensitivity!

Gamma-ray emission

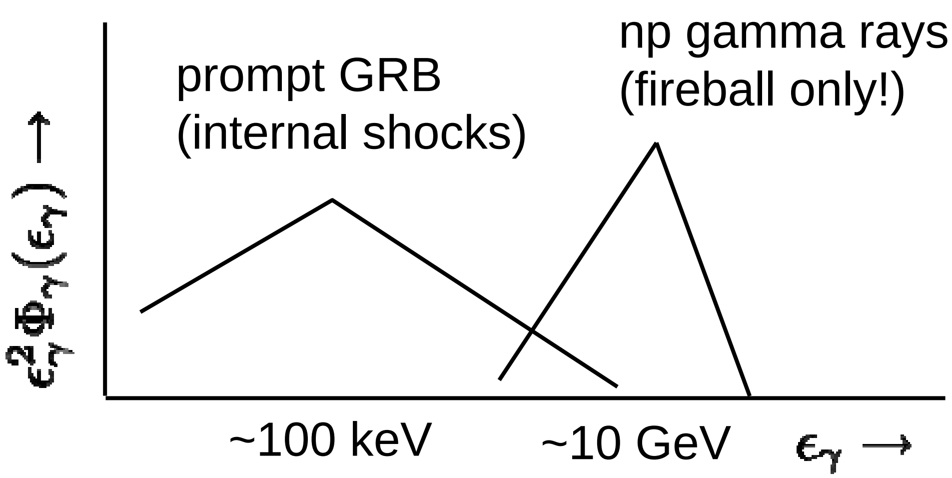
Gamma rays

- Produced in decay of **pizero mesons** in inelastic np collisions
- Flow is very optically thick to these high-energy gamma rays
- Energy is **reprocessed** and outputted in a different energy range

Resulting energy:

- **AC model**: ~100 keV
- **Fireball model**: ~10 GeV

[Razzaque & Mészáros 2006;
HK & Giannios 2007]



Conclusion

The difference in dynamics between fireball and AC models leads to a different signature of neutrinos from nucleonic interactions. However the fluences are too low to differentiate between models with IceCube at < 100 GeV energies.

High-energy gamma-ray emission (~10 GeV) simultaneous with the prompt emission would provide evidence for the fireball model with a relatively pure flow.

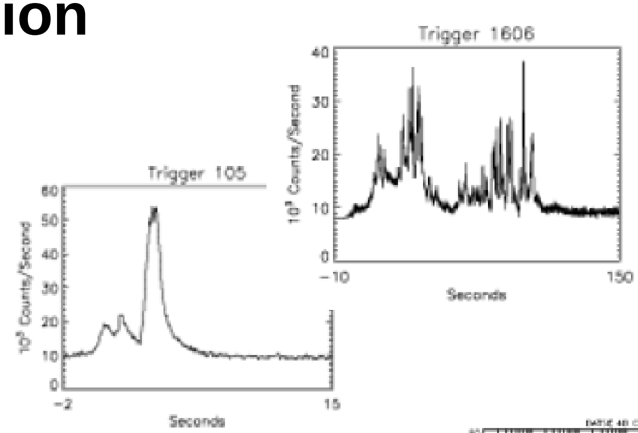
Conclusion

Neutrino emission is a promising way to probe the physics of GRBs, especially for the earliest phases.

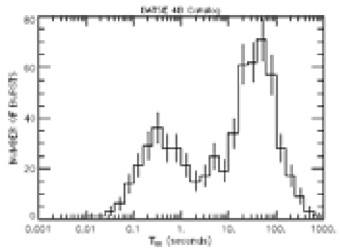
However it remains a challenging task to identify concrete realizations of this potential.

Observations: the prompt emission

Key features of the prompt emission



- **Irregular lightcurves:**
  "if you've seen one GRB..."
- **Rapid varibility**, up to 10^{-3} sec.

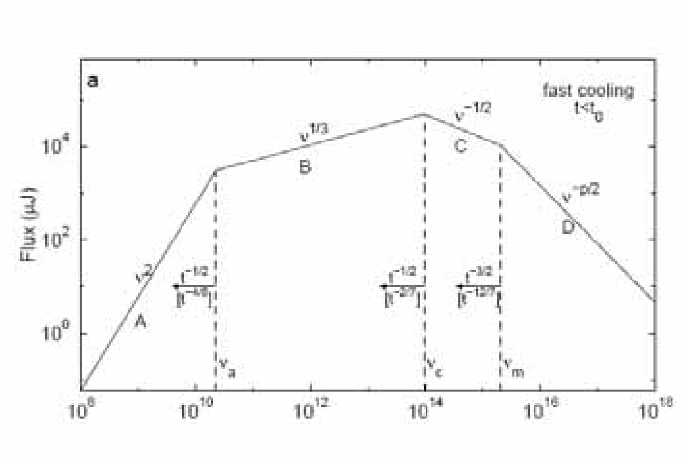


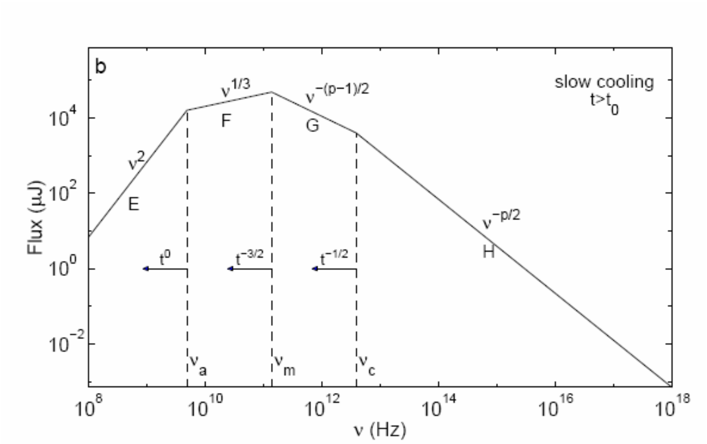
- Duration from 10^{-2} s – 10^{3} s, subdivided into
  long GRBs (~20 sec) and **short** GRBs (~0.2 sec)
- **Non-thermal** spectrum (broken power-law),
  peaking around ~100 keV;
  occasionally extending to very high energies (> GeV... TeV?)

Observations: afterglow

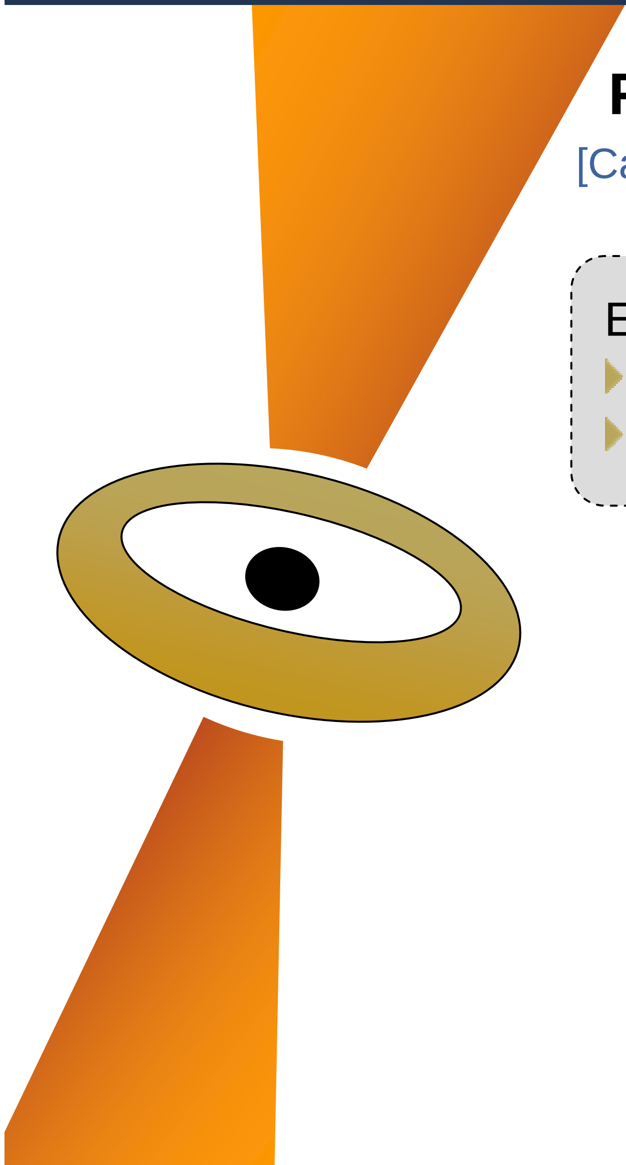
Key features of the afterglow

- **Broad-band** spectrum over many decades in energy (radio, optical/IR, X-ray)
- Characteristic break energies compatible with **synchrotron emission**
- **Slowly declining** (typically power-law) lightcurve (sometimes detectable up to years)





The fireball model



Fireball model

[Cavallo & Rees 1978; Paczynski 1986; Mészáros & Rees 1992, 1993]

Energy reservoir
- BH spin energy
- Accretion disk binding energy

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Thermal energy in fireball

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Acceleration due to radiation pressure

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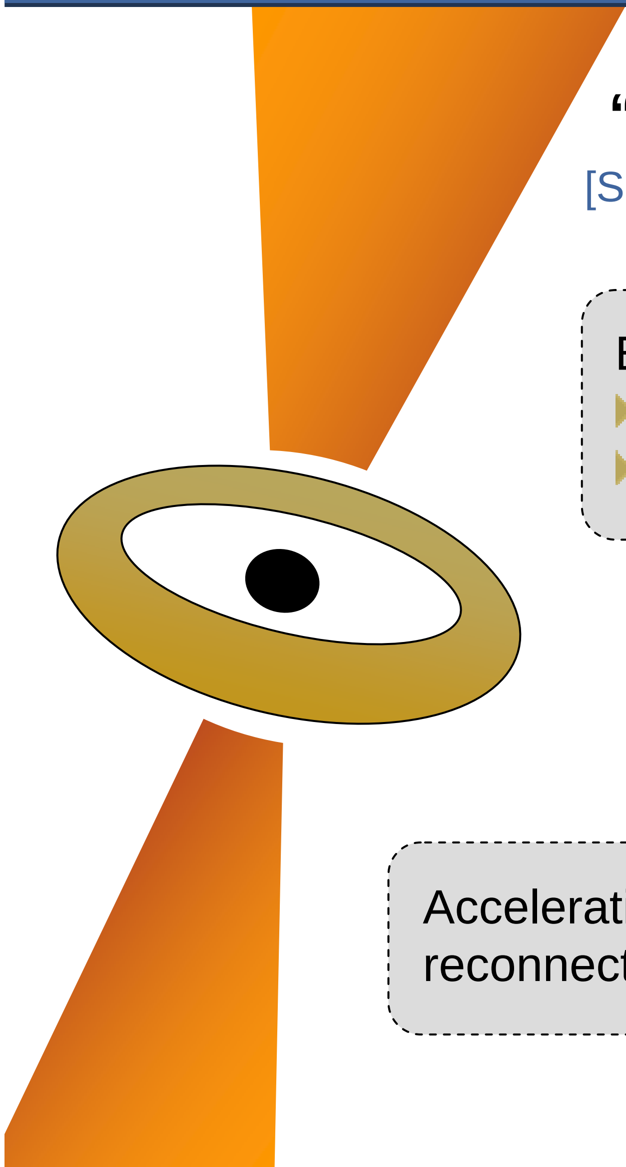
Gamma-ray emission due to internal dissipation (shock acceleration)

GRB models



"AC" model (magnetic reconnection)

[Spruit et al. 2001, Drenkhahn 2002, Giannios & Spruit 2005]

Energy reservoir
- BH spin energy
- Accretion disk binding energy

↓

Poynting-flux dominated MHD outflow

↓

Acceleration due to magnetic reconnection

Gamma-ray emission due to magnetic reconnection