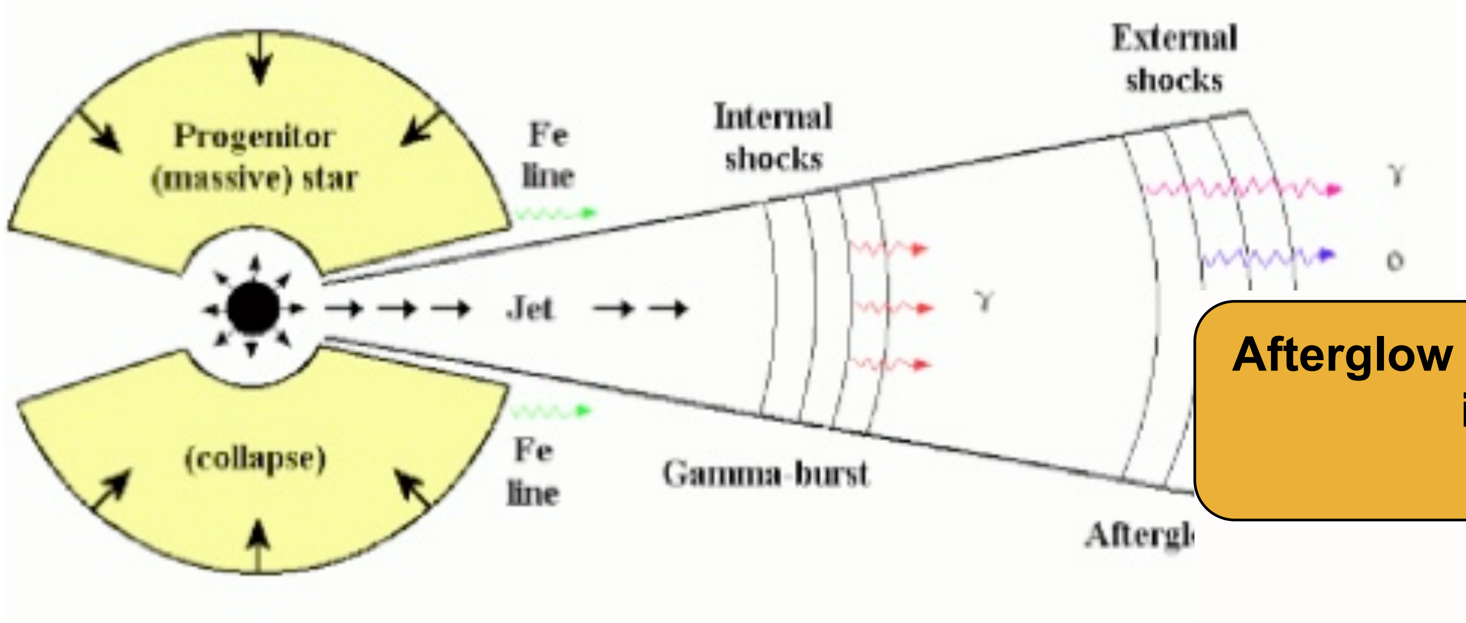
The engines of Gamma Ray Bursts

Niccolo' Bucciantini

INAF Osservatorio Astrofisico di Arcetri

http://www.arcetri.astro.it

GRB from the engine side



Central engine
BH-AD or NS
10^{6-7} cm

Stellar confinement
or Ejecta
Typical radius
10^{10-11} cm

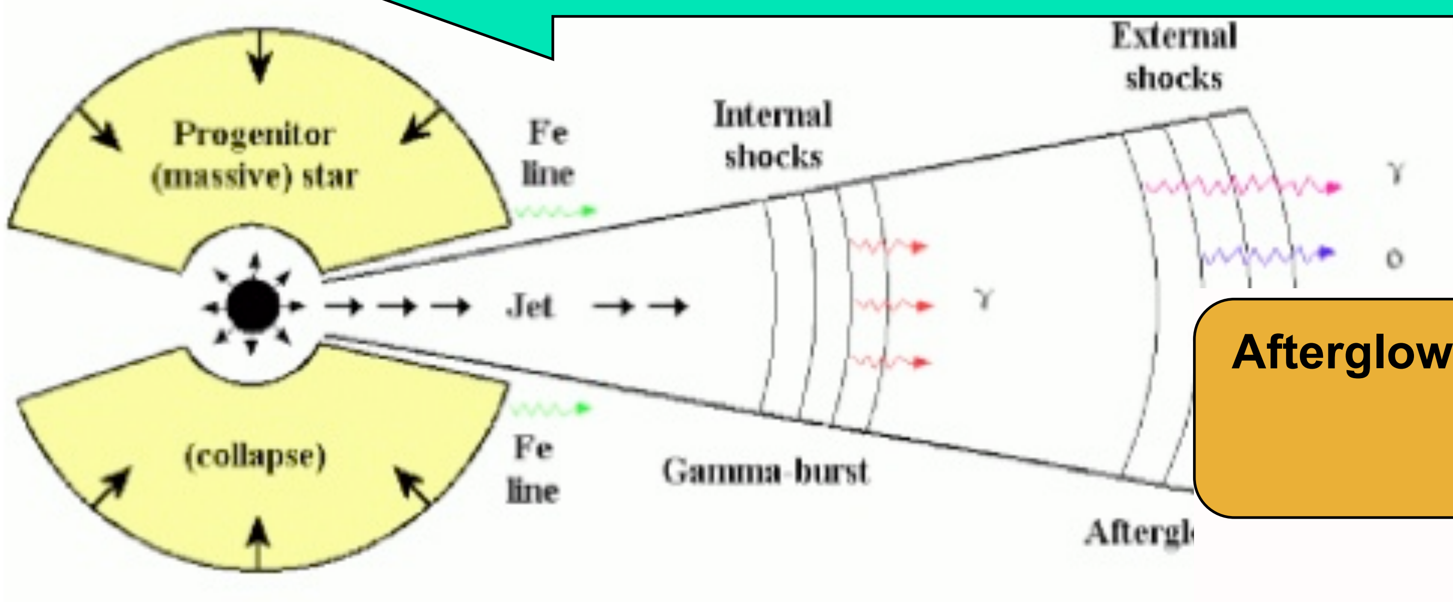
Prompt gamma-ray emission
from internal dissipation
10^{13-15} cm

Afterglow from forward shock
in the ISM
10^{16-17} cm

GRB from the engine side

From the engine to the emission region

From the emission region to the engine



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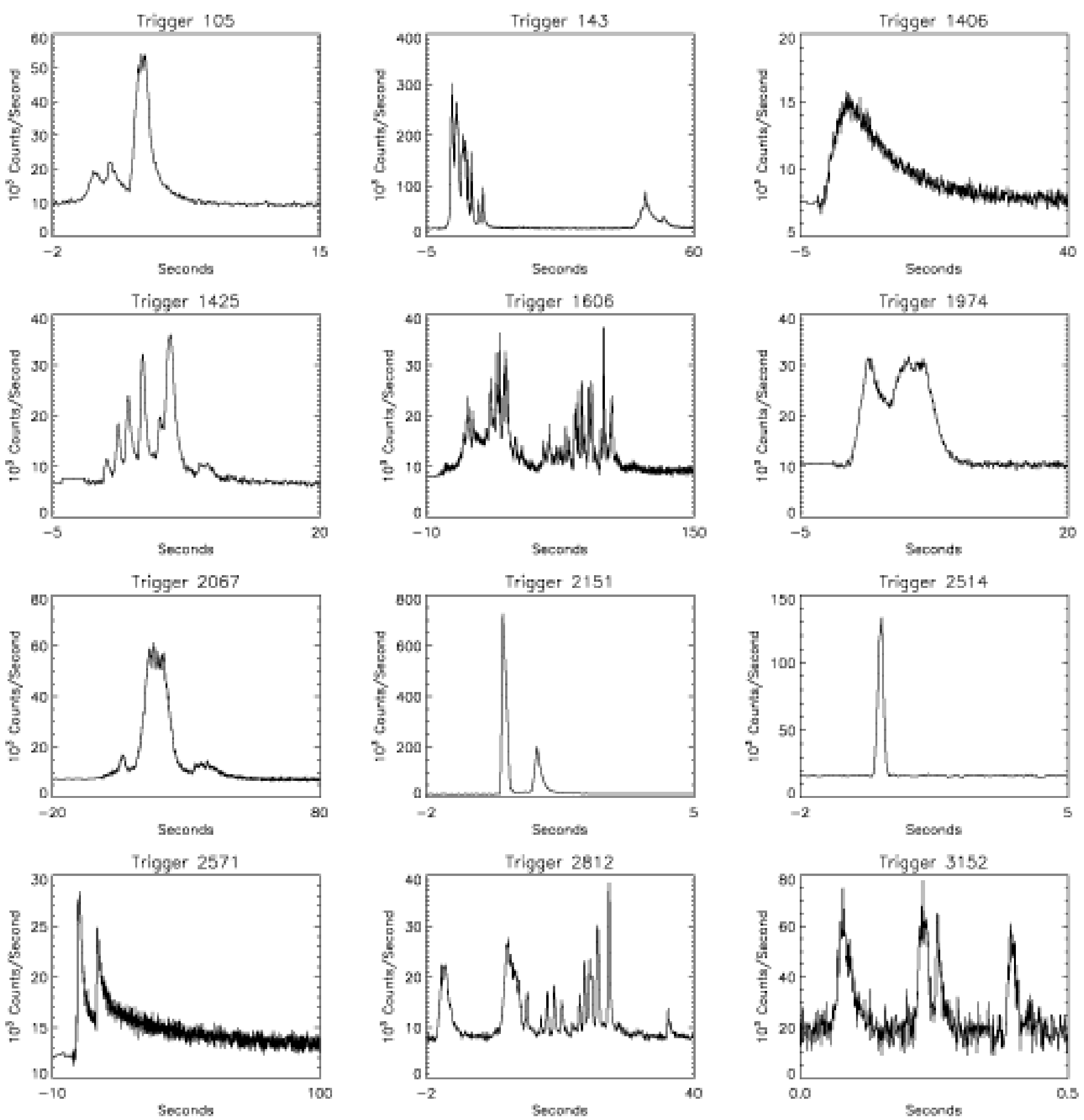
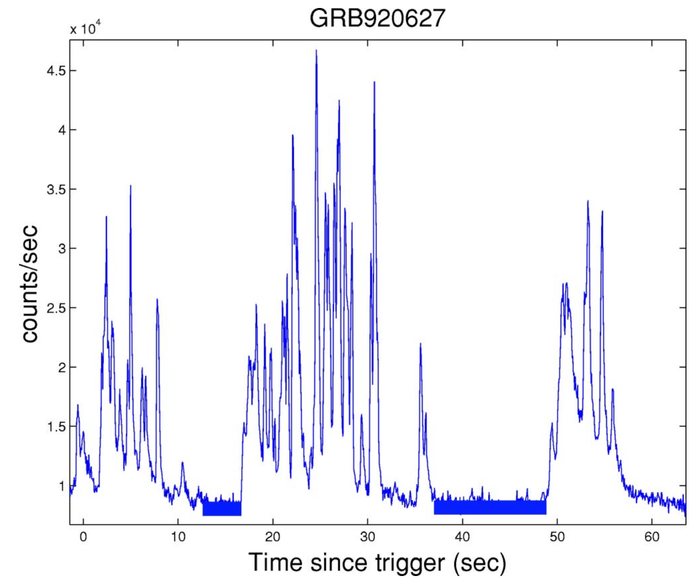
Temporal Properties

Prompt light-curve is not informative - too much variety



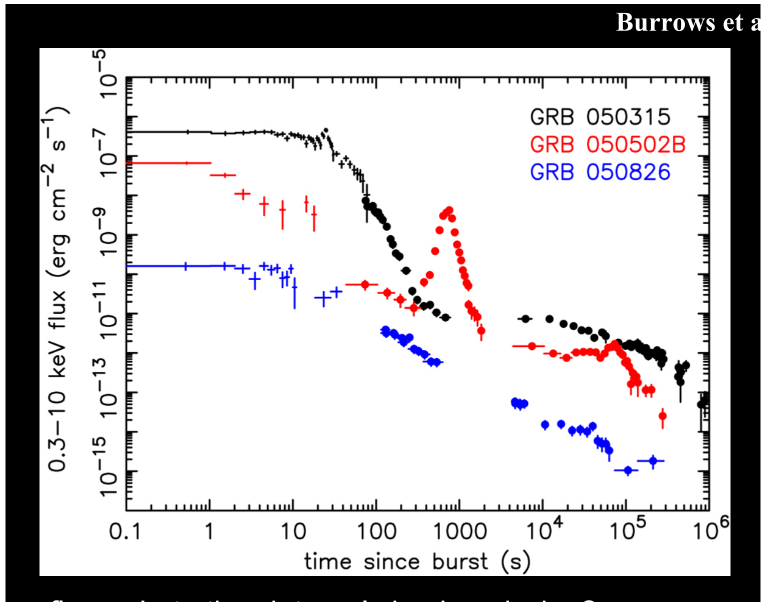
Variability up to ms



Variability timescale ~ ms implies a compact stellar mass engine

Variability shorter than duration implies continuous injection

Late engine activity in GRBs



Late time X-ray flares
10^2-10^5 seconds after burst

Late phase plateau indicates continuos energy supply

Rowlinson et al 2010

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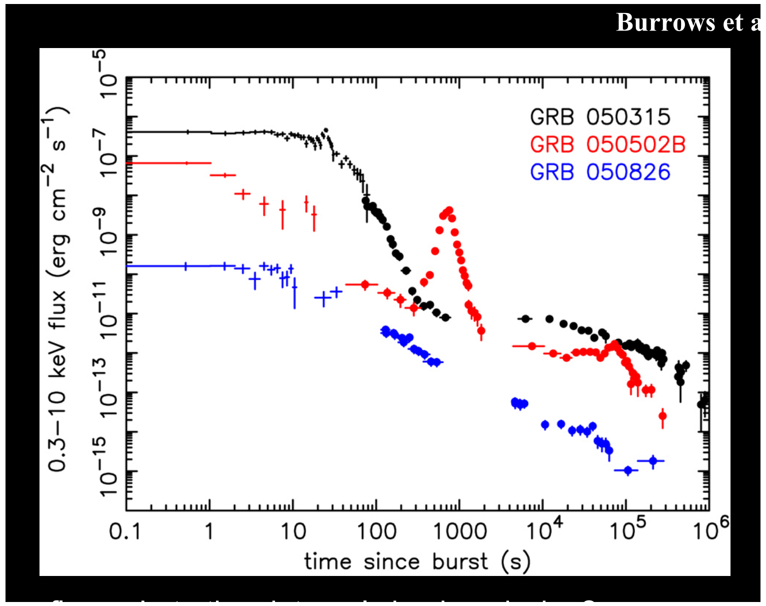

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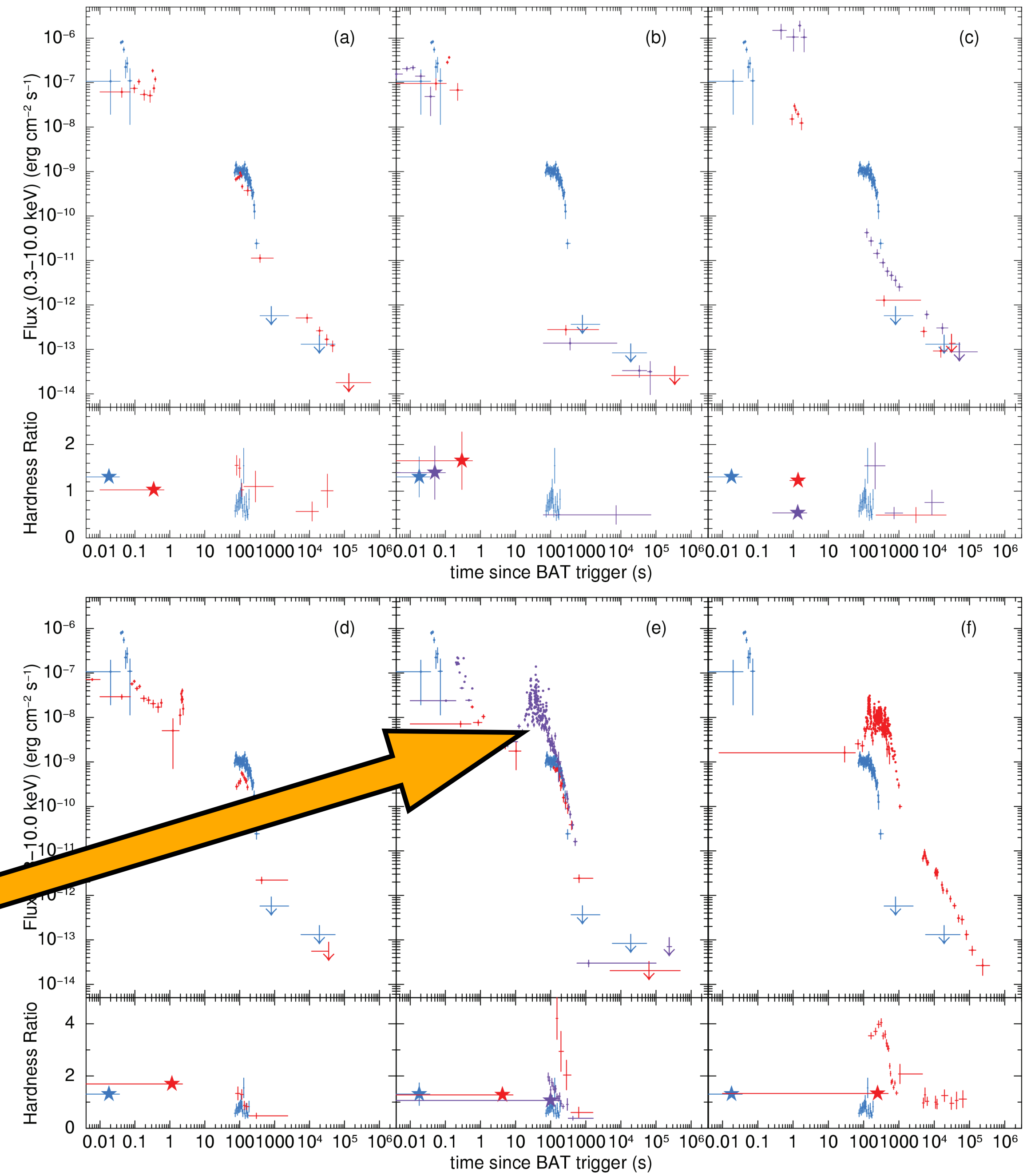
10^2-10^5 seconds after burst

Late phase plateau indicates continuos energy supply

Plateau at 10-100 sec

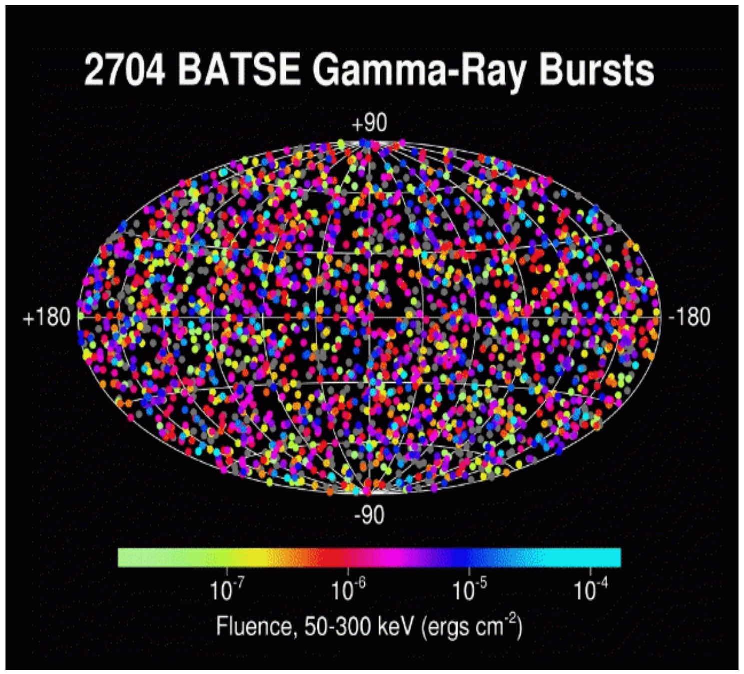
>> 1 sec (dynamical timescale for accretion on BH)



Rowlinson et al 2010

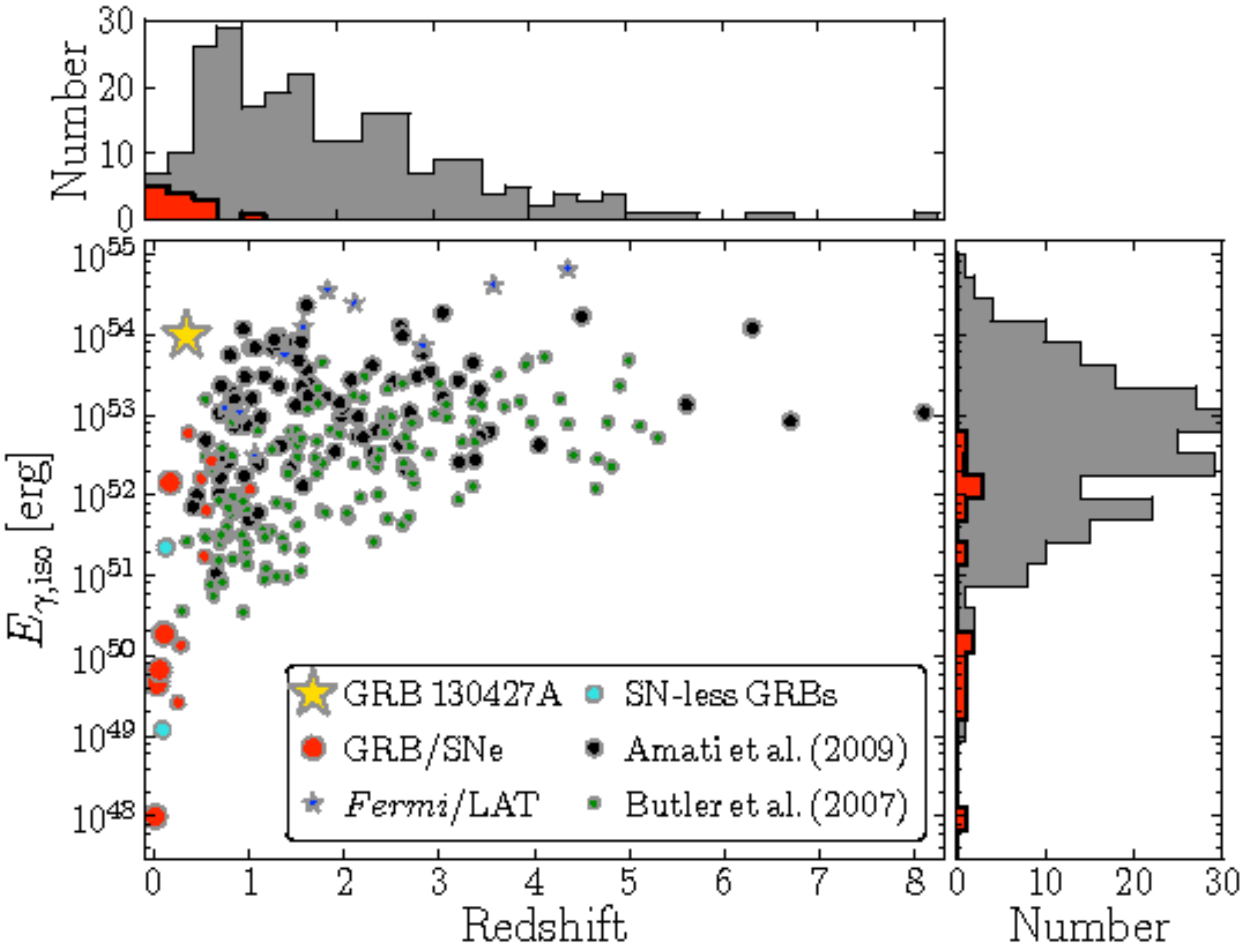
Energetics

Uniform Distribution



Concentrate at redshift ~ 2

E_{iso} can reach 10^{54}



Xu et al 2010

Energetics - Limits

Measuring the true energetics of the GRB:
E photon (prompt) + E kinetic (later non-rel. expansion)

Emission is beamed in ~ 10 deg

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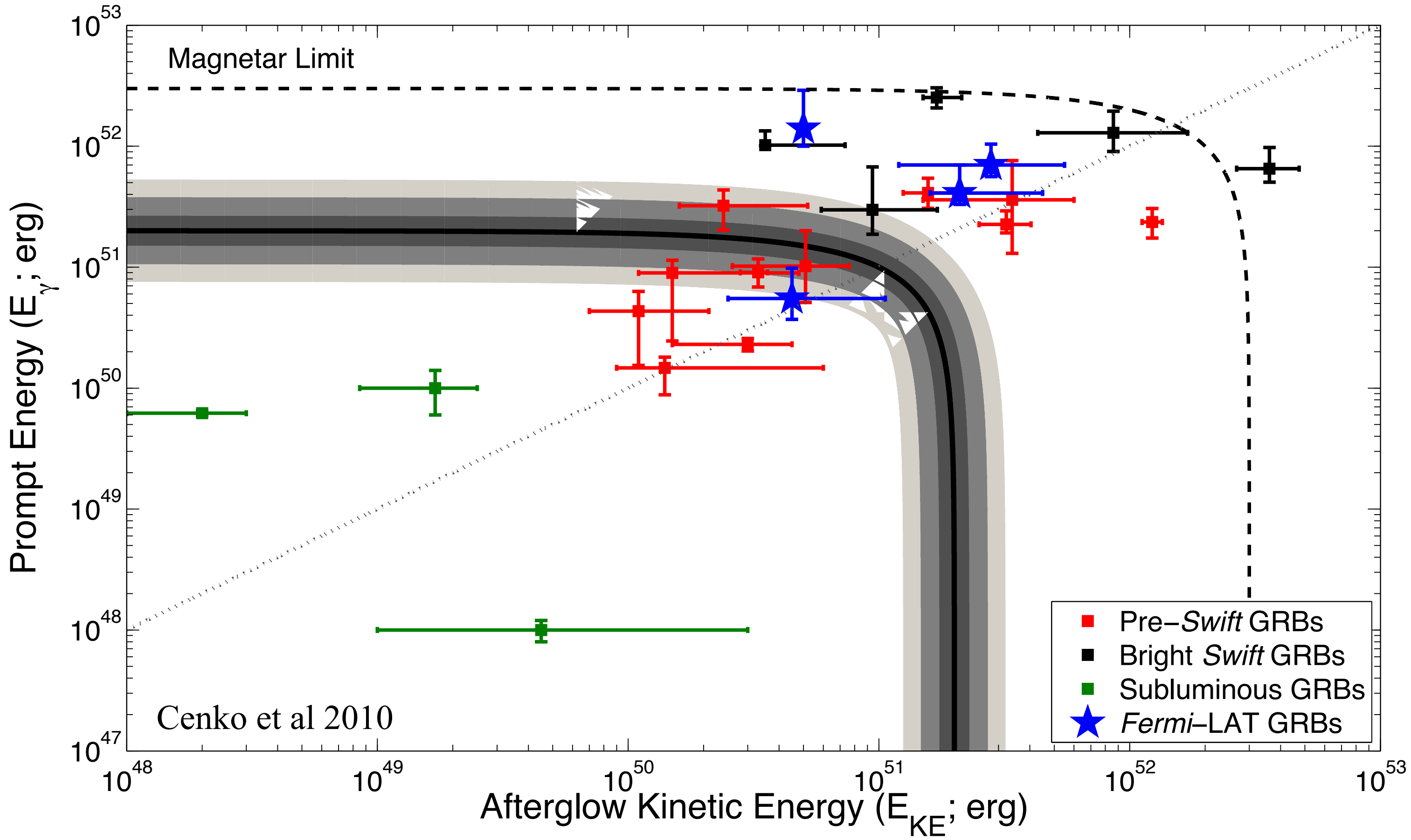

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Selected sample with jet opening angle

Prompt Y-energy must be corrected for beaming

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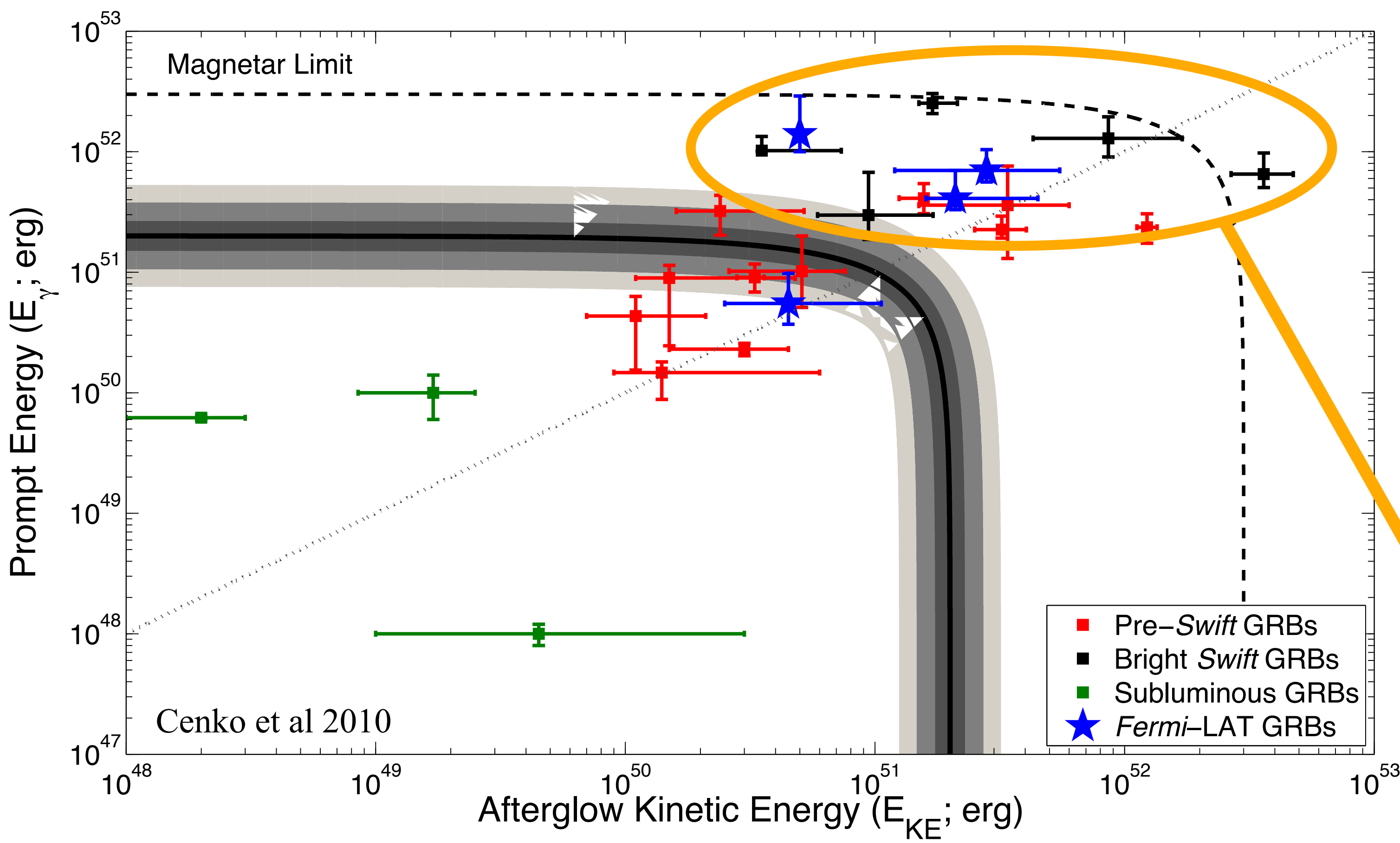

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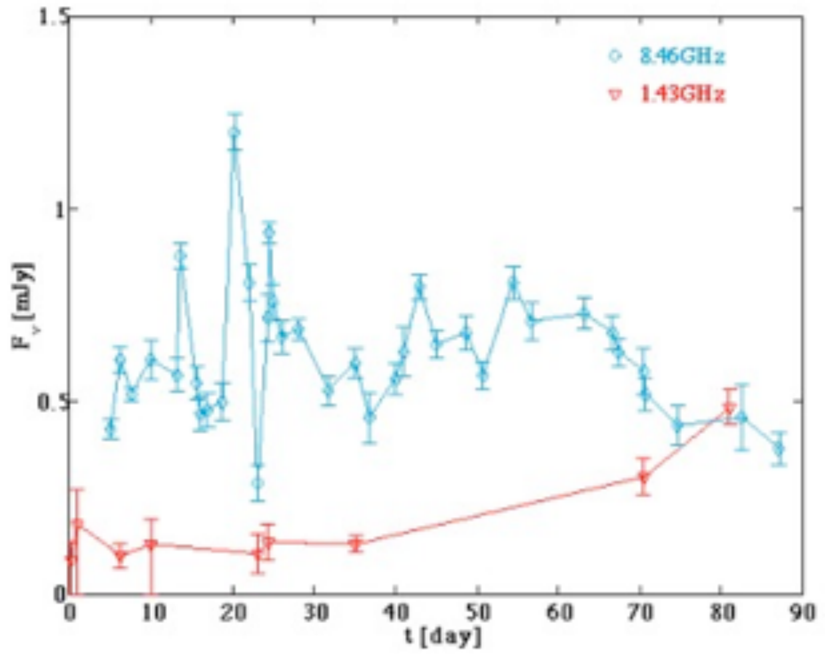
Selected sample with jet opening angle

Prompt Y-energy must be corrected for beaming

Very energetic events.
ATT! Prompt energy is sensitive to viewing angle assumptions

Lorentz factor

GRB are seen to scintillate in radio for several days after the burst



For typical galactic ISM variation the scintillation radius of an extragalactic source is

This implies an expansion speed ~ c

Cavallo Rees Argument

$$L\Delta t = \eta \frac{4\pi}{3} R^3 n m_p c^2$$

$$\Delta t > \frac{R}{c}(1 + \sigma_T n R)$$

$$\frac{L}{\Delta t} < \eta \frac{2\pi}{3} \frac{m_p c^4}{\sigma_T} = \eta 2 \times 10^{42} erg/s$$

But typical energetics of GRB is ~ 10^{50} erg/s^2

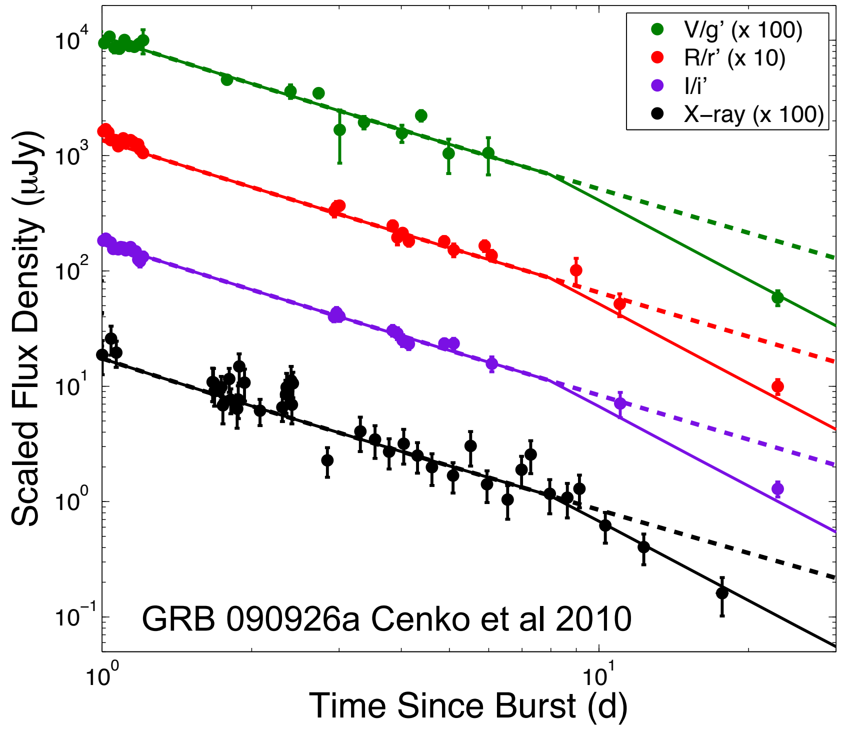
If the source is moving at a Lorentz factor Y, the luminosity is enhanced by a factor Y^3
Implies Y~ 100-1000

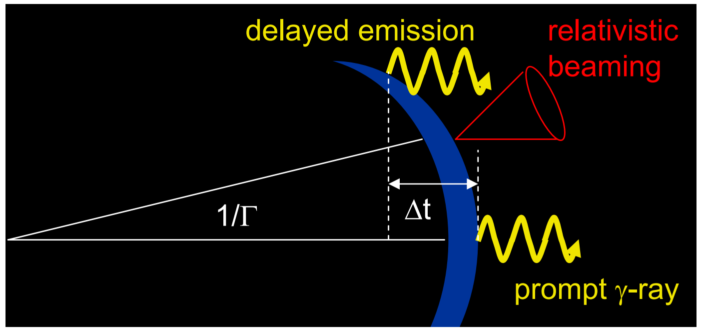
Geometry of the Outflow

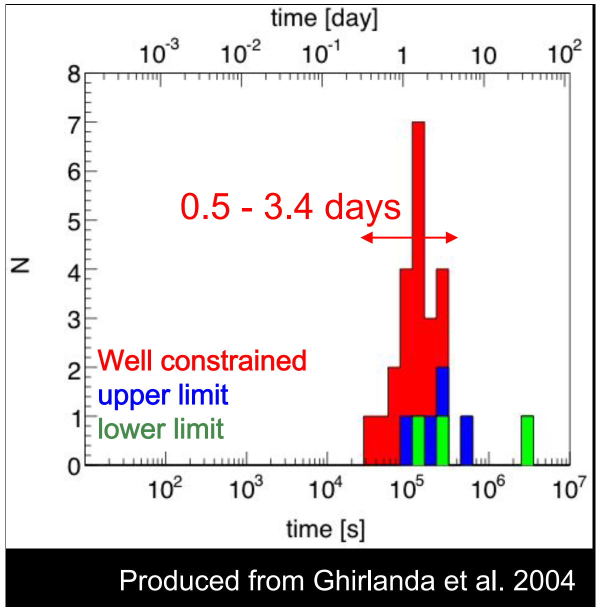
Evidence for collimation from so called "jet-breaks"

In a relativistic front emission is observable only within a cone θ~1/Γ
As the outflow slows down Γ decreases
For Γ > 1/θ_{jet} a larger area of the front becomes visible
For Γ < 1/θ_{jet} the visible area of the front is the same

Achromatic and no spectral change



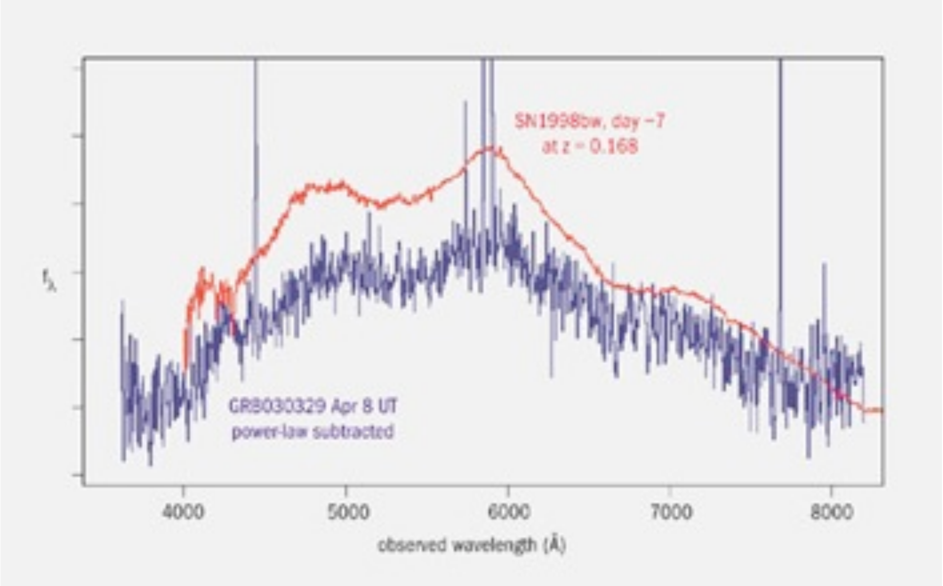




$$t_j \approx 3.9(1+z)E_{\rm iso,53}^{1/3} n_0^{-1/3} \left(\frac{\theta_0}{0.2}\right)^{8/3} \ \text{days},$$

The typical opening angle is ~ 10 deg

SN-Long GRB connection



Hjorth et al. 2000

SN 1998bw and SN2003dh were coincident with GRBs within days.

SN Ib/c

SN are very energetic and bright:
E_{kin} ~ 10^{52} ergs, V_{ej} ~ 2×10^4 Km/s
1M_{sun} of Ni^{56}

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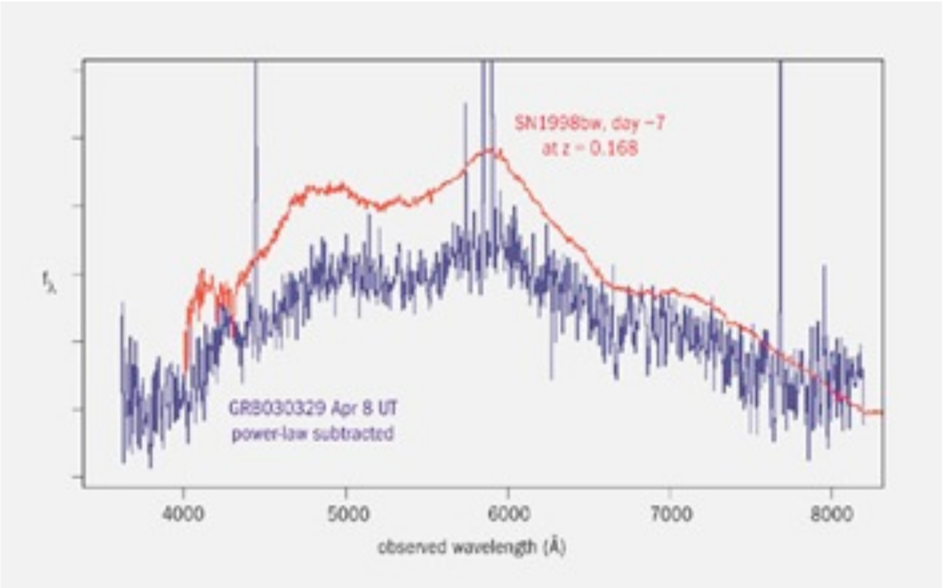

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Not all SN Ib/c are associated with LGRBs
Rate of LGRB/SN Ib/c is ~ 1.6-0.2%
Rate of Hypernovae/SN Ib/c ~ 8%
Evidence for metallicity dependence

GRB conditions are rare even among massive stars

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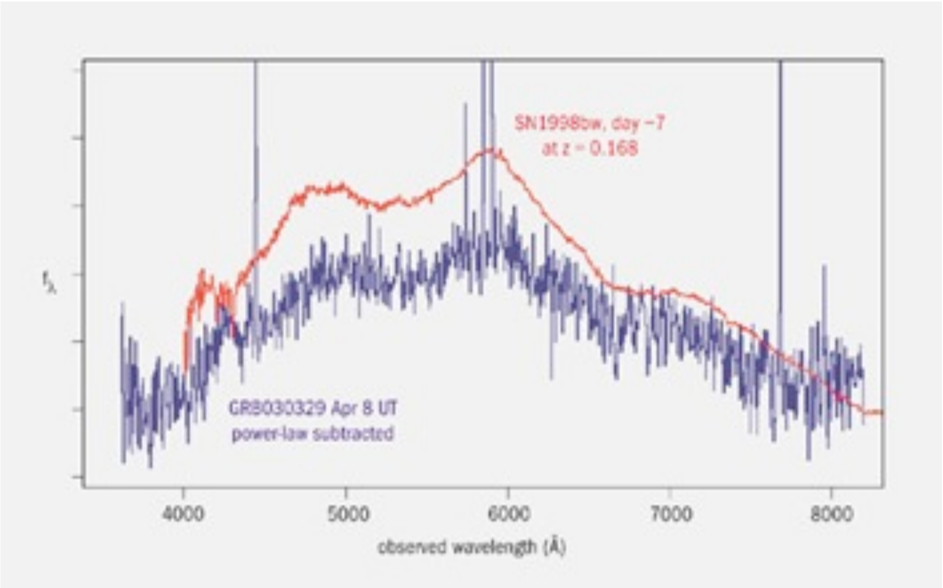

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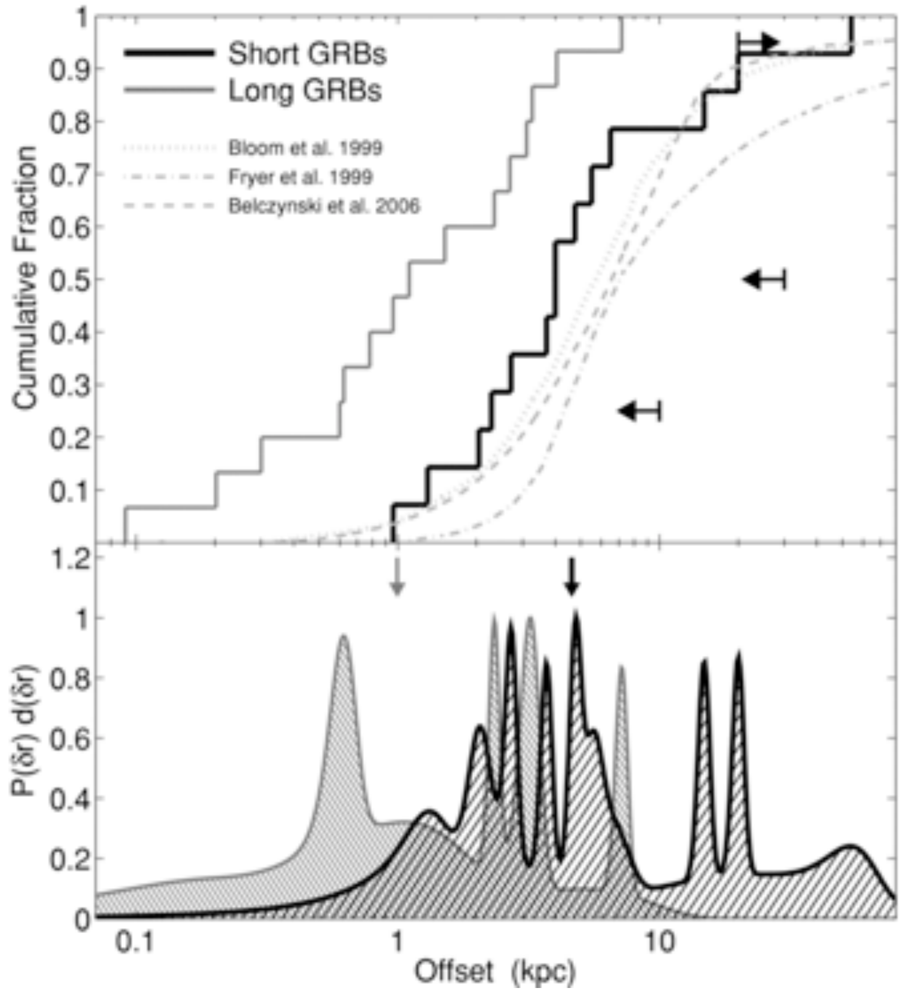
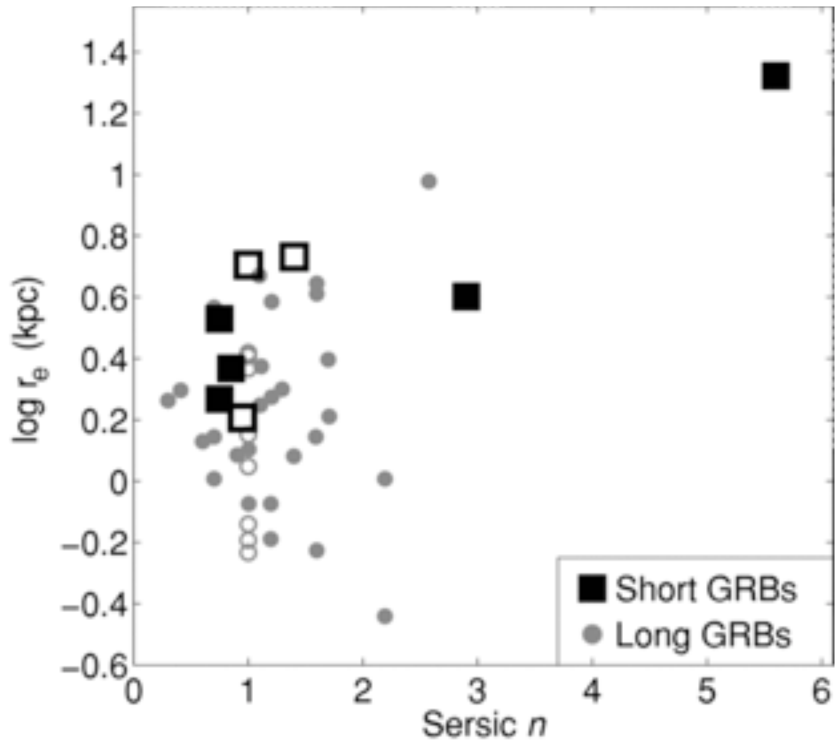
"Almost all GRBs seem to be associated with Luminous and Energetic SN

There are however Luminous and Energetic SN which show no sing of GRBs (orphan afterglows)"

SGRB host galaxies





There are field galaxies including elliptical ones N tells how intensity varies with distance (Sersic value) - high n -> elliptical

SGRB have larger offset from the center of galaxies - where most stars are - old stars

Short GRB do not select for metallicity - they trace field population

Constraints on the central engine

- **High energy ~ 10^{51-52} ergs → large energy reservoir**
- **$E_{tot} < E_{iso}$ → collimation**
- **Millisecond variability → compact objects (BH or NS)**
- **$T/\delta T >> 1$ → quasi-steady energy injection (not an explosion)**
- **100 sec duration of LGRB and SGRBEE >> engine timescale**
- **High energy non-thermal spectrum → relativistic outflows (Γ>100)**
- **Late time activity → long lived engine**

SGRBs

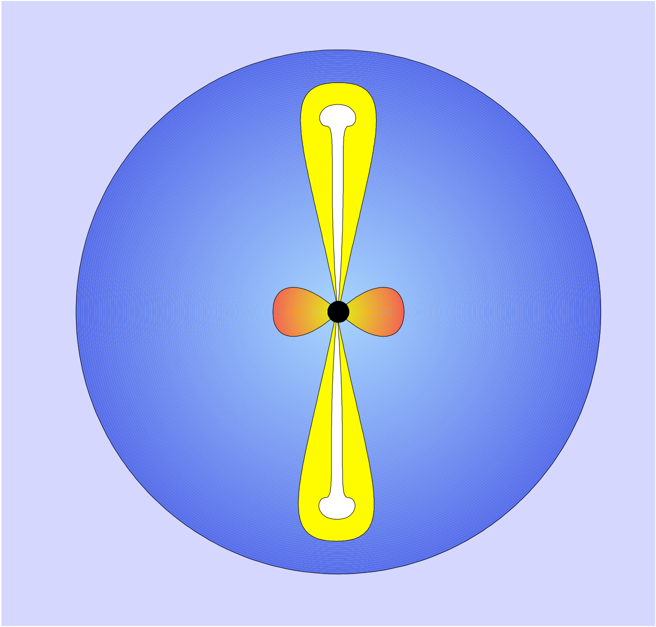
Associated with old galactic population
Found in the outer region of host galaxy
Weak afterglows

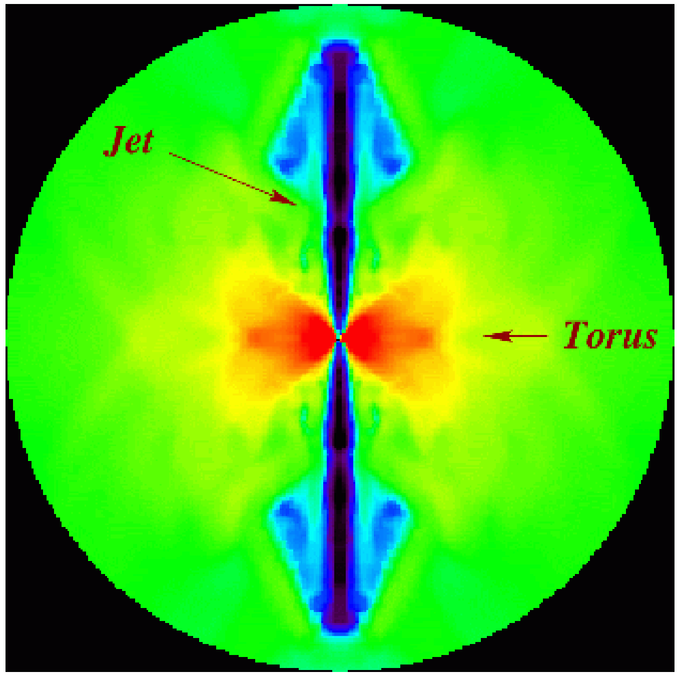
LGRBs

Associated with young galactic population
Found in star forming regions of host galaxy
Associated with core-collapse events

Collapsar

The core of a rotating massive star collapses to a black hole
Material far from the axis does not fall straight in but form an accretion disk
Dissipation in the disk convert kinetic energy into heat
Magnetic field power accretion (MRI)
A jet is launched





Hawley et al.

Energy can be extracted in various ways:

Neutrino heating in the polar region
Wind from the disk (Blandford-Payne)
Angular momentum from BH (Blandford-Znajek)

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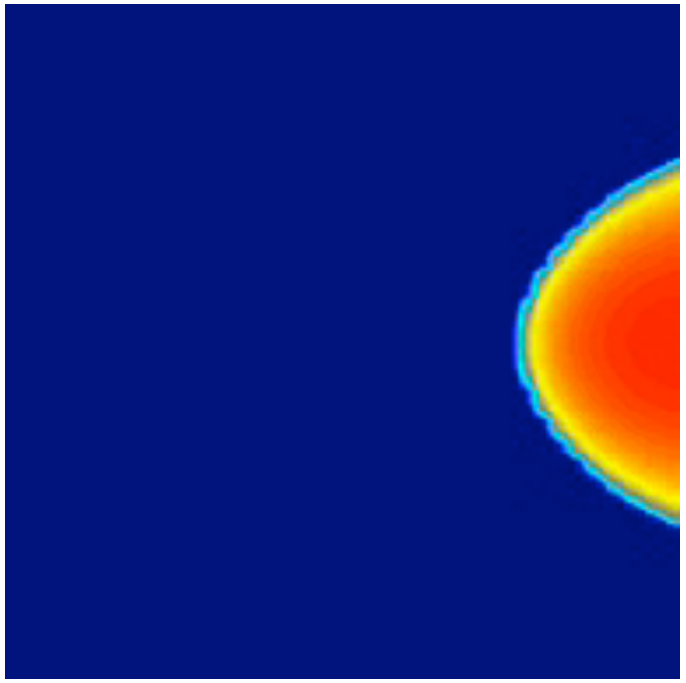

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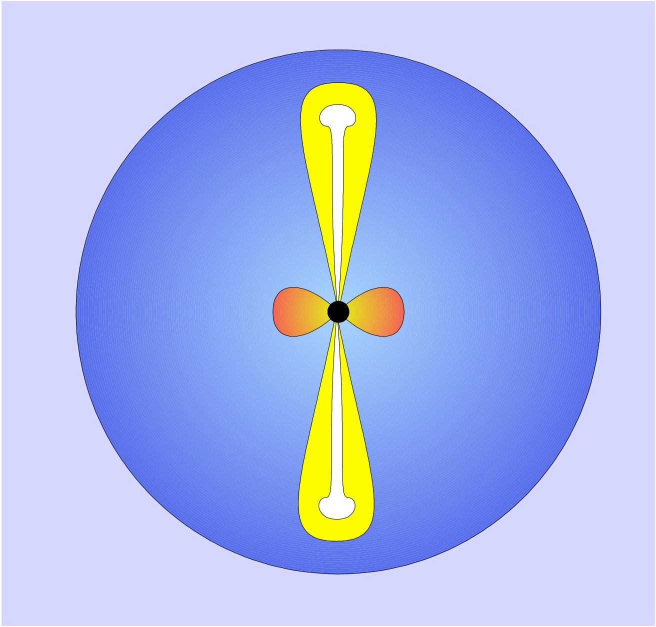

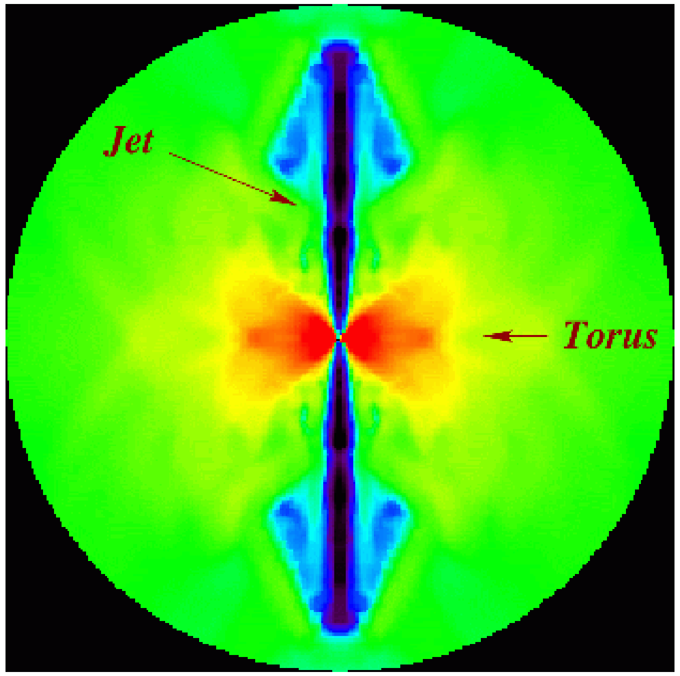

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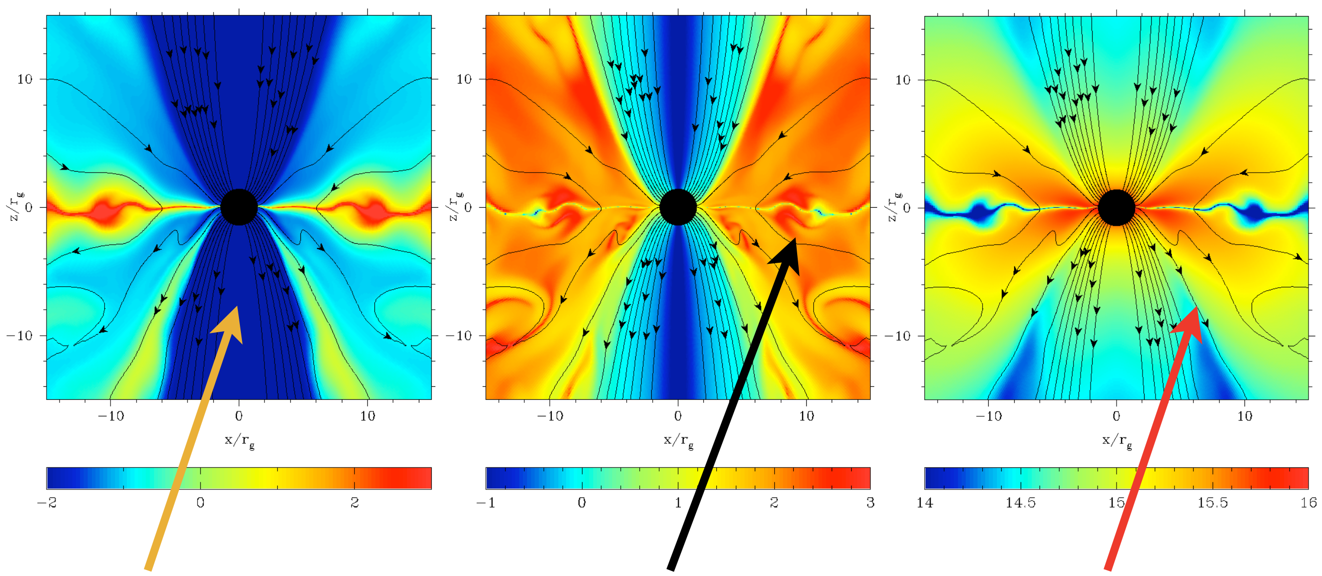
Properties of collapsar

Komissarov & Barkov 2007



BZ jet **Hot torus** **Disk wind**

Possible avenues to drive a GRB:

v-v Annihilation driving a wind
Disk wind powered by BP
BZ extracting enegy from the BH

Pro

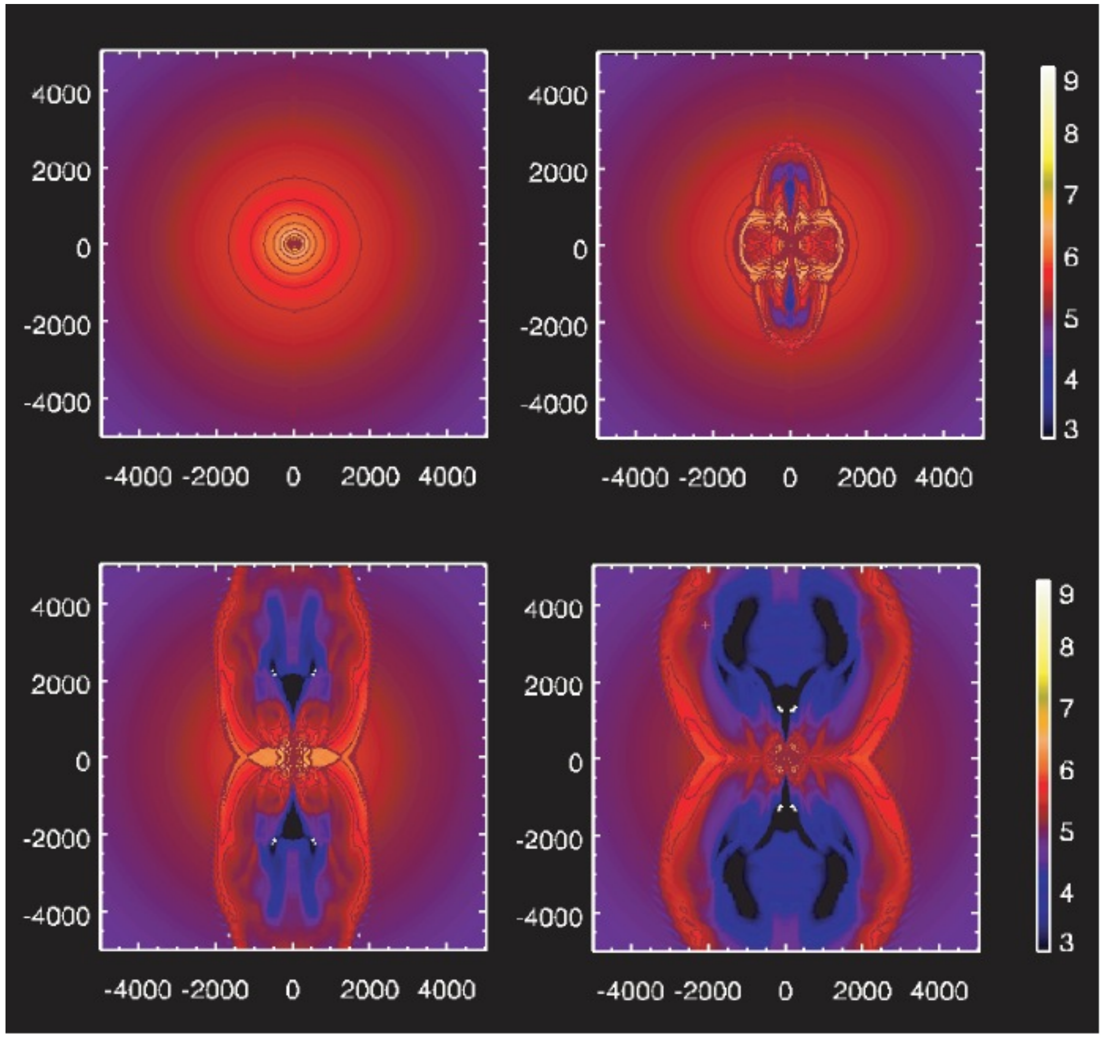
Collapse in high mass stars favors BH
Jets are naturally associated with accretion disks
Disk wind can give the correct Ni^{56} load
Very high Γ can be achieved in the jet
Fragmentation of the torus can lead to late time accretion events (flares)
Accretion can be sustained for a long time

Cons

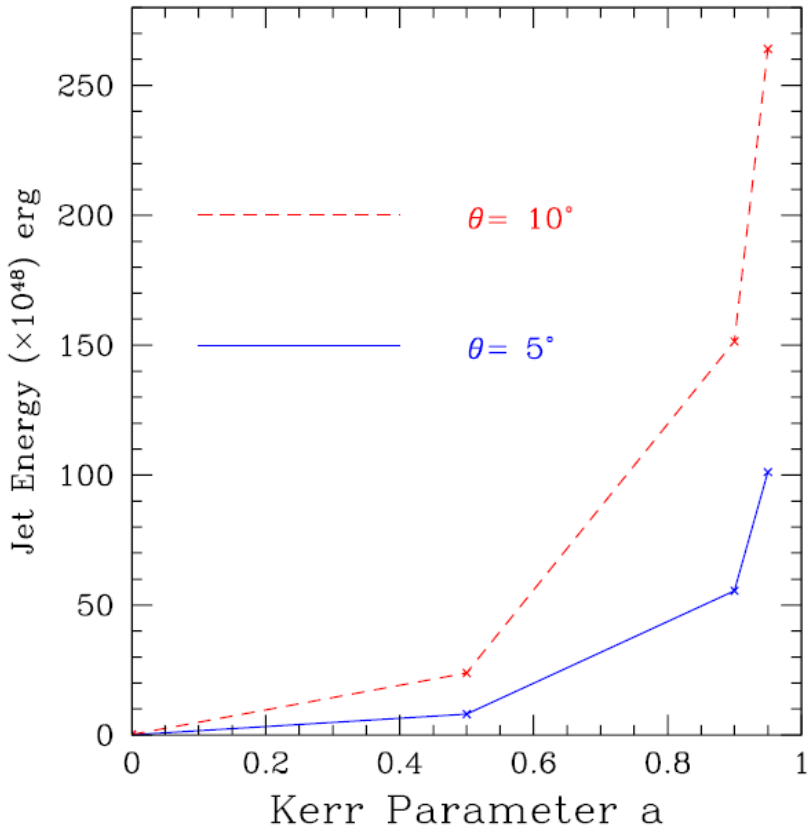
Need rapidly rotating BH
There is a J_{max} for the envelope
Γ is set by non obvious mass loading
Need ordered seed magnetic field
Need a long surviving torus inside SN
Direct collapse to BH not obviously produces SN shock

Faster is better

What is the role of the BH rotation?
IS rotation important for the jet?



Nagataki 2012



Kerr parameter a > 0.5 for efficient jet.
At ~ 1.5 sec the jet is still non-relativistic.

The milisecond-magnetar

Magnetars have fields ~ $10^{14\text{-}15}$ G
They might be born as fast rotators
Efficient dynamo implies P ~ t_{conv} ~ ms

Millisecond magnetar have the correct energy

$$E_{Rot} \approx 2\times 10^{52}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-2} \mathrm{ergs}$$

Pro

NS are naturally associated to core collapse SN
Less angular momentum required than BH-AD
NS population can explain transition from asymmetric SNe to XRFs to GRBs
Magnetar can show energetic bursts

Typical spin-down times are ~ 100-1000 sec

$$\dot{E} \approx 10^{49}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-4}\left(\frac{B_{Dip}}{10^{15}\ \mathrm{G}}\right)^{2} \mathrm{ergs\ s^{-1}}$$

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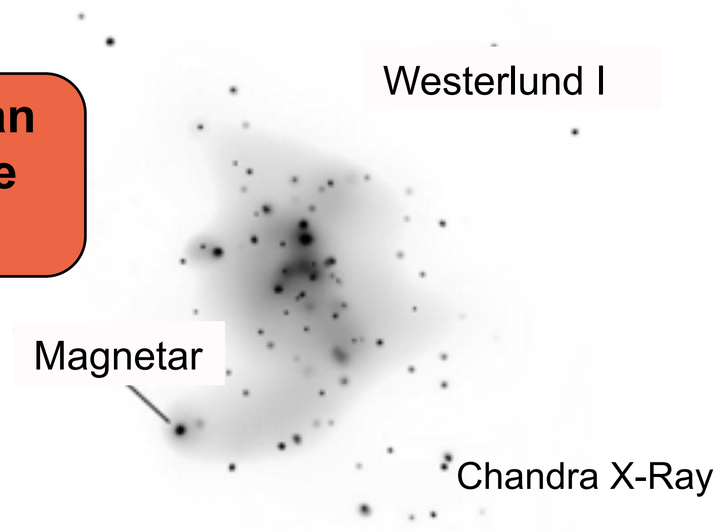
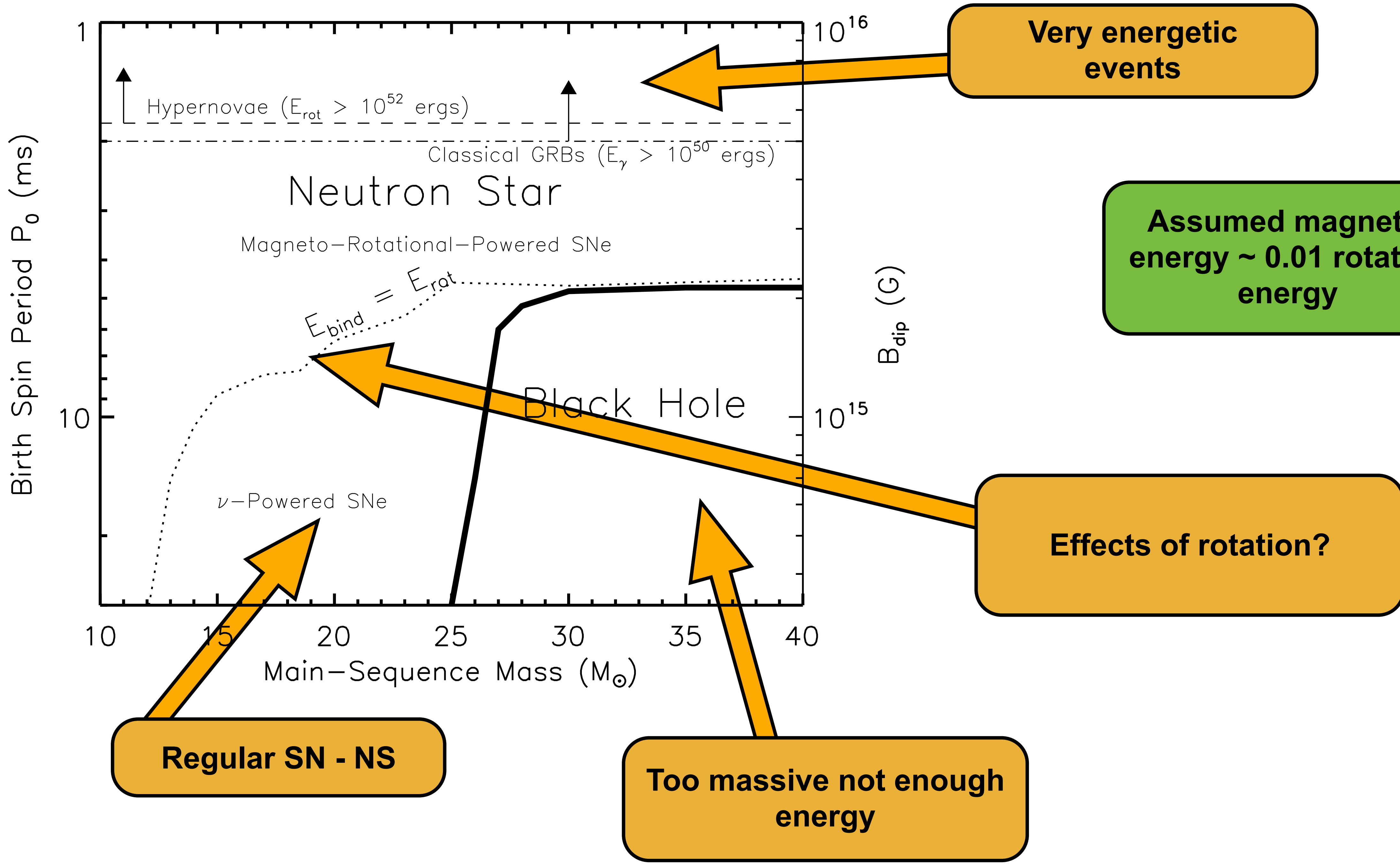
Pulsars have relativistic winds

Magnetars can have massive progenitors



Faintest Cluster Members are O7 (Muno 2006)

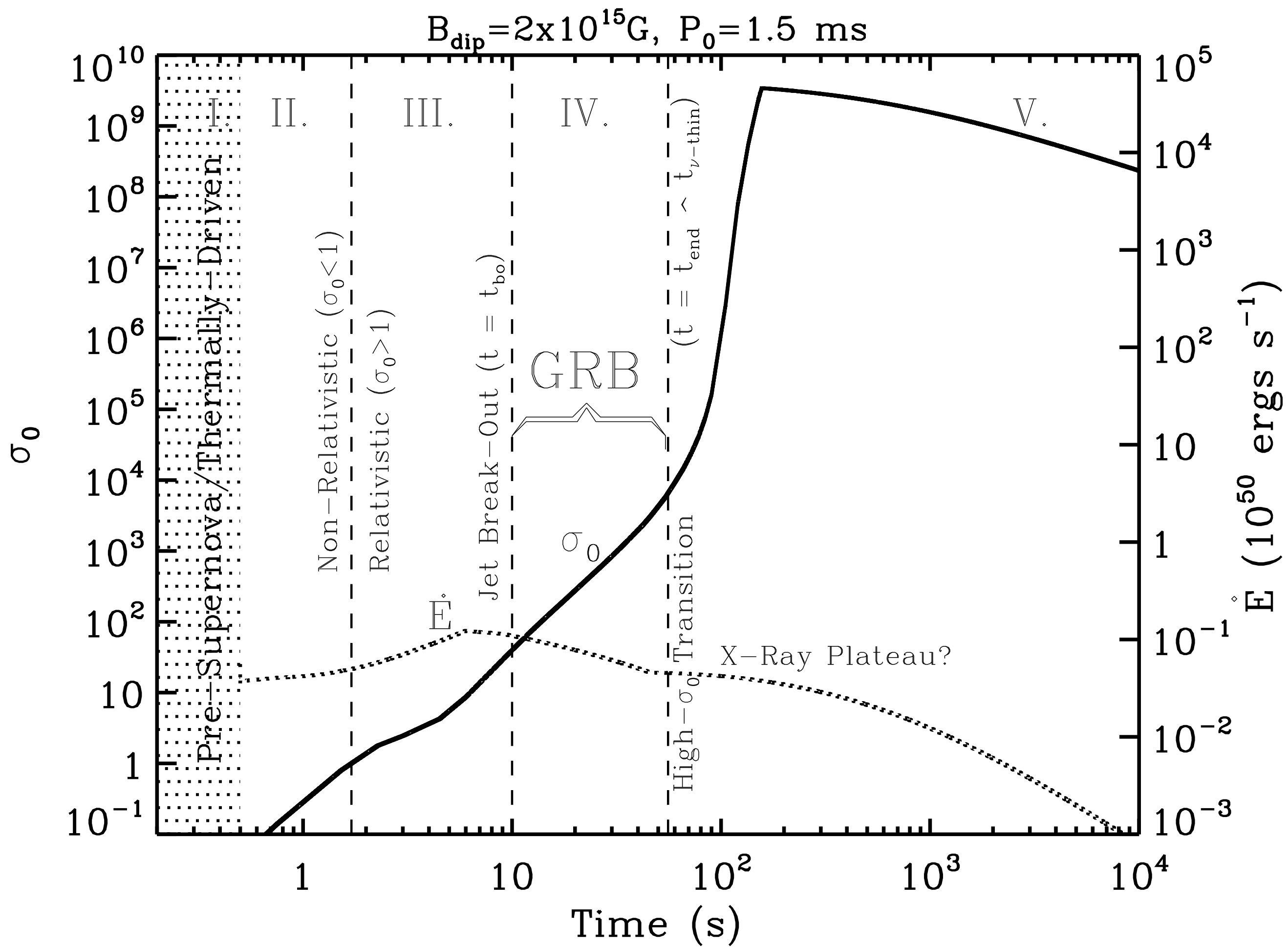
The end of a star

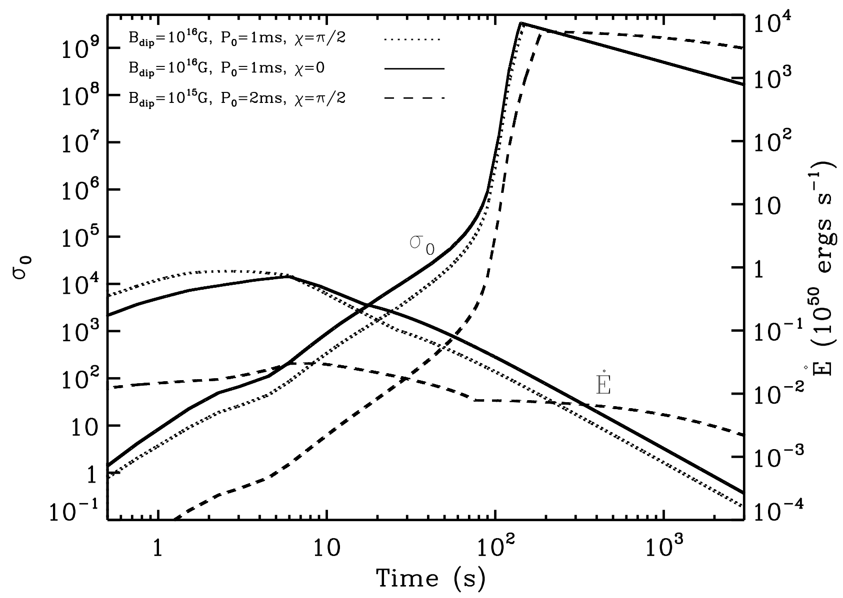


Assumed magnetic energy ~ 0.01 rotation energy

Magnetar spin-down evolution

5





$$\sigma_0 \equiv \frac{\phi^2\Omega^2}{\dot{M}c^3},$$

$$\frac{\dot{\Omega}}{\Omega} = -\frac{2\dot{R}_{\rm ns}}{R_{\rm ns}} - \frac{2\dot{E}}{E_{\rm rot}},$$

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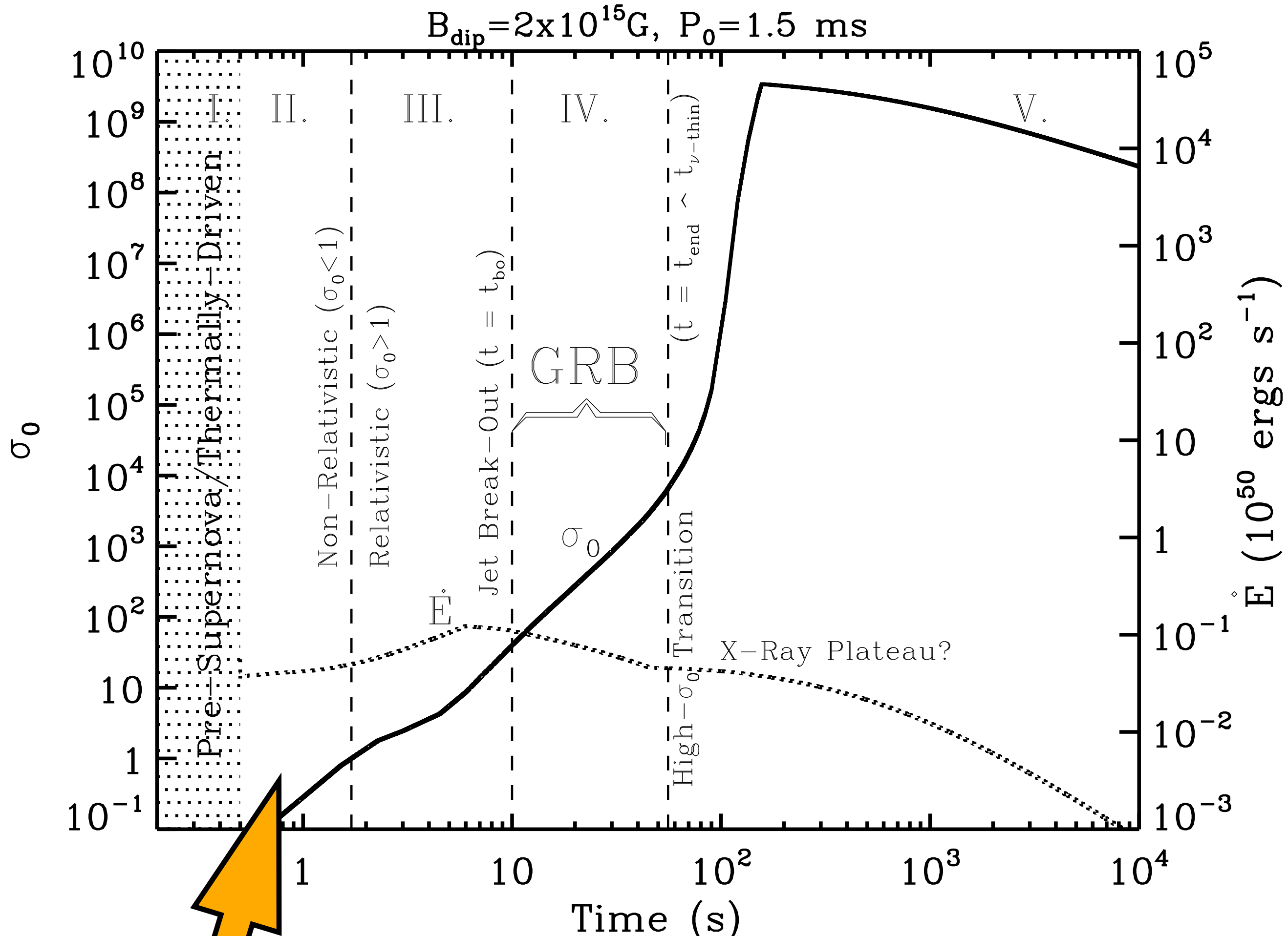

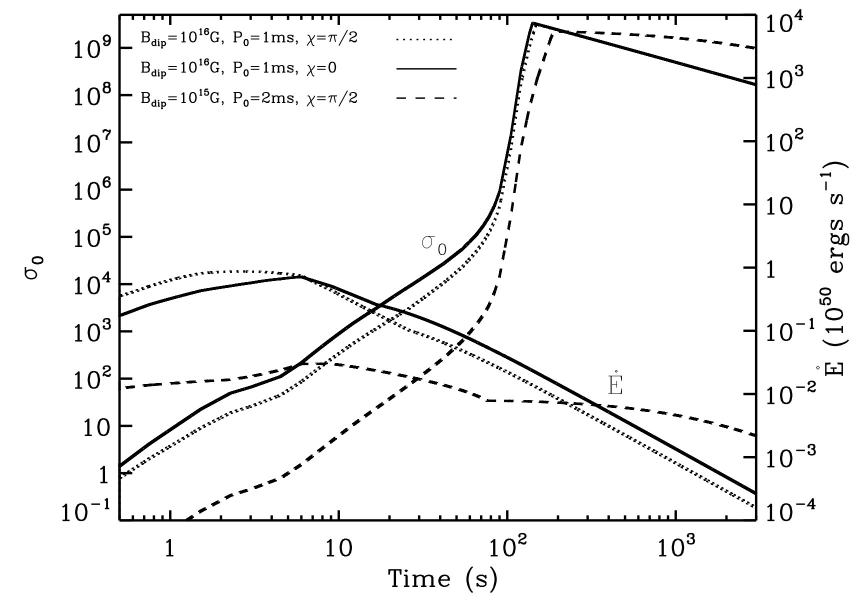

Early non-rel magnetic dominated phase - contraction

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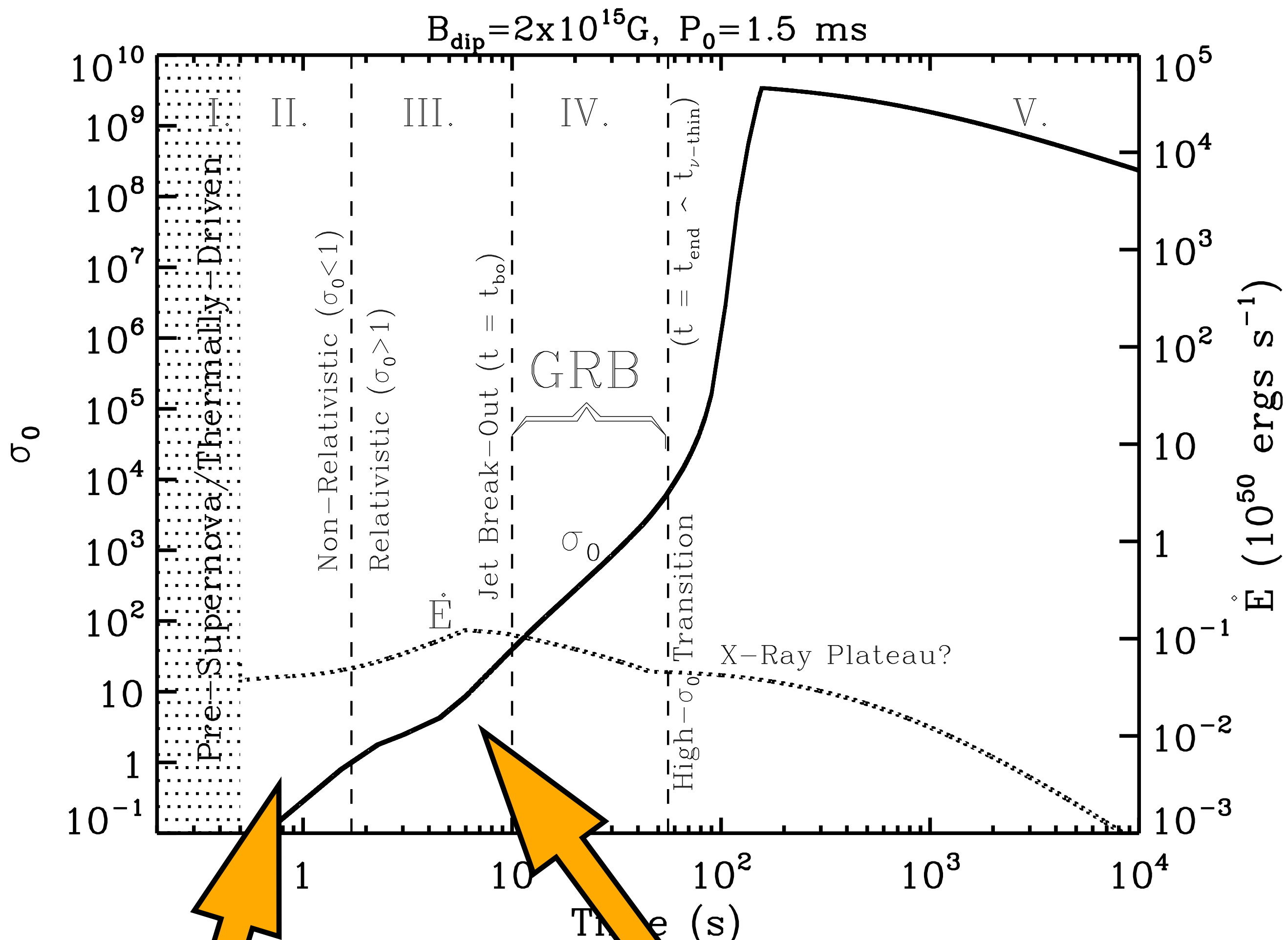

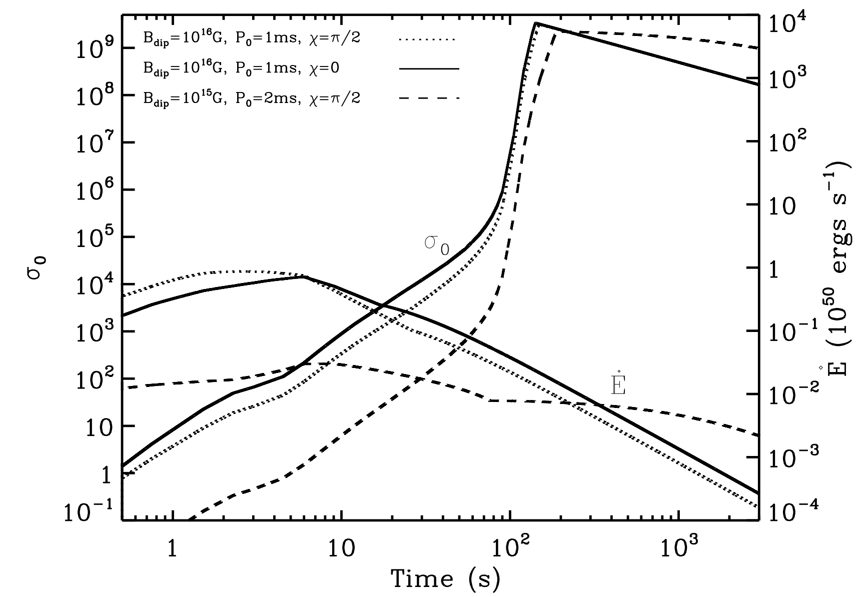

Early non-rel magnetic dominated phase - contraction

Moderately relativistic phase

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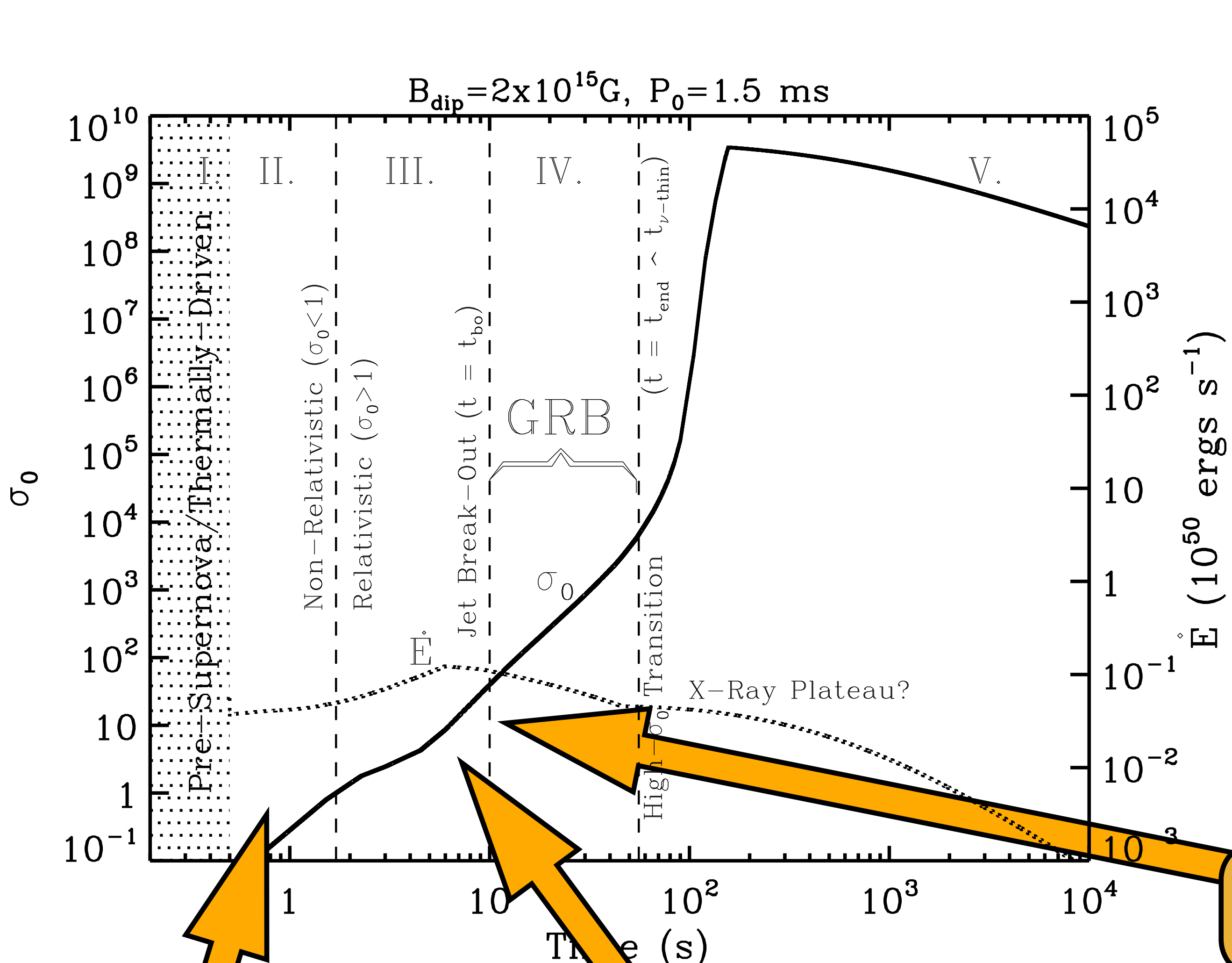
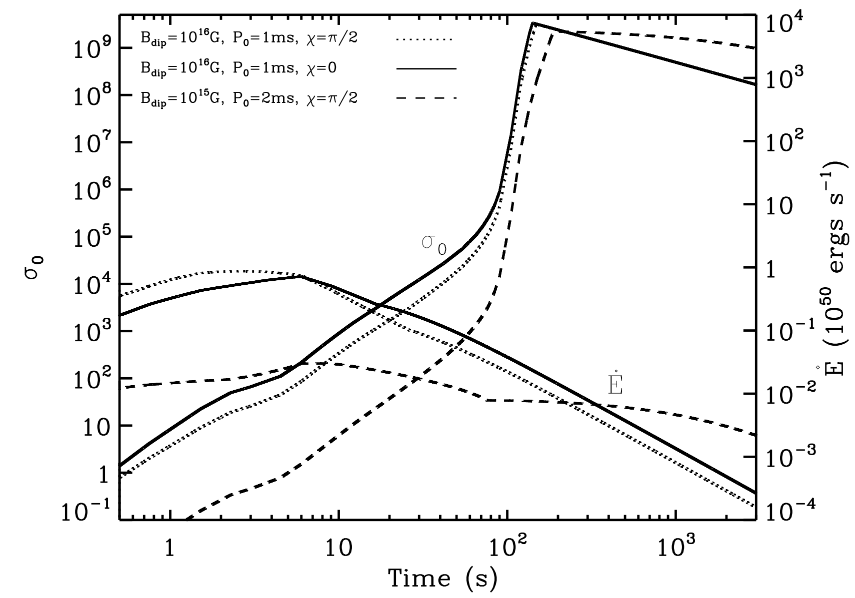
Magnetar spin-down evolution





Break out time

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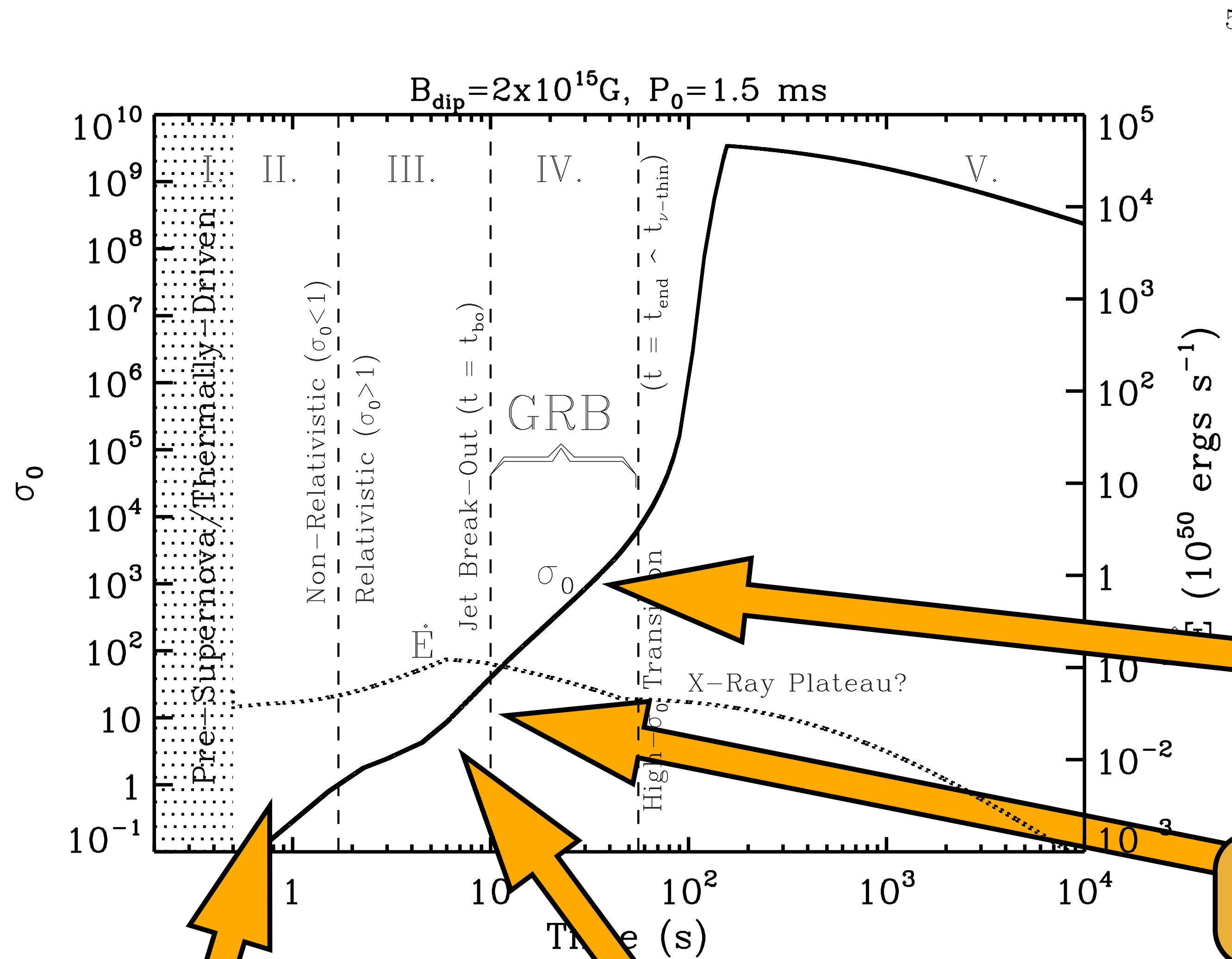
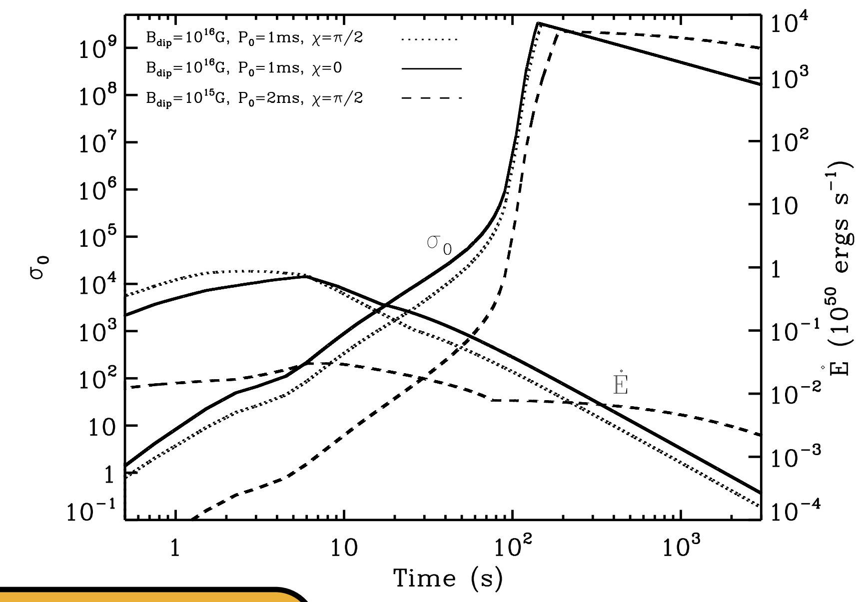
Magnetar spin-down evolution





GRB

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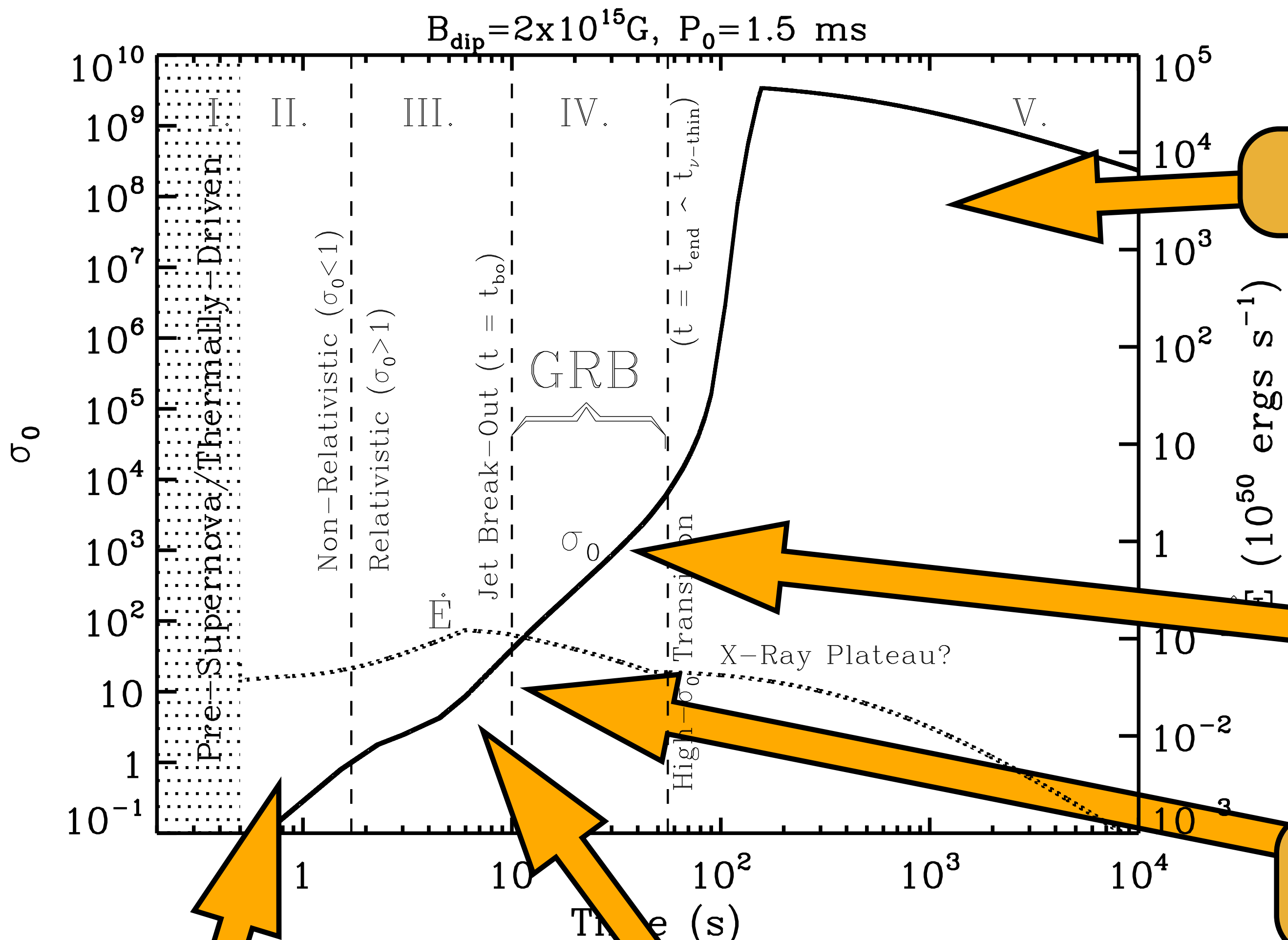

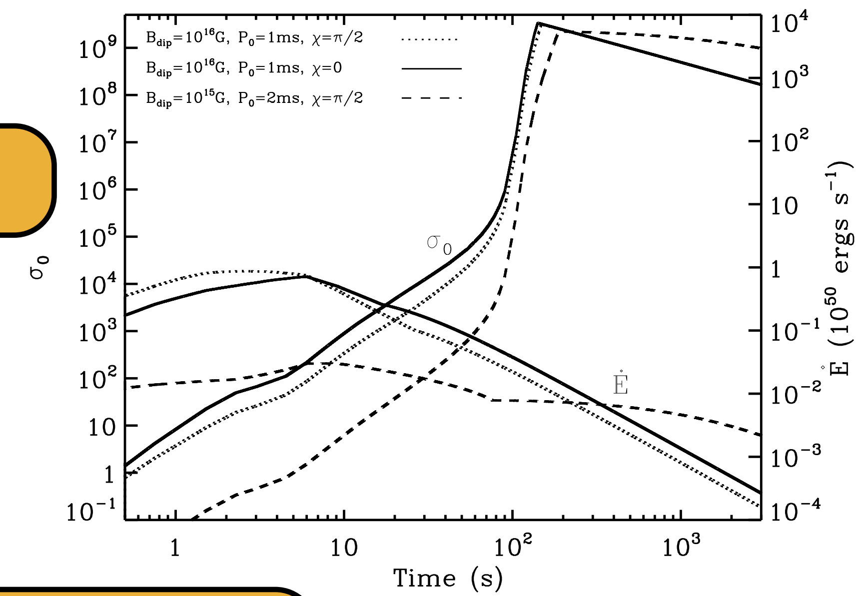

Late activity

GRB

Break out time

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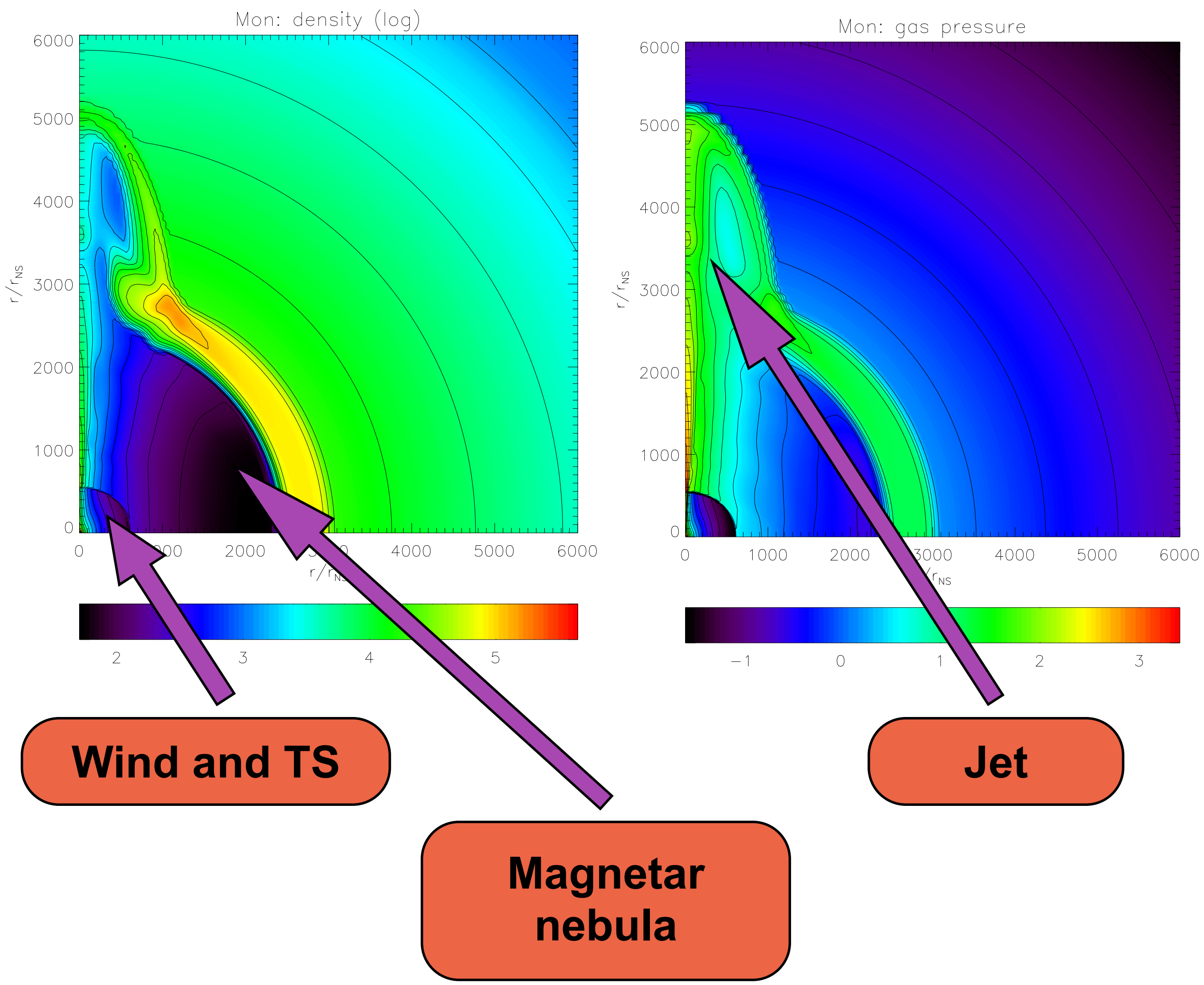
Interaction with the progenitor

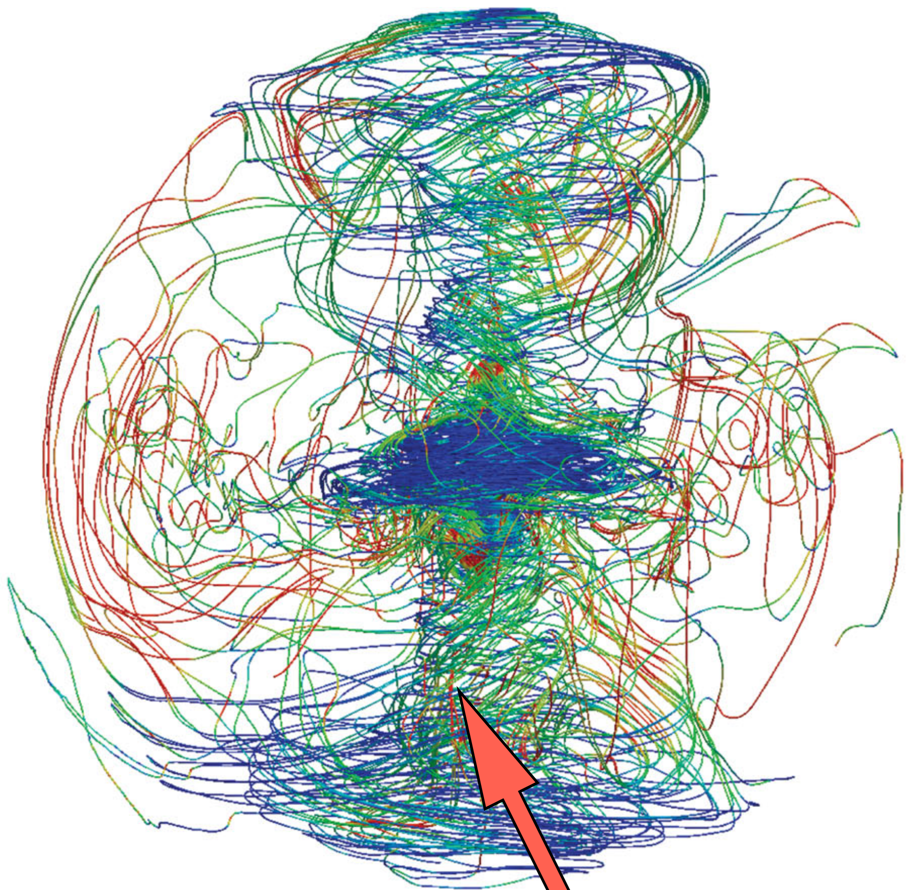


Recent numerical study investigates the transition from the matter dominated phase to the magnetic dominated phase

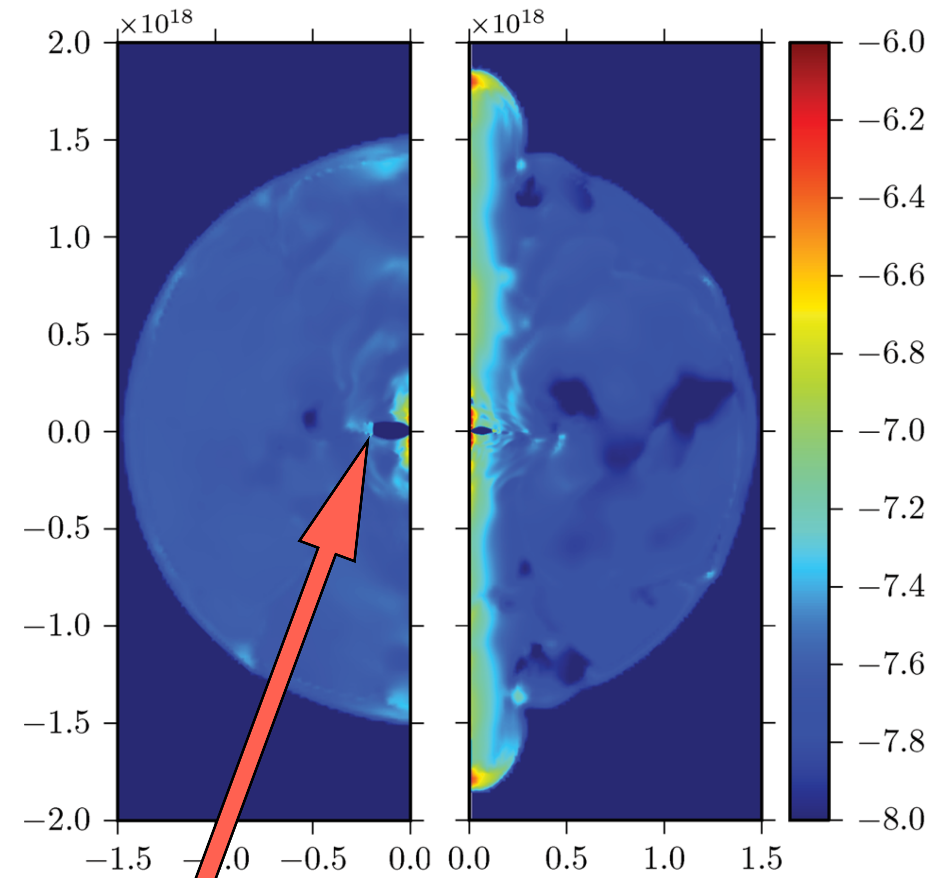
Jet are ubiquitous feature originating from the confinement of a toroidally dominated magnetic field.

Dissipative processes affect the acceleration of the jet but not the collimation

3D vs 2D



Porth et al 2013



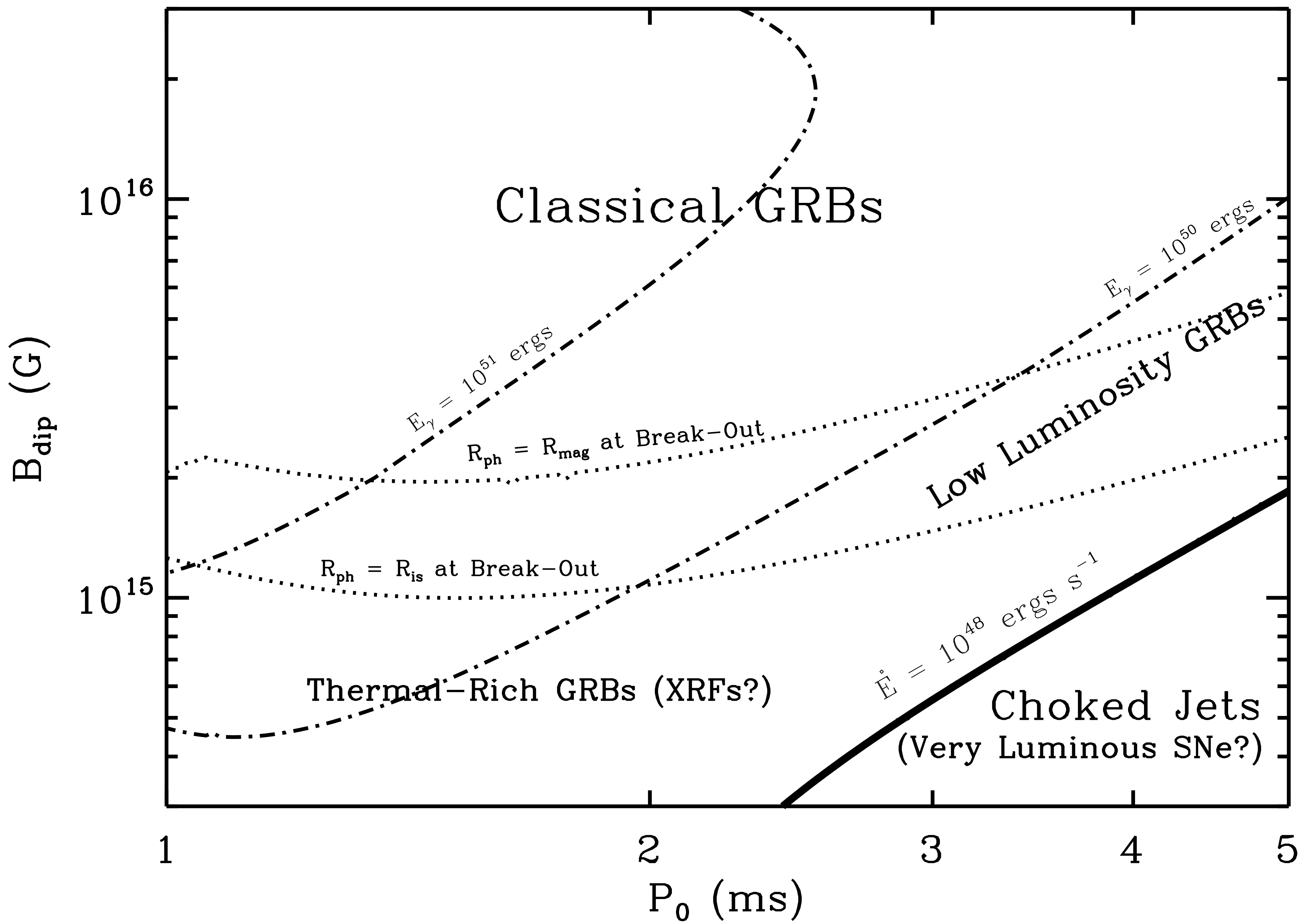
Instabilities of the jet (kink) reduce its penetration

The jet is still present but much weaker and broader than in 2D

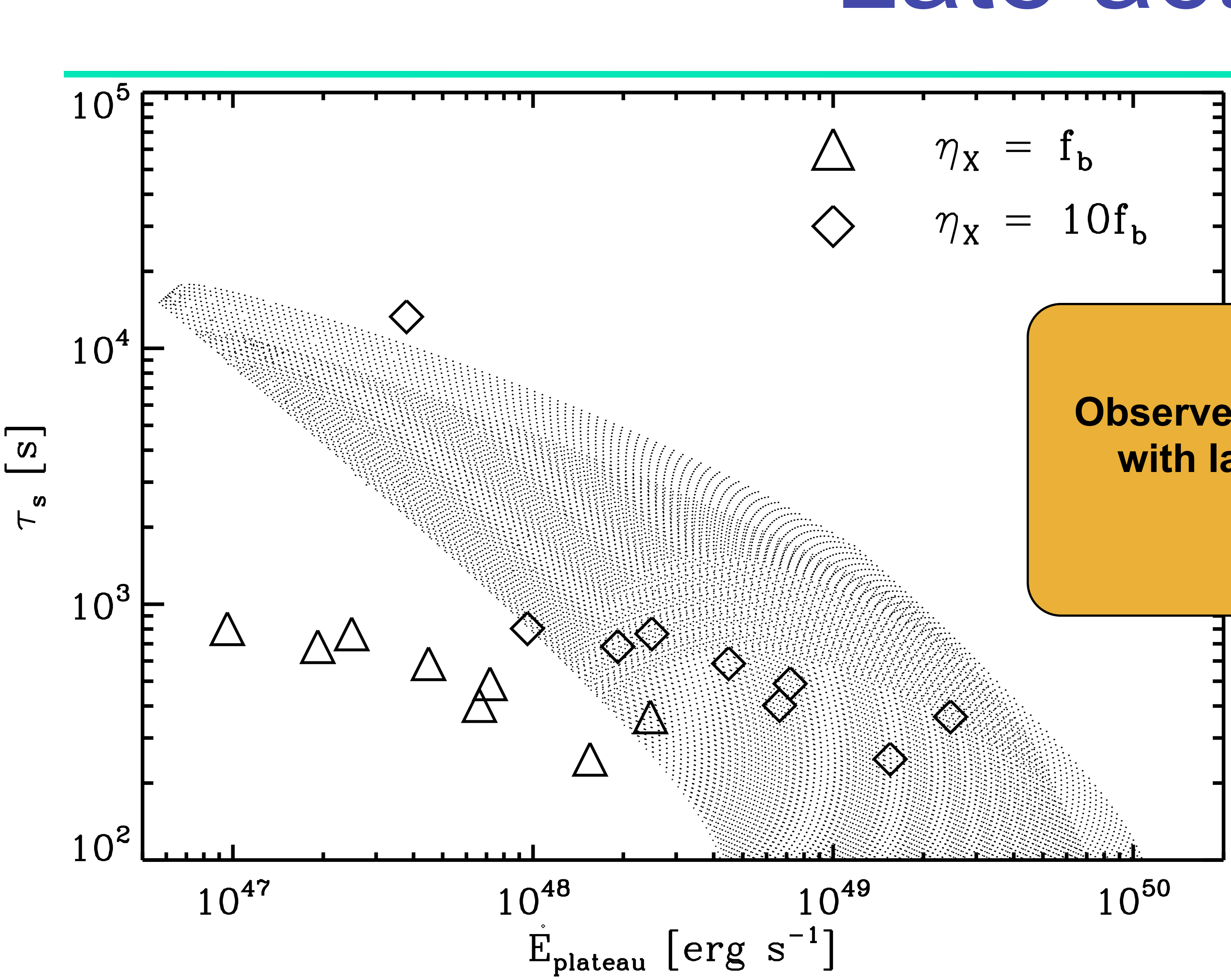
Timescale and energetics?

Diversity

19

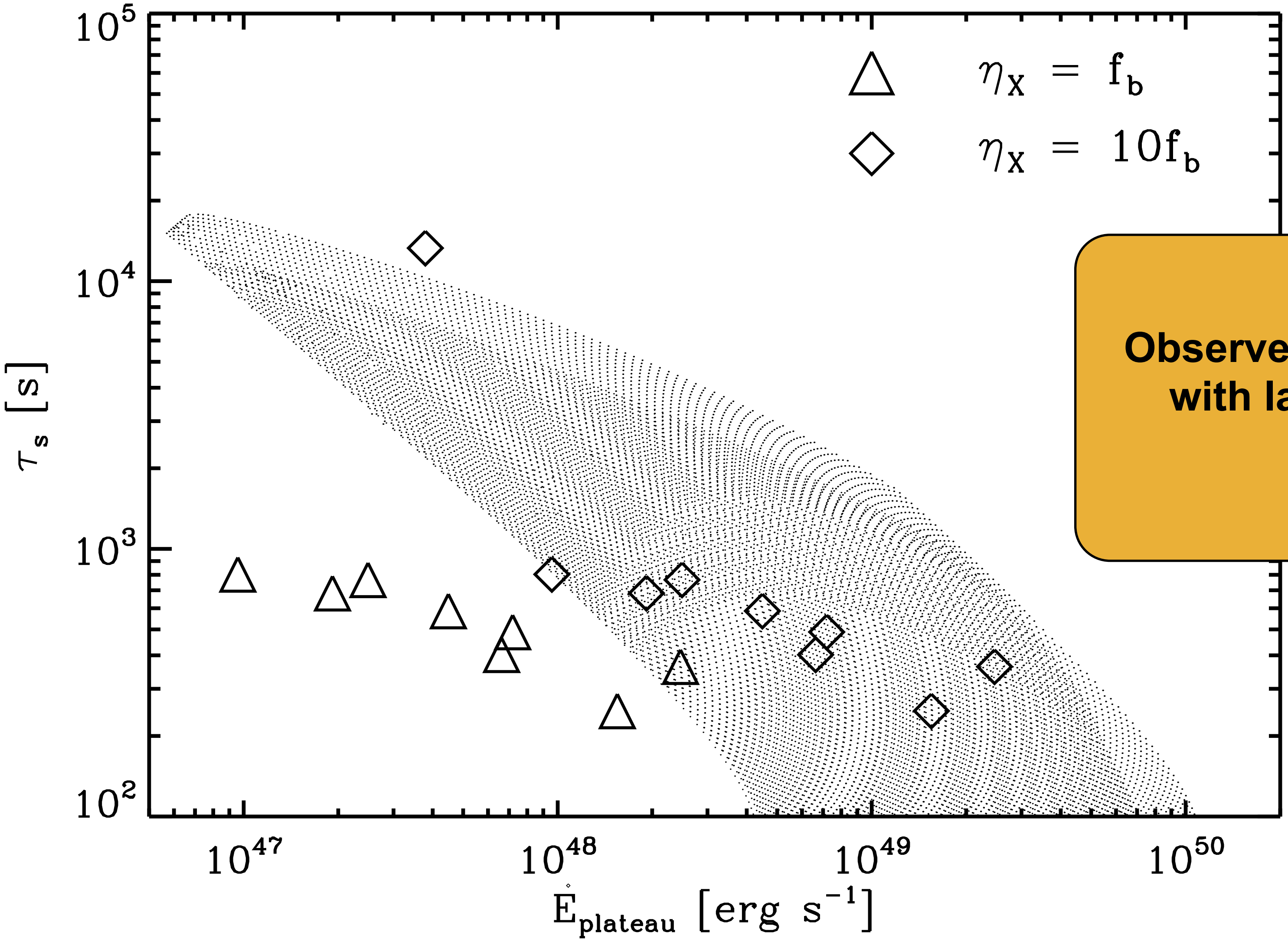


Late activity



Observed plateau energies are compatible with late spin-down injection from the magnetar.

Late activity



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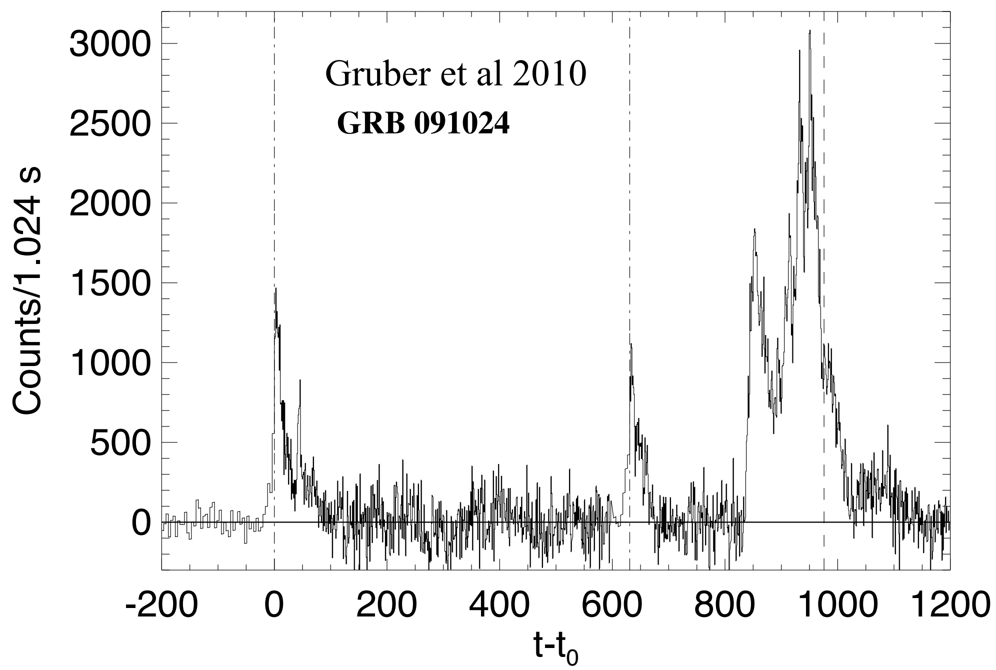
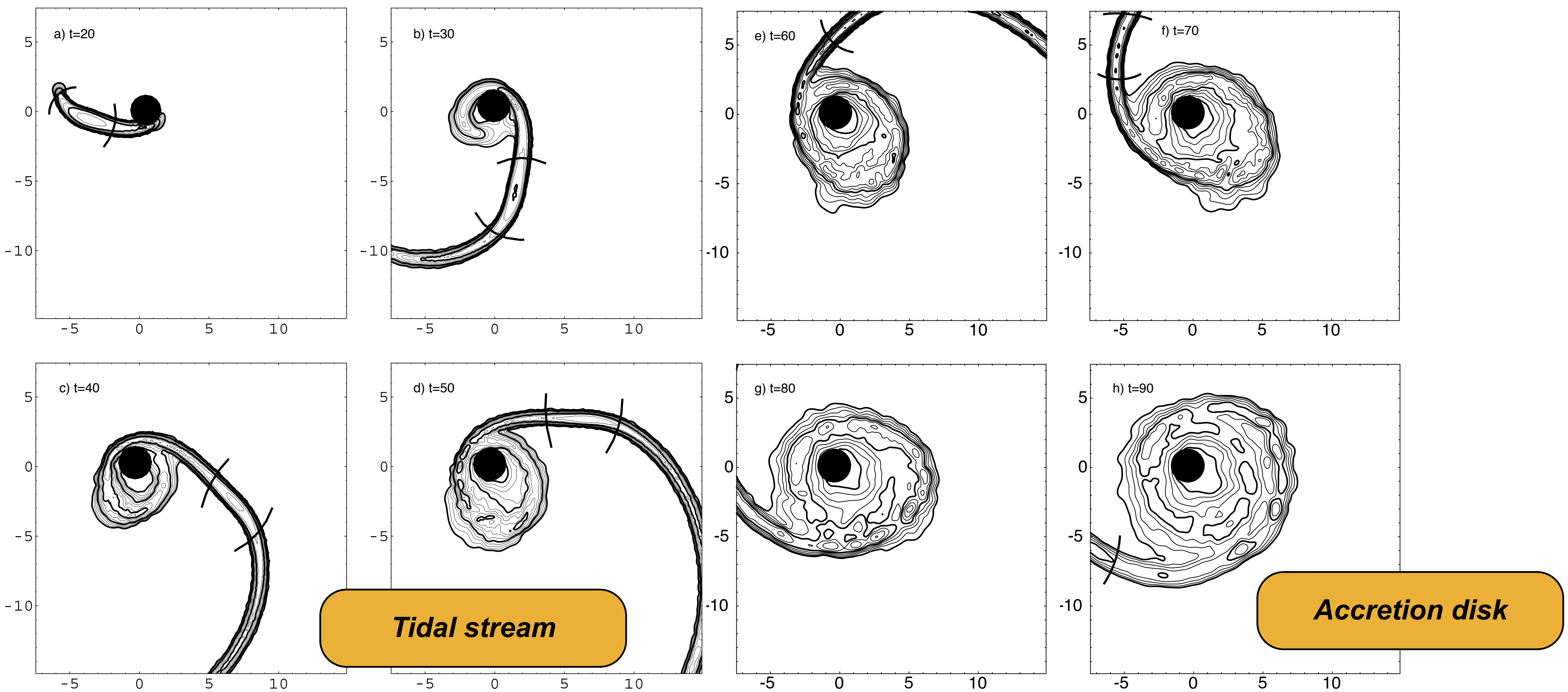


What about duration?
Can we have very long prompt phases?

SGRBs Merger model

The fate of a BH-NS merger
What is left?



SGRBs time-scales

What are the typical time-scales of the merger evolution?

Coalescence time-scale

$$10^9 P^{8/3} M_1^{-5/3} (1+q)(1+1/q) yr$$

Old systems

Burst duration

Disk accretion time-scale

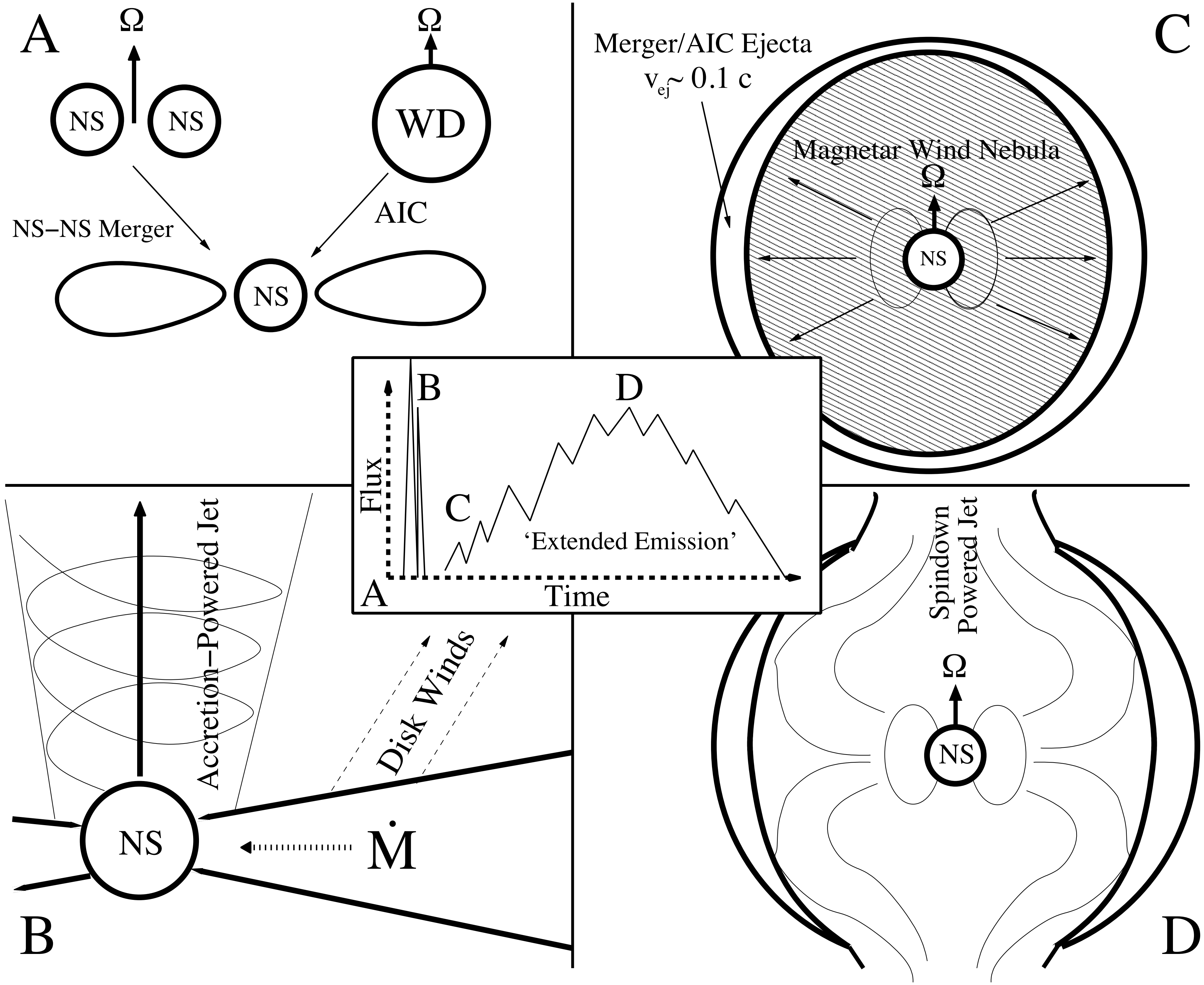
$$0.2 \left(\frac{M_{BH}}{4M_\odot}\right)^{0.5} \left(\frac{R_{circ}}{R_{Sch}}\right)^{0.5} \left(\frac{\alpha}{0.01}\right)^{-1} \left(\frac{c_s}{10^9 cm/s}\right)^{-2} s$$

Tidal stream fallback time-scale

Tidal tail return in about 10^{3-4} sec and circularize at larger distances and colder temperatures

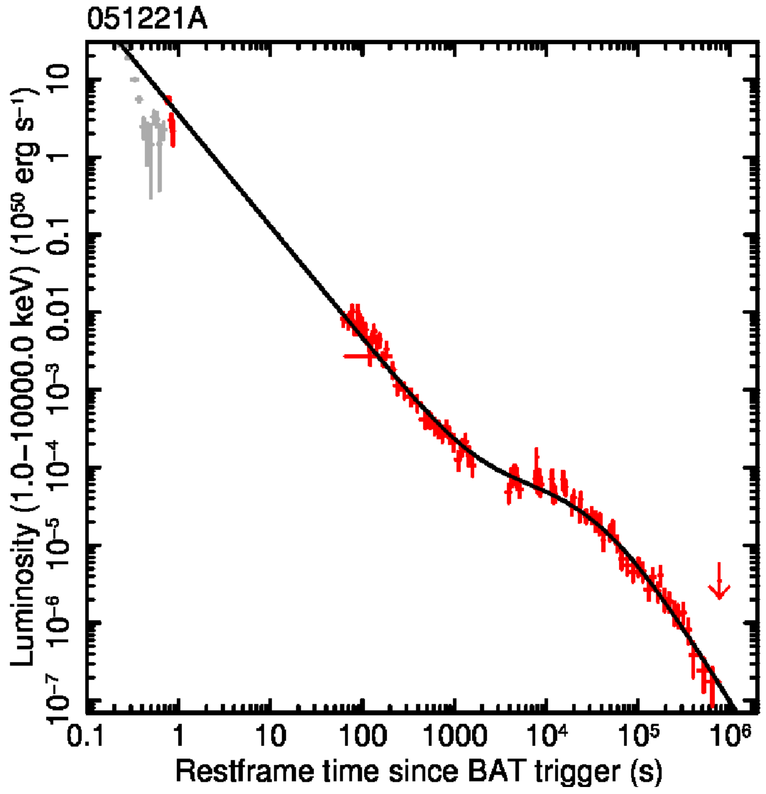
Late time engine activity

Collapse to Magnetar

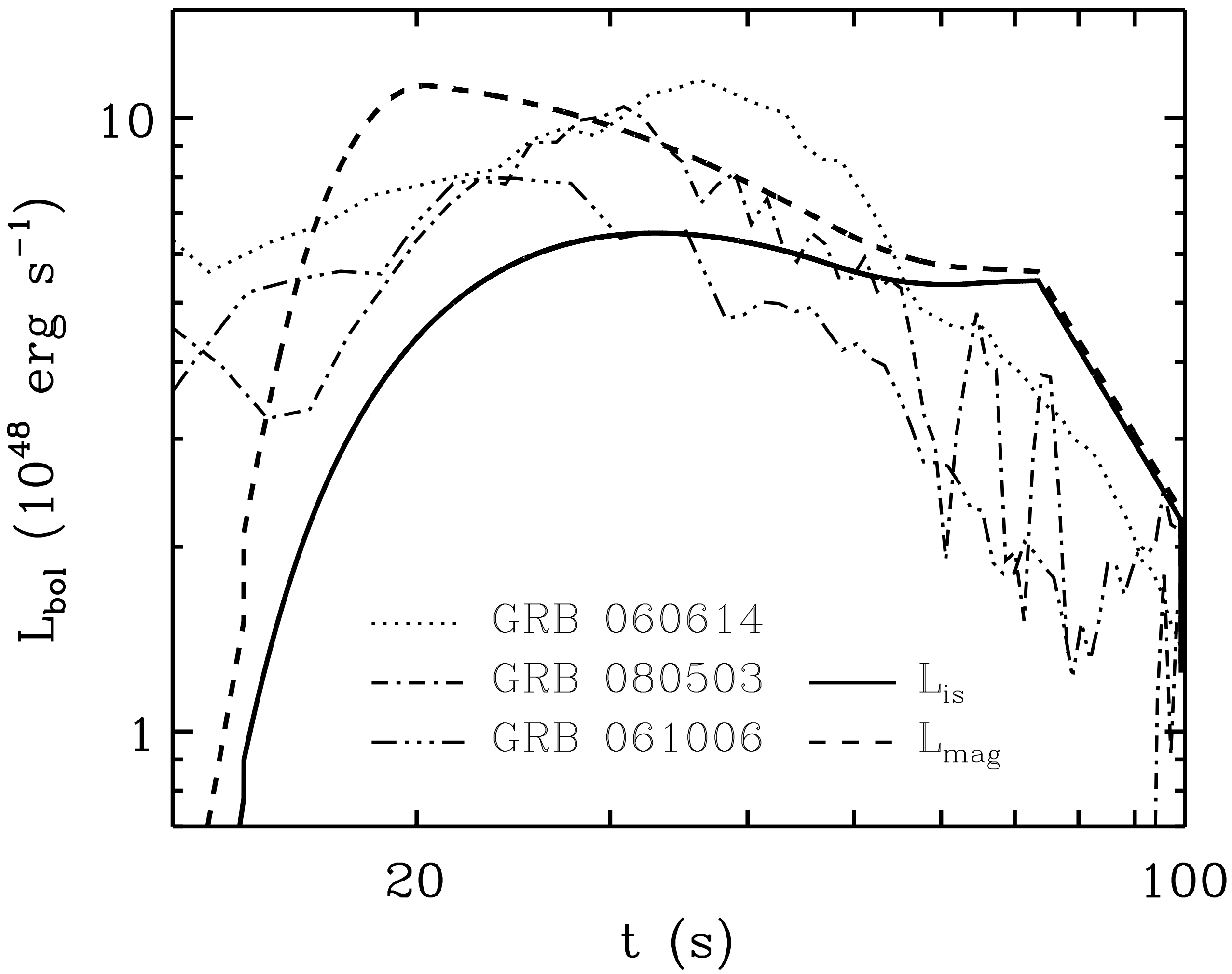


Extended activity

In the magnetar model the EE is explained in the same way as the prompt for the LGRBs



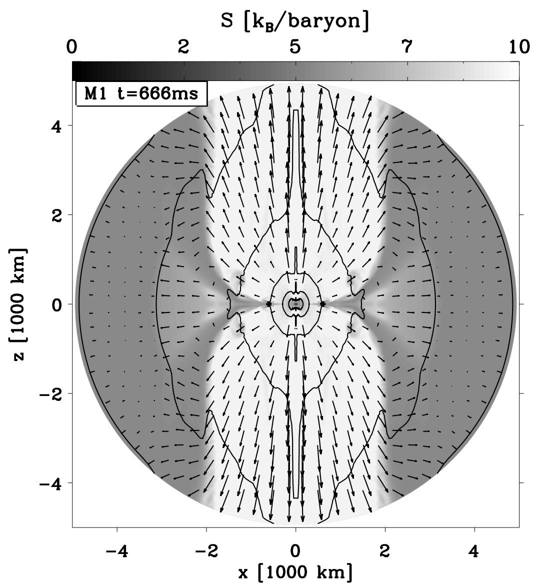
Rowlinson & O'Brien 2012

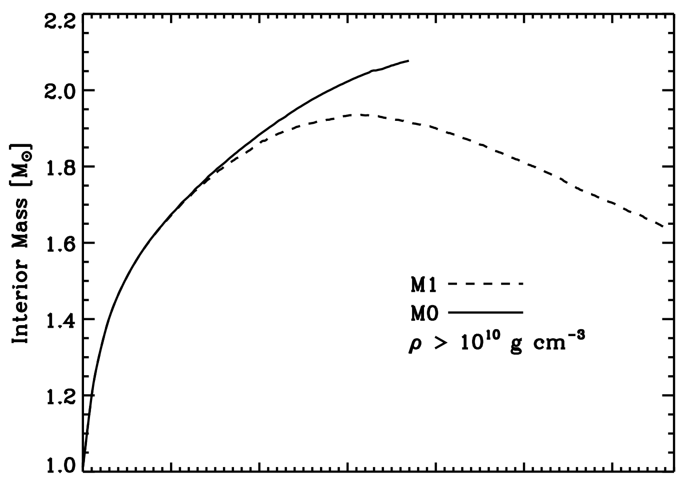


While plateaus and later activity are usually attributed to the late pulsar like spin-down

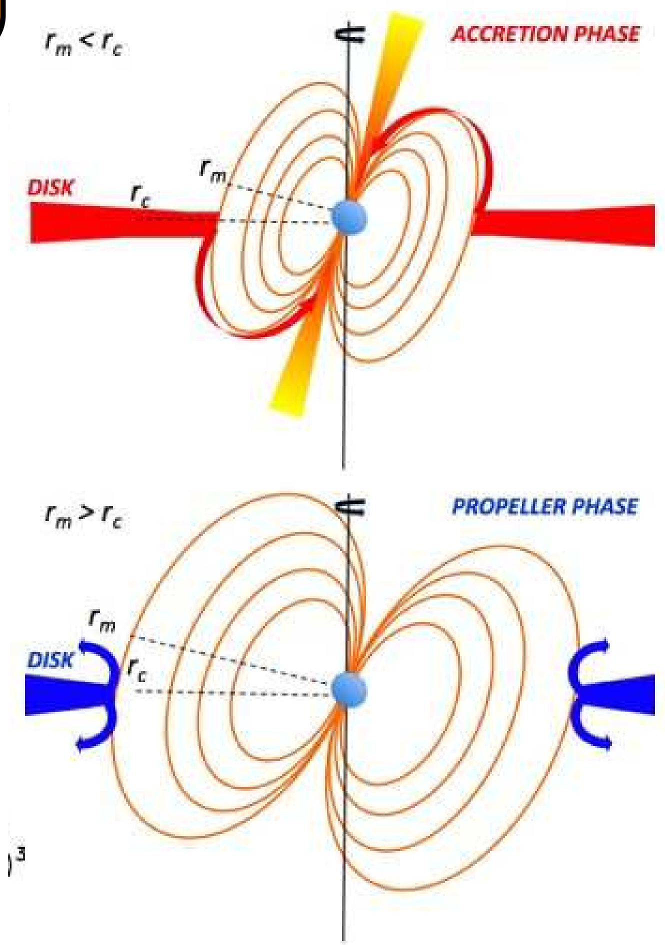
Turning Magnetar into BH

Nothing forbid matter to accrete onto the newly born magnetized PNS





Dessart et al 2008



Magnetic field can turn an accreting NS into an accreting BH

With all the on-off phenomenology of BH-AD systems

Bernardini et al 2014

Turning a BH into a Magnetar

Is the BZ solution the only possible FF magnetospheric solution for a rotating BH?

Turning a BH into a Magnetar

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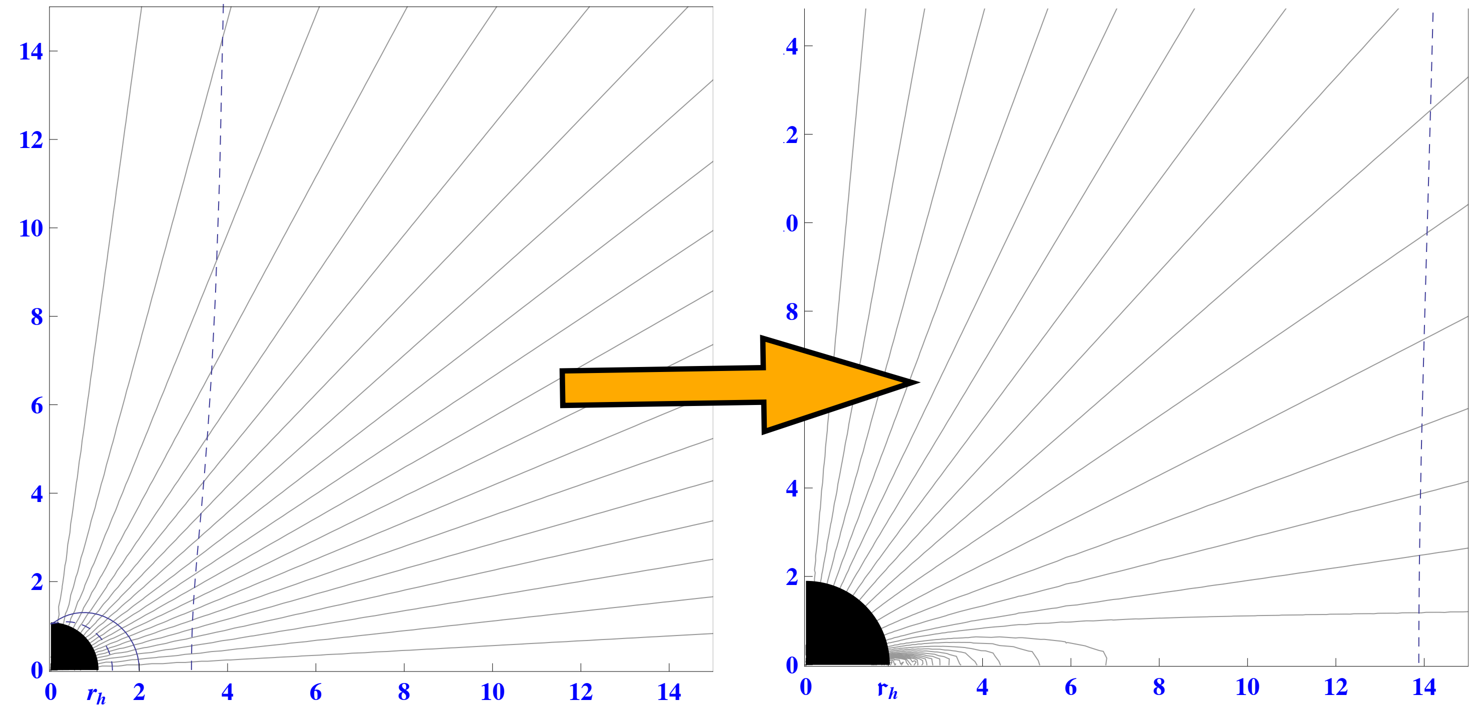
Can a BH have a net charge?



Contopoulos et al 2013

Turning a BH into a Magnetar

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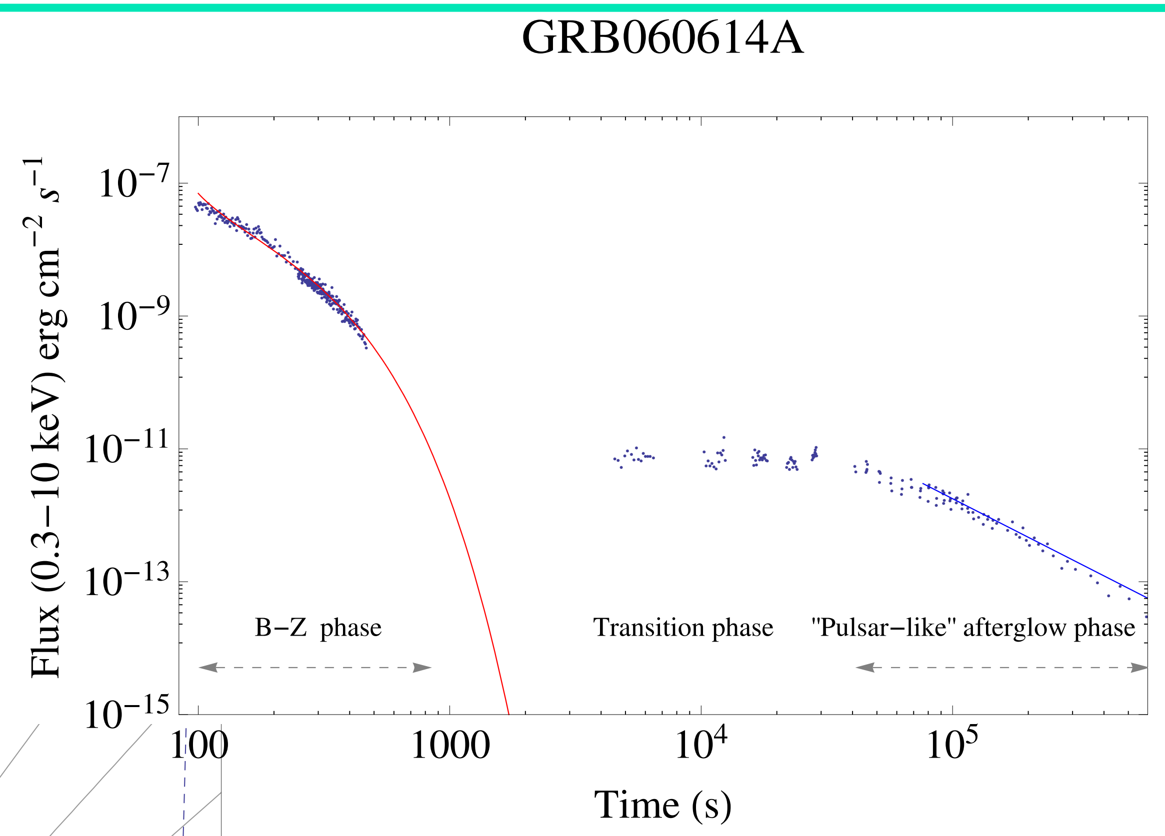

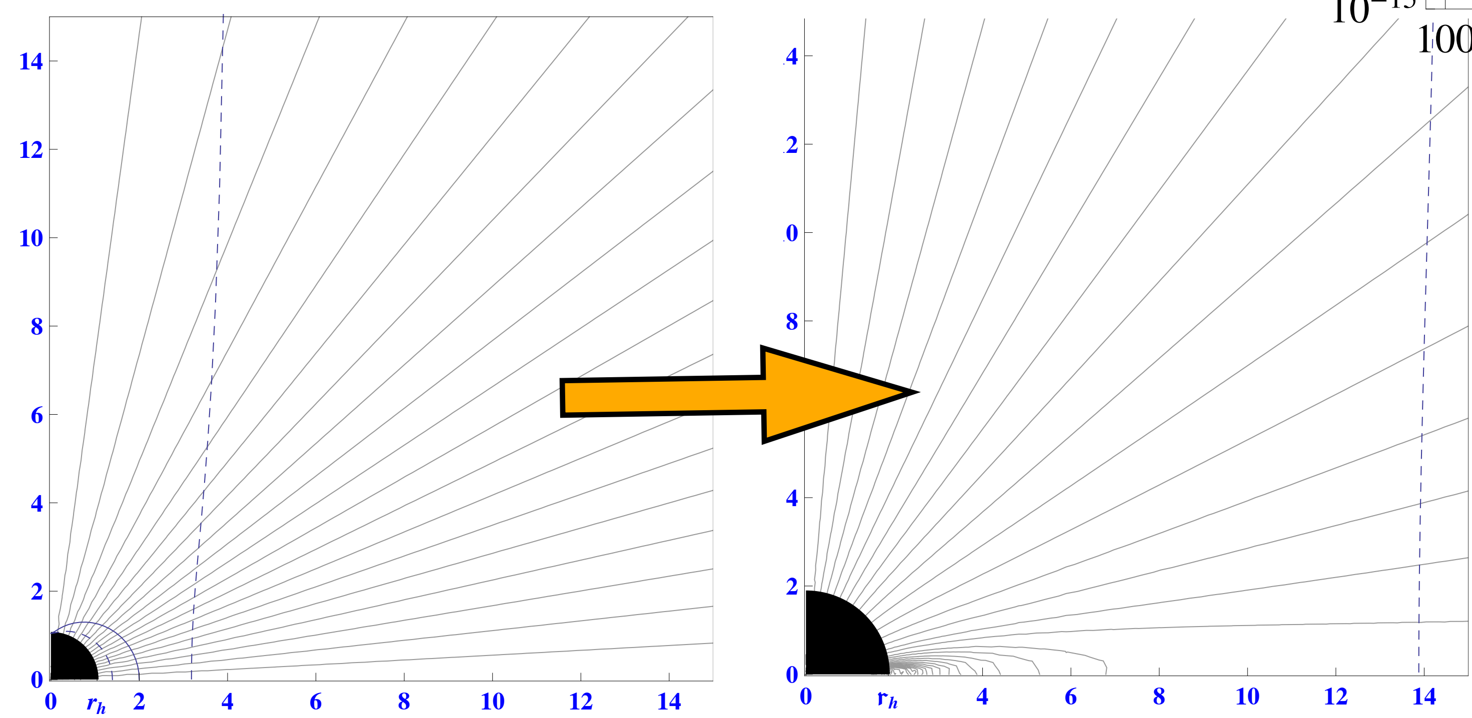

A BH can have a late pulsar like spin-down.

Contopoulos et al 2013

Conclusions

- There are few well defined properties of GRBs that constrain directly the engine
- Late activity / Extended Emission clearly point to long lived engine
- The standard BH Collapsar is in general less constrained but more adaptable
- The Millisecond Magnetar model naturally provides a long lived engine, but it is more constrained
- Not clear what is the imprint of different engines on the associated SN or KN
- The magnetar model is more promising for SGRBs
- Beware that at the end, engines can be made to look quite similar!

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Thank you