
Perspectives on Gamma Ray Bursts (GRBs) - Enigma and a Tool
Tsvi Piran
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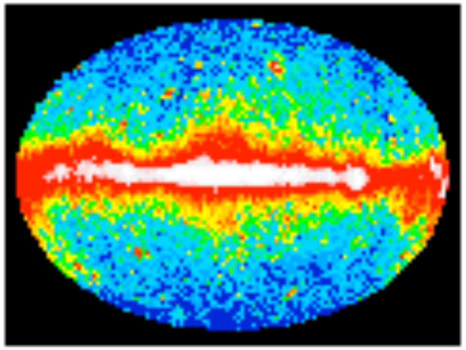
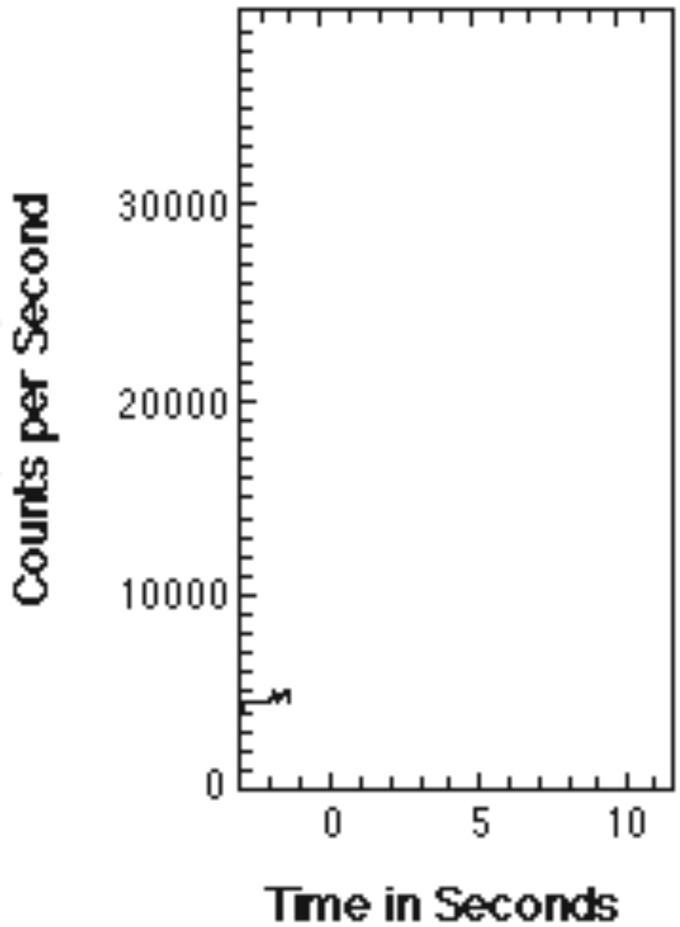
GRBs are the (electromagnetically) brightest objects in the Universe. Only ~8 orders of magnitude less then the theoretically maximal * luminosity (c^5/G)~10^{59} erg/sec .

$$\frac{Mc^2}{GM/c^3}$$

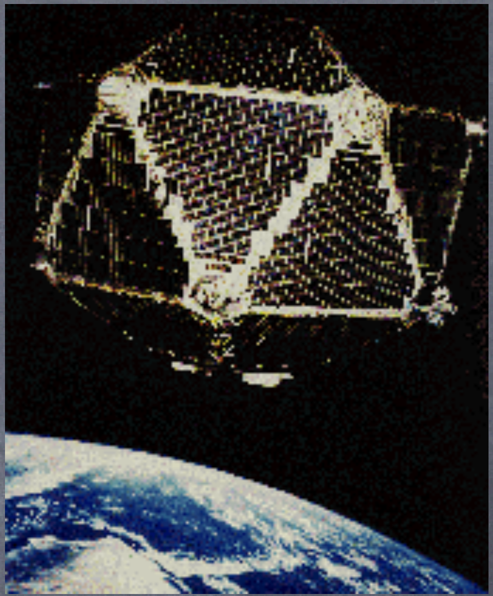
* Up to relativistic corrections.

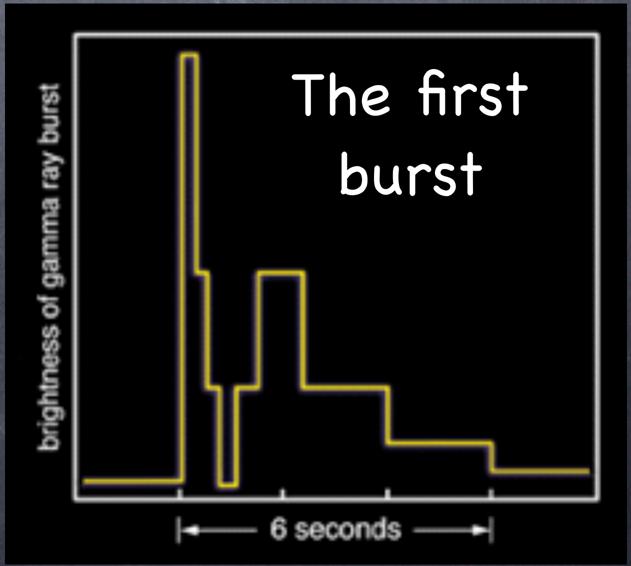



Counts per Second
30000
20000
10000
0
0
5
10
Time in Seconds

The Vela Satellites

GRBs were discovered accidentally at the late 60ies by the Vela satellites, defense sattelites built to monitor the outer space treaty that forbade nuclear explosions in space. At that time - the late sixties - it was considered “impolite” to launch a spy sattelite.





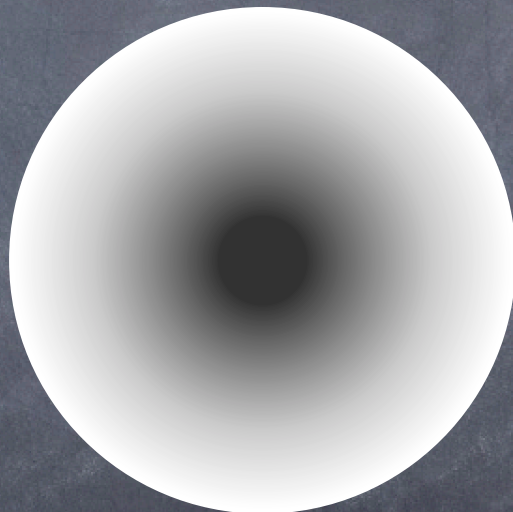
An invited prediction ?

Prompt gamma rays and X rays from supernovae

Stirling A. Colgate

Canadian Journal of Physics, 1968, 46:(10) S476-S480, 10.1139/p68-274

Gamma ray Burst at shock break out from Supernova explosion



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Shock breakout
“first light”

Properties

- Duration 0.01-1000s

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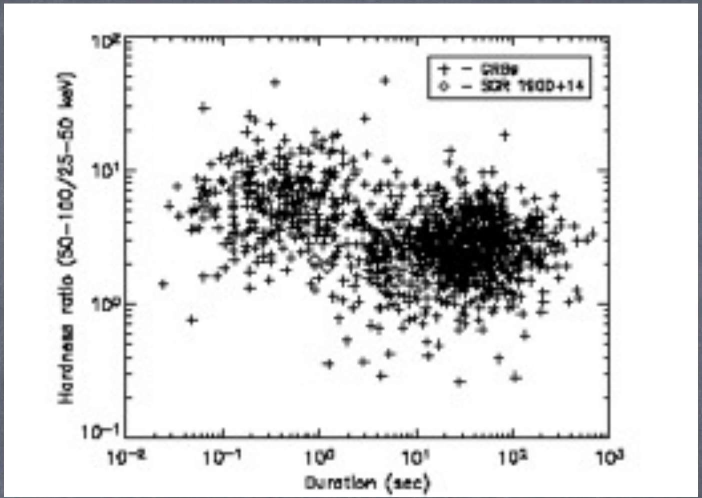

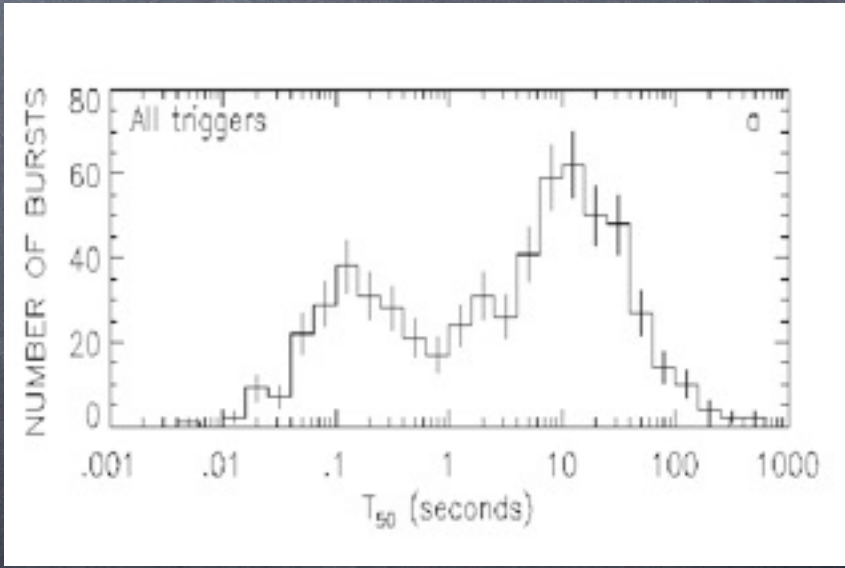

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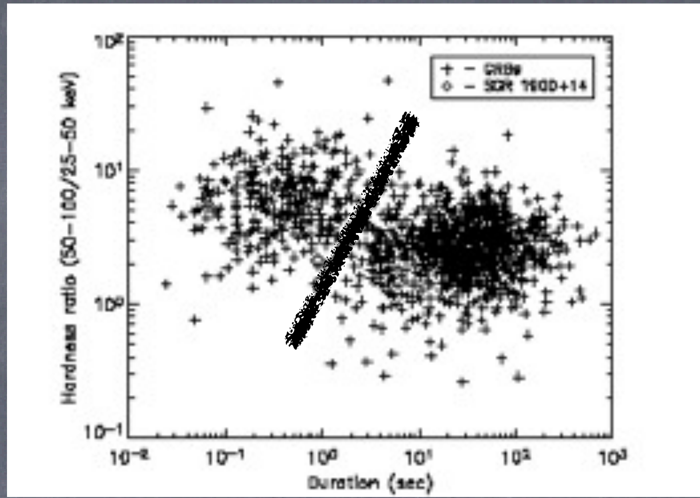

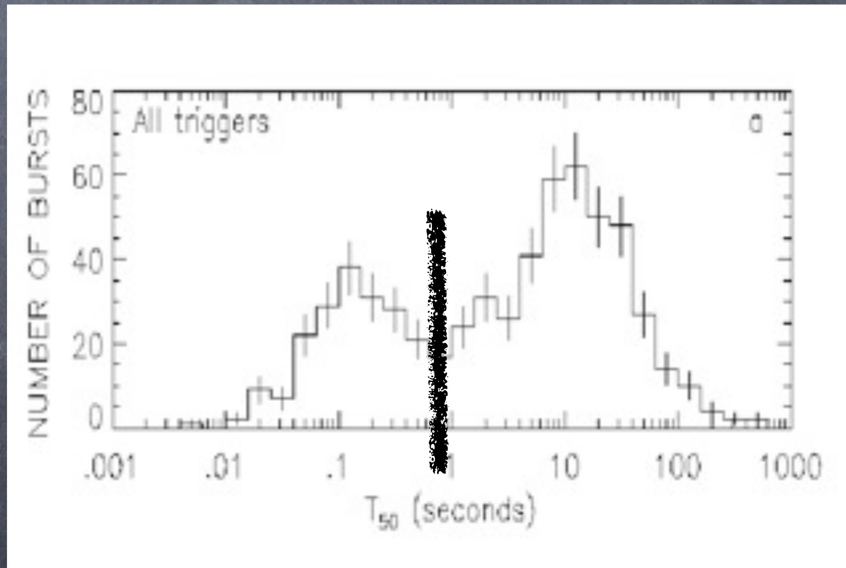

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  (very high energy tail,

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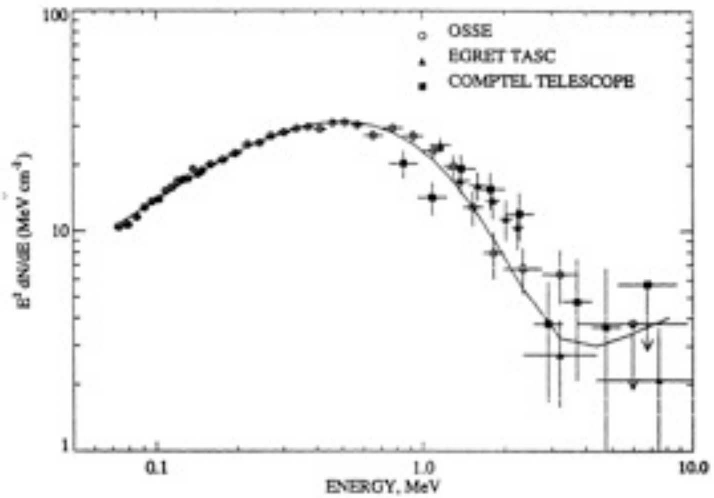

Figure 9 The spectrum of GB 910601 observed over a wide energy range, as measured by three experiments on *CGRO* (Share et al 1994). A typical broad spectrum with a peak power at about 600 keV is seen. (The fitted spectral up-turn above 4 MeV is not significant.)

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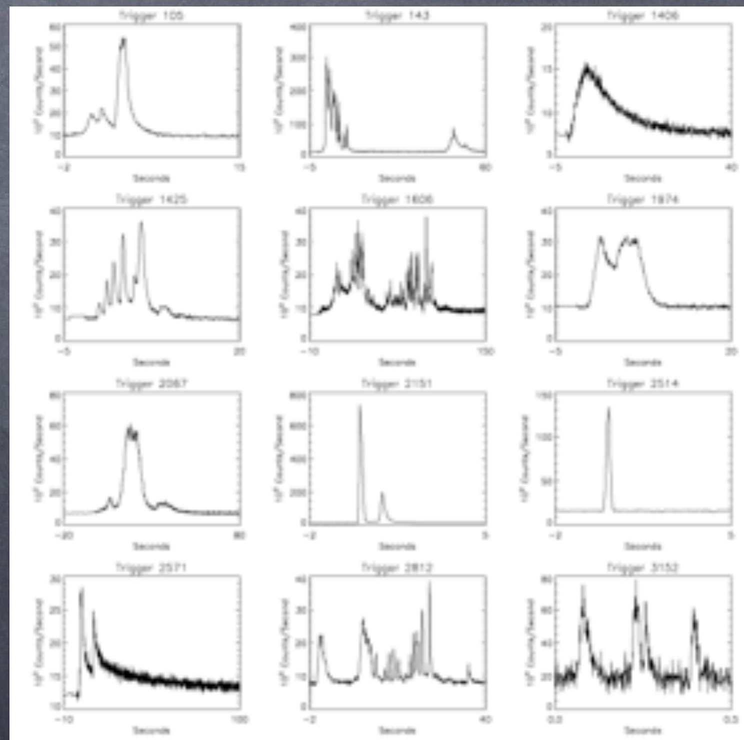

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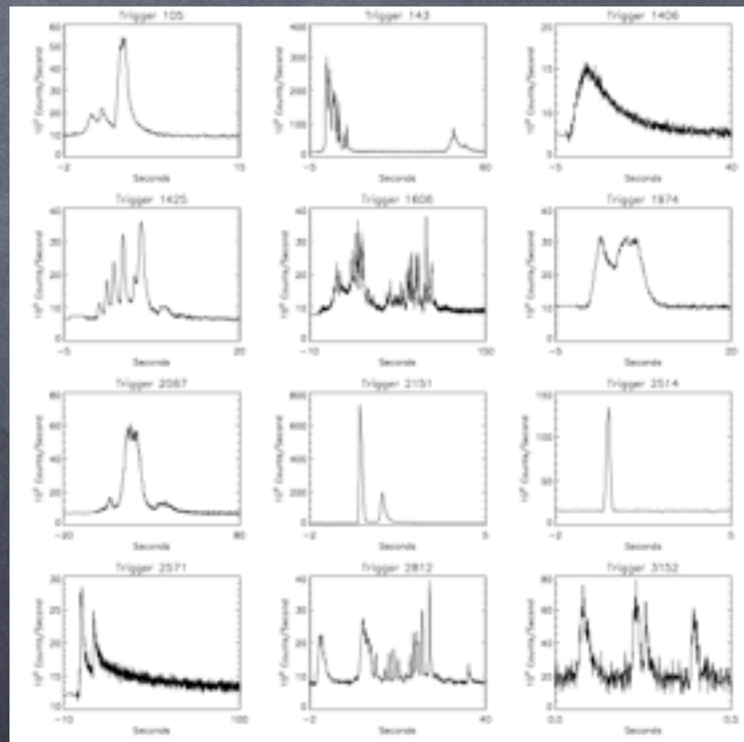

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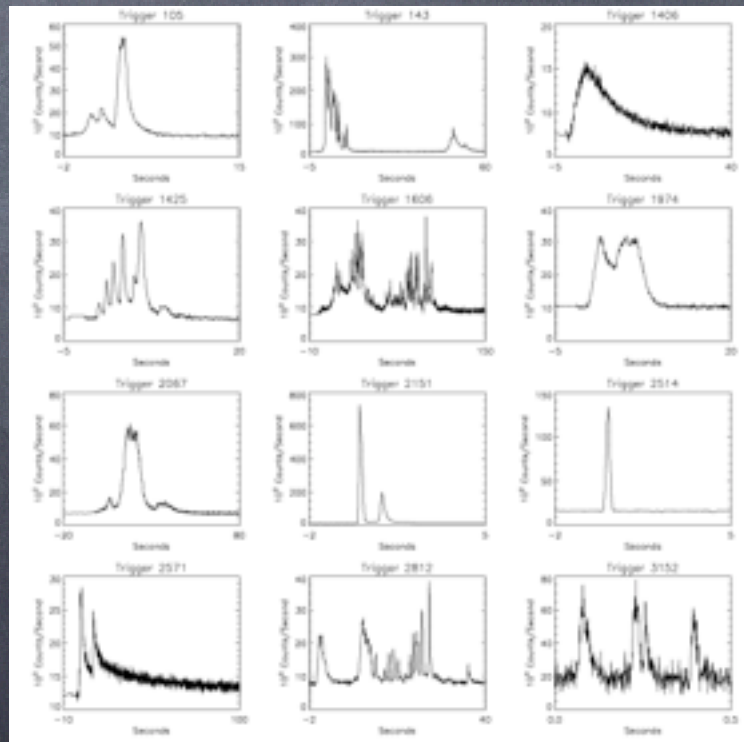

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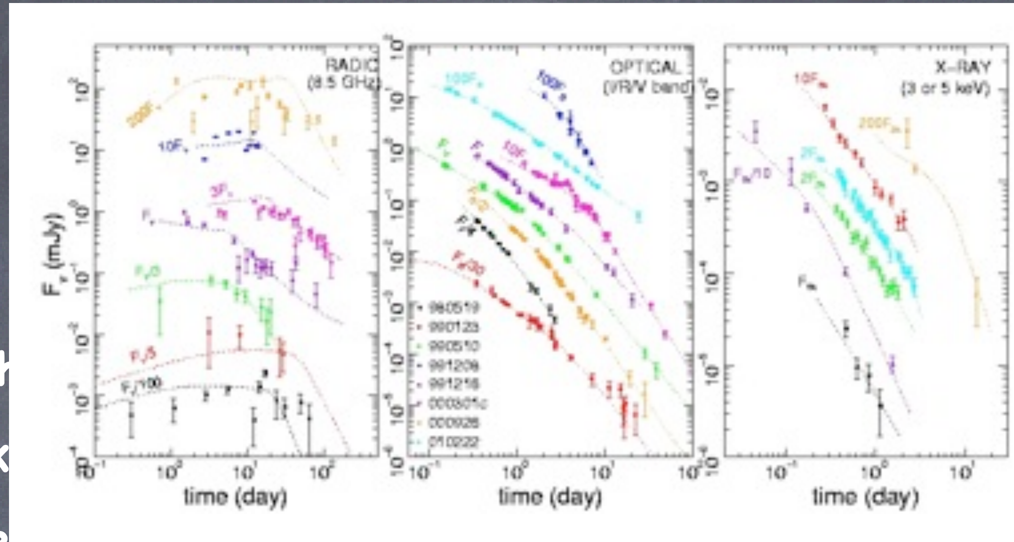
  Afteglow



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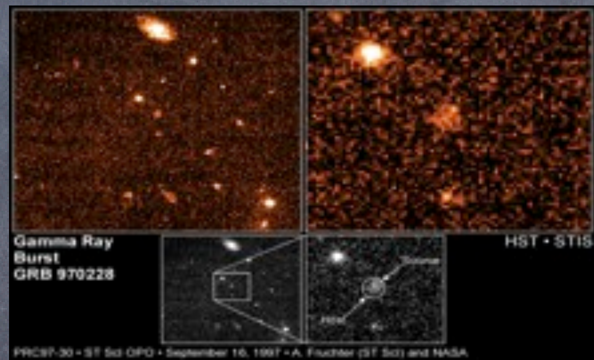
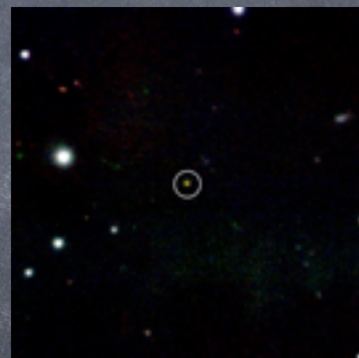
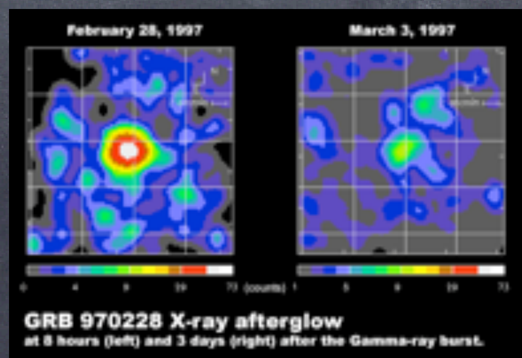
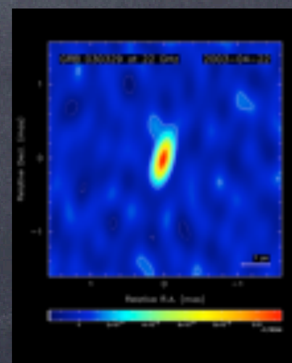


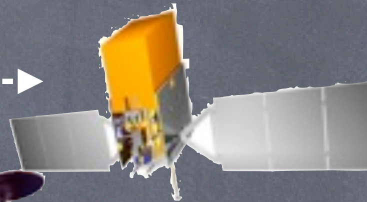




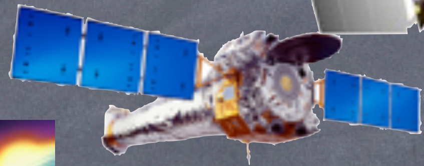


The ultimate multimessangers

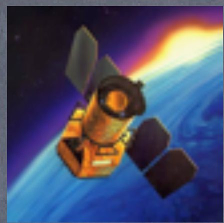
- γ-rays: up to 33 GeV



- X-rays: 0.1kev - 100 kev

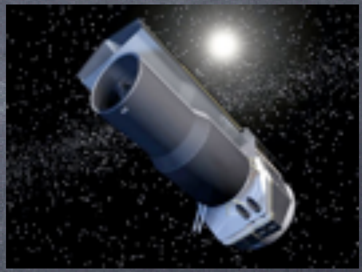


- uv



- optical

- IR



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- UHE neutrinos
- Gravitaiotnal Radiation
- UHECRs?

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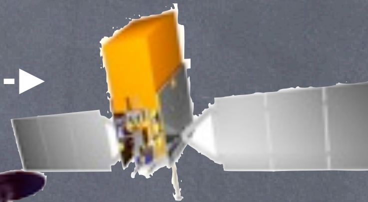

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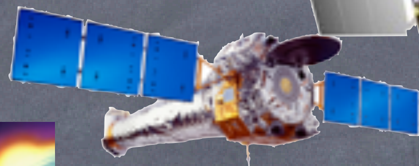

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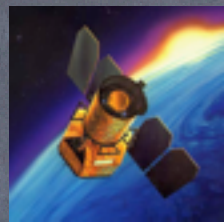

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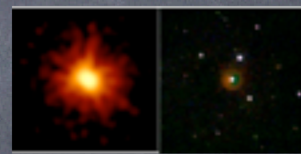

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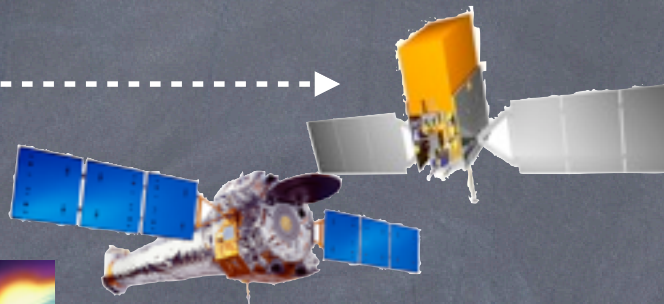

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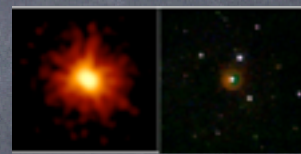

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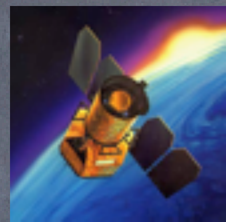

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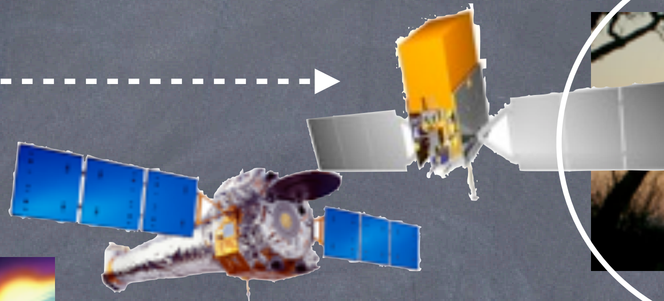

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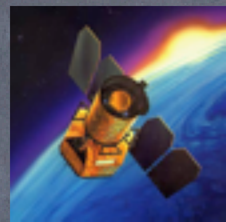

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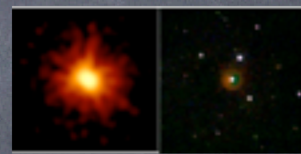

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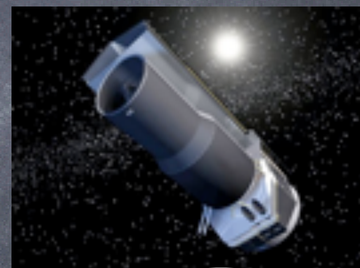

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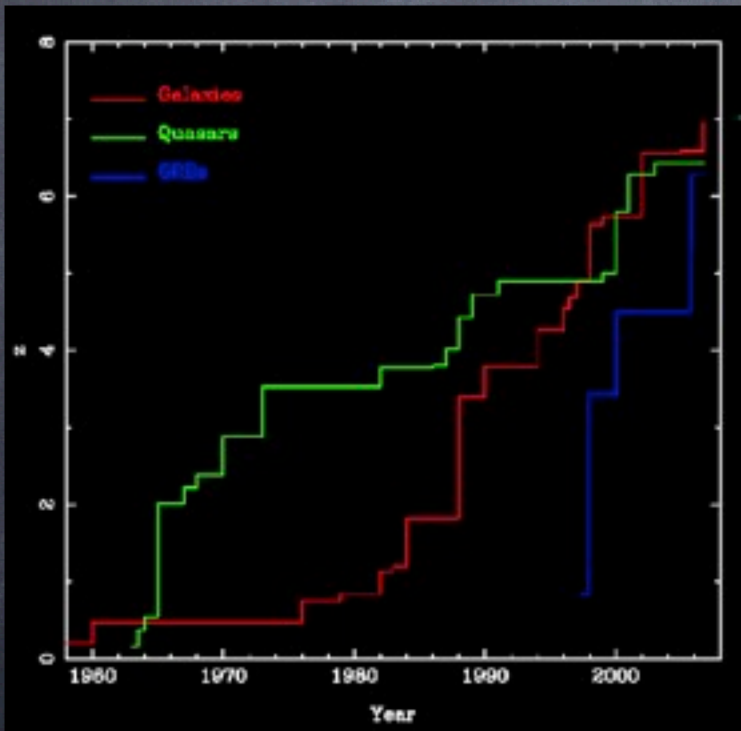
The Bahcall Symposium (1995): Some Open Question in Atrsonomy

- Where?
- What?
- How?
- Why?

Where ?

High redshift GRBs

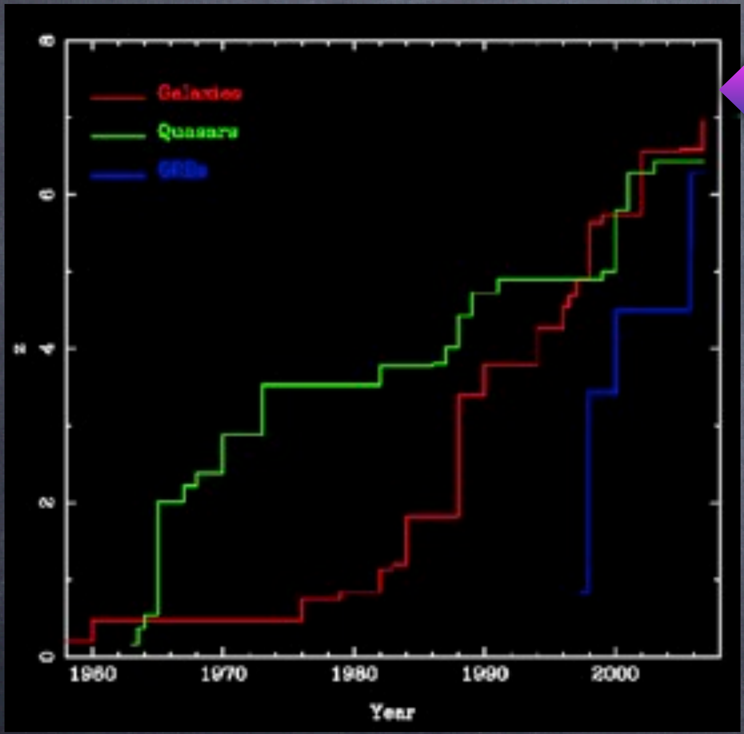


N. Tanvir, 2006

- GRB 090423 at a redshift 8.26 is the most distant object seen so far*. At that time the Universe was 640 million years old, or less than 5 percent of its present age.

* two other GRBs with claimed but unconfirmed yet higher redshift (9.4 and > 10)

High redshift GRBs



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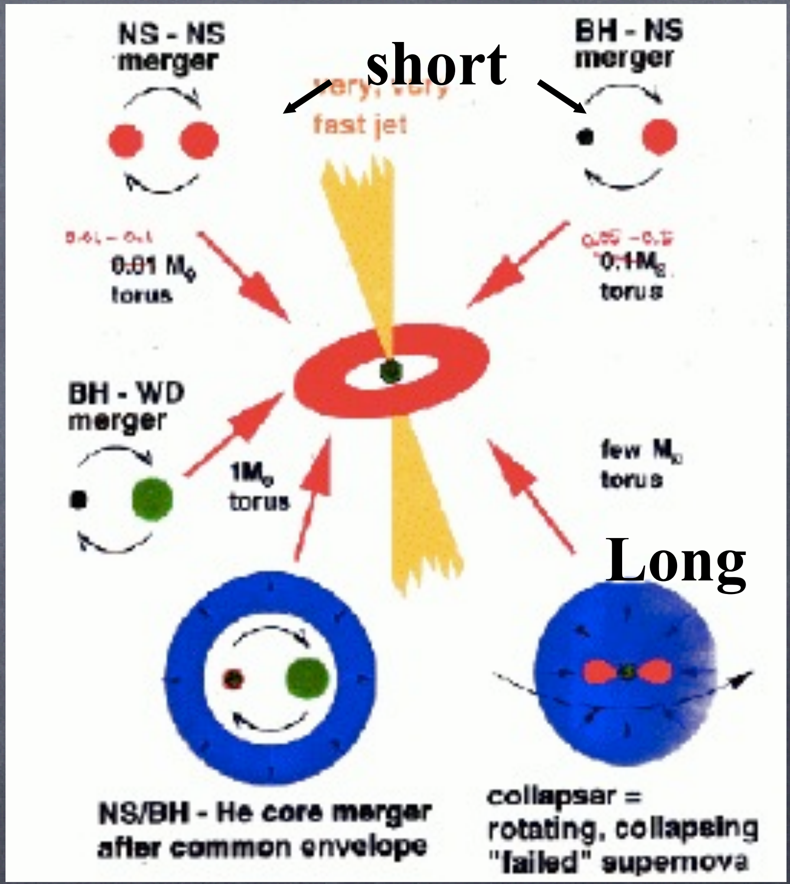
What ?

Energy, Energy, Energy + Time

- $E \approx 10^{51}$-10^{52} ergs ≈ the binding energy of a compact stellar mass object.
- 0.01-100 sec + $E \approx 10^{51}$-10^{52} ergs
  ⇒ a newborn stellar mass compact object.
- ⇒ Collapsing stars or mergers of compact objects

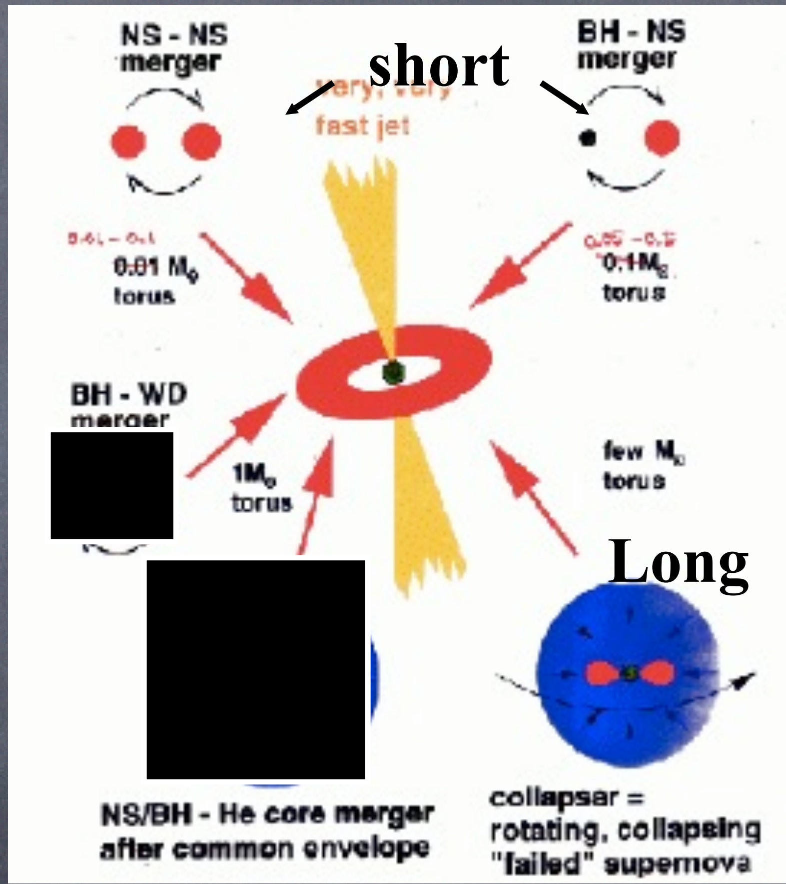
Different routes can lead to a Black-hole - disk-jet system:

- NS/BH-NS merger
- BH-WD merger
- NS/BH-He core merger
- Collapsar

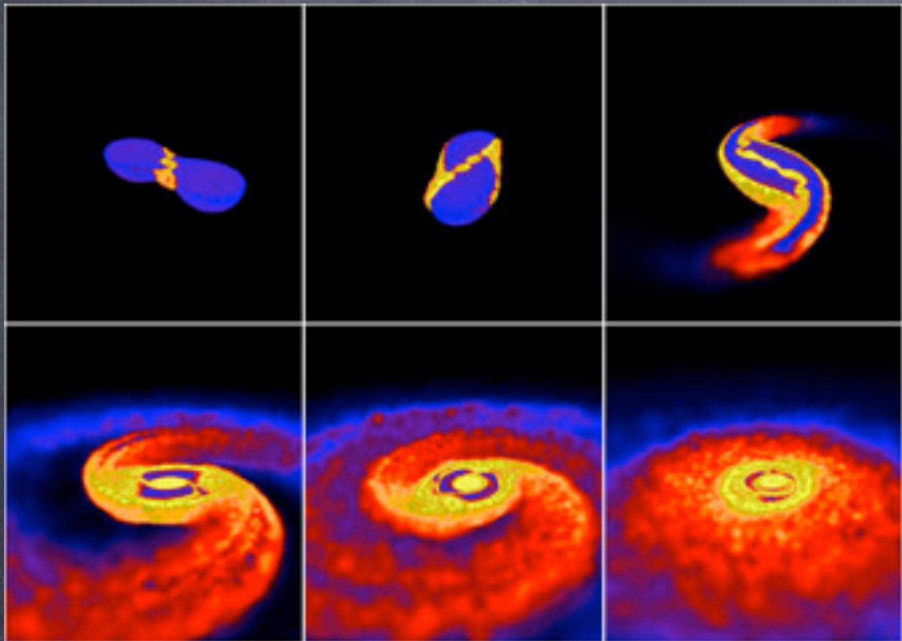


Different routes can lead to a Black-hole - disk-jet system:

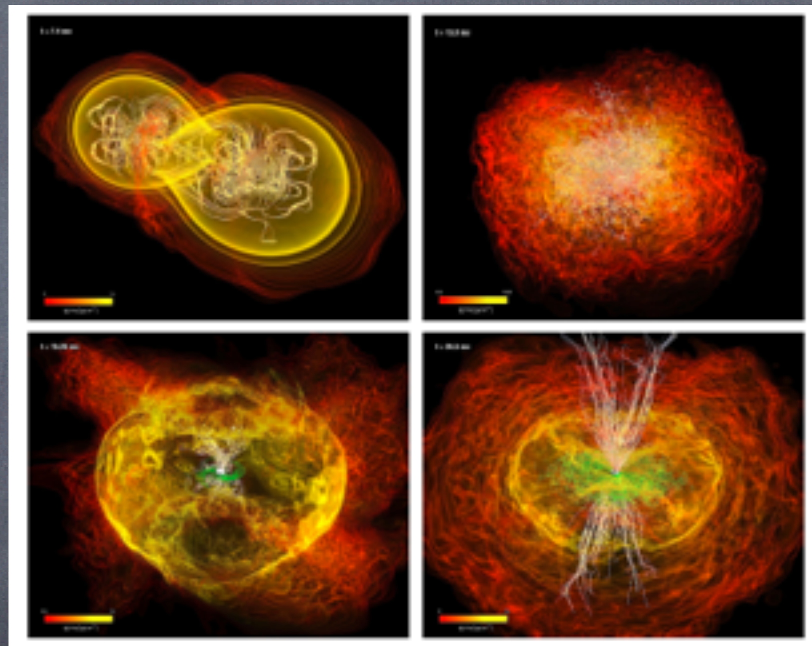
- NS/BH-NS merger - **SHORT**
- ~~BH-WD merger~~
- ~~NS/BH-He core merger~~
- Collapsar - **LONG**



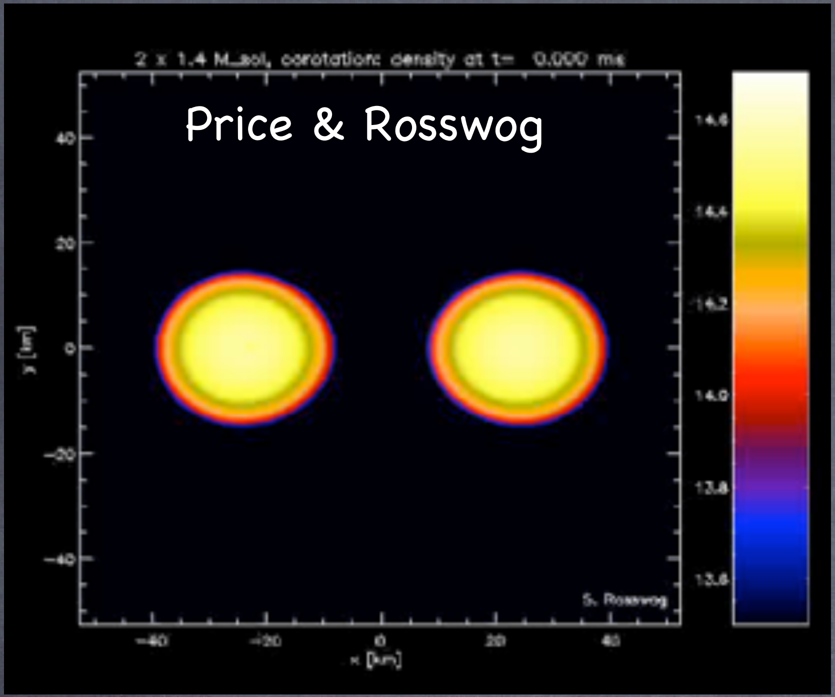
Neutron star mergers as progenitors of short GRBs (Eichler Livio, TP, Schramm, 1988)

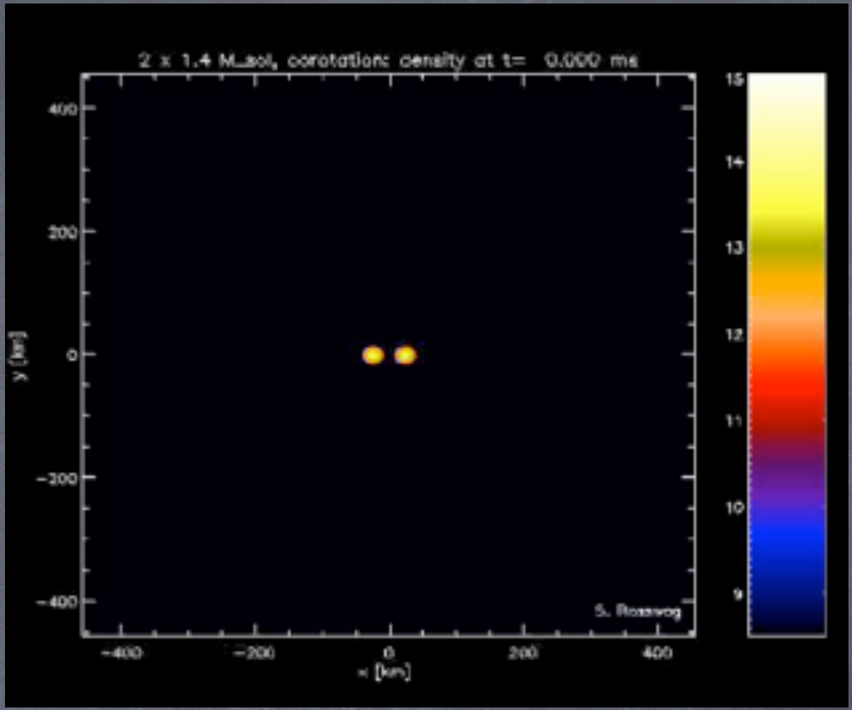


NS merger simulations Price & Rosswog 2007



Magnetic field jet arising from NS merger Rezolla et al., 2011


2 x 1.4 M_sol, corotation: density at t= 0.000 ms
Price & Rosswog
y [km]
x [km]
S. Rosswog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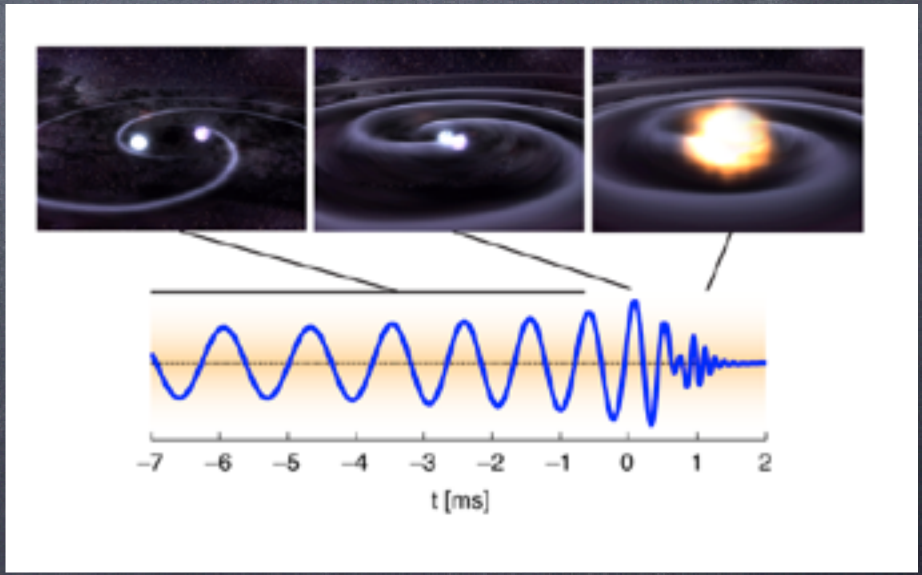
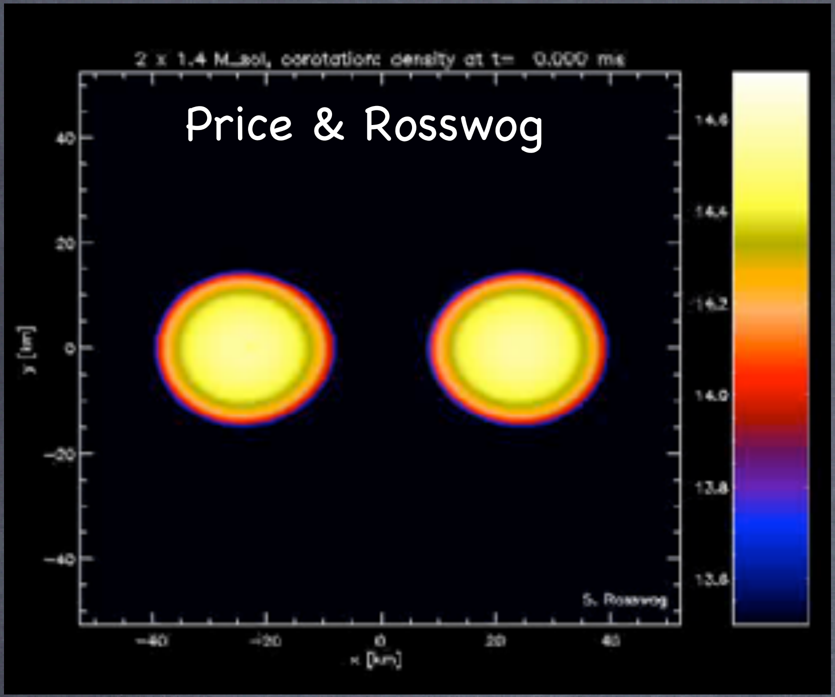

−7 −6 −5 −4 −3 −2 −1 0 1 2
t [ms]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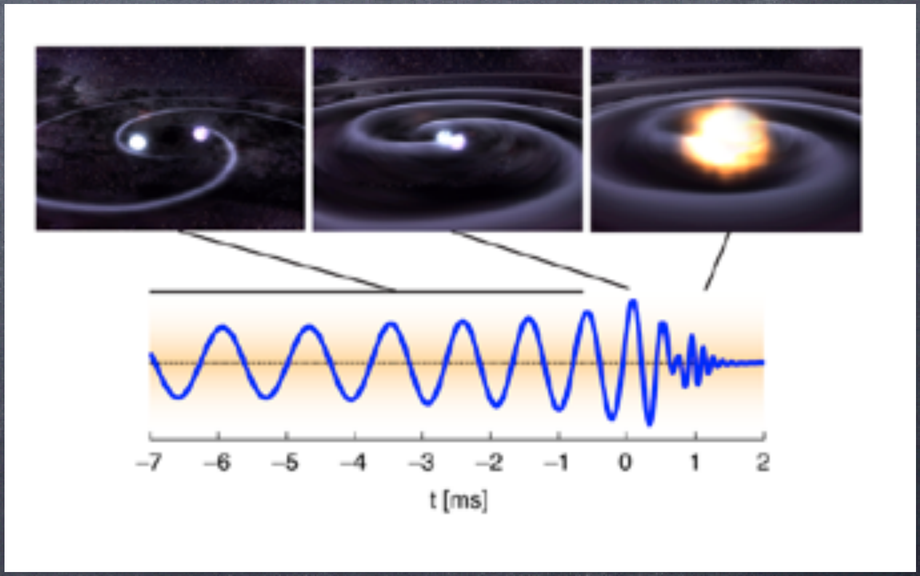
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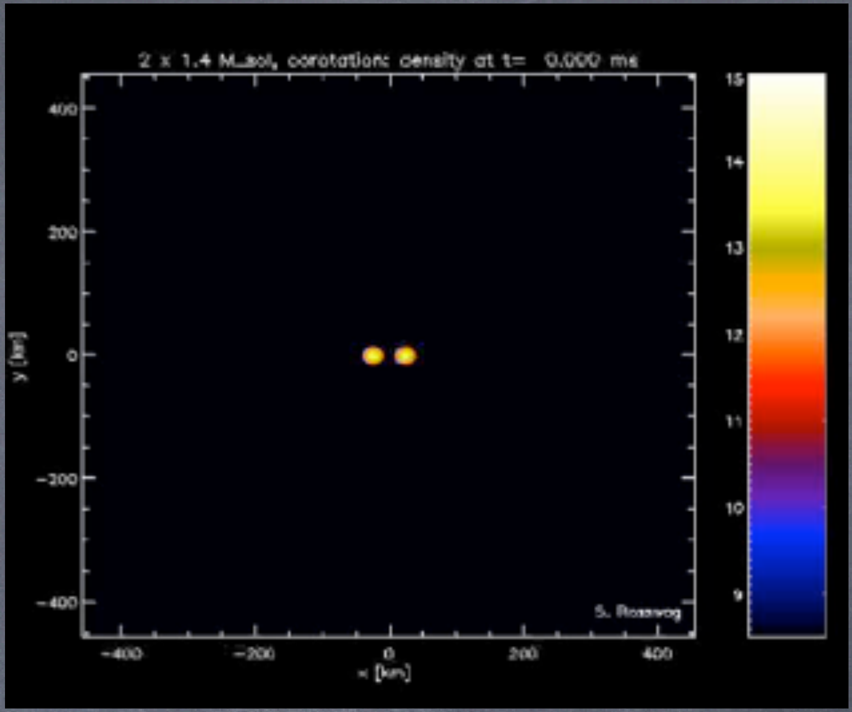
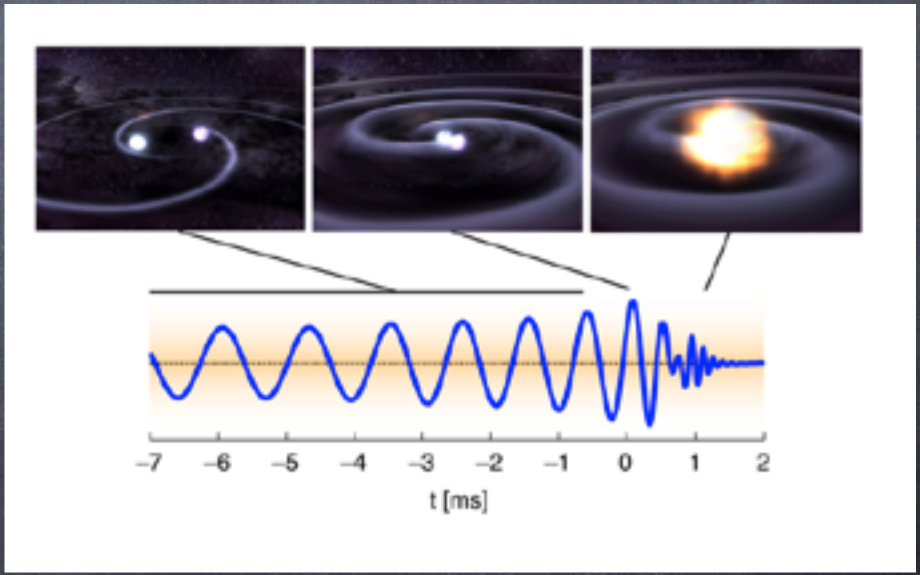
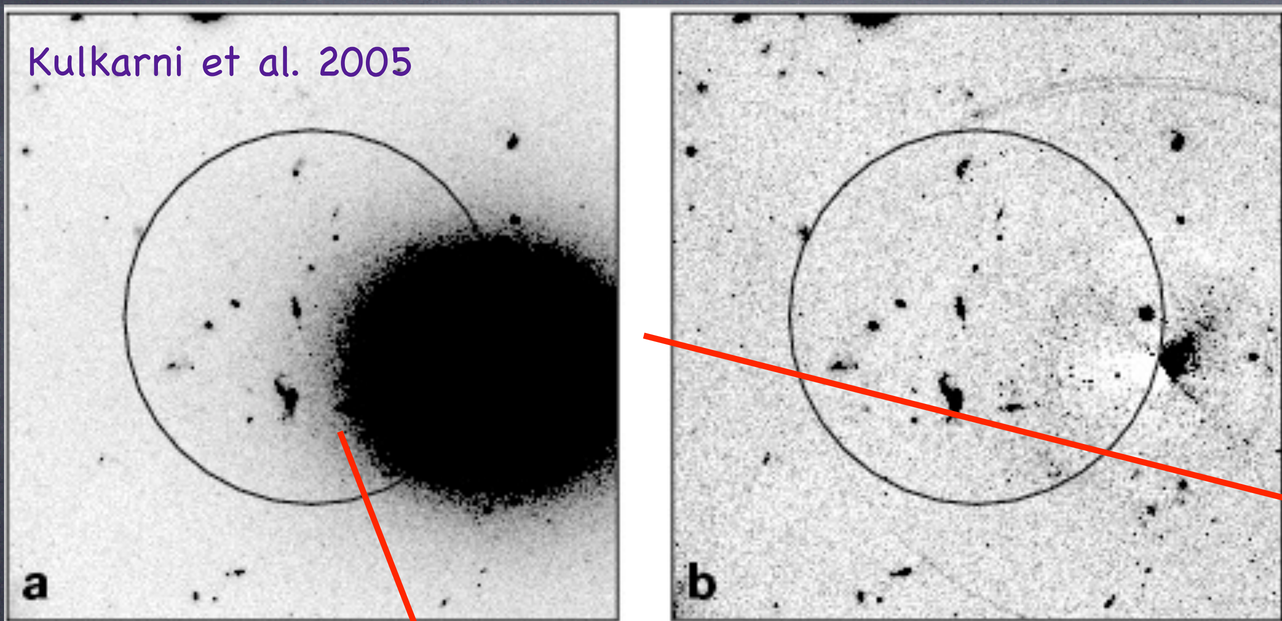




Short GRBs - GRB 050509b

Swift/XRT position intersects a bright elliptical at z = 0.226

No optical/radio afterglow



Elliptical host

⇓

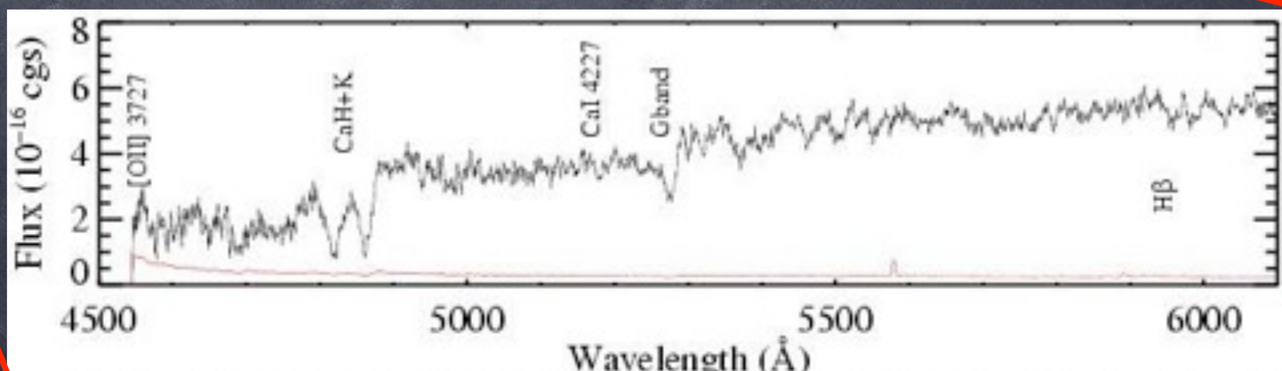
Old stellar population

Bloom et al. 2005

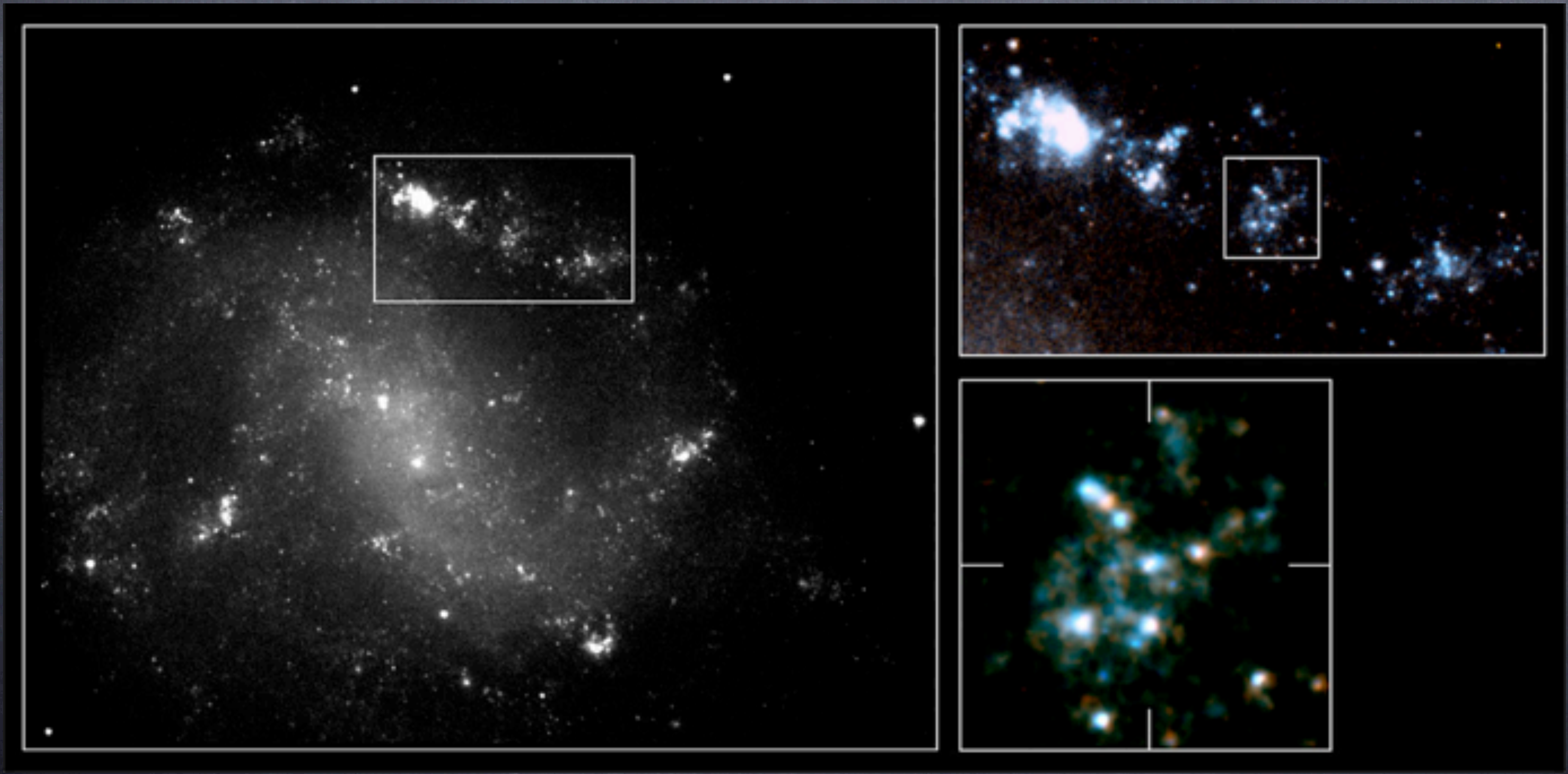
Castro-Tirado et al. 2005

Gehrels et al. 2005

Hjorth et al. 2005

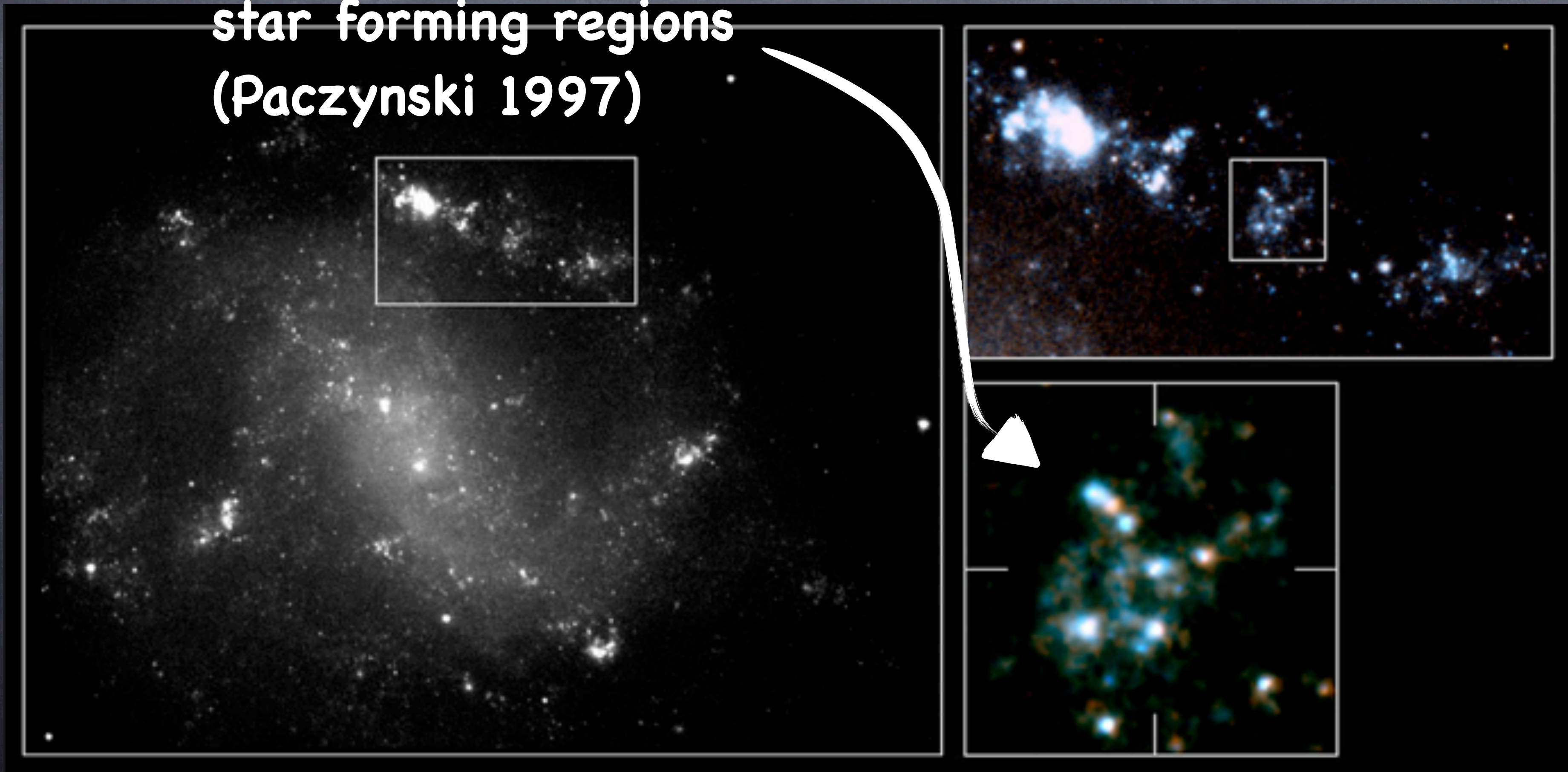


The (long) GRB-Supernova connection



The (long) GRB-Supernova connection

- **Observational indications**
  - **Long GRBs arise in star forming regions (Paczynski 1997)**



The Smoking Gun

GRB030329-SN 2003dh - a regular GRB with a 98bw like supernova.

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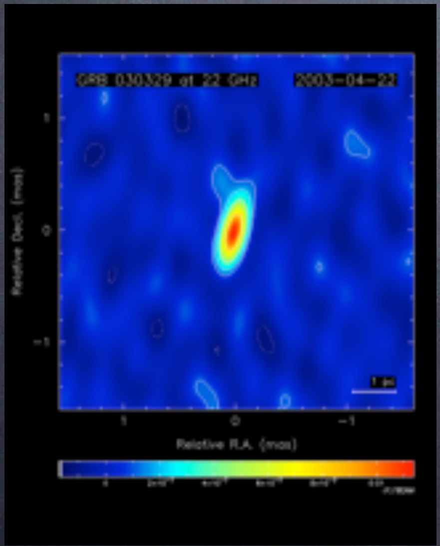

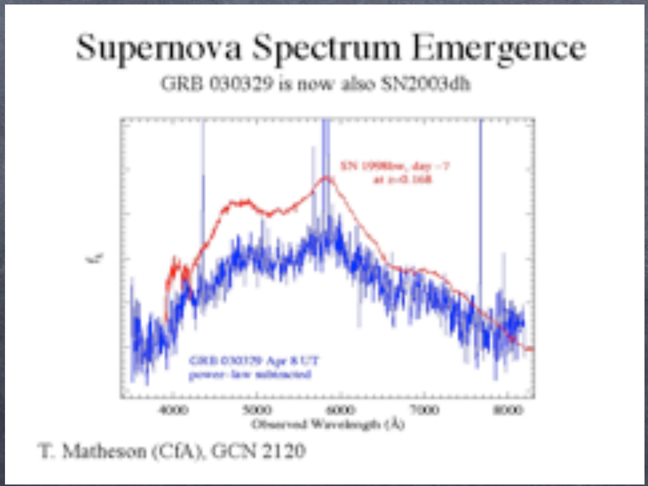

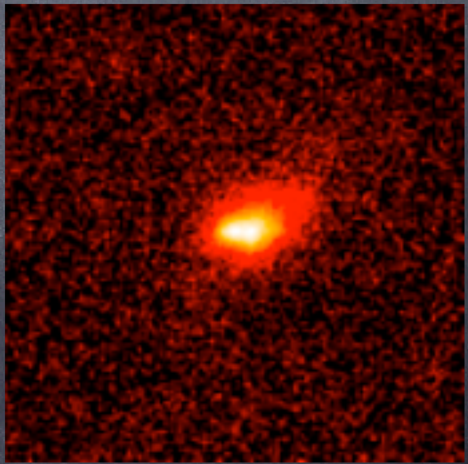

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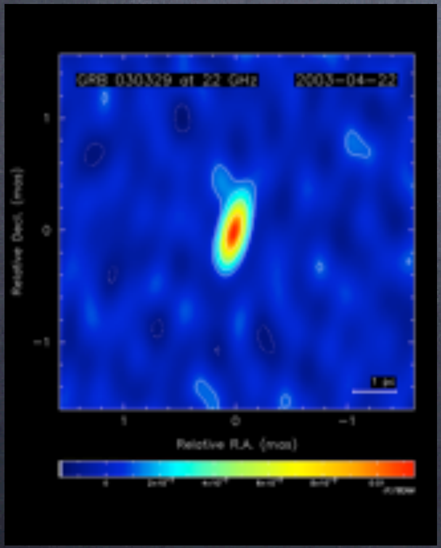
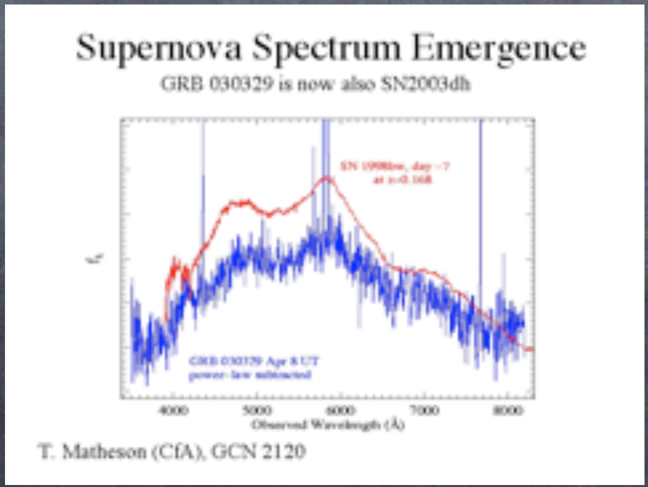
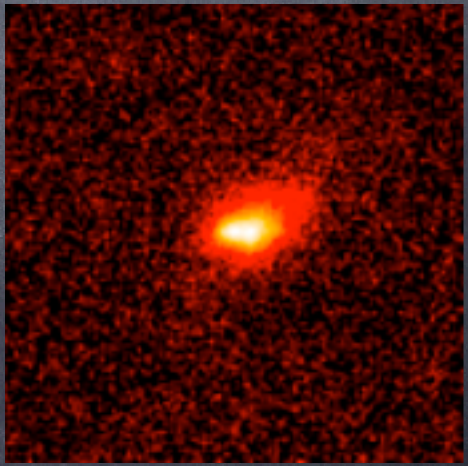
GRB030329-SN 2003dh - a regular GRB with a 98bw like supernova.

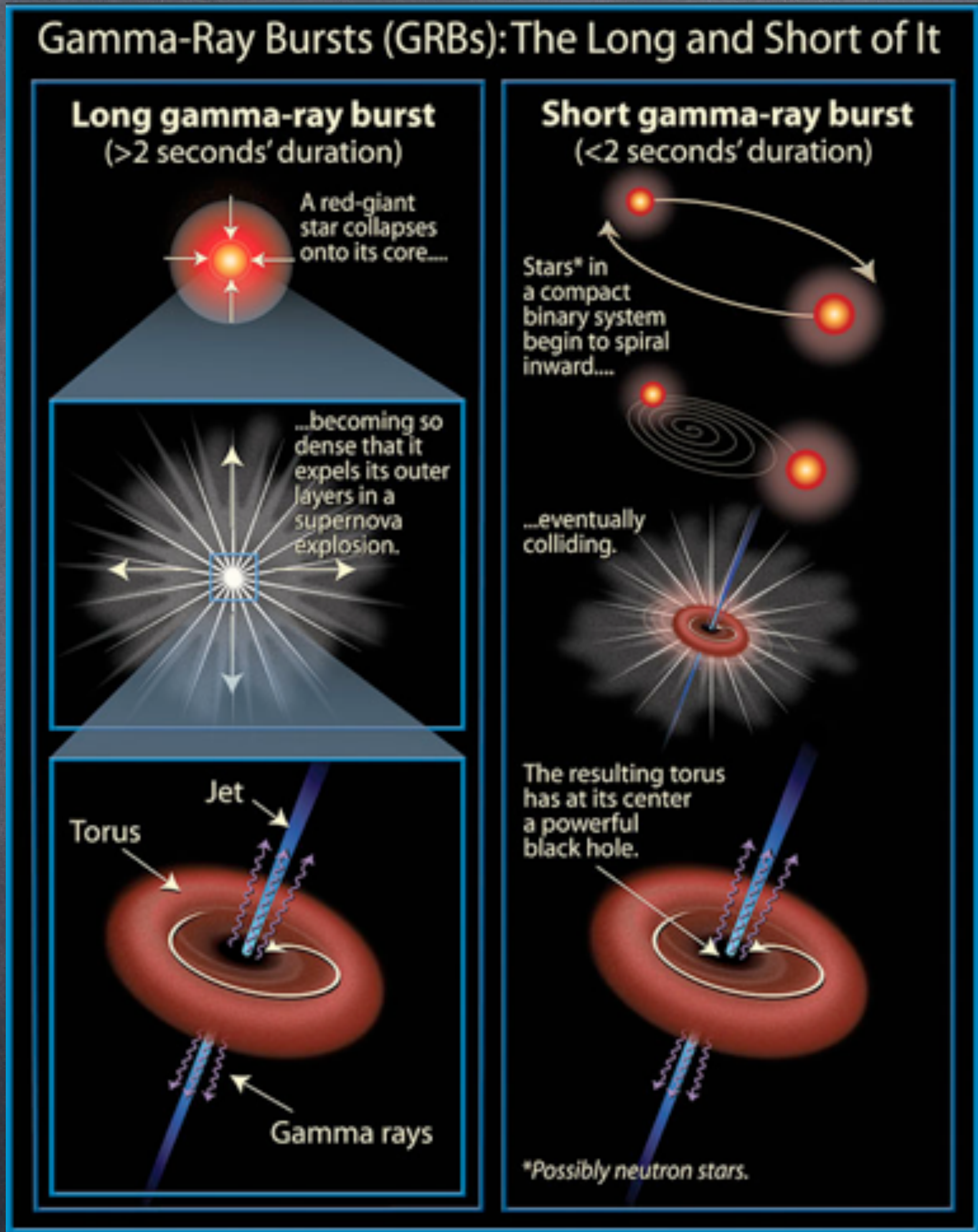






- **Recently we have also GRB101219B - SN 2010ma**

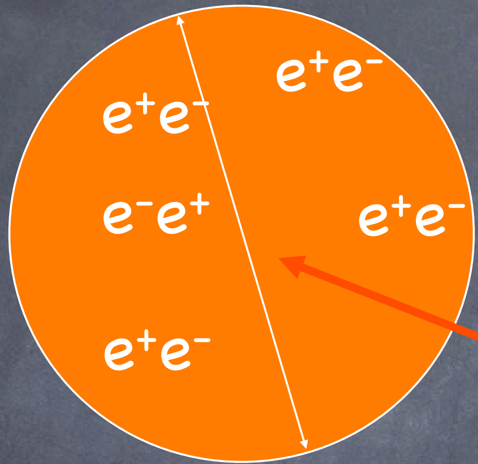
Route to GRBs



How ?

Enigma

The Compactness problem



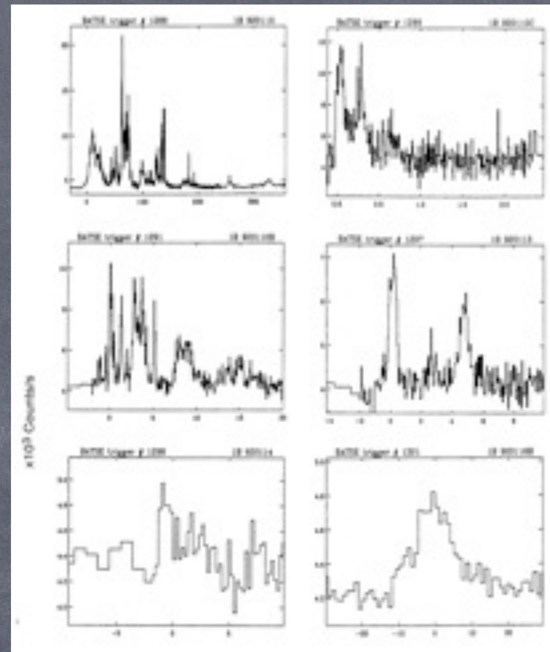
10^{51} erg

Variability

$\delta t=0.1$sec

$\Downarrow$

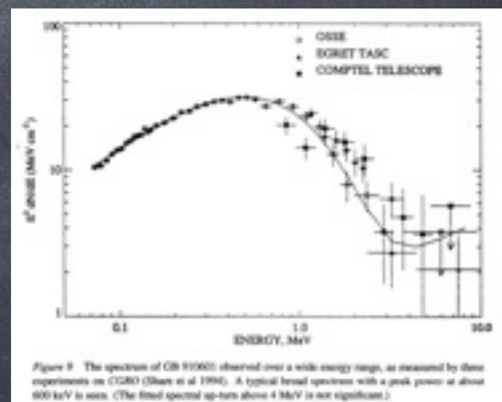
$R<c\ \delta t=3\times10^{9}$cm



$\gamma\gamma \rightarrow e^+e^-$

$\tau \sim 10^{15}$

One should expect a thermal spectrum. BUT ⟶



Relativsitic Motion

- $R \leq \Gamma^2 c\delta T$
- E_{ph} (obs) = ΓE_{ph} (emitted)
- $\tau_{\gamma\gamma} = \Gamma^{-(2+2\alpha)} n_\gamma \sigma_T R \approx 10^{15}/\Gamma^{(2+2\alpha)}$

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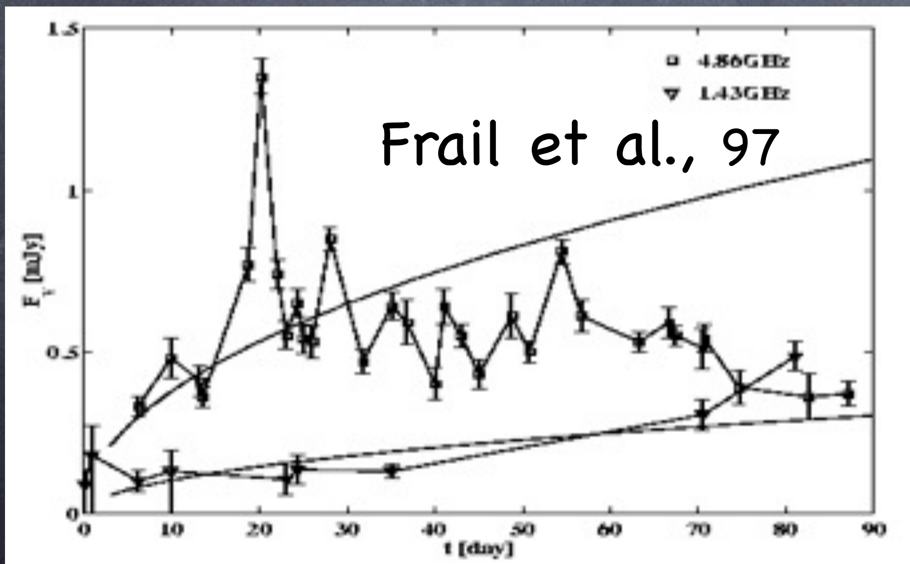
$\tau<1 \rightarrow \Gamma>100$

Confirmation of Relativistic Motion

Confirmation of Relativistic Motion

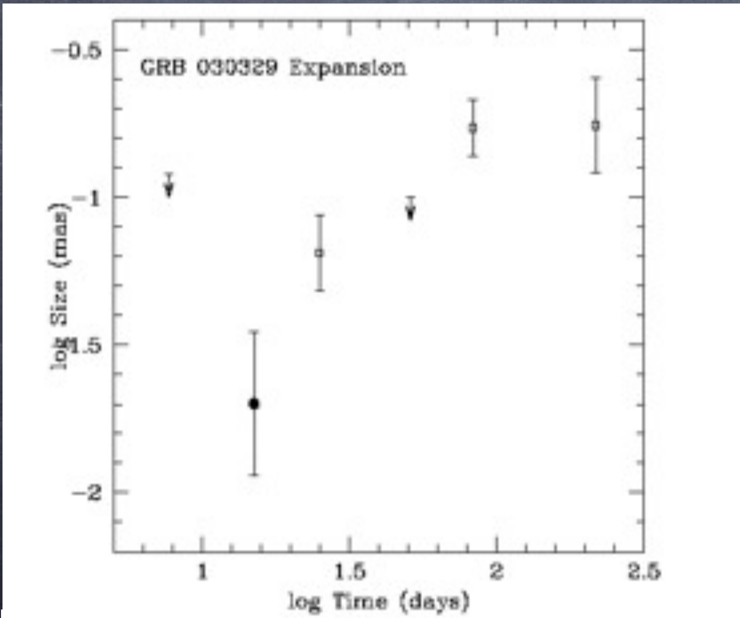


GRB 970508

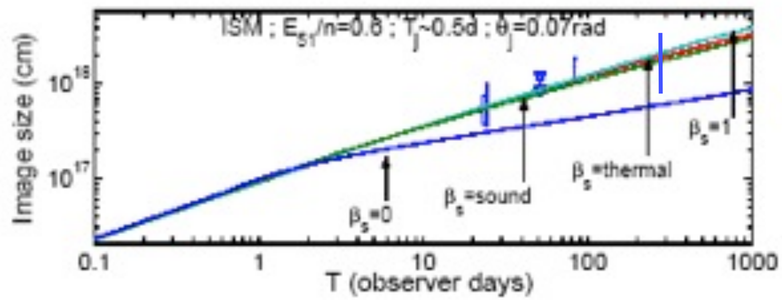
R=10^{17}cm t=1 month

Confirmation of Relativistic Motion

GRB 030329
$R=10^{18}$ cm
t=100 days



Taylor et al., 04



Oren, Nakar, TP, 04

Some bursts show an "isotropic equivalent" energy of >10^{54} ergs. This is more than a solar rest mass -> The emission must be beamed

Relativistic Jets

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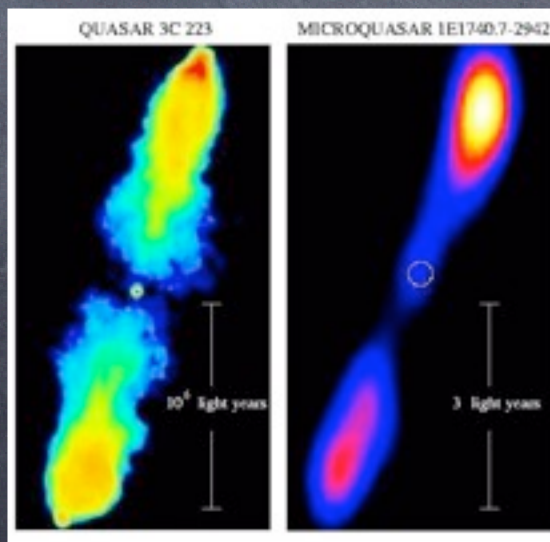
Relativistic Jets



Internal External Shocks

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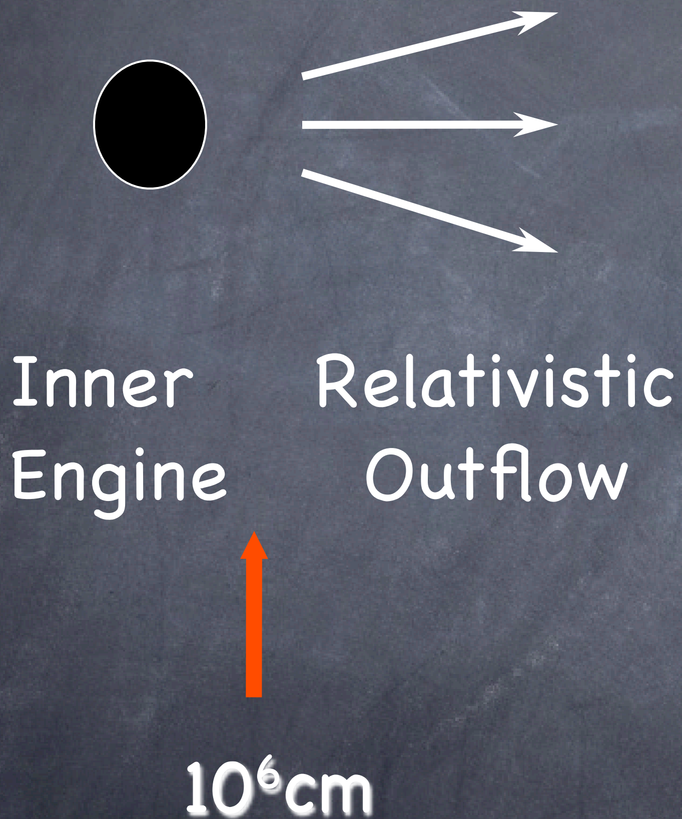
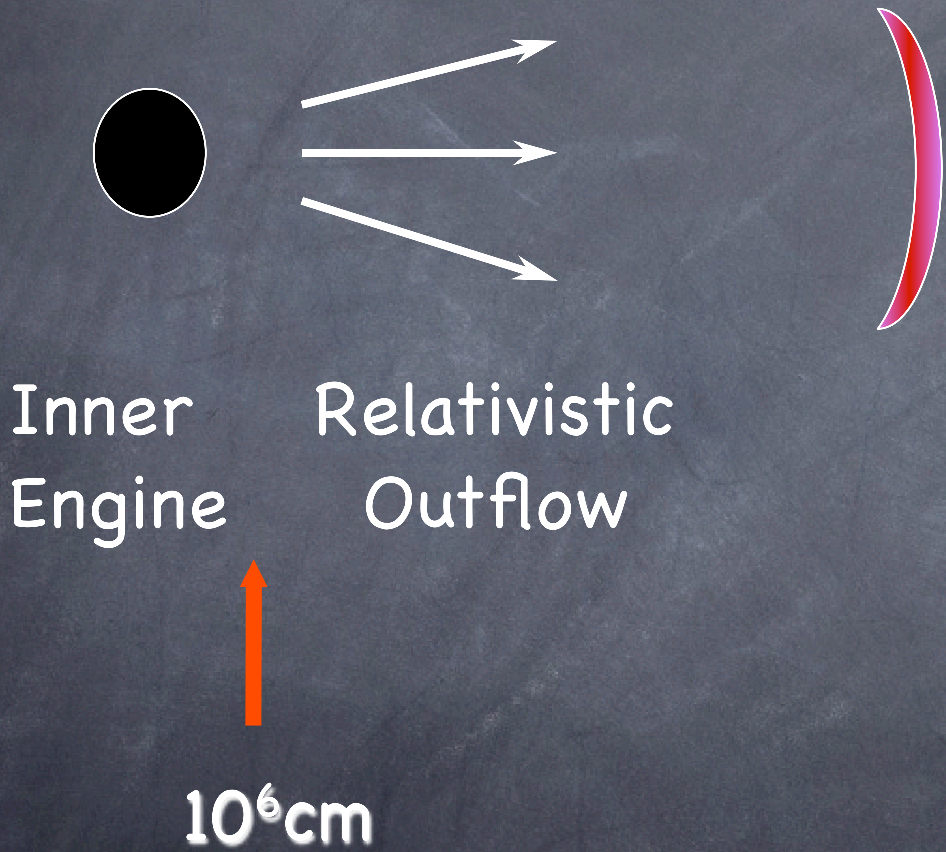
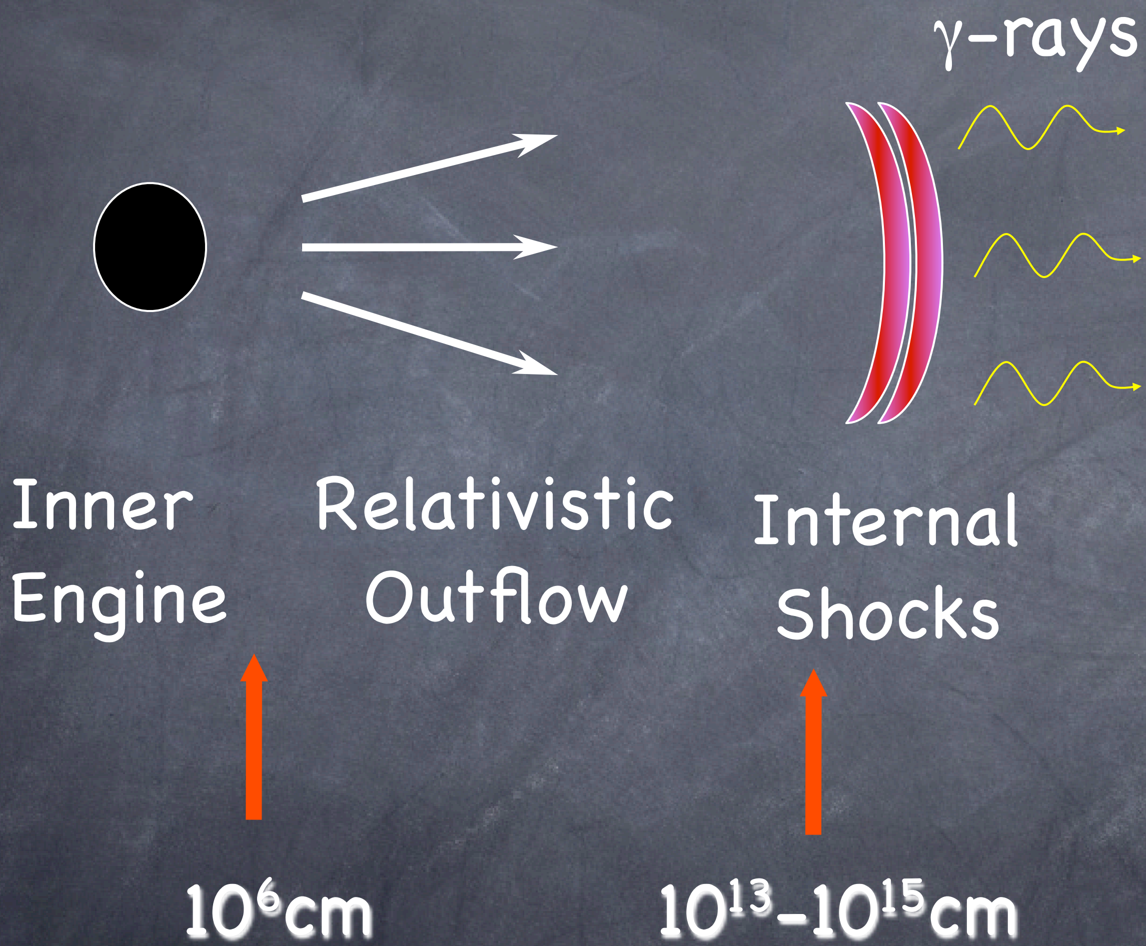


Internal External Shocks



Internal External Shocks



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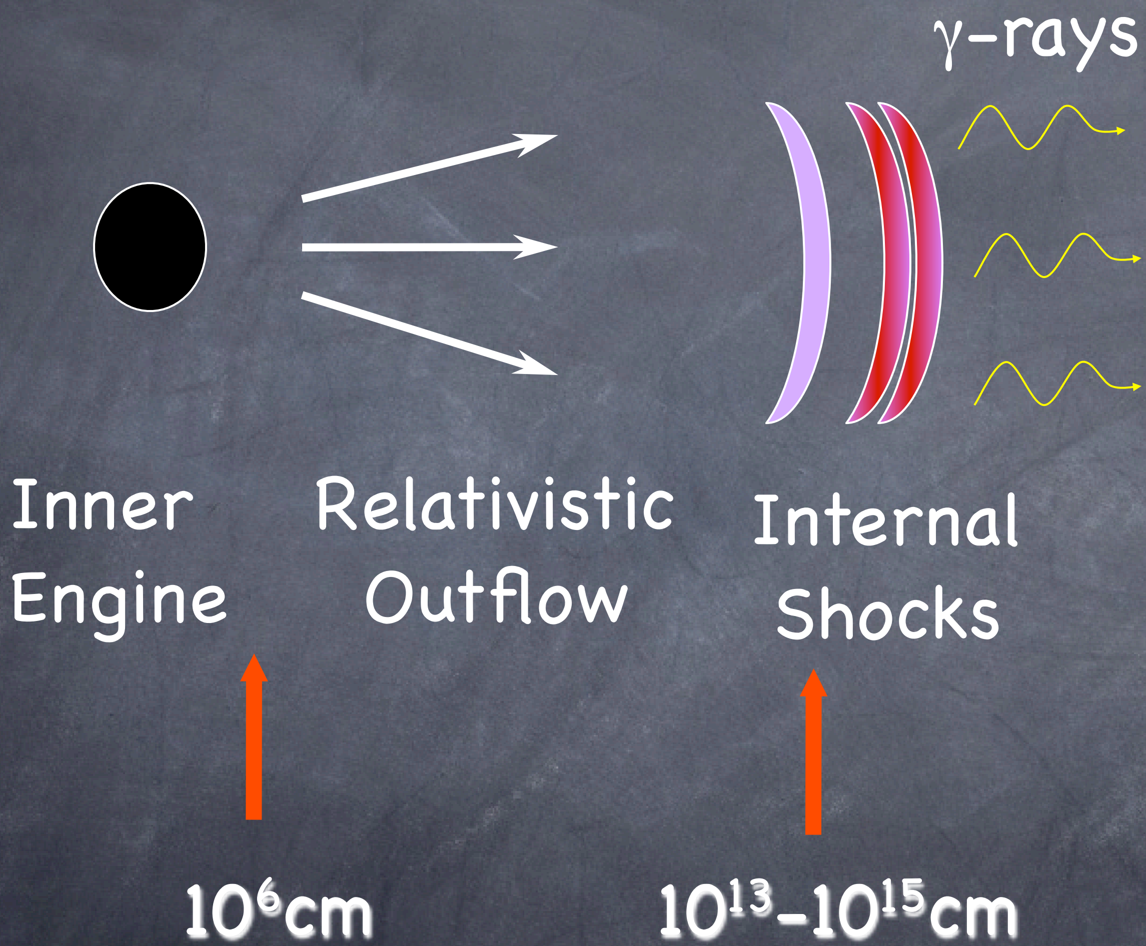
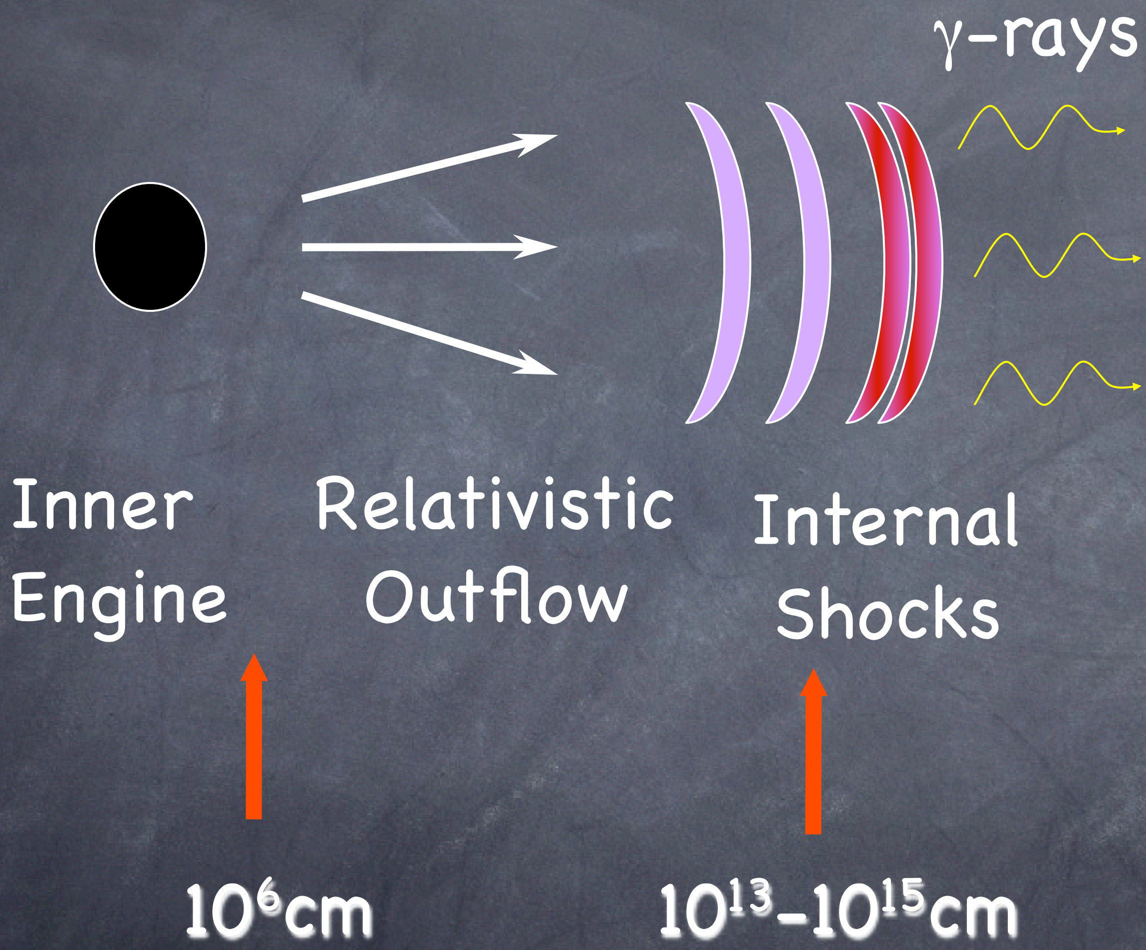
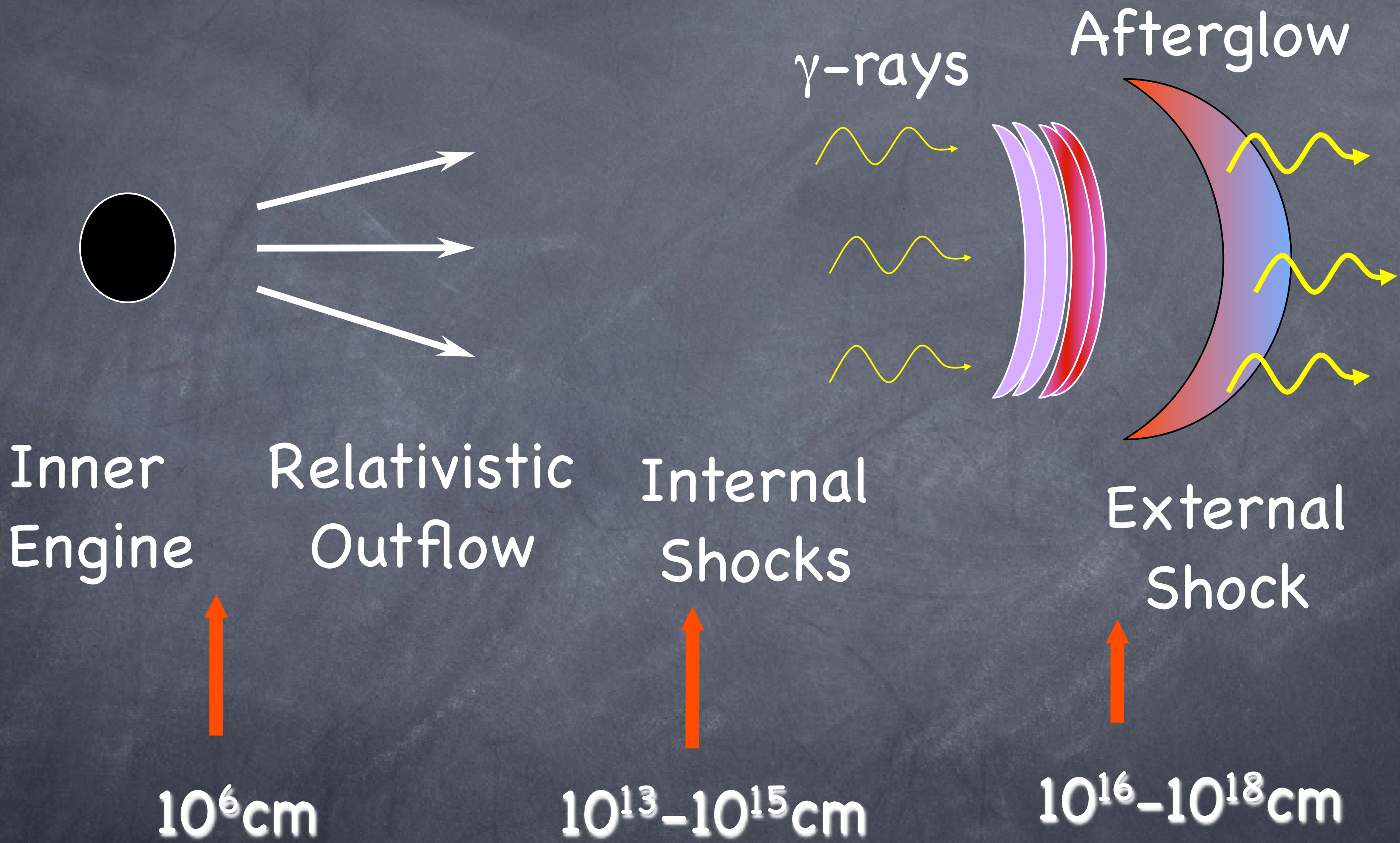
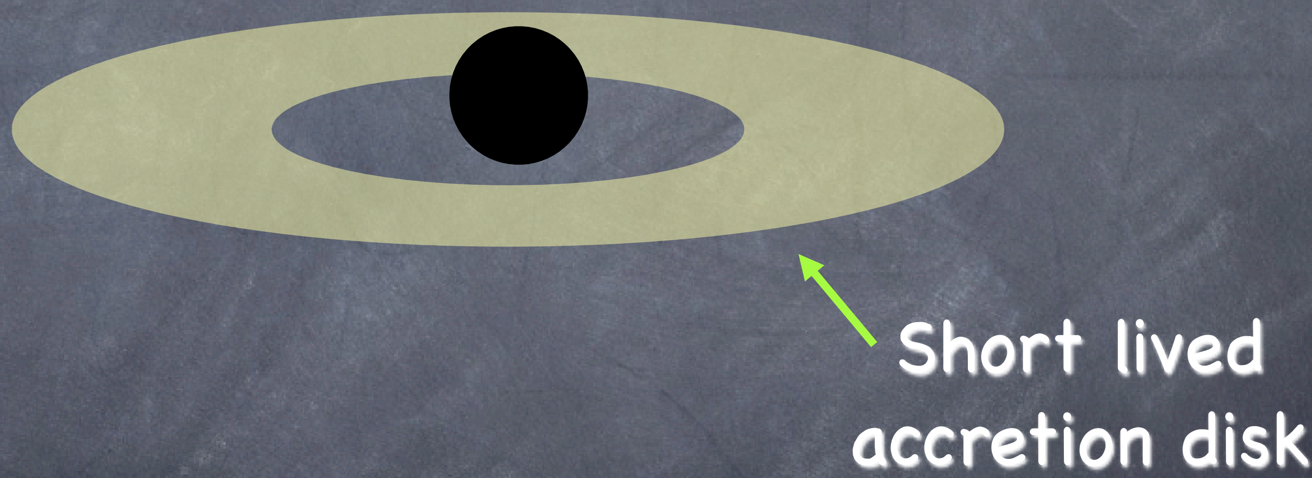


Internal External Shocks

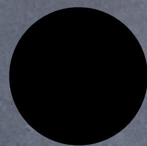


Internal External Shocks




Short lived
accretion disk

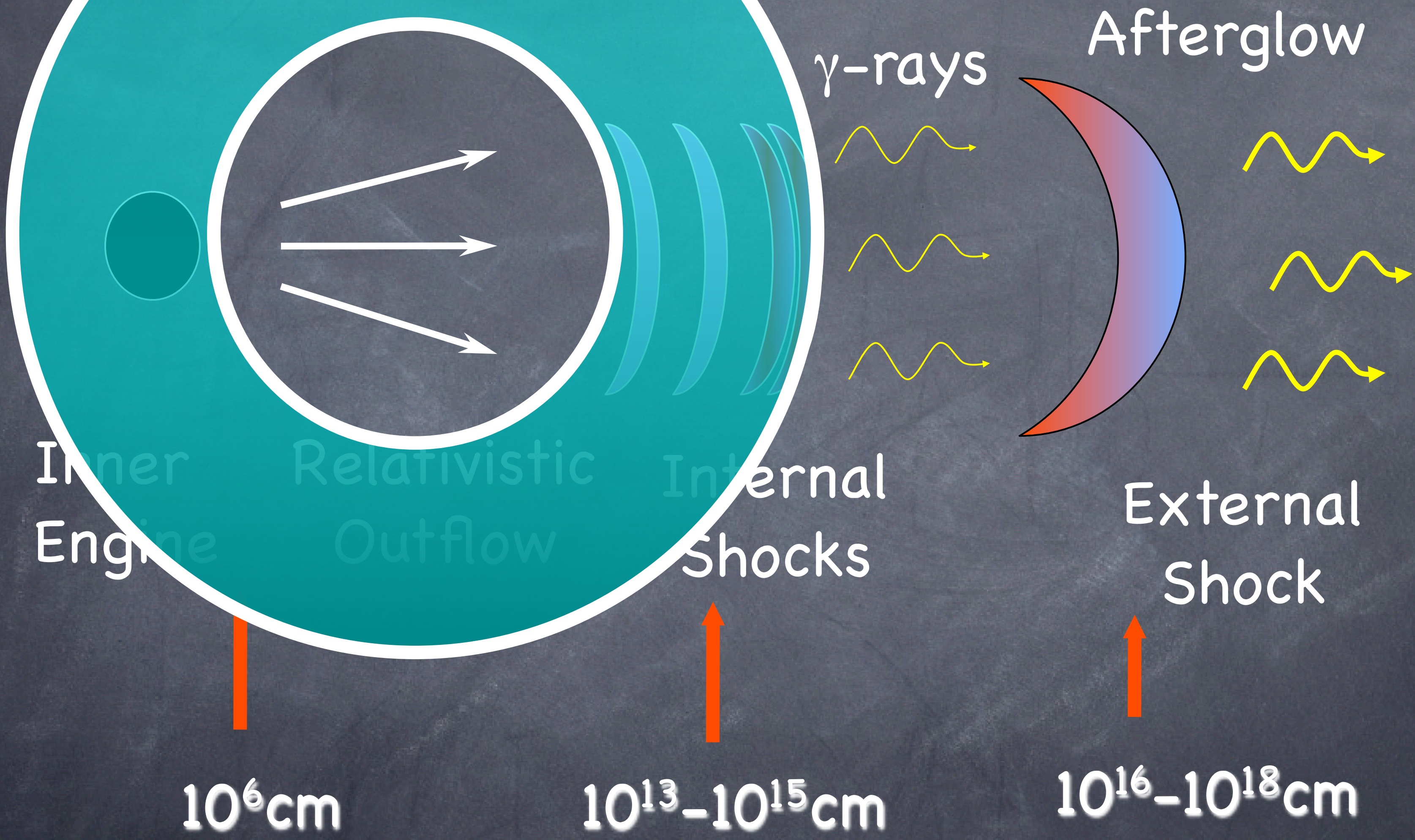
Duration ~30 sec - accretion time scale.



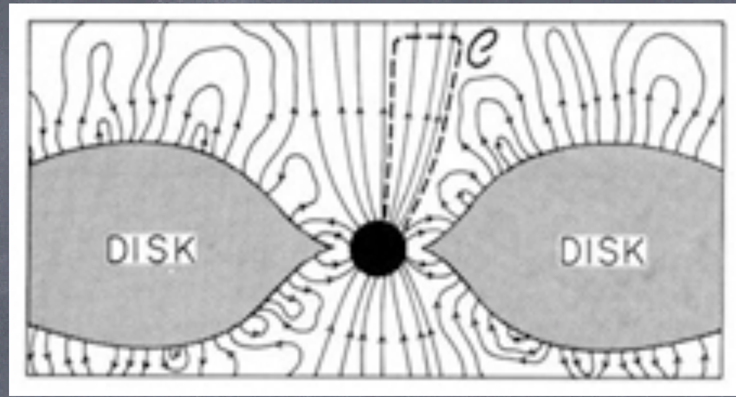
Variability ≤ 0.1 sec - fluctuation time scale.

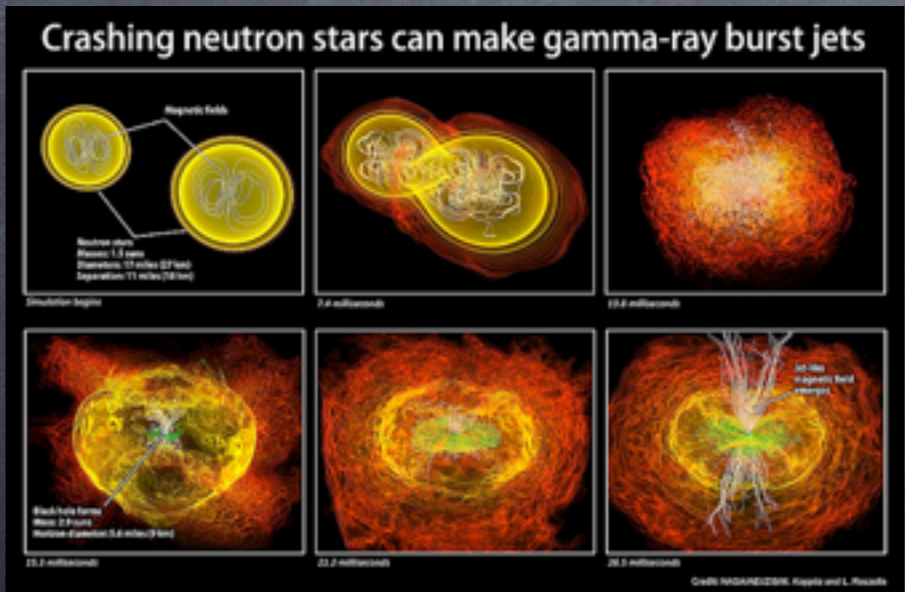
BUT - Numerous open questions

How is the jet generated?

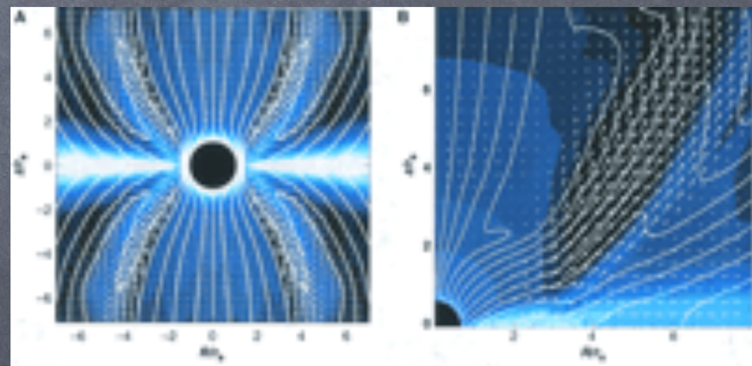


Blandford Znajek?



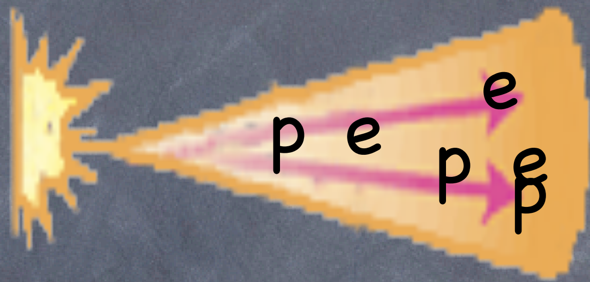


Rezolla+ 2011



Uchida + 2001

Jet Composition?
Baryonic



Inner
Engine

Relativistic
Wind

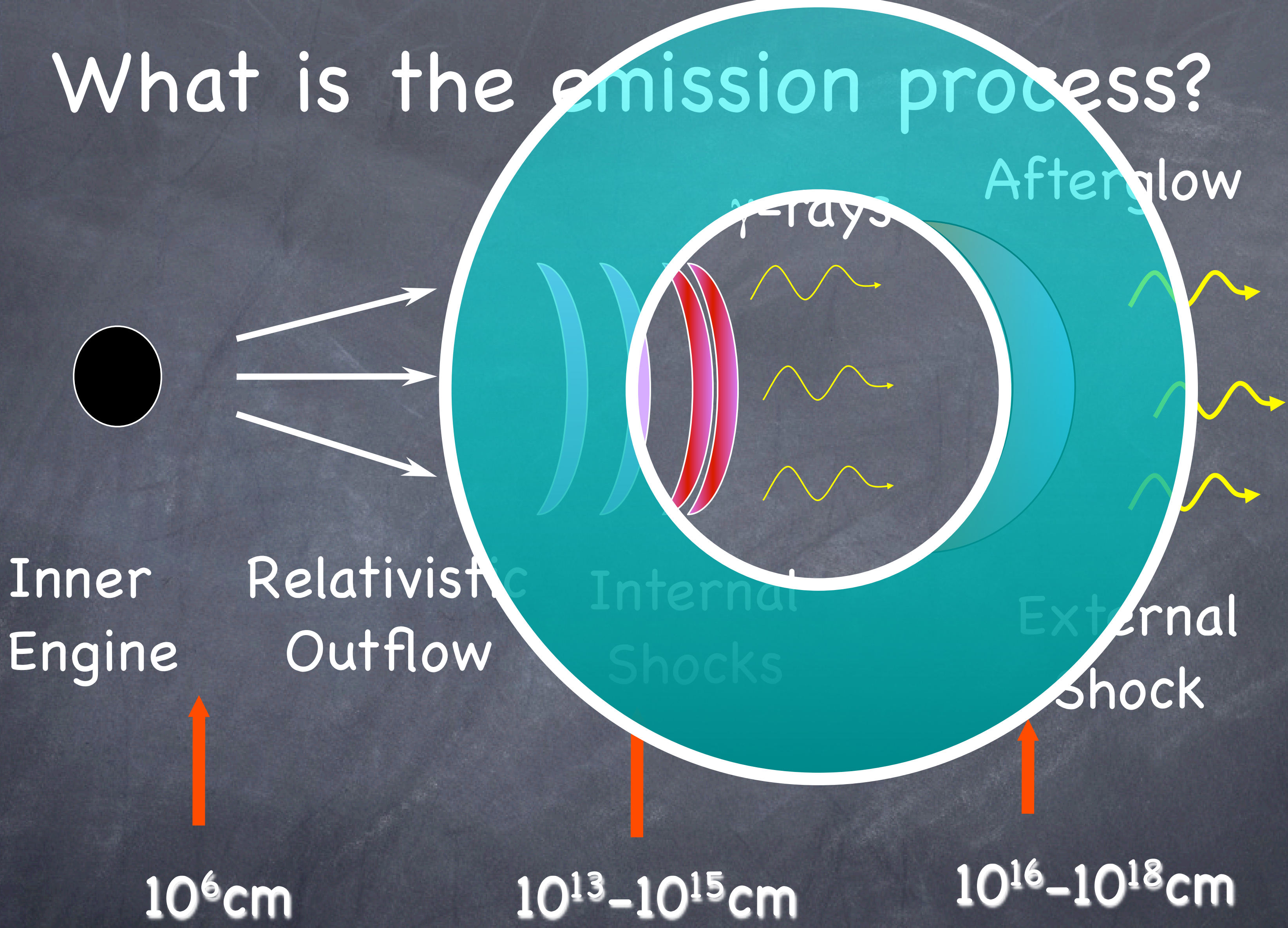
$$\sigma \equiv \frac{B^2}{8\pi\rho} > 1$$

Jet Composition? or Poynting Flux

~10^{16}G
Inner Engine

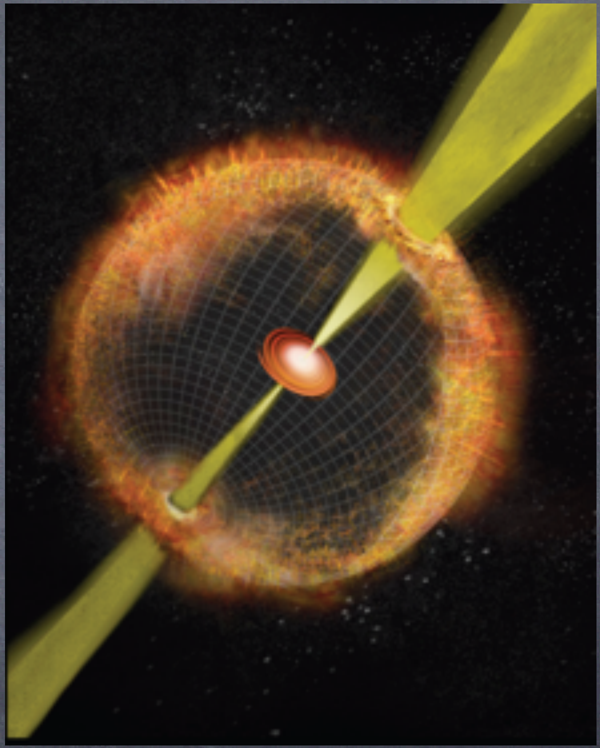
Relativistic Wind

What is the emission process?



The Collapsar Model

(MacFadyen & Woosley 1998)



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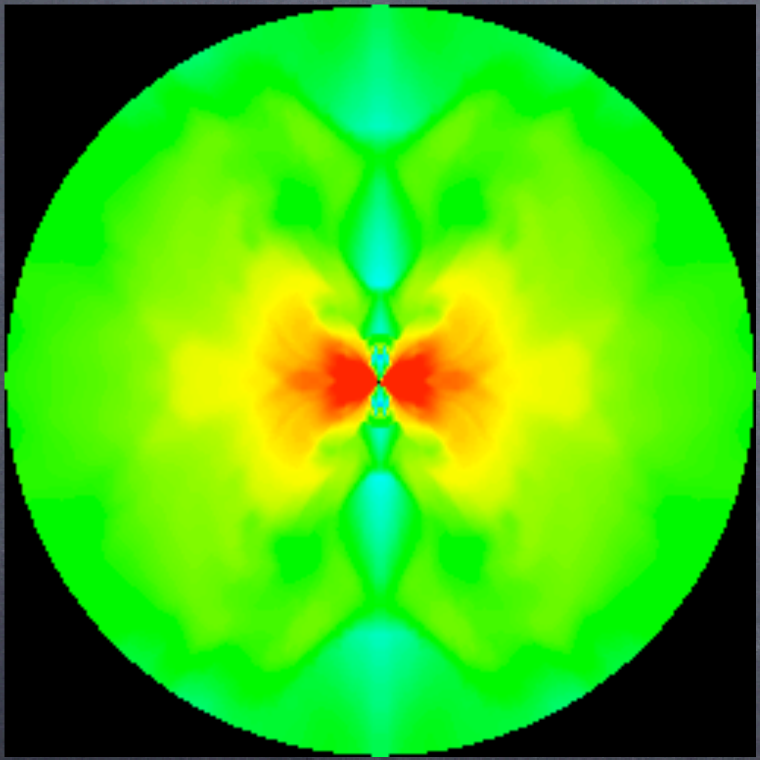
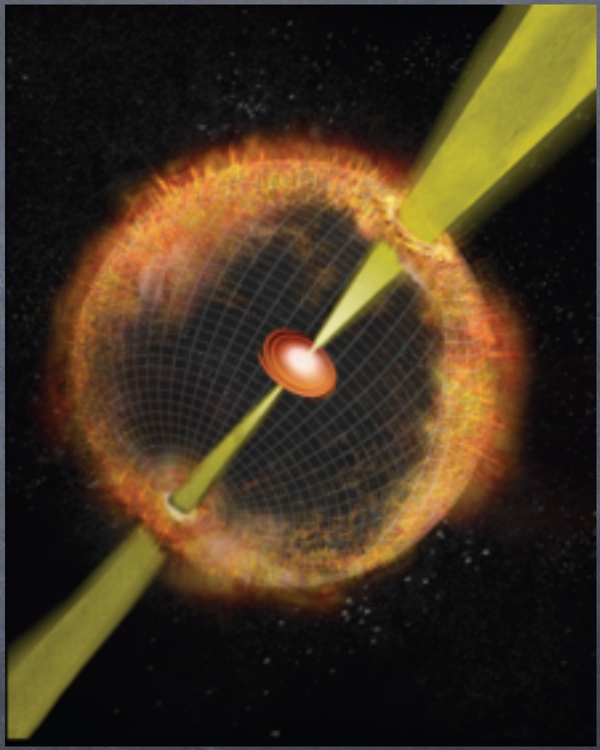


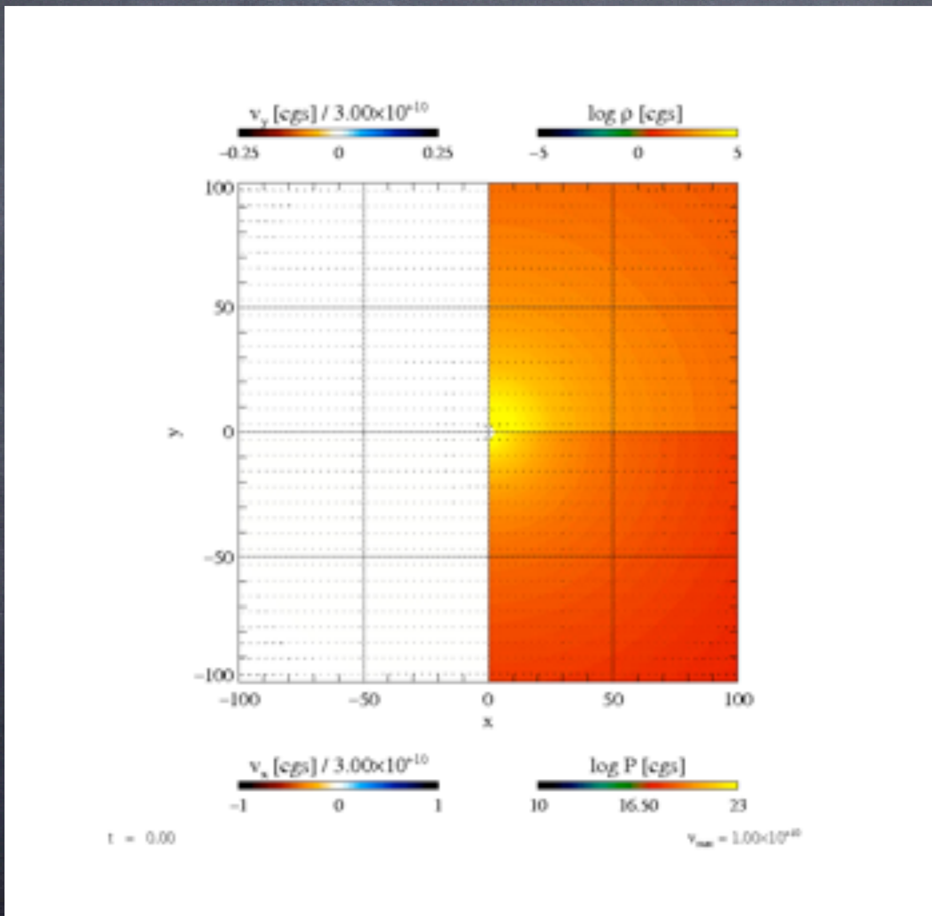


The Jet drills a hole in the star Model

Zhang, Woosley & MacFadyen 2004

Jet Simulations

(Obergaulinger, Piran + 11)



Opening angle of 15° degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, 5 * 10^{50}erg /s, through the entire run of the model. Lorentz factor at injection 7

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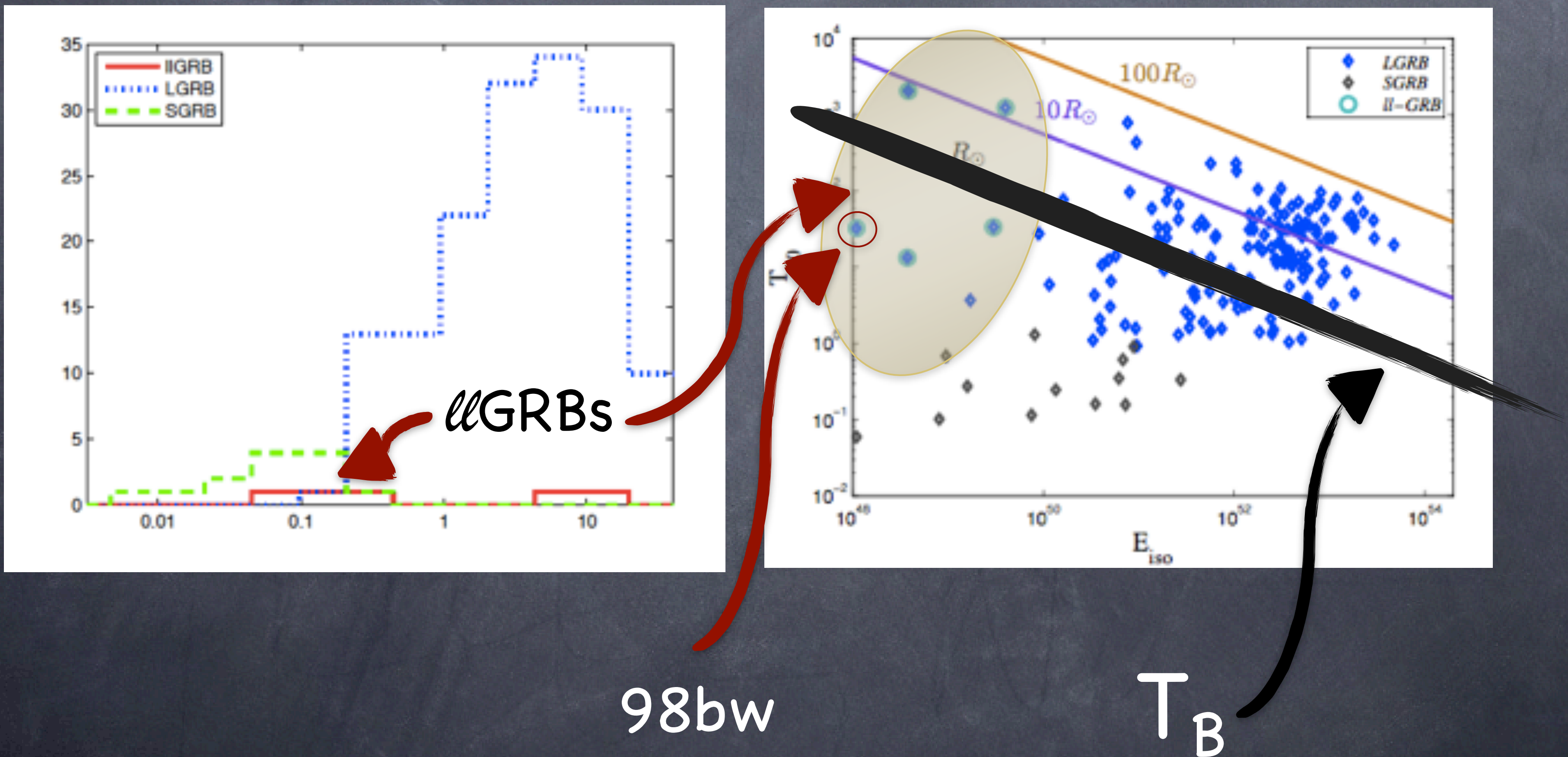
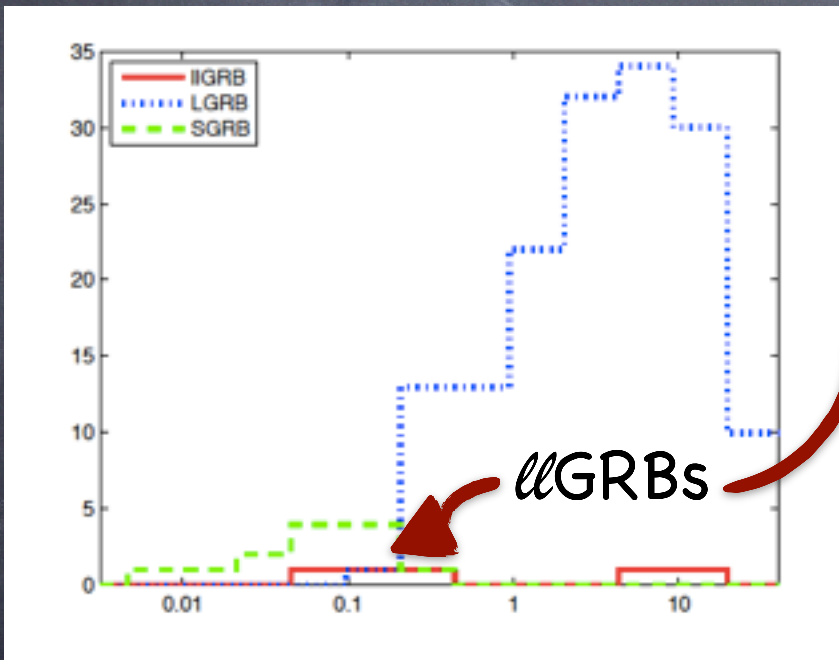
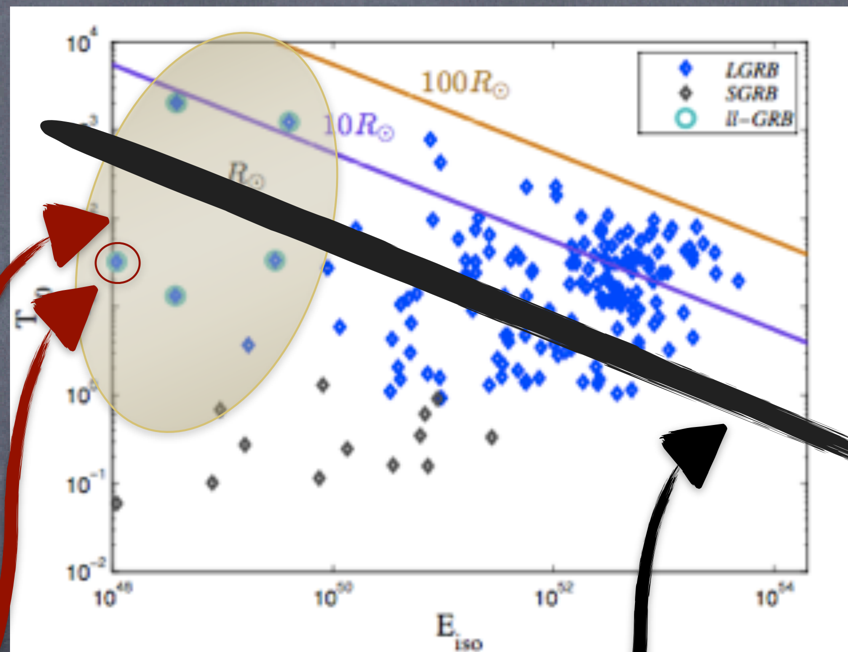

llGRB
LGRB
SGRB
0.01
0.1
1
10
$100R_\odot$
$10R_\odot$
$R_\odot$
LGRB
SGRB
ll-GRB
E_{iso}
ℓℓGRBs
98bw
T_B

Low luminosity GRBs - ℓℓGRBs don't arise from Collapsars





ℓℓGRBs

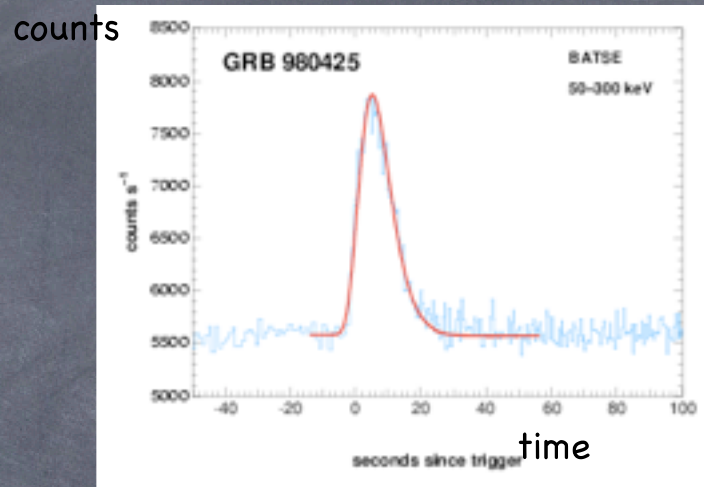
98bw

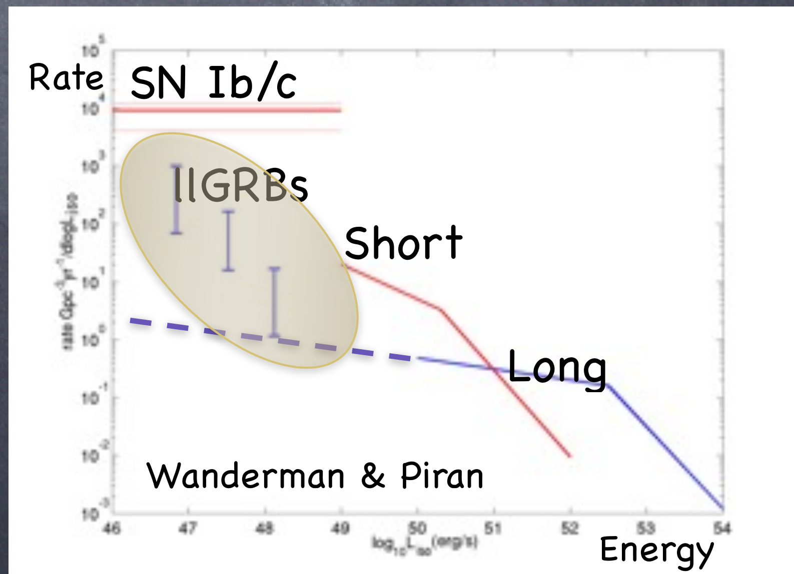
T_B

Low Luminosity GRBs - $\ell\ell$GRBs

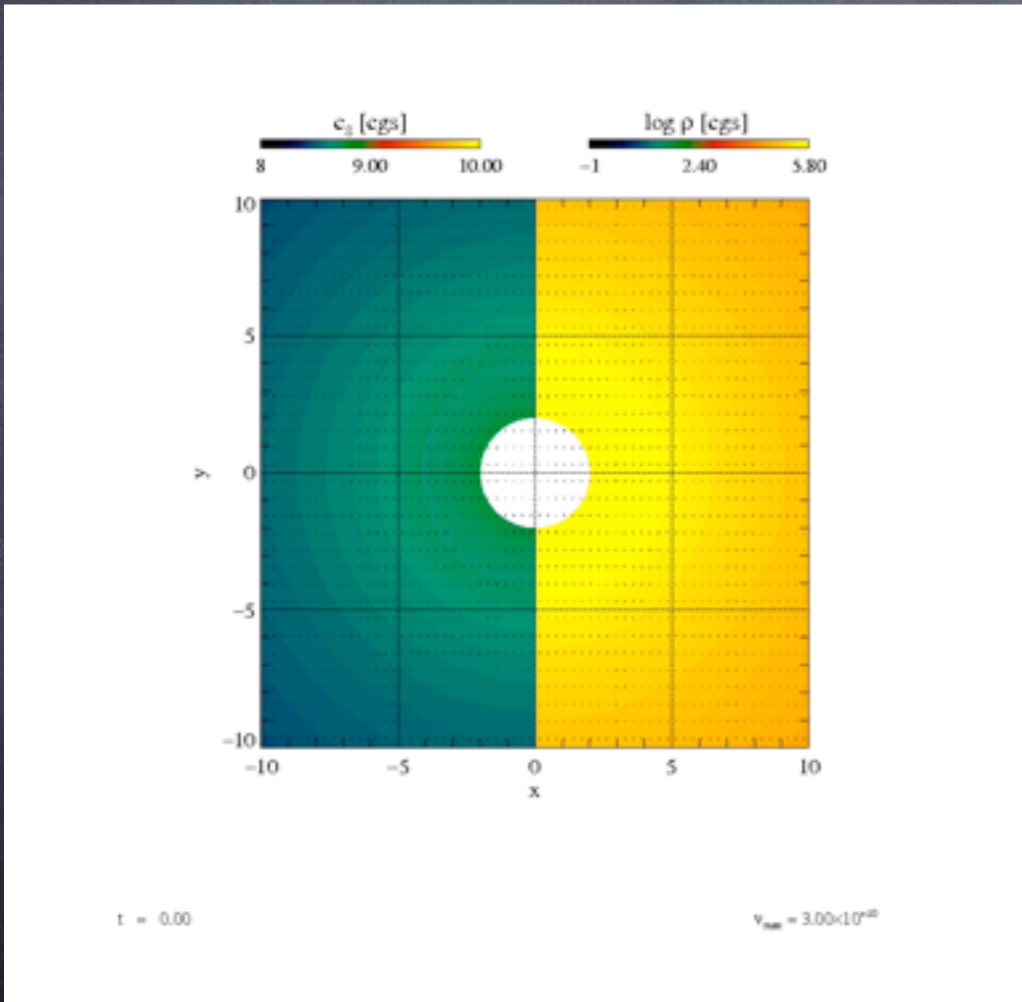
Bromberg Nakar, TP, 11 ApJL 2011

- Low luminosity GRBs:
  - E_{iso}~10^{48}-10^{49} ergs
  - **Smooth** single peaked light curve.
  - **Soft** Emission (E_{peak} <150 keV)
  - Much more numerous than regular long GRBs!
  - $\ell\ell$GRBs dont have enoug power to penetrate the star



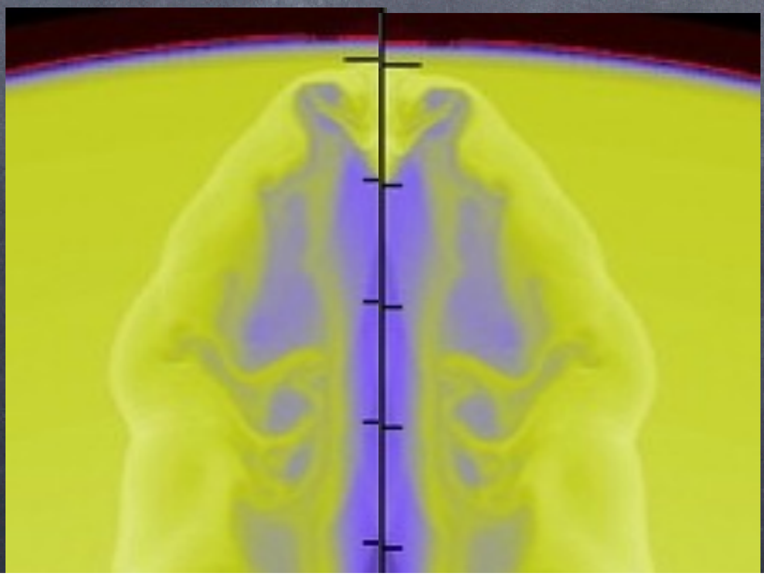


Jet Simulations - A Failed Jet (Obergaulinger, Piran + 11)



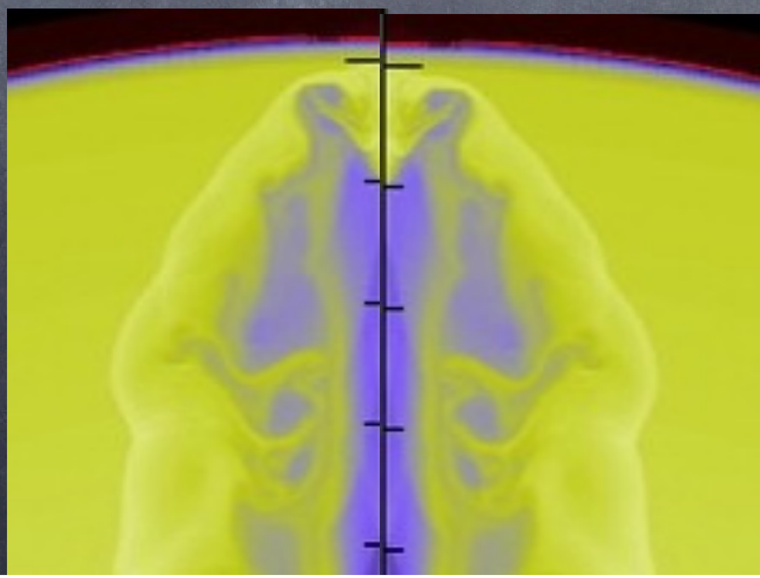
Opening angle of 15° degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, $5{*}10^{50}$erg/s, for 2 seconds.

What makes a ℓℓGRBs?



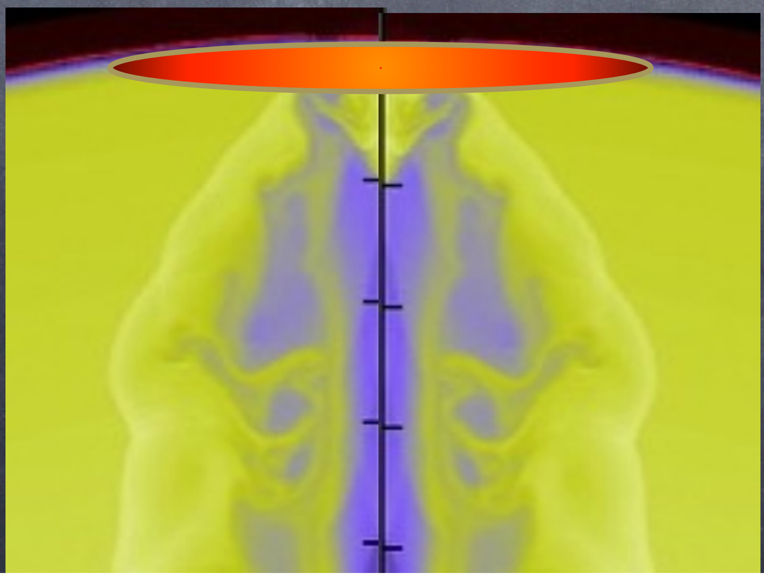
What makes a *ll*GRBs?

- A weak jet that fails to break out ("**a failed GRB**").



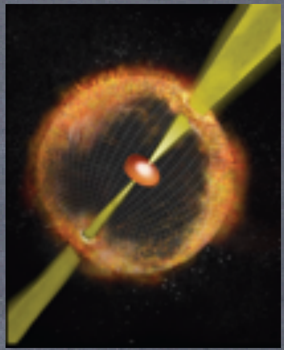
What makes a $\ell\ell$GRBs?

- A weak jet that fails to break out ("**a failed GRB**").
- We observe the shock breakout form the stellar envelope (Colgate, 1967; Katz, Budnik, Waxman, 2010; Nakar & Sari, 2011)

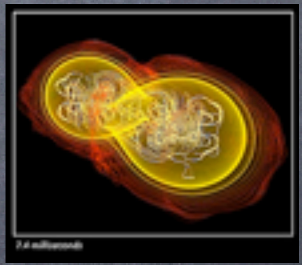


Three types of GRBs

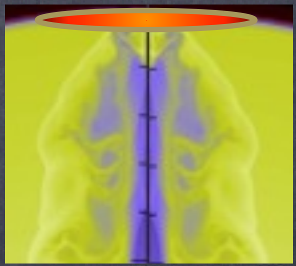
- Collapsars - collapse of a massive star - generation of a jet that penetrates the envlope and produces γ - rays at a large distance



- Mergers - mergers of two neutron stars produce short GRBs



- *low luminosity* GRBs - produced by a shock breakout from a supernova.



Why ?

A Tool

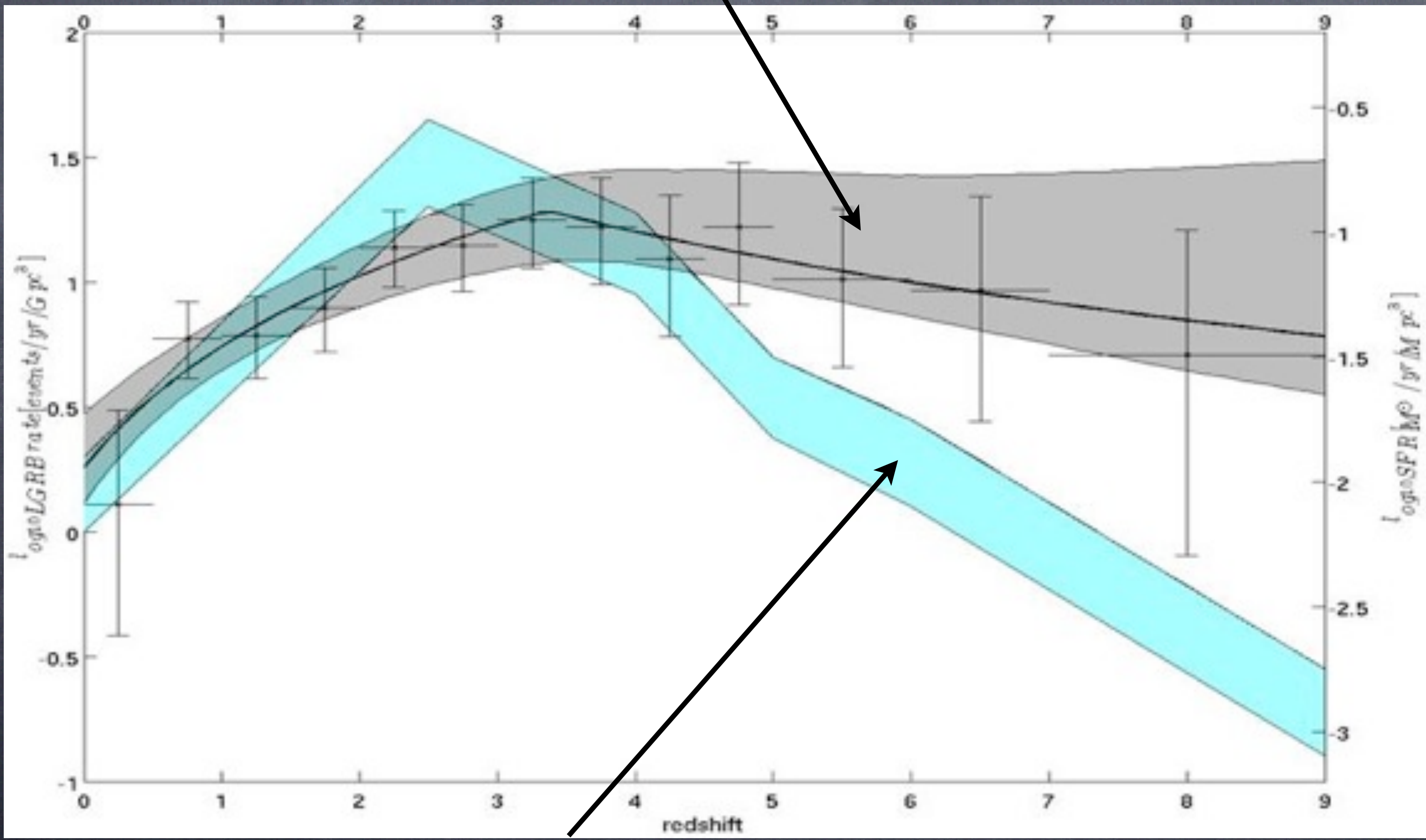
Standard Candles for cosmological parameters?

- But GRBs are NOT standard candles*

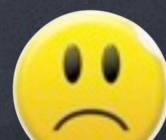
★ The GRBs'Philips relation was not discovered yet
(see however Amadi relations and Yonetoko relations).

Measure the Cosmic Star fromation rate?

GRBs (Wanderman & TP 10)



SFR (Bouwens+10)



Laboratory for Extreme Conditions near Black Holes

- Extreme gravitational fields
- Huge magnetic fields
- Ultra-relativistic shocks
- Super Eddington accretion

F. Mirabel

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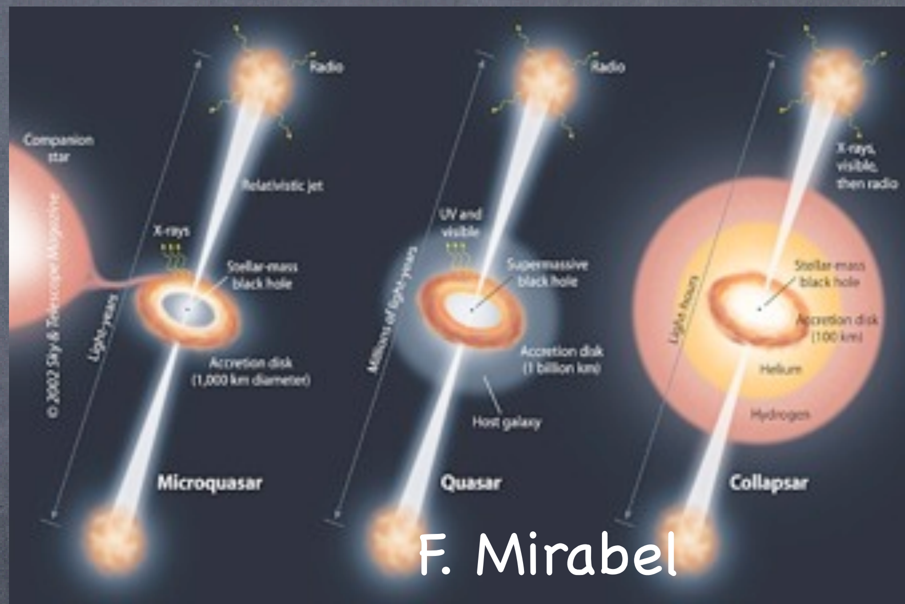
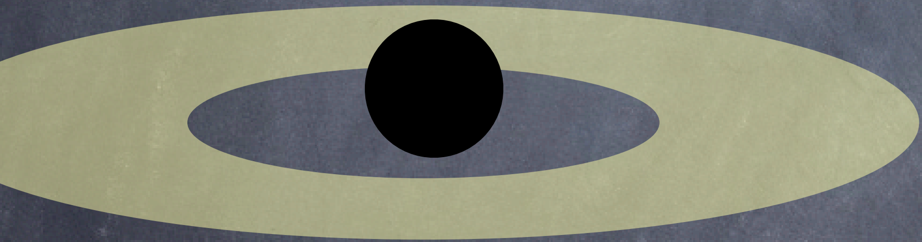


F. Mirabel

Gravitational Radiation from Jet Acceleration



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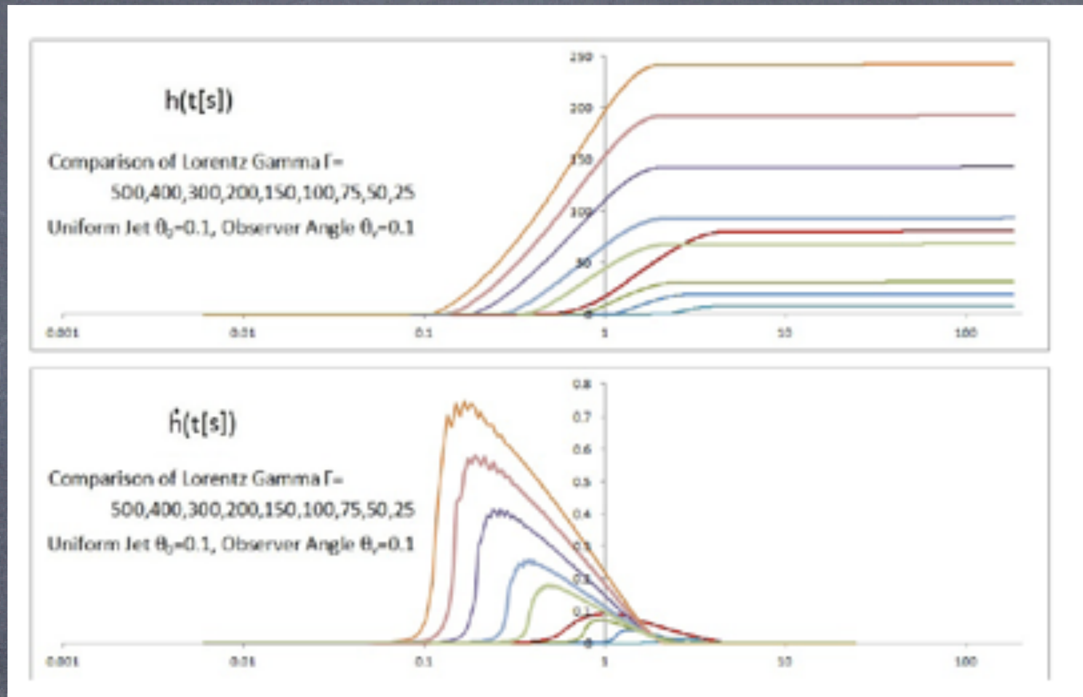

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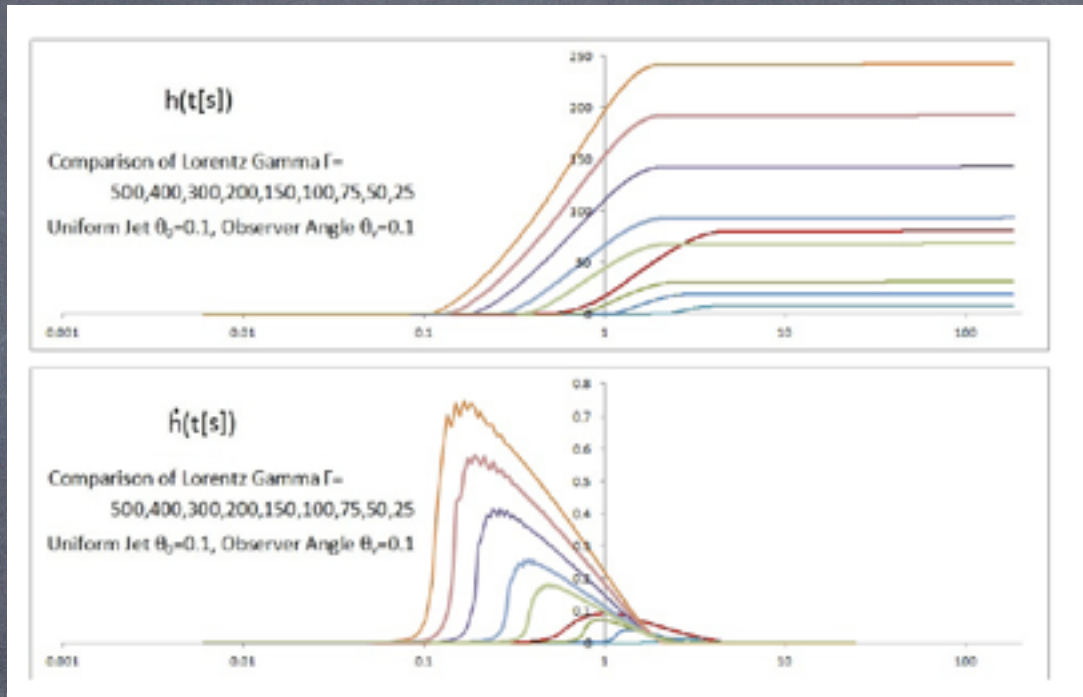

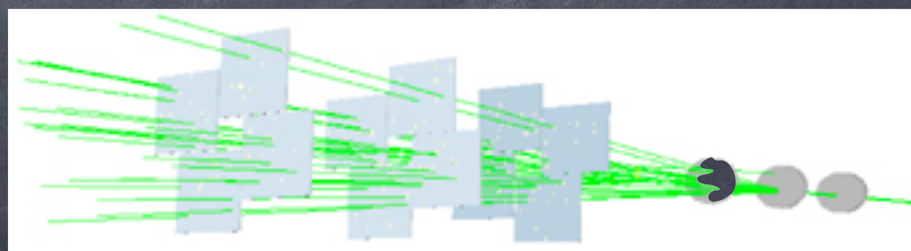

Nakamura minijet model

GRBs are good for many things:

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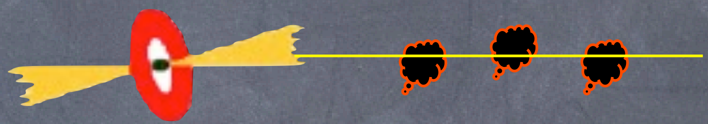
- **Determining the high redshift history of the universe ?**



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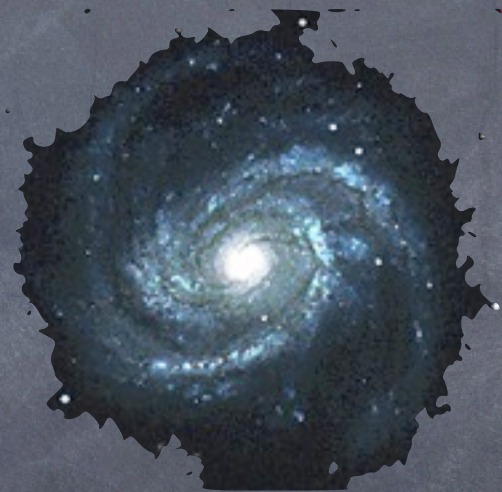

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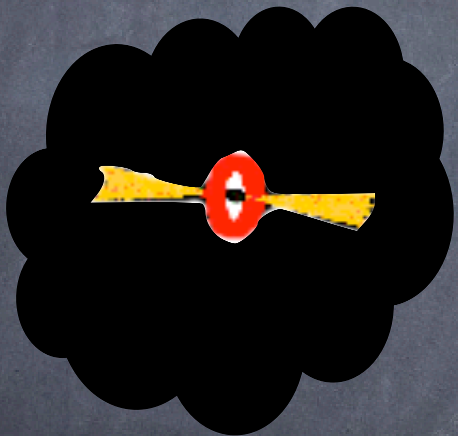

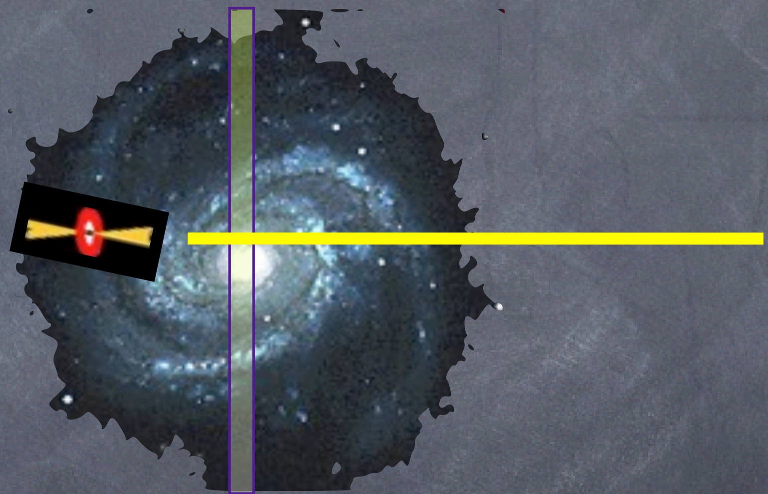

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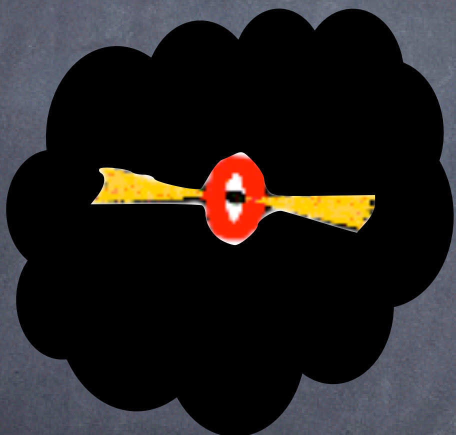
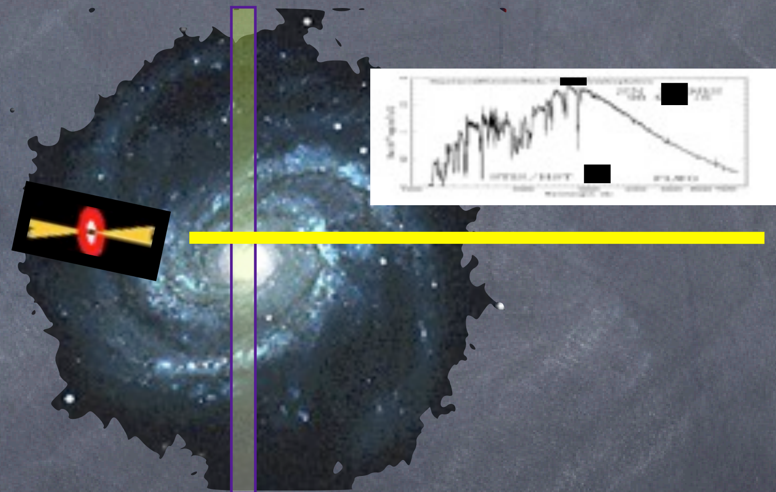
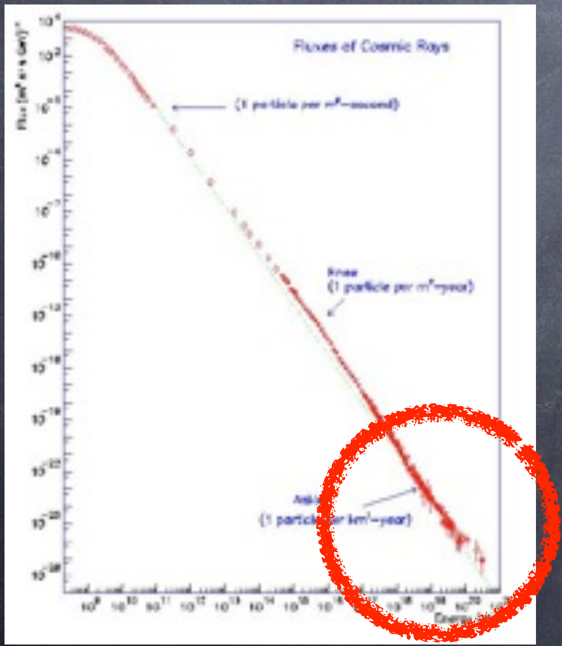




GRBs are good for many things:

- **Determining the high redshift history of the universe ?**
- **Source of Ultra High Energy Cosmic Rays?**



GRBs are ~~good~~ bad for many things:

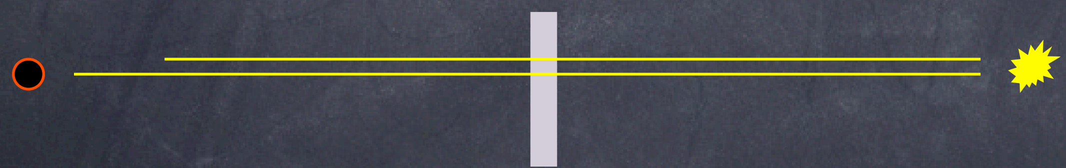
- **Determining the high redshift history of the universe ?**
- **Source of Ultra High Energy Cosmic Rays?**
- **Destroy Life on Earth (mass extinction) ??**

GRBs are good for many things:

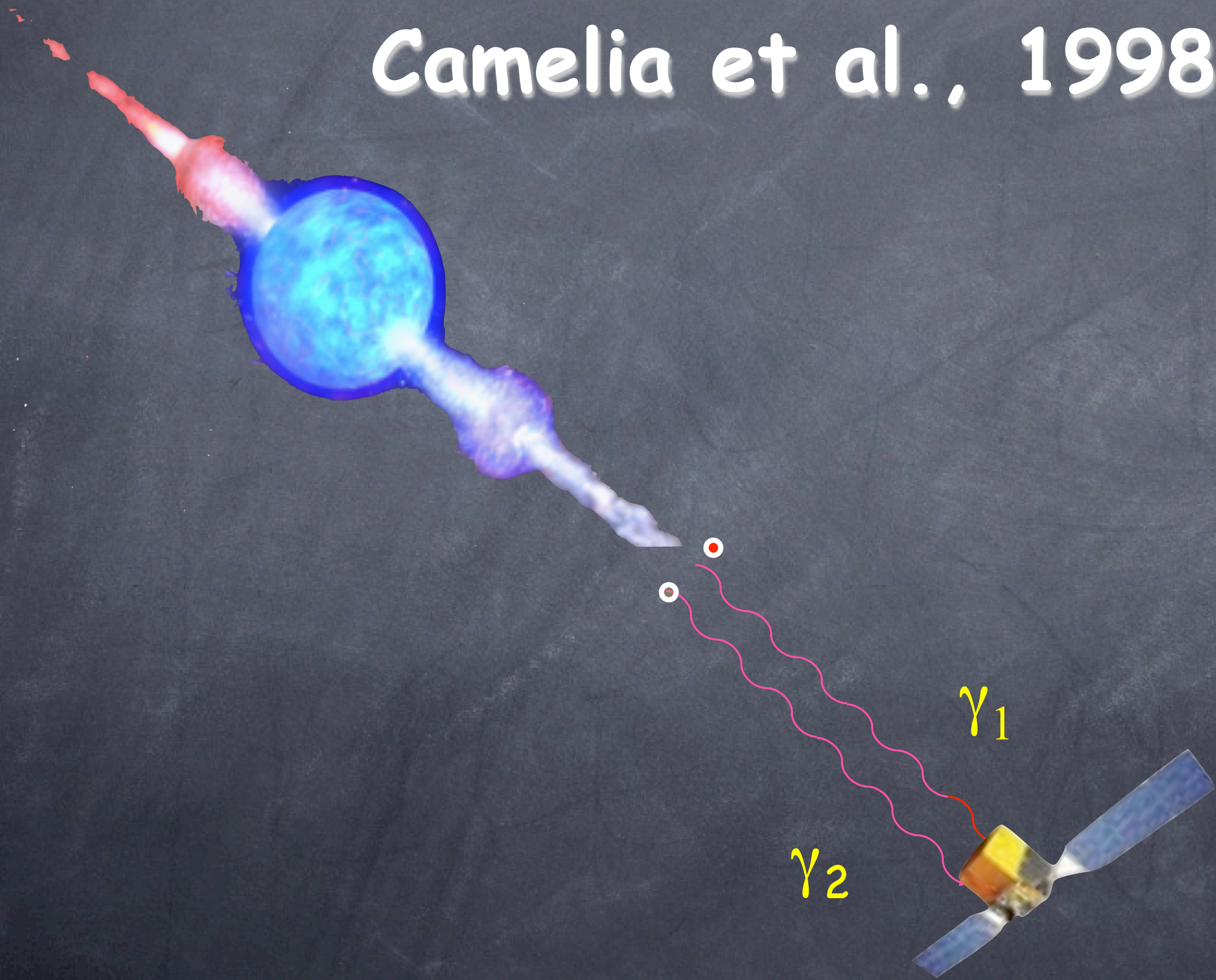
- Determining the high redshift history of the universe ?
- Source of Ultra High Energy Cosmic Rays?
- Destroy Life on Earth (mass extinction) ??
- Creat Life on Earth (trigger planet formation)?

GRBs are good for many things:

- Determining the high redshift history of the universe ?
- Source of Ultra High Energy Cosmic Rays?
- Destroy Life on Earth (mass extinction) ??
- Creat Life on Earth (trigger planet formation)?
- Measuring quantum gravity effects



Lorentz Invariance Violation and GRB (Amelino-Camelia et al., 1998)



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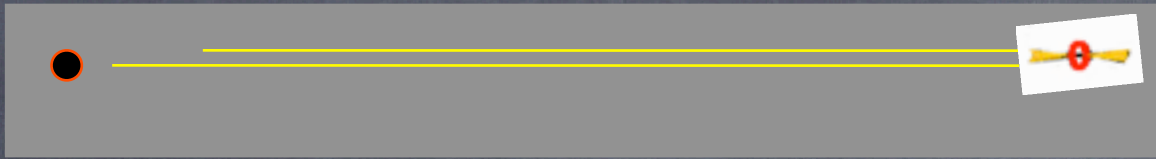
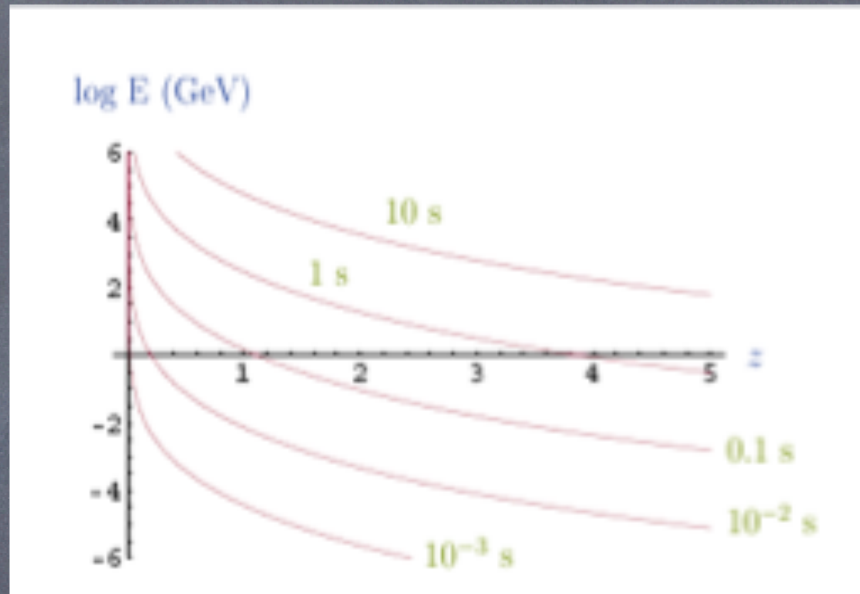
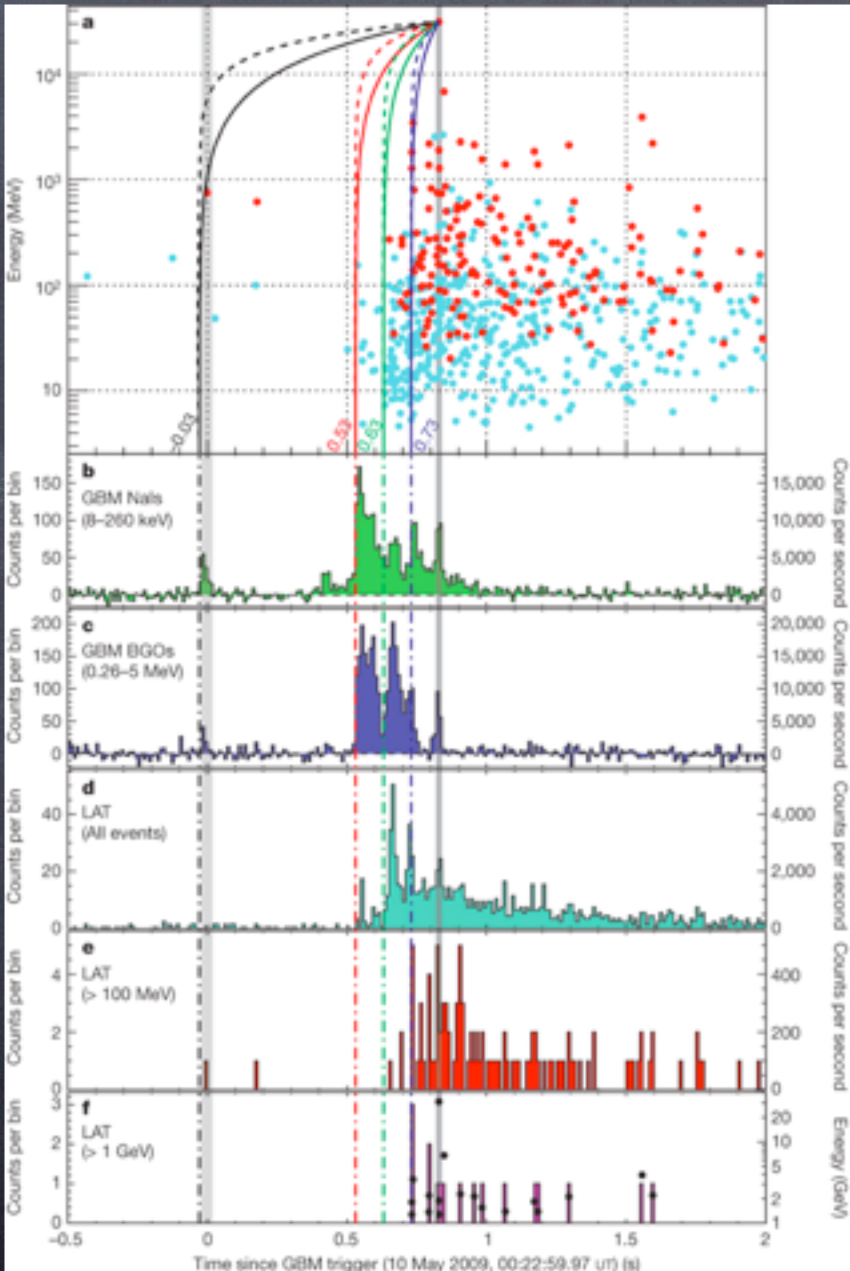


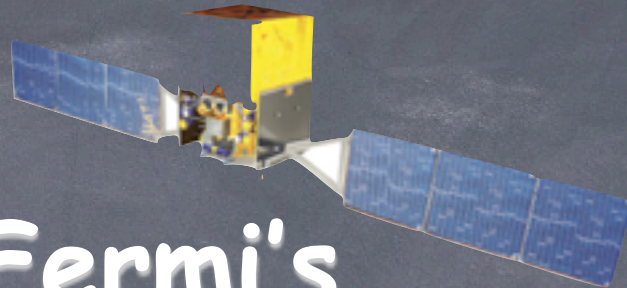
$$E^2 \approx (pc)^2 \left[1 + \left(\frac{E}{\xi m_{pl}}\right)^n\right]$$



$$v \approx c\left[1 + \frac{(1+n)}{2}\left(\frac{E}{\xi m_{pl}}\right)^n\right]$$

$$dt \approx \pm \frac{d}{c}\left(\frac{E}{\xi_n m_{pl}}\right)^n \approx 10^{-2-(n-1)19}\,\mathrm{sec}\left(\frac{E}{\xi_n \mathrm{GeV}}\right)^n$$



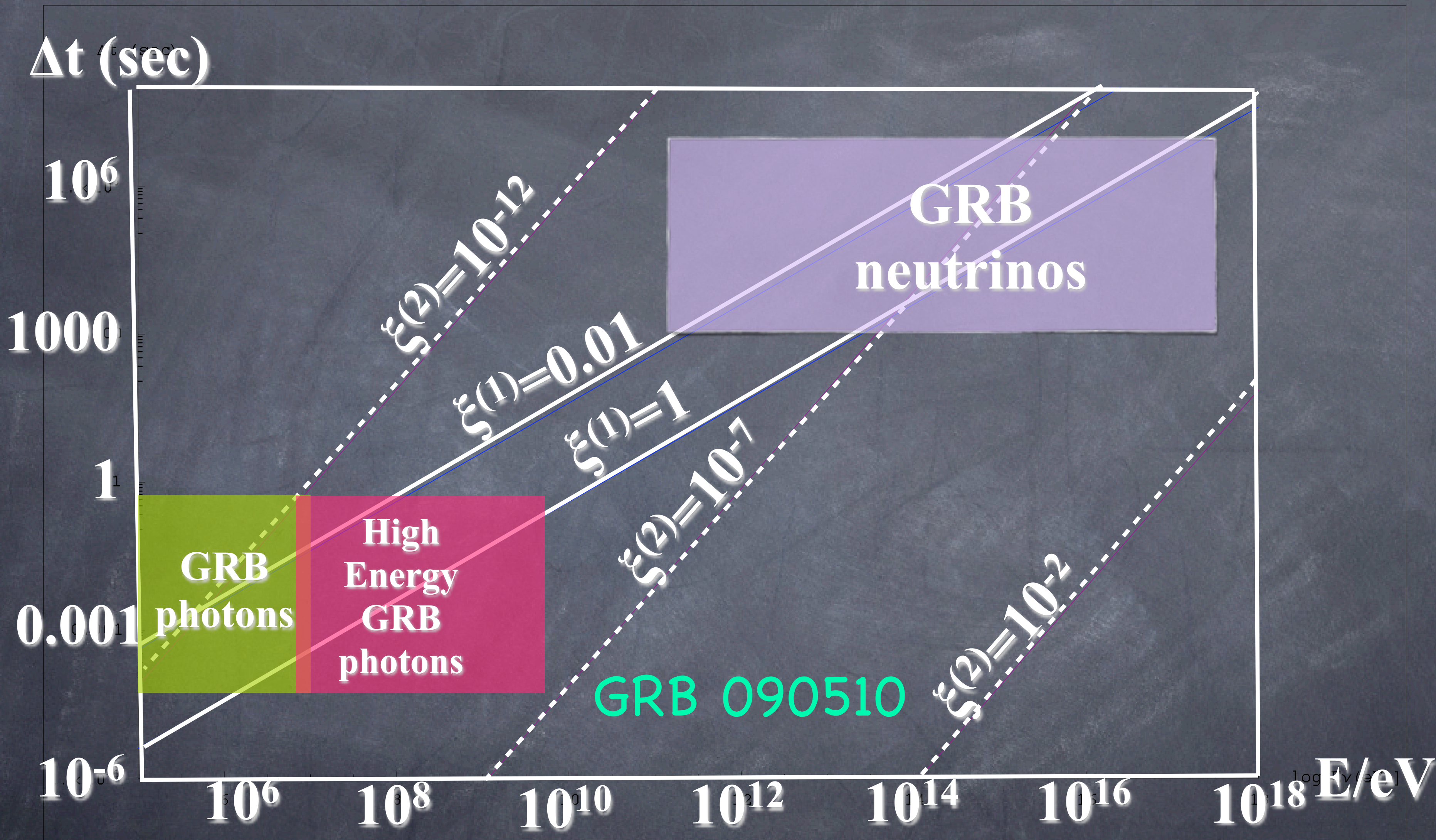


Fermi's observations of GRB090510

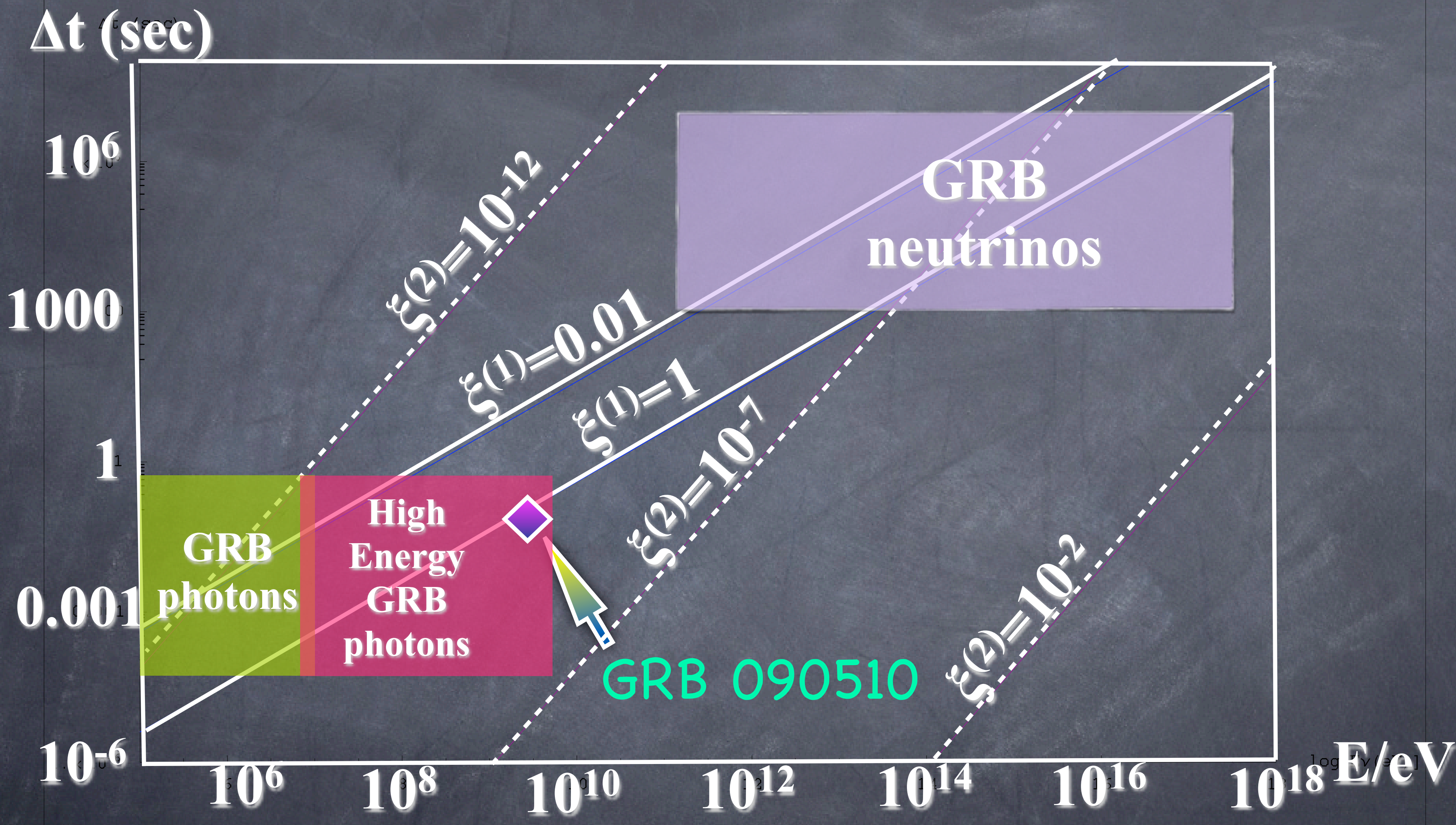
$dt_{35MeV-31GeV} < 0.1$ sec

$\Rightarrow \xi^{(1)} > 1.2$

$\Rightarrow E^{(1)}_{LiV} > 1.4\ 10^{19}$ GeV



$\xi^{(1,2)}=E_{LiV}/M_{pl}$



$\xi^{(1,2)} = E_{LiV}/M_{pl}$

Summary

- GRBs are the brightest explosions in our Universe
- GRBs hearlds the formation of a compact object - most likely a black hole
  - Long GRBs = Collapsars,
  - Short GRBs ≈ Mergers
  - *low luminosity* GRBs (≠ Collapsar) ≈ shock break out
- GRBs are the best natural laboratories to study physics under extreme conditions
- The Bright GRB explosion and their afterglow can serves as a tool to explore the early Universe
- Might be sources of UHECRs, UHE neutrinos and GW