Title: The Birth of Neutron Stars and Black Holes

Date: Sep 14, 2009 04:30 PM

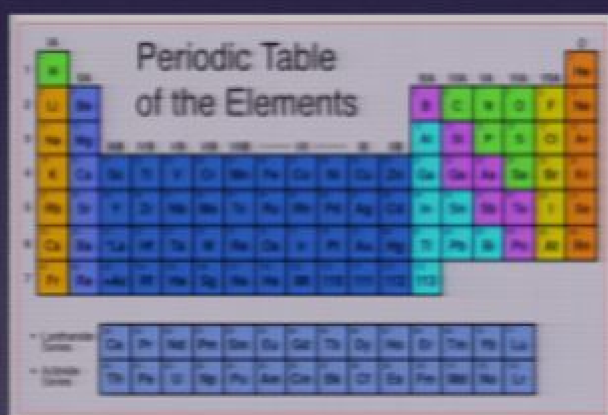
URL: http://pirsa.org/09090028

Abstract: Gamma-ray bursts (GRBs) -- rare flashes of ~ MeV gamma-rays lasting from a fraction of a second to hundreds of seconds -- have long been among the most enigmatic of astrophysical transients. Observations during the past decade have led to a revolution in our understanding of these events, associating them with the birth of neutron stars and/ or black holes during either the collapse of a massive star or the merger of two compact objects (e.g., a neutron star and a black hole). GRBs are particularly interesting since NS-NS and NS-BH mergers are the primary target for km-scale gravitational wave observatories such as Advanced LIGO; GRBs are also one of the most promising astrophysical sources of very high-energy neutrinos and may produce many of the neutron-rich heavy elements in nature. In this talk, I will describe the physics of these enigmatic events and summarize outstanding problems. Combined electromagnetic and gravitational-wave observations of these sources in the coming decade have the potential to produce major advances in both astrophysics and fundamental physics (tests of General Relativity and of the equation of state of dense nuclear matter).

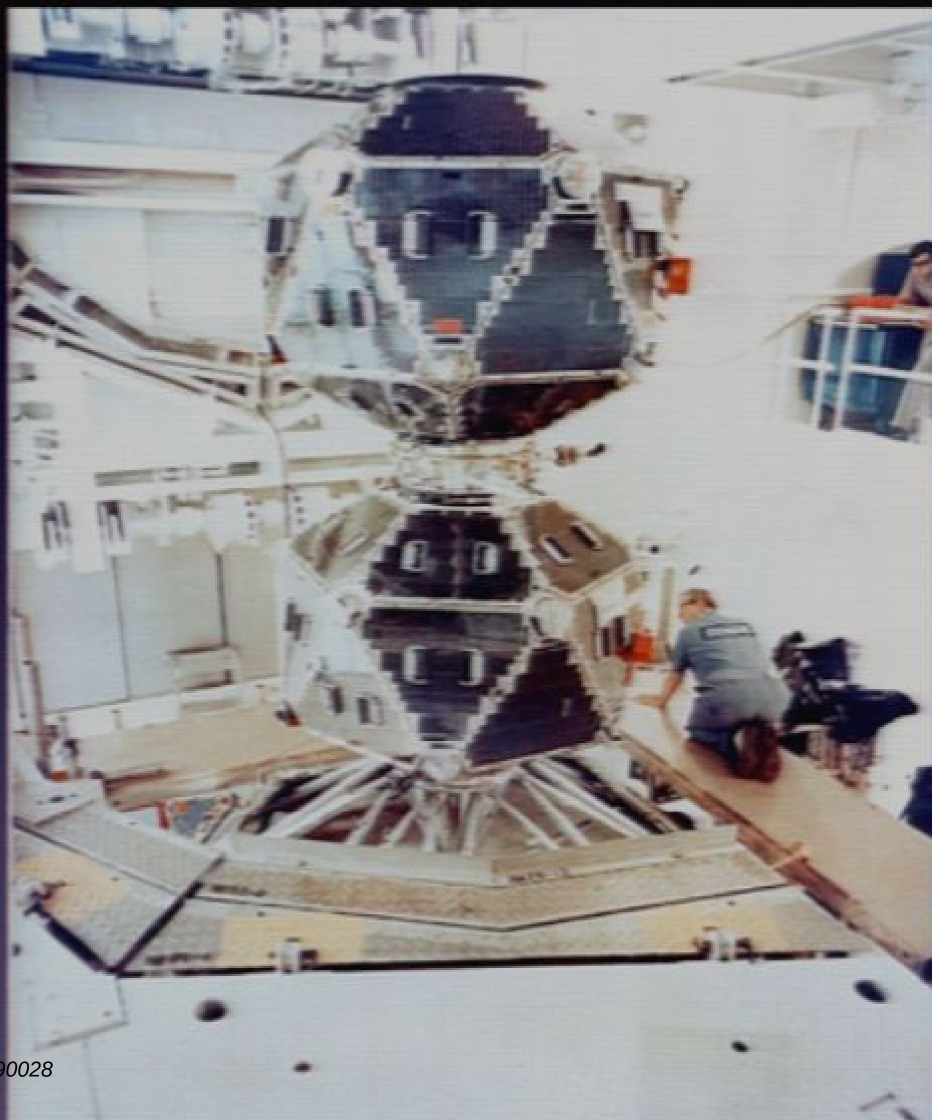
# The Birth of Neutron Stars and Black Holes in Gamma-ray Bursts

Eliot Quataert (UC Berkeley)

w/ **Brian Metzger**, Todd Thompson, Tony Piro, & Niccolo Bucciantini




# Serendipitous Science: "Gamma-ray Bursts"

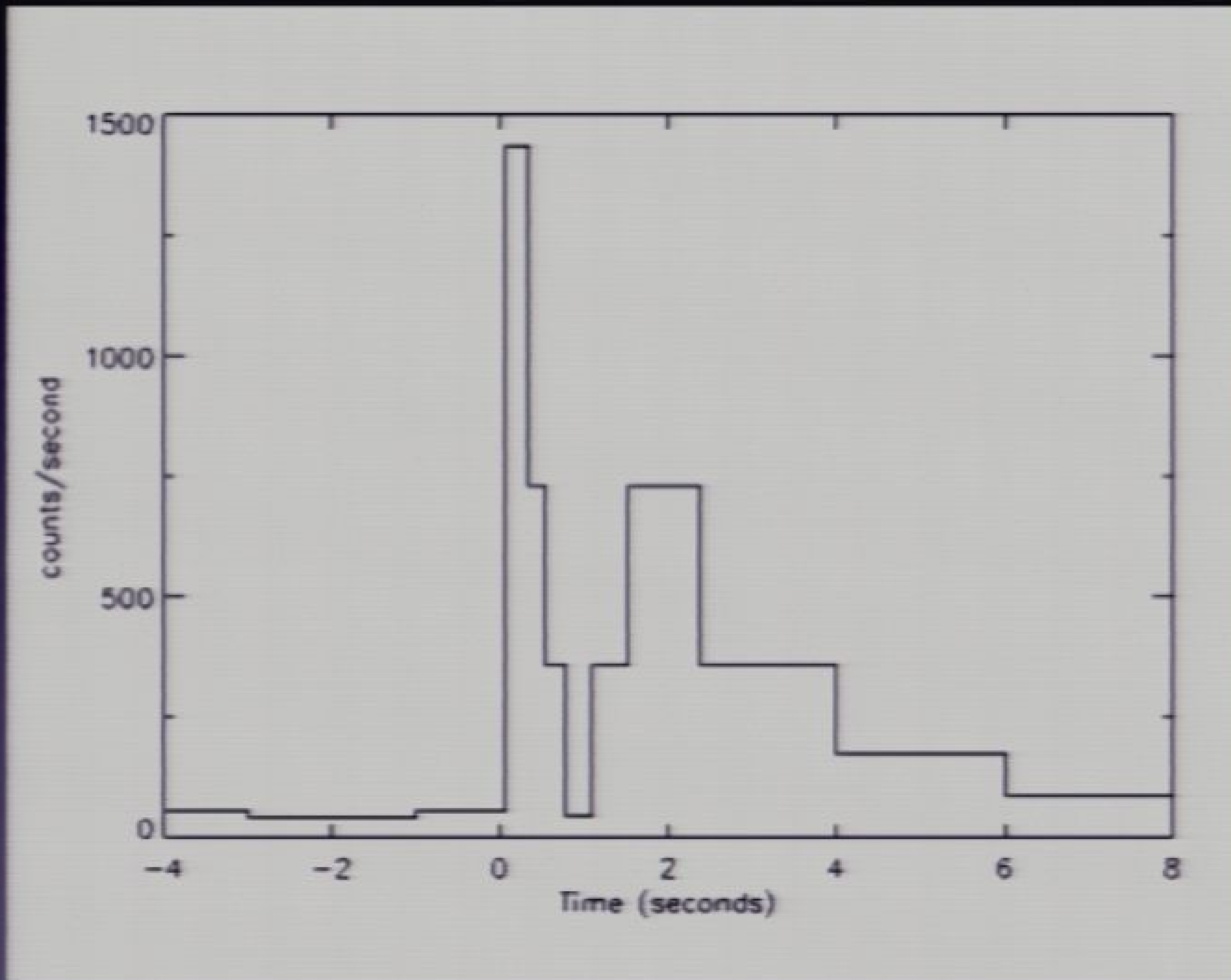


Vela satellites launched in 1960s

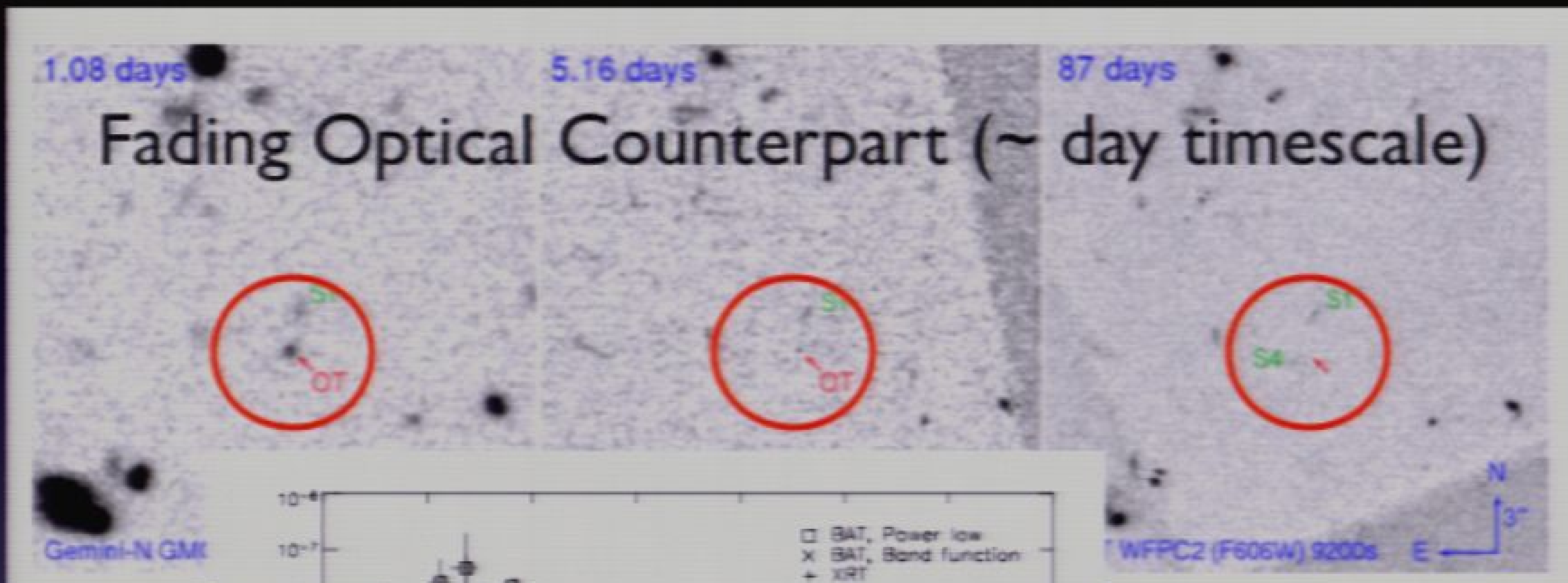
x-ray, gamma-ray, & neutron detectors to search for atmospheric nuclear bombs

# GRB #1: July 2 1967

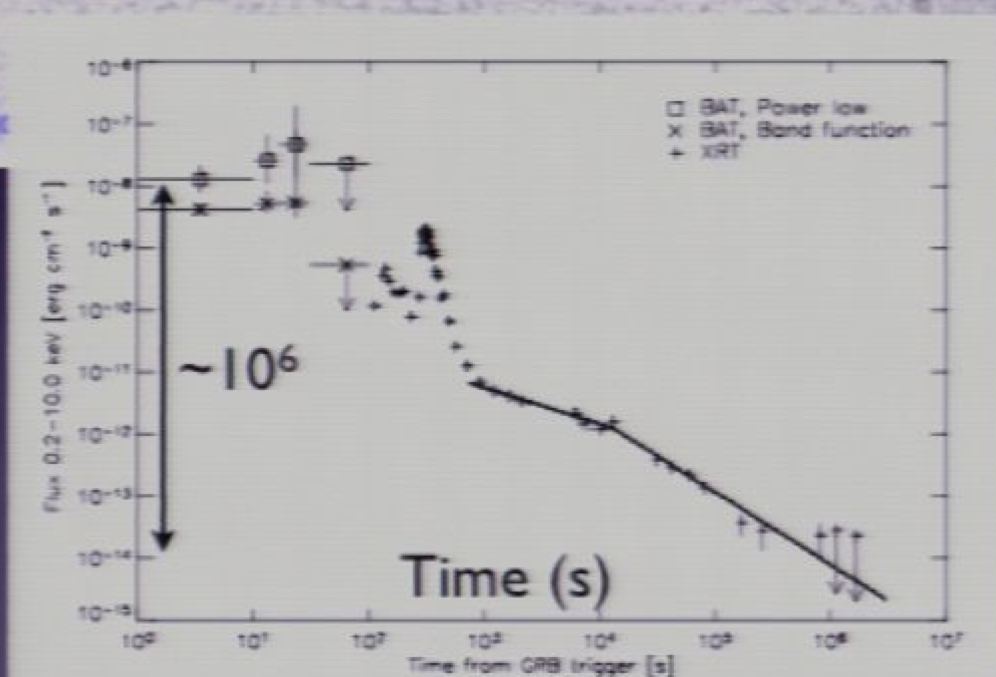
Counts of ~ MeV Gamma-rays



# "Afterglow": Longer wavelength (x-ray, optical, radio) & timescale (~ day-yr) counterparts to GRB

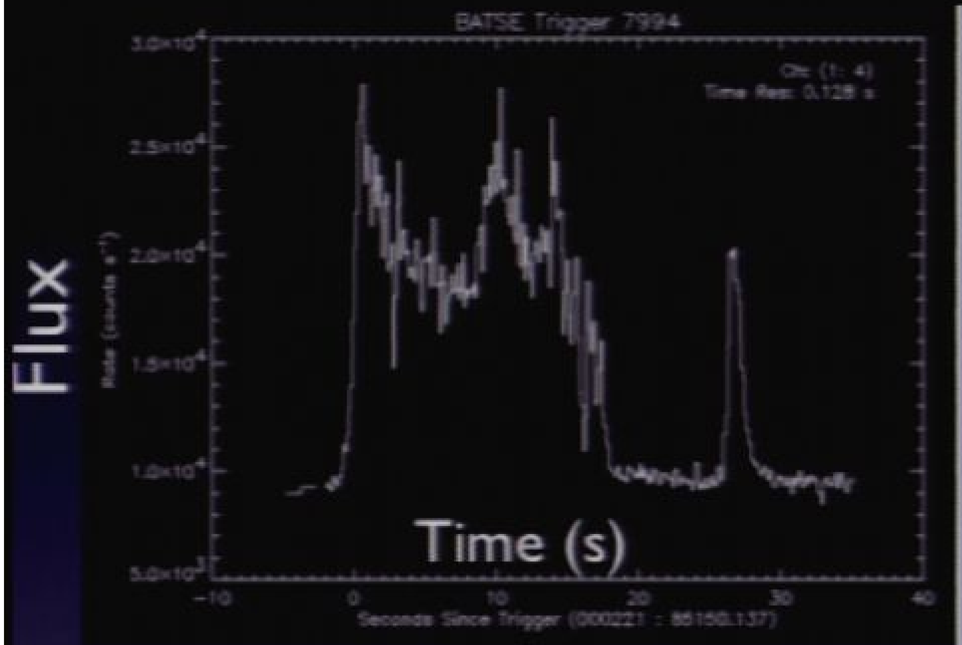


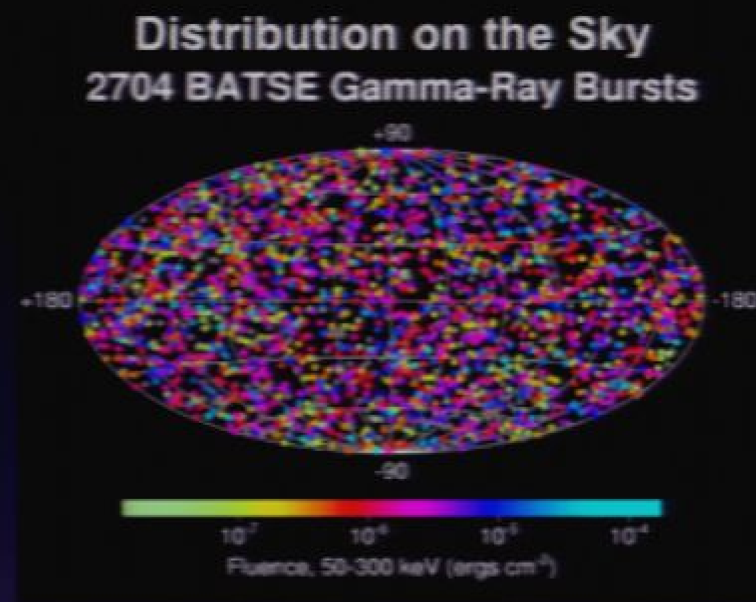

X-ray Flux (~ keV)

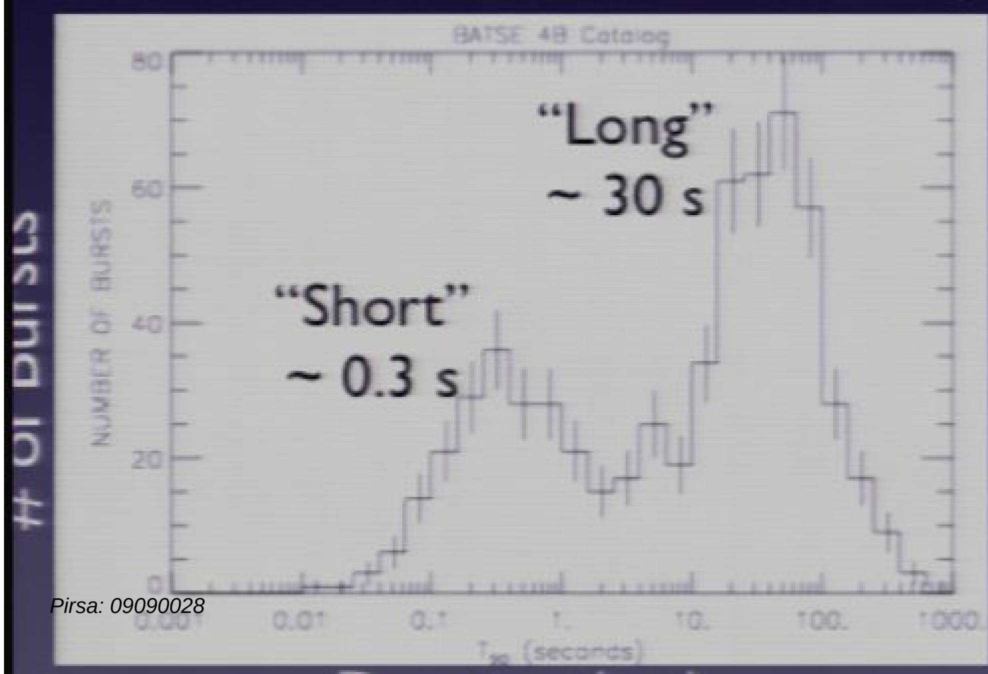



Afterglows discovered in 1997: provided first precise positions, distances, and energetics

# Gamma-Ray Bursts

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- Isotropic on the Sky
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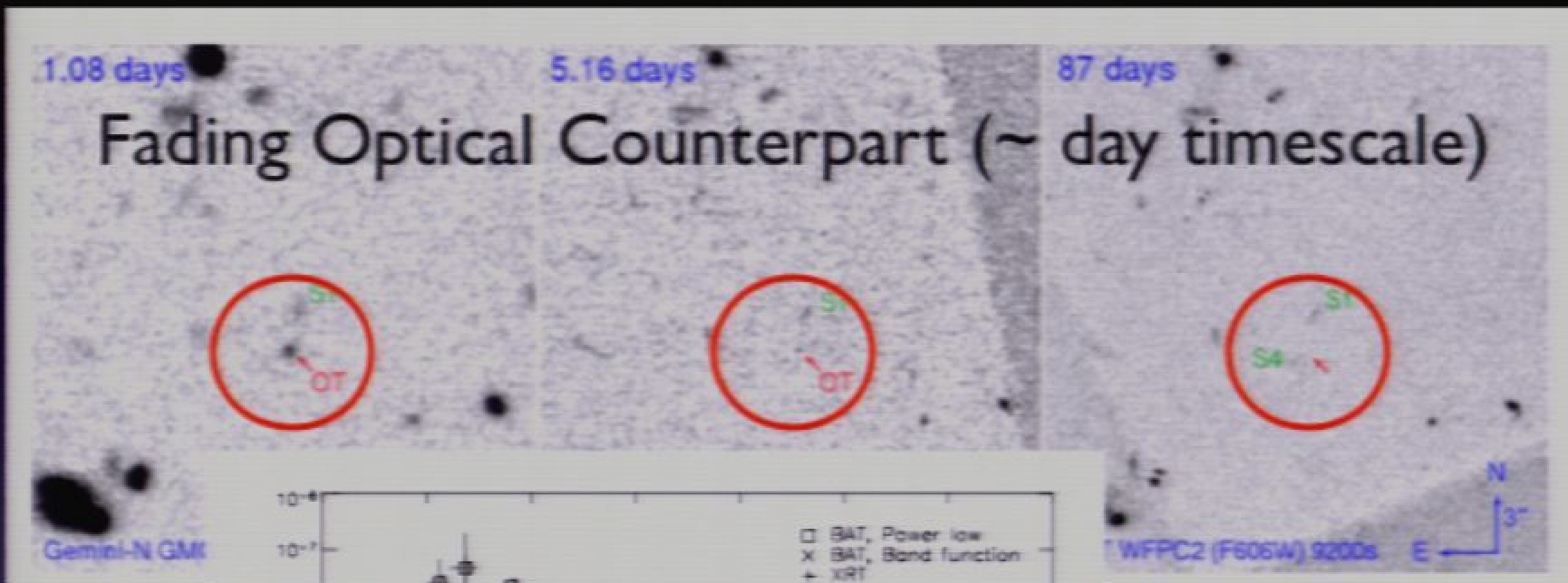


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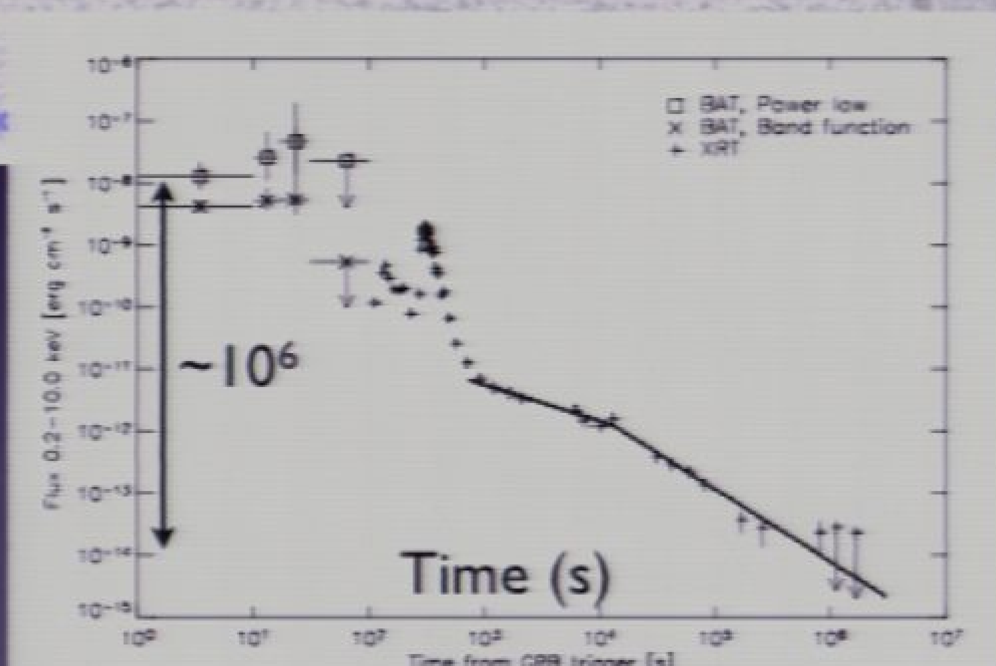


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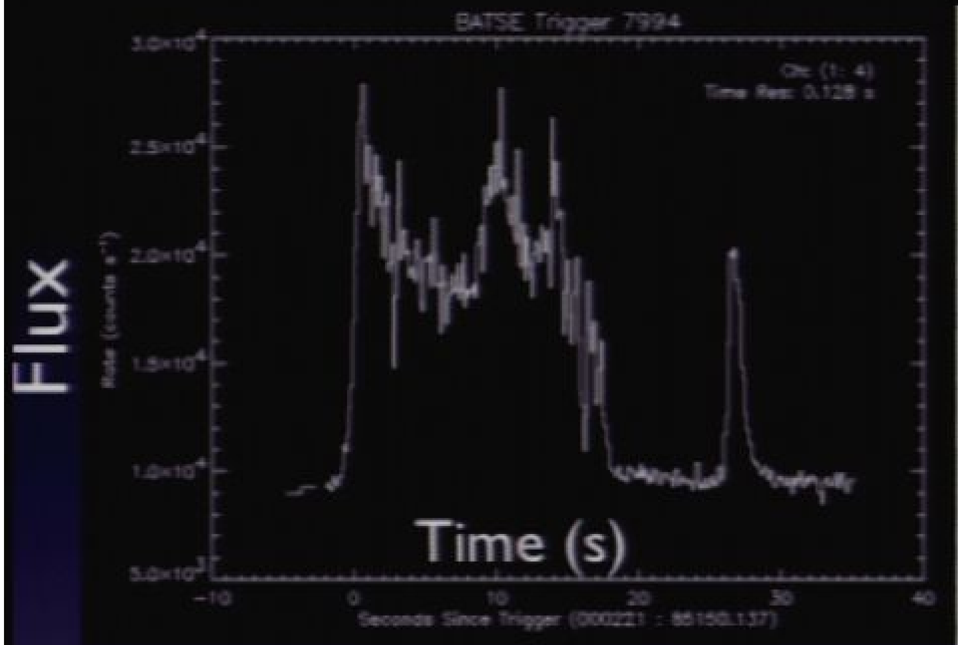


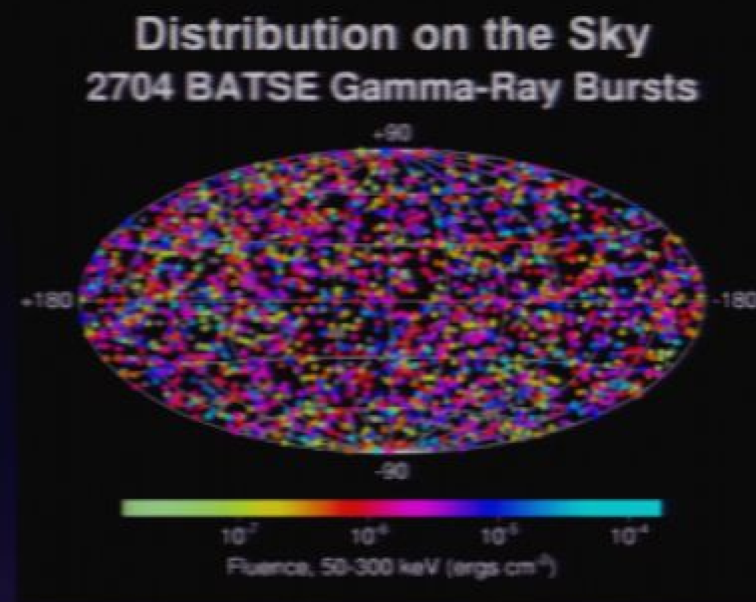


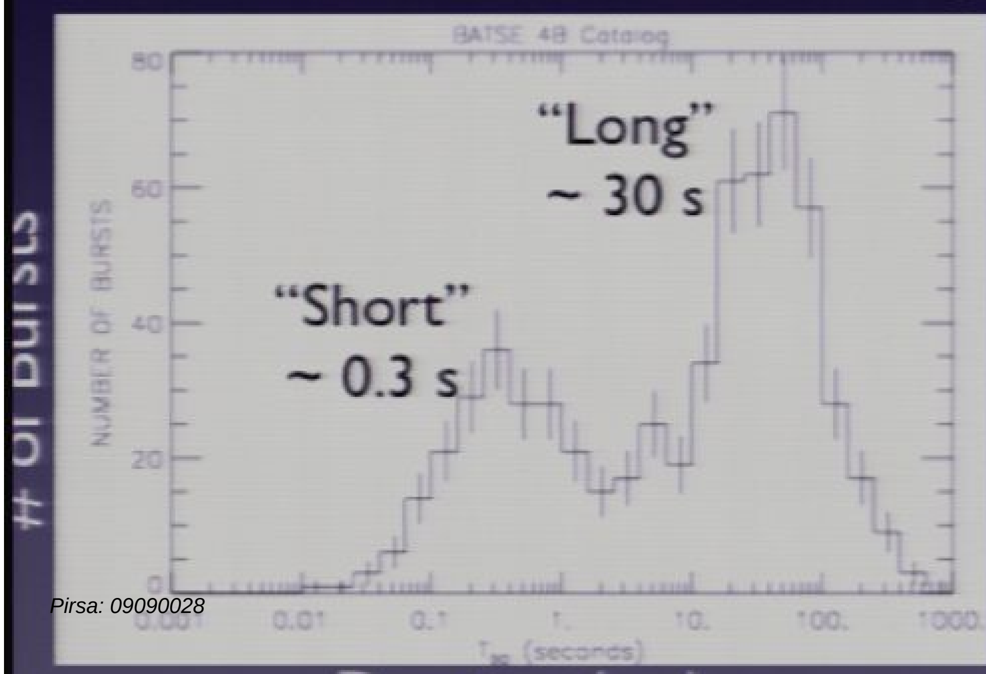


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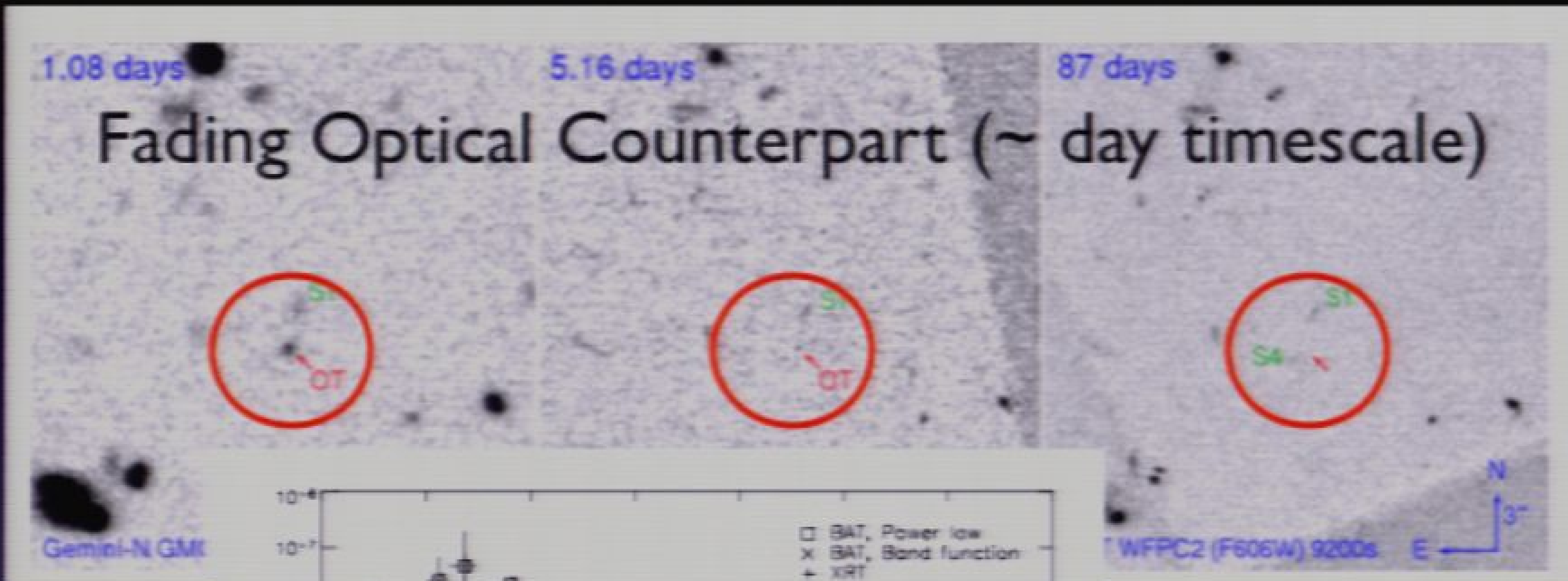


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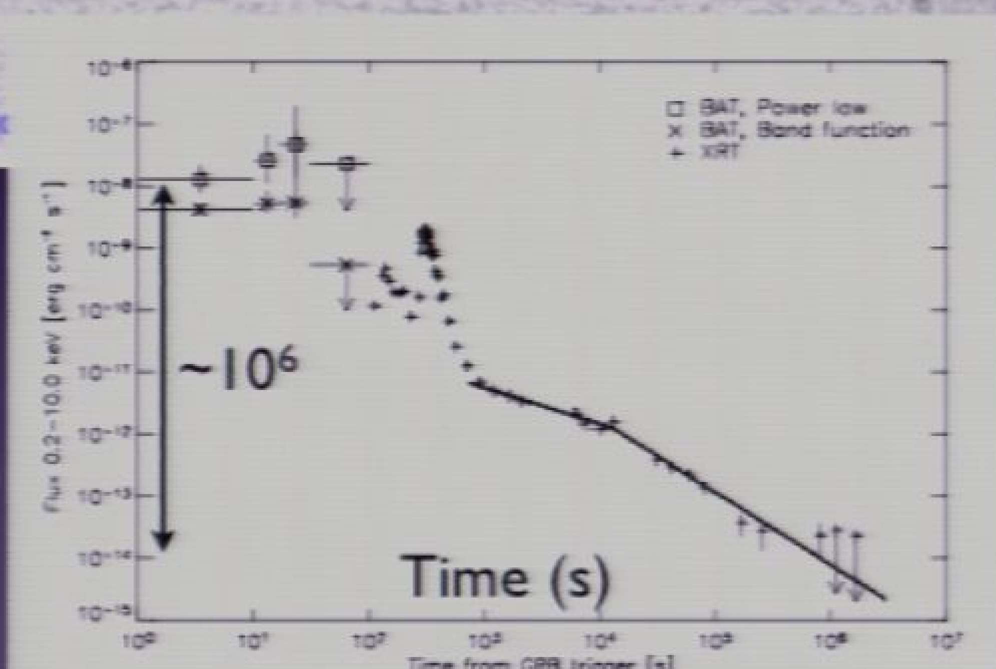


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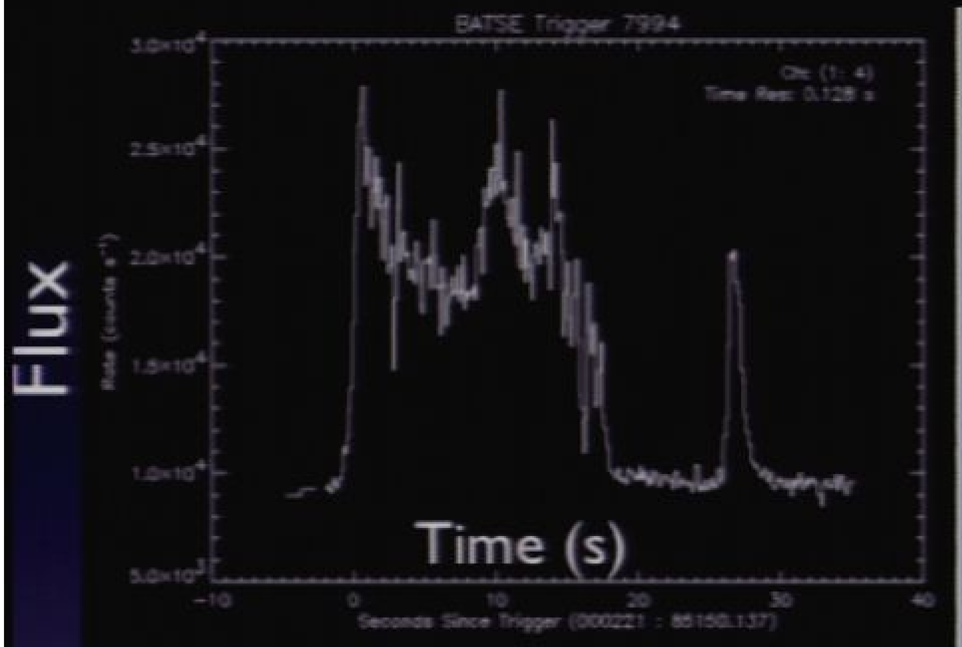


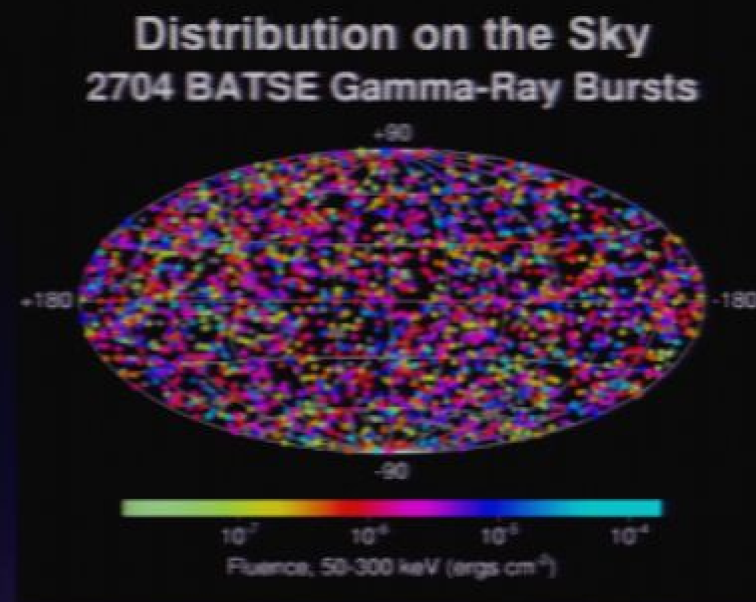


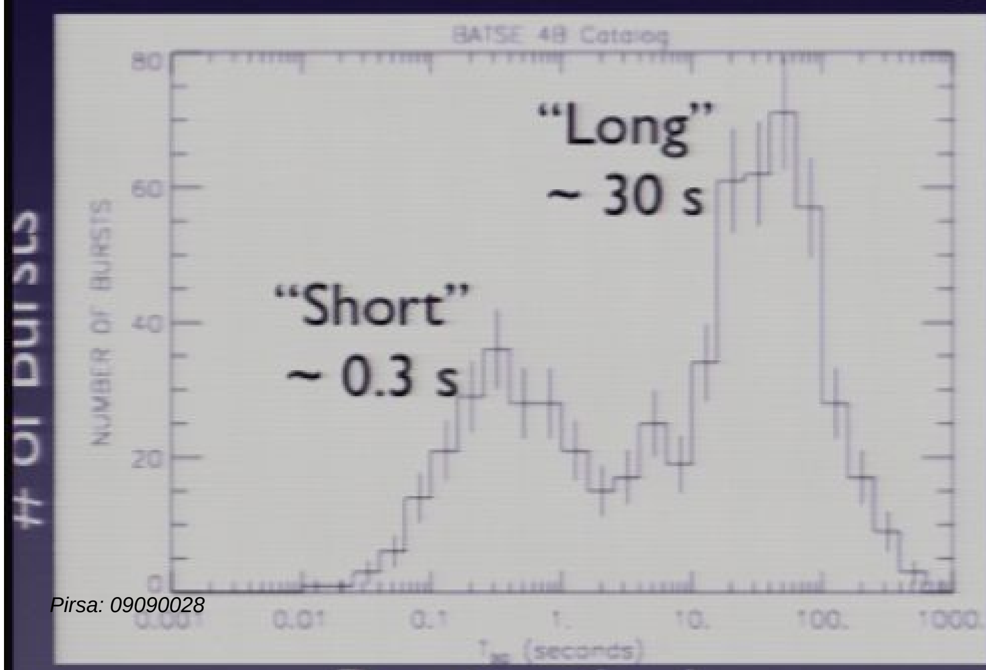


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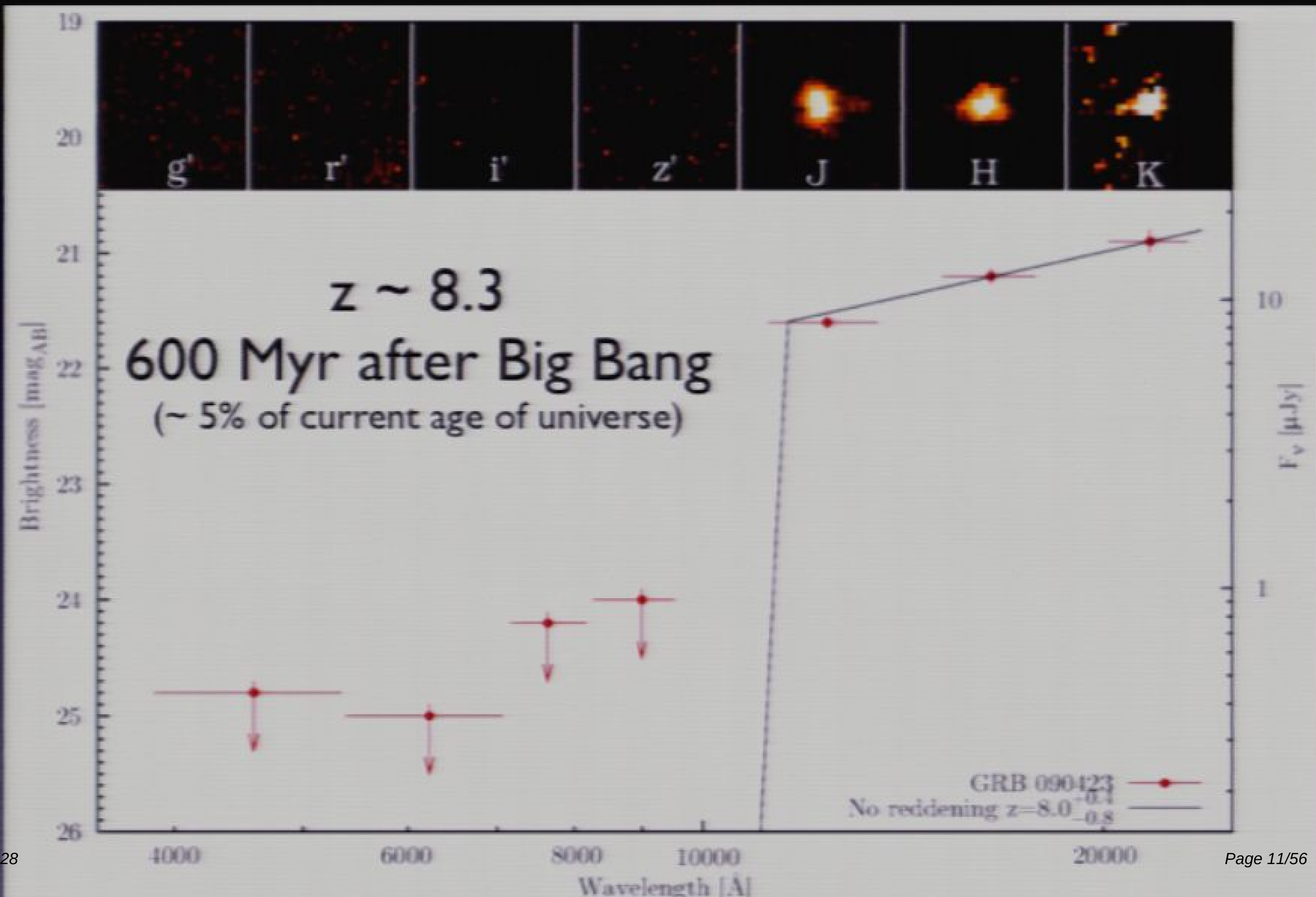
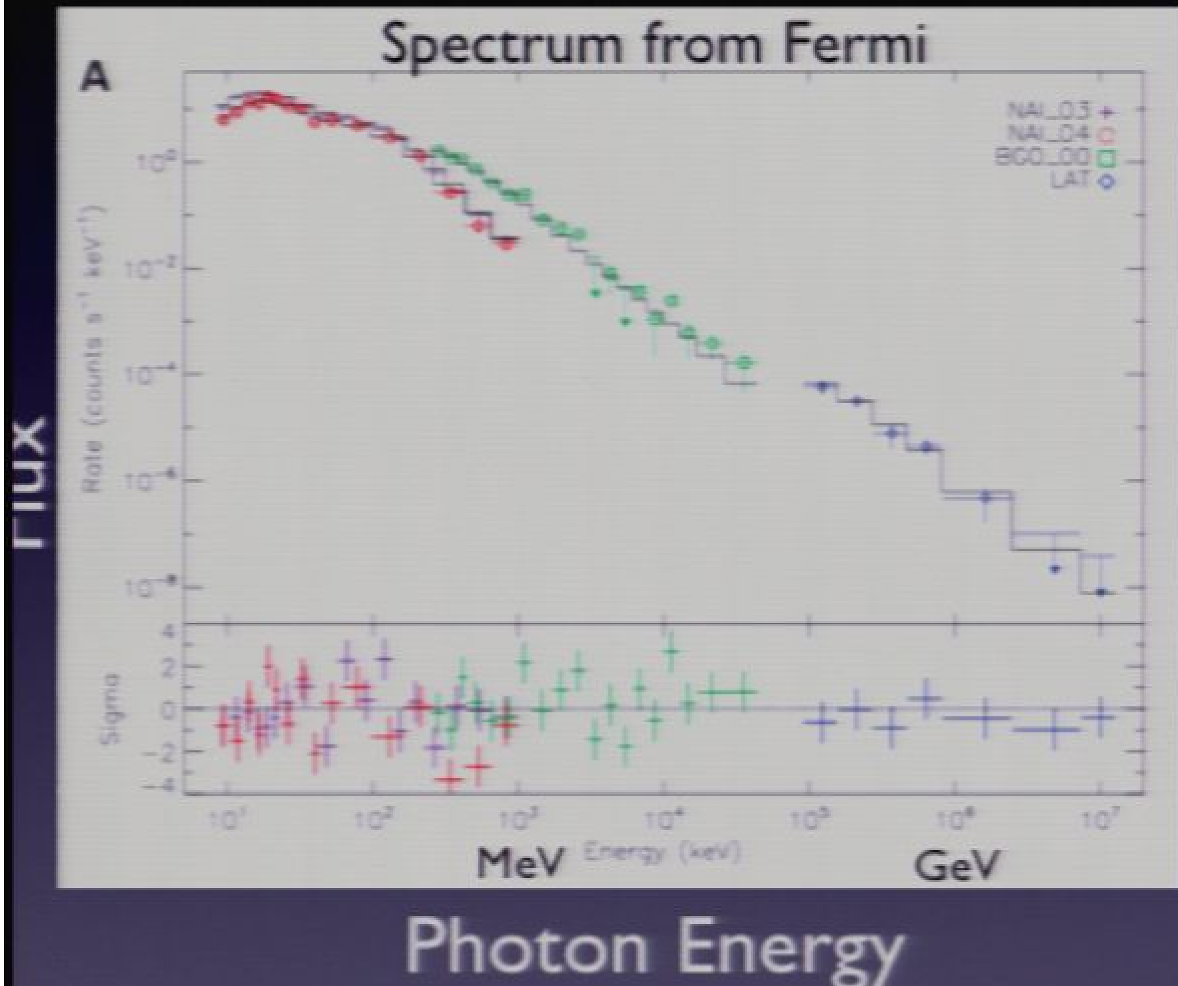
# The Most Distant (known) Object in the Universe is a GRB




Flux

Greiner 2009

# GRBs Require Ultrarelativistic Outflows: Bulk Lorentz Factors $\Gamma \gtrsim 10^2$-$10^3$




- Huge energy ≳ 511 keV
  - short timescales → opaque → thermalize

$$\gamma + \gamma \leftrightarrow e^+ + e^-$$

  - **spectrum not bbody**!

(Aside: provides very tight constraints on photon dispersion)

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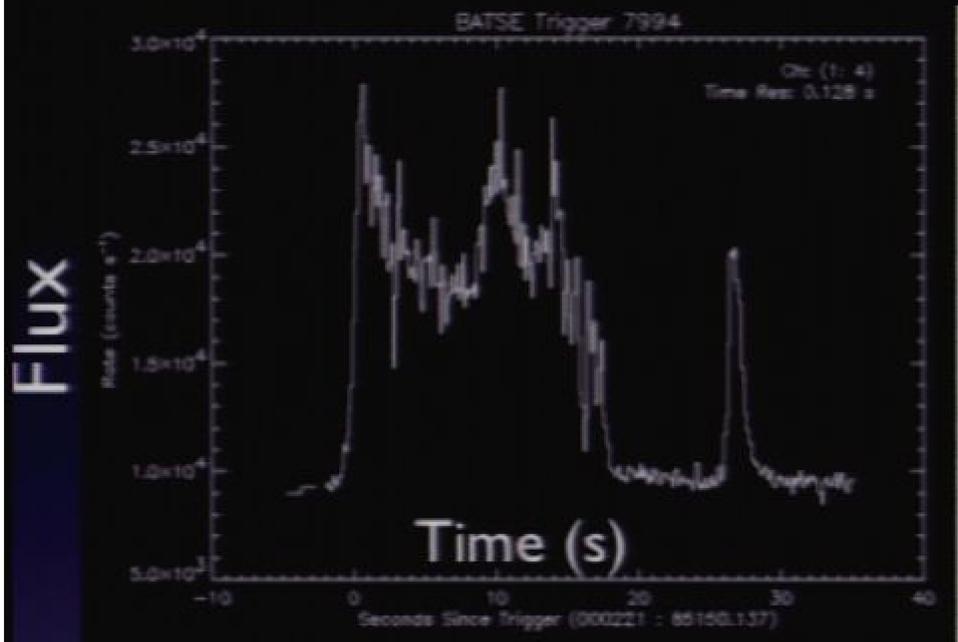


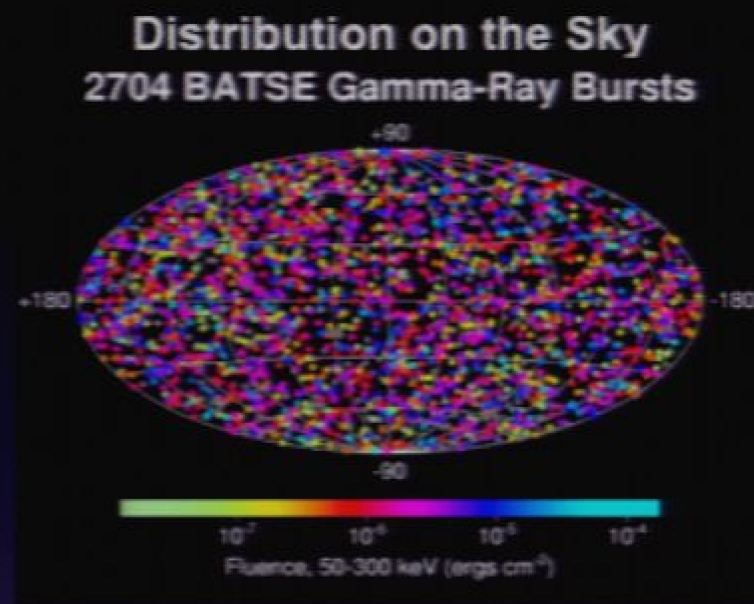


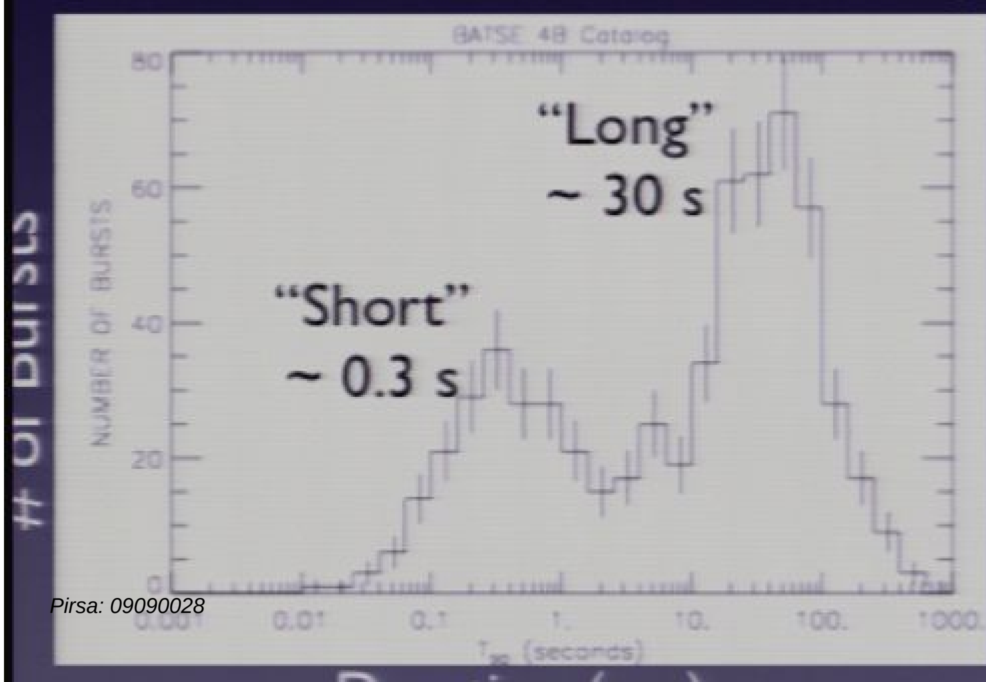


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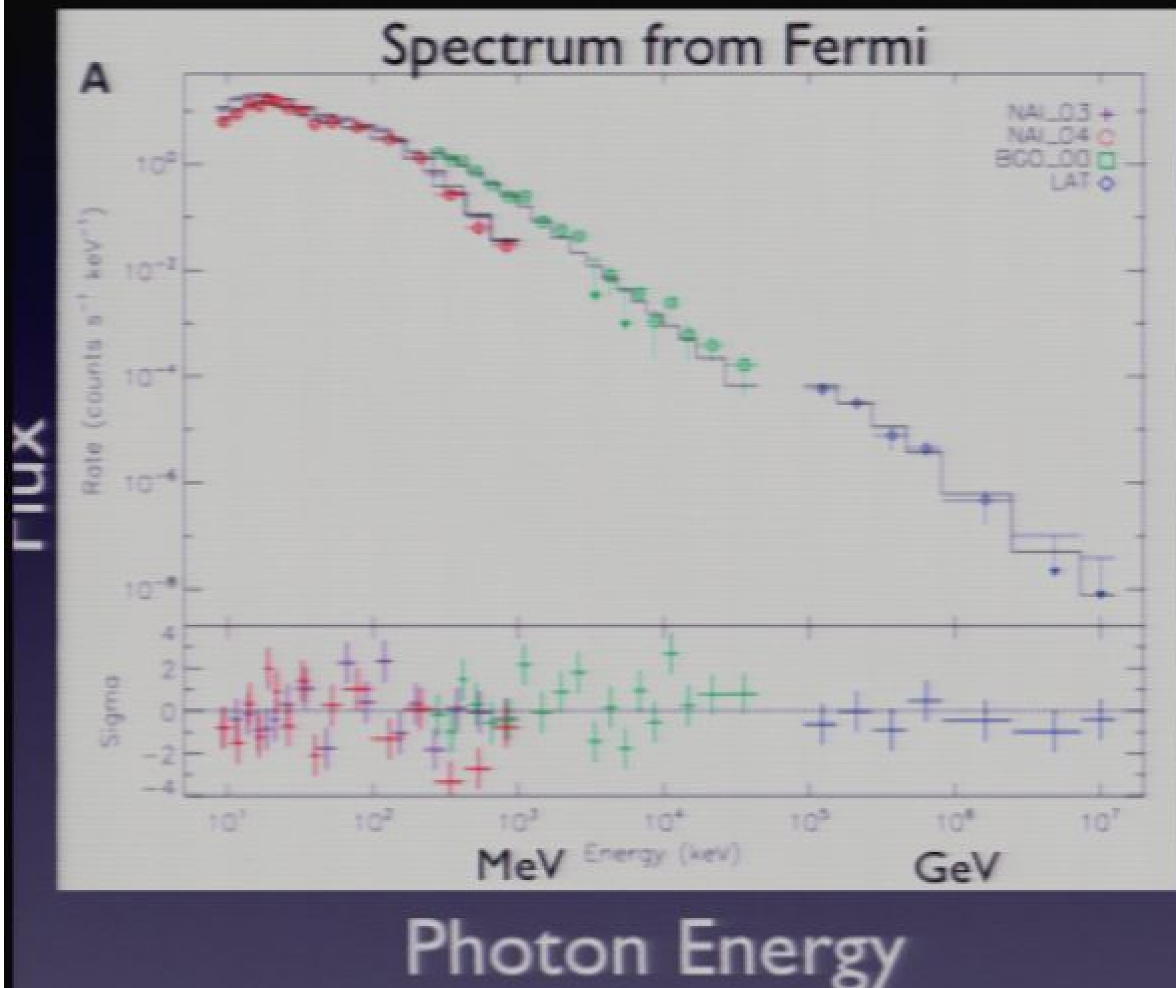


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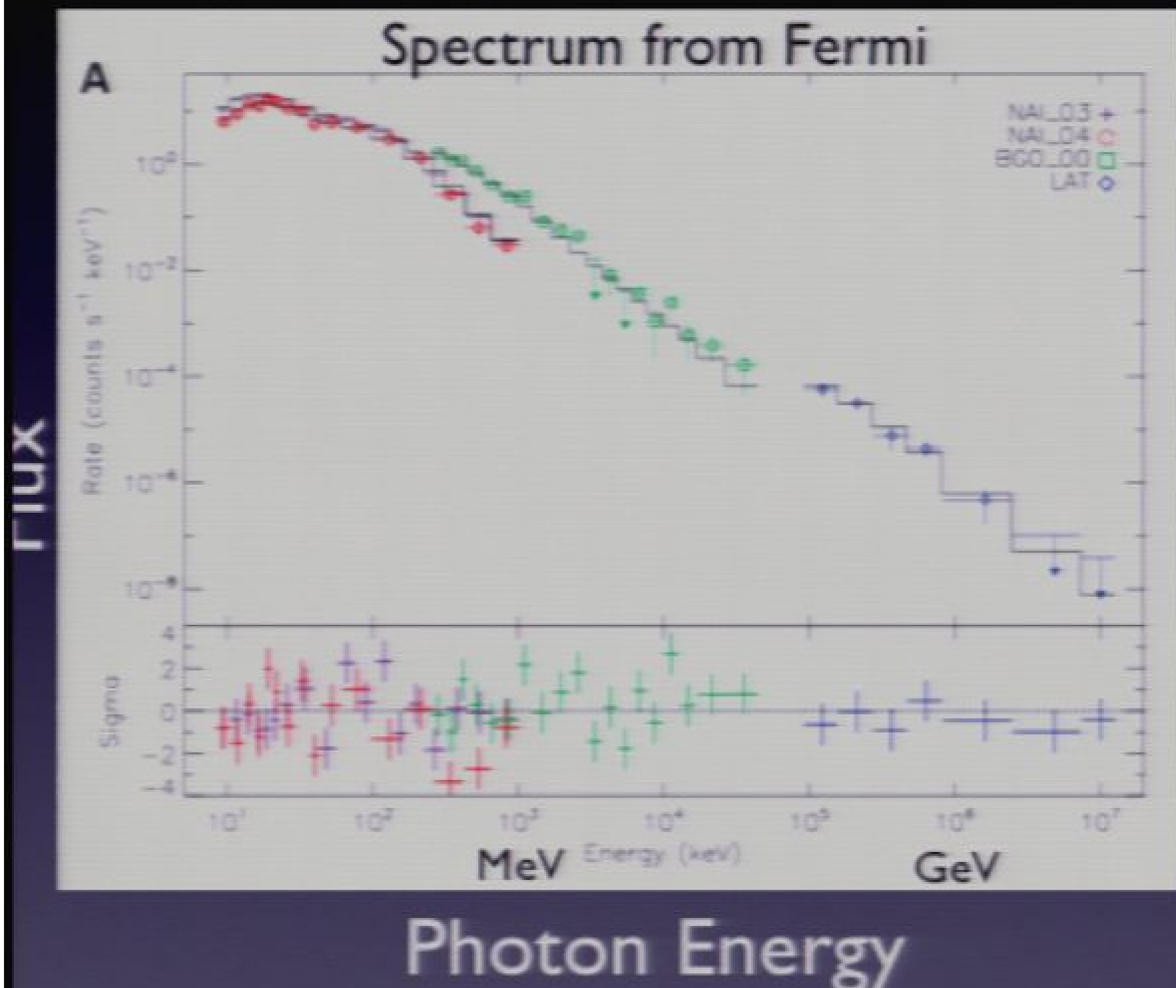


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- **Outflow w/ $\Gamma \gtrsim 10^2$-$10^3$**
  (e.g., Goodman 1986; Paczynski 1986)
  - no pair production problem
    - rest frame photon energies <<; size >>



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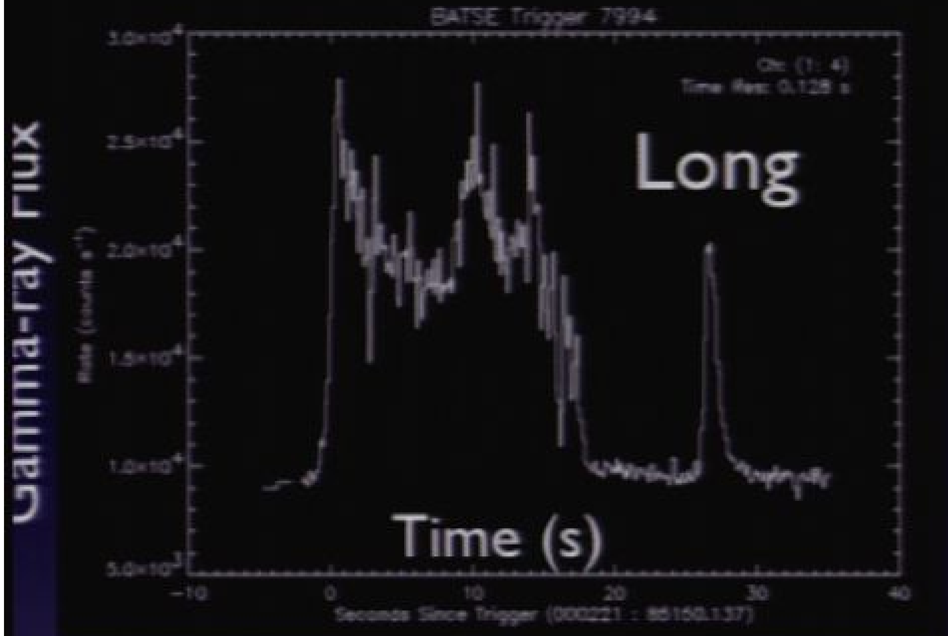
# The Physical Origin of Gamma-Ray Bursts





Requirements:

***Release E ~ 0.01$M_{sun}c^2$ on***
***t ~ 0.1-100 sec in***
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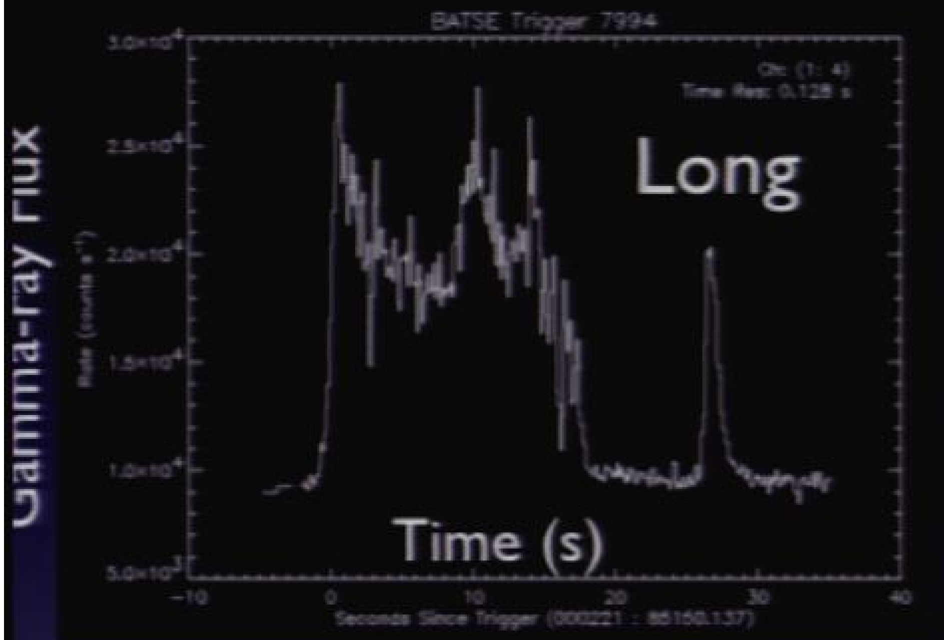



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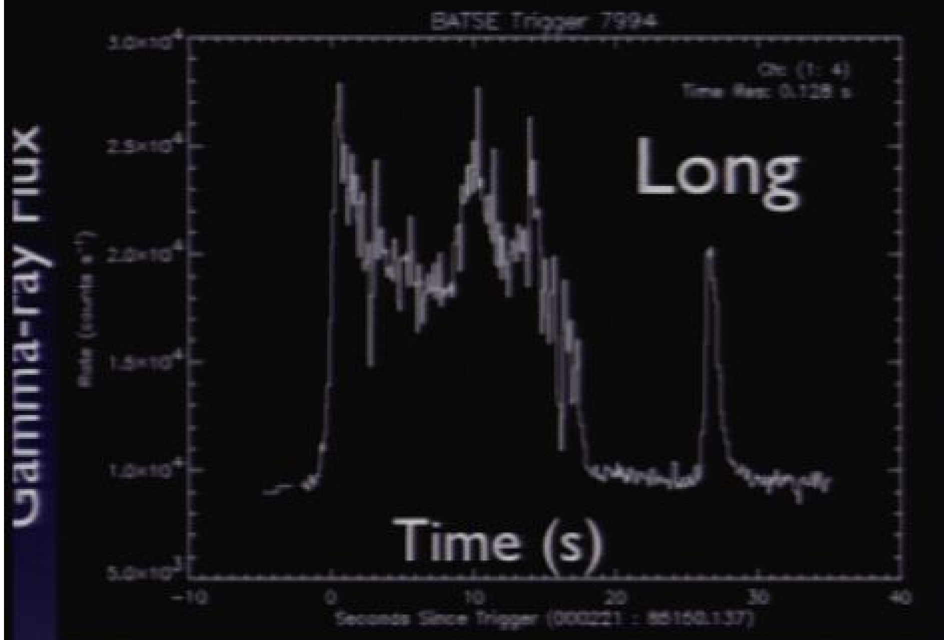



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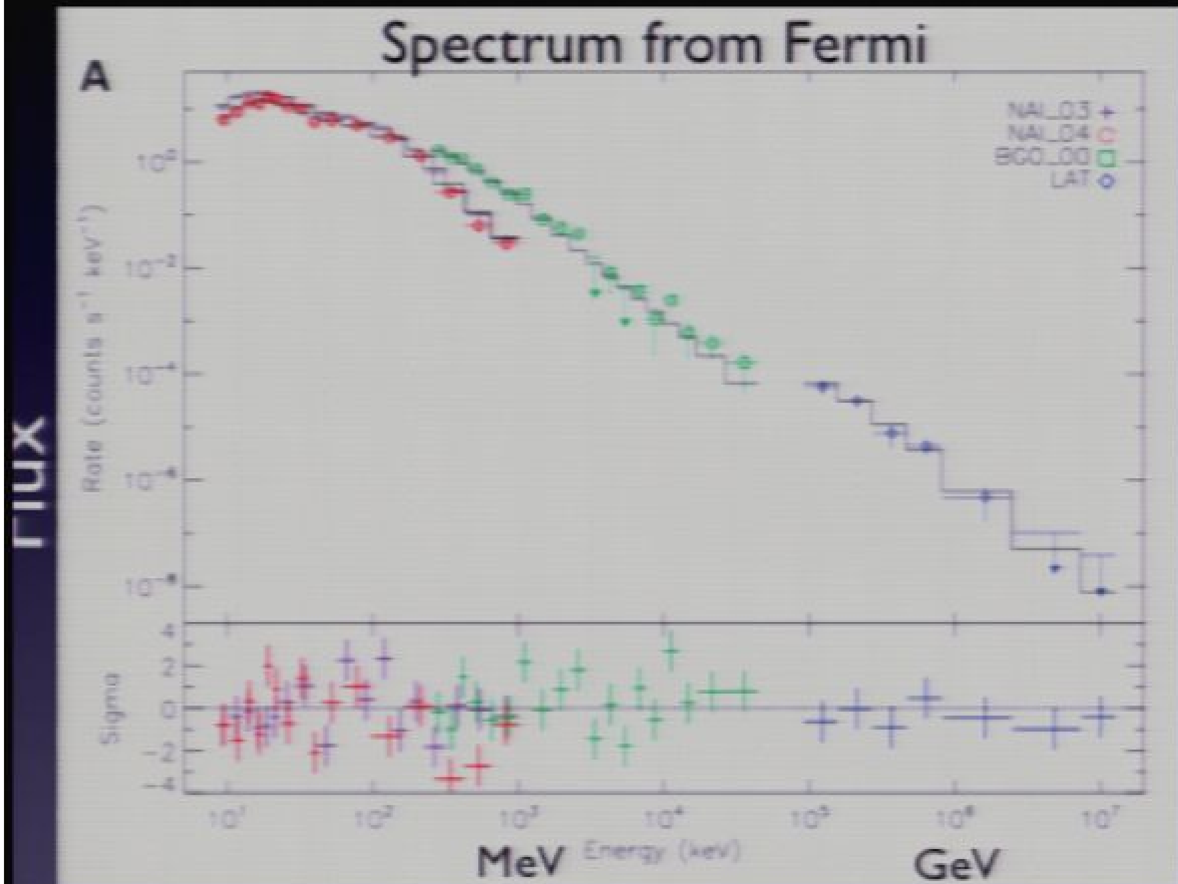


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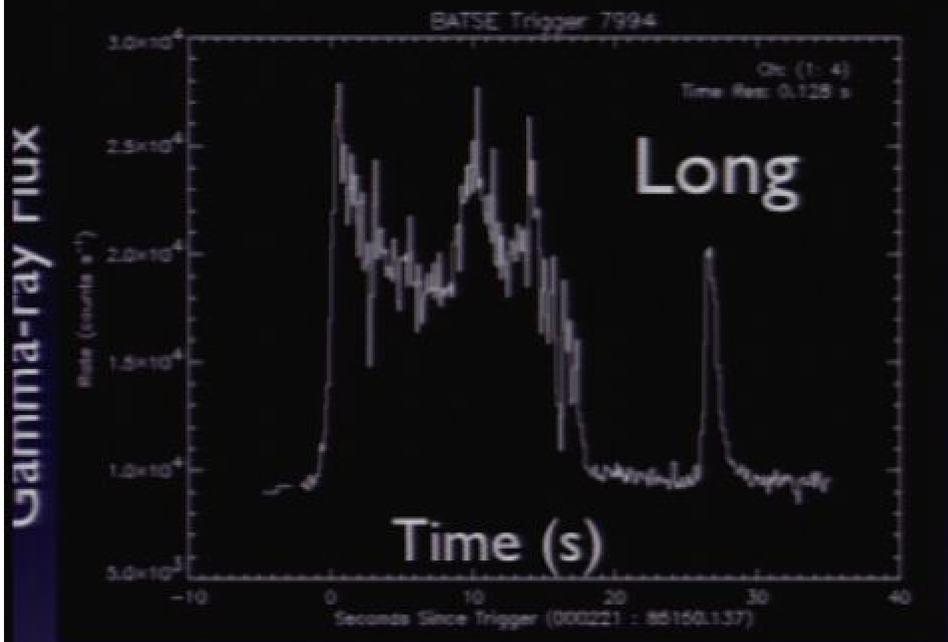



Requirements:

***Release $E \sim 0.01 M_{sun}c^2$ on***
***$t \sim 0.1$-$100$ sec in***
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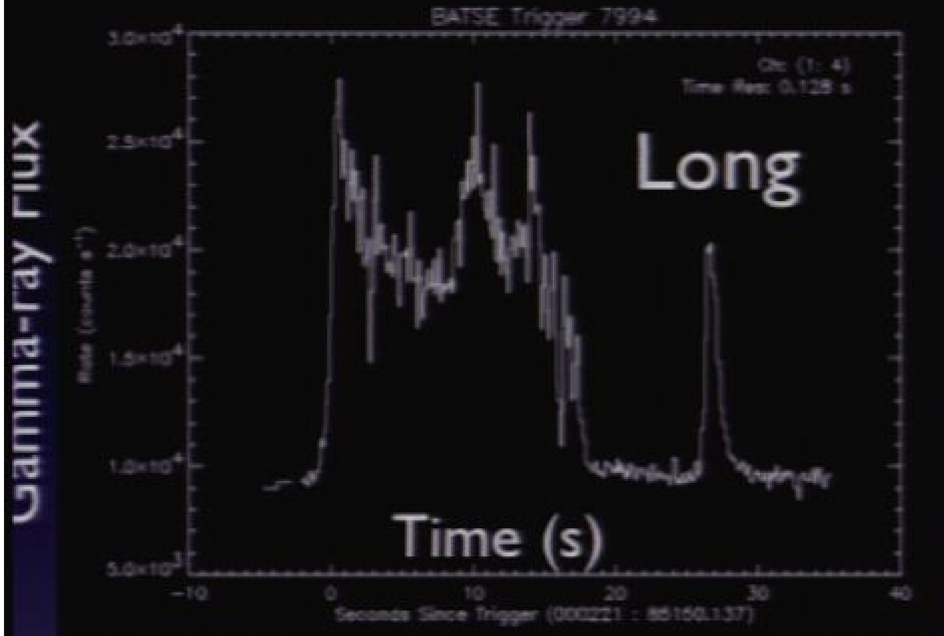



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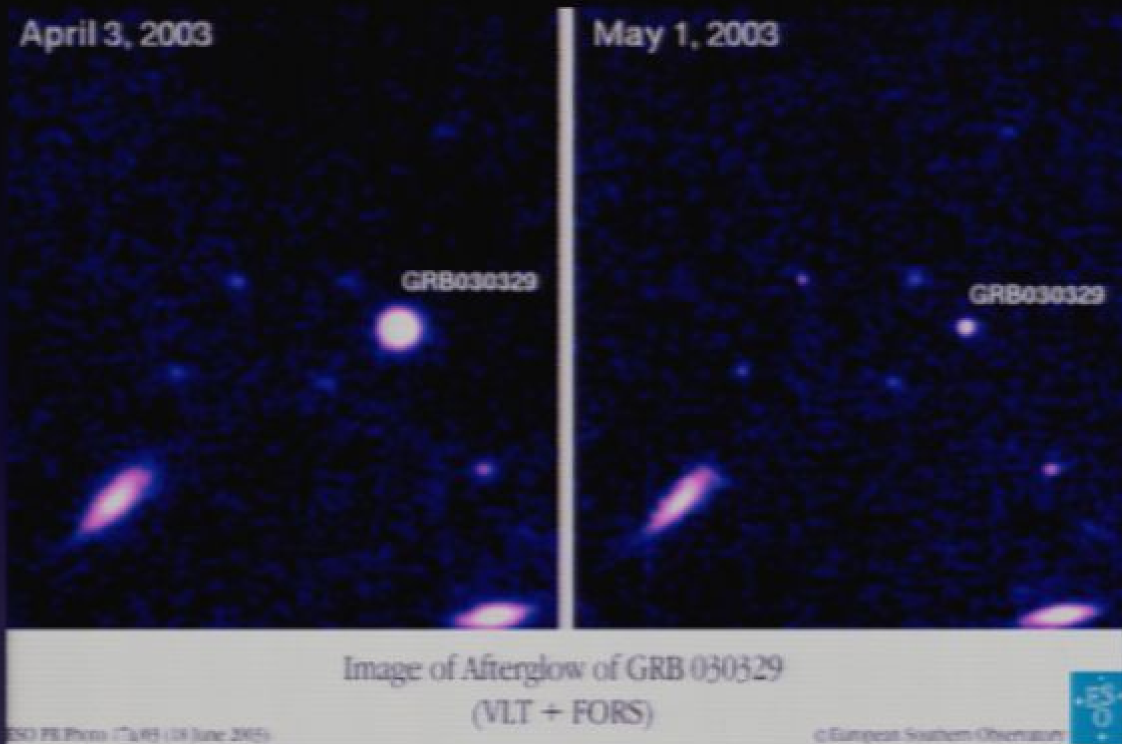
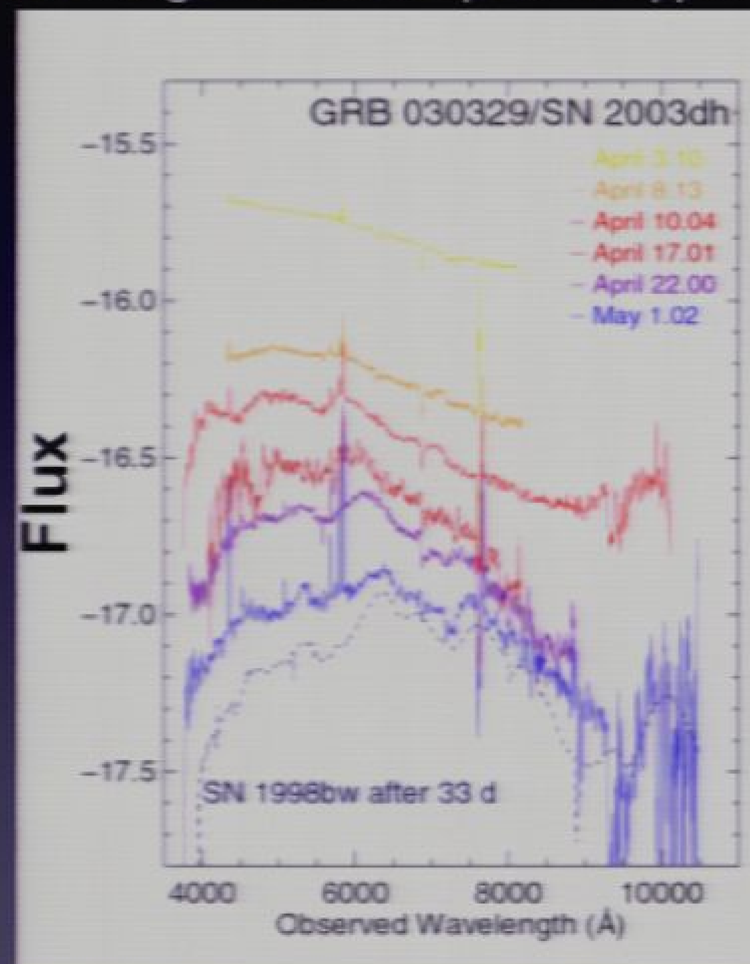
# Long-Duration GRBs




As afterglow fades, a supernova appears

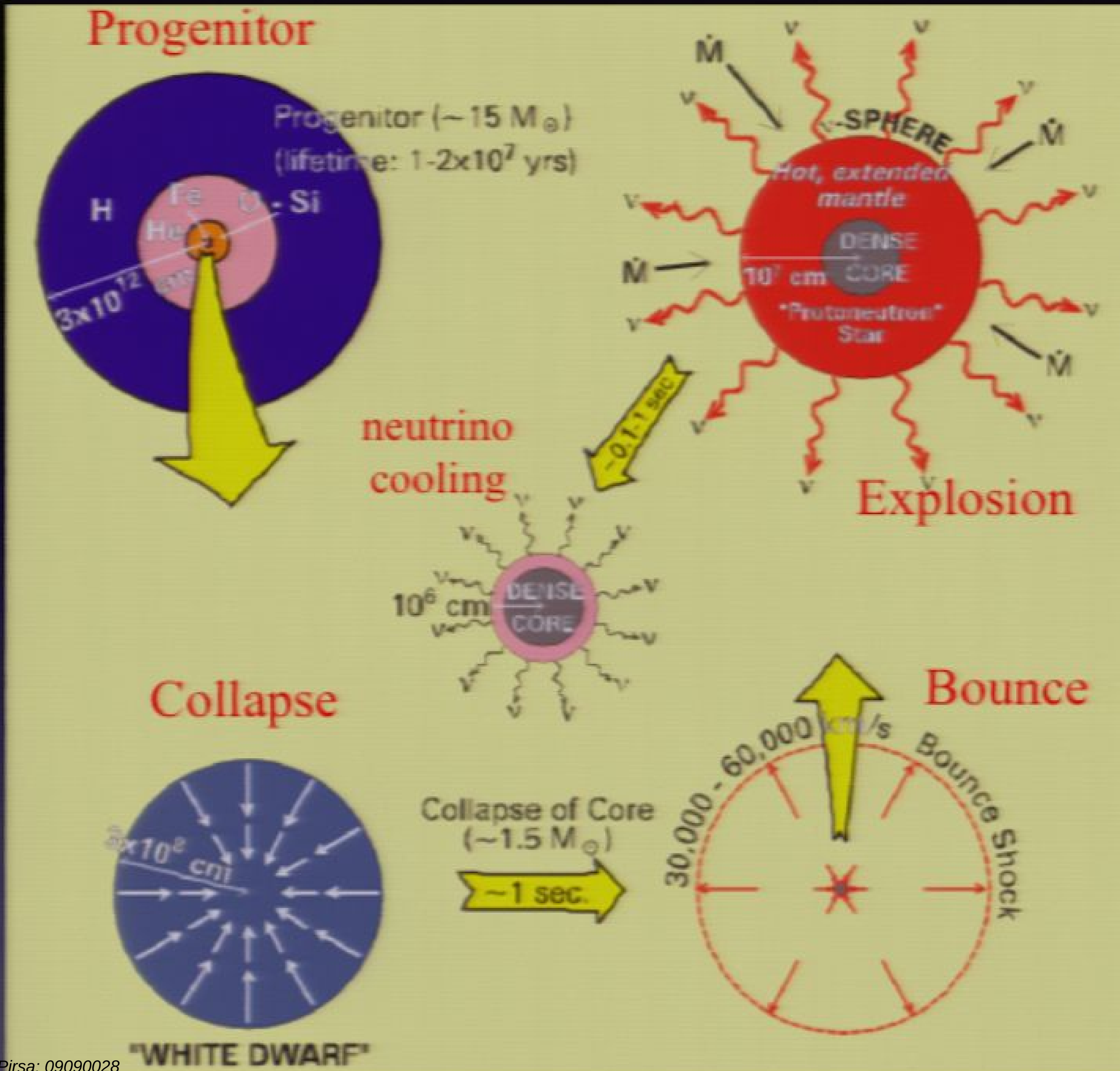



Hjorth et al; Stanek et al.

Associated with massive star formation and supernovae (stellar explosions)

→ **Birth of a Neutron Star or Black Hole**

**(not the converse; GRB rate ~ $10^{-3}$ SNe rate)**




**Progenitor Star Collapses**

⇓

**Bounce at nuclear densities stops infall**

⇓

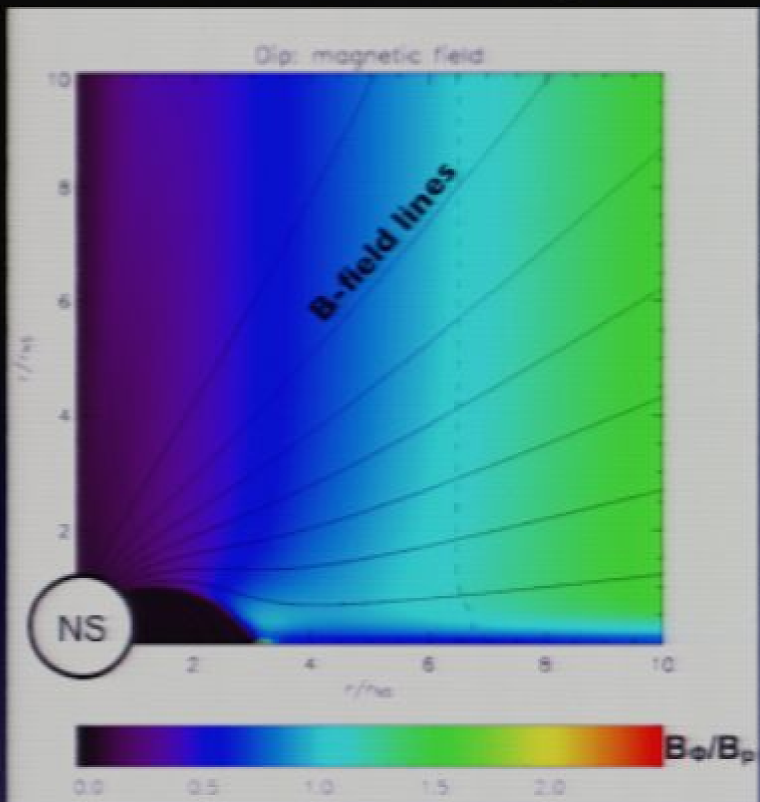
**Explosion (?) (~ 1 sec)**

⇓

**NS &/or BH formed w/ ejecta moving at ~ $10^4$ km/s**

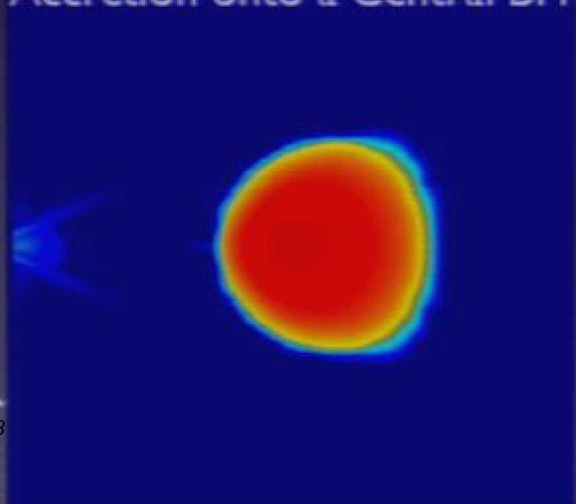
Burrows

## General Relativistic NS Spindown




Bucciantini, Quataert, et al.

## Accretion onto a Central BH



## Spindown of a Rotating NS

$$E_{rotation} \simeq 10^{-2} \left(\frac{P}{1\,\mathrm{ms}}\right)^{-2} M_{sun}\, c^2$$

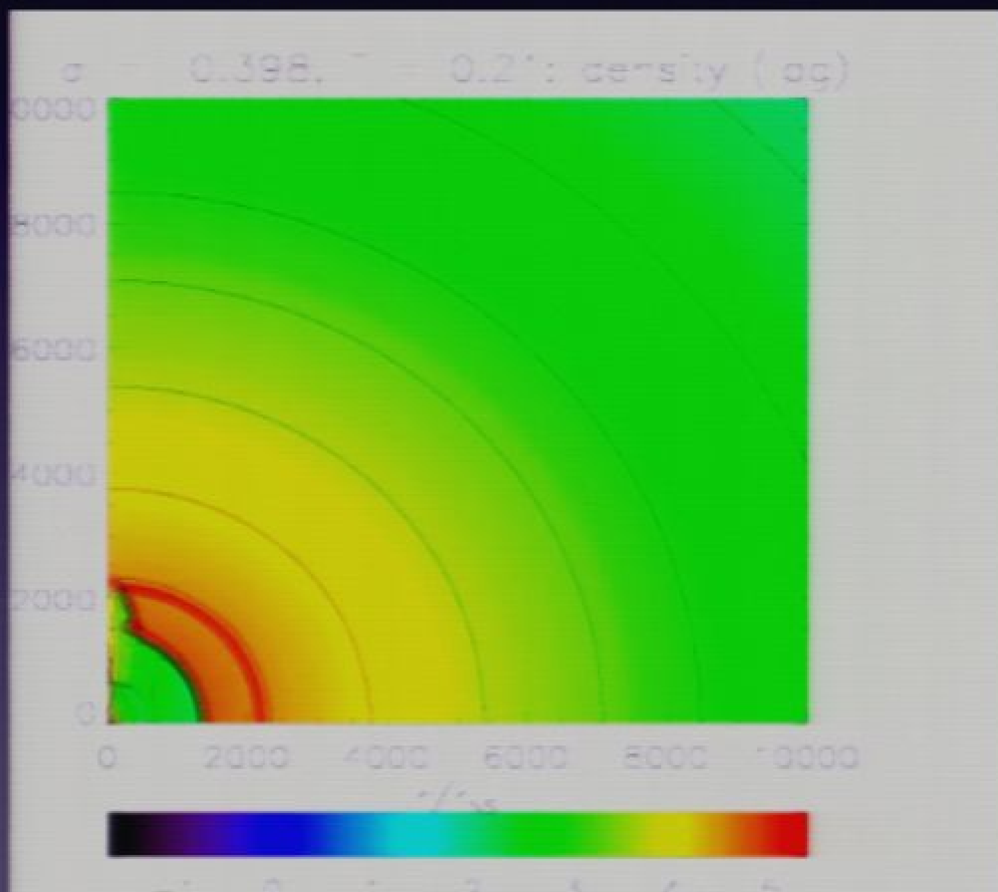
$$\text{Spindown in} \sim 10^3 \left(\frac{P}{1\,\mathrm{ms}}\right)^{-2} \left(\frac{B}{10^{15}\,\mathrm{G}}\right)^{-2} \mathrm{sec}$$

## Accretion via a Disk

$$E_{\mathrm{accretion}} \sim 0.1\, M_{\mathrm{accreted}}\, c^2$$

(w/ some fraction of $E_{\mathrm{accretion}}$ in outflows)

Simulation of
the impact of
a magnetized
outflow from
a NS (or BH)
on its host star
color is density;
duration ~ 3 s)

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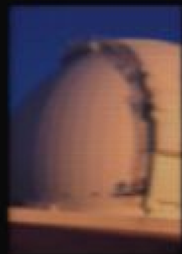

# Observe GRB & then Supernova

Emission beamed
in direction of motion
bec. $\Gamma >> 1$

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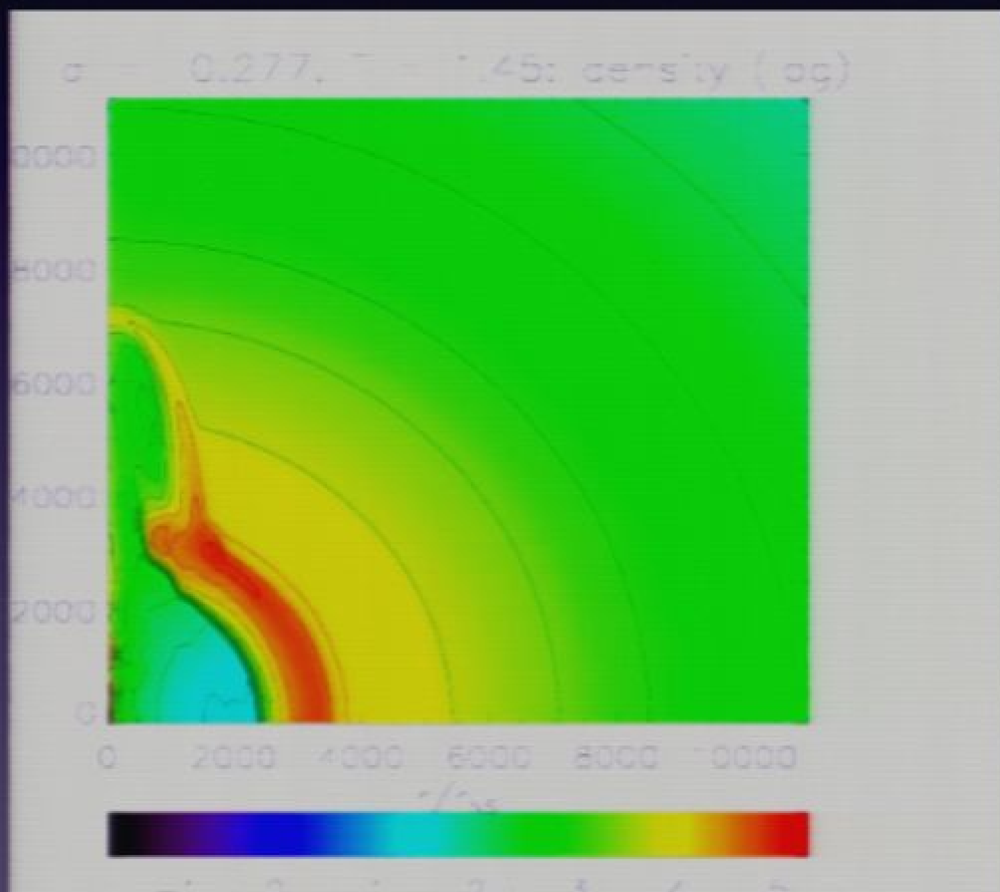


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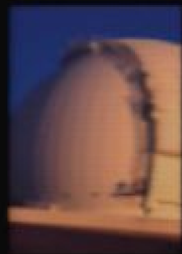

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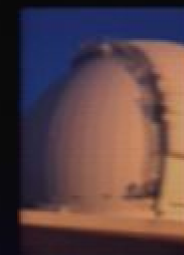

# Observe Supernova (not GRB)

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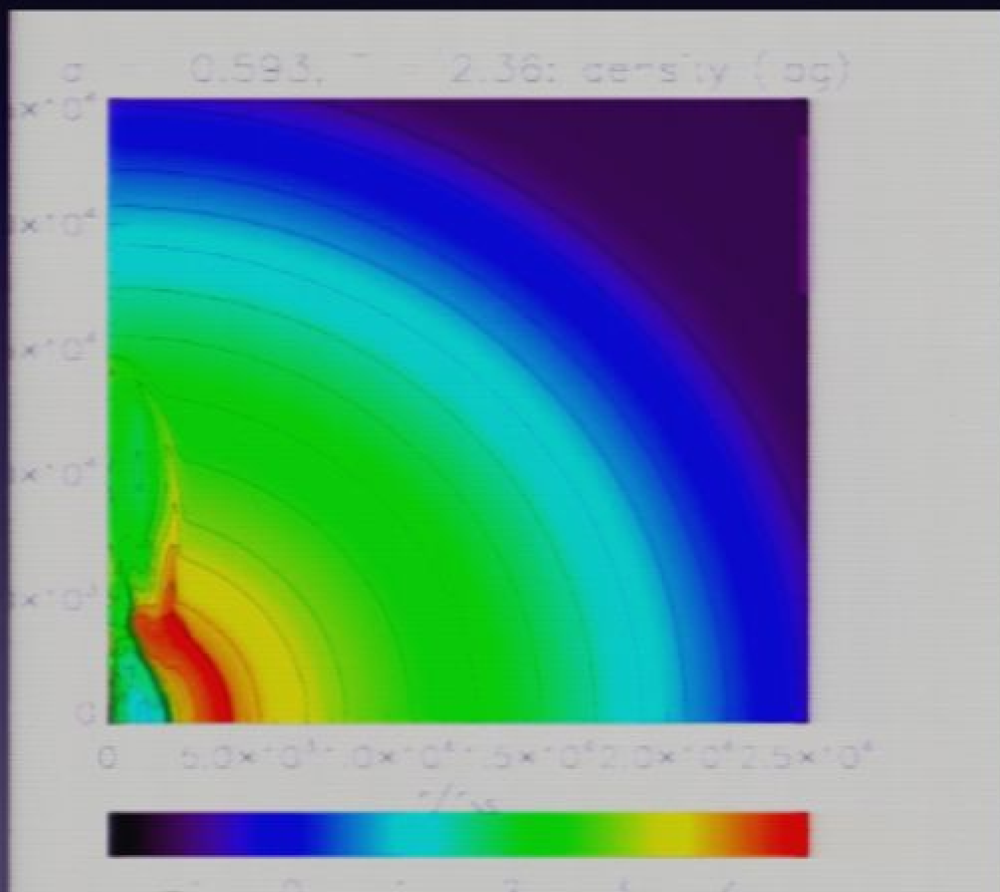


Bucciantini, Quataert, et al.

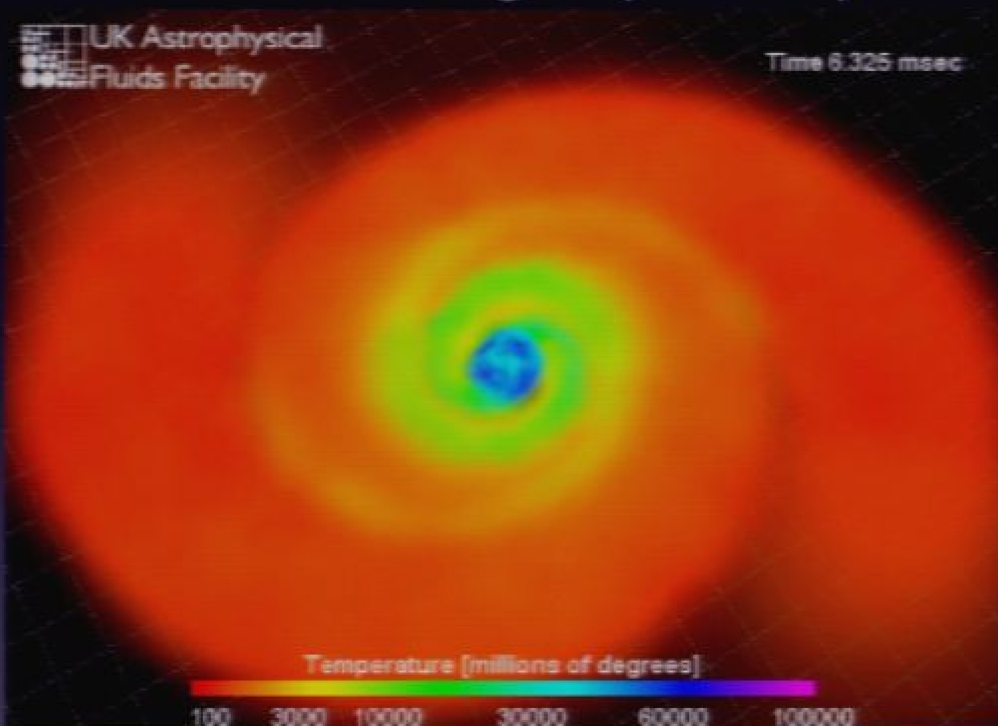
Collimation in a jet critical to getting energy out unpolluted by the surrounding star (maintaining $\Gamma >> 1$):

**reduces energy reqd & increases rate**

# Compact Object Mergers

(Paczynski 1986; Goodman 1986; Eichler et al. 1989; Narayan et al. 1992 ....)

## NS-NS Merger (~ 8 ms)




Rosswog

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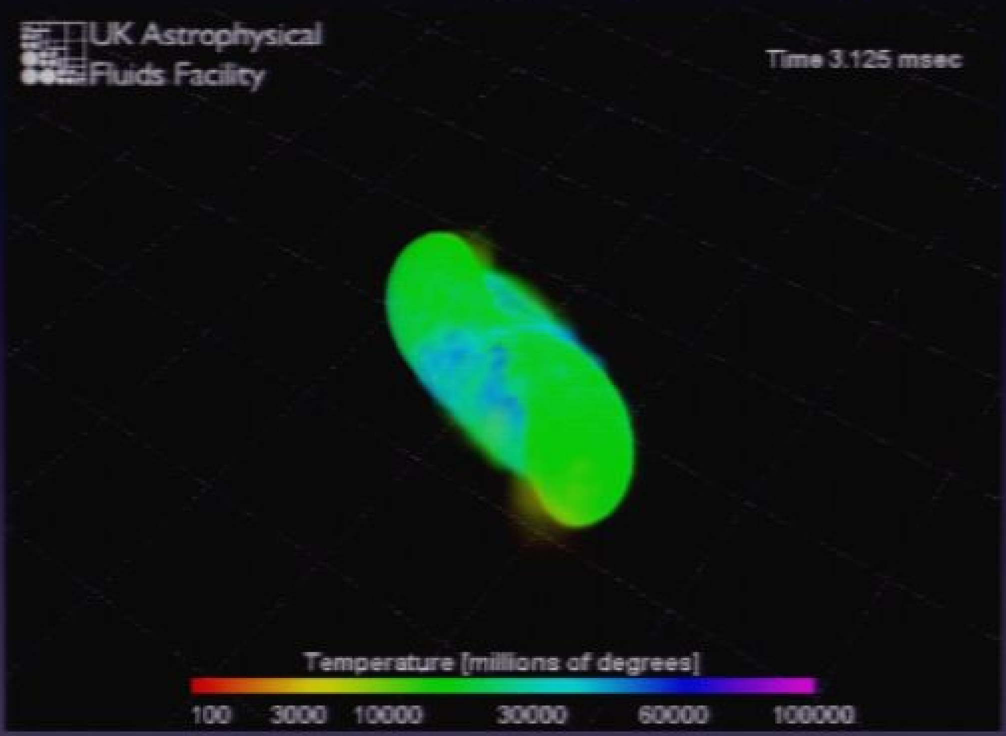


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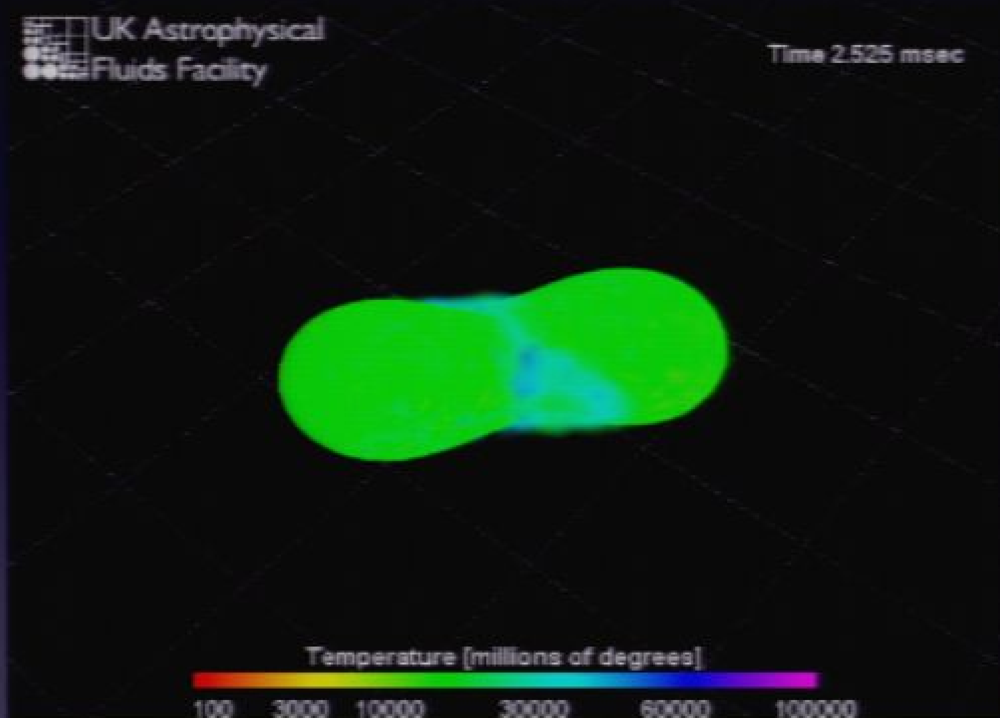
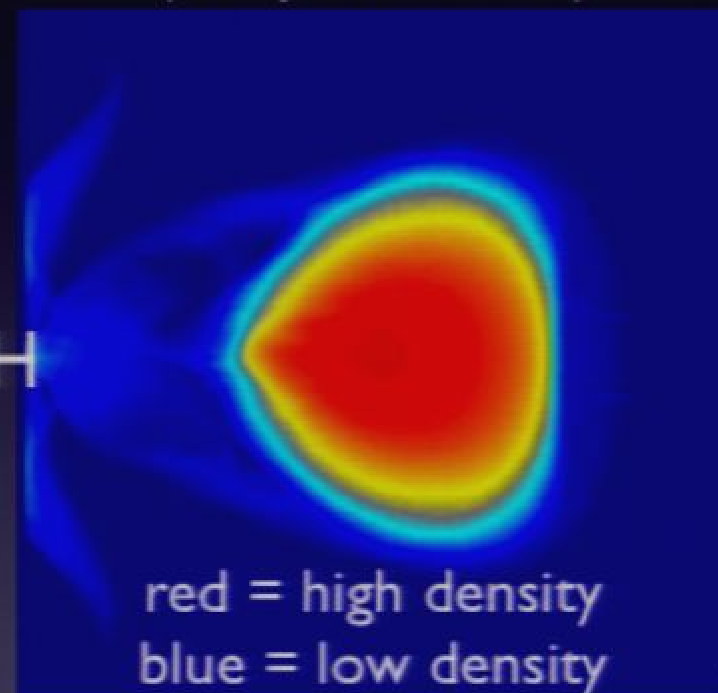



Rosswog




Hawley

accretion of remnant disk consistent w/ short GRB properties (e.g., $t_{accretion}$ ~ 0.1-1 sec)

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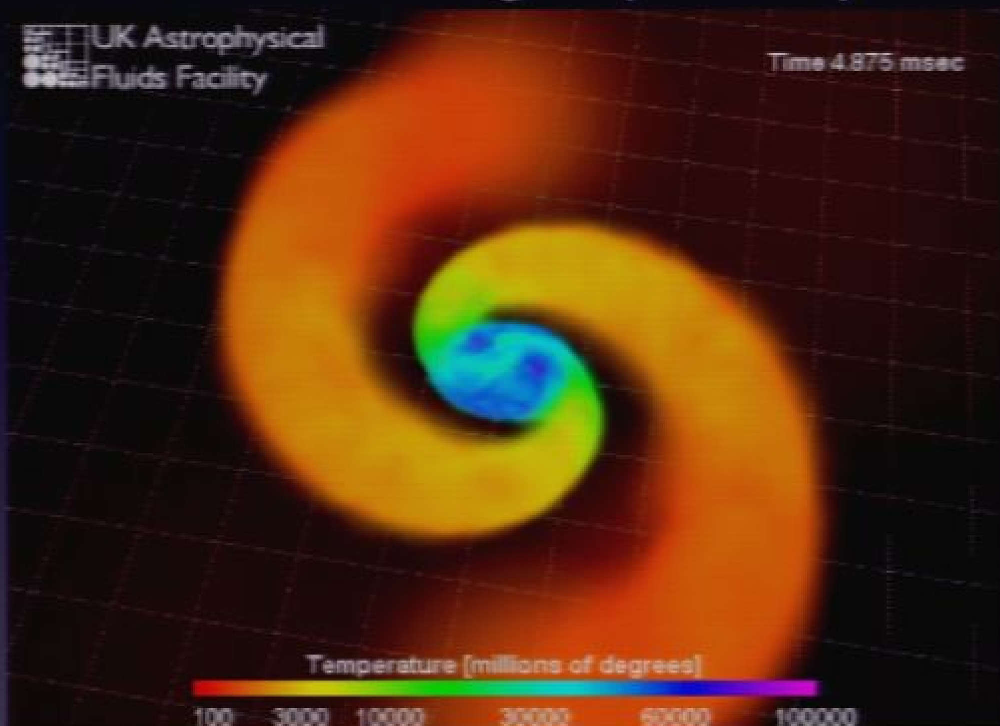
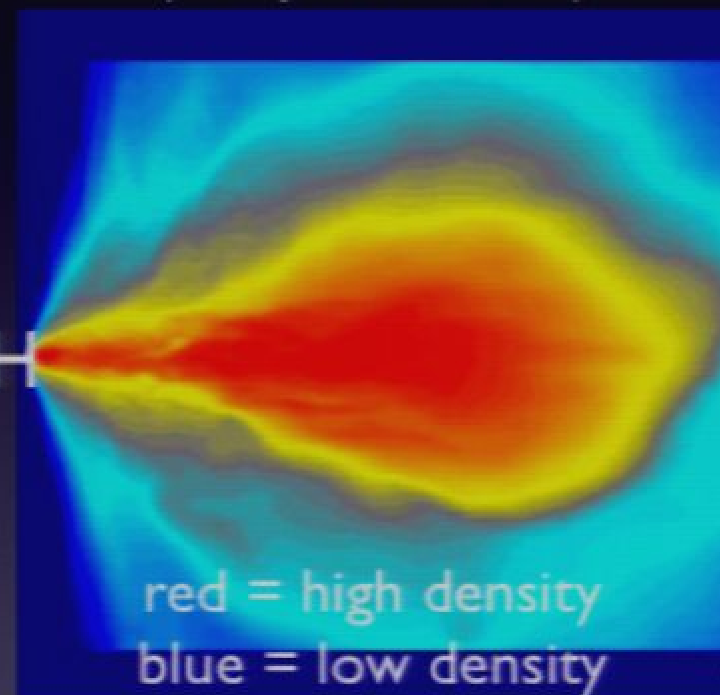



Rosswog

BH

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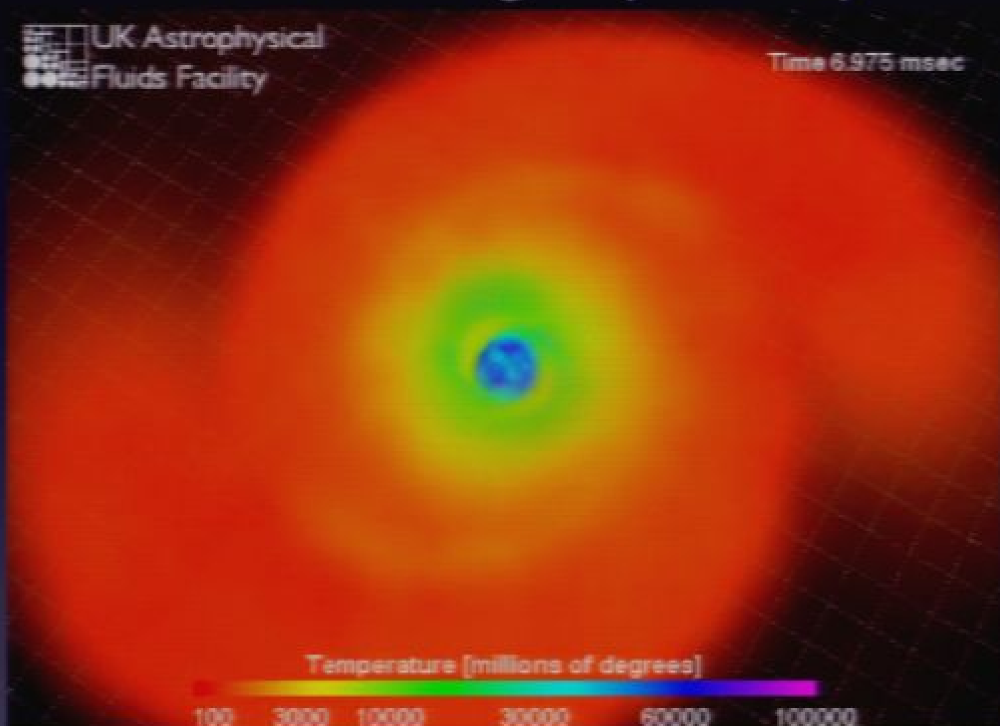


Rosswog

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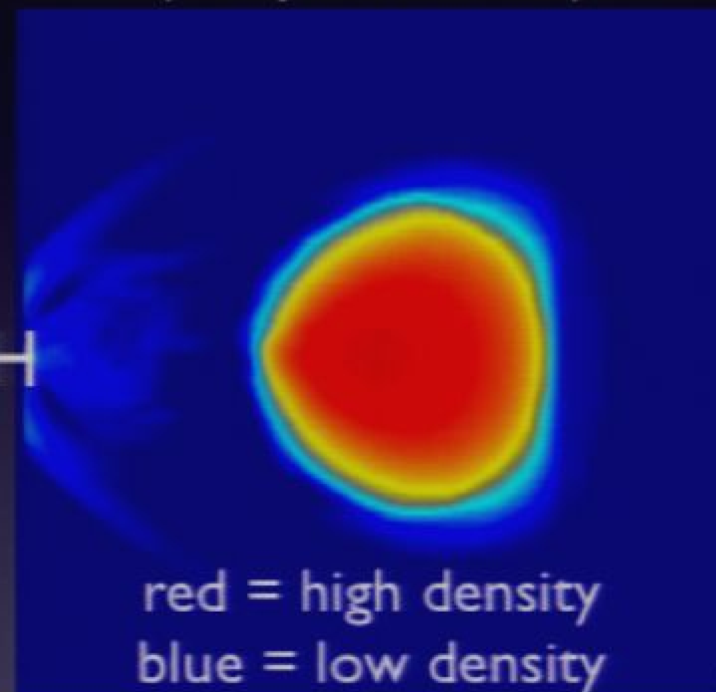


Hawley

accretion of remnant disk consistent w/ short GRB properties (e.g., $t_{accretion}$ ~ 0.1-1 sec)

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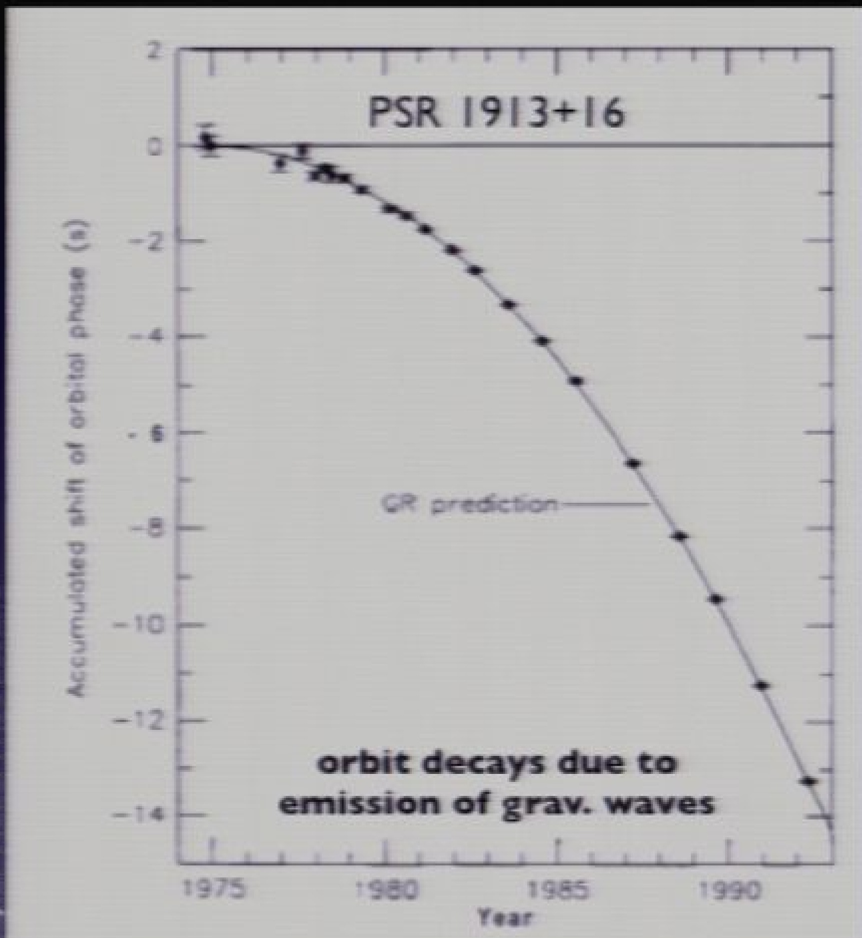


Taylor Nobel Prize Lecture

3 known NS-NS binaries in our galaxy will merge in a Hubble time (no BH-NS systems known)

$$\dot{N}_{merge} \sim 10^{-4} - 10^{-5}\,\mathrm{yr}^{-1}$$

(Kalogera et al. 2004)

~ short GRB rate

**Primary Target for km-scale gravitational wave observatories (e.g., Advanced LIGO)**

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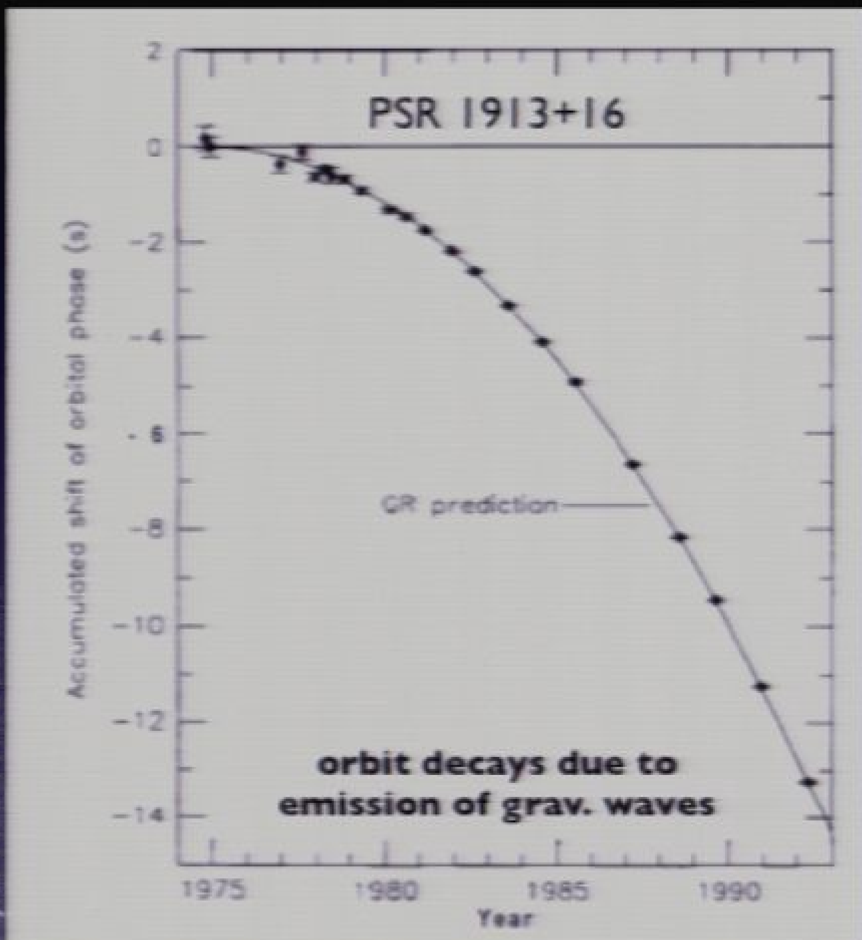


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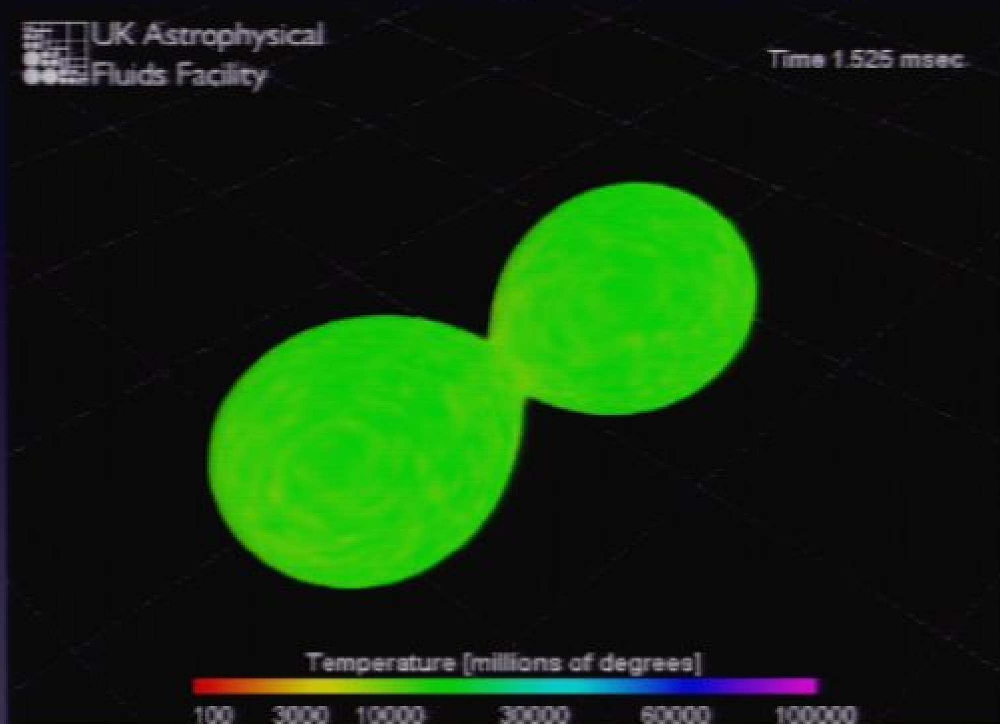


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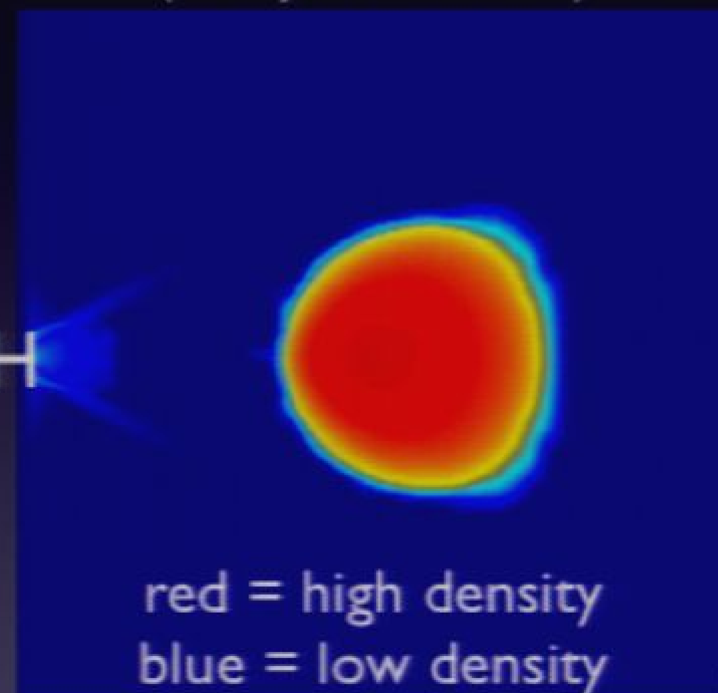


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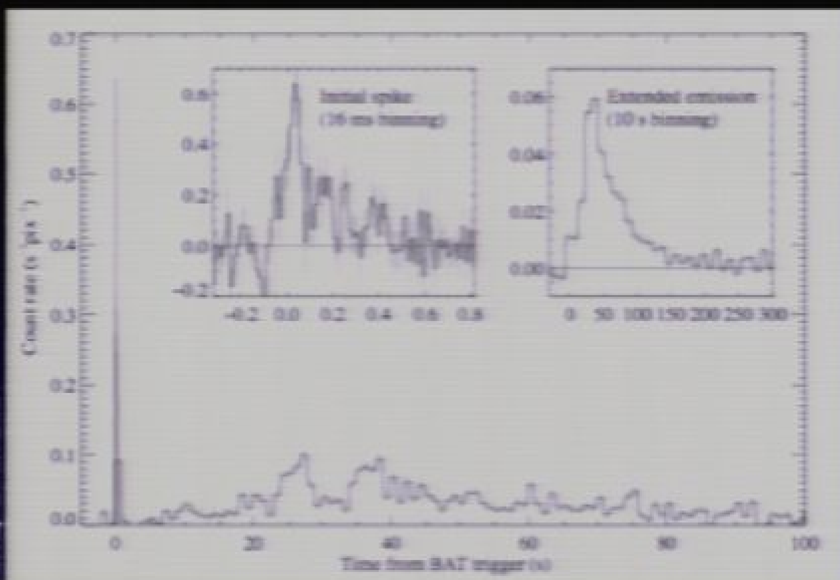
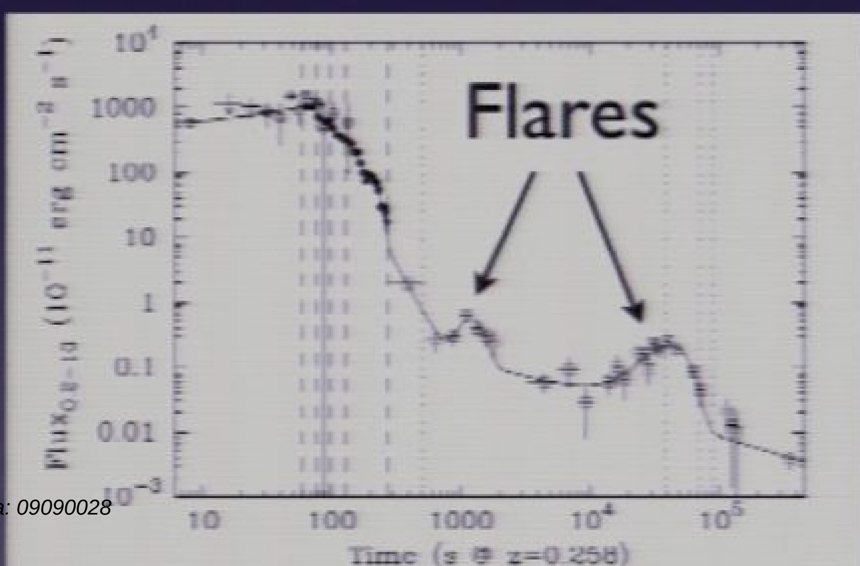
# New Puzzles in short GRBs

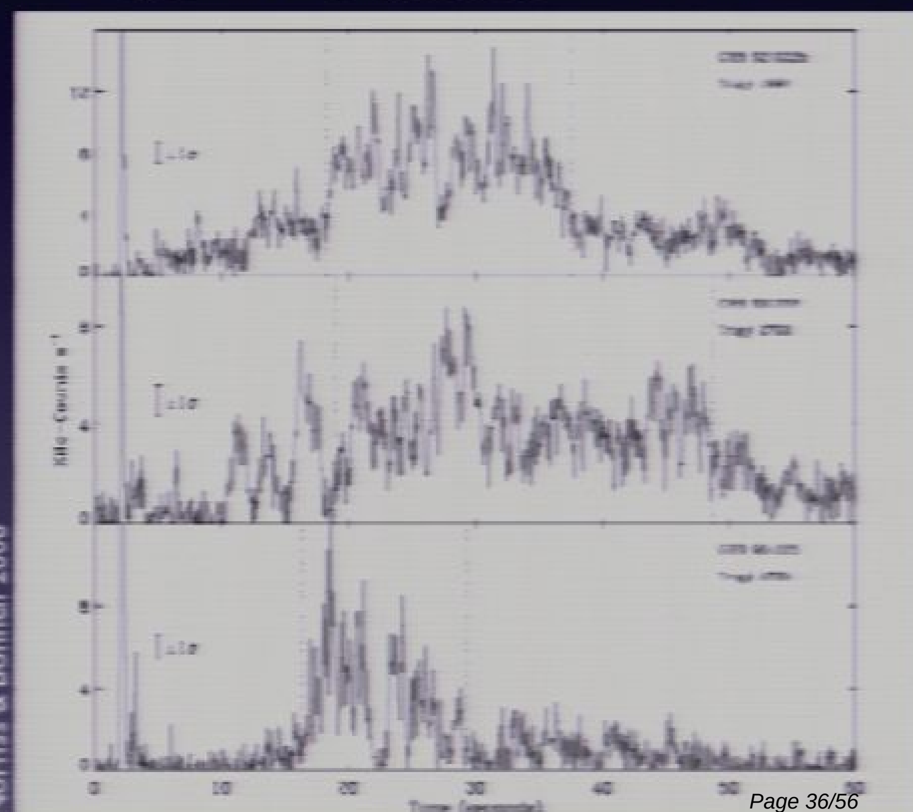
## Swift Satellite




Perley et al. 2009




~ 25% of short Bursts show
Extended Emission ~ 30-100 sec
Flares on yet longer Timescales
Energy up to ~ 10 x Initial Burst
?? $t_{dyn}$ ~ ms; $t_{accretion}$ ~ 0.1-1 sec ??



Norriss & Bonnell 2006

BATSE Examples

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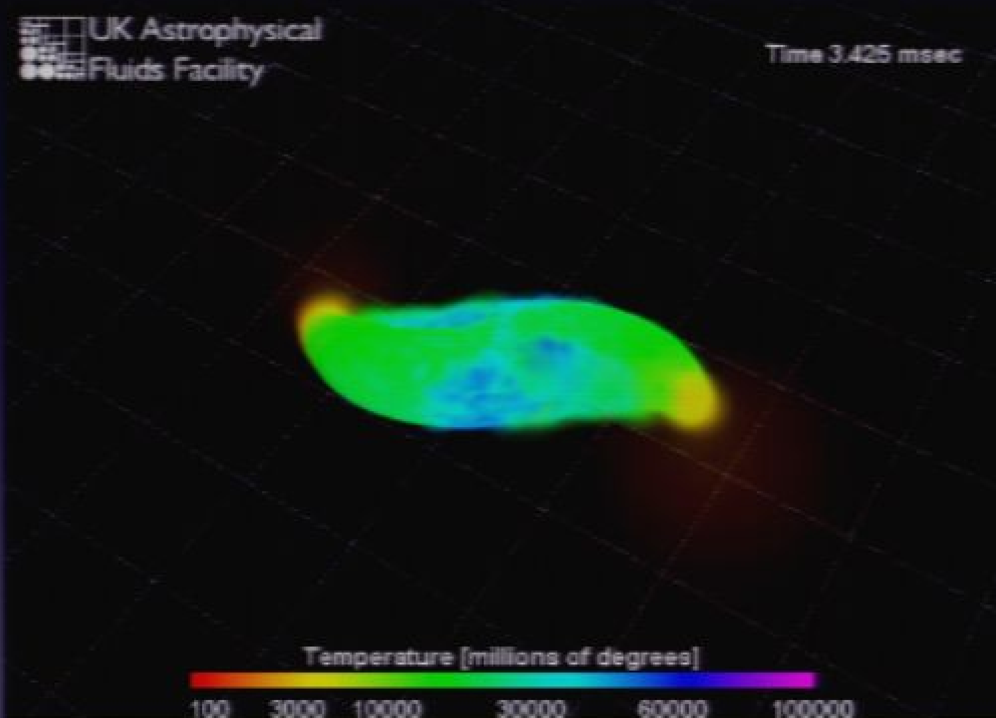


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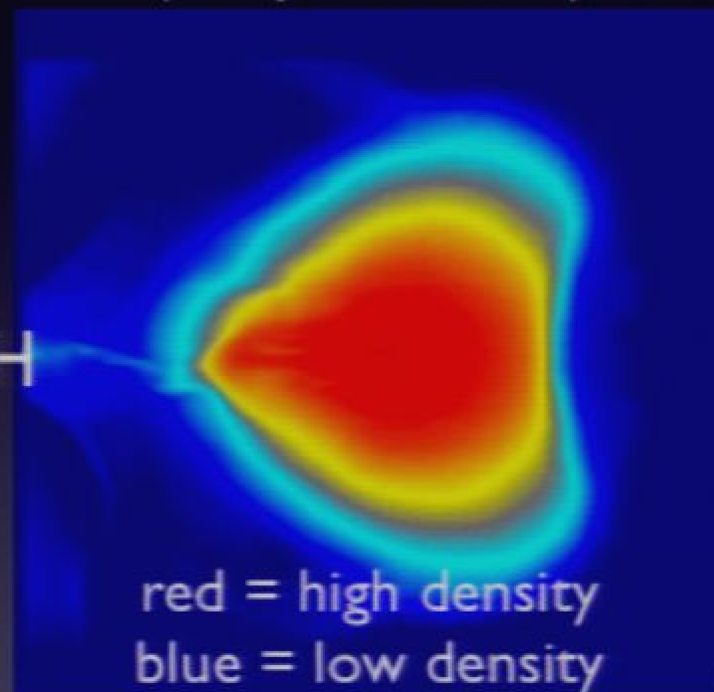


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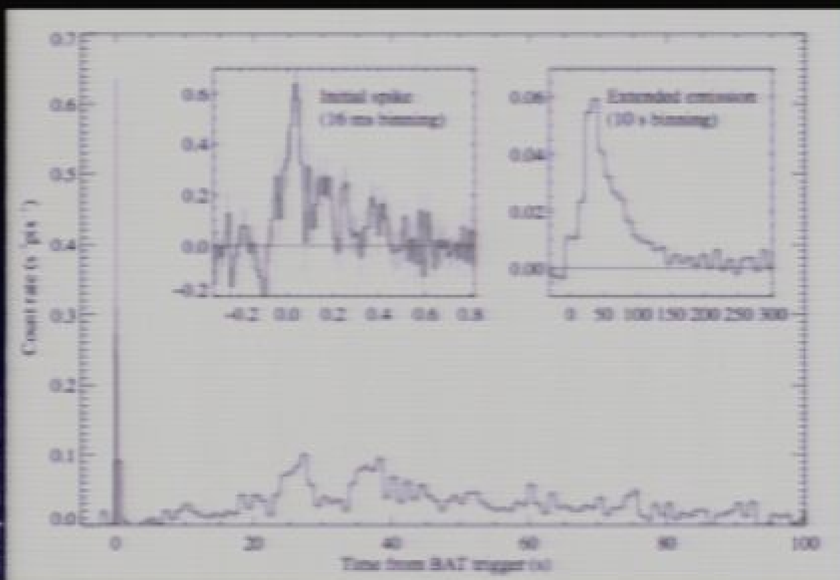


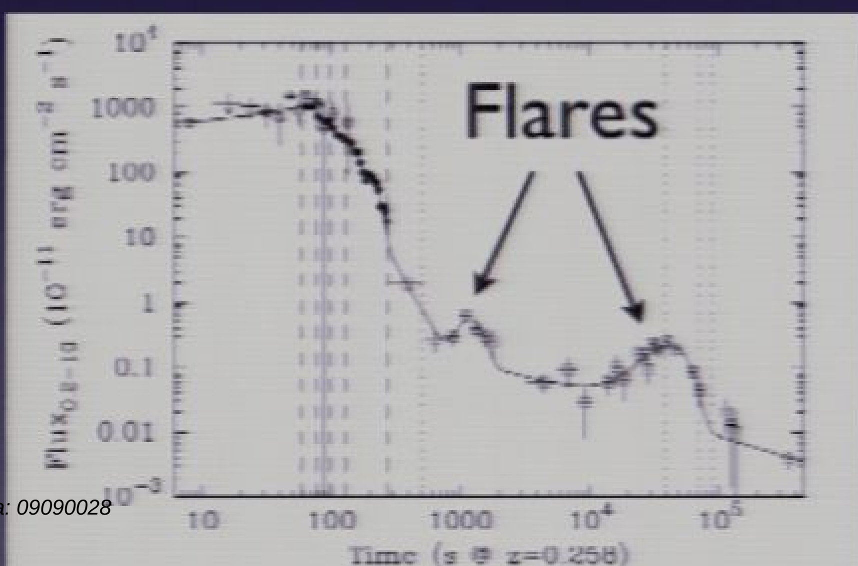


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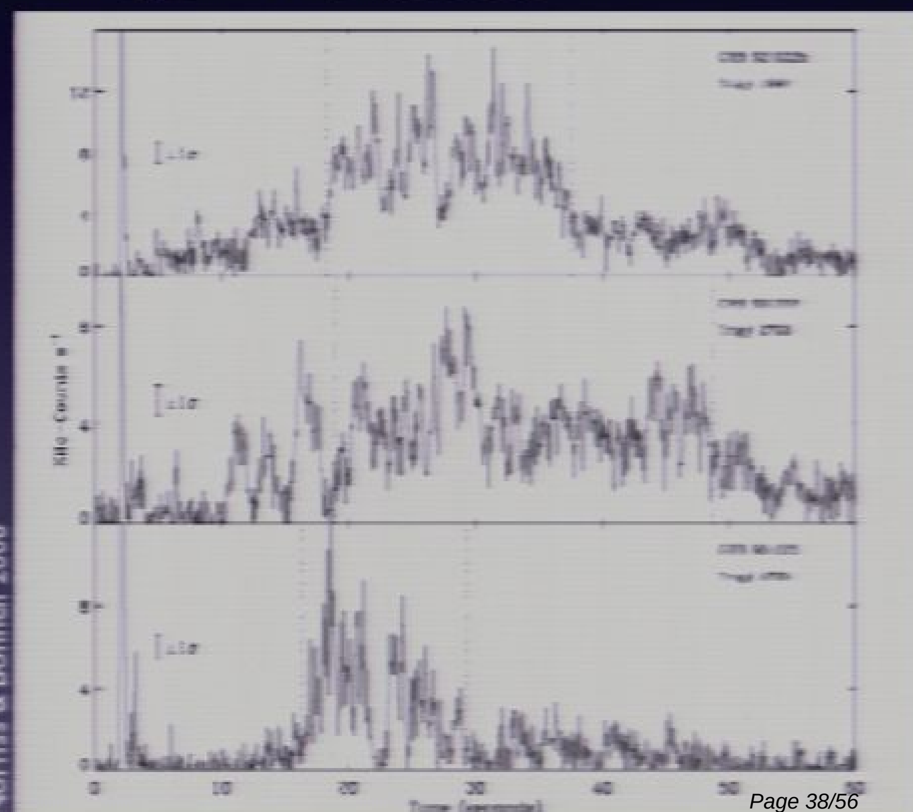
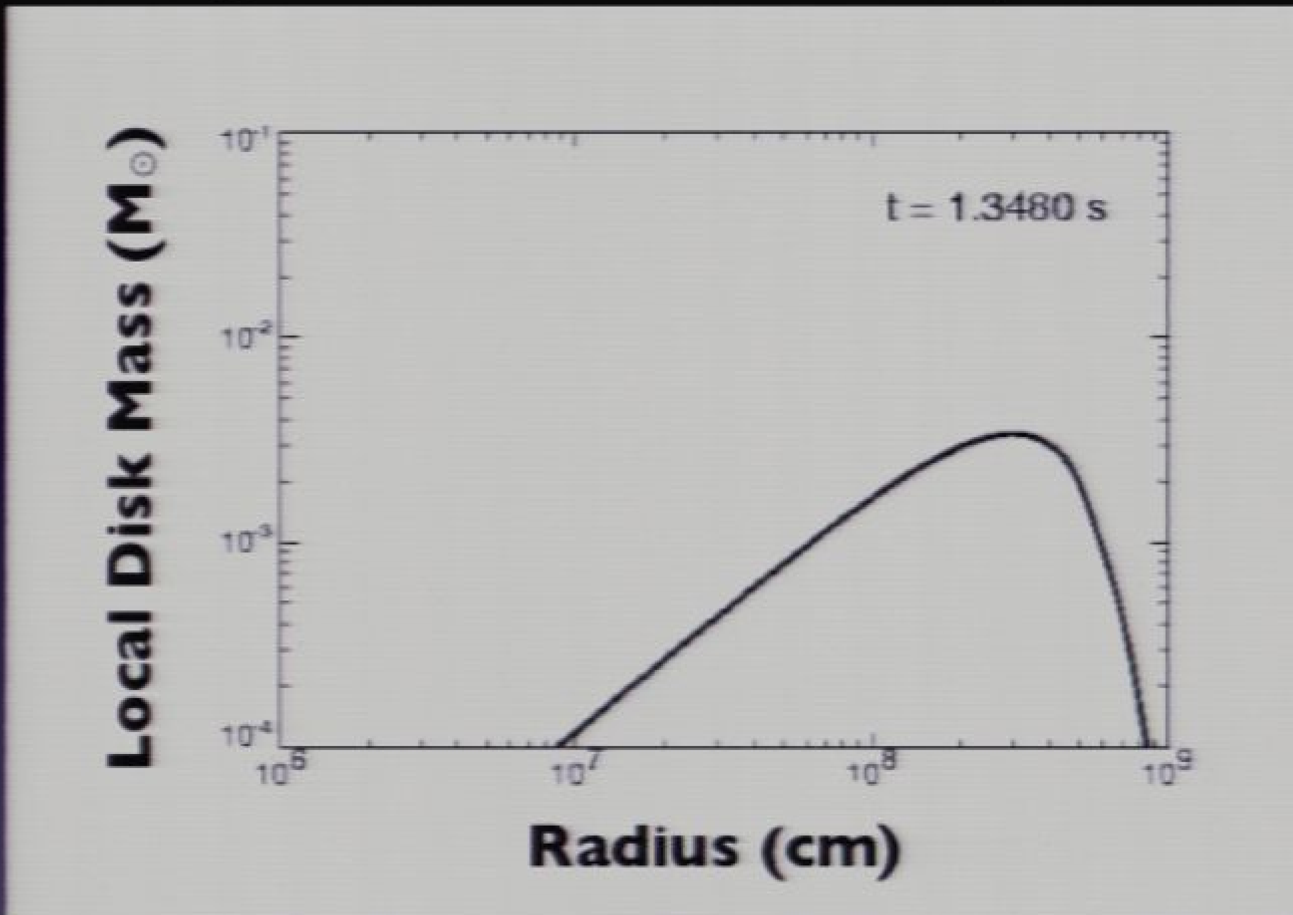


BATSE Examples

# The Evolution of the Remnant Disk

ang momentum conservation → disk spreads




## 1D time-dependent Models

(T ~ MeV; $\rho \sim 10^{12}$ g cm$^{-3}$; initially free nucleons)

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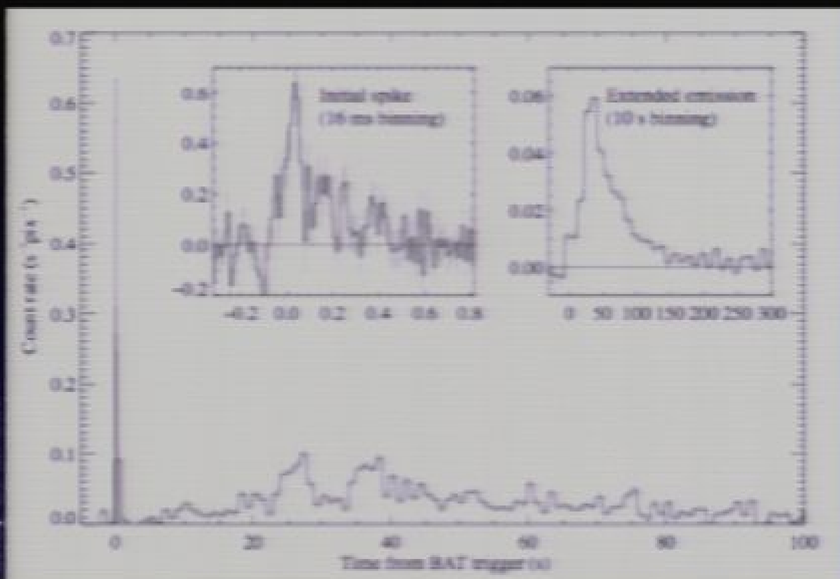


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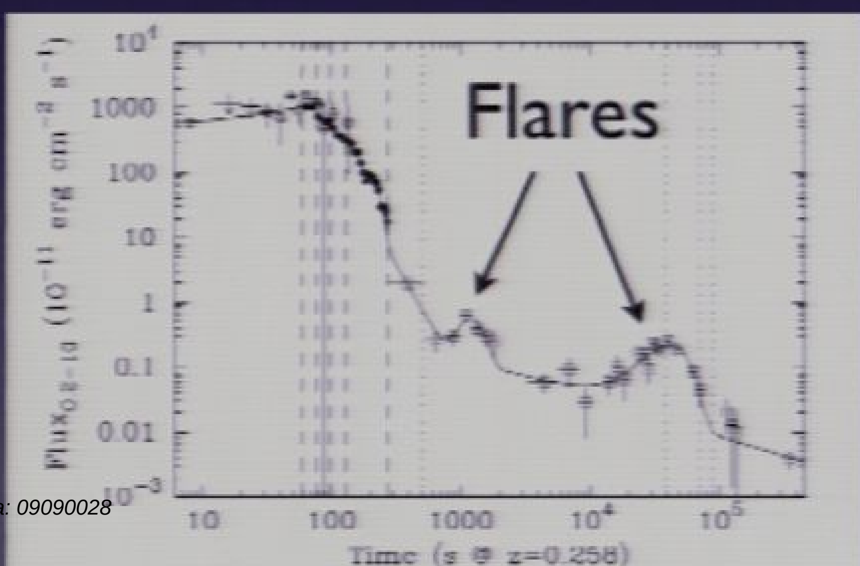


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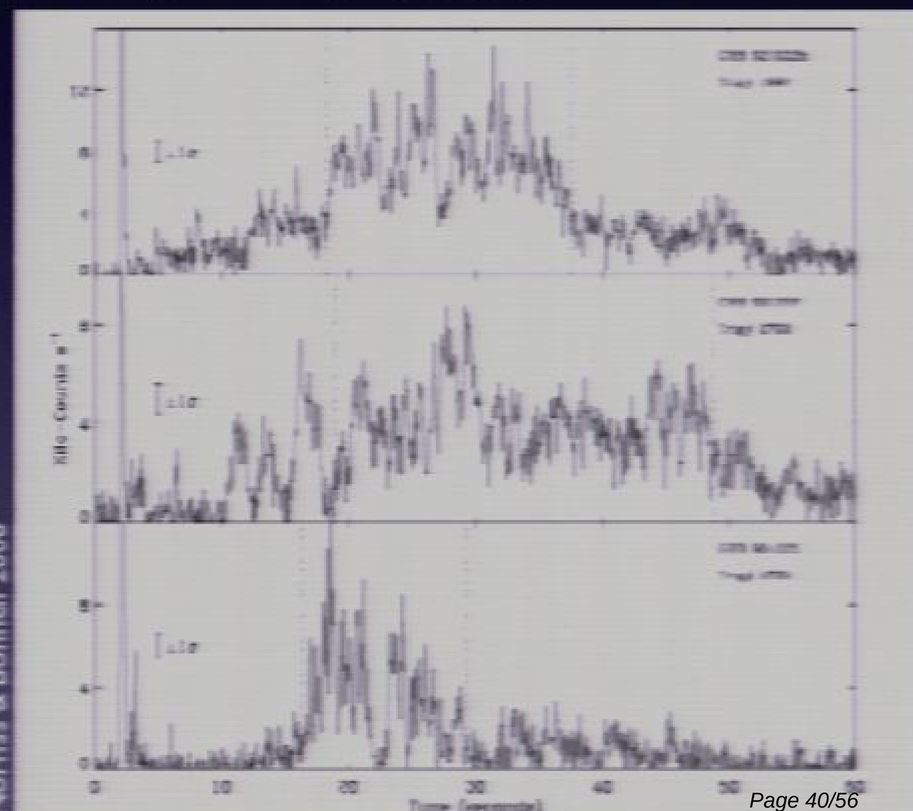


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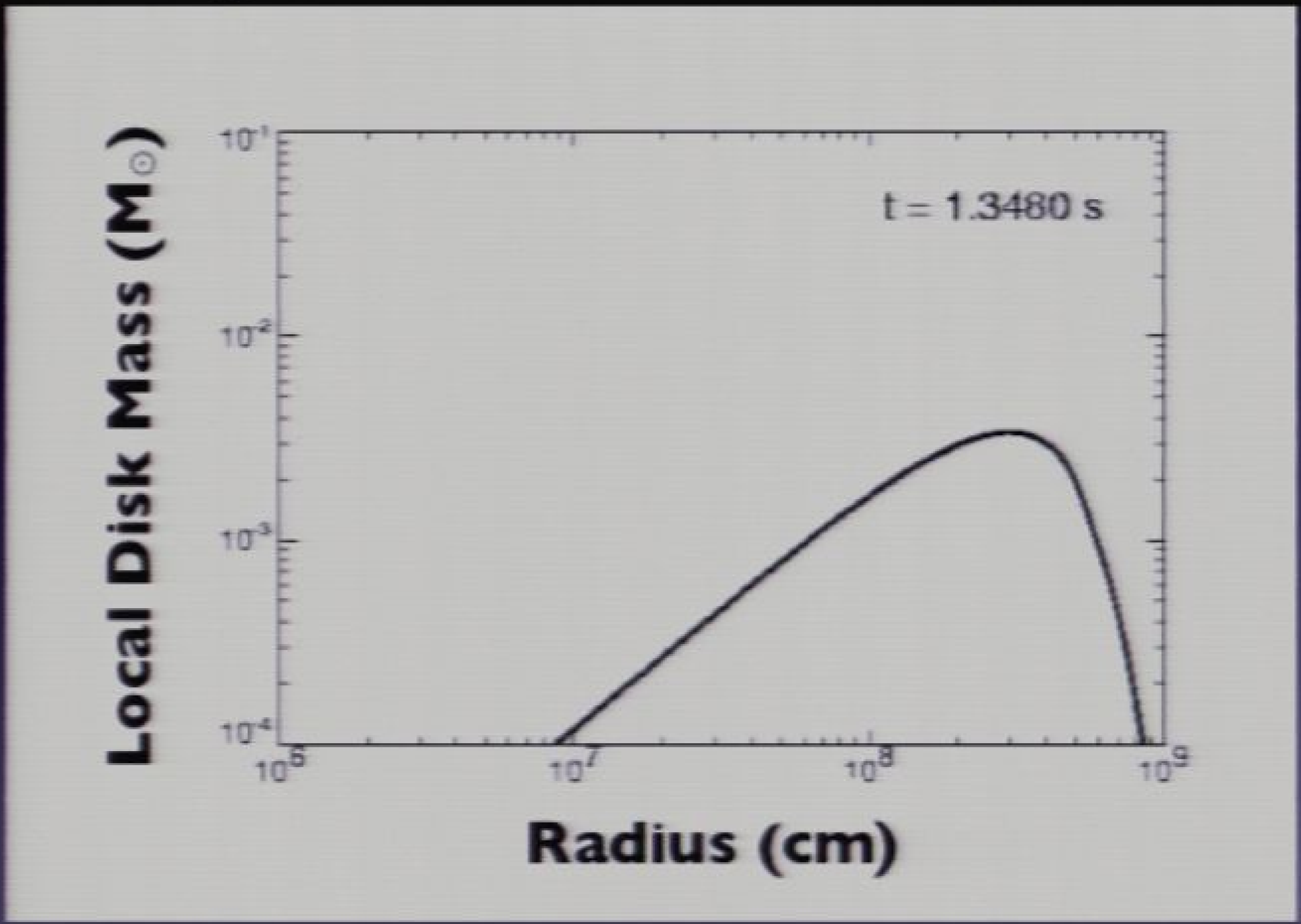


# 1D time-dependent Models

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# The Little Bang

Initially, disk radiates energy efficiently by neutrinos & composition set by weak interactions

$$e^- + p \rightarrow \nu_e + n$$

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Neutron-rich:

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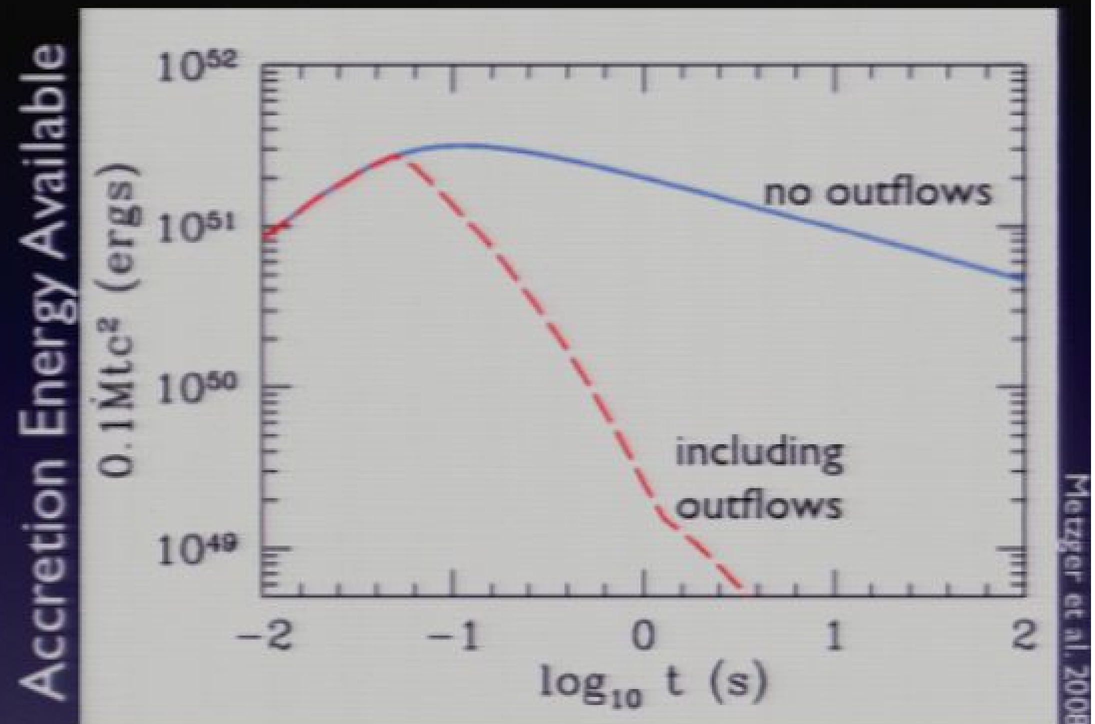


**Accretion of the Initial Disk Cannot Power Late Time Activity in SGRBs**

Origin of late-time activity remains a significant puzzle

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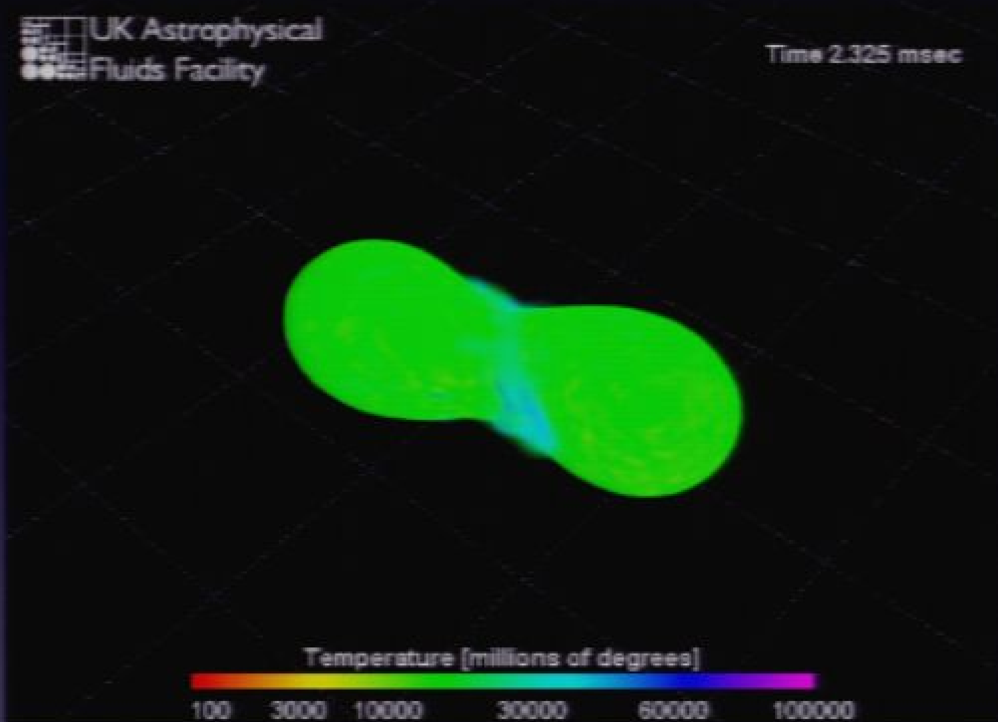


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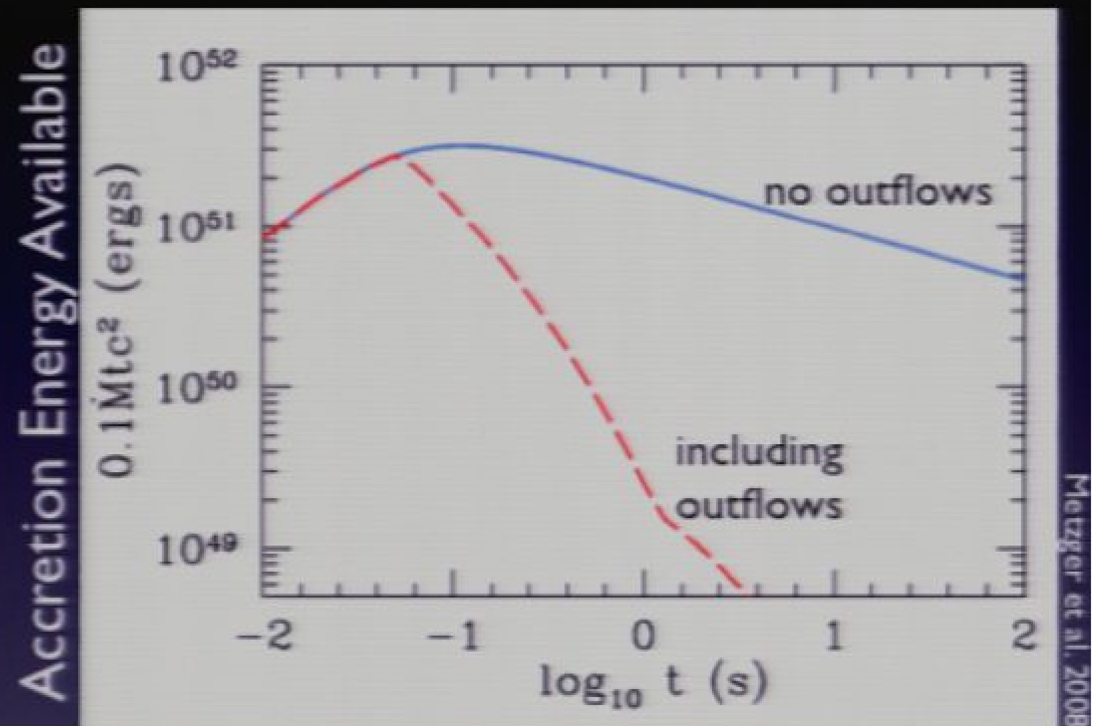


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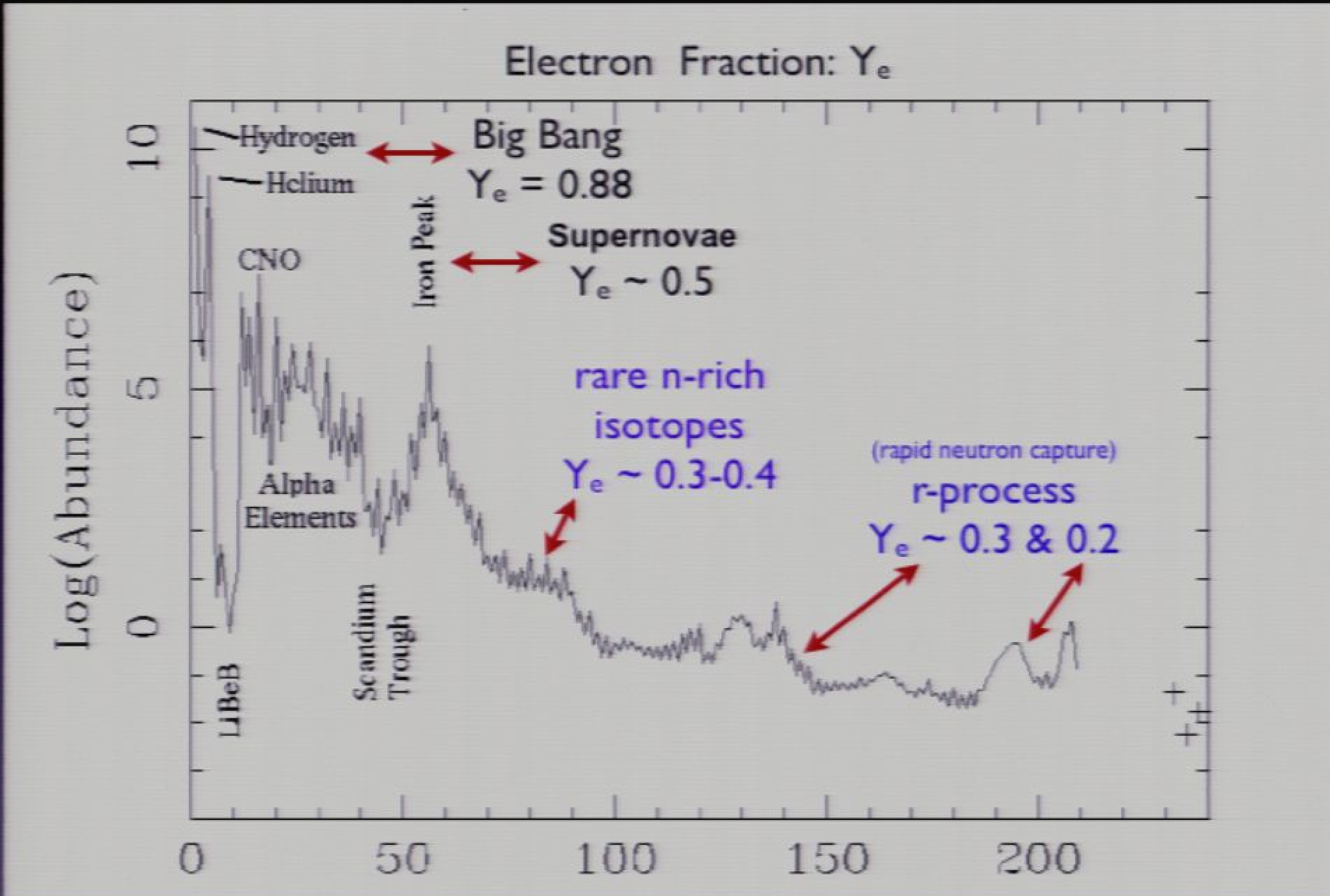


Atomic Mass

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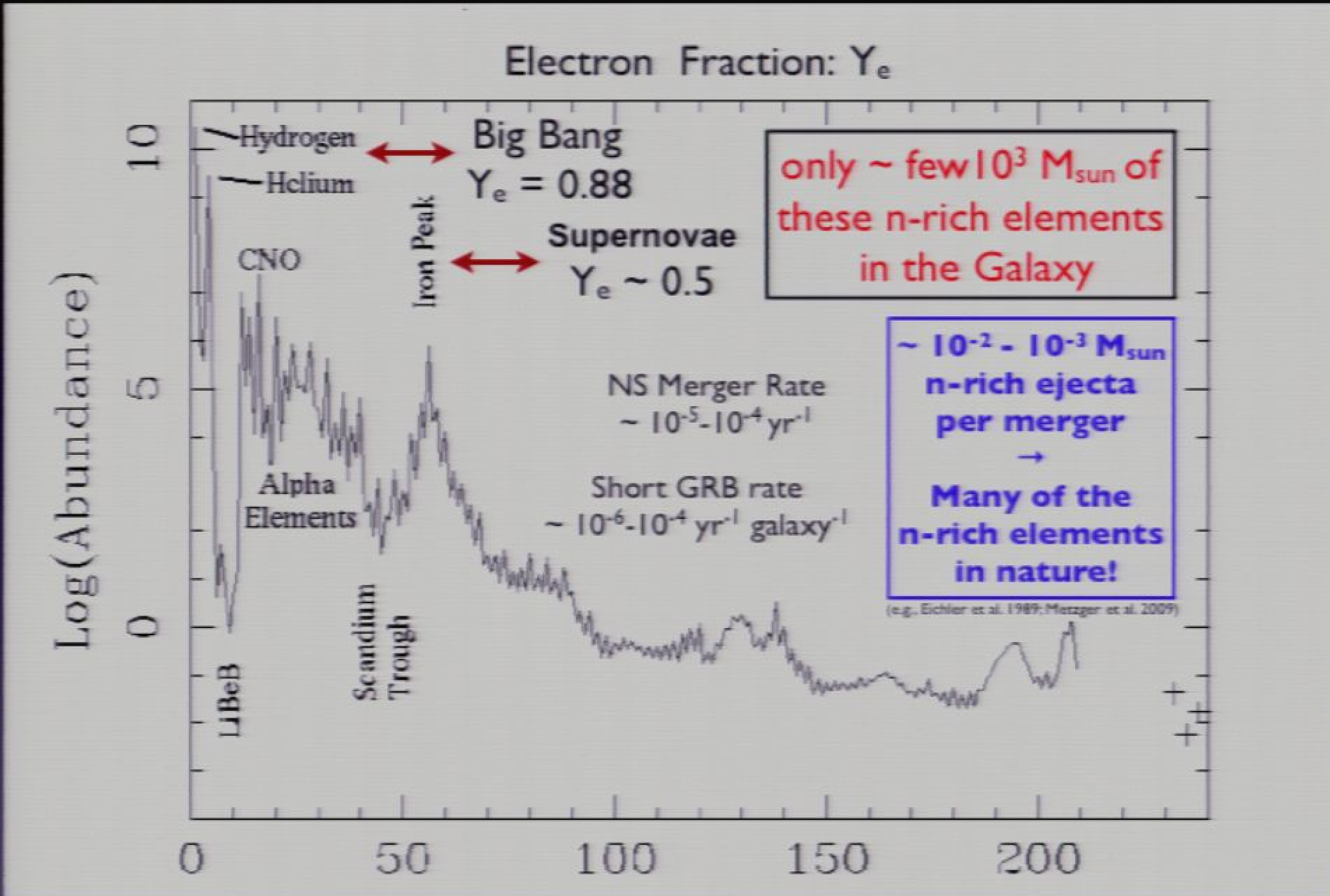


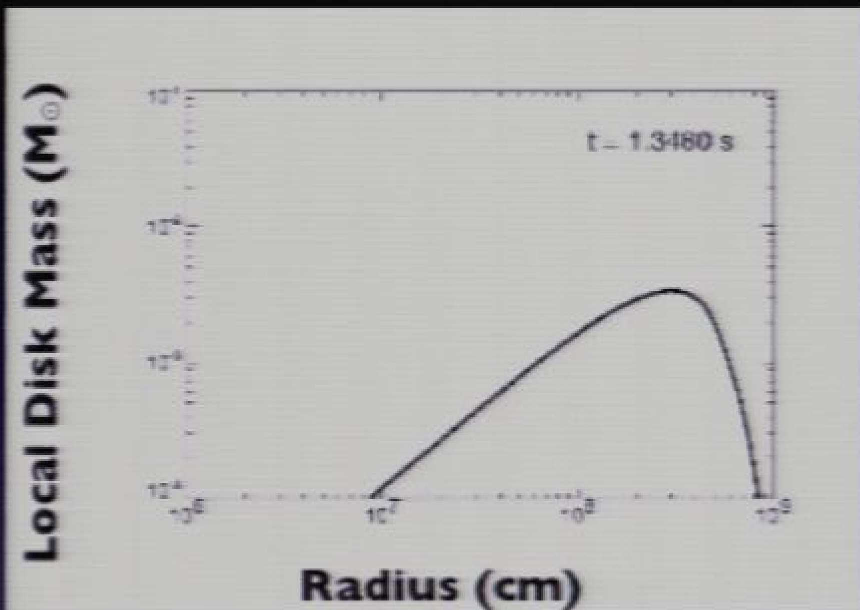



Atomic Mass

# Future Prospects

- GRBs are unique probes of the high redshift universe
- GRBs very promising high energy ν sources (photo-pion)
- Gravitational wave detections probable within ~ 10 yrs
  - **NS-NS & BH-NS mergers**; rare (very highly rotating) core-collapse SNe possible
    - tests of GR & the equation of state of nuclear matter
    - constrain the origin of short (and maybe long ...) GRBs
    - & the origin of many of the n-rich elements in nature

# The Little Bang

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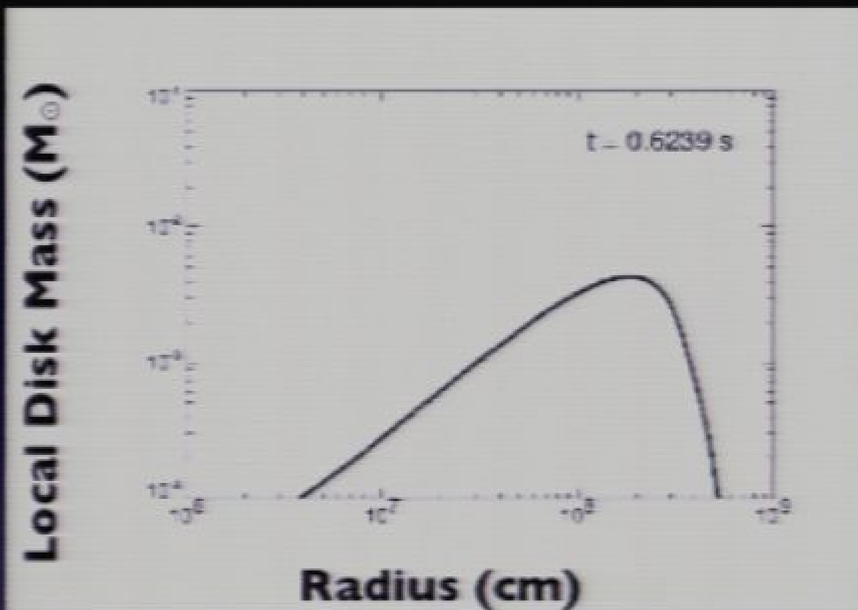


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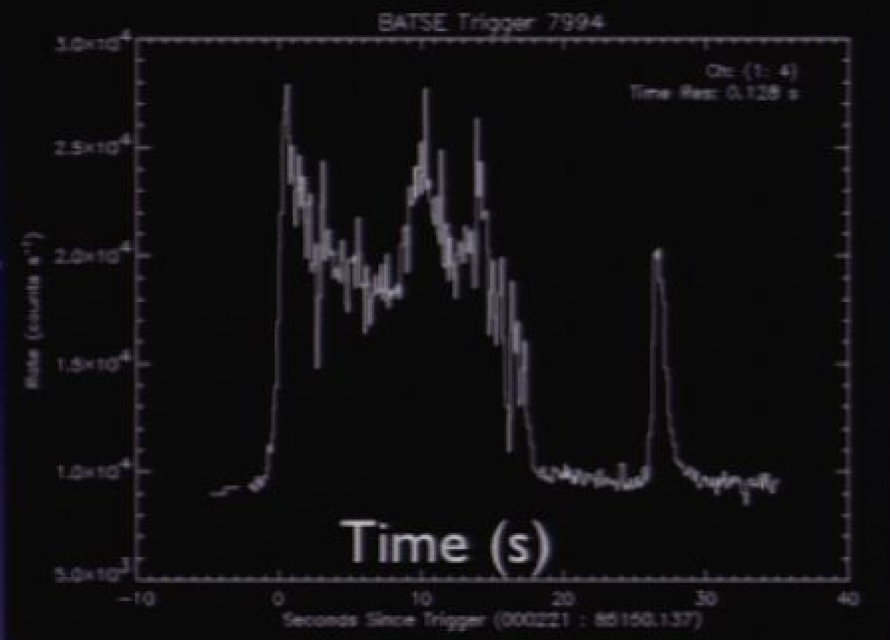
Neutron-rich

**optical transient coincident w/ GRB**


radioactive decay of Ni & fission of n-rich elements produces a new kind of supernova

L ~ $3\times10^{41}$ erg/s; few day - week timescale

# The Physical Origin of Gamma-Ray Bursts




Requirements:

***Release E ~ 0.01*** $\boldsymbol{M_{sun}c^2}$ ***on***
***t ~ 0.1-100 sec in***
$\Gamma \gtrsim$ ***10²-10³ outflows***

## Long Bursts

associated w/ death of massive stars (supernovae)

**→ the birth of a NS or BH**

## Short Bursts

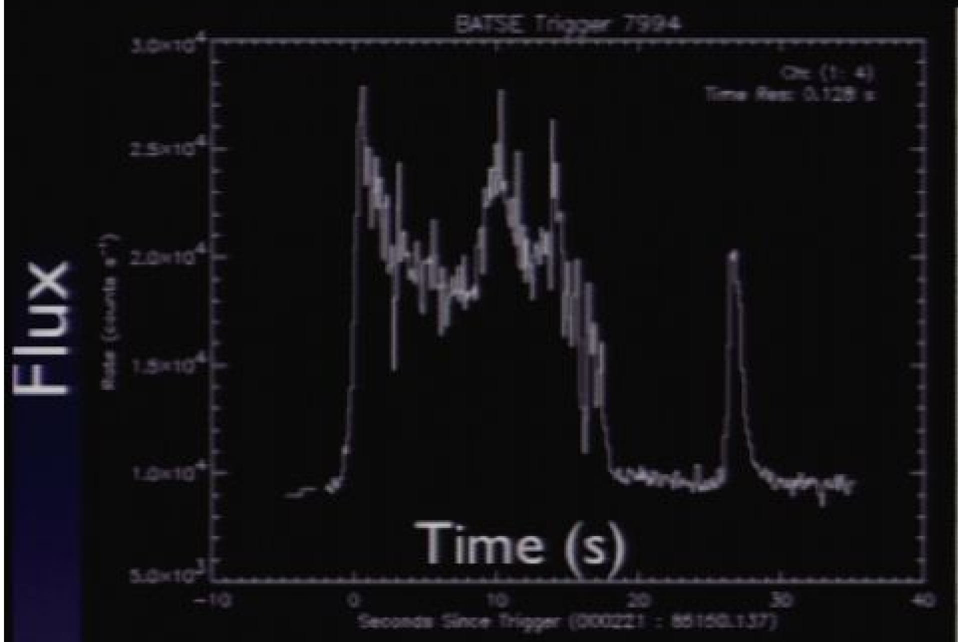
not associated w/ massive stars or SNe

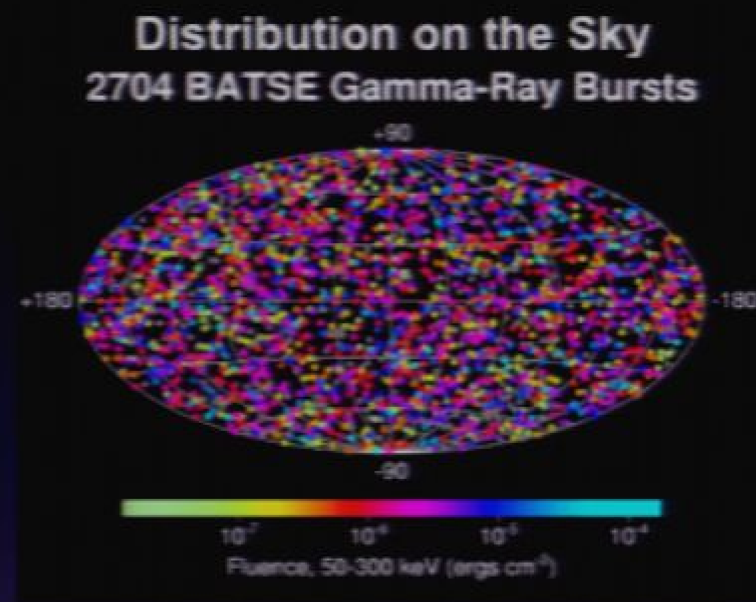
**→ NS-NS &/or NS-BH mergers;**
**perhaps collapse of a WD to a NS**

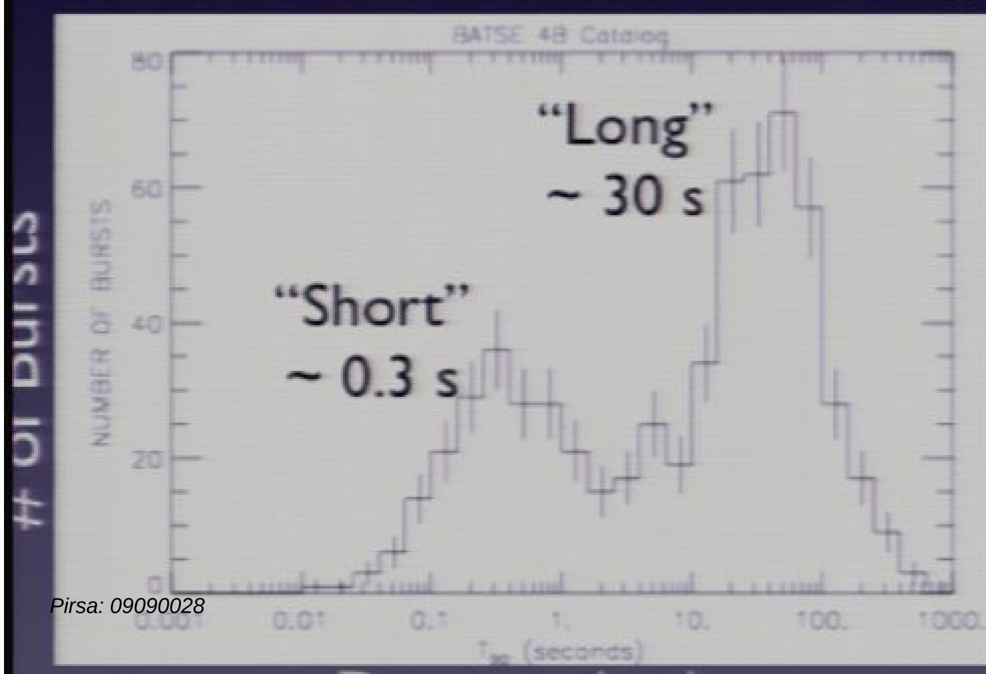
## Compelling Opportunities

Tremendous prospects for fundamental physics
(tests of GR, EOS of dense matter, ...) & astrophysics ("first stars";
origin of n-rich elements, physics of stellar explosions, ...)

# Gamma-Ray Bursts

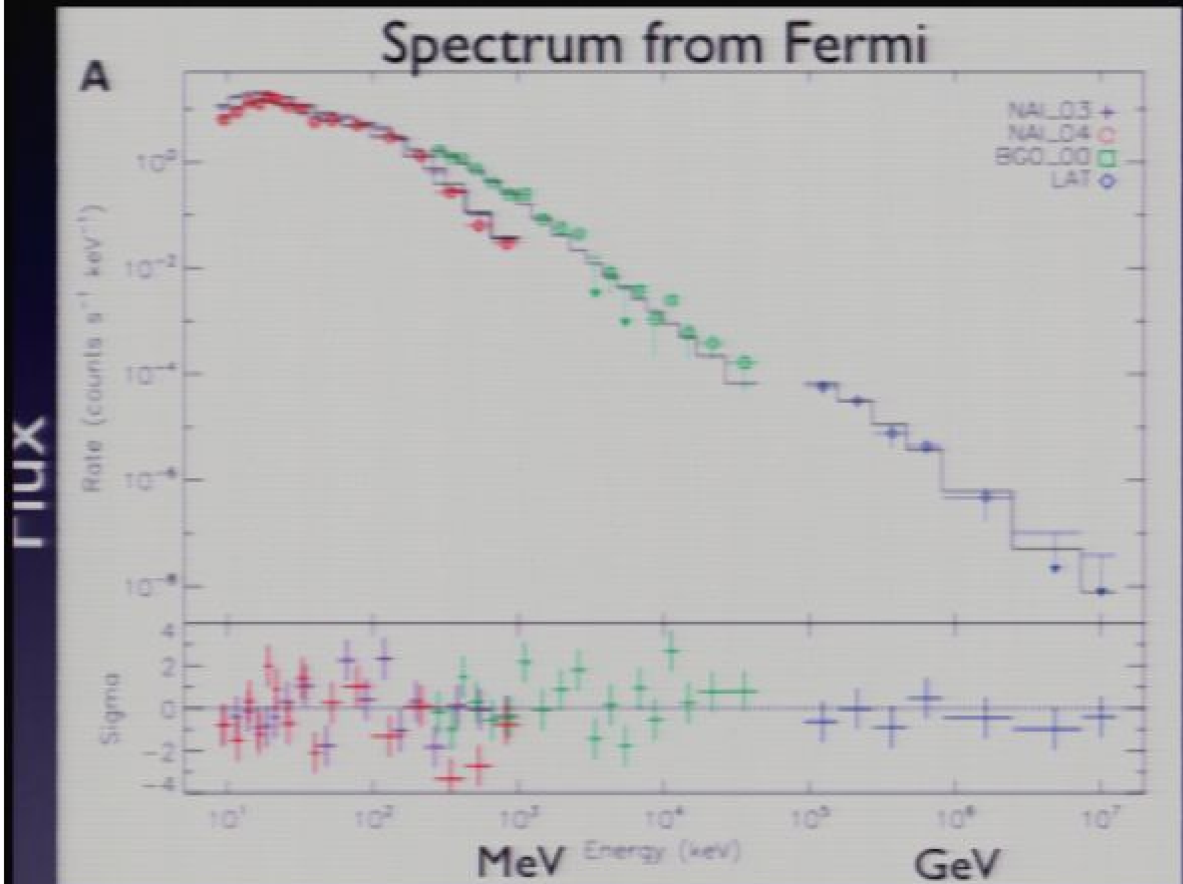



- Flashes of ~ 0.1-10 MeV γ-rays
- "Long" (~ 30 s) & "Short" (~ 0.3 s) Events
- Isotropic on the Sky
- Cosmological Distances: Redshifts ~ 0 - 8.3
- Brightest EM sources in the Universe (briefly)
  - ~ $10^{49-55}$ ergs ~ $10^{-6}$-10 $M_{sun}c^2$ (isotropic)
- Rare: ~$10^{-5}$/yr/galaxy ~$10^{-3}$ SNe rate

# GRBs Require Ultrarelativistic Outflows: Bulk Lorentz Factors $\Gamma \gtrsim 10^2$-$10^3$




Photon Energy

- Huge energy ≳ 511 keV
  - short timescales → opaque → thermalize

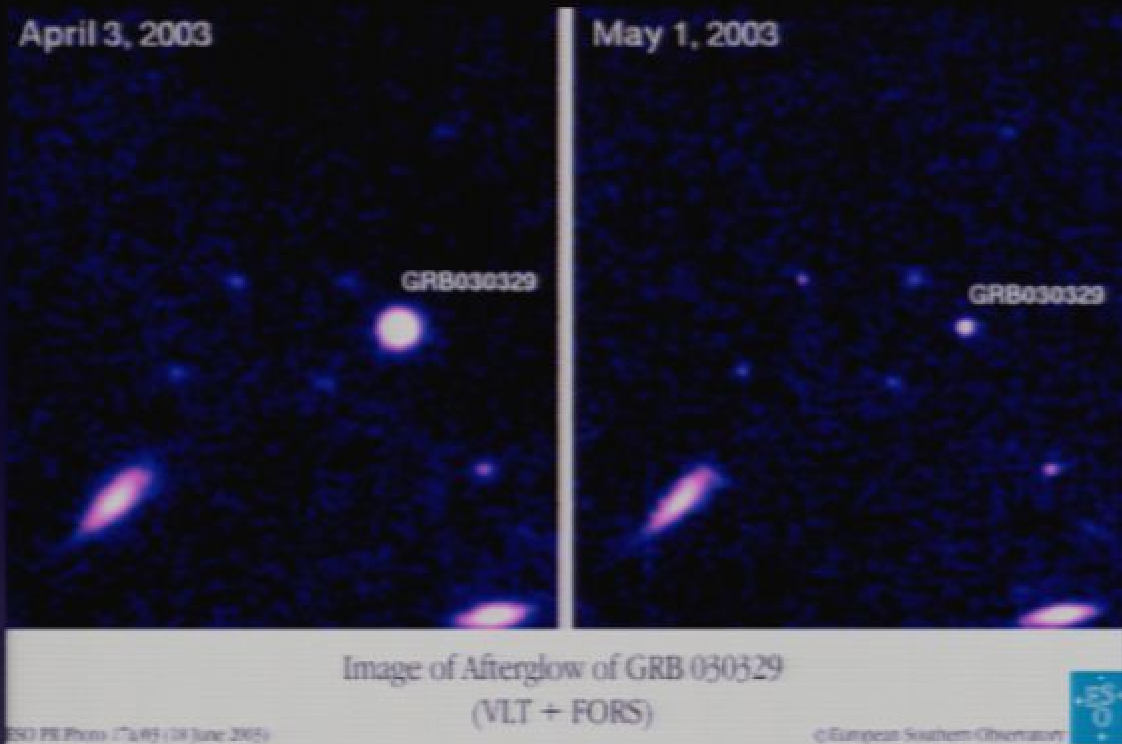
$$\gamma + \gamma \leftrightarrow e^+ + e^-$$

  - **spectrum not bbody**!
- **Outflow w/ $\Gamma \gtrsim 10^2$-$10^3$**
  (e.g., Goodman 1986; Paczynski 1986)
  - no pair production problem
    - rest frame photon energies <<; size >>

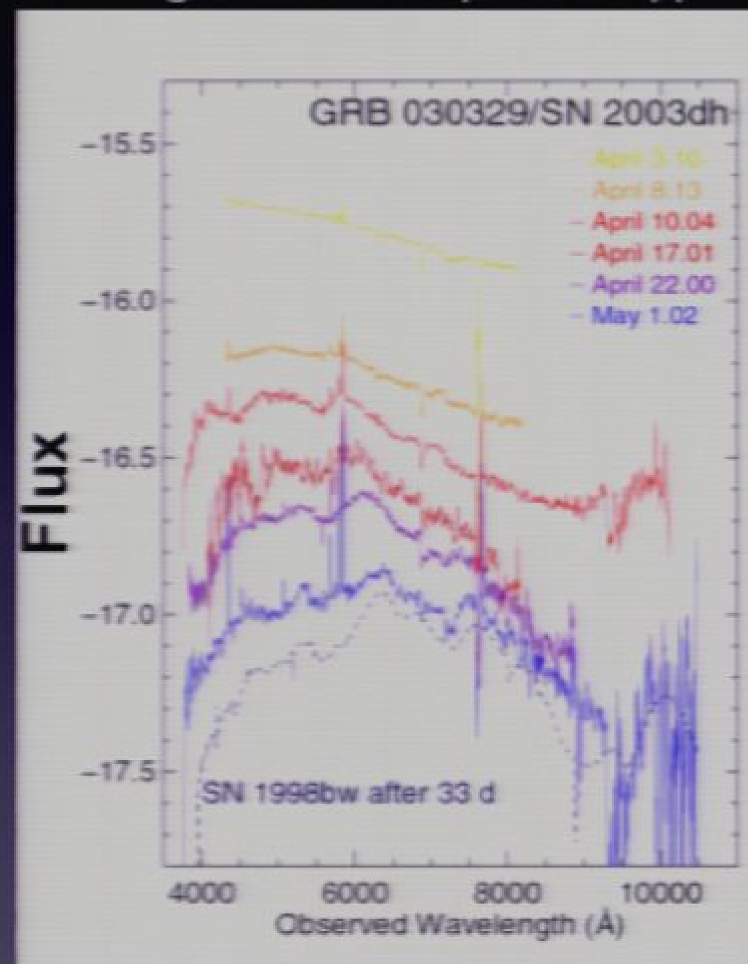


(Aside: provides very tight constraints on photon dispersion)

# Long-Duration GRBs




As afterglow fades, a supernova appears




Hjorth et al; Stanek et al.

Associated with massive star formation and supernovae (stellar explosions)

→ **Birth of a Neutron Star or Black Hole**

**(not the converse; GRB rate ~ $10^{-3}$ SNe rate)**