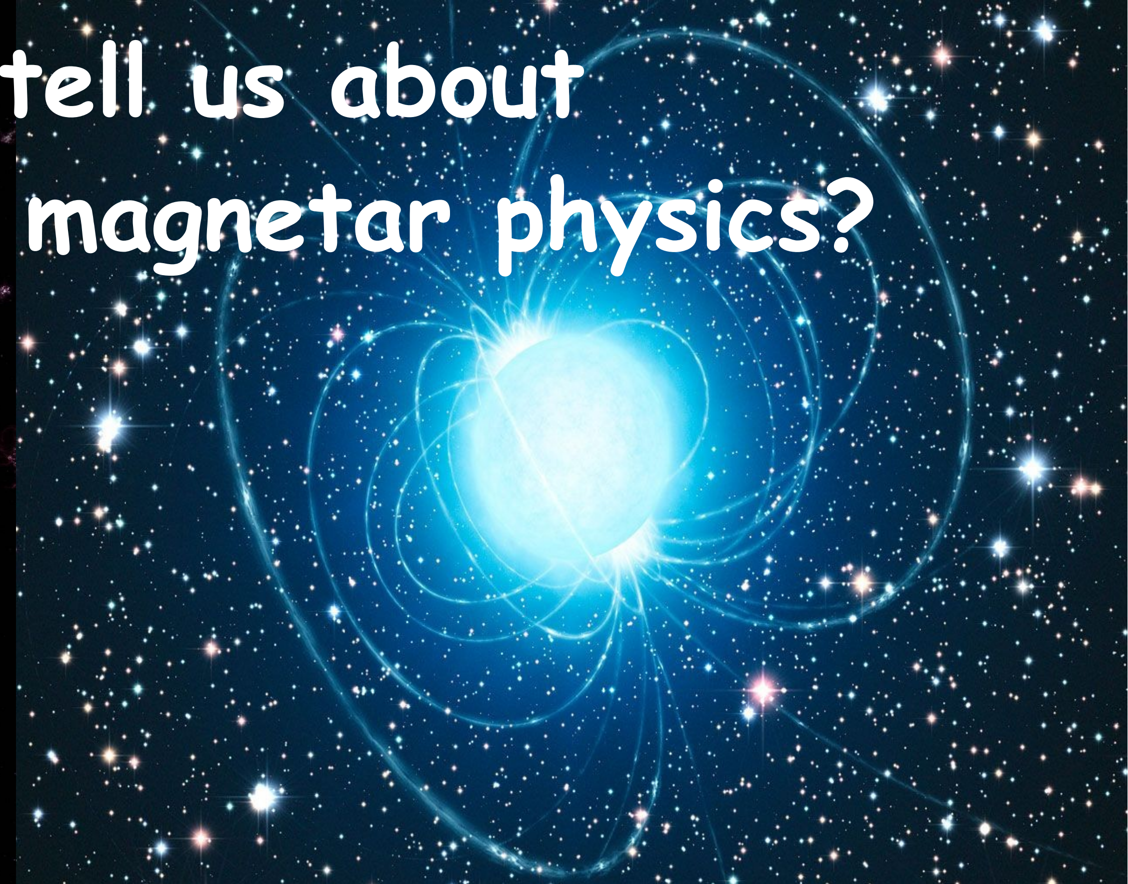
What X-rays could tell us about Gamma-ray burst & magnetar physics?

Olivier Godet

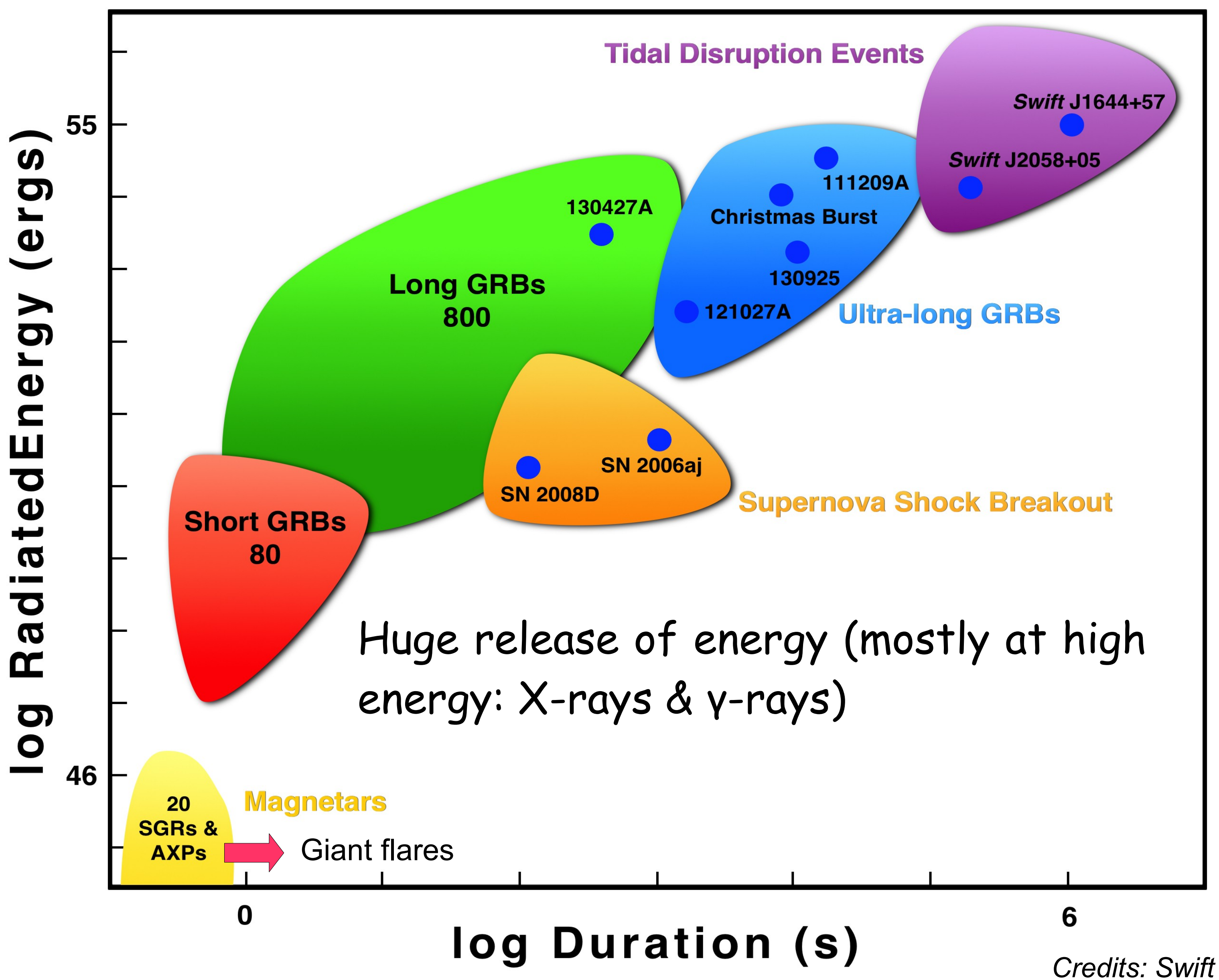


Lecture given by
Matteo Bacchetti

You just saw a GRB located at 7.5 Gly
with your naked eyes !!!
(Racusin+08)

A transient and energetic Universe

All these transients objects involve compact objects (formation or evolution)



Huge release of energy (mostly at high energy: X-rays & γ-rays)

Aims of this lecture

- Present the main observing properties of GRBs and magnetars from an X-ray point of view (link to other wavelengths or messengers)

- Give the basis of the theoretical framework to understand these objects

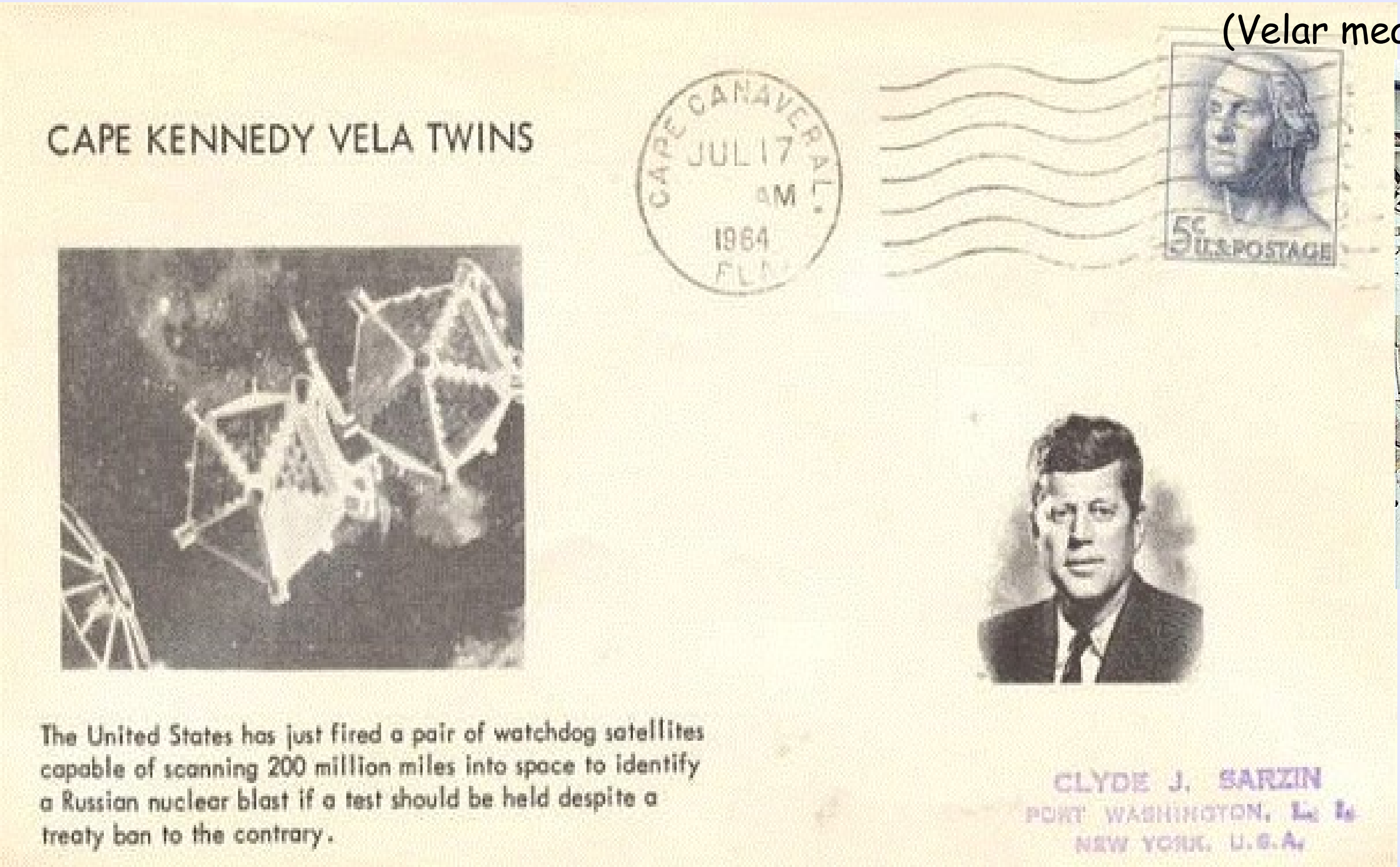
- Discuss how X-rays (spectroscopy & timing) could help us unveiling the physical mechanisms at work in these objects

- Discuss why we should care studying these objects ➡ links with other fields of astrophysics and fundamental physics

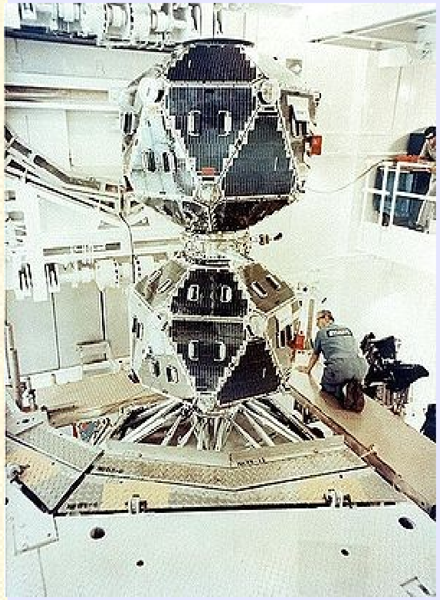
- Discuss possible connections GRB – magnetar

A short tale about GRB / magnetar discovery

- Once upon a time (in the 60's),



Vela satellites
(Velar means 'to watch' in Spanish)

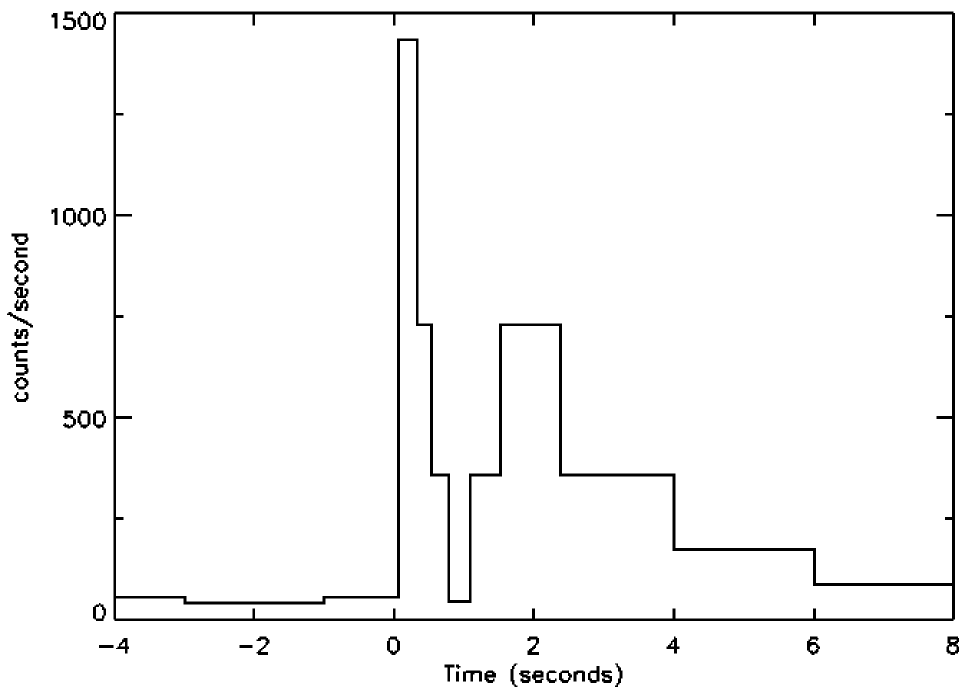


- The Soviet Union did the same (just in case) ... and found the same results.

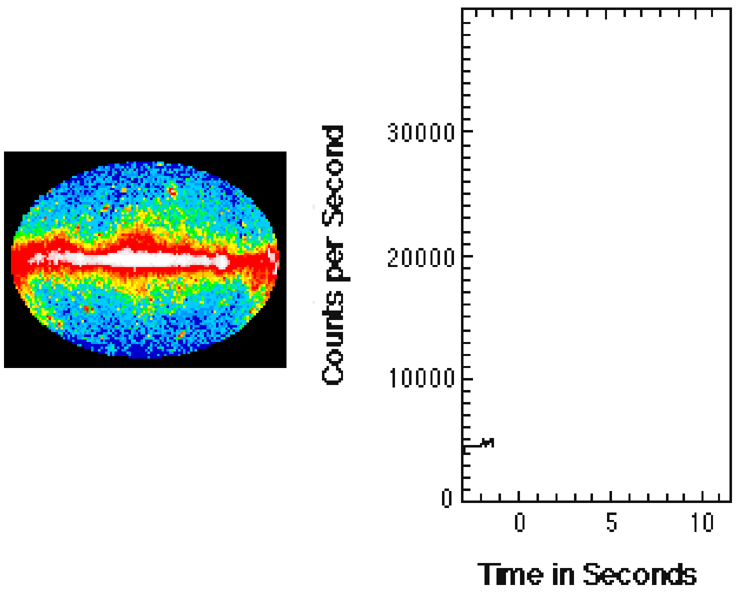
A short tale about GRB / SGR discovery

- Nothing coming from Earth was found, but this enabled the discovery of 2 new astrophysical phenomena (Gamma-ray bursts and Soft-Gamma Repeaters)

Klebesadel et al. 1973



First published GRB lightcurve



- Even if at the time scientists did not know yet!

Energetics

- Both types of events are really energetic.

- GRB luminosity with measured distances = 10^{50-54} erg/s
  → Making them the most violent phenomena in the Universe

- Let's take the March 1979 giant SGR flare (Mazets et al. 1979) located in LMC.

- Its Gamma-ray luminosity reached 4×10^{44} erg/s
  → Making this event the most powerful one ever detected since GRB distances were still unknown at the time.

Outlines

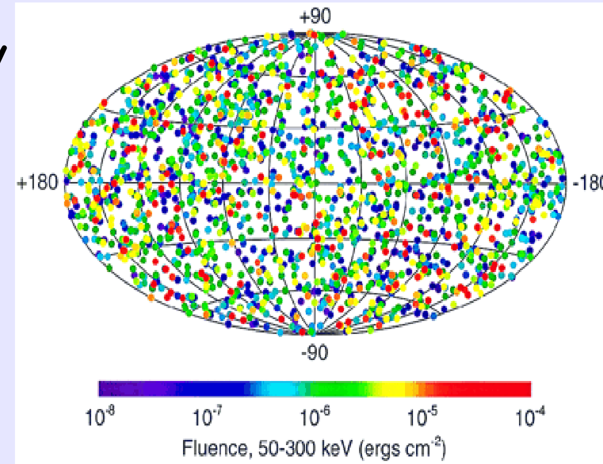
1. Properties of GRBs
2. Theoretical framework
3. GRB progenitors
4. Why should we care about GRBs?
5. Soft Gamma-ray Repeaters
6. How do magnetars work ?
7. Why should we care about magnetars?
8. Connection GRB – magnetar?

PART I

Gamma-ray bursts

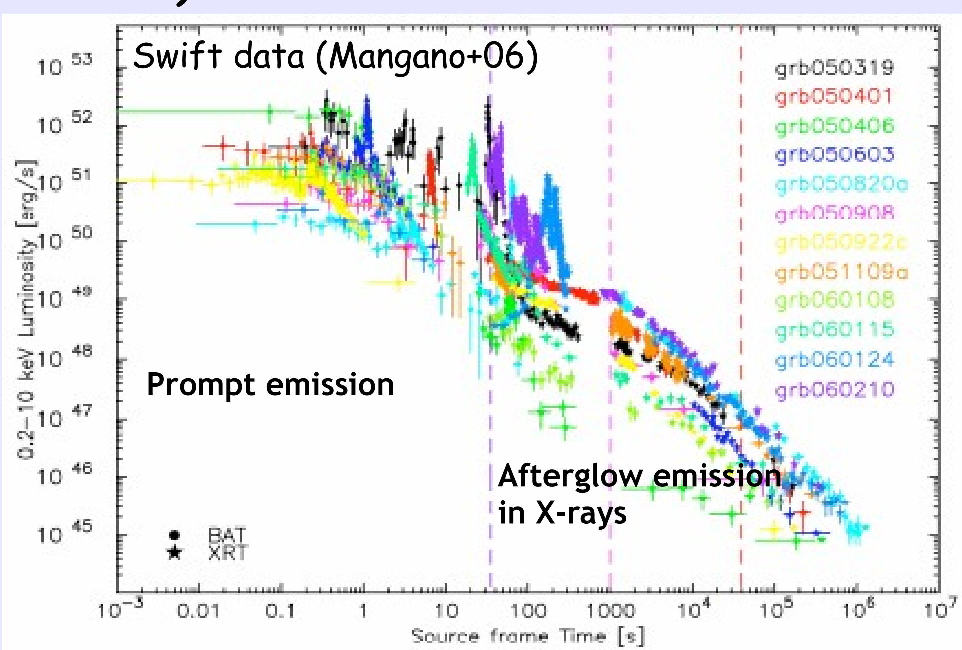
Properties of GRBs

• GRBs appear randomly over the sky and in time as …

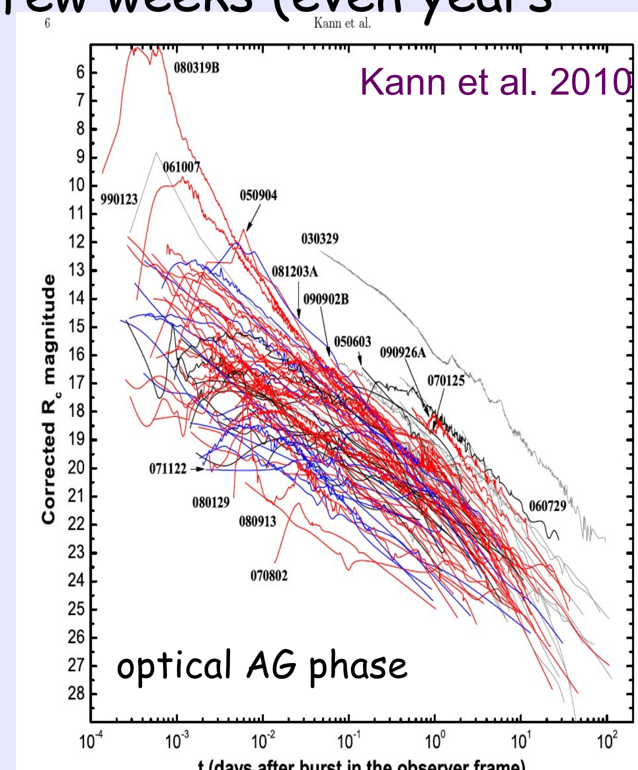


Paciesas et al. 1999
CGRO/BATSE
9 yrs of observation

• Brief X-/Gamma-ray flashes (prompt emission) followed by multi-wavelength afterglow emission over timescales from a few min to a few weeks (even years in radio)



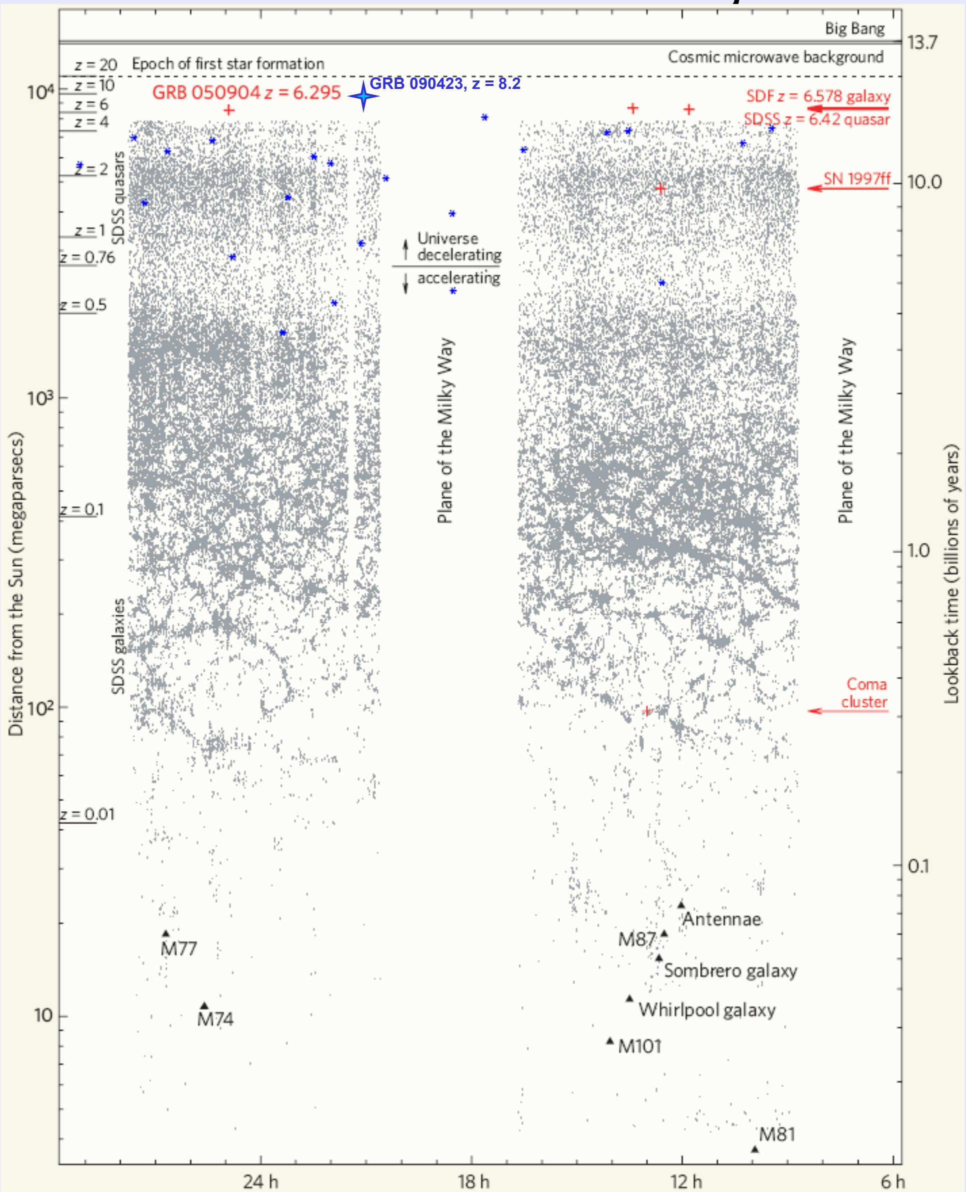
AG flux decreases rapidly with time.

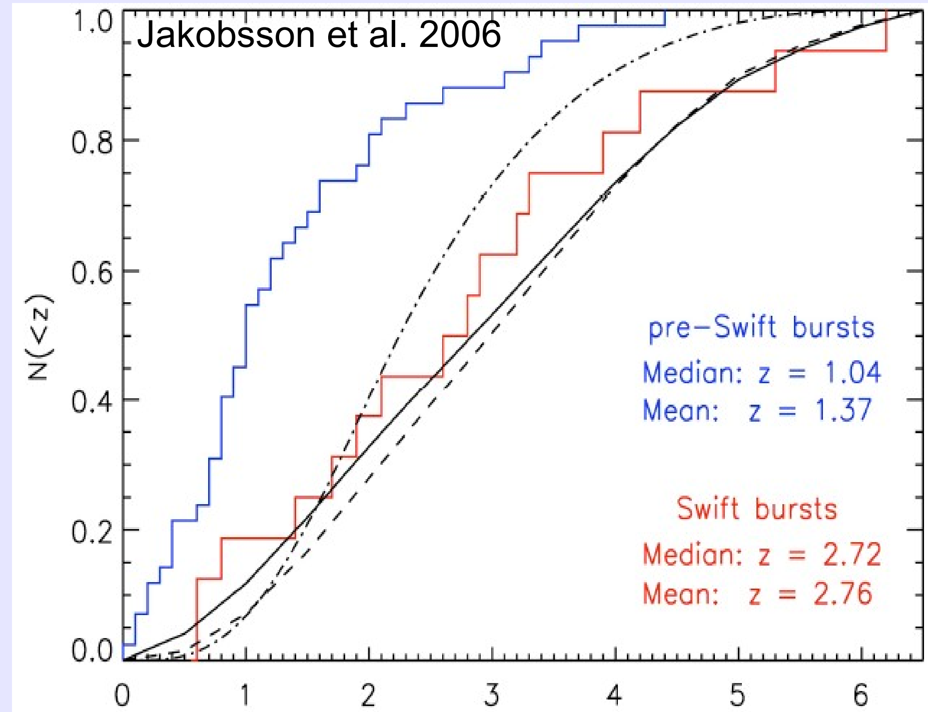


Properties of GRBs

Source distance

- GRBs are located at cosmological distances (from z = 0.033 to z = 8.2, maybe 9.4)





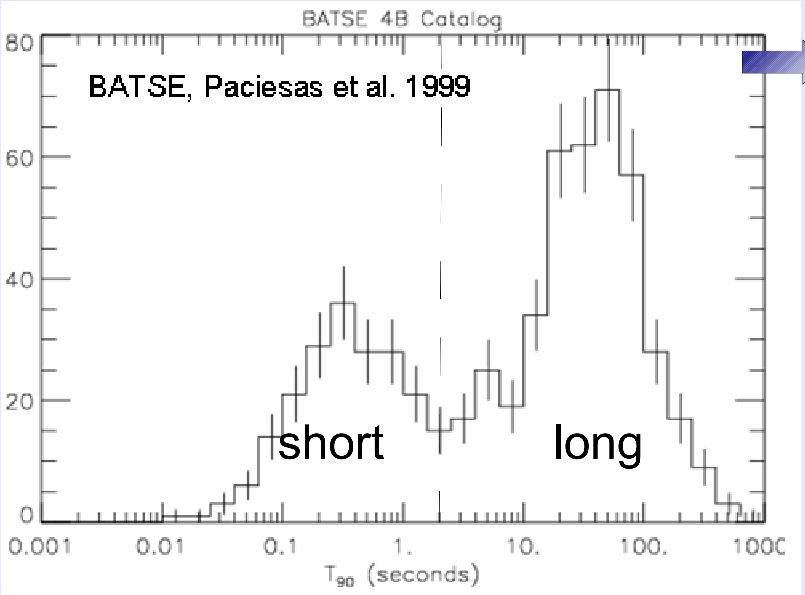
- **GRB 090423 with z =8.2 (Tanvir et al. 2009)**
- GRB 080913 with z=6.7
- GRB 050904 with z=6.3 (Haislip et al. 2006)
- z = 8.2 i.e. ~ 625 million years after the Big Bang & light travel ~ 13 Giga years!
- z = 0.033 i.e. light travel ~ 440 Million years

Properties of GRBs

Duration

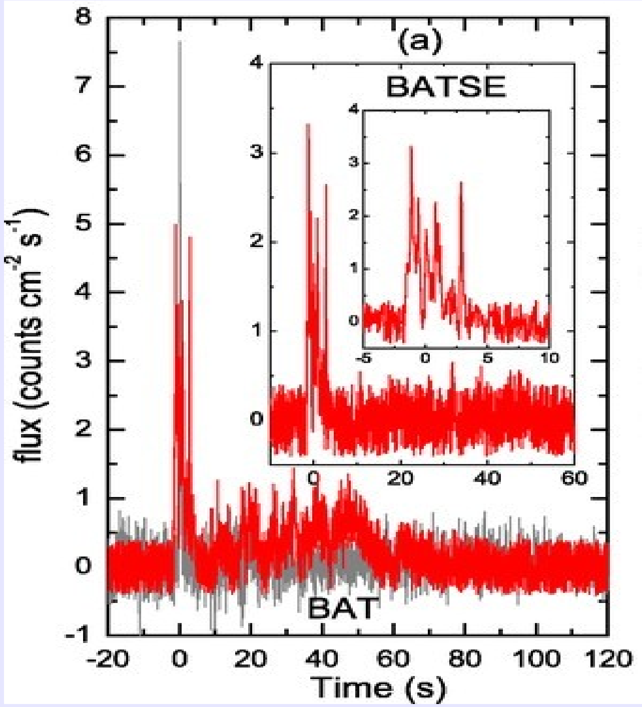
• From CGRO/BATSE, bimodal distribution

➡ hints for 2 populations ➡ different progenitors?



➡ Ultra-long GRB (few hours) (Levan+15)

GRB 060614 – Long GRB detectec by Swift/BAT (low E thresh. ~ 15 keV)



Zhang et al. 2007

• Measured duration sometimes biased by instrumental effects (energy range and sensitivity)

GRB 060614 would have been detected as a short GRB by BATSE (low E thresh. ~ 30 keV)

Properties of GRBs

Energetics

- Cosmological distances

➡ Huge isotropic energy with $E_{iso} = 10^{48}$-10^{55} erg over a few hundreds of seconds at most!

40W electric bulb
$E \sim 1.3\ 10^{16}$ erg
over 1 year

Tsar H-bomb
E = 50 Mt TNT ~ $2.1\ 10^{24}$ erg

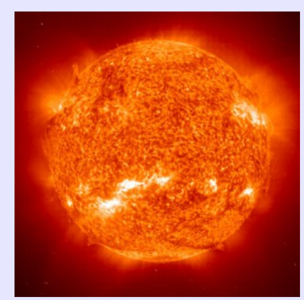
Supernovae
$E \sim 10^{51}$ erg

1 erg = 10^{-7} J
1 eV = $1.6\ 10^{-12}$ erg
10^{17} erg ~ 2.4 tonnes TNT

Milky Way
$L \sim 10^{44}$ erg/s

Nuclear plant
$P_{mean} \sim 1$ GW
$E \sim 3\ 10^{23}$ erg
over 1 year

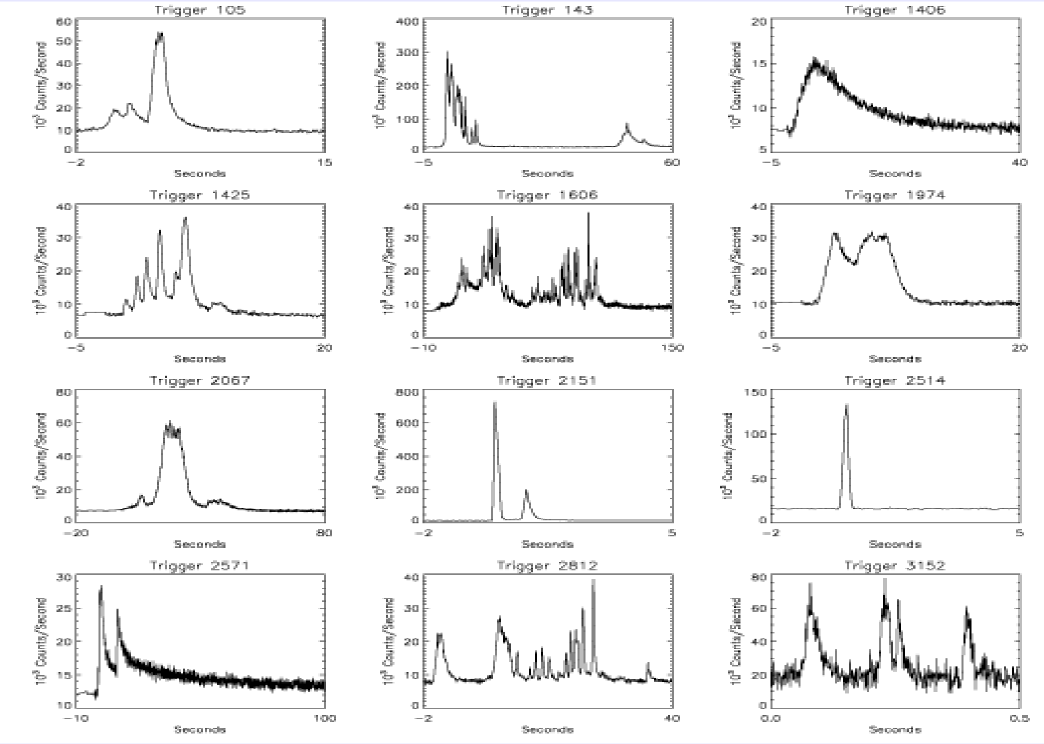
1 km asteroid impact
$E \sim 1.3\ 10^{28}$ erg



Sun
$L \sim 4\ 10^{33}$ erg/s
$E \sim 6\ 10^{50}$ erg over 5 Gyrs

Properties of GRBs

Gamma-ray variability



BATSE GRB lightcurves

- Structured and highly variable over timescales down to 1 ms.

- Assuming $\delta t \sim 0.1$ s, then the size of the system is $\delta d \sim c \times \delta t \sim 3\text{x}10^{9}$cm !! (Sun Diameter = $1.392\text{x}10^{11}$ cm).

Question: What type of object could then be the central source in GRBs?

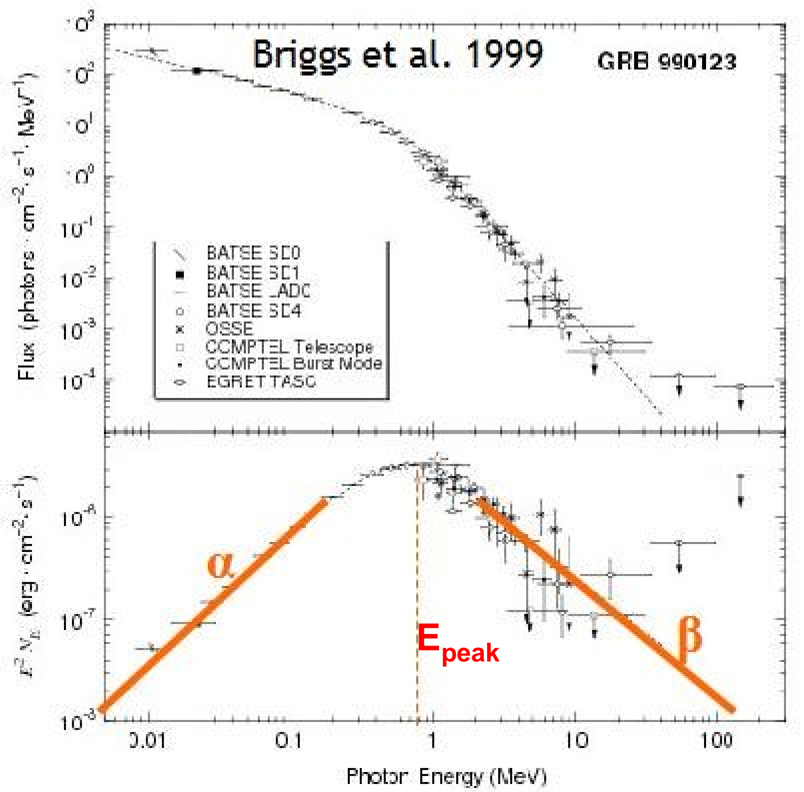
Answer: a compact object (neutron star or black hole)

Question: What mechanism involving compact objects could release large amount of energy?

Answer: Accretion ➡ However, the outflow must be collimated to avoid energy budget crisis

Properties of GRBs

Non thermal spectra



• Spectra described by a Band function (3 parameters) – Band et al. 1993

• Compacity problem (Cavallo & Rees 1978):
High density of Gamma-rays produces lots of e_-/e_+ pairs. The pair opacity is then given by:

$$\tau_{\gamma\gamma} \propto \frac{N\sigma_T}{R^2} \text{ with } N = \frac{E_{iso}}{<h\nu>}$$

• Assuming $<h\nu>$=1MeV, $E_{iso} = 10^{53}$ erg and R ~ 3 10^9 cm, $\tau_{\gamma\gamma} \sim 4.6 \times 10^{15} >> 1$

➡ GRB spectra should be thermal !

• Circumvened if Gamma-ray emission produced in an ultra-relativistic outflow (material becomes transparent) with Γ > 100

➡ Detection of GeV photons with Fermi implies Γ > 500 (Abdo et al. 2009).

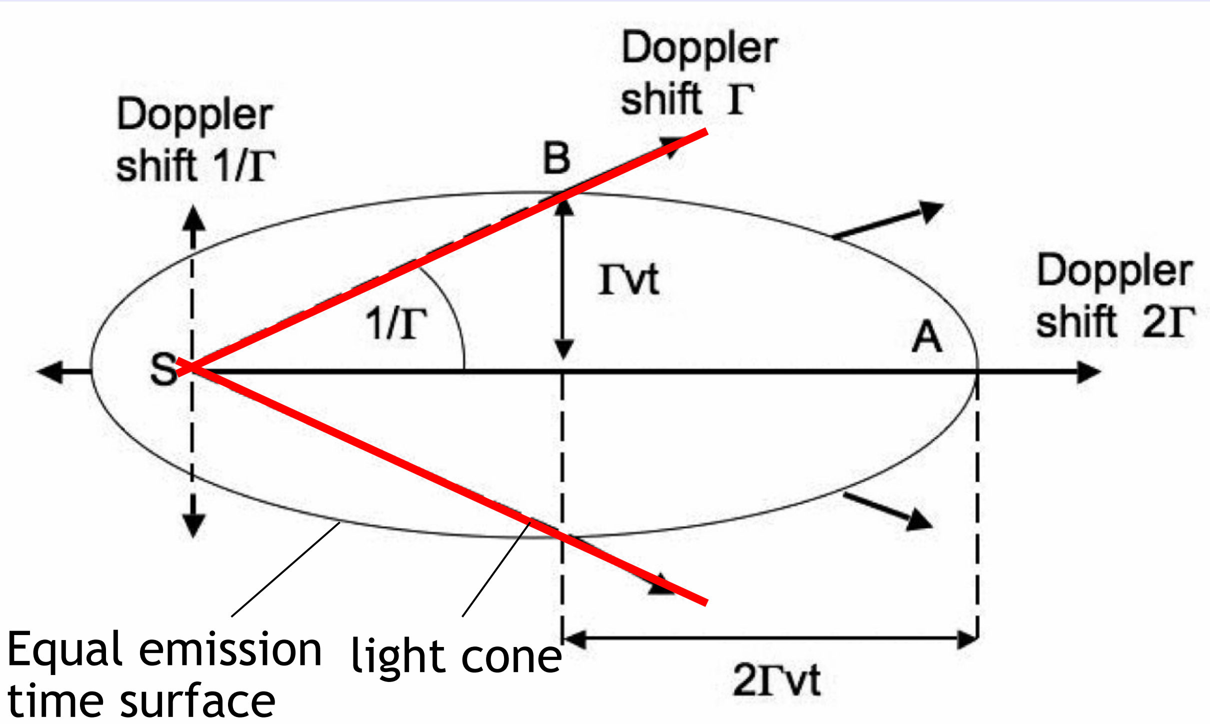
• Long GRB with E_{peak} < 50 keV are called X-ray flashes.
• In average, short GRBs harder than long ones

Properties of GRBs

Relativistic outflows

• Relativistic Doppler boosting (i.e. enhancement of the emission flux & increase in photon energy) – maximum along the observer's line of sight → Beamed emission

• Assuming a shell of matter expanding at relativistic speeds & spherically emitting in its rest-frame some radiation, for a distant observer the emission will no longer be spherical but elongated towards the direction of propagation of the shell.



Γ = Lorentz factor
v = outflow velocity
t = observer time

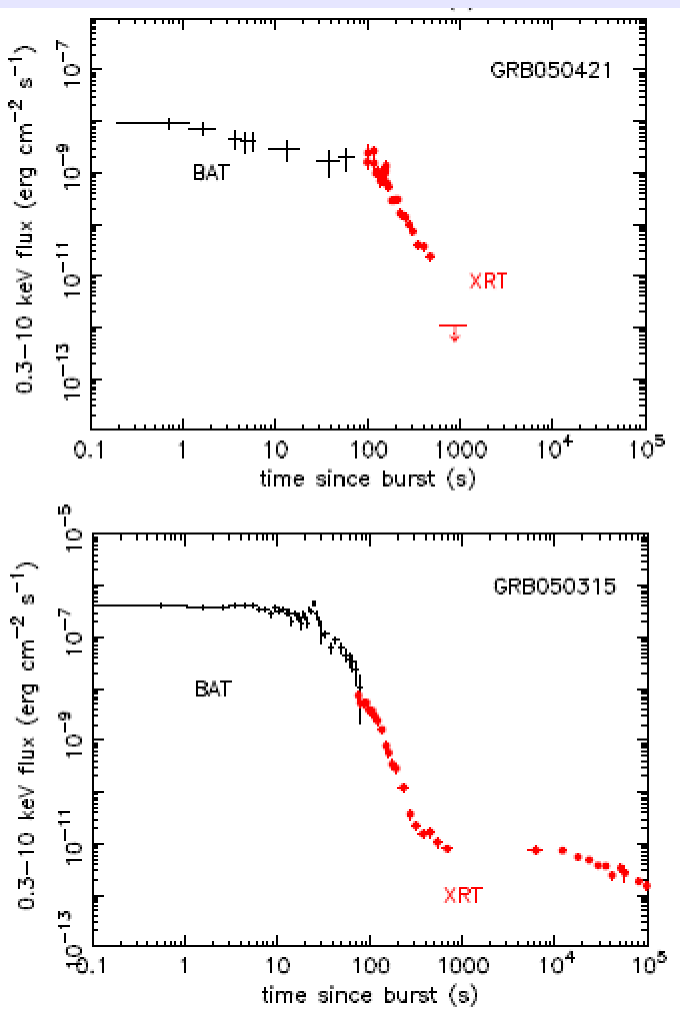
• The light emission coming from $\theta < 1/\Gamma$ is dominant.

•If outflow seen sideways, emission less intense and softer

Properties of GRBs

High lattitude emission

O'Brien+06



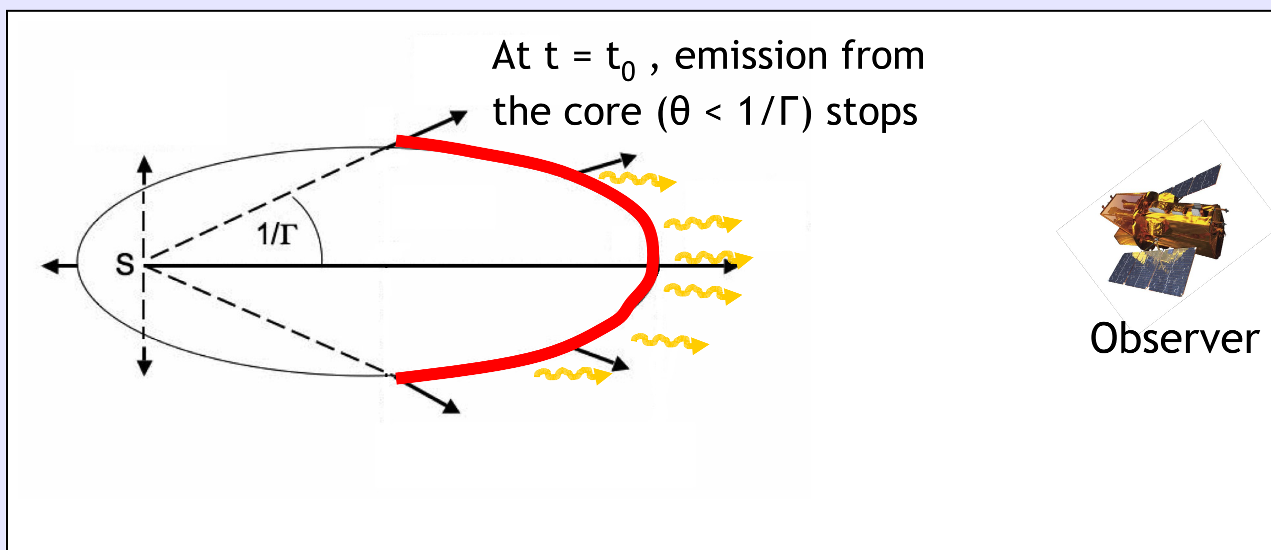
- Fast decline $t^{-\alpha}$ during transition prompt - AG

➡ End of the prompt emission

- ~60% of the afterglows
- $\alpha \sim 3 - 6$ (e.g. Tagliaferri et al. 2005, Nature)
- Possible interpretation: high latitude emission (Kumar & Panaitescu 2000)

➡ Model predicts $\boldsymbol{\alpha = 2 + \beta}$ with β, X-ray spectral index

- Importance of the zero time associated to the last emitting shell (cf. Liang+06)



Properties of GRBs

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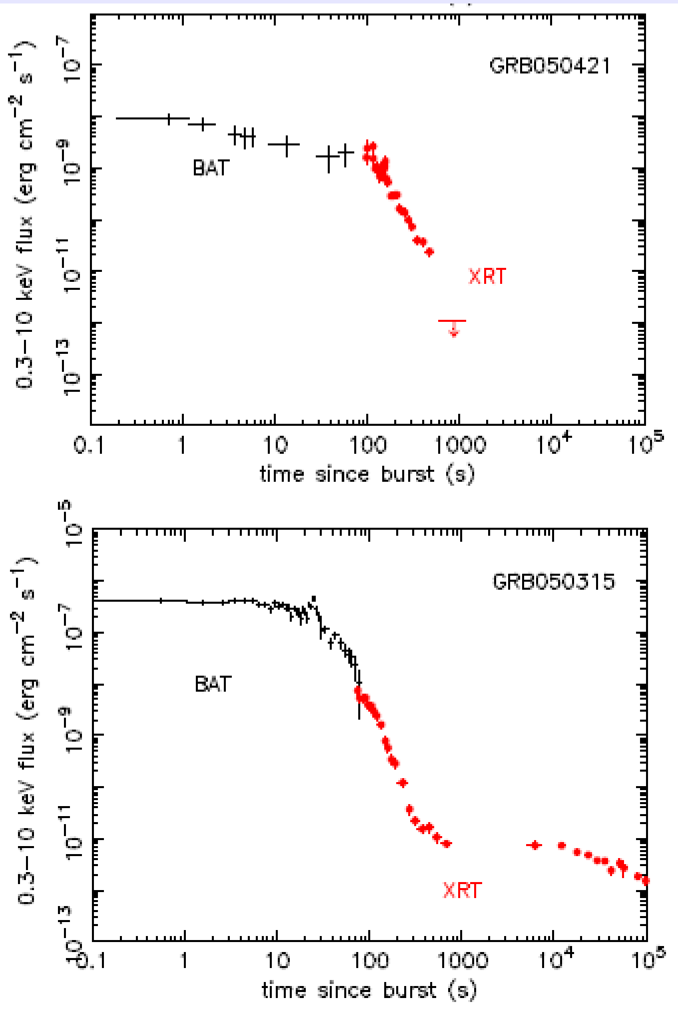

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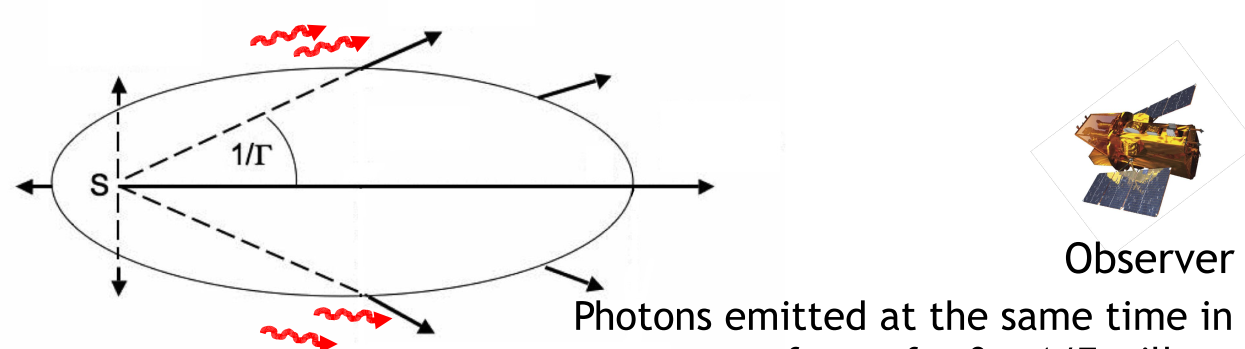


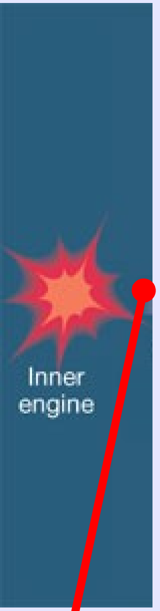
Photons emitted at the same time in the source rest frame for $\theta > 1/\Gamma$ will reach the observer with a certain delay.

Theoretical framework

Internal/external non collisional shock model (e.g. Meszaros & Rees 1993)

- Central source ejects shells of matter with inhomogenous Γ-distribution

(Piran, Nature, 2003)



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OPAQUE FIREBALL
(large γ-γ opacity)
Conversion of internal energy to kinematics energy → acceleration phase up to coasting radius above which Γ = cst

Theoretical framework

Internal/external non collisional shock model (e.g. Meszaros & Rees 1993)

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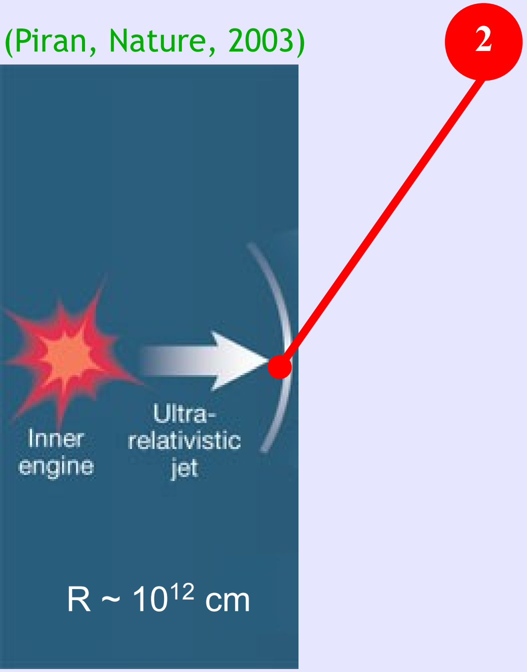

TRANSPARENT FIREBALL
(photospheric emission)
A modified black-body

Theoretical framework

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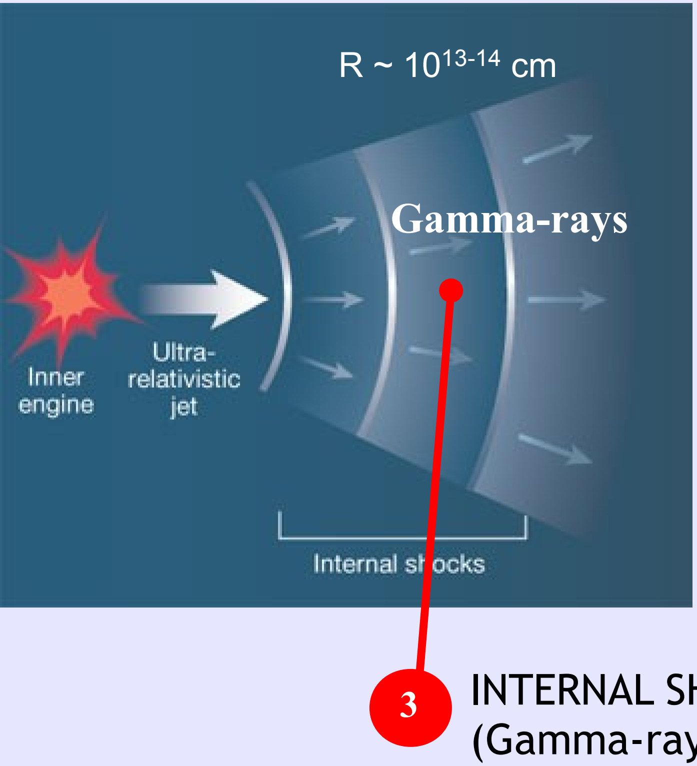

INTERNAL SHOCKS
(Gamma-rays are emitted by accelerated electrons)
Prompt emission

Radiation mechanism still unknown

Theoretical framework

Internal/external non collisional shock model (e.g. Meszaros & Rees 1993)

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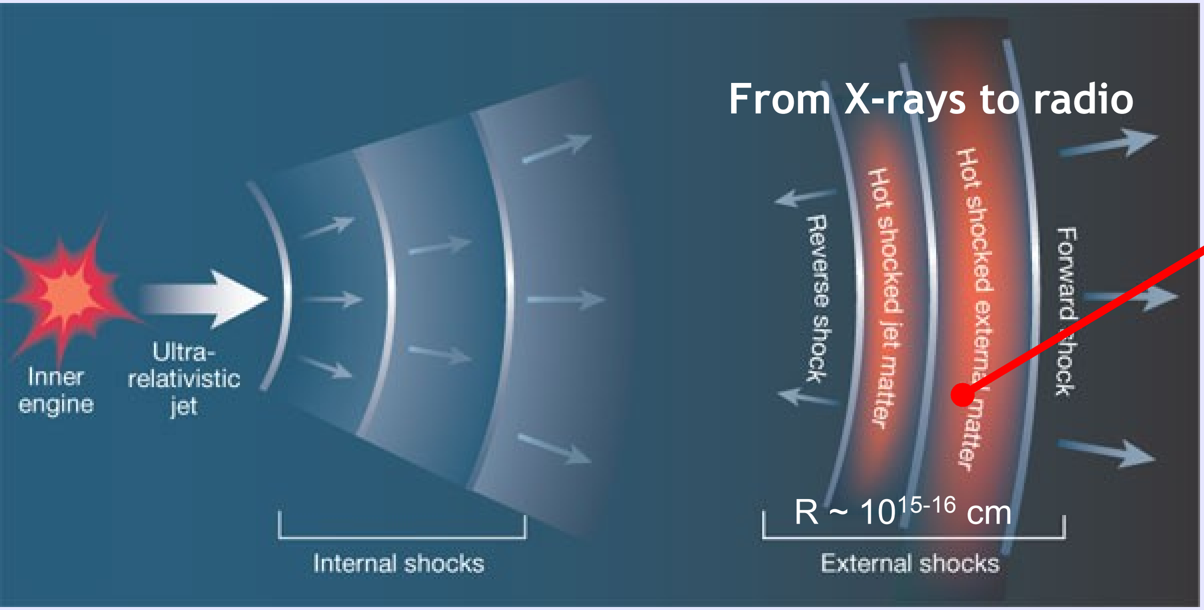
(Piran, Nature, 2003)



4 EXTERNAL SHOCKS
(forward shock waves propagate in ISM accelerating electrons that produce synchroton multi-wavelength radiation)
Afterglow emission

Theoretical framework

Internal/external non collisional shock model (e.g. Meszaros & Rees 1993)

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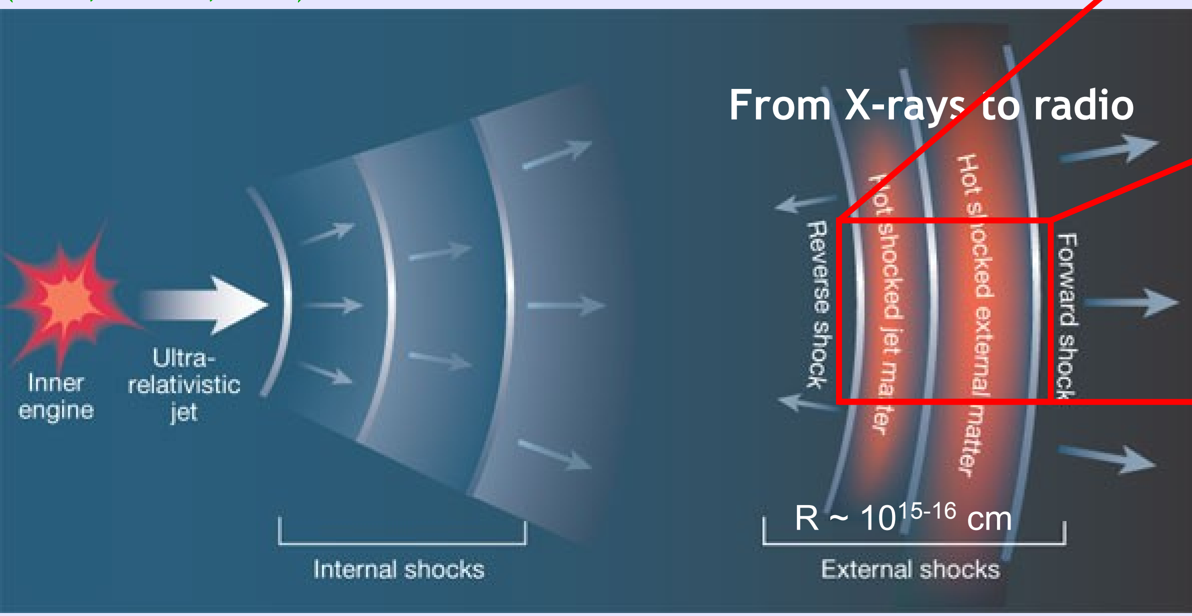
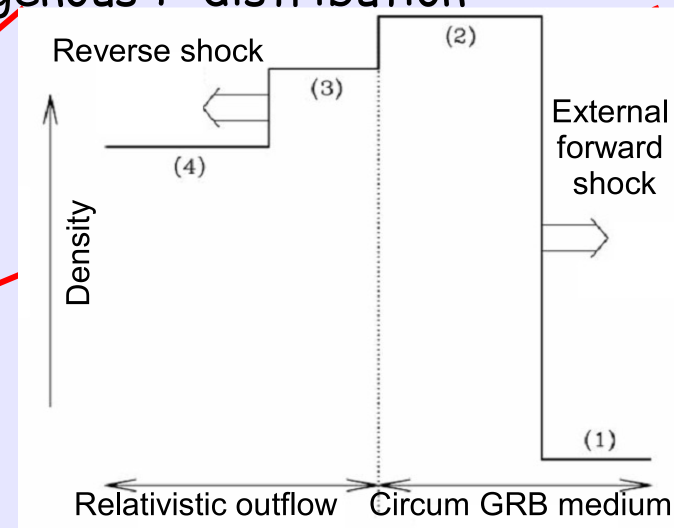
(Piran, Nature, 2003)





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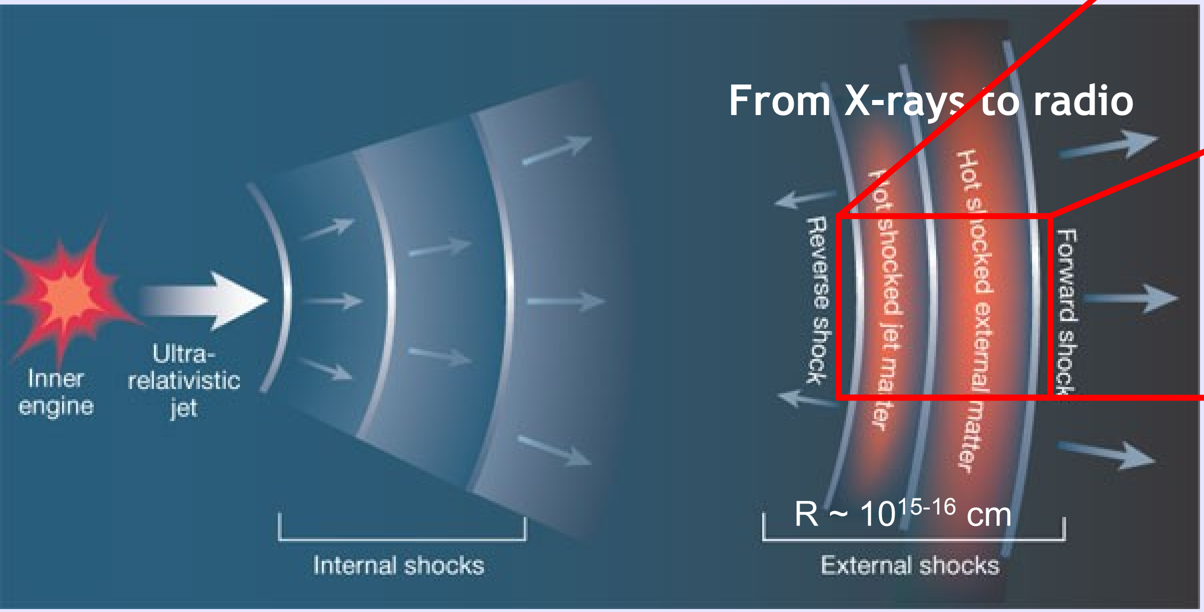
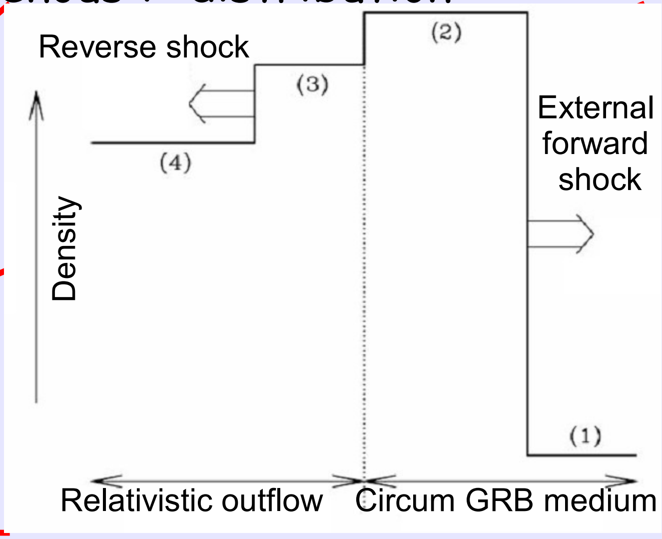




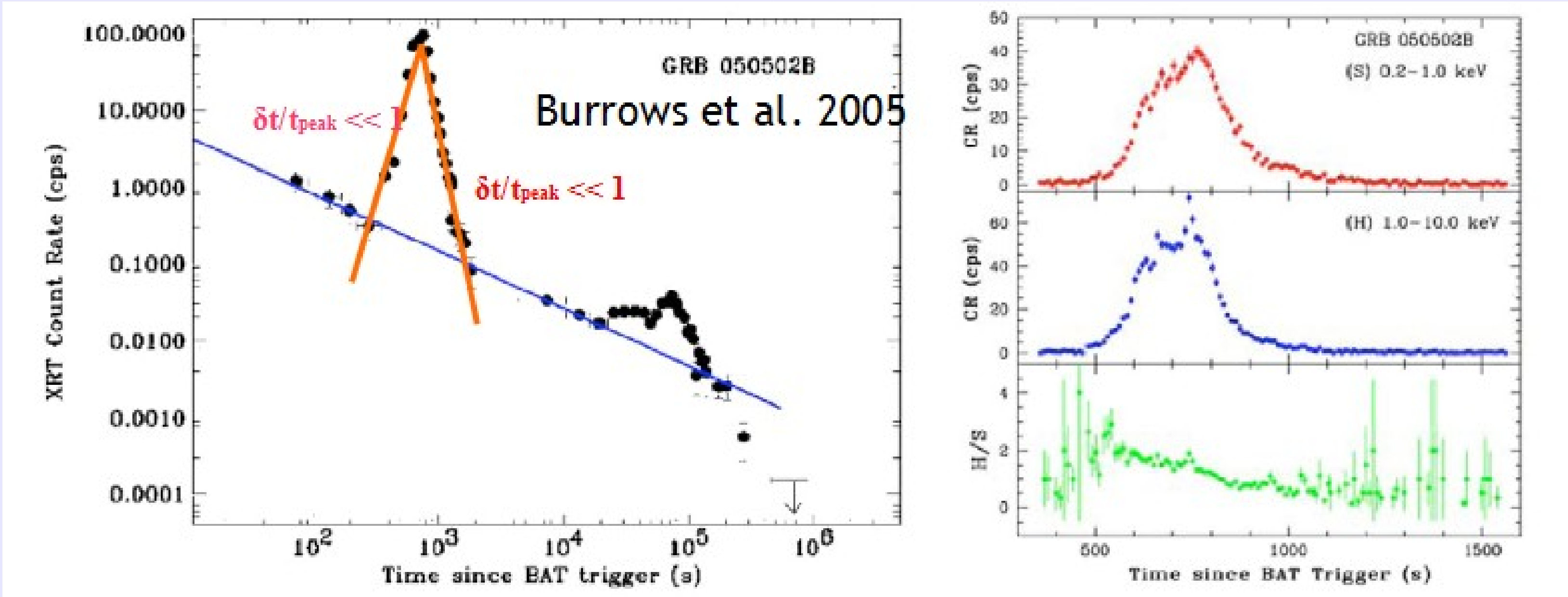
• AG emission dominated by forward shock

• Outflows deccelerate when sweeping through the circum GRB environment (Γ decreases)
– transverse spread of the jet

• Building up of magnetic fields into shocks

Restart of the central engine?

- End of the prompt emission = stop of any activity from the central source
- X-ray flares present (at early and late times) in > 50% of the GRBs (long & short) detected by *Swift*
- Similar spectral properties to those of the Gamma-ray peaks

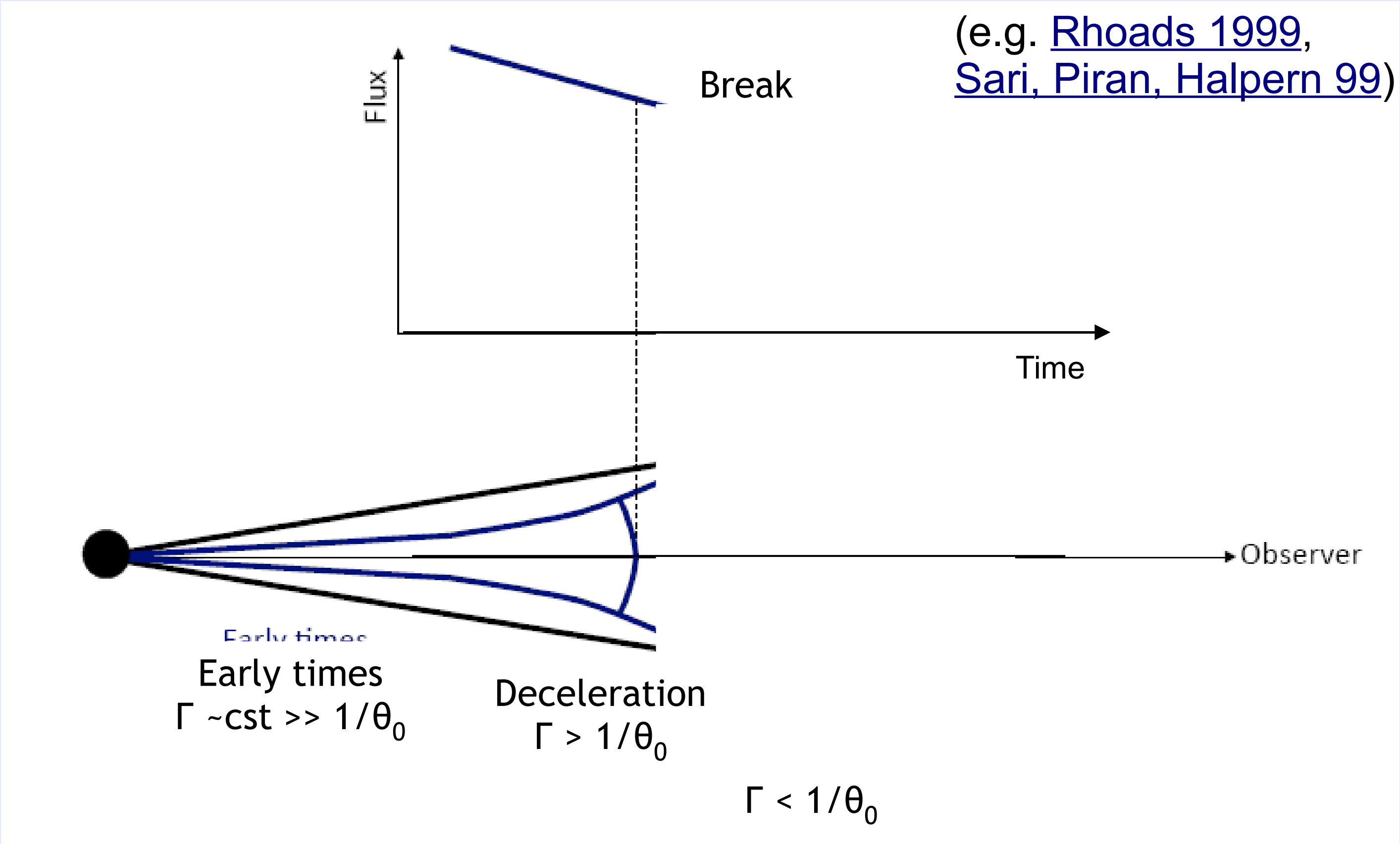


(e.g. Falcone et al. 2007; Chincarini et al. 2010)

- External origin?
  Energetic issues argues against an origin due to external shocks (e.g. Zhang+06)

- All evidence points towards an origin internal to the jets (internal shocks, magnetic reconnection?)
- Problem: this implies an extended activity of the central engine or a restart of the central engine up to several days in some cases (e.g. King et al. 2005; Proga & Zhang 2006).

Jet breaks



Question: What will happen when the blastwave will start decelerating?

- The jet break being a hydrodynamical effect, it should be an achromatic break.
- The observation of jet breaks enables us to derive the jet opening angle.

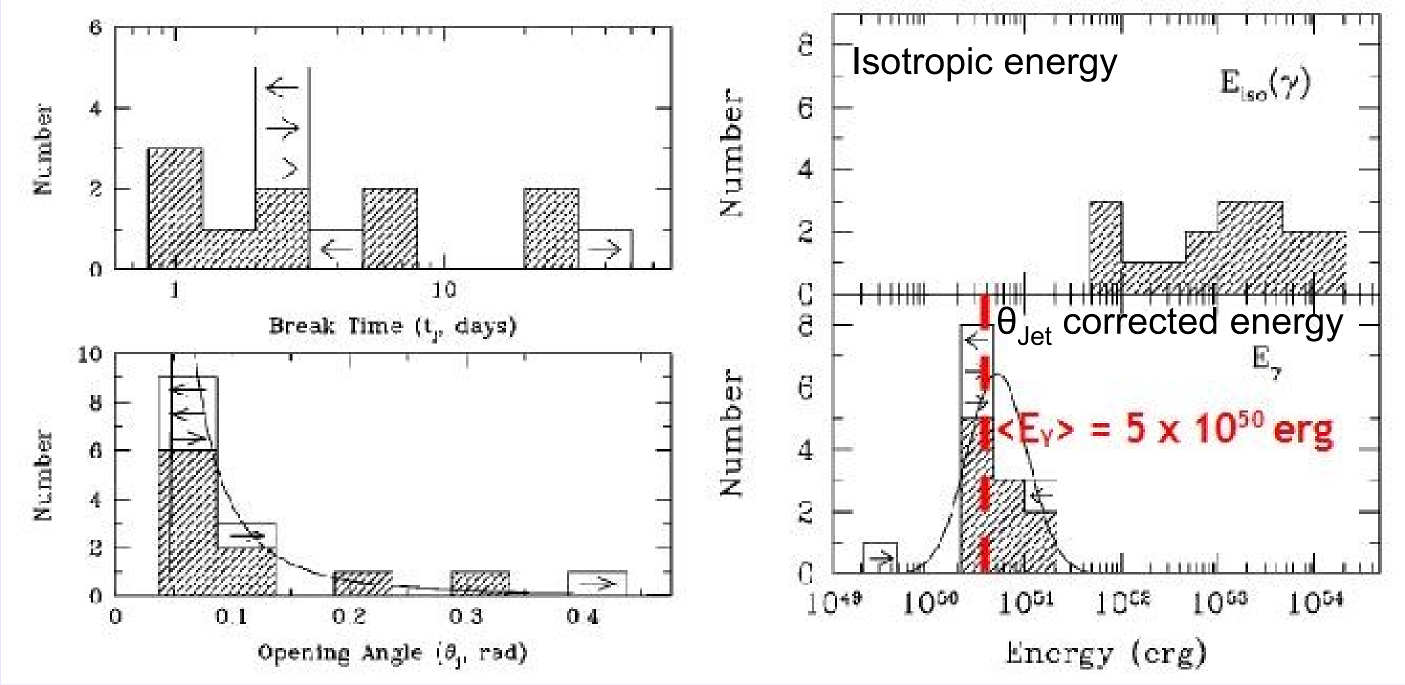
If jets seen sideways, increase in the emitting surface visible by the observer

→ rebrightening before flux decreases

Corrected energetics & GRB rate

- In the pre-*Swift* era, some jet breaks were observed, but mostly in optical.
- Only a few were observed in several energy bands.

- From the observed jet breaks, the jet opening angle was estimated.



Frail et al. 2001

- Observed rate ~ 1 per day with BATSE over 9 yrs – but probably more due to beaming

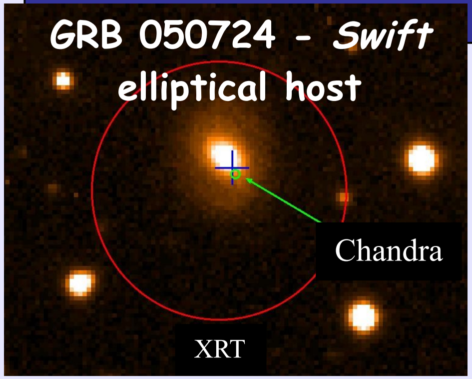
- Rate for long GRBs ~ 100-1000 events / Gpc^3 / yr ~ 1-10% of rate of Ib/c SNe

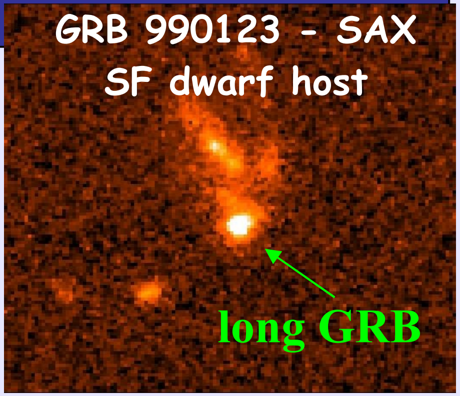
GRB progenitors

- Lower Redshifts
  - ✓ < z > = 0.4 short
  - ✓ < z > = 2.8 long
- Weaker Afterglows
  - ✓ $< F_{X\ short} > = 7 \times 10^{-10}$ erg cm^{-2} s^{-1}
  - ✓ $< F_{X\ long} > = 3 \times 10^{-9}$ erg cm^{-2} s^{-1}
- Less Jet Collimation?
  - ✓ $\theta \sim 15^\circ$ (wide spread) short
  - ✓ $\theta \sim 5^\circ$ (wide spread) long
- Less Total Energy
  - ✓ $E_{rad} \sim 10^{49}$ ergs short
  - ✓ $E_{rad} \sim 10^{51}$ ergs long

Short GRBs

- Hosts: non star-forming (e.g. elliptical) & star-forming galaxies
- GRBs located in the outskirts of SF galaxies or far from SF regions
- SF galaxies with SF rate less than for long GRB hosts



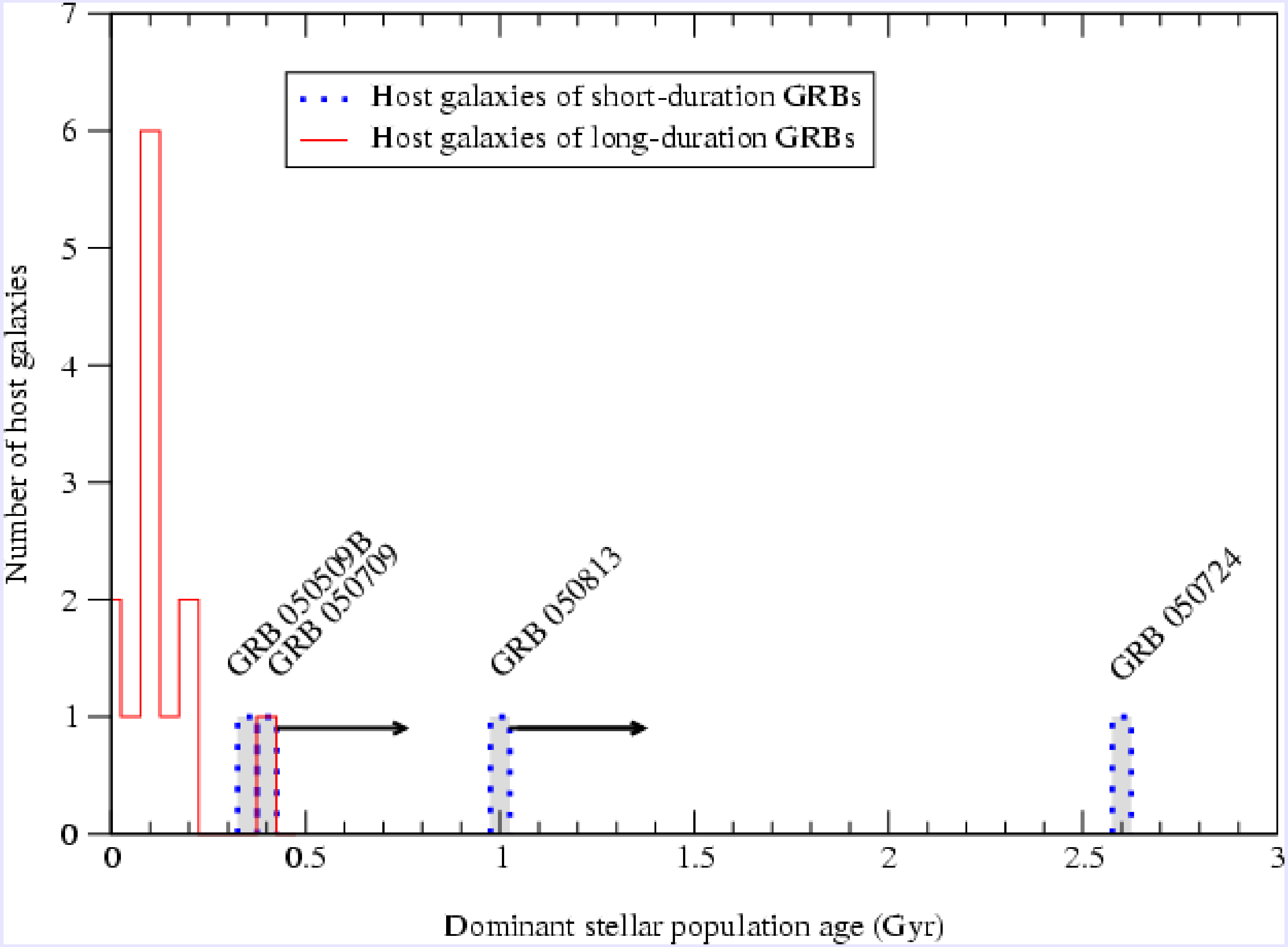


Long GRBs

- Hosts: dwarf, spiral & irregular star-forming galaxies
- GRB positions associated with brightest parts of the host galaxy (assumed to be star-forming regions)

GRB progenitors

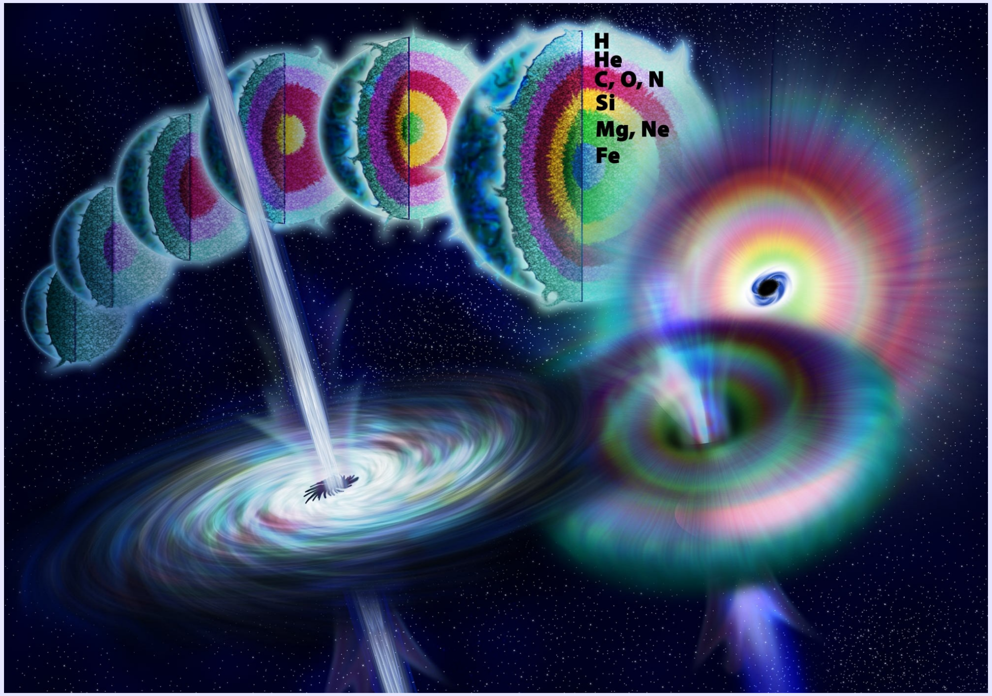
Grosabel et al. (2006)

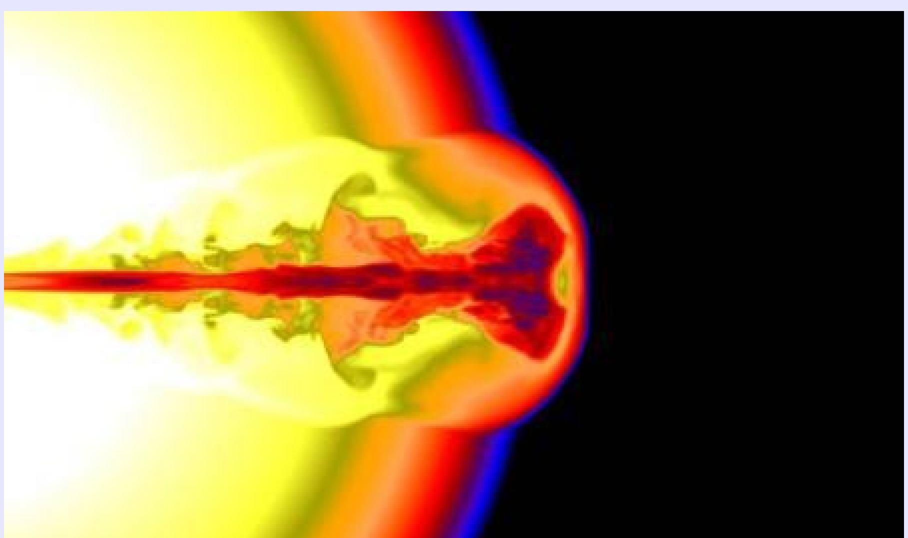


- 2 main formation paths : merger of NS-NS or collapsar

GRB progenitors

Collapsar (e.g. MacFadyen & Woosley 1999)





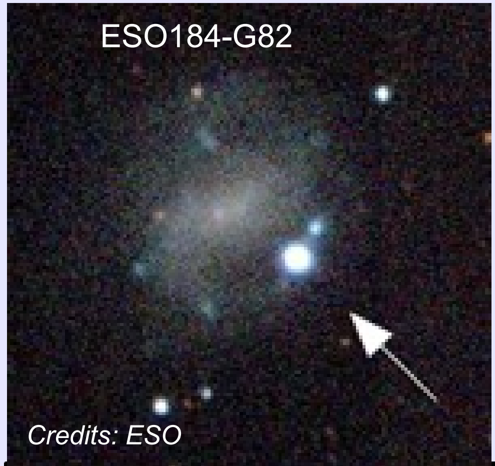
- Compact massive star (Wolf-Rayet C,N,O star)

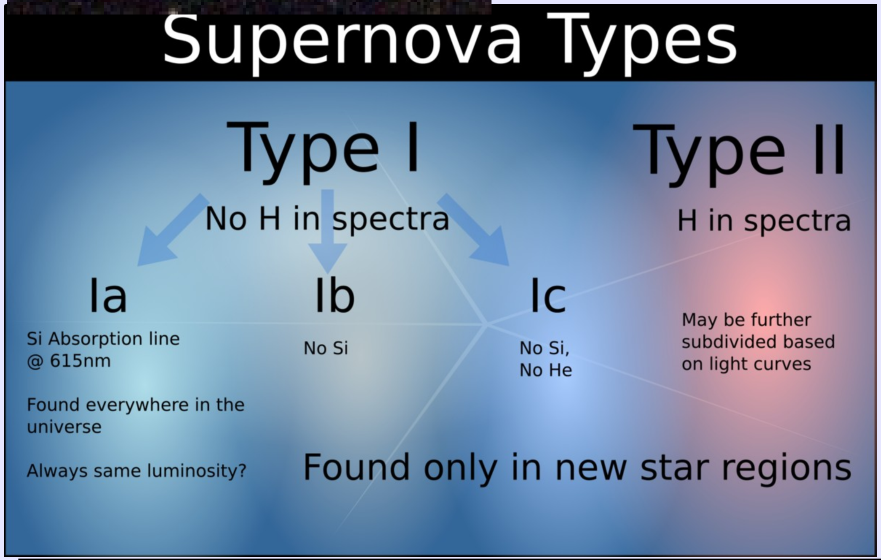
- Stars with high angular momentum and low metallicity
  - Catastrophic formation of a BH coupled with an accretion disk
  - Energy emitted through polar regions – jets (funnel and lateral collimation from ram pressure in the envelop) – launch mechanism unknown
  - Envelop of the star collimates jet
  - Jet breakout from the stellar envelop after a tens of seconds.
  - Conversion of internal energy after breakout to kinetic energy (large Lorentz factors)
  - strong winds from accretion disk energizes the material from the star envelop (hypernovae)

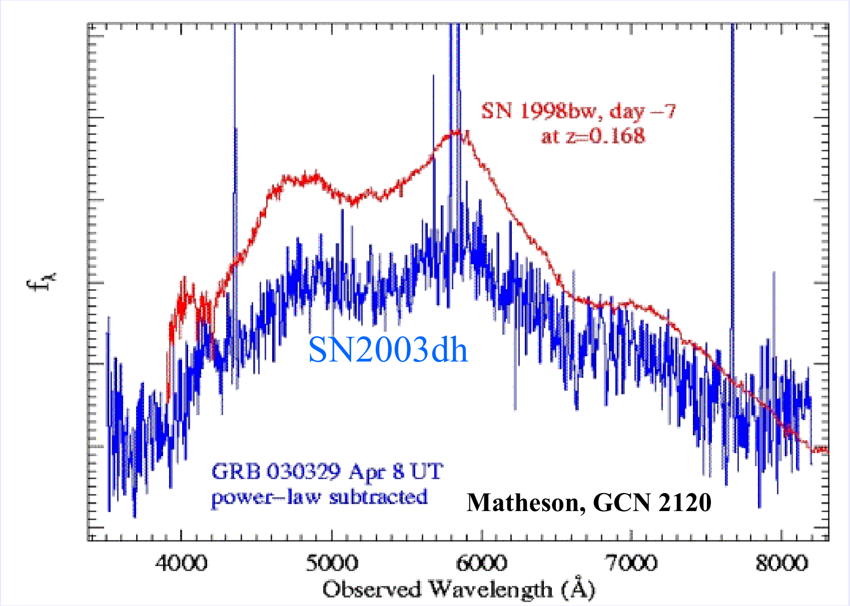
GRB progenitors

Collapsar

- Association GRB/XRF with very bright Type Ib/c SNe (hypernovae)
  - GRB980425 & SN1998bw: first association between an underluminous GRB ($E_{iso} \sim 10^{48}$ erg) and a SN Ib/c (Galama et al. 1998, Nature)





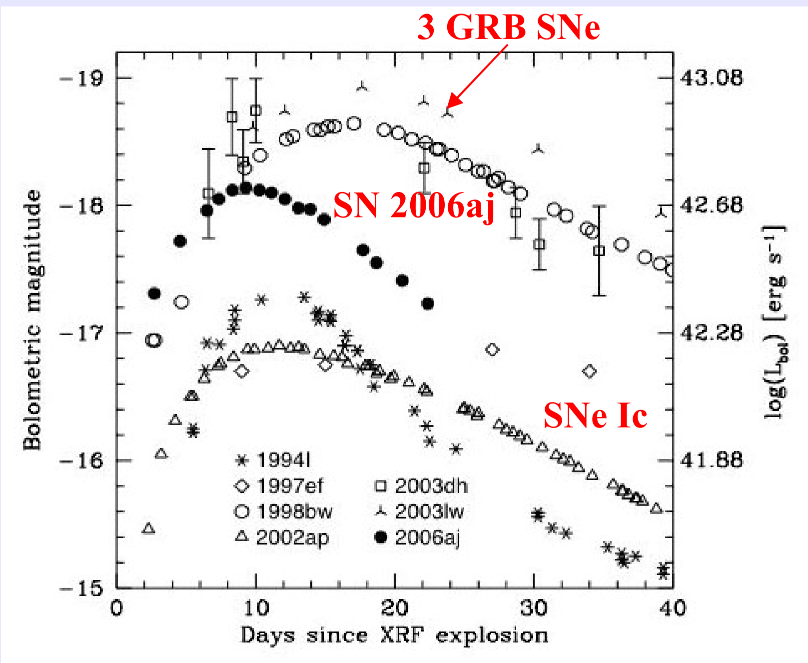


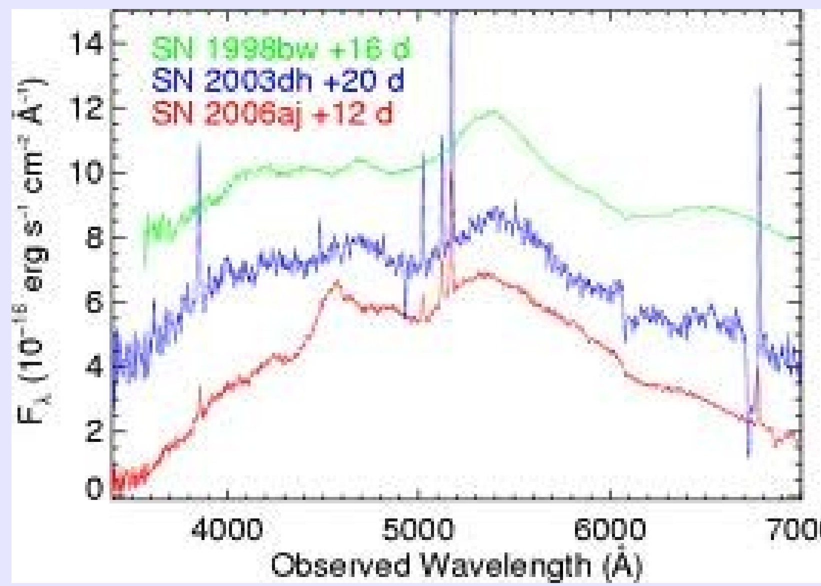
  - GRB 030329: First connections between long classical GRBs & SNe Ib/c (HETE-2; Stanek et al. 2003)

GRB progenitors

Collapsar

• Their spectra in general show that the ejected matter moves ten times faster than that observed in normal SNe Ib/c ➡ **Energy injection by the central engine**

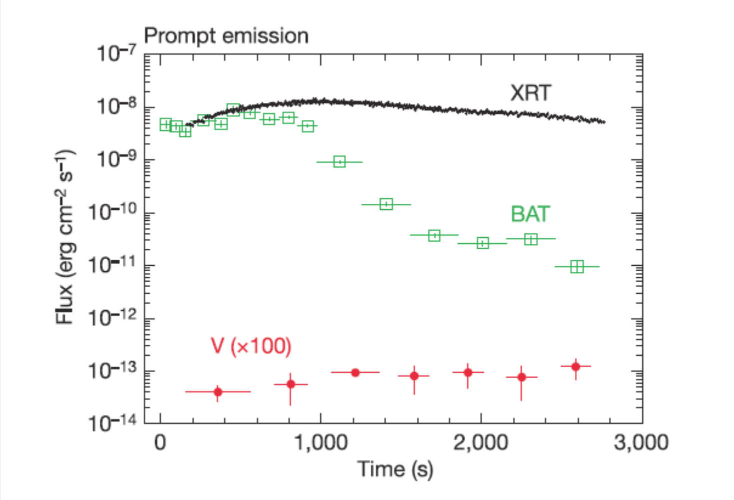




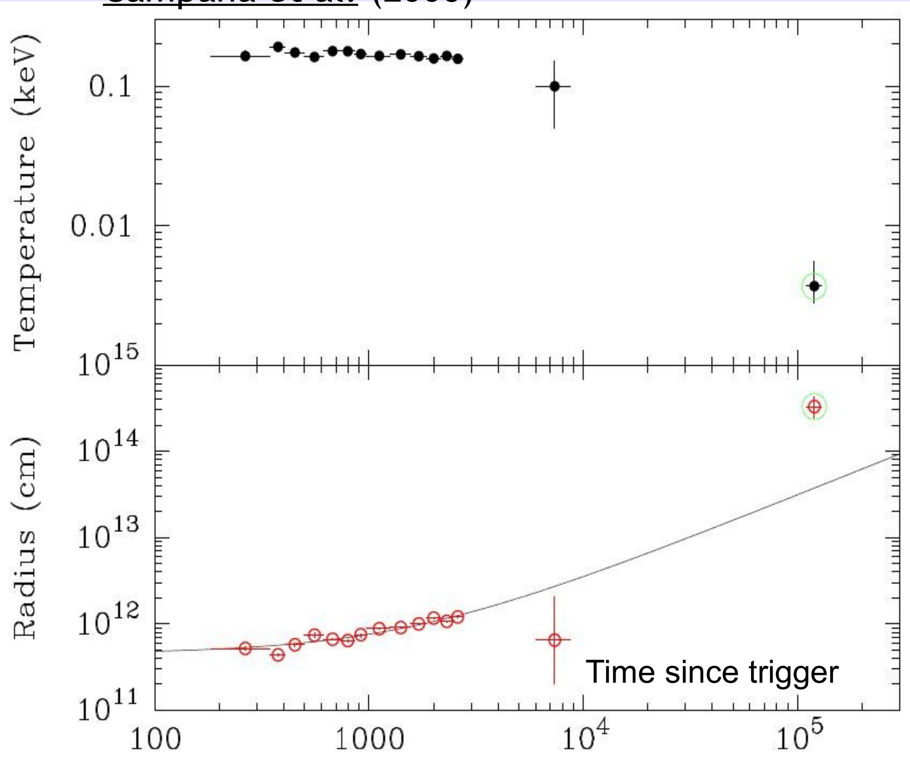
GRB progenitors

Campana et al., Pian et al., Soderberg et al. (2006)

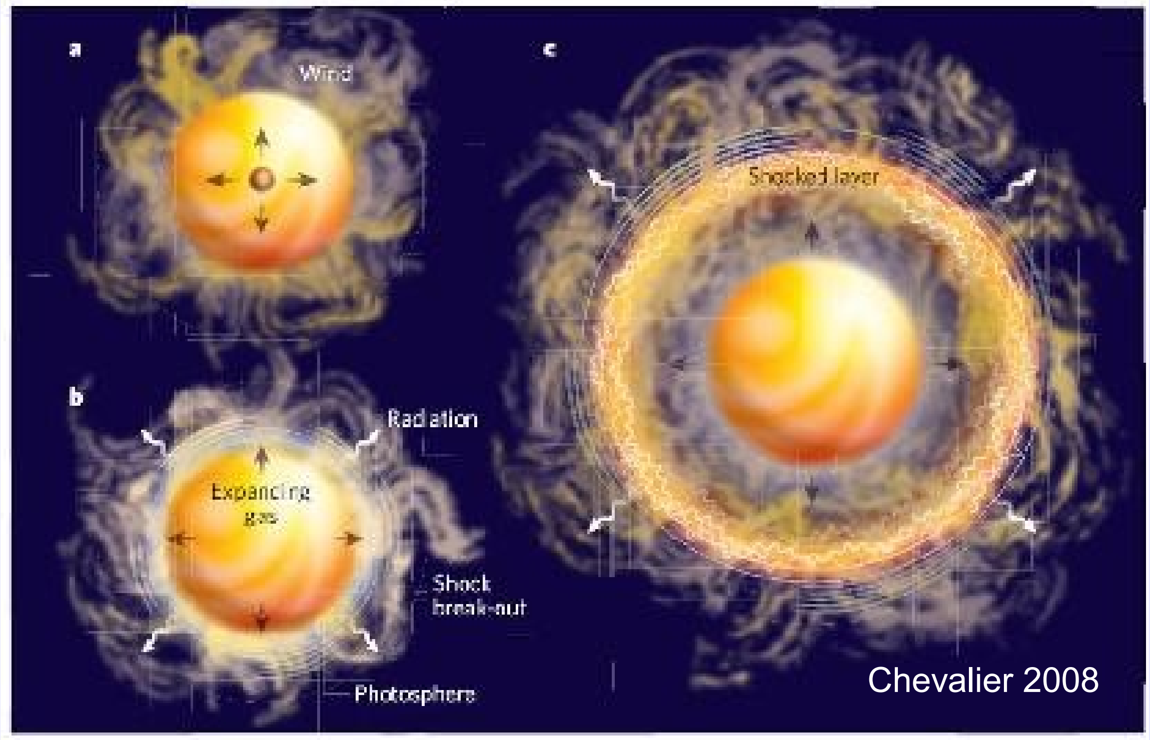
Shock breakout



Campana et al. (2006)

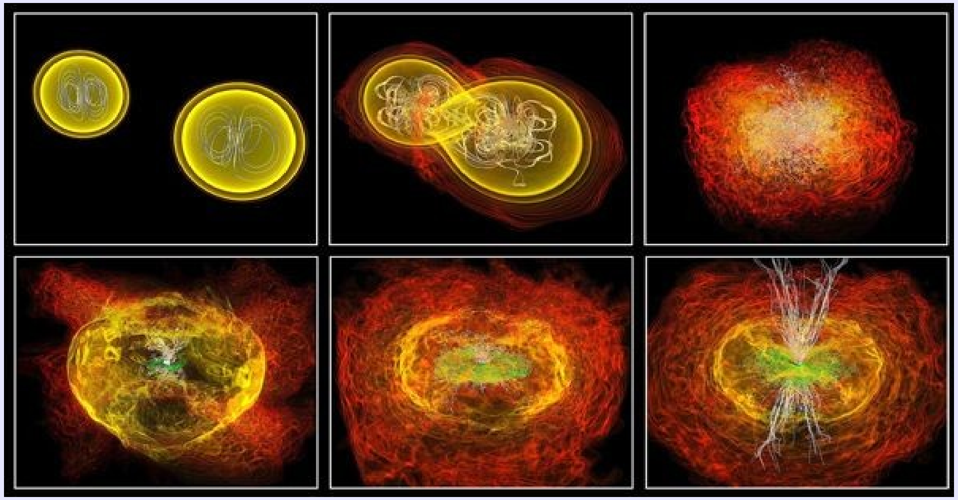


- Super-long GRB T_{90} ~35 minutes associated with SN 2006aj SN Ib/c
- BAT, XRT, UVOT observed simultaneously
- z = 0.033 (145 Mpc) → closest GRB
- E_{iso} = few x 10^{49} erg - underluminous
- Thermal component in XRT data ➡ Shock break-out seen for first time (from X-ray to UV/opt.)
- R_{star} ~ 4 x 10^{11} cm (consistent with Wolf Rayet stars)



GRB progenitors

Merger of NS-NS (NS-BH) (e.g. Eichler et al. 1989; Narayan et al. 1992)



• Alternative progenitor BH-BH merger

• Direct GW detection by aLIGO (Abbott+16)

Merger of 2 massive stellar mass BHs (>20 M_{Sun})

• Possible electromagnetic prompt counterpart by Fermi? (Connaughton+16)

• Accretion from residual matter onto the newly formed 62 M_{Sun} BH (Loeb16) or charged BHs (more speculative!!)

• Binary formation
  - Binary of massive stars evolved in 2 NS
  - Dynamical capture (e.g. within globular clusters)

• When formed NSs receive a dynomical kick (a few 100 km/s) ➡ Ejection from their birthplace

(ISM with small density → weaker AG emission)

• Timescale of the merger ~ ms

• No or very weak SNe (kilonovae) expected

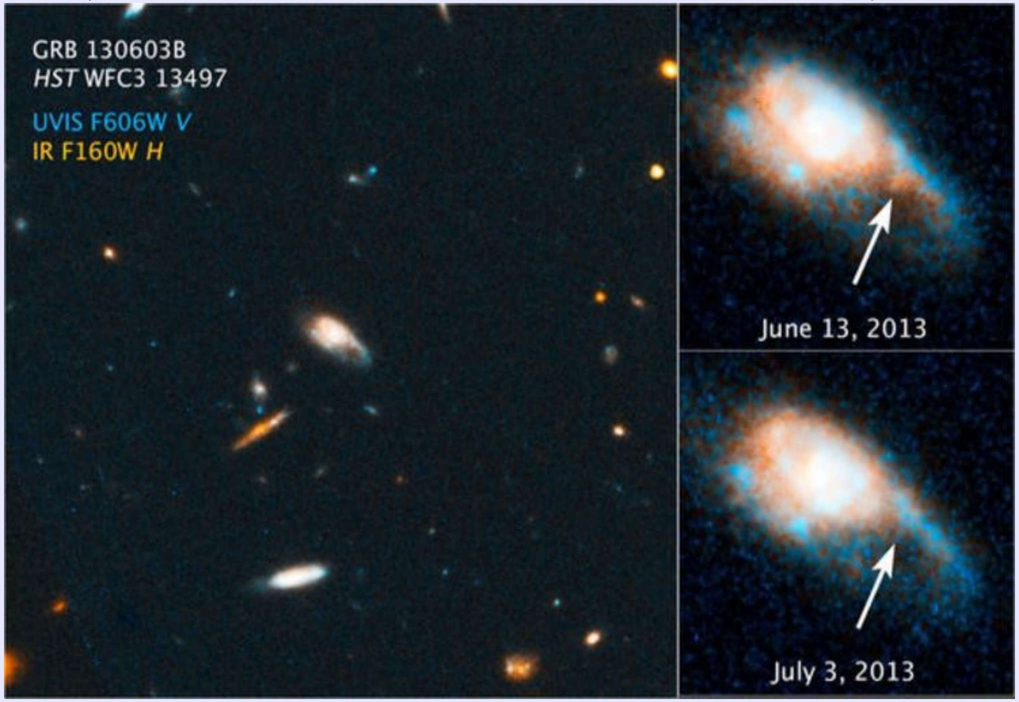
• Less collimation is also expected.

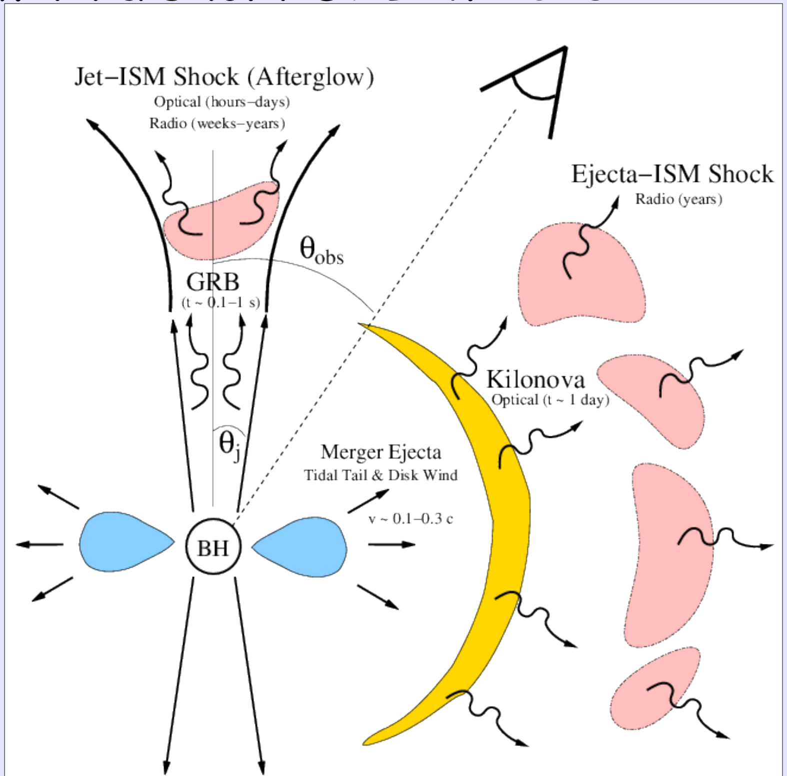
• Energy reservoir smaller

GRB progenitors

Merger of NS-NS (NS-BH)

- First detection of a kilonova associated with a short GRB in 2013 (GRB130603B - Tanvir et al. 2013)





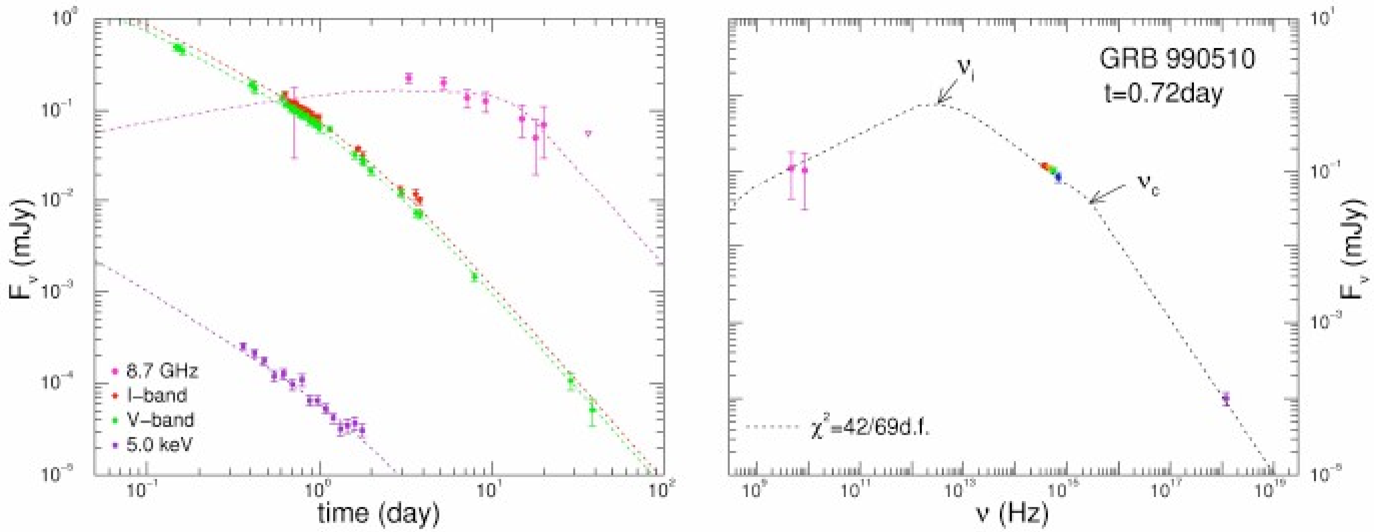
Metzger & Berger 2012

- Following the merger of 2 NS, neutron rich matter can be ejected.
- Ejected material undergoes rapid neutron capture (r-process), creating heavy elements from merger of original nuclei with the available neutrons.
- When those elements undergo radioactive decay, light emitted in the optical and near-IR bands. The energy emitted can reach 10^3 times that coming from a nova.

AG standard emission model

Panaitescu & Kumar (2001) (see also Sari, Piran & Narayan 1998)

Simple physics : Blandford-McKee (dynamics) + synchrotron radiation = 6 parameters



$$N_{e^-} \propto E^{-p}$$

(non-thermal distribution)

- *Acceleration mechanism still unknown*

- Model predictions depend on the nature of the circum-burst environment

➡ Possibility to probe the close environment of GRB by modeling the AG emission and micro-physics (ε_e & ε_B = shock equipartition parameters for e- et magnetic fields)

- Powerlaw segments & spectral breaks evolving with time

- 3 specific frequencies depending on time :
  - ν_m = synchrotron freq. → maximum emission
  - ν_c = cooling freq. → electrons above ν_c could cool efficiently by emitting photons
  - ν_a = self-absorption freq. → synchroton photons get absorbed by emitting medium

AG standard emission model

TEMPORAL INDEX α AND SPECTRAL INDEX β IN VARIOUS AFTERGLOW MODELS.

		no injection		injection	
	β	α	$\alpha(\beta)$	α	$\alpha(\beta)$
ISM	slow cooling				
$\nu < \nu_m$	$-\frac{1}{3}$	$-\frac{1}{2}$	$\alpha = \frac{3\beta}{2}$	$\frac{5q-8}{6}$ (-0.9)	$\alpha = (q-1) + \frac{(2+q)\beta}{2}$
$\nu_m < \nu < \nu_c$	$\frac{p-1}{2}$ (0.65)	$\frac{3(p-1)}{4}$ (1.0)	$\alpha = \frac{3\beta}{2}$	$\frac{(2p-6)+(p+3)q}{4}$ (0.3)	$\alpha = (q-1) + \frac{(2+q)\beta}{2}$
$\nu > \nu_c$	$\frac{p}{2}$ (1.15)	$\frac{3p-2}{4}$ (1.2)	$\alpha = \frac{3\beta-1}{2}$	$\frac{(2p-4)+(p+2)q}{4}$ (0.7)	$\alpha = \frac{q-2}{2} + \frac{(2+q)\beta}{2}$
ISM	fast cooling				
$\nu < \nu_c$	$-\frac{1}{3}$	$-\frac{1}{6}$	$\alpha = \frac{\beta}{2}$	$\frac{7q-8}{6}$ (-0.8)	$\alpha = (q-1) + \frac{(2-q)\beta}{2}$
$\nu_c < \nu < \nu_m$	$\frac{1}{2}$	$\frac{1}{4}$	$\alpha = \frac{\beta}{2}$	$\frac{3q-2}{4}$ (-0.1)	$\alpha = (q-1) + \frac{(2-q)\beta}{2}$
$\nu > \nu_m$	$\frac{p}{2}$ (1.15)	$\frac{3p-2}{4}$ (1.2)	$\alpha = \frac{3\beta-1}{2}$	$\frac{(2p-4)+(p+2)q}{4}$ (0.7)	$\alpha = \frac{q-2}{2} + \frac{(2+q)\beta}{2}$
Wind	slow cooling				
$\nu < \nu_m$	$-\frac{1}{3}$	0	$\alpha = \frac{3\beta+1}{2}$	$\frac{q-1}{3}$ (-0.2)	$\alpha = \frac{q}{2} + \frac{(2+q)\beta}{2}$
$\nu_m < \nu < \nu_c$	$\frac{p-1}{2}$ (0.65)	$\frac{3p-1}{4}$ (1.5)	$\alpha = \frac{3\beta+1}{2}$	$\frac{(2p-2)+(p+1)q}{4}$ (1.1)	$\alpha = \frac{q}{2} + \frac{(2+q)\beta}{2}$
$\nu > \nu_c$	$\frac{p}{2}$ (1.15)	$\frac{3p-2}{4}$ (1.2)	$\alpha = \frac{3\beta-1}{2}$	$\frac{(2p-4)+(p+2)q}{4}$ (0.7)	$\alpha = \frac{q-2}{2} + \frac{(2+q)\beta}{2}$
Wind	fast cooling				
$\nu < \nu_c$	$-\frac{1}{3}$	$\frac{2}{3}$	$\alpha = \frac{1-\beta}{2}$	$\frac{(1+q)}{3}$ (0.5)	$\alpha = \frac{q}{2} - \frac{(2-q)\beta}{2}$
$\nu_c < \nu < \nu_m$	$\frac{1}{2}$	$\frac{1}{4}$	$\alpha = \frac{1-\beta}{2}$	$\frac{3q-2}{4}$ (-0.1)	$\alpha = \frac{q}{2} - \frac{(2-q)\beta}{2}$
$\nu > \nu_m$	$\frac{p}{2}$ (1.15)	$\frac{3p-2}{4}$ (1.2)	$\alpha = \frac{3\beta-1}{2}$	$\frac{(2p-4)+(p+2)q}{4}$ (0.7)	$\alpha = \frac{q-2}{2} + \frac{(2+q)\beta}{2}$

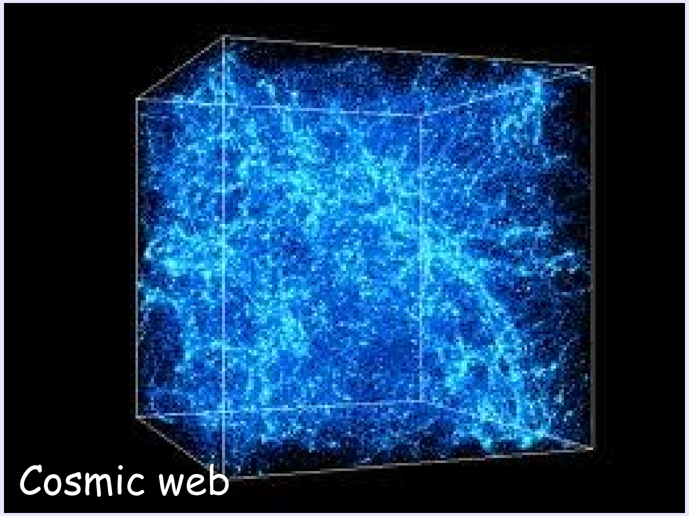
NOTE. — This is the extension of the Table 1 of Zhang & Mészáros (2004), with the inclusion of the cases of energy injection. The case of $p < 2$ is not included, and the self-absorption effect is not discussed. Notice that a different convention $F_\nu \propto t^{-\alpha}\nu^{-\beta}$ is adopted here (in comparison to that used in Zhang & Mészáros 2004), mainly because both the temporal index and the spectral index are generally negative in the X-ray band. The temporal indices with energy injection are valid only for $q < 1$, and they reduce to the standard case (without energy injection, e.g. Sari et al. 1998, Chevalier & Li 2000) when $q = 1$. For $q > 1$ the expressions are no longer valid, and the standard model applies. An injection case due to pulsar spindown corresponds to $q = 0$ (Dai & Lu 1998a; Zhang & Mészáros 2001). Recent *Swift* XRT data are generally consistent with $q \sim 0.5$. The numerical values quoted in parentheses are for $p = 2.3$ and $q = 0.5$.

- ISM model (Sari+98), n = cst & $\nu_c \sim t^{-1/2}$
- Wind mode (Chevalier & Li 2000) $n \sim r^{-a}$ avec $a > 2$ & $\nu_c \sim t^{1/2}$

- From the data, a constant ISM model seems to be favoured in most cases.
- From *Swift* data, p is sometimes less than 1.5 (e.g. Willingale et al. 2007).
- For comparison, p = 2.1-2.2 for Fermi acceleration
- Particle acceleration mechanism still unknown

What should we care about GRBs?

- Long GRBs associated with death of massive stars and amongst the furthest objects visible in the Universe
  - Constraints on the stellar formation rate at high redshift ($z > 6$)
  - Constraints on the pop. III stars



- GRBs are very bright and far away.
  - Study the evolution of foreground structures / Warm Hot Intergalactic Medium (e.g. Branchini+09)

    → evolution of hot and diffuse component of baryons along the line of sight

    ➡ High resolution spectroscopy (species, temperature, dynamics, ionization state, column density) with Athena for instance

    → constraints on the epoch of reionization of neutral gas
  - Study of GRB environment / gas in host galaxy
  - Estimate content of metal in high-z galaxies

What should we care about GRBs?

- Are GRBs possible sites of ultra high energy cosmic rays? (e.g. Baerwald+14 / Icecube+16)

- Constraints on modified gravity theories (violation of Lorentz invariance ; Abdo et al. 2009a / Adbo et al. 2009b)

- Short GRBs involved mergers of compact objects
  - GW detectors sensitive enough to make direct detections (Abbott+16)
    → constraints on the progenitor stars, the NS EOS, the newly formed object (nature, mass, spin)

Additional references

- References accessible via the NASA/ADS web interface
- http://adsabs.harvard.edu/abstract_service.html

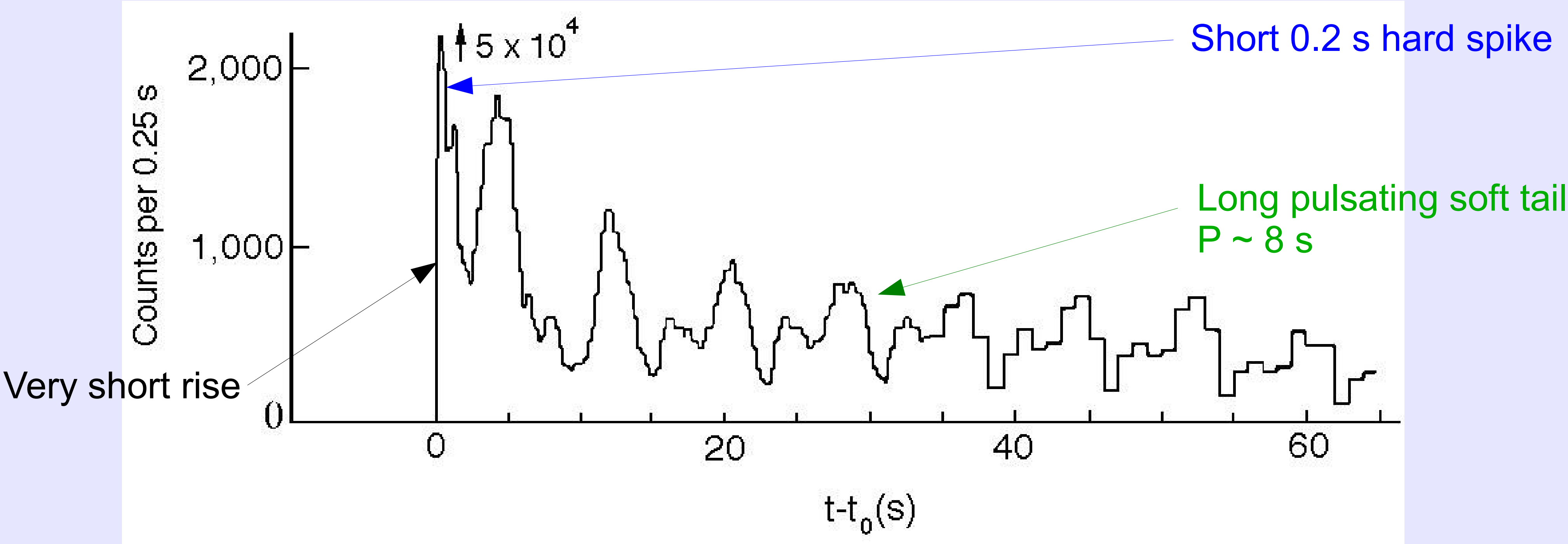
- Gehrels & Meszaros (2012)
- Zhang, B. 2007
- Godet, O & Mochkowitz, R. 2011

PART II

Magnetars

SGR Giant flare on 5th March 1979

- Let's consider the giant SGR flare on 5th March 1979 (Terrell+80, Helfand & Long 79)
- Detected by all missions with onboard Gamma-ray detectors



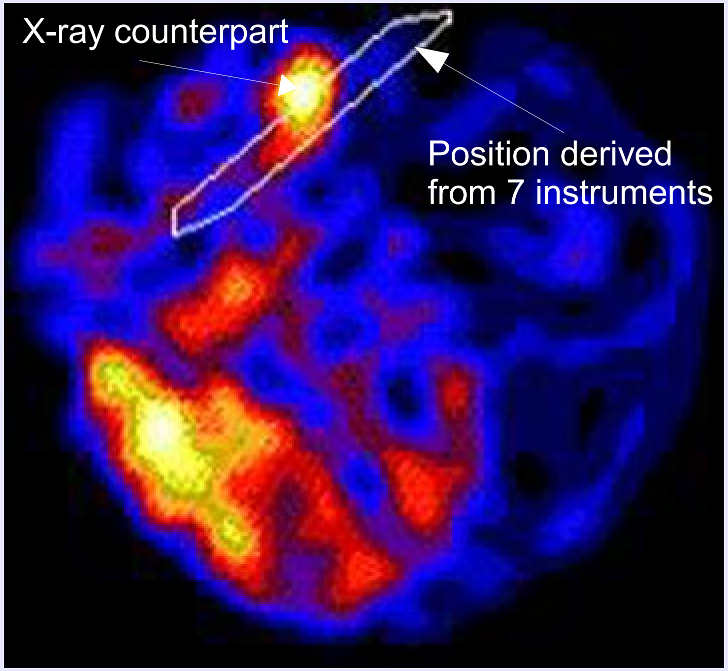
Lightcurve of the March 1979 event from Venera 12 (Mazets+79)

Question: what all of this tell you about the possible progenitor?

Answer: a rotating NS

- 14.5 h later another (fainter) 1,5 burst was detected. More short bursts were detected up to 1983 from the source ➡ So, they repeat! ≠ from GRBs

Nature of SGRs



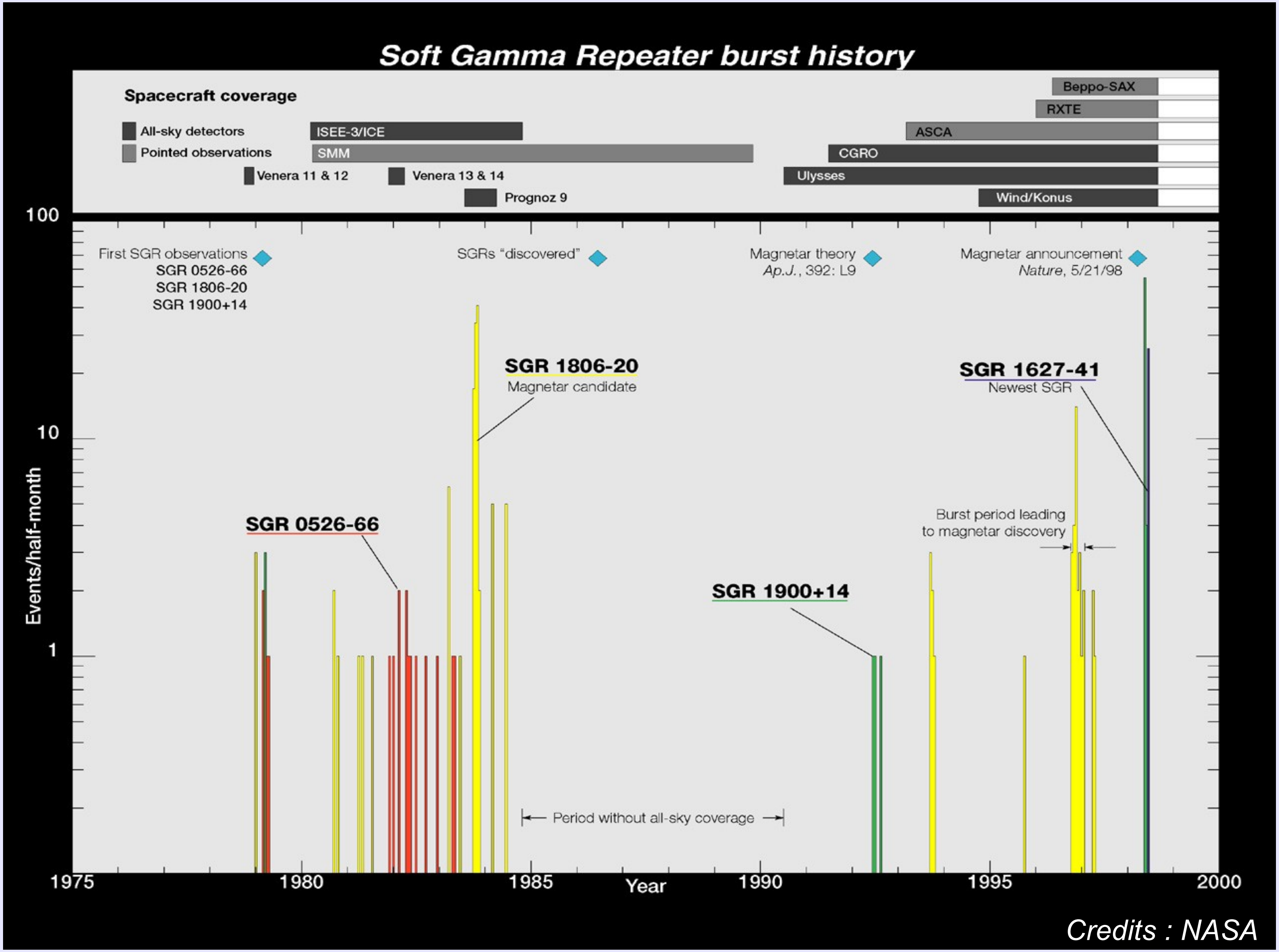
ROSAT X-ray image of the SNR N49 in the LMC (e.g. Marsden+96)

- Position of the giant SGR flare coincident with the supernova remnant N49 in the LMC
- Isotropic peak luminosity ~ 4 10^{44} erg/s !
- Total released energy ~ 5 10^{44} erg/s
- SNR age ~ 5000 yrs ➡ young object
- SNRs older than a few 10^4 yrs no longer visible

- X-ray counterpart off center ➡ NS is moving very fast (~1000 km/s) – Natal kick → likely isolated NS

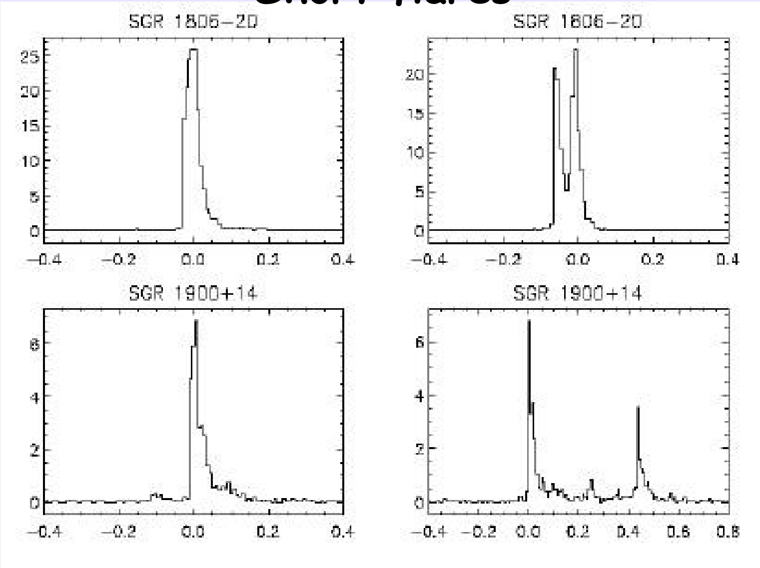
Properties of SGRs

• Other SGRs were found and are still found by high energy missions like Swift.



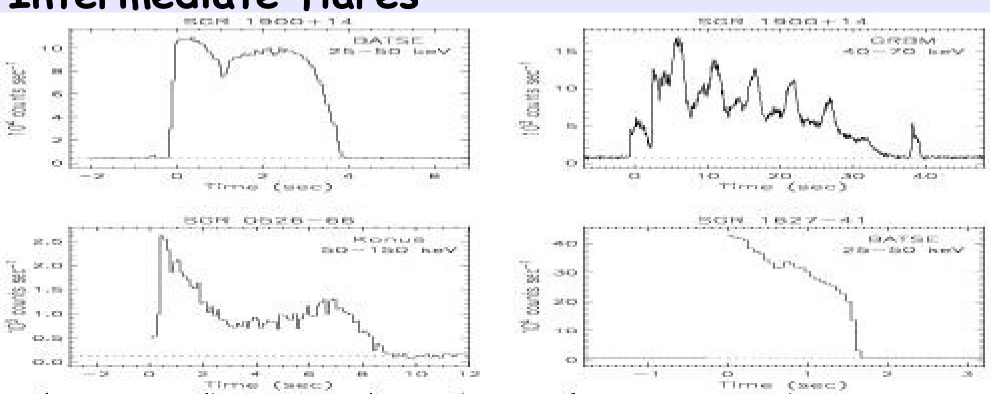
Properties of SGRs

Short flares



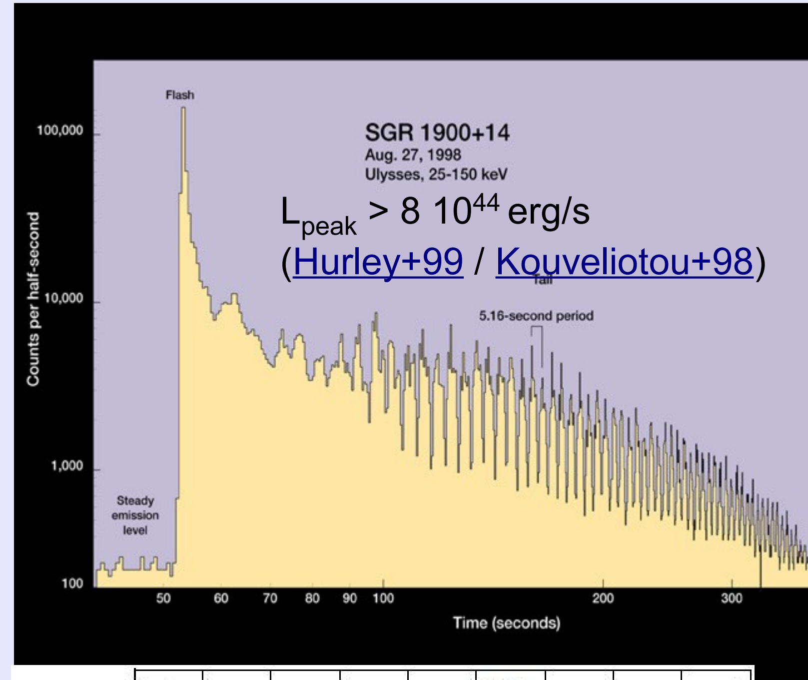
Most frequent
Duration ~ 0.1s
L_{peak} ~ 10^{41} erg/s
Thermal spectral in hard X-rays or soft Gamma-rays

Intermediate flares

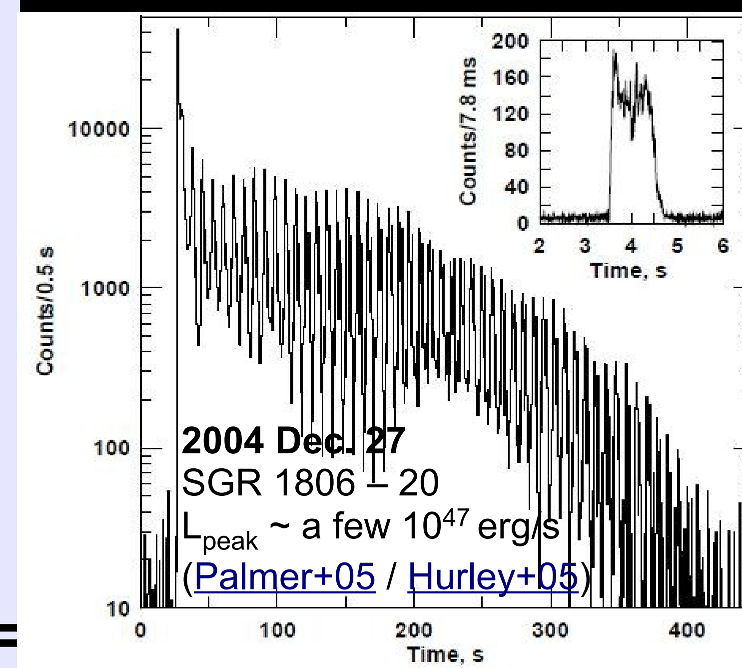


Duration ~ 1 – 40s
L_{peak} ~ 10^{41-43} erg/s
Thermal spectral in hard X-rays

Giant flares



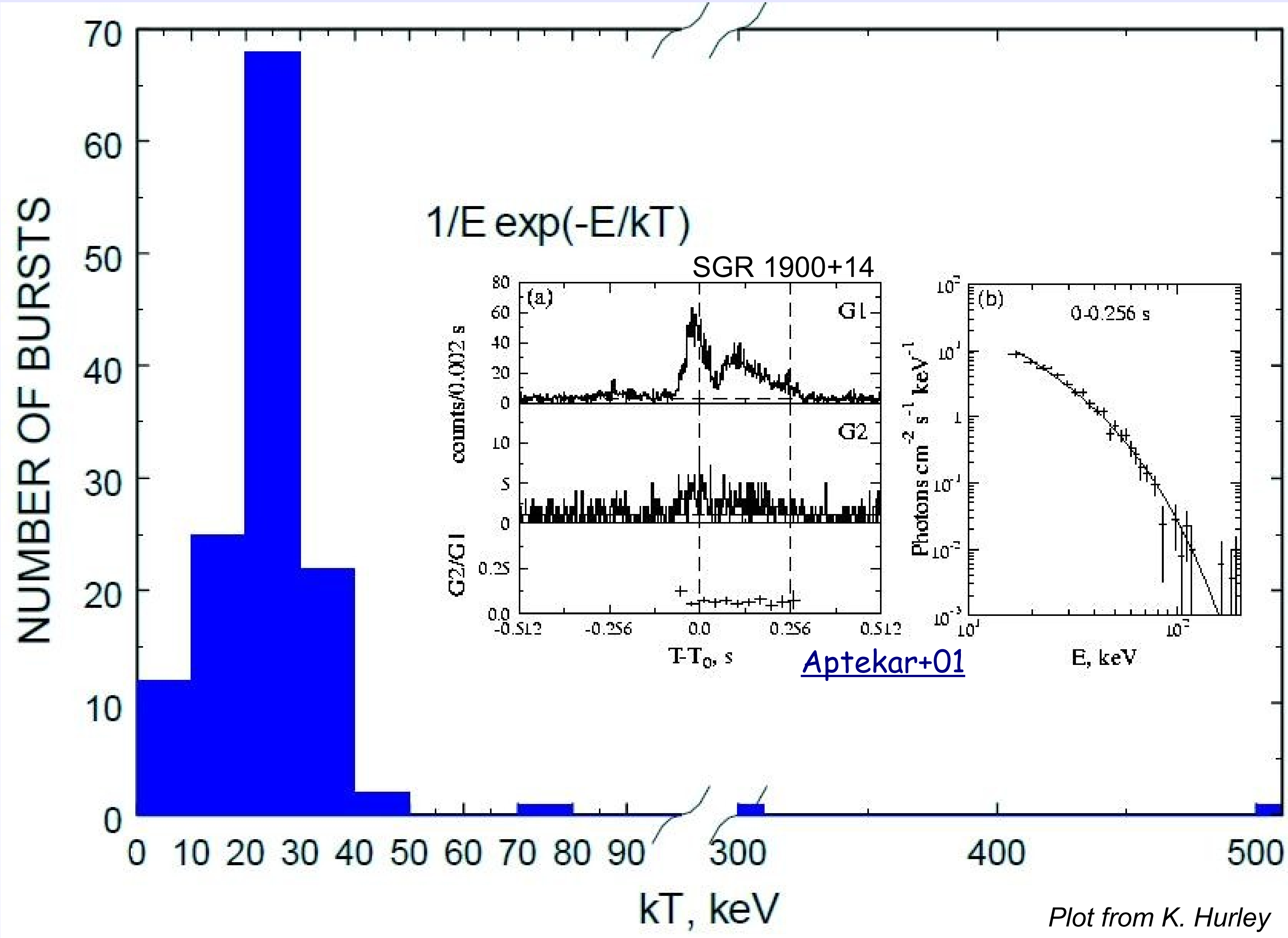
L_{peak} > 8 10^{44} erg/s
(Hurley+99 / Kouveliotou+98)



2004 Dec. 27
SGR 1806 – 20
L_{peak} ~ a few 10^{47} erg/s
(Palmer+05 / Hurley+05)

Properties of SGRs

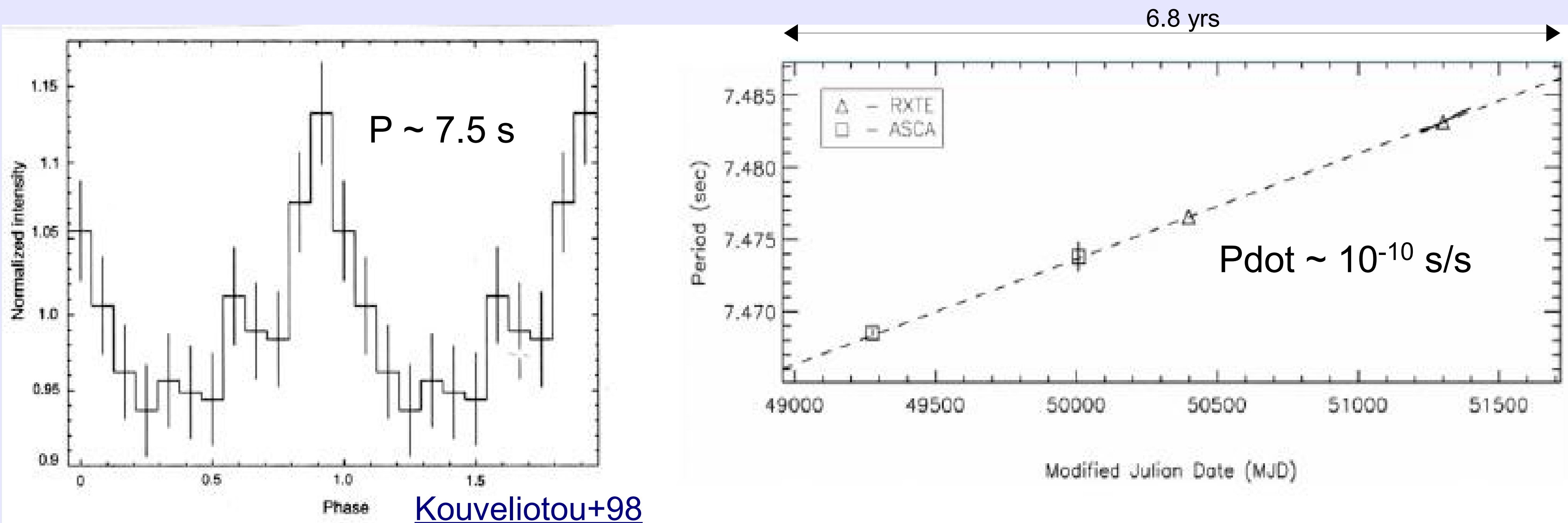
- Emission from short bursts/flares < 100 keV



Properties of SGRs

• When in quiescence, SGRs appear as moderately bright X-ray sources L_X~10^{34-36} erg/s

• NS pulsations could be found when the sources are in quiescence and the spin-down (Pdot) of the NSs could be measured as well.



Kouveliotou+98

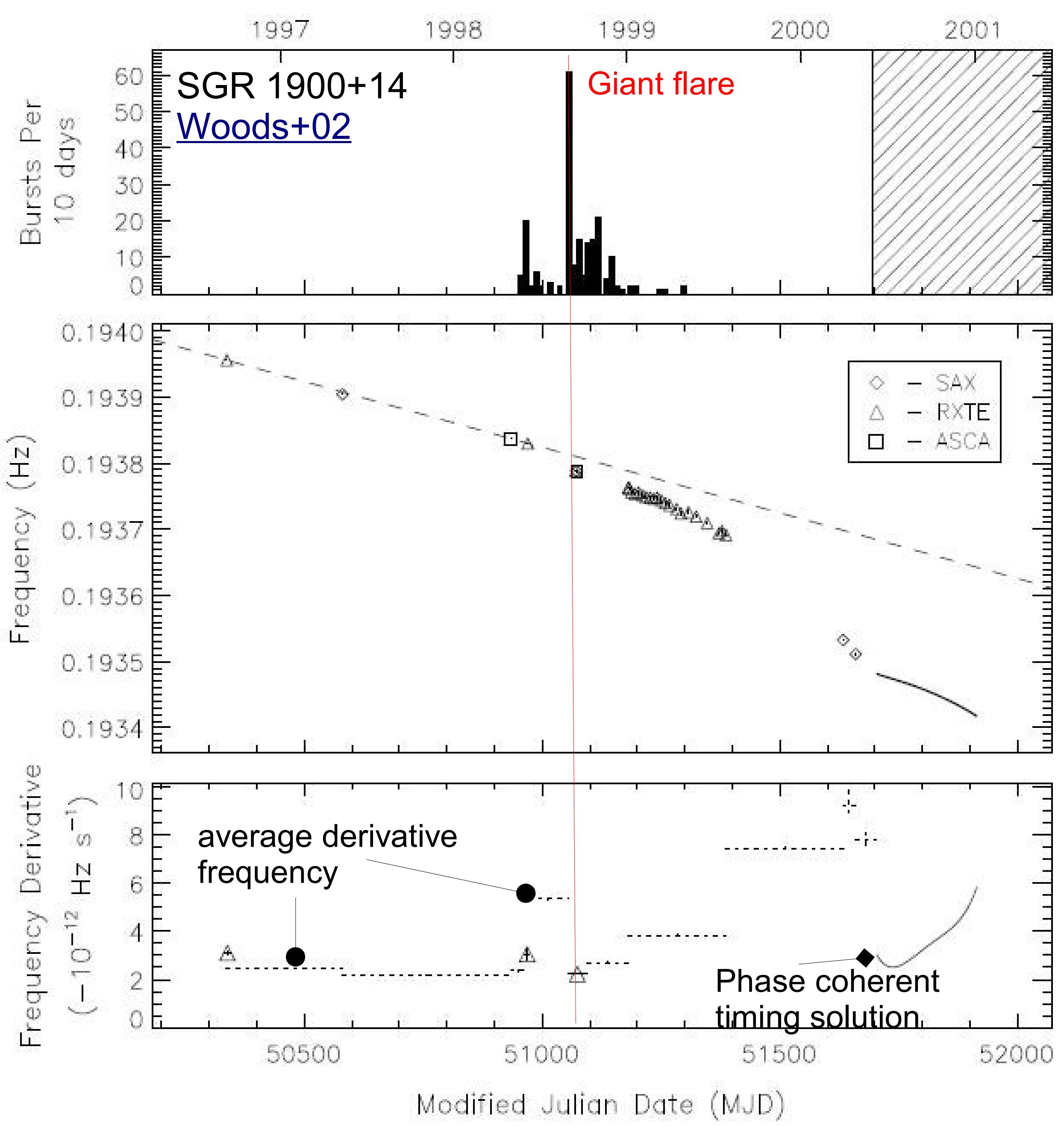
Using 2-10 keV data from SGR 1806-20

Properties of SGRs

- Spindown irregular

- Not related to bursting events

→ Accretion unlikely to power bursts



Properties of SGRs

- 15 discovered to date mostly in our Galaxy (11 confirmed & 4 candidates – see Olausen & Kaspi14 or http://www.physics.mcgill.ca/~pulsar/magnetar/main.html)

- Discovered mostly in hard X-rays

- Low rotators with periods P = 5-9 s

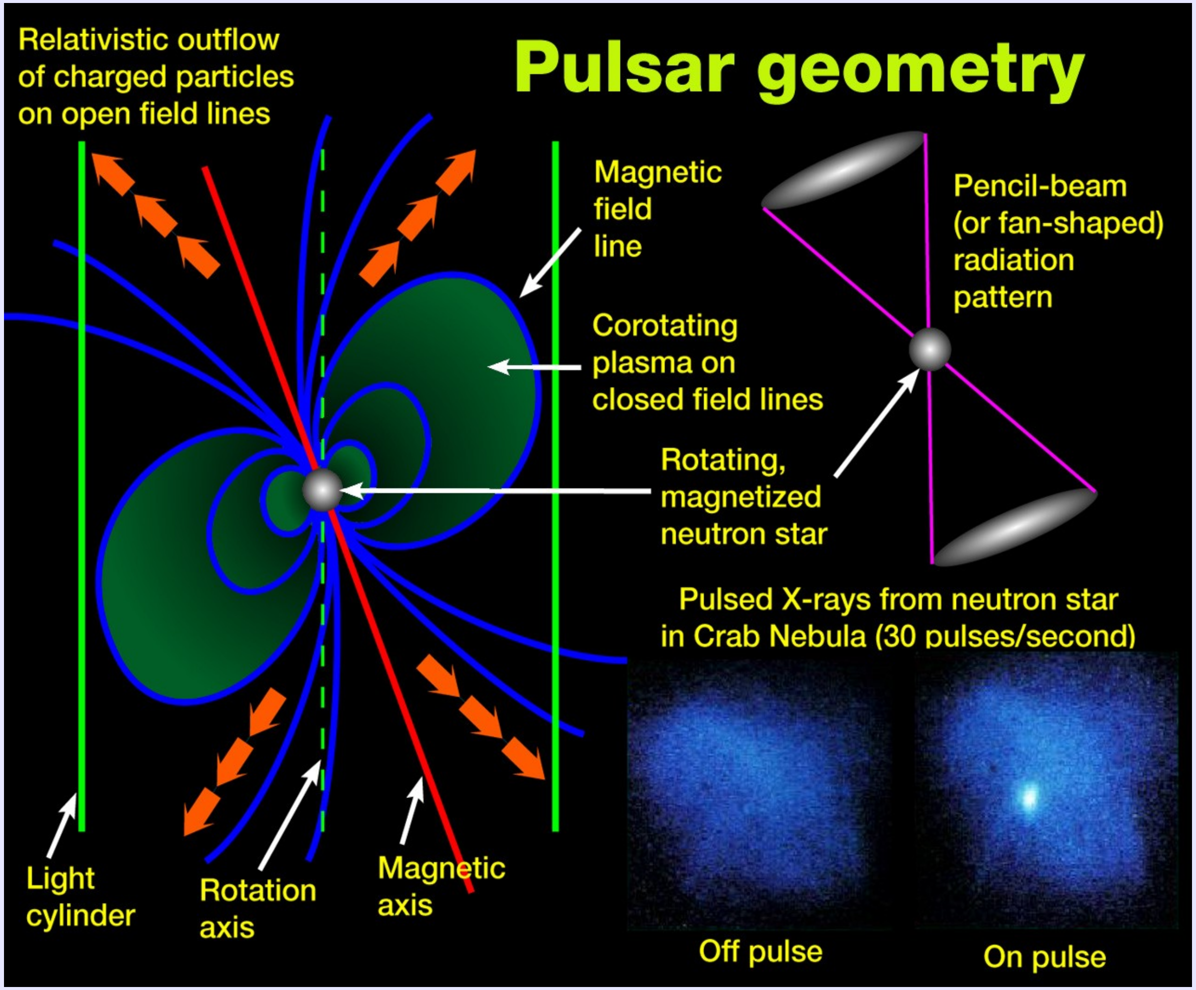
- Large spin down periods Pdot ~ 10^{-12} – 10^{-10} s/s

- When not in outburst, bright X-ray sources $L_X \sim 10^{34-36}$ erg/s

- Isolated NSs

- A few associated with SNR

NS magnetic dipole emission model



- Pulsars are rotation-powered NSs
- NS rotational energy is tapped and converted to radiation
  → NS spin-down
- Rotational energy loss
  Edot = I Ω Ωdot

  I = moment of inertia
  Ω = 2π / P
  Ωdot = dΩ/dt
- Characteristic age T = 0,5 P/Pdot
  → NSs are young (T < 10^5 yrs)
- Magnetic field strength at the poles $B_p \sim \sqrt{(P\ Pdot)}$
  → Magnetic field are huge !! Bp ~ 10^{14} - 10^{15} G
- Quiescent X-ray luminosity cannot be powered by rotation (L_X >> Edot)

Anomalous X-ray pulsars

• Class of objects sharing several similarities with SGRs (e.g. Woods & Thompson 2006 ; Gavriil, Kaspi & Woods 2002)

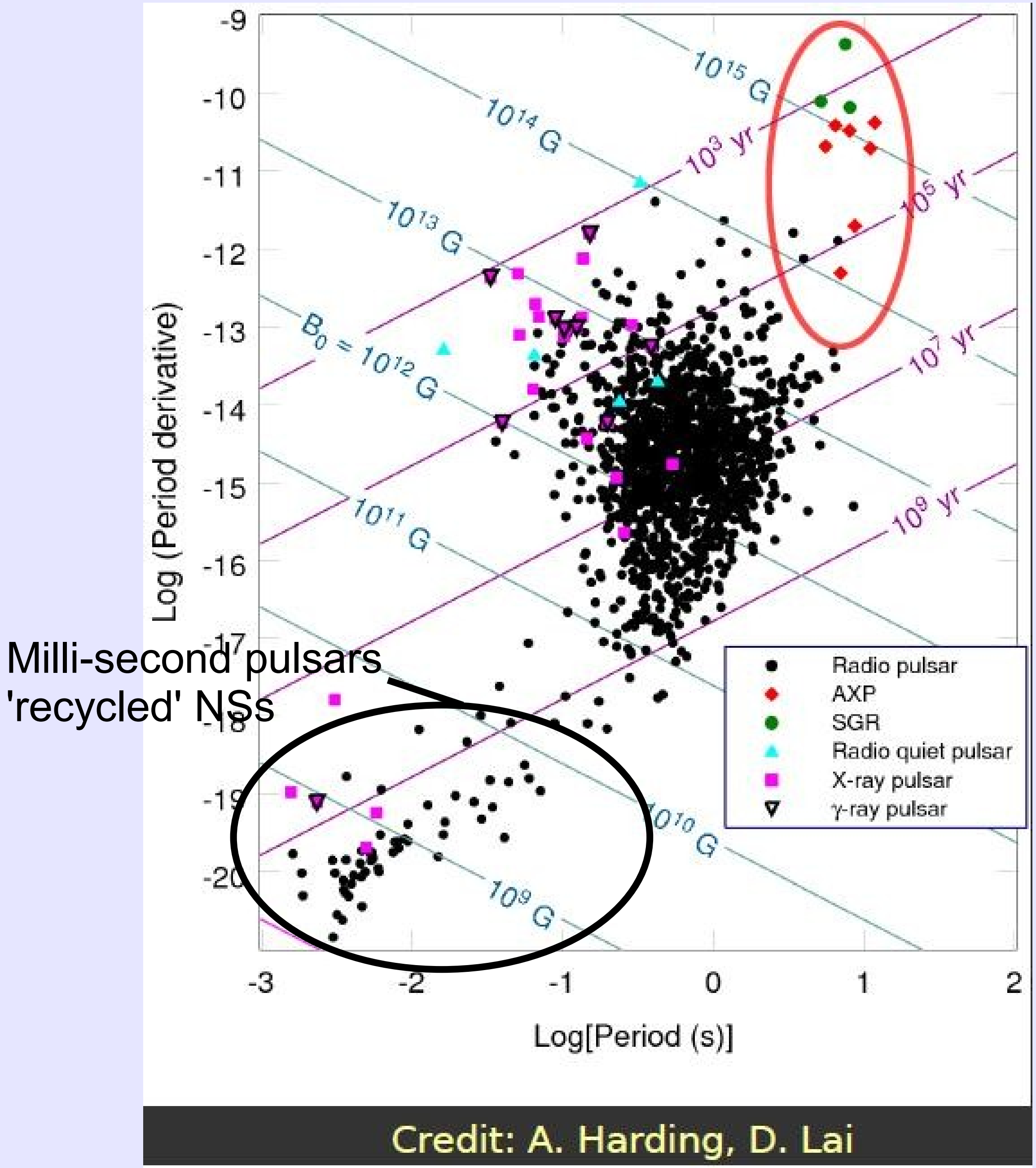
• Young NSs / some associated with SNRs / unlikely to be powered by accretion

• 14 AXPs known (12 confirmed + 2 candidates) – see Olausen & Kaspi14

	SGRs	AXPs
Small Bursts	Frequent	Rare Gavriil, Kaspi & Woods 02
Giant Flares	Yes	No
Quiescent X-rays	Yes	Yes
Periods	5.2 – 8 s	5.5 – 11.8 s
Spindown	$6.1 - 20 \times 10^{-11}$ s/s	$0.05 - 10 \times 10^{-11}$ s/s

Table from one of K. Hurley's talks (not up-to-date)

P–Pdot diagram



• SGRs and AXPs harbour recently formed NSs with very high magnetic fields.

• Bursts and quiescent X-ray luminosities not powered by accretion or by rotation.

• Duncan & Thompson (1992) proposed they are powered by magnetic energy.

• They are part of the same family called **magnetars** for « magnetically powered stars ».

How do magnetars form?

• Gravitational collapse of massive stars could lead to the formation of NSs.

• Newly formed NSs have a strong spin (down to a few ms) because of conservation of angular momentum (large star radius → NS radius)

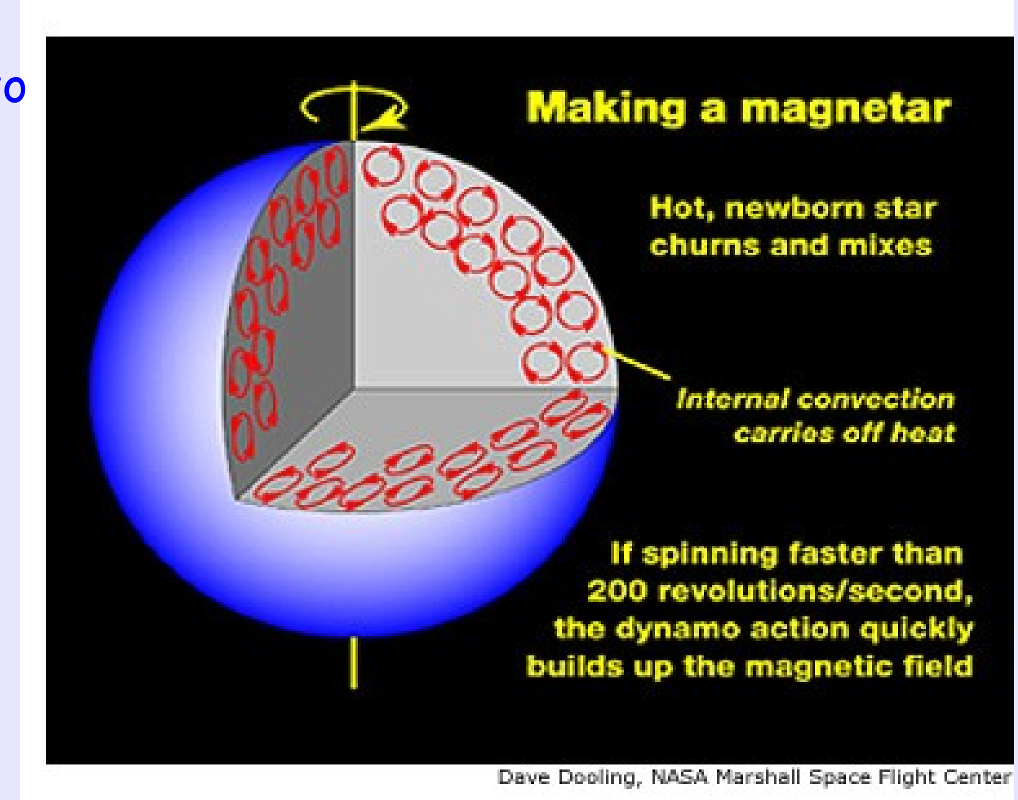
• Newly formed NSs are also very hot (T_c ~ 20-50 MeV – Lattimer & Prakash07).

→ convection in the hot and ultra-dense neutron fluid under the crust takes place to cool down the star (Burrows & Lattimer 88)

→ Neutron fluid conducts electricity due to presence of free e- & p+

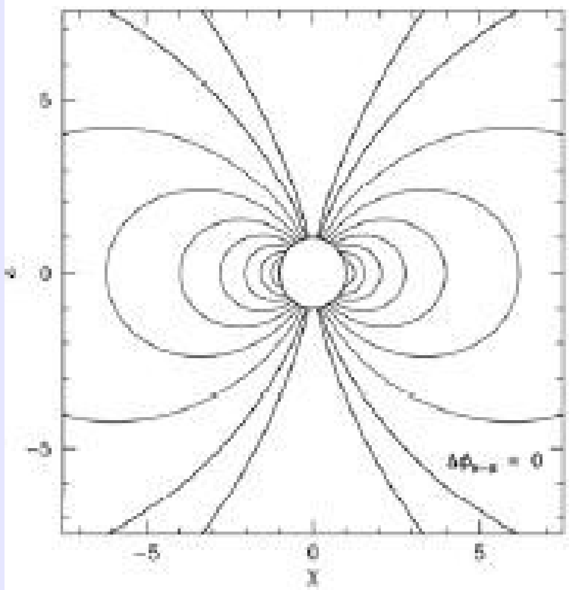
→ B lines drag into the fluid (convection & rotation)

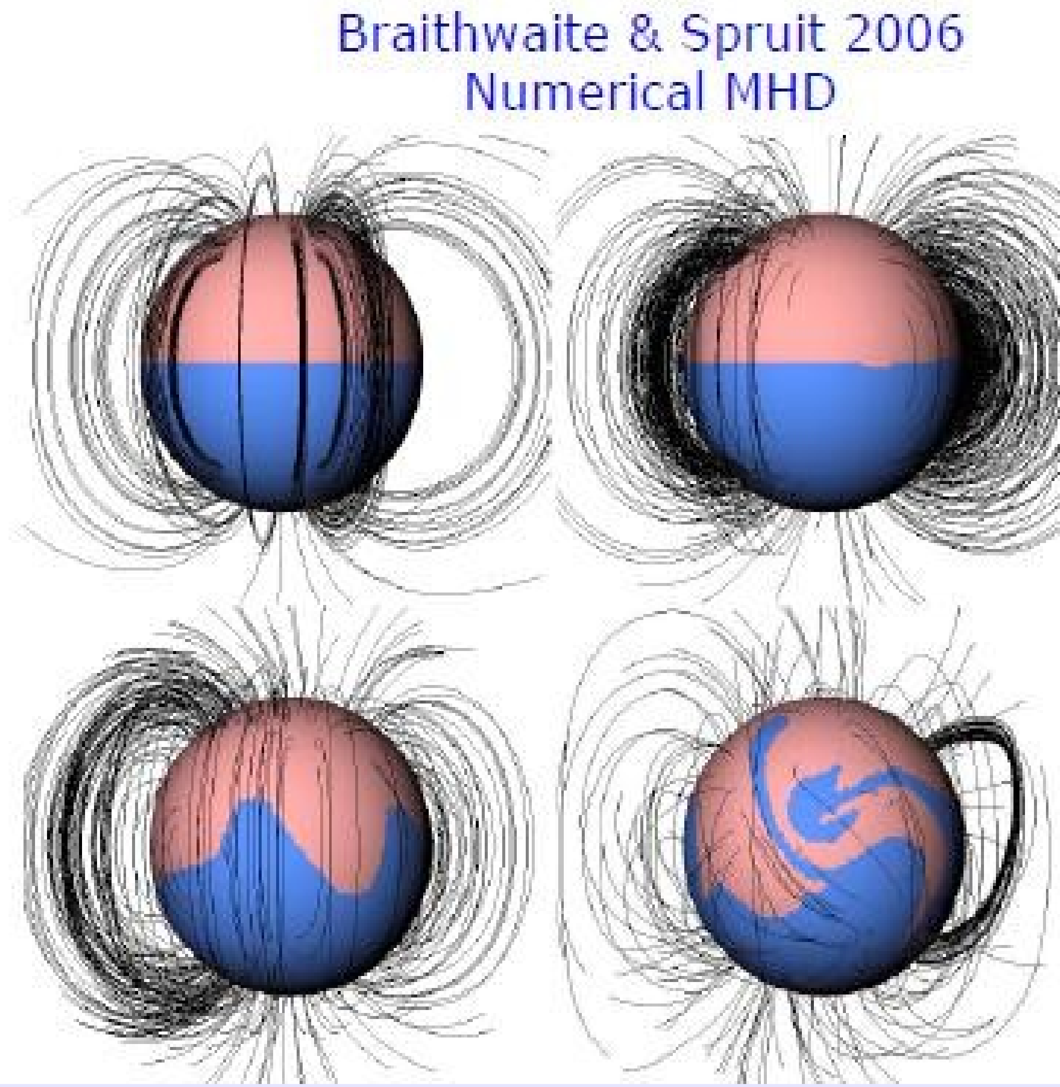
• If NS rotation is large enough $P < P_{Crab}$, a strong dynamo could build up magnetic fields inside the star core (wound-up B field) up to 10^{16} G over a timescale of 10-20 s. (Duncan & Thompson 1992)



How do magnetars work?

• At large distance, B field dipolar, but closer to the NS surface structure more complicated.





How do magnetars work?

• Strong external magnetic fields imply faster spin down for magnetars than for pulsars (compare Pdot values) through efficient emission of magnetic waves.

• Observed magnetars are slow rotators

→ Pulsar mechanism (see Natalie Webb's talk) is no longer working → no radio pulses expected

• Dissipation of internal magnetic energy heats the core/crust and keeps the NS hot.

→ Emission peaks in X-rays

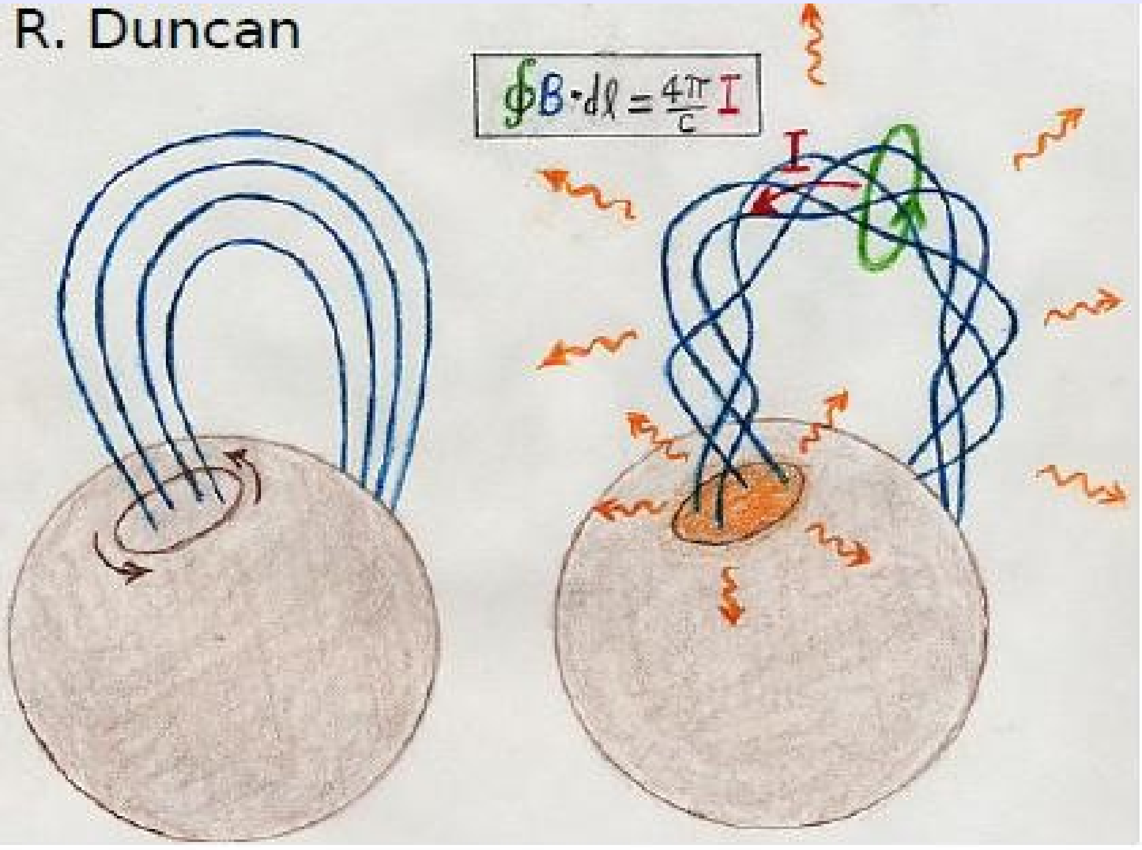
• Internal magnetic fields also generate strong stresses on the NS crust inducing elastic deformation

→ no vertical motion because of high pressure and gravity, but rather horizontal

→ drifts of magnetic loop footsteps since B field lines anchored to the crust

→ twists of magnetic field lines

How do magnetars work?



- Twists of magnetic field lines create strong currents (from Ampere's law) ...

  → energize particles trapped in magnetic field loops

  → particles almost e- & e+

  → accelerated particles emit radiation (mostly in X-rays) and hit the crust that heats up to high temperature (X-rays)

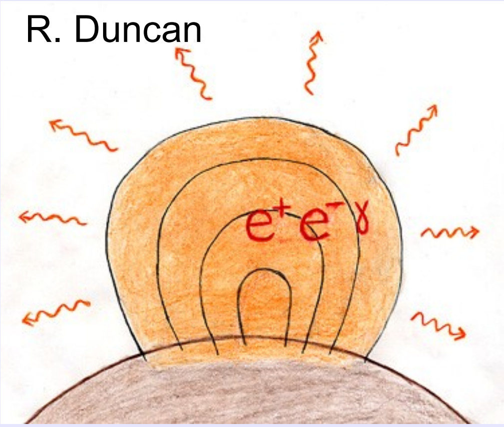
- associated with rapid magnetic reconnection

  → lead to SGR bursts

- Analogy with solar flares

How do magnetars work?

• Where does the soft pulsating tail seen in SGR giant bursts come from?



• Electrons and positrons are trapped in the magnetic loops ...

→ motion only along the B field lines

• as well as X-ray/Gamma-ray photons

→ interacting with particles

→ Gamma-rays → e+/e- pairs → Gamma-rays

→ photons could not get away from the loops (optically thick) → **trapped fireball**

• At the loop surface, photons could escape and annihilation of e-/e+ also removes energy

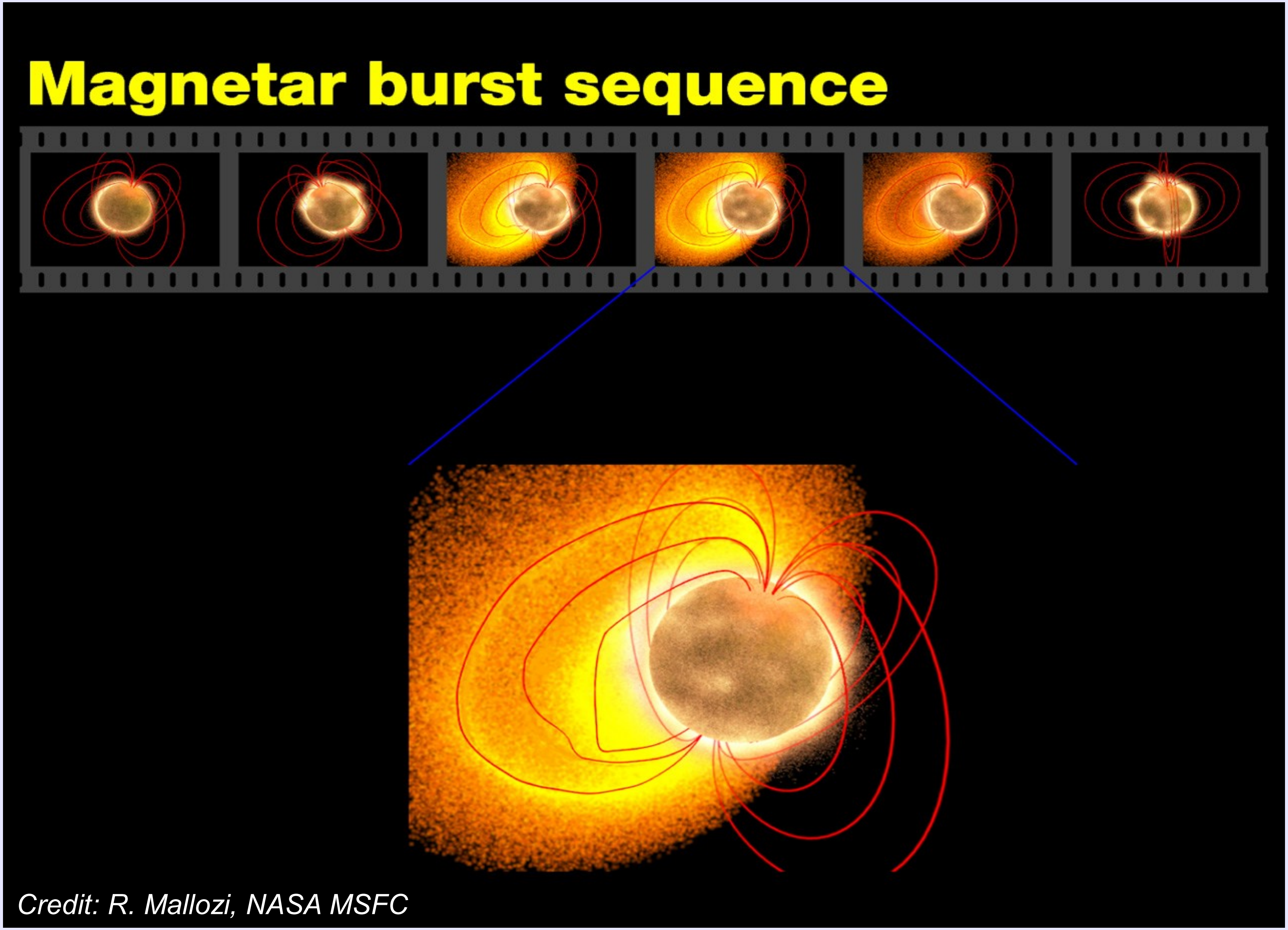
→ emptying the energy content of the fireball over time

→ luminosity decreases

• Since B field lines anchored to the crust, the fireball moves when the NS rotates

→ NS rotation creates the flux modulation observed during the tail depending if the fireball is visible for the observer or not.

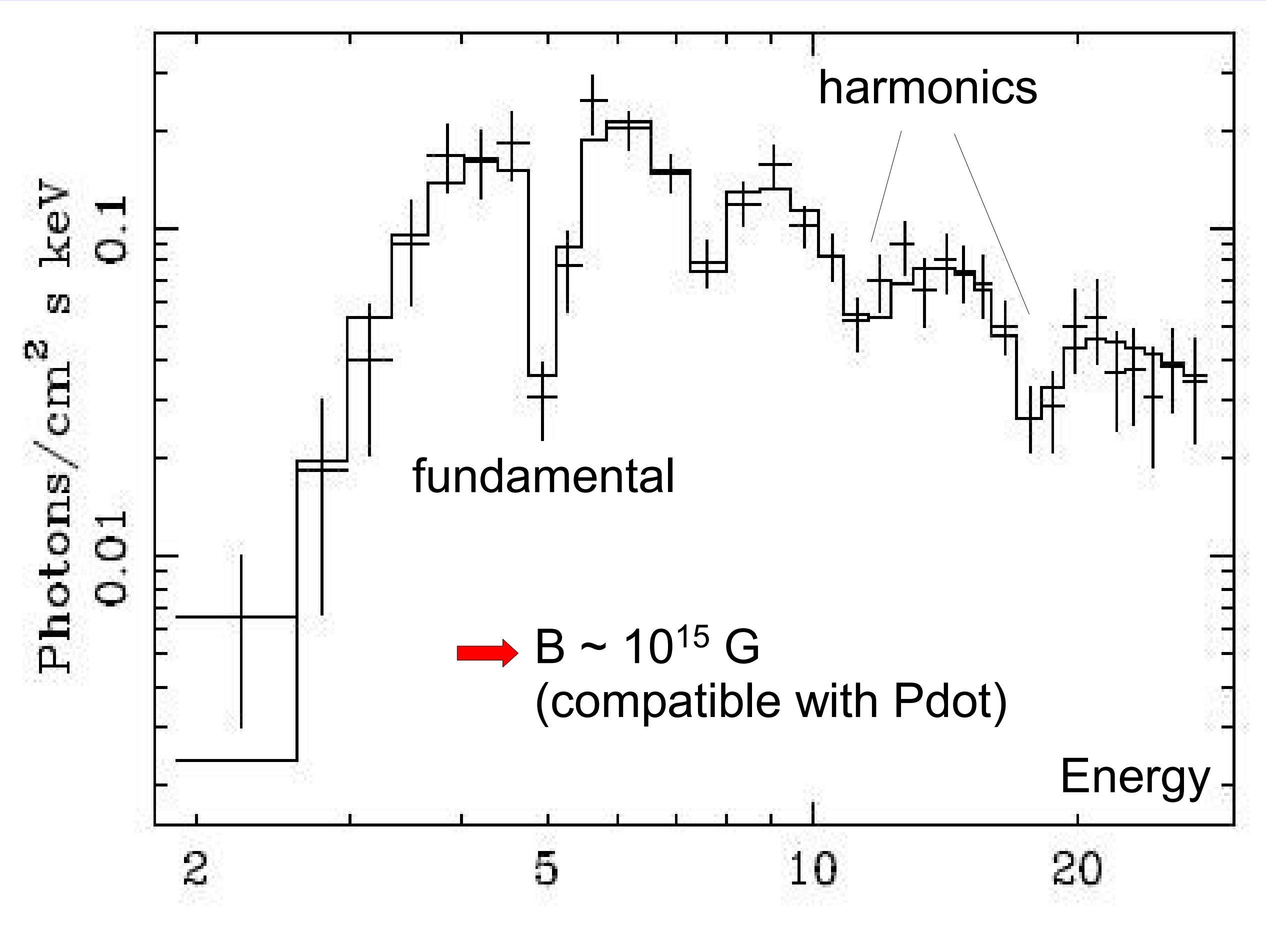
How do magnetars work?



Direct evidence for very high B fields?

- Large spin down and low periods are indirect evidence of high B fields.

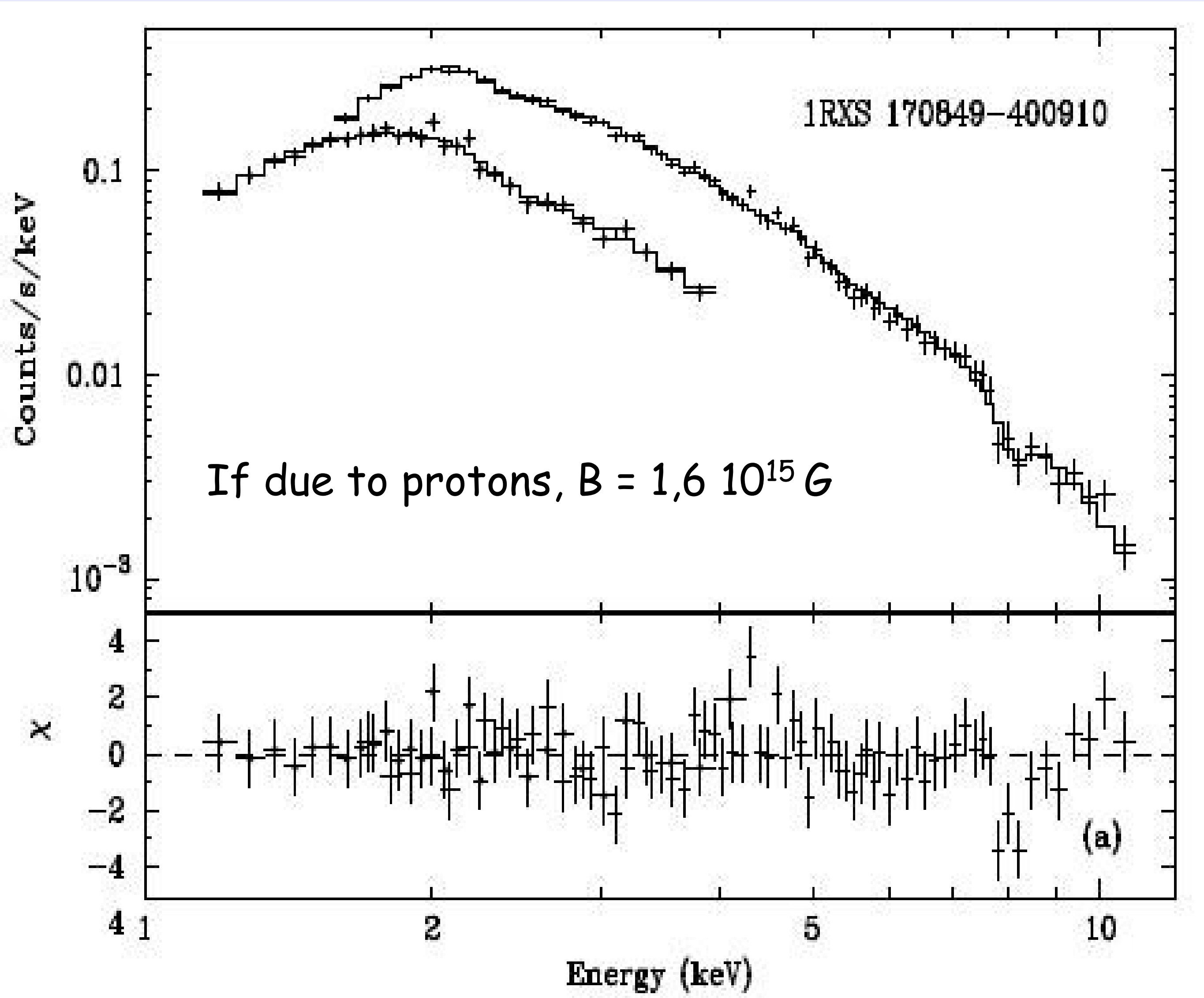
- Ibrahim+02 discovered proton cyclotron lines in a precursor event from SGR 180 -20 / features too narrow to be due to e- cyclotron lines seen in pulsars



This discovery was later
Disputed by the same authors
See Ibrahim+07, ApSS

Direct evidence for very high B fields?

- Rea+04 reported the identification of a resonant cyclotron lines in an AXP.



How do magnetars evolve?

- Rate ~ up to 10% of formed NSs could be magnetars.

- If so, why do we not see more magnetars?

- Duncan & Thompson (1996) proposed that frictions due to ambipolar diffusion of the B field dissipate magnetic energy and result in heating up the NS
  → accelerate magnetic energy dissipation

- If the NS cools below a threshold temperature, this process stops
  → the intense B field stays trapped within the star
  → source powering magnetar activity vanishes
  → could happen over a 10^4 yr timescale

- See also Vigano+13

Why should we care about magnetars?

- B field strength in magnetars > quantum electrodynamics field strength B_Q

- $B_Q = 2\pi\, m_e^2\, c^3 / h\, e = 4.4 \times 10^{13}$ G

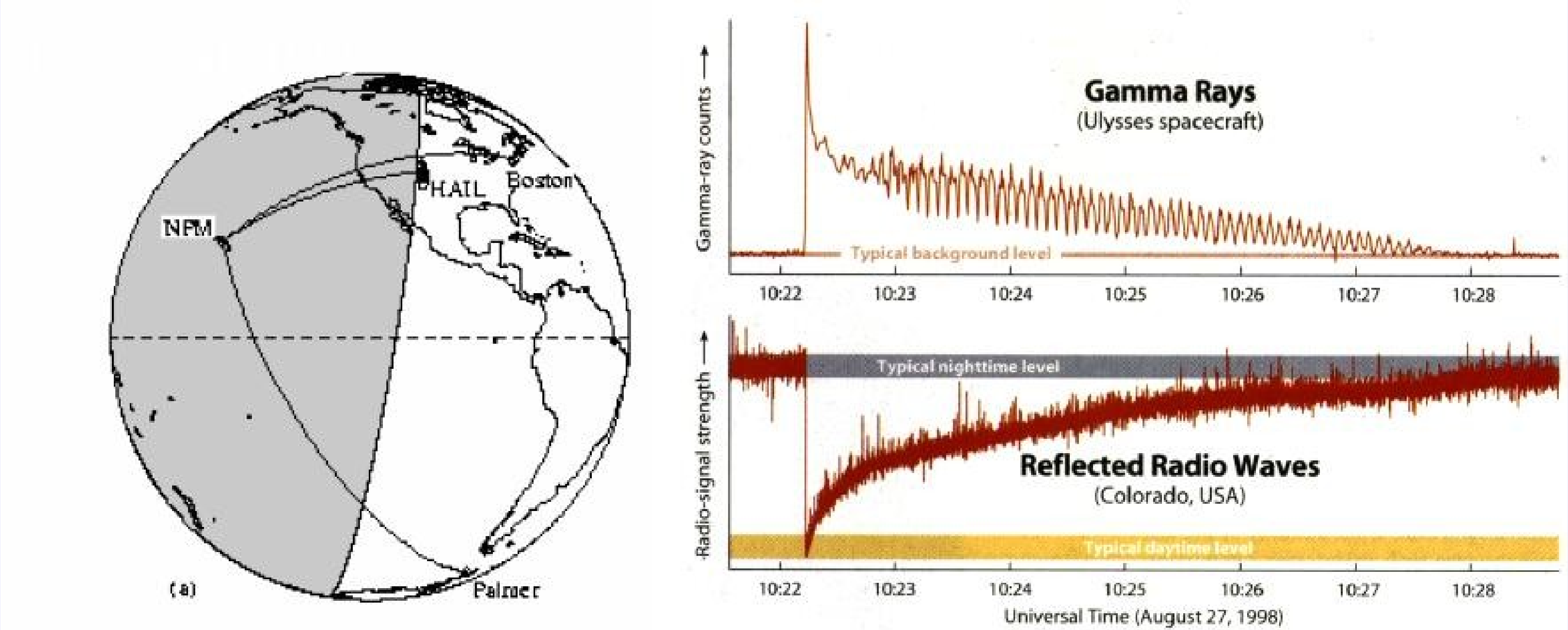
- Electrons gyrating B field lines are relativistic.

- Magnetars could help investigating weird effects on quantum vacuum, matter and photons (e.g. photon splitting!) in this physical regime
  (see Duncan 2000 – take your time to read it:))

- QED effects negligible in pulsars because $B \ll B_Q$

For fun

- When 1998 giant flare of SGR 1900-14 pertubated Earth ionosphere



K. Hurley's plot

- Modification of the propagation of Very Low Frequency (21 kHz) waves
- You could even do nice science using VLF waves!! (e.g. Tanaka+08 – see also Raulin+14)

Additional references

- References accessible via the NASA/ADS web interface
- http://adsabs.harvard.edu/abstract_service.html

- Turolla, Zane & Watts, 2015, Reports on Progress in Physics, 78, Issue 11

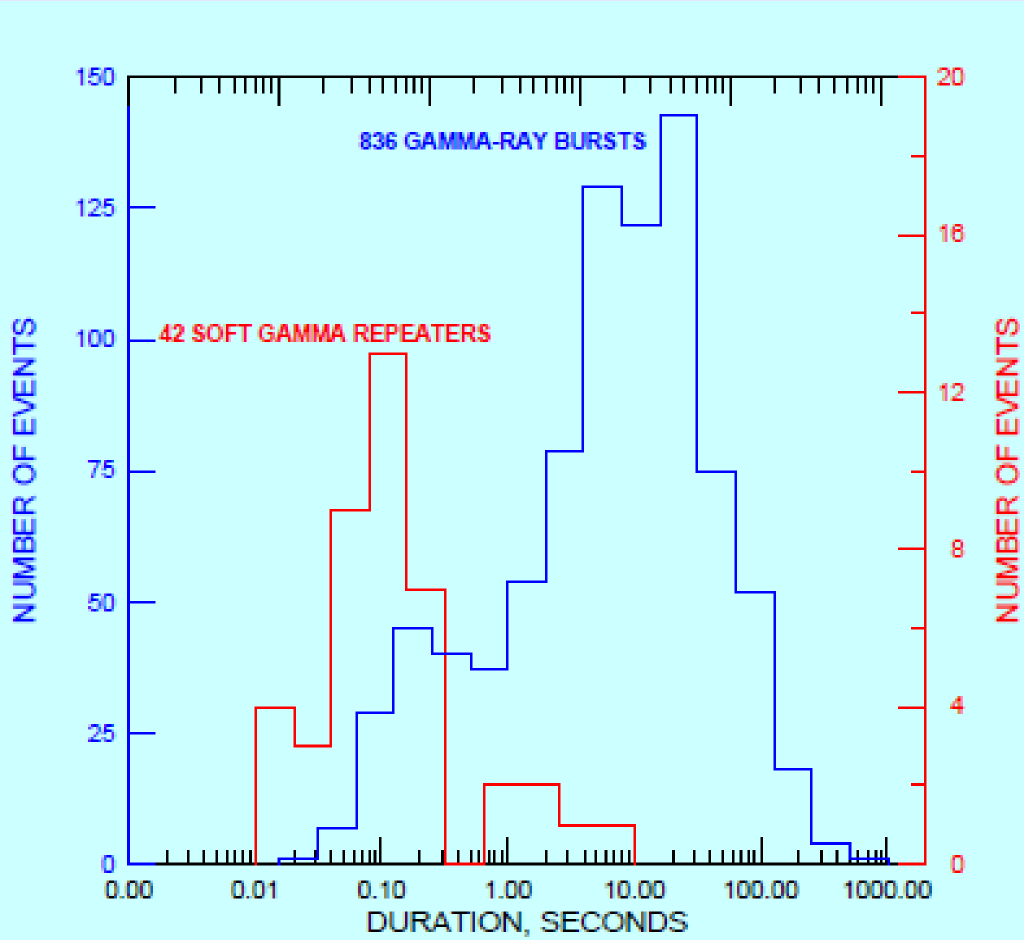
- Site R. Duncan : http://solomon.as.utexas.edu/magnetar.html#Strong_Magnetic_Fields

- Mereghetti, Pons & Melatos, 2015, Space Science Reviews, 191, 315

PART III

Connection GRBs – Magnetars

Could magnetars produce short GRBs?



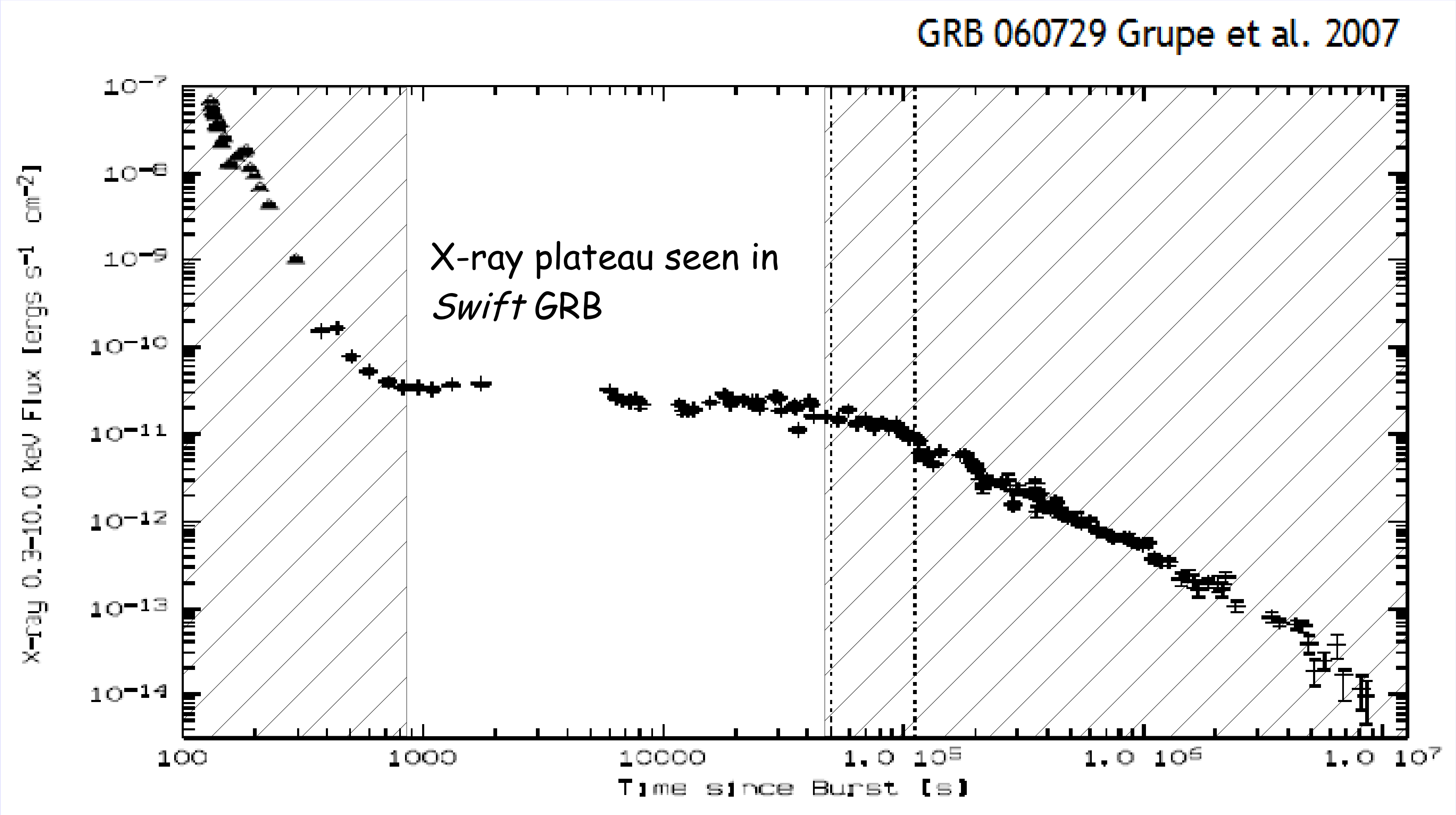
K. Hurley

- Magnetar burst duration consistent with duration of short GRBs
- Magnetar bursts have softer spectra than classical bursts.
- Initial short spikes of giant flares (~0.2 s) are harder than small magnetar flares
- Tail contains only 1/1000th of the total radiated energy
- At large distance, tail invisible → resemble short GRBs

- Detectable < 100 Mpc

- Possible candidates for short GRBs, but what fraction?

GRB X-ray plateaus



- Not consistent with *AG* standard model

- See also Zhang+06 et Nousek+06

GRB X-ray plateaus

- Possible interpretations:
  - Energy injection into the forward shock to refresh it and to avoid the blastwave decelerating (e.g. Zhang et al. 2006)

    → Imply extended activity of the central source sometimes up to 10^5 s after the trigger (related to X-ray flares)

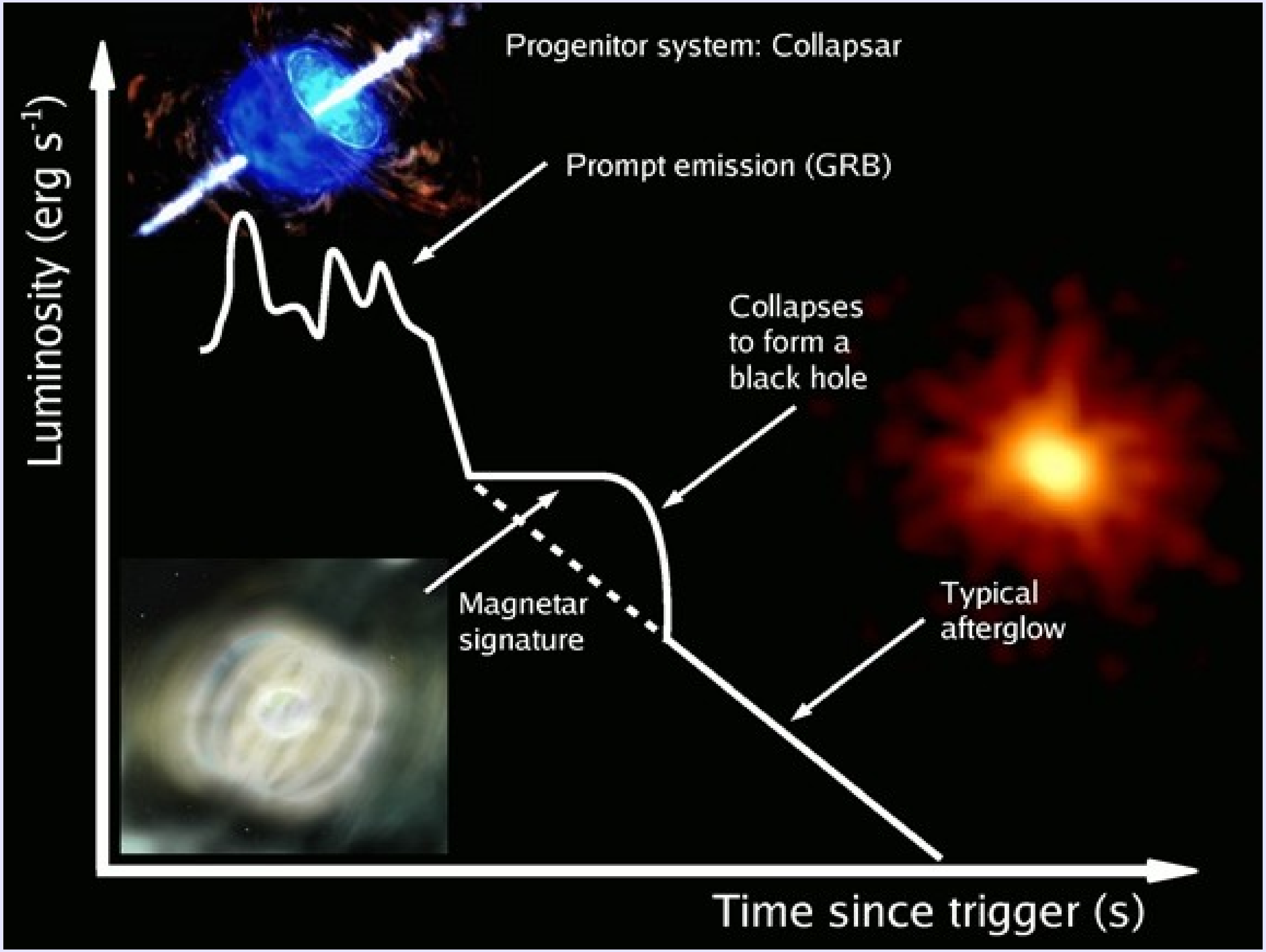
    → Energy injection by a newly formed magnetar before collapsing to form a BH due to fall-back matter

  - Hydrodynamical effect related to the deceleration of the blastwave (Kobayashi & Zhang 2007)

    → Not able to explain all observed plateaus

GRB X-ray plateaus

- Swift-XRT observed a weird afterglow from GRB090515 (Rowlinson+10)



(see also Lyons+10 ; Gompertz+15)

Additional references

- Greiner+15 : A very luminous magnetar-powered supernova associated with an ultra-long γ-ray burst

- Rea+15 : Constraining the GRB-Magnetar Model by Means of the Galactic Pulsar Population

- Mazzali+16 : Spectrum formation in superluminous supernovae (Type I)

PART IV

Summary

Summary

• GRBs and magnetars could give rise to powerful transient events.

→ GRBs are on-shot events as far as we know

→ magnetars could be repetitive

• Both types of events involved compact objects (NSs and/or BHs) during their birth or during their evolution

• GRBs are cosmological events while known magnetars are mostly Galactic (even if their giant flares could be detected in the local Universe < 100 Mpc)

• Both phenomena involve extreme physics (ultra-relativistic jets & hyper-accretion for GRBs / ultra intense magnetic fields and ultra-dense matter for magnetars)

• They could be used as tools to probe fundamental physics (QED and ultra-dense matter for magnetars / modified gravity theories & GWs for GRBs / ultra high energy cosmic rays for both)

• Possible connections between GRBs and magnetars outlined (also with some type of supernovae, the superluminous SNe)

Summary

- Numerous open issues → that will keep us busy for a while !

- **GRBs:**
  - Nature of the X-ray plateaus
  - Does the X-ray AG really track the optical AG?
  - Nature of the jet outflow (fraction of baryon loading)
  - Particle acceleration mechanism(s)
  - Emission mechanism(s) of the prompt emission
  - Evolution of GRB rate with redshift?
  - Differences between XRFs/GRBs
  - … (could continue for a while :))

- **Magnetars:**
  - What is the magnetar birthrate?
  - What ingredients from the star progenitors could lead to their formation?
  - What are magnetar lifetimes?
  - What are the connections between SGRs and AXPs?
  - Where is the population of dead magnetars?
  - …

Prospects

- GRBs are cosmological events:
  → help observing missing baryons in the WHIM
  → constraints on the reionisation phase of the Universe with high-z GRBs
  → connection GRB – pop. III stars
  → content of metals in high-z galaxies / formation of the first galaxies
  → constraints on cosmological parameters if GRB could be standardized as SNeIa

- Multi-messenger astronomy is starting now!! (new GW and particle facilities with much improved sensitivity)
  → This is a fantastic time and I hope you realise how lucky we all are :)
  → Detection of short GRBs coincident with GW (possible BH-BH merger?) or neutrino signals
  → possible detection of GW signals due to asymetric NSs because of magnetic field deformation

- Fast (ms) Radio Bursts (FRBs) a new class of transients recently detected in radio.
  → Spitler+16 observed repeating signals from a FRB (see Scholz+16).
  → Could these events be due to magnetars (e.g. Katz 2016)?

Prospects

• In X-rays, new instrumentation like X-IFU on Athena in 2028 will open new avenues in the study of these objects with high-resolution spectroscopy. Shame we lost HITOMI :(

• SVOM (French-Chinese GRB mission) in 2020 will help improving our understanding of GRBs.

• New more sensitive instrumentation from 2020's in other wavelengths (e.g. JWST, LSST, CTA, SKA, ...) will also have a profound impact in our understanding on these fascinating objects and will surely bring lots of new discoveries/surprises!

HOPE THERE WILL BE STILL SOMEBODY AWAKE !!

MANY THANKS TO MATTEO !!!