Gamma-Ray Bursts in the local universe

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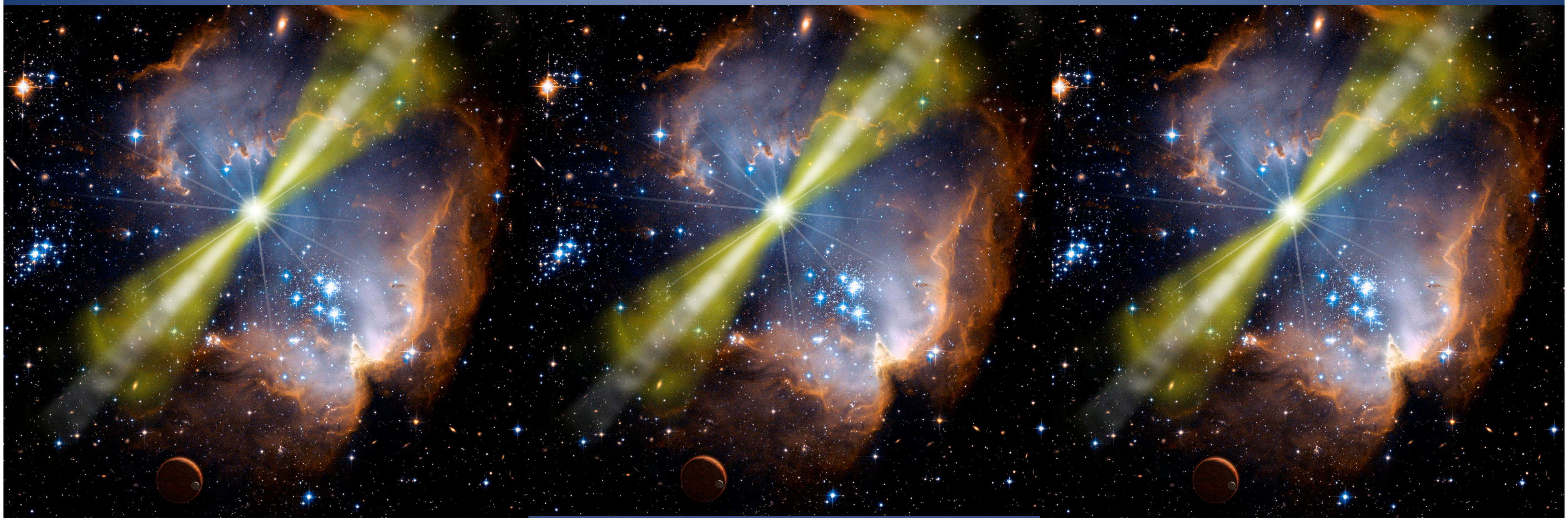


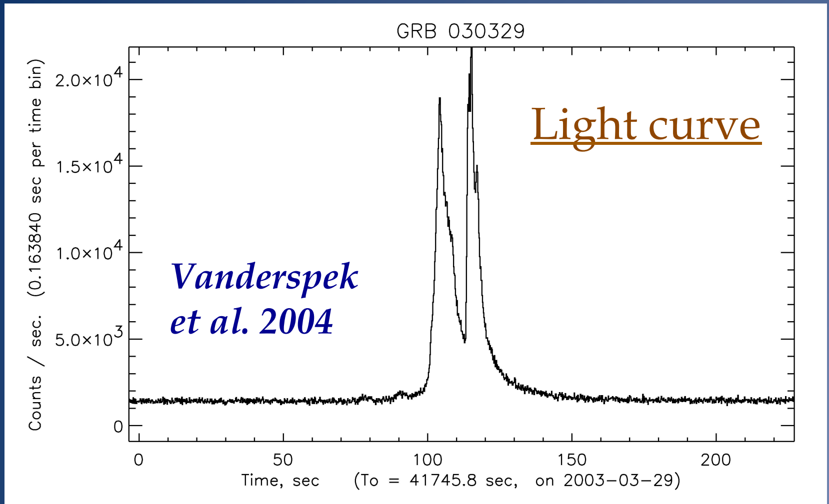
Outline

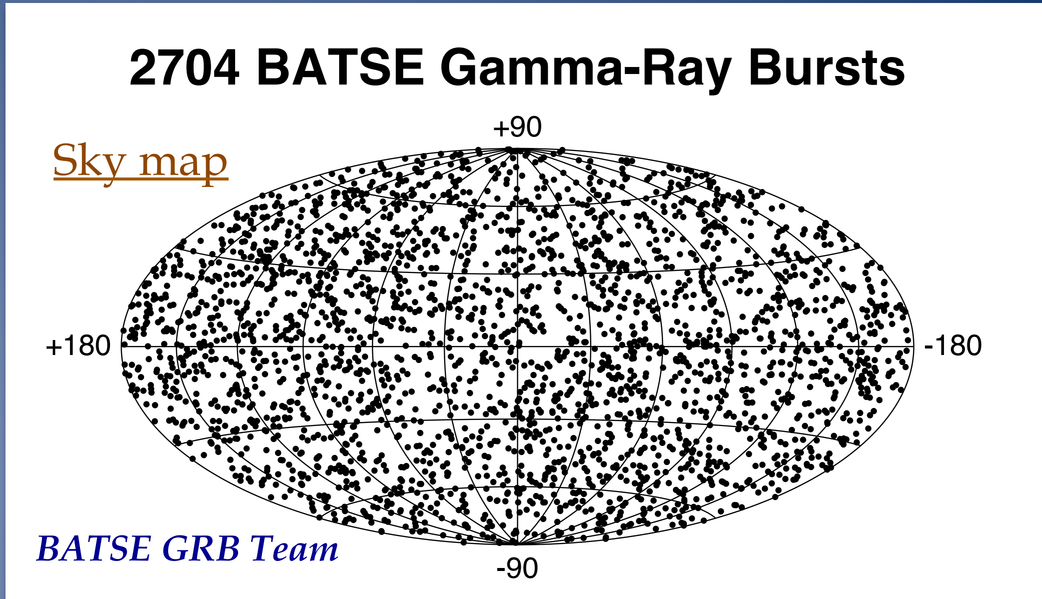
- Gamma-ray bursts
- A census of local GRBs
  - Long / Short / Shock breakout
- Some scientific issues
  - Low-luminosity GRBs
  - The GRB-SN connection, the local environment of GRBs
- Observational perspectives
  - LSST and orphan afterglows
  - GW detectors and mergers

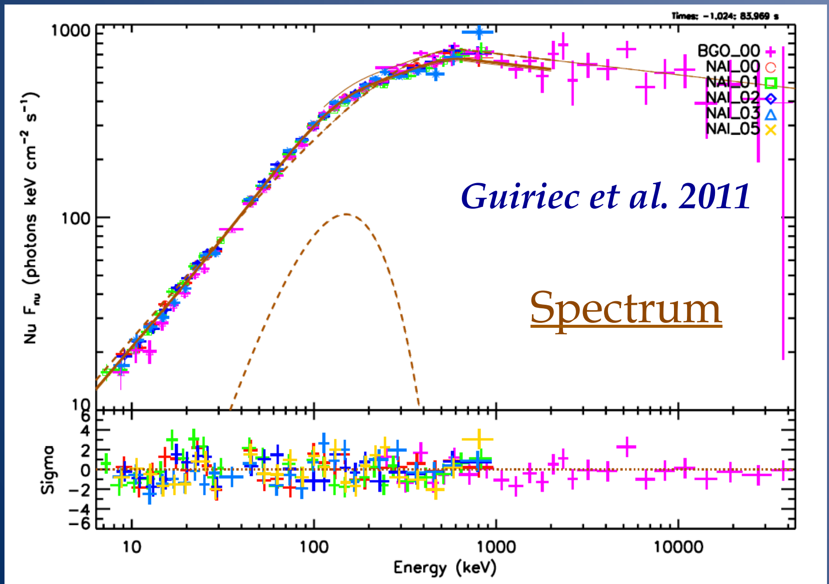
Gamma-Ray Bursts (GRBs)

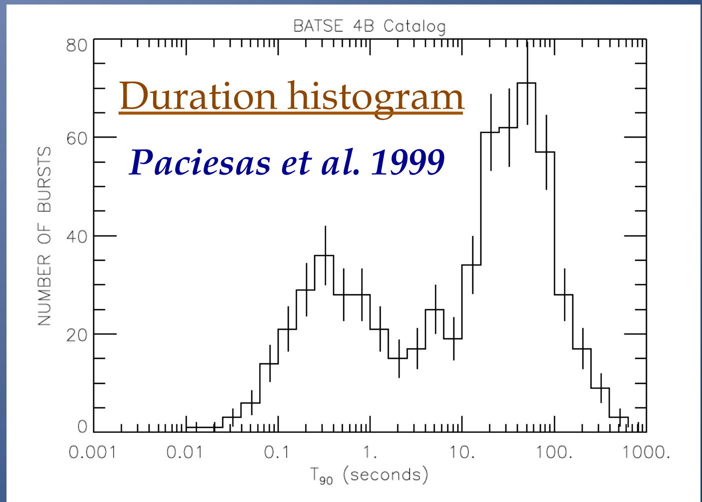
- GRBs are ***gamma-ray flashes*** coming from very distant galaxies.
- They point to ***transient relativistic jets*** directed towards us.
- A bright afterglow radiating at radio, optical and X-ray wavelengths follows the γ-ray signal. This afterglow is due to the shock of the jet on the gas surrounding the source.

The prompt GRB – 2 classes (at least)



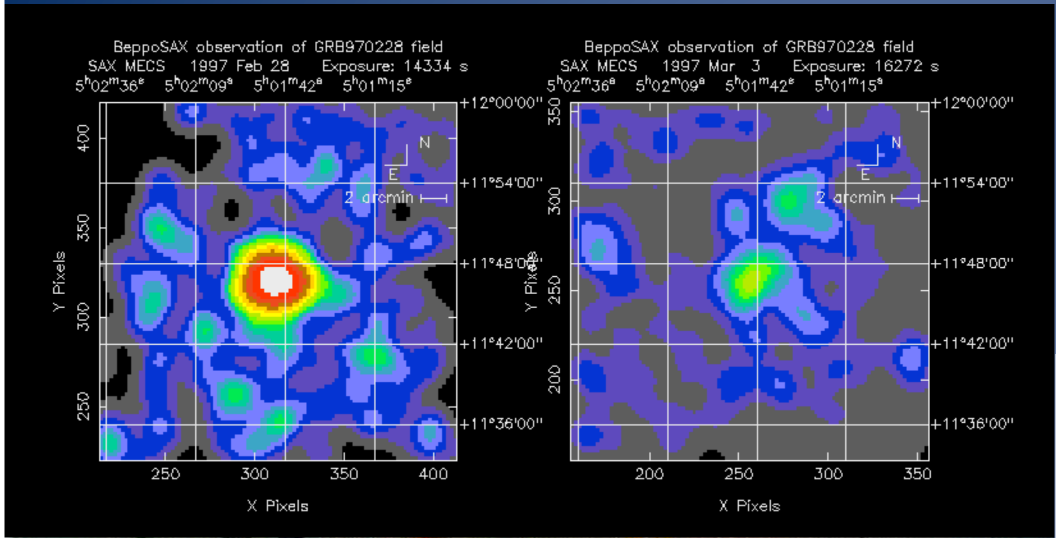




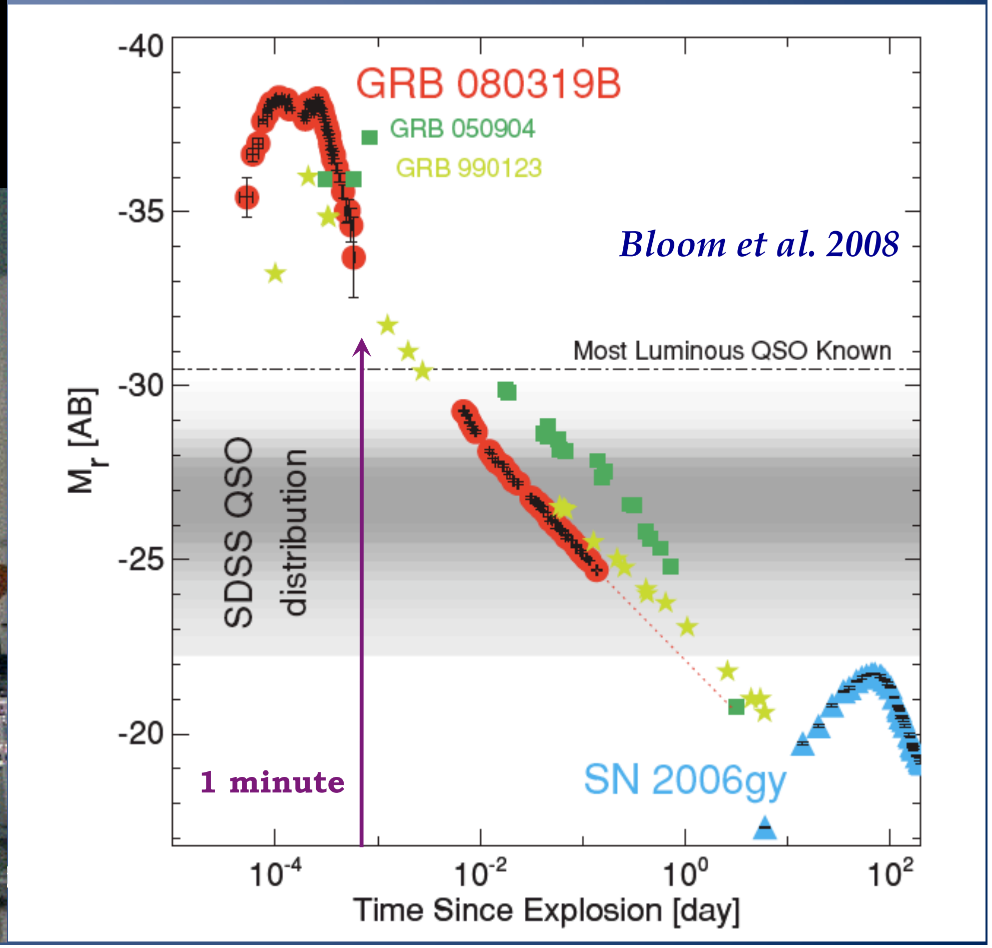


GRB afterglows

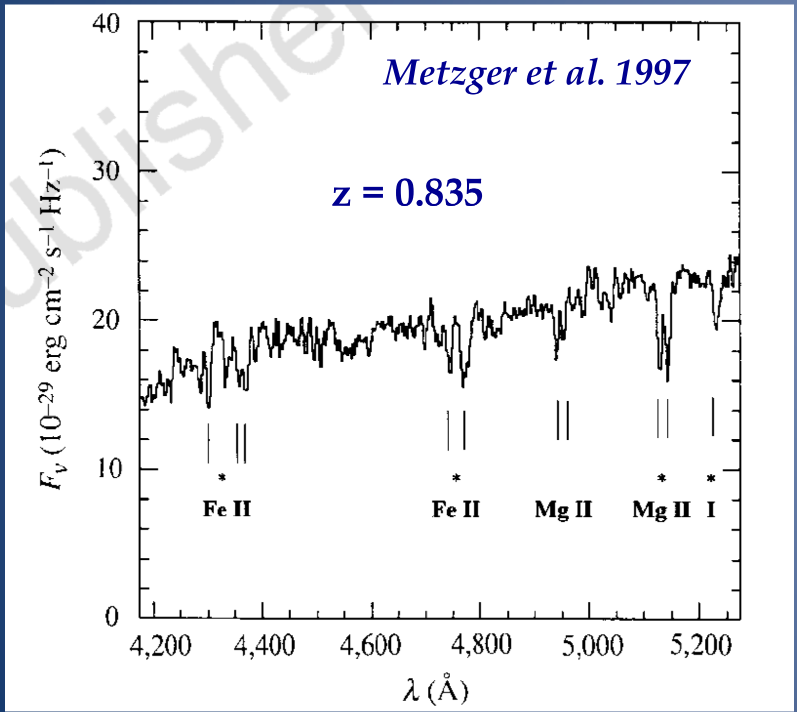
GRB 970228 – *Costa et al. 1997*

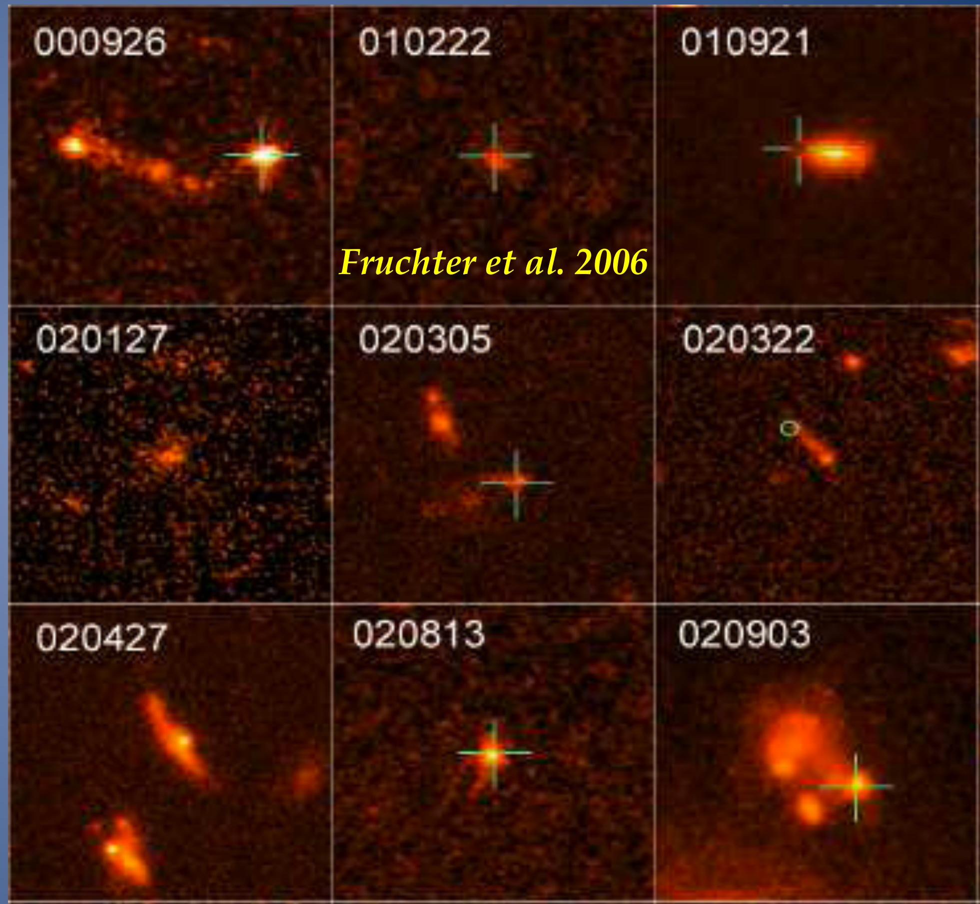


- GRBs are followed by bright multi-wavelength afterglows

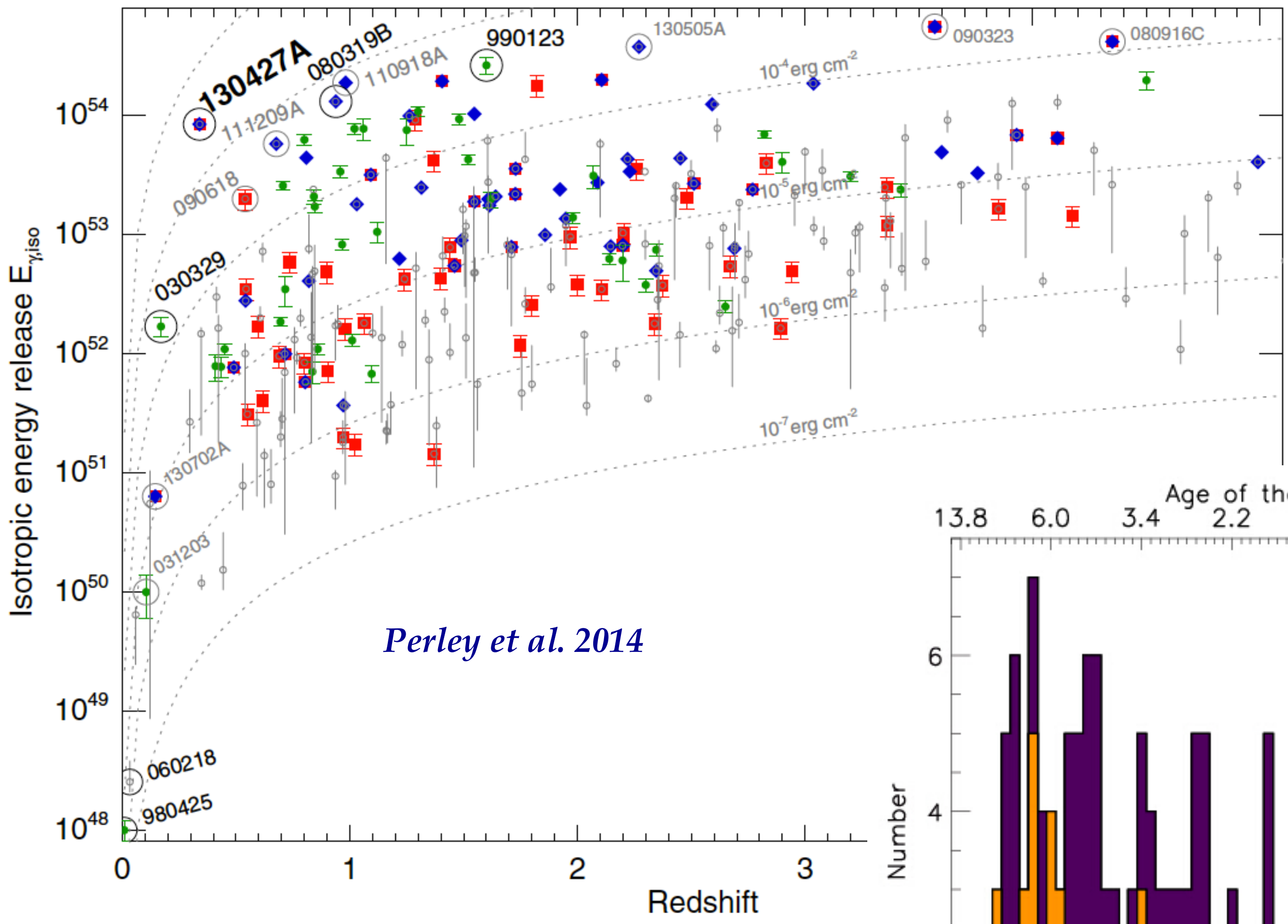


GRB afterglows and host galaxies



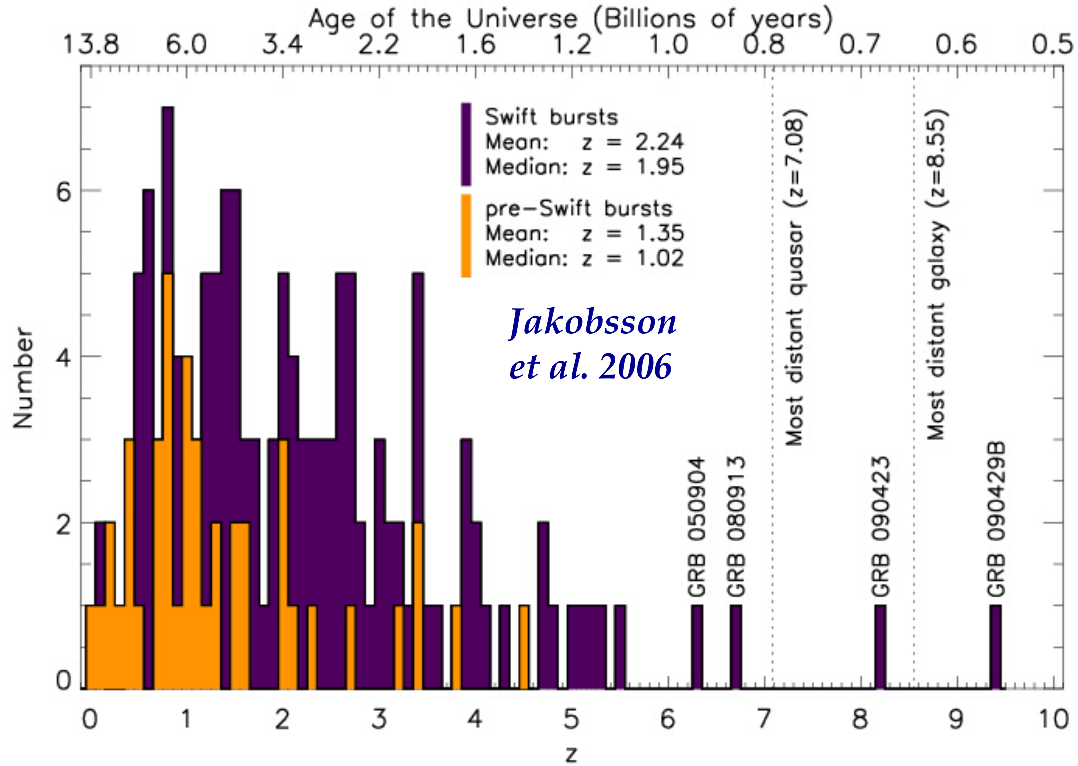


Resdshift and luminosity distributions



41 redshifts
before Swift

~300 redshifts
with Swift



Gamma-Ray Bursts

- GRBs are rare and powerful events.

- How powerful?
  - GRBs are seen out to large redshifts: z = 8-9, when the universe was only 500-600 million years old
  - Assuming isotropic radiation, some GRBs emit >10^{54} erg in γ-rays.
    This is larger than the energy radiated by the Sun during its entire life, and only in γ-rays:
    → ***GRBs must be jetted***

- How rare?
  - There are ~1000 classical long GRBs/yr all sky.
  - This translates into ~1 GRB/Gpc^3/yr in the local universe
    (1 Gpc^3 contains >10^7 galaxies like the MW → less than 1 GRB every 10^7 yr in our Galaxy)
  - In comparison there are 10^5 SNII/Gpc^3/yr in the local universe, of which ~10% are of type Ibc

  !! These numbers are not corrected for beaming

GRBs require beaming and relativistic motion

- High luminosity regions are opaque to MeV photons.
  MeV γ-rays interact with low energy γ-rays to create pairs ($\gamma + \gamma \rightarrow e^+ + e^-$), producing a pair fireball ***with a photosphere which emits blackbody radiation***. It is very difficult to avoid pair creation at very high photon luminosities.

- One solution is ***relativistic motion***.
  - If the radiating plasma moves towards the observer at speed v close to c, we define the Lorentz factor as $\Gamma = 1/\sqrt{(1-\beta^2)}$, where $\beta = v/c$
  - In the source frame, ***the photon-photon opacity is reduced by a factor ~Γ^6 and γ-rays can escape!***
  - For an observer in the jet direction ***the luminosity of the source is enhanced by a factor ~Γ^4***
  - GRBs require ***Γ ~ 100***, since $\Gamma = \Delta E / \Delta Mc^2$ --> clean fireballs!

- GRBs beaming helps relaxing energy requirements

Relativistic GRB jets

- The prompt GRB is produced within the jet, while the afterglow is due to the shock of the jet on the surrounding medium

- The prompt GRB contains 10-50% of the energy, the dissipation in the jet must be very efficient

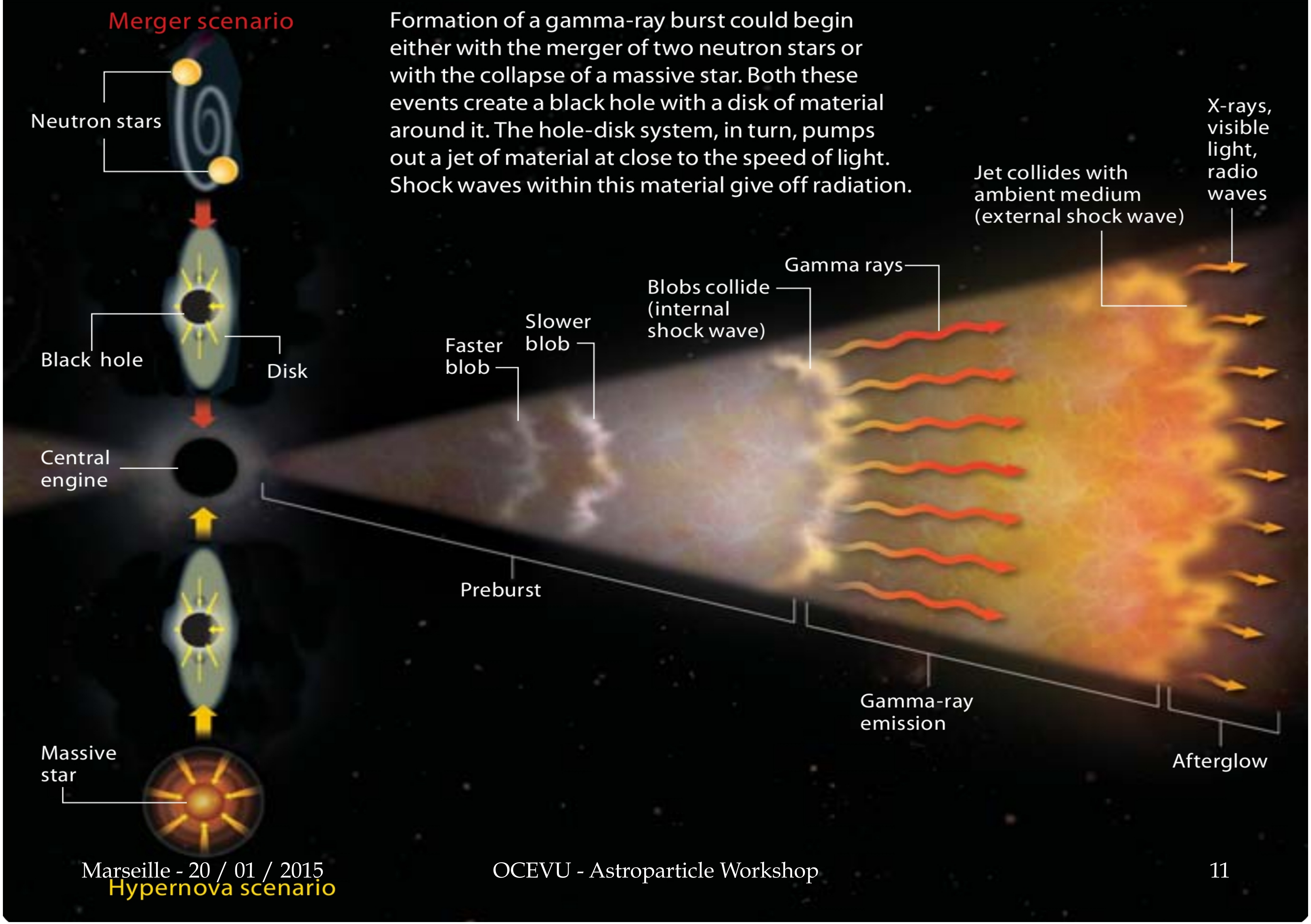
- The jet moves at the speed of light. Radiation from the various regions arrive at the same time, complicating the interpretation.

- Achromatic breaks provide a measure of the opening angle of the jet

- Many questions remain:
  - What is the nature of GRB jets: baryonic or magnetically dominated?
  - Physics of the jets: dissipation, radiation processes, beaming
  - *GRBs are extreme cases of cosmic accelerators, and unique tools to study the nature and the physics of relativistic jets.*

Bursting Out

Formation of a gamma-ray burst could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.



The progenitors of long GRBs

- Long GRBs = massive star explosions with transient relativistic jets
  - Nearby GRBs are associated with hypernovae: SN Ibc with large kinetic energy of the ejecta. They require the production of a large amount of Nickel 56 (for the supernova) ***and*** existence of a central engine active during seconds! (for the GRB)
  - The energetics may be dominated by the jet or by the supernova (e.g. low-luminosity GRBs)
  - At most a few % of SN Ibc produce GRBs
- Nature of the central engine?
  - Black hole? Magnetar?
  - The progenitor must have a large angular momentum to produce the fast rotating torus feeding the black hole (or the fast spinning magnetar)

Some questions

- How can the star keep enough angular momentum in the core, while ejecting the envelope?
  - Possible solutions: low metallicity, binarity
- What makes GRBs so rare, only few % of SN Ibc?
- What are nearby long GRBs without supernova light?
  - e.g. GRB 060505 at z= 0.089 → *C. Fryer (2013) has several suggestions!*
- Why afterglow modeling fits the observations better when one assumes a constant density ISM around the explosion?
  (one would expect a stellar wind)
- Can we infer the nature of the central engine (magnetar vs black hole) and its properties (mass, spin) from the properties of the burst?

The progenitors of short GRBs

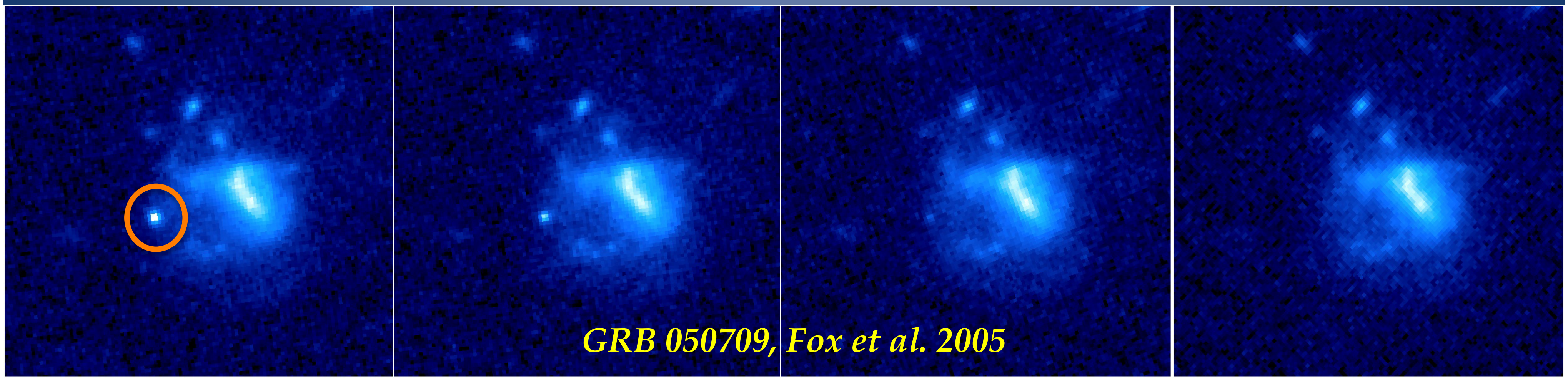
- Short GRBs occur in all types of galaxies, and even outside galaxies
- They are not connected with recent star formation

- The favorite model involves the coalescence of two compact objects: NS +NS or BH+NS

- The location, energetics and rate are compatible with this hypothesis

- Short GRBs seem to have wider jets than long GRBs

- Short GRBs may be privileged sources of gravitational waves



GRB 050709, Fox et al. 2005

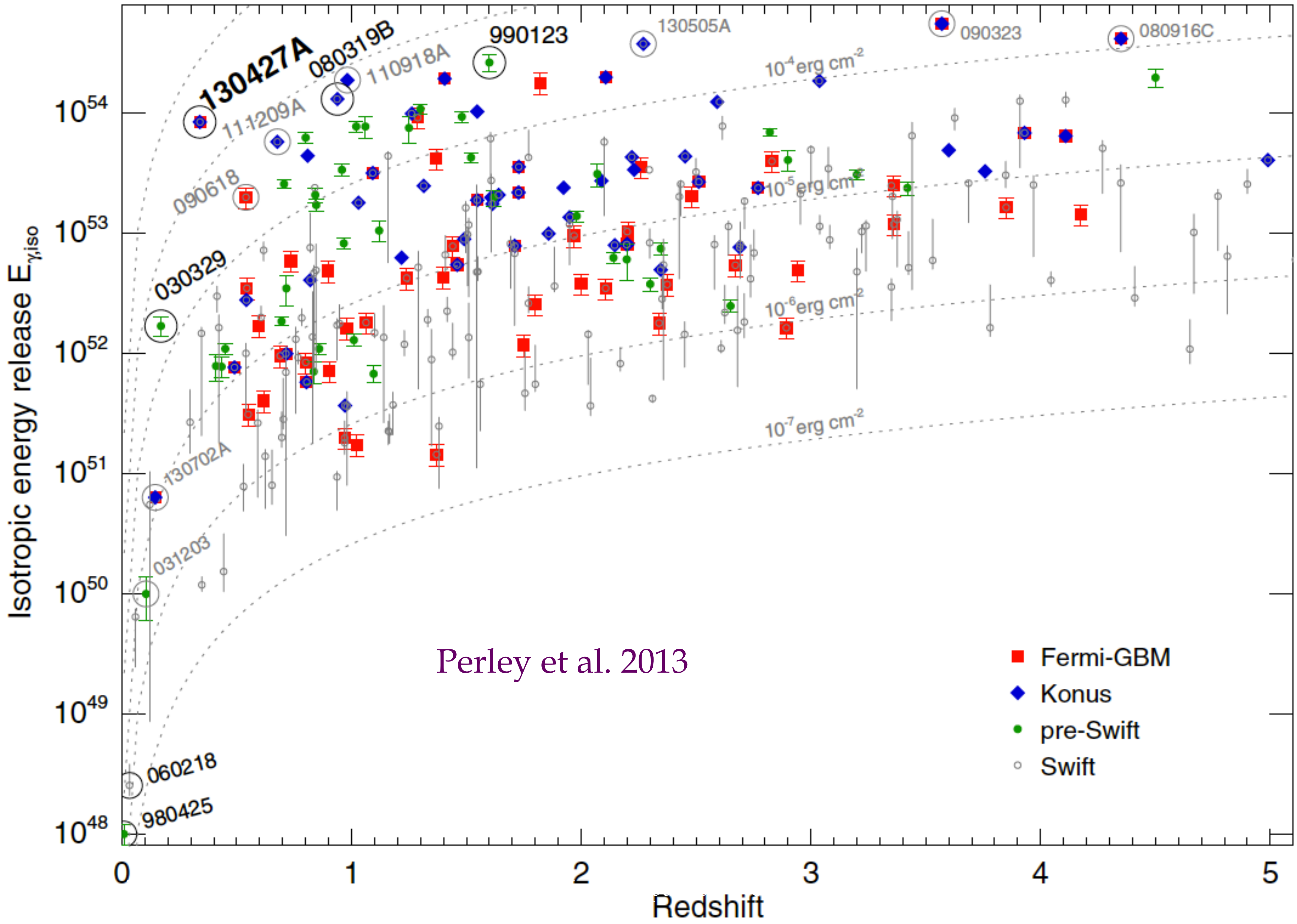
GRB statistics – corrected for beaming

- For long GRBs, the beaming angle is estimated to be few degrees, we see one GRB out of several hundreds.
- The jets of short GRBs could be more open (10°-30°), and we may see one short GRBs out of several tens.

- The energy budget is strongly reduced
  - Long GRBs: $E_\gamma \approx 10^{51-52}$ erg
  - Short GRBs: $E_\gamma \approx 10^{48-49}$ erg

- The space density of GRBs is increased
  - Long GRBs: 100-1000/Gpc^3/yr – few % of the rate of SN Ibc (~9000/Gpc^3/yr)
  - Short GRBs: 100-1000/Gpc^3/yr – comparable to the rate of NS-NS mergers

- In the near future the detection of *orphan afterglows* may lead to more precise estimates



Isotropic energy release $E_{\gamma,iso}$
Redshift
130427A
080319B
110918A
990123
130505A
090323
080916C
111209A
090618
030329
130702A
031203
060218
980425
10^{-4} erg cm^{-2}
10^{-5} erg cm^{-2}
10^{-6} erg cm^{-2}
10^{-7} erg cm^{-2}
Fermi-GBM
Konus
pre-Swift
Swift
Perley et al. 2013

The local universe

From

- http://www.astro.ucla.edu/~wright/CosmoCalc.html
- http://www.atlasoftheuniverse.com/

z	Dl (Mpc) (Ho=70 ; Ω_M=0.3)	V (Gpc^3)	Ngal (small)
0.01	43	0.0003	$5\ 10^4$
0.05	222	0.04	
0.1	460	0.31	$60\ 10^6$
0.2	980	2.3	
1	6607	151	
5	46640	1970	$\geq 10^{12}$

Horizon of GW detectors

Note: The Star Formation Rate was about 20 times larger at redshift z=1

A census of local GRBs

•	**Collapsars:**				
•	980425	BATSE	0.0085	$1\ 10^{48}$	55 keV
??	060505	Swift	0.089	$3\ 10^{49}$	>160 keV
•	031203	Integral	0.105	$5\ 10^{49}$	20 or 200 keV
•	130702A	Fermi/GBM	0.145	$7\ 10^{50}$	~15 keV
•	030329	Hete2	0.168	$2\ 10^{52}$	100 keV
•	**Mergers:**				
??	060614ee	Swift	0.125	$3\ 10^{51}$	<100 keV
•	061201	Swift	0.111?	$1\ 10^{50}$?	1000 keV
•	080905	Swift	0.1218	$7\ 10^{50}$	600 keV
•	050709ee	Hete2	0.1606	$3\ 10^{49}$	100 keV
•	**SN shock breakout:**				
•	060218X	Swift	0.0331	$6\ 10^{49}$	5 keV
•	100316D	Swift	0.059	$6\ 10^{49}$	~30 keV

GRBs in the local universe

- The GRB local population is diverse
  - Short, long, SN shock breakout, low-luminosity?
  - Energy ranging over 4 (6) orders of magnitude: 10^{48} to 10^{52} erg (GRB 130427 at z=0.334, with Eiso = 10^{54} erg)
- A few words about low-luminosity GRBs
- Most local GRBs are unseen since their jet is not pointed towards the Earth
- In the coming years, astronomers will get new tools to observe GRBs in the local universe: LSST, GW interferometers…

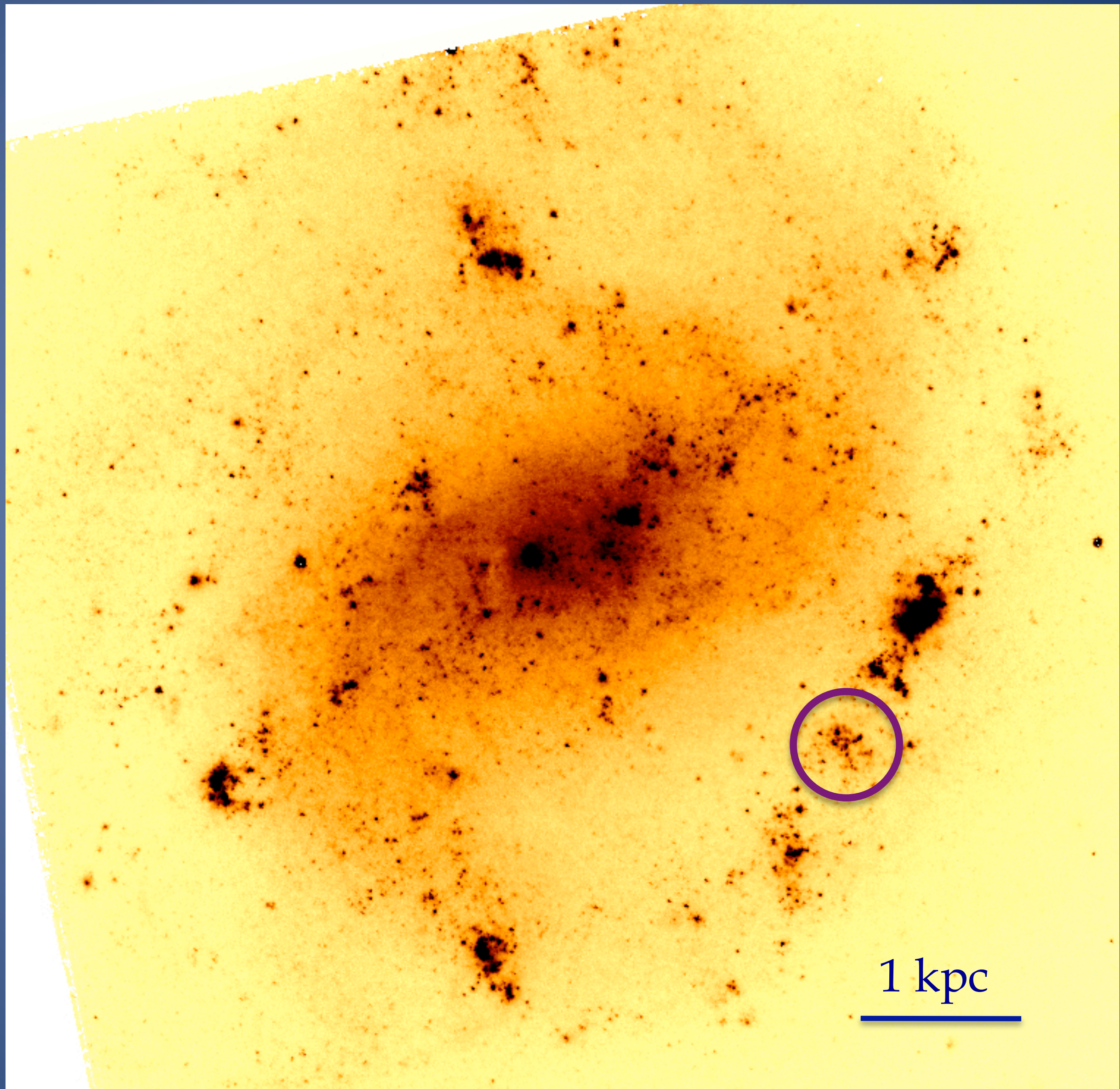
Low-luminosity GRBs

- Low-luminosity GRBs have an energy typically 100 times smaller than classical long GRBs.
  - GRB 980425 ($z=0.0085$, $E_{iso}=10^{48}$ erg) is the prototype of sub-luminous GRBs
- Low-luminosity GRBs are associated to type Ic supernovae
- Low-luminosity GRBs have a much smaller detection volume. Despite their rarity, there could thus dominate the GRB population with a rate of occurrence of $100\text{-}300 * f_b / Gpc^3 / yr$.
- Low-luminosity GRBs cannot be strongly beamed ($f_b \leq 10$), otherwise their rate would exceed the rate of Type Ic supernovae ($\sim 9000 / Gpc^3 / yr$)
- It has been suggested that low-luminosity GRBs could have distinct progenitors, for instance magnetars instead of black hole

The GRB-SN connection

The host galaxy of
GRB 980425 at 36 Mpc

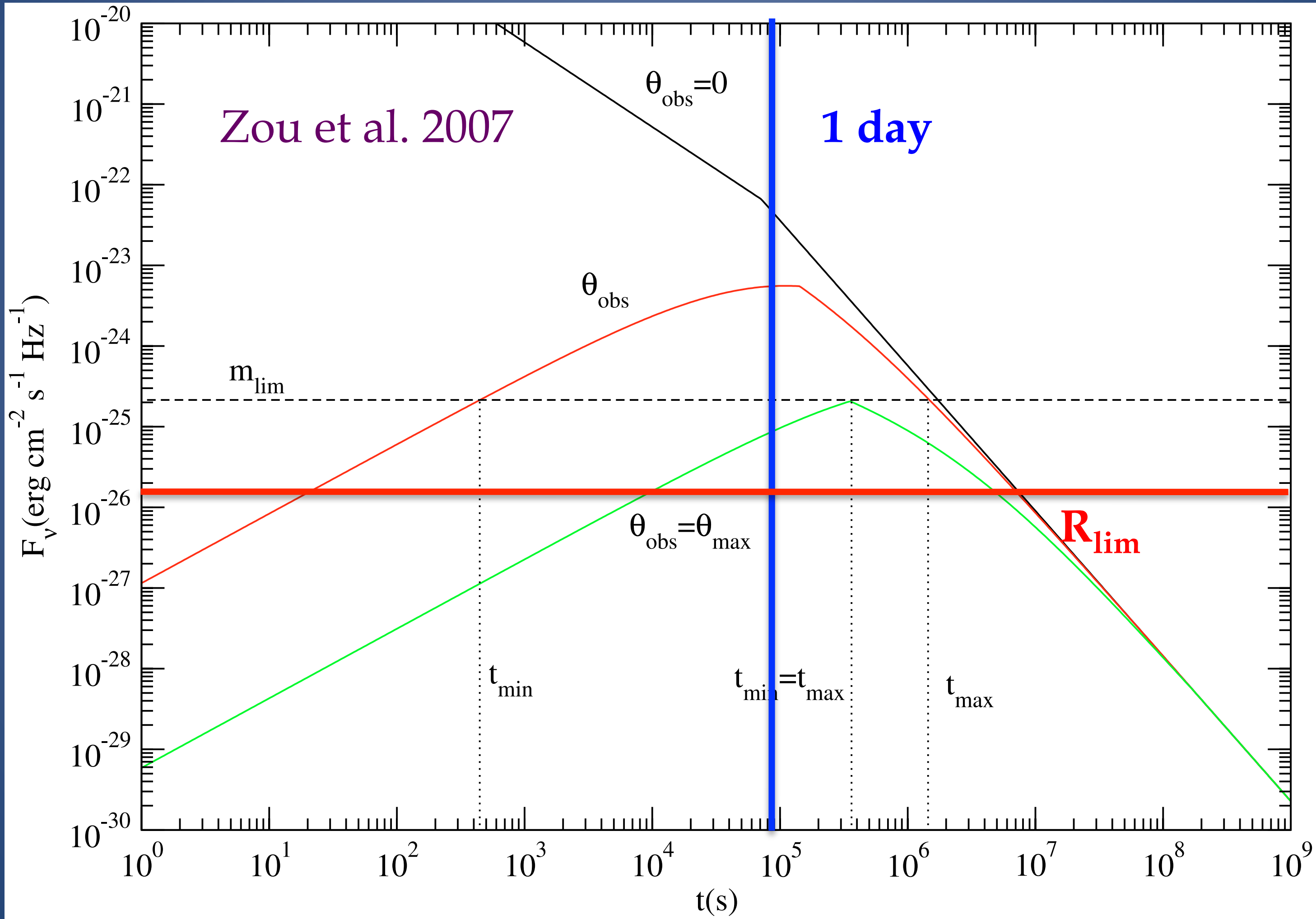
Nearby GRBs allow studying the regions of GRB formation within their host galaxies. This way we may learn more on the progenitors.



Orphan GRB afterglows with LSST

- There are ~10^3 classical GRB/yr all sky
- Beaming implies that GRBs are 10^2-10^3 time more frequent than the observed rate → prediction of the existence of ***orphan afterglows***
- LSST will permit the detection of GRBs from their optical emission, with a reasonable rate for the first time → ***untriggered afterglows***
- In the next decade LSST may detect a few tens of GRBs/yr, with selection effects quite different from GRB detectors in space: LSST will open a new window for GRB studies.
  – Orphan afterglows are faint and numerous: most orphan afterglows will be from local GRBs
  – Finding orphan afterglows will provide clues about GRB beaming
  – GRBs detected with LSST and SVOM (or another GRB satellite) will be crucial to calibrate LSST-only GRBs.

Orphan afterglows…



Mergers and gravitational waves

- The next generation of GW interferometers (adv. LIGO, adv. VIRGO) may detect NS-NS mergers to 200 Mpc and NS-BH mergers to 500 Mpc, providing a unique opportunity to confirm the origin of short GRBs.

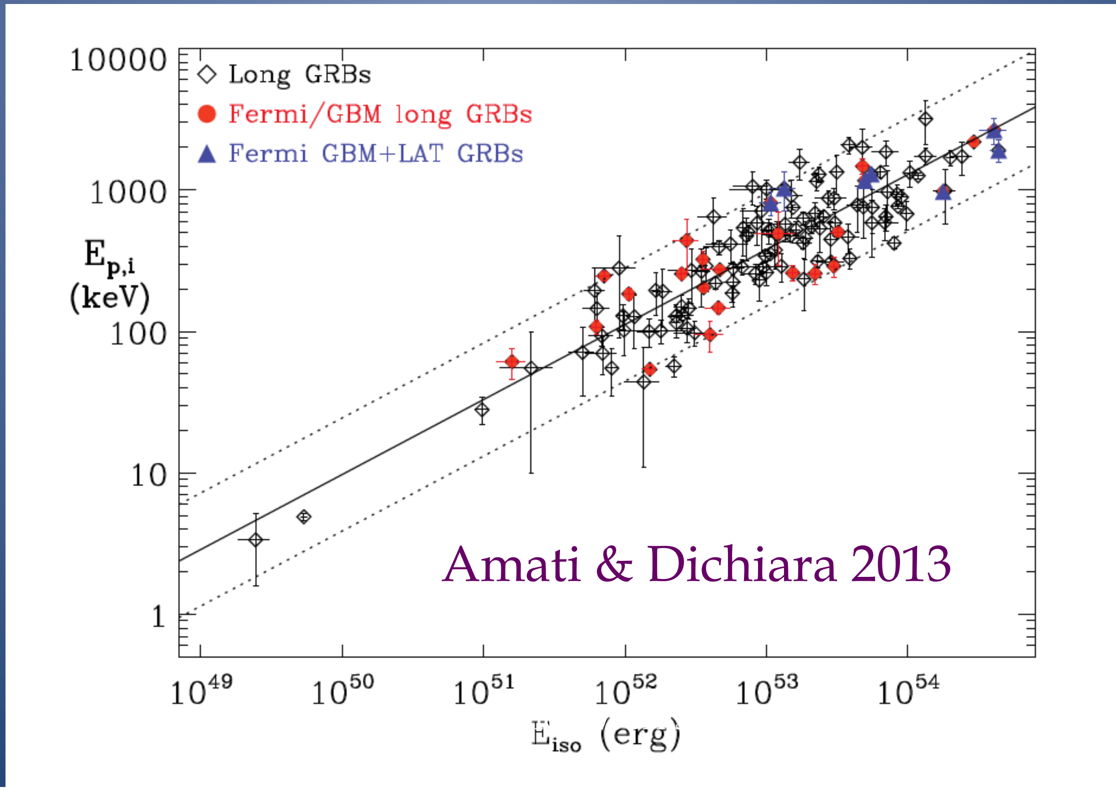
- Belczynski et al. (2008) predict a rate of NS-NS mergers of 100-1000 $Gpc^{-3}\ yr^{-1}$. With an horizon of ~200 Mpc for NS-NS mergers, Advanced GW detectors may detect 3-30 mergers/yr.

- Most often GW detections will not be associated with a short GRB.
  - The beaming of short GRBs is uncertain: $4 \ll f_b^{-1} < 100$
  - May expect 1 coincidence GW ⇔ short GRB after ~1 year at full sensitivity
  - Use macronova optical emission to confirm merger origin of GW signals not associated with a short GRB?

The GRB-SN connection

- The detection of GRBs in the local universe ($z \leq 0.1$) provides crucial clues to understand the SN-GRB connection.
- In the local universe, it is more probable to detect low-luminosity GRBs (they are more numerous and detectable).
- Low-luminosity GRBs with low Epeak are more easily detected (since they have more photons).

→ SVOM/ECLAIRs has a low energy threshold at 4 keV, allowing the detection of faint and soft nearby GRBs



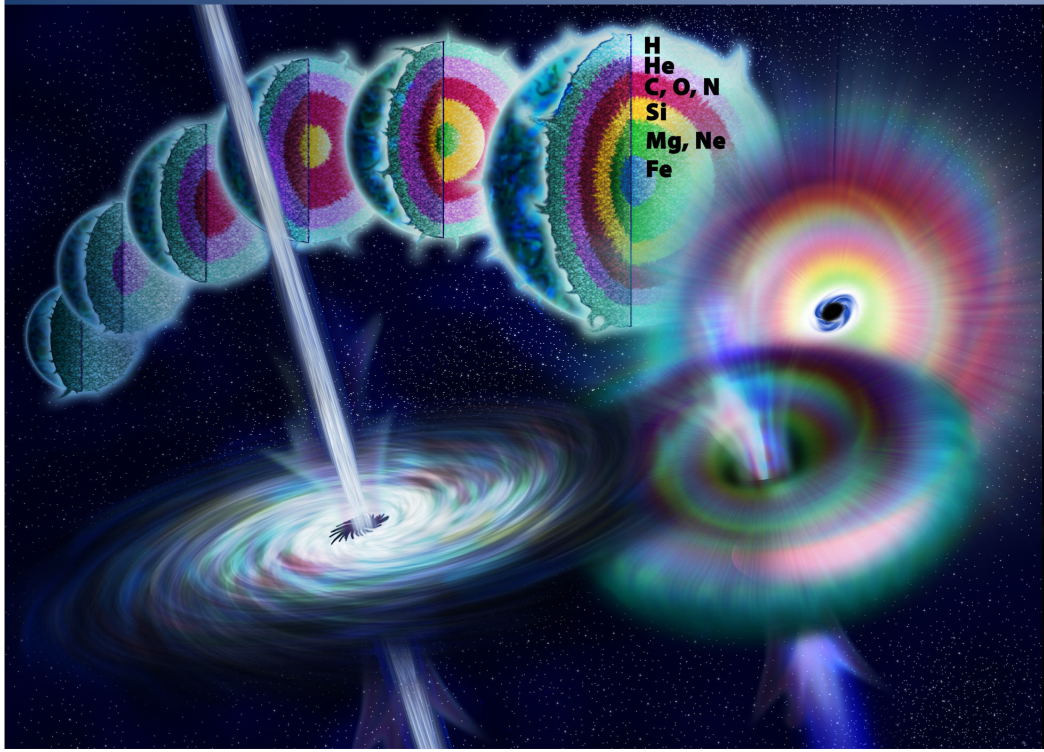
Summary

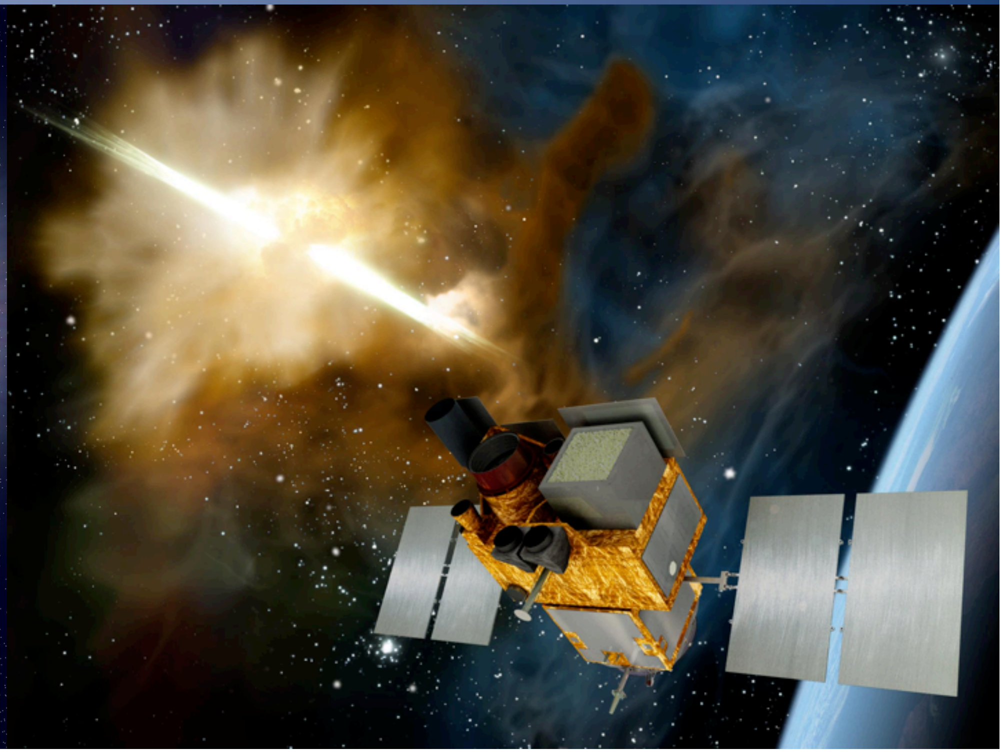
Local GRBs are crucial sources for multi-messenger astrophysics. In the coming years, significant progress is expected on local GRBs with:

- LSST: orphan afterglows from local GRBs
  - Beaming angle (but how do we know an afterglow is an orphan?)
- Advanced gravitational waves detectors
  - Are short GRBs mergers?
  - Beaming angle of mergers
- SVOM: soft GRBs and XRFs
  - Study of the GRB – SN connection

- Don't forget failed GRBs (e.g. neutrinos)!

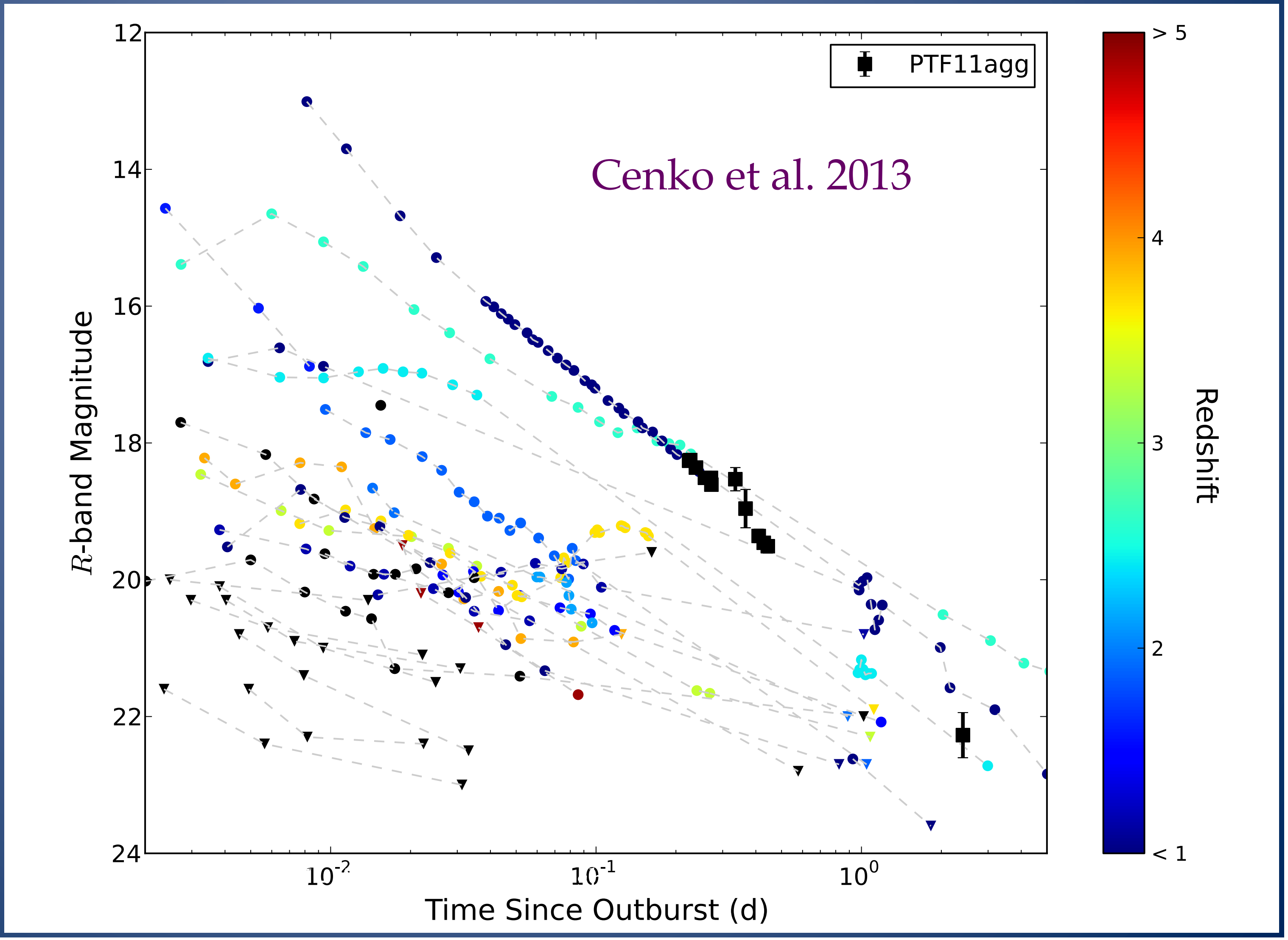
The end





PTF11agg, The first "untriggered" GRB afterglow?

- Cenko et al. 2013: « Discovery of a Cosmological, Relativistic Outburst via its Rapidly Fading Optical Emission »



Detecting GRB afterglows with LSST

- LSST will arrive on the spot 1-4 days after the GRB. The afterglow will typically be visible in 1 to 3 « visits »
- Don't use LSST for the follow-up of well localized GRBs!
- GRB afterglows will be difficult to recognize if we don't know that there was a burst (with the prompt high energy emission)
- *Orphan afterglows* will be even more difficult to recognize