Gamma-Ray Bursts:

EVLA, ALMA, and Multi-Wavelength Observations

Edo Berger (Harvard)

Ashley Zauderer, Tanmoy Laskar, Wen-fai Fong

Outflows, Winds and Jets: From Young Stars to Supermassive Black Holes – March 4, 2012

Outline

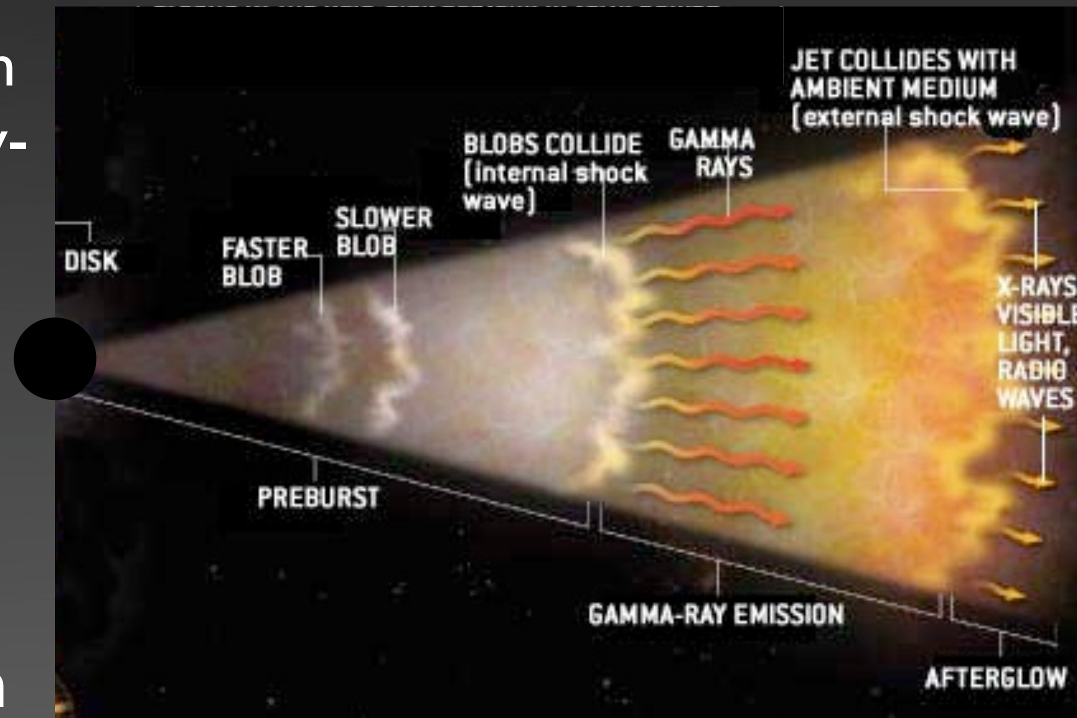
- *GRBs as spectacular collimated explosions:*
  - *The properties of the ejecta*
  - *Jets, energetics, and environments*
  - *Dark GRBs*
  - *Short GRBs: progenitors, jets, energetics*

- *GRBs as probes of high redshift galaxies:*
  - *Optical absorption studies of atomic interstellar gas at high redshift*
  - *EVLA/ALMA absorption studies of molecular gas at high redshift*

★*A new frontier: EVLA/ALMA synergy*

Explosion Physics & Energetics

Relativistic expansion required for optically-thin non-thermal γ-ray spectrum

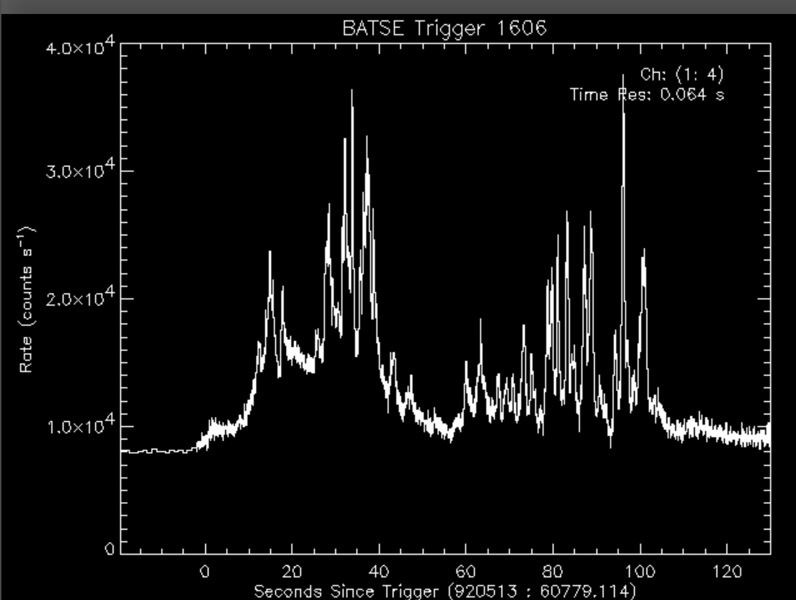


$\Gamma \sim 10^2 - 10^3$

$R \sim 10^{14} - 10^{15}$ cm

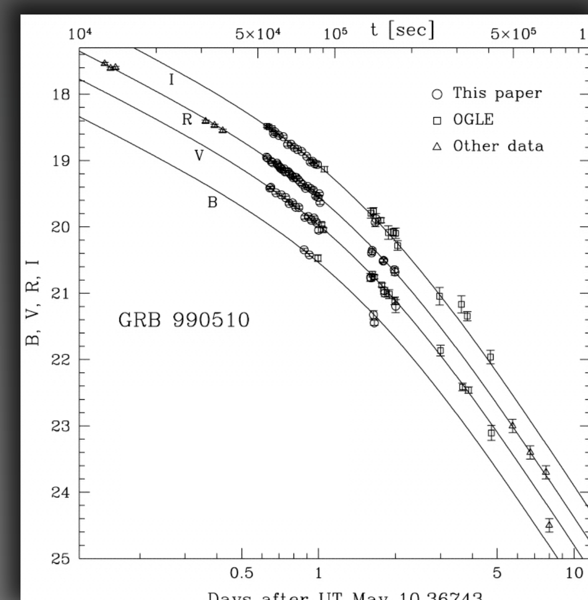
$\Gamma \sim 10$

$R \sim 10^{17}$ cm



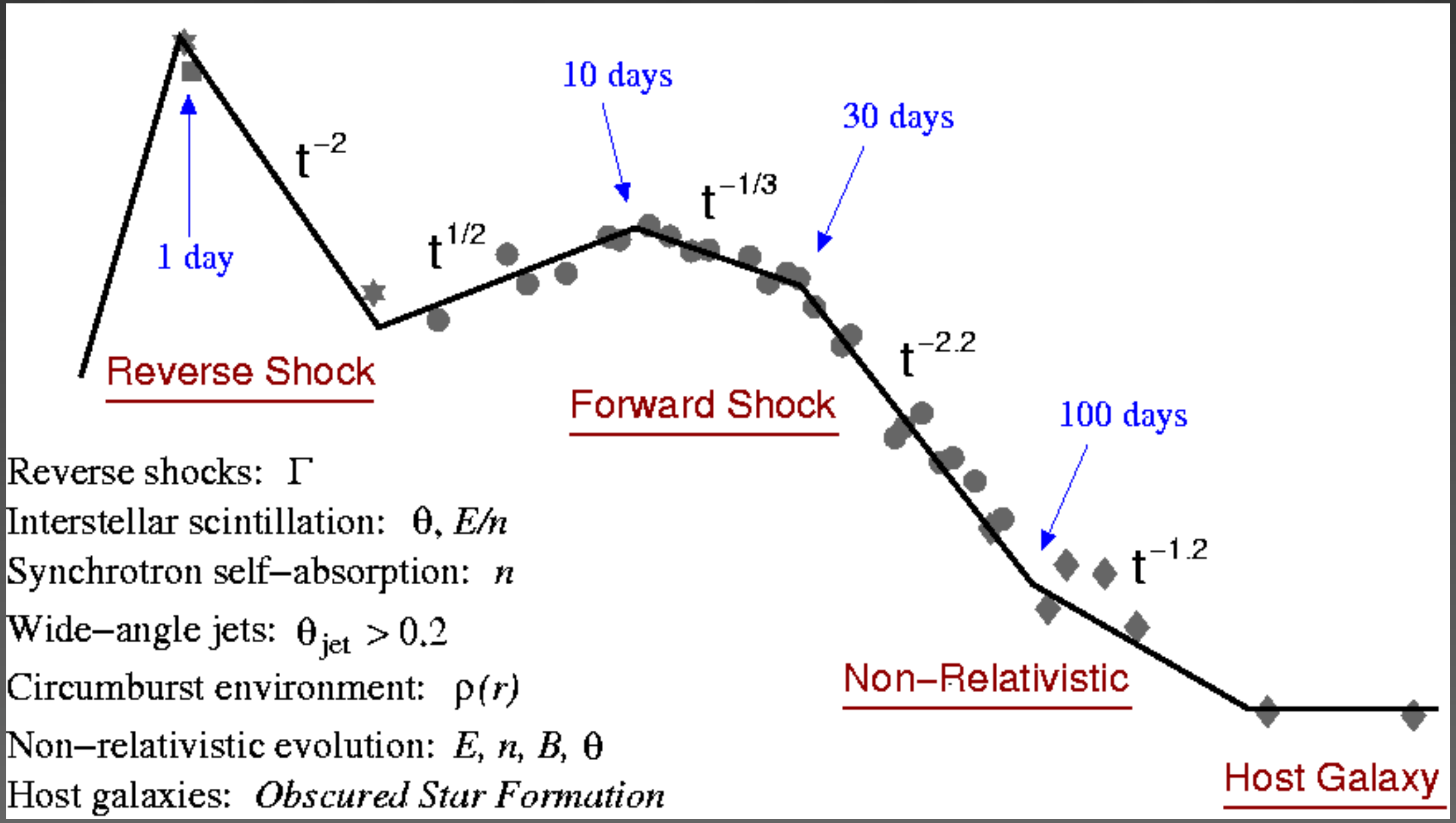
internal shocks / mag. dissipation

external shock reverse shock



Radio Observations

1 hour ⟷ ~few years

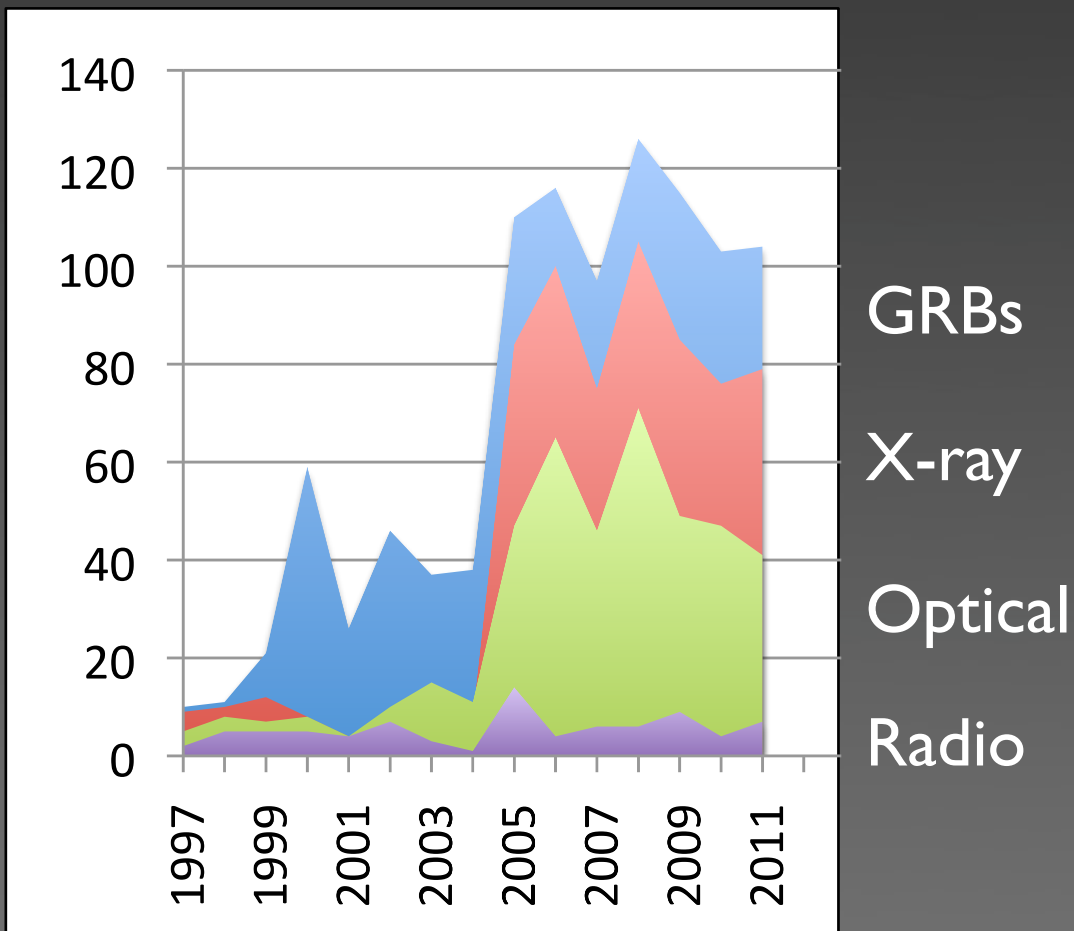


Berger PhD thesis

Radio observations provide information on energy, expansion, geometry, local environment, galactic environment

Radio Observations

Pre-EVLA/ALMA, radio afterglow detection rate is only ~10%



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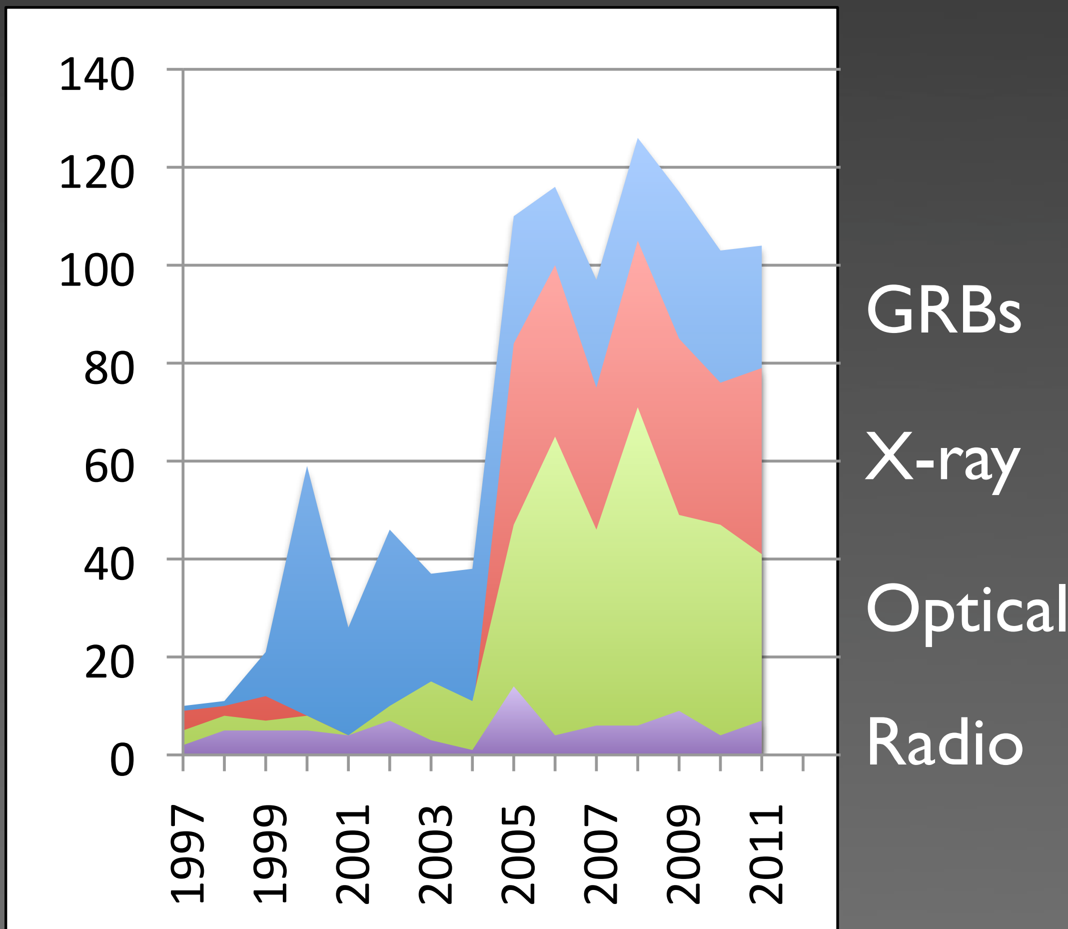

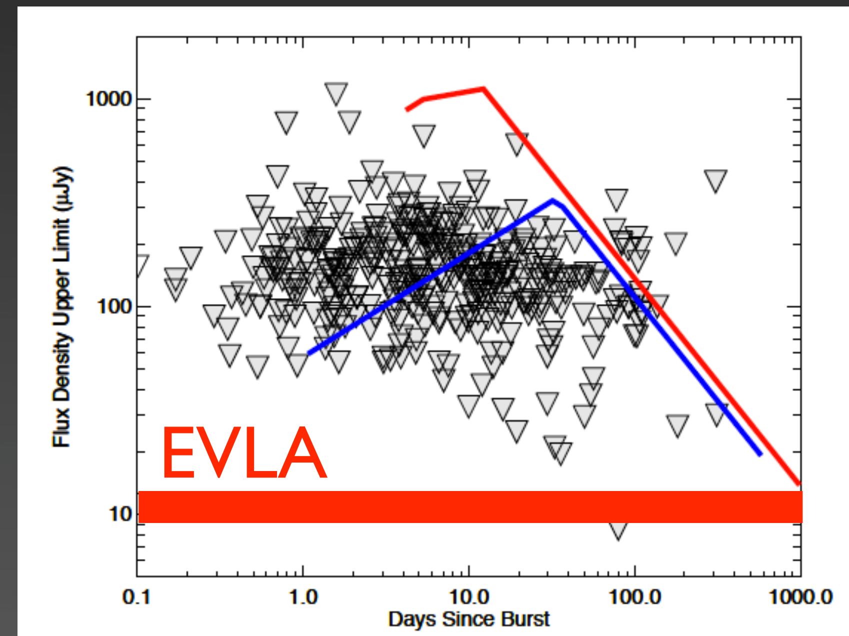

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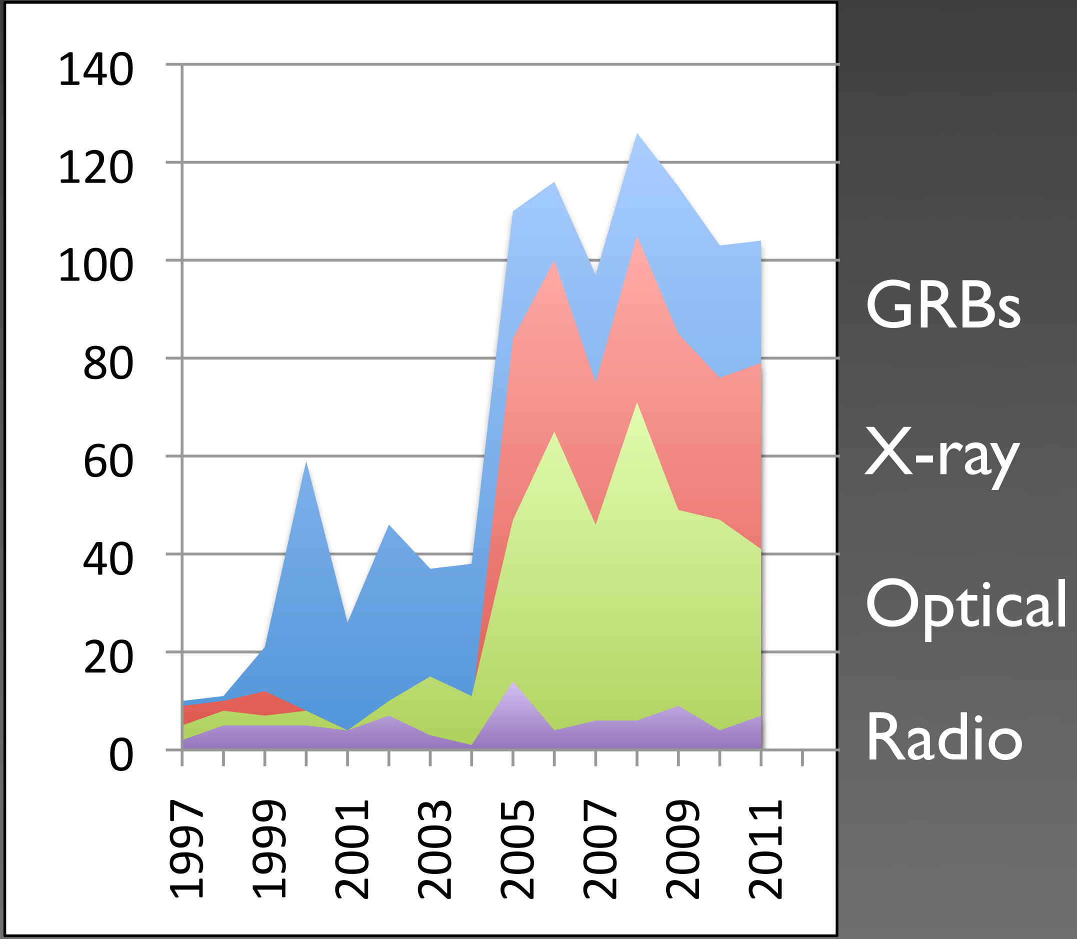
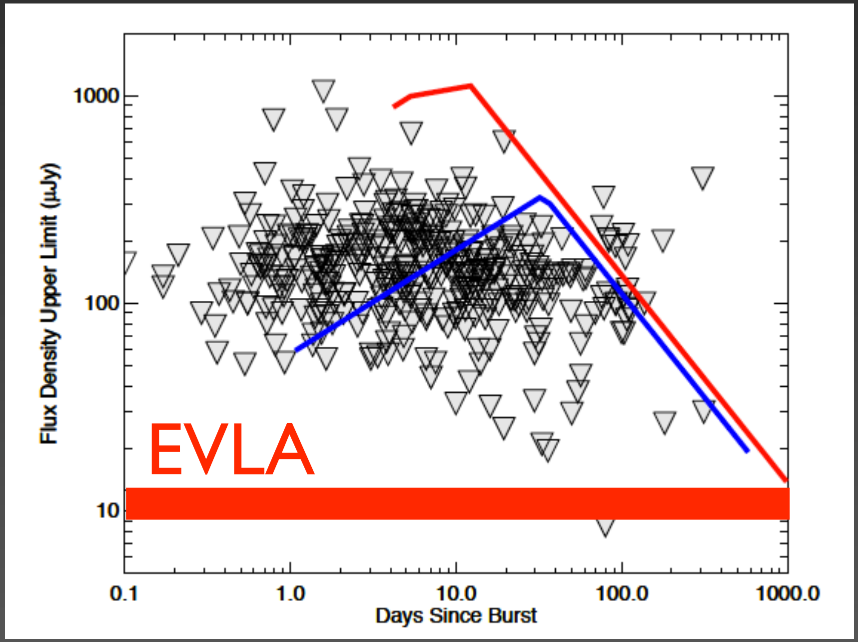
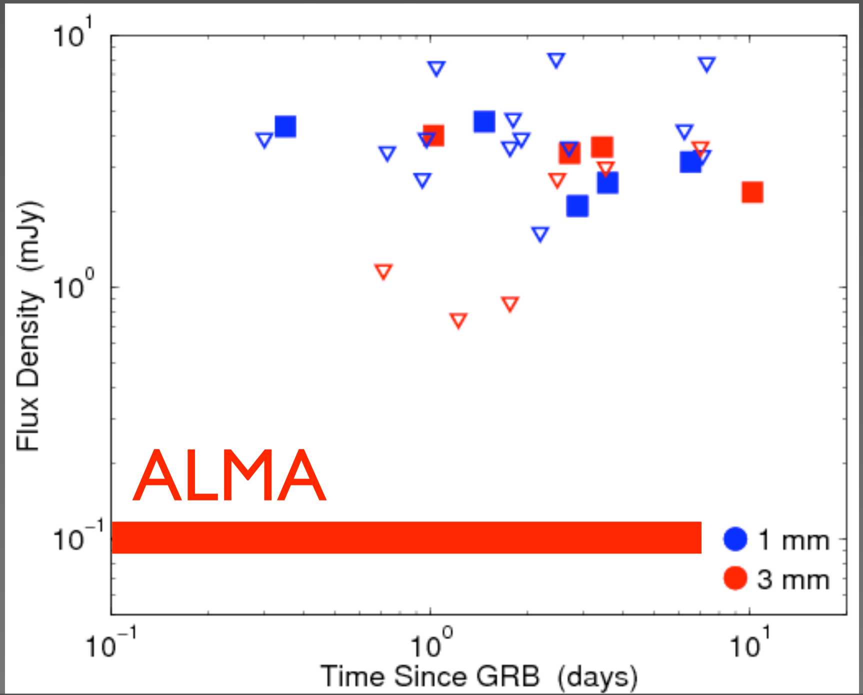
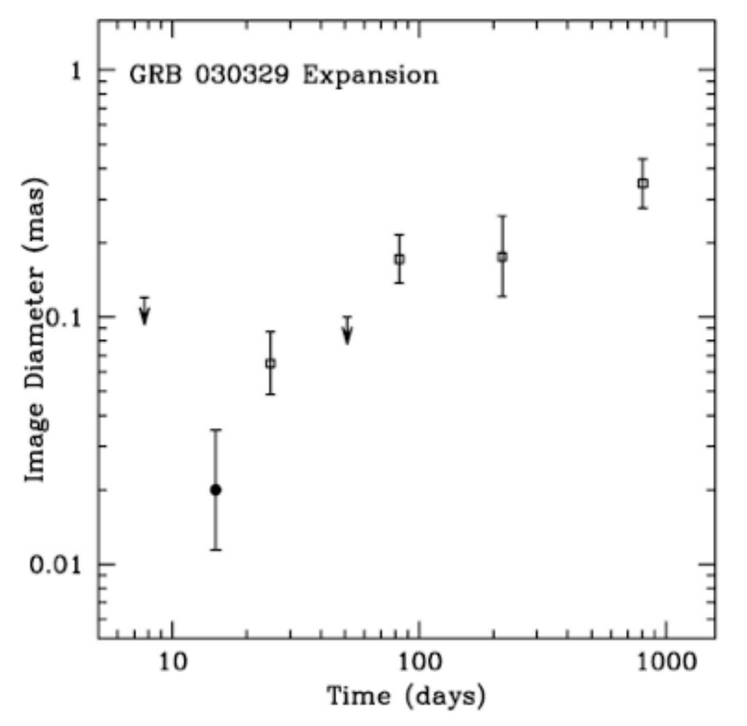
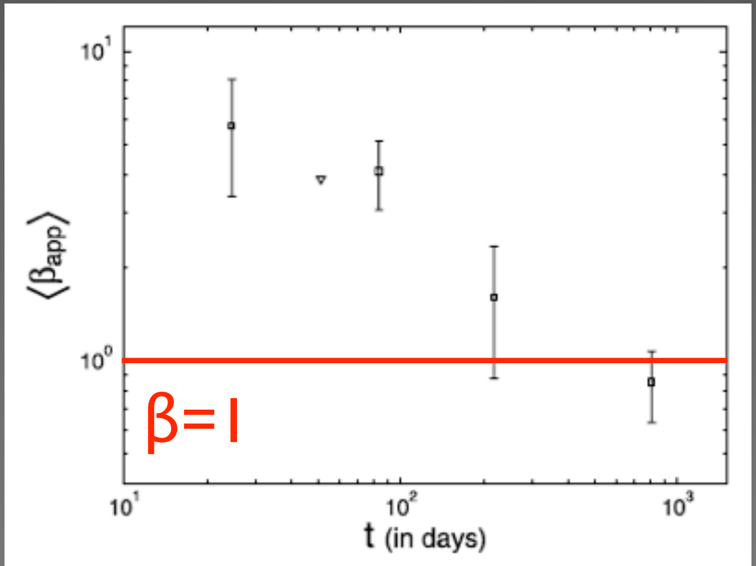






Relativistic Expansion



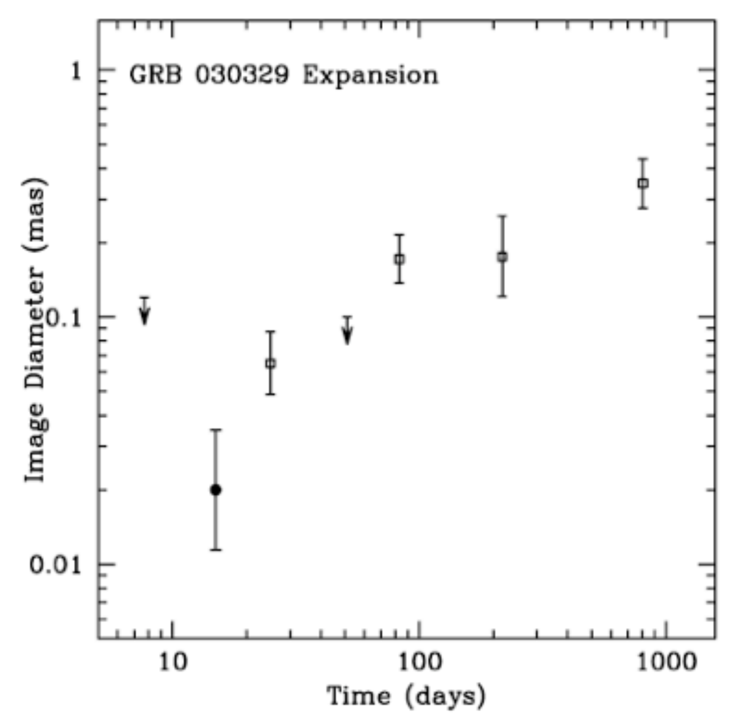


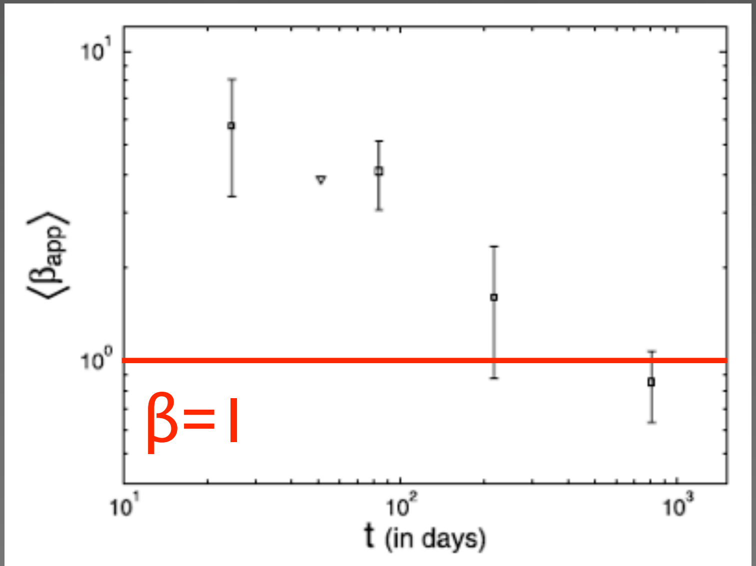
VLBI

Pihlstrom et al. 2007

Relativistic Expansion

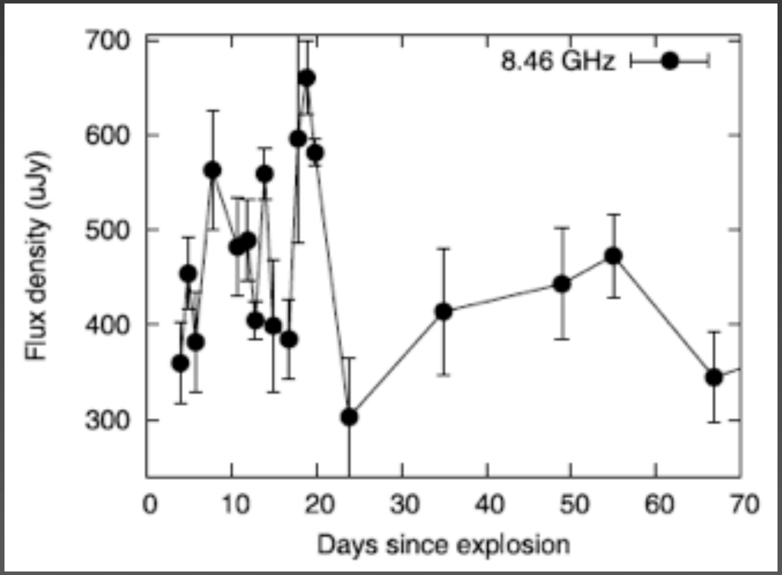
VLBI

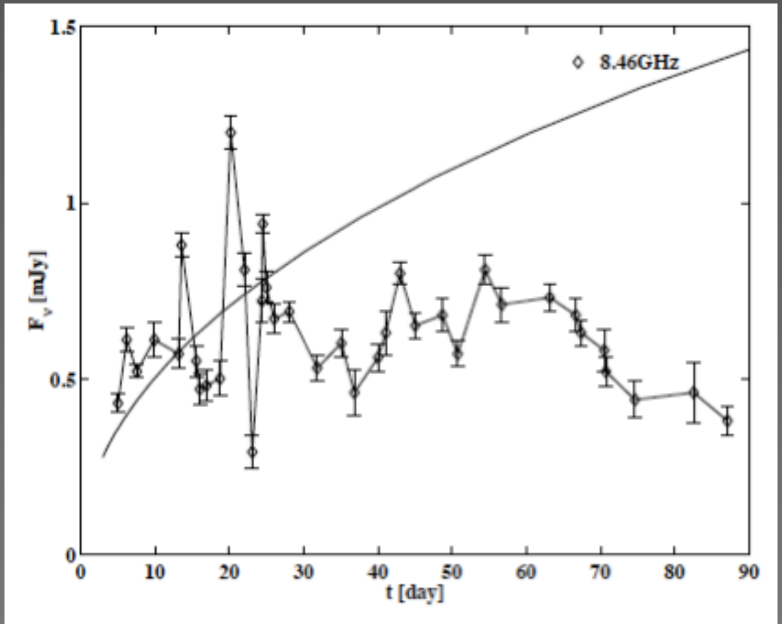




Pihlstrom et al. 2007

Interstellar scintillation



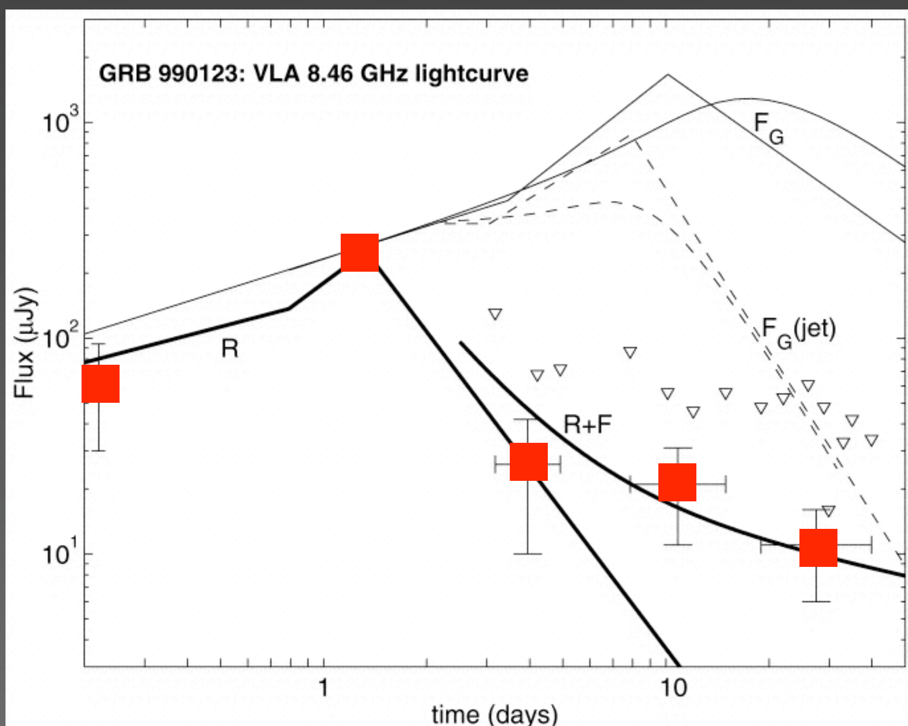


e.g. Waxman et al. 1998; Chandra et al. 2008

The Properties of the GRB Ejecta

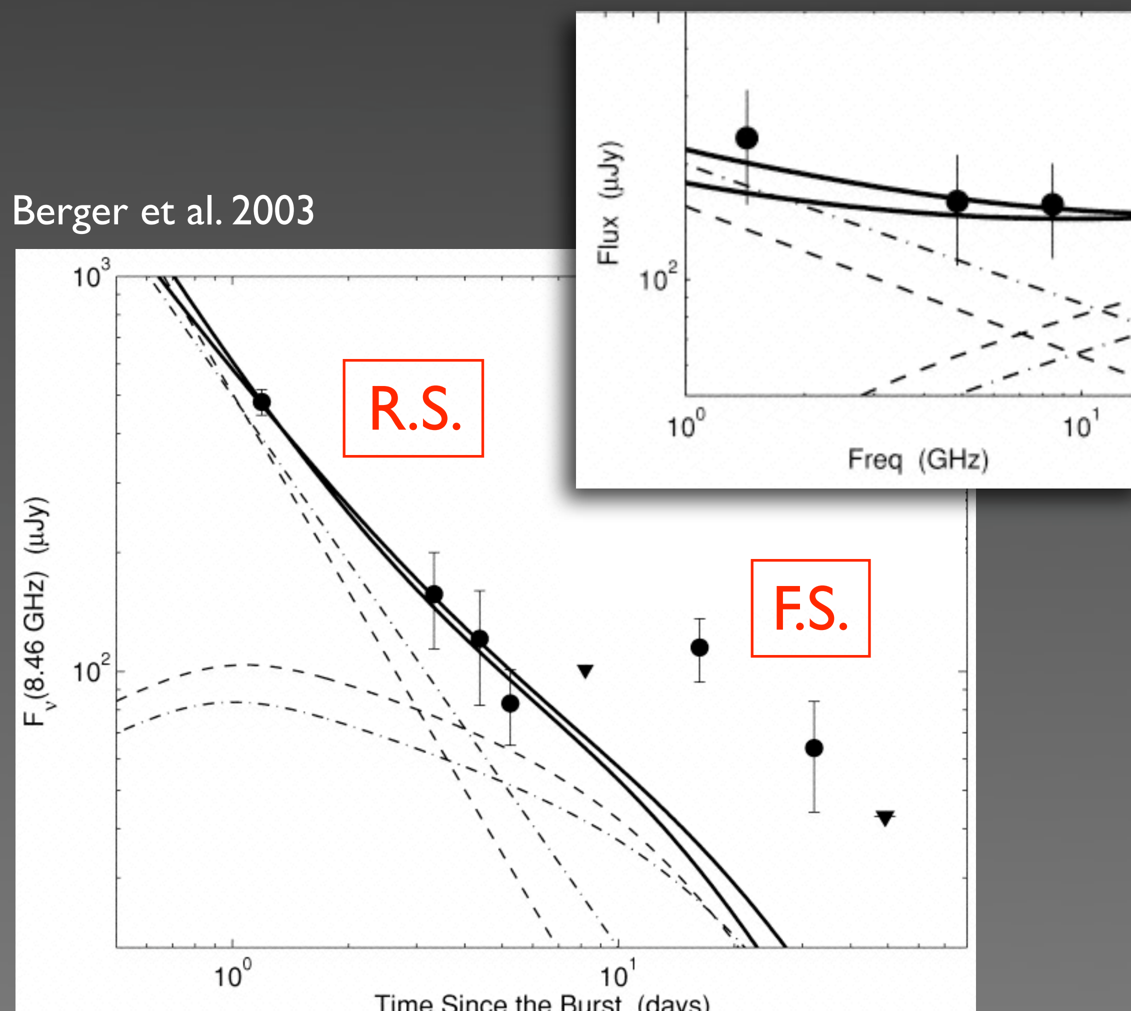
Afterglow emission is due to interaction with the circumburst environment (*forward shock*) and with the ejecta (*reverse shock*)

⇒ R.S. probes ejecta composition, Lorentz factor; peaks in the cm/mm



Kulkarni et al. 1999

Berger et al. 2003



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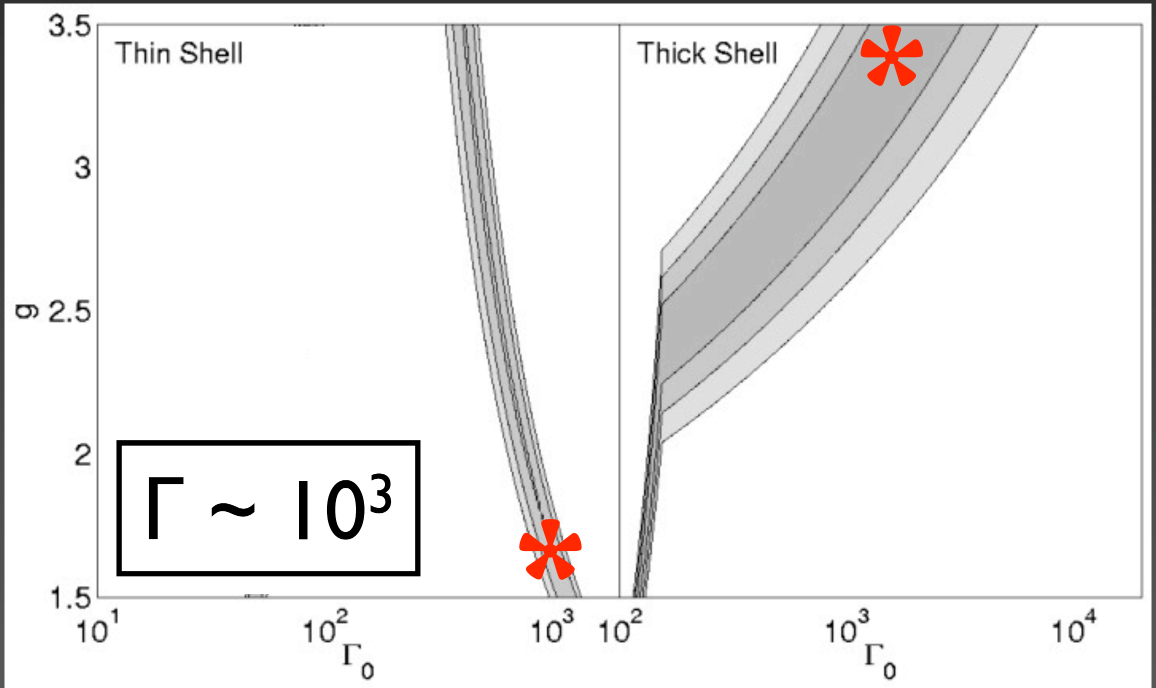

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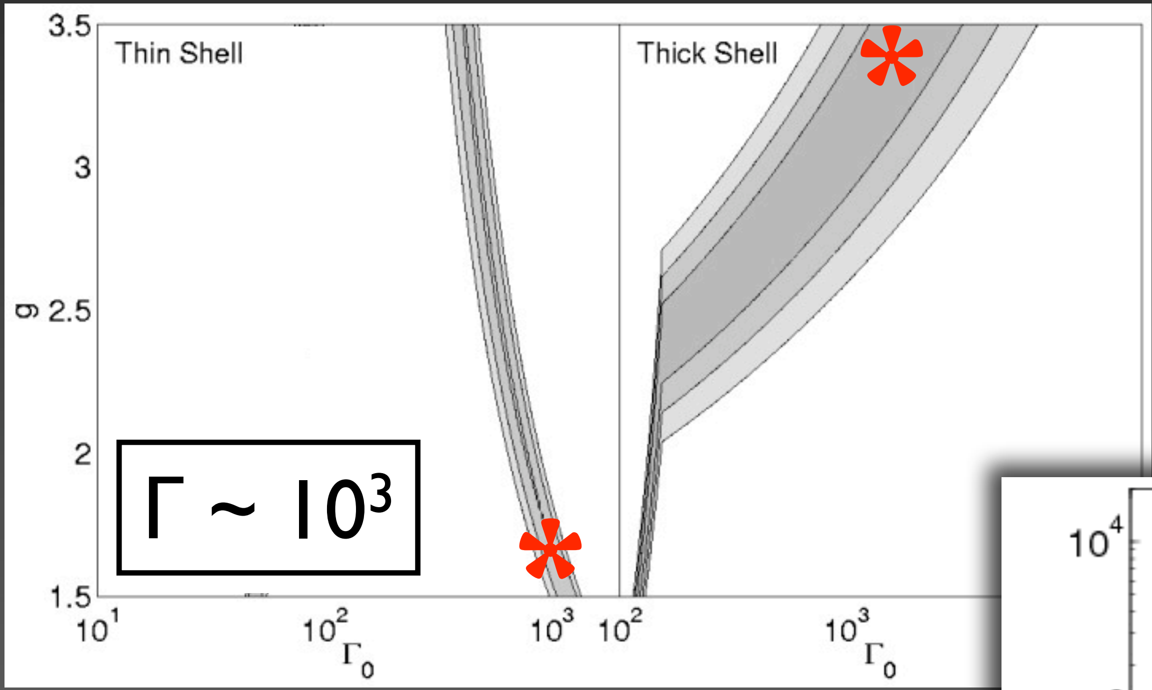
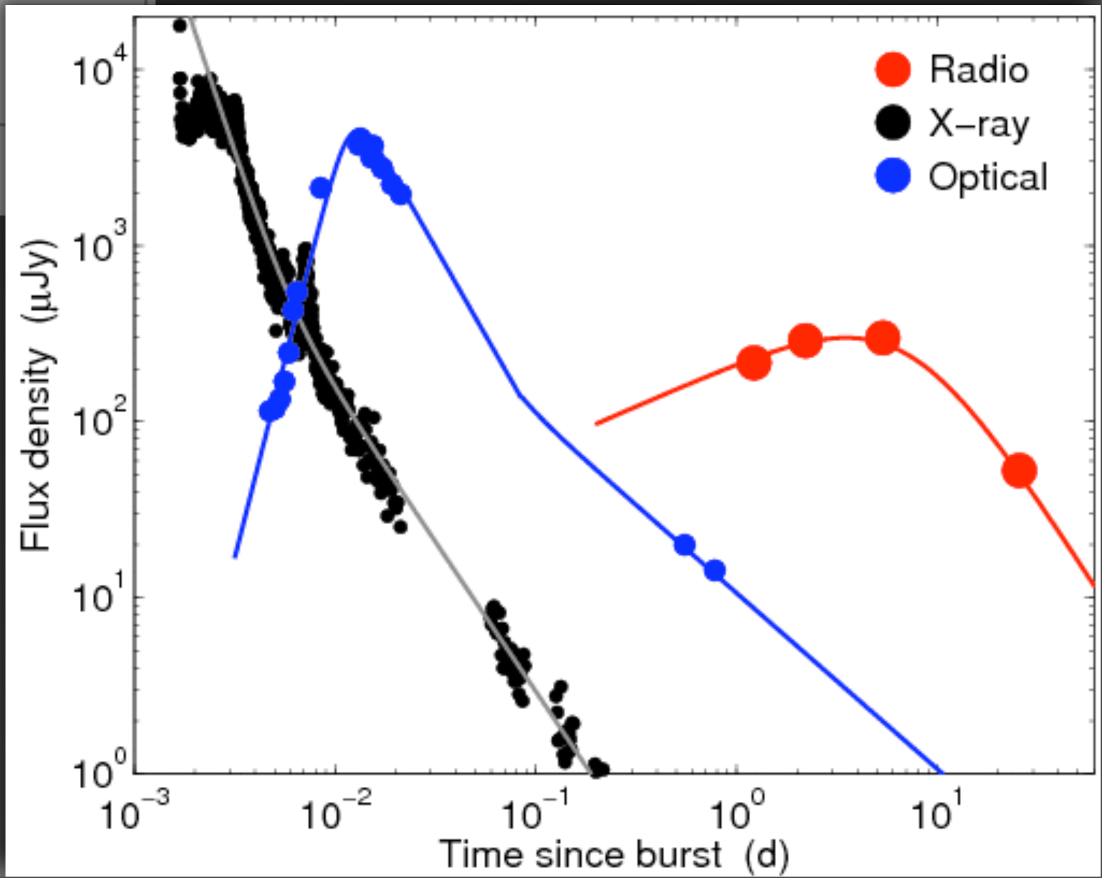


Berger et al. 2003

Routine detections and unique interpretation require deep multi-frequency radio data

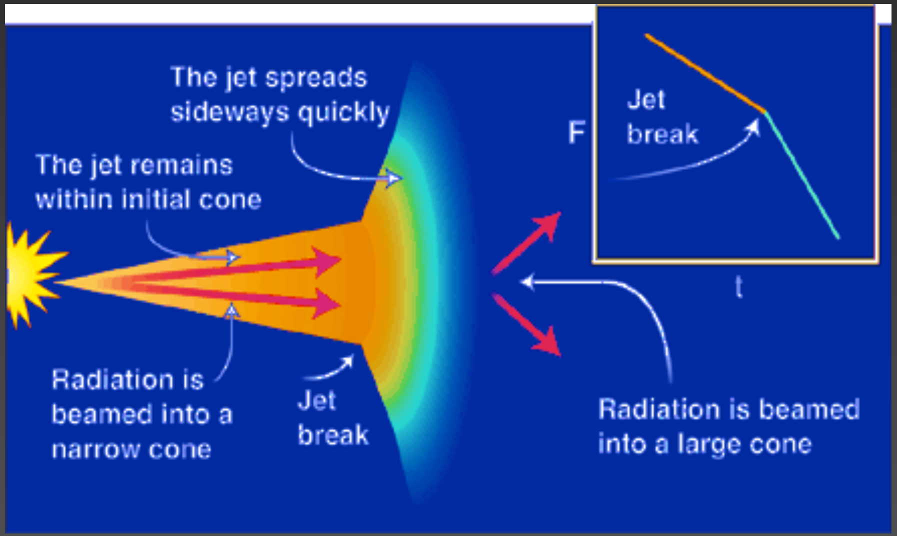
⇒ EVLA + ALMA

Laskar et al. in prep.

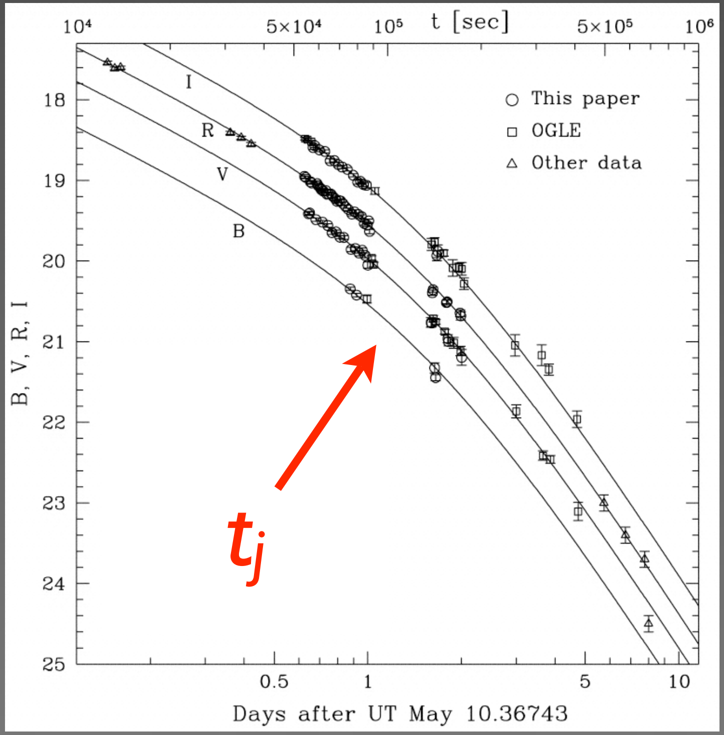


In 2011, we observed 25 GRBs at $\delta t < 1$ day and have 10 detections; non-detections to ~15 μJy; polarization?

Energetics: Jets & γ-rays



$$E = [1 - \cos(\theta_j)]E_{\rm iso}$$



$$\theta_j \sim 1/\Gamma \propto t_j^{3/8}$$

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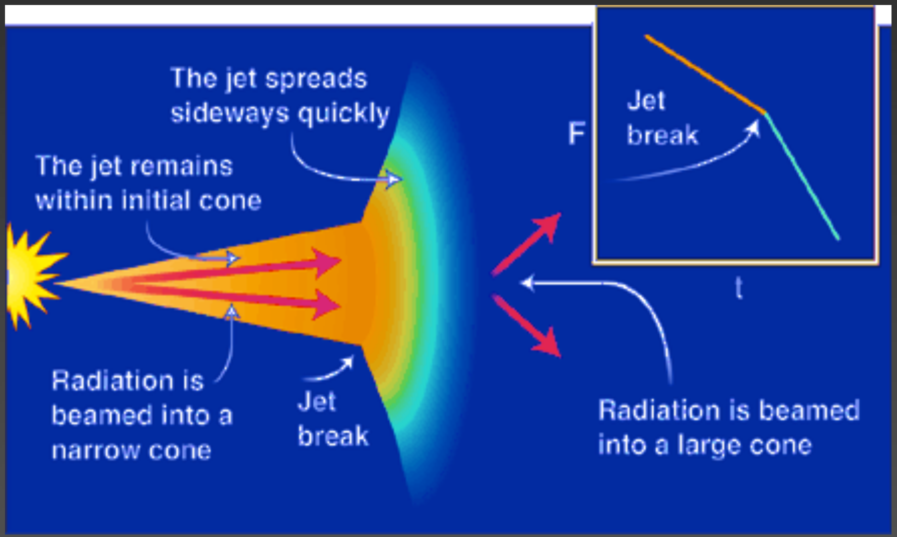
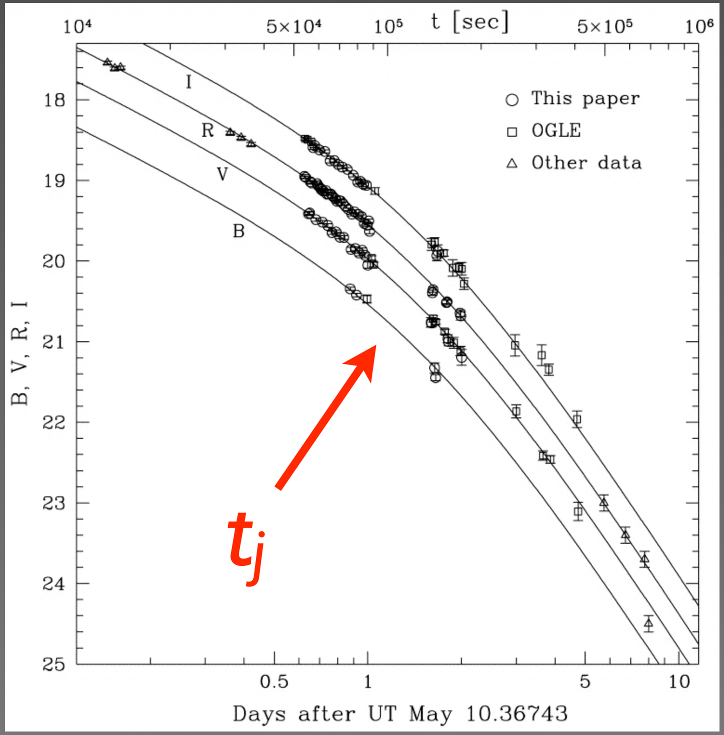


$$E = [1 - \cos(\theta_j)]E_{\rm iso}$$

$$\theta_j \approx 3 - 15°$$



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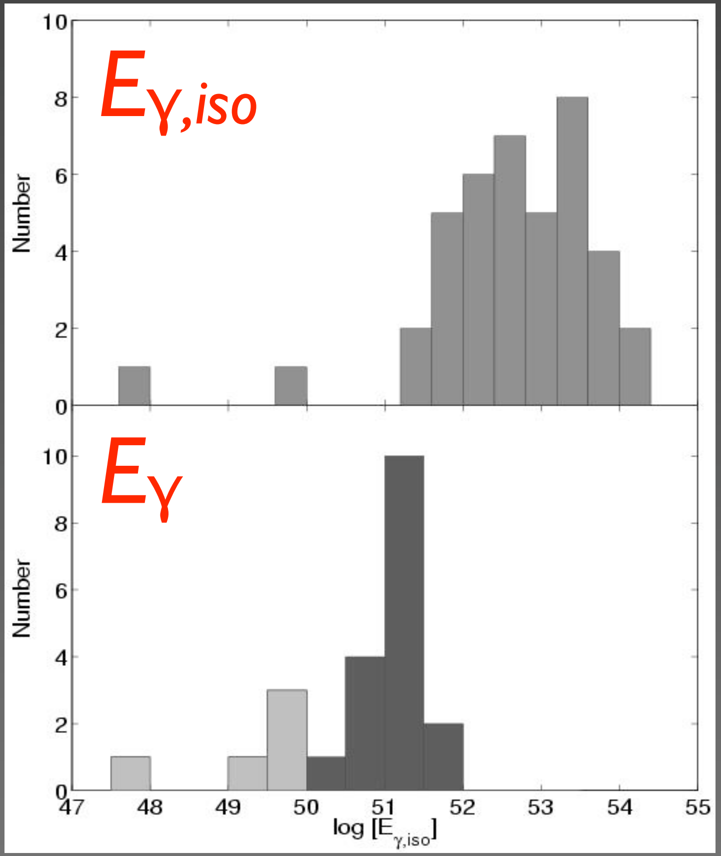
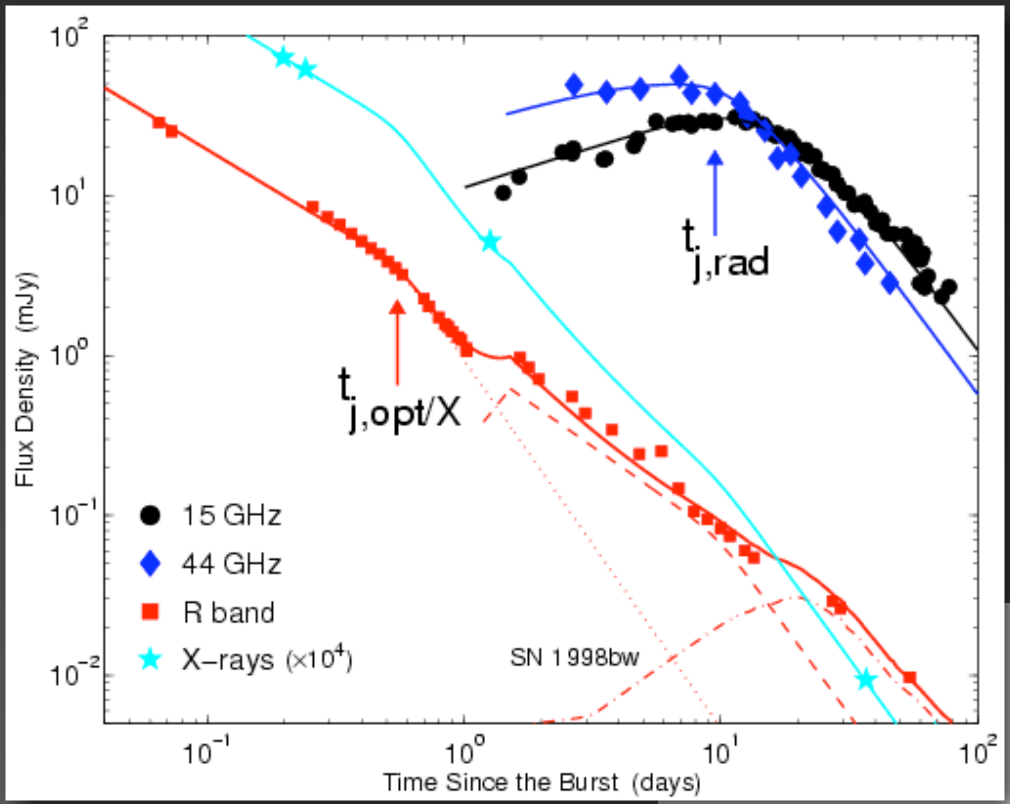


Frail et al. 2001; Bloom et al. 2003; Berger et al. 2003

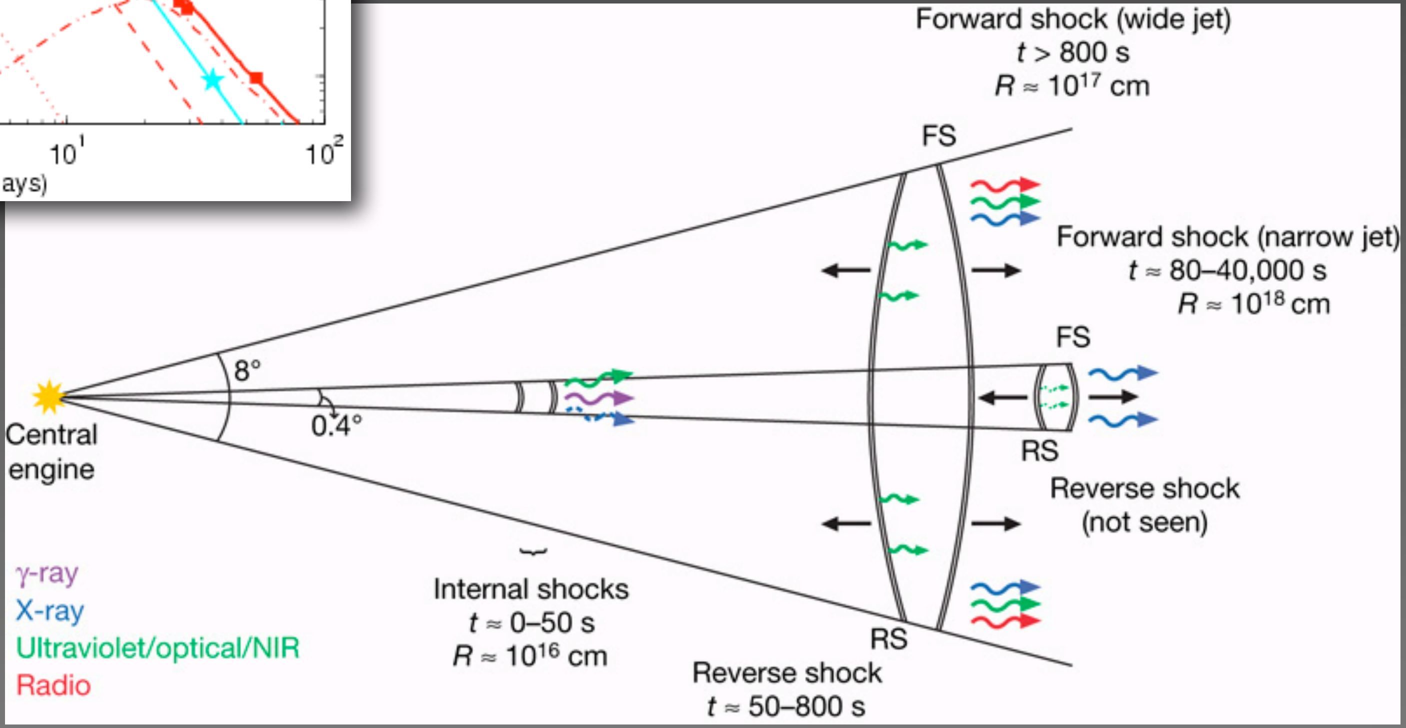
Energetics: Jet Structure



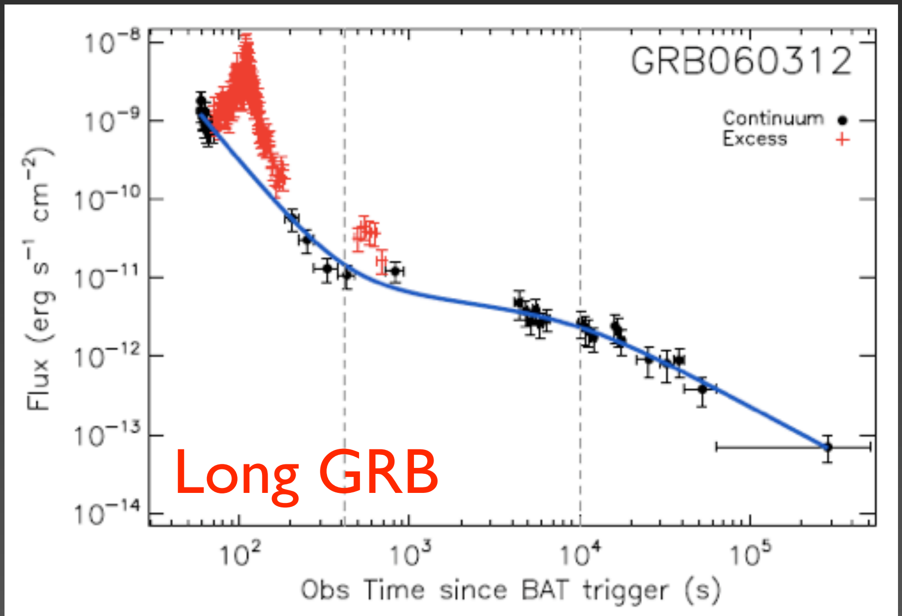
$\theta_{j,O/X} \approx 5$ deg
$E_\gamma \approx 5\times10^{49}$ erg

$\theta_{j,rad} \approx 17$ deg
$E_K \approx 8\times10^{50}$ erg

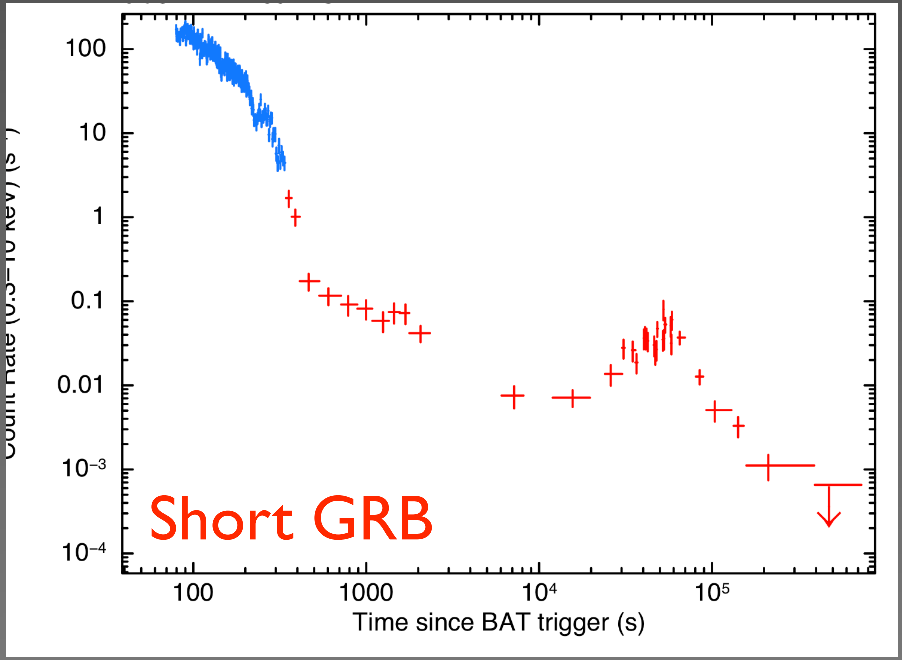
Berger et al. 2003; Racusin et al. 2008



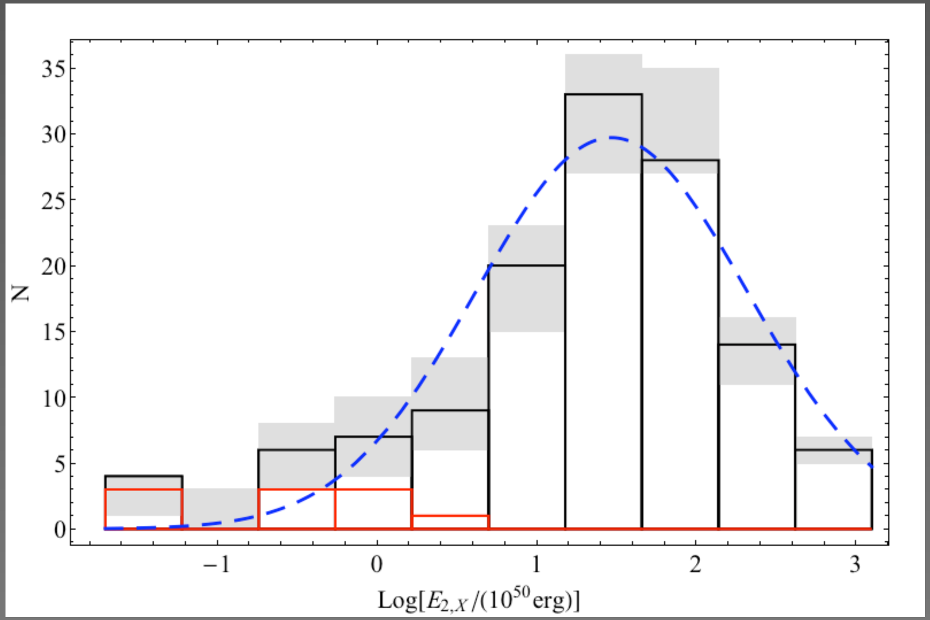
Energetics: X-rays Flares



- X-ray flares at ~10^2-10^4 sec have energy of ~10-100% of E_γ
  ⇒ *on-going engine activity*
- X-ray plateaus require energy injection into forward shock of ~10-100% of E_K
  ⇒ *wide distribution of Lorentz factors*



Margutti et al. 2010, 2011



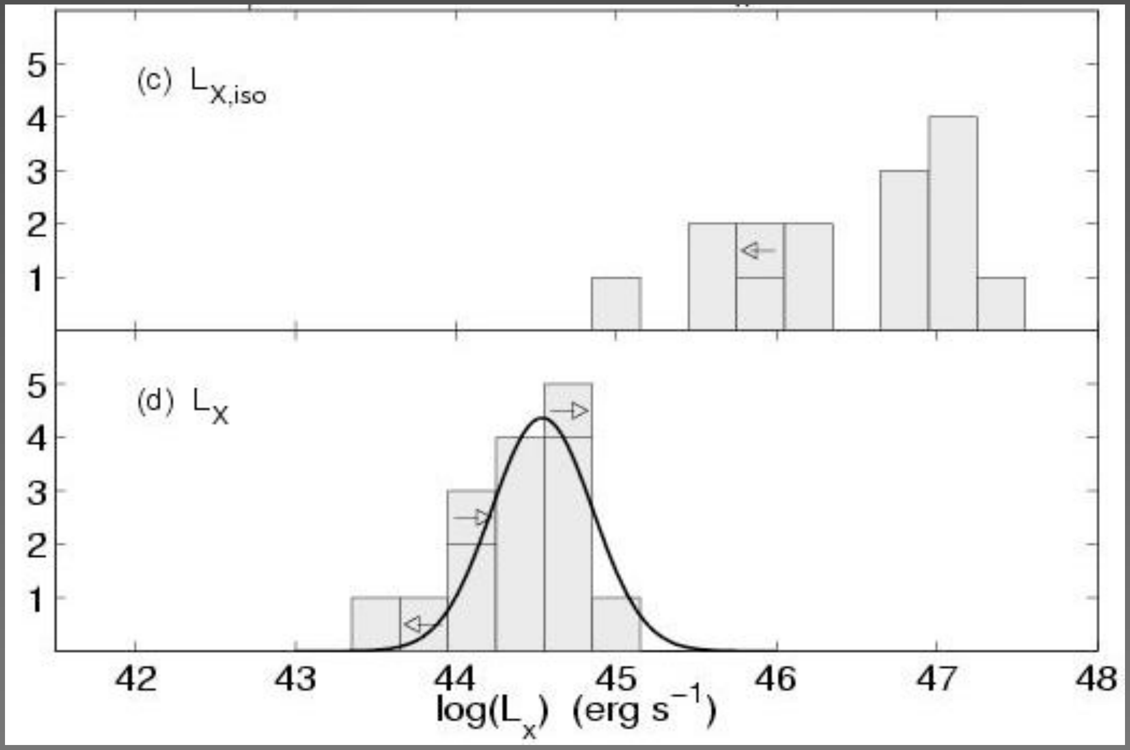
Energetics: Blastwave Energy

The X-ray afterglow luminosity at ~1 day provides a direct measure of the blastwave kinetic energy ($\Gamma \sim 10$); *independent of density*.

$$L_{X,\mathrm{iso}} \propto \epsilon_e E_{K,\mathrm{iso}} \quad \Rightarrow \quad L_X \propto \epsilon_e E_K$$

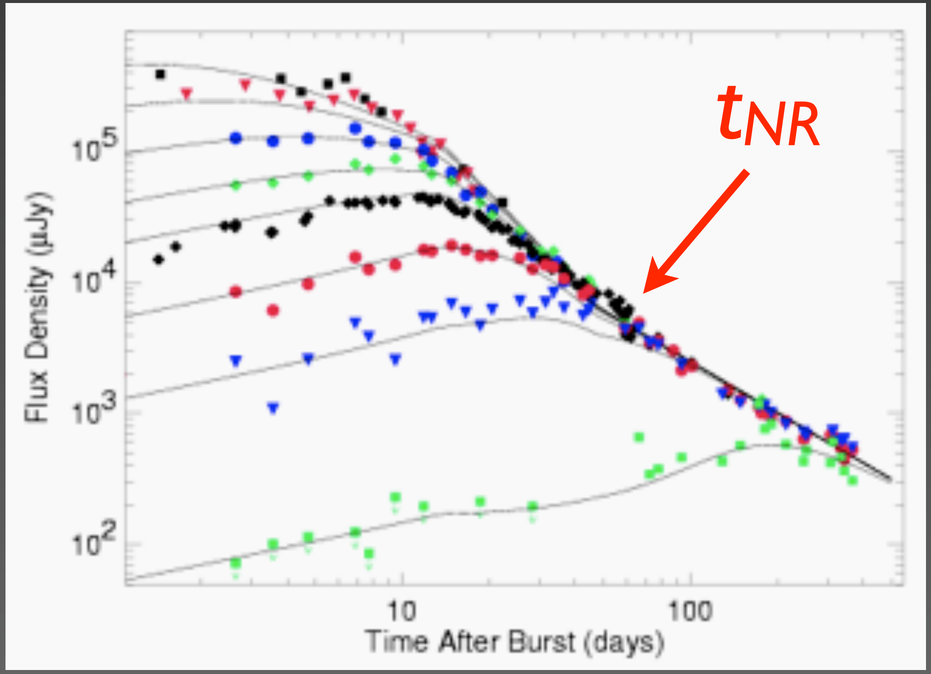
Narrow distribution with $E_K \sim 10^{51}$ erg

Berger et al. 2003



Energetics: Radio Calorimetry

When M_{swept} ~ E_K/c^2 the blastwave becomes non-relativistic and spherical; *energy can be measured independent of initial beaming* (peaks in radio).



Frail et al. 2000, Berger et al. 2004

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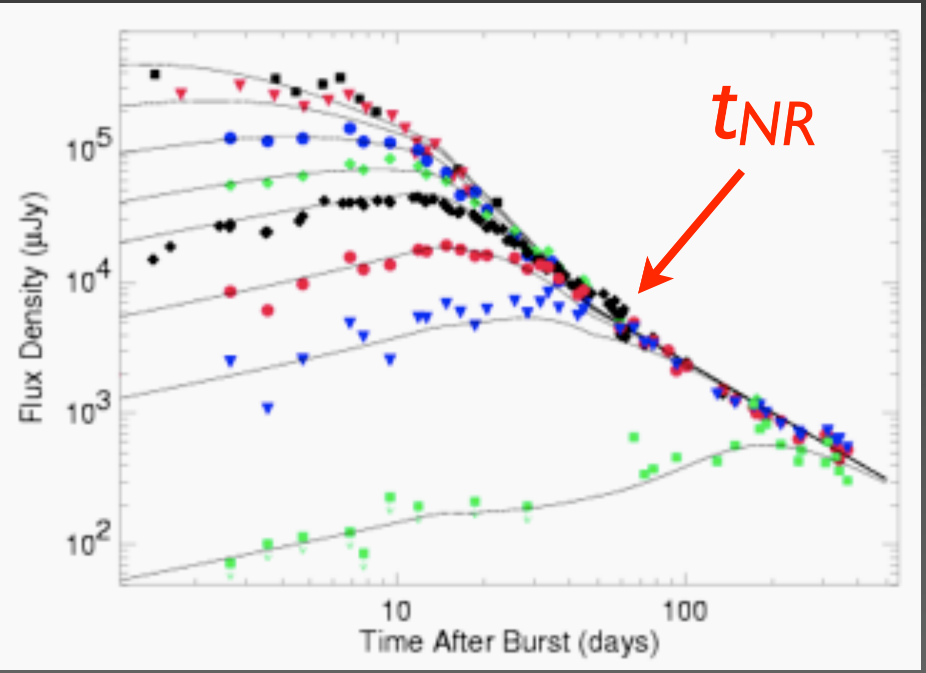
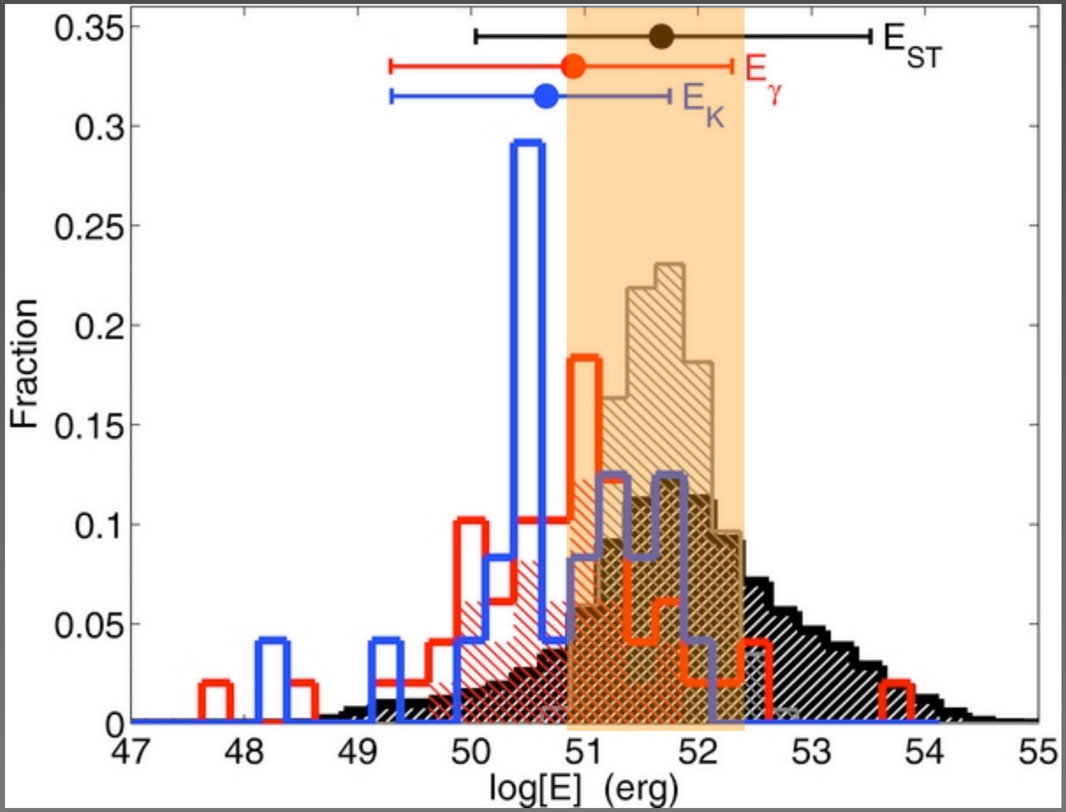


Frail et al. 2000, Berger et al. 2004

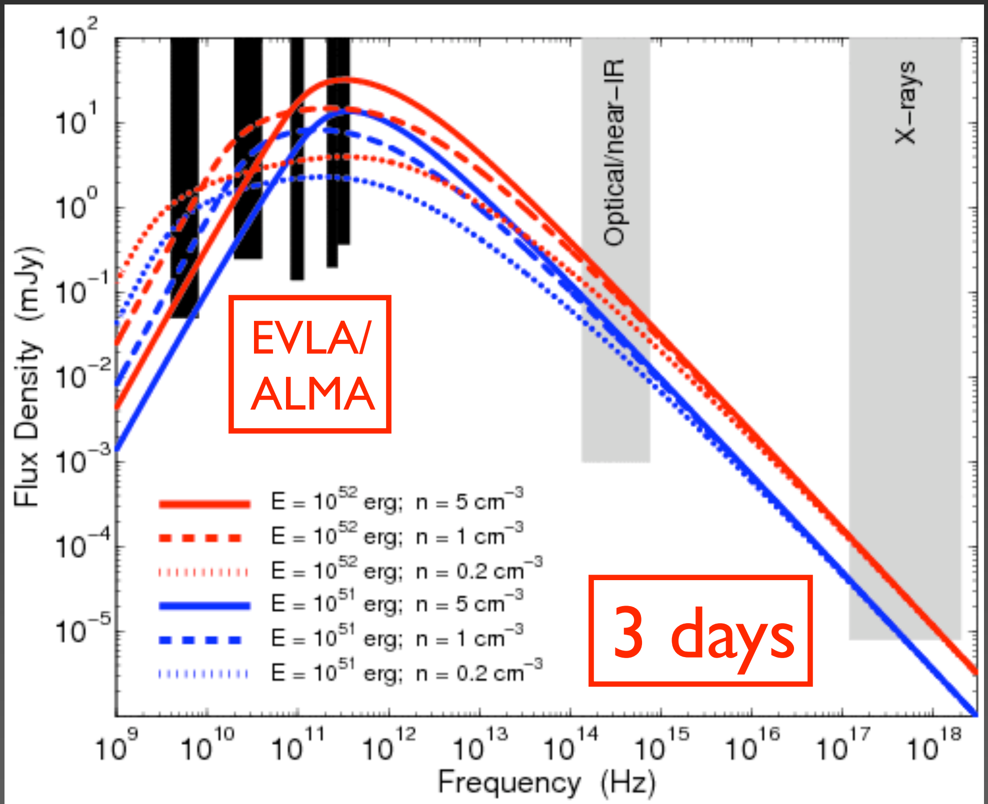
Can be done routinely with EVLA

Shivvers & Berger 2011

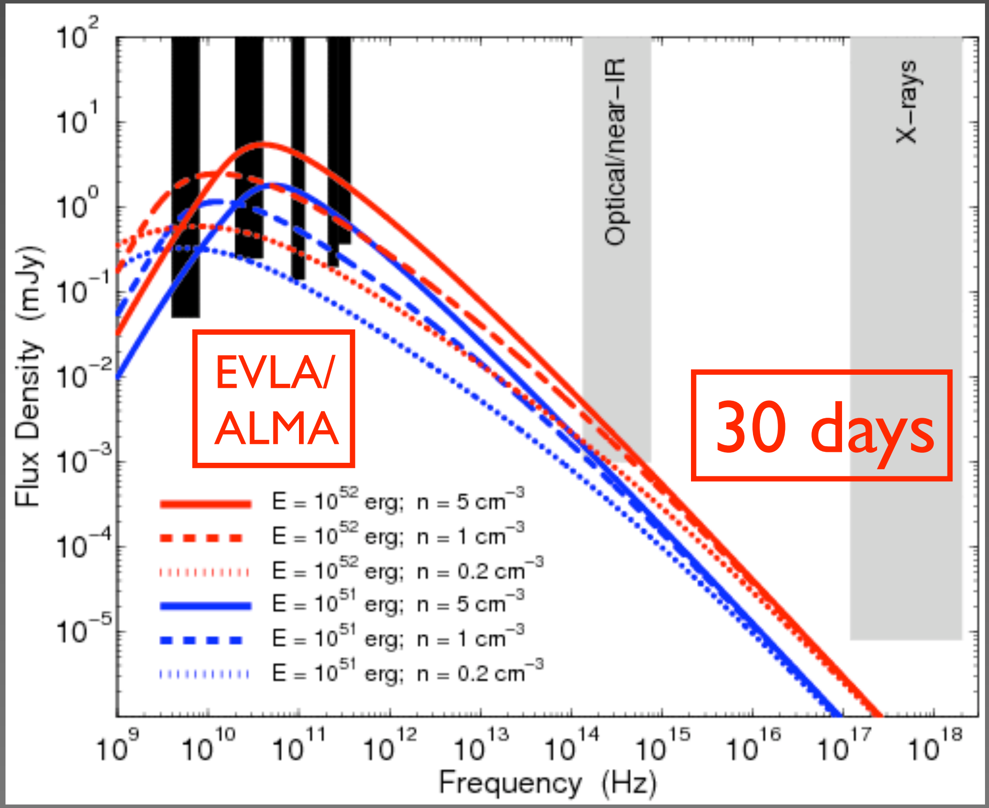


Snapshot radio SED at ~1 year can provide E_K with similar accuracy to multi-wavelength modeling.

Environment: Circumstellar Environment



cm/mm observations (EVLA/ALMA) uniquely determine the density profile (optical/X-ray degenerate)



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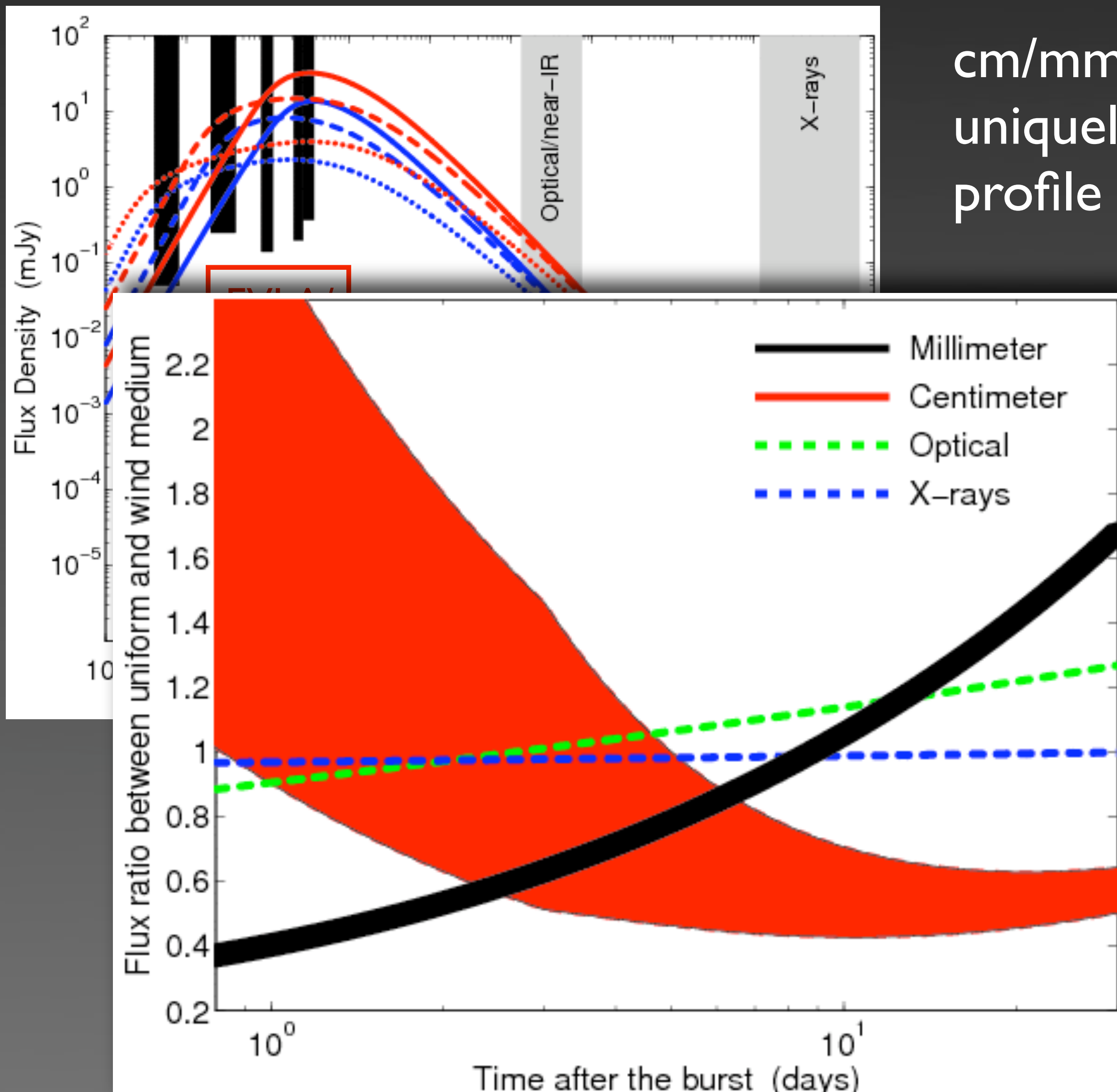
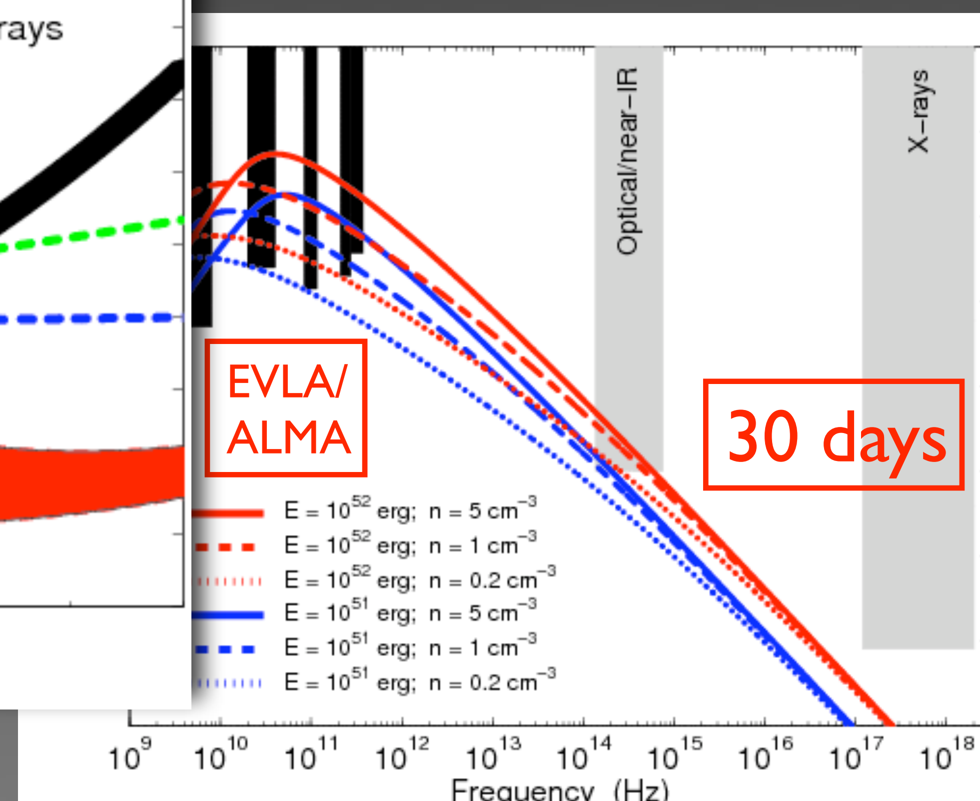


cm/mm observations (EVLA/ALMA) uniquely determine the density profile (optical/X-ray degenerate)

ISM: $\rho(r) = \text{const}$

Wind: $\rho(r) \propto r^{-2}$



Dark Bursts: Signposts for Obscured SF?

"Dark bursts" lack optical afterglows:

- High redshift?
- Dust extinction?

Using radio + X-rays we can infer the required extinction & determine positions for host galaxy searches.

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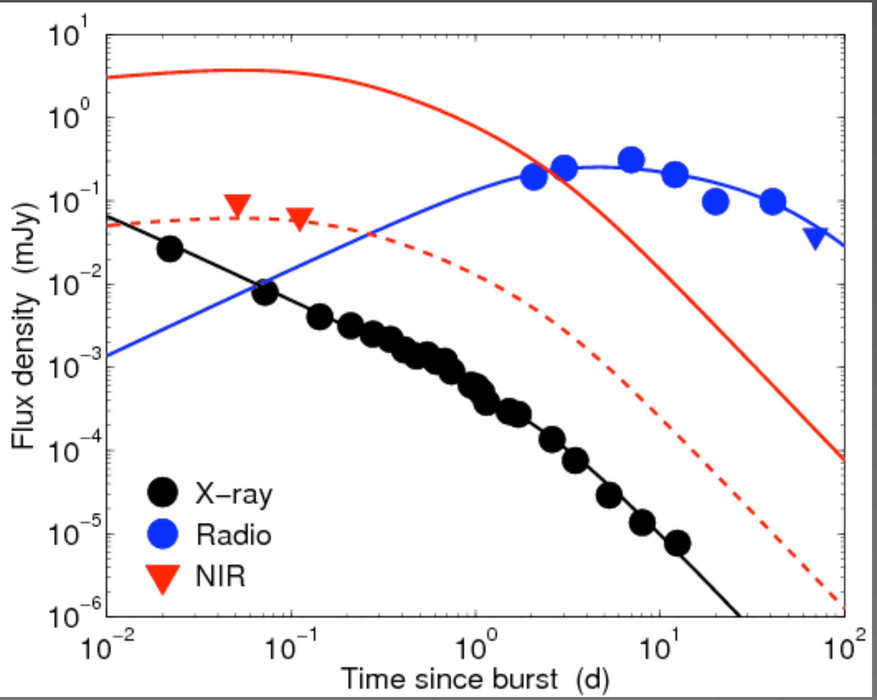

$E_{\mathrm{K,iso}} = 7 \times 10^{52}$ erg

$\dot{M} = 6 \times 10^{-6}\ M_\odot/\mathrm{yr}$

$\epsilon_e = 0.02$

$\epsilon_B = 0.10$

$t_{\mathrm{jet}} = 3$ d

$\theta_j = 4.5°$

$E_K = 2 \times 10^{50}$ erg

$E_\gamma = 9 \times 10^{50}$ erg

$A_V > 6$ mag

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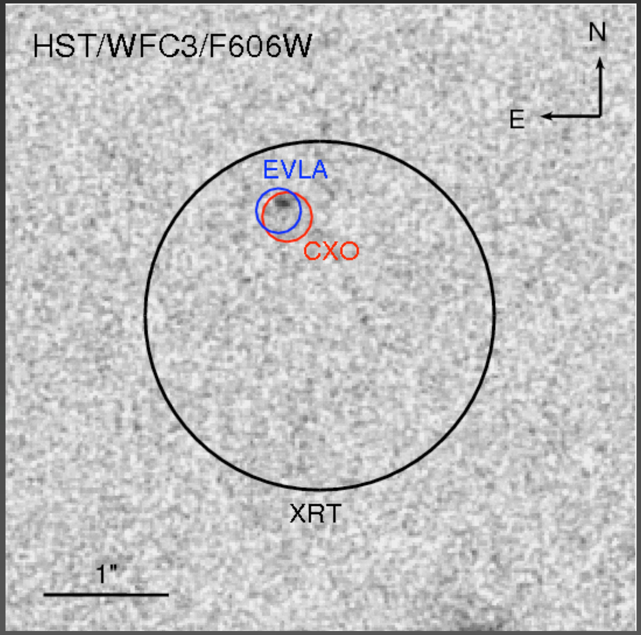

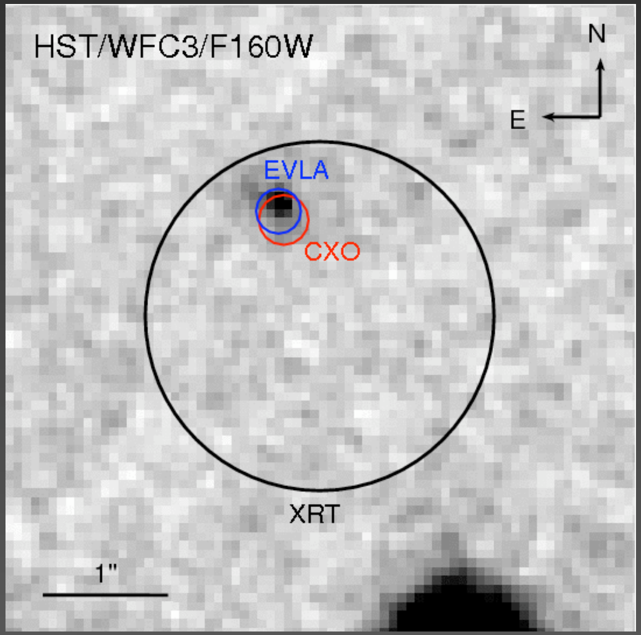

z < 3.5 based on host

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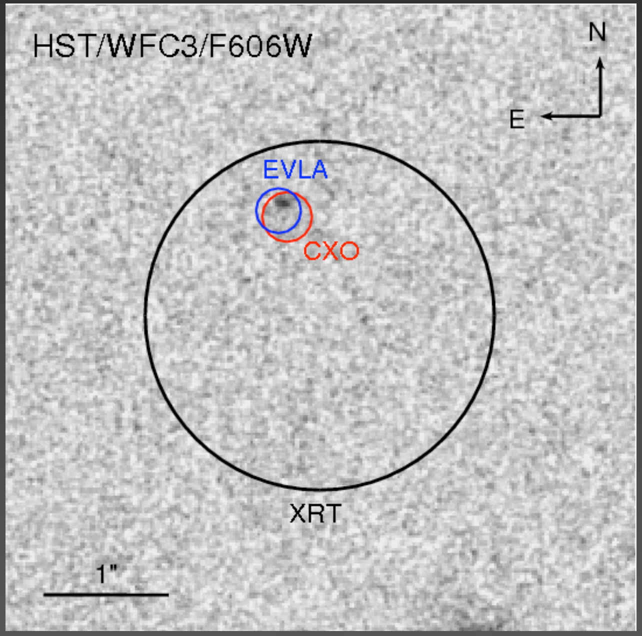

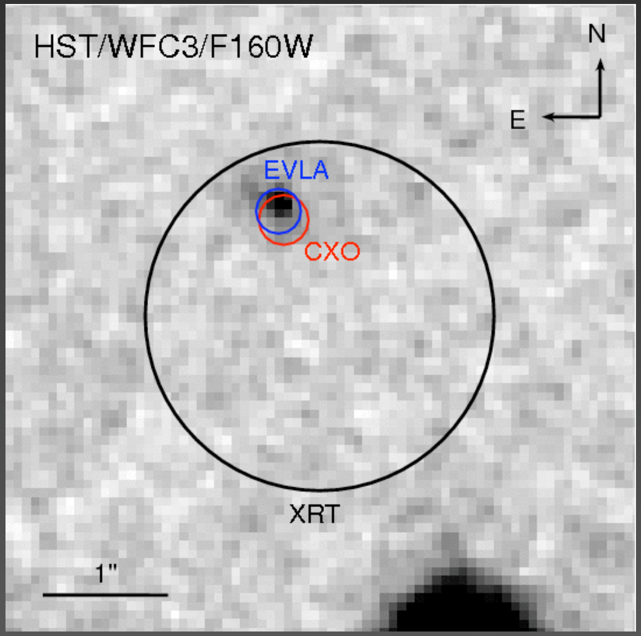

$$E_{\rm K,iso} = 3\times10^{53}\ \ {\rm erg}$$
$$\dot{M} = 2\times10^{-6}\ \ M_\odot/{\rm yr}$$
$$\epsilon_e = 0.005$$
$$\epsilon_B = 0.01$$
$$t_{\rm jet} = 15\ \ {\rm d}$$
$$\theta_j = 8.5^\circ$$
$$E_K = 4\times10^{51}\ \ {\rm erg}$$
$$E_\gamma = 2\times10^{51}\ \ {\rm erg}$$
$$A_V > 9\ \ {\rm mag}$$

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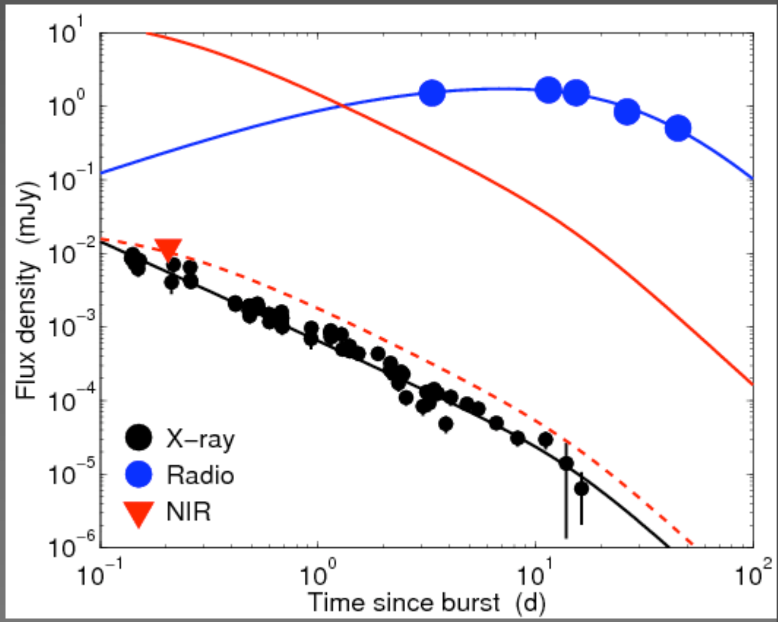

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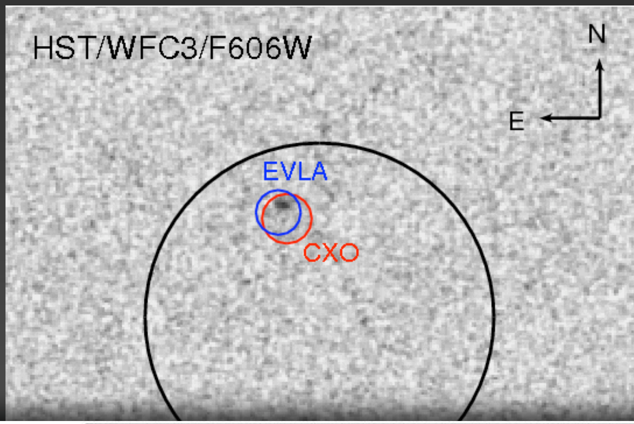

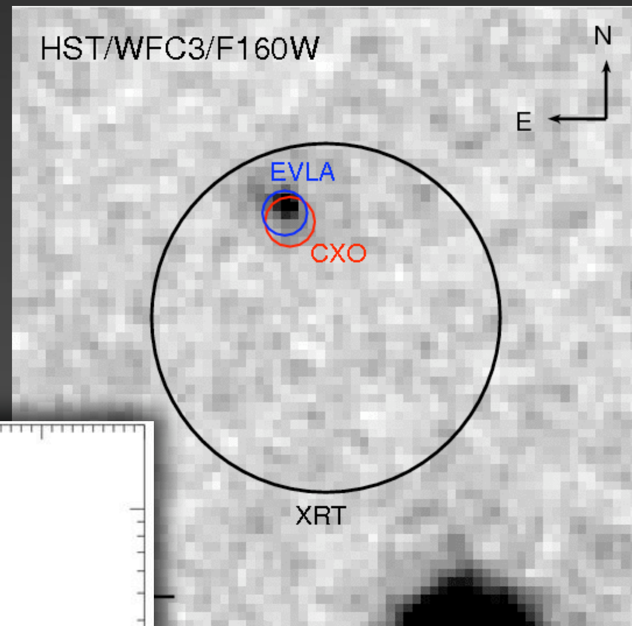

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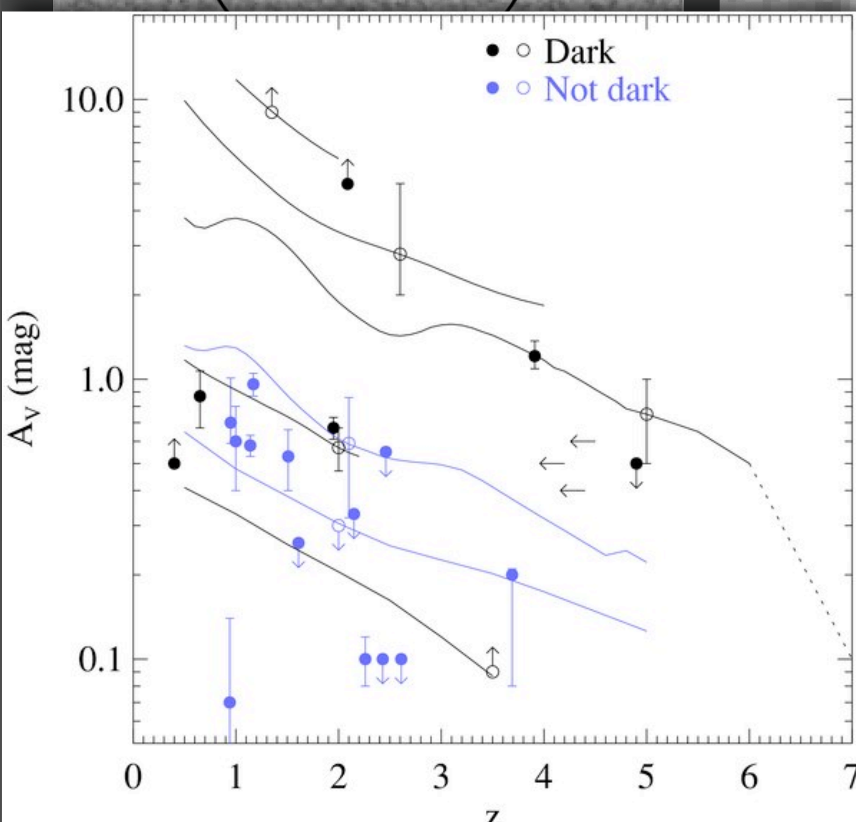

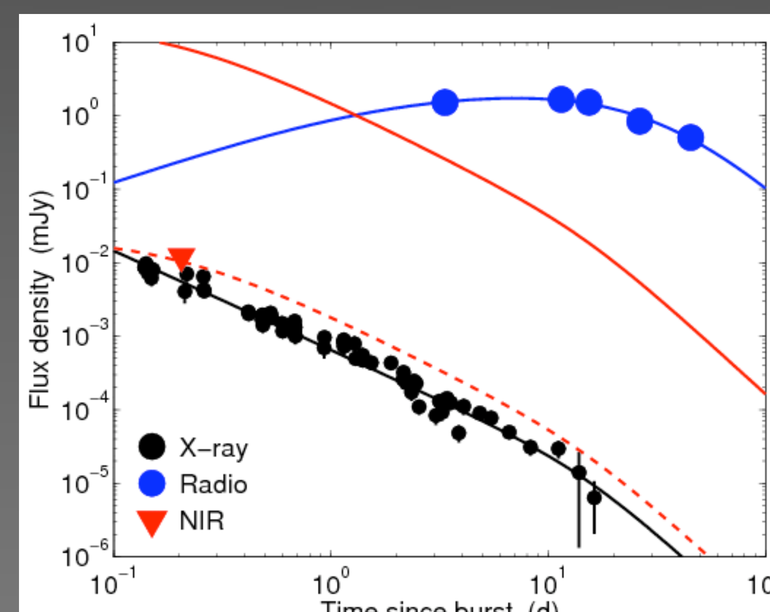

Perley et al. 2009; Zauderer et al. in prep.

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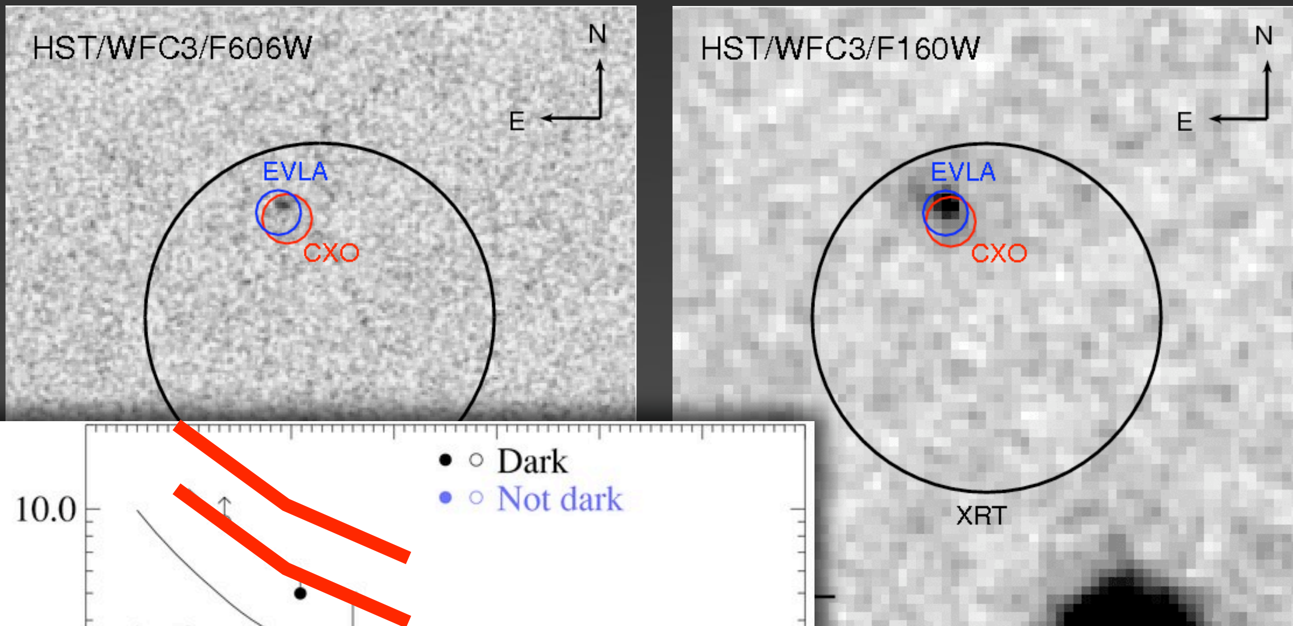

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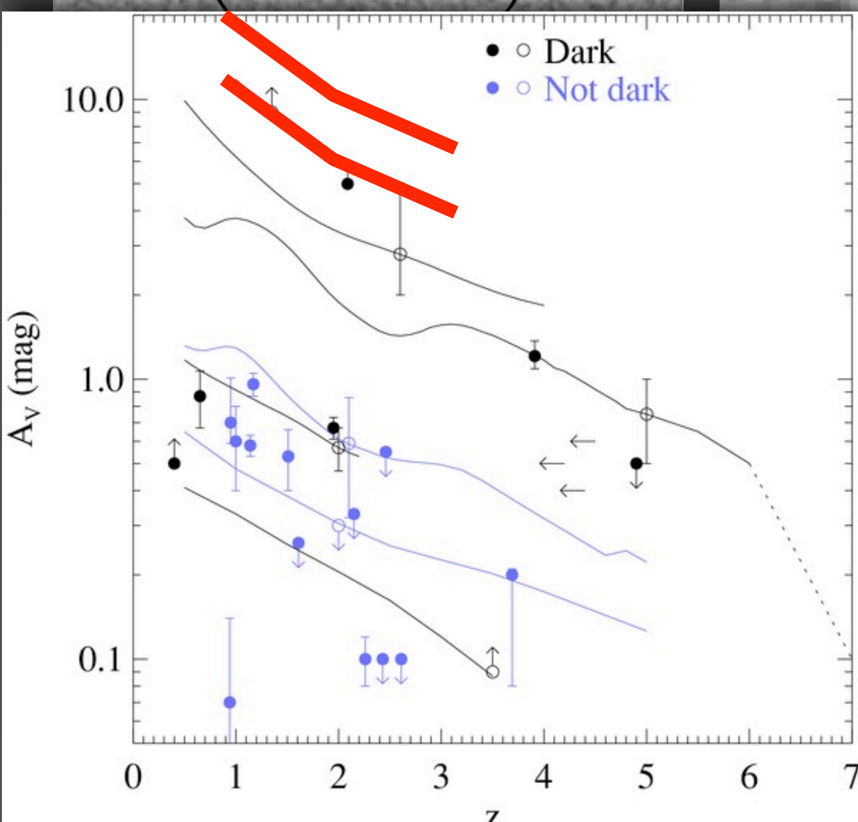

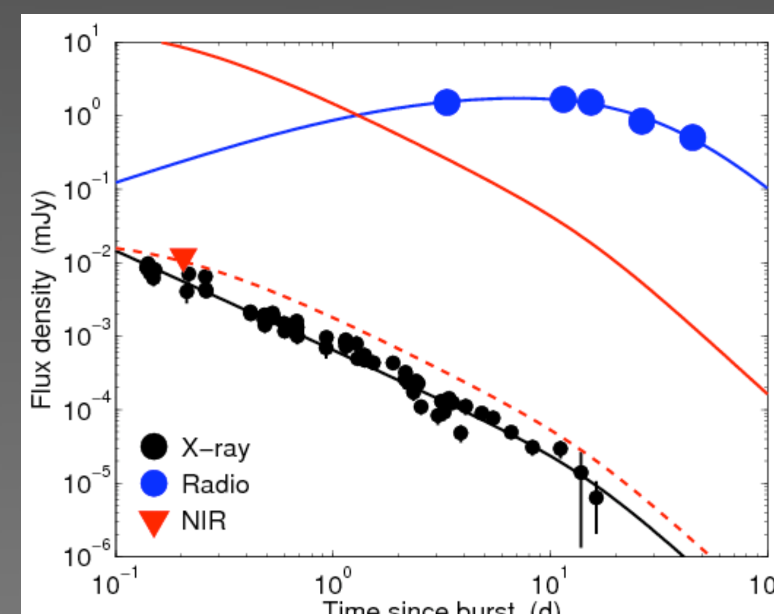

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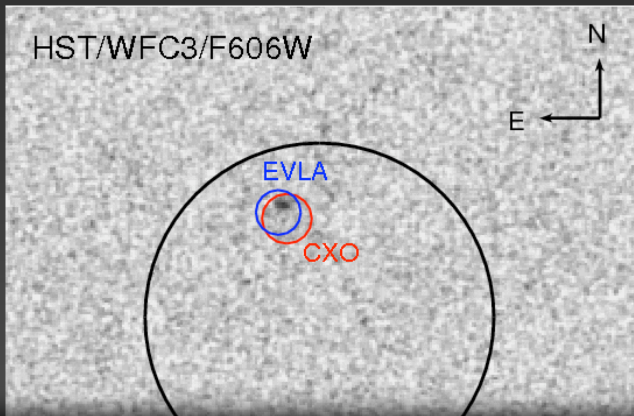

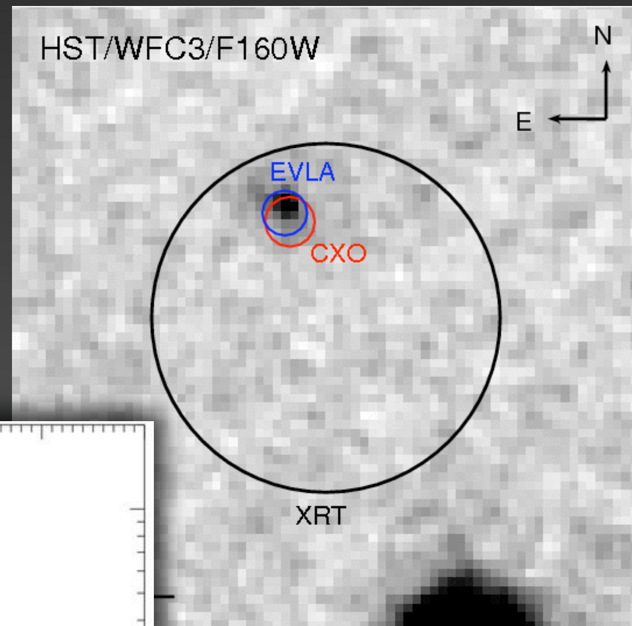

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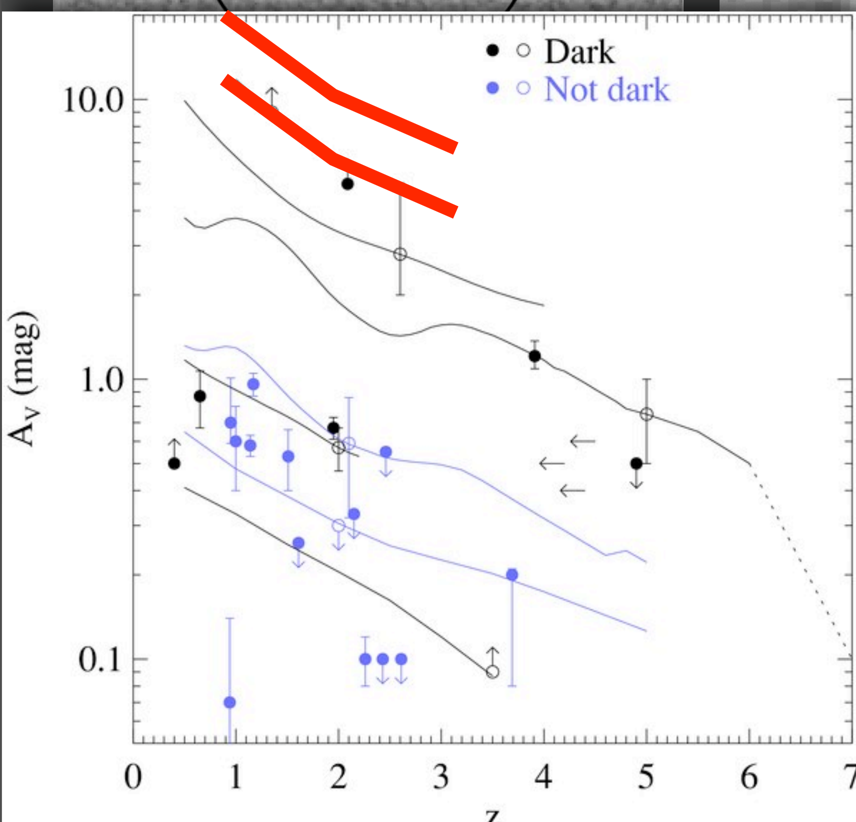
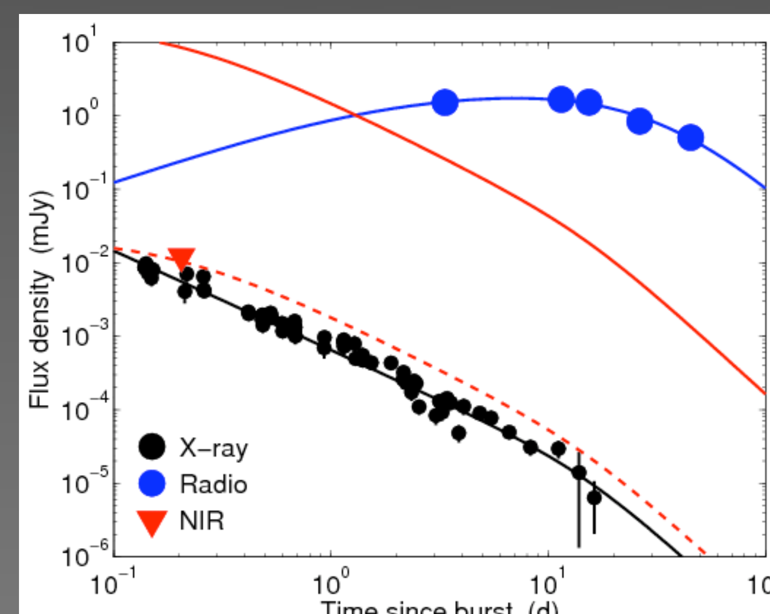
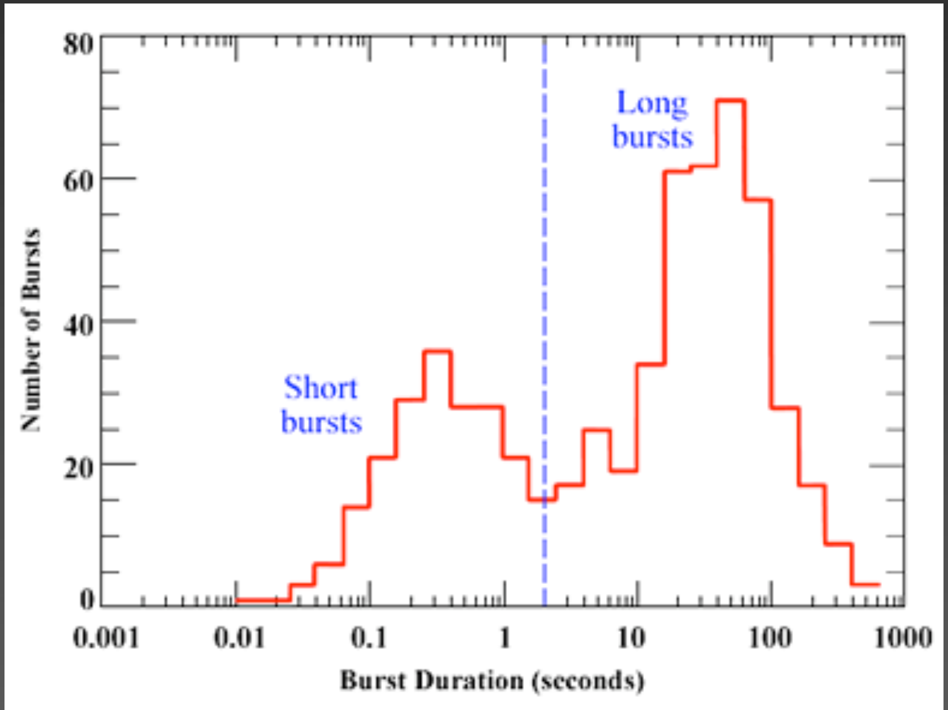


Hosts of dark bursts are potential sites for the study of obscured star formation at z>1 (ALMA)



Perley et al. 2009; Zauderer et al. in prep.

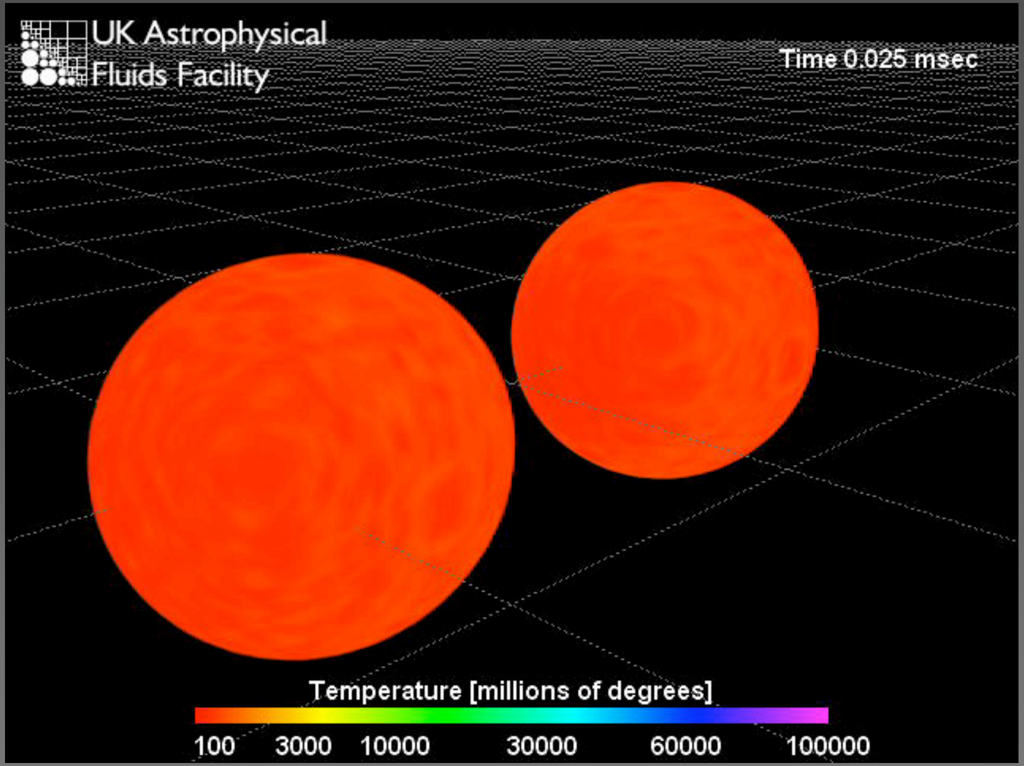
The Progenitors of Short GRBs?



NS-NS / NS-BH

Eichler et al. 1989;
Narayan et al. 1992

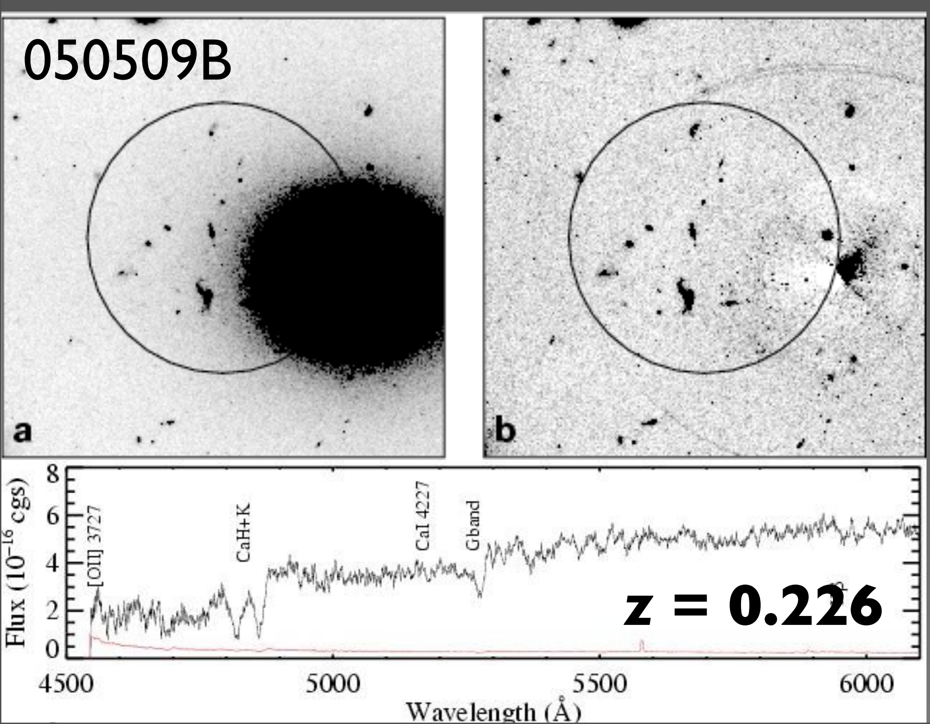
- Broad delay-time distribution
- Diverse environments / redshifts
- "Kicks"
- *Gravitational waves*

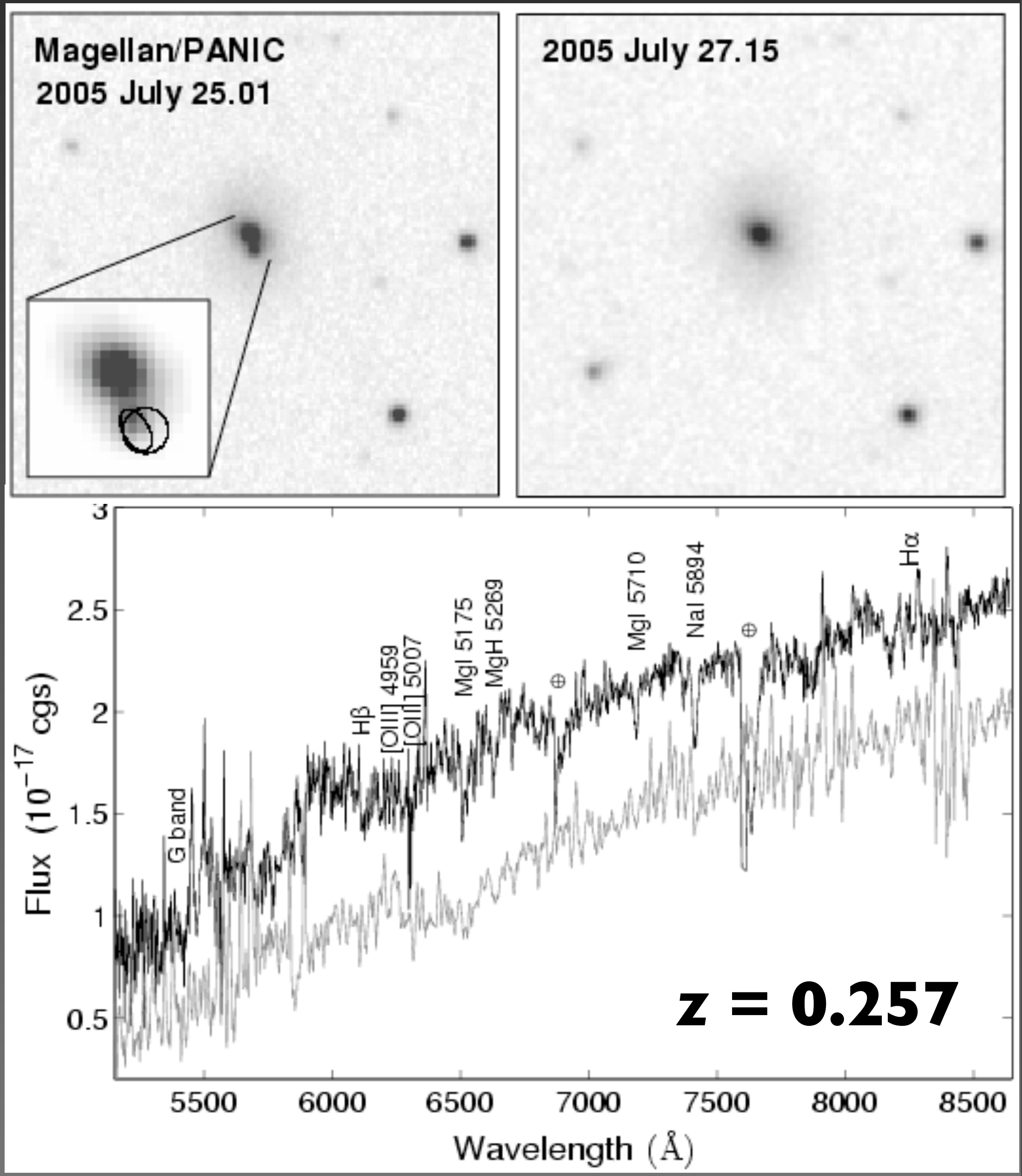


Short GRB Hosts

Association with elliptical galaxies & no accompanying supernova

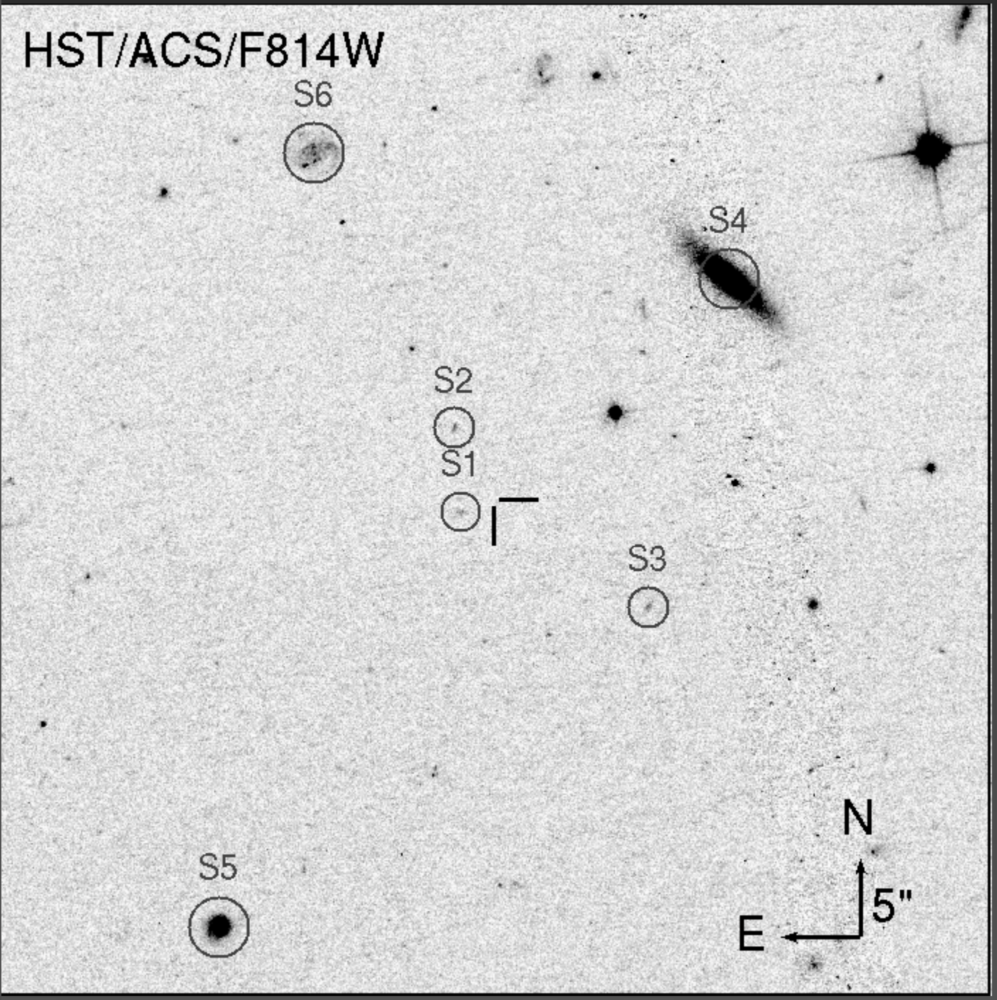
Castro-Tirado et al. 2005; Gehrels et al. 2005; Hjorth et al. 2005; Bloom et al. 2006; Prochaska et al. 2006





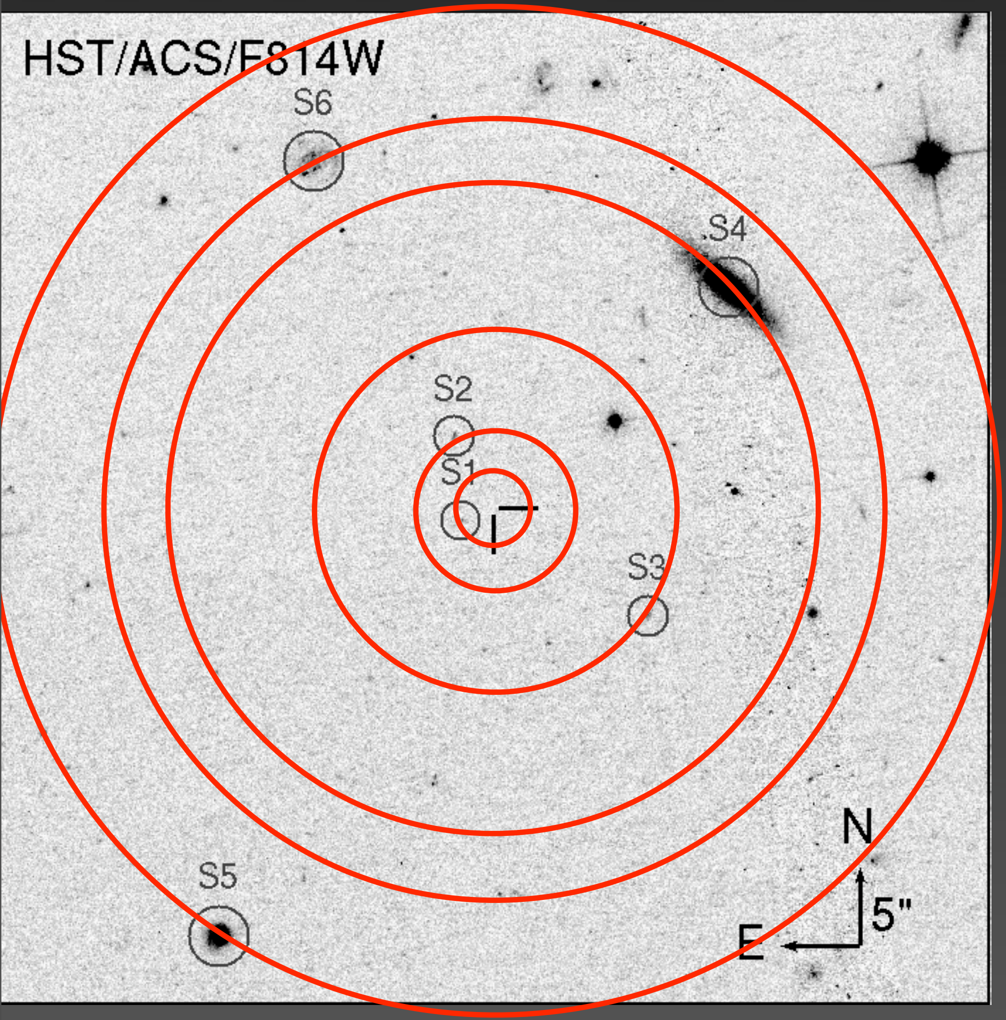
Berger et al. 2005

Short GRB Kicks?



Berger 2010

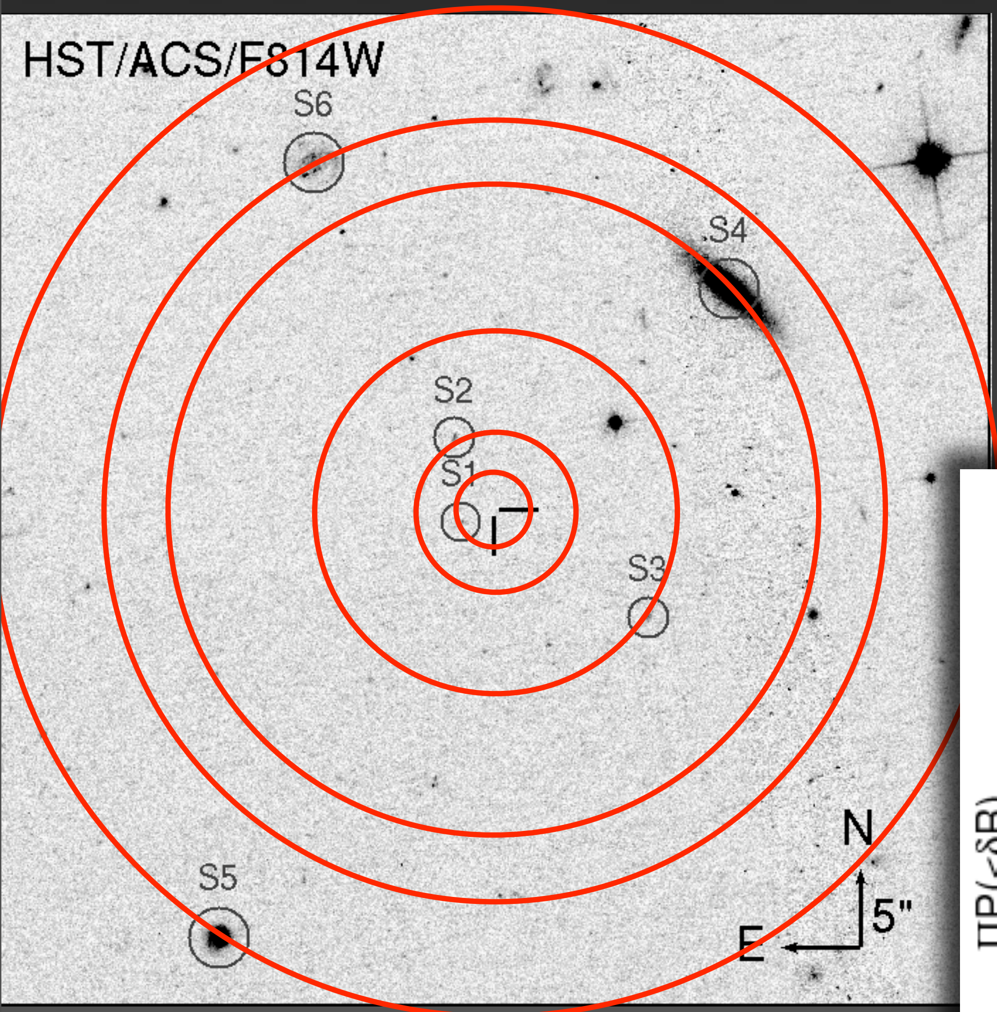
Short GRB Kicks?



Berger 2010

$$P(\leq \delta R) = 1 - e^{-\pi(\delta R)^2 \Sigma(\leq m)}$$

Short GRB Kicks?



Berger 2010

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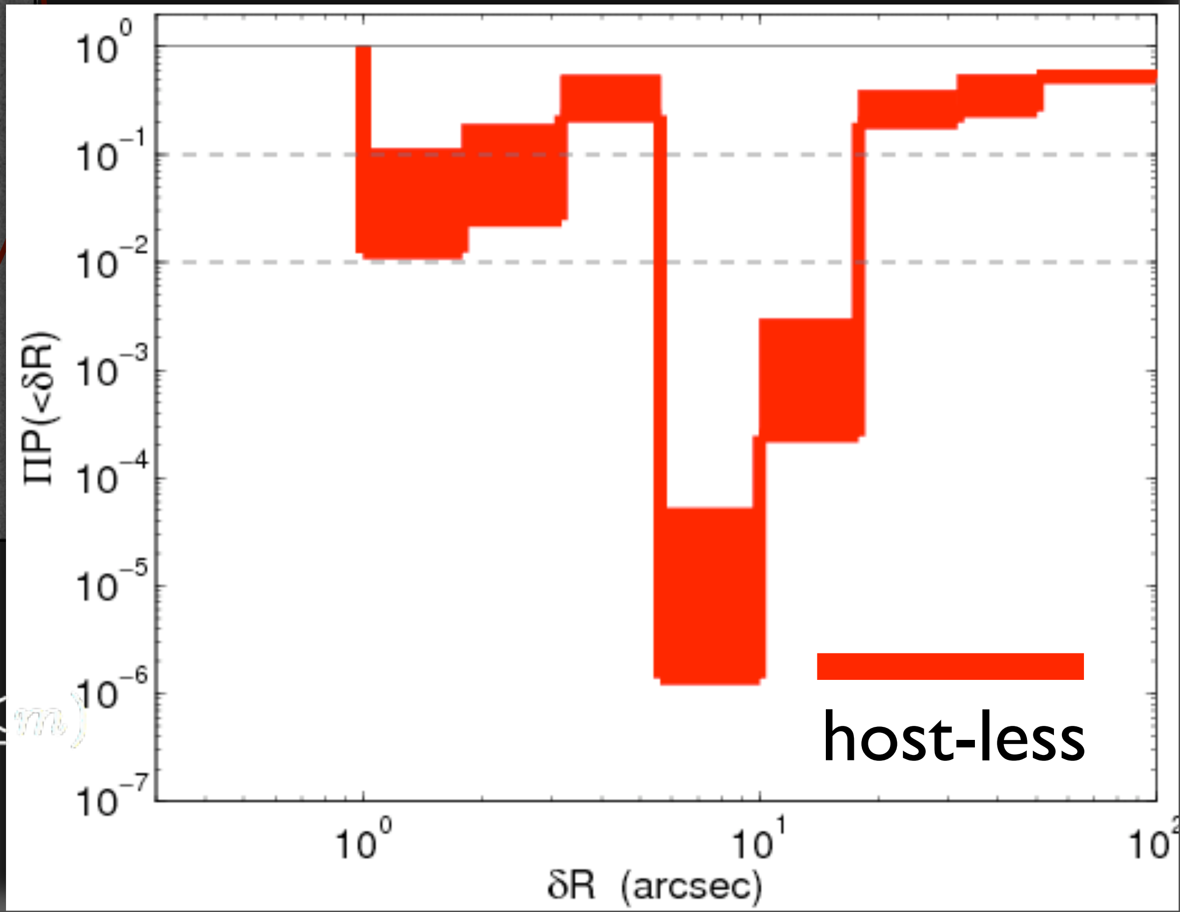
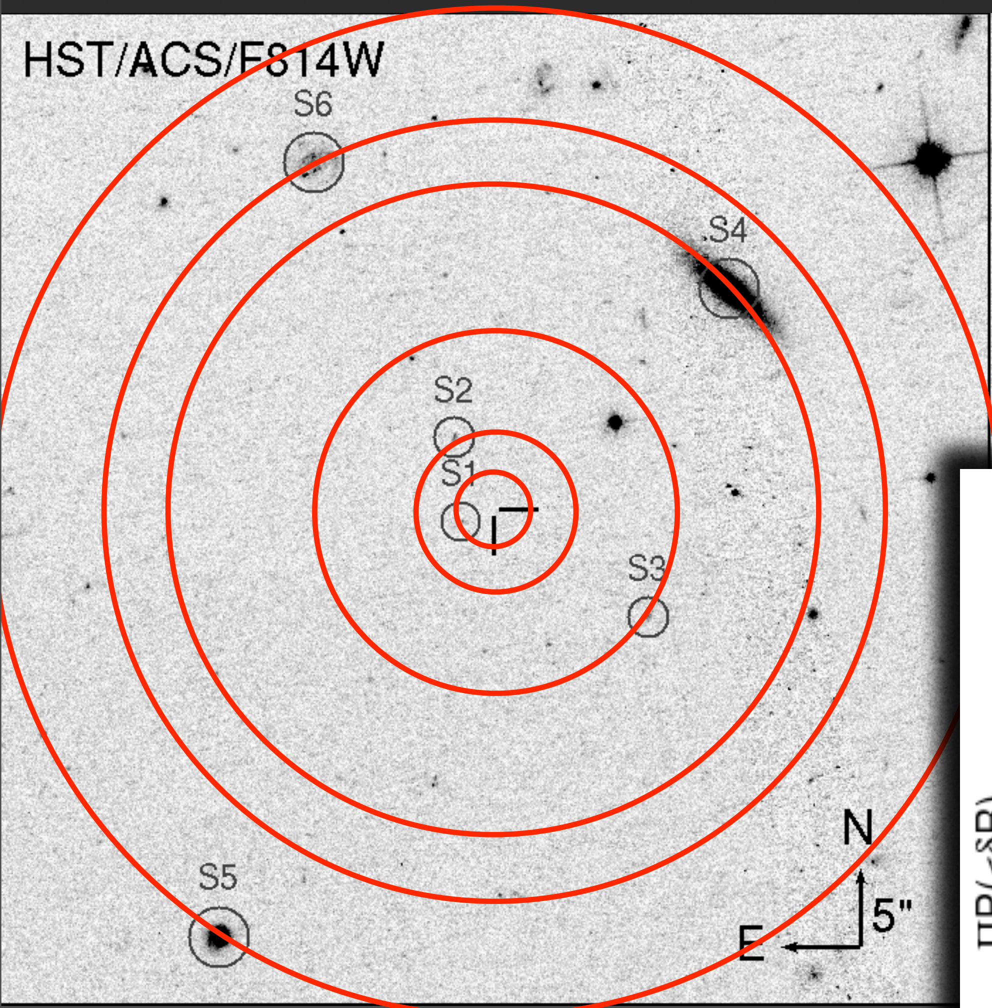
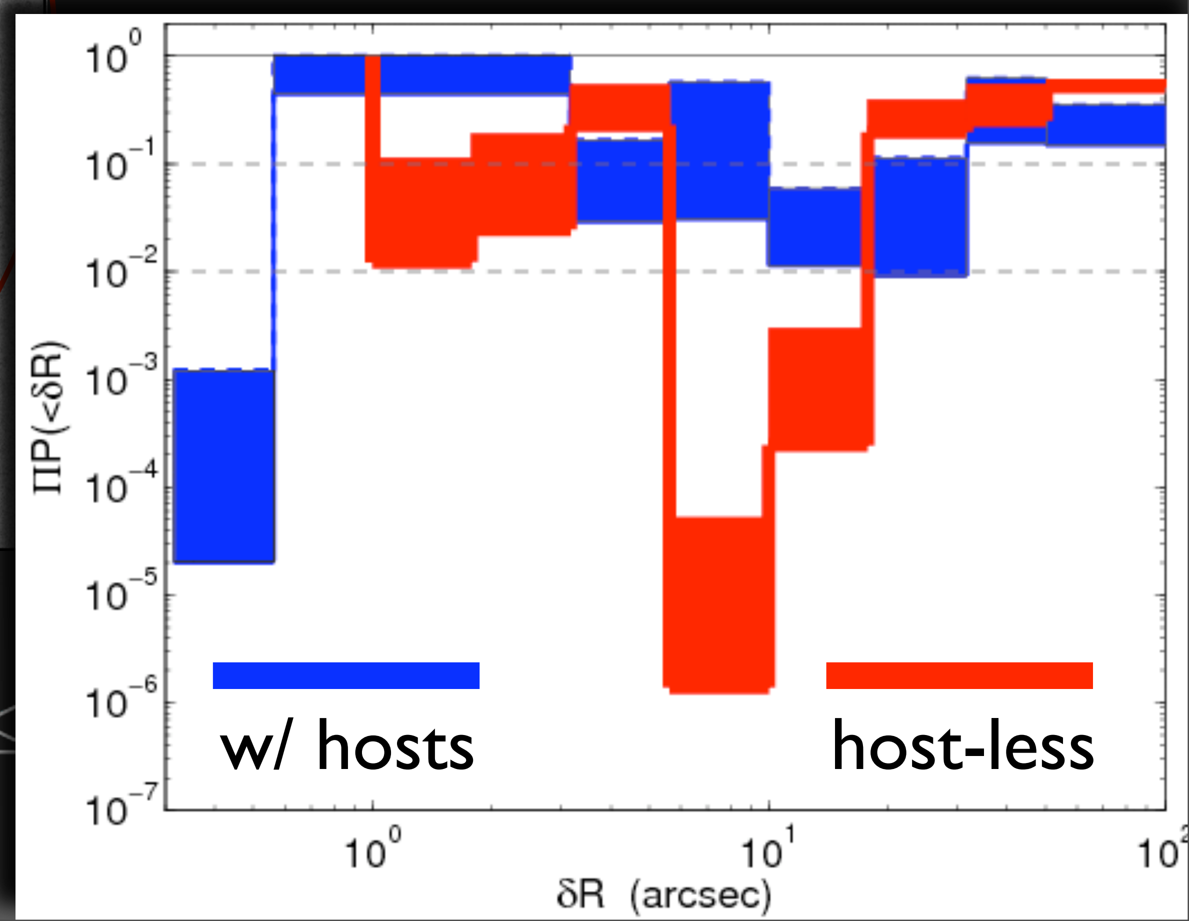


Short GRB Kicks?

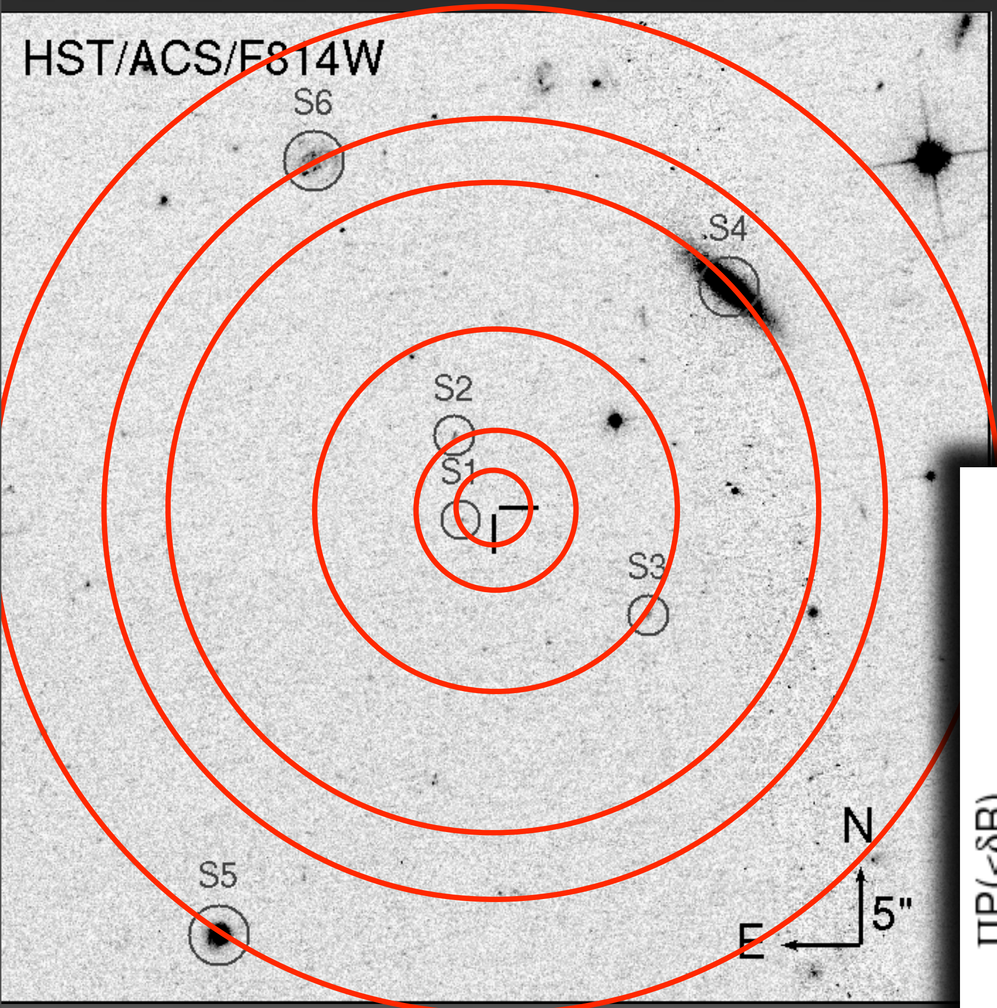


Berger 2010

$$P(\leq \delta R) = 1 - e^{-\pi(\delta R)^2 \Sigma(\leq}$$



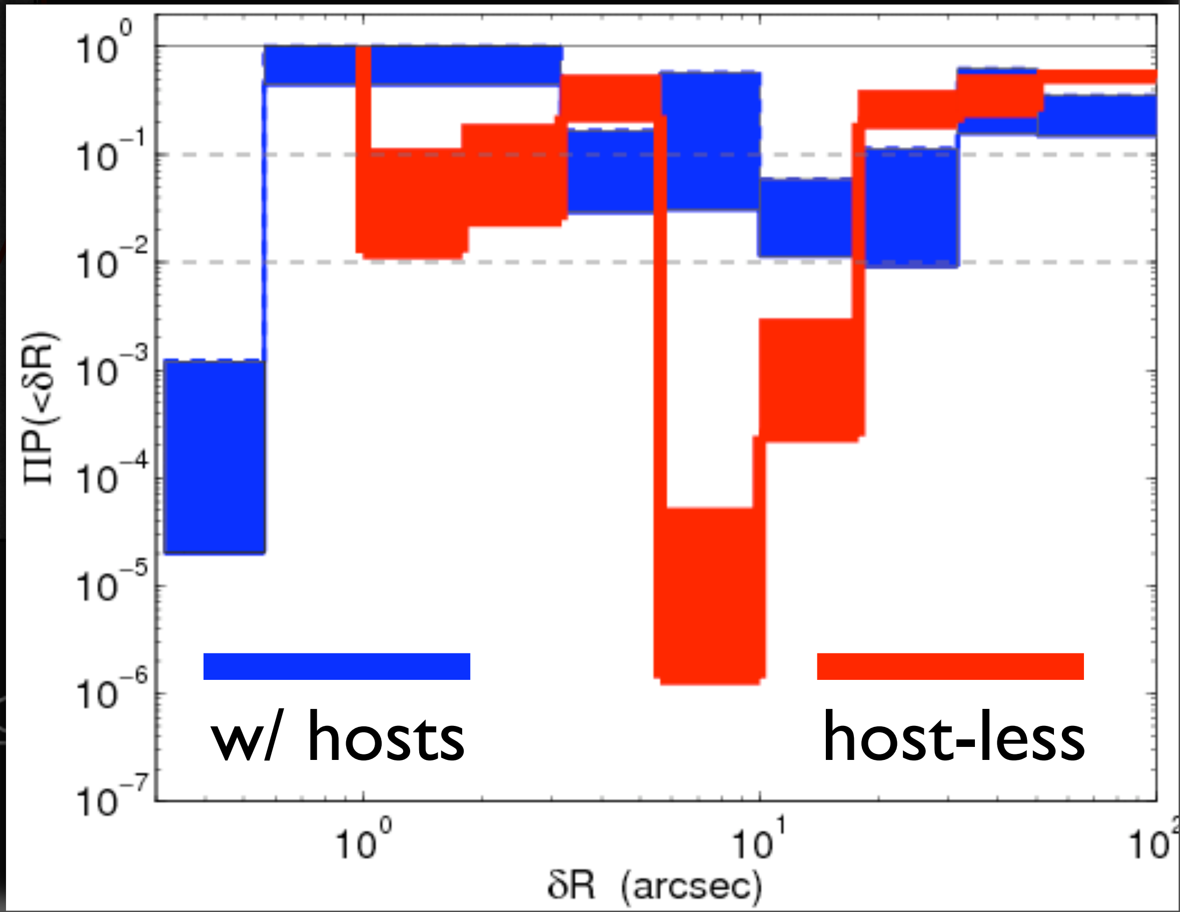
Short GRB Kicks?



Berger 2010

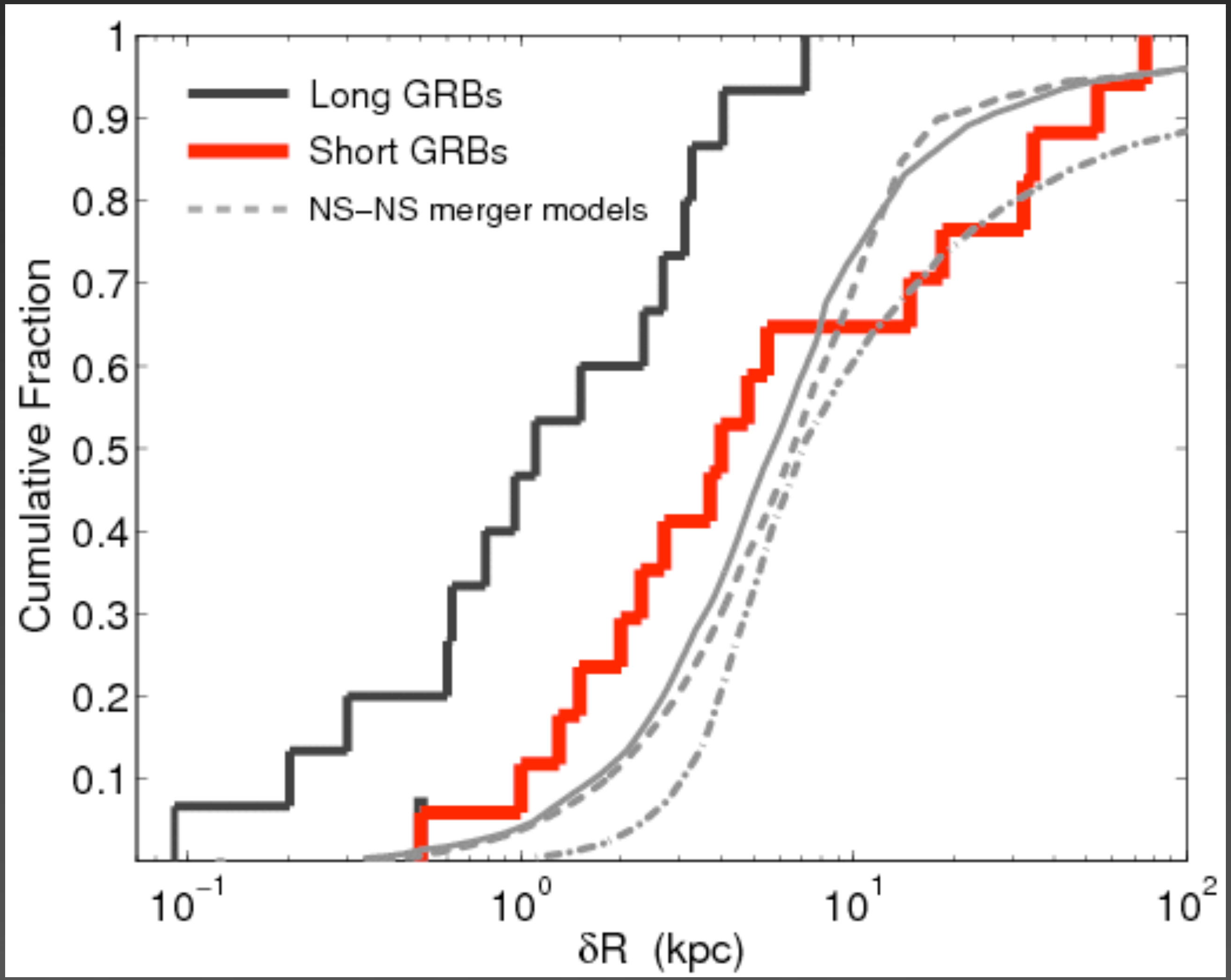
z ~ 0.1-0.5 ⇒ ~10" = 50-100 kpc

$$P(\leq \delta R) = 1 - e^{-\pi(\delta R)^2 \Sigma(\leq}$$



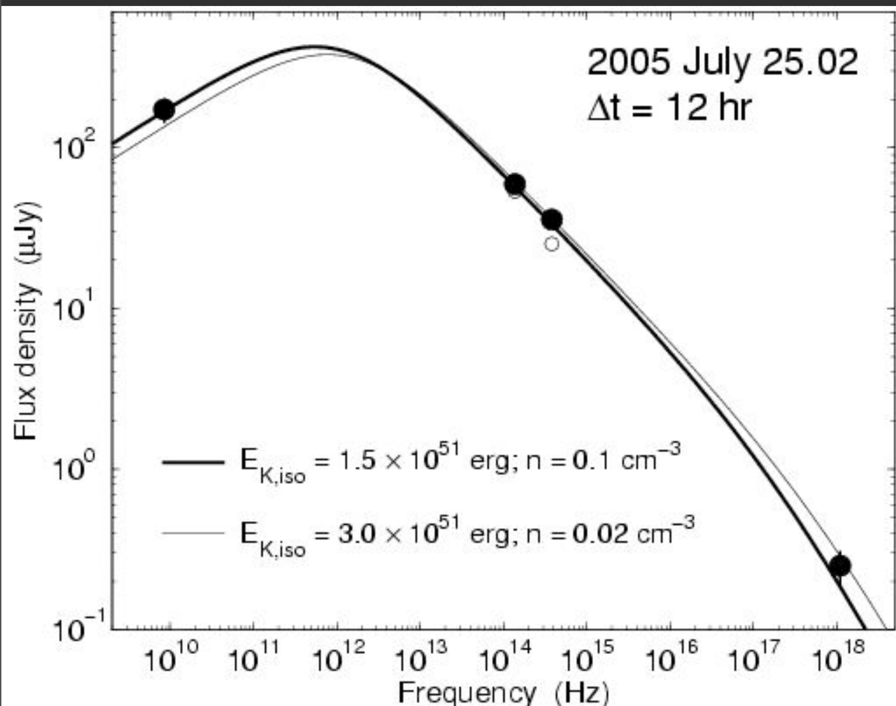
Short GRB Kicks?

Berger 2010



Short GRB offsets agree with NS-NS merger models. Large offsets not expected in other models.

Short GRB Afterglows



Berger et al. 2005

$\theta_j > 25$ deg

$E_{\gamma,iso} \approx 4\times10^{50}$ erg ($>4\times10^{49}$ erg)

$E_{K,iso} \approx 2\times10^{51}$ erg ($>2\times10^{50}$ erg)

$n \approx 0.01-0.1$ cm^{-3}

Afterglow physics similar to long GRBs, but lower *E*, *n*

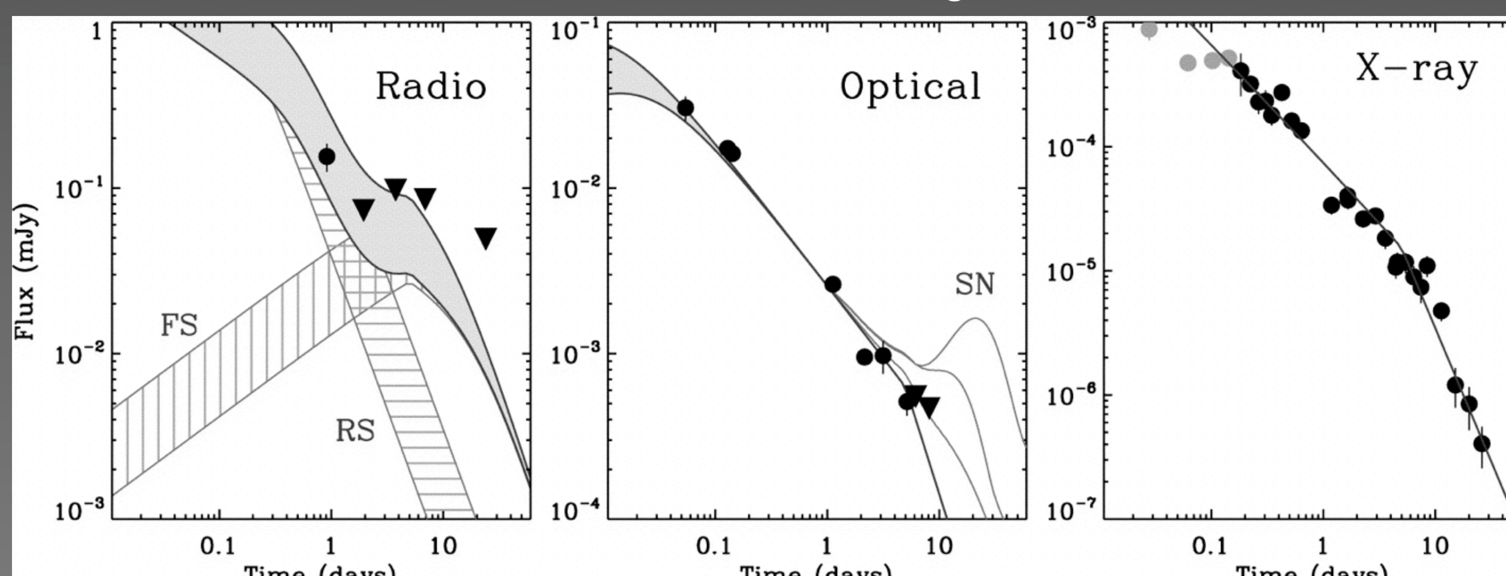
Soderberg et al. 2006; Burrows et al. 2006

$\theta_j \approx 7$ deg

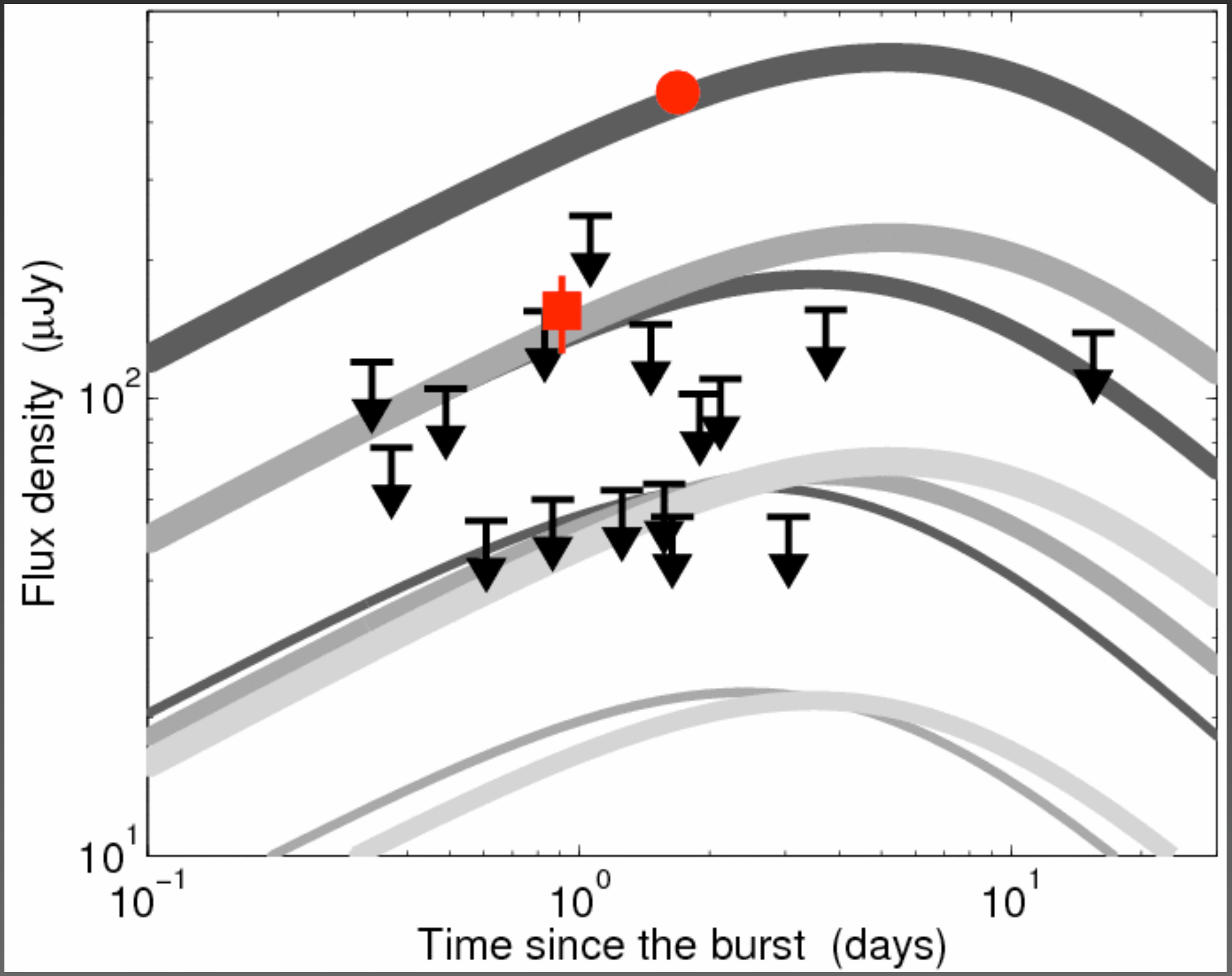
$E_\gamma \approx 1.5\times10^{49}$ erg

$E_K \approx 0.8\times10^{49}$ erg

$n \approx 1.5\times10^{-3}$ cm^{-3}



Short GRB Afterglows



$n = 1\ \mathrm{cm}^{-3}$

$n = 0.1\ \mathrm{cm}^{-3}$

$n = 0.01\ \mathrm{cm}^{-3}$

$E_K = 10^{51}$ erg

$E_K = 3\times10^{50}$ erg

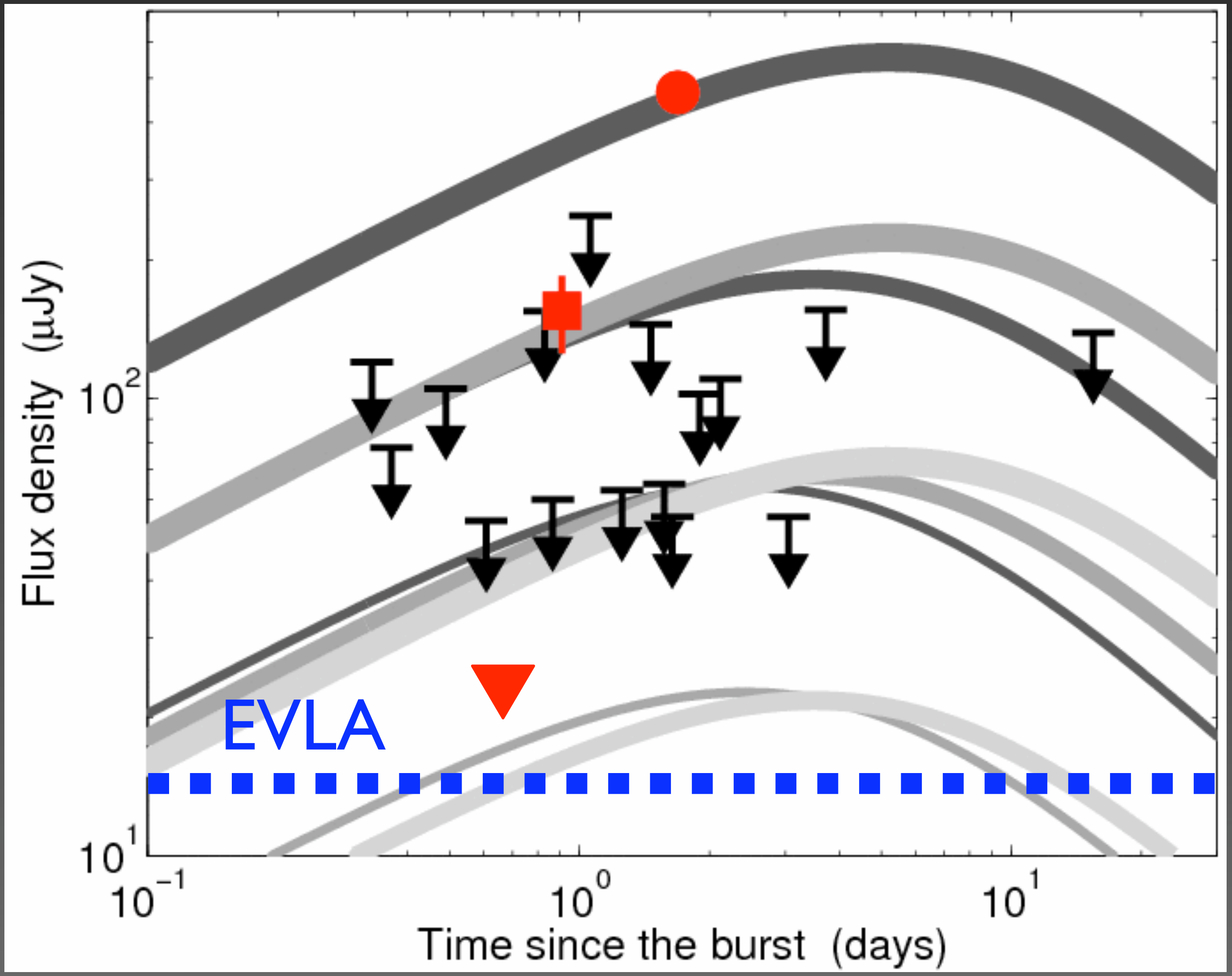
$E_K = 10^{49}$ erg

Fong et al. in prep.

Existing radio data*: $n_0^{1/2}\, E_{\mathrm{K},51}^{5/6} \lesssim 0.03$

* long GRBs: ~1

Short GRB Afterglows



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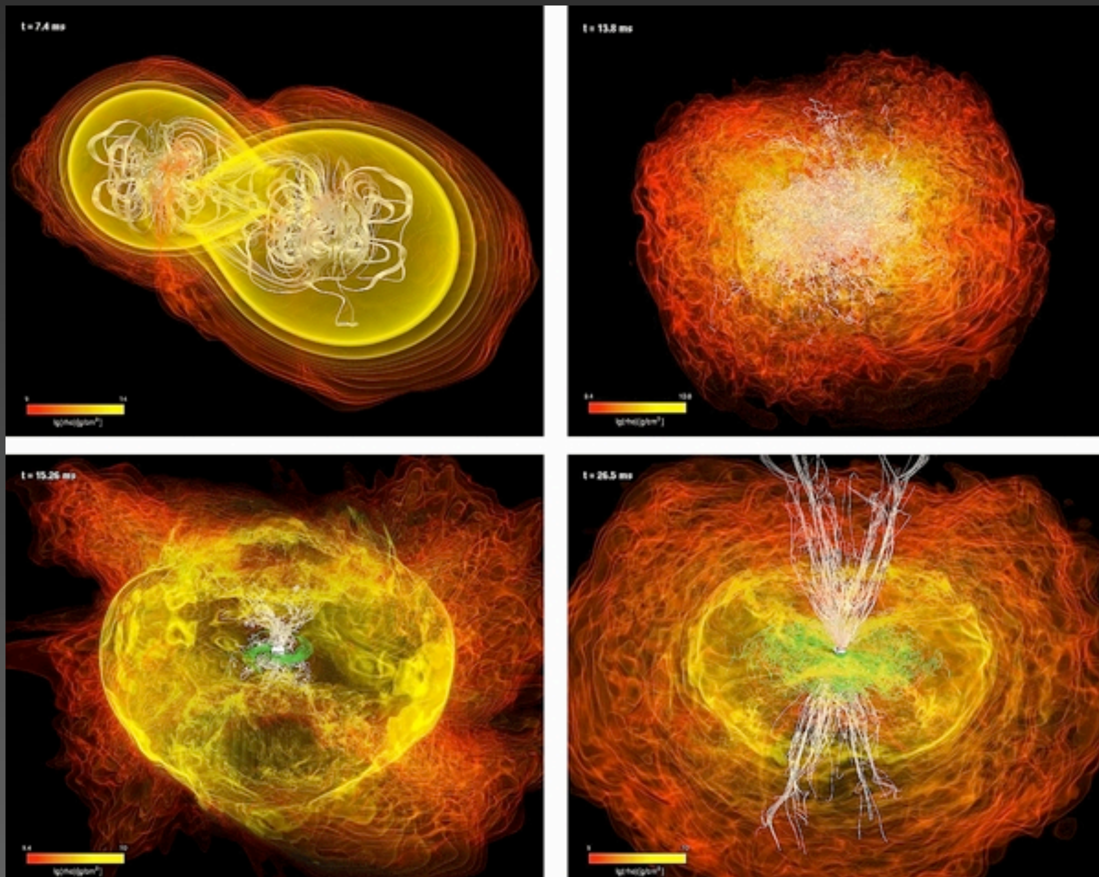
Short GRB Jets

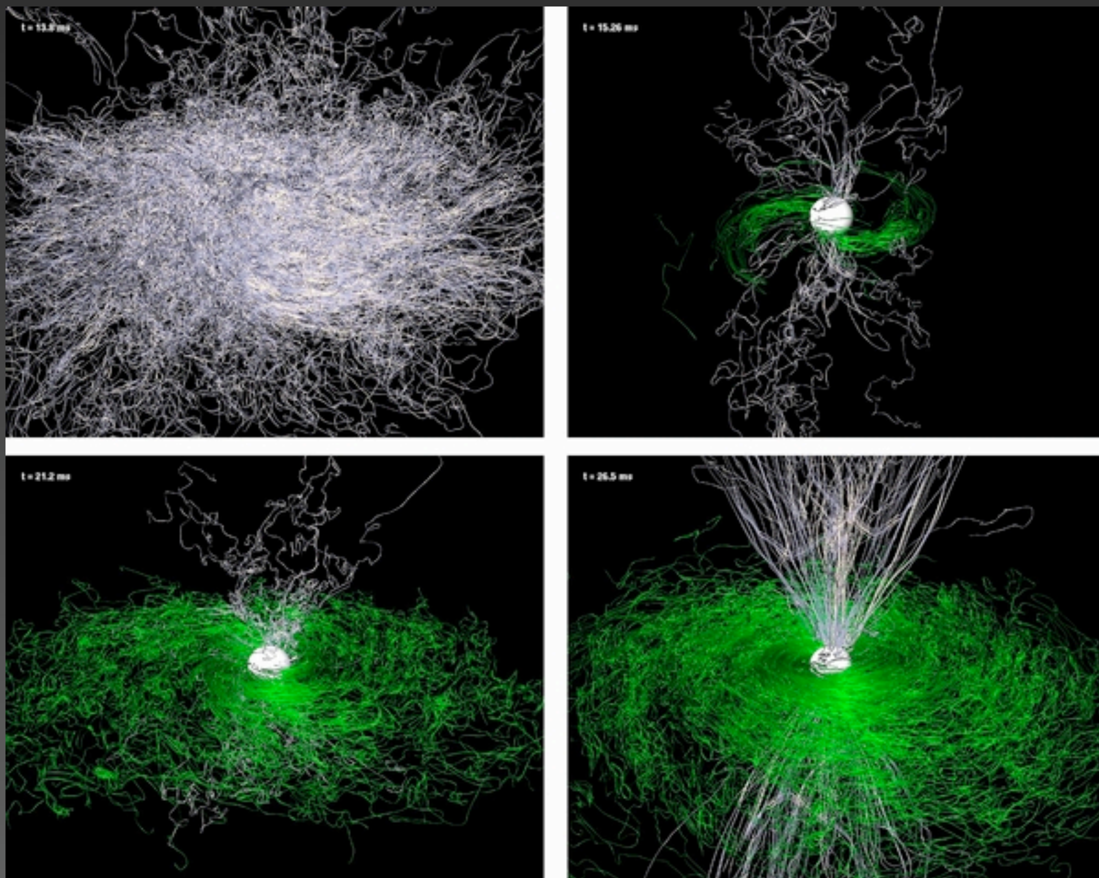


Rezzolla et al. 2012

$$\theta_j \approx 10 - 30^\circ$$

$$E_{\mathrm{B-Z,iso}} \approx 10^{51} B_{15}^2 \ \ \mathrm{erg}$$

Short GRB Jets



Rezzolla et al. 2012

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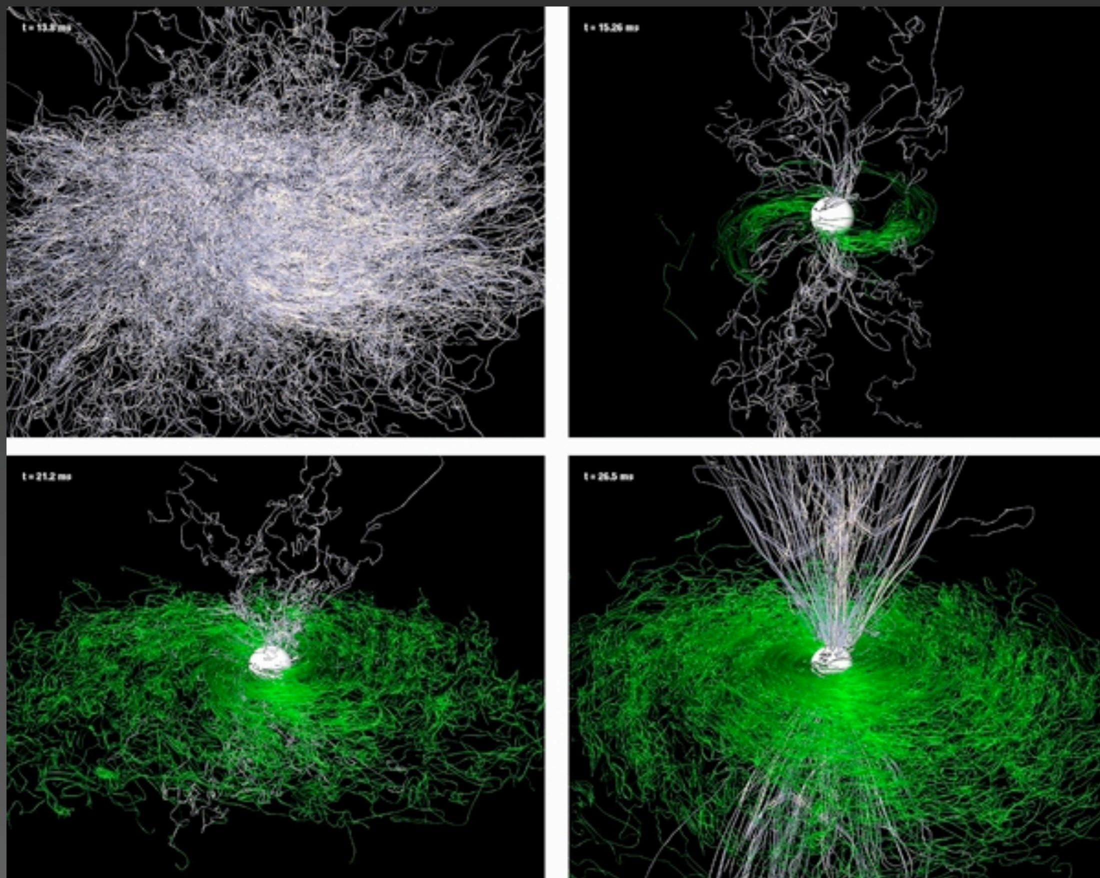
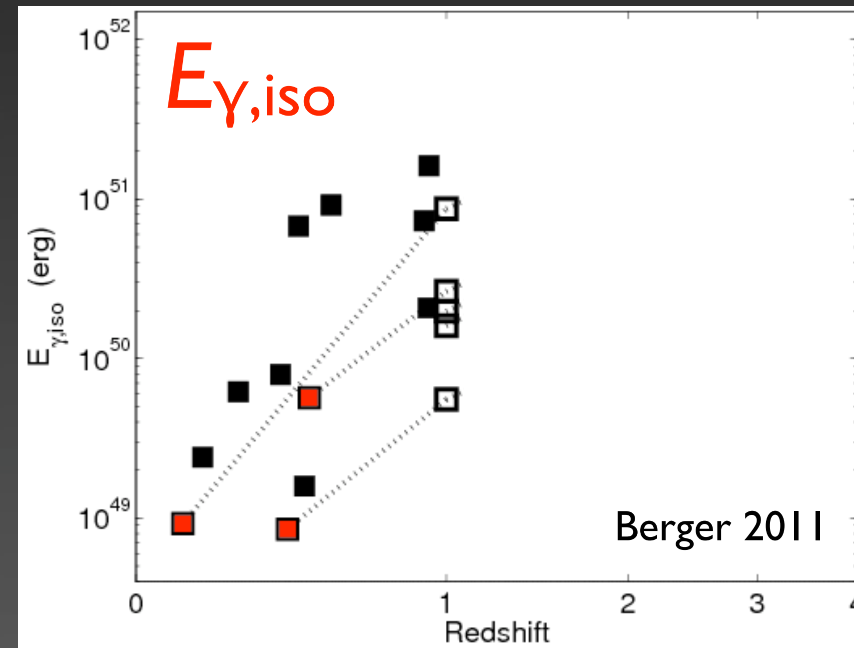
Short GRB Jets



Rezzolla et al. 2012



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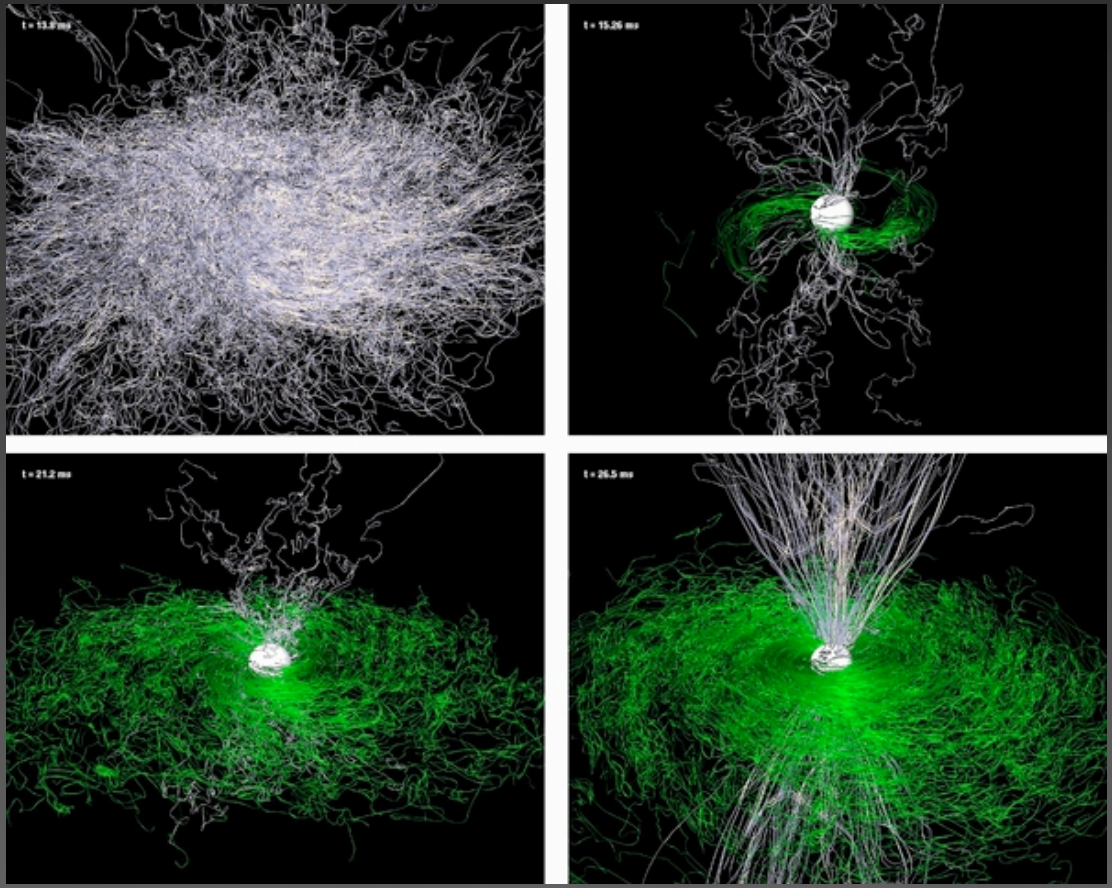
Short GRB Jets



Rezzolla et al. 2012

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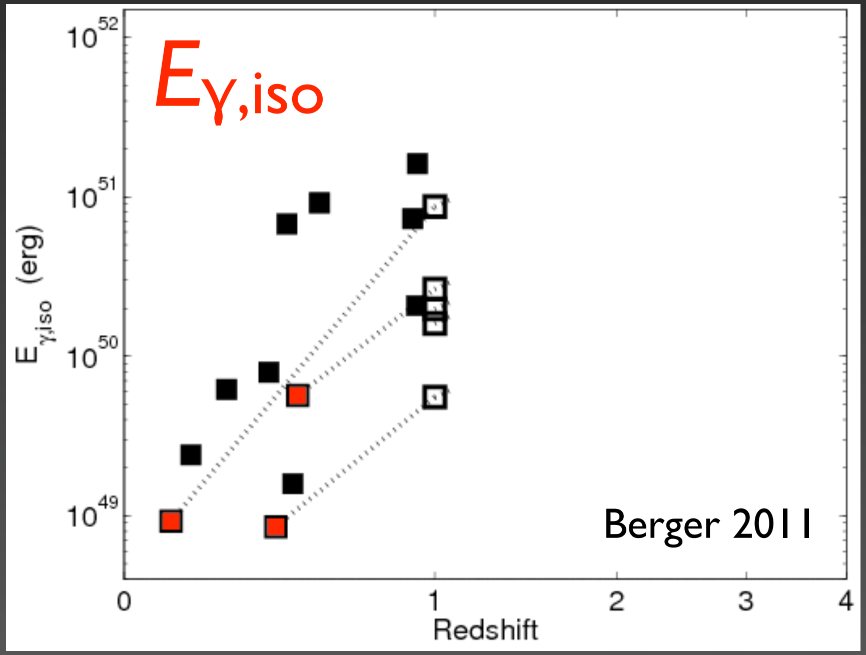
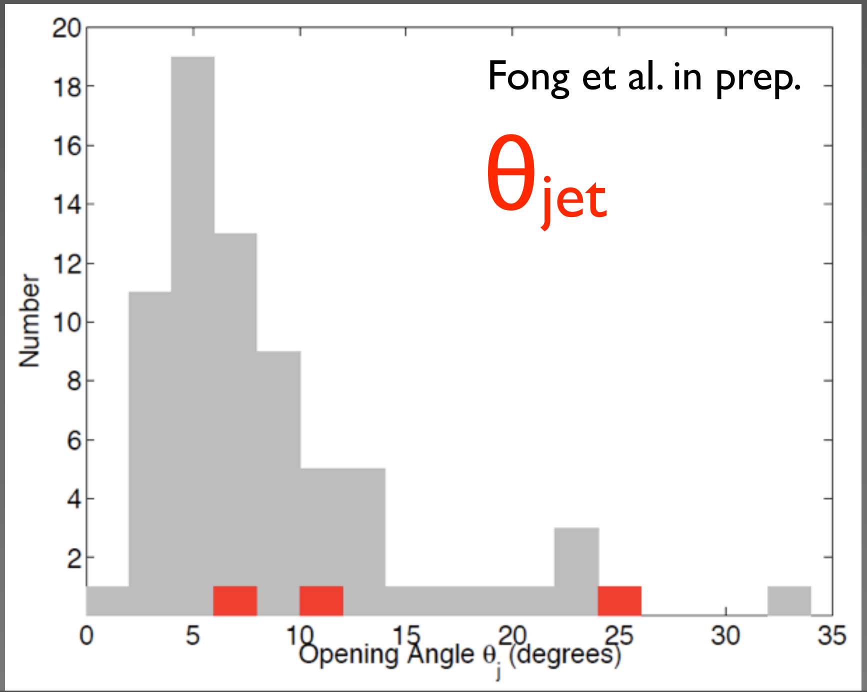
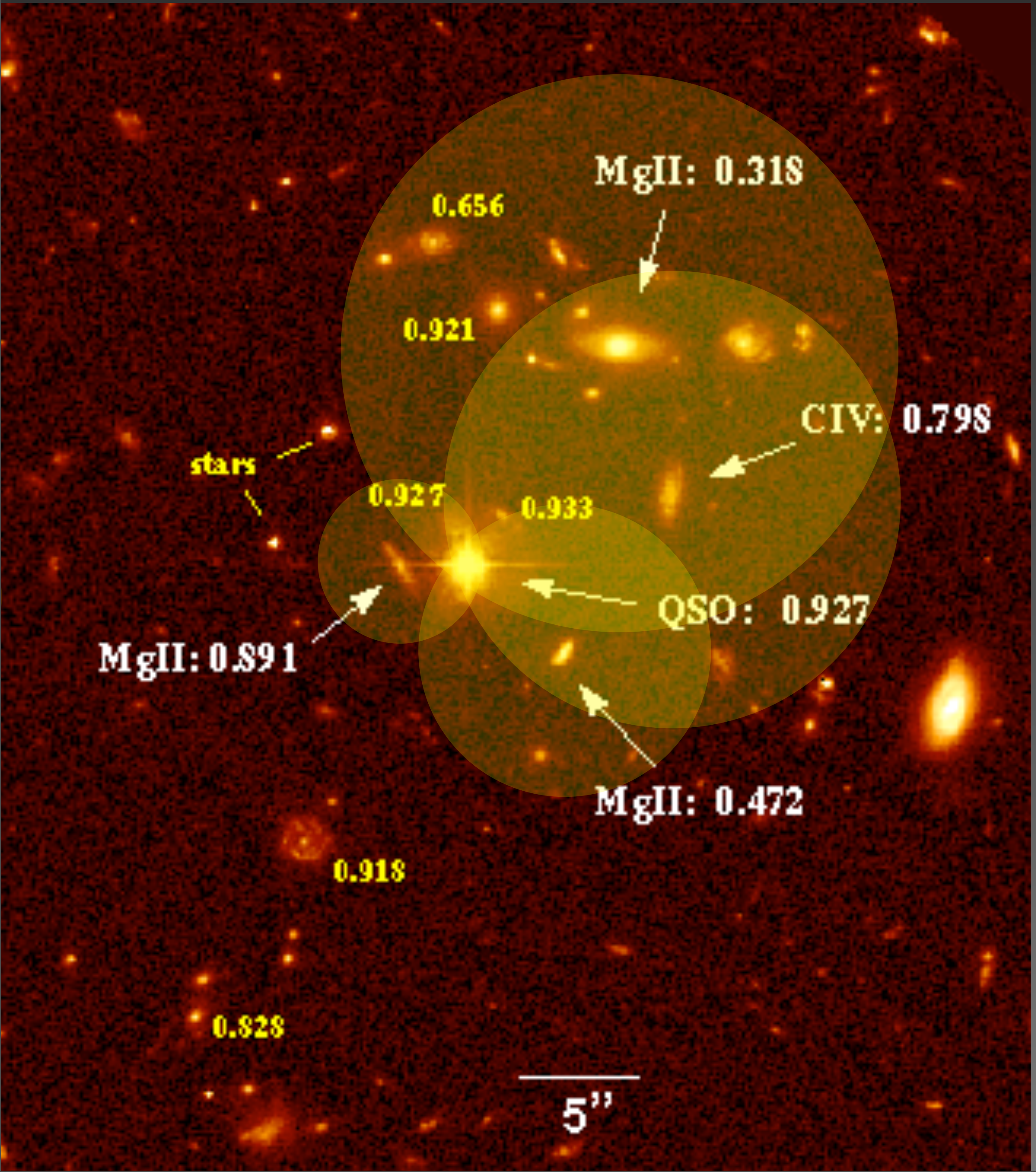




GRBs as Cosmological Probes



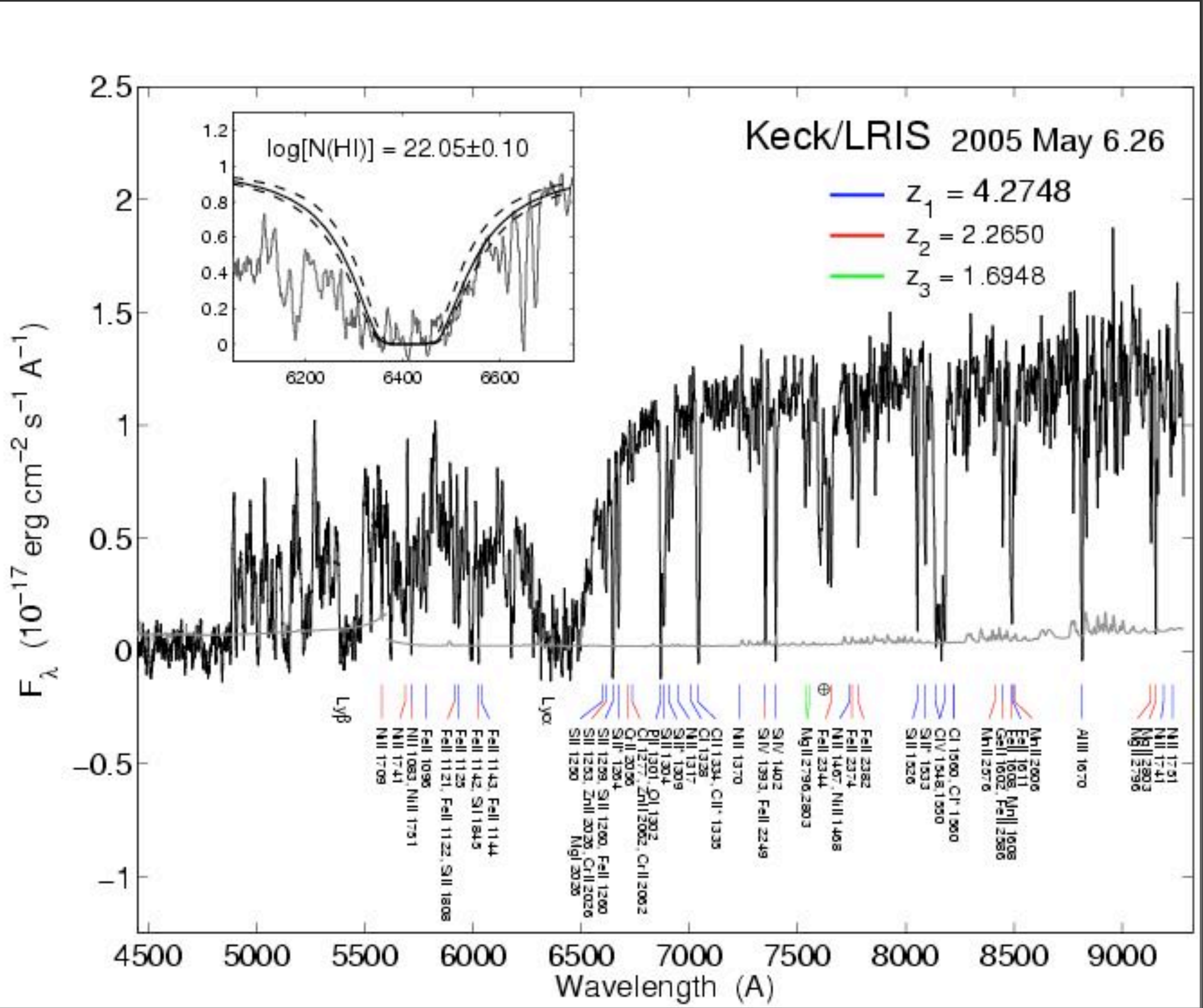
QSOs act as background sources of illumination

GRBs are embedded within their host galaxies

GRBs vs. quasars:

- *In star forming regions*
- *No Mpc proximity effect*
- *Higher redshifts*

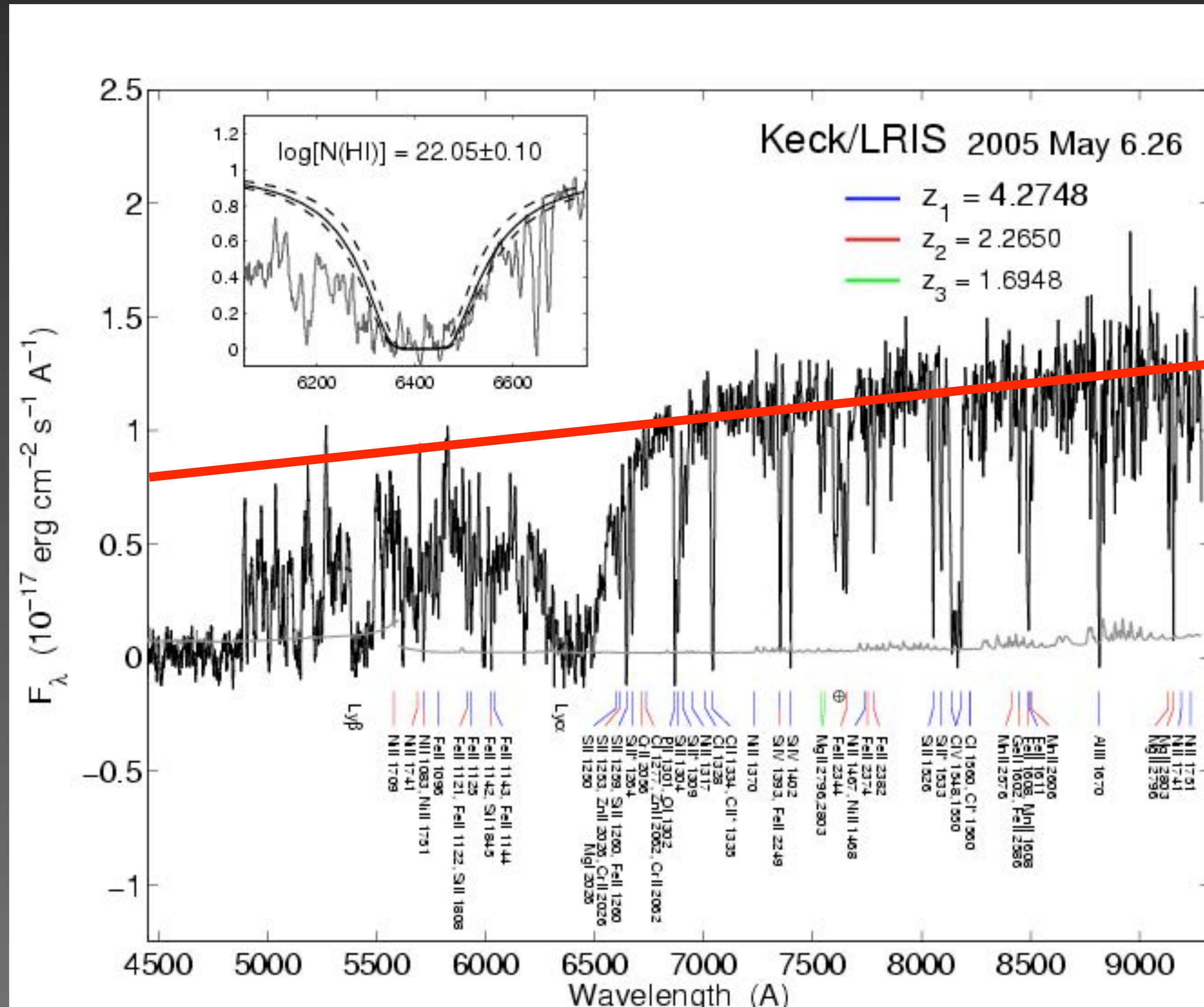
GRBs as Cosmological Probes



Berger et al. 2006

GRBs as Cosmological Probes

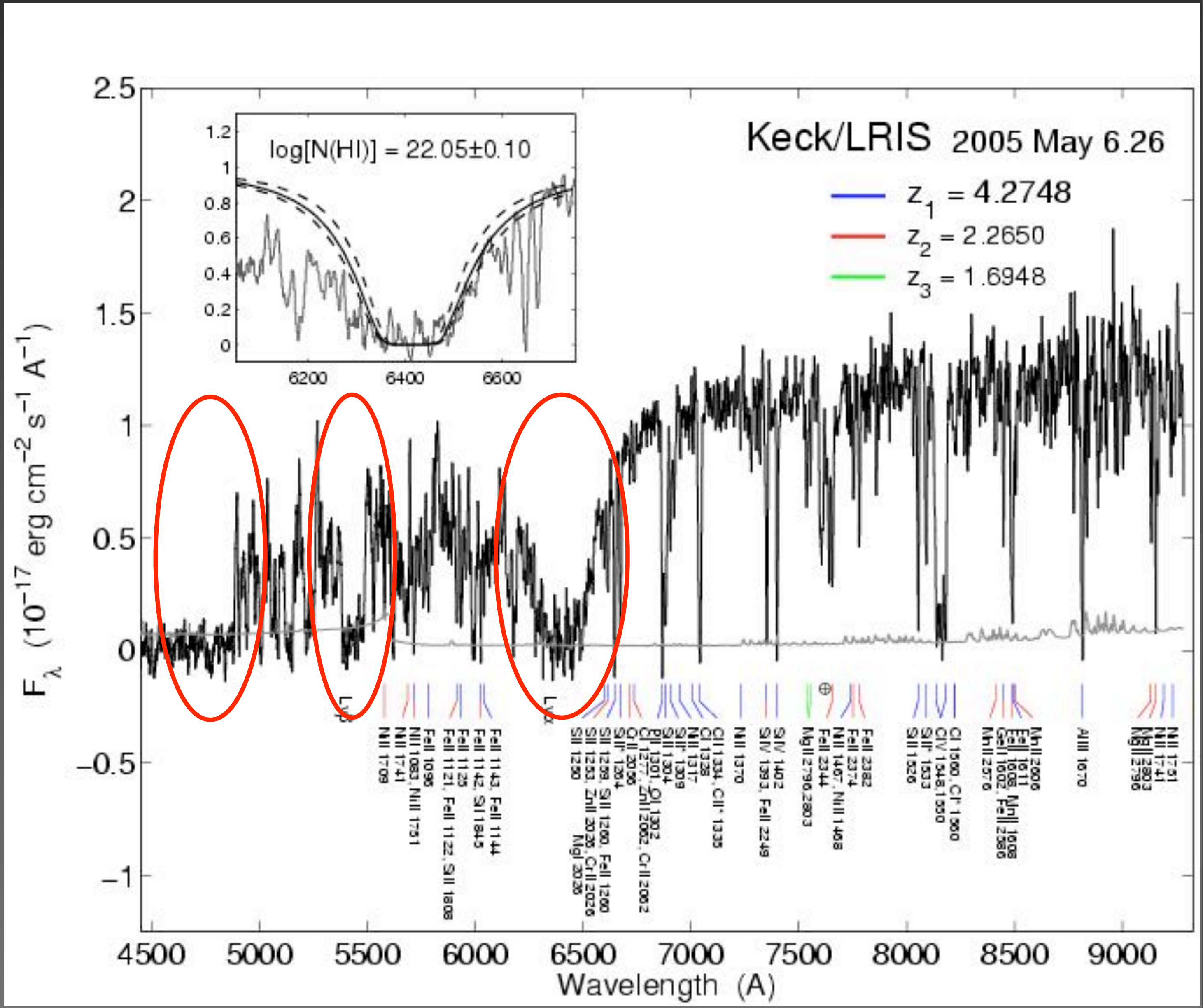
Intrinsic



Berger et al. 2006

GRBs as Cosmological Probes

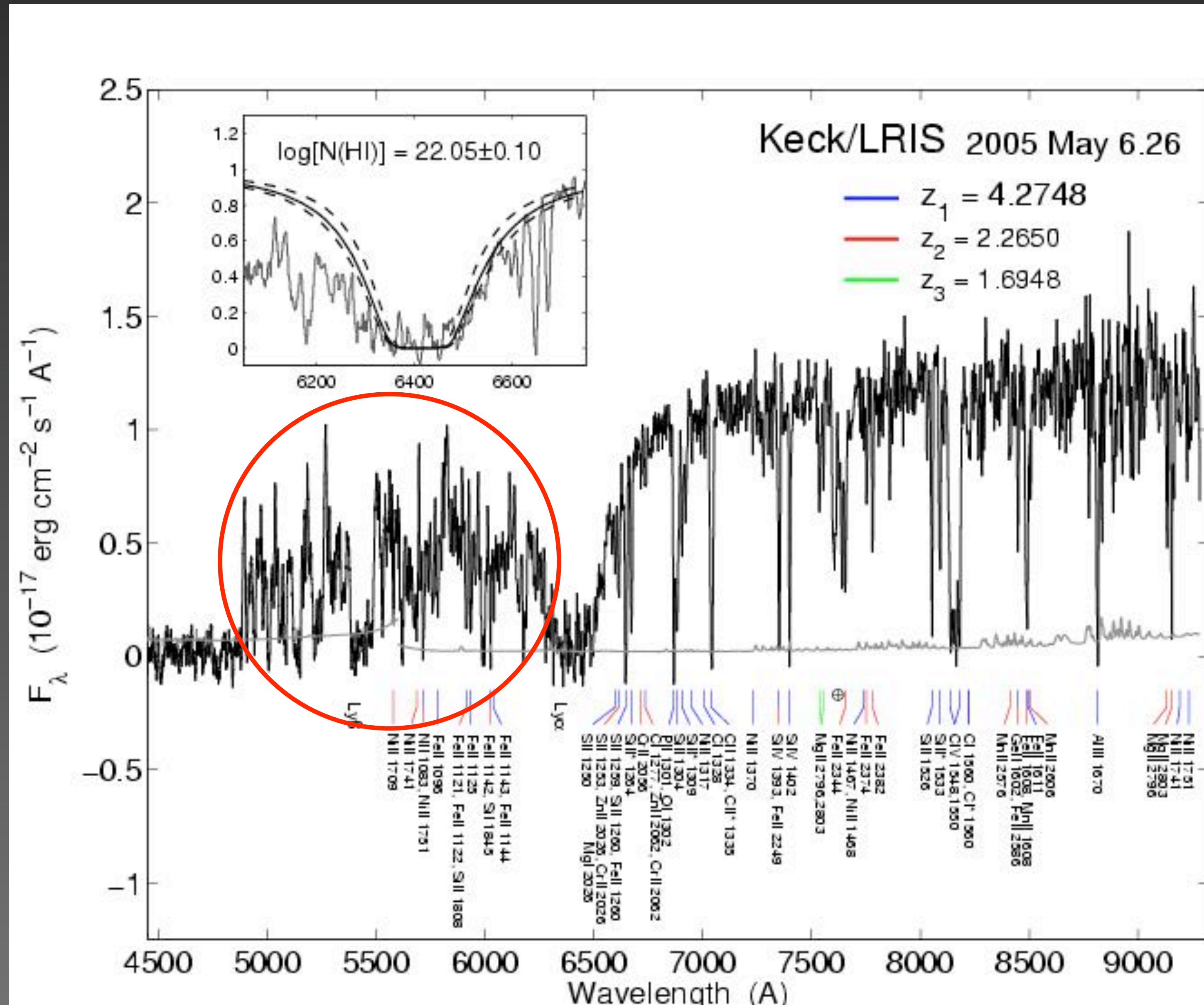
Ly series absorption



Berger et al. 2006

GRBs as Cosmological Probes

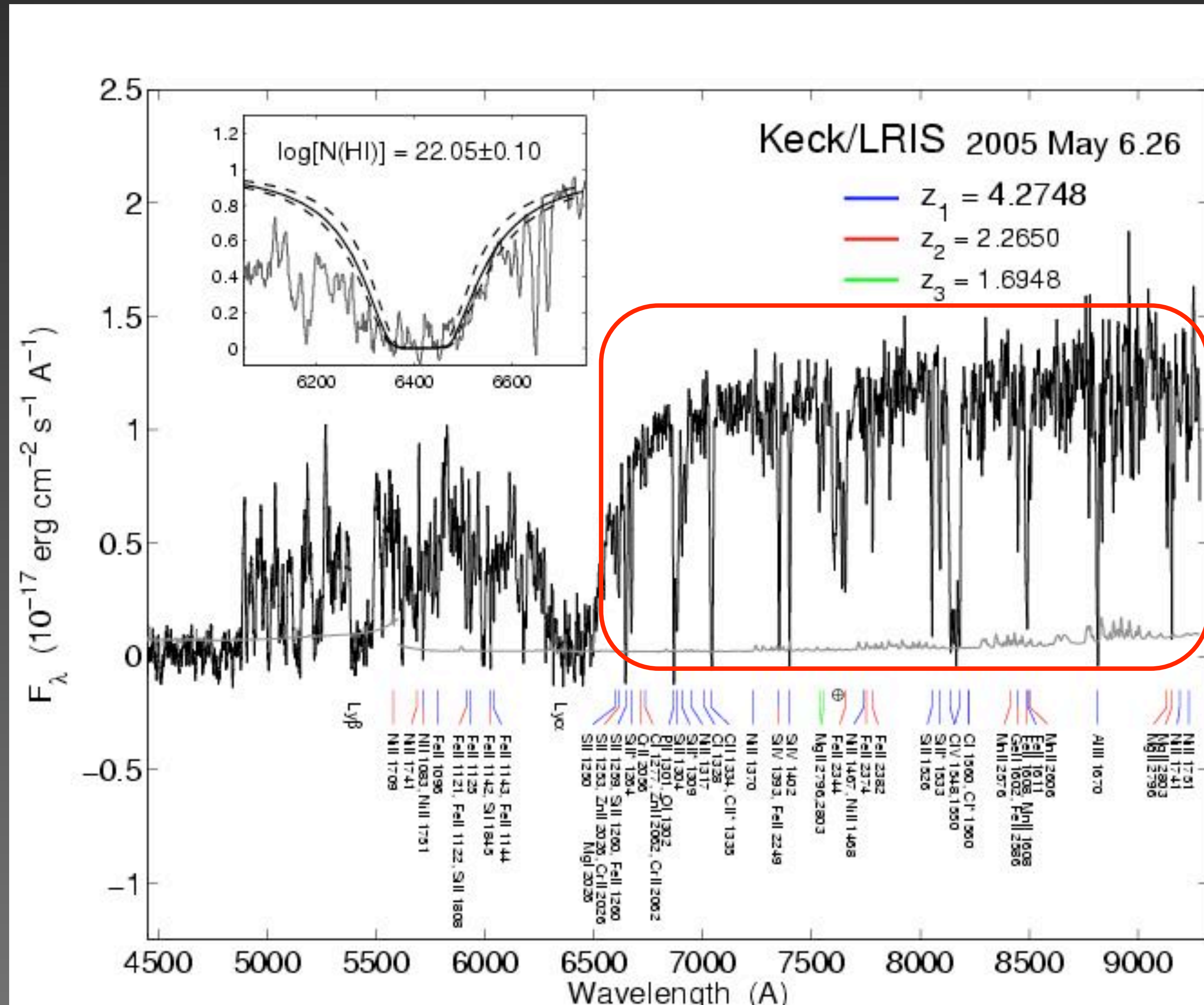
Lyα forest



Berger et al. 2006

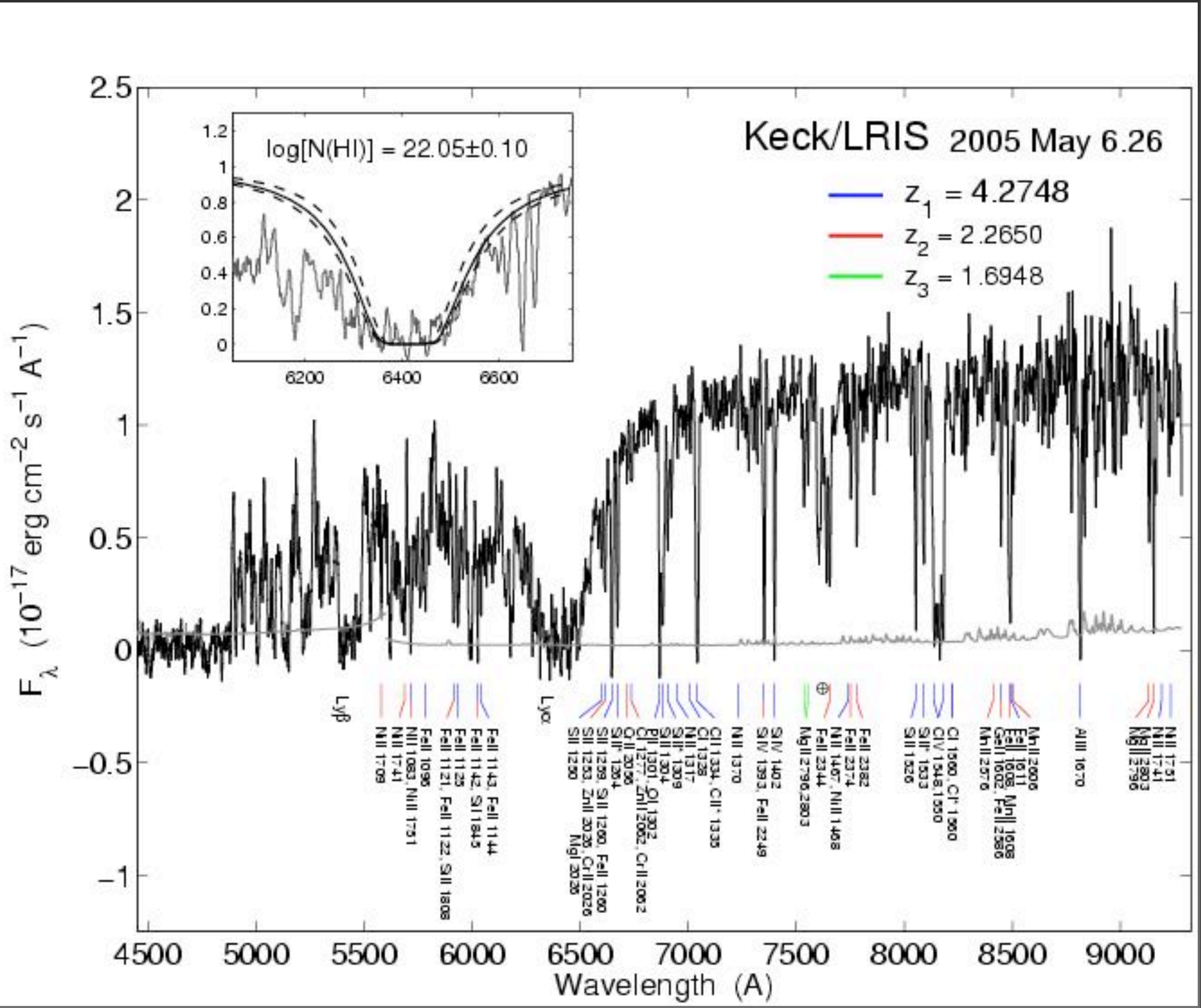
GRBs as Cosmological Probes

Metals



Berger et al. 2006

GRBs as Cosmological Probes

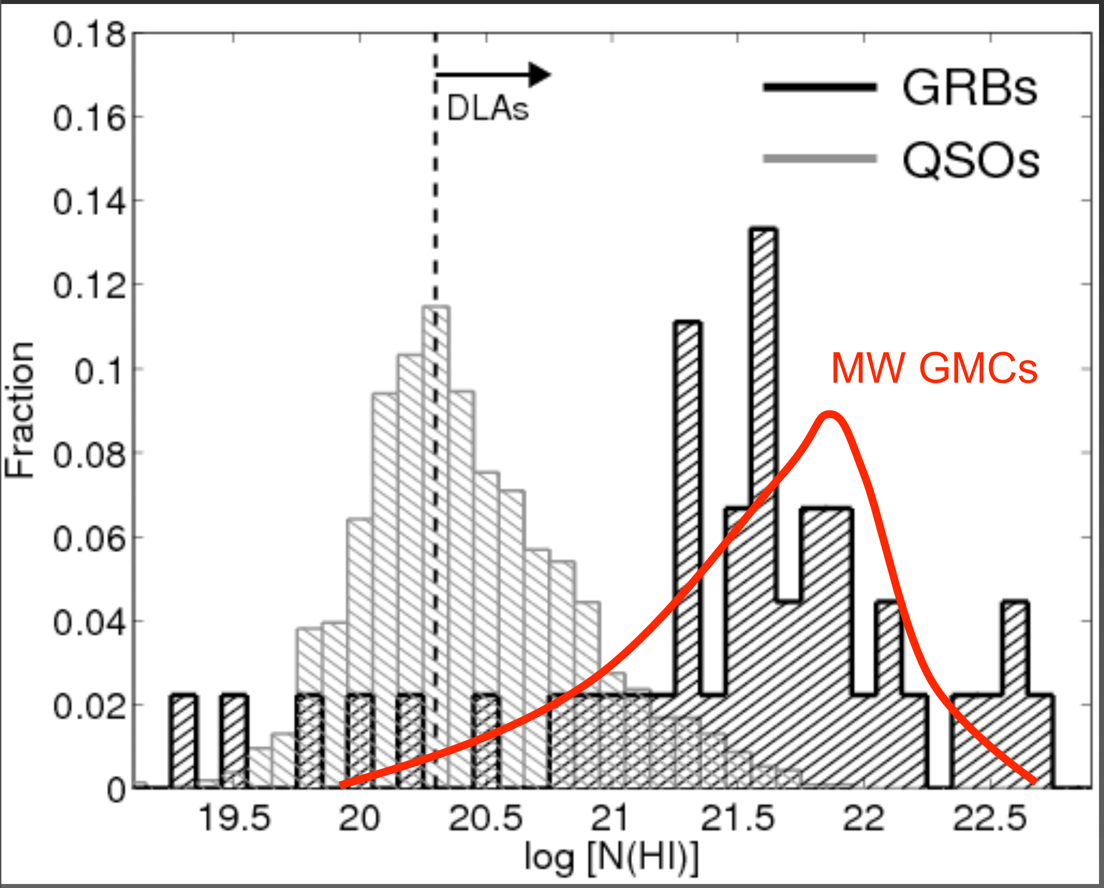


Berger et al. 2006

log N_H =22.1±0.1

[S/H] = 0.06 $Z_\odot$

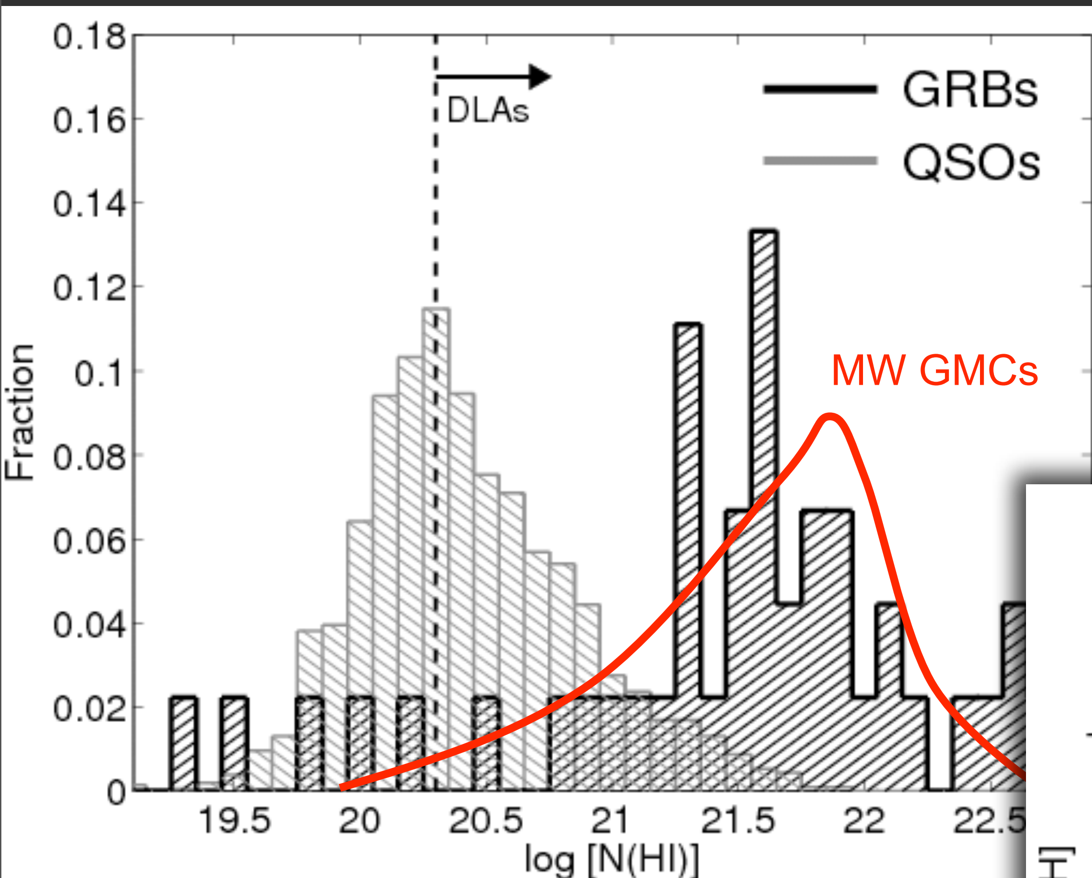
GRBs as Cosmological Probes



Berger et al. 2006

$\langle N(HI)_{GRB} \rangle \sim 10 \times \langle N(HI)_{QSO} \rangle$

GRBs as Cosmological Probes

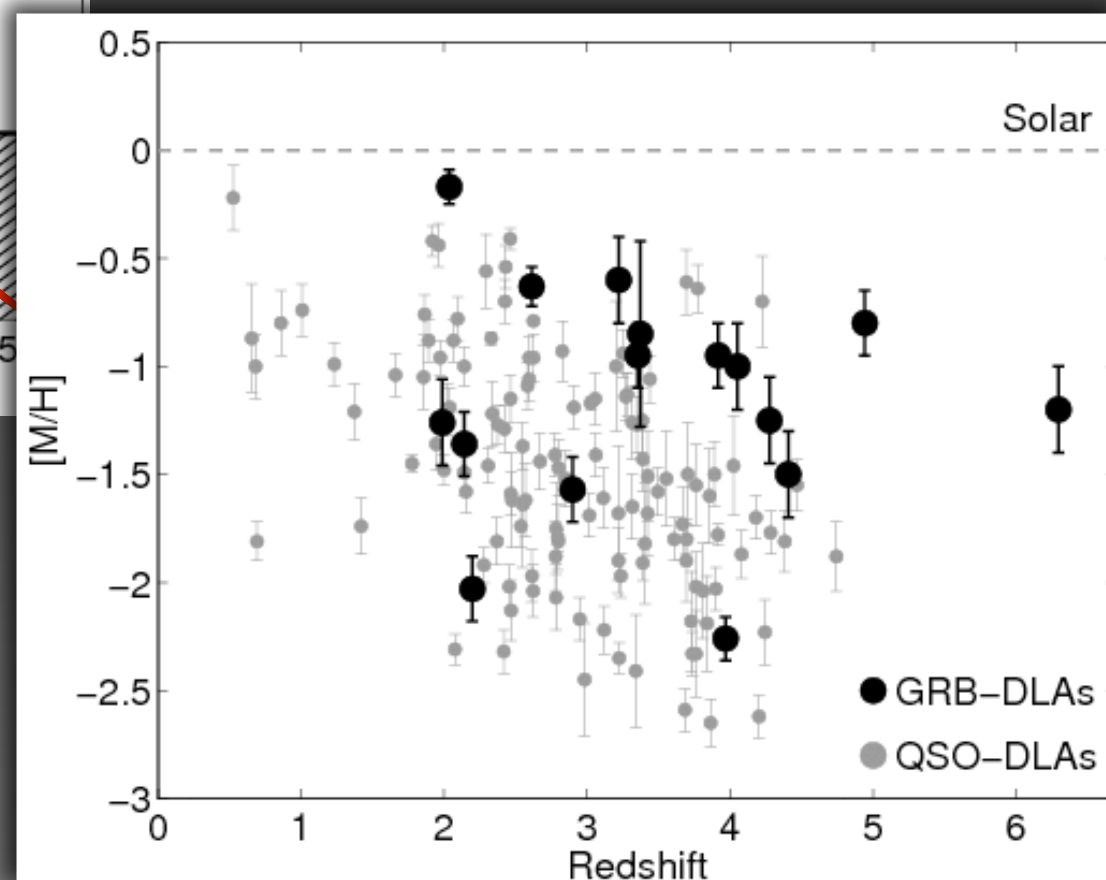


Berger et al. 2006

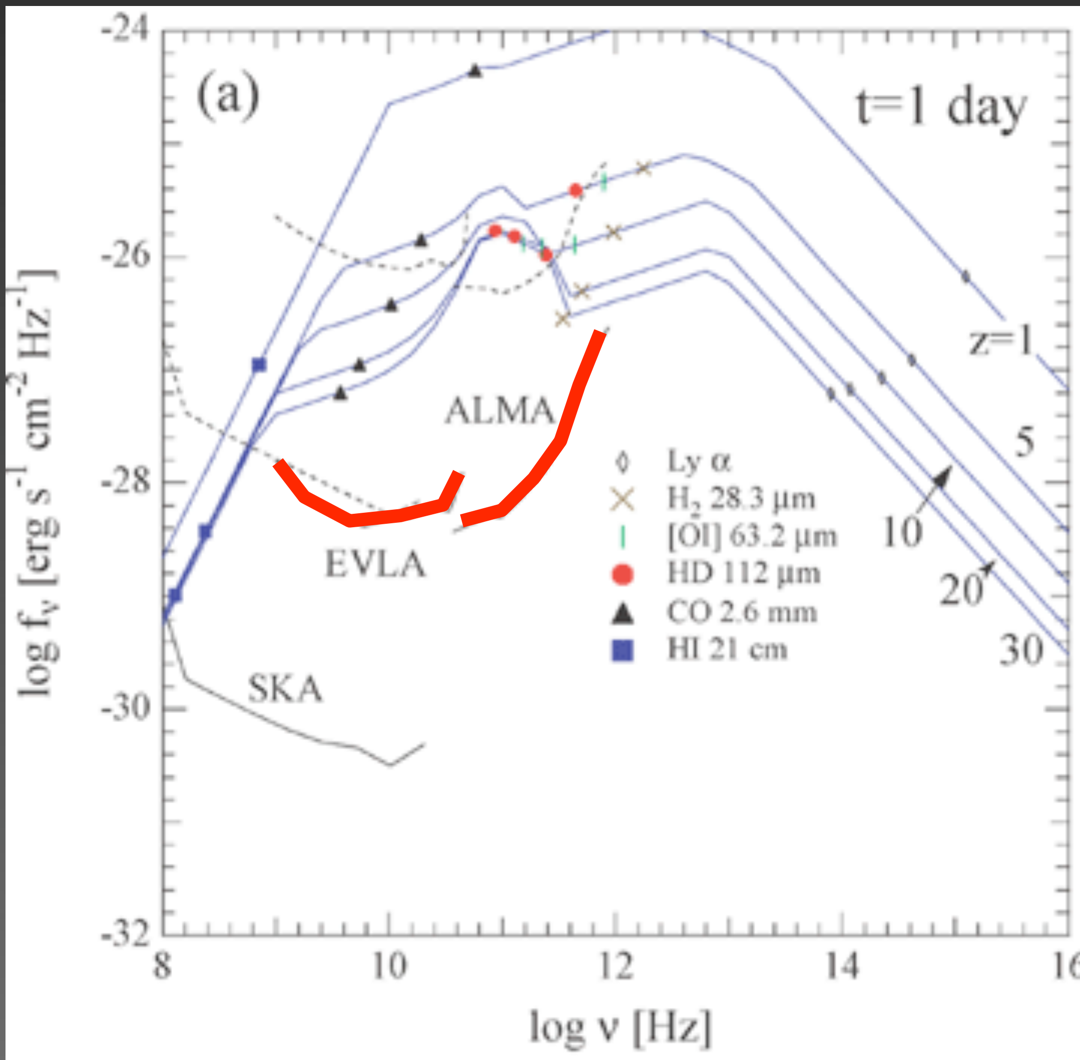
$\langle N(HI)_{GRB} \rangle \sim 10 \times \langle N(HI)_{QSO} \rangle$

$\langle Z_{GRB} \rangle \sim 3 \times \langle Z_{QSO} \rangle$

Berger et al. 2006; Prochaska et al. 2007; Savaglio et al. 2007



Molecular Absorption Spectroscopy



Inoue et al. 2007

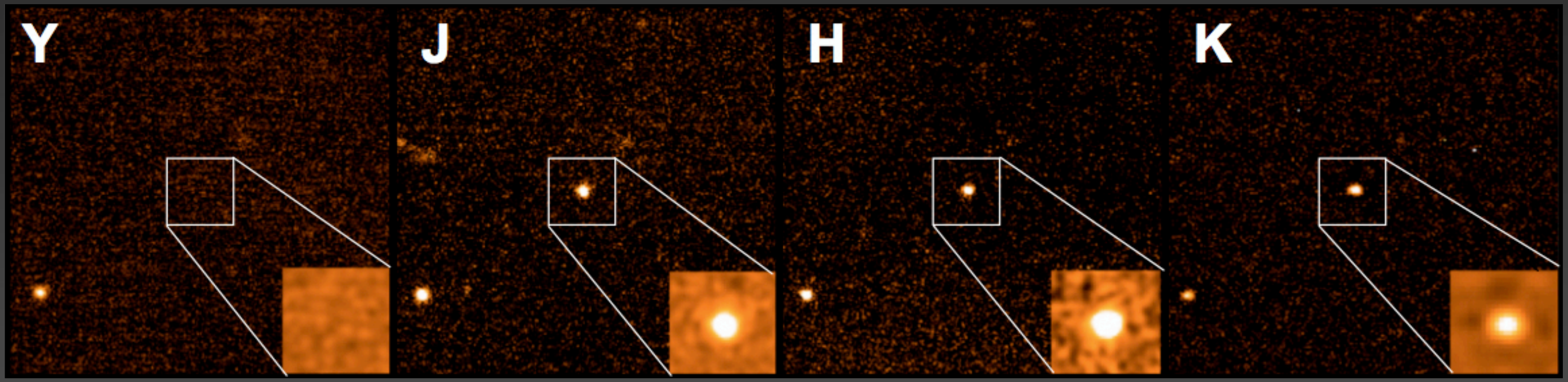
Absorption spectroscopy of cm/mm emission can probe molecular gas (e.g. CO, HD, etc.) <u>in normal galaxies</u>.

Independent of galaxy mass, SFR, redshift.

Connect atomic and molecular gas information with galaxy SFR, M, etc.

Can be done for free with TOO observations (Cycle 1 proposal).

High-Redshift GRBs

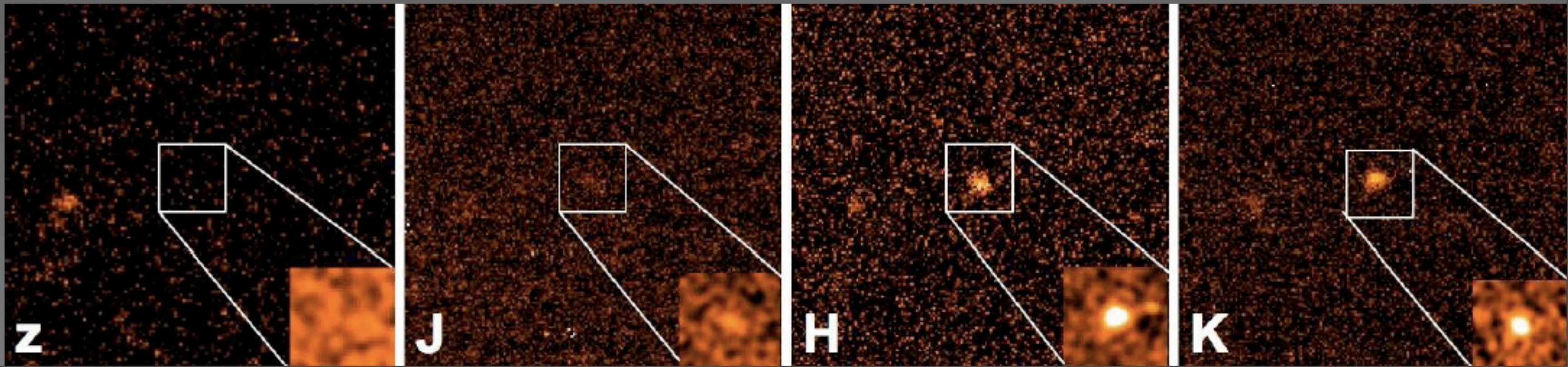


$z \approx 8.26$
(625 Myr)

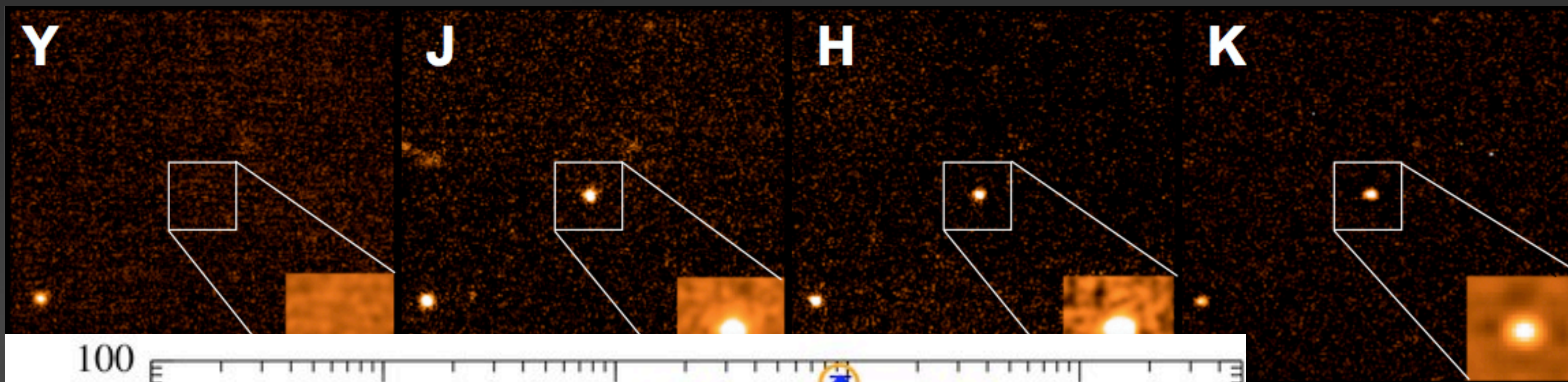
Tanvir, Berger, et al. 2009

Cucchiara, Berger, et al. 2010

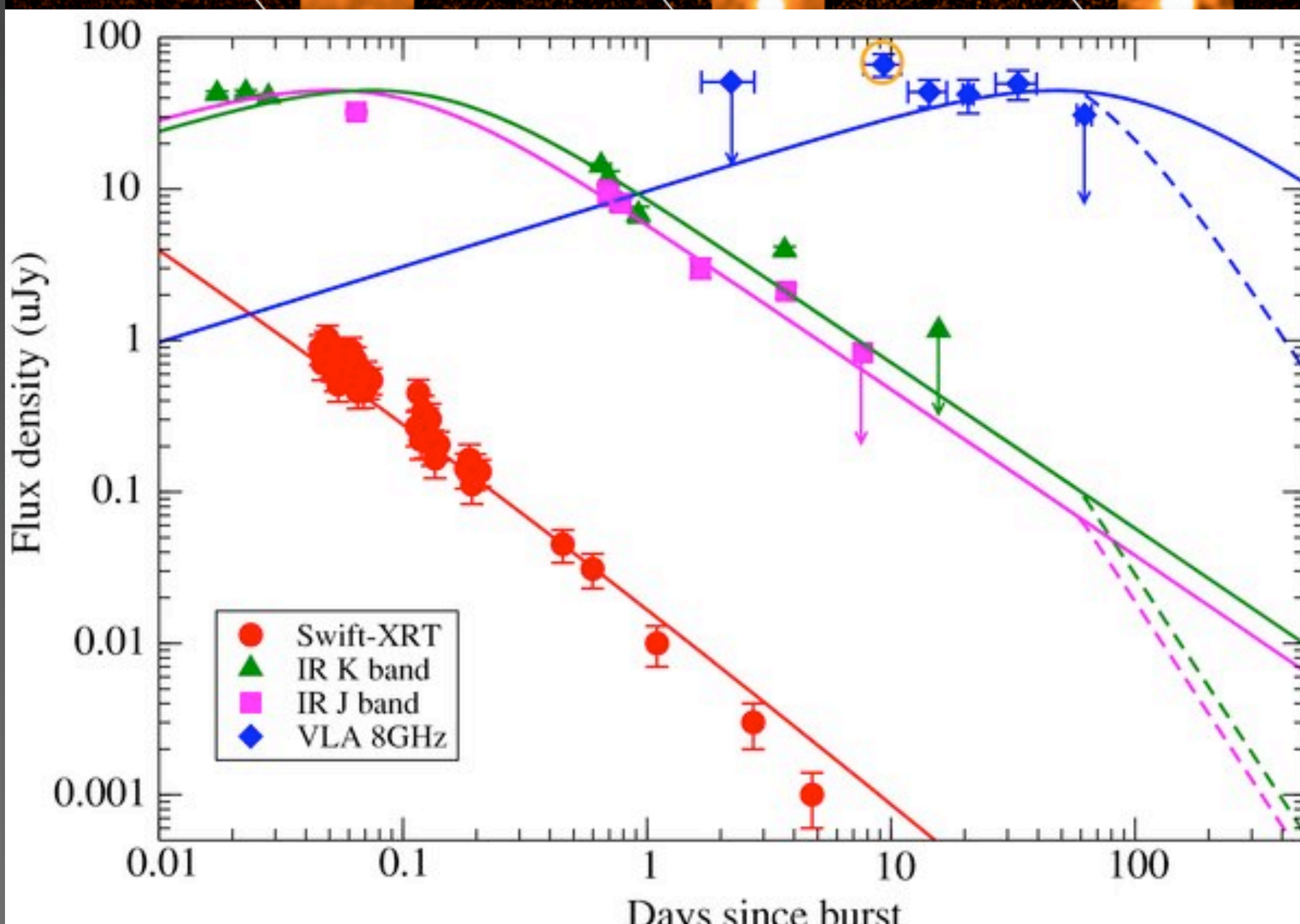
$z \approx 9.4$ (525 Myr)



High-Redshift GRBs

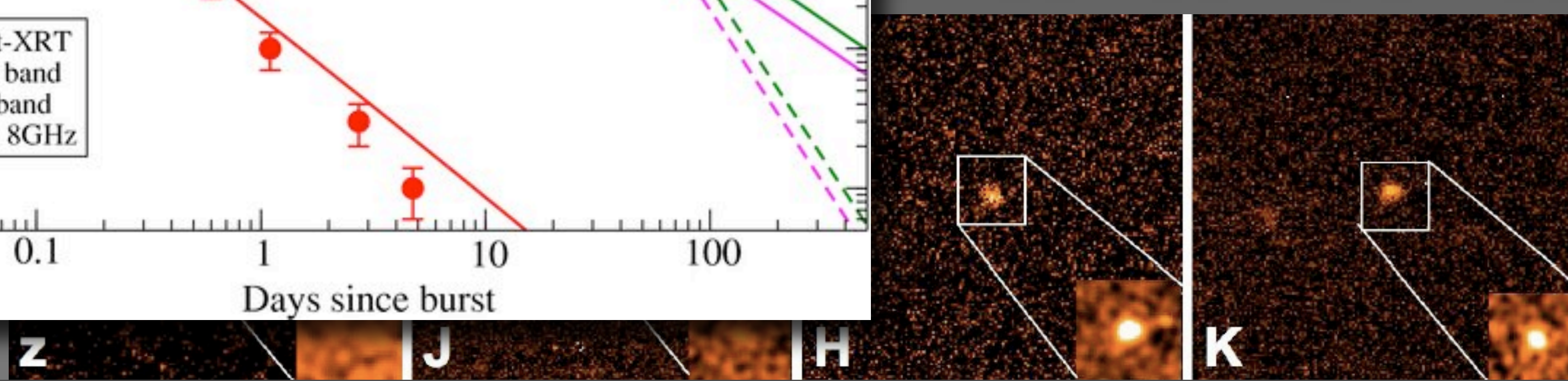


z ≈ 8.26 (625 Myr)



Radio emission can be detected at z>8; can provide a probe of Pop III stars

z ≈ 9.4 (525 Myr)



Conclusions

- GRBs are laboratories for the structure, composition, evolution of highly relativistic jets.

- Evidence for collimation in short GRBs (NS-NS/NS-BH mergers).

- EVLA+ALMA synergy will revolutionize studies of GRB energetics, environments, hosts (obscured SF, molecular gas).