

Title: Short Gamma-Ray Bursts and the Electromagnetic Counterparts of Gravitational Wave Sources

Date: Sep 18, 2013 02:00 PM

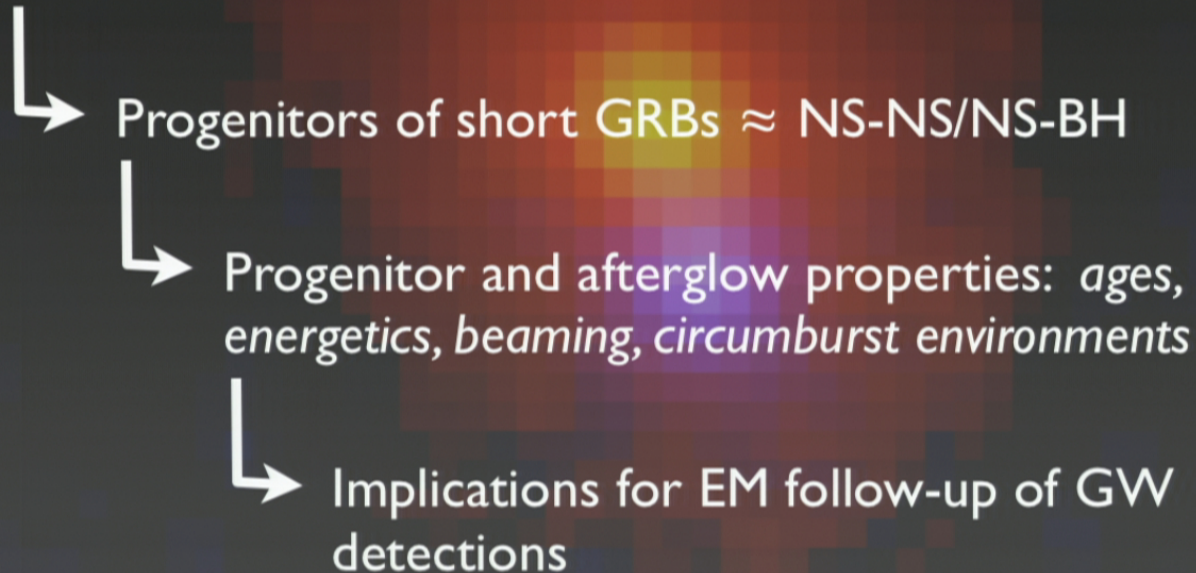
URL: <http://pirsa.org/13090050>

Abstract: Gamma-ray bursts are the most luminous and energetic explosions known in the universe. They appear in two varieties: long- and short-duration. The long GRB result from the core-collapse of massive stars, but until recently the origin of the short GRBs was shrouded in mystery. In this talk I will present several lines of evidence that point to the merger of compact objects binaries (NS-NS and/or NS-BH) as the progenitor systems of short GRBs. Within this framework, the observational data also allow us to independently determine the merger rate of these systems as input to the Advanced LIGO event rate, to infer the merger distribution timescale, and to determine the energy scale of the mergers. In addition, using radio to X-ray observations of short GRBs we can determine the expected electromagnetic properties of Advanced LIGO sources.

Outline

GRB primer: brief history, basic model

Progenitors of short GRBs $\neq$ Progenitors of long GRBs

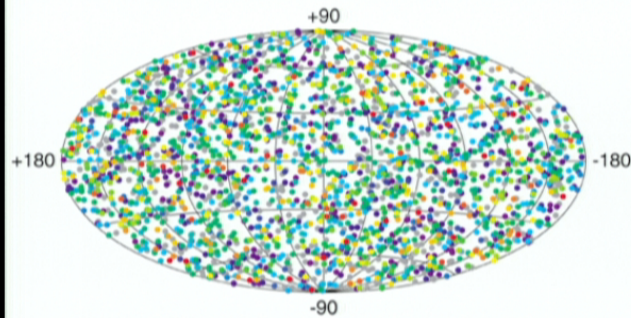


GRB 050724: Berger et al. 2005, Nature, 438, 988

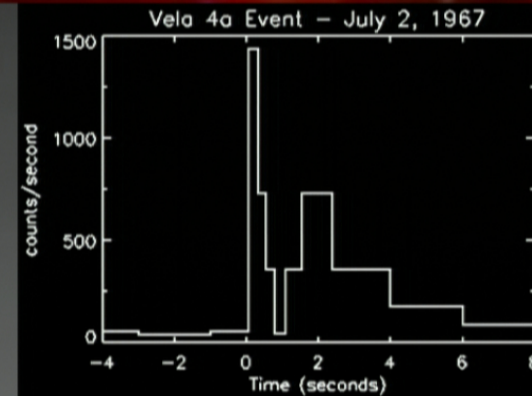
The Essential History (1967-1997)

1967: Accidental discovery of bursts of γ -rays from outside the solar system

2704 BATSE Gamma-Ray Bursts

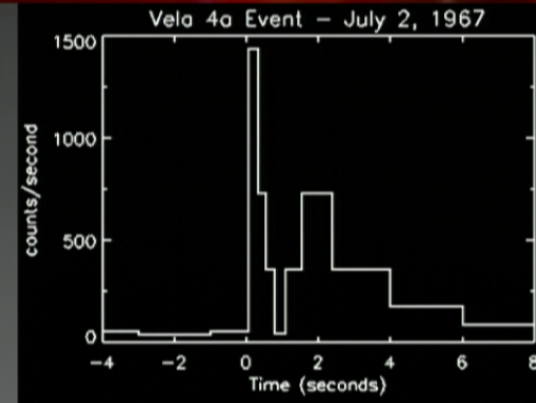


Early 1990s: BATSE reveals a uniform distribution on the sky

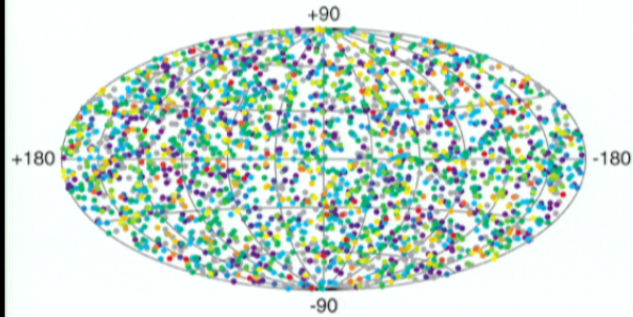


The Essential History (1967-1997)

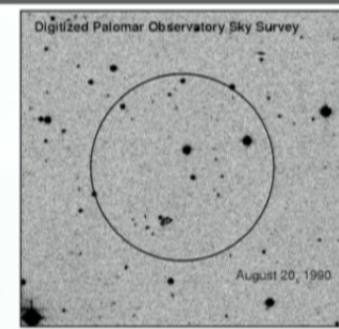
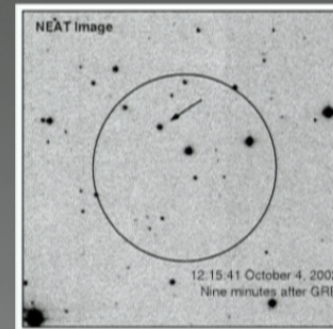
1967: Accidental discovery of bursts of γ -rays from outside the solar system



2704 BATSE Gamma-Ray Bursts

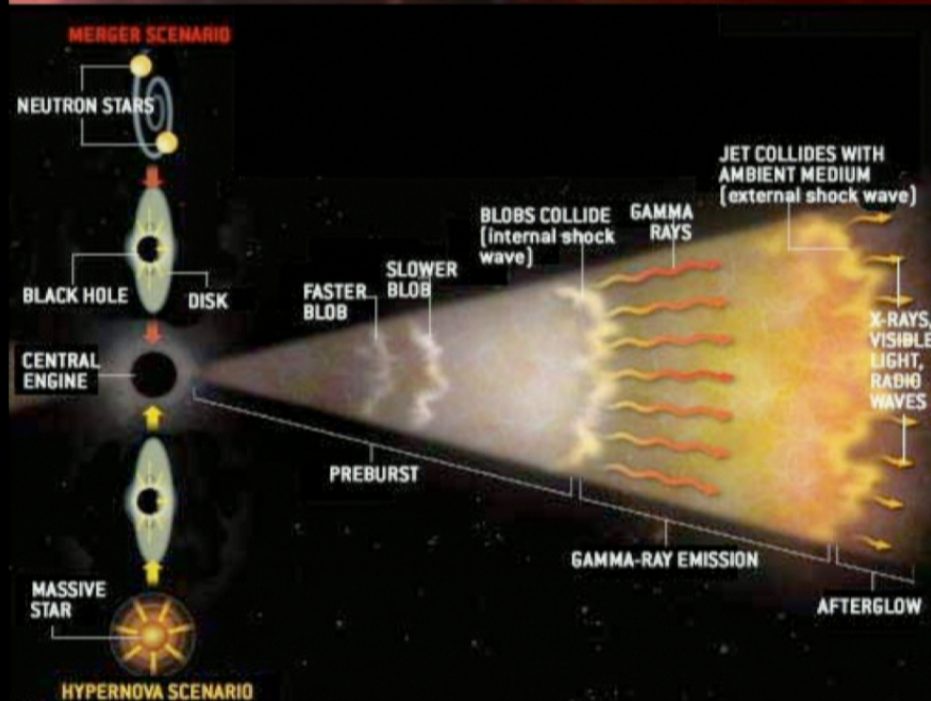


Early 1990s: BATSE reveals a uniform distribution on the sky

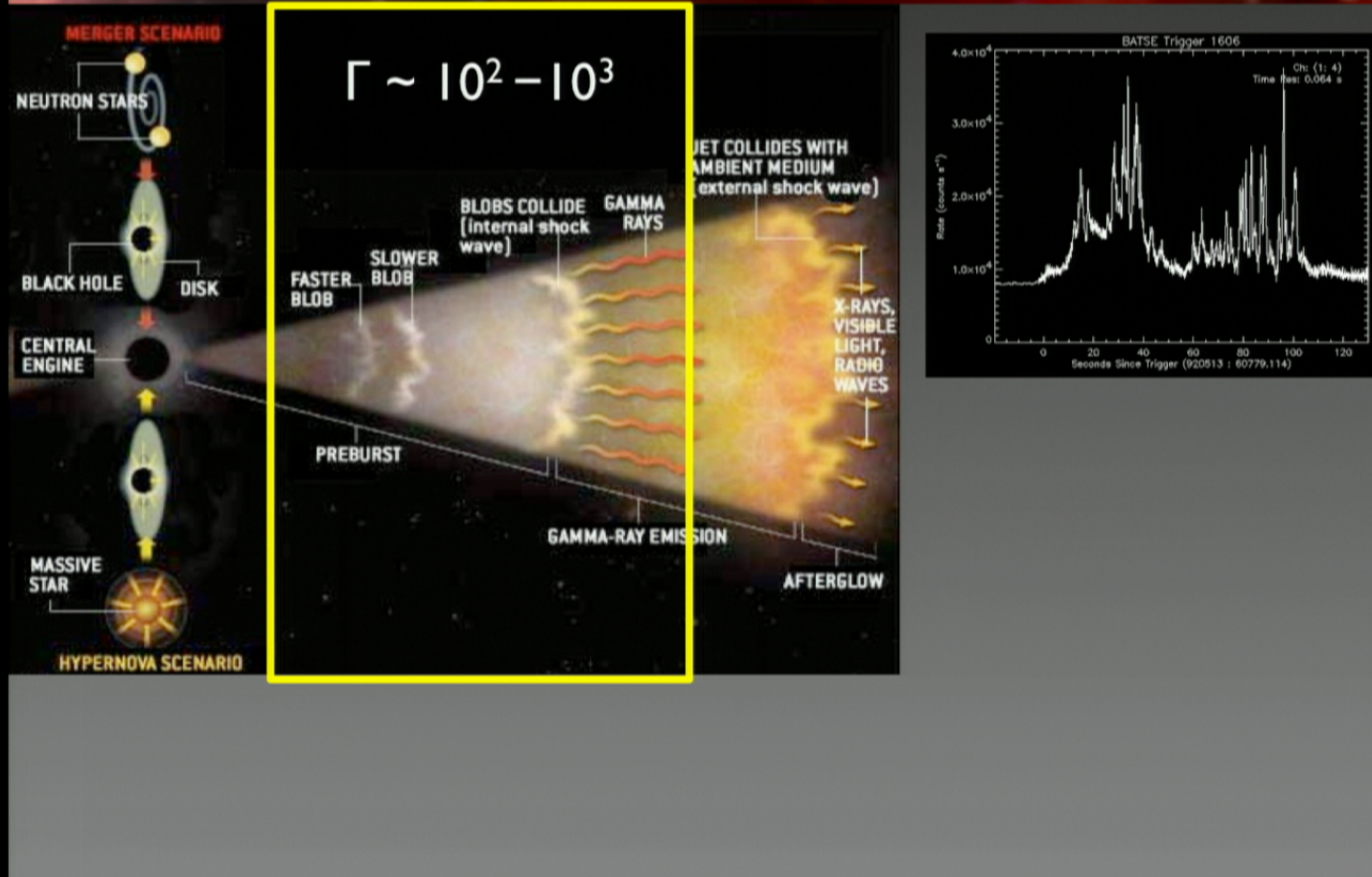


1997: Afterglows & cosmological origin for long GRBs

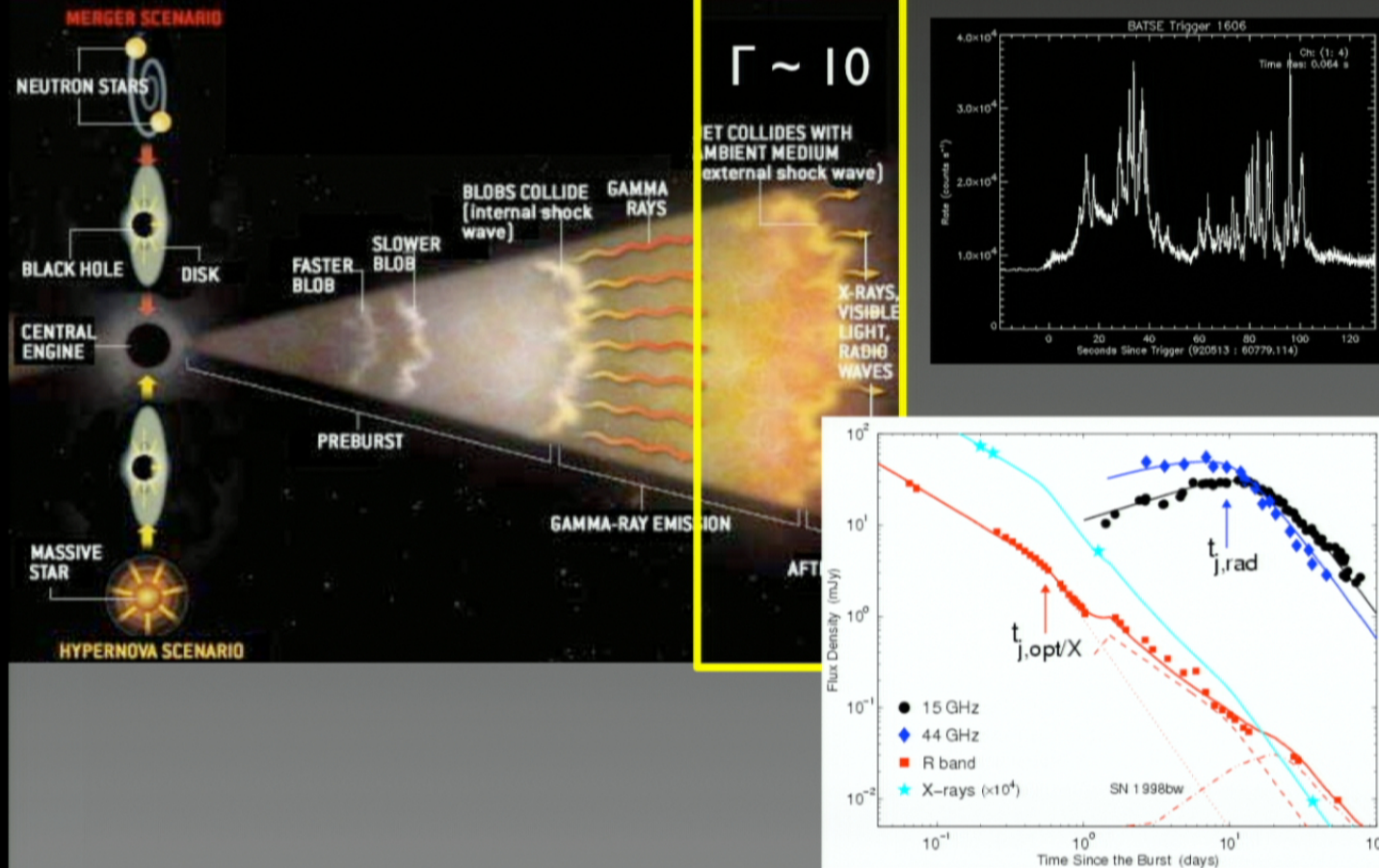
The Fireball Model



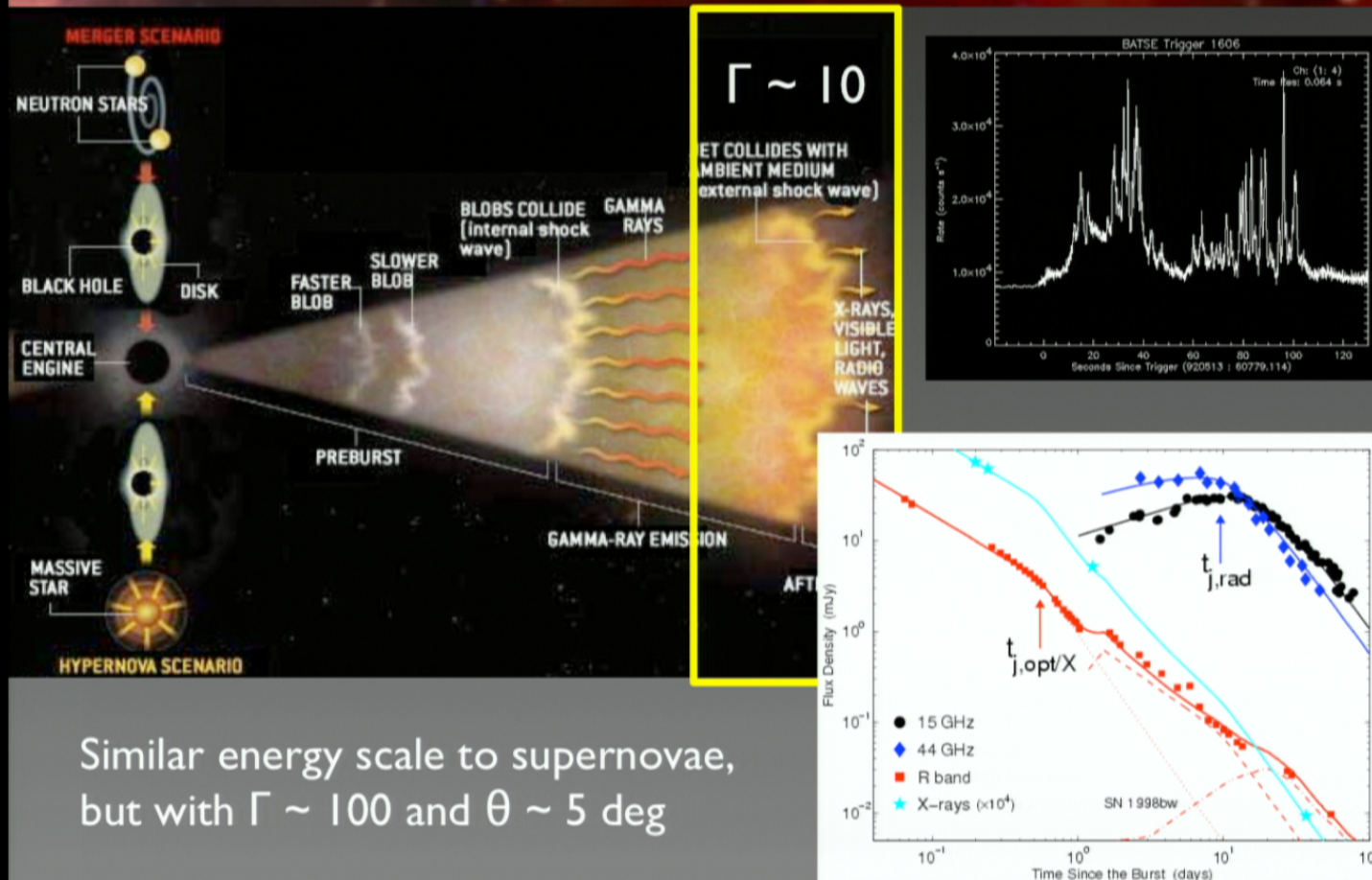
The Fireball Model



The Fireball Model

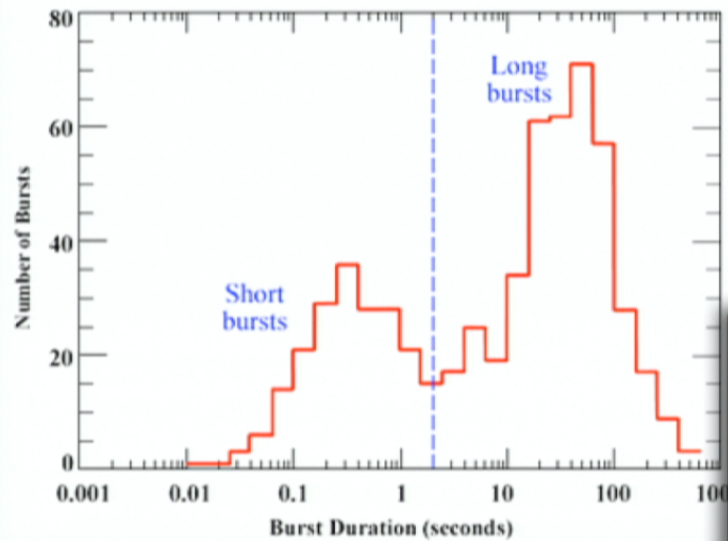


The Fireball Model



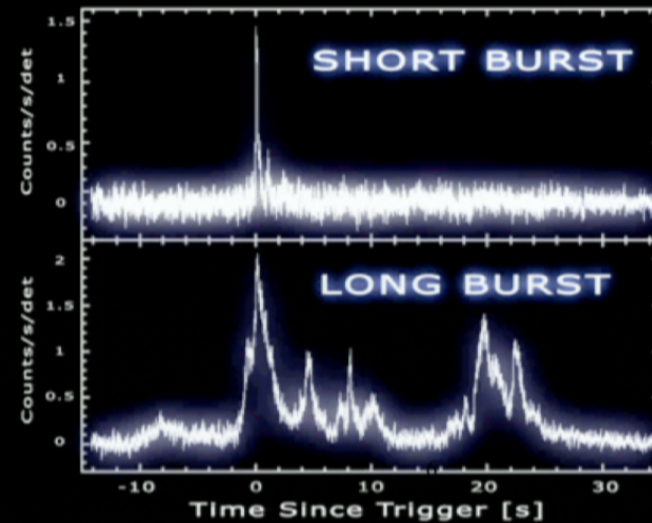
Similar energy scale to supernovae,
but with $\Gamma \sim 100$ and $\theta \sim 5$ deg

Short vs. Long GRBs

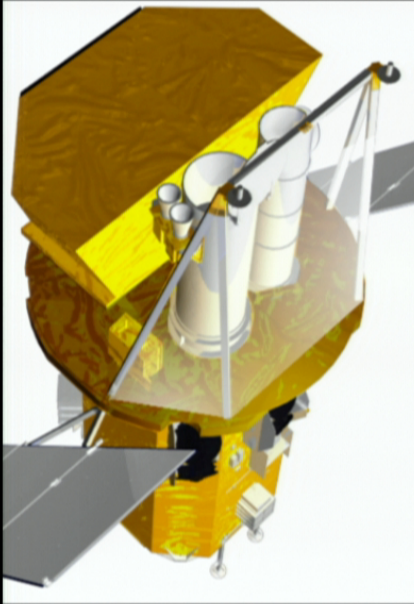


BATSE – short:long = 1:3

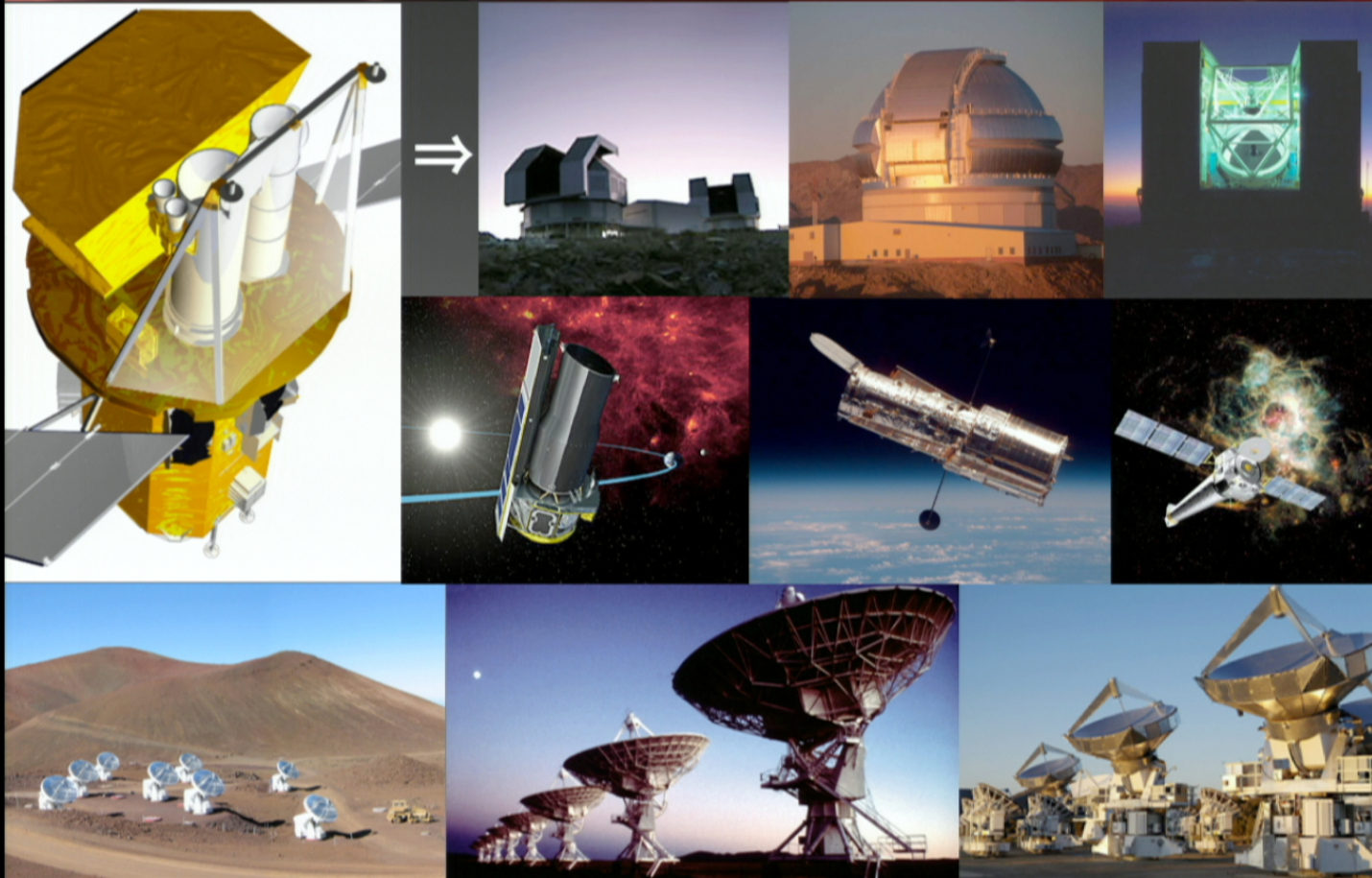
Swift – short:long = 1:10



The Harvard GRB Program: Radio $\rightarrow$ X-rays



The Harvard GRB Program: Radio $\rightarrow$ X-rays



Example: GRB 130603B

June 3, 15:49 UT: *Swift* discovers a short GRB

+28 min: Magellan observations to search for optical afterglow triggered

+35 min: VLA observations to search for radio afterglow triggered

+5.9 hr: Optical afterglow discovered $\sim 1''$ from a faint galaxy

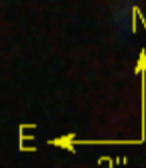
+8.8 hr: Redshift of afterglow and galaxy measured ($z=0.356$)

+9.5 hr: Radio afterglow discovered

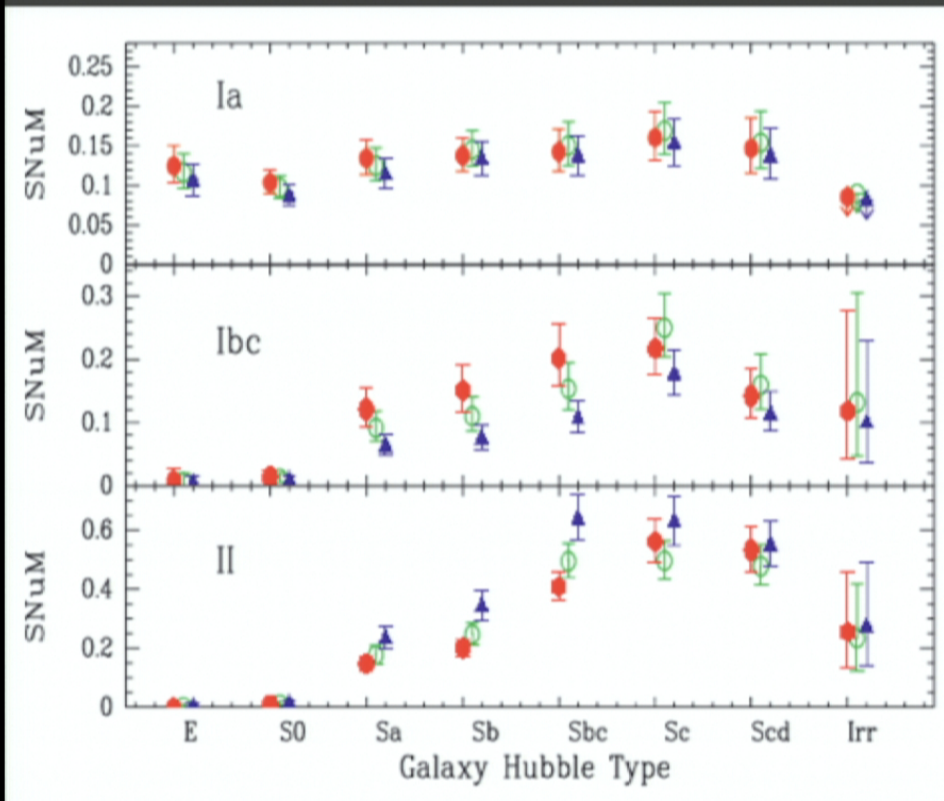
+11 hr: XMM-Newton search for jet collimation triggered

+9 days: Hubble Space Telescope observations acquired

+13 days: *Paper submitted!*

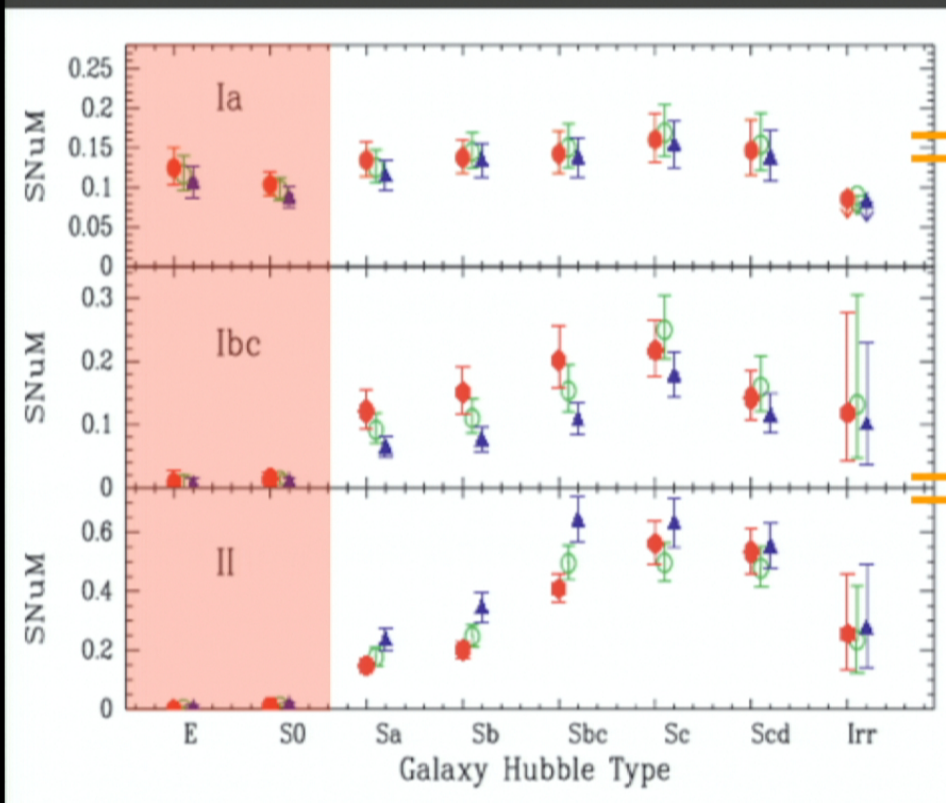


Location, Location, Location



Li et al. 2011

Location, Location, Location



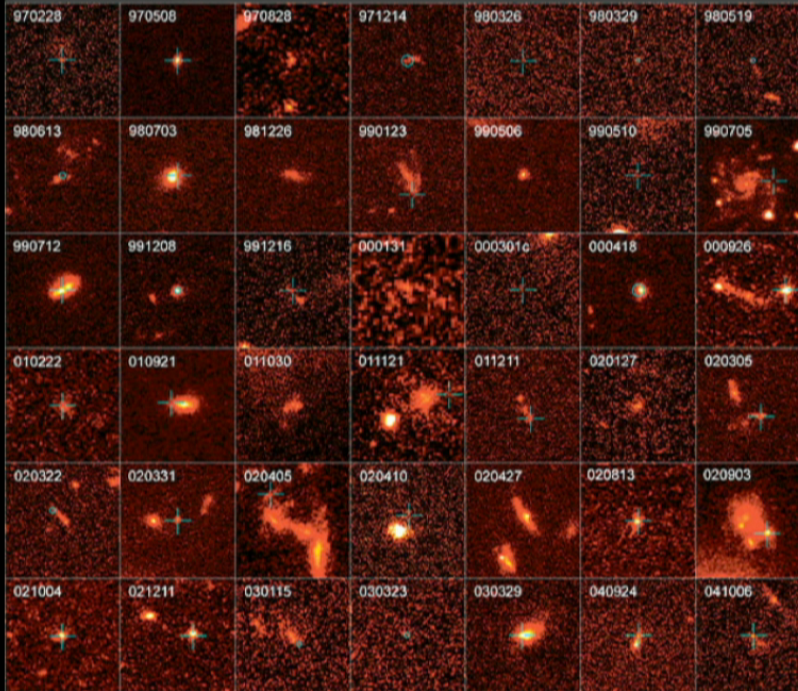
old stellar population

young stellar population

Li et al. 2011

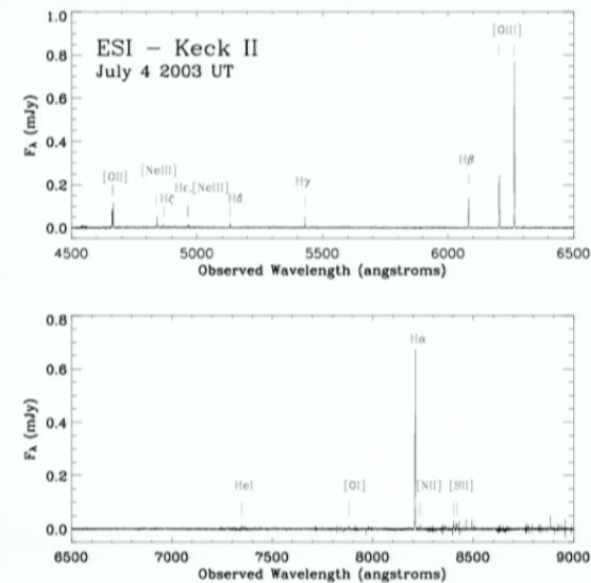
Long GRBs: The Death of Massive Stars

Fruchter et al. 2006; Wainwright, Berger, & Penprase 2007



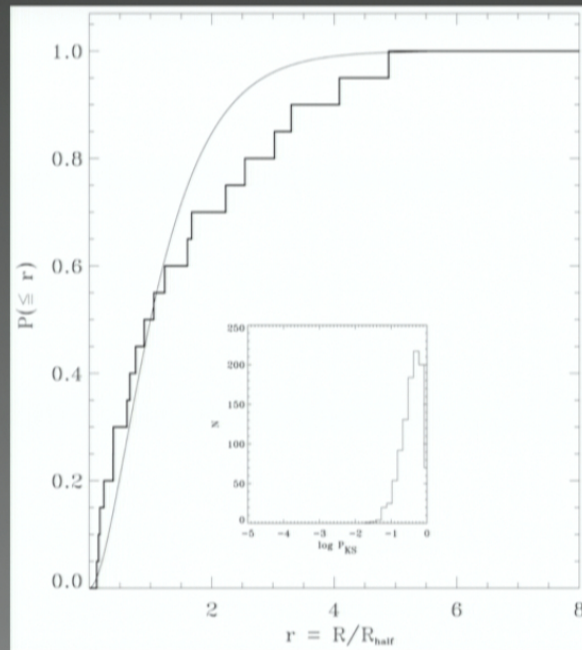
I. Exclusively in star-forming galaxies

Soderberg et al. 2003



Long GRBs: The Death of Massive Stars

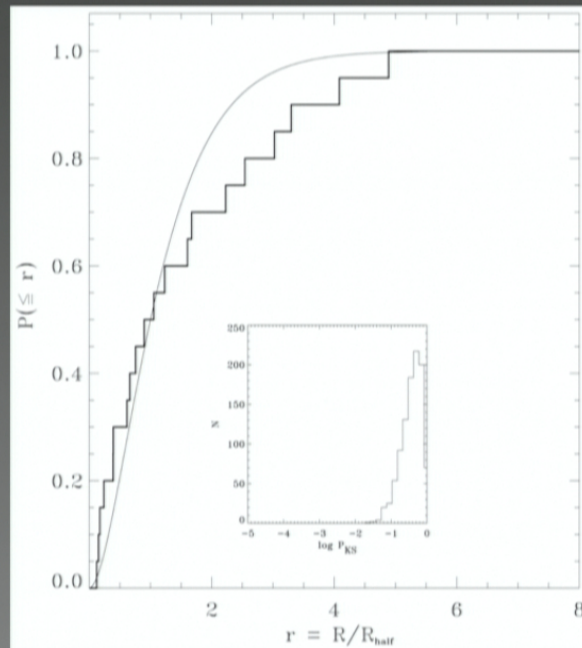
2. Offsets trace star formation in an exponential disk



Bloom et al. 2002

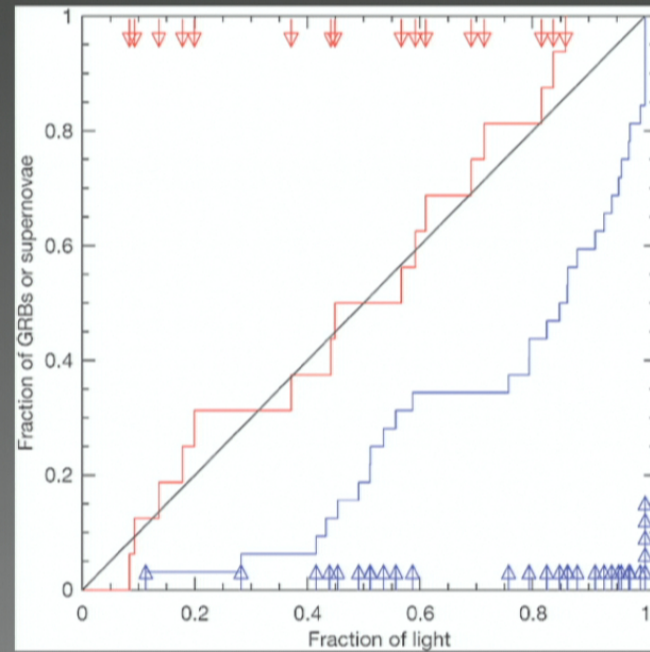
Long GRBs: The Death of Massive Stars

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Bloom et al. 2002

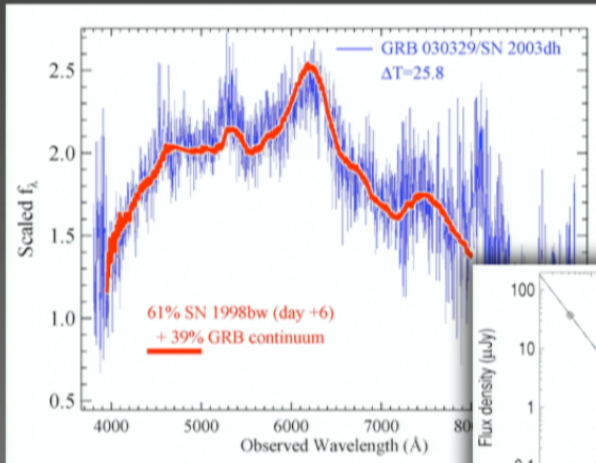
3. Coincident with the brightest UV regions of their hosts



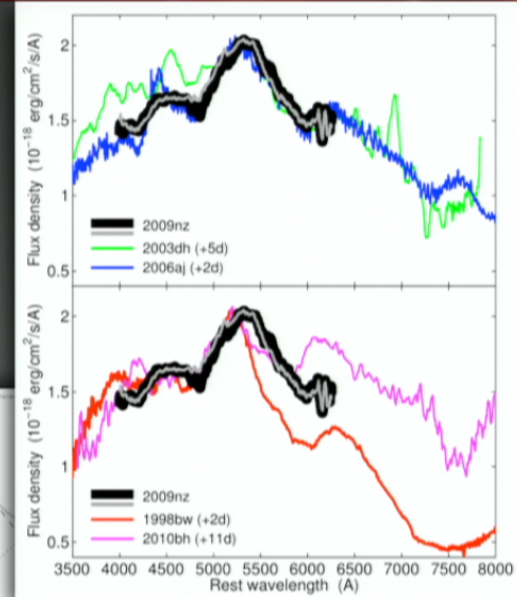
Fruchter et al. 2006

Long GRBs: The Death of Massive Stars

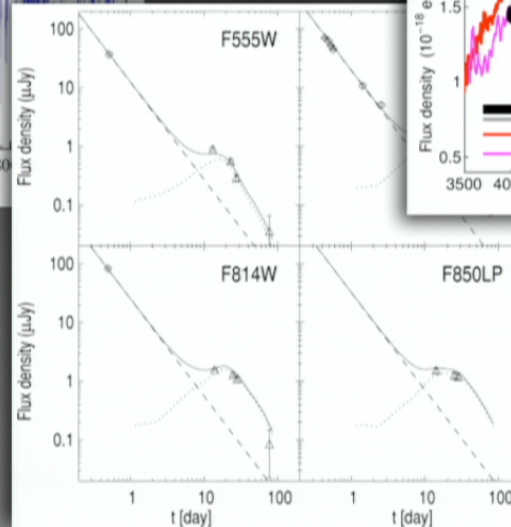
4. Supernova associations



Hjorth et al. 2003;
Matheson et al. 2003

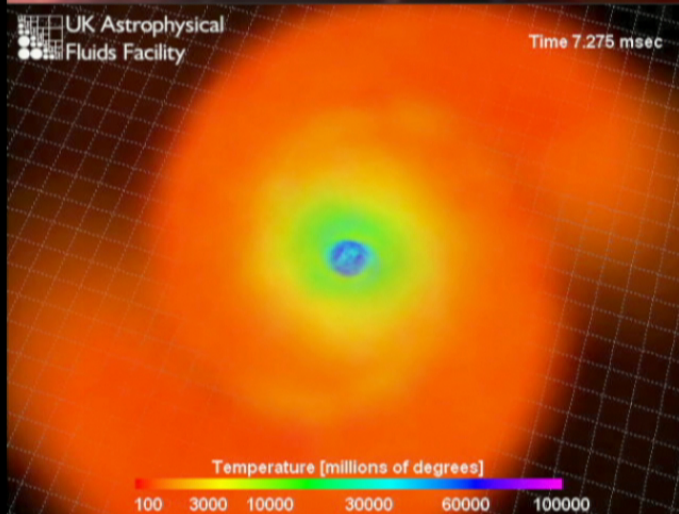


Berger et al. 2011



Bloom et al. 2002

Short GRB Progenitor Models

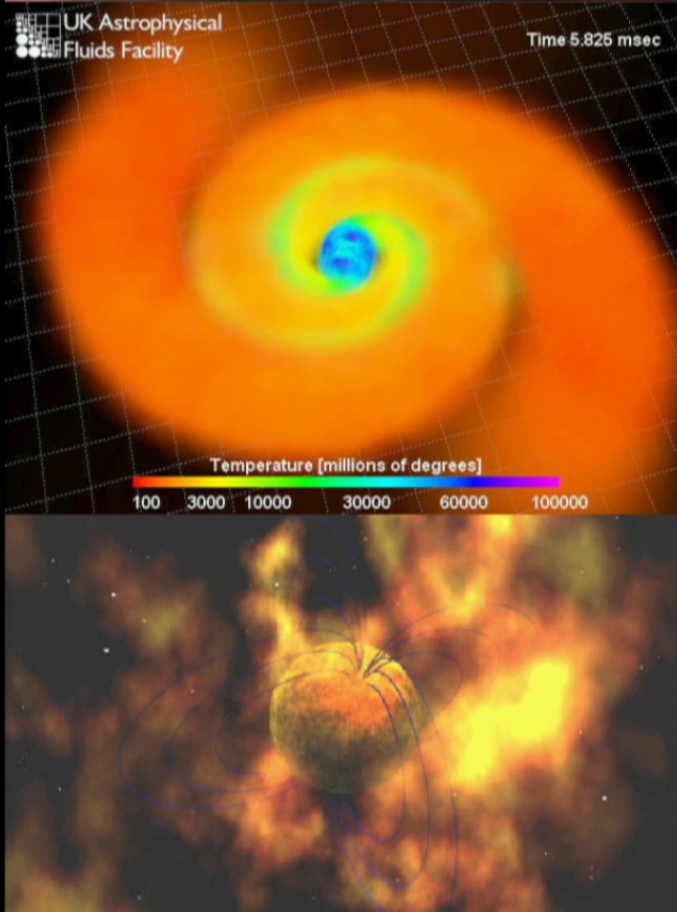


NS-NS / NS-BH

Eichler et al. 1989;
Narayan et al. 1992

- No supernova association
- Broad delay-time distribution
- Diverse environments / redshifts
- “Kicks” $\Rightarrow$ offsets, low density
- r -process nucleosynthesis
- Gravitational waves

Short GRB Progenitor Models



NS-NS / NS-BH

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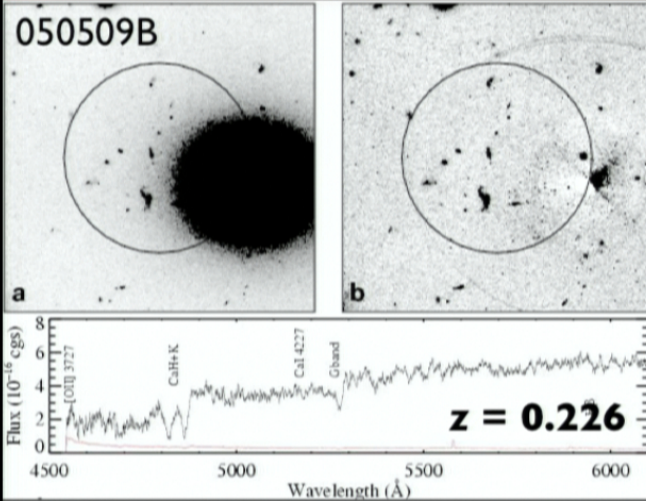
- No supernova association
- Broad delay-time distribution
- Diverse environments / redshifts
- “Kicks” $\Rightarrow$ offsets, low density
- r -process nucleosynthesis
- Gravitational waves

Magnetar Giant Flares

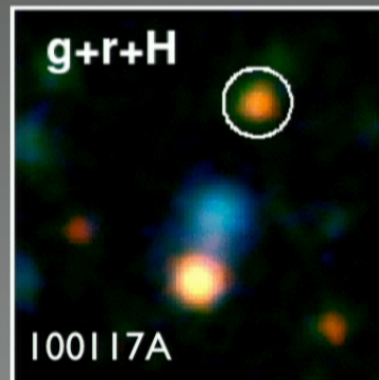
- Young systems
- Star forming galaxies
- Nearby?
- Small offsets

Usov 1992; Thompson
& Duncan 1995

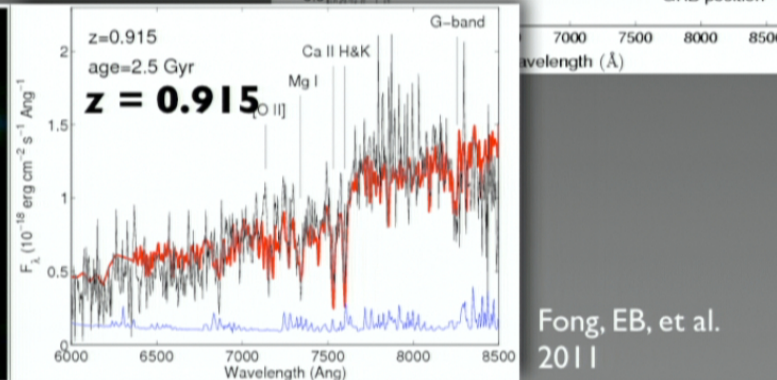
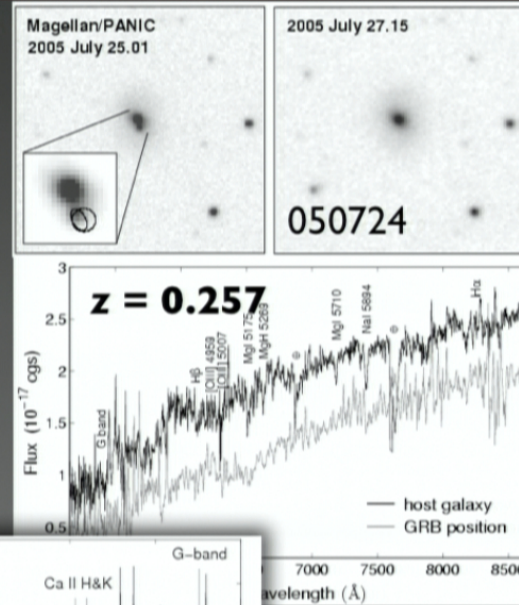
Short GRBs in Elliptical Galaxies



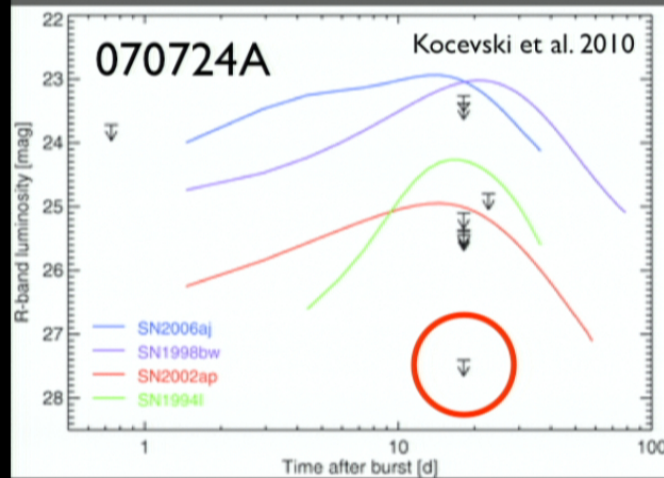
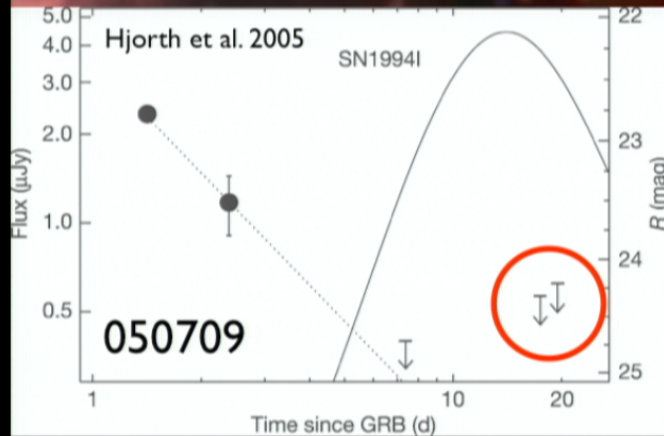
Castro-Tirado et al. 2005; Gehrels et al. 2005; Hjorth et al. 2005; Bloom et al. 2006; Prochaska et al. 2006



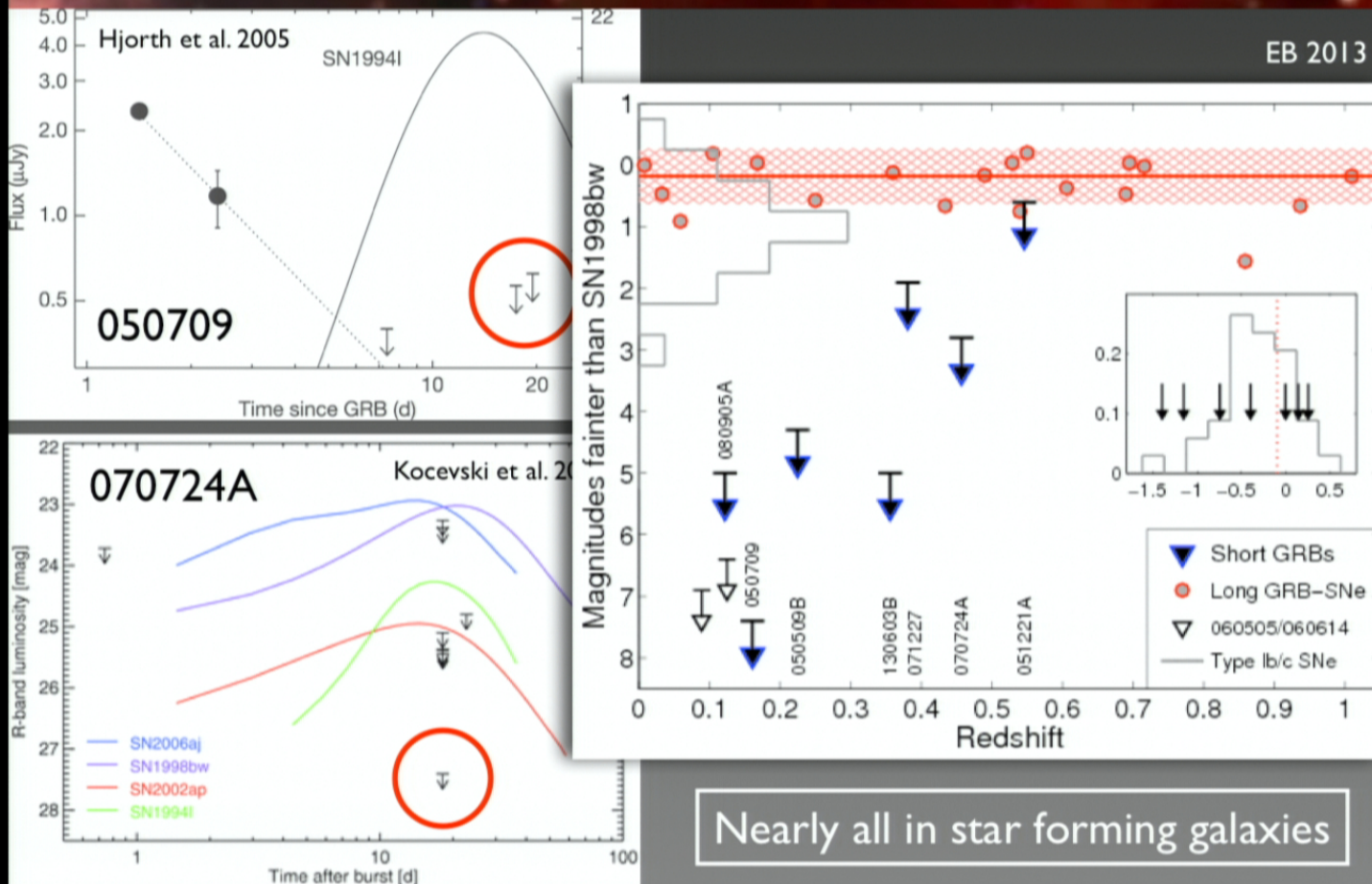
EB et al. 2005



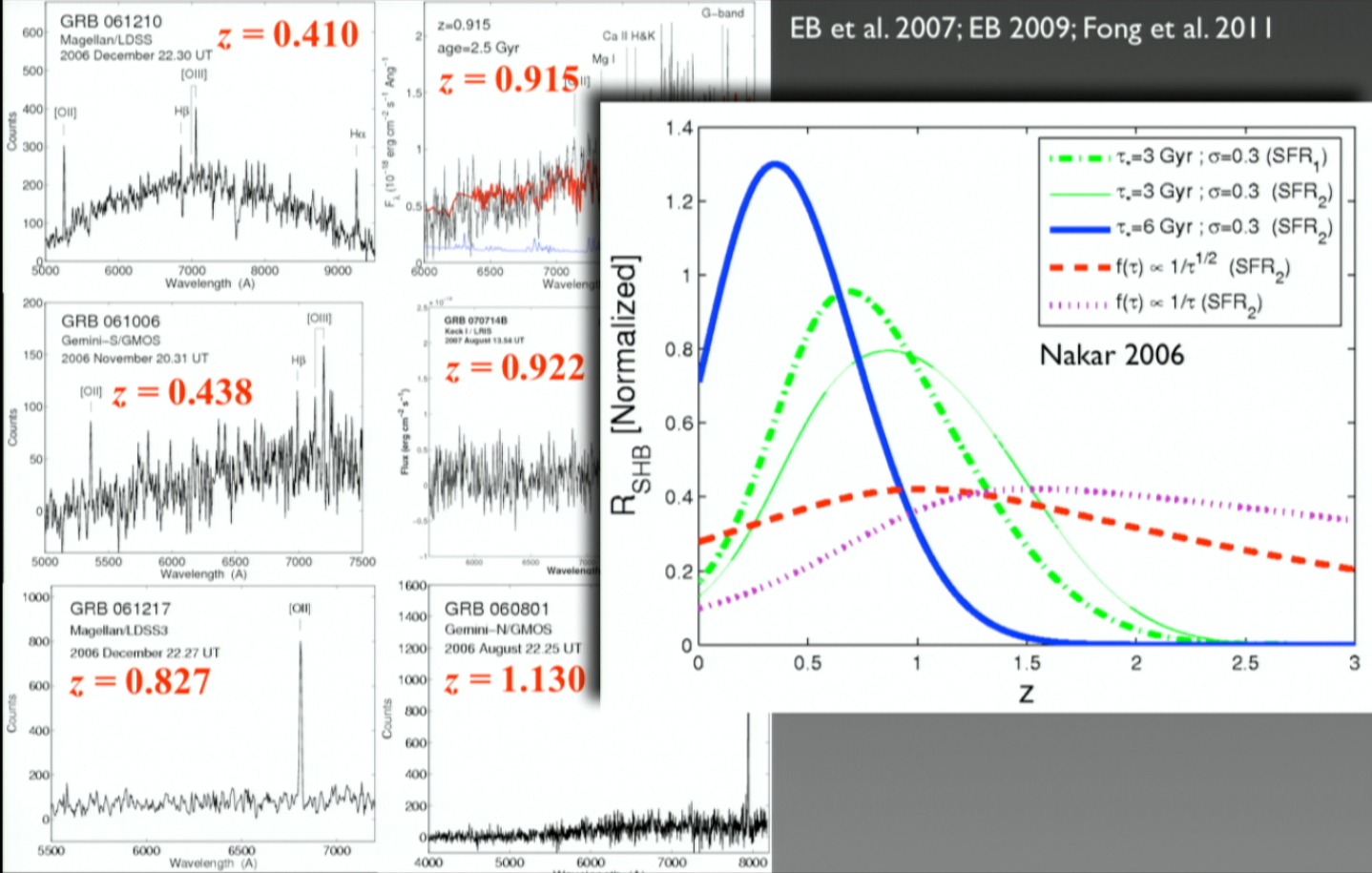
Short GRBs Lacking SN Associations



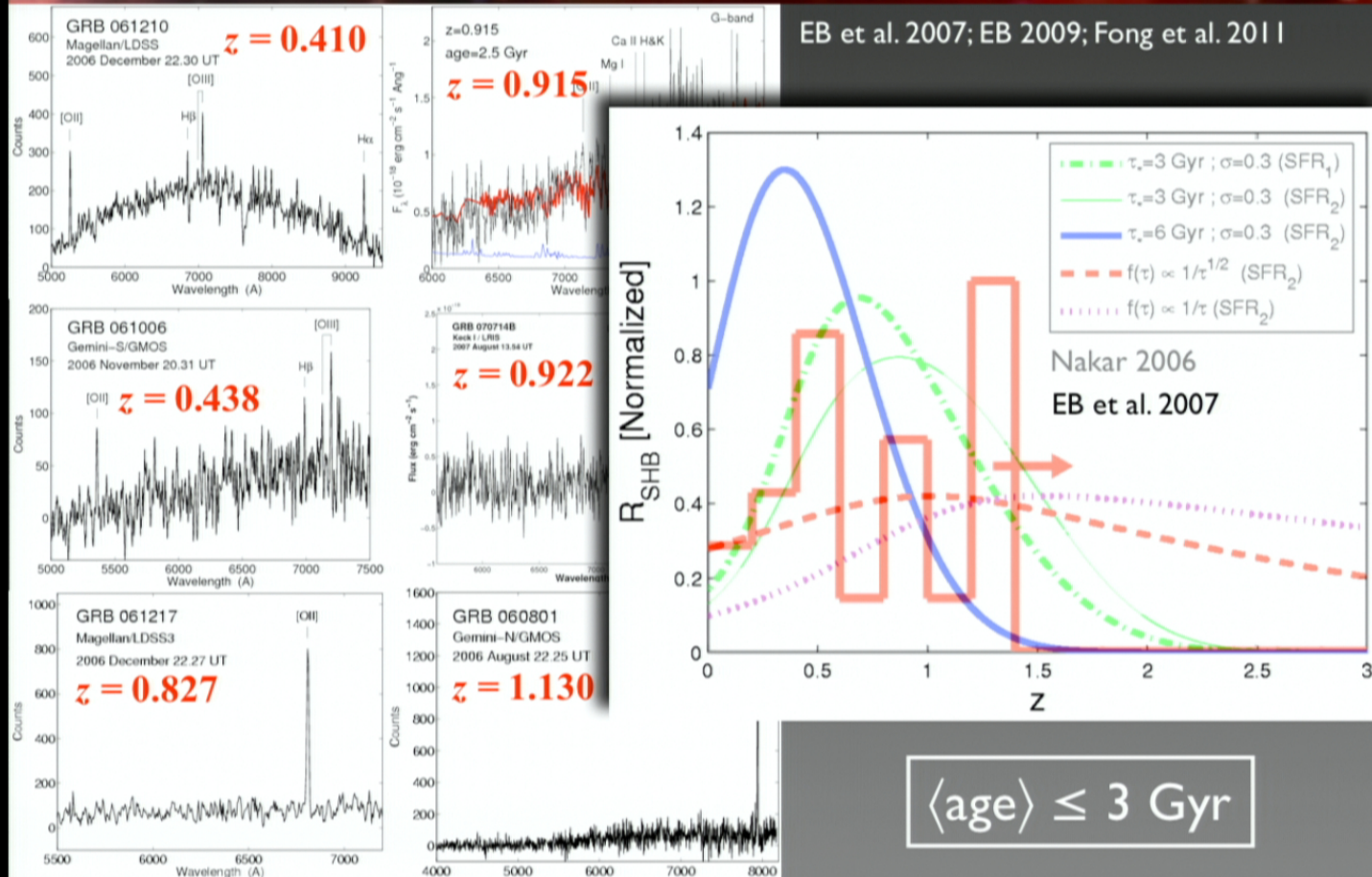
Short GRBs Lacking SN Associations



Redshifts



Redshifts



Host Galaxy Demographics

Progenitors that track star formation should be in star-forming only; those that track only stellar mass should be 1:1 in star-forming and ellipticals

Fong, EB, et al. 2013

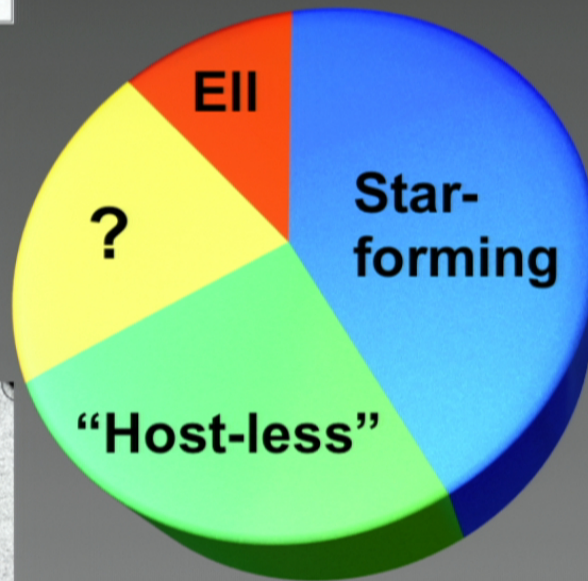
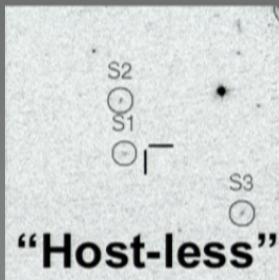
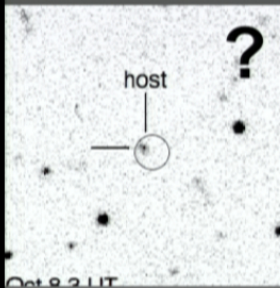
Host Galaxy Demographics

2005 July 27.15

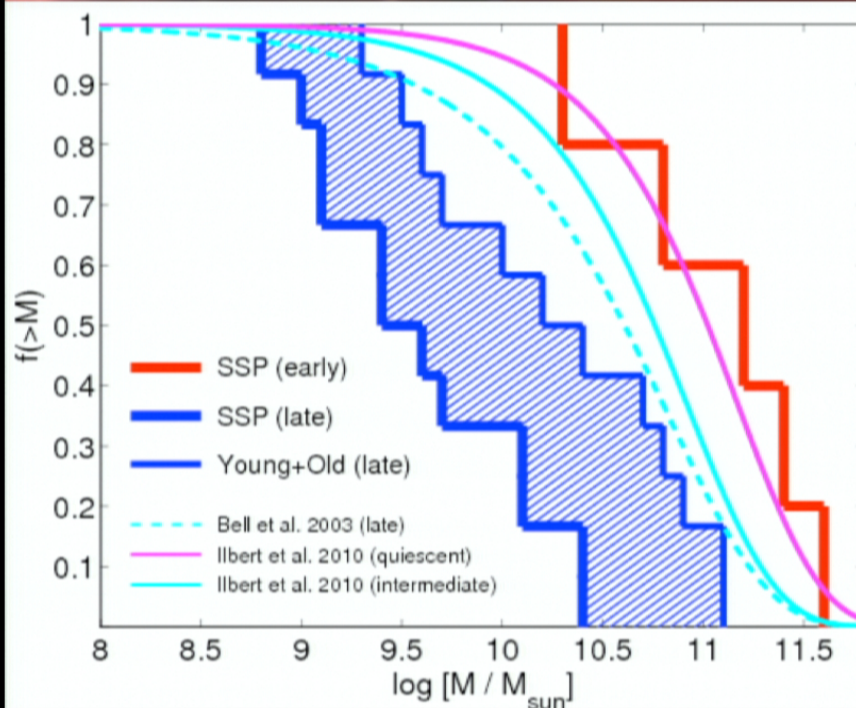
EII

Progenitors that track star formation should be in star-forming only; those that track only stellar mass should be 1:1 in star-forming and ellipticals

Fong, EB, et al. 2013



Stellar Masses & Rates



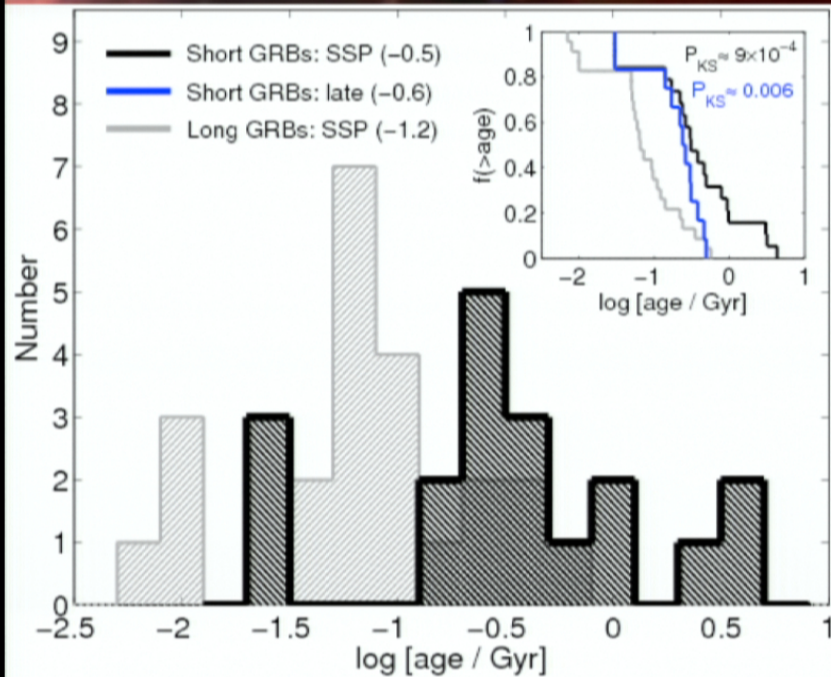
Leibler & EB 2010

$$R_{SF} \sim 3 \times R_{El}$$

per unit stellar mass

Elliptical hosts track stellar mass, but star-forming hosts have lower masses than expected $\Rightarrow$ star formation plays a role

Stellar Population Ages & Delay Times



Leibler & EB 2010

$$\tau_{short,SF} \sim 0.3 \text{ Gyr}$$

$$\tau_{short,El} \sim 3 \text{ Gyr}$$

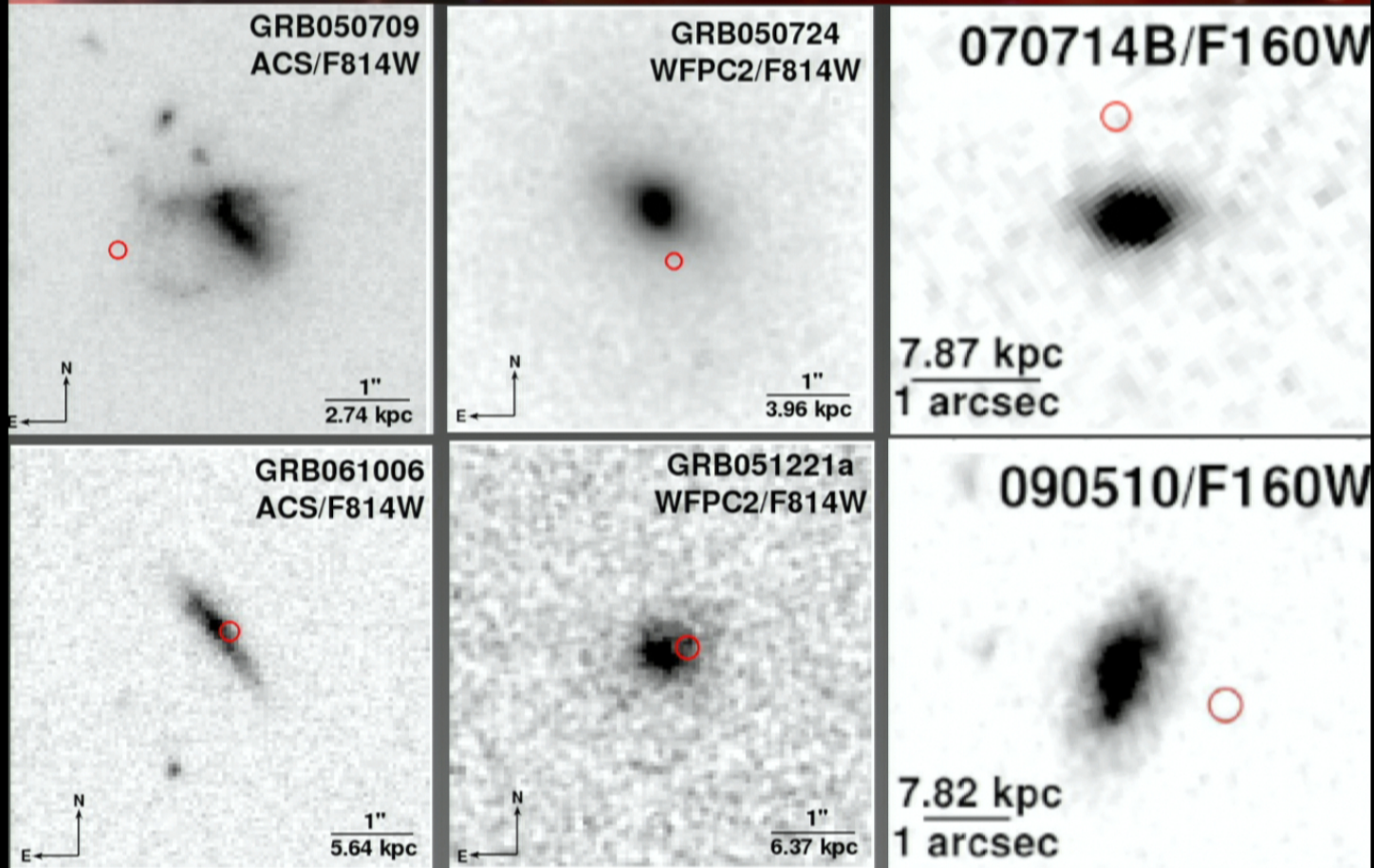
consistent with $P(\tau) \propto \tau^{-1}$

Stellar population ages are a proxy for the delay-time distribution
 $\Rightarrow$ progenitors span ages of ~ 0.1 –5 Gyr, with peak at ~ 0.3 Gyr

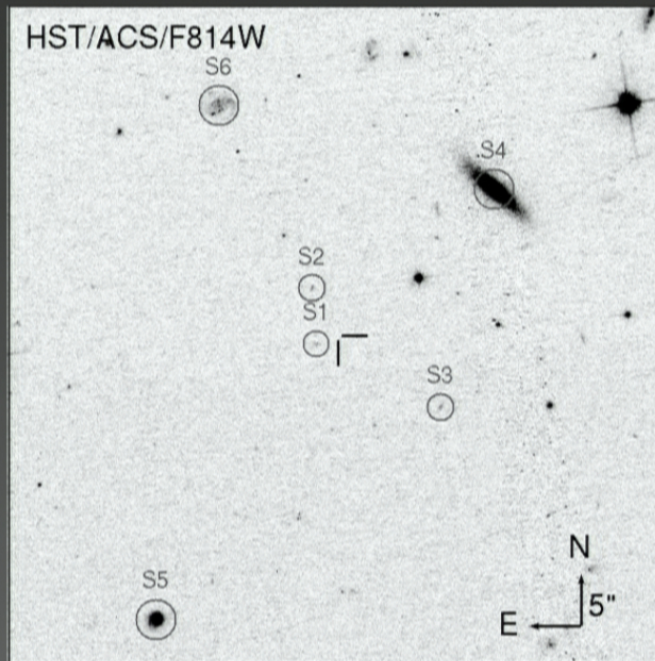
Intermediate Conclusions

- Short GRBs in ellipticals and lack of SN associations
⇒ *progenitors are not massive stars*
- The star-forming hosts of short GRBs are distinct from those of long GRBs ⇒ *progenitors are not massive stars*
- Host demographics, stellar masses, stellar population ages
⇒ *the rate depends on mass and star formation ($\sim \tau^{-1}$)*

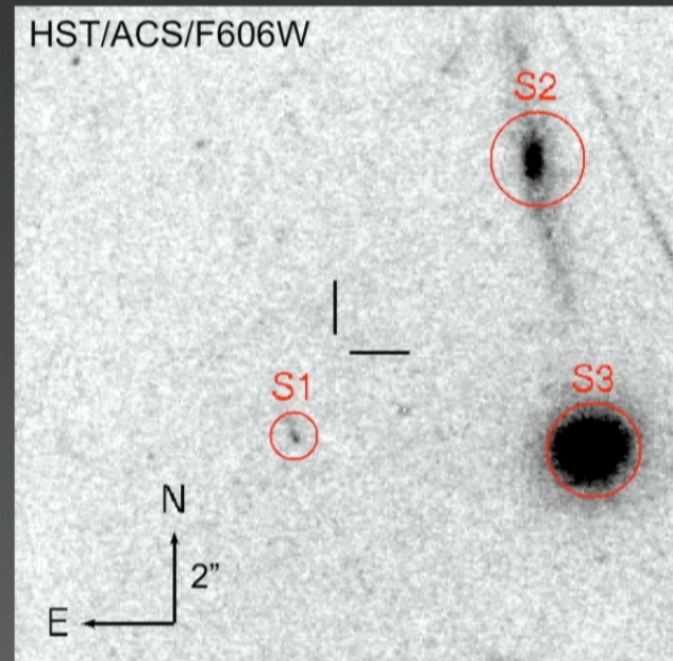
Locations within / around Host Galaxies



Offsets: “Host-less” Bursts

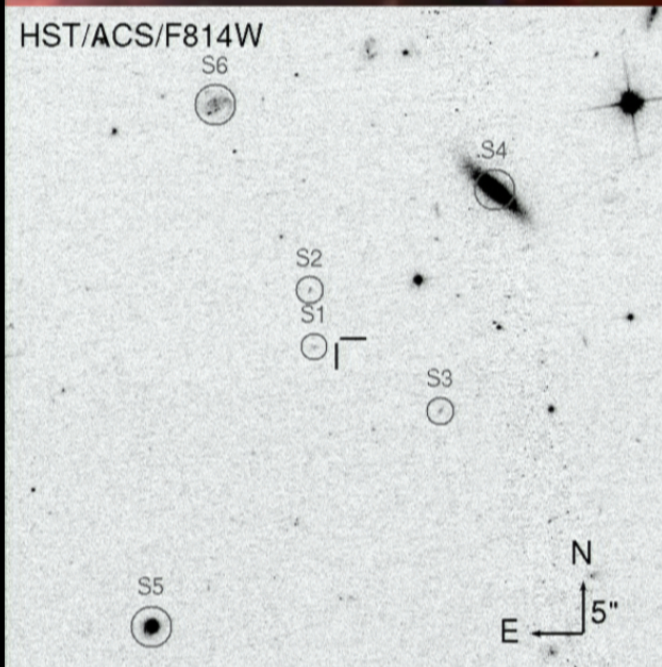


EB 2010



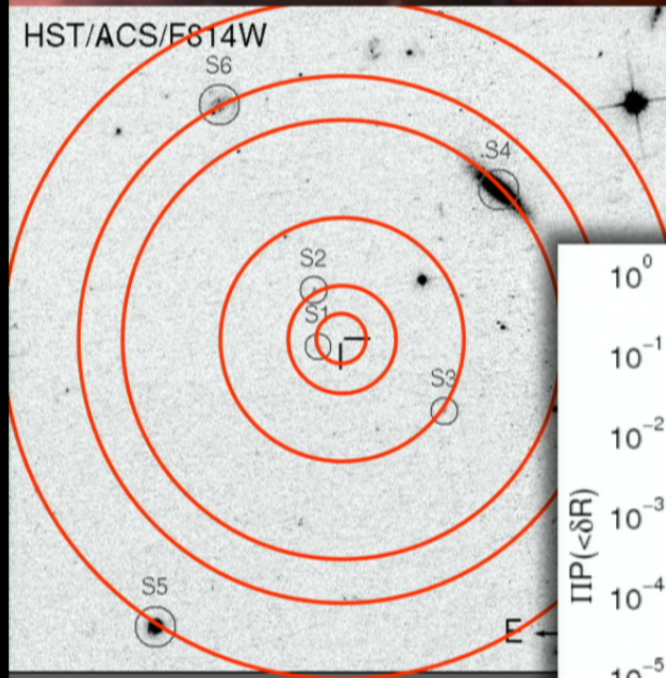
~20% of short GRBs with optical afterglows have no coincident hosts to $>27^{\text{th}}$ mag in optical/NIR.

Locations in & around Host Galaxies



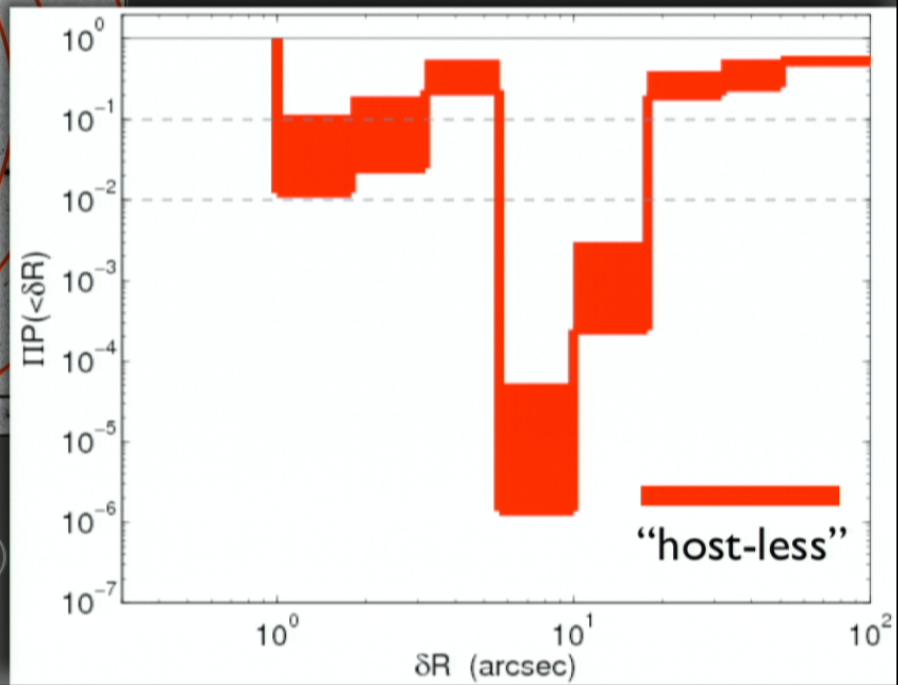
EB 2010

Locations in & around Host Galaxies

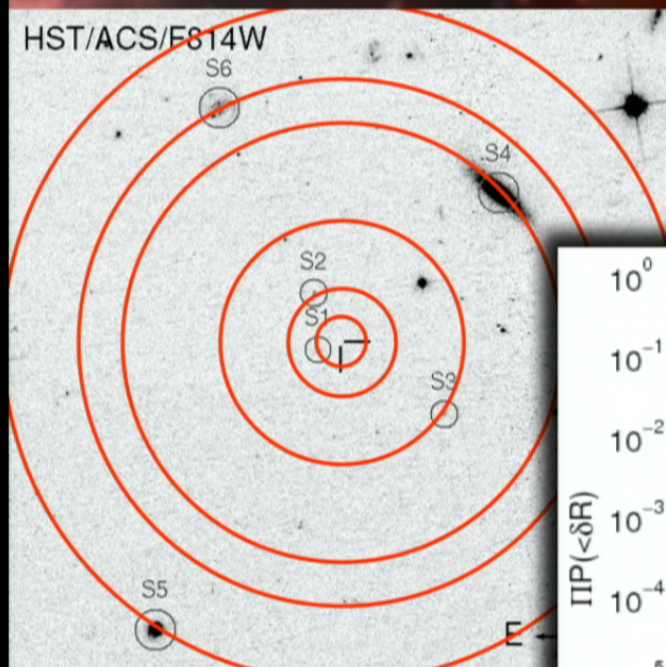


EB 2010

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

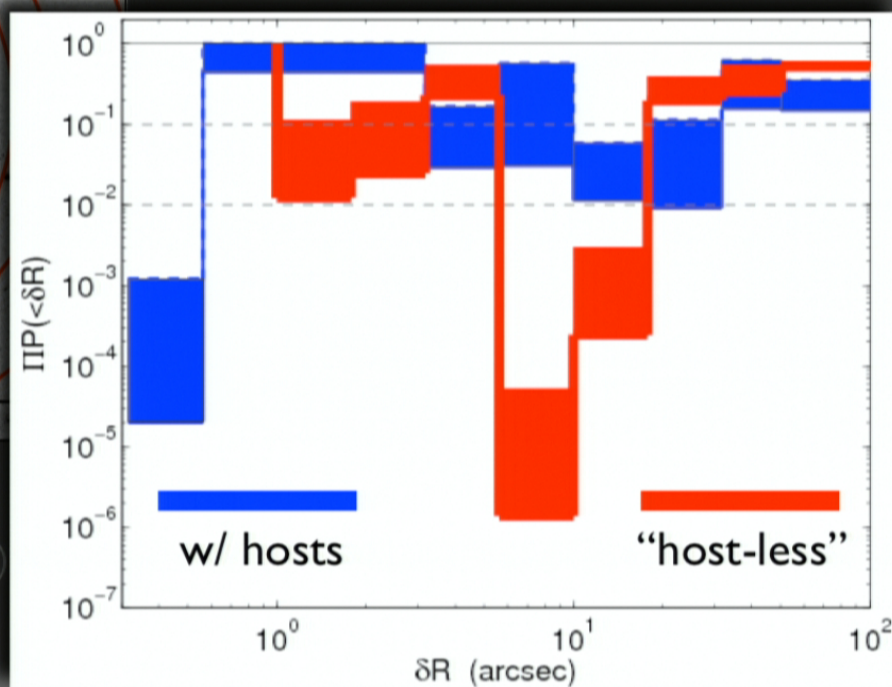


Locations in & around Host Galaxies

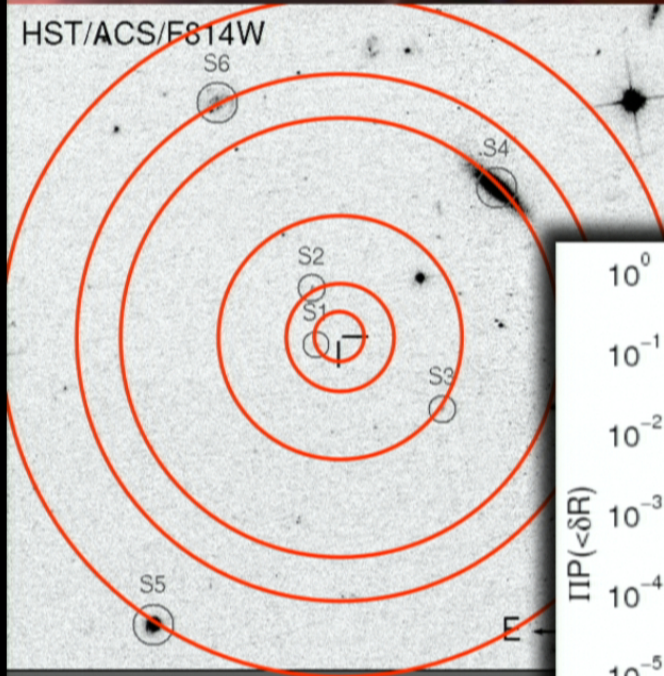


EB 2010

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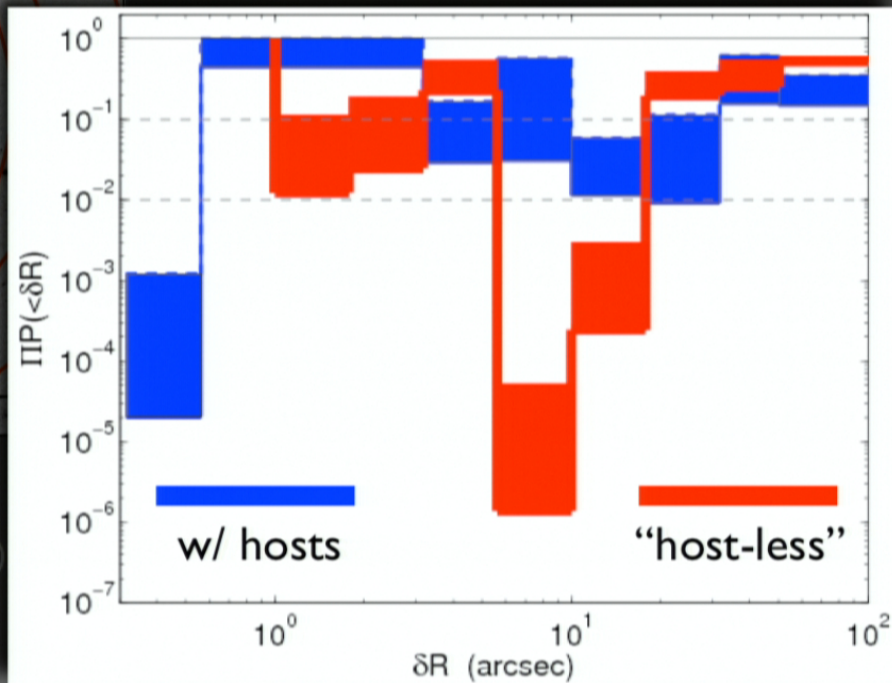
Locations in & around Host Galaxies



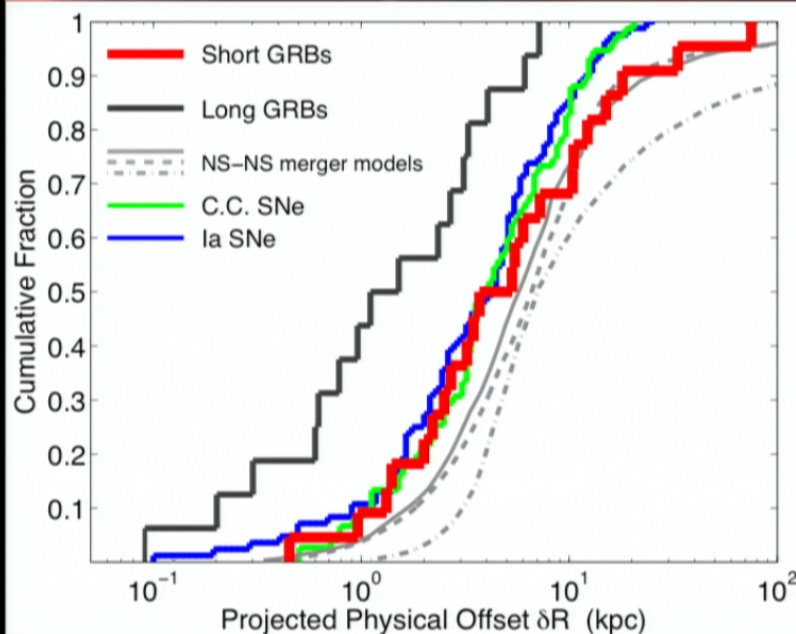
EB 2010

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

$z \sim 0.1-0.5 \Rightarrow \sim 10'' = 50-100 \text{ kpc}$



Locations in & around Host Galaxies

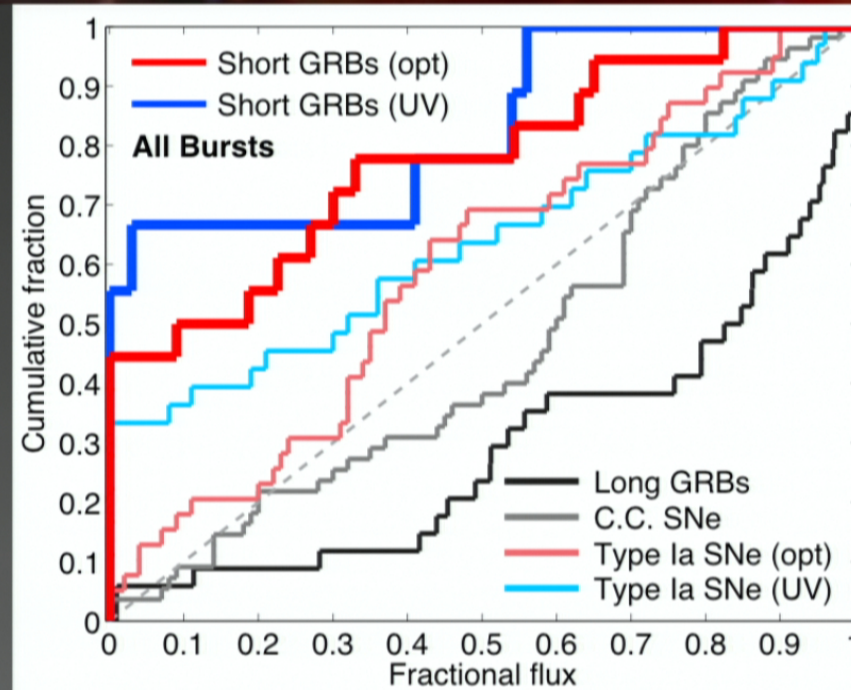


Fong et al. 2010; EB 2010; Fong & EB 2013

Short GRB offsets are $\sim 5\times$
larger than for long GRBs

good agreement with
NS-NS/NS-BH
population synthesis

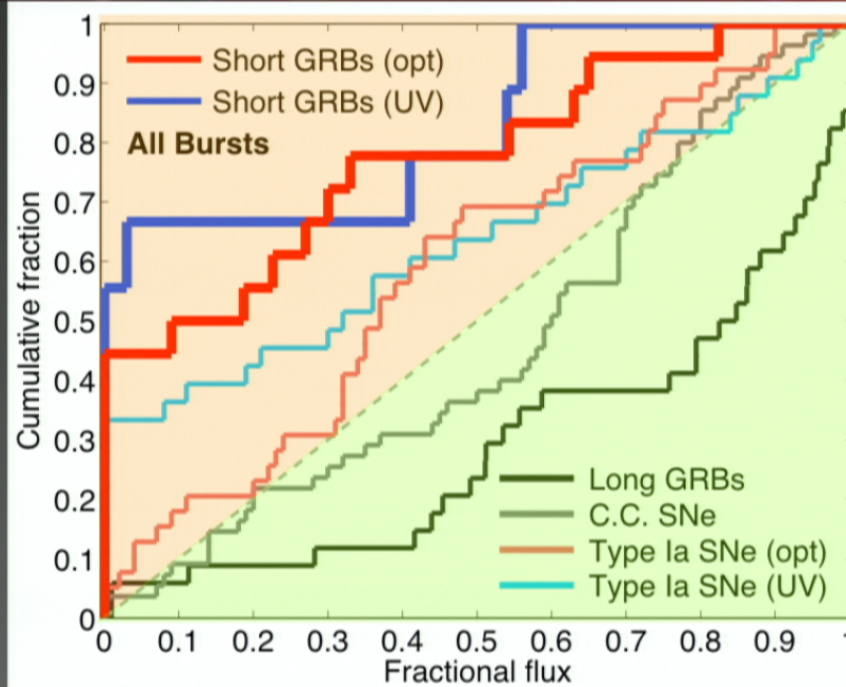
Locations in & around Host Galaxies



Fong & EB 2013

Locations in & around Host Galaxies

Weakly
correlated

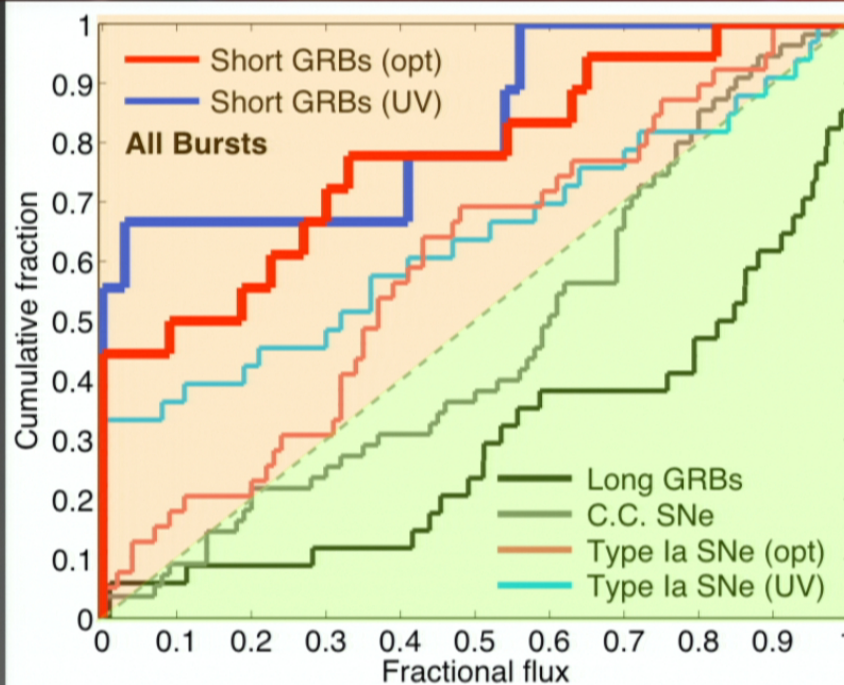
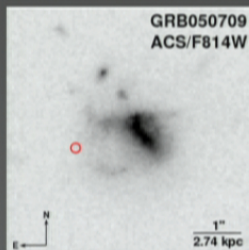
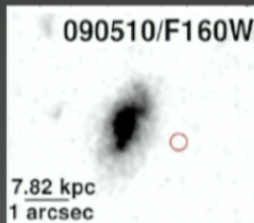


Fong & EB 2013

Strongly
correlated

Locations in & around Host Galaxies

*Weakly
correlated*

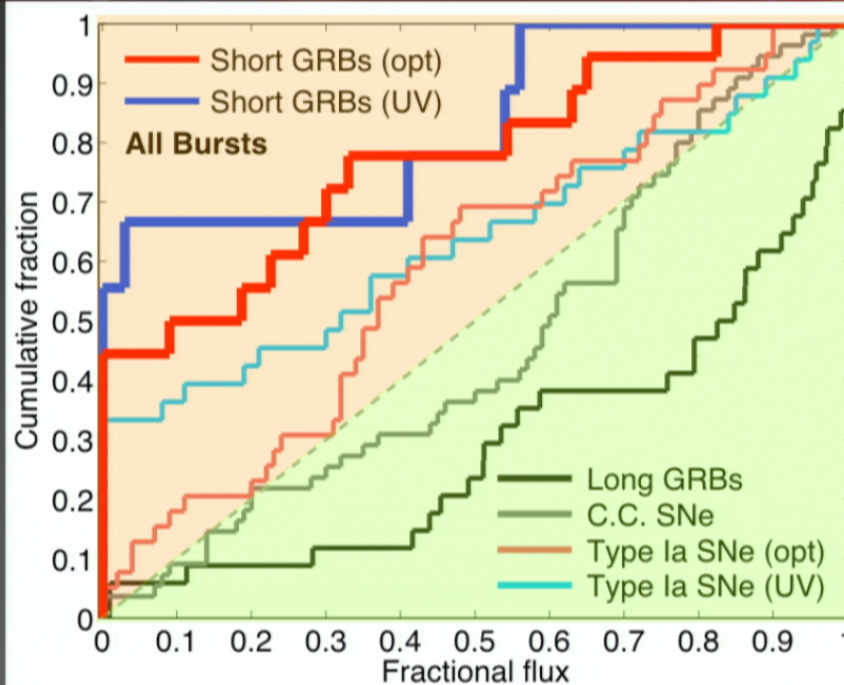
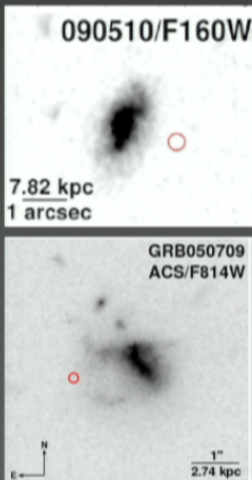


Fong & EB 2013

*Strongly
correlated*

Locations in & around Host Galaxies

*Weakly
correlated*

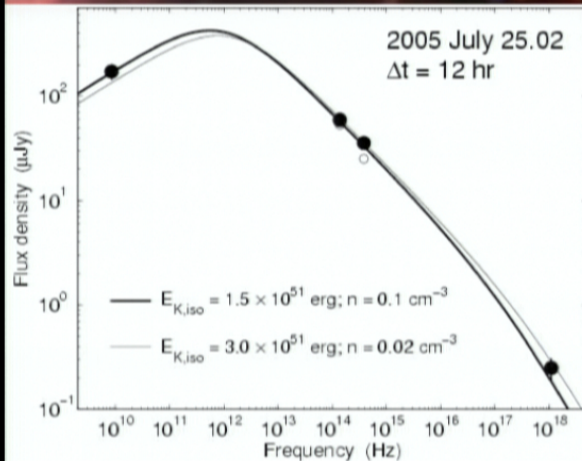


Fong & EB 2013

*Strongly
correlated*

Short GRB locations are de-correlated from stellar mass or star formation; progenitors migrate from birth to explosion sites.

Afterglows



$$\theta_j > 20 \text{ deg}$$

$$E_{Y,iso} \approx 4 \times 10^{50} \text{ erg } (> 4 \times 10^{49} \text{ erg})$$

$$E_{K,iso} \approx 2 \times 10^{51} \text{ erg } (> 2 \times 10^{50} \text{ erg})$$

$$n \approx 0.02 - 0.1 \text{ cm}^{-3}$$

Afterglow physics similar to long GRBs
lower energy and density

EB et al. 2005

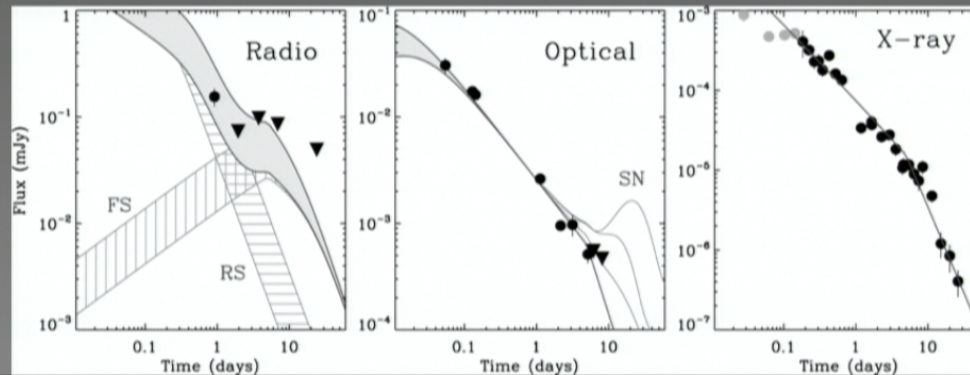
$$\theta_j \approx 7 \text{ deg}$$

$$E_Y \approx 1.5 \times 10^{49} \text{ erg}$$

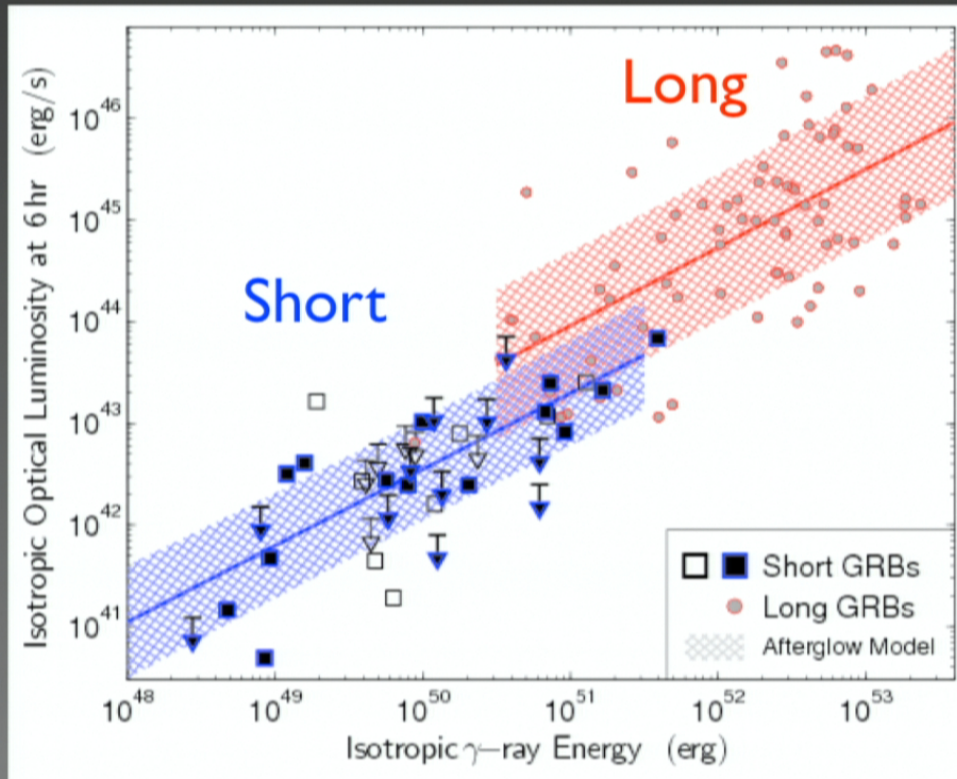
$$E_K \approx 0.8 \times 10^{49} \text{ erg}$$

$$n \approx 2 \times 10^{-3} \text{ cm}^{-3}$$

Soderberg, et al. 2006



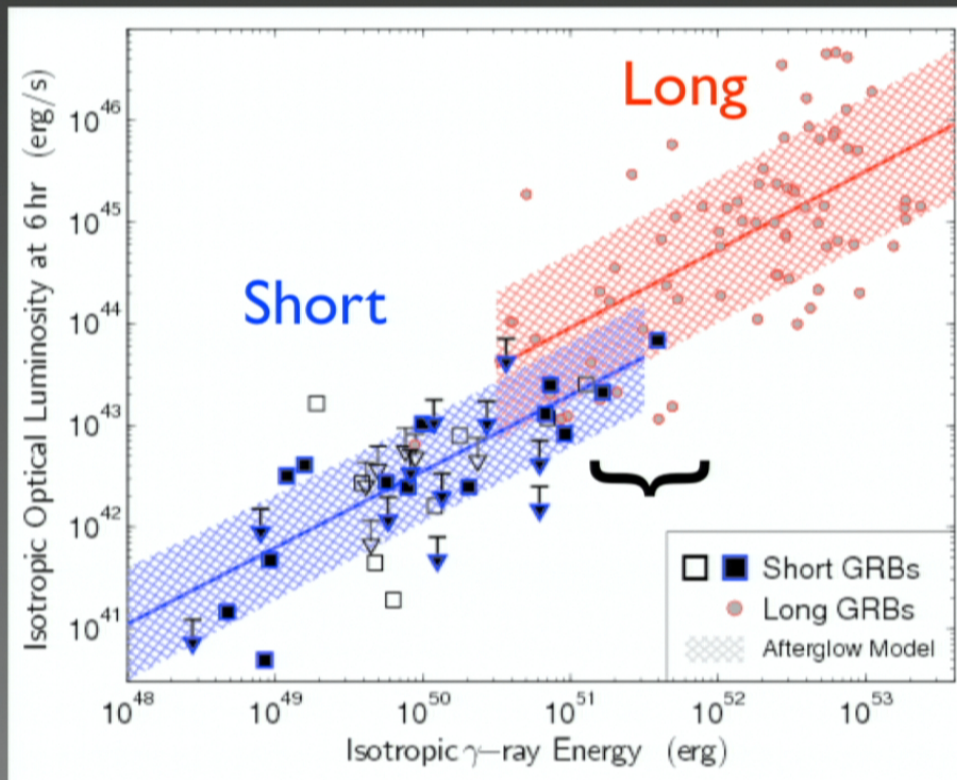
Afterglows



$$L_{\nu, \text{opt}} \propto n^{1/2} E_{\text{K, iso}}^{4/3}$$

Fong, EB, et al. in prep.

Afterglows

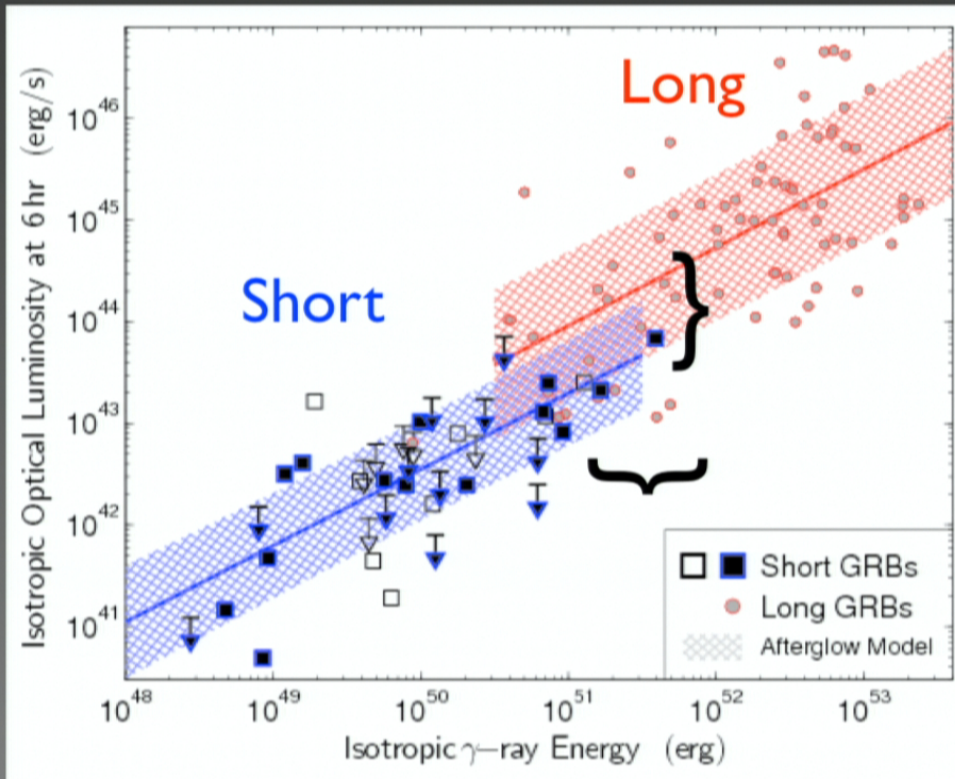


$$L_{\nu, \text{opt}} \propto n^{1/2} E_{K, \text{iso}}^{4/3}$$

Lower energy
scale

Fong, EB, et al. in prep.

Afterglows



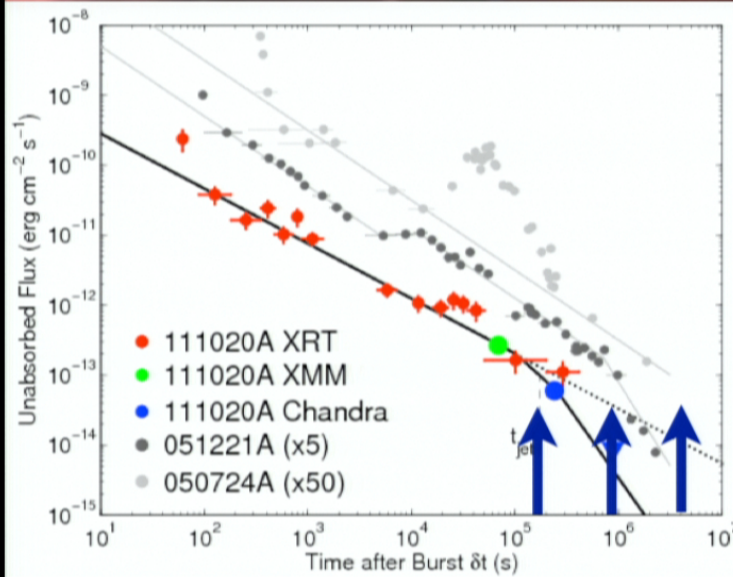
$$L_{\nu, \text{opt}} \propto n^{1/2} E_{\text{K, iso}}^{4/3}$$

Lower energy
scale

Lower density
scale

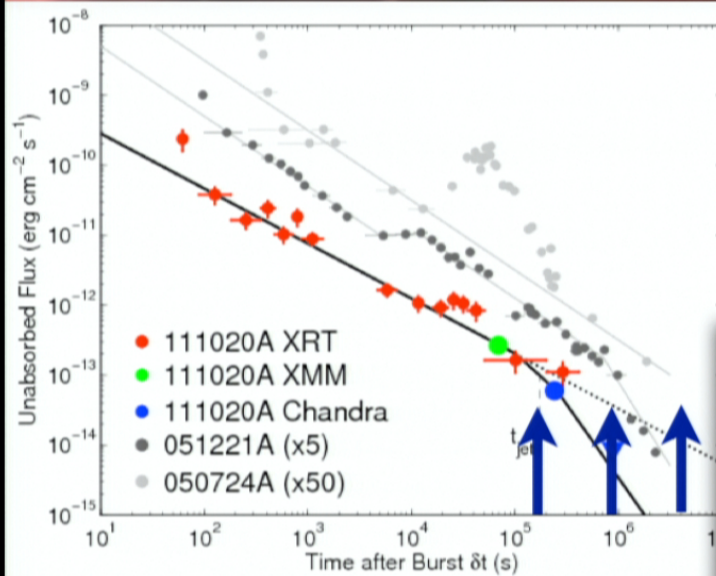
Fong, EB, et al. in prep.

Jets: Energetics & Rates

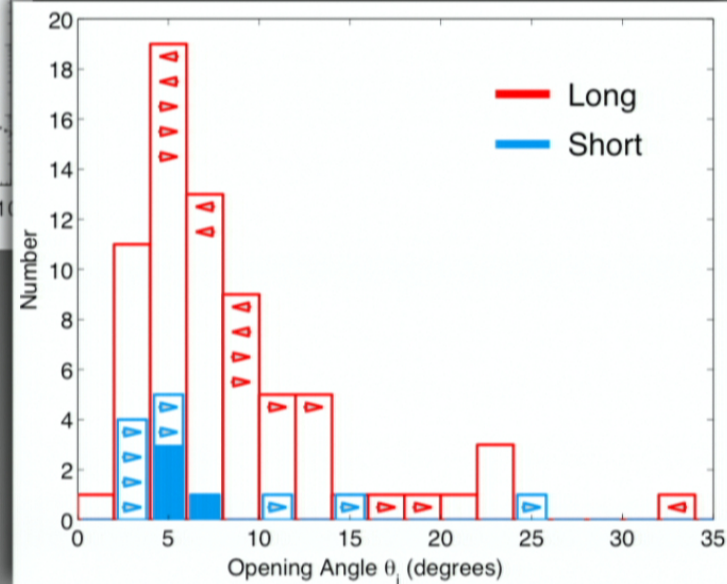


Fong, EB, et al. 2012

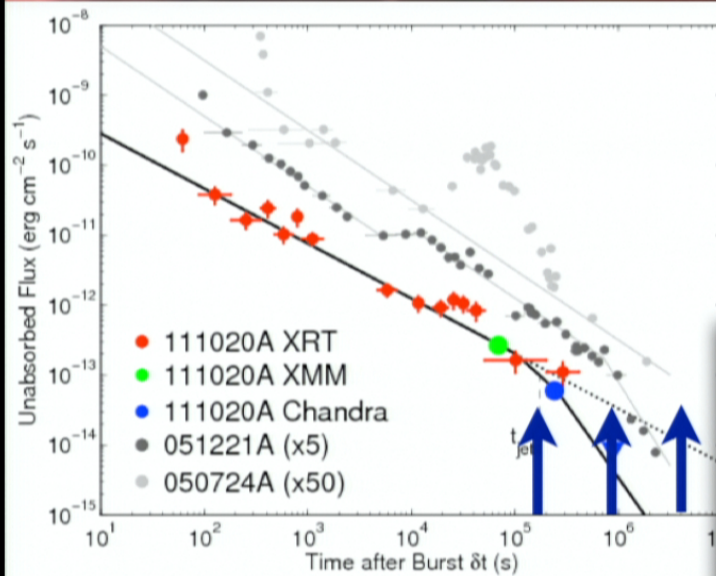
Jets: Energetics & Rates



Fong, EB, et al. 2012



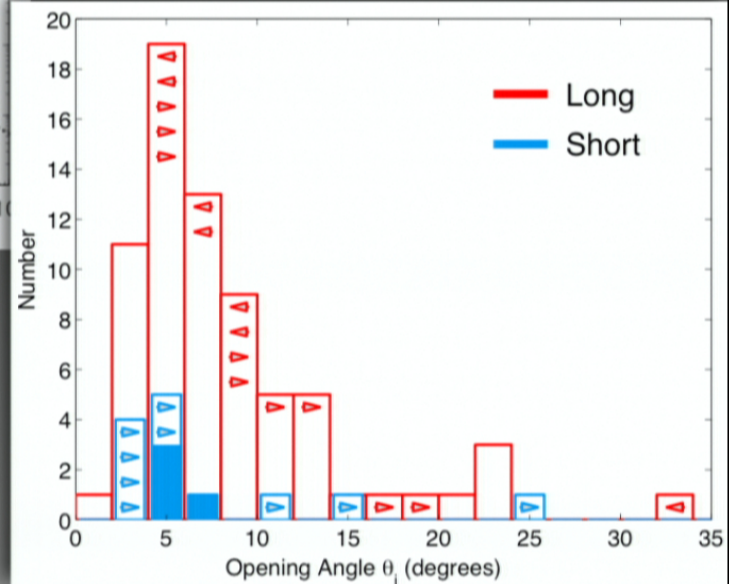
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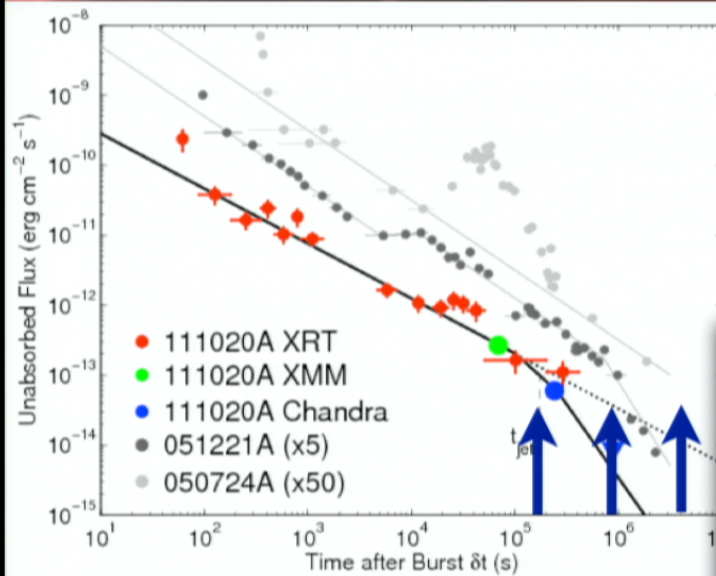
Fong, EB, et al. 2012

$$\theta_j \sim 10^\circ$$

$$E_Y \sim E_K \sim 10^{49} \text{ erg}$$



Jets: Energetics & Rates



Fong, EB, et al. 2012

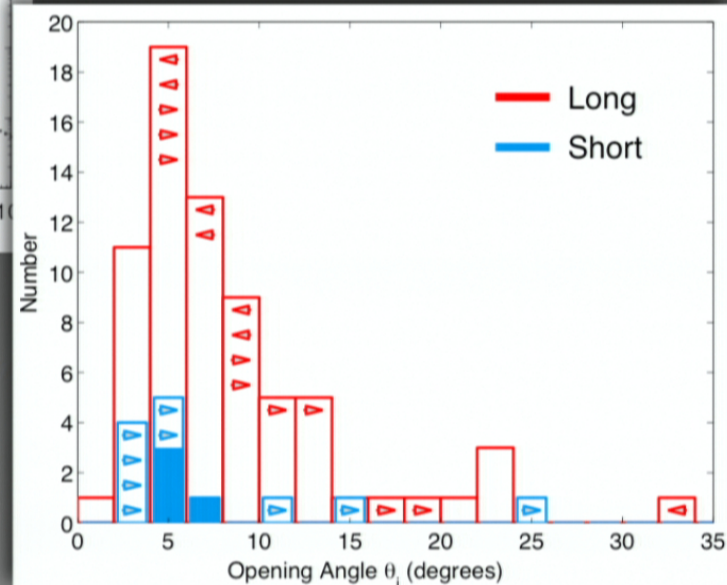
$\mathcal{R} > 10 \text{ Gpc}^{-3} \text{ yr}^{-1}$ Nakar et al. 2007

$f_b \sim 30-100$ Fong et al. 2012

$\mathcal{R} \sim 20 \text{ yr}^{-1}$ (ALIGO range)

$$\theta_j \sim 10^\circ$$

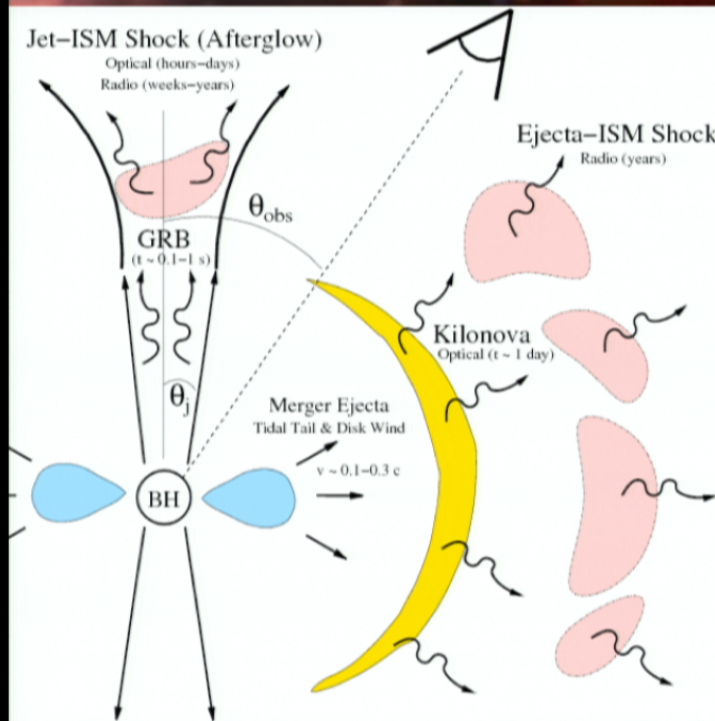
$$E_\gamma \sim E_K \sim 10^{49} \text{ erg}$$



Joint GW/EM Detections

- Distance (energy scale)
- Astrophysical context (NS/BH formation; binary formation)
- Nature of compact remnant
- Behavior of matter (jet formation, hydrodynamics)

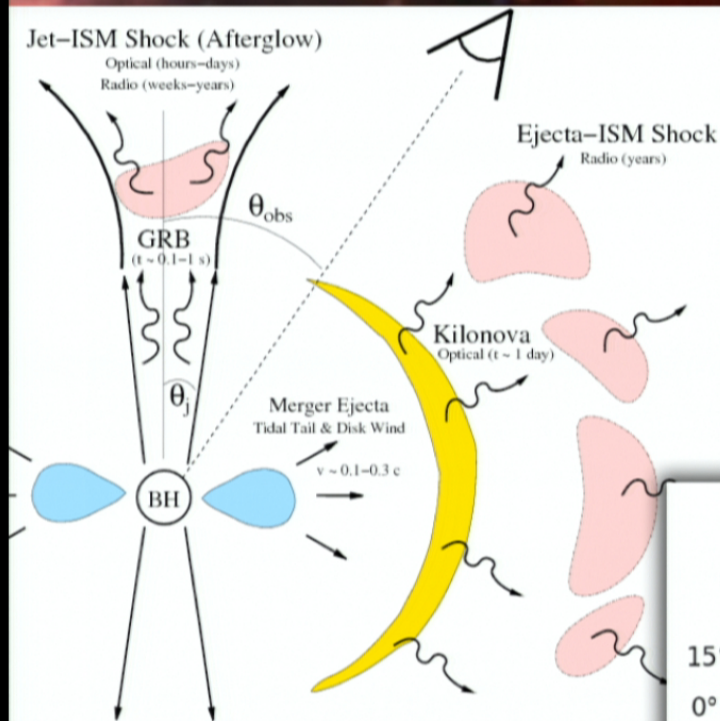
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Metzger & EB 2012

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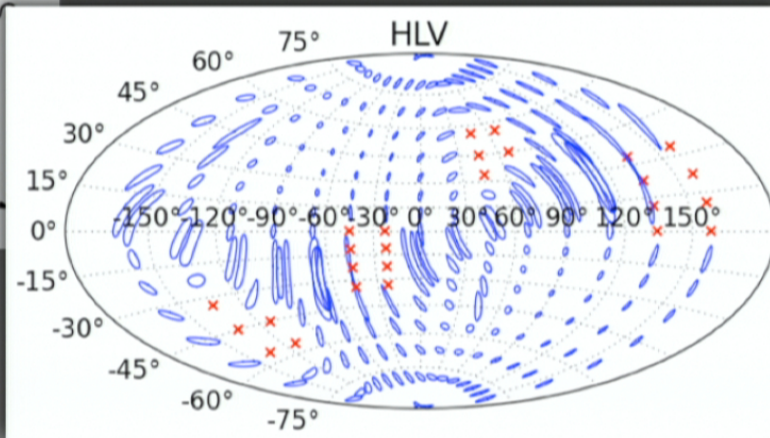
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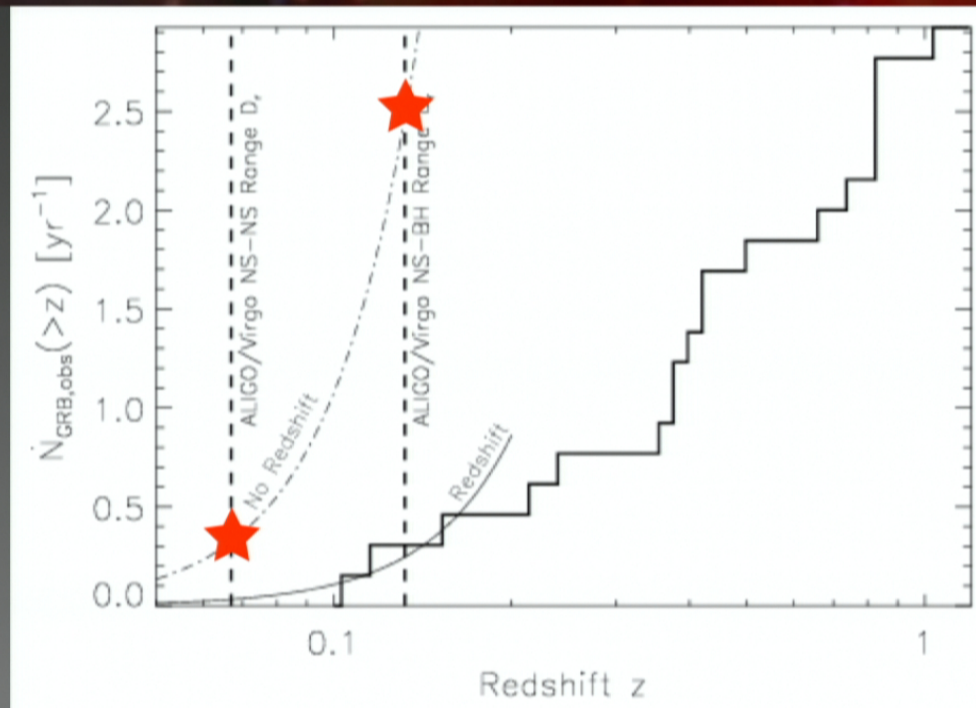
Metzger & EB 2012

Typical GW localization $\sim 100 \text{ deg}^2$

- Distance (energy scale)
- Astrophysical context (NS/BH formation; binary formation)
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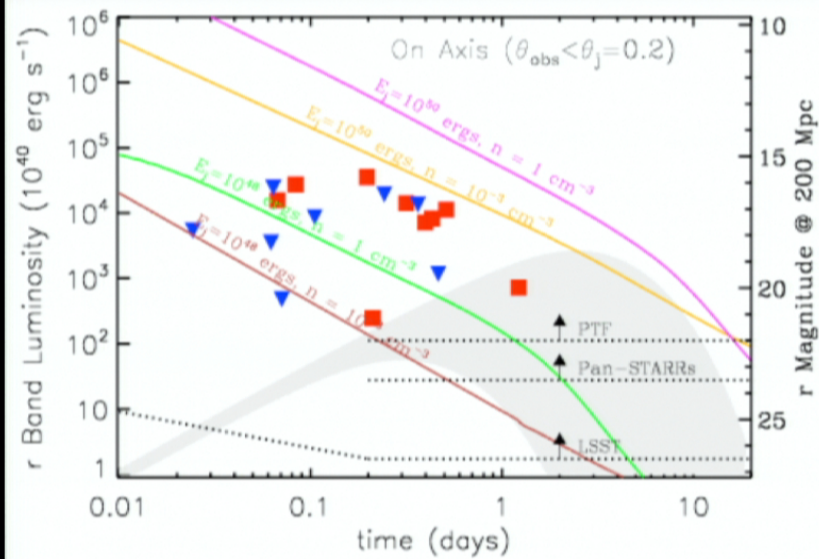
γ -rays



Metzger &
EB 2012

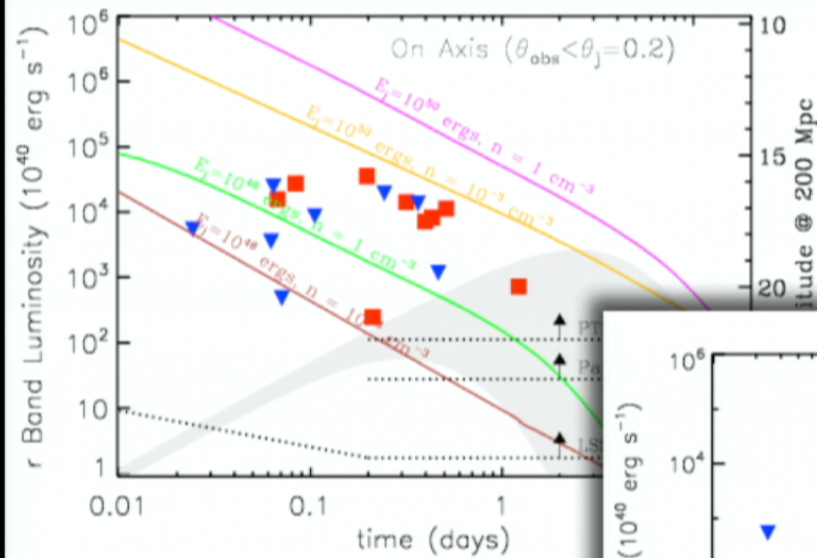
The short GRB rate in the ALIGO volume is low; all-sky coverage is more important than accurate positions (*temporal coincidence*)

Optical Afterglows: On- & Off-Axis



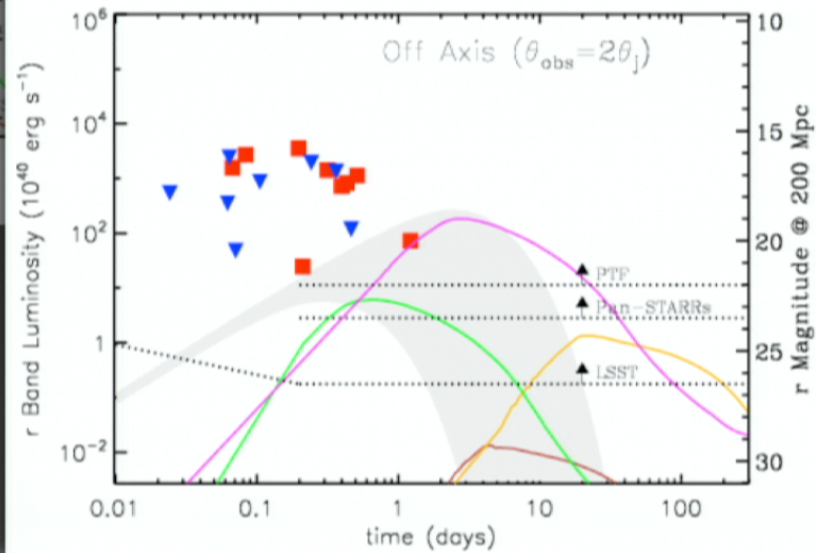
Metzger & EB 2012

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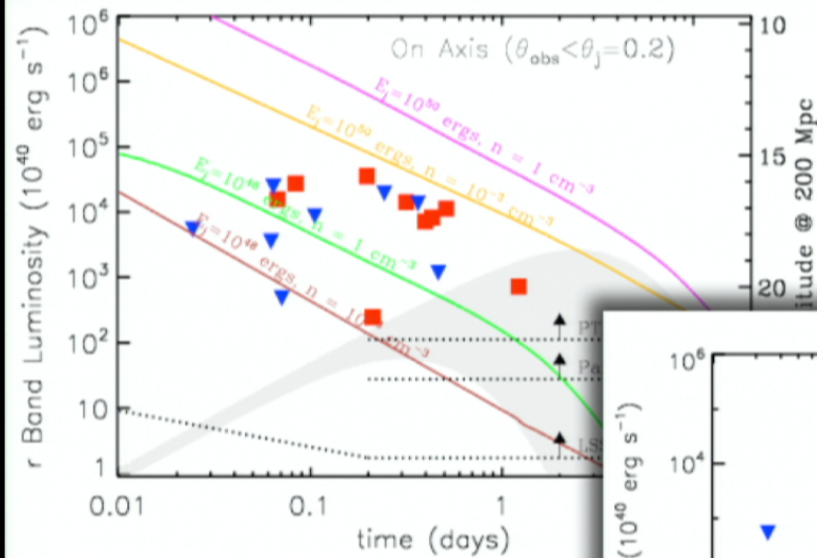


Metzger & EB 2012

$$f_{\text{opt}} \approx 7 \bar{\theta}_j^2 \approx 0.1$$

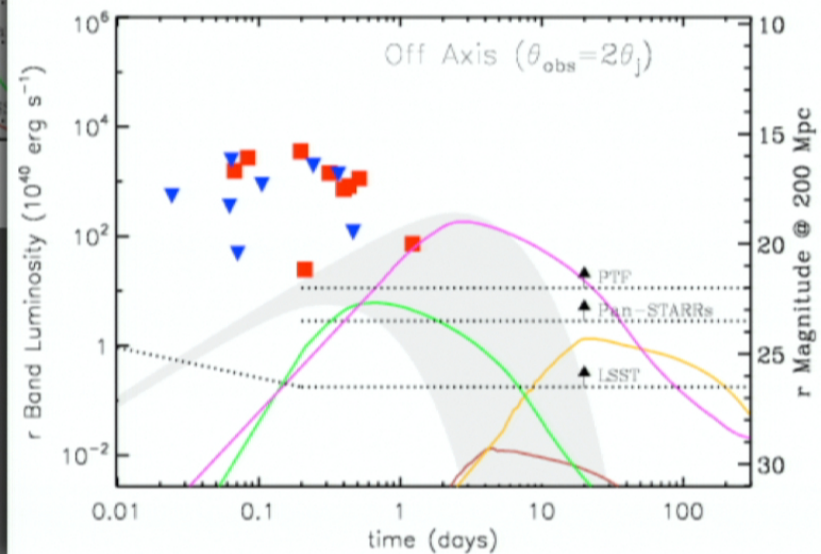


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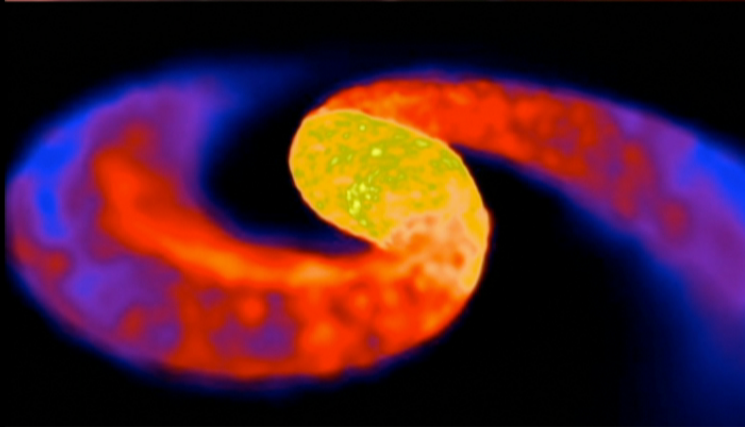


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“Kilonovae”



neutron-rich ejecta:

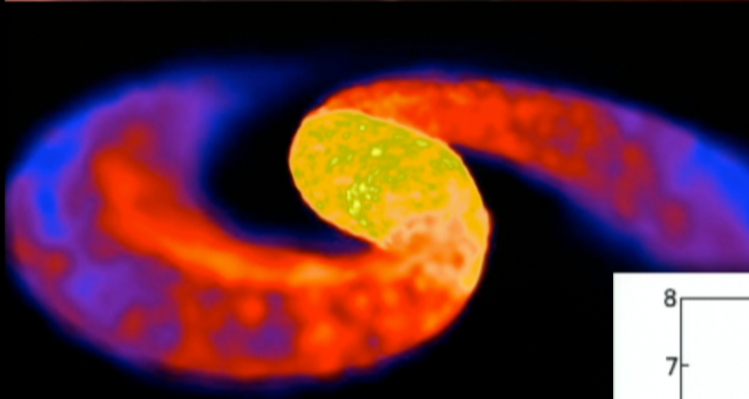
- Tidal tails
- Accretion disk outflows

Decompressed neutron-rich ejecta $\Rightarrow$ R-process ($A \sim 100$)

$$\left. \begin{array}{l} v_{ej} \sim 0.1 - 0.3 \, c \\ M_{ej} \sim 0.01 - 0.03 - 0.05 \, M_{\odot} \end{array} \right\} \begin{array}{l} L_p \sim 10^{41} \, \text{erg/s} \\ t_p \sim \text{day} \end{array}$$

Li & Paczynski 1998; Metzger et al. 2008; Rosswog et al. 2012; Kasen et al. 2013

“Kilonovae”



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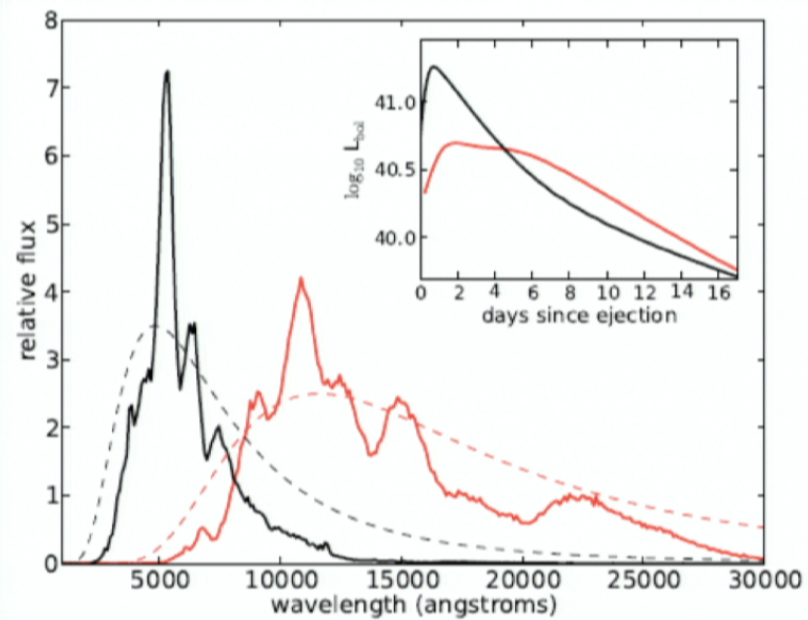
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Decompressed neutron

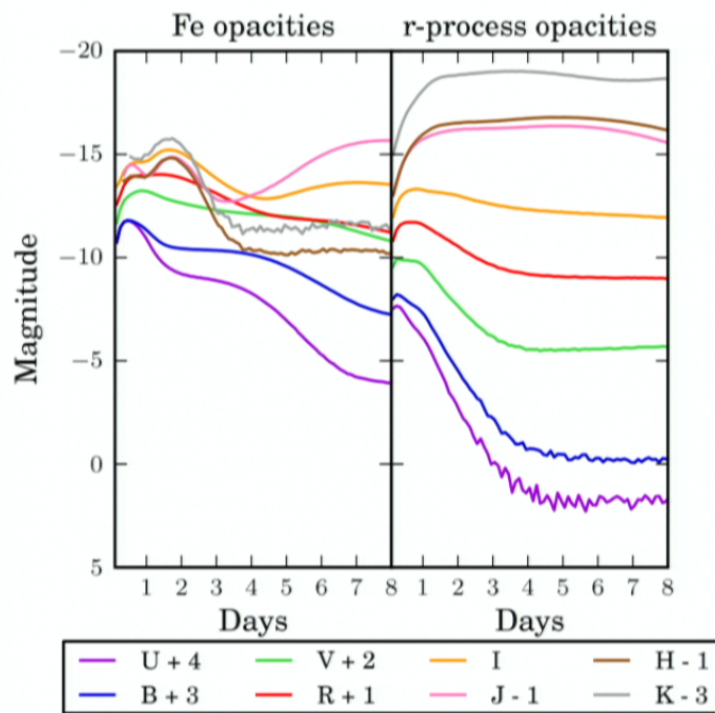
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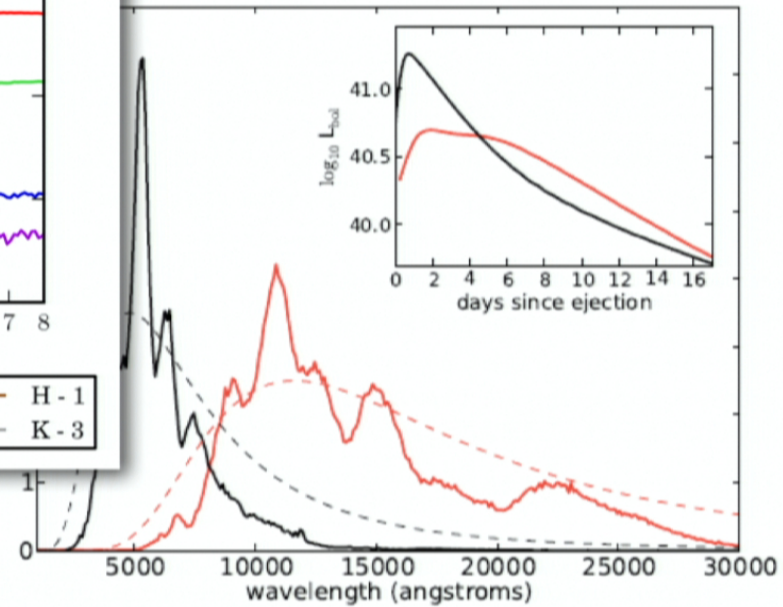


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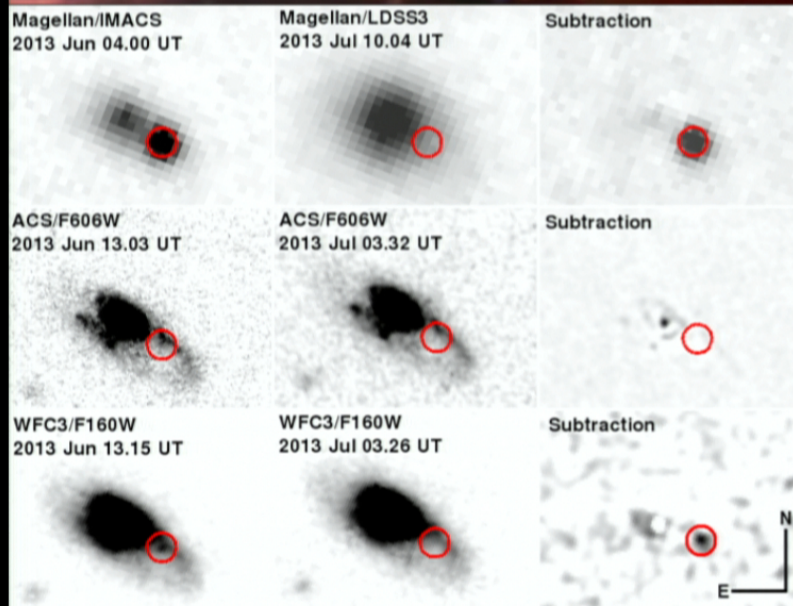
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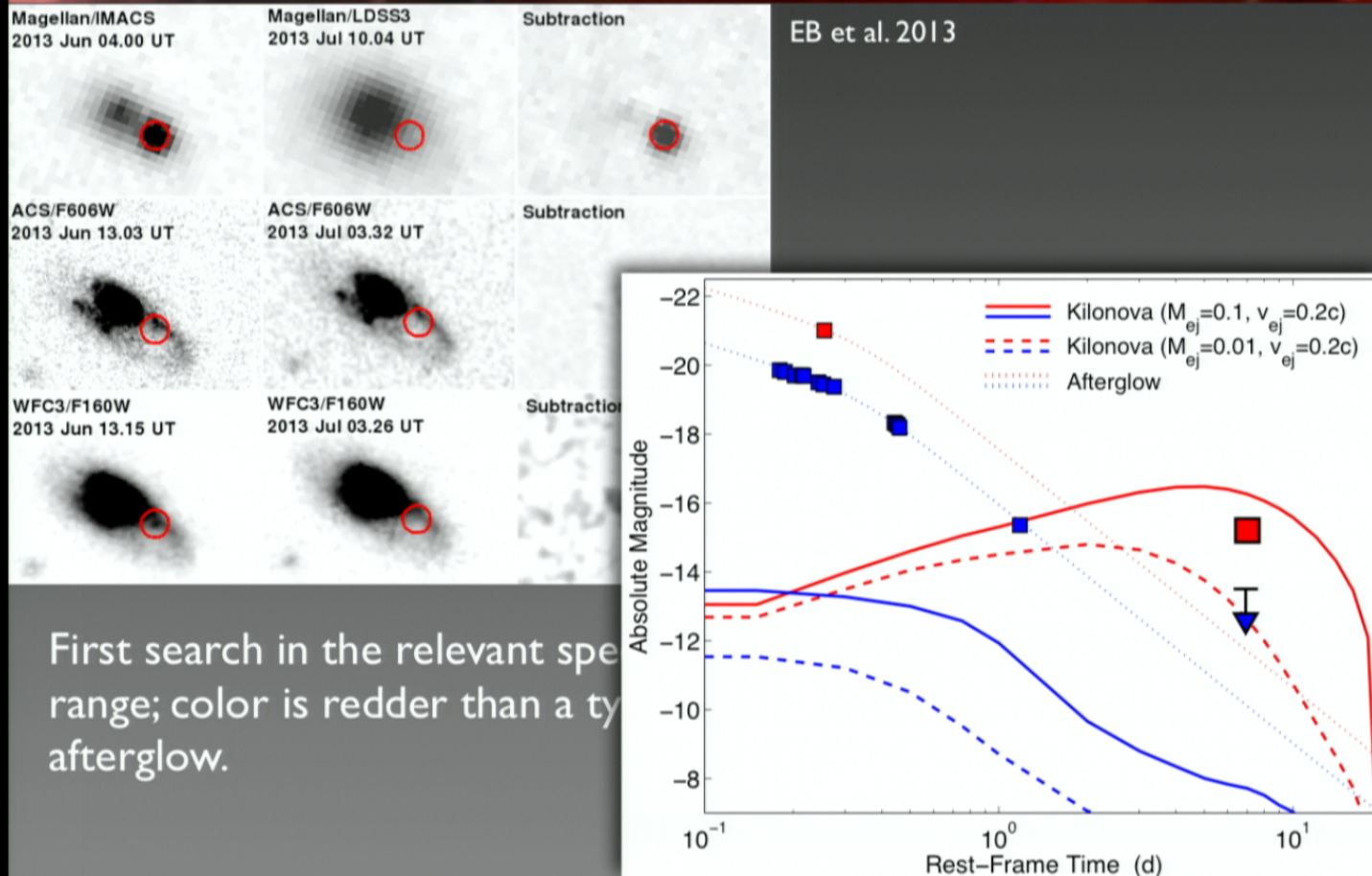
GRB 130603B: The First Kilonova



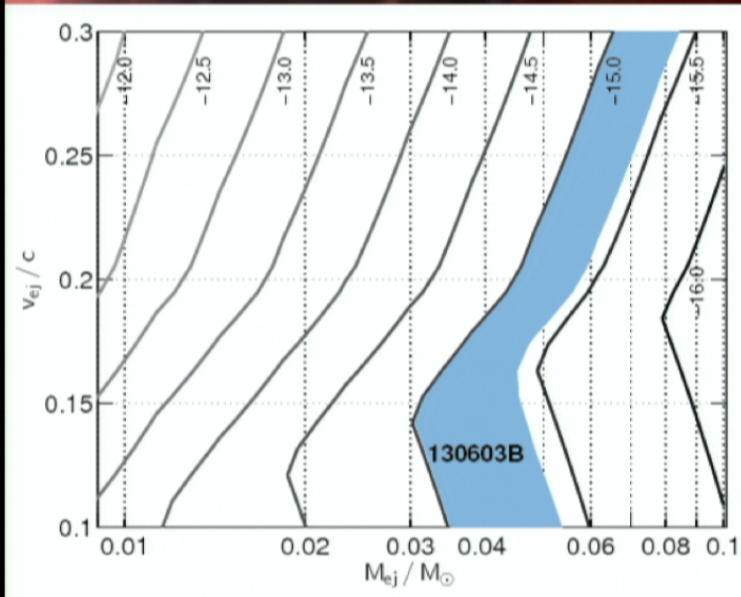
EB et al. 2013

First search in the relevant spectral range; color is redder than a typical afterglow.

GRB 130603B: The First Kilonova



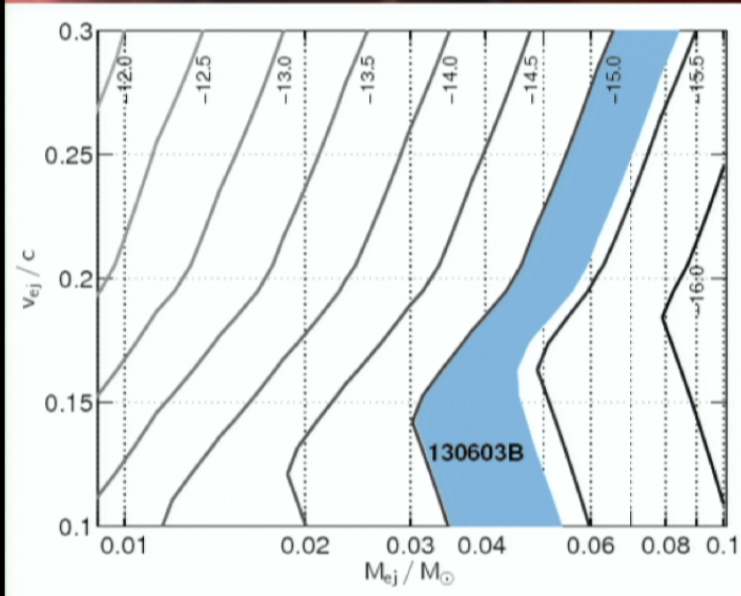
GRB 130603B: The First Kilonova



EB et al. 2013

Ejecta mass is $\sim 0.05 M_{\odot}$

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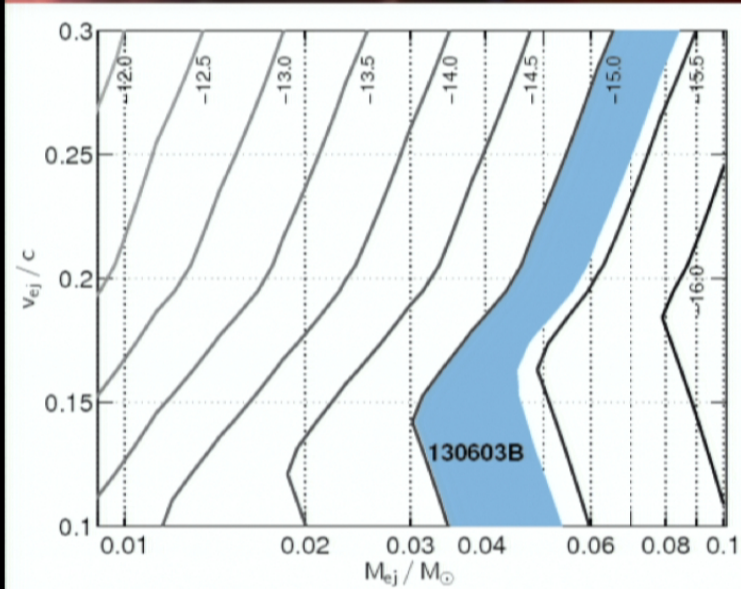


- Direct evidence for compact object mergers

EB et al. 2013

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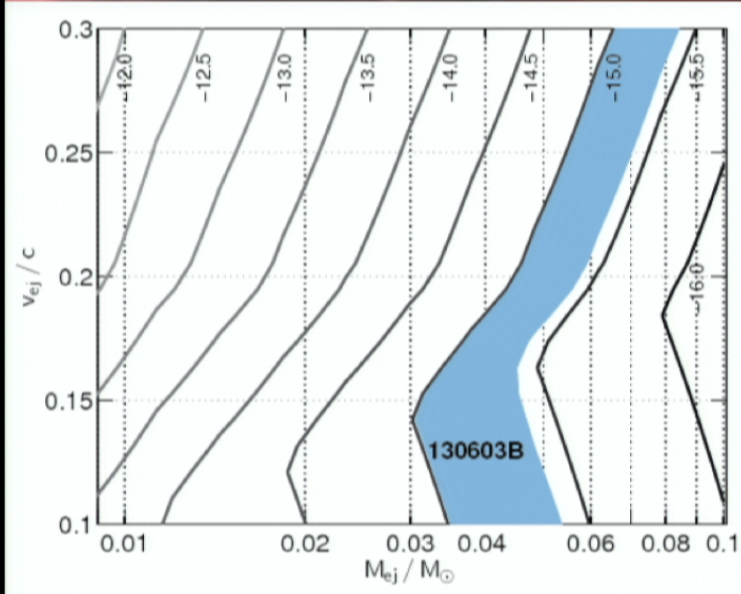


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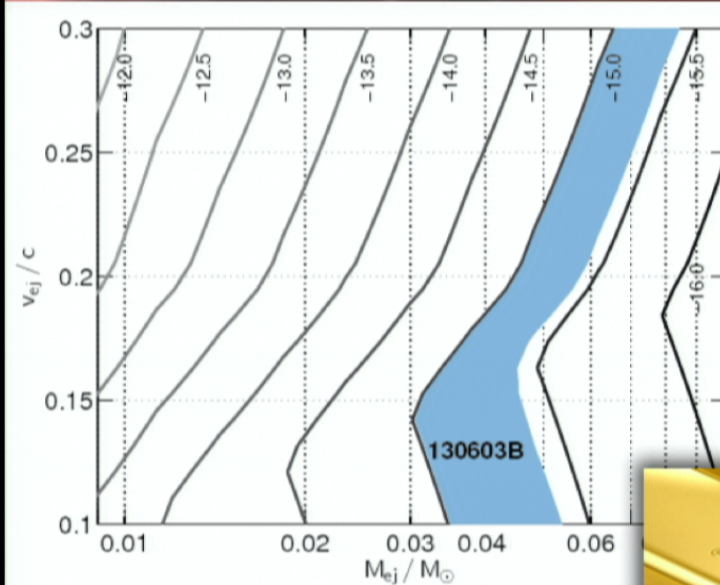


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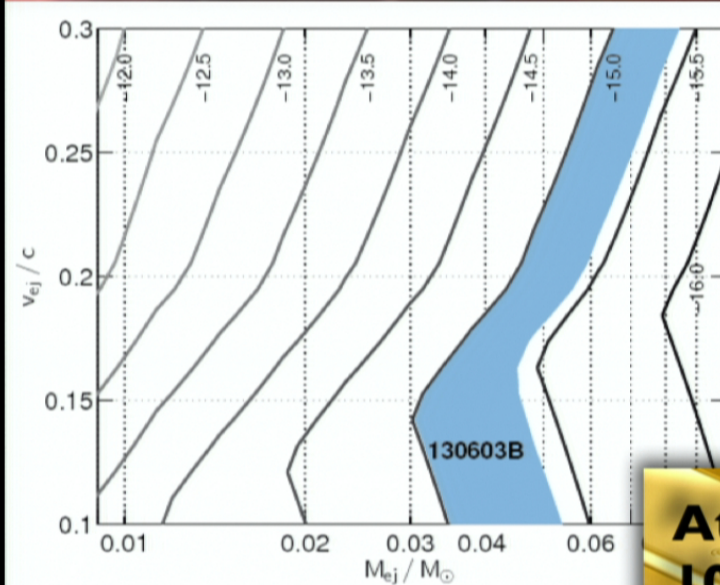
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**At today's market rate:
10 octillion dollars**

**\$10,000,000,000,000,
000,000,000,000,000**

Summary

- Short GRB progenitors are an evolved population with a wide range of ages (~ 0.1 -5 Gyr); not massive stars.
- There is growing evidence for NS-NS/NS-BH mergers:
 - offsets of $\sim$ few-100 kpc (agreement w/ NS-NS mergers)
 - weak spatial correlation with stellar mass or star formation
 - low densities on $\sim$ pc scales ($< 0.1 \text{ cm}^{-3}$)
 - kilonova in GRB 130603B
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- Evidence for beaming ($f_b \sim 50$; $E_\gamma \sim E_K \sim 10^{49} \text{ erg}$; $\mathcal{R}_{\text{GW}} \sim 20 \text{ yr}^{-1}$)
- *Since short GRBs most likely NS-NS/NS-BH merger, we have already seen the on-axis EM counterparts of mergers (and a kilonova)*
- The detection of EM counterparts to GW sources is challenging; optical/ γ -ray searches offer the best approach