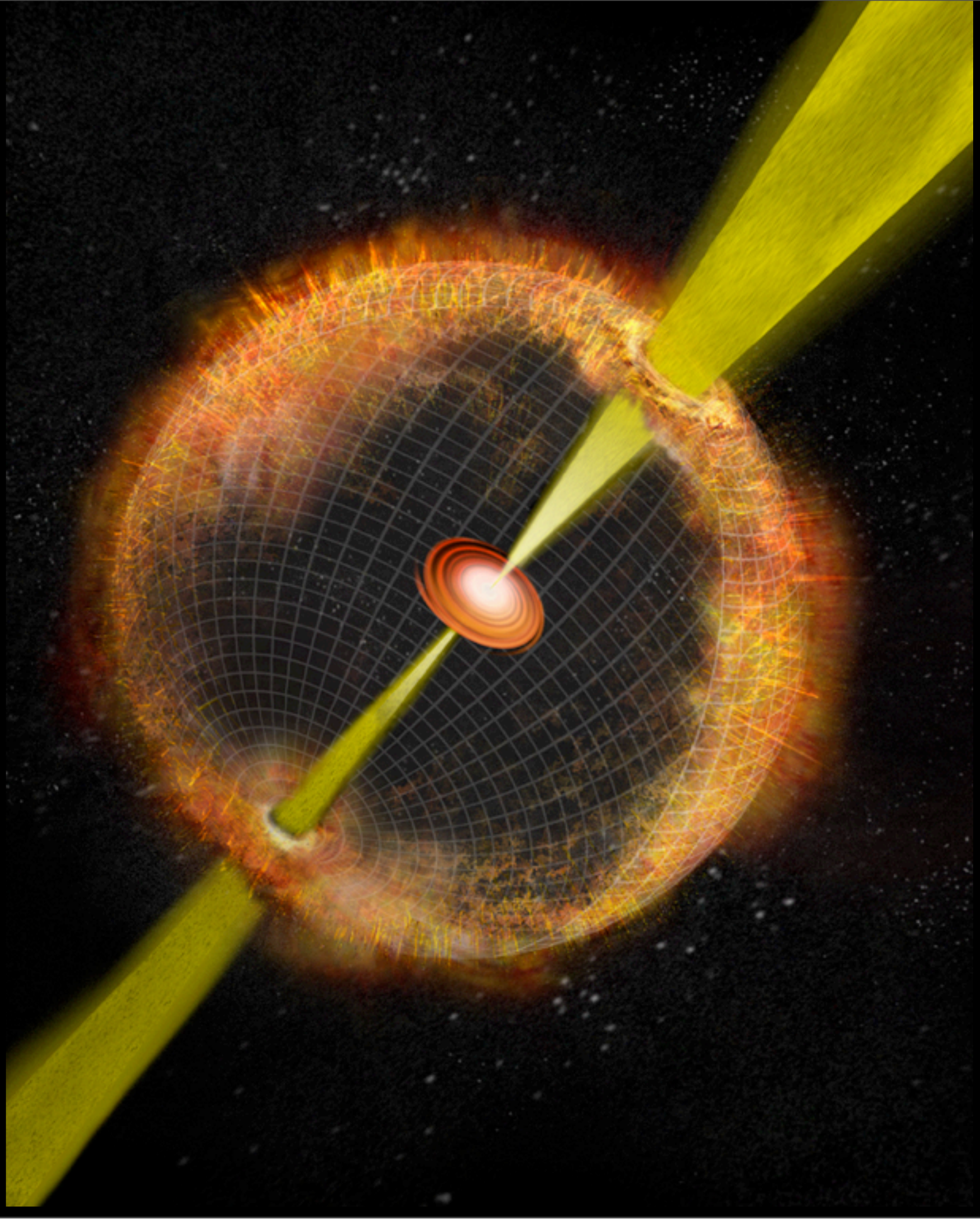


A Holistic View of the GRB-SN Connection

Alicia M Soderberg

Harvard University

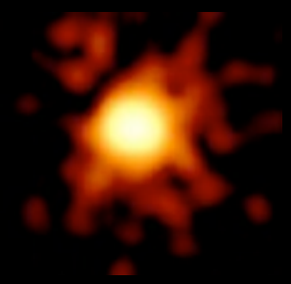
Thanks to:

Maria Drout *(Cambridge)*

Emily Levesque *(UC Boulder)*

Sarah Wellons *(Princeton)*

Laura Chomiuk *(Harvard/CfA)*

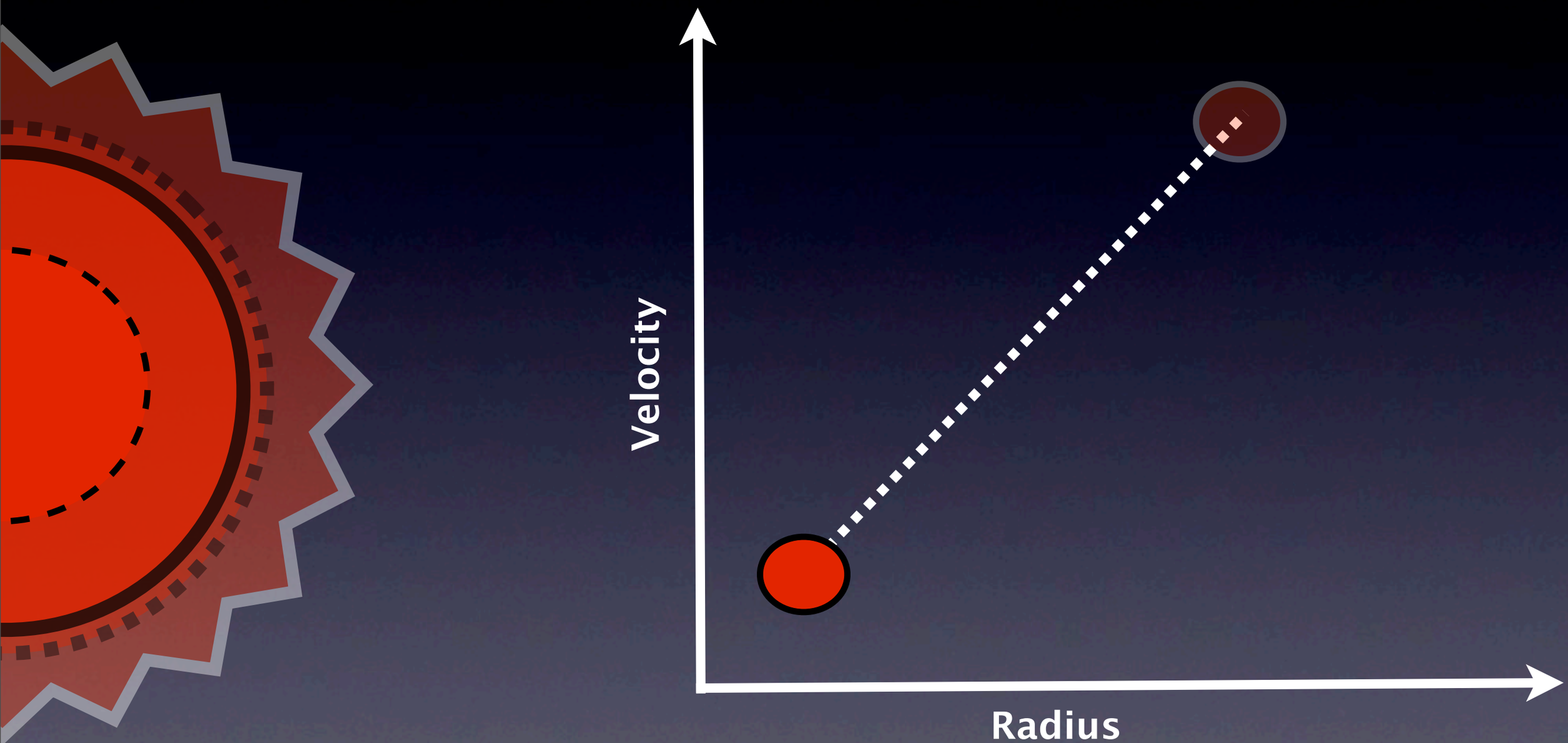


What Distinguishes GRB-SNe from SNe?

- Review: basic picture
- Blastwave diagnostics *(E, v)*
- Optical SN properties *(L, v_{ph})*
- Local CSM densities *(n_e, profile)*
- Host galaxy properties *(Z, SFR)*

→ Progress

SNe are Homologous Explosions



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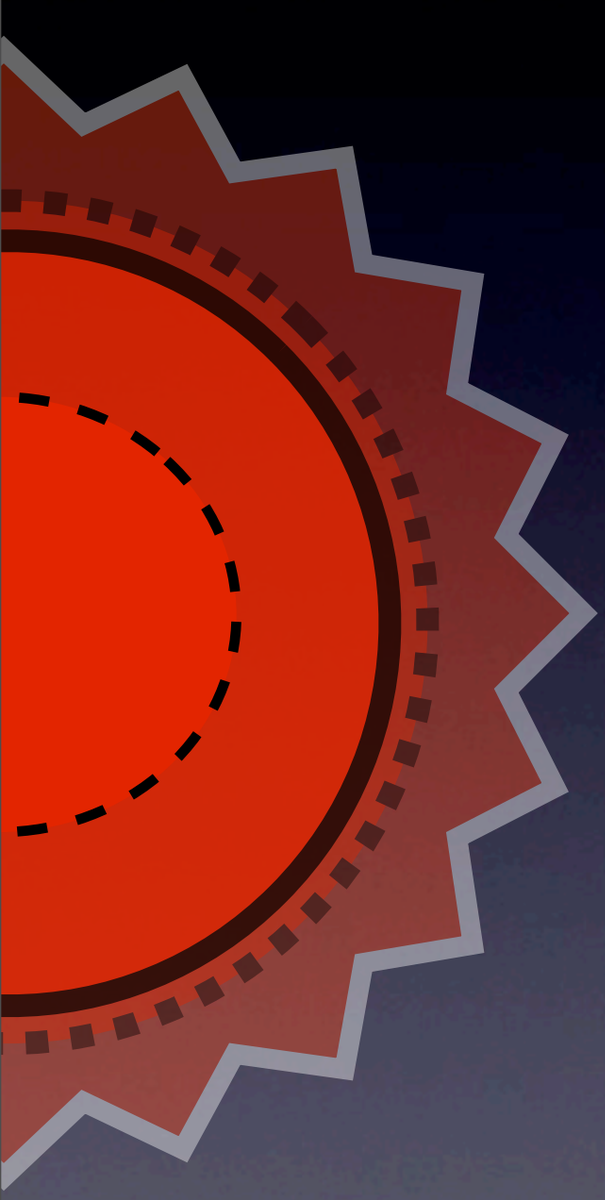

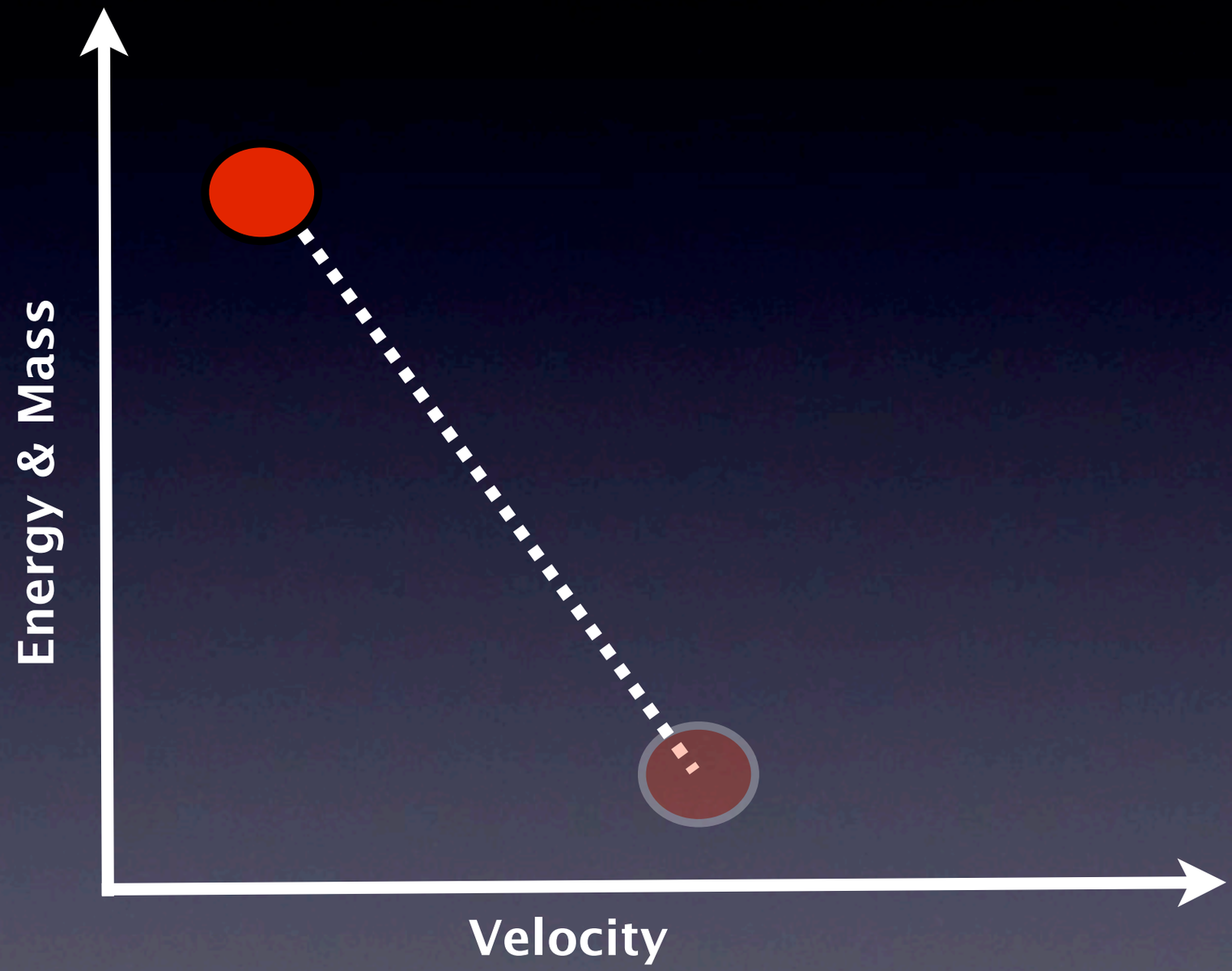

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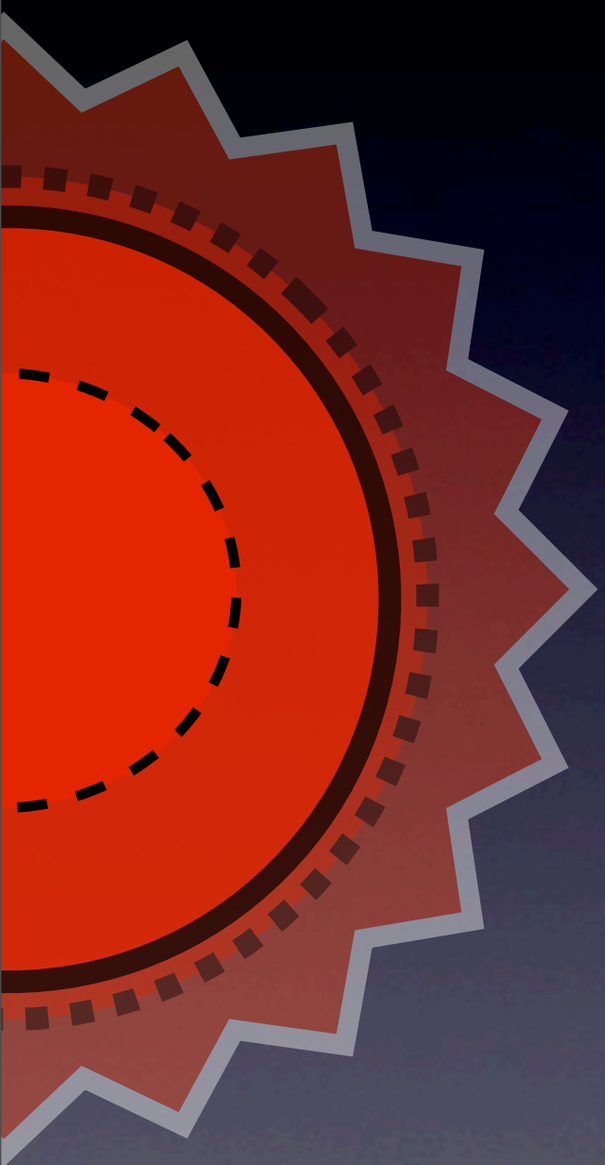
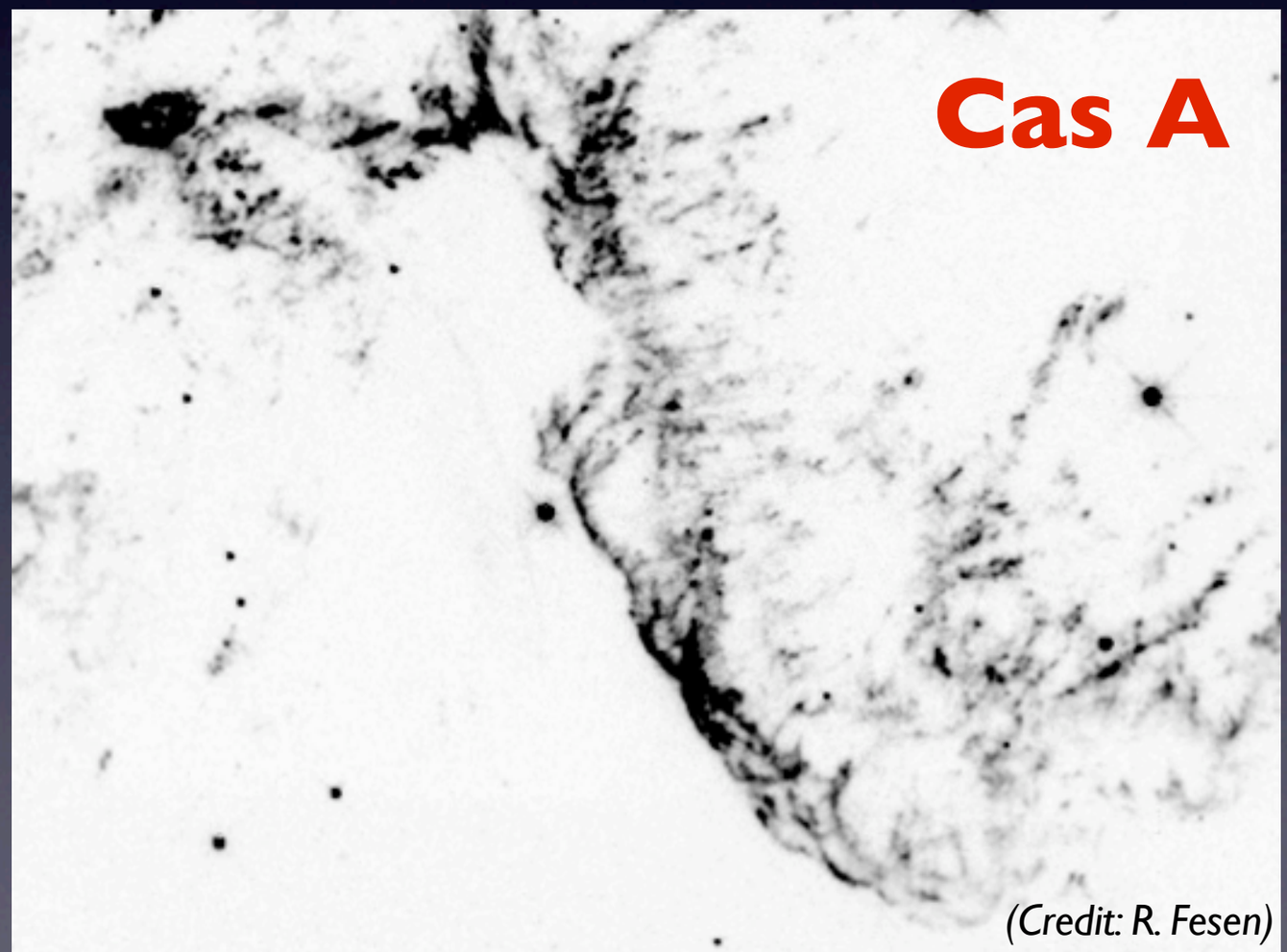


Double Shock System

Optical = slow ejecta (*thermal*)

Radio/X-ray = fast ejecta (*non-thermal*)



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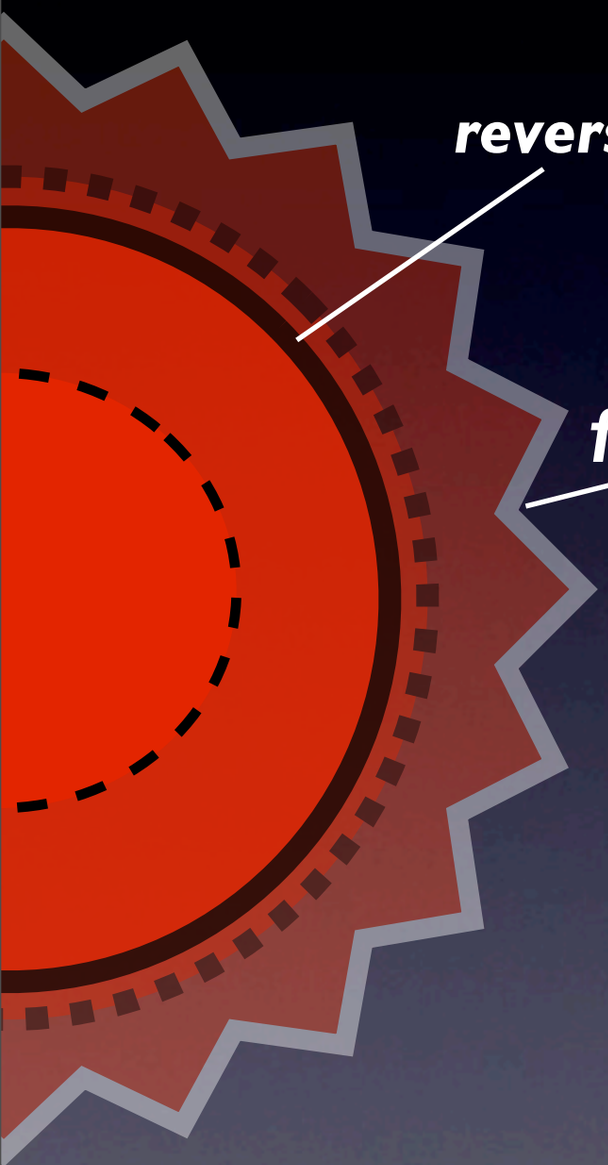

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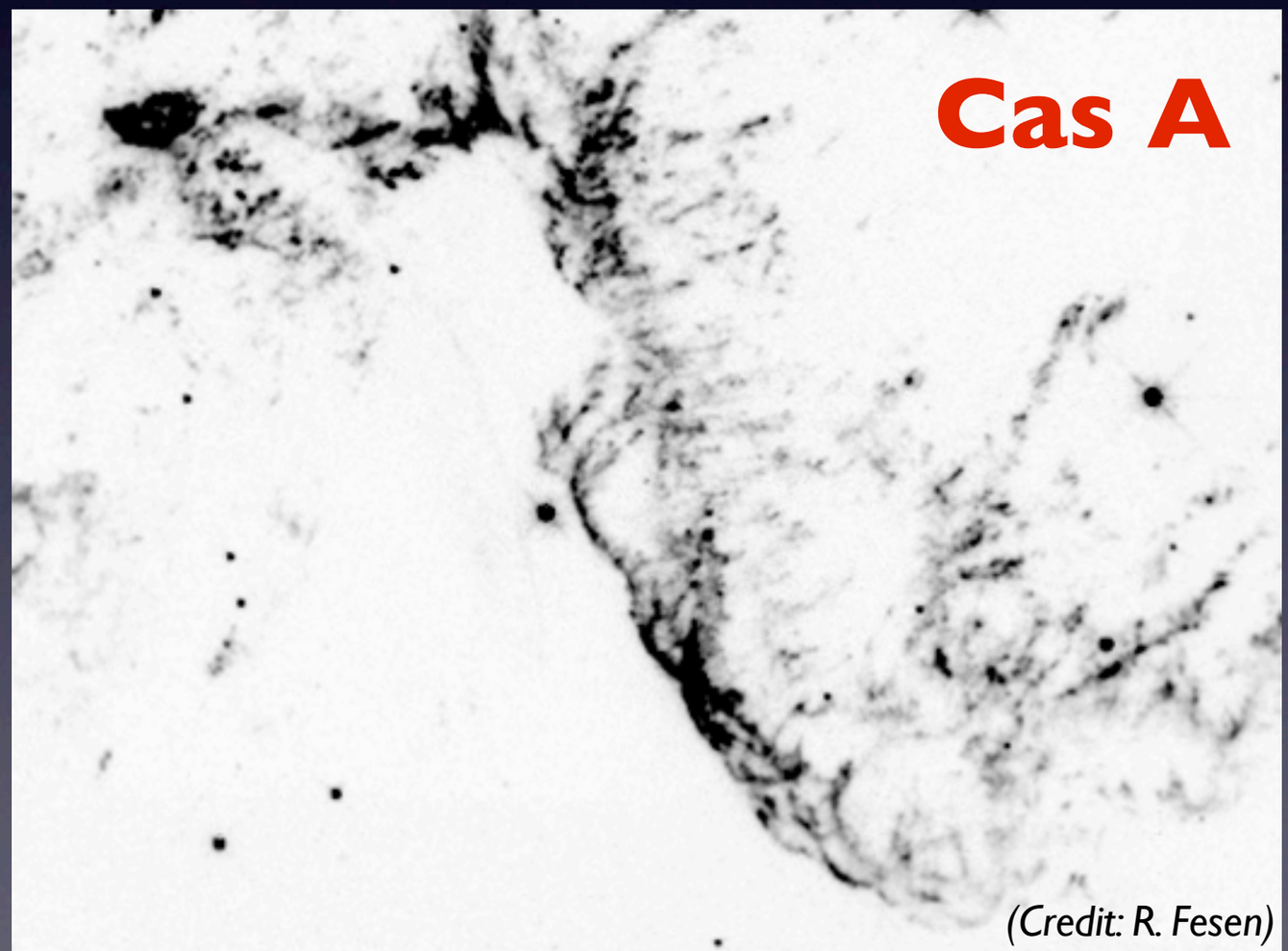

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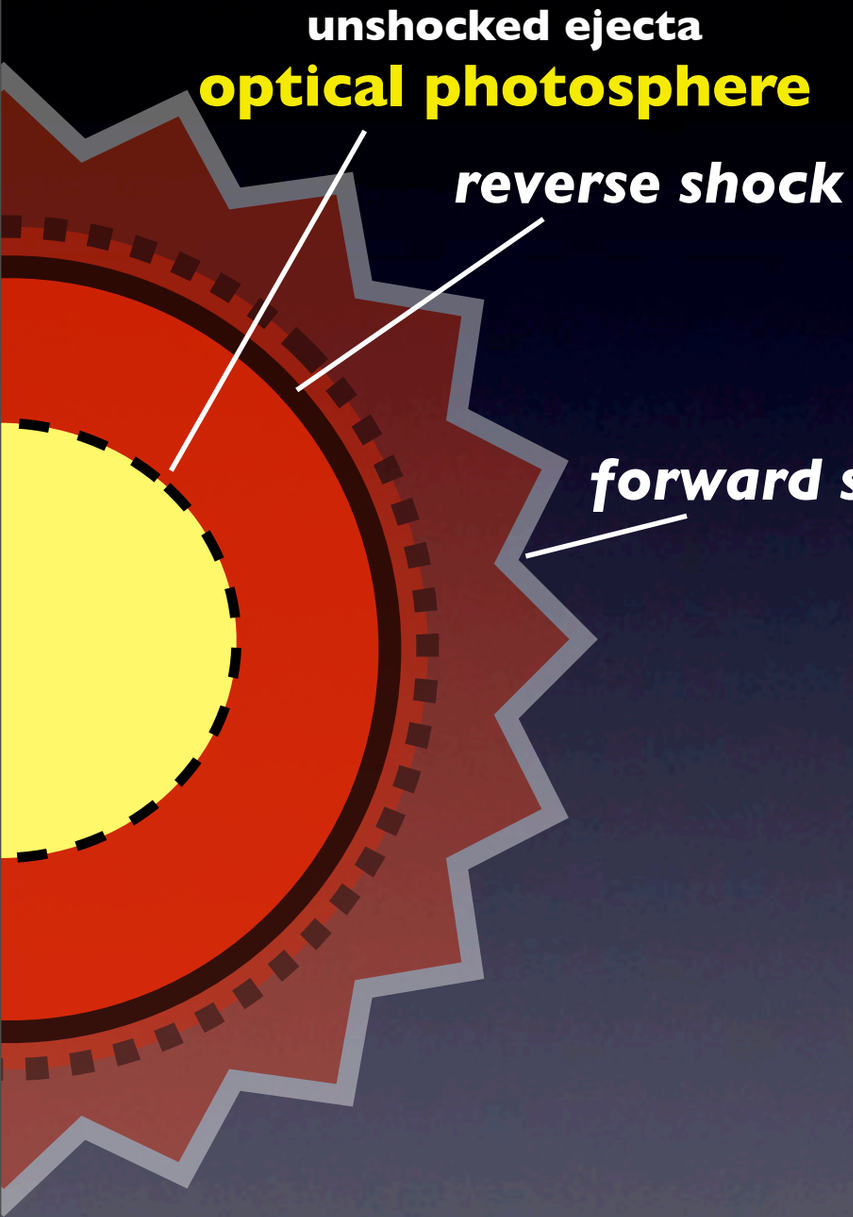

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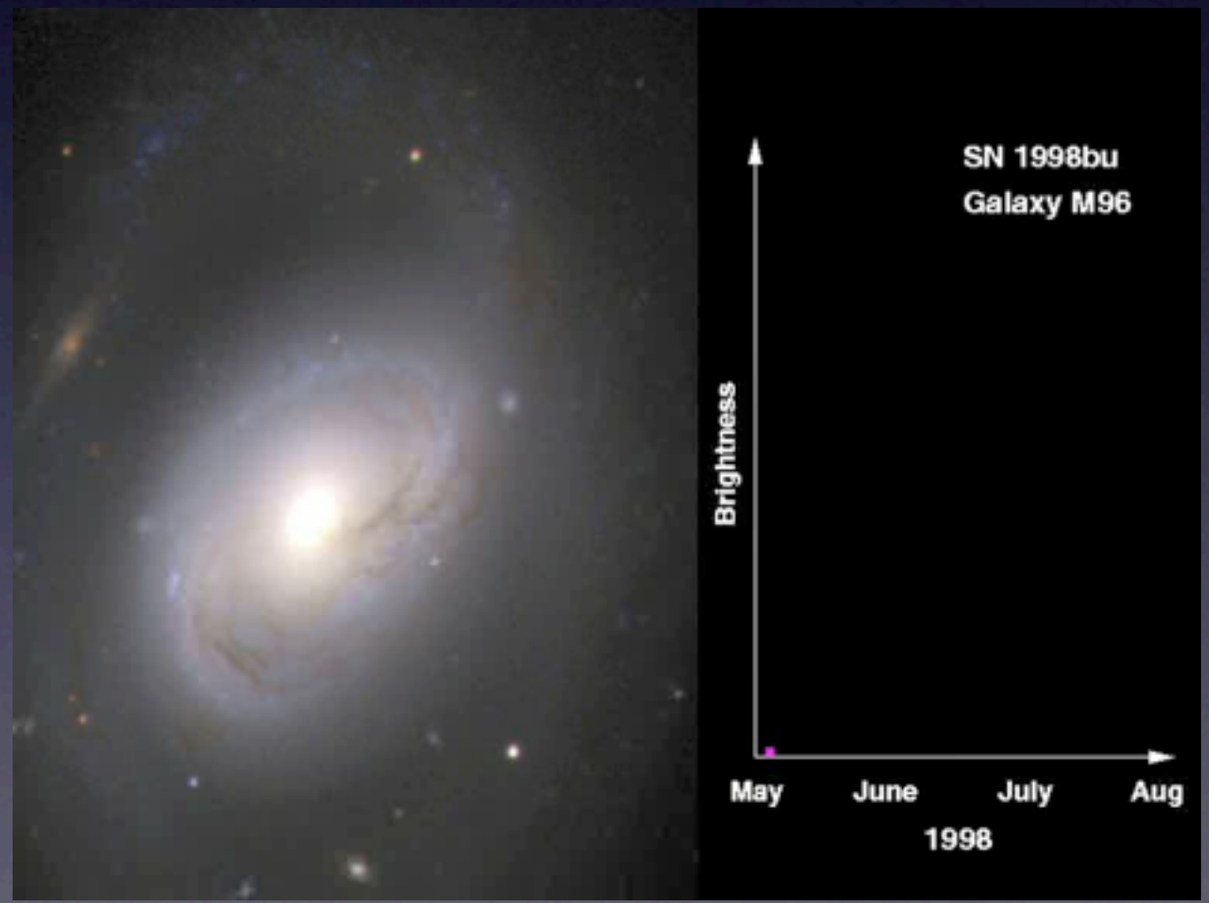

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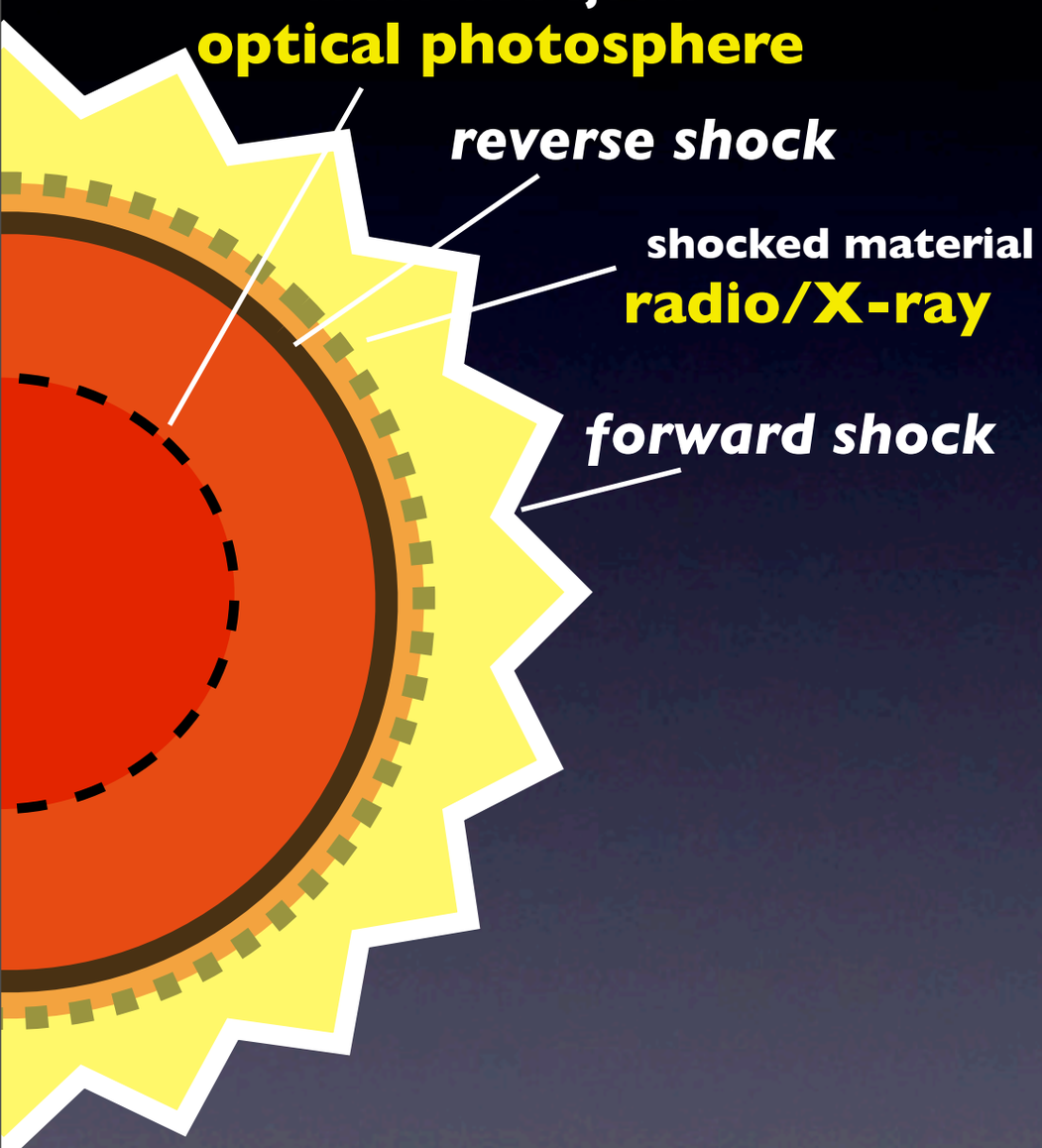

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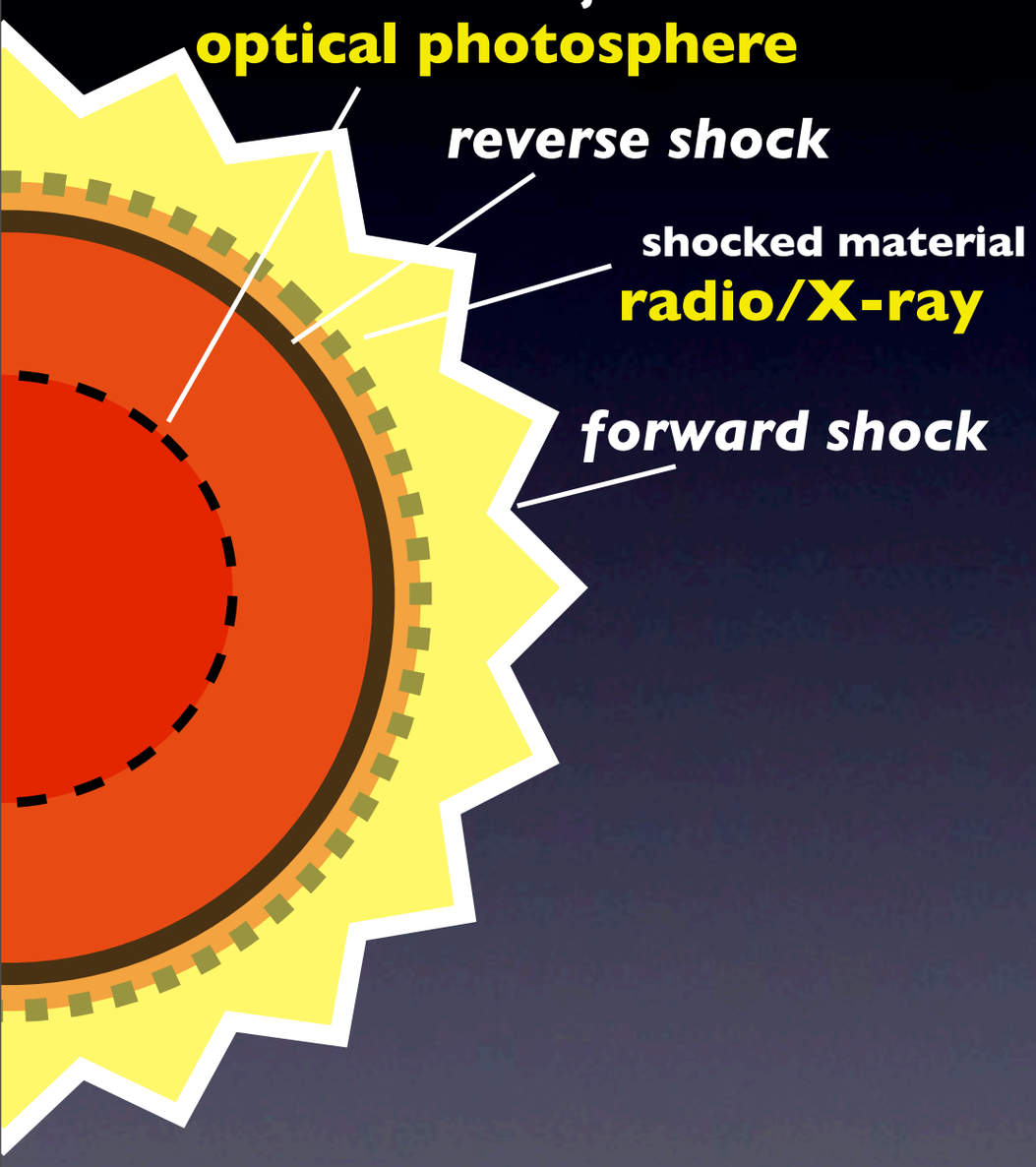

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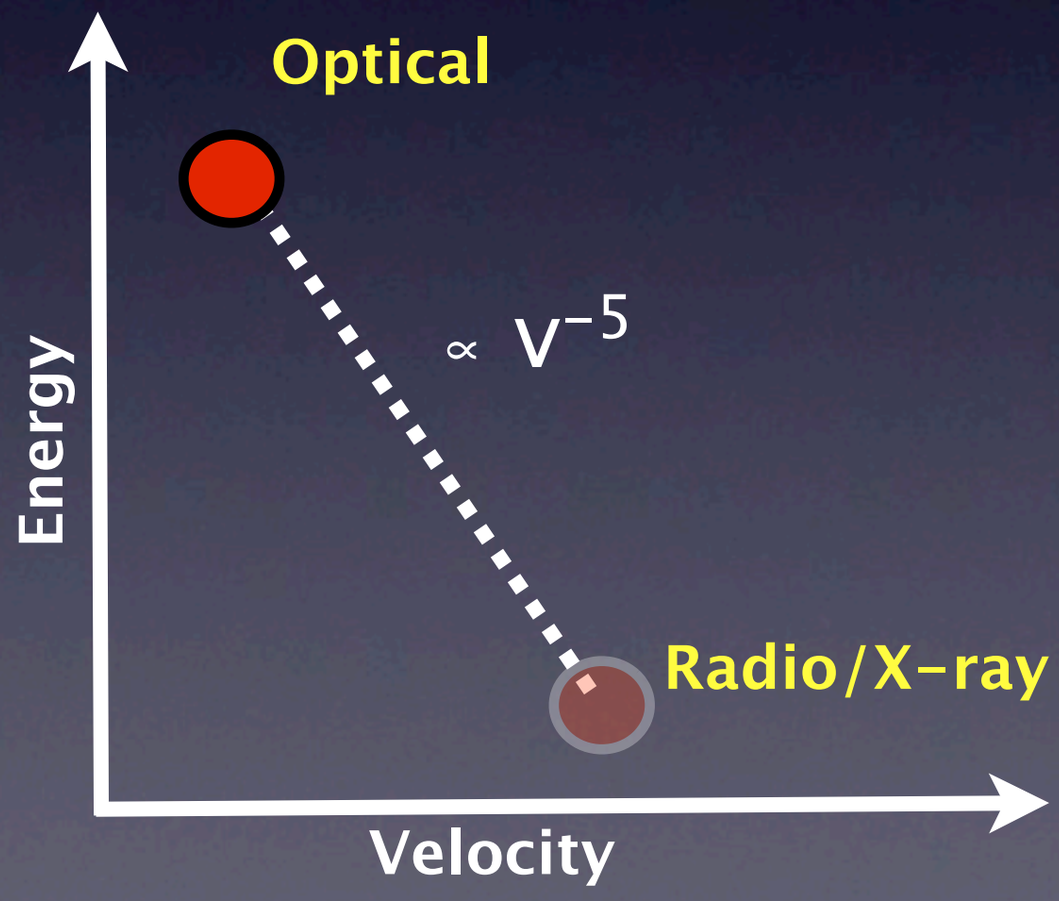
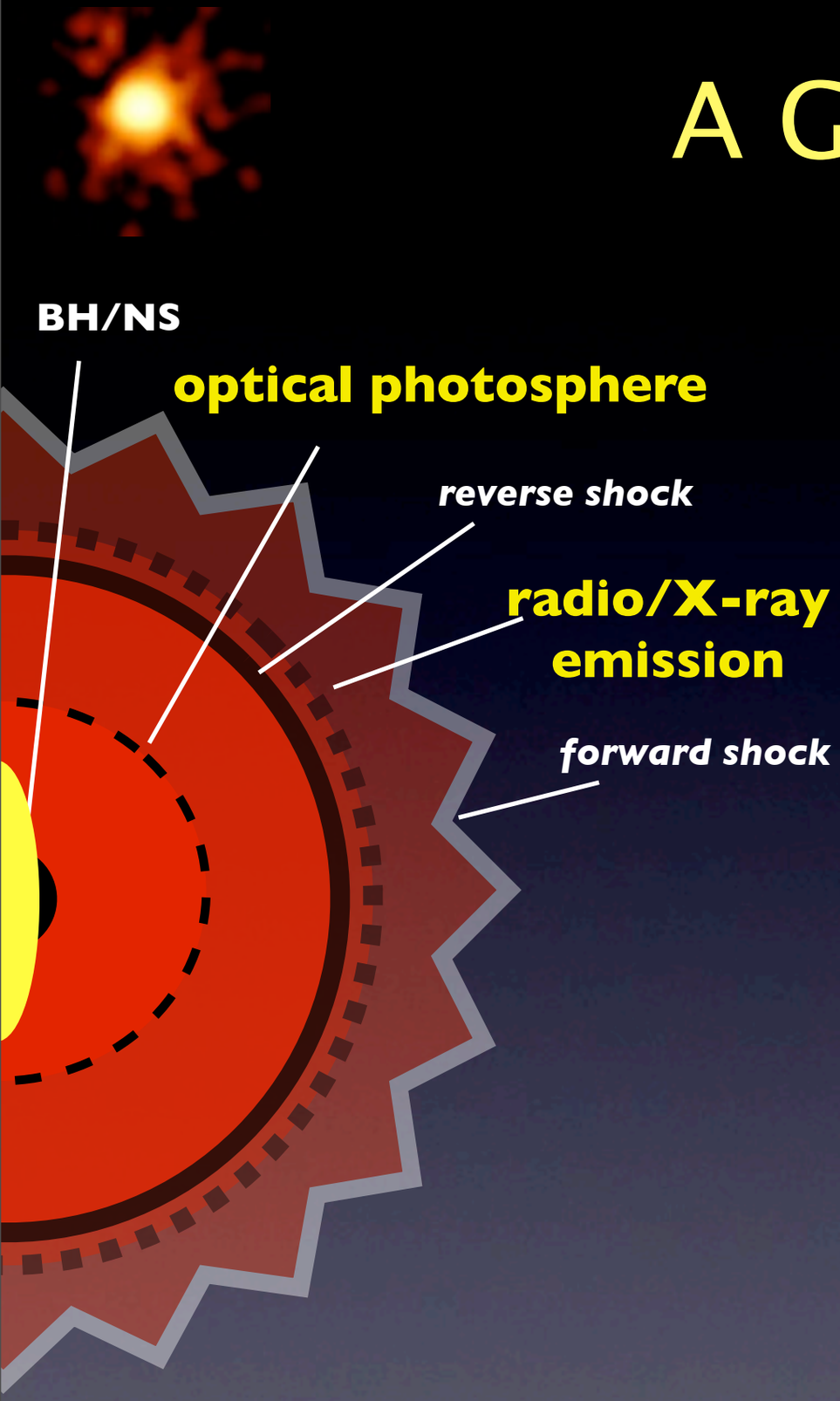
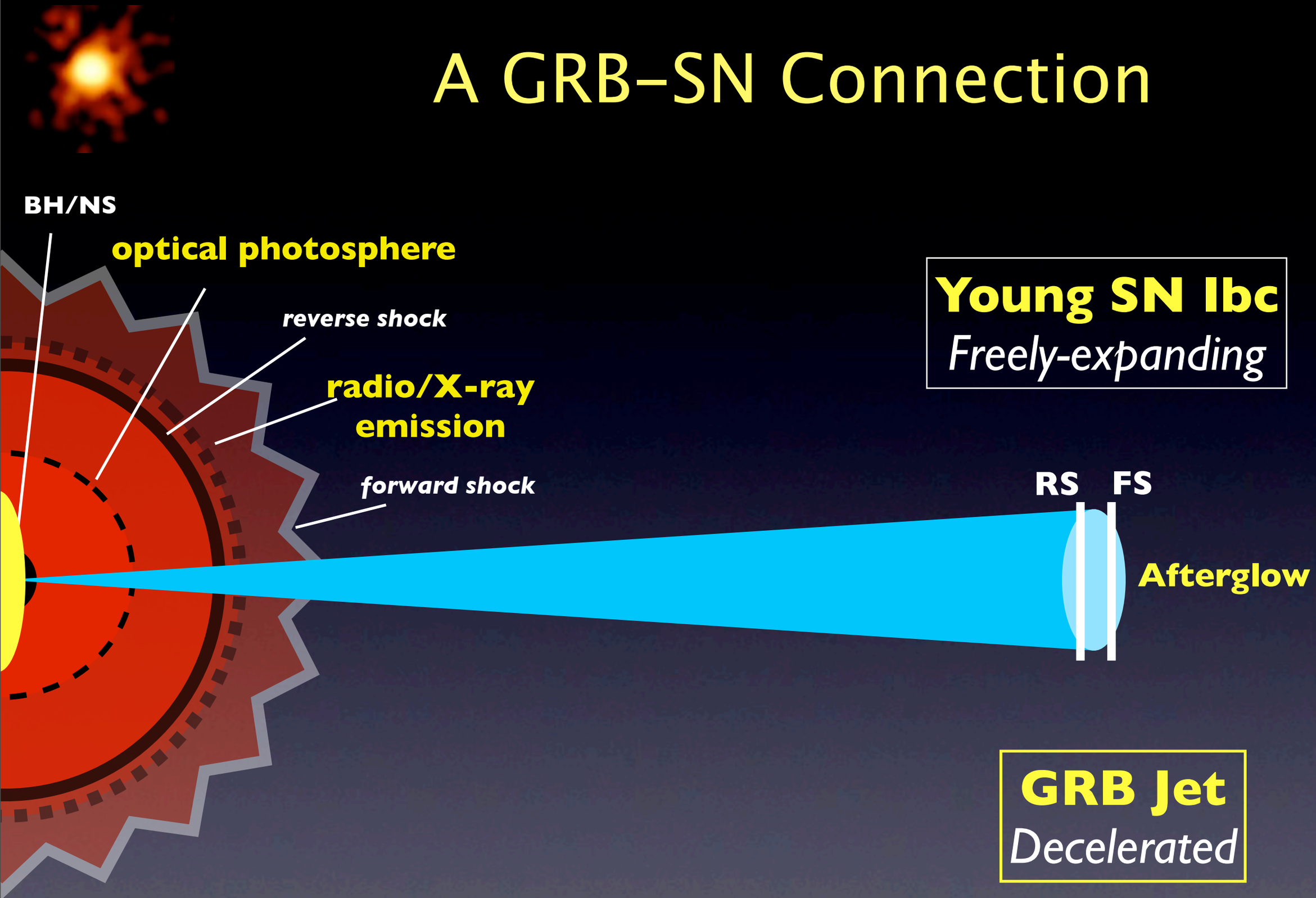


A GRB–SN Connection



Young SN Ibc
Freely-expanding

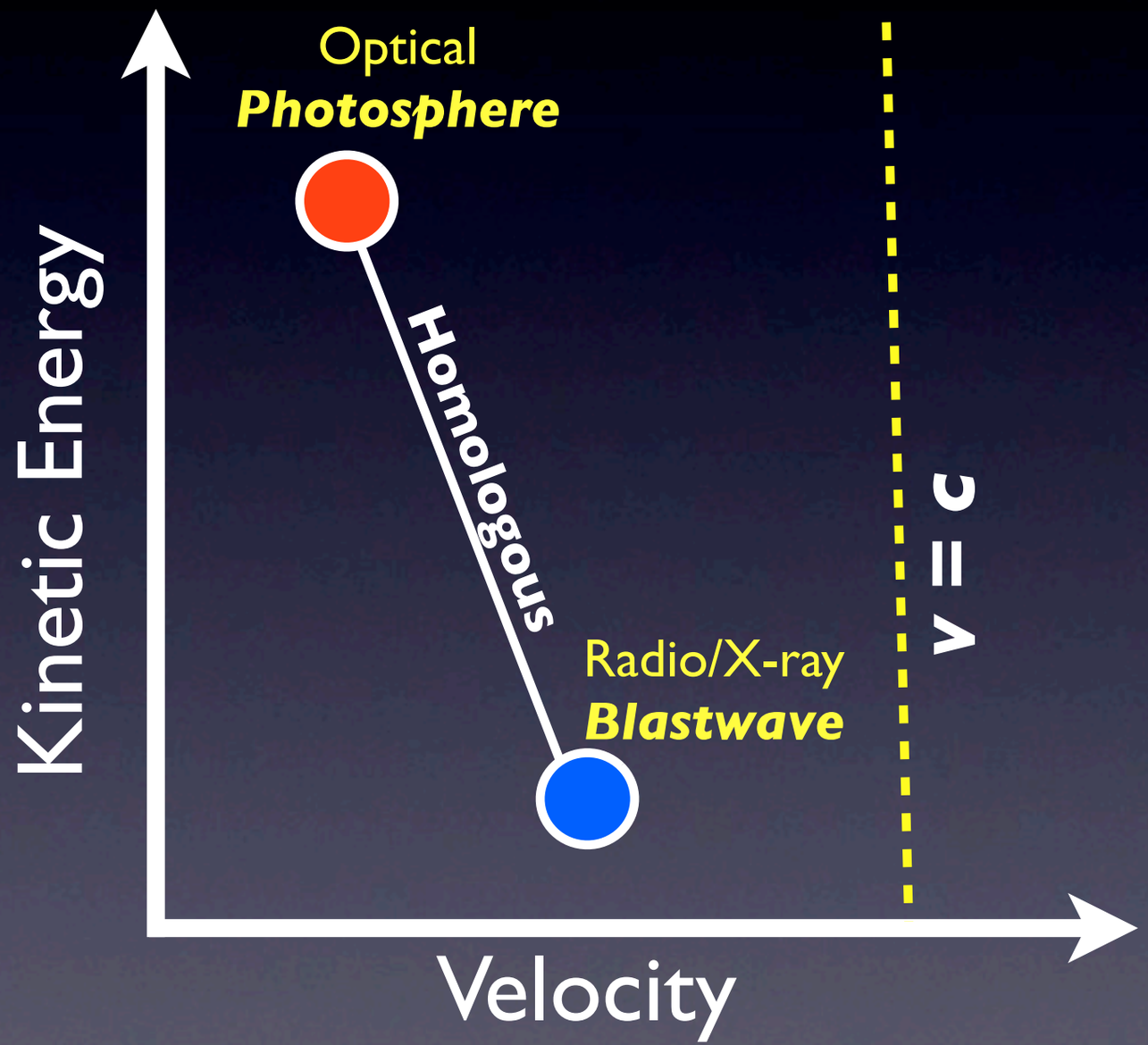
A GRB–SN Connection



Young SN Ibc
Freely-expanding

GRB Jet
Decelerated

Energy–velocity coupling



Ordinary SNe Ibc:

Homologous

$E \sim v^{-5}$

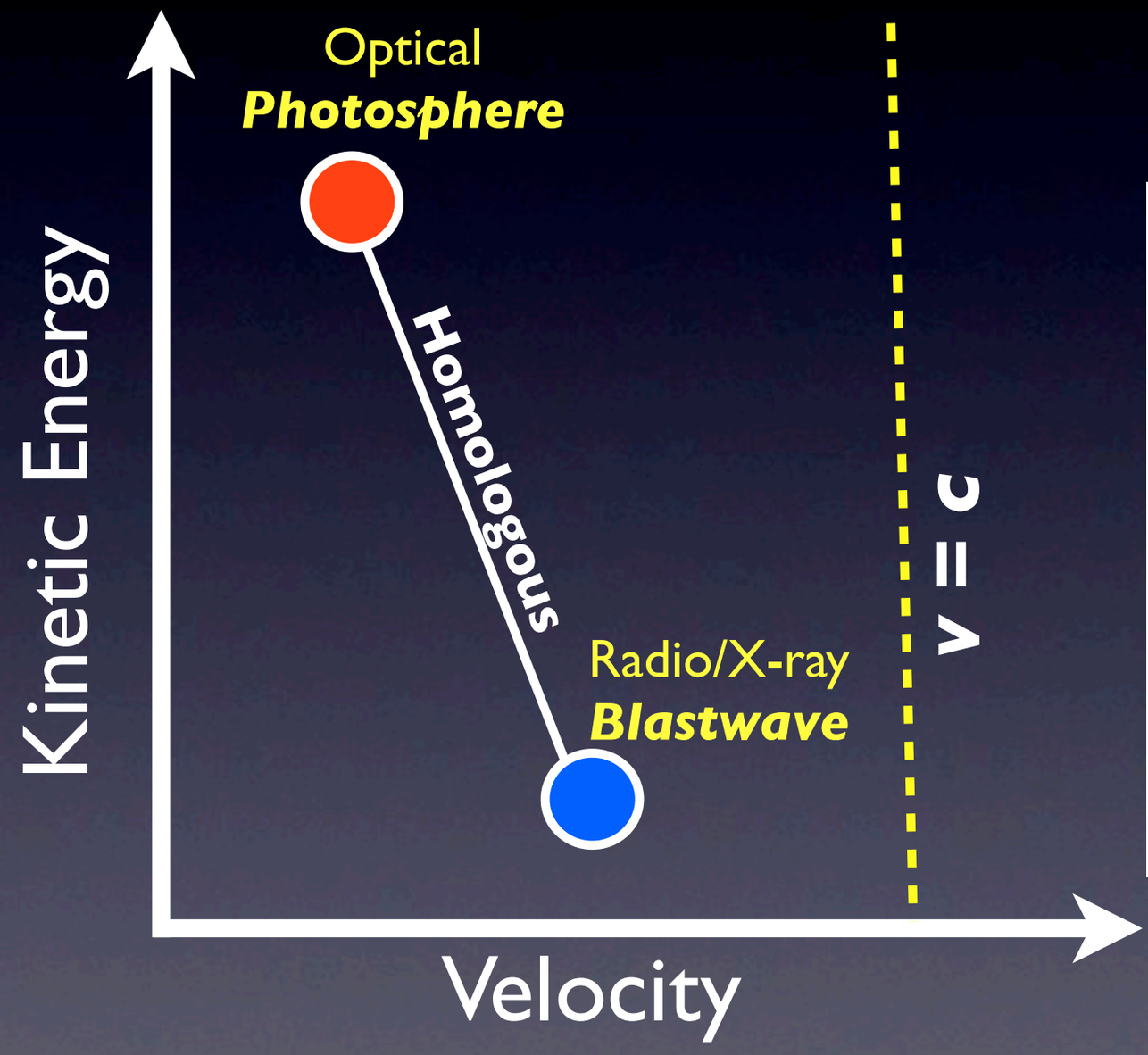
Optical ~ E_{tot}

Radio ~ 0.01% x E_{tot}

v* ~ *c *is possible*

(Tan, Matzner, McKee 2001)

Energy–velocity coupling



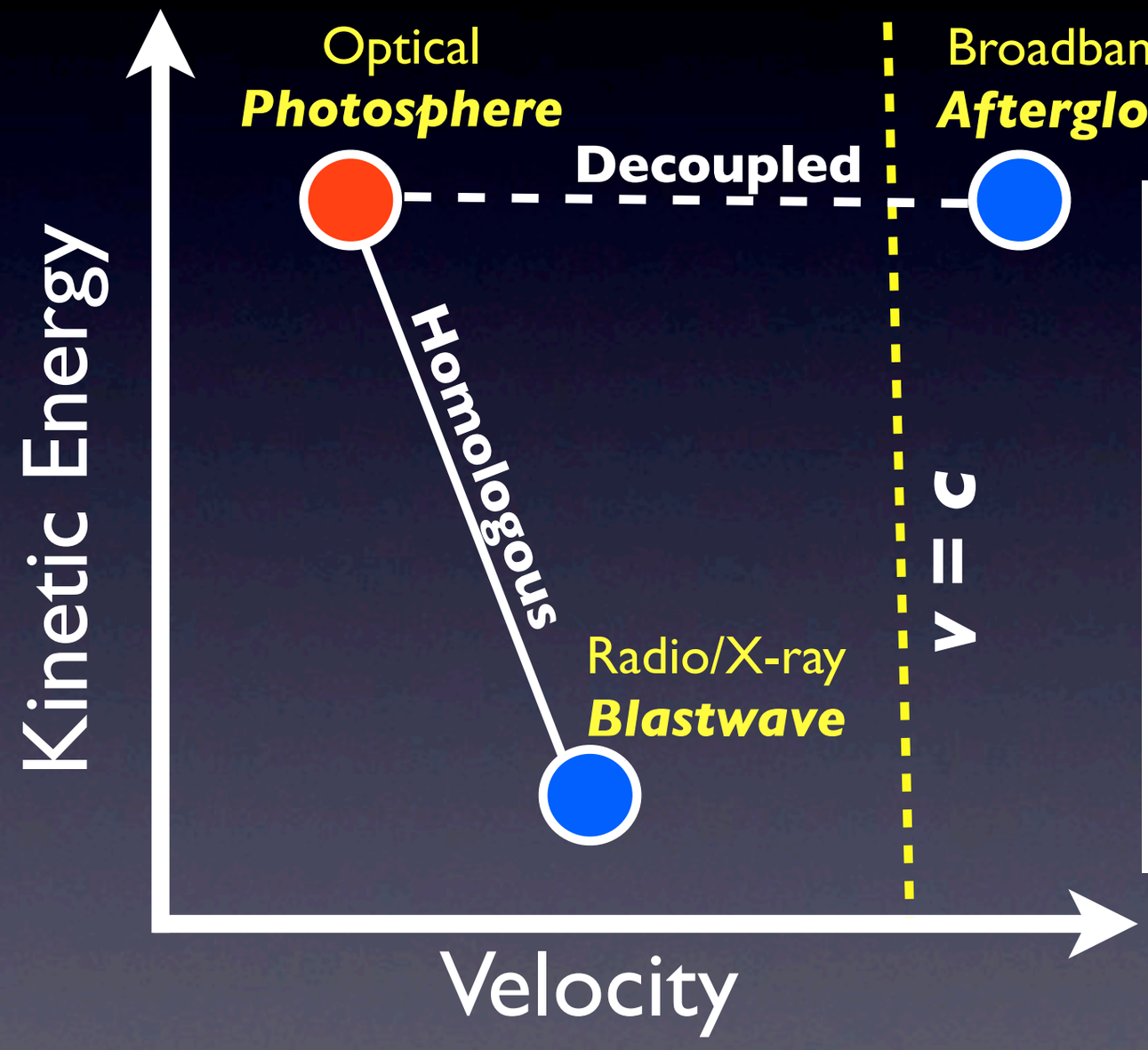
GRB-SNe

(Credit: A. MacFadyen)

GRB = decoupled ejecta

Requires a *central engine*

Energy–velocity coupling



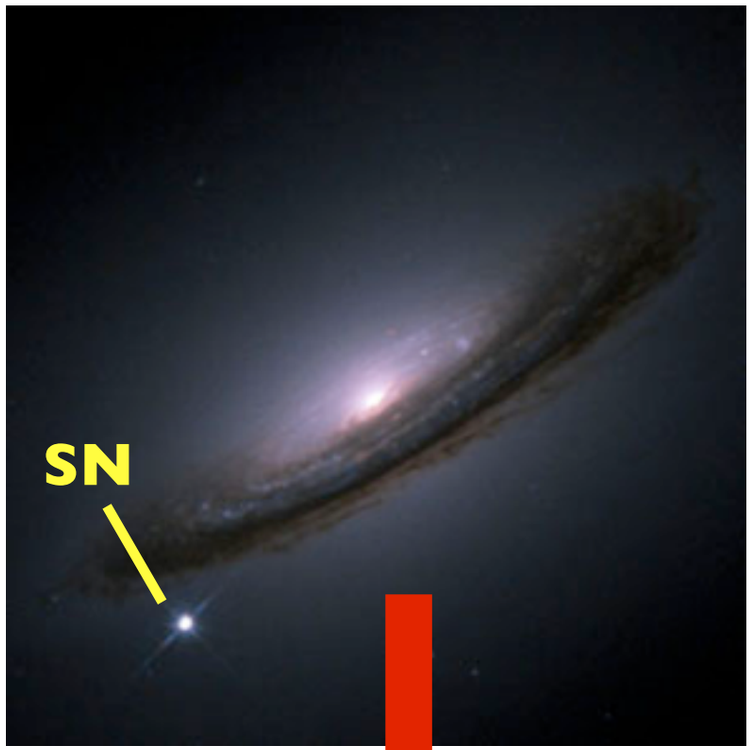
GRB-SNe

(Credit: A. MacFadyen)

GRB = decoupled ejecta

Requires a *central engine*

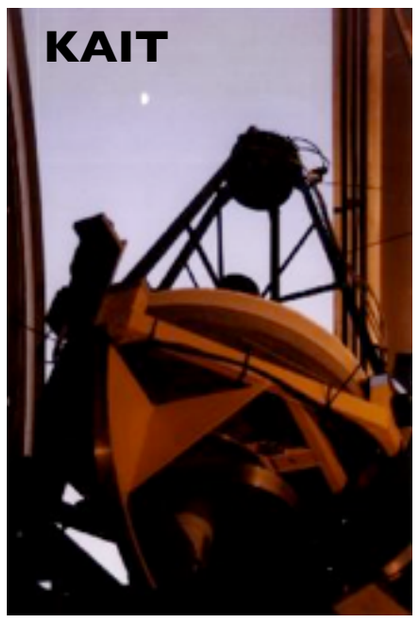
I. Radio Hunt for Engine-powered SNe



Target optically discovered SNe Ibc

- *why?* nearly all GRBs have a SN
- satellites miss *weak GRBs, off-axis GRBs*
- SN discoveries rapidly, *publicly announced*
- VLA ToO's for all SNe Ibc at *z < 0.04*
- *8-year* baseline

Amateur Astronomers



Robotic Searches

Circulars: IAUC, CBET, ATEL, GCN

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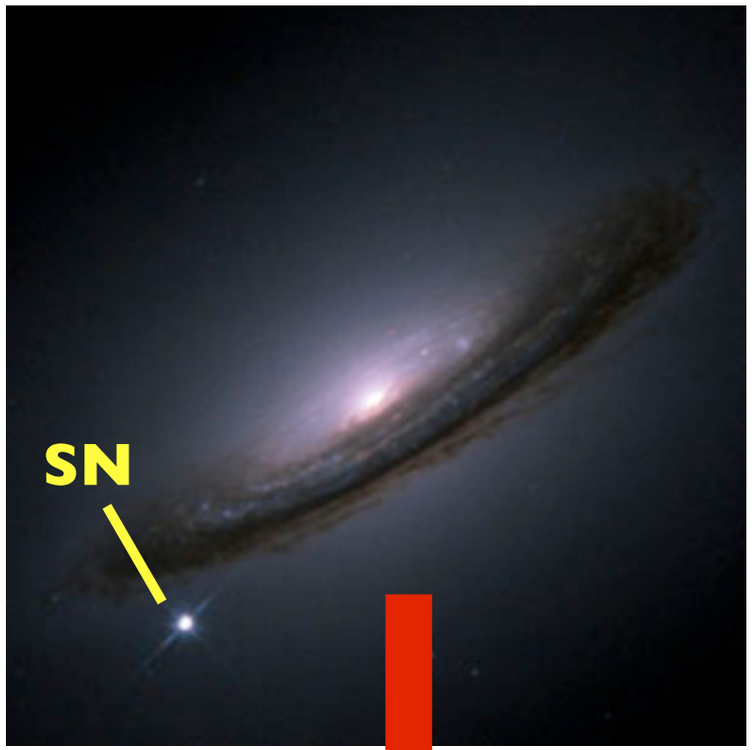
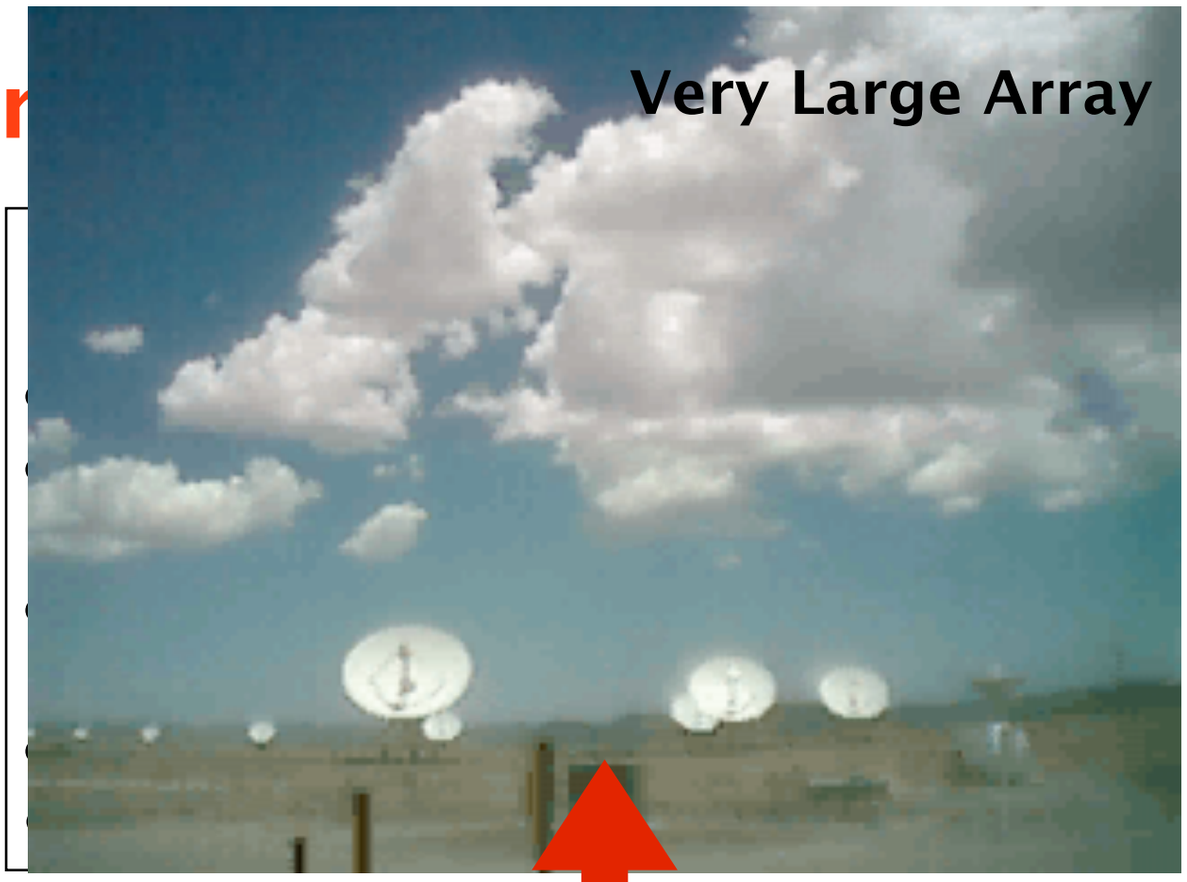
SUPERNOVA 2005ck

Independent discoveries of a supernova in the Abell galaxy cluster 1656 have been reported on unfiltered CCD images by H. Pugh and W. Li (LOSS/KAIT; cf. IAUC 8541) and by R. Quimby, F. Castro, P. Hoeflich, J. C. Wheeler (all at the University of Texas), and C. Gerardy (of Imperial College); Quimby's group used the ROTSE-IIIb telescope (cf. IAUC 8508). Pugh and Li provide the following prec[illegible] position for SN 2005ck: R.A. = 13h02m18s.72, Decl. = [illegible].5 (equinox 2000.0), which is 58".3 east and 24".3 south [illegible] of an apparent host galaxy. Quimby et al. report pos[illegible]nd figures 18s.77, 43".8 for the new object. Approximate magn[illegible]des for SN 2005ck: 2004 Dec. 15, [18.8 (ROTSE-IIIb); 2005 Jan. 14, [18.8 (ROTSE-IIIb); Apr. 17.26 UT, [19.5 (KAIT); May 23.25, [18.5 (KAIT); June 1.26, 19.0: (KAIT; hint of object near limit of image); 5.27, 18.7 (ROTSE-IIIb); 8.25, 18.6 (ROTSE-IIIb); 12.24, 18.6 (KAIT); 13.24, 18.5 (KAIT). Quimby adds that a spectrum (range 420-890 nm) of SN 2005ck, obtained on June 13.22 with the 9.2-m Hobby-Eberly Telescope (+ Marcario Low-Resolution Spectrograph) by S. C. Odewhan and E. Terrazas, shows it to be a type-Ia supernova; the spectrum is very similar to that of SN 1994D near maximum light (Patat et al. 1996, MNRAS 278, 111). Using 1994D as a template, they find an approximate redshift of z = 0.08, ruling out any association to the neighboring Coma-cluster galaxies, leaving the host as yet unidentified.

Radio Hunt for Er





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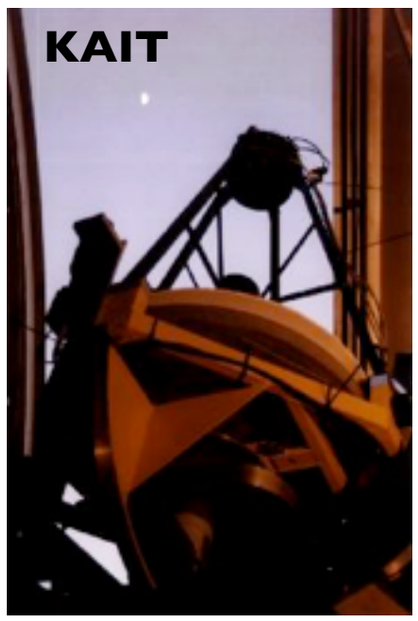

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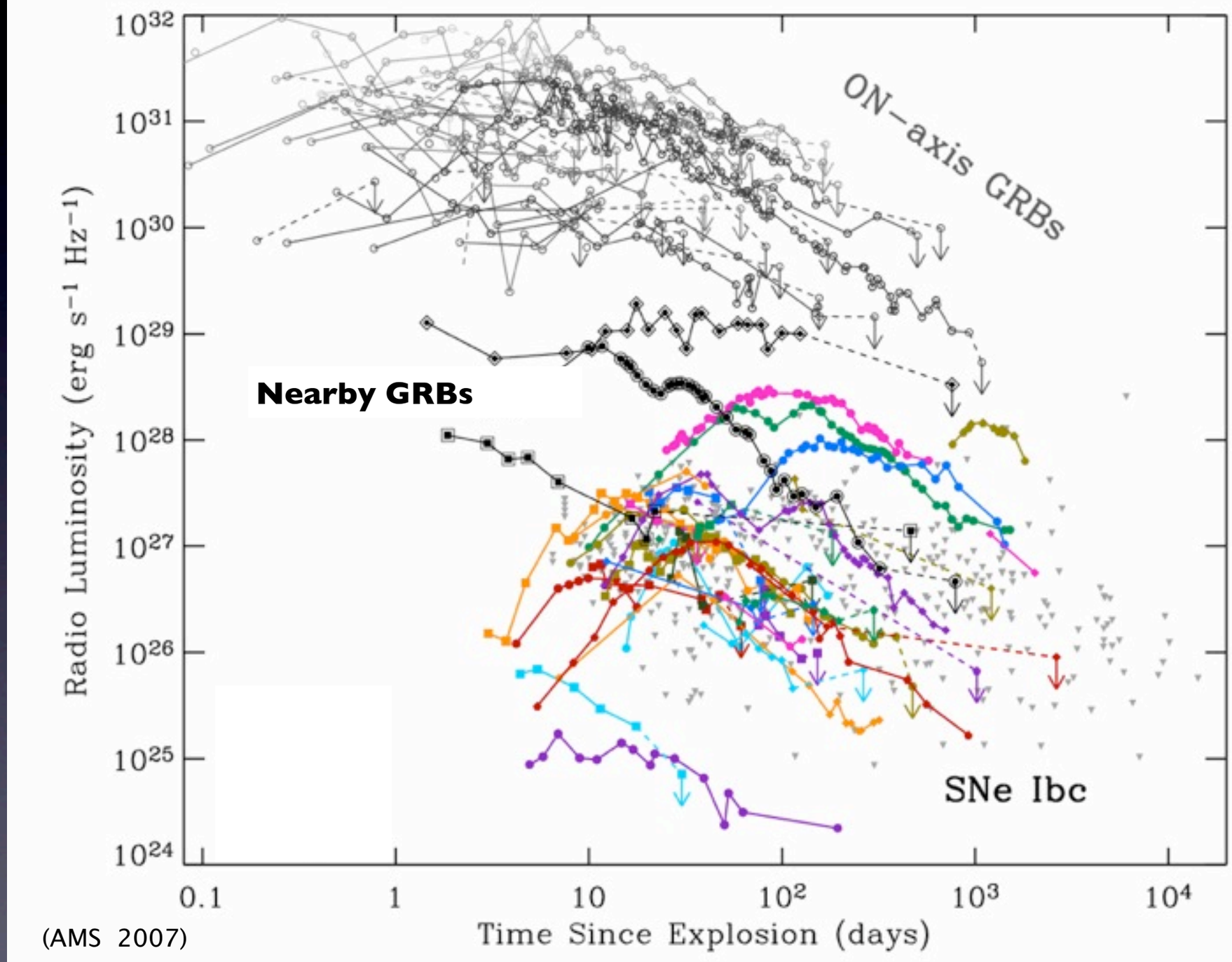
Radio Light-curves



(AMS 2007)

- 180 SNe Ibc
- detected 15%
- complete to 30 Mpc
- equal Ib/Ic/Ic-BL

- **Broad Diversity**
- ***None* like GRBs**

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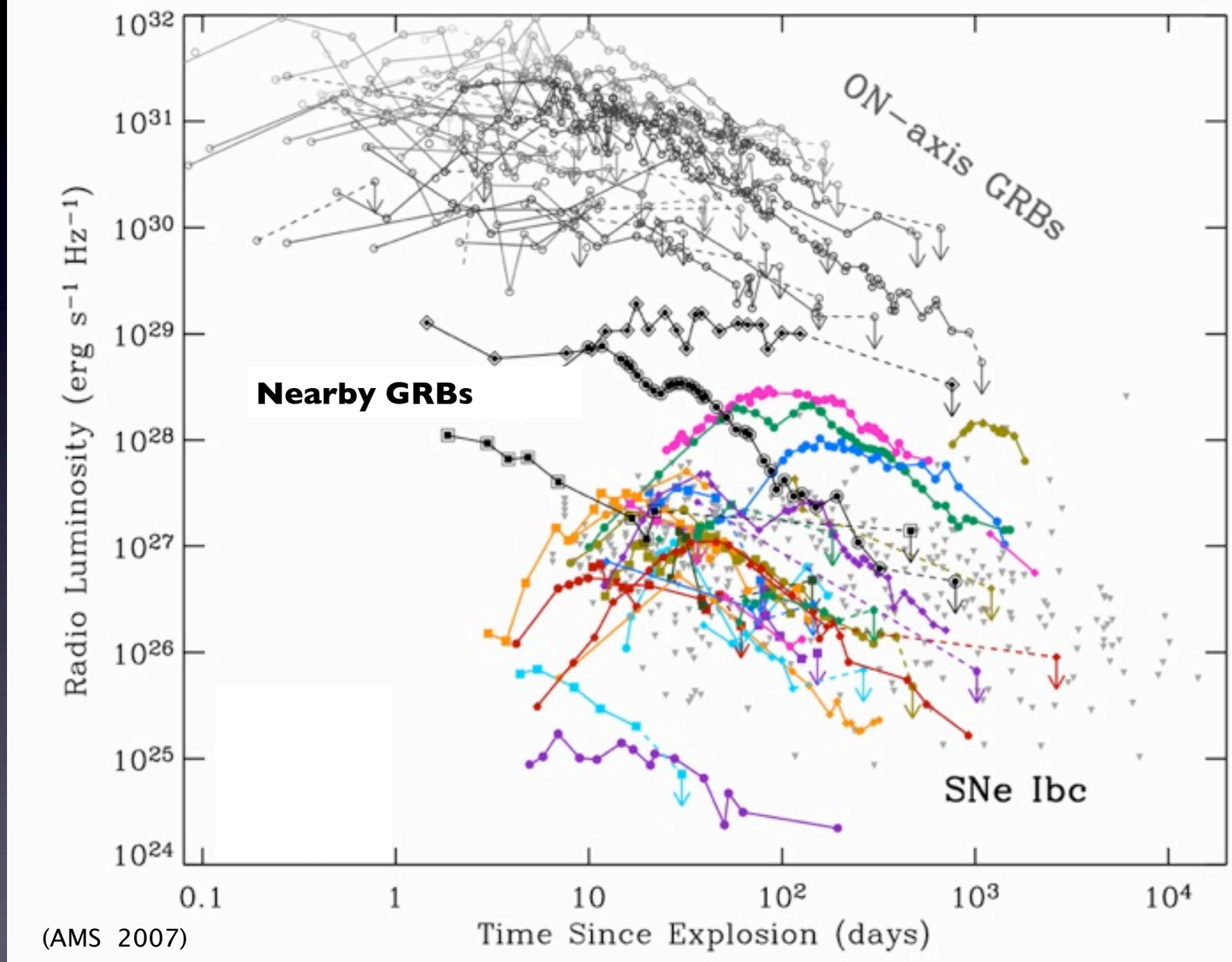

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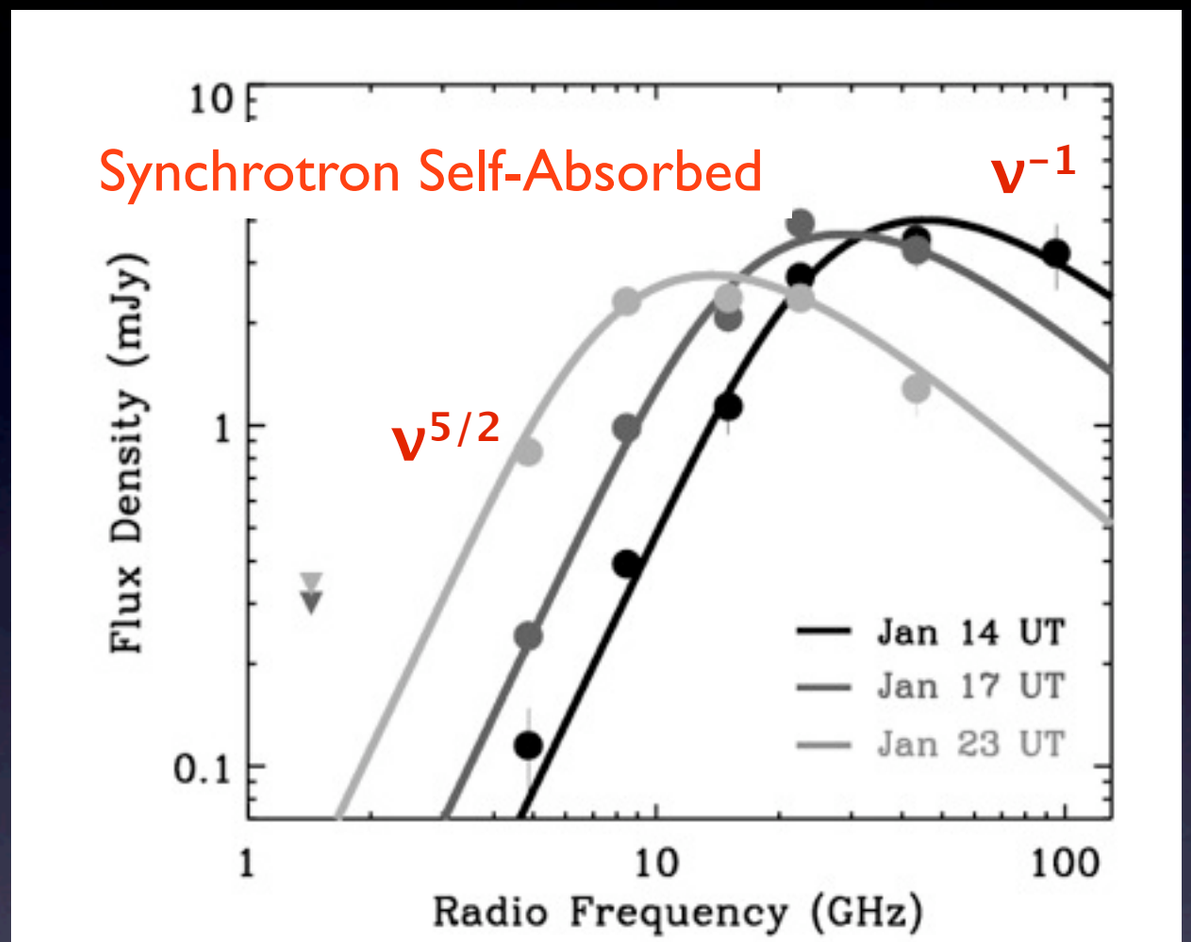
- ***None* like GRBs**

Radio SNe Ibc are DIVERSE. ***None as luminous as GRBs.***

Radio Modeling of SNe Ibc



$$\nu_m < \nu_a < \nu_c$$

- measure peak flux, peak frequency
- assume near equipartition (e^- & B)

$$T_B \propto L_\nu \nu^{-2} R^{-2} \sim 5 \times 10^{11}\ K$$

$$R \propto L_\nu^{9/19} \nu^{-1}$$
$$E \propto L_\nu^{23/19} \nu^{-1}$$
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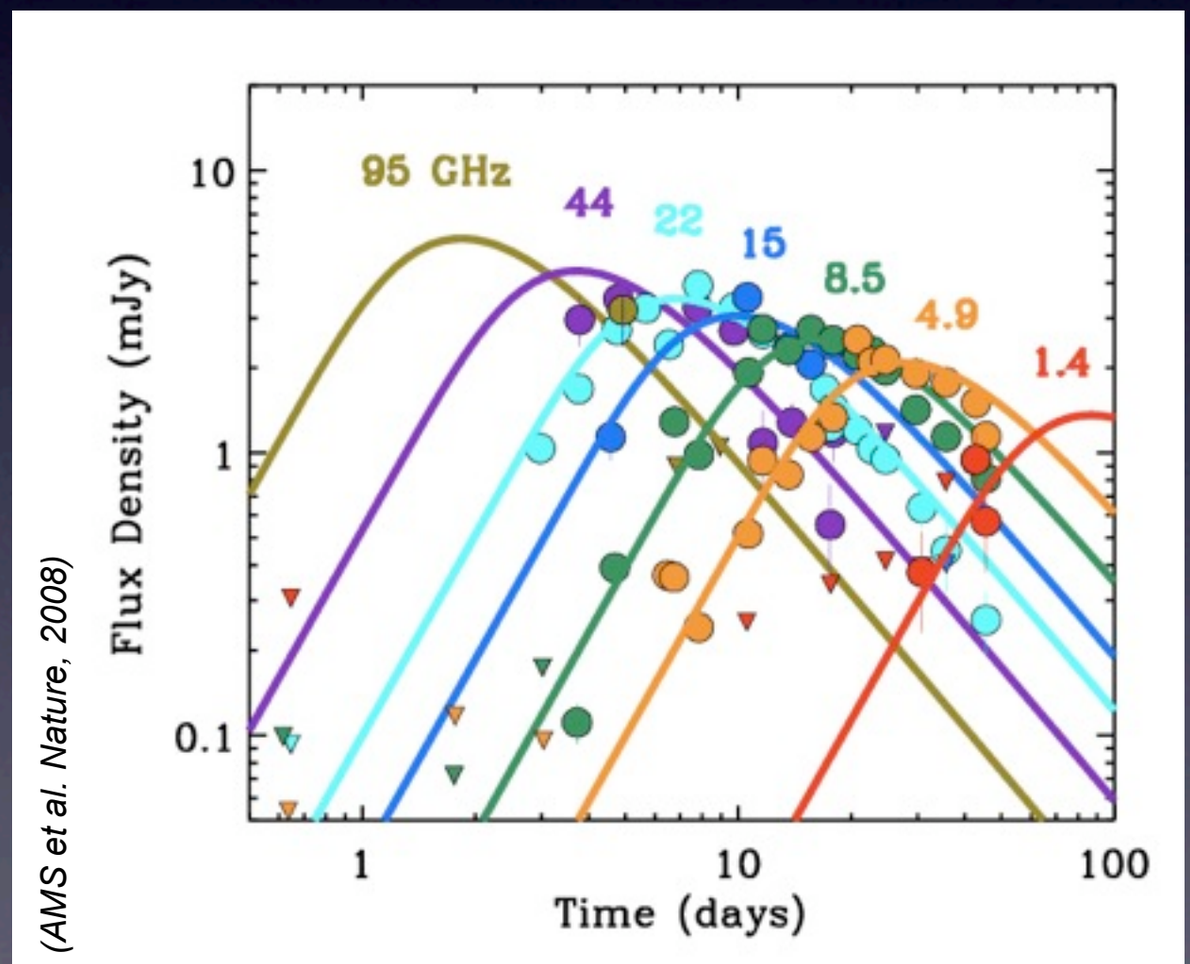

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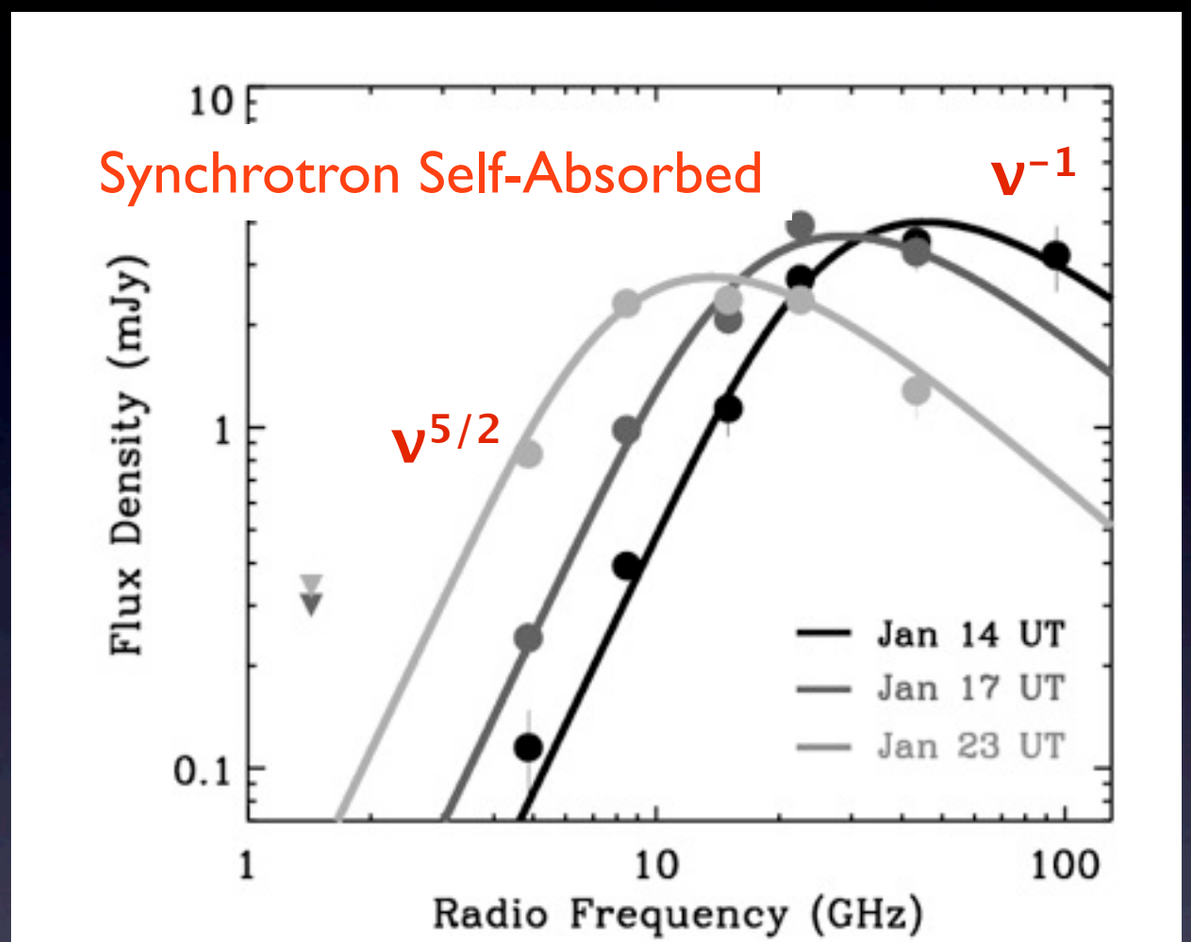

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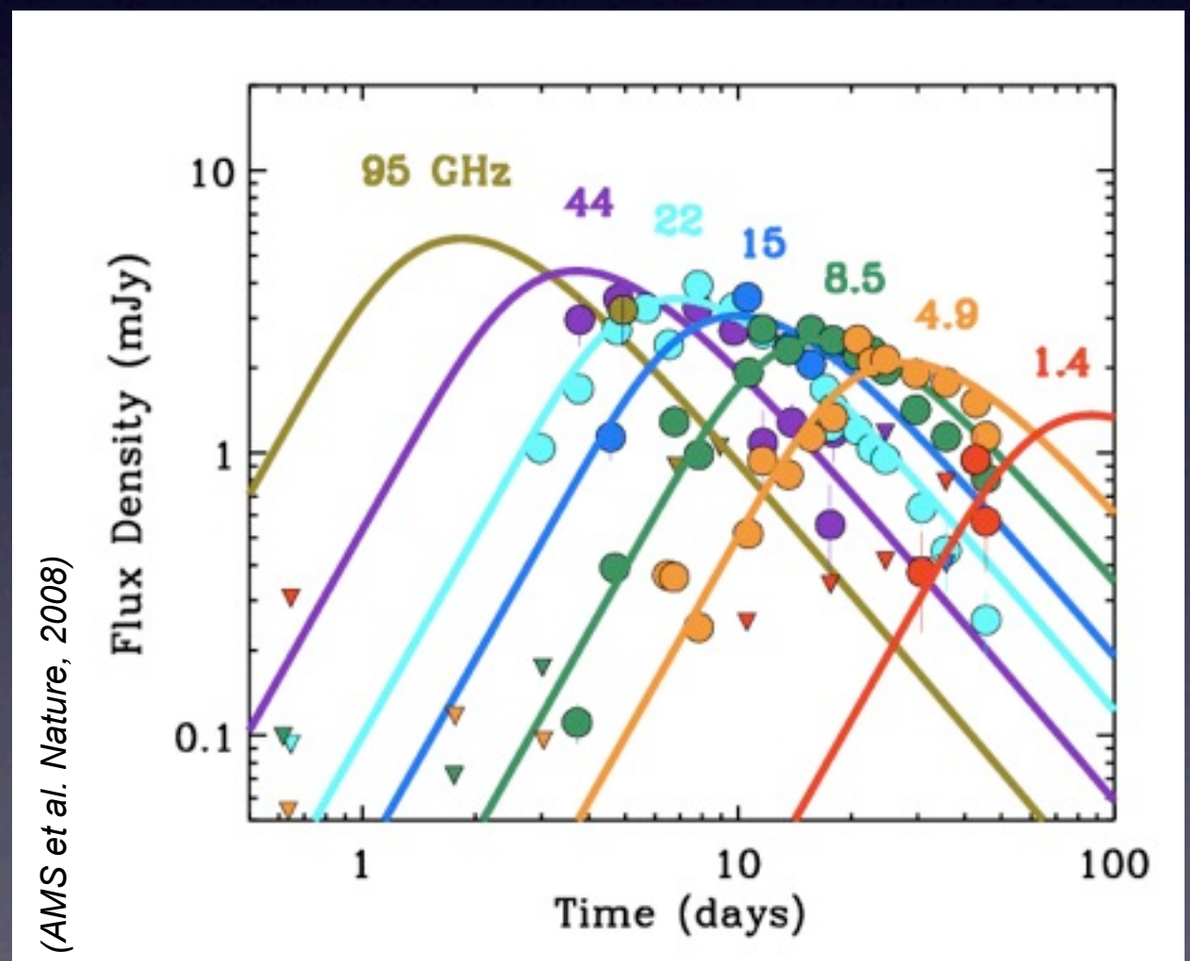

(AMS et al. Nature, 2008)

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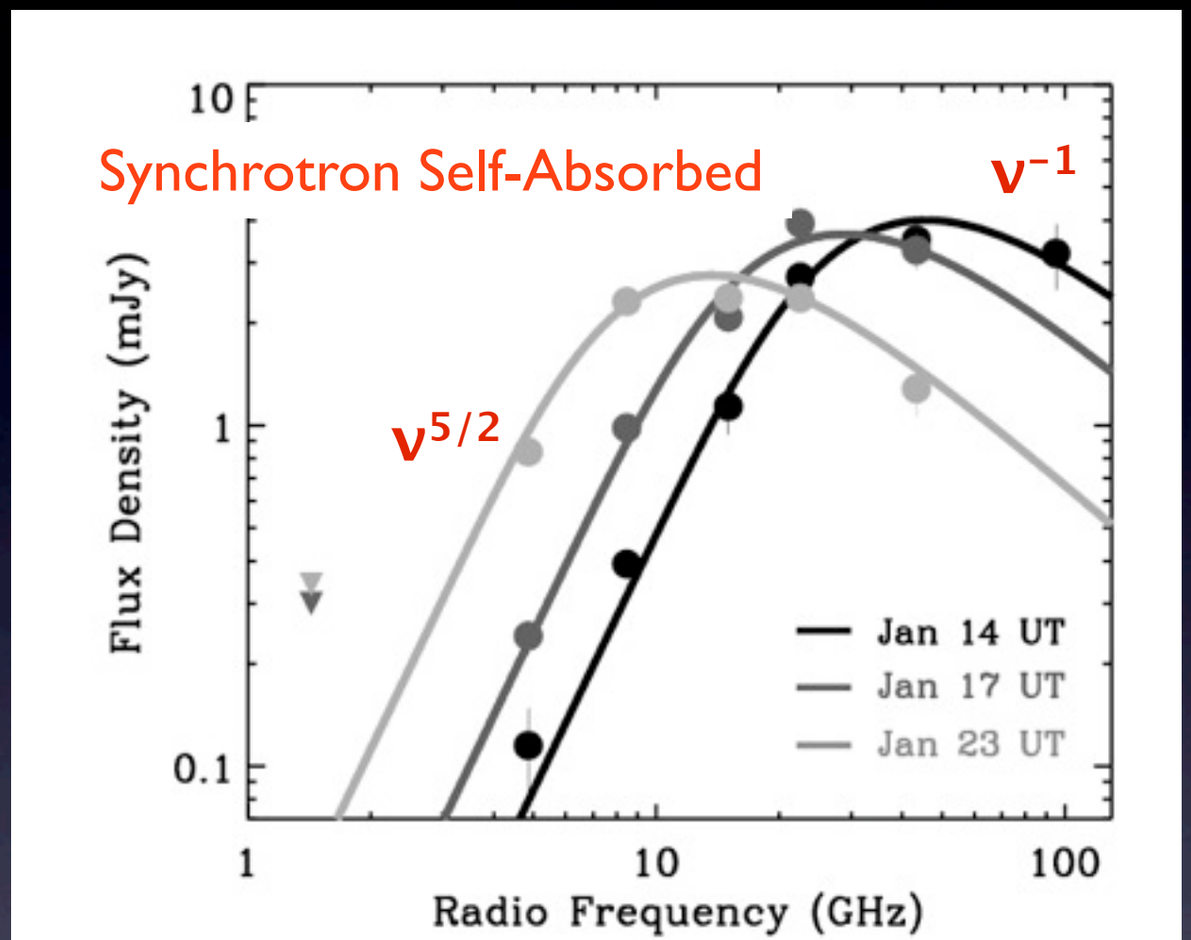

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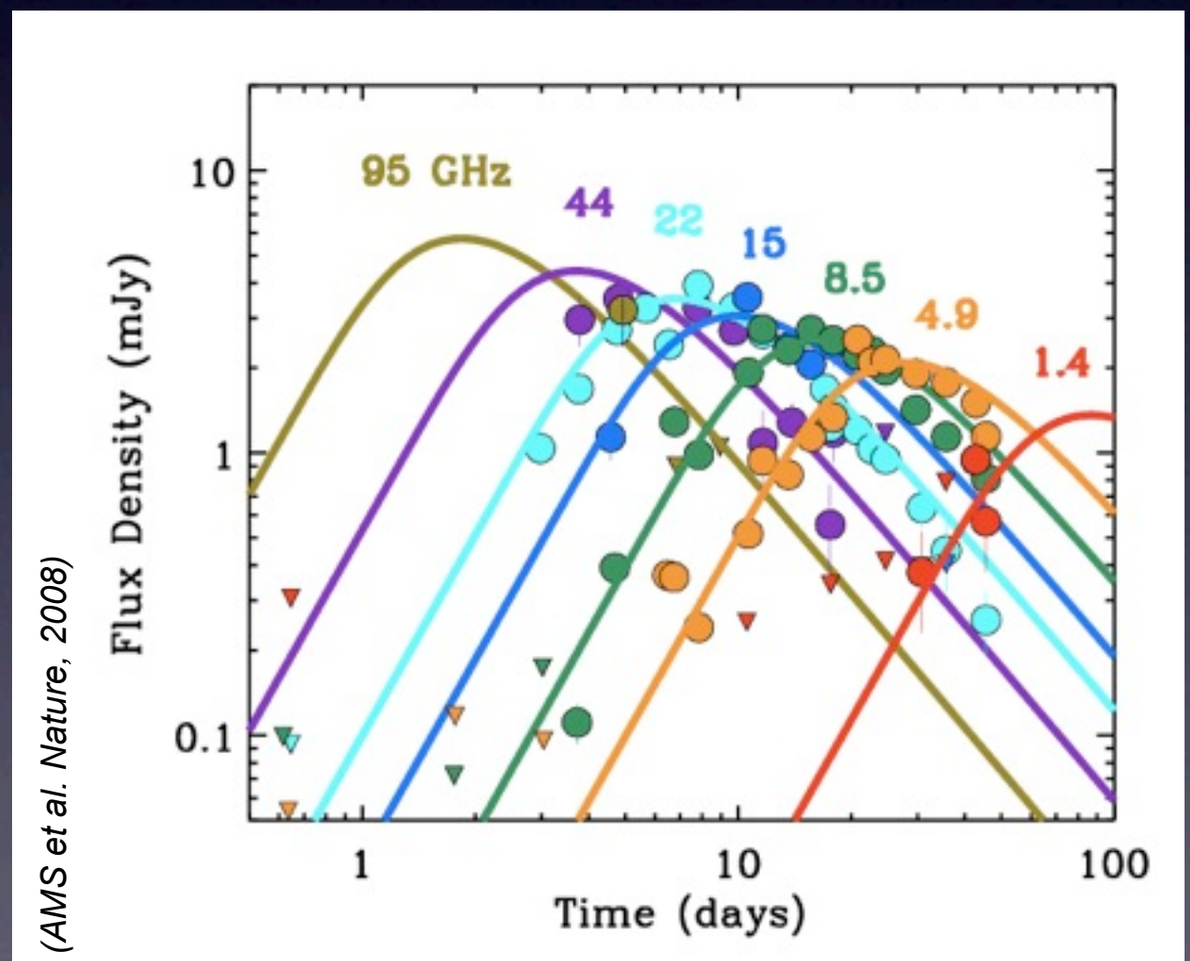

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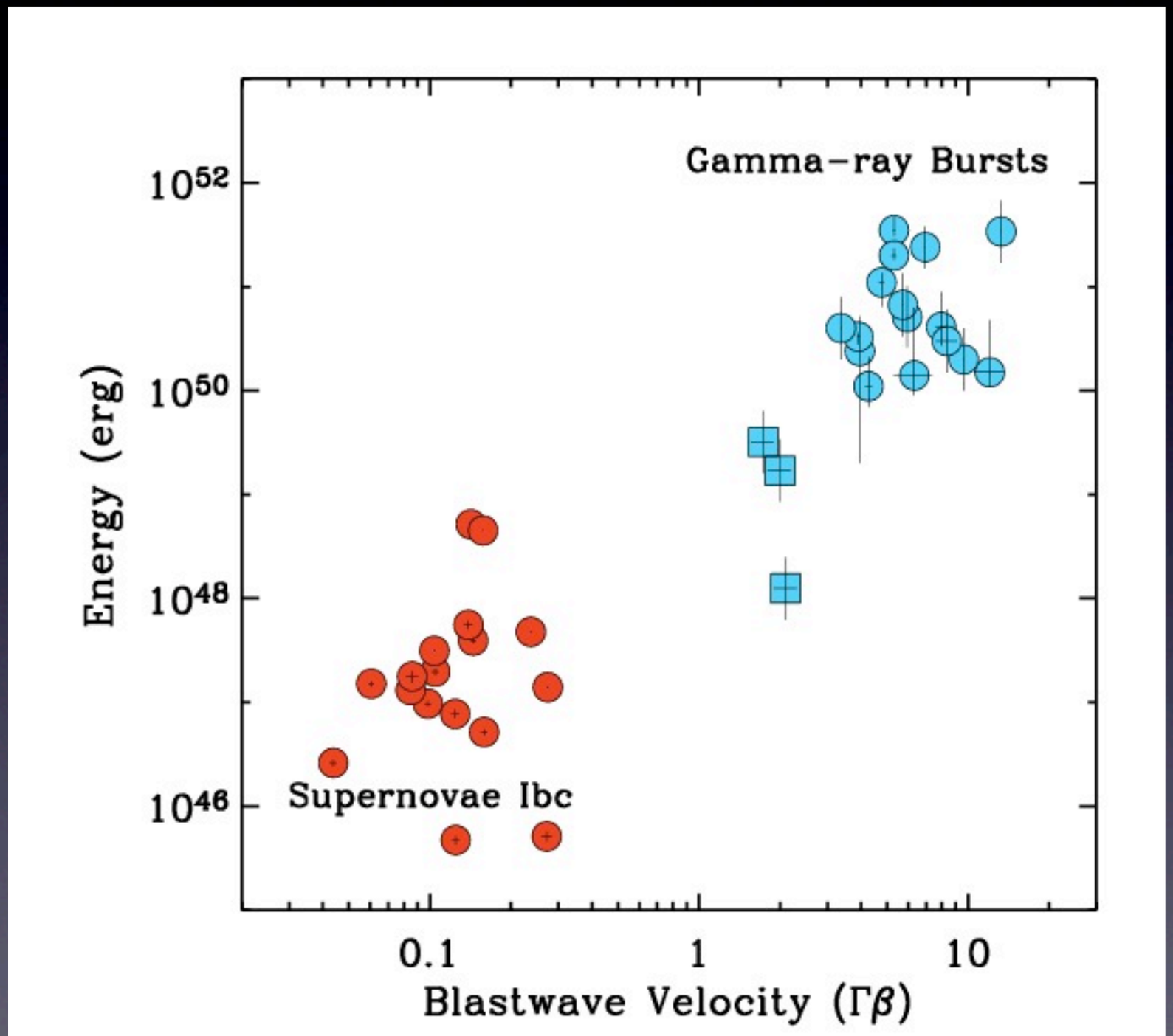


Ordinary Type Ibc SNe

$v \approx 0.15c$

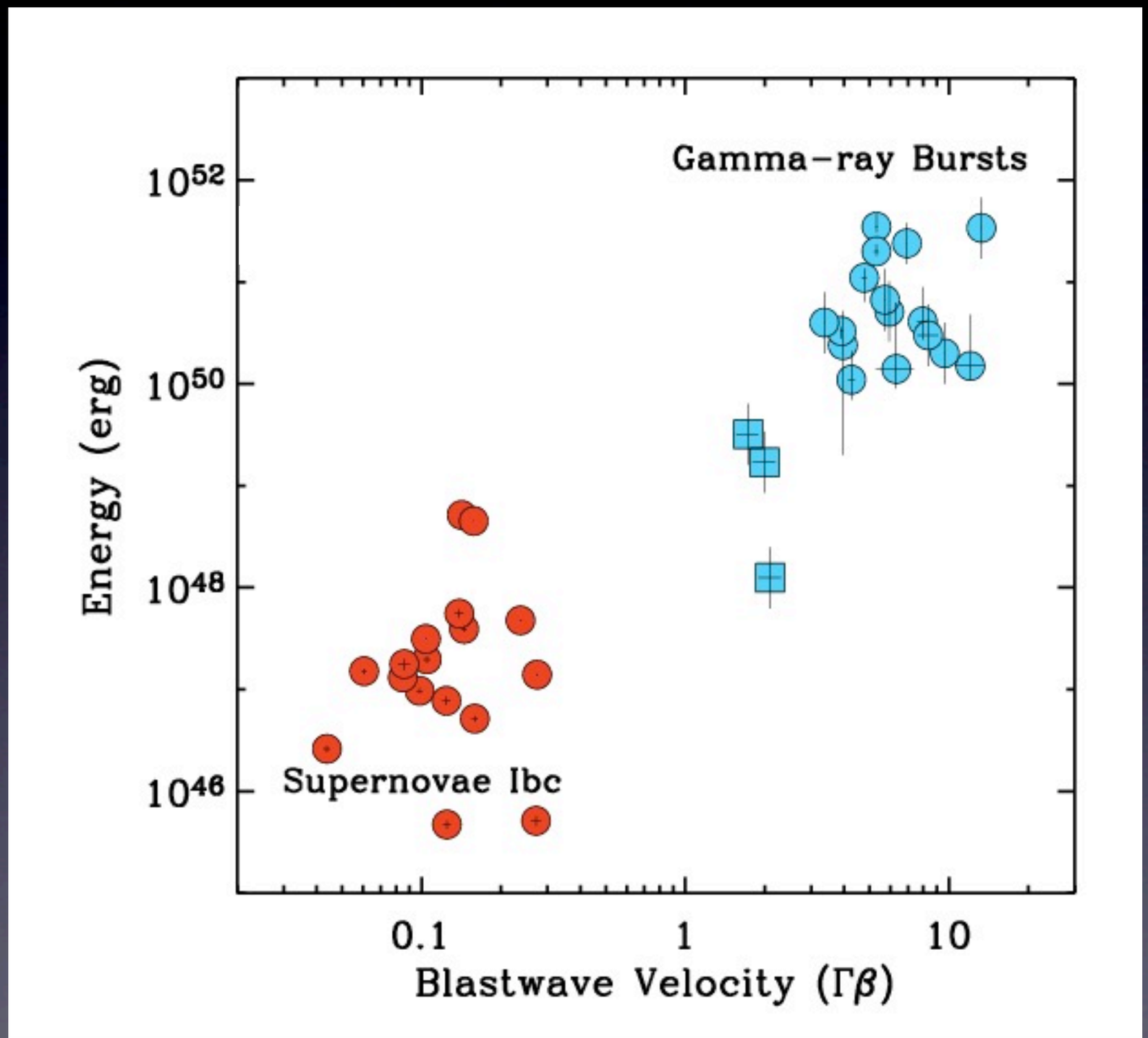
$E \approx 10^{47}$ erg

Engine-driven Supernovae

$\Gamma\beta > 1$

$E_K > 10^{48}$ erg

The *Extra*-ordinary SN 2009bb



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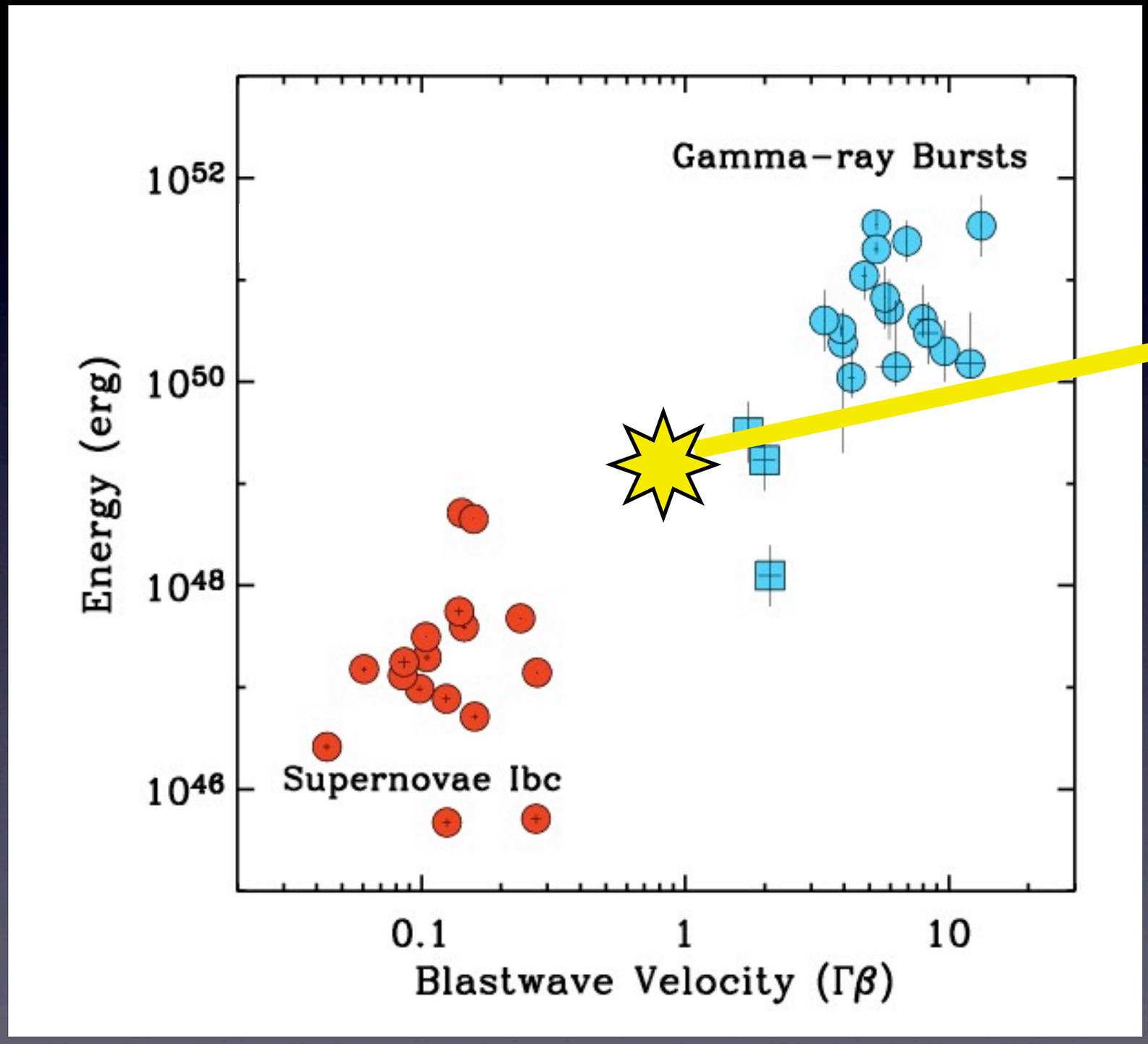

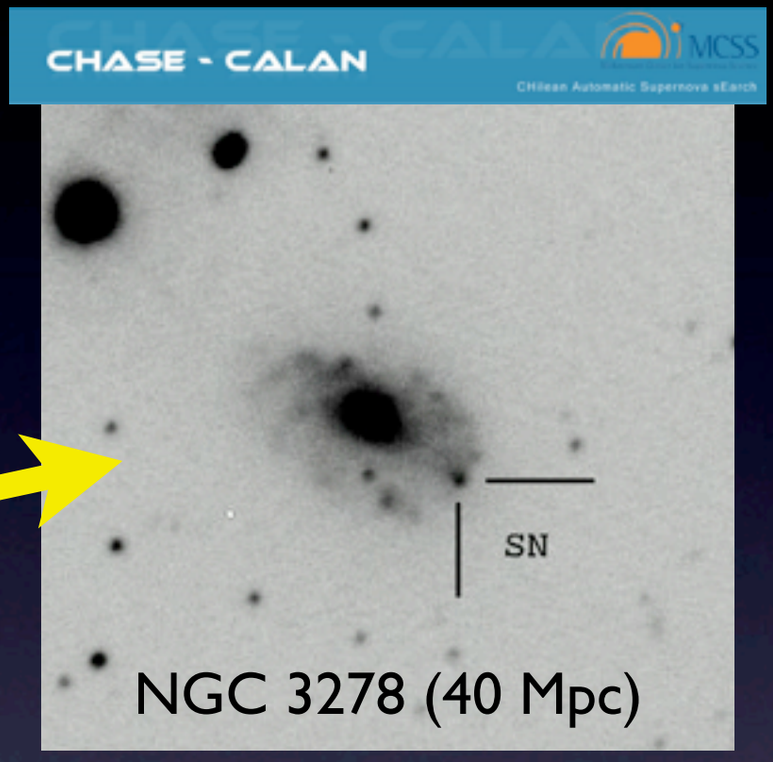

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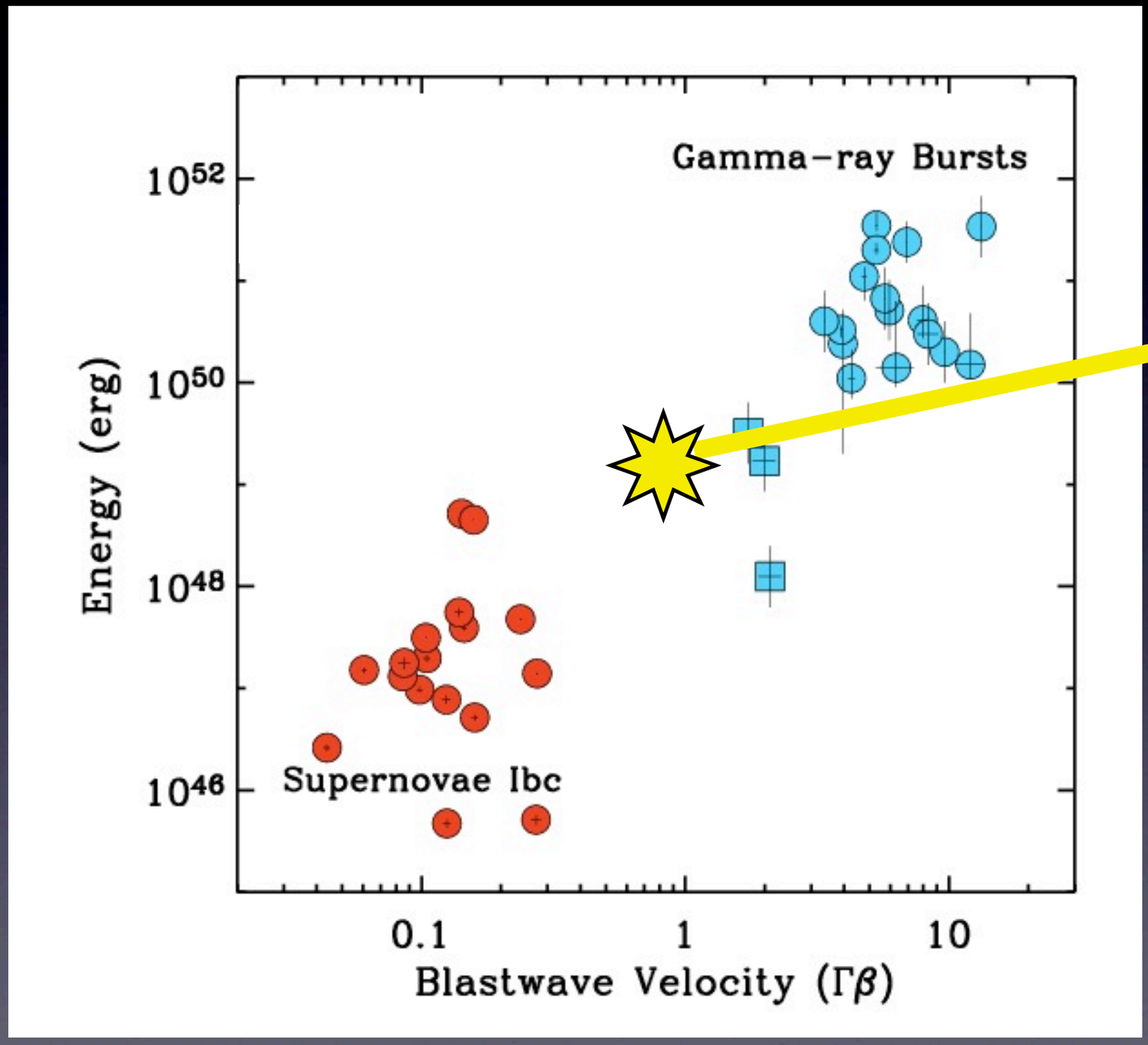
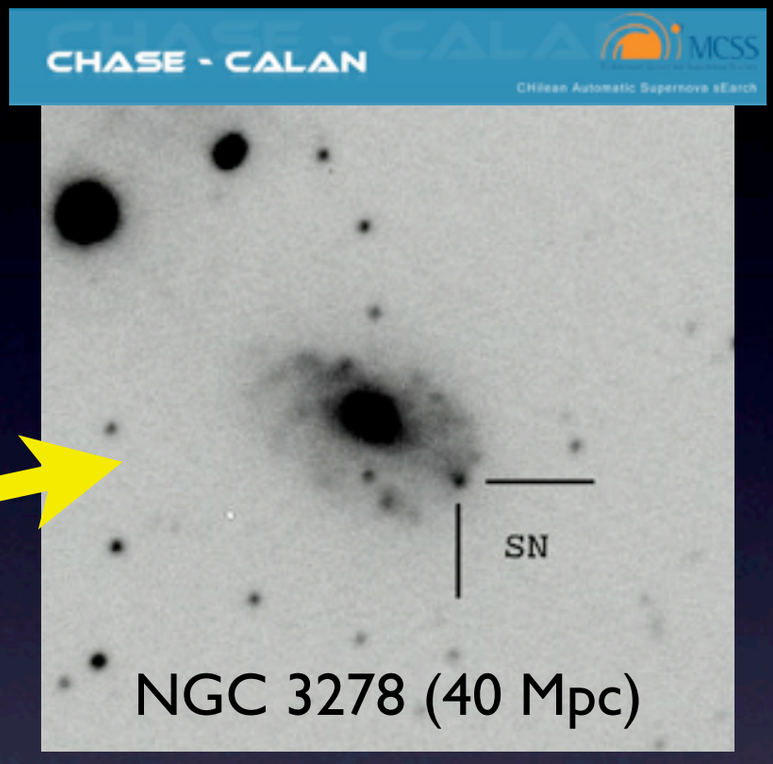




SN 2009bb

Discovered: Mar 21 2009

Explosion Date: Mar 19 +/- 1 day

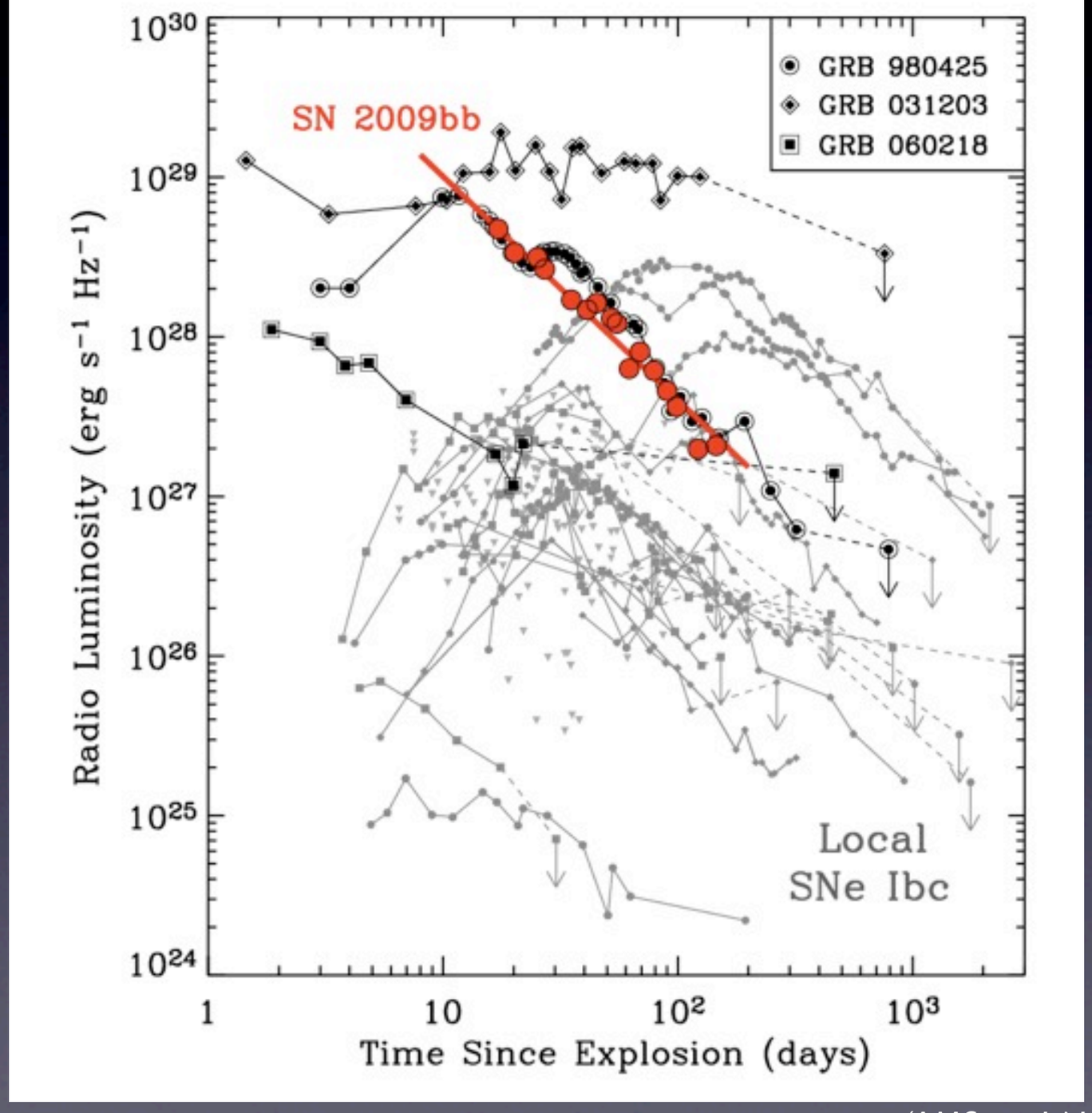
SN Ic-BL

(Pignata et al 2010)

NO coincident GRB

$E_\gamma < 10^{48}$ erg

An Engine-driven SN without a GRB trigger

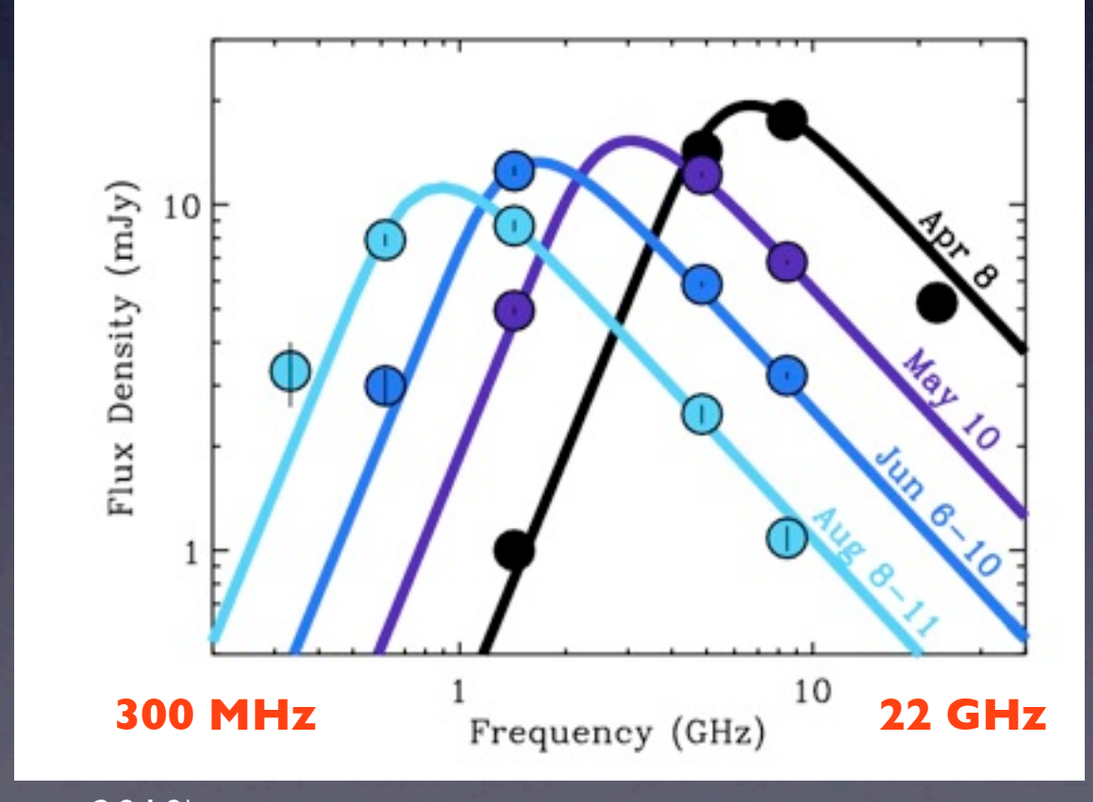


$L_\nu \sim 5 \times 10^{28}$ erg/s/Hz

(more luminous than 142 VISioNS *SNe Ibc)*

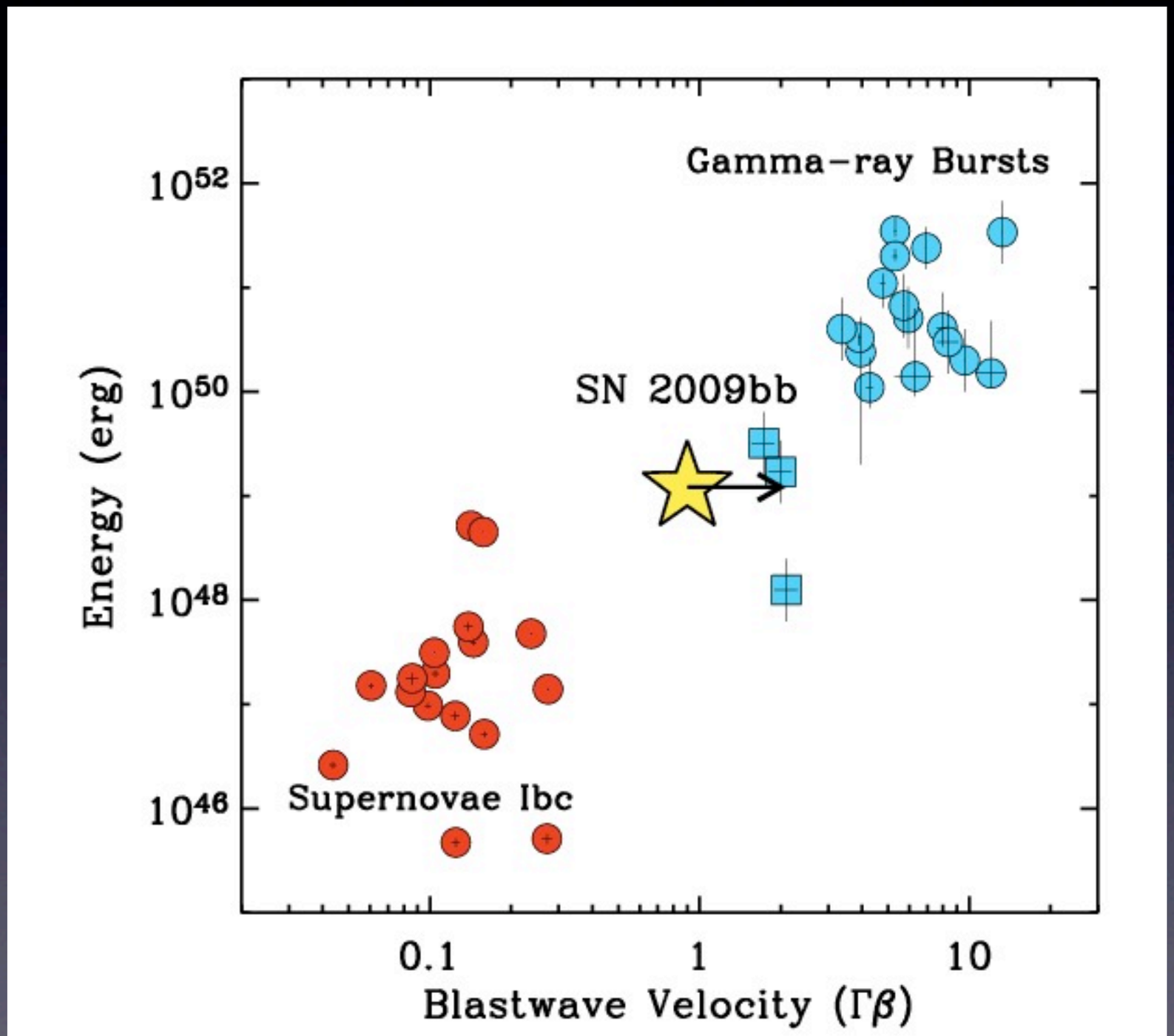
VLA + Giant Meterwave Radio Telescope

Synchrotron self-absorbed radio spectra



(AMS et al. Nature, 2010)

An Engine-driven SN without a GRB trigger



$v \approx 0.9c$

$\Gamma \sim 1.3$

$E > 10^{49}$ erg

(AMS et al. Nature, 2010)

Shock acceleration

requires $\mathbf{E_{tot} > 10^{53}}$ **erg**

09bb powered by a

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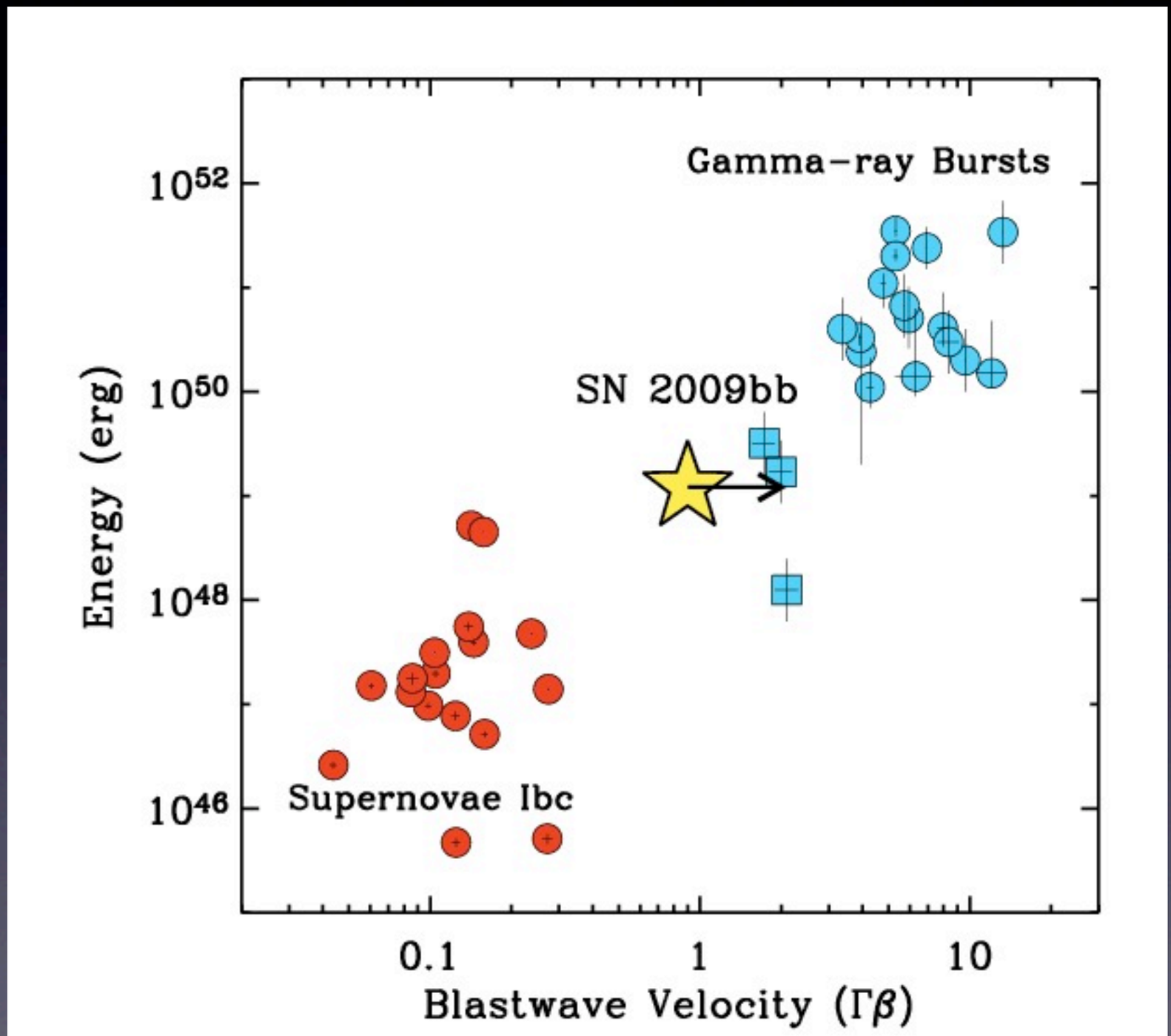

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09bb powered by a ***central engine***

Independent Measurement of the Volumetric Rates

Supernovae Ibc

10^4 Gpc^{-3} yr^{-1}

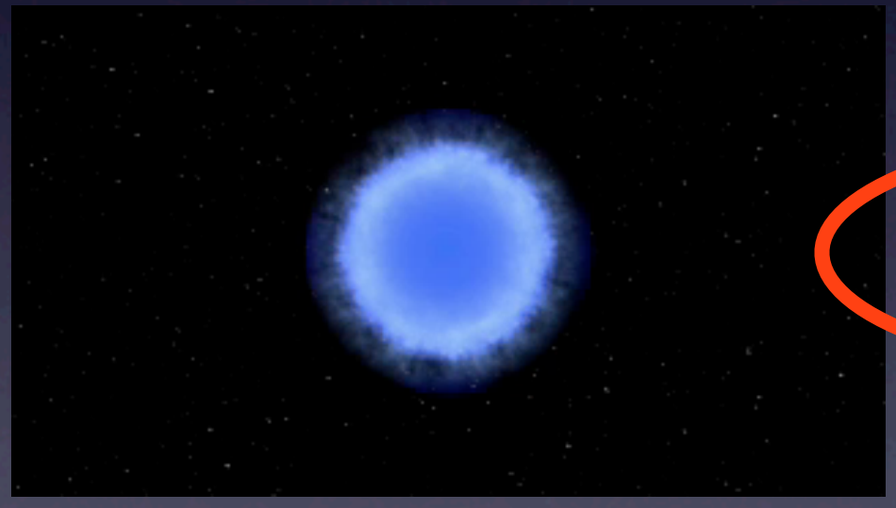
Long GRBs

0.5 Gpc^{-3} yr^{-1} (*on-axis*)

jets ~ 5-10 deg

50 Gpc^{-3} yr^{-1}

(0.5%)



$\times\ 0.7^{+1.6}_{-0.6}\% =$

✓ Consistent with rate of nearby GRBs

Revealing engine-driven SN without a satellite trigger

PALOMAR TRANSIENT FACTORY

Expanded Very Large Array

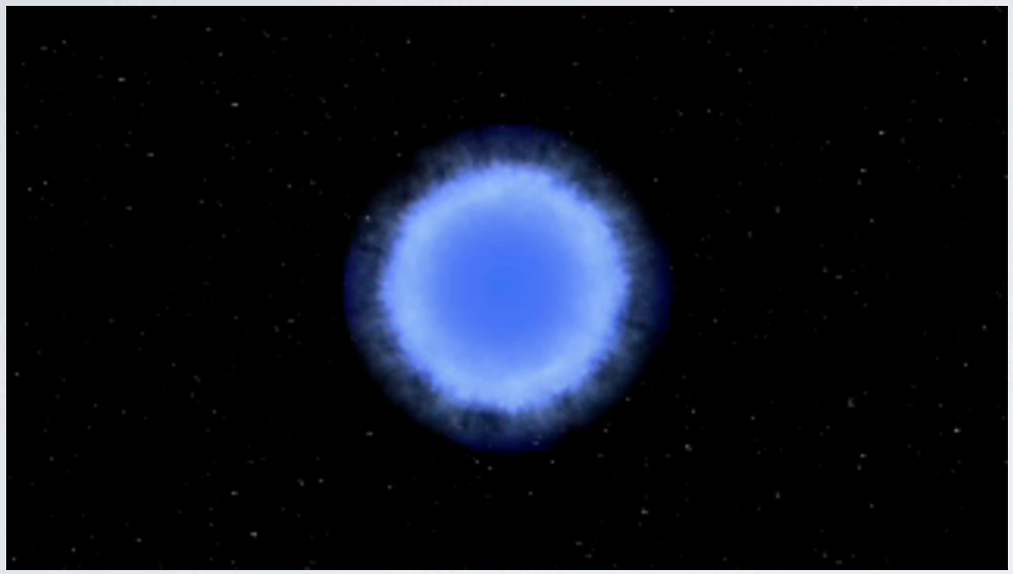
Nearby GRB-SNe *(z < 0.1)*

γ-ray satellites ➠ 0.3 engine-driven SN/yr

optical + radio ➠ 1 engine-driven SN/yr

3 x higher discovery rate

II. **Optical Properties:** SNe Ibc



First recognized in 1985

- Spectra: No H-features, IME
  25% He-features, 5-10% BL
- Light-curves: bell-shaped (e.g. Ia)

➔ core-collapse of *NAKED* massive stars

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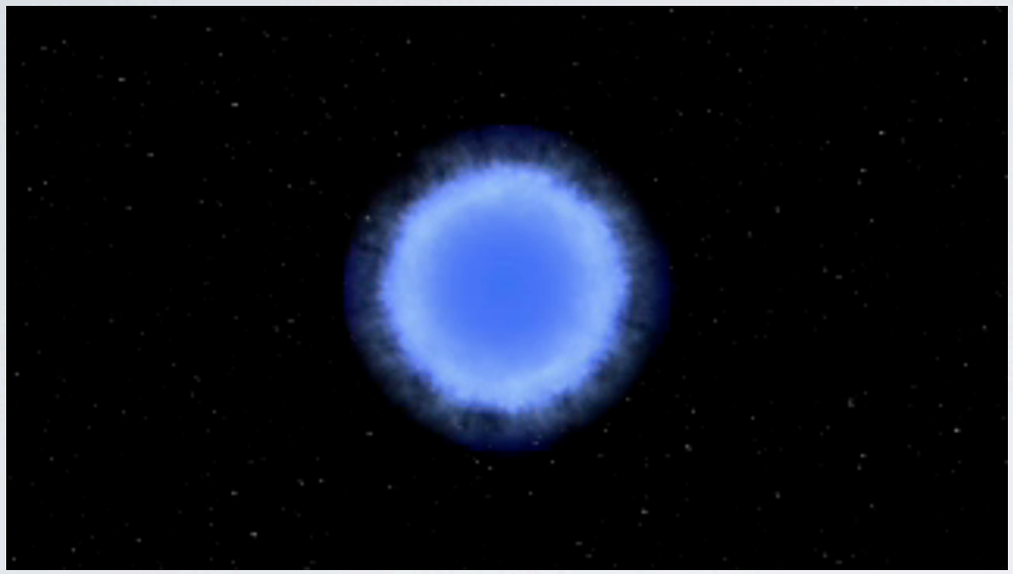

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Progenitors not yet identified directly in pre-explosion imaging ***(Smartt 2009)***

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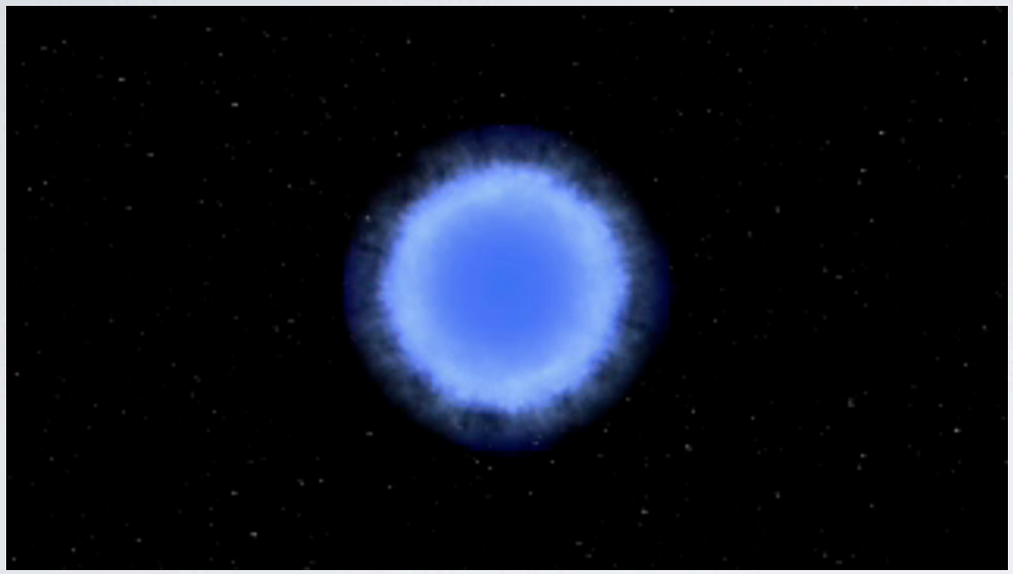

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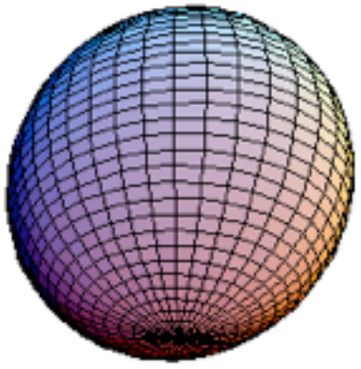
Isolated Wolf-Rayet Star

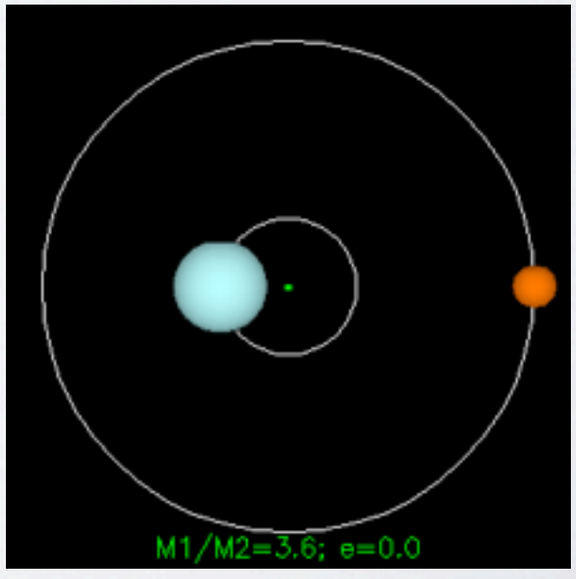
M > 20 M⊙



Two Primary Channels

Binary System

M > 8 M⊙



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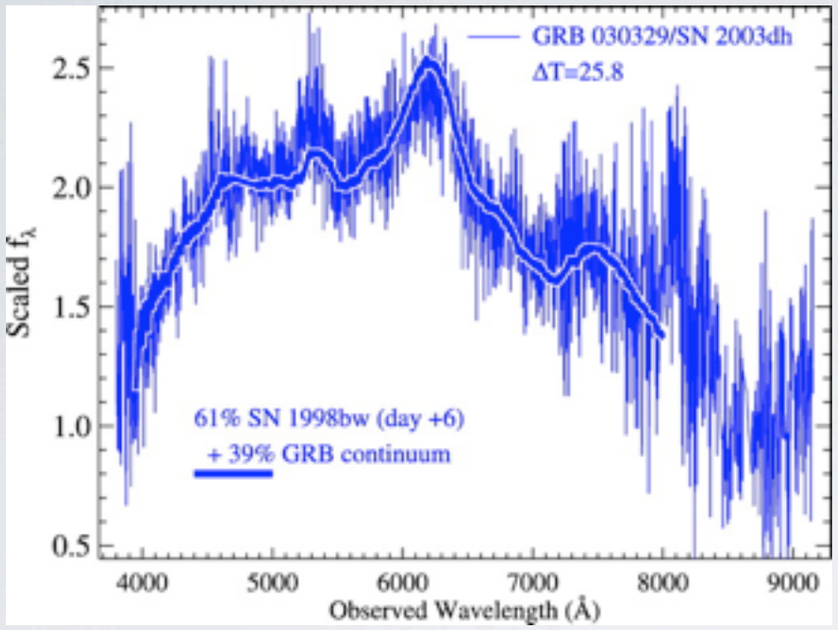
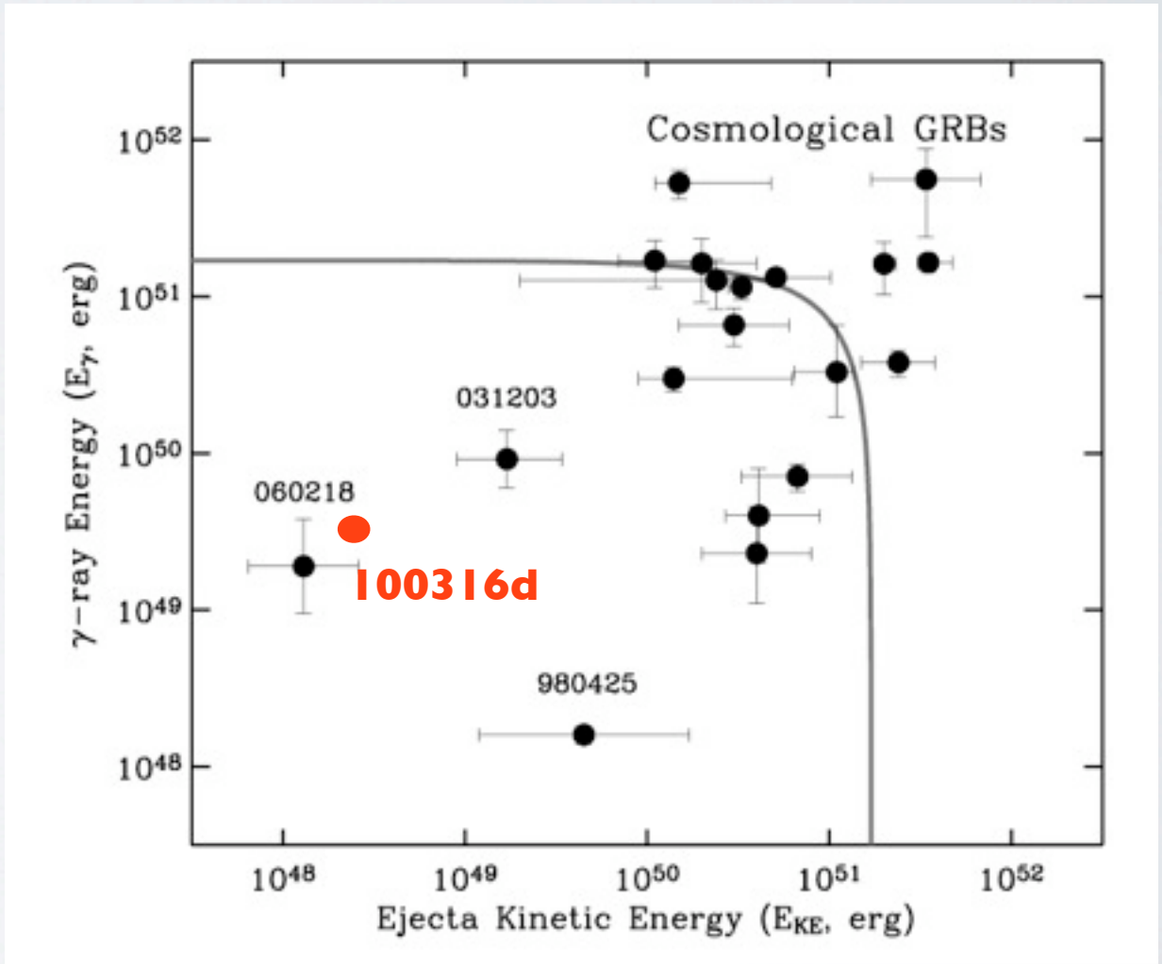


(Matheson et al 2003)

GRB-SNe:

- (almost) *all* nearby GRBs have SNe
- GRB-SNe *always* SNe Ic-BL
- Often quoted as *over-luminous*



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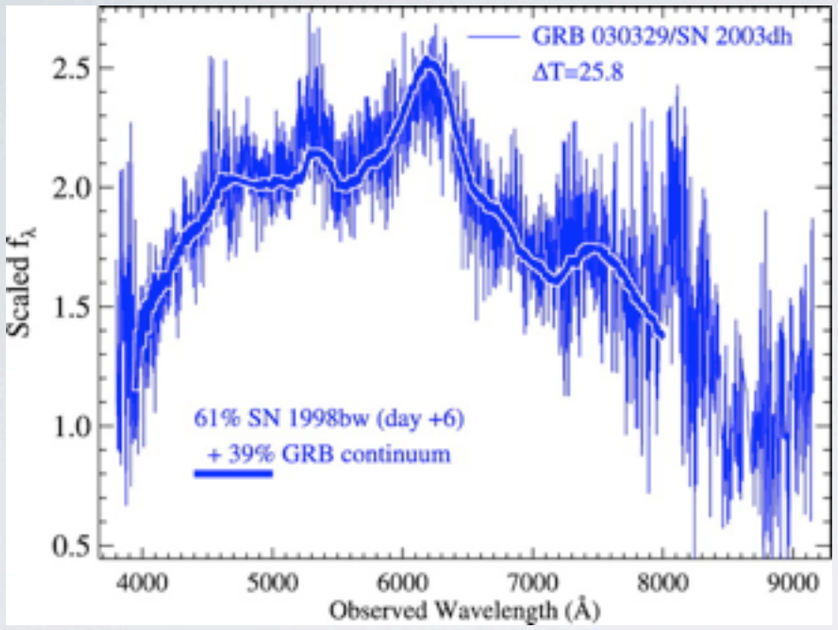

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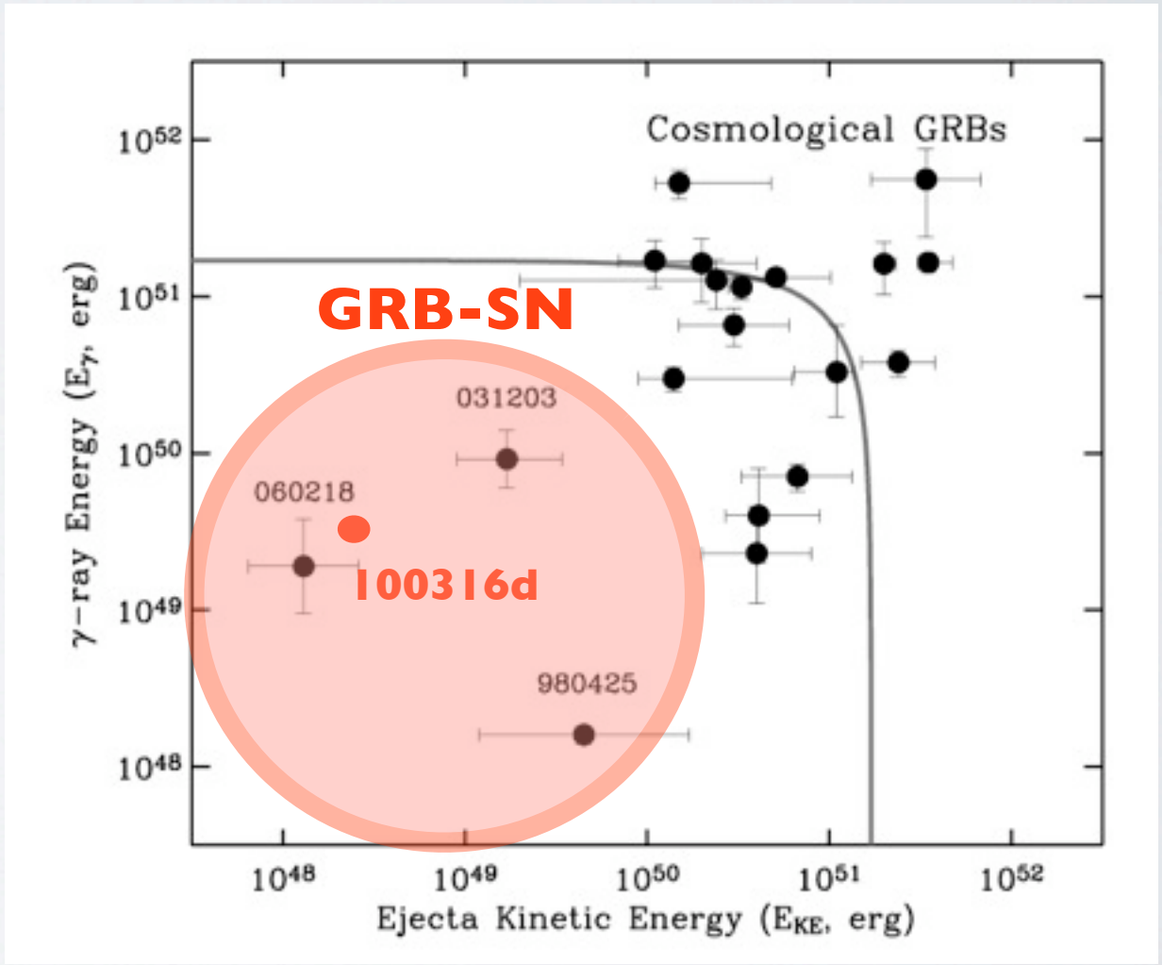

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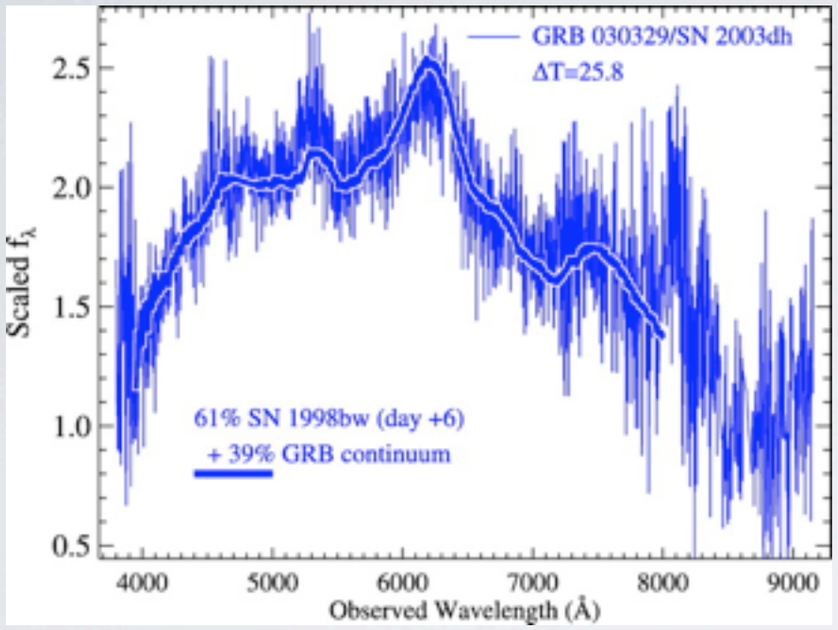

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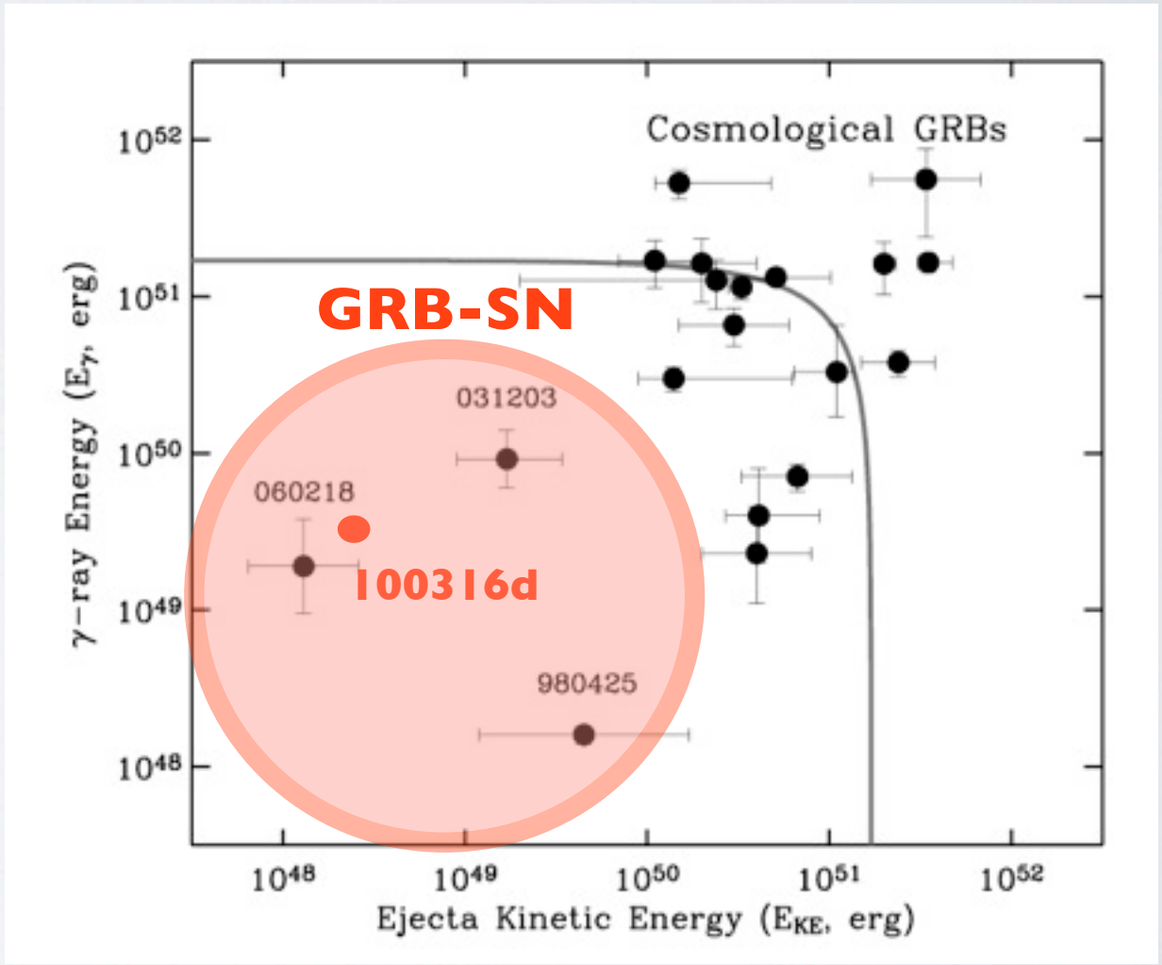
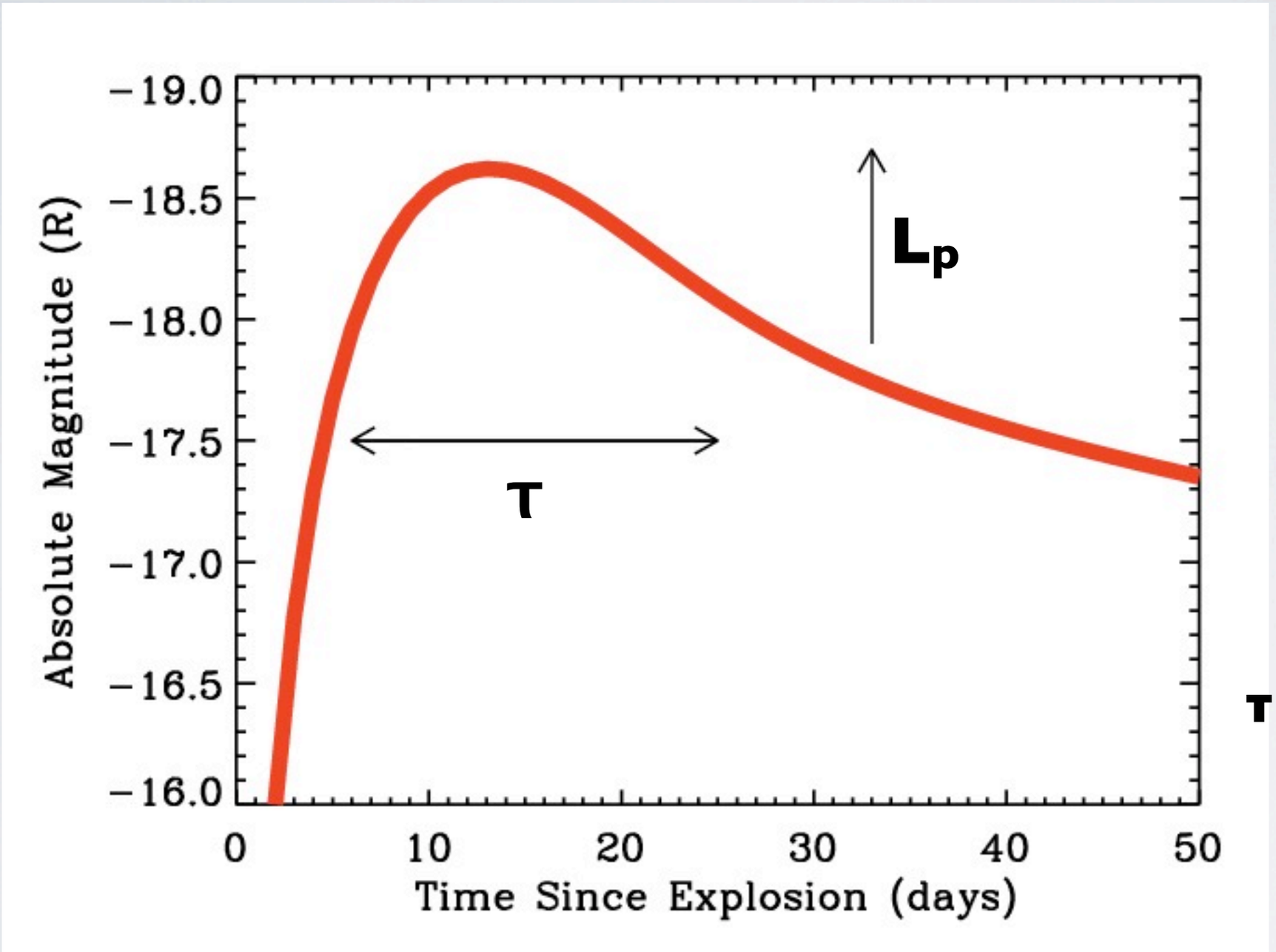


1% of SNe Ibc harbor an additional key ingredient

Optical Light-Curve SN Ibc Diagnostics



3 parameters:

E_K, M_{ej}, M_{Ni}

$$L_p \propto M_{Ni}$$

$$\tau \propto M_{ej}^{3/4} E_{K,51}^{-1/4}$$

(e.g., Arnett 1982)

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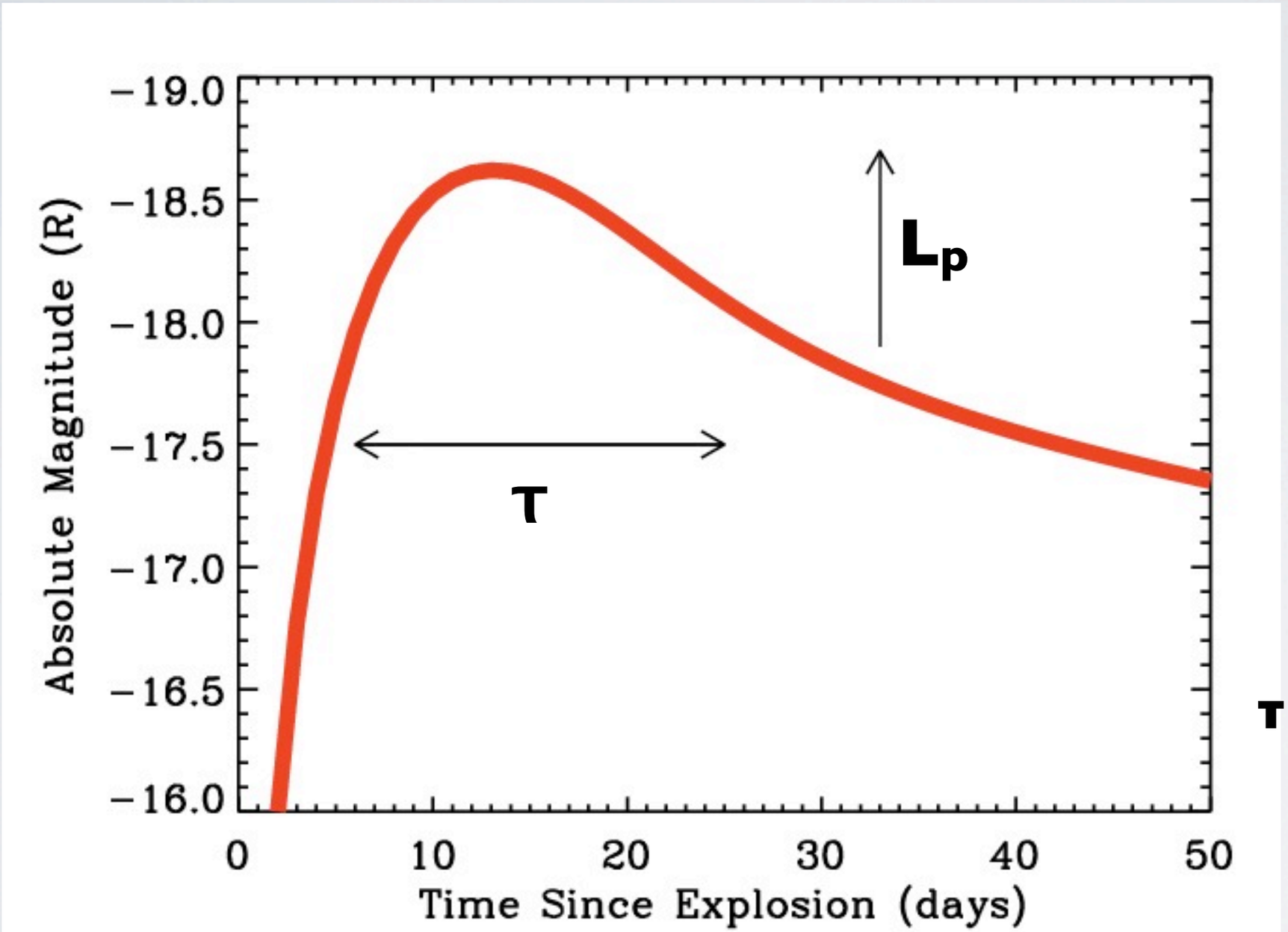

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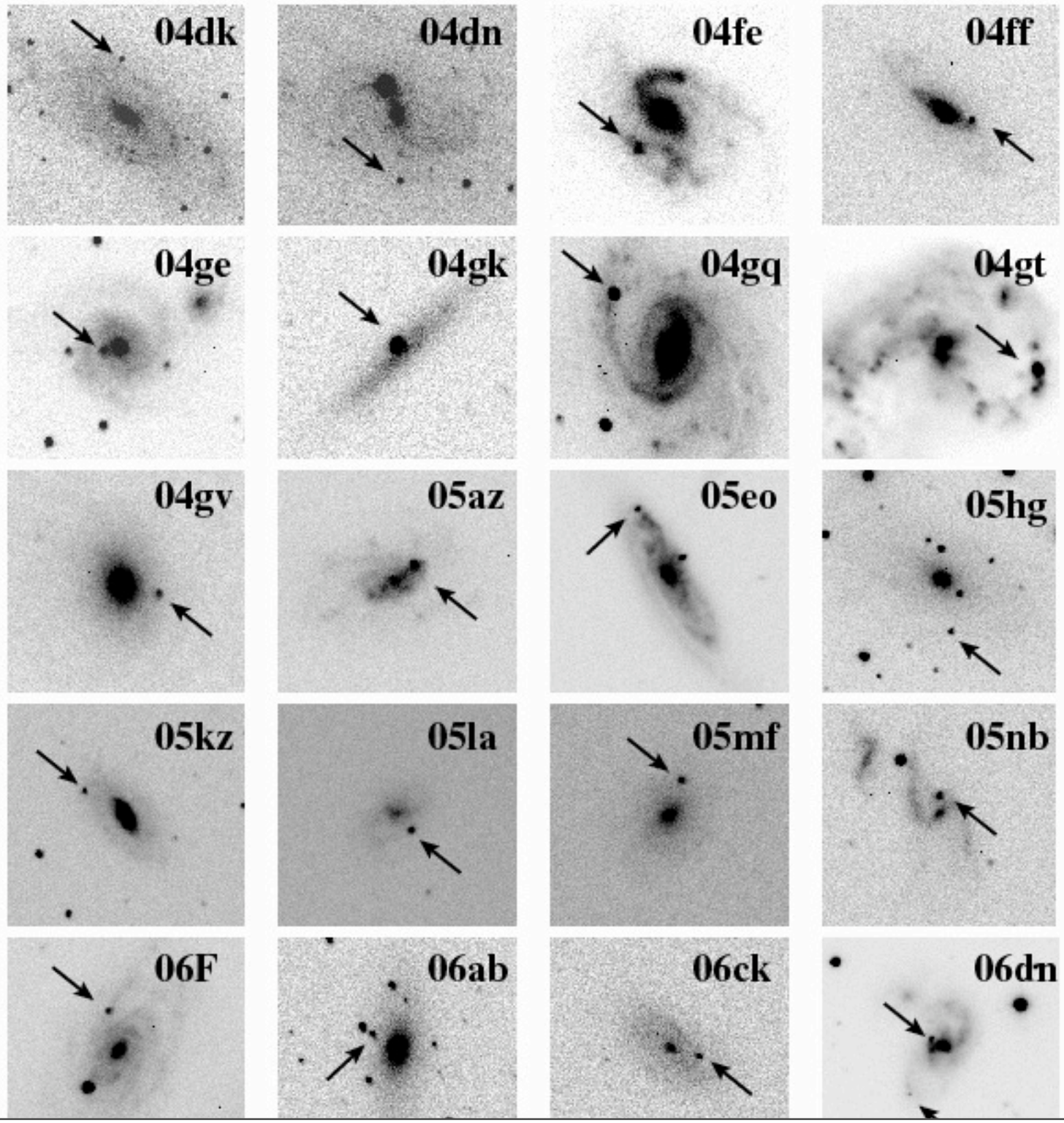
Parameters determined for just 10 SNe Ibc to date, 3 Engine-driven SNe

A Systematic Study of SN Ibc Light-curves



25 SNe Ibc
d < 150 Mpc
V- and R-band photometry

(Drout, AMS et al 2010)

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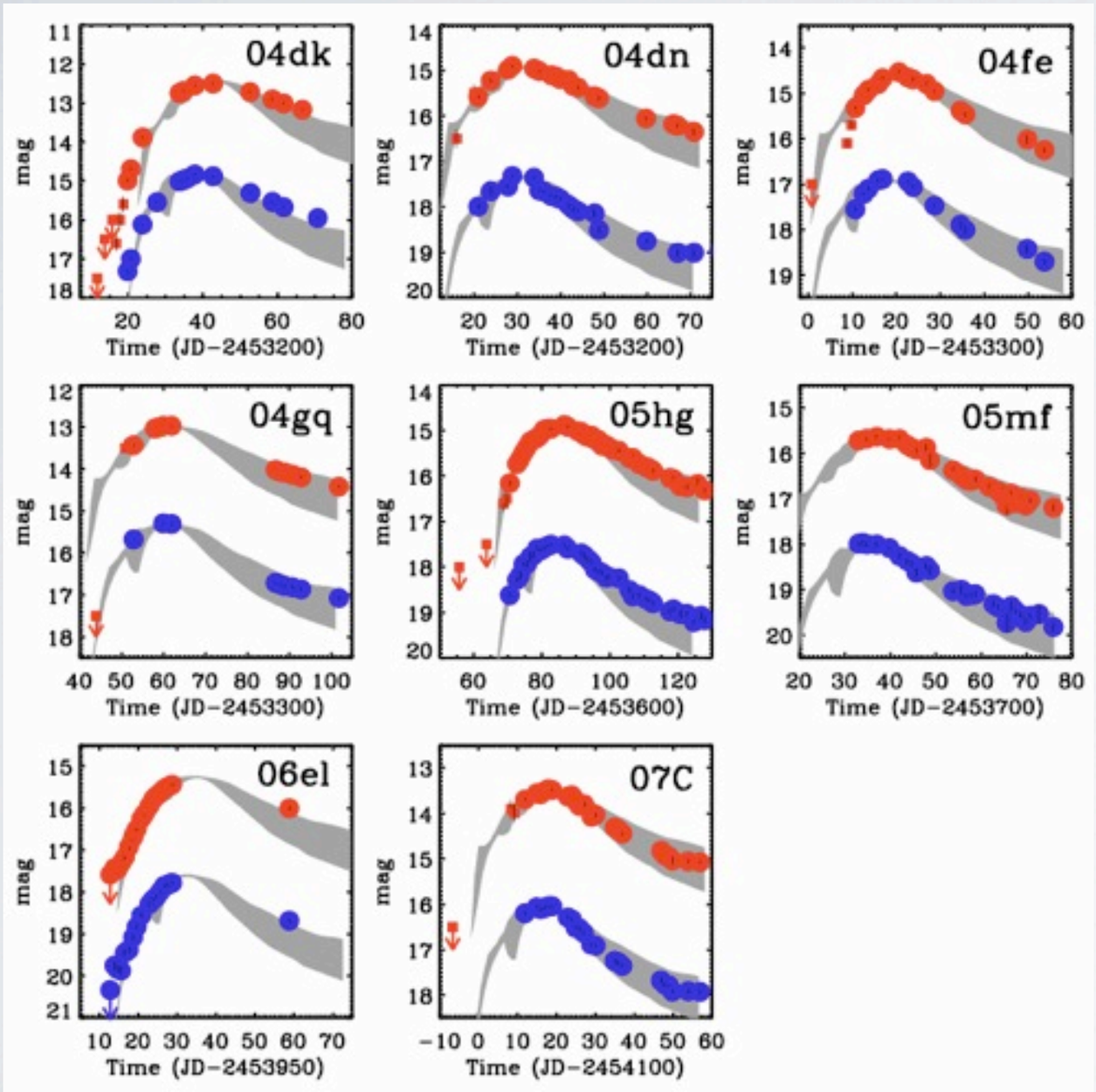

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L_p, τ measured for 17 SNe Ibc

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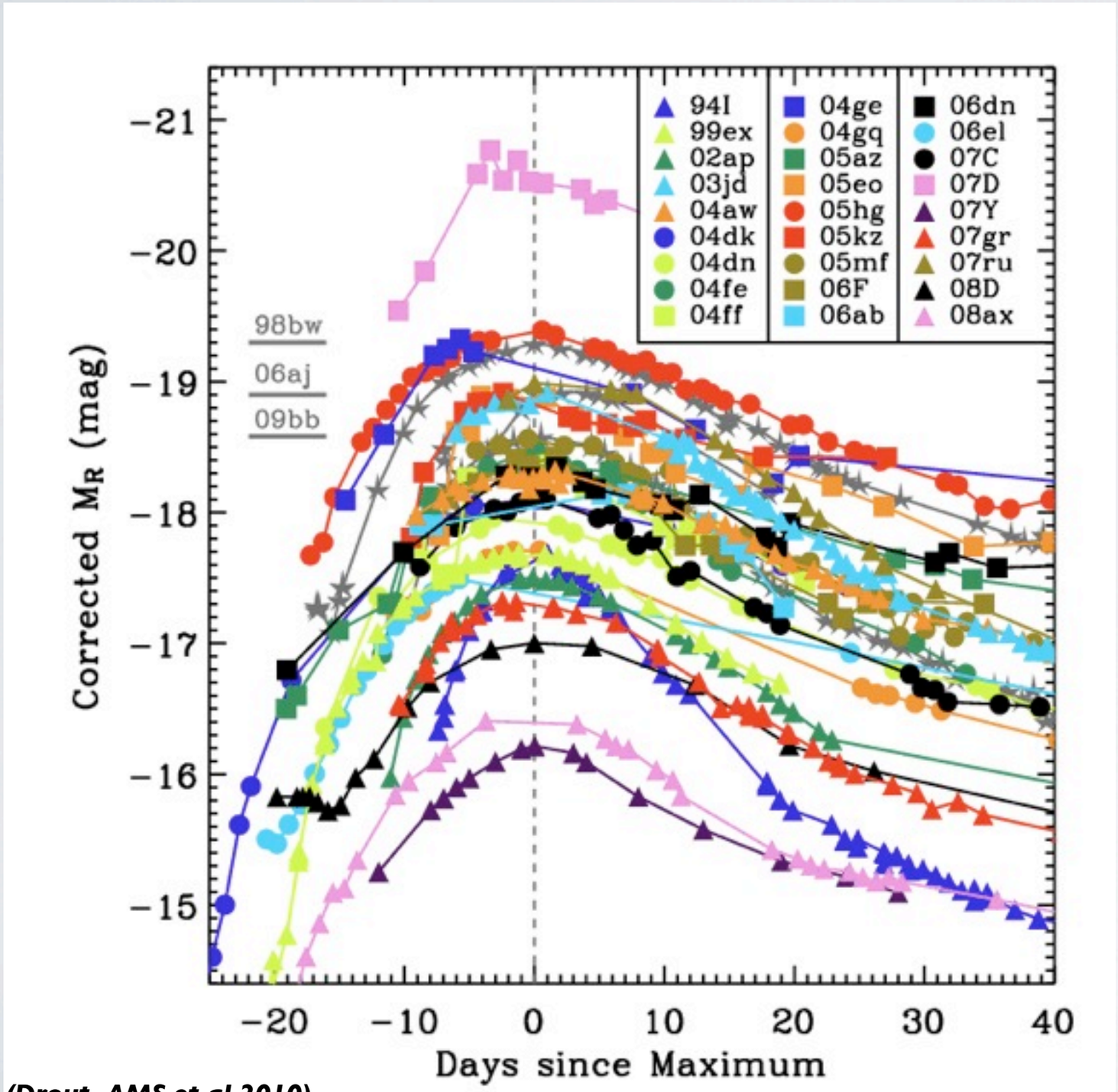

(Drout, AMS et al 2010)

Mp = -16 to -20.5 mag

τ = 7 to 18 days

Engine SNe similar to ***brightest*** SNe Ibc

Highly extinguished ***E(B-V) ~ 0.3 mag***

Optical Diagnostics

SNe Ib

- M_R ~ -17.9 mag
- τ ~ 13 days
- M_{Ni} ~ 0.2 M⊙
- M_{ej} ~ 2 M⊙
- E_K ~ 10^{51} K

SNe Ic

- M_R ~ -18.3 mag
- τ ~ 14 days
- M_{Ni} ~ 0.2 M⊙
- M_{ej} ~ 2 M⊙
- E_K ~ 10^{51} K

SNe Ic-BL

- M_R ~ -19.0 mag
- τ ~ 13 days
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GRB-SNe

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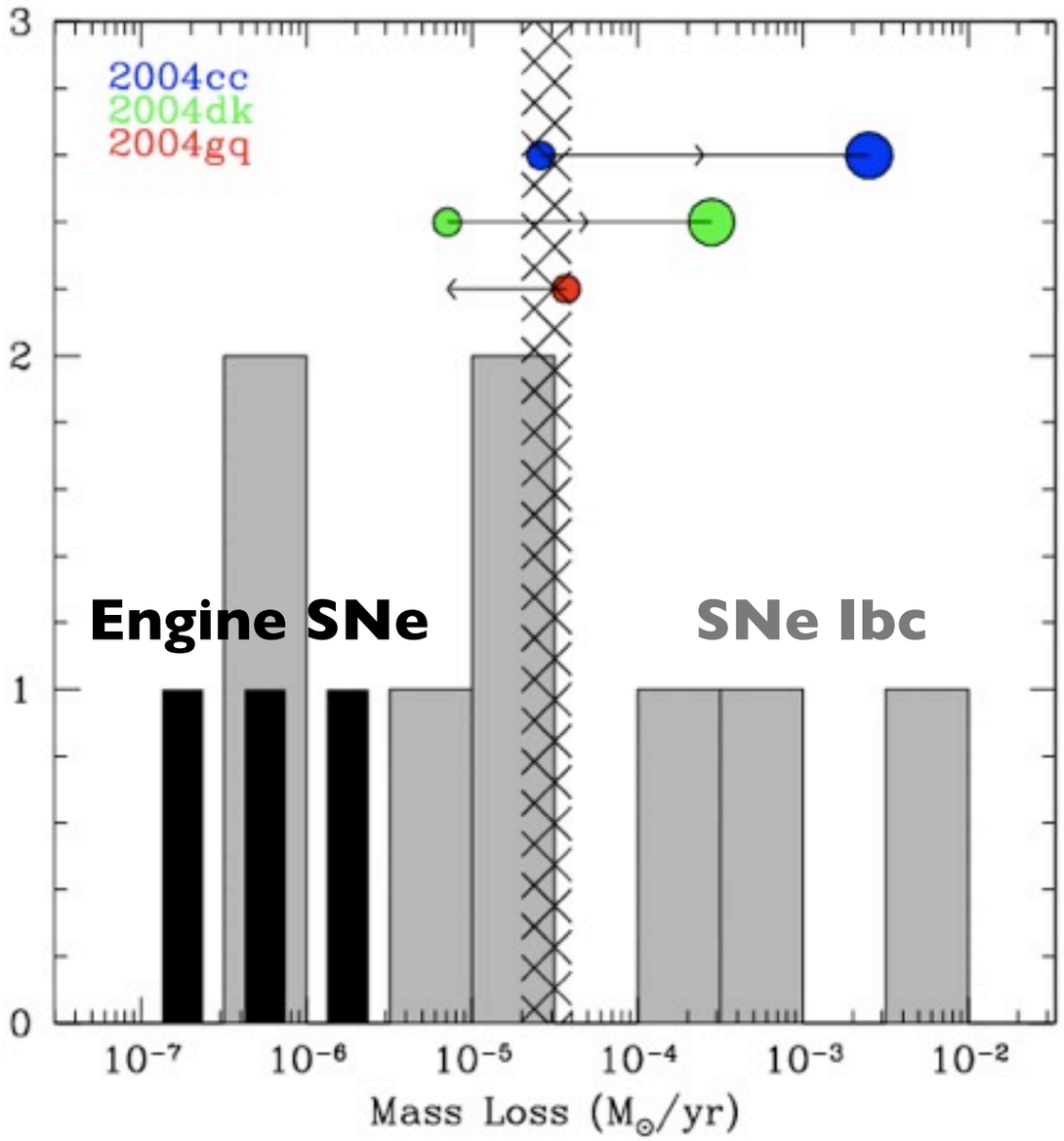
Statistical Tests:

- **No** statistical difference between SNe Ib and Ic
- **2%** probability that SNe Ic-BL are drawn from Ibc progenitors
- **40%** probability that GRB-SNe drawn from SNe Ic-BL pop'n

Watch for Drout, AMS et al on arxiv for details!

III. Progenitor Mass loss rates



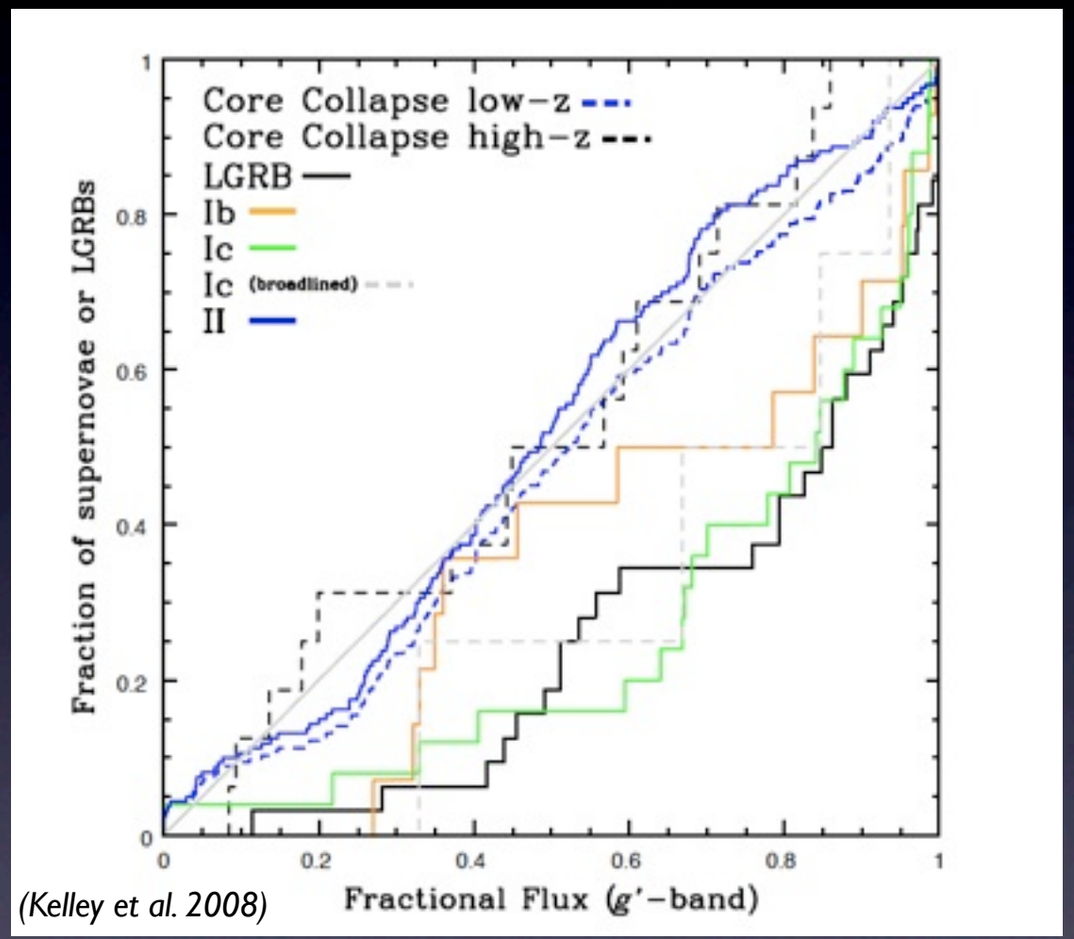
(Wellons, AMS in prep)

Density, Profile, "Bumps"

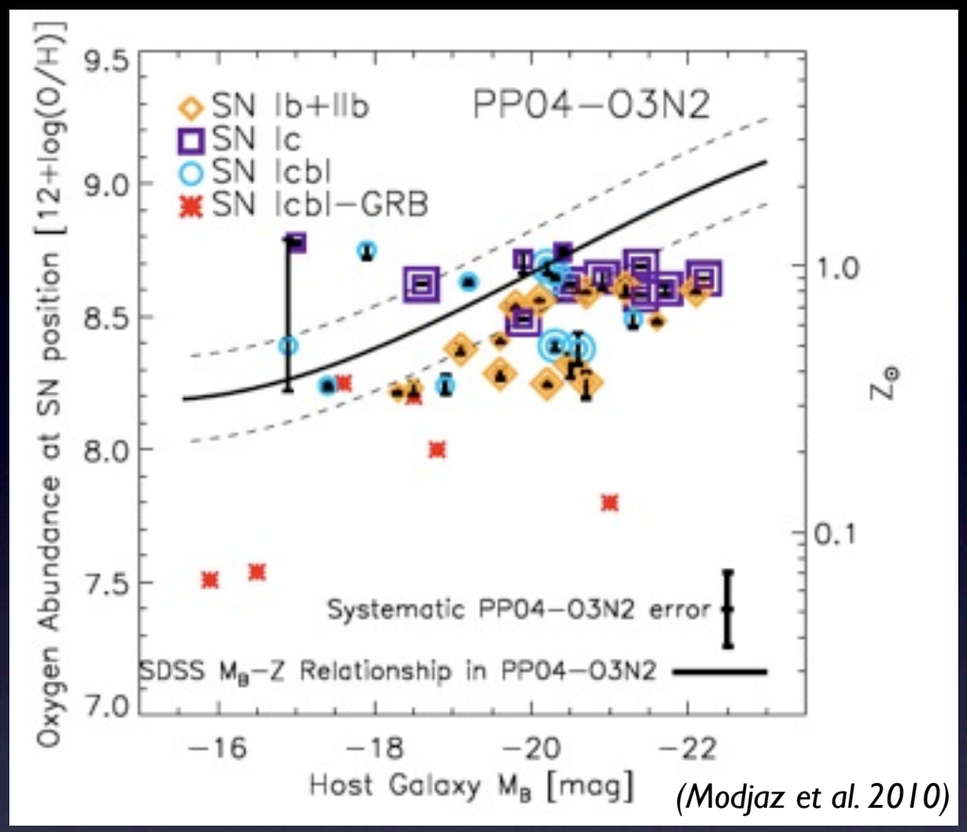
- SNe Ibc always show *stellar winds*
  (AMS 2007)
- *Half* of SNe Ibc show CSM "bumps"
  (AMS et al 2006)
- Broad range of mass loss rates
  ➔ *consistent with line-driven winds?*
  (Wellons, AMS 2010)
- Engine-driven SNe: *lower density*

Might expect $M_{dot} \sim Z$

IV. Host Galaxy Diagnostics



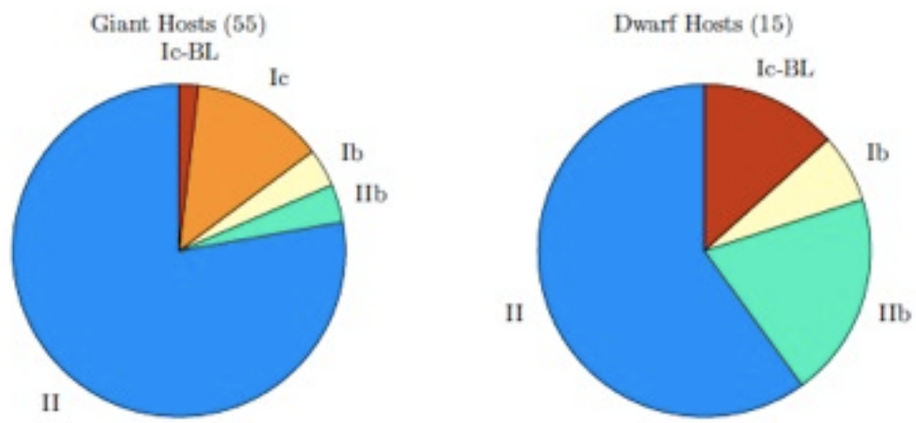
(Kelley et al. 2008)



(Modjaz et al. 2010)

SFR: *Ib → Ic → Ic-BL(?)*

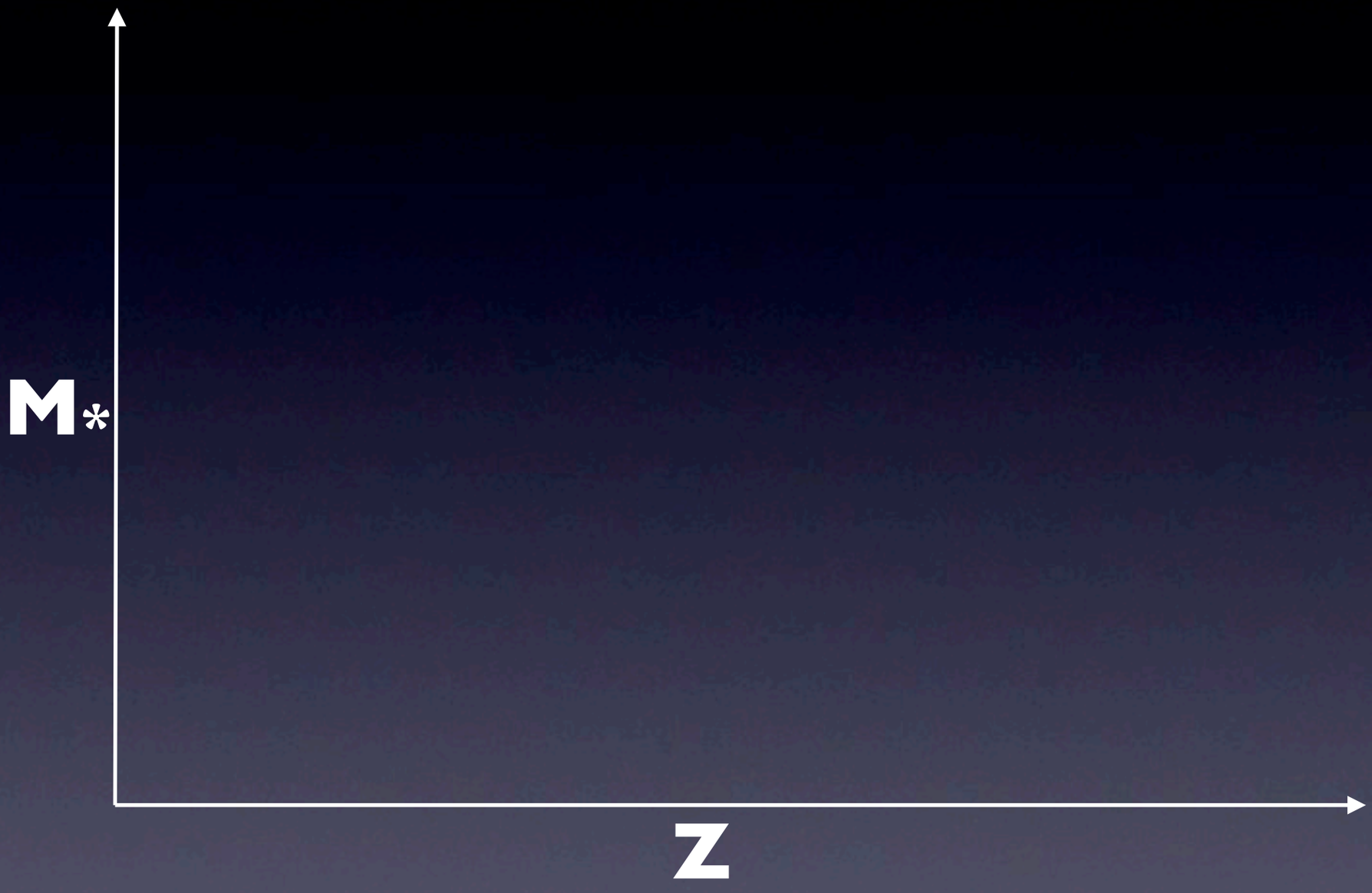
(see Emily Levesque's talk)



(Arcavi et al. 2010)

Z: *Ib → Ic-BL → Ic*

What are we learning?



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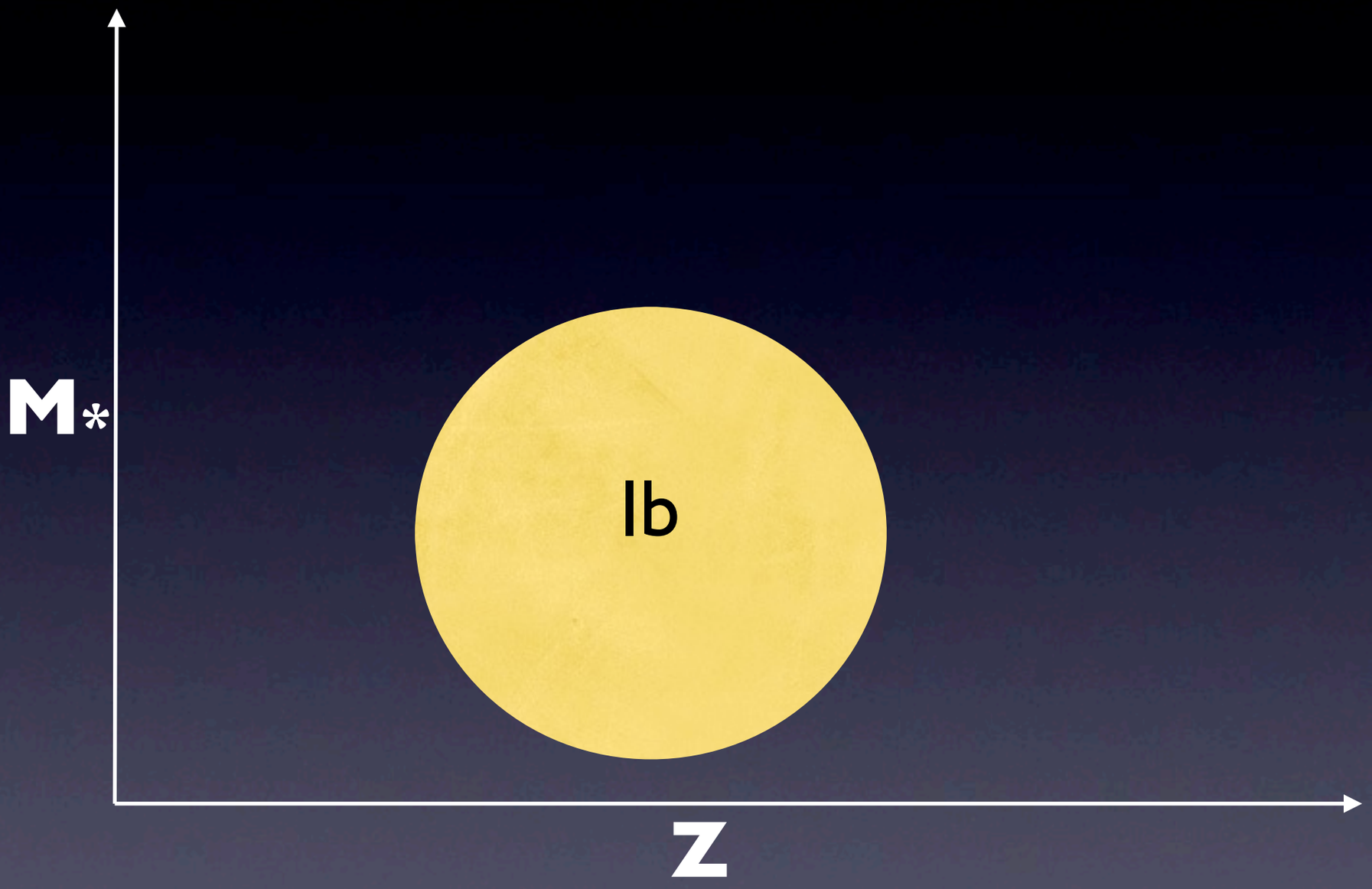

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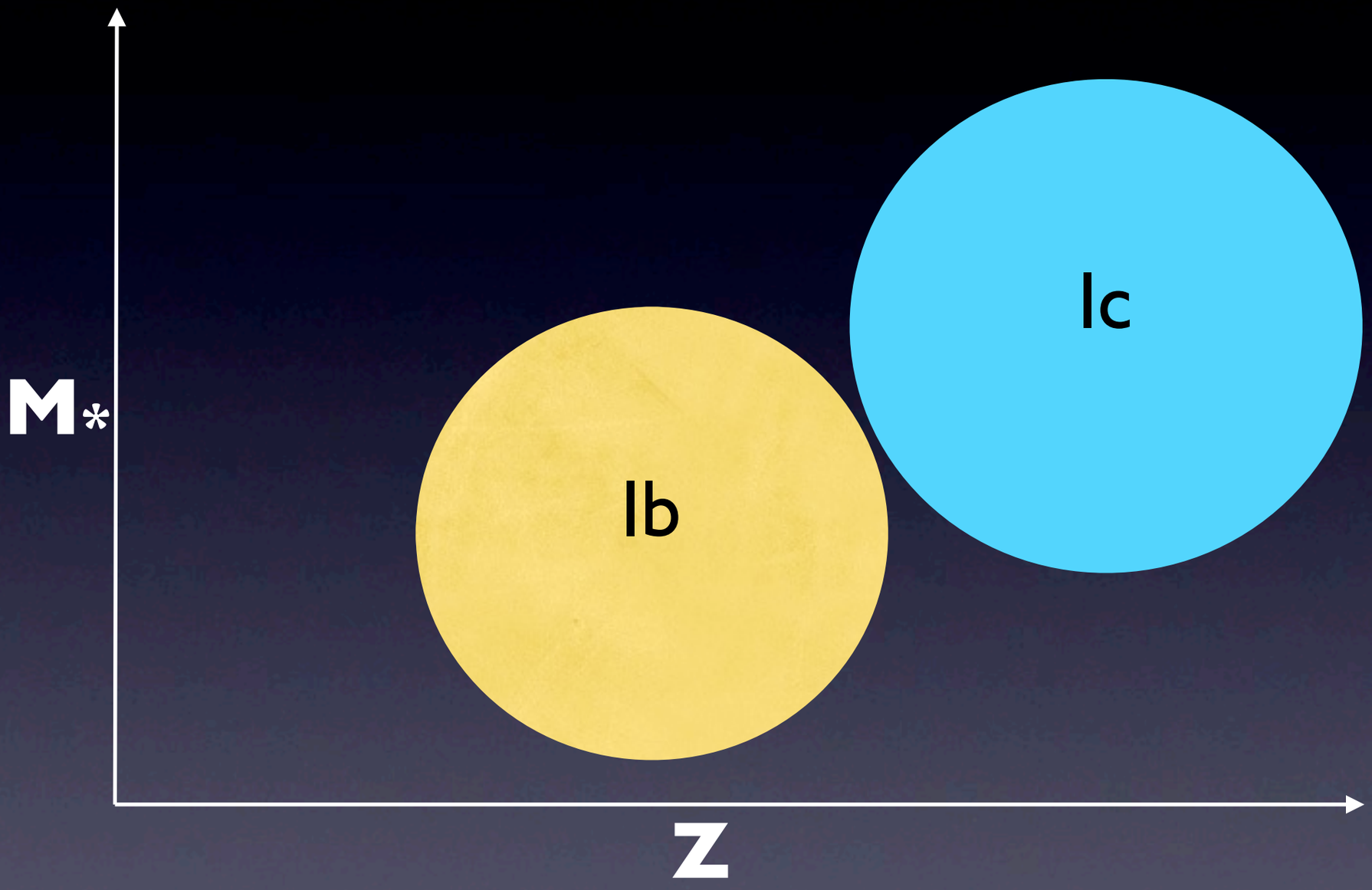

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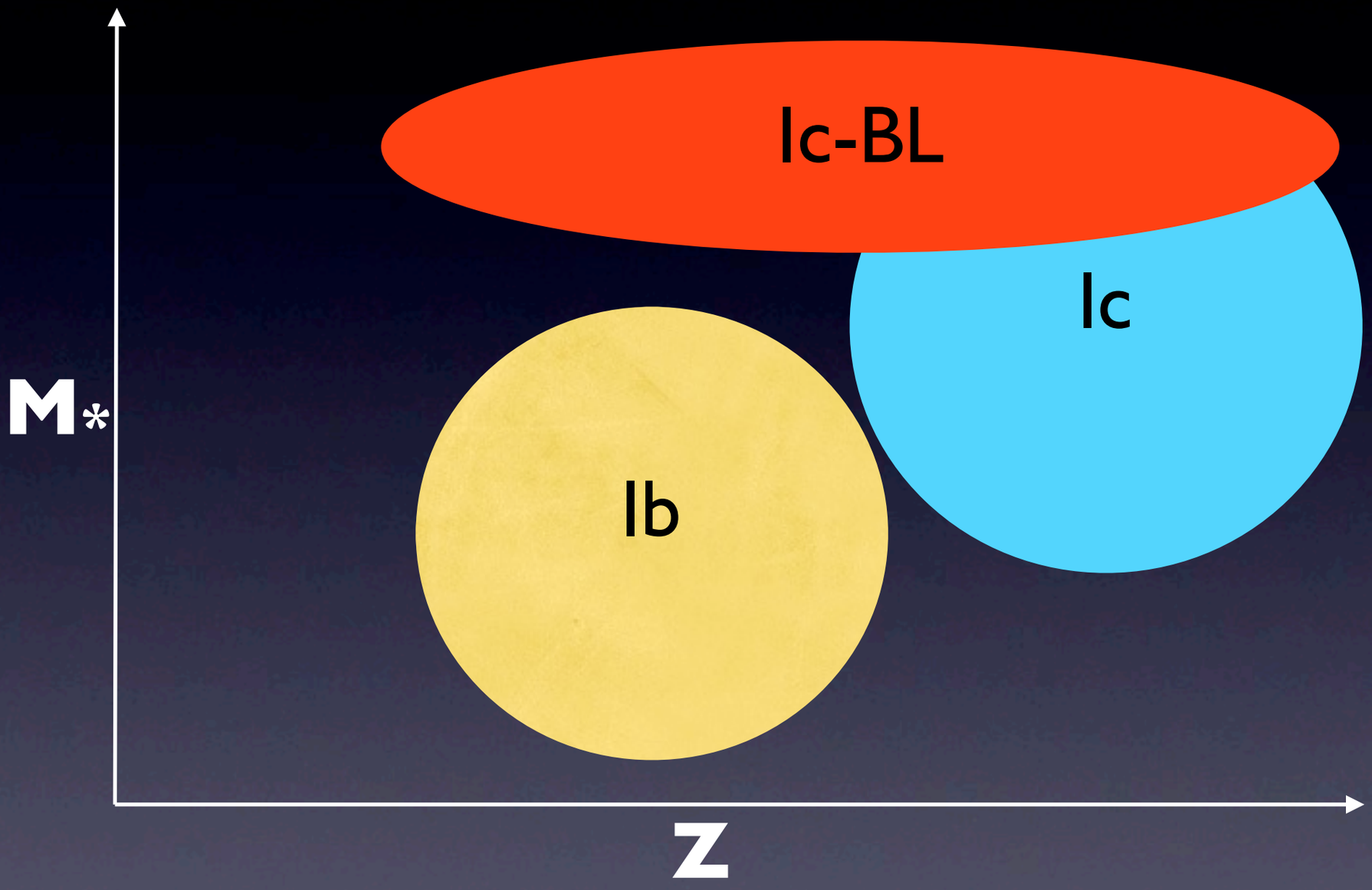

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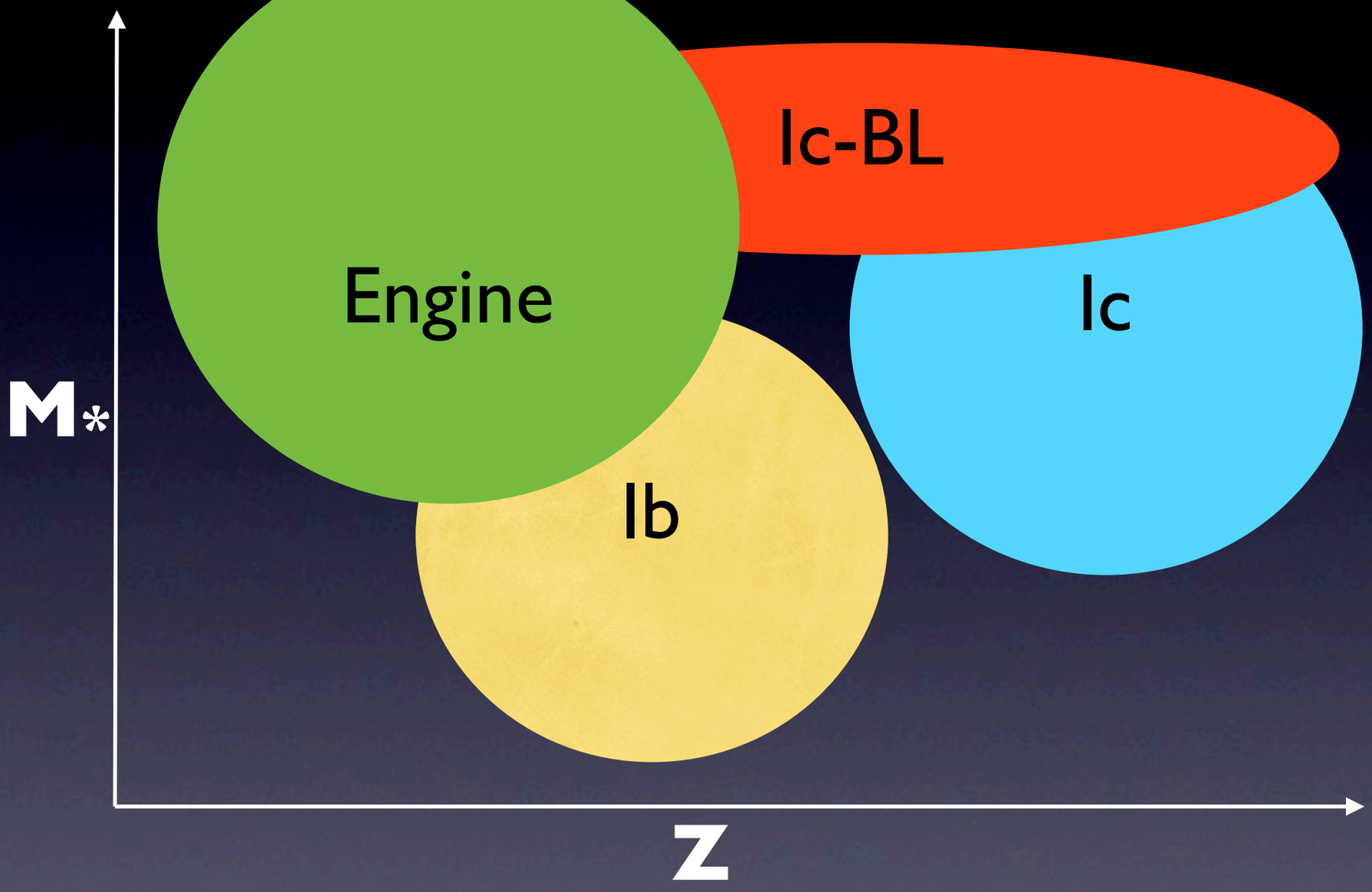
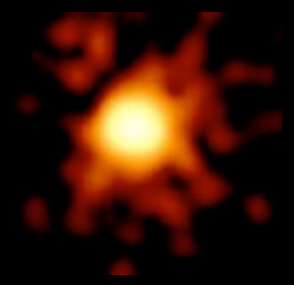
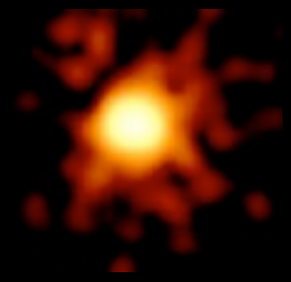




Conclusions

- GRB-SNe are relativistic, ordinary SNe are not
- GRB-SNe harbor central engines and they can be identified without a gamma-ray satellite
- GRB-SNe and SNe Ic-BL optically indistinguishable
- GRB-SNe show lower CSM densities than SNe Ibc
- GRB-SNe prefer low-Z galaxies while SNe Ic-BL do not



Dynamics

Explode!

$E_K = 10^{51}$ erg

$M_{ej} = 1\ M_\odot$

v = 10,000 km/s

Free Expansion

velocity = constant

M_{swept} *increasing*

Energy *increasing*

x 100 yrs =

Sedov-Taylor

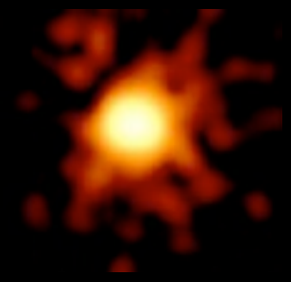
velocity *decreasing*

$M_{swept} = M_{ej}$

Energy = constant

Blandford McKee

GRB **Remnant**



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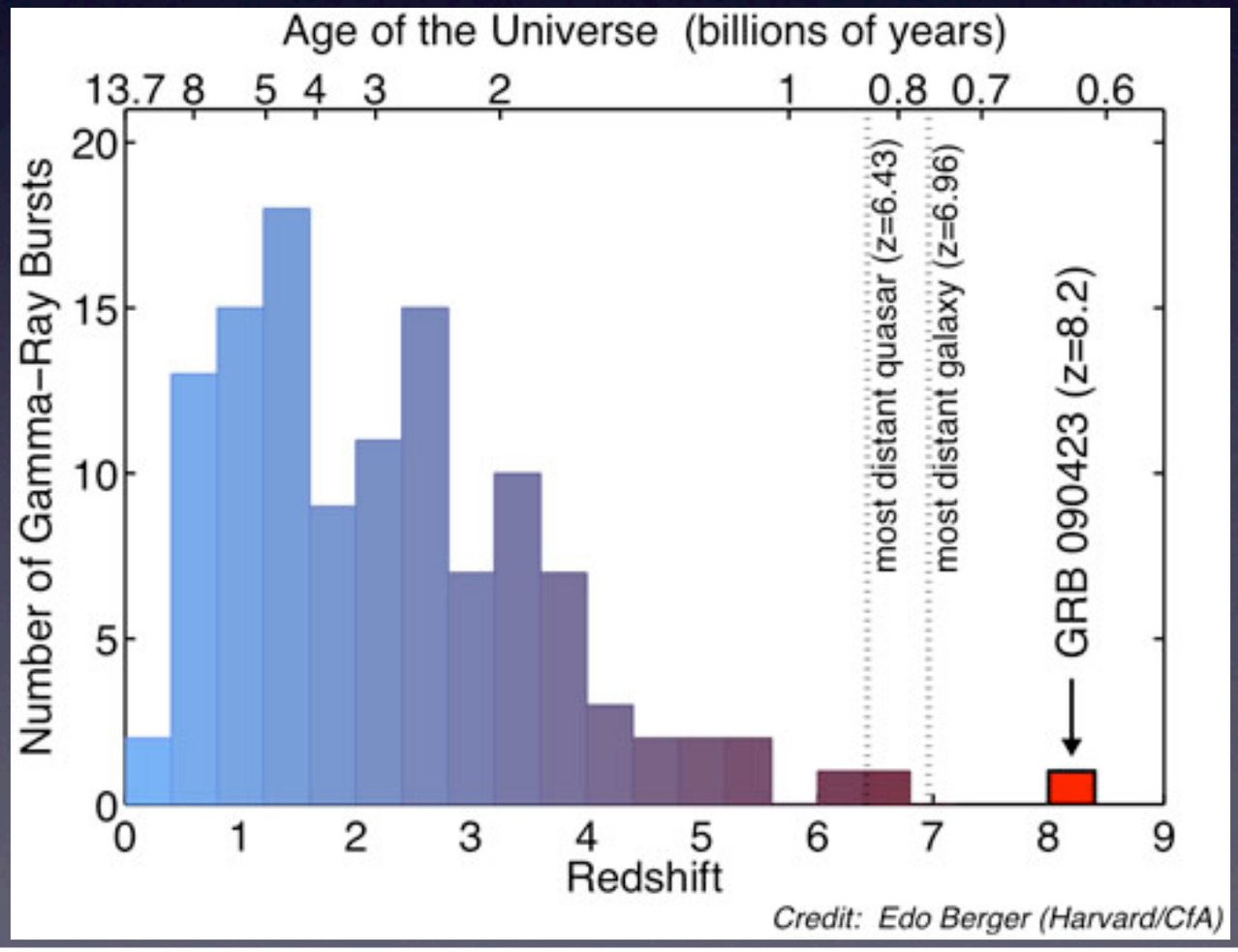
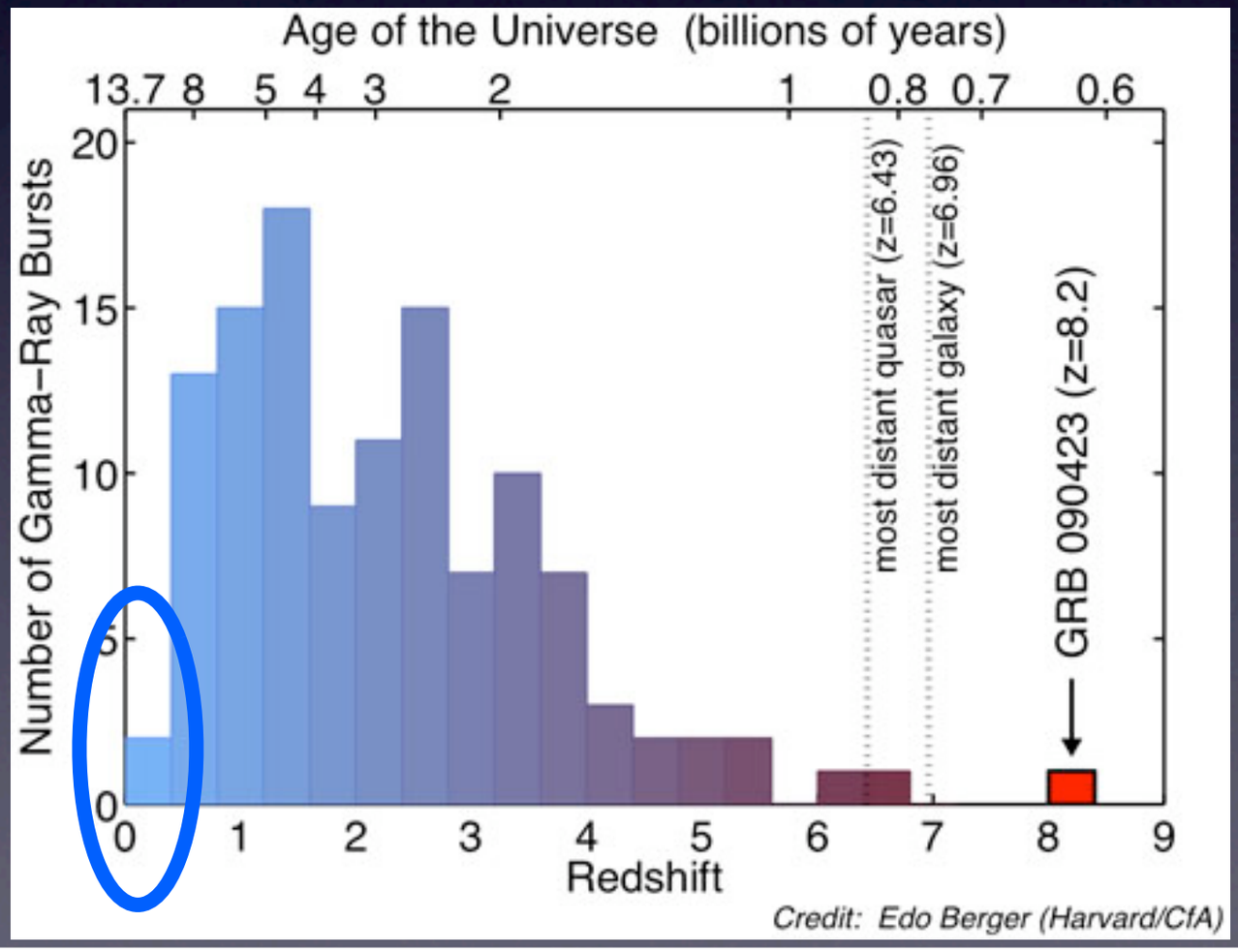

Age of the Universe (billions of years)
13.7
8
5
4
3
2
1
0.8
0.7
0.6
Number of Gamma-Ray Bursts
0
5
10
15
20
0
1
2
3
4
5
6
7
8
9
Redshift
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
Credit: Edo Berger (Harvard/CfA)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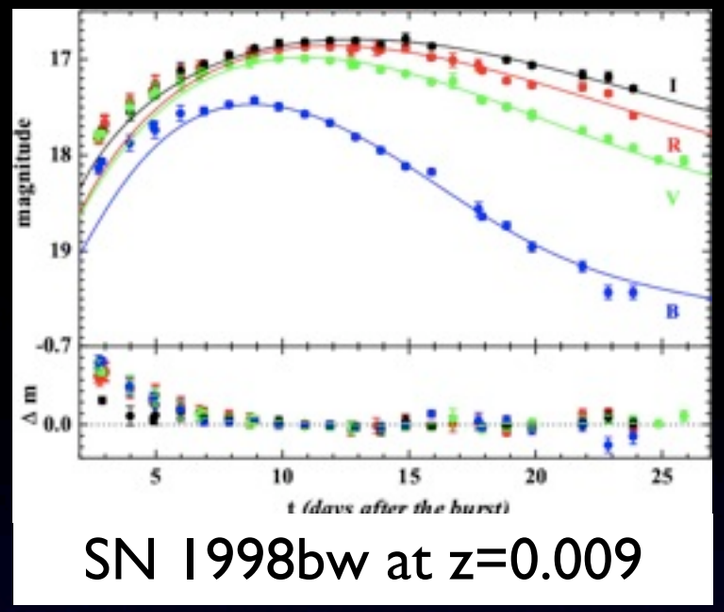
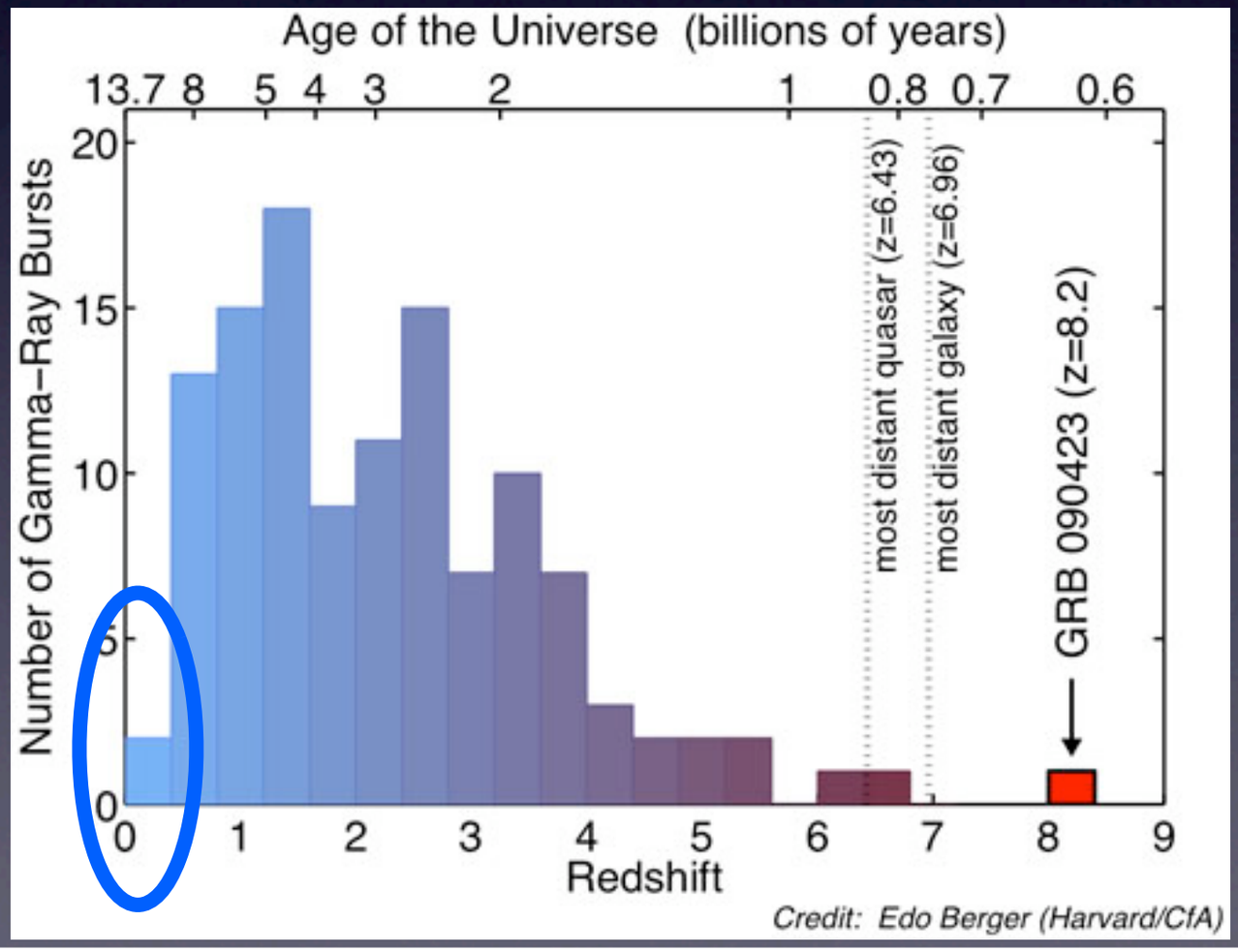
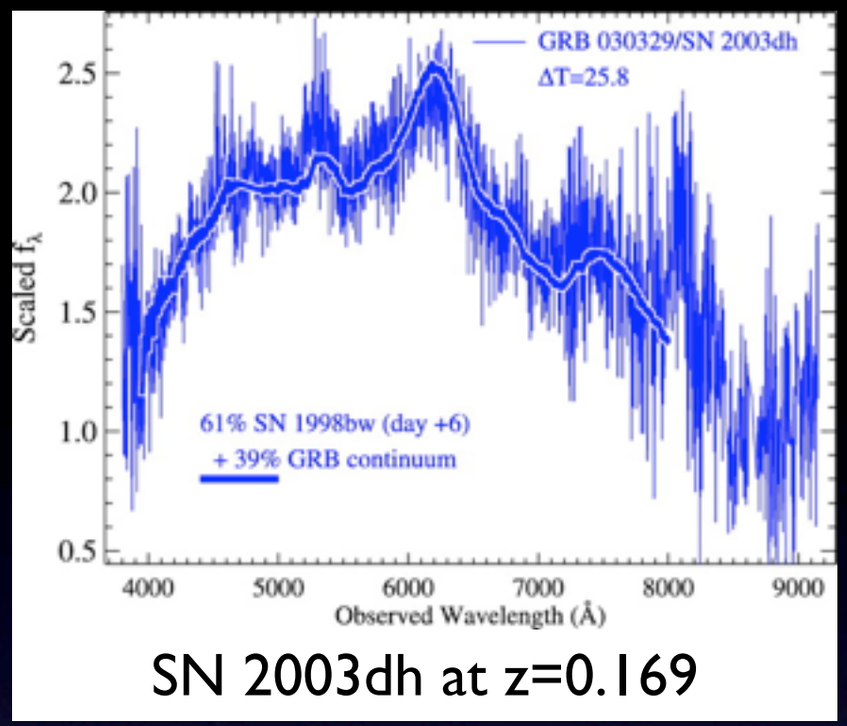
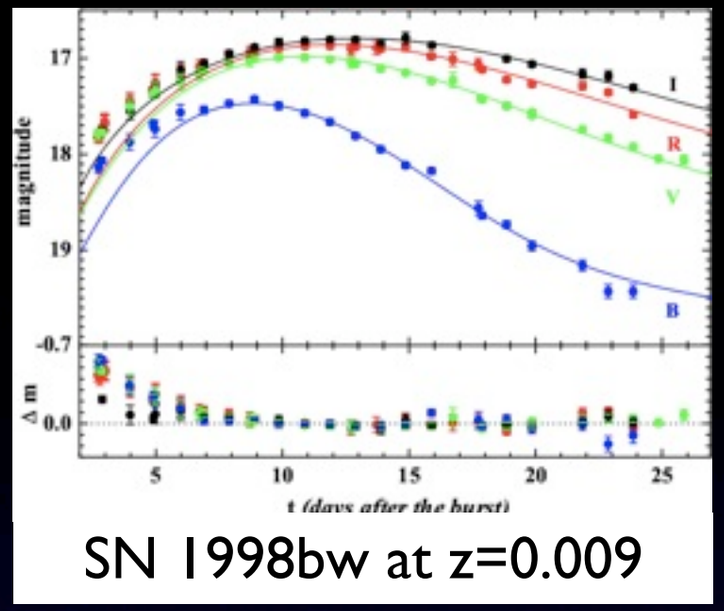


SN 1998bw at z=0.009

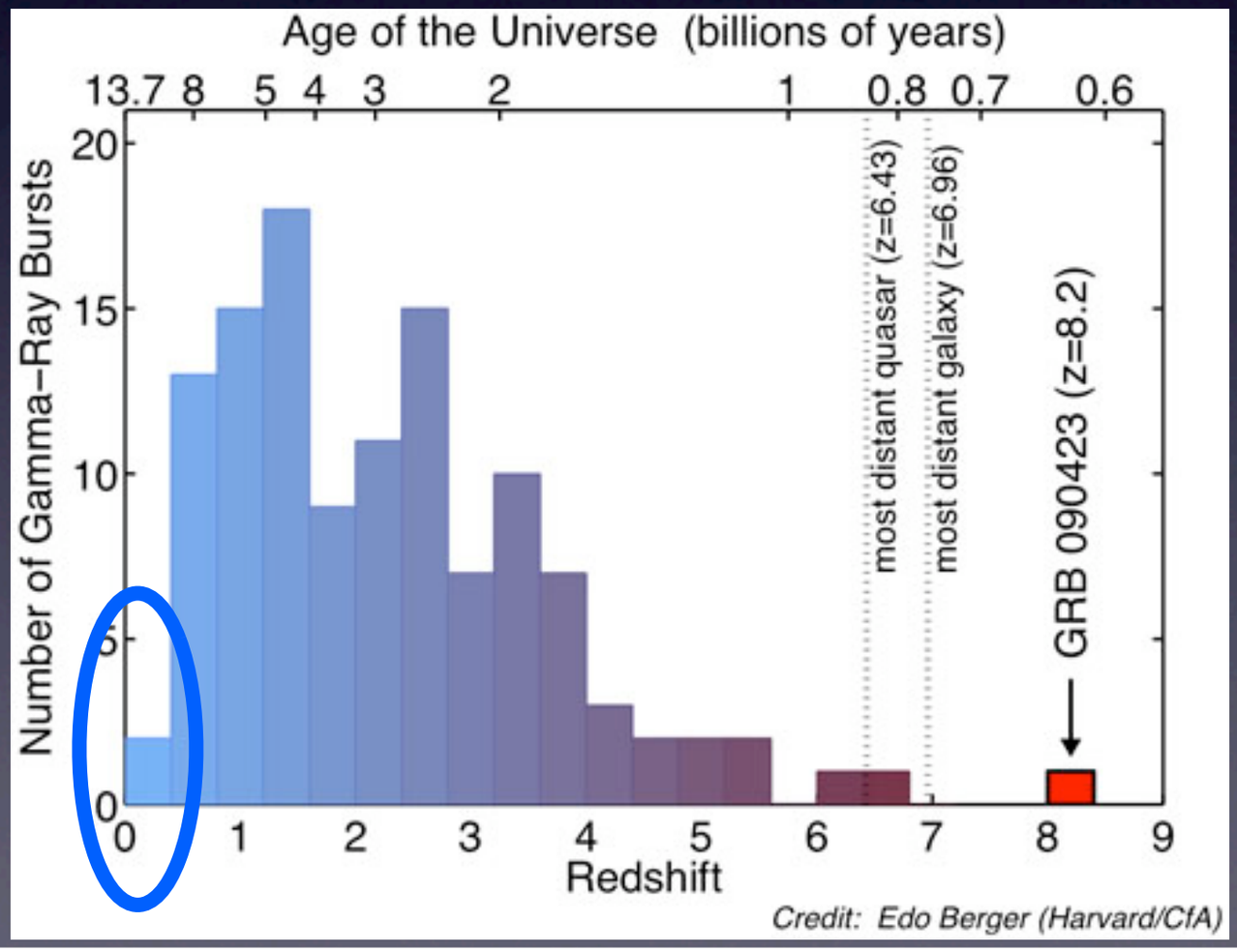


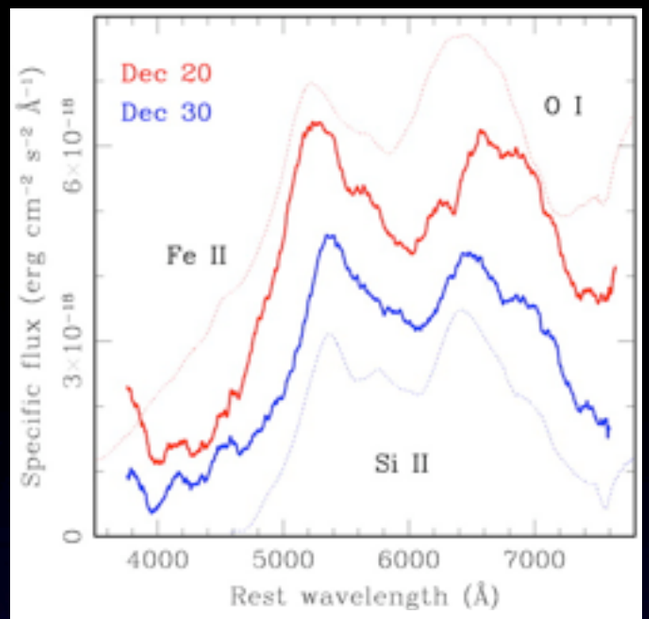


SN 2003dh at z=0.169

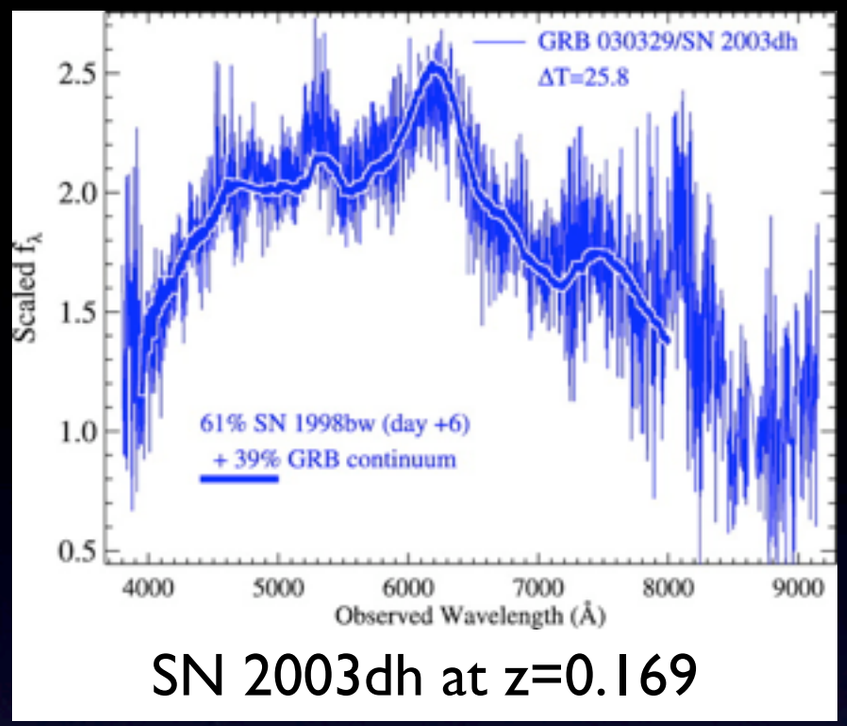


SN 1998bw at z=0.009

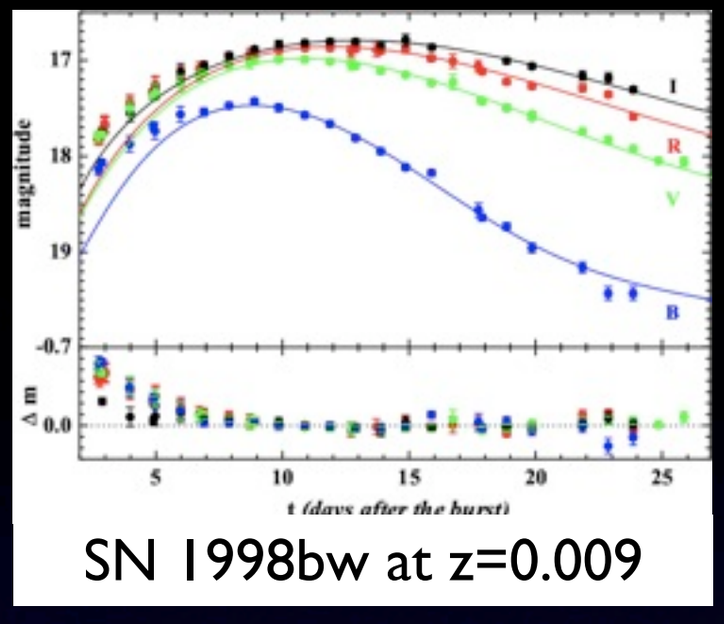




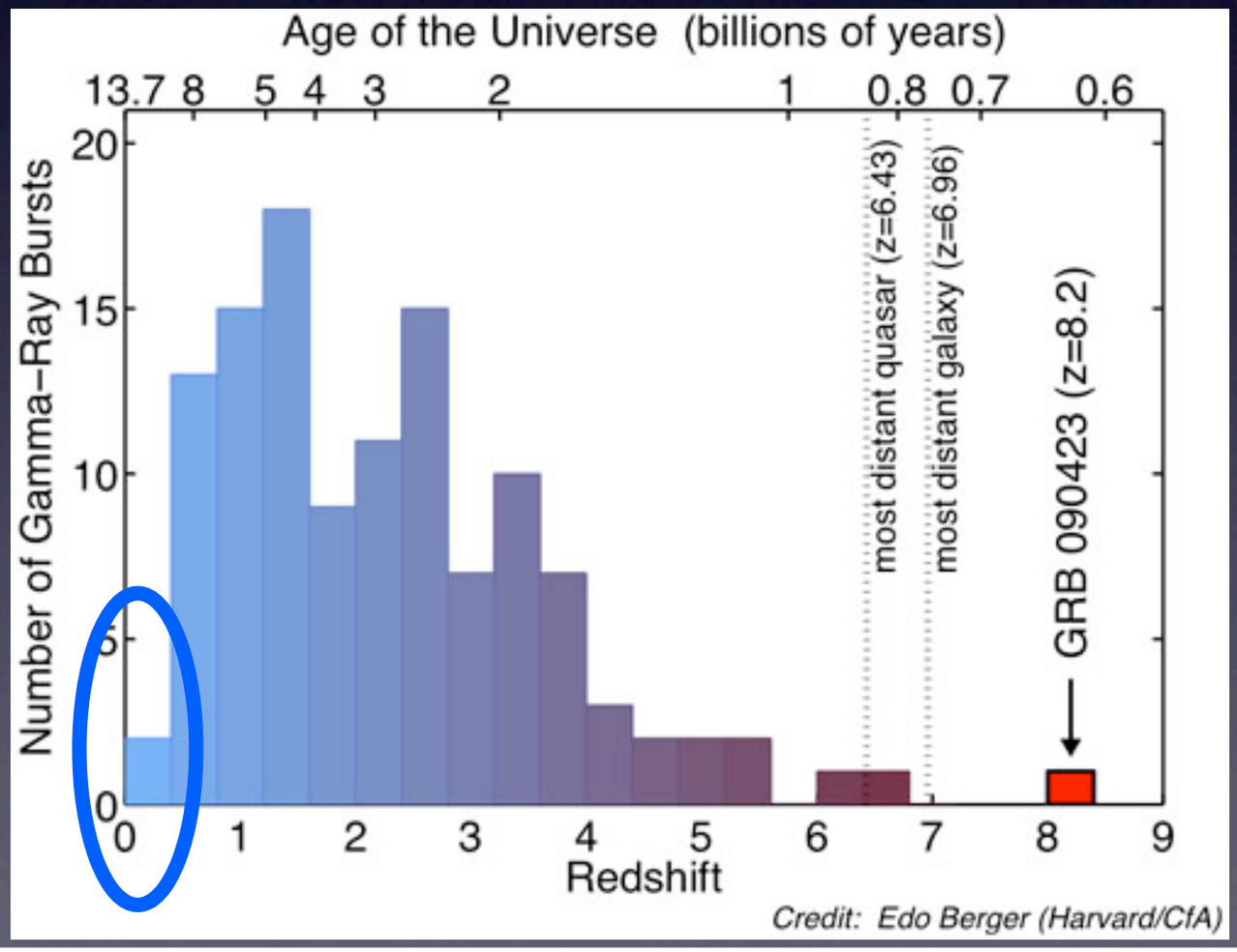
SN 2003lw at z=0.10

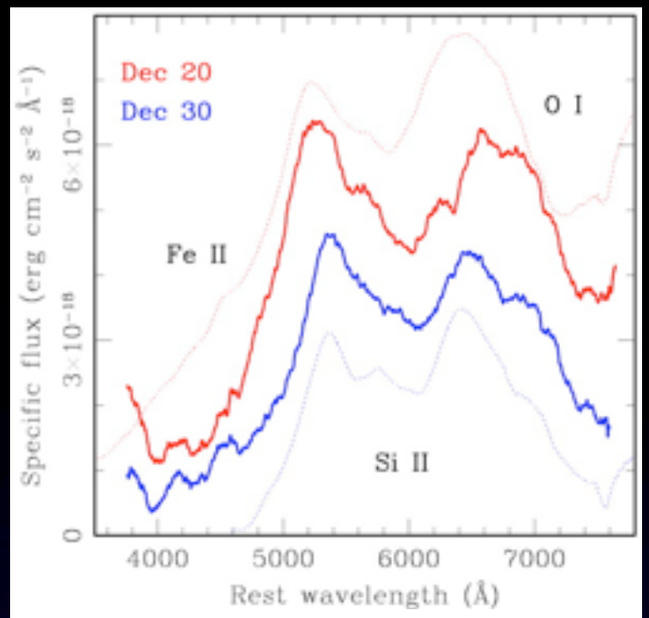


SN 2003dh at z=0.169



SN 1998bw at z=0.009





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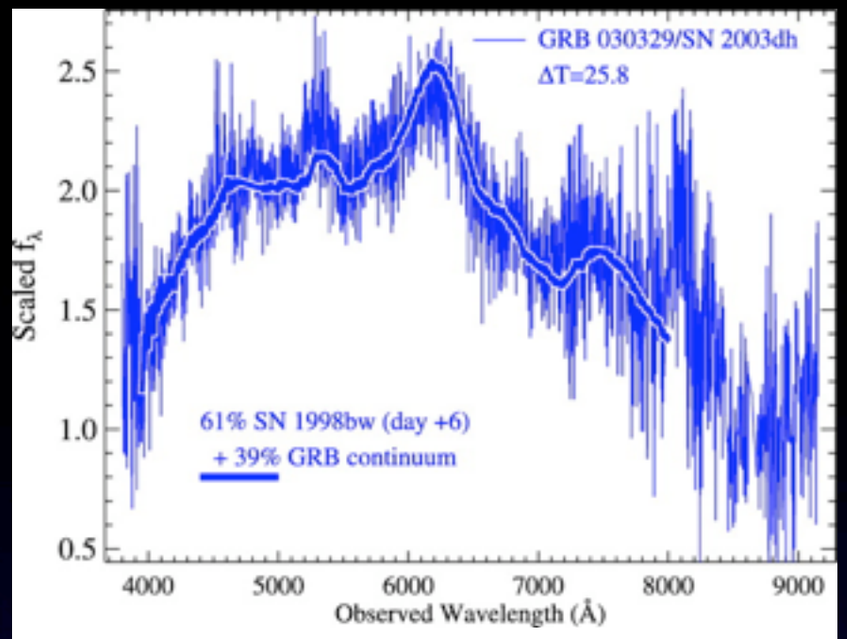

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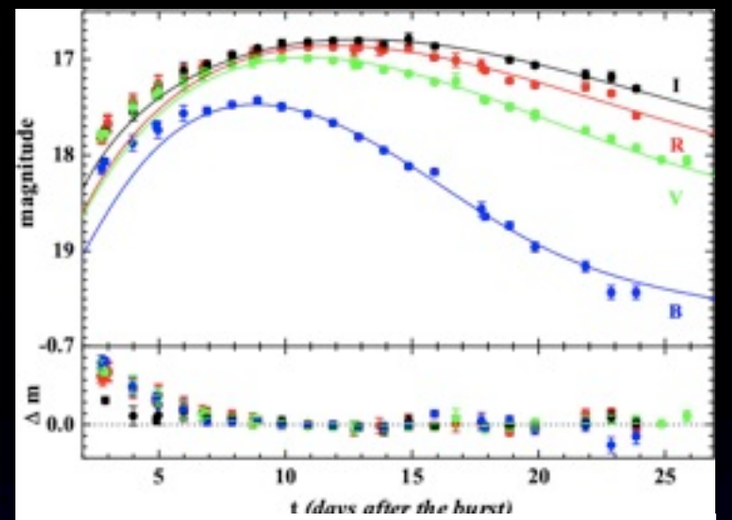

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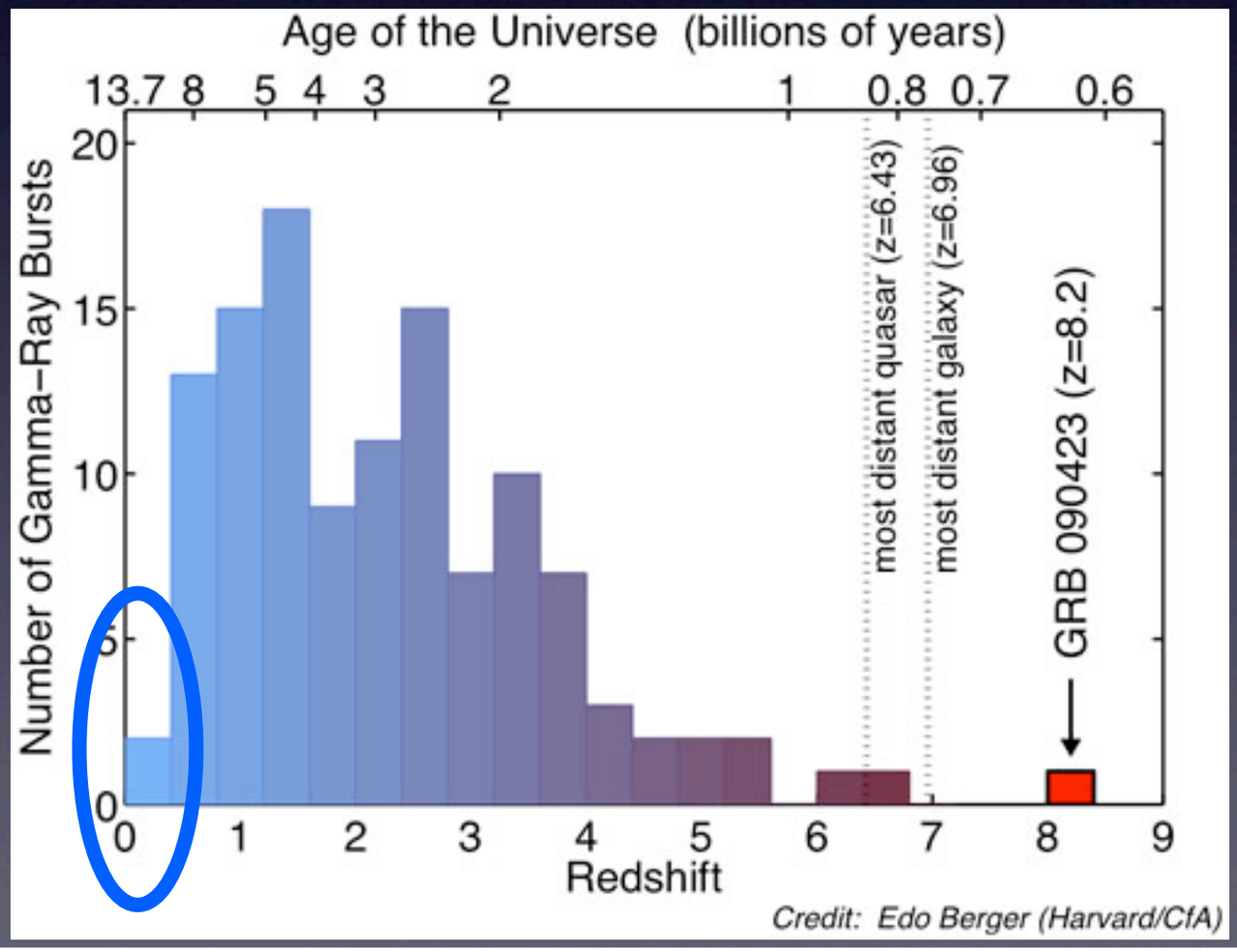
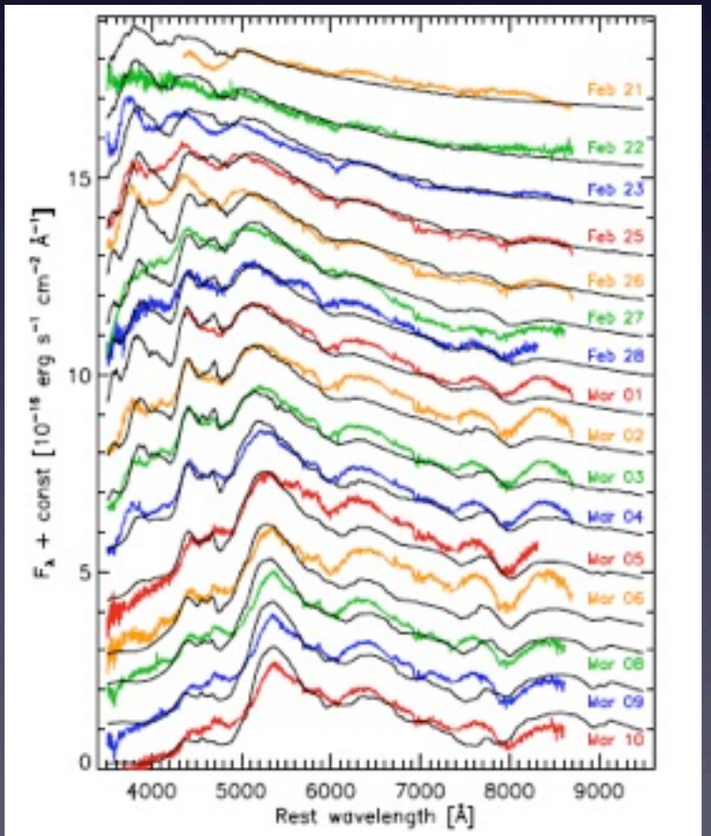
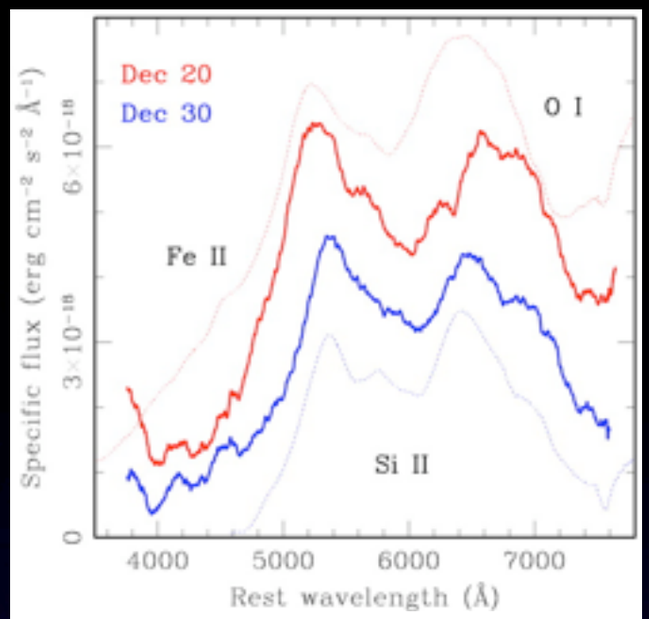
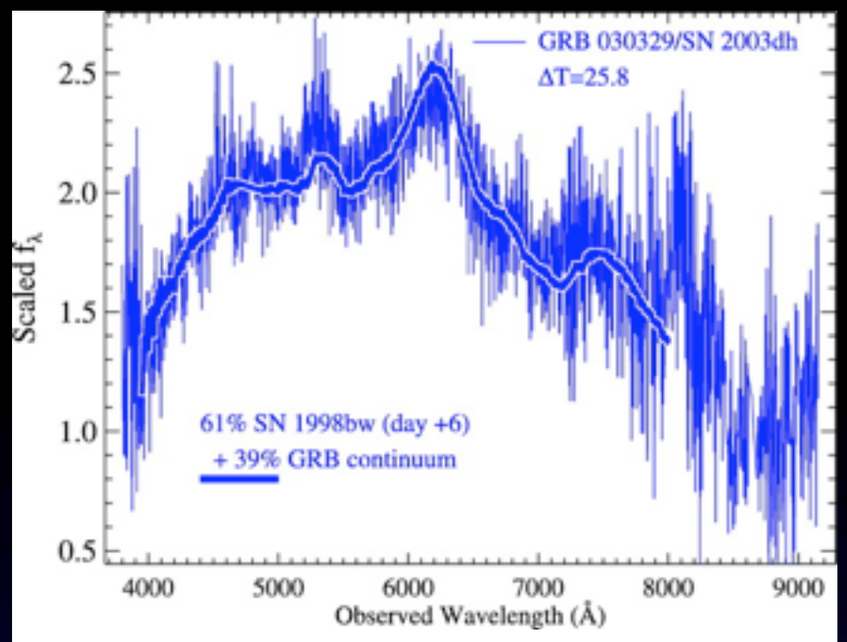




SN 2006aj at z=0.03



SN 2003lw at z=0.10



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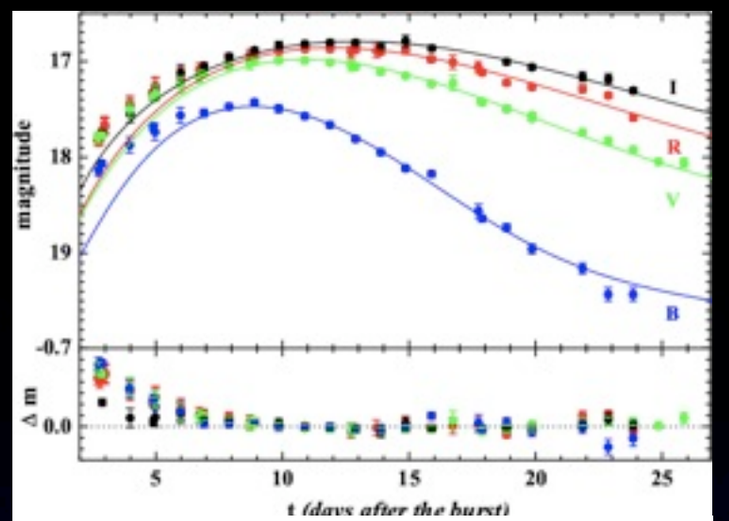

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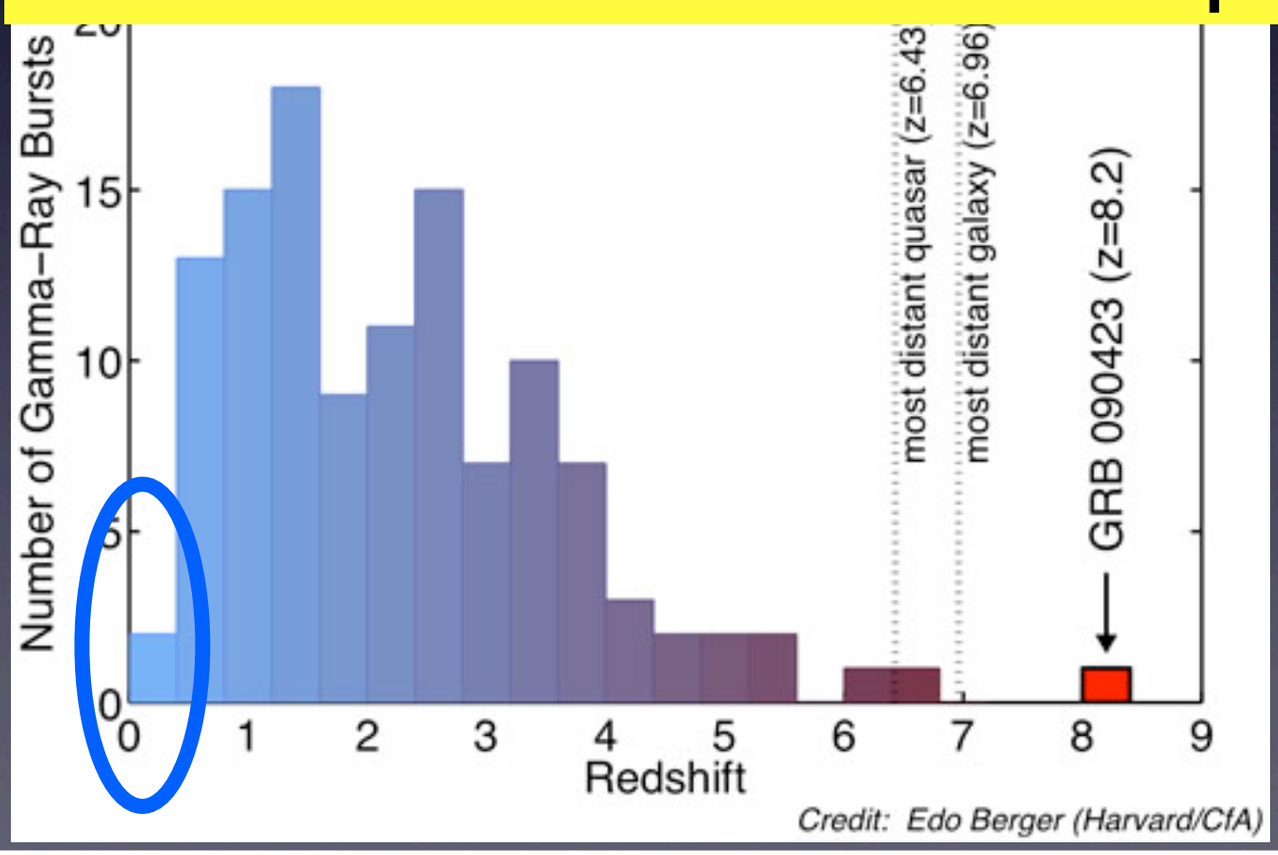
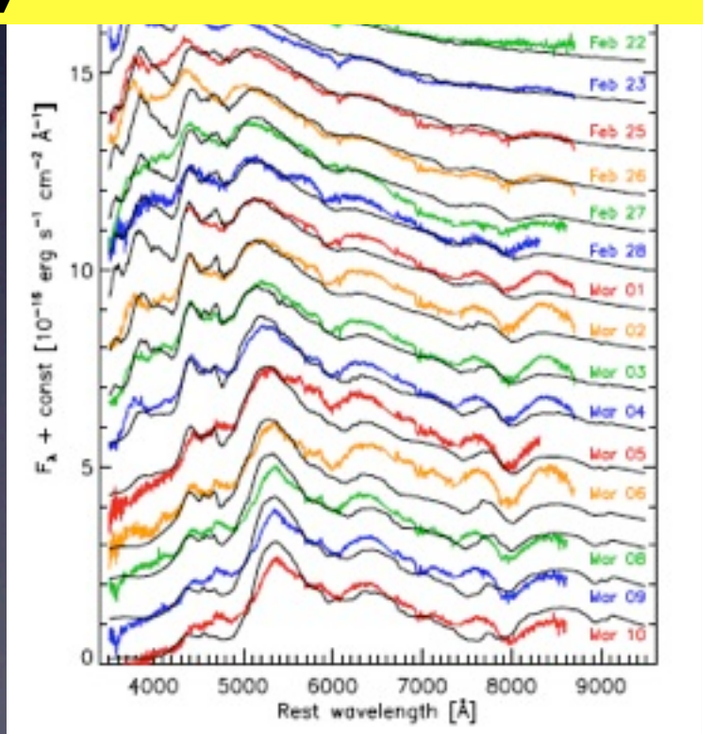
Most GRBs accompanied by SNe Ic





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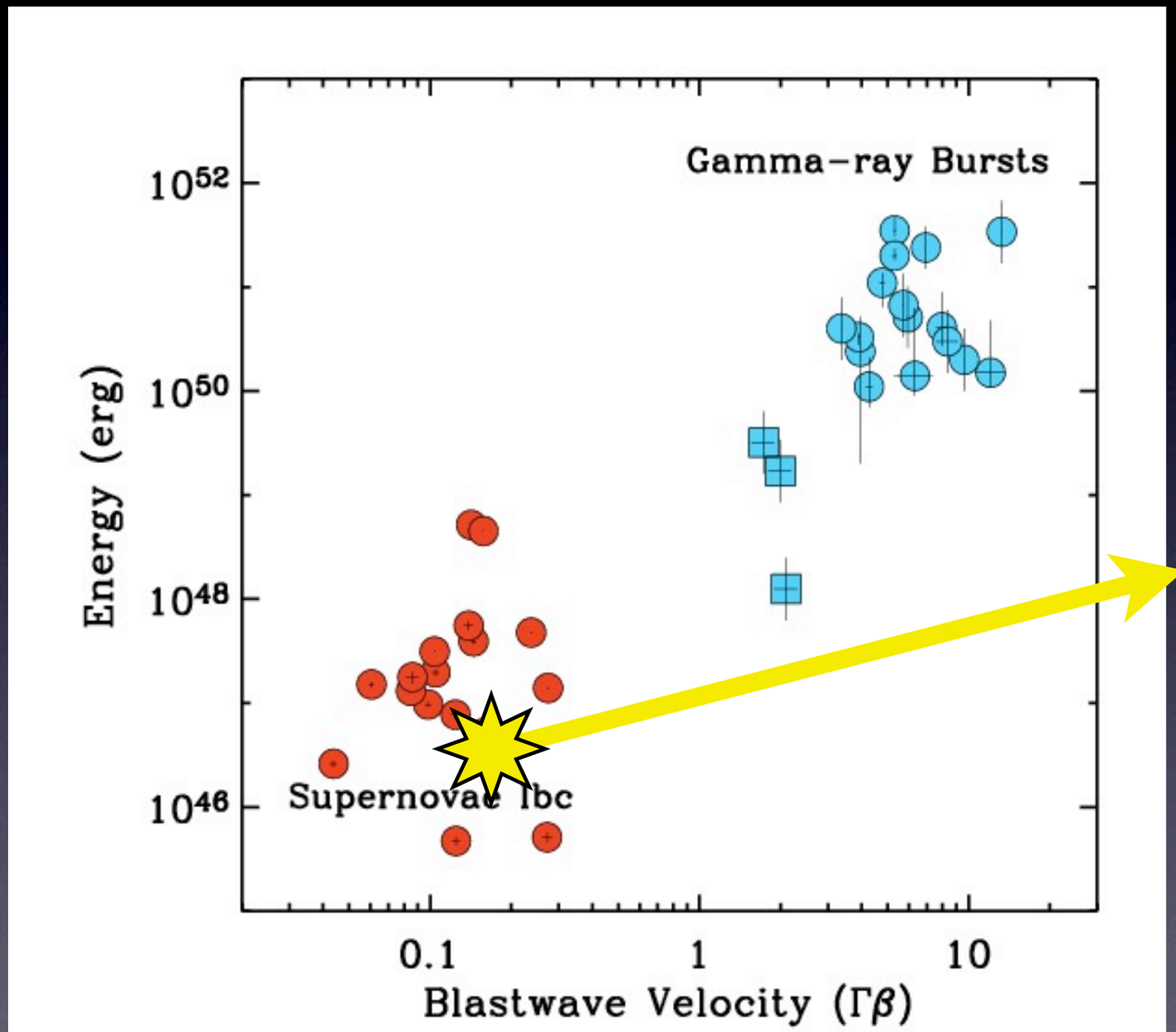
The Ordinary SN 2007gr



NGC 1058

d=10 Mpc

The Ordinary SN 2007gr

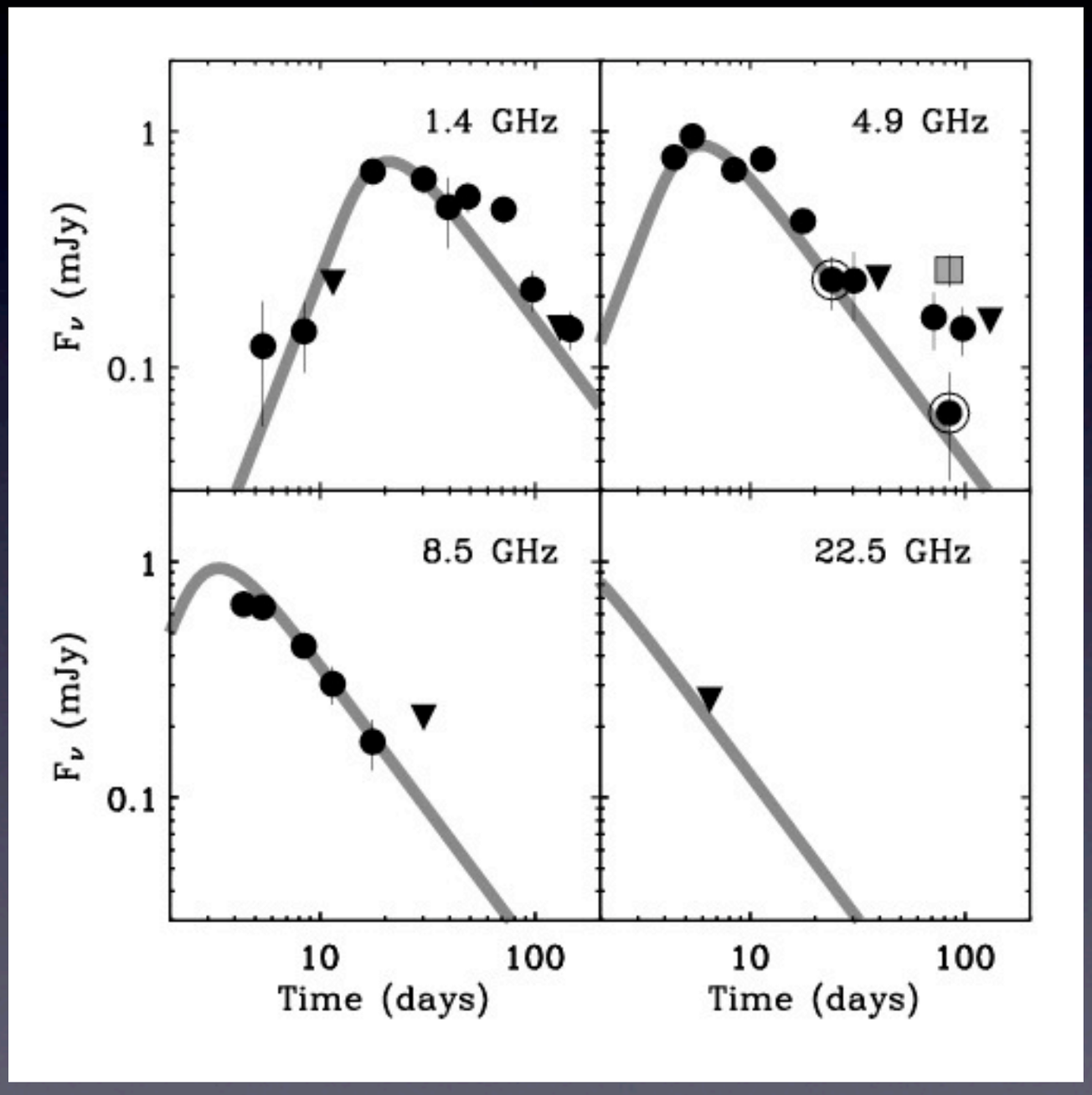
Freely expanding

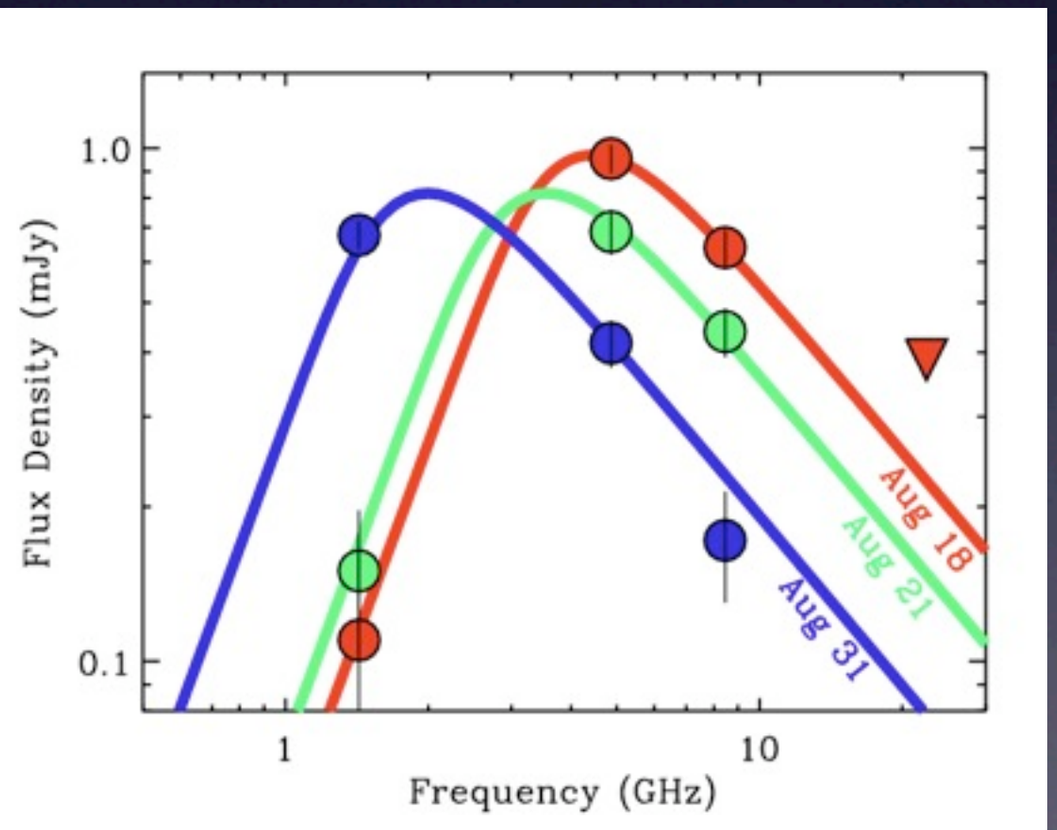
$L_\nu \sim 10^{26}$ erg/s/Hz

v ~ 0.2c

E ~ 2 x 10^{46} erg

(AMS et al., 2010)





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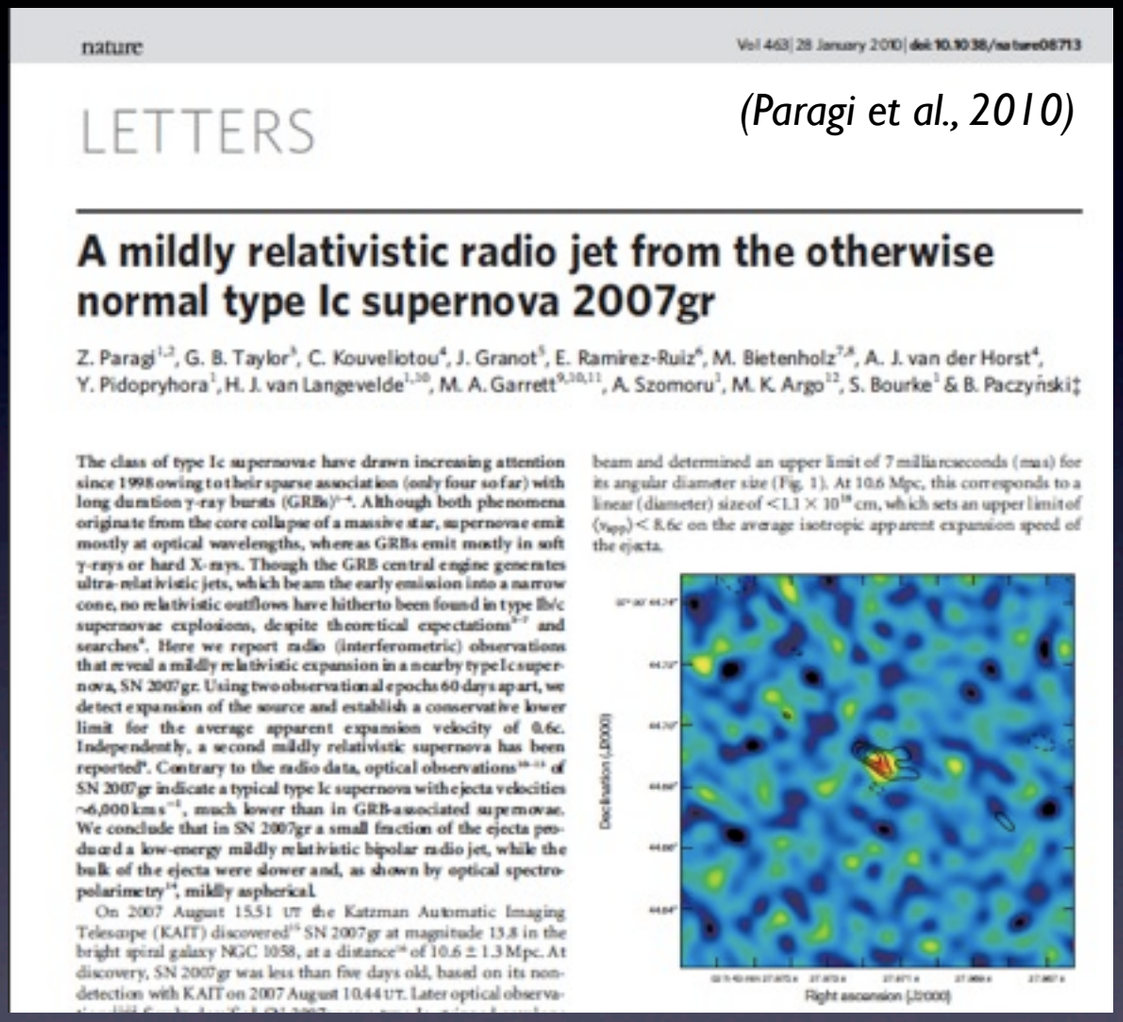

nature

Vol 463 | 28 January 2010 | doi:10.1038/nature08713

LETTERS

(Paragi et al., 2010)

A mildly relativistic radio jet from the otherwise normal type Ic supernova 2007gr

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The class of type Ic supernovae have drawn increasing attention since 1998 owing to their sparse association (only four so far) with long duration γ-ray bursts (GRBs)[1–4]. Although both phenomena originate from the core collapse of a massive star, supernovae emit mostly at optical wavelengths, whereas GRBs emit mostly in soft γ-rays or hard X-rays. Though the GRB central engine generates ultra-relativistic jets, which beam the early emission into a narrow cone, no relativistic outflows have hitherto been found in type Ib/c supernovae explosions, despite theoretical expectations[5–7] and searches[8]. Here we report radio (interferometric) observations that reveal a mildly relativistic expansion in a nearby type Ic supernova, SN 2007gr. Using two observational epochs 60 days apart, we detect expansion of the source and establish a conservative lower limit for the average apparent expansion velocity of 0.6c. Independently, a second mildly relativistic supernova has been reported[9]. Contrary to the radio data, optical observations[10–13] of SN 2007gr indicate a typical type Ic supernova with ejecta velocities ~6,000 km s^{-1}, much lower than in GRB-associated supernovae. We conclude that in SN 2007gr a small fraction of the ejecta produced a low-energy mildly relativistic bipolar radio jet, while the bulk of the ejecta were slower and, as shown by optical spectropolarimetry[14], mildly aspherical.

On 2007 August 15.51 UT the Katzman Automatic Imaging Telescope (KAIT) discovered[15] SN 2007gr at magnitude 13.8 in the bright spiral galaxy NGC 1058, at a distance[16] of 10.6 ± 1.3 Mpc. At discovery, SN 2007gr was less than five days old, based on its non-detection with KAIT on 2007 August 10.44 UT. Later optical observa-

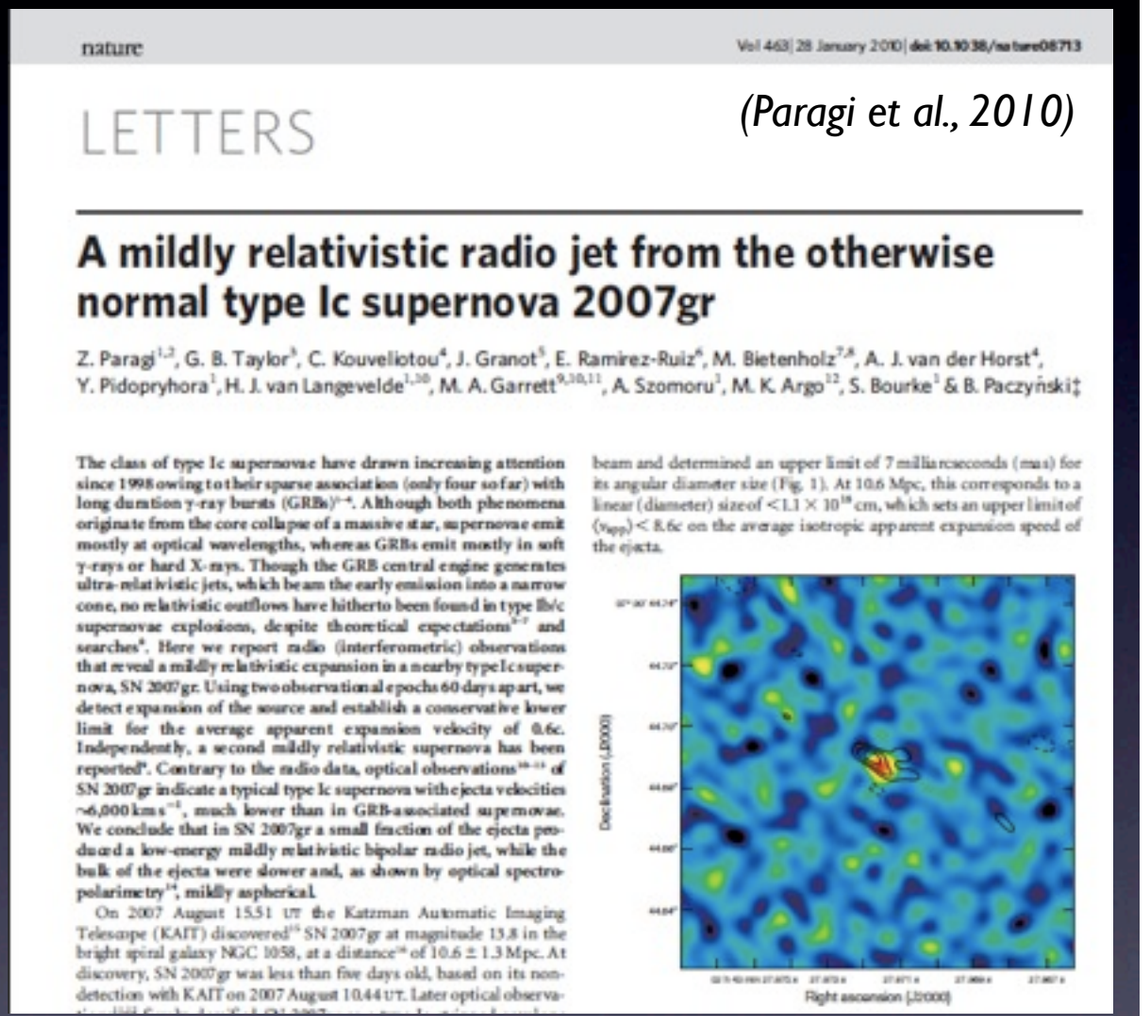
beam and determined an upper limit of 7 milliarcseconds (mas) for its angular diameter size (Fig. 1). At 10.6 Mpc, this corresponds to a linear (diameter) size of $< 1.1 \times 10^{16}$ cm, which sets an upper limit of $\langle v_{app} \rangle < 8.6c$ on the average isotropic apparent expansion speed of the ejecta.

Low S/N VLBI data at t=84 days

Fν = 60 μJy (expect 150 +- 40 μJy)

decoupled jet, **v > 0.6c ?**

The Ordinary SN 2007gr



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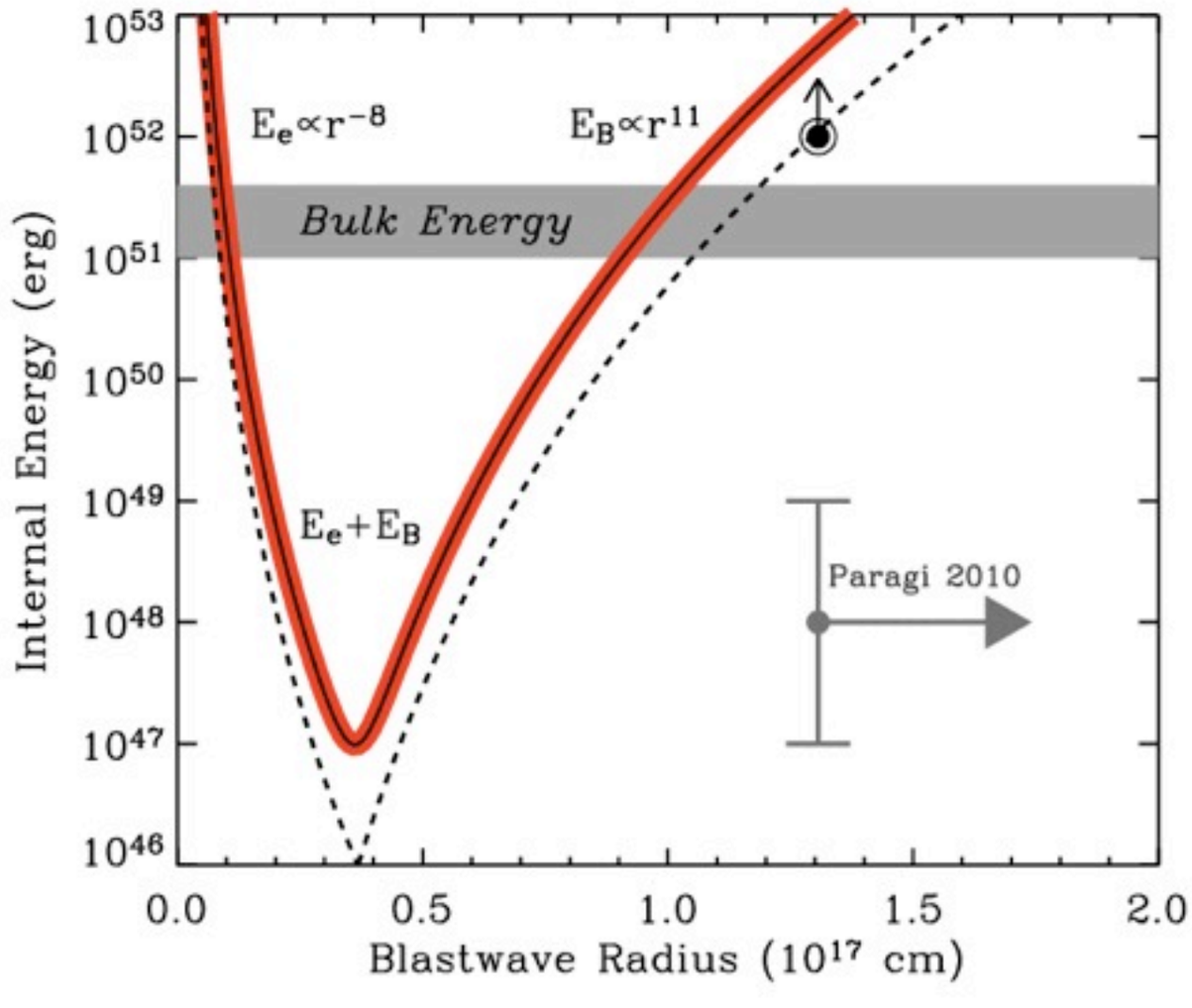

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εe/εB < 10^{-9}

VLBI likely suffers from systematic effects

Free-expansion more natural explanation

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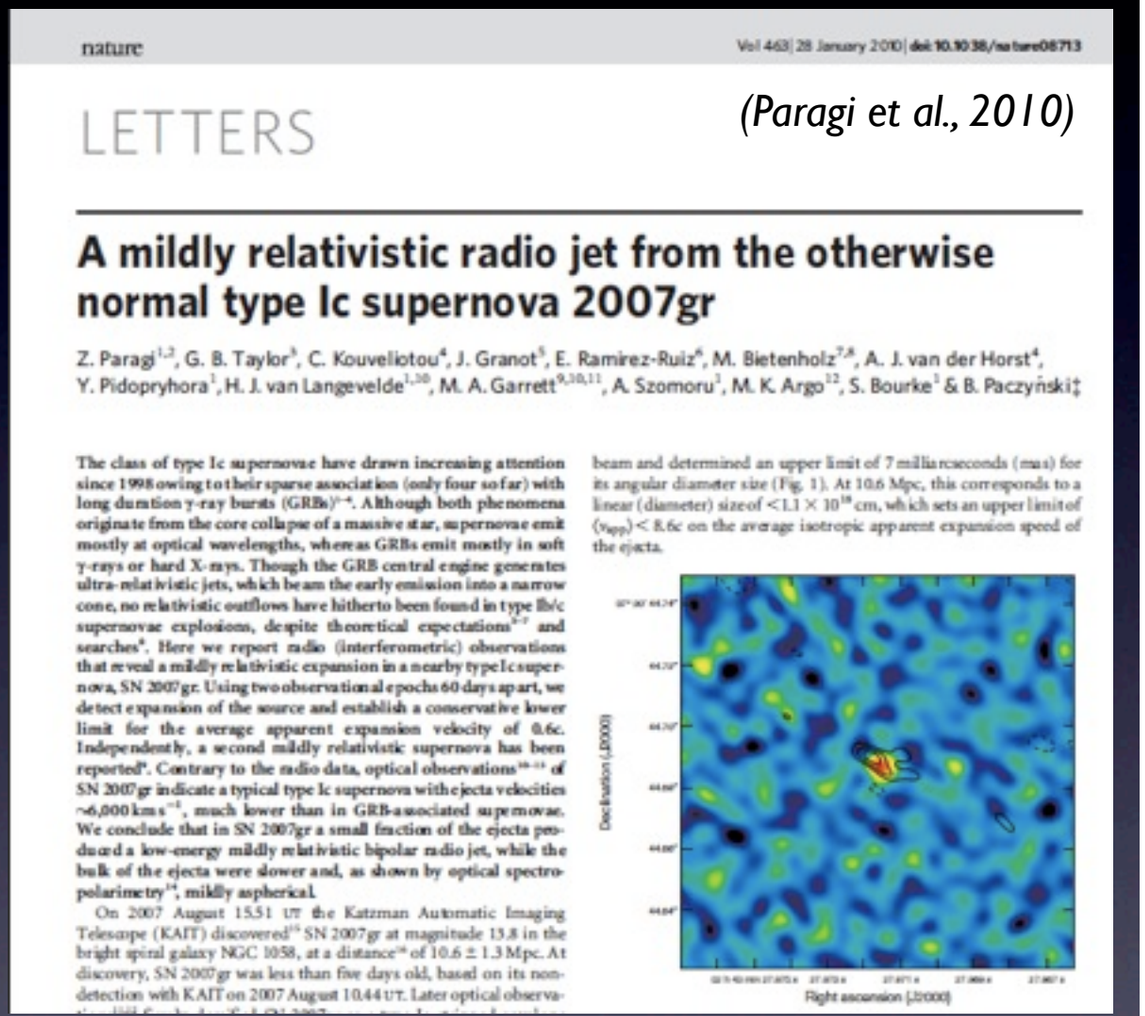

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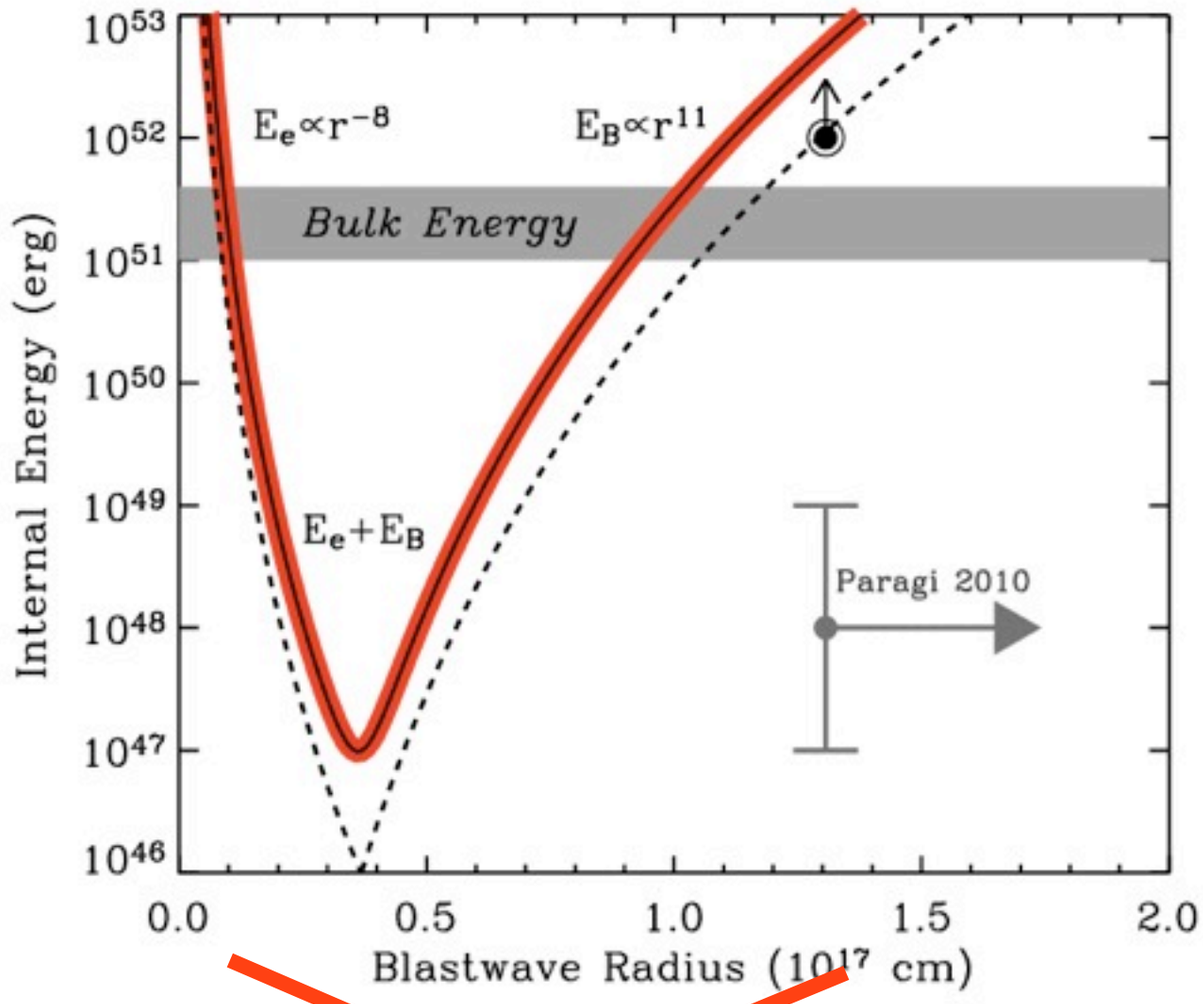

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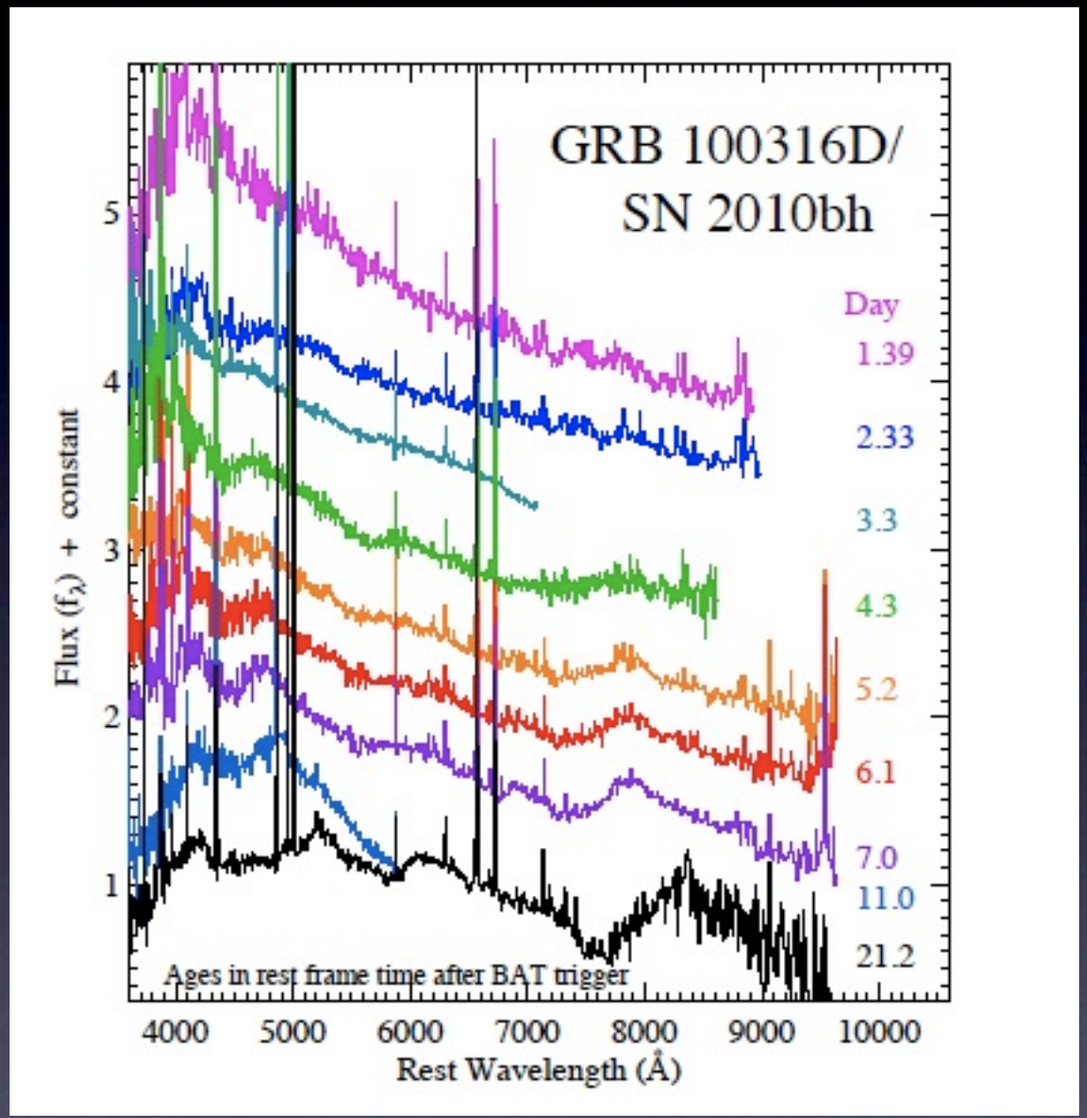
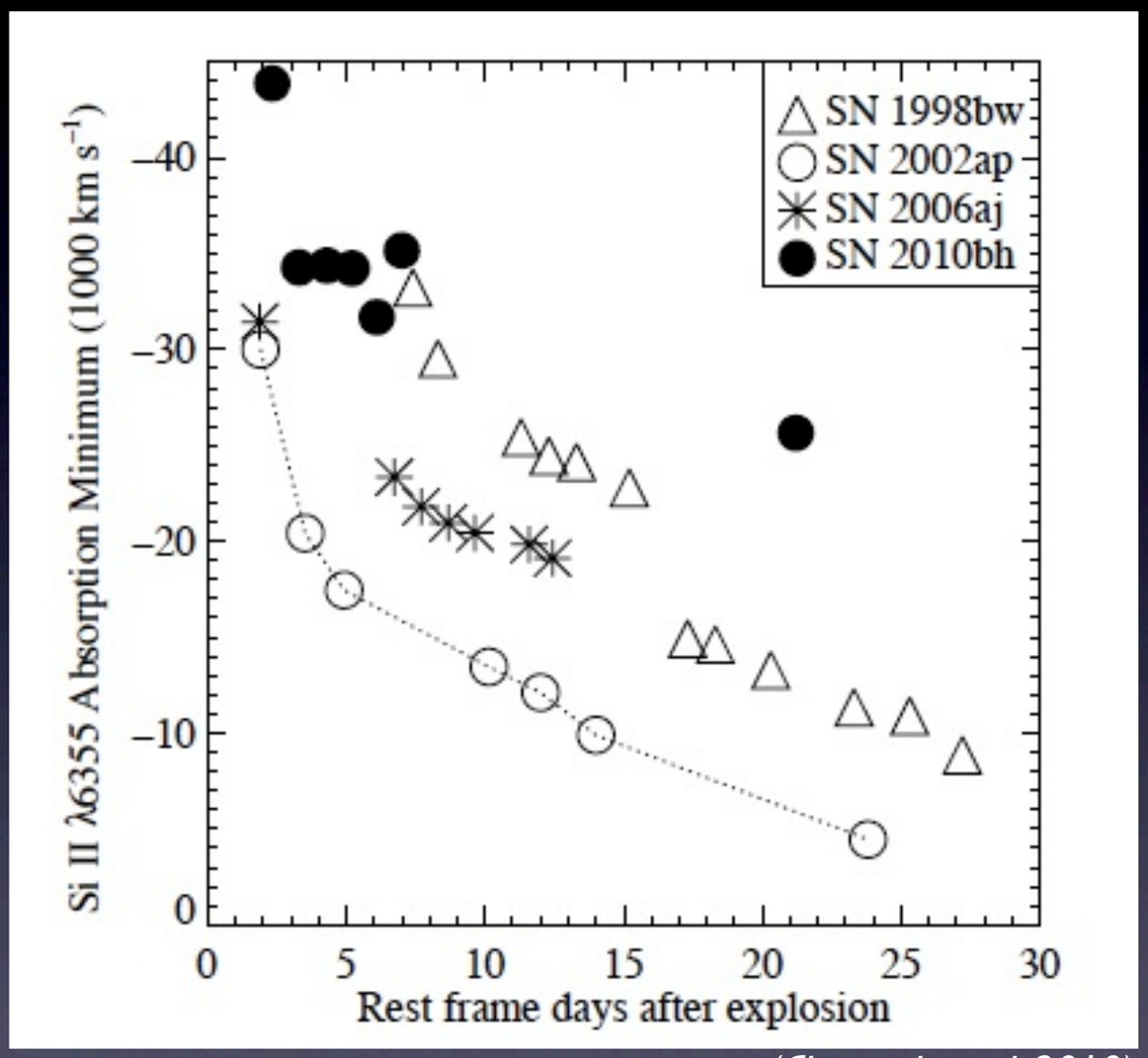
Welcome, GRB100316D / SN2010bh

z=0.059





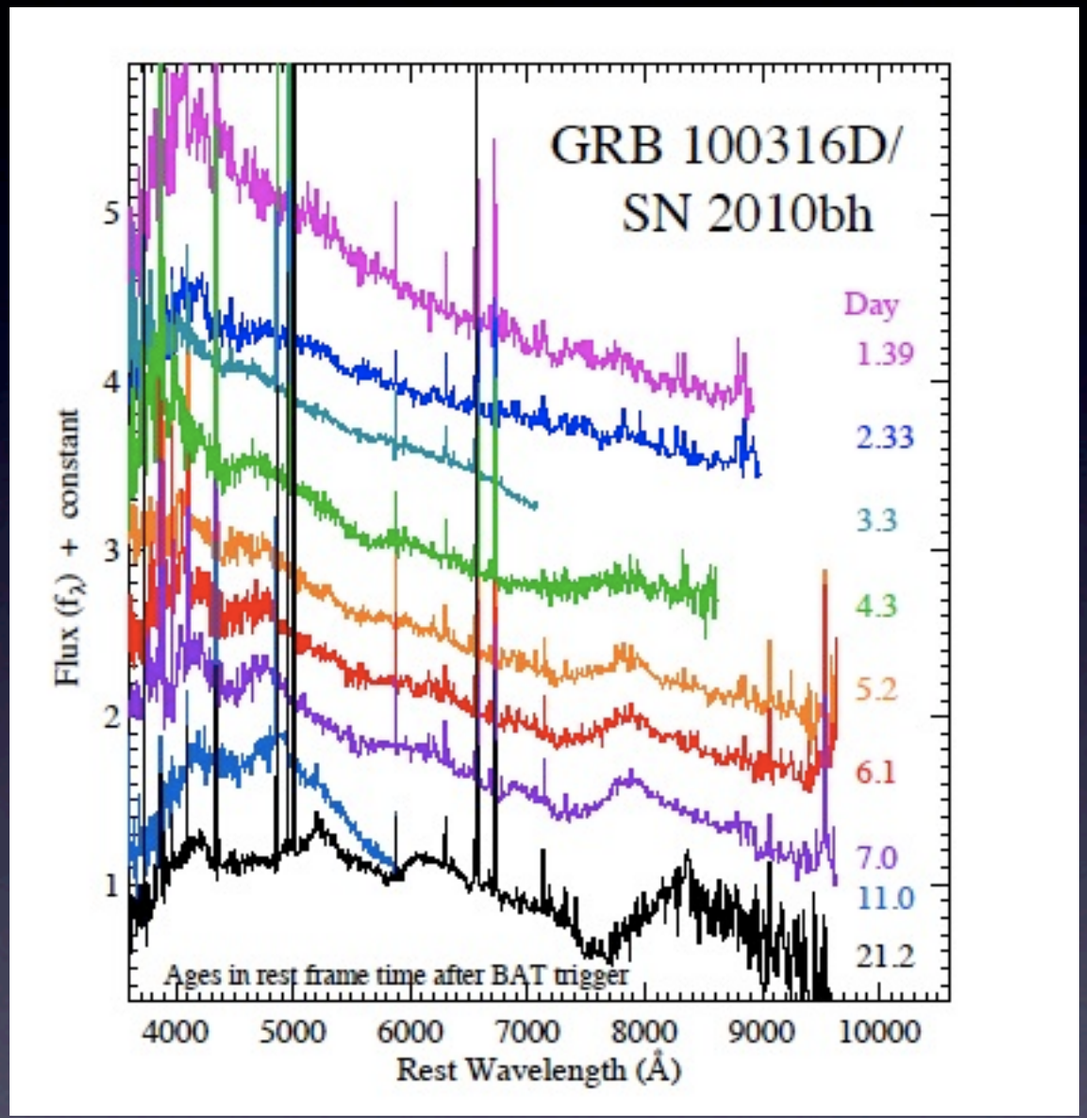
(Chornock et al. 2010)

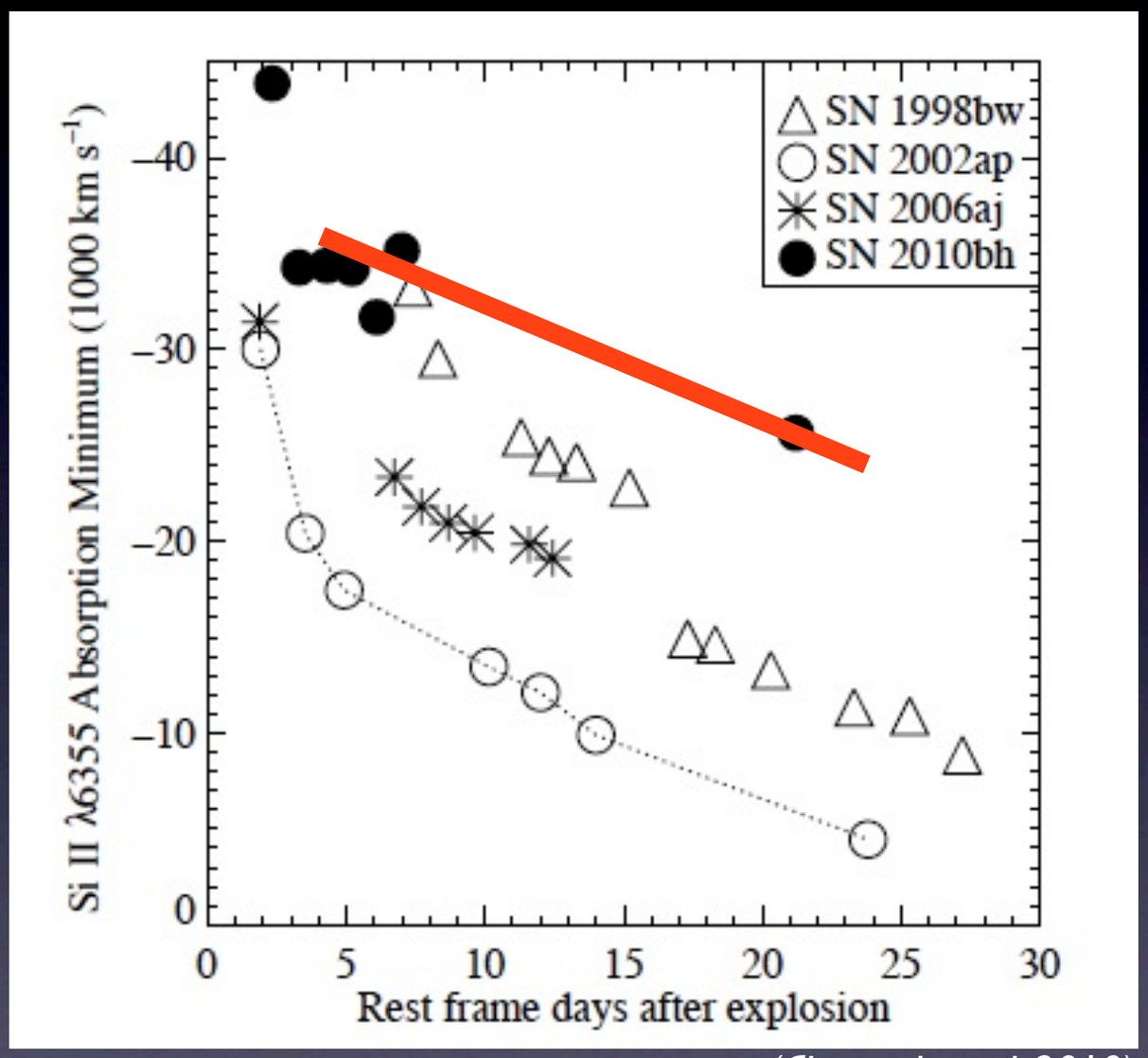
Broad-lined SN Ic

Fastest GRB-SN

Welcome, GRB100316D / SN2010bh

z=0.059





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