A Radio Perspective on Relativistic Supernovae

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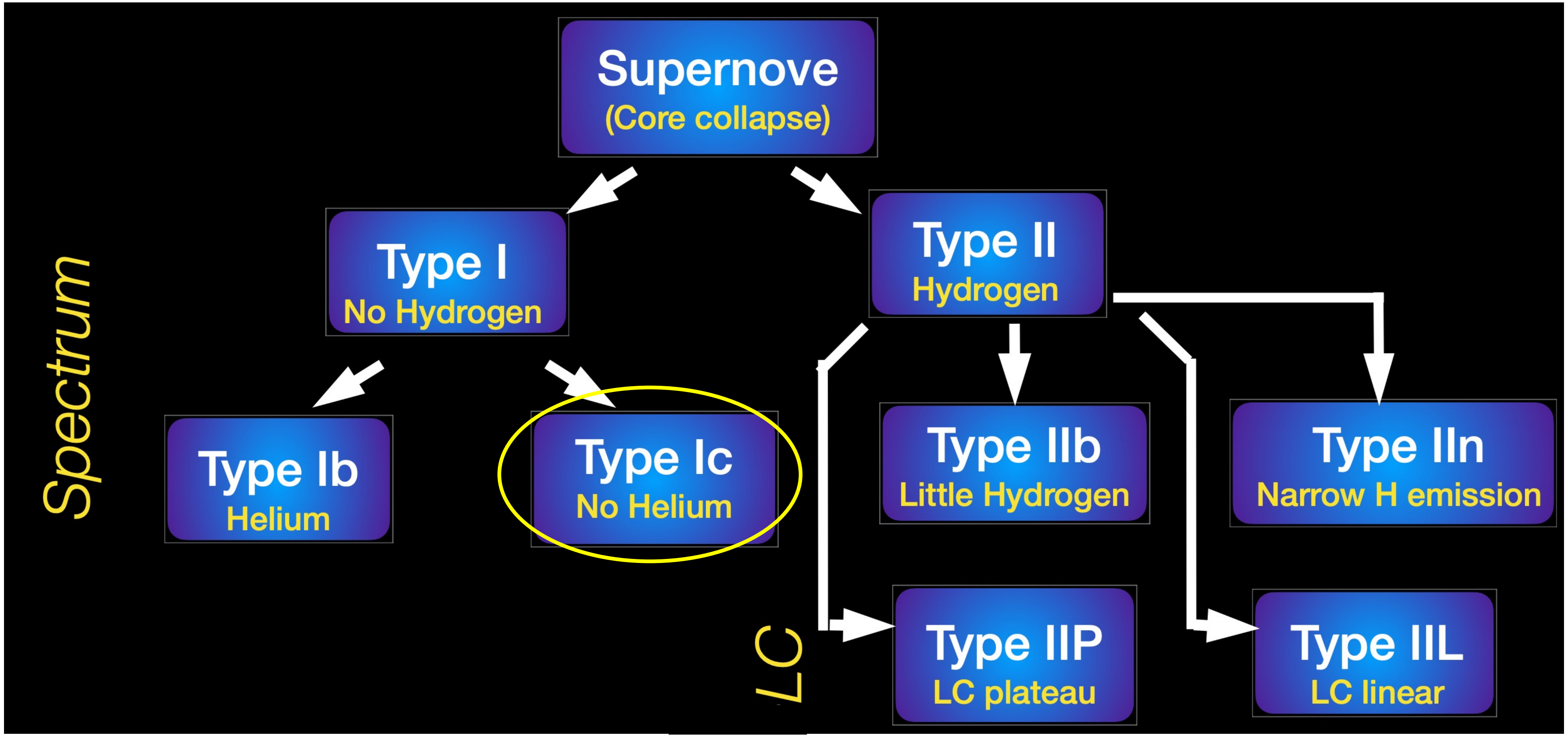
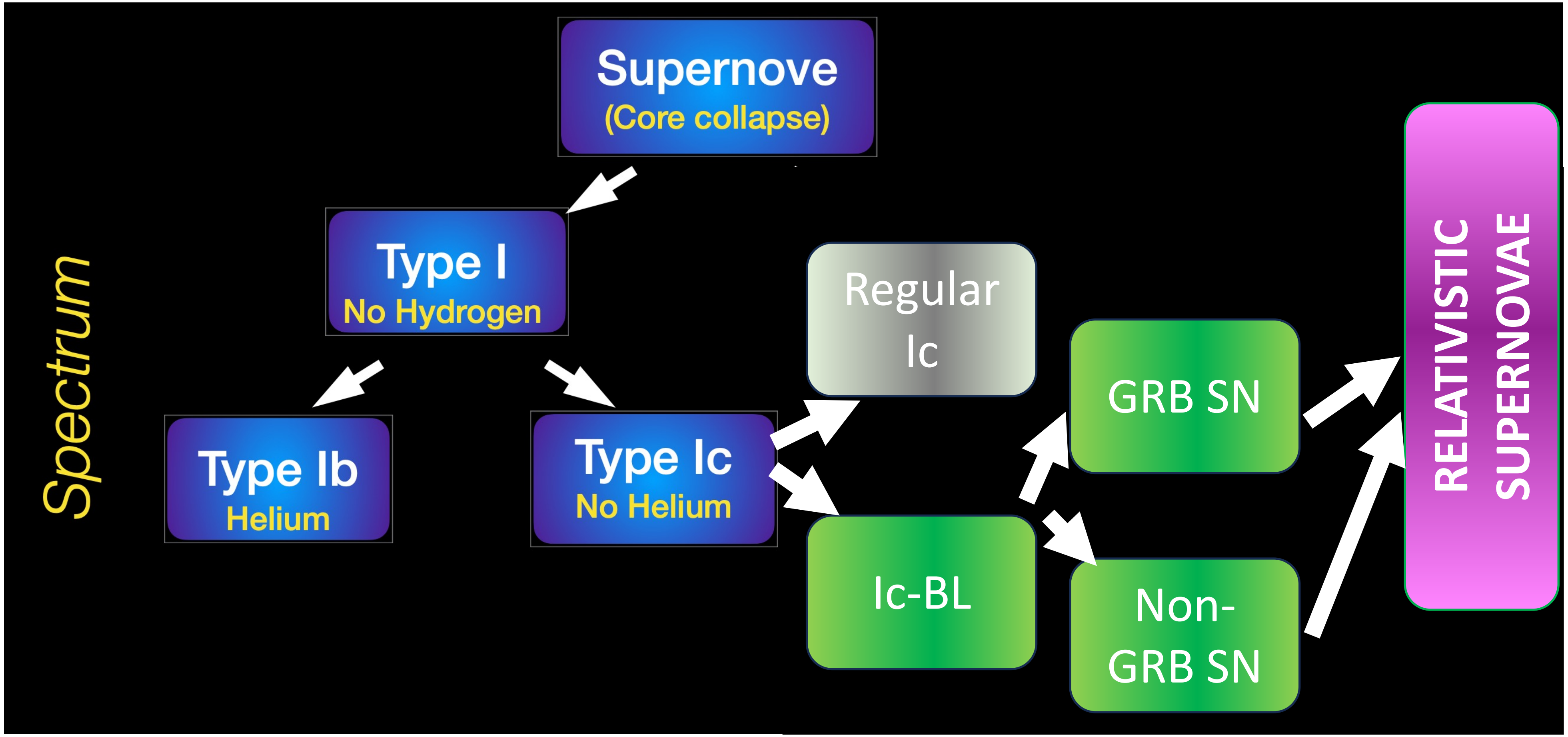
FEET 24 – A ThinkShop on fast evolving extragalactic transients, 26-29 Feb 2024

Supernovae


Supernove
(Core collapse)
Type I
No Hydrogen
Type II
Hydrogen
Spectrum
Type Ib
Helium
Type Ic
No Helium
Type IIb
Little Hydrogen
Type IIn
Narrow H emission
LC
Type IIP
LC plateau
Type IIL
LC linear

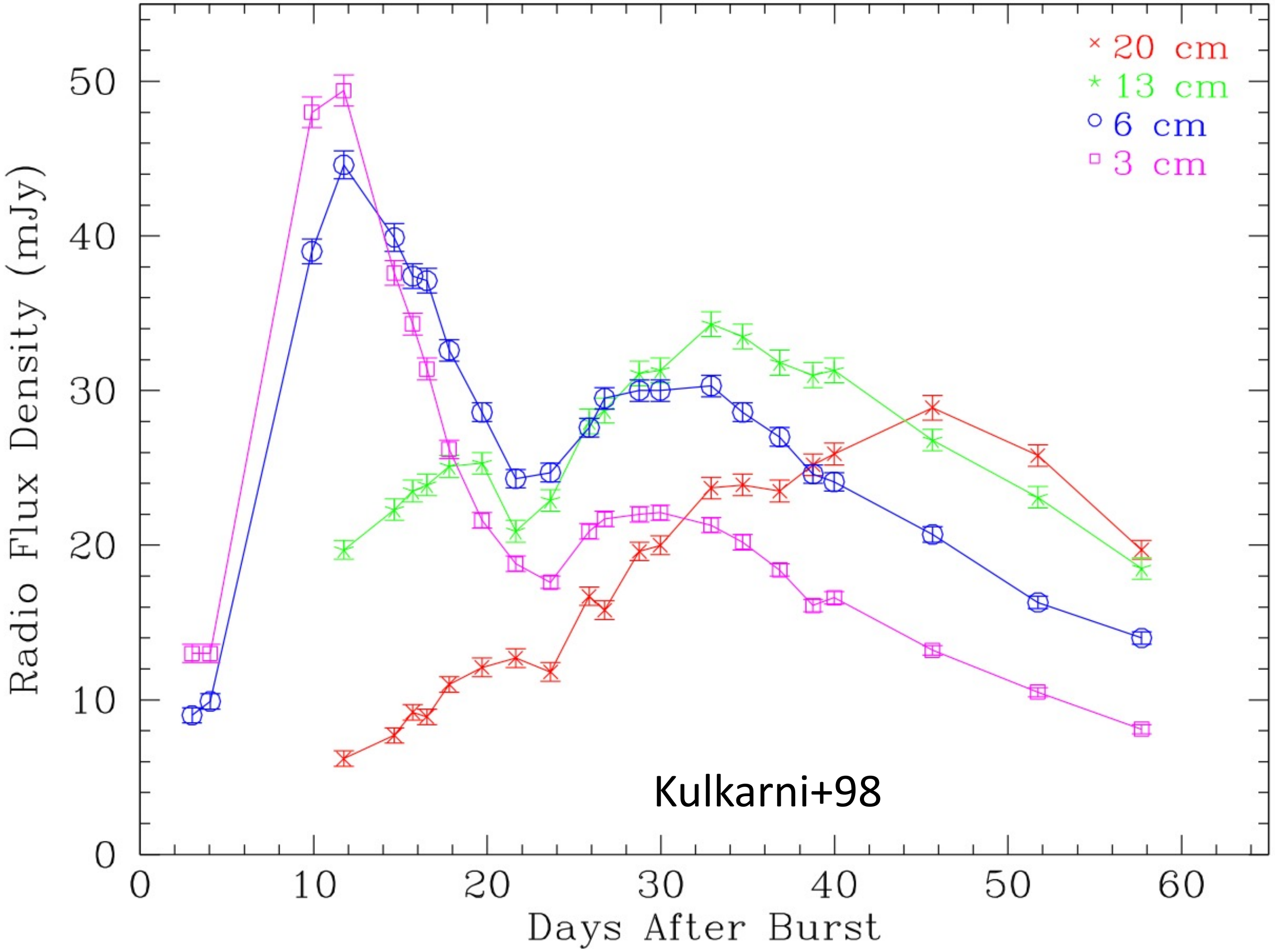
Supernovae


Supernove
(Core collapse)
Type I
No Hydrogen
Type Ib
Helium
Type Ic
No Helium
Spectrum
Regular Ic
Ic-BL
GRB SN
Non-GRB SN
RELATIVISTIC SUPERNOVAE

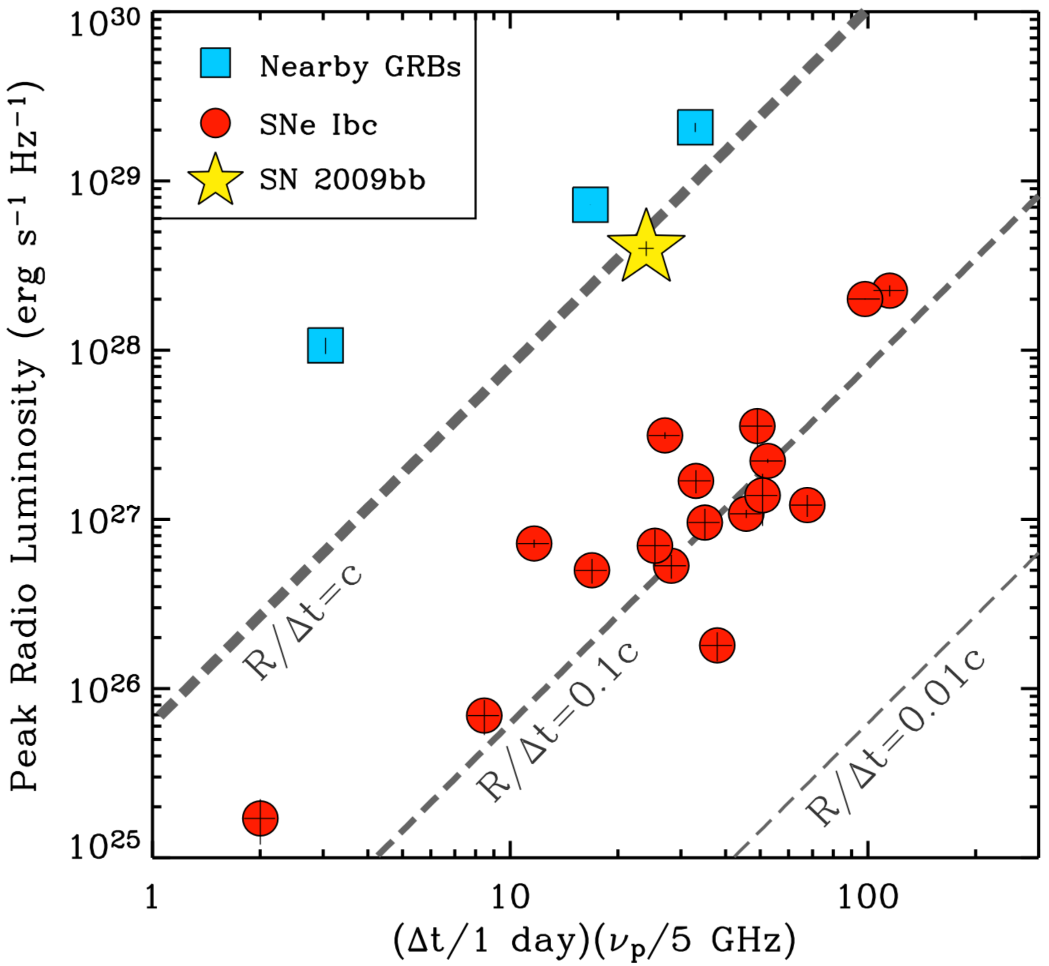
SN 1998bw – first relativistic supernova

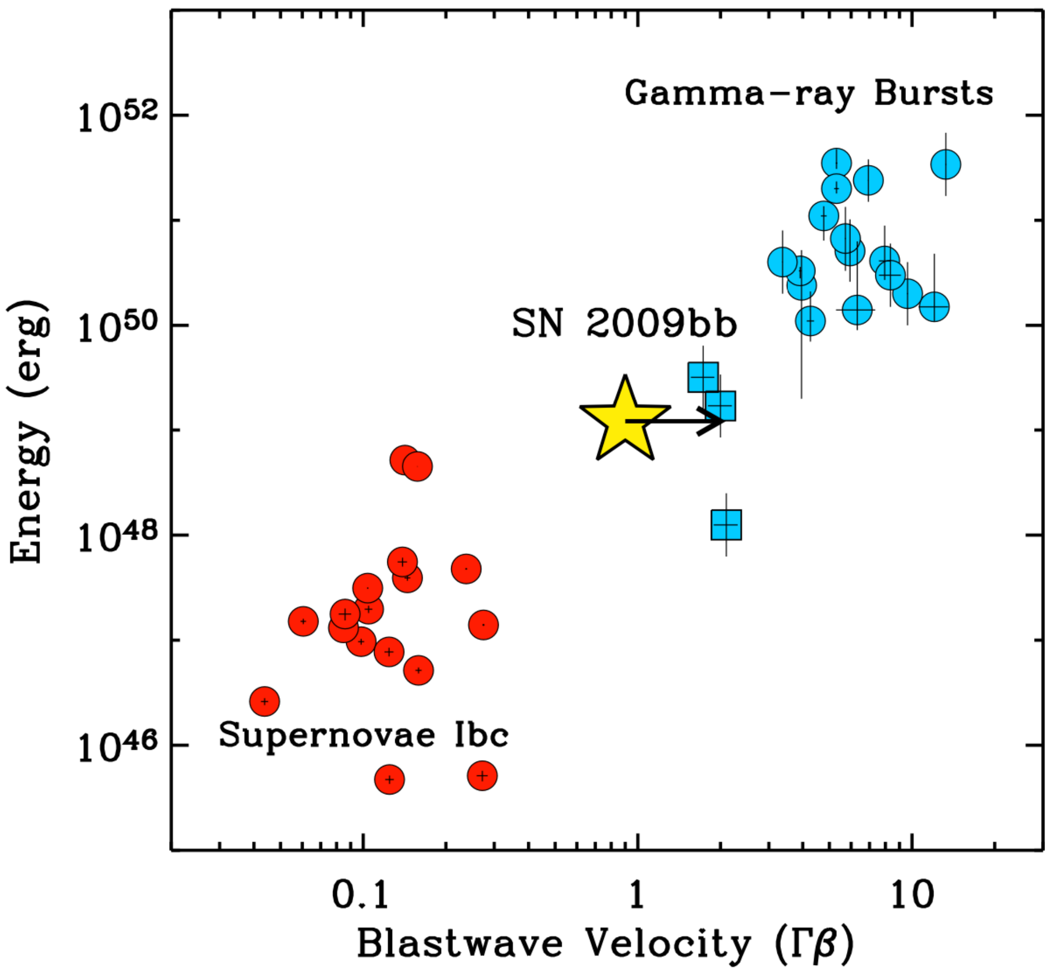
- SN 1998bw/GRB 980425 (Kulkarni+98)

- GRB ~ 10^{48} erg
- SN - apparent velocity ~2c=> a shock wave moving at relativistic speed.
- -More relativistic SNe/GRBs - SN 2003dh-GRB030329 (Hjorth et al. 2003), SN 2006aj- XRF060218 (Soderberg et al. 2006) etc



First relativistic supernova without GRB – SN 2009bb

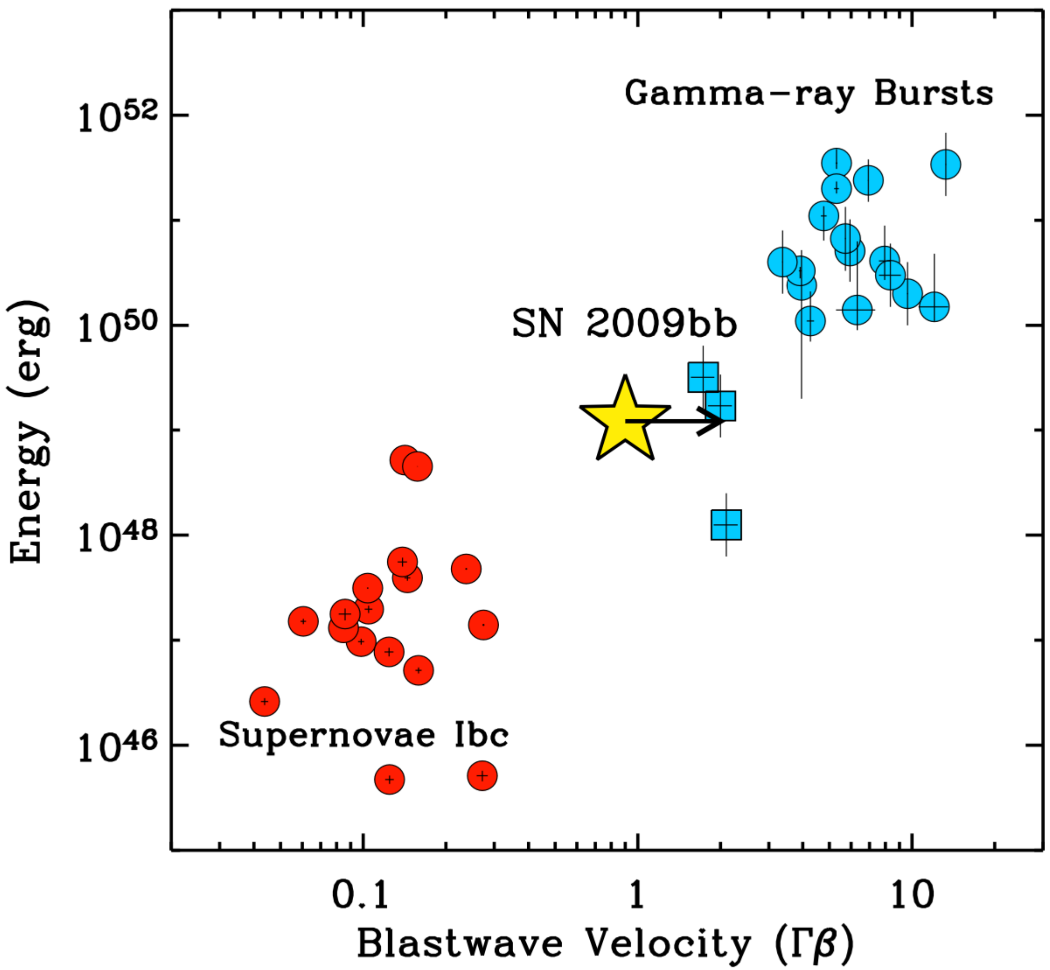




Soderberg…PC..+2010

First relativistic supernova – SN 2009bb

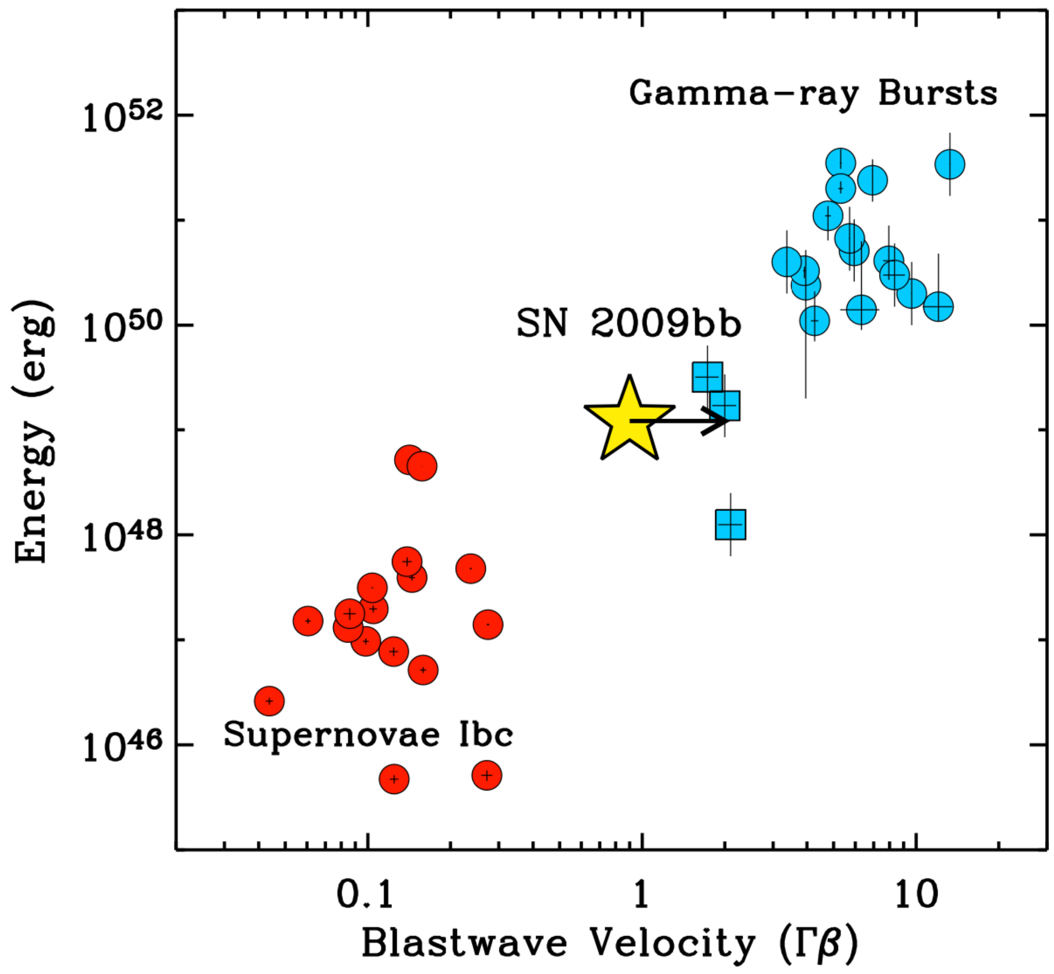
- Radio imaging v=0.85c
- Corresponding Lorentz factor 1.3
- Energy 1.3E49 erg needed coupled to the relativistic outflow
- If purely by shock acceleration then total SN energy >10^{53}erg
- Another energy reservoir needed
  - A central engine



Soderberg…PC..+2010

First relativistic supernova – SN 2009bb

- Exploded in super-solar metallicity environment (Levesque+10)
- Nearly free expansion for a year – Baryon loaded ejecta (Chakraborti+11)
- Possible sources of post-GZK cosmic ray production (Chakraborti+10)



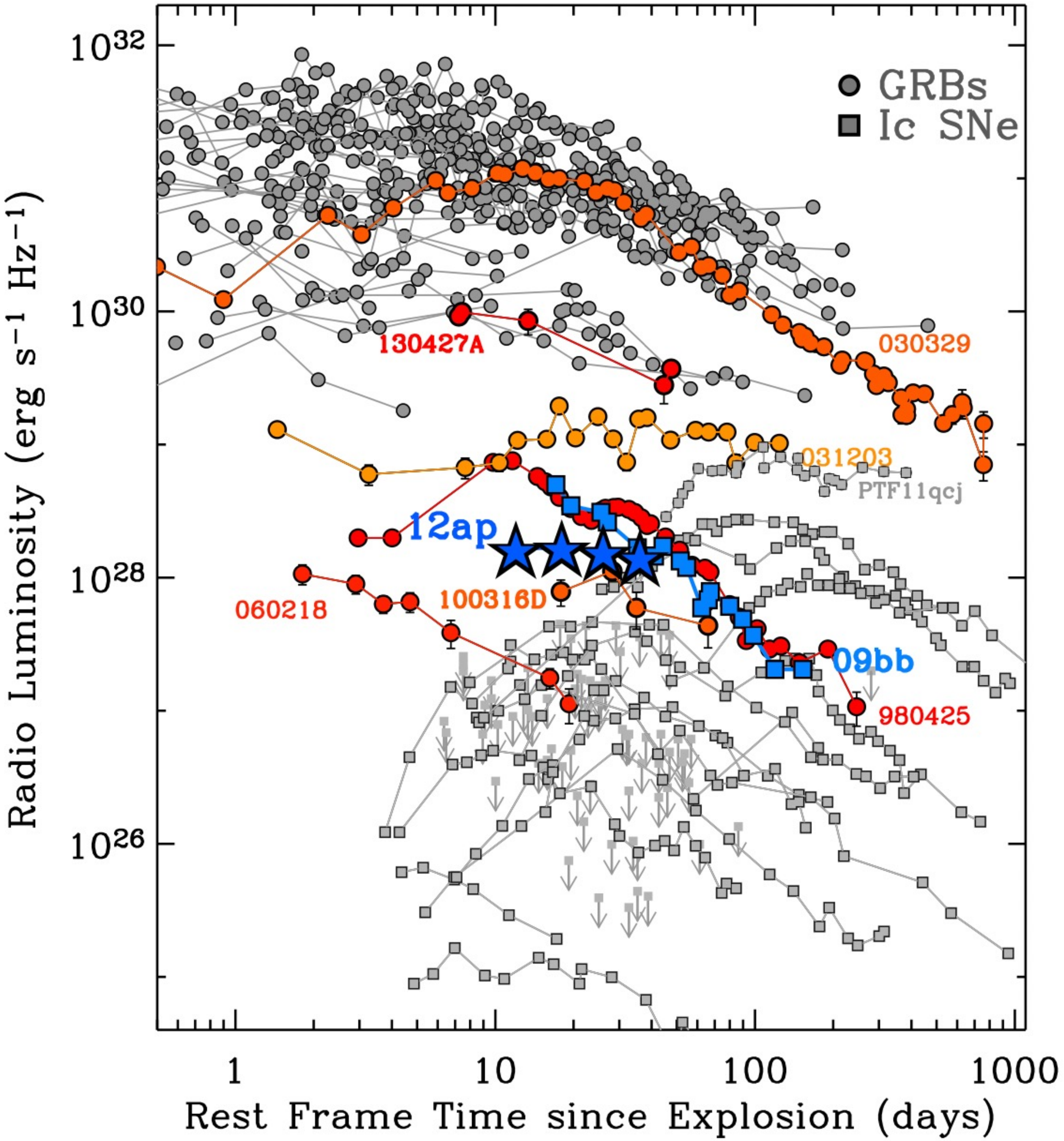
Soderberg...PC..+2010

SN 2007gr – almost a candidate

- A 0.6c expansion in a nearby type Ic supernova, SN 2007gr – radio VLBI 60 days apart (Paragi+10)
- Regular Ic (and not Ic-BL) - Optical observations - ejecta velocities ~6,000kms^{-1}.
- Modeling of 6 months of X-ray and radio observations – 0.2c speed and ~$2x10^{46}$ erg energy in the radio emitting material (Soderberg+10)
- Independent analysis of VLBI data - VLBI data and propose that a modest loss of phase coherence

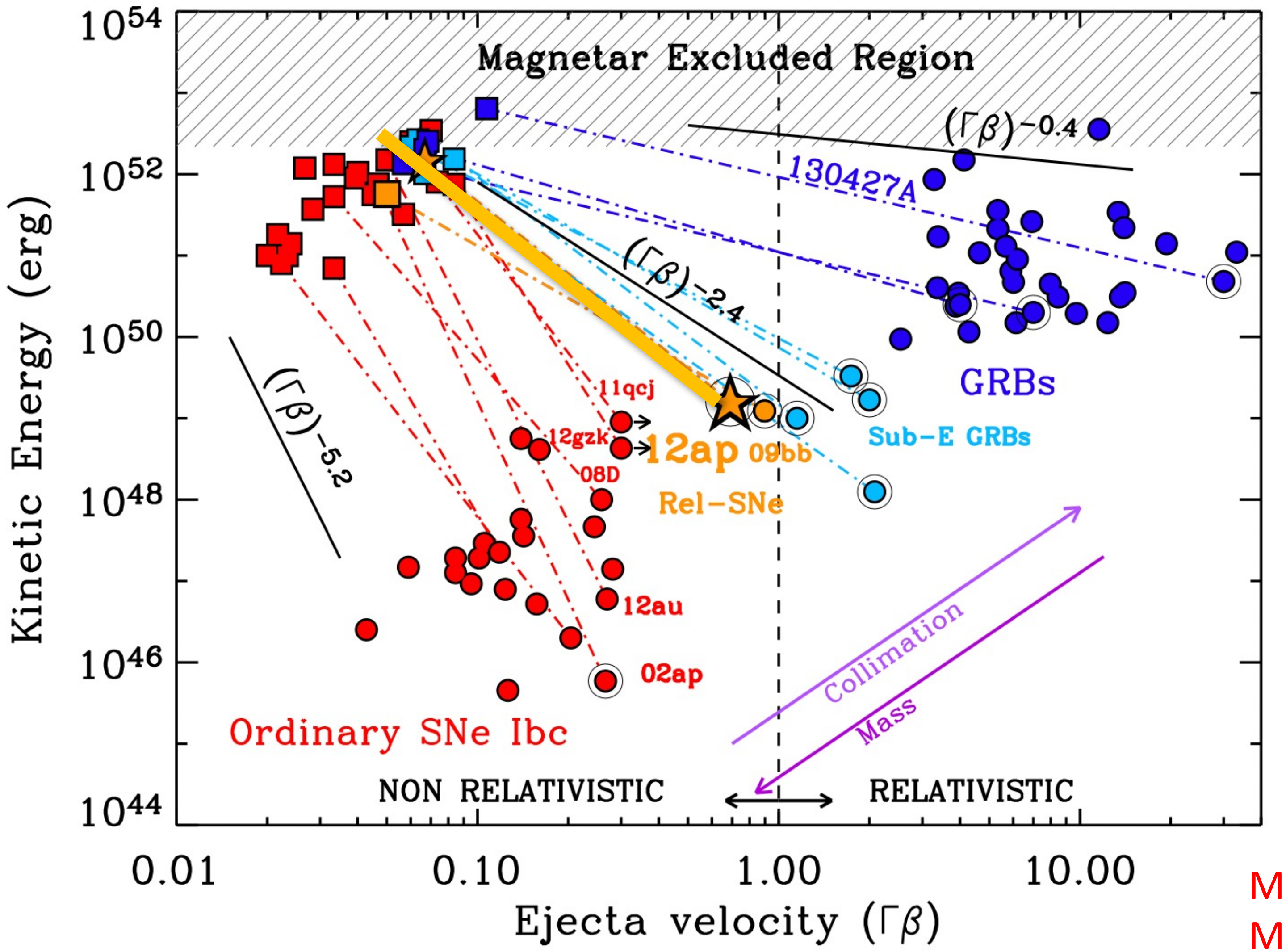
SN 2012ap – a rapidly decelerating mildly relativistic SN

- SN 2012ap - A Ic-BL SN 40 Mpc away.
- Mildly relativistic ejecta 0.7c but with fast deceleration (Chakraborti+13, Margutti+14)



Margutti+14

Fast deceleration in SN 2012ap

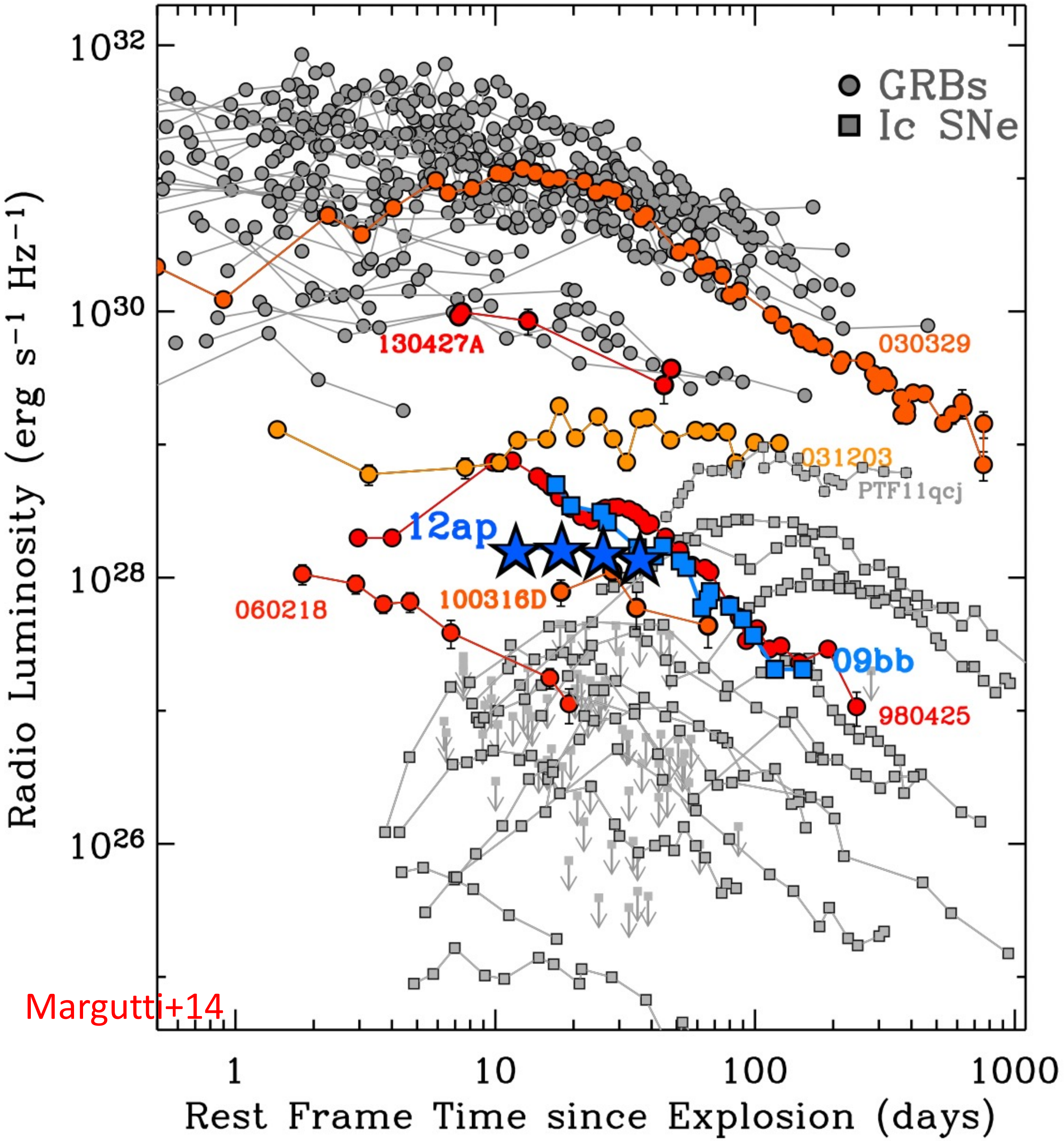


- Kinetic energy evolution steeper than GRBs but shallower than regular Ibc supernovae
- Consistent with sub-energetic GRBs

Models from Lazzati+12, Margutti+14

Central engine!

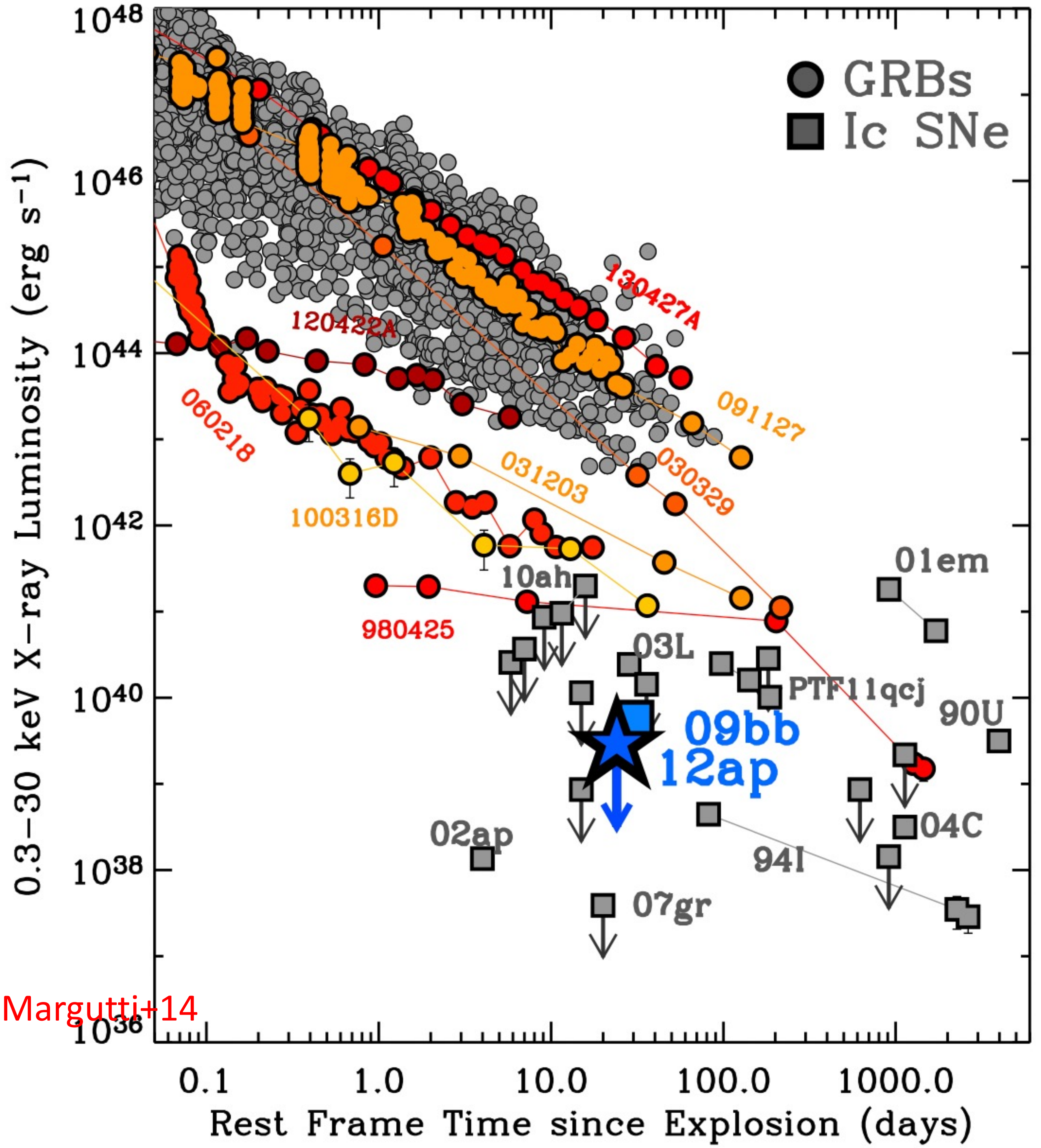
- If SN 2012ap low-luminosity GRB seen off-axis?
- Radio luminosity comparable to off-axis GRBs



Margutti+14

Central engine!

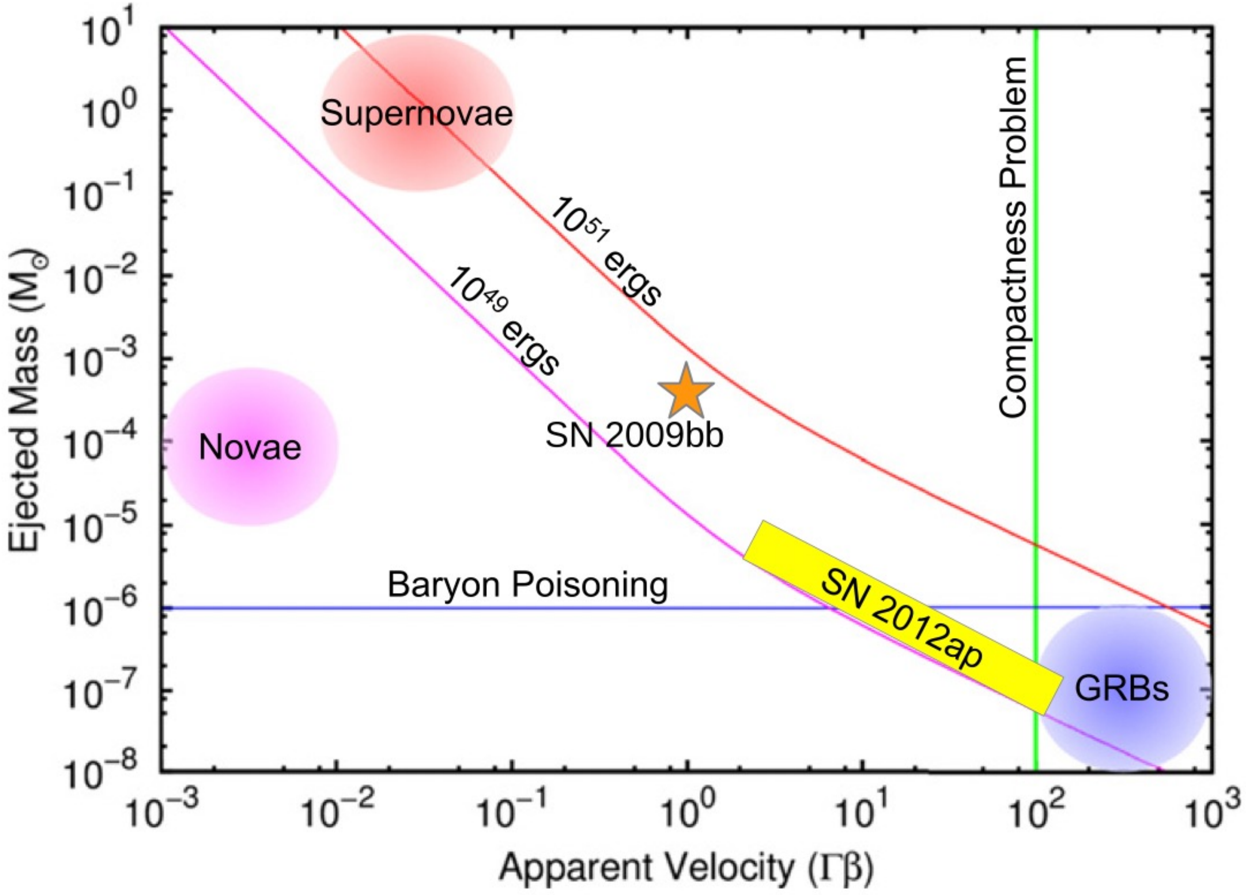
- Radio luminosity comparable to off-axis GRBs
- X-ray – 100 times fainter
- Not explained by GRB seen off-axis
- The difference between relativistic SNe and sub-energetic GRBs is intrinsic and not due to line-of-sight effects.



Margutti+14

Fast deceleration in SN 2012ap

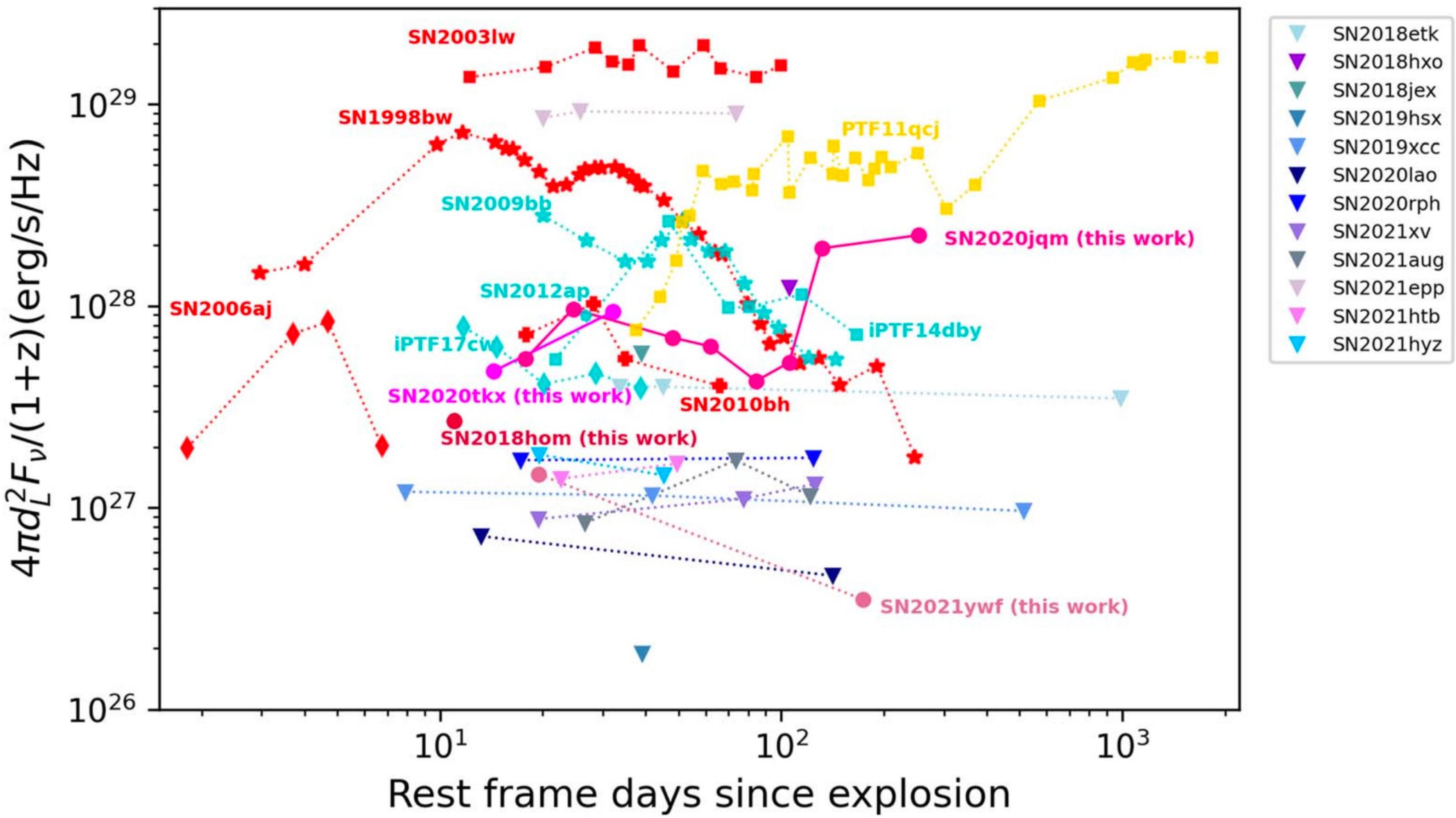
- Not a baryon loaded SN
- A link connection between Supernovae and GRBs



Chakraborti+14

More relativistic supernovae without GRBs

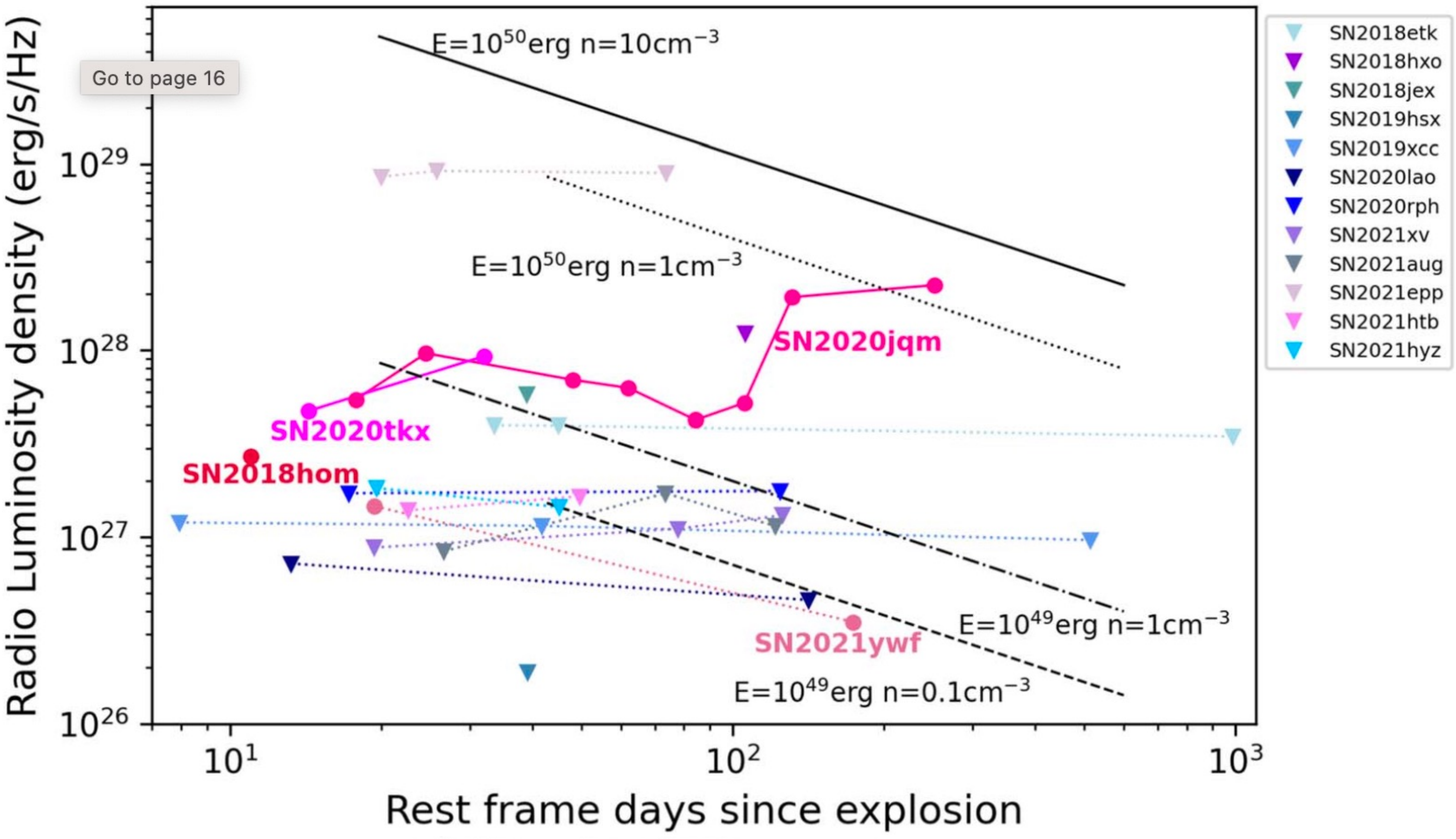
- iPTF17cw - ~0.6c speed (Corsi+17)
- Survey of ~15 iPTF Ic-BL to search for relativistic ejecta (Corsi+16)
- Survey of ~16 ZTF Ic-BL to search for relativistic ejecta (Corsi+23)



Corsi+23

More relativistic supernovae without GRBs

- <19% Ic-BL associated with relativistic ejecta
- Exclude an association of SNe Ic-BL with largely off-axis GRB afterglows with energies $E > 10^{50}$ erg expanding in ISMs with densities > 1 cm^{-3}.



Corsi+23

Central engines of relativistic supernovae

- Low luminosity GRBs seen off-axis
- Proto-magnetar (Shankar+21)
- Cocoon model (De Colle+18, Gottlieb+22)

Central engines of relativistic supernovae

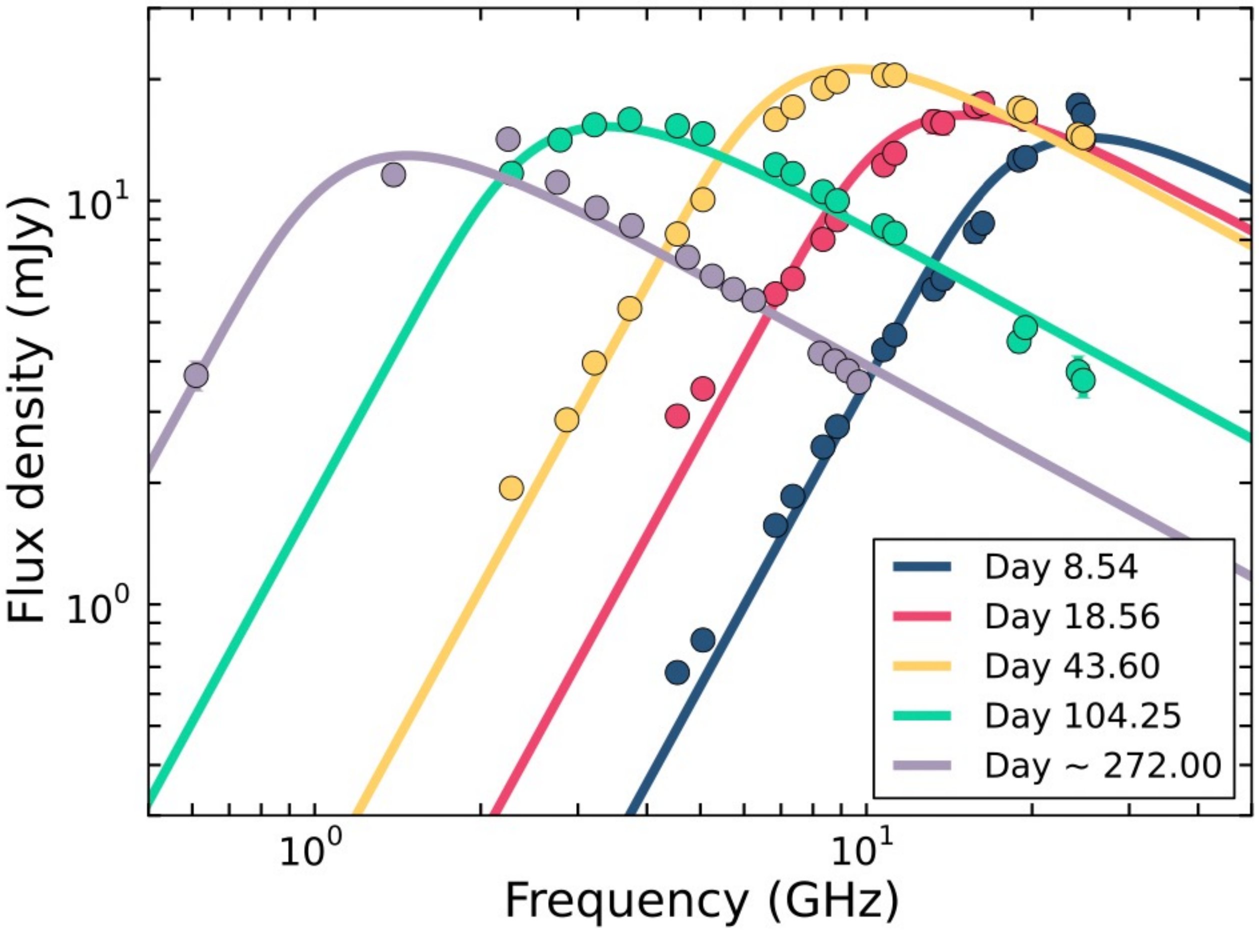
- Similarities SN 200bb and SN 2012ap
  - solar and super-solar metallicity (Levesque+10, Millisavjevic+14) environment
  - Presence of Helium in both SNe (Margutti+14, Pignata+11)
- Differences - SN 200bb and SN 2012ap
  - SN 2009bb – free expansion
  - SN 2012ap – fast deceleration
  - Baryon loading factor

Central engine of relativistic supernovae

- Shorter lived engine- a different lifetime of the central engine - the entire zoo of relativistic SNe, low-luminosity GRBs, and ordinary GRBs) Lazzati et al. 2012.
- Central engine duration determines the radio luminosity and fastest shock speed.

ASASSN-16fp – a non-relativistic Ic BL

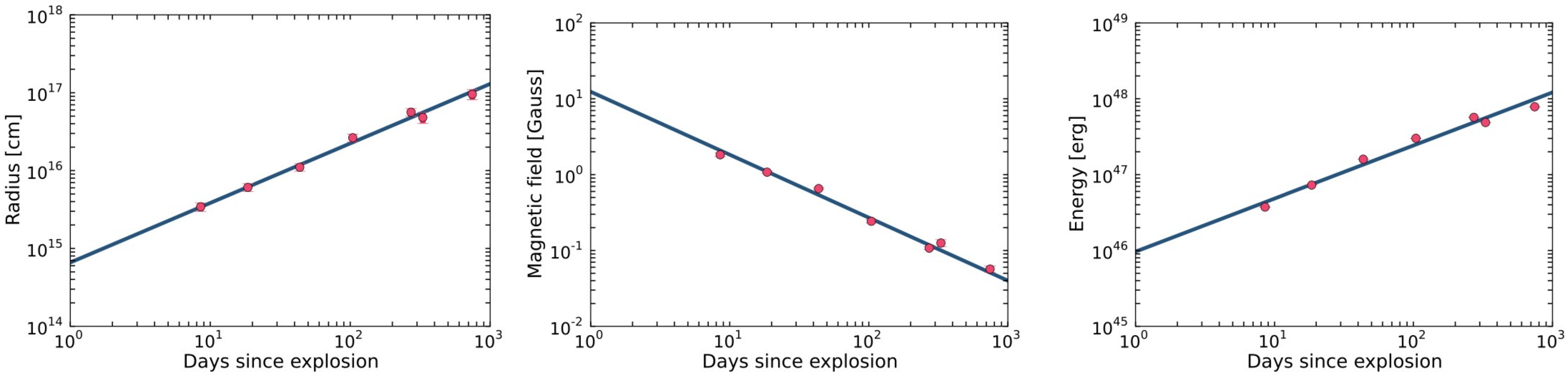
- Freq coverage 0.33–25 GHz, light curves 1200 days (Nayana & Chandra 2020)
- 0.2c ejecta, Evolution of ejeta for ~300 days
- Radio luminosity similar to SN2009bb (Soderberg et al. 2010b) and SN 2012ap (Chakraborti et al. 2015).
- Is central engine driven? (Probably not)- mass loss rate $10^{-5} M_{sun}$/yr- Wolf-Rayet!



Days since SN

Nayana and Chandra 2020

ASASSN-16fp – a non-relativistic Ic BL



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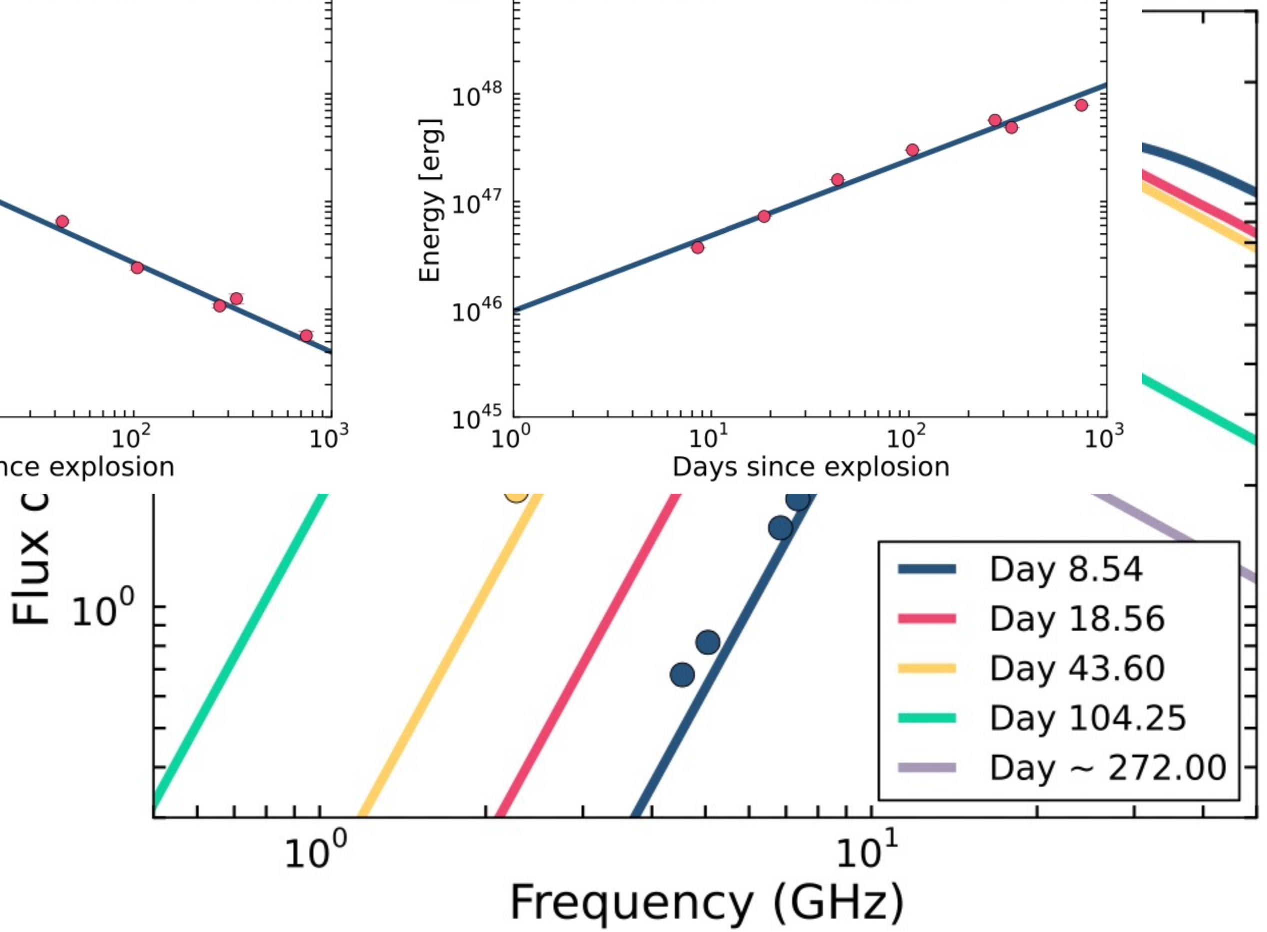


Days since SN

Nayana and Chandra 2020

Central engine of relativistic supernovae

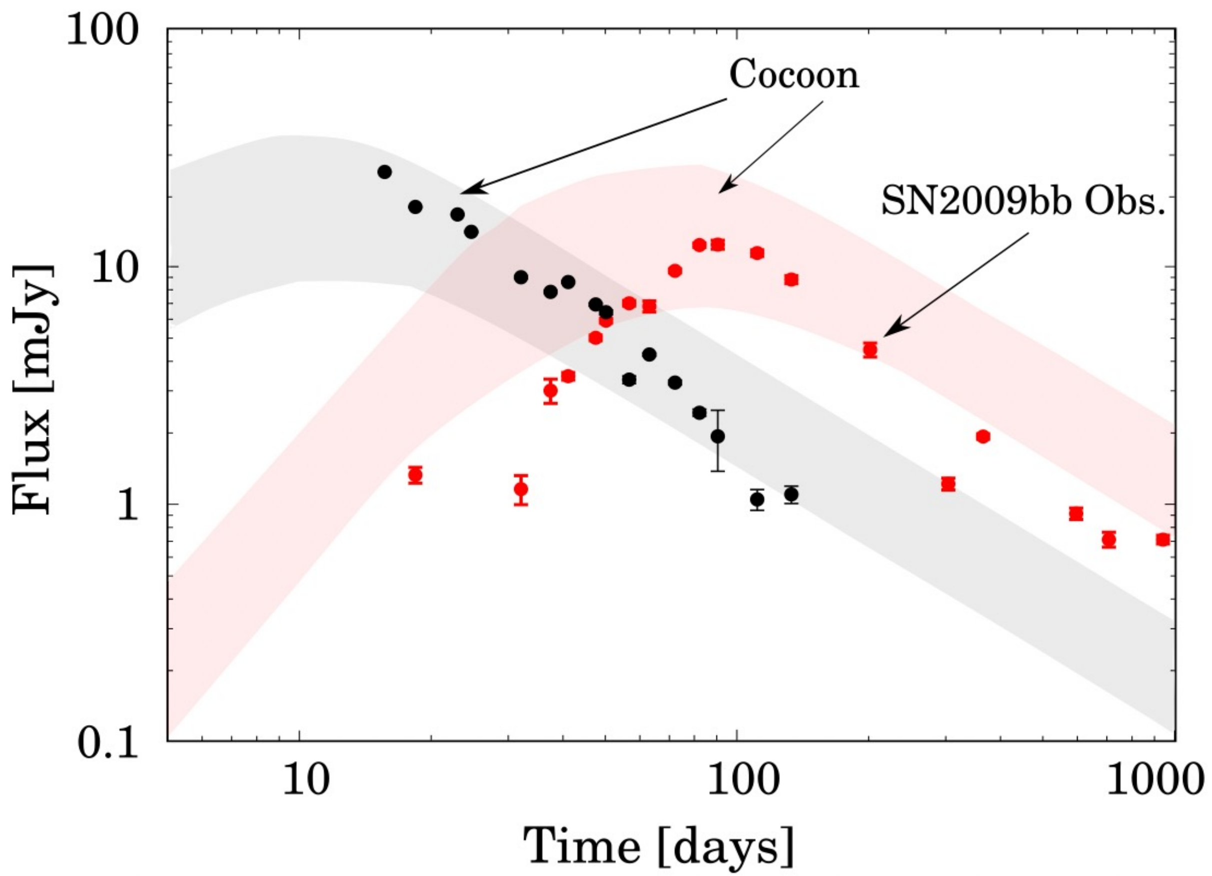
- Off-axis model:
  - high-energy (X-rays and γ -rays) properties vastly different
    - The different levels of X-ray emission between relativistic SNe and sub-E GRBs cannot be ascribed to beaming collimated emission away from our line of sight.
  - metallicity environment,
    - higher metallicity of the progenitors of relativistic SNe inhibited the formation of a powerful jet able to pierce through the stellar envelope.
  - presence of helium in their ejecta.
    - jet failed because it was dumped by the additional helium layers of the stellar progenitors of relativistic SNe.
  - Intrinsically different emissions

Central engine of relativistic supernovae

- Proto-magnetar
- jets from proto-magnetars - viable engines for SNe Ic-bl (Shankar+21).
- Central engines with smaller opening angles ($\sim 11^{\circ}$) associated with GRB
- Relativistic Ic-bl's without GRBs - associated with wider outflows.

Central engine of relativistic supernovae

- Cocoon emissic e Colle+ 2018, Gottlieb+:
- Cosmological lo cessfully from the stellar e
- Low-luminosity (d

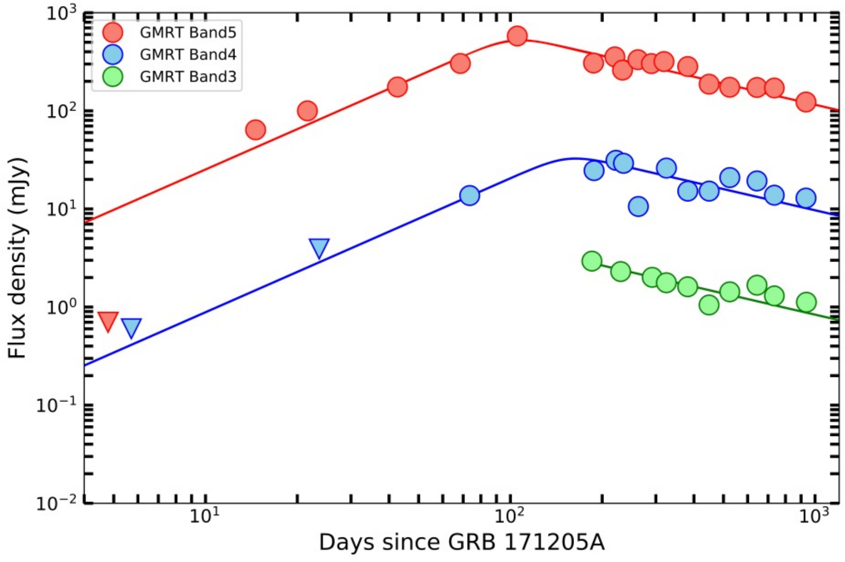


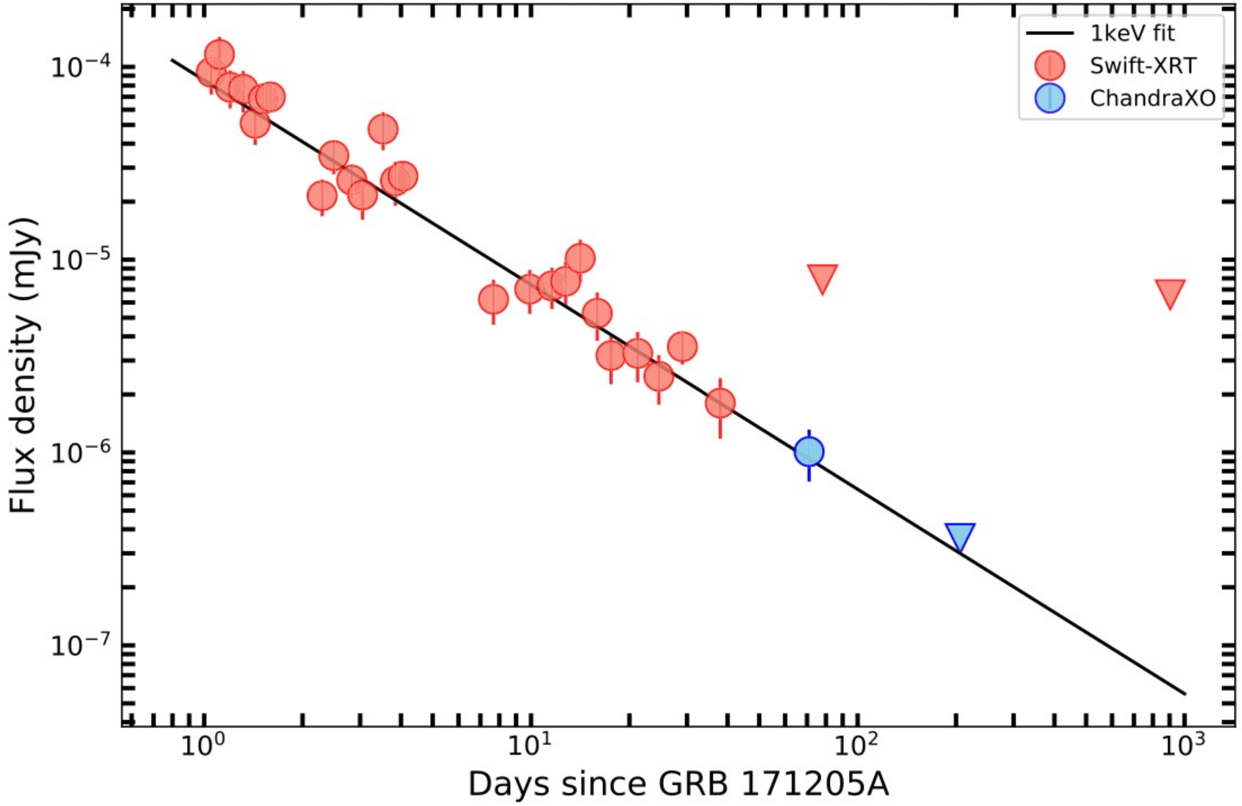
De Colle+18

SN 2017iuk/GRB 171205

Also see Izzo's talk

- 1000 days study (Maity & Chandra (2021)

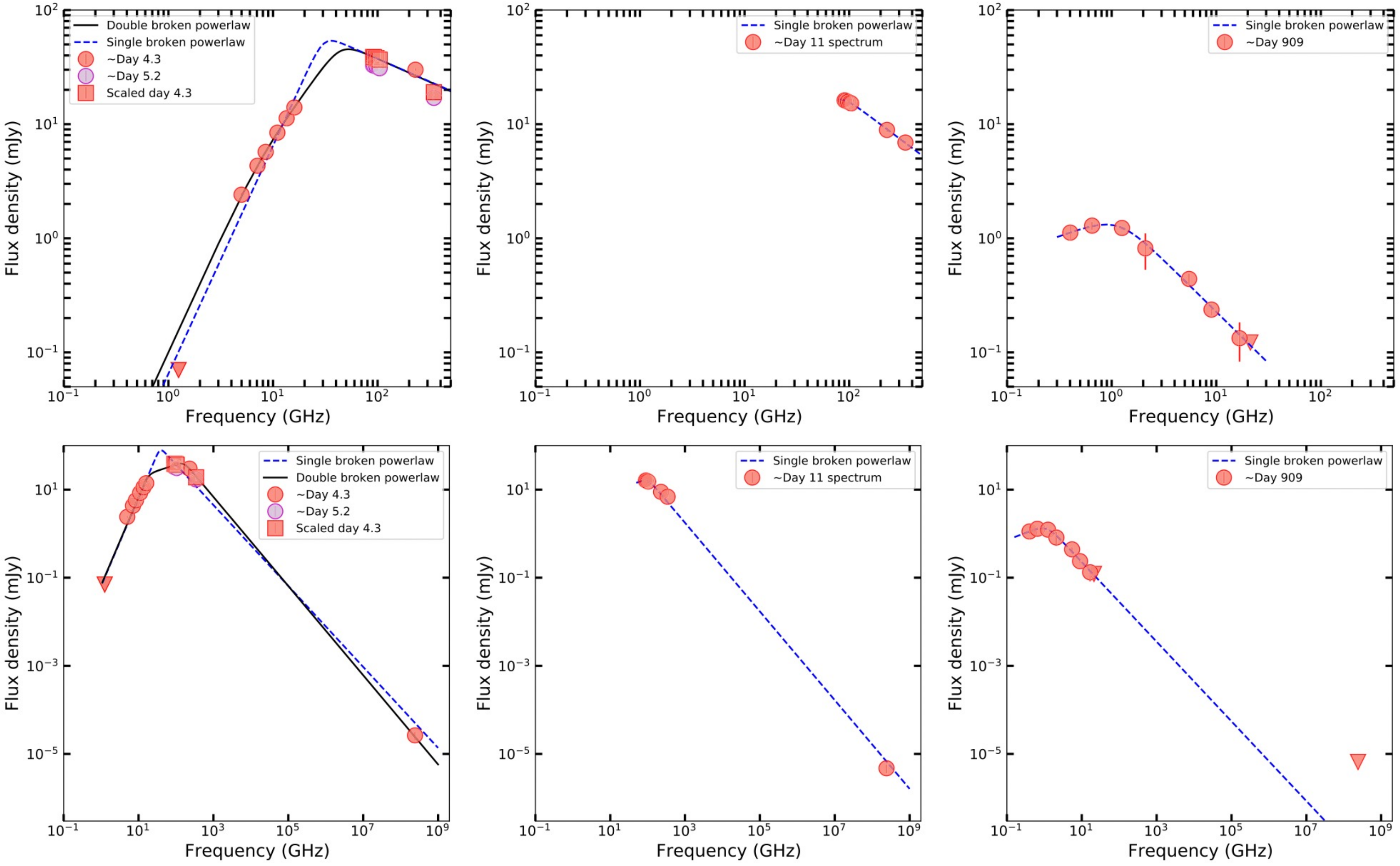




Maity & Chandra 2021

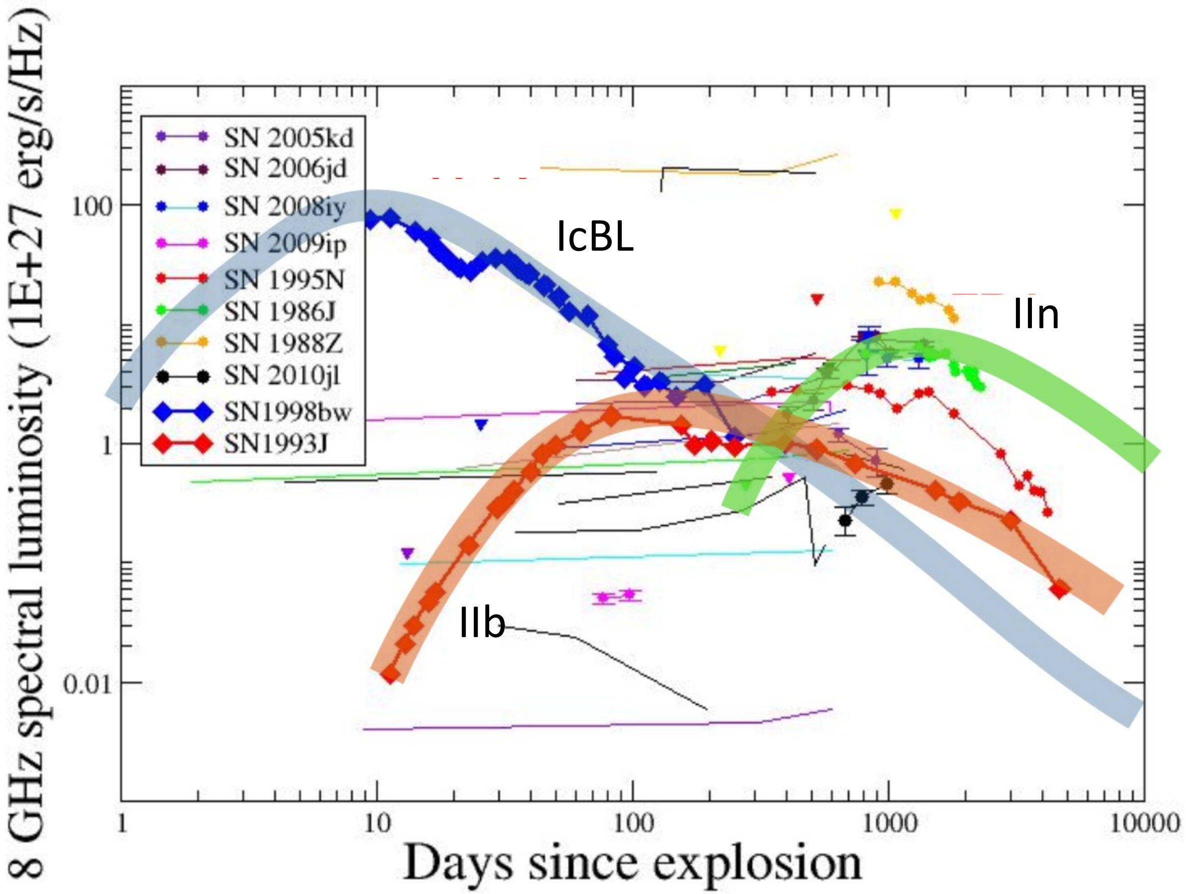
SN 2017iuk/GRB 171205

- Early radio cocoon dominated
- Late radio jet dominated
- Slightly off-axis jet (Izzo+19)



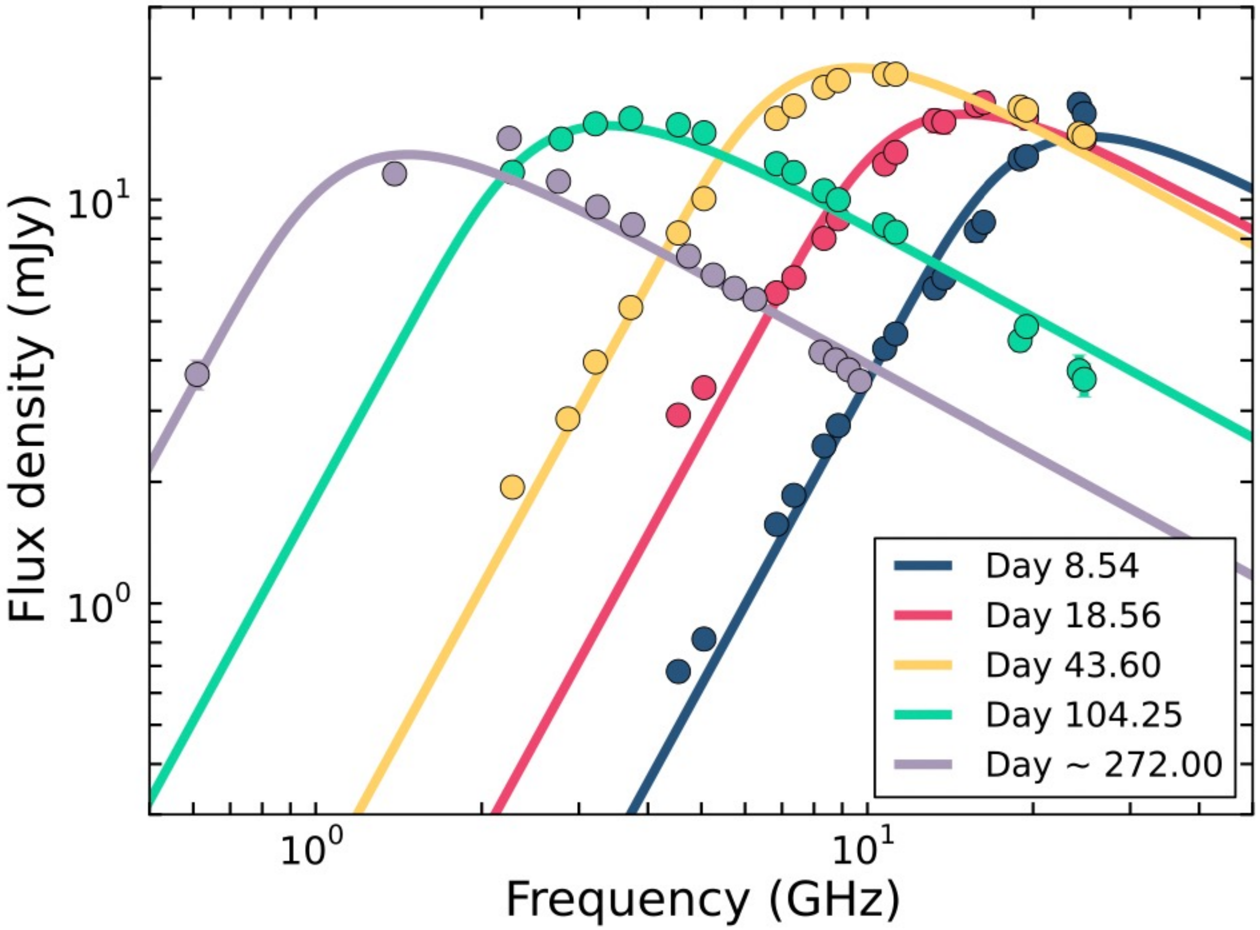
Maity & Chandra 2021

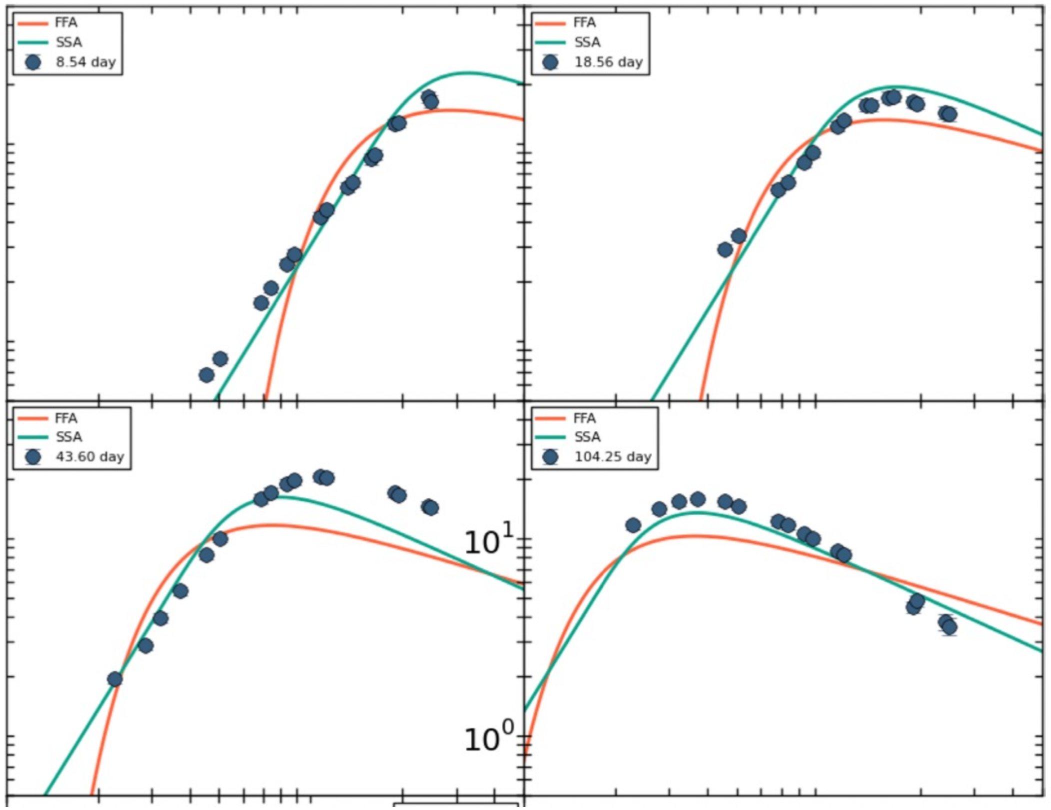
Role of radio observations



Chandra+

Are some Ic-BL associated with off-axis jets – long time measurements needed

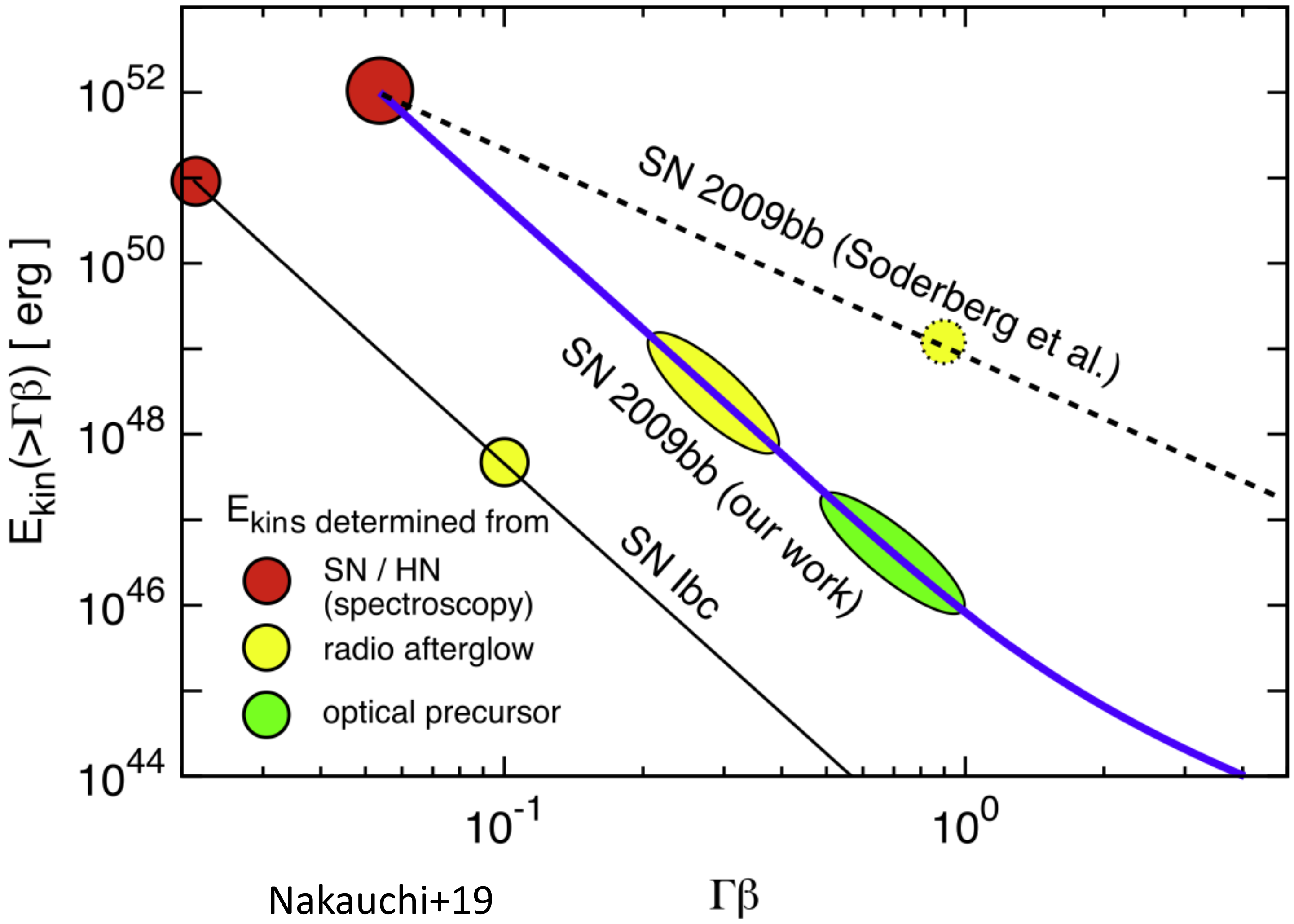




Nayana and Chandra 2020

Role of Radio observations – removing degeneracies

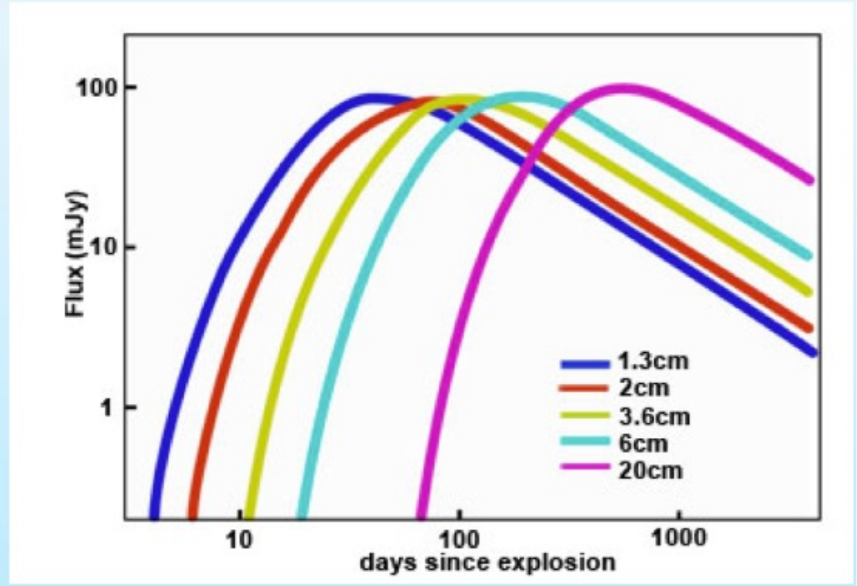
- Nakauchi+19- Overestimation of speed- by overlooking some factors related to the minimum energ[y] of non-thermal electrons.



Nakauchi+19

Role of radio observations - – removing degeneracies

- Wide band radio measurements needed to fix microscopic parameters
- Size measurements may be wrong due to assumption of equipartition



- Size from peak of radio emission
- Assumption of equiparititon and filling factor

Role of radio observations

- Wide band radio measurements needed to fix microscopic parameters
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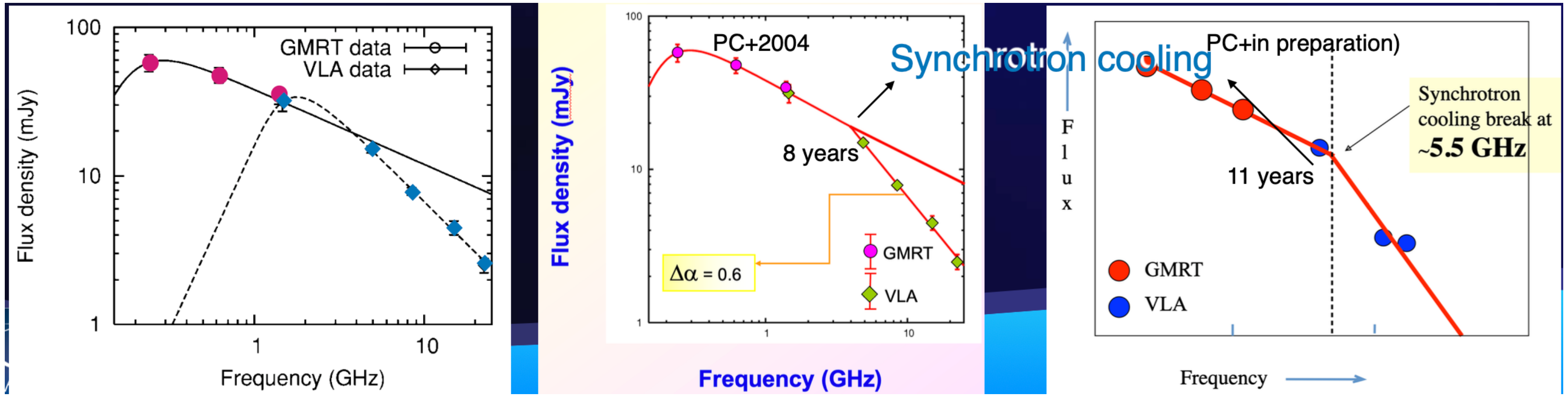
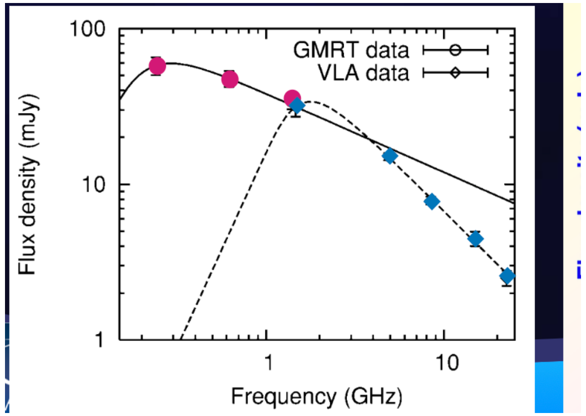
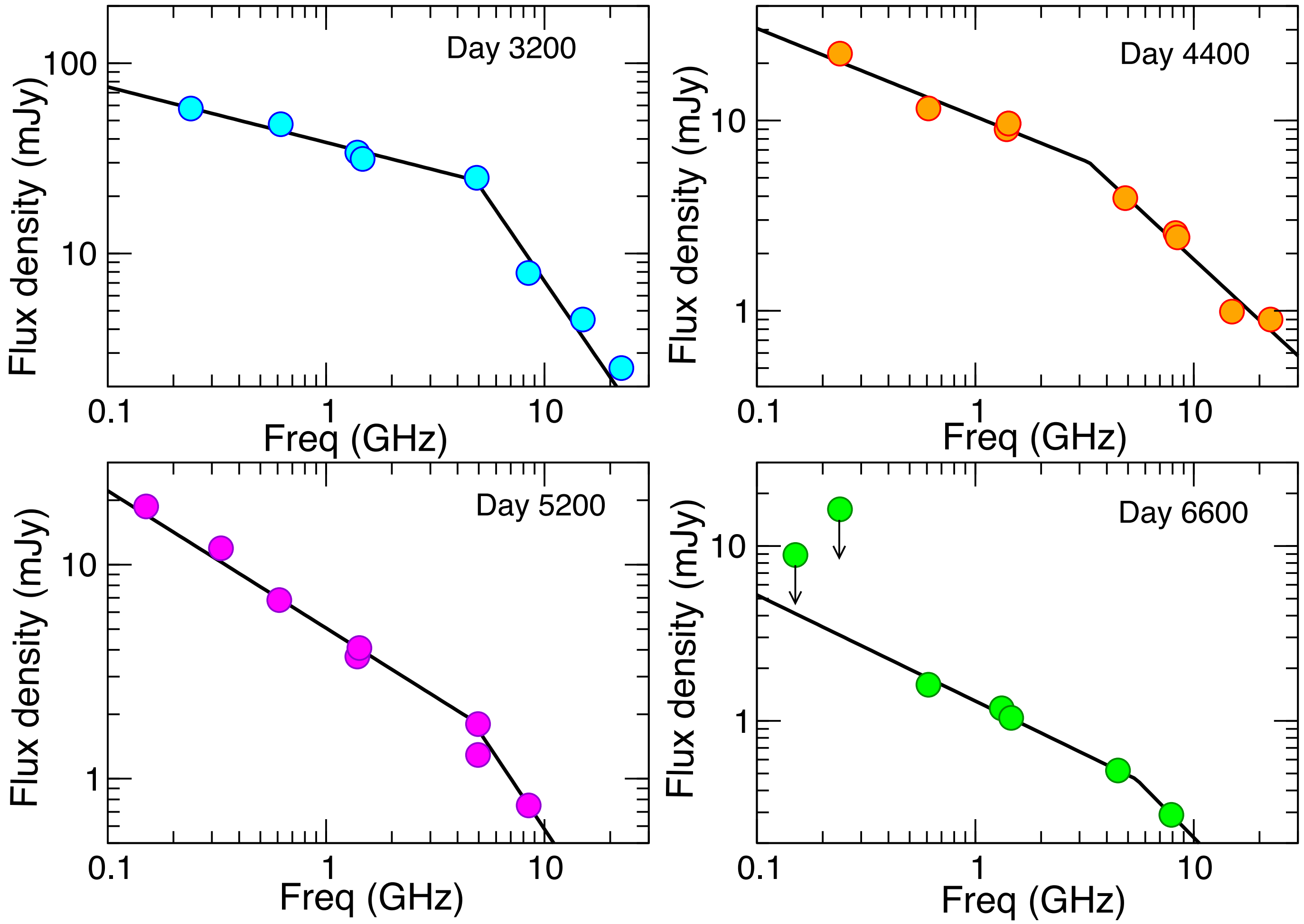


SN 1993J- Magnetic energy 10000 larger than relativistic electrons
PC+04a,b

Role of radio

- Wide band radio m parameters
- Size measurement equipartition

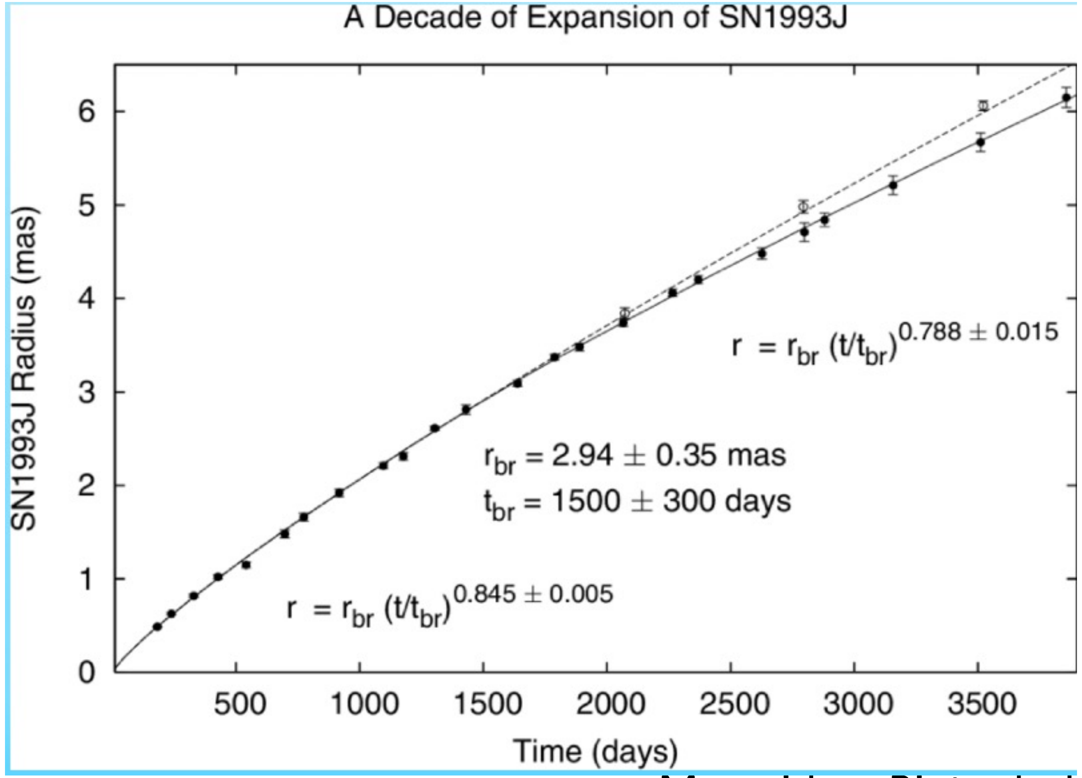


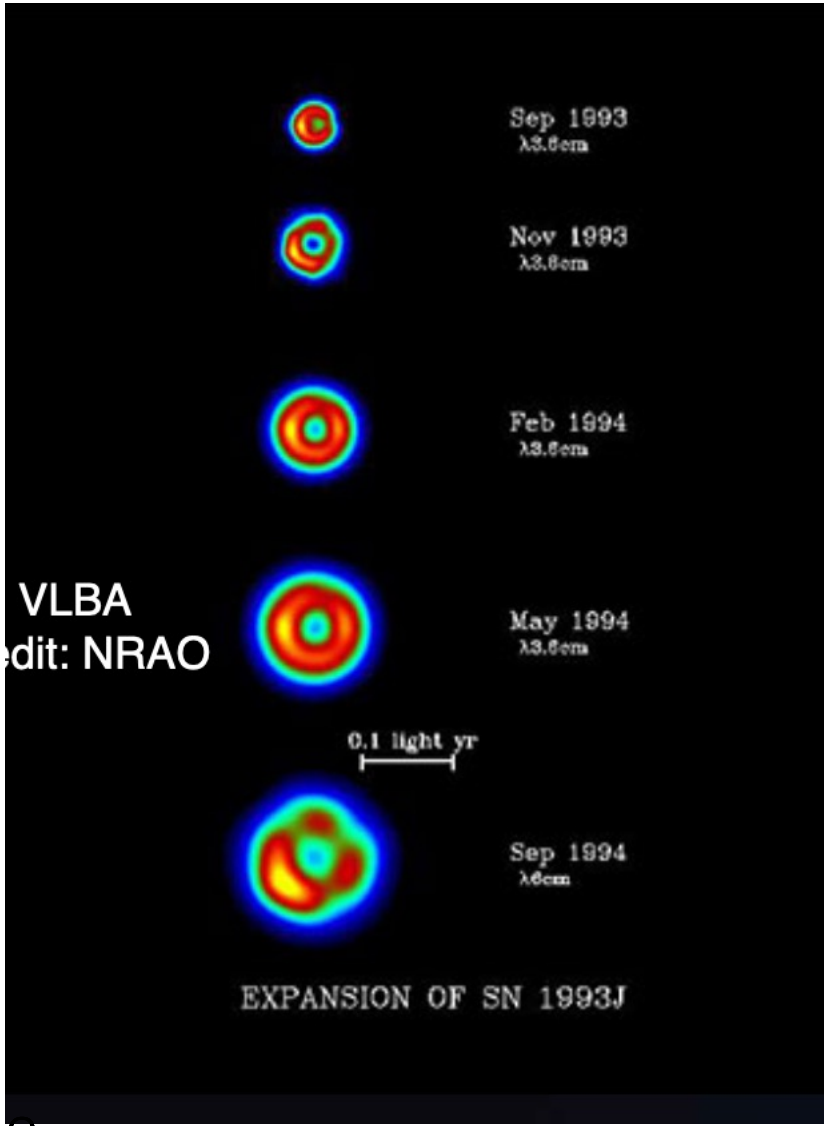


SN 1993J- Magnetic energy 10000 larger than relativistic electrons
PC+04a,b

Role of radio observations

- Radio VLBI – direct estimation of size
- Only a few cases

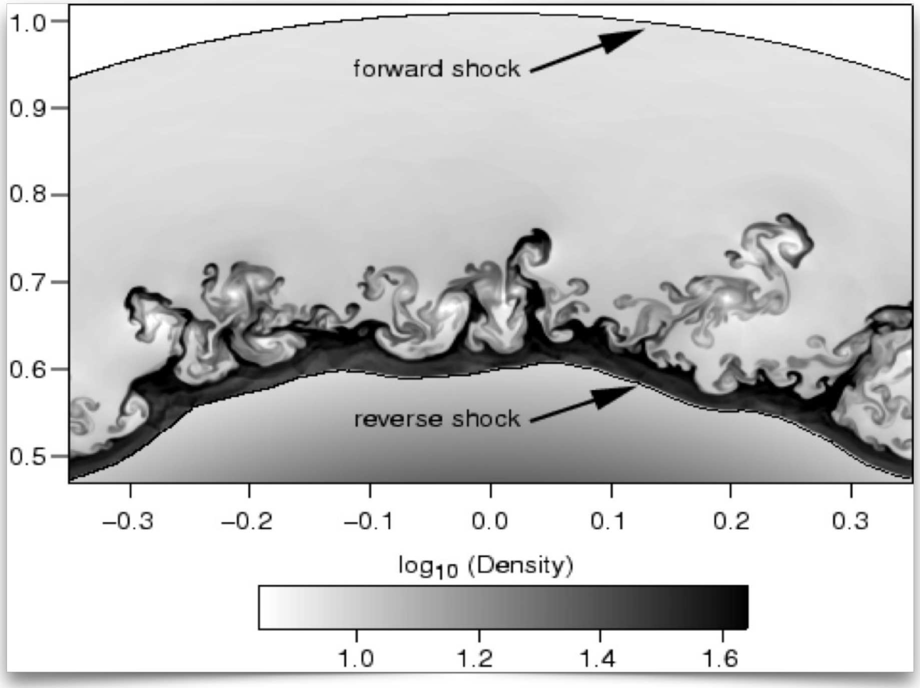


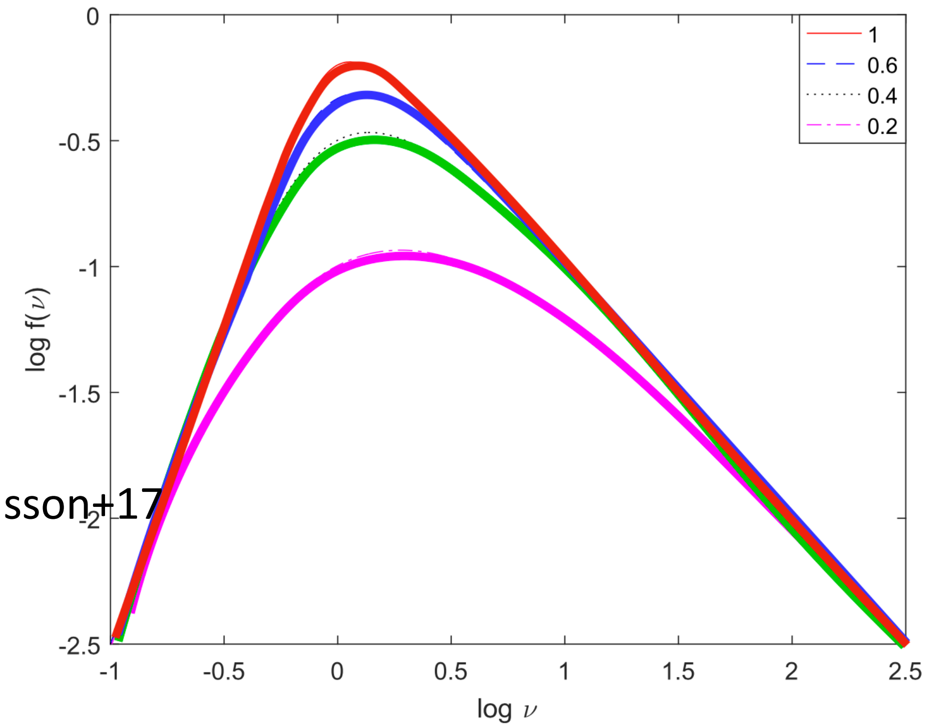


Marcaide+, Bietenholz+, NRAO

Inhomogeneities in shocks- incorrect measurements of shocks sizes

- Radio spectra/light curve- superposition of synchrotron spectra of varying optical depths (due to inhomogeneous B field)
- Broadening in the resulting spectrum





Bjornsson+17

Inhomogeneities in shocks- incorrect measurements of shocks sizes

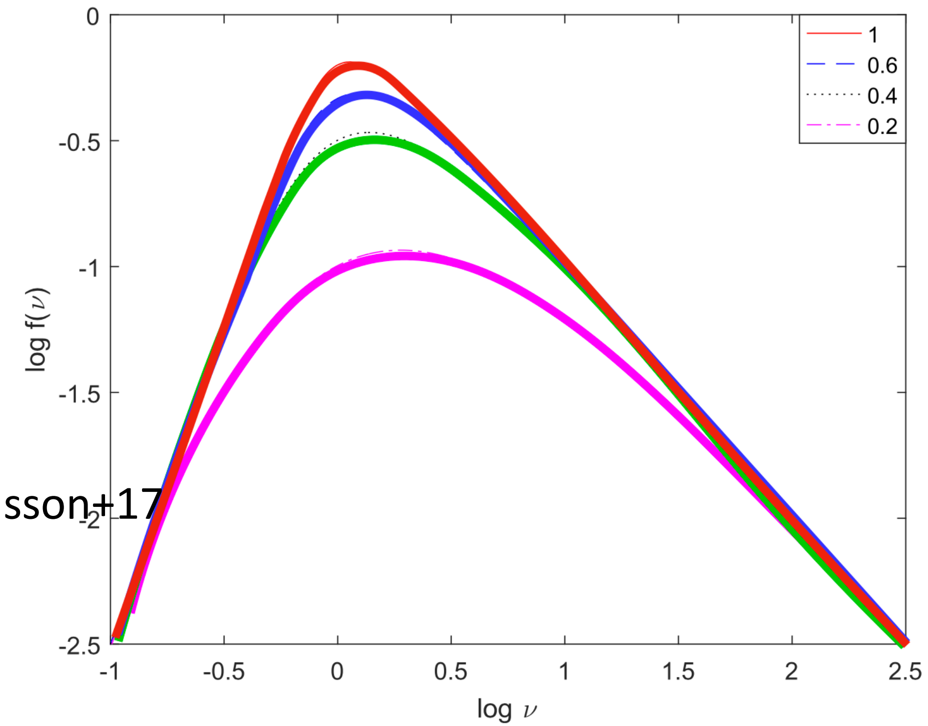
$F_{\rm peak}$ $\quad$ $F_{\rm peak}/f_{\rm B,cov}$

$$R = R_* \times (f_{\rm B,cov})^{\frac{-p-6}{2p+13}}$$

$$B = B_* \times (f_{\rm B,cov})^{\frac{2}{2p+13}},$$

$$E = E_* \times f_{\rm B,cov}^{\frac{-3p-14}{2p+13}}$$

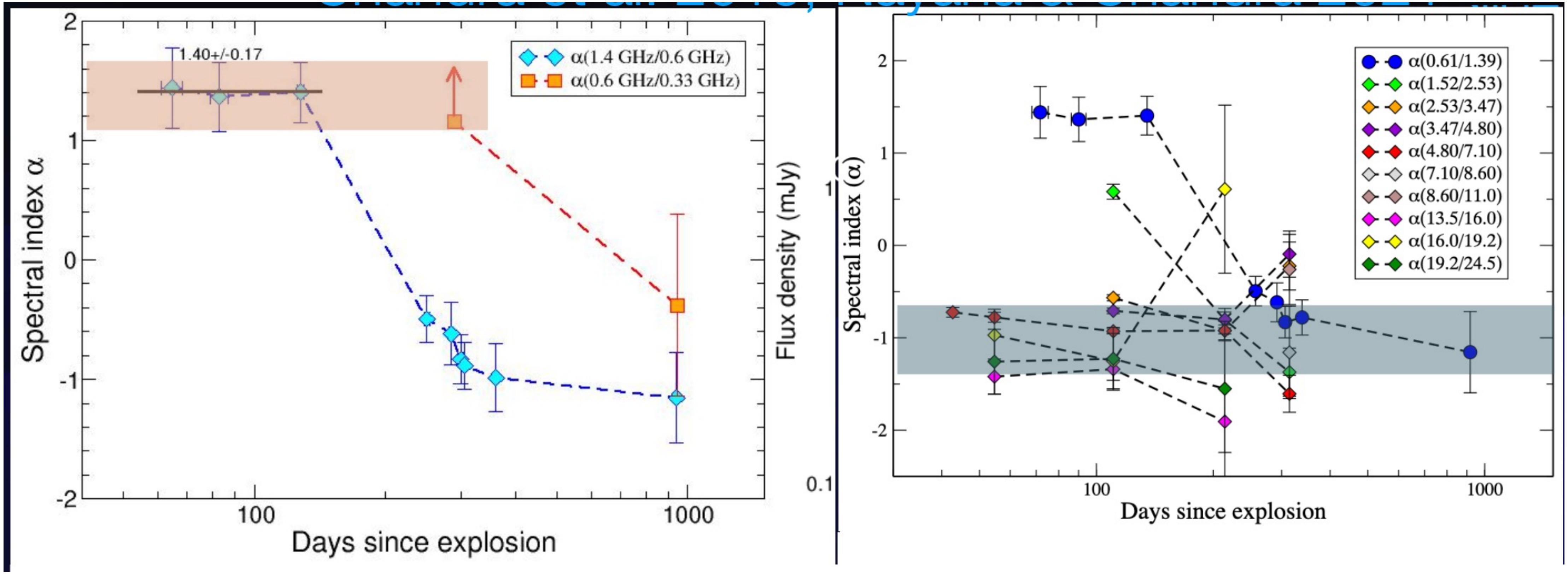
$$\dot{M} = \dot{M}_* \times f_{\rm B,cov}^{\frac{4}{2p+13}}.$$



Bjornsson+17

Role of radio observations – SN J1104

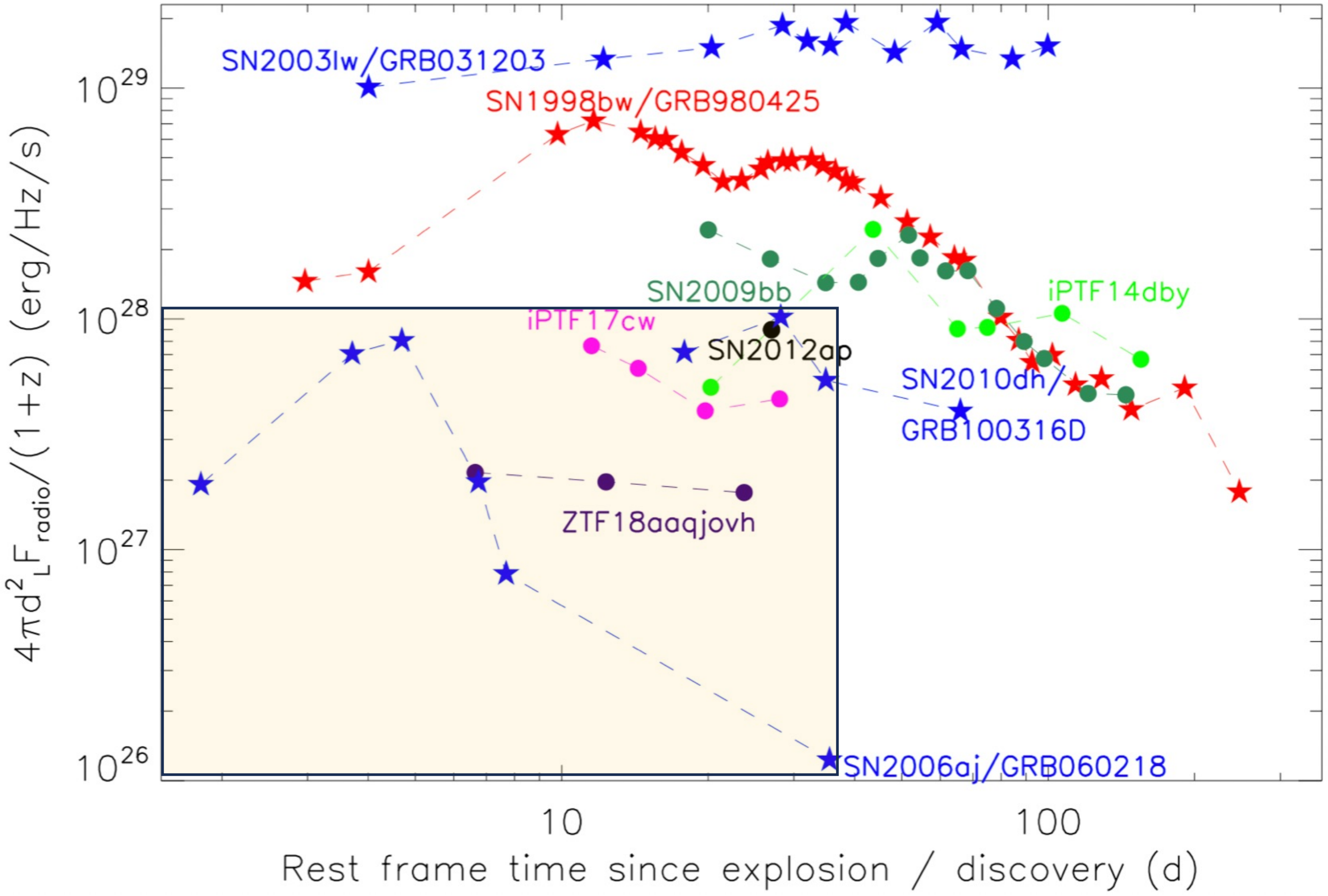
- Huge underestimation of the blast wave radius and flattening of electron index by assuming homogeneous model (Chandra, Nayana+19)



Chandra, Nayana+19

Role of radio observations

- Missing SN 2006aj kind events
- Fast follow up



Corsi+23

Summary and Future Prospects

- Central engine of relativistic supernovae?
- What fraction of BL-Ic SNe make a successful GRB jet, at least from some viewing angle – long term radio measurements needed
- Engine duration vs different progenitor structure - multiwaveband
- A coordinated optical, radio and X-ray follow up needed
- LSST – transient discovery machine, ngVLA high frequency and mas resolution, SKA low frequency critical