A grin without a cat: the first central engine driven SN 2009bb without the associated GRB

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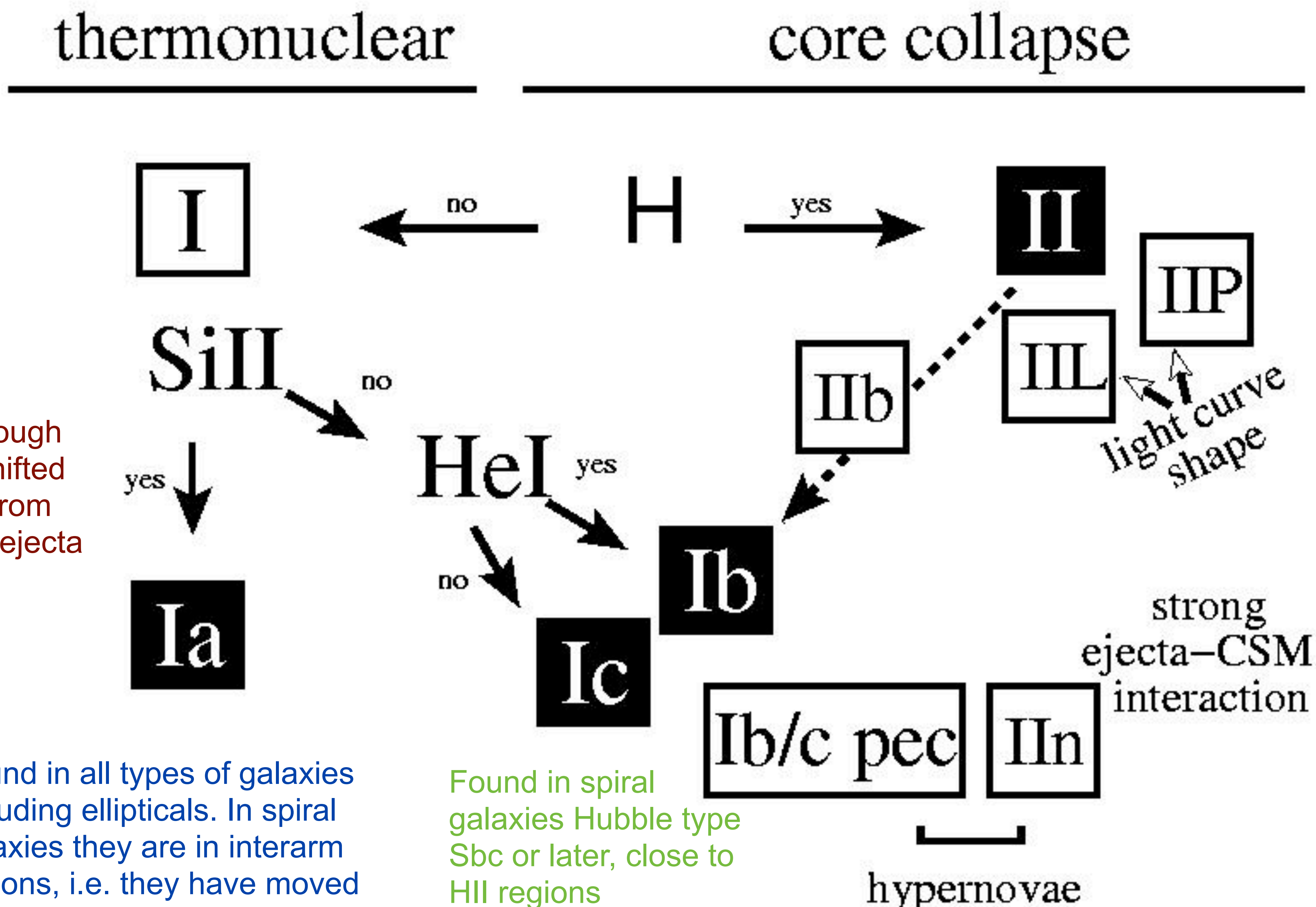
Core-collapse supernovae SNe and their relation with GRBs

- Result from collapse of iron cores of massive stars M>8 Msun. They lead to neutron stars, black holes as compact stellar remnants.
- A subset of core-collapse SNe of type Ic's have been found in some cases to be associated with long duration Gamma Ray Bursts. For example SN 1998bw was found to be coincident with GRB 980425.
- Normally a typical SN would show a non-relativistic outflow of its outermost layers as seen by the non-thermal radio emission from it, whereas a GRB outflow is initially relativistic, believed to be powered by a "central engine".

Different types of Supernovae



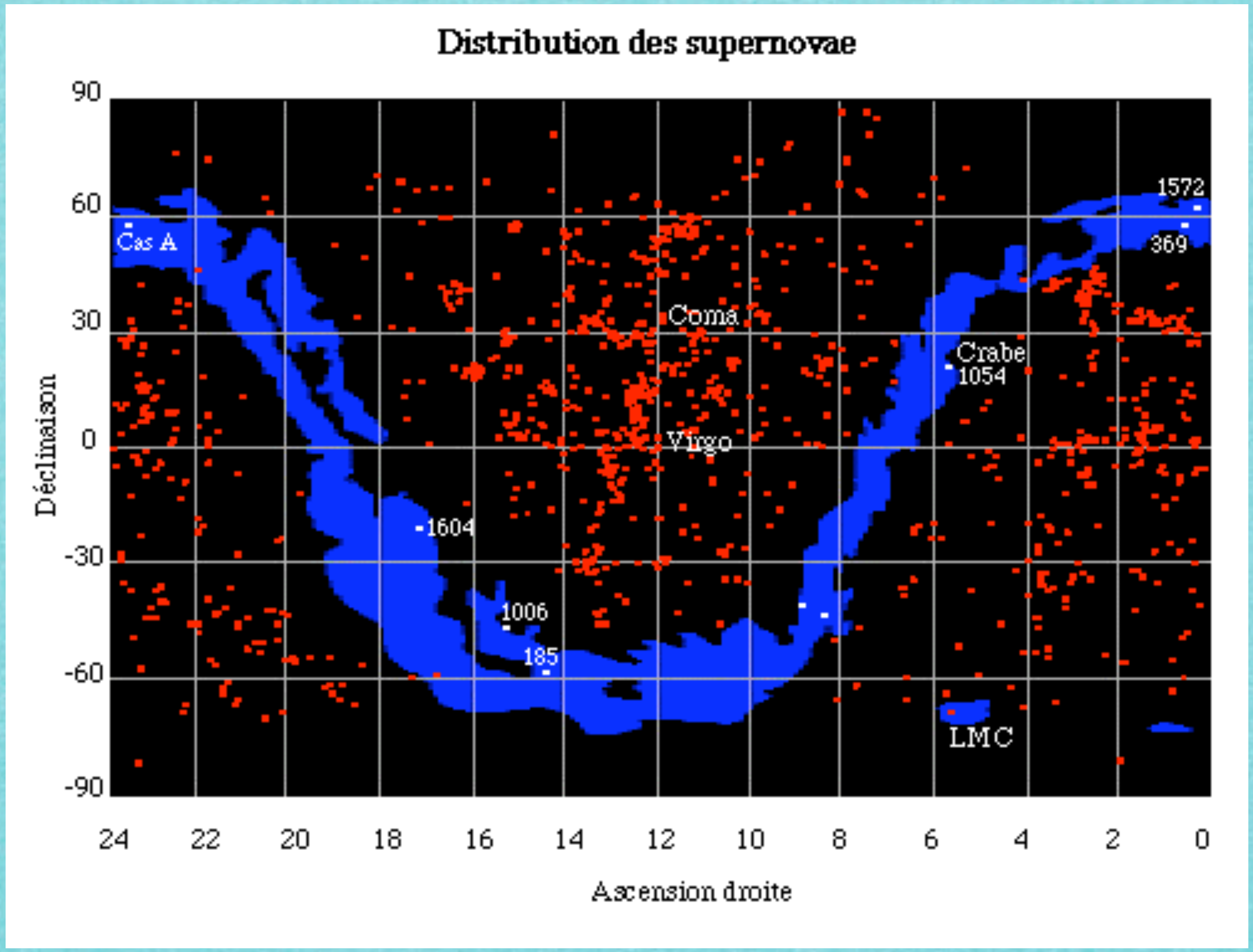
6150A deep absorption trough due to blueshifted 6355A lines from high velocity ejecta

Found in all types of galaxies including ellipticals. In spiral galaxies they are in interarm regions, i.e. they have moved from their birthplace

Found in spiral galaxies Hubble type Sbc or later, close to HII regions

After M. Turatto 2004

Past Supernovae in the Milkyway: they are in the galactic plane



Credit:

Supernovae take place from stars heavier than ~3 times that of the sun occur mostly in the galactic plane, i.e. in the spiral arms. Stars heavier than 8 MSUN lead to core collapse SNe.

Gamma-Ray Bursts

- Discovered by military satellites looking for near earth Atomic Bomb Tests in the late 1960s. Prompt emission: Long GRBs (> 2sec); Short GRBs

- Isotropic (apparent) luminosities: 10^{51}- 10^{52} erg/s; but narrowly beamed => total energies only around 10^{51} erg. Prompt emission followed by a long lasting lower energy "Afterglow" in X-ray, optical and radio. Afterglow => host galaxies at large distances even upto z = 8.3

- Some GRBs are associated Temporally and spatially with freshly exploded supernovae

- Fireball & Internal-External shock model: Kinetic energy of *relativistic outflow* is dissipated. Inner engine that drives a relativistic outflow => energetics and timescales imply the formation of a Black-Hole after stellar collapse or neutron stars merger. GRBs' prompt emission => *Internal* dissipation within the flow. GRB Afterglow => due to Shock's *external* interaction with circumburst medium.

Piran, Rev. Mod Phys (2004); Gehrels et al ARAA 2009; Ruderman (1975) 7th Texas Symposium

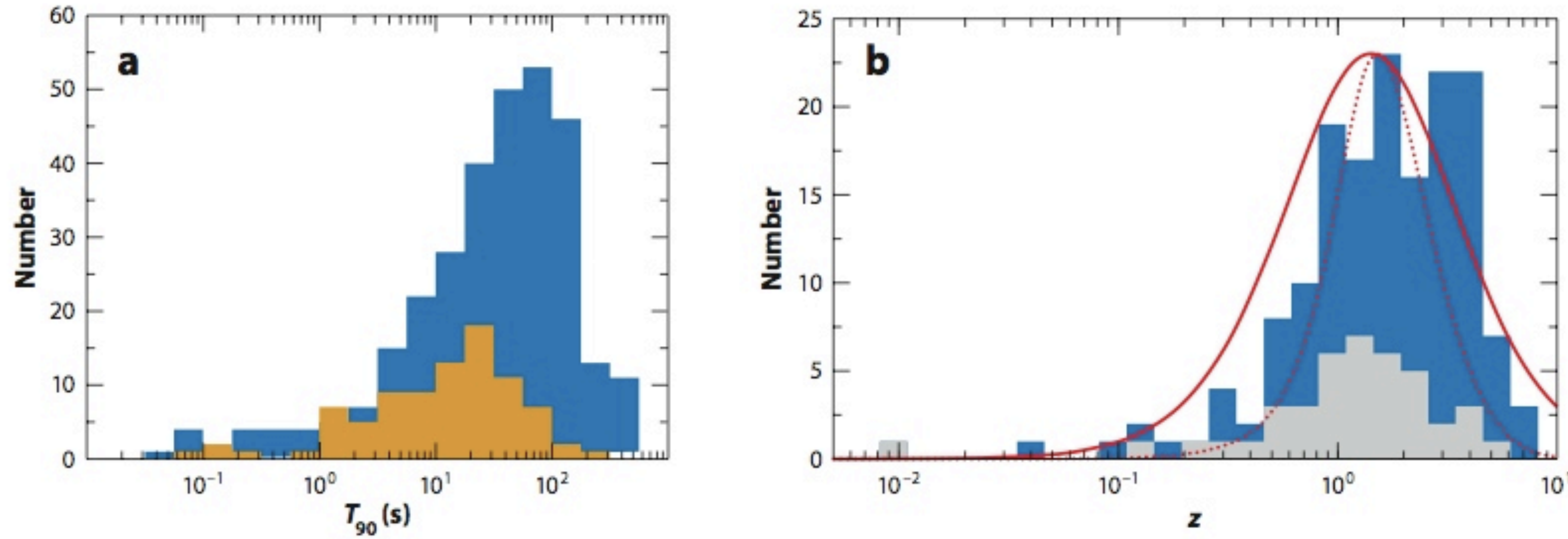
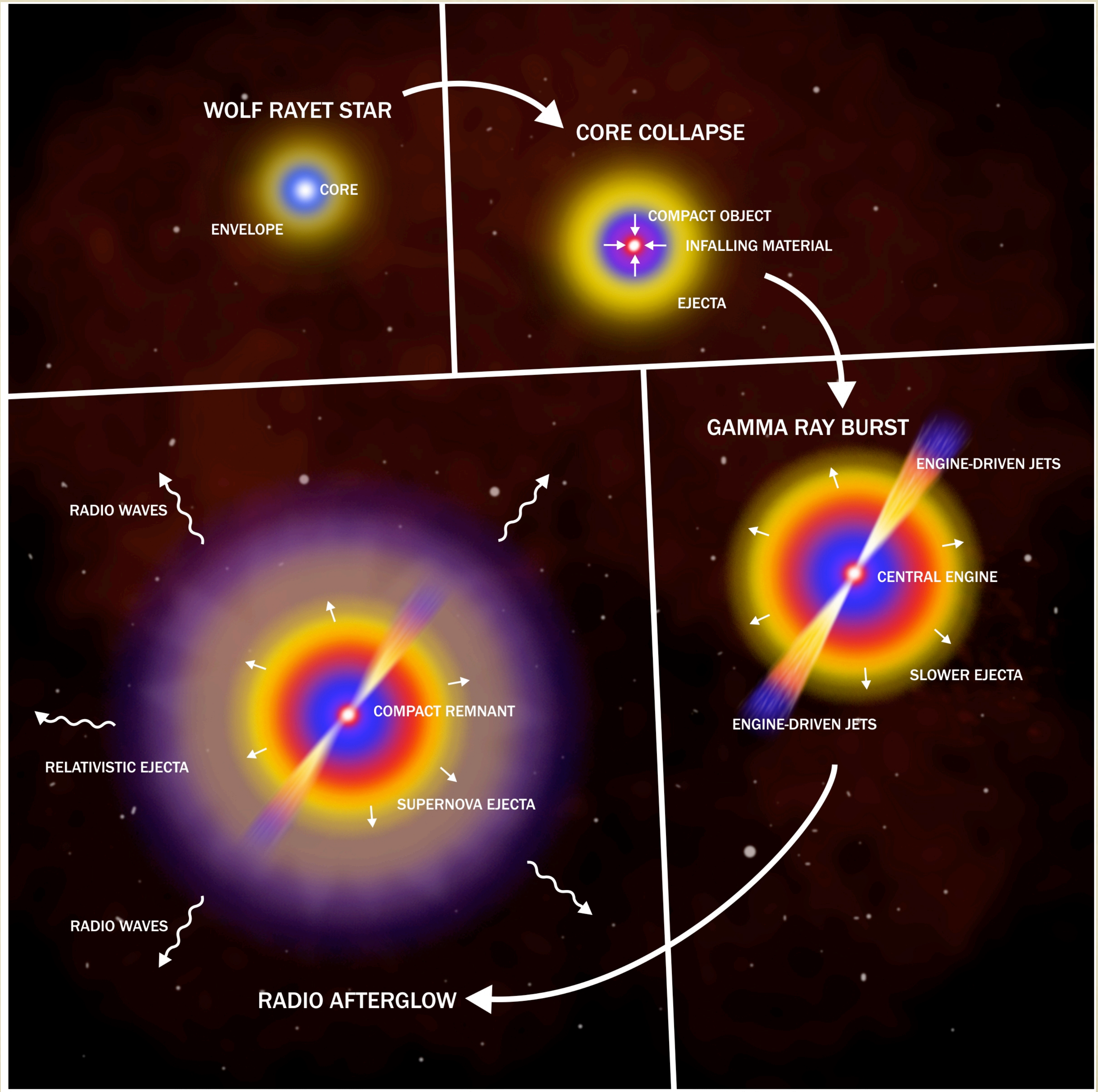


Figure 4

Duration and redshift distribution for *Swift* GRBs. (*a*) The duration distribution. The blue histogram is the measured T_{90} distribution; the orange one is corrected to the source frame: $T_{90}/(1 + z)$. (*b*) The redshift distribution for *Swift* GRBs in blue and pre-*Swift* GRBs in grey. *Swift* is detecting higher redshift bursts on average than pre-*Swift*. The thick solid red theory curve illustrates the evolution of a comoving volume element of the Universe; the thin dotted red curve is a convolution of the comoving volume with a model for the star-formation rate as calculated by Porciani & Madau (2001).

Gehrels, Ramirez-Ruiz, Fox, ARAA 2009

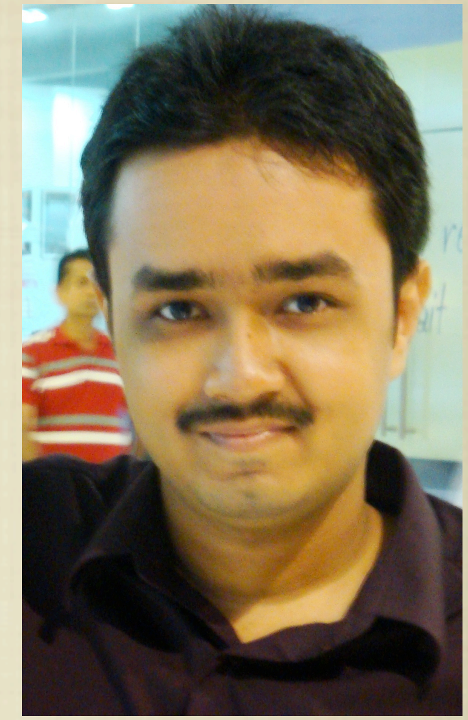

WOLF RAYET STAR
CORE
ENVELOPE
CORE COLLAPSE
COMPACT OBJECT
INFALLING MATERIAL
EJECTA
GAMMA RAY BURST
ENGINE-DRIVEN JETS
CENTRAL ENGINE
SLOWER EJECTA
ENGINE-DRIVEN JETS
RADIO WAVES
COMPACT REMNANT
RELATIVISTIC EJECTA
SUPERNOVA EJECTA
RADIO WAVES
RADIO AFTERGLOW

First central engine driven SN 2009bb without associated GRB

Alicia Soderberg

"I wish you wouldn't keep appearing and vanishing so suddenly: you make one quite giddy!"
"All right" said the Cat; and this time it vanished quite slowly, beginning with the tail,
and ending with the grin, which remained some time after the rest of it had gone.
"Well ! I've often seen a cat without a grin" thought Alice:
"but a grin without a cat! It's the most curious thing I ever saw in my life!"

Sayan Chakraborti



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LETTERS

A relativistic type Ibc supernova without a detected γ-ray burst

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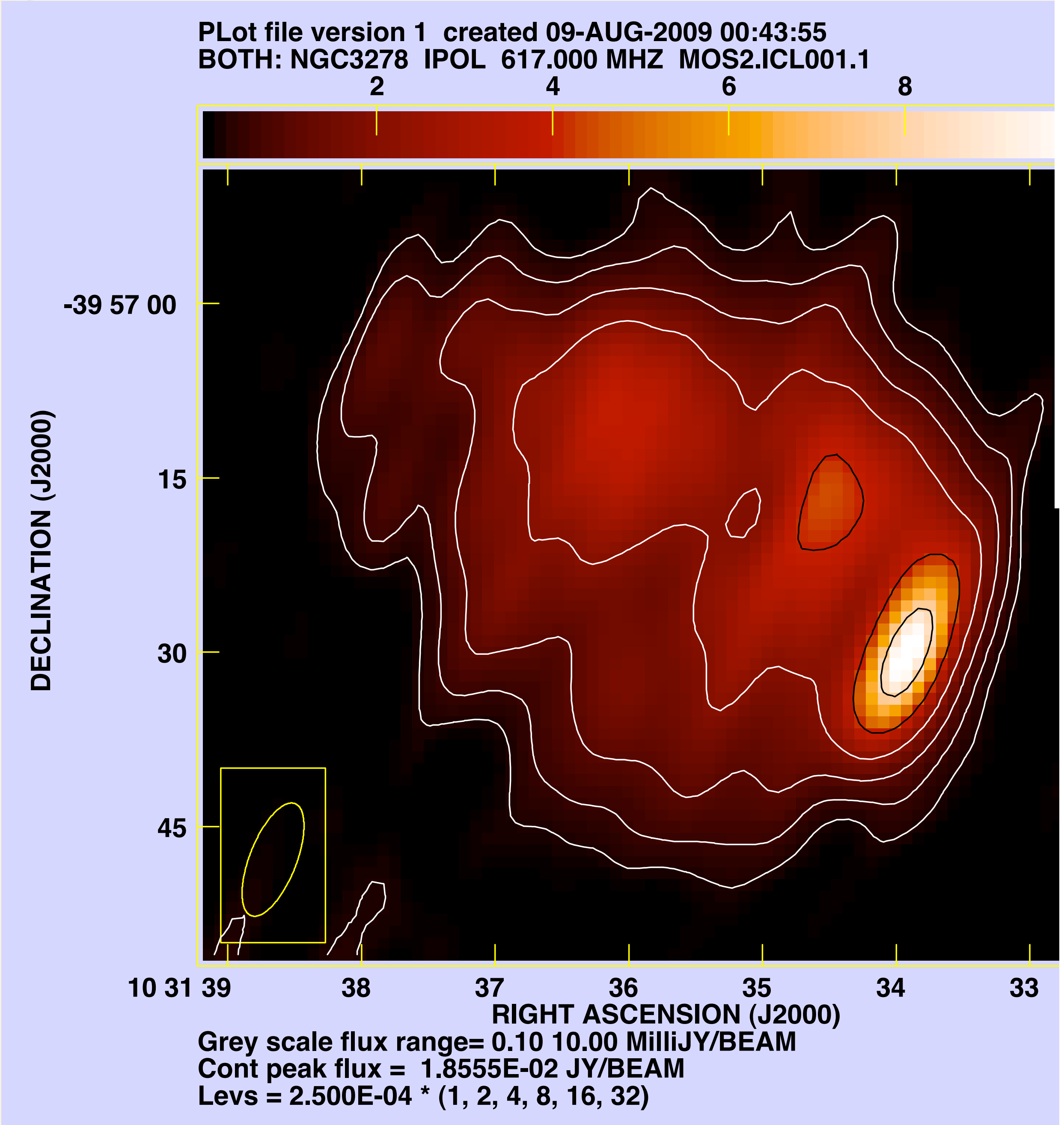
Poonam Chandra

SN 2009bb observed with GMRT & VLA

λ = 50cm map with GMRT



The Giant Meterwave Radio Telescope (GMRT) of TIFR

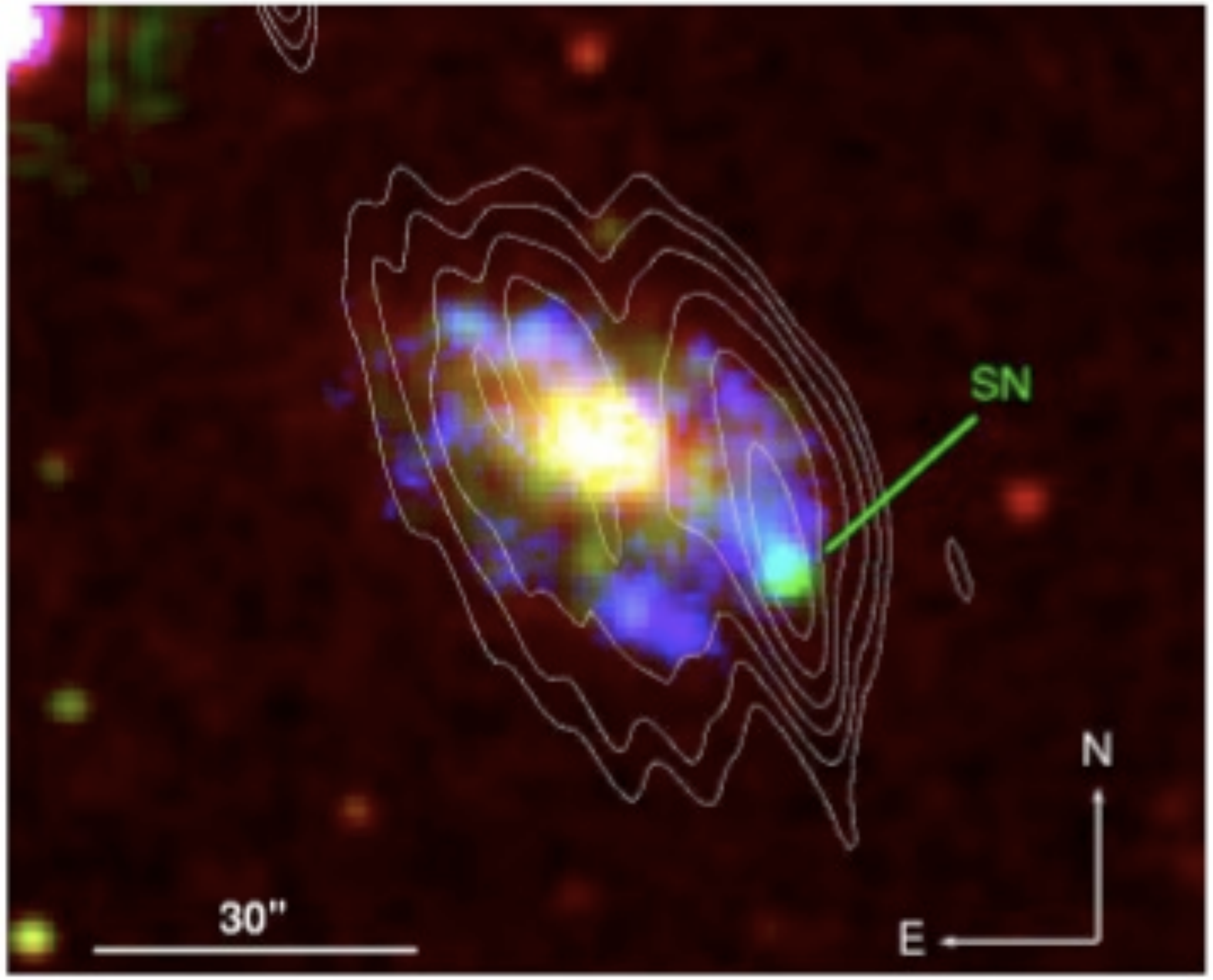


Figure 1. A composite image of the host galaxy of SN 2009bb, NGC 3278, constructed from 2MASS near-IR (red), *Swift*/UVOT optical (V-band, green) and UV (UVW2-filter, blue) images. Contours defining the structure of the diffuse radio (1.43 GHz) emission as observed with the VLA in B-configuration are over-plotted and trace the regions of star-formation in the galaxy. The SN is clearly detected in the radio and optical images (labeled) and lies within a strongly star-forming region of the galaxy.

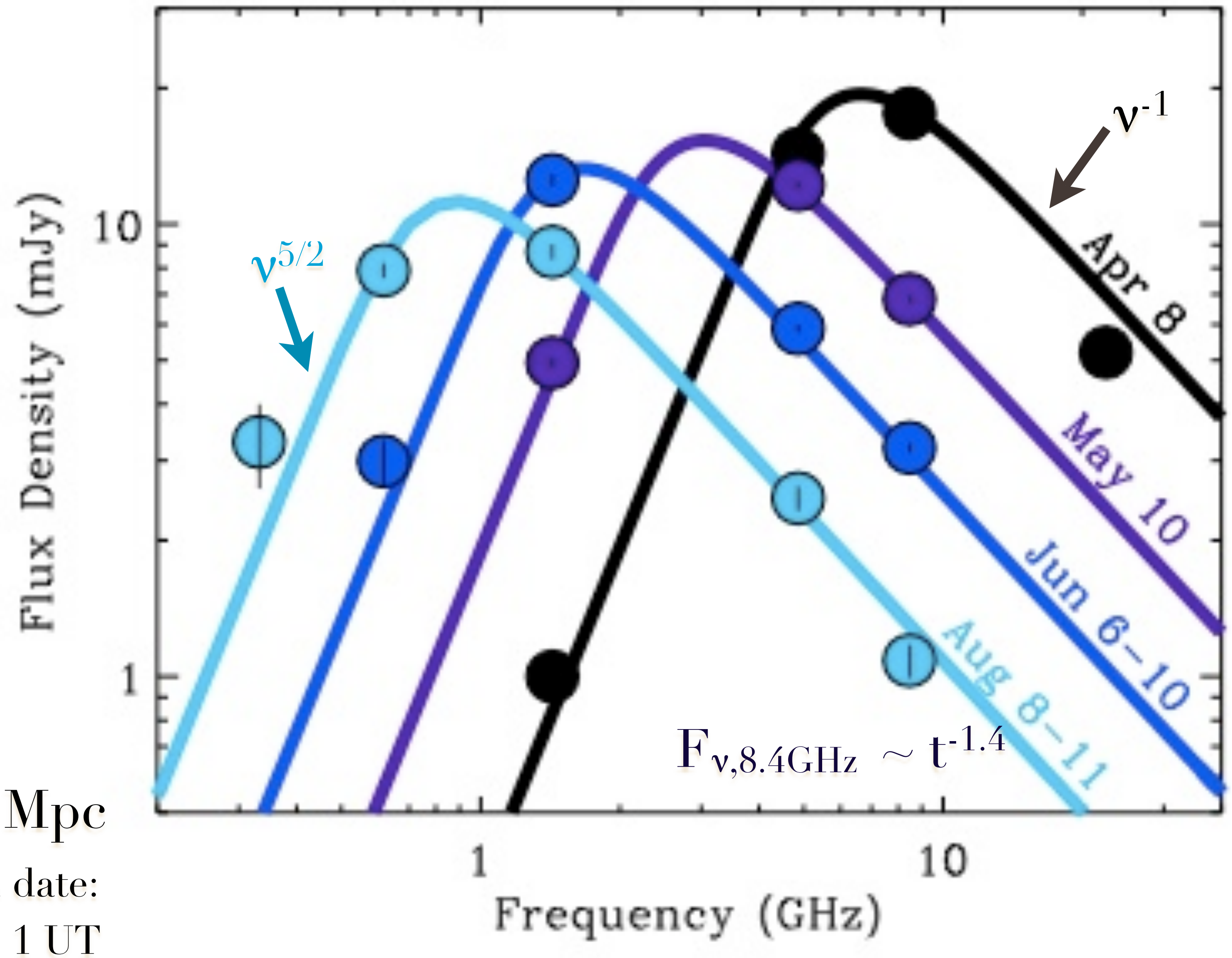
Type Ic SN

SN2009bb: a SN powered by a *central engine driving a relativistic plasma outflow* but without a detected GRB

No GRB found by all-sky IPN network; $E_\gamma \sim < 10^{48}$ erg (25-120 keV)

Synchrotron self-absorbed spectrum

Due to relativistic electrons accelerated around the forward shock



D ~ 40 Mpc

Explosion date:

Mar 19 +/- 1 UT

Radio emission traces the fastest (outermost) ejecta

Measure peak flux density and peak frequency gives under assumption of equipartition of relativistic particles and magnetic field, the Brightness temperature which in turn gives the radius of the radio emitting zone.

$$R_p \propto F_\nu^{9/19} D^{18/19} \nu^{-1}$$

This gives velocity, since R is measured at different times

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

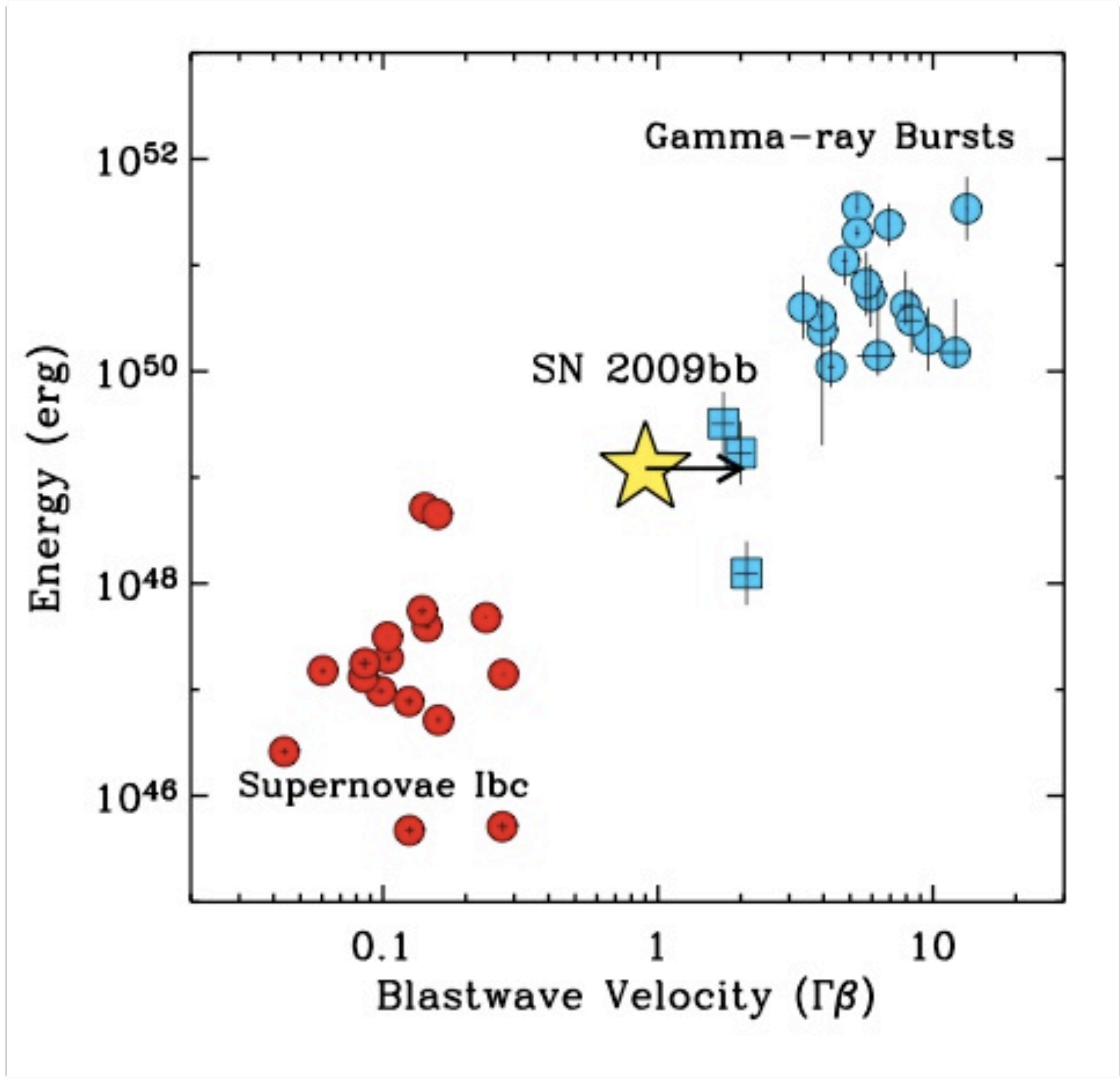
$R \approx 2.9 \times 10^{16} (L_{\nu,p}/10^{28}\ \mathrm{erg\ s^{-1}\ Hz^{-1}})^{9/19} (\nu_p/5\ \mathrm{GHz})^{-1}\ \mathrm{cm}$

$B \approx 0.43 (\epsilon_e/\epsilon_B)^{-4/19} (f/0.5)^{-4/19} (L_{\nu,p}/10^{28}\ \mathrm{erg\ s^{-1}\ Hz^{-1}})^{-2/19} (\nu_p/5\ \mathrm{GHz})\ \mathrm{G}$

$E_{\mathrm{min}} \approx 8.3 \times 10^{46} (f/0.5)(B/\mathrm{G})^2 (R/10^{16}\ \mathrm{cm})^3\ \mathrm{erg}$

Internal energy of radio emitting source $E = E_{min}/\varepsilon_B$

GMRT + VLA Radio Spectrum

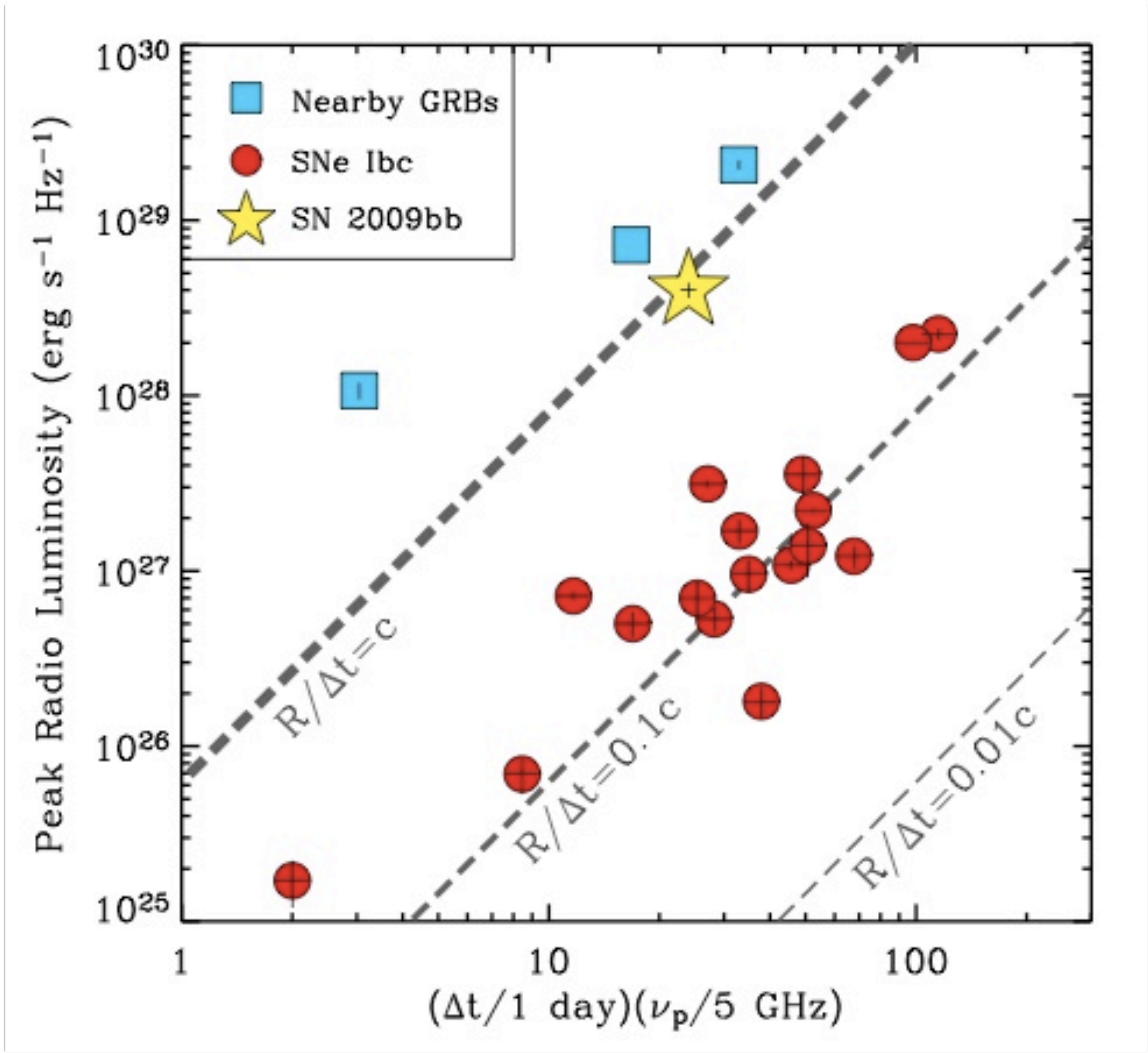


E_{min} =(1.3 +/- 0.1) 10^{49} erg

Mdot =(2 +/- 0.2) 10^{-6} Msun/yr

like other type Ibc SNe & GRBs

SN 2009bb and other non-relativistic SNe and nearby GRBs



SN 2009bb & other SNe and nearby GRBs

SN 2009bb enviornment falls on supersolar lines of constant metallicity between 1.7 Zsun & 3.5 Zsun

SN2009bb Explosion Environment 7

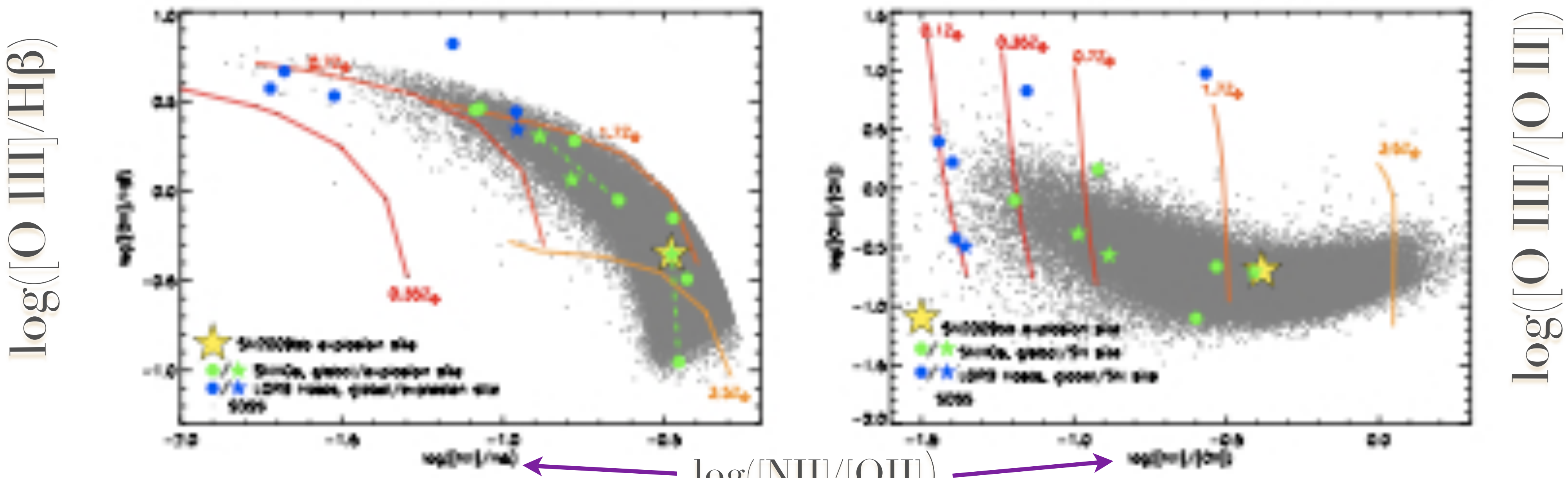


FIG. 4.— Comparison of our SN2009b host galaxy emission line features to a variety of galaxy samples and stellar population synthesis models (Levesque et al. (2009b). On the [NII]/Hα vs. [OIII]/Hβ (left) and [NII]/[OII] vs. [OIII]/[OII] (right) emission line ratio diagnostic diagrams, we compare the SN2009bb explosion site (yellow star) to ratios for SNe Ic host galaxies and explosion sites (Modjaz et al. 2008; green circles and stars), long-duration GRB host galaxies and explosion sites (Levesque et al. 2009a, Christensen et al. 2008; blue circles and stars), and a sample of 60920 star-forming SDSS galaxies (Kewley et al. 2006; points). The Levesque et al. (2009b) models assume a zero-age instantaneous burst star formation history, an electron density of $n_e = 100$ cm $^{-3}$, and a range of ionization parameter $-3.5 < U < -1.9$ (Levesque et al. 2009b).

Levesque, Soderberg, ..., Chakrborti, Ray, ..., Chandra, ... 2009 ApJL (to appear)

Broad diversity in the environments of engine driven explosions. Host galaxy properties like the metallicity alone cannot be used to distinguish between ordinary and engine driven SNe.

Radio to Optical spectral energy density of host galaxy NGC 3278 gives the Star Formation Rate

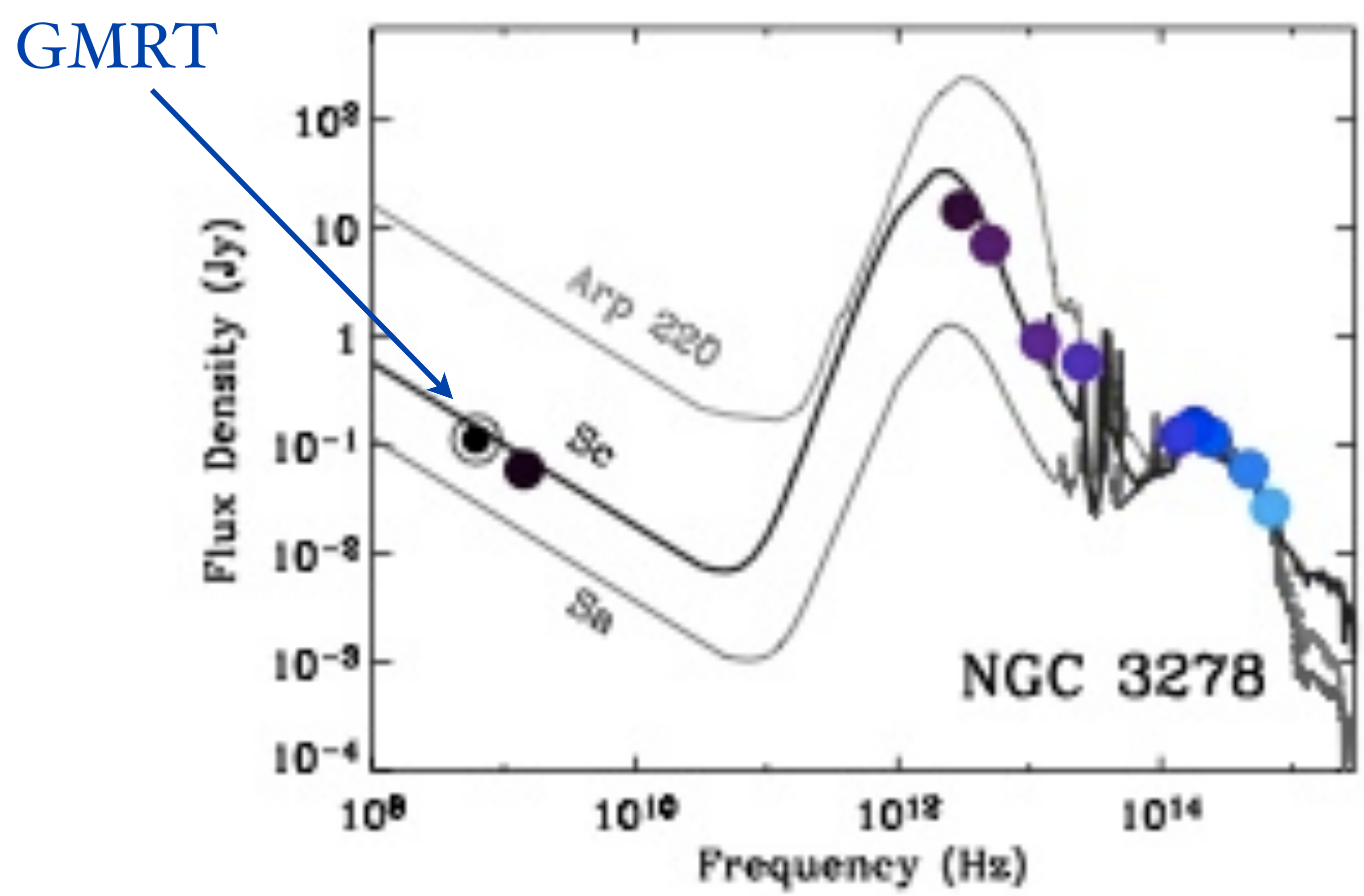


FIG. 3.— The spectral energy distribution is shown for the host galaxy, NGC 3278, from radio to optical frequencies. We compiled integrated broadband flux densities for NGC 3278 extending from the optical (Lauberts & Valentijn 1989) and near-IR bands (Two Micron All Sky Survey; 2MASS), to the mid-IR (IRAS; Sanders et al. 2003) radio wavelengths (VLA; Mauch & Sadler 2007) and combined them with our 617 MHz measurements from the GMRT (this work). The galaxy is strongly star-forming (SFR $\approx 5 - 7\ M_{\odot}\ yr^{-1}$) as evidenced by the bright mid-IR emission. In comparison with standard galaxy templates (gray lines, from Silva et al. 1998), the spectrum of the host galaxy is most consistent with the broadband spectrum of an Sc galaxy with a star-formation which is elevated compared to a standard Sa spiral galaxy, but not as high as Arp 220.

SFR = 5 - 7 Msun/yr
a la Kennicutt (1998)
Yun & Carilli (2002)

Levesque, Soderberg,..., Chakraborti, Ray,..., Chandra et al ApJL (2010)

How many central engine driven relativistic supernova among SN Ibcs ?

VLA made an extensive radio survey of 143 optically discovered local SN Ibc and found 1 object (SN 2009bb) with relativistic outflow. Implied fraction of engine driven SNe is ~ 0.7 %.
Wide-field optical surveys (Palomar Transient Factory (~ 50 SN Ibc per yr), Pan-STARRS (25 SN Ibc per yr) etc) will quadruple the discovery rate young local type Ibc SNe in the next 3-5 years (assuming volumetric rate of 1.7 10^4 $Gpc^{-3} yr^{-1}$.

Together with the ten-fold increase in the sensitivity of the Expanded VLA, relativistic SNe will be uncovered at an increased rate of ~ 1 per year within d < 200 Mpc.

This is ~ 3 times higher than the rate at which nearby GRBs are discovered by current Gamma-ray satellites. Thus radio surveys will soon provide a more powerful tool to pinpoint the nearby engine driven relativistic SNe compared to detections made by their Gamma-ray emission. Radio SN 2009bb like objects with light curves upto 100 days can be detected out to a distance of ~ 130 Mpc at current VLA sensitivities (0.1 mJy in 15 min).

Need wide-field, pan-chromatic, radio detector Array & low frequency survey

- Beamsizes are large at low frequencies. Wider sky coverage. Pan-chromatic response may help weed out terrestrial Radio Frequency Interference.

- Need sensitivity typically few to 10 milli Jansky per beam.

- Use Ooty Radio Telescope with wide-beam coverage @ 327 MHz in drift-scan mode for a baseline survey to be used for reference map.

- Also need some higher frequency coverage to about 5 Ghz, since SNe turn on first at high frequencies. This is a competing requirement vis a vis the wide field criterion.

- GRBs detected at 1 Burst per day currently. GRBs may be 1000 x more numerous at Radio wavelengths (spectral modelling by Perna and Loeb 1998).

- a 5 GHz survey of 10 square degrees with Allen Telescope Array will detect in 12 hrs upto 100 GRBs. A comparable VLA survey requires 200 hrs.

Relativistic GRB Jet breakout for a 15M_{sun} Wolf-Rayet Star

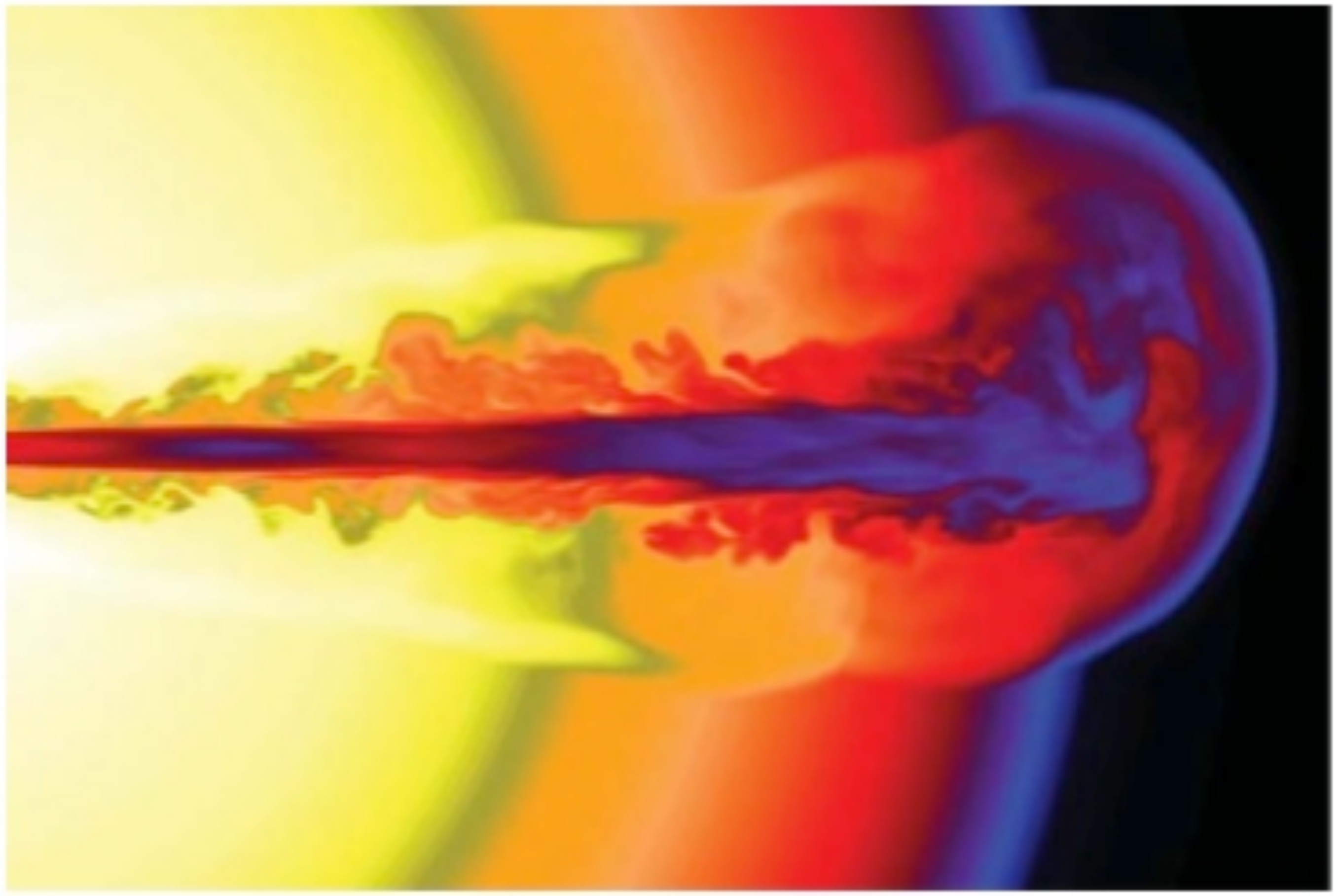


Figure 8

Break out of a relativistic γ-ray burst jet with energy 3×10^{50} erg s^{-1} 8 s after it is launched from the center of a 15 $M_{\odot}$ WR star. The radius of the star is 8.9×10^{10} cm and the core jet, at infinity, will have a Lorentz factor $\Gamma \sim 200$. Note the cocoon of mildly relativistic material that surrounds the jet and expands to larger angles. Once it has expanded and converted its internal energy this cocoon material will have Lorentz factor $\Gamma \sim 15$–30. An off-axis observer may see a softer display dominated by this cocoon ejecta. If the star were larger or the jet stayed on a shorter time, the relativistic core would not emerge, though there would still be a very energetic, highly asymmetric explosion. (Zhang, Woosley & Heger 2004.)

Woosley & Bloom
ARAA 2006

Hydro simulations of γ-ray burst jets through the progenitor star

- Morsony, Lazzati and Begelman (arXiv: 1002.0361) investigate the effects of variability of the central engine luminosity and light relativistic jet propagation through the star with a special relativistic adaptive mesh refinement hydrodynamic code FLASH in 2D.
- MLB (2007) started simulations from a stellar model 16TI from Woosley and Heger (2006) of a Wolf-Rayet star with an initial mass of 16 M_{sun} . Also used are other initial models.
- Three phases of Jet propagation: 1) Precursor phase (wide angle release of mildly relativistic material); 2) Shocked Jet phase (jet material that flows out of the star has been heavily shocked; the energy flow is highly variable; the jet is highly collimated); 3) Third phase jet has a freely expanding core surrounded by a shocked layer at the boundary with cocoon material. Energy flow is almost constant and jet opening angle increases with log t.

Variable injected luminosity of the central engine

Variability in GRBs 7

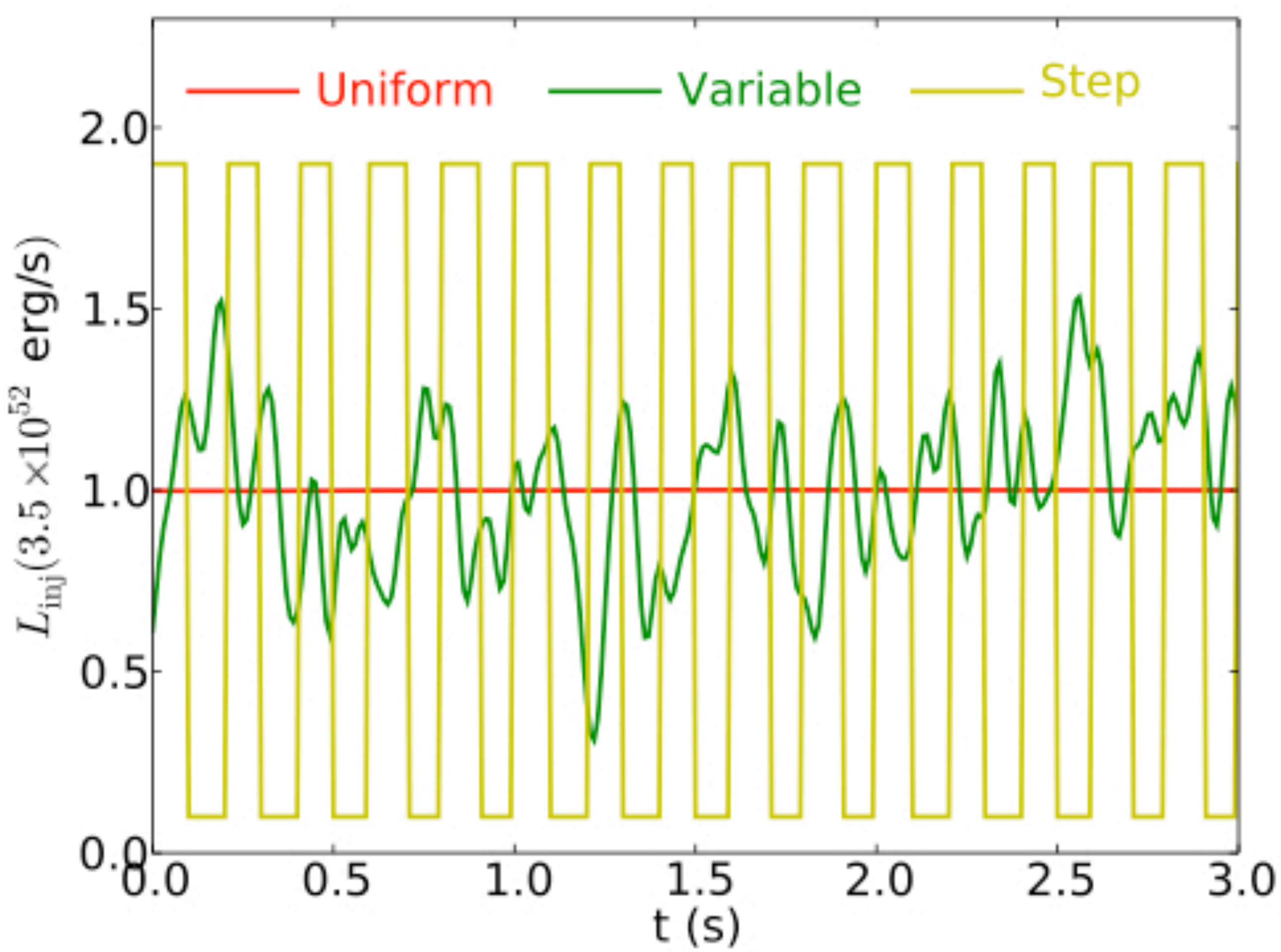


FIG. 1.— Luminosity injected by the central engine for the four simulations described in the text. The figure shows only a 3 seconds zoom of the simulations that last a total time of 50 seconds. The luminosity is normalized to the average isotropic equivalent luminosity of $L_{\{\rm inj,iso\}} = 3.5 \times 10^{52}$ erg/s. The injected luminosity for the variable entropy and variable baryon load simulations is the same.

$$\eta = L / \dot{m} c^2$$

Variable Entropy: Change luminosity by changing entropy η while holding mdot constant

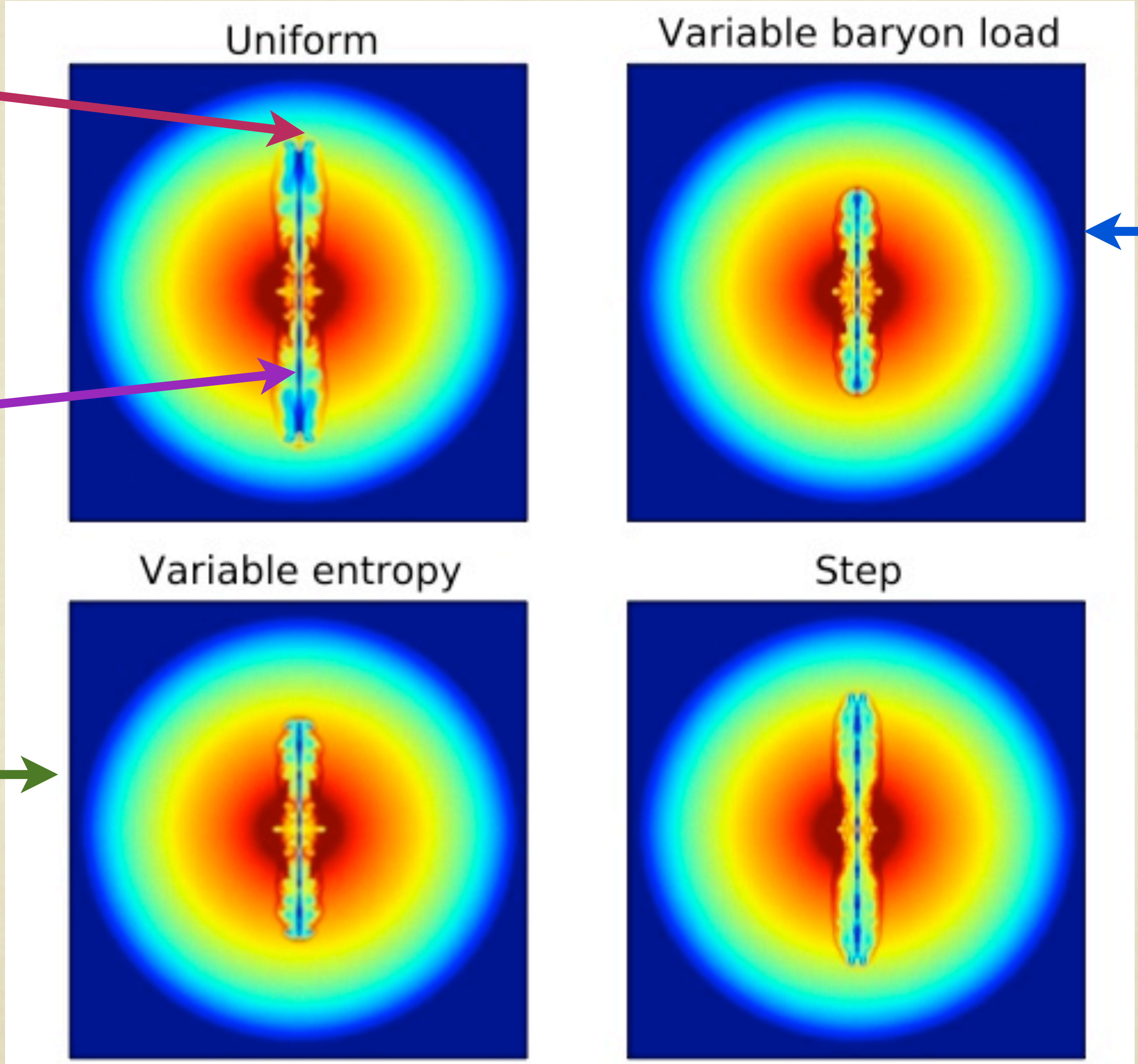
- Morsony, Lazzati and Begelman (arXiv: 1002.0361) investigate the effects of variability of the central engine luminosity and jet propagation through the star with a special relativistic adaptive mesh refinement hydrodynamic code FLASH.

Jet Propagation with variable central engine Luminosities

Logarithmic density contours for four simulations upto t= 5.5 s

Narrow low density Jet

Turbulent Cocoon made of shocked stellar material



Density images of our four simulations 5.5 seconds after the onset of the central engine.

Morsony etal 2010

Variable Baryon Load: Change luminosity by changing baryon load mdot

$$\eta = L / \dot{m} c^2$$

Variable Entropy: Change luminosity by changing entropy η while holding mdot constant

Jet penetrates the core to differing extents depending upon Engine activity and propagation time

Hydro simulations of γ-ray burst jets through progenitor star: Morsony etal 2010

- Shortest propagation time for a uniform injected luminosity with the head of the jet breaking out of the star's surface is ~6.2s.
- Variability in the γ-ray light curve may be due to: 1) intrinsic variability of the engine (ms periods) 2) star induced variability.
- If the engine is active for a shorter time than propagation time, an engine driven SN is likely produced, rather than a successful GRB.
- Variability properties on Seconds scales depend upon progenitor structure & insensitive to the outflow injected by central engine. Fast variability --> nature of central engine.

Neutrino signals of smothered Jets in γ-ray dark SNe?

- Look for $E_\nu > 100$ GeV cascades in Km^3 detectors a la: Razzaque, Meszaros & Waxman (2003 PRD) and Ando & Beacom models for a Central Engine driven SN/GRB within 10 Mpc. They predict very soft neutrino spectrum in IceCube. Taboada (arXiv: 1002.0593) calculates event rate for core collapse SNe as observed by DeepCore at ~ 10 GeV. Takes into account vacuum oscillations of the flavor flux ratios at Earth for both pion and kaon produced neutrinos.

- Observations of neutrinos at > 10 GeV are mostly sensitive to the Pion component of neutrino production in the Choked Jet, whereas the > 100 GeV component mainly depends upon the Kaon production and decay into neutrinos. These signal detections have to be in coincidence with optical observations of the rising light curve of a supernova at the same place and in a 100 s signal search window (Rstar/c) to discount accidental coincidence of atmospheric neutrino background.

- High energy neutrinos are produced both in pγ and pp interaction, (E_p ~ 10^{15} eV on γ-photons of E_γ ~ 10^6 eV: $p\,\gamma \rightarrow \Delta \rightarrow n\,\pi^+$ and $p\,\gamma \rightarrow n\,\pi^0$ and secondary $n\,\gamma \rightarrow p\,\pi^-$ reactions) dominantly through secondary pions $\pi^{+-} \rightarrow \mu\,\nu_\mu \rightarrow e\,\nu_e\,\nu_\mu\,\underline{\nu_\mu}$. Kaons are also produced in photo-hadronic reactions and then decay via (e.g. $K^+ \rightarrow \mu^+\nu_\mu$ (63%)).

Choked Jets in GRBs and Neutrinos

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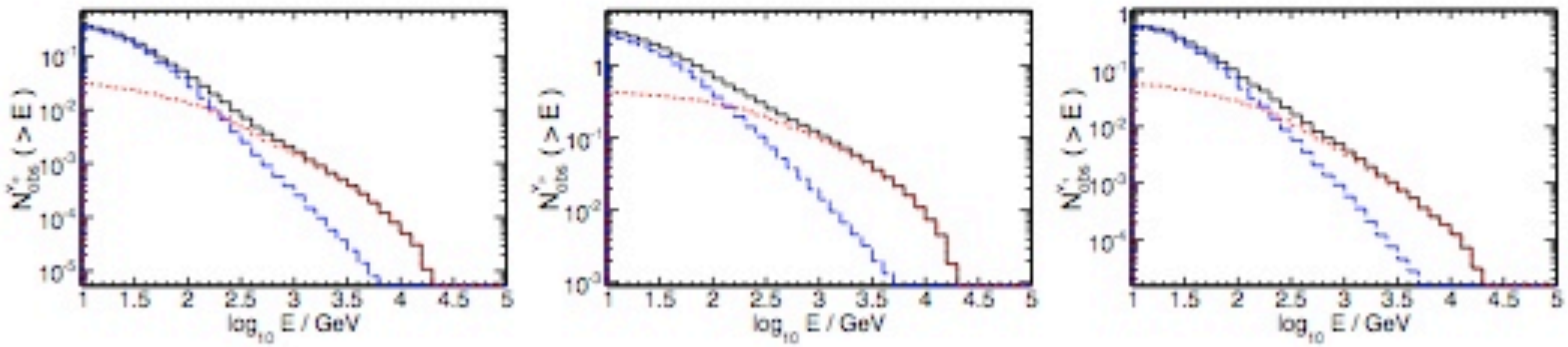

FIG. 2: The panels show the expected signal above a given energy for DeepCore for ν_e (left), ν_μ (center) and ν_τ (right). The solid (black in the online version) histogram is the total expectation of the RMW/AB model, the long dashed histogram (blue in the online version) is the pion contribution and the short dashed (red in the online version) histogram is the kaon contribution.

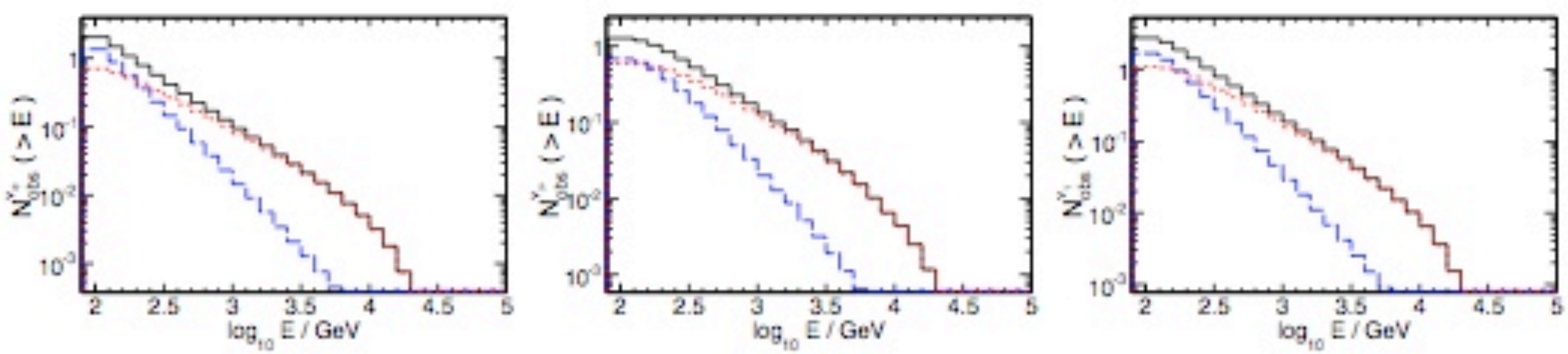

FIG. 3: The panels show the expected signal above a given energy for cascades in IceCube/KM3Net for ν_e (left), ν_μ (center) and ν_τ (right). The solid line (black in the online version) is the total expectation of the RMW/AB model, the long dashed line (blue in the online version) is the pion contribution and the short dashed line (red in the online version) is the kaon contribution.

- Taboada finds 3.3 ν_μ Events in IceCube for a 10 Mpc SN due to ν_μ Effective areas attributed to threshold effects near 100 GeV (Different from IceCube published). Similarly the neutrino induced cascades expected in IceCube is 6.1 events. In DeepCore all flavour expectation is 4 events.

Conclusions

- Supernova's central engine can be revealed in the radio frequency bands by detecting the relativistic motion of the external plasma. Important to look for signals beyond those from (or even without) the deep core signals, e.g. γ-rays. Engine driven SNe do occur in high metallicity environments, i.e. there seems to be no cutoff metallicity for relativistic SNe.

- There may be smothered jets of GRBs that are buried deep in core of the star. High energy neutrinos (> 10-100 GeV) IceCube / DeepCore may reveal these.

- Wide field optical surveys (e.g. Palomar Transient Factory, Pan-STARRS) will quadruple discovery rate of local SN Ibc, and EVLA upgrade will make radio discovery of relativistic SNe exceed the discovery through the GRB channel by a factor of 3.

THE END

Thank you