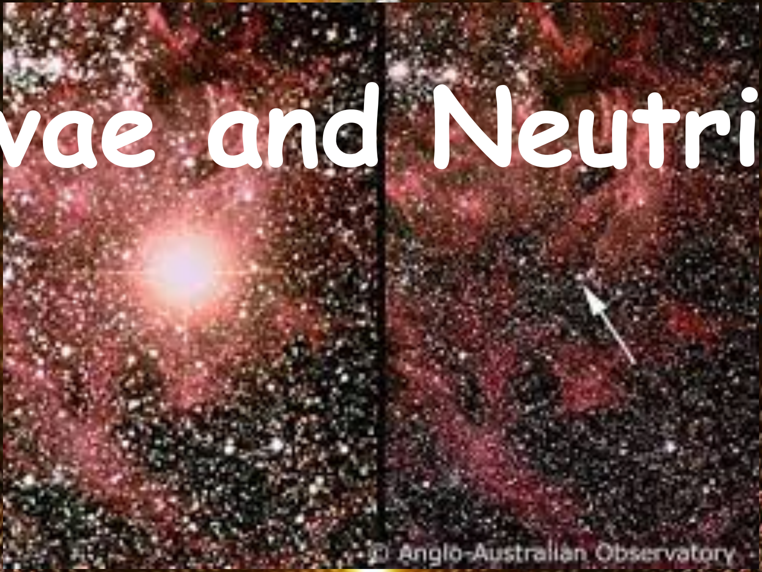
Supernovae and Neutrinos rates



Massimo Della Valle
Capodimonte Observatory, INAF-Naples
Catania 26-28 Novembre 2019

Summary

The SN basics

Expected ν flux from SNe at different distance scales

High energy neutrinos from SNe powered by relativistic/chocked jets

Astrophysics with Supernovae

- Explosive Death of Stars
- Metal Enrichment
- Energy Injection

Physics of compact objects

Evolution of stellar populations and galaxies

- Distance Indicators
- Tracers of Stellar Populations
- Tracers of cosmological models

Cosmology

- Bright Background Sources
- Bright Echoes
- Cosmic Rays

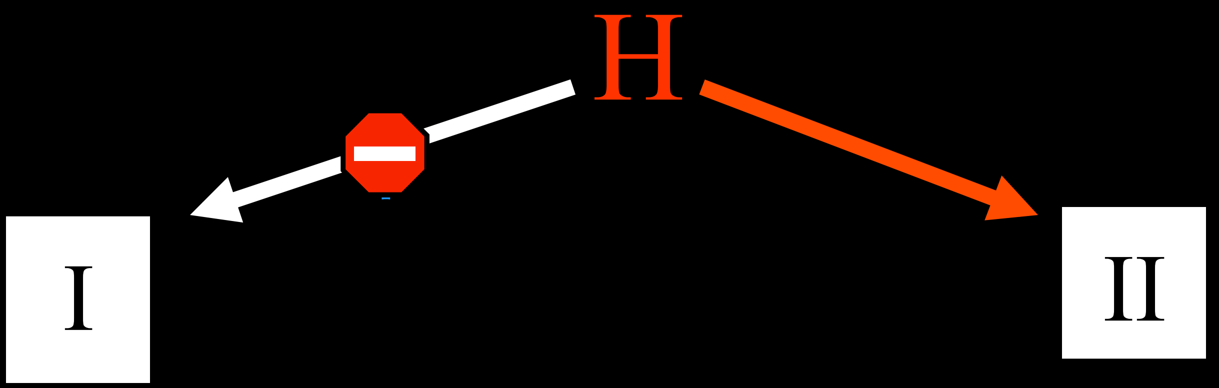
ISM-IGM Studies at high z

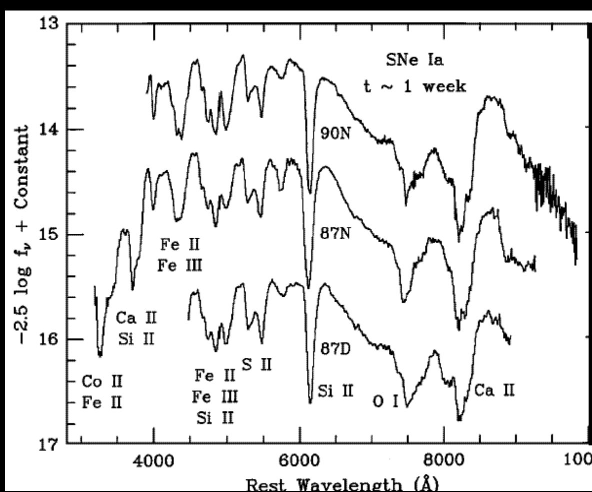
3-D Structure of ISM

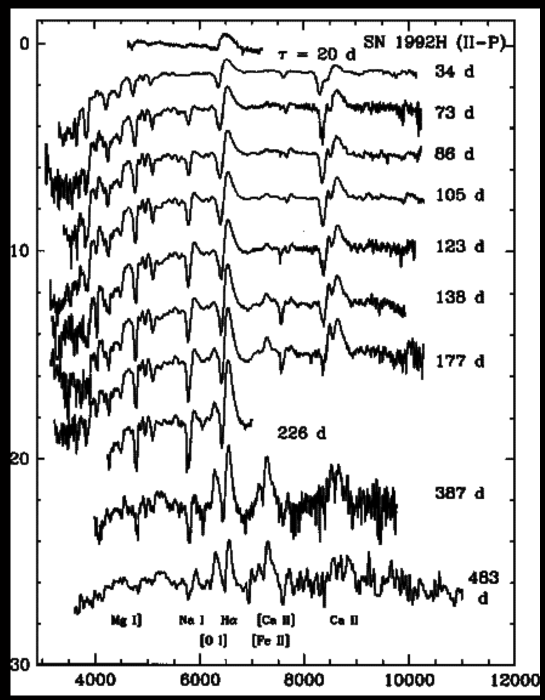
- GWs
- Neutrinos

Multi-Messenger

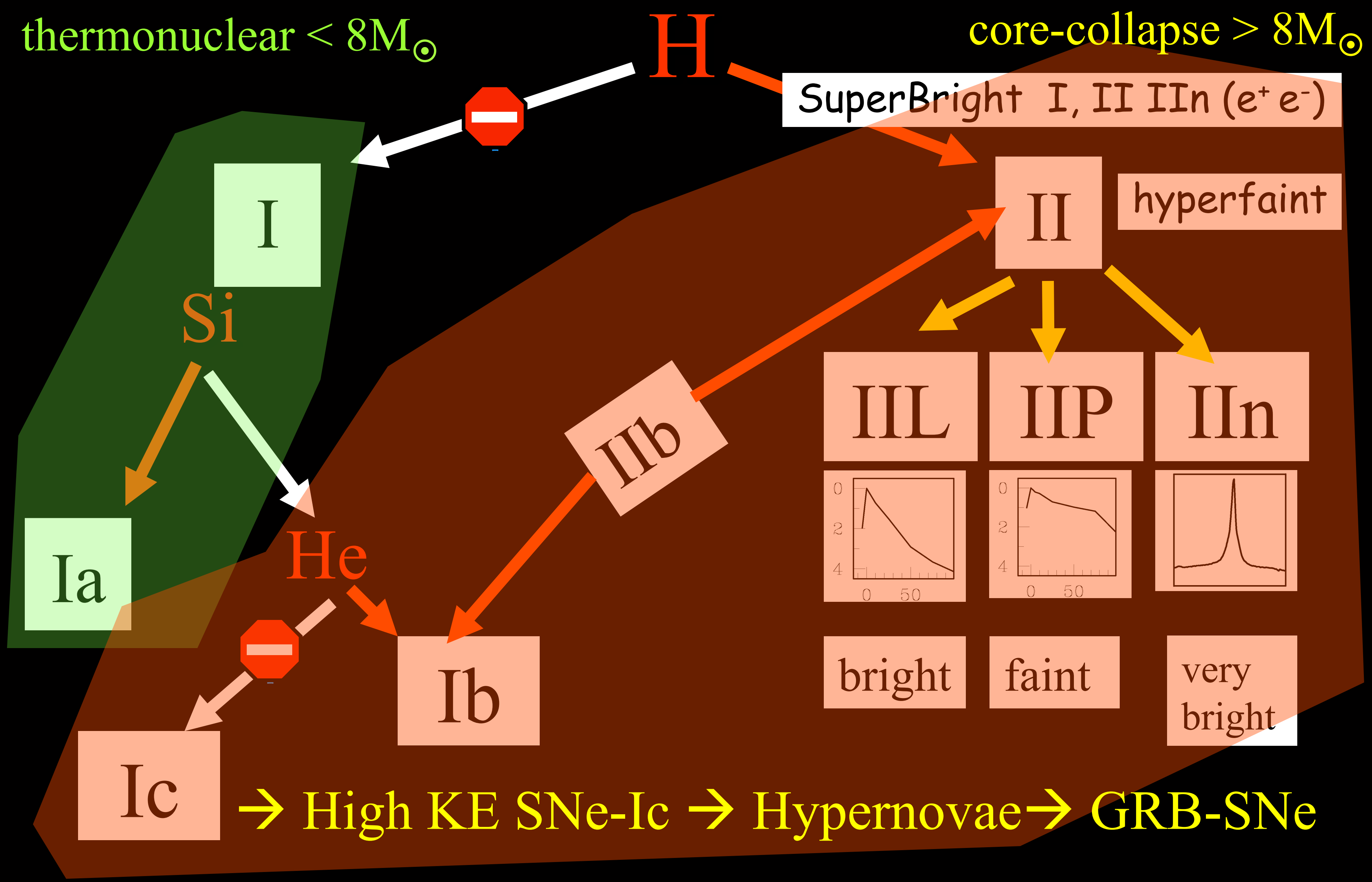
Supernova taxonomy







Supernova taxonomy

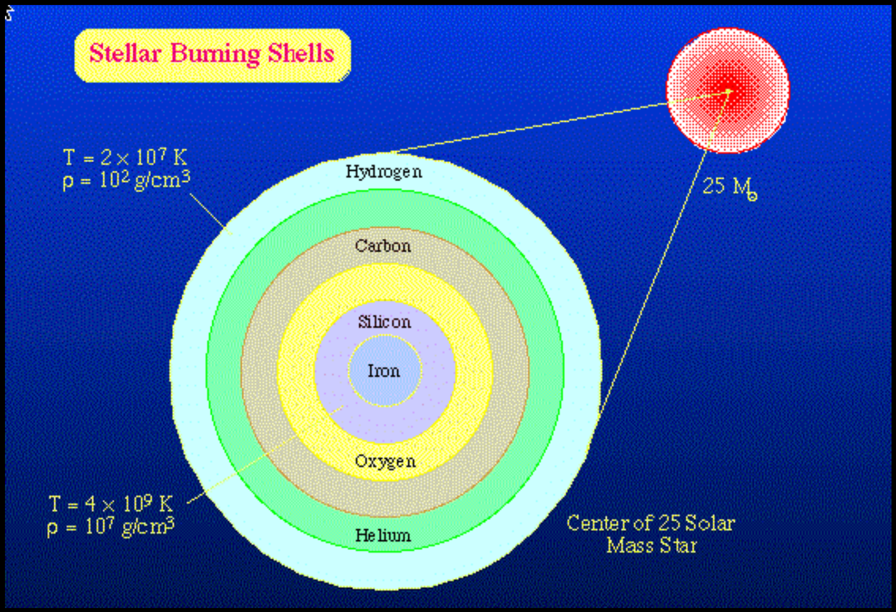


Energetics of Supernova Explosions

	Nuclear Explosion	**Core Collapse**
Progenitors	3-8$M_{\odot}$ in binary systems	Massive stars >8$M_{\odot}$
Mass ejected	about 1 $M_{\odot}$	1-40 $M_{\odot}$
Ni/Co/Fe fraction	about 0.7 $M_{\odot}$	< 0.1 $M_{\odot}$ (HNe)
Mag at max (V)	-19.5 (but 91bg)	-13/-19.5/-22
Radiation	10^{49} erg	10^{49-52} erg
Neutrinos	10^{51} erg	10^{53} erg
Kinetic Energy	10^{51} erg	10^{51-52} erg
Stellar remnant	none	NS/BH
Site of explosion	**E/S0/Spirals/Irr**	**Spirals/Irr**
SN Types	**Ia**	**II, IIn, Ib/c, HNe ,SLSNe**

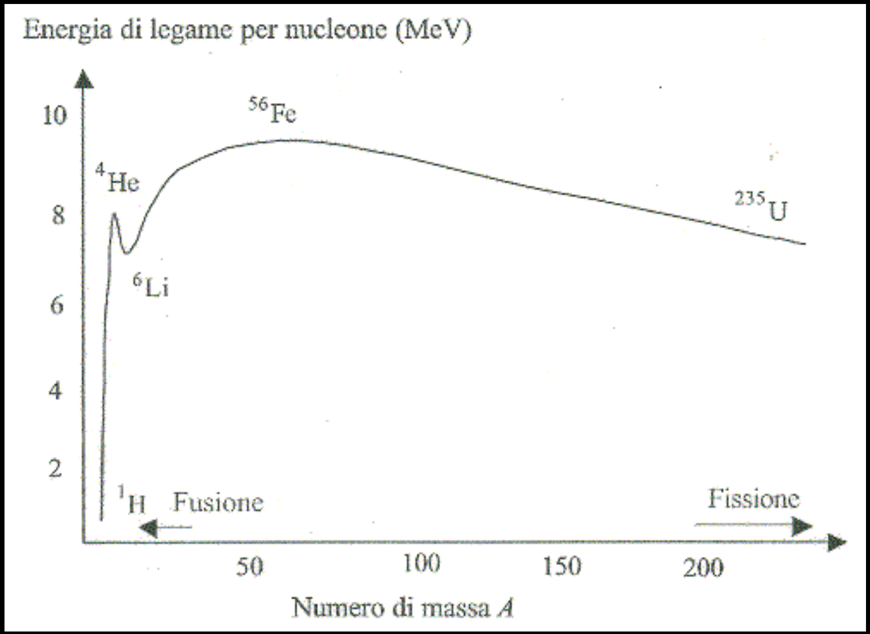
CC SNe have never been observed in E's.

This leads to the idea that their progenitors are massive stars that undergo core-collapse.



"*With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star consisting mainly of neutrons. Such a star may possess a very small radius and extremely high density.*" *Baade & Zwicky ('34)*

What would cause a massive star to explode?



Fe is at the top of the average binding energy curve, so that Fe can only decompose into elements of lower binding energy, which means a net absorption of energy and the ultimate collapse of the core: at about 6×10^{9} K the photdisintegration of the Fe gives:

$\gamma + {}^{56}\mathrm{Fe} \rightarrow 13\ {}^{4}\mathrm{He} + 4n$ (about 124MeV)

$\gamma + {}^{4}\mathrm{He} \rightarrow 2p + 2n$ (about 28 Mev)

This robs the core of energy and so it contracts more rapidly

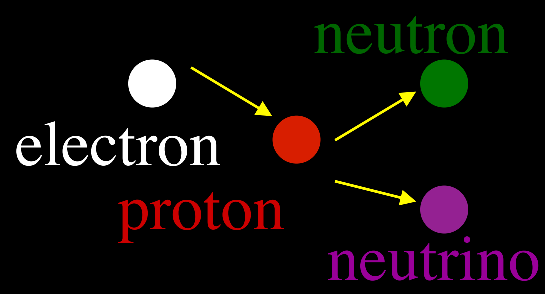
What would cause a massive star to explode?

There are three consequences:

a) **Neutrons are made available for forming heavy elements via rapid and slow process. r and s referring to how fast the process goes relative to beta decay: n→ p + e^- + ν (about 15m)**

b) **The matter falling onto the degenerate core, bounces back through the entire star (at several x 10^4 km/s) . The formation of the shock wave is considered the begining of the SN explosion phenomenon. → Observational aspect→ X and UV flares (SN shock break-out) → star blows out**

c) Due to high density electrons are squeezed into the protons to form neutrons and creating more neutrinos: $p + e^- \rightarrow n + \nu$ converts the core to a degenerate neutron gas (=NS)- a neutron ‘’pudding” ($\rho \sim 10^{14}$ g/cm^3; e- and p < 1%). This is a degenerate neutron gas that stops the collapse, unless the mass of the core is > $3M_\odot$

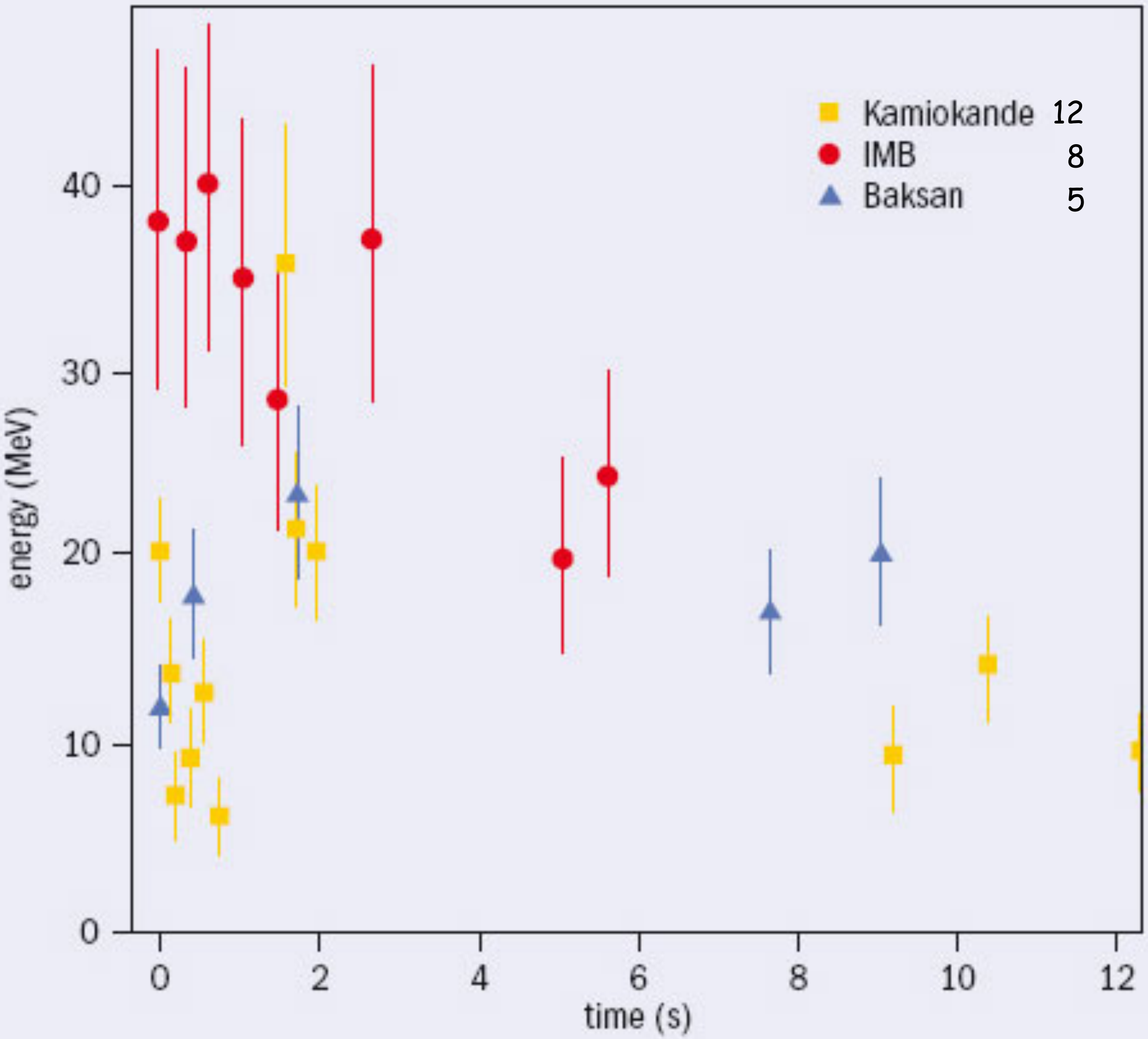


Neutrinos detection confirms that a NS is the residual of a CC SN explosion.

SN 1987A in the LMC

30 Dor Nebula after
SN 1987A explosion

30 Dor Nebula before
SN 1987A explosion



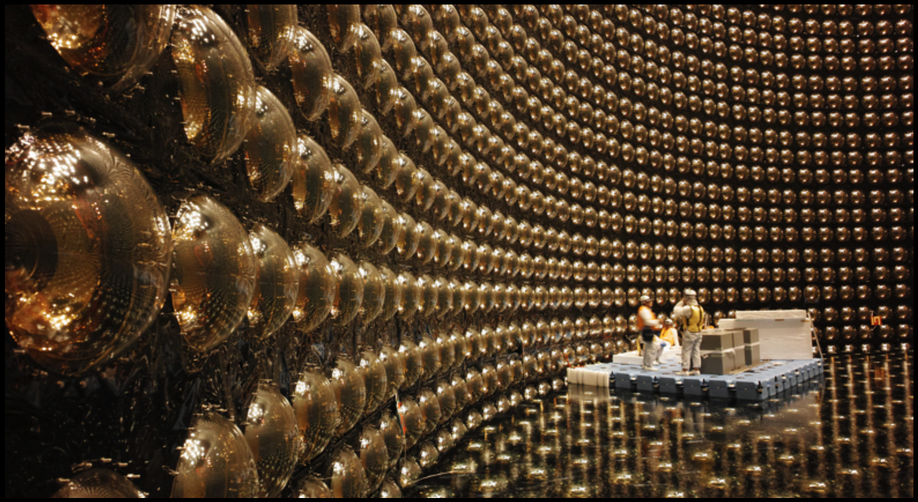
$$m^2 = \frac{19.4\,\delta t}{D\left(\frac{1}{E_1^2} - \frac{1}{E_2^2}\right)}$$

D is distance in kpc

$\boxed{m(\bar{\nu}_e) <}$ a few eV

see Vissani et al. 2010)

Are we prepared to observe the next SN ?



Expected SN/Neutrinos rates

galaxy type	N. SNe* Ia	Ib/c	II	rate [SNu] Ia	Ib/c	II
E-S0	22.0			0.18 ± 0.06	< 0.01	< 0.02
S0a-Sb	18.5	5.5	16.0	0.18 ± 0.07	0.11 ± 0.06	0.42 ± 0.19
Sbc-Sd	22.4	7.1	31.5	0.21 ± 0.08	0.14 ± 0.07	0.86 ± 0.35
Others#	6.8	2.2	5.0	0.40 ± 0.16	0.22 ± 0.16	0.65 ± 0.39
All	69.6	14.9	52.5	0.20 ± 0.06	0.08 ± 0.04	0.40 ± 0.19

Asiago Survey
(Cappellaro et al. 1999; see also VST Survey, Botticella et al. 2017)

Rate	SN Ia	SN Ibc	SN II
Early(fiducial; SNuK)	$0.064^{+0.008}_{-0.007}(^{+0.013}_{-0.013})$	$0.008^{+0.006}_{-0.004}(^{+0.002}_{-0.002})$	$0.004^{+0.003}_{-0.002}(^{+0.001}_{-0.001})$
Late(fiducial; SNuK)	$0.074^{+0.006}_{-0.006}(^{+0.012}_{-0.012})$	$0.096^{+0.010}_{-0.009}(^{+0.018}_{-0.018})$	$0.172^{+0.011}_{-0.011}(^{+0.045}_{-0.036})$
Early(LF-average; SNuK)	$0.048^{+0.006}_{-0.005}(^{+0.010}_{-0.010})$	$0.006^{+0.004}_{-0.003}(^{+0.002}_{-0.002})$	$0.003^{+0.002}_{-0.001}(^{+0.001}_{-0.001})$
Late(LF-average; SNuK)	$0.065^{+0.006}_{-0.005}(^{+0.010}_{-0.010})$	$0.083^{+0.009}_{-0.008}(^{+0.016}_{-0.016})$	$0.149^{+0.010}_{-0.009}(^{+0.039}_{-0.031})$
Vol-rate (10^{-4} SN Mpc^{-3} yr^{-1})	$0.301^{+0.038}_{-0.037}(^{+0.049}_{-0.049})$	$0.258^{+0.044}_{-0.042}(^{+0.058}_{-0.058})$	$0.447^{+0.068}_{-0.068}(^{+0.131}_{-0.111})$

Lick Survey
(Li et al. 2011)

GRB rate: 0.7 GRB Gpc^{-3} yr^{-1}

HN rate: 0.07 $R_{SN\text{-}Ibc}$

Guetta & DV 2007

Expected SN/Neutrinos rates

SNe within the Milky-Way ~ 10 Kpc, good statistics: $5 \times 10^3 \div$ a few $\times 10^4$ neutrinos/SN; but 1 SN ~ 50 years

(Cappellaro et al. 1999)

SNe within ~ 15 Mpc: ~ 0.1 neutrinos per SN ~ 1 SN/yr (0.29 Ibc; 0.7 II; 0.1 HNe; 0.01 GRB/SNe)

CC-SNe ~ Gpc: ~ 0.76×10^{-4} Mpc^{-3} yr^{-1}

~ 10^5 SNe/yr → < 1 neutrino/year

→ diffuse neutrino background

Conclusions

The situation appears desperate

Relativistic Jets in Core-collapse Supernovae

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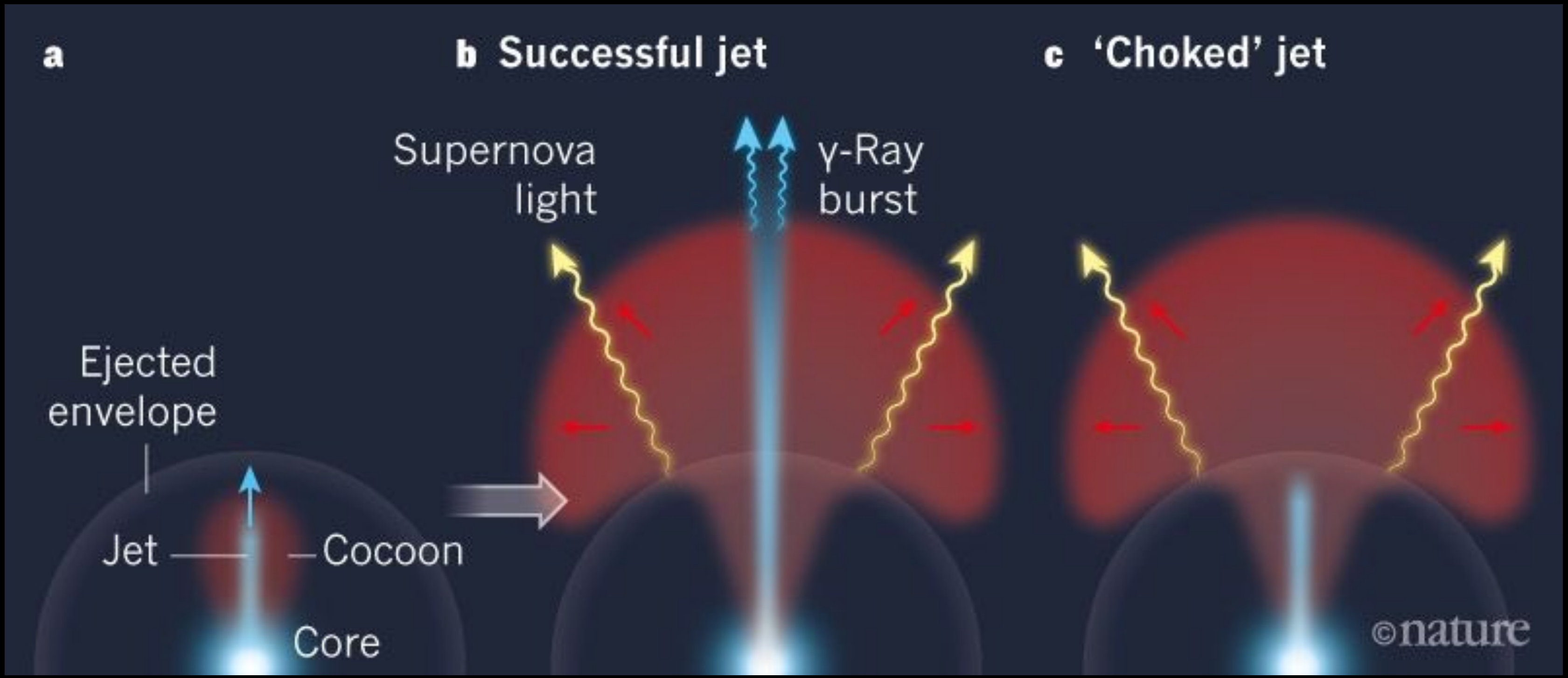
Received 2018 December 20; revised 2019 January 7; accepted 2019 January 17; published 2019 January 28

Table 1
Properties of the SNe Discussed Here

SN	Type	E_{tot} [a]	M_{ej} [b]	E_j [a]	M_c [b]	θ_c	Comments
1997ef (1)	Ic-BL	20	8	9	0.4	20°	No GRB
1998bw (2)	Ic-BL	50	11	$\gtrsim 2$	⋯	⋯	//GRB980425
2002ap (3)	Ic-BL	4	2.5	0.3	⋯	⋯	No GRB
2003bg (4)	IIb	5	4.5	1	0.2	20°	No GRB
2008D (5)	Ib	6	7	1.4	⋯	⋯	X-ray burst
2016jca (6)	Ic-BL	50	10	$\gtrsim 2$	⋯	⋯	GRB161219b

All HNe (CC-SNe?) may be preceded by a GRB. But most times the gamma-ray bursts transfer so much of their own energy to these cocoons that there's not enough left for the GRB to break through.



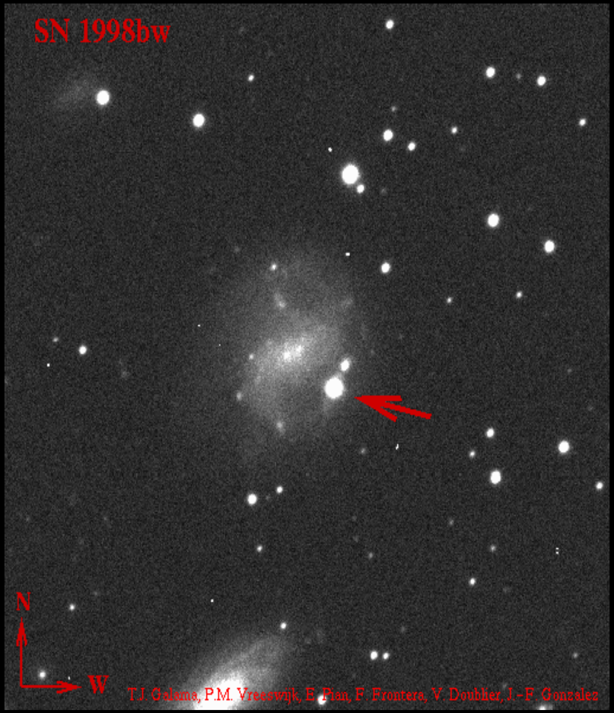
The inner material transported by the jet interacts with the external layers and the medium surrounding the progenitor star spreading sideways

Courtesy of Ore Gottlieb & Ehud Nakar

No-GRB Hypernovae

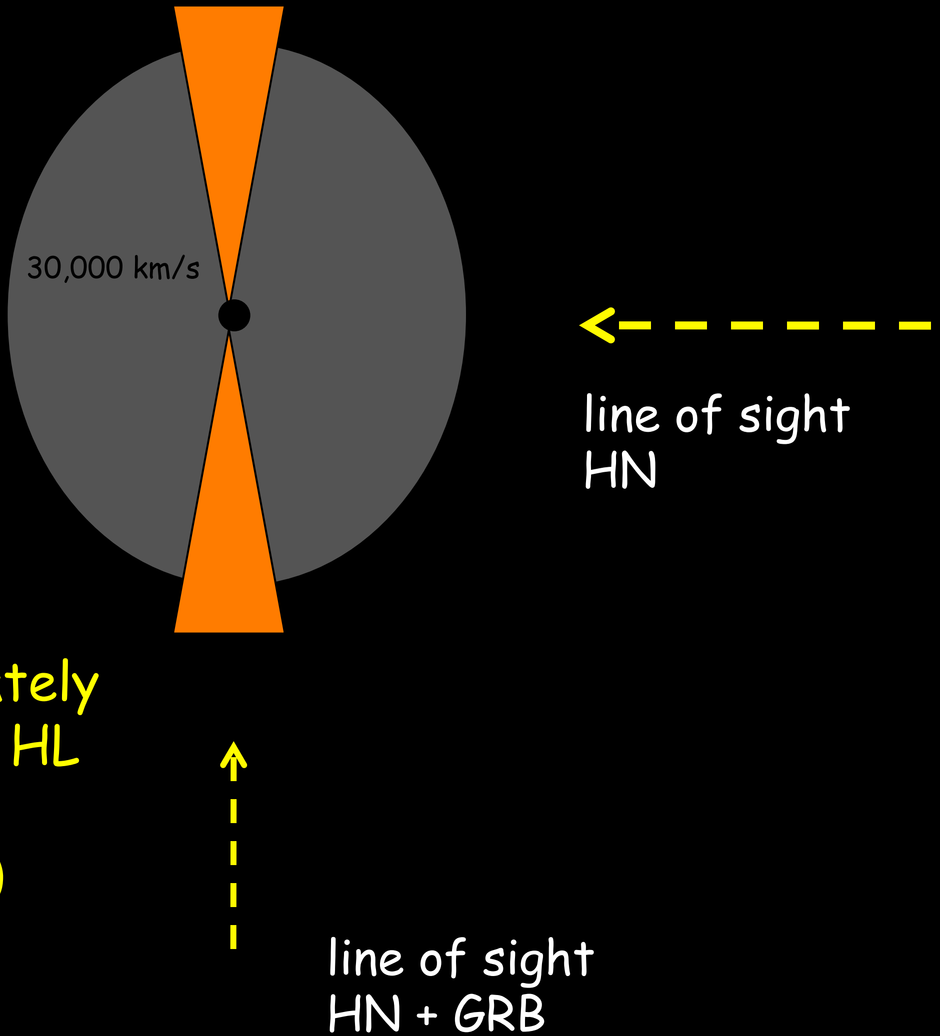
GRB/SNe-Ibc: < 1.5%

HNe/SNe-Ibc: ~ 7%



The simplified scheme for a GRB-SN event

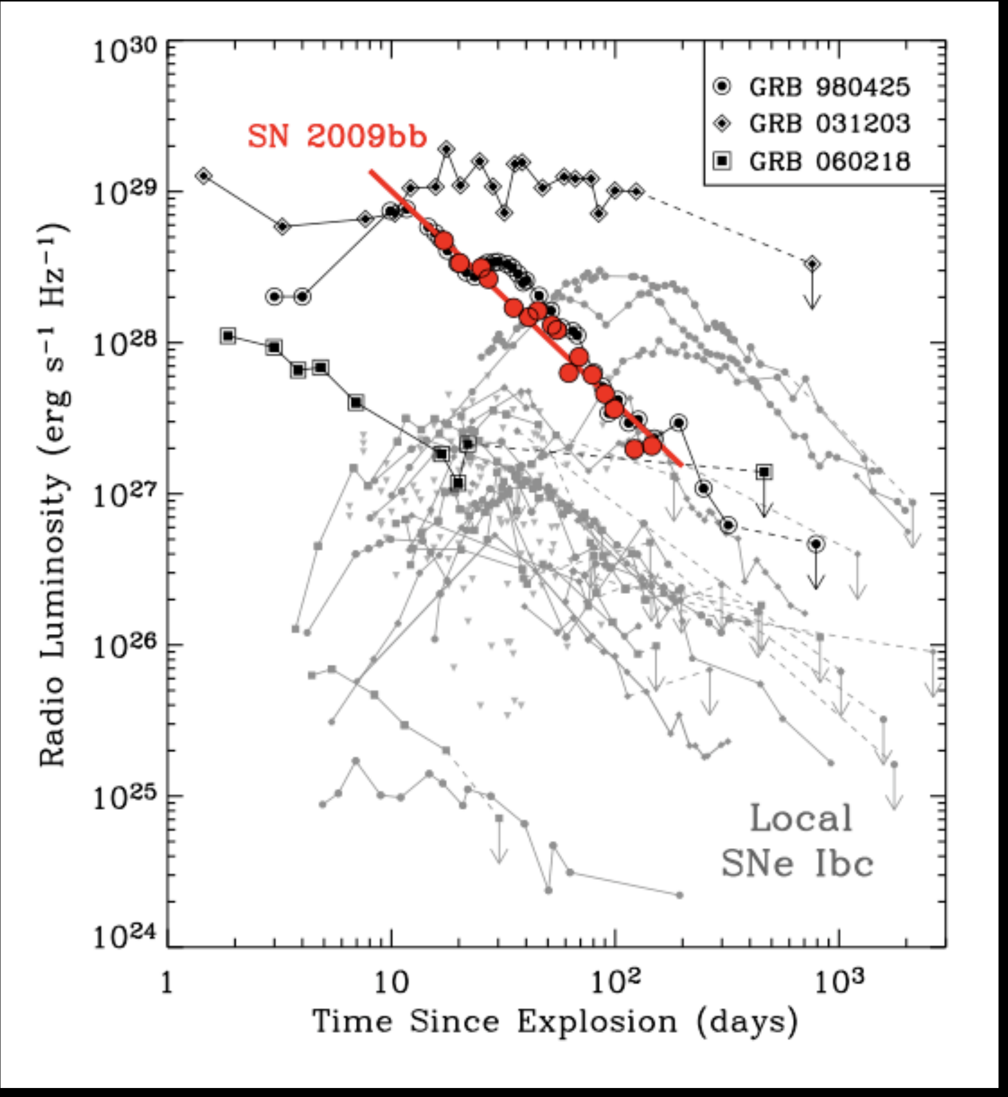
Grey: an almost isotropic component carrying most energy 10^{52} erg and mass ($\sim$5-10$M_\odot$) moving at several x 10^4 km/s



Orange highly collimated/moderately collimated component 4°/20° for HL and LL GRBs , containing a tiny fraction of the mass ($10^{-3/-5}$ $M_\odot$) moving at $\Gamma \sim$ x 10^{2-3}

Discovery of a Relativistic Supernova without a Gamma-ray Trigger 2010

A. M. Soderberg[1], S. Chakraborti[2], G. Pignata[3], R. A. Chevalier[4], P. Chandra[5], A. Ray[2], M. H. Wieringa[6], A. Copete[1],



LATE-TIME RADIO OBSERVATIONS OF 68 TYPE Ibc SUPERNOVAE: STRONG CONSTRAINTS ON OFF-AXIS GAMMA-RAY BURSTS

A. M. Soderberg,[1] E. Nakar,[2] E. Berger,[3,4,5] and S. R. Kulkarni[1]

Received 2005 July 5; accepted 2005 October 24

ABSTRACT

We present late-time radio observations of 68 local Type Ibc supernovae, including six events with broad optical absorption lines ("hypernovae"). None of these objects exhibit radio emission attributable to off-axis gamma-ray burst jets spreading into our line of sight. Comparison with our afterglow models reveals the following conclusions. (1) Less than ~10% of Type Ibc supernovae are associated with typical gamma-ray bursts initially directed away from our line of sight; this places an empirical constraint on the GRB beaming factor of $\langle f_b^{-1} \rangle \lesssim 10^4$, corresponding to an average jet opening angle, $\theta_j \gtrsim 0.8^\circ$. (2) This holds in particular for the broad-lined supernovae (SNe 1997dq, 1997ef, 1998ey, 2002ap, 2002bl, and 2003jd), which have been argued to host GRB jets. Our observations reveal no evidence for typical (or even subenergetic) GRBs and rule out the scenario in which every broad-lined SN harbors a GRB at the 84% confidence level. Their large photospheric velocities and asymmetric ejecta (inferred from spectropolarimetry and nebular spectroscopy) appear to be characteristic of the nonrelativistic SN explosion and do not necessarily imply the existence of associated GRB jets.

"Our observations……rule out the scenario in which every broad-lined SN harbors a (detectable) GRB at the 84% confidence level"

Confirmed by Bietenholz et al. 2014

Letter | Published: 16 January 2019

Signatures of a jet cocoon in early spectra of a supernova associated with a γ-ray burst

L. Izzo, A. de Ugarte Postigo, K. Maeda, C. C. Thöne, D. A. Kann, M. Della Valle, A. Sagues Carracedo, M. J. Michałowski, P. Schady, S. Schmidl, J. Selsing, R. L. C. Starling, A. Suzuki, K. Bensch, J. Bolmer, S. Campana, Z. Cano, S. Covino, J. P. U. Fynbo, D. H. Hartmann, K. E. Heintz, J. Hjorth, J. Japelj, K. Kamiński, L. Kaper, C. Kouveliotou, M. Krużyński, T. Kwiatkowski, G. Leloudas, A. J. Levan, D. B. Malesani, T. Michałowski, S. Piranomonte, G. Pugliese, A. Rossi, R. Sánchez-Ramírez, S. Schulze, D. Steeghs, N. R. Tanvir, K. Ulaczyk, S. D. Vergani & K. Wiersema - Show fewer authors

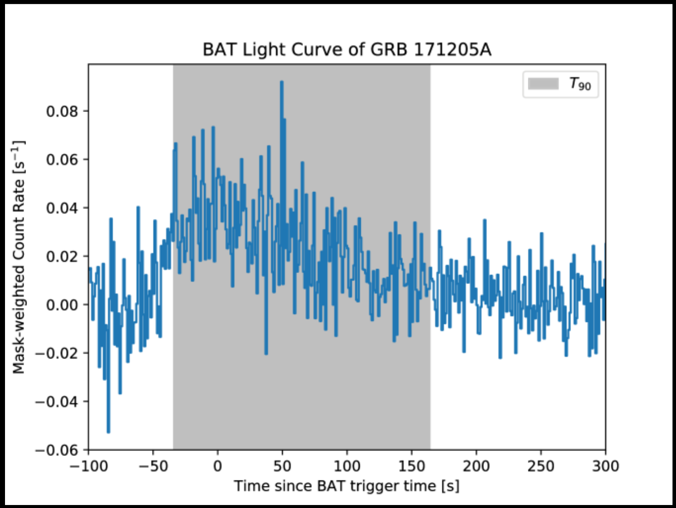
Nature **565**, 324–327 (2019) | Download Citation

GRB 171205A

i) third closest GRB-SN $z = 0.0368$ (160 Mpc)

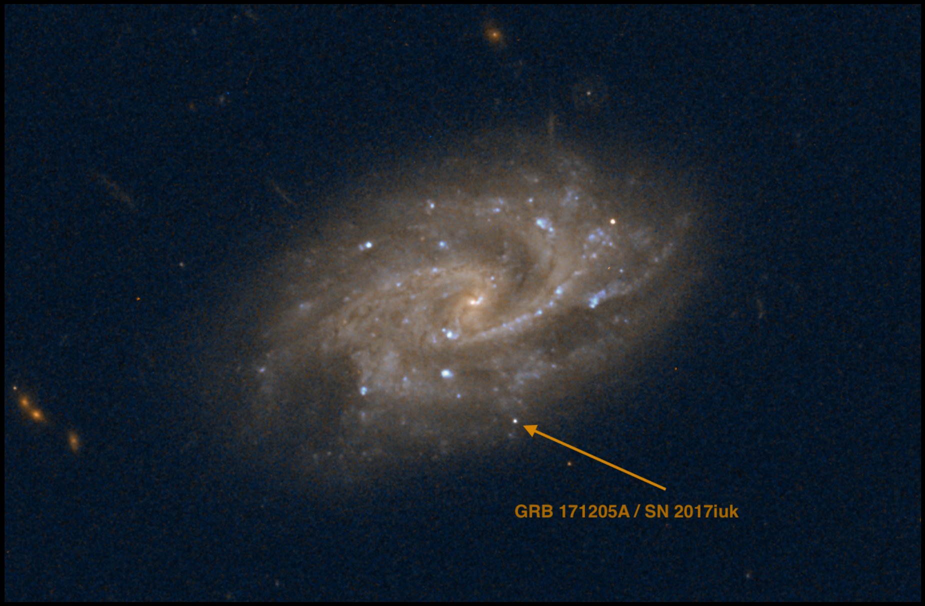
ii) low-luminous GRB $E_{iso} \sim 10^{49}$ erg

iii) grand-design spiral host galaxy

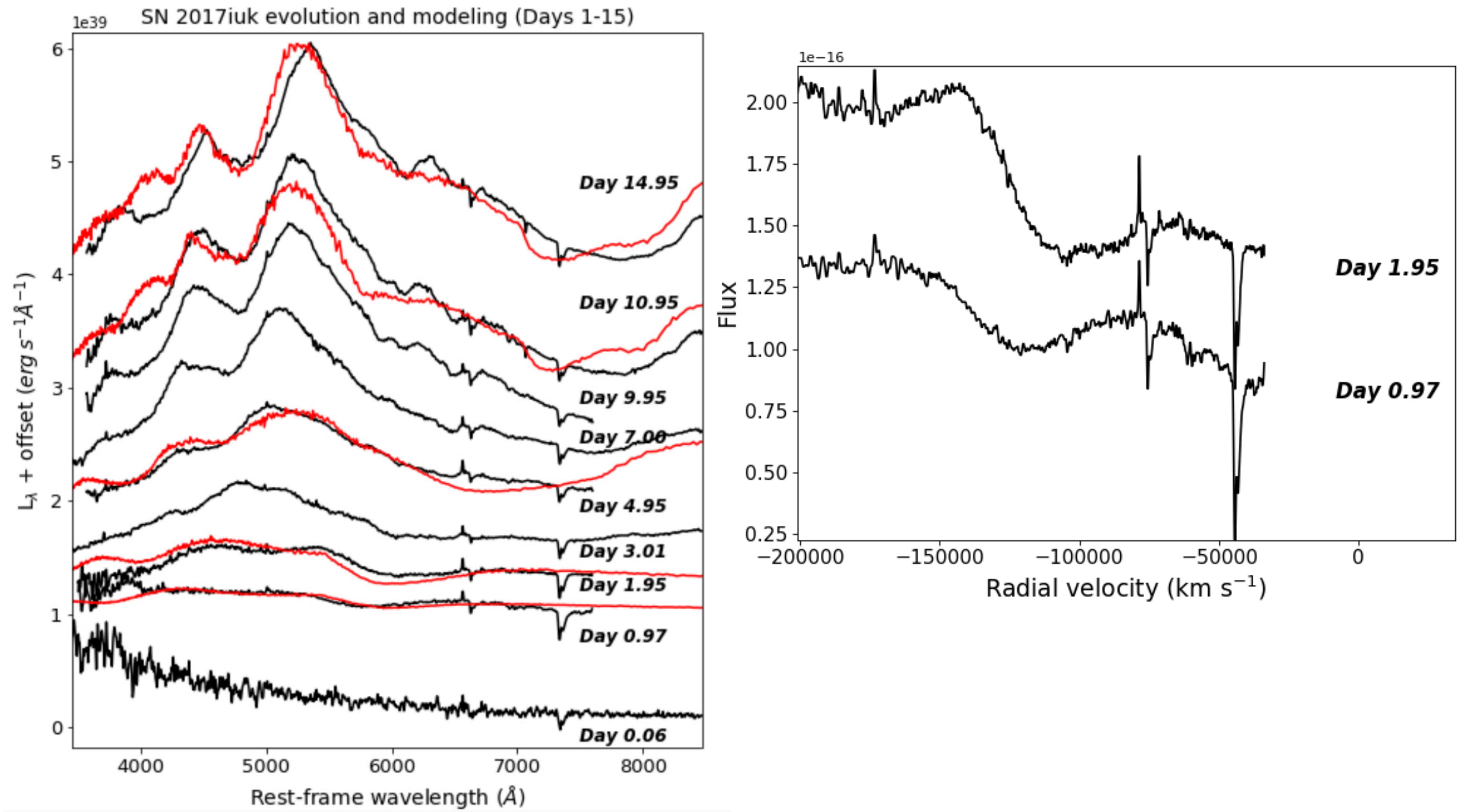


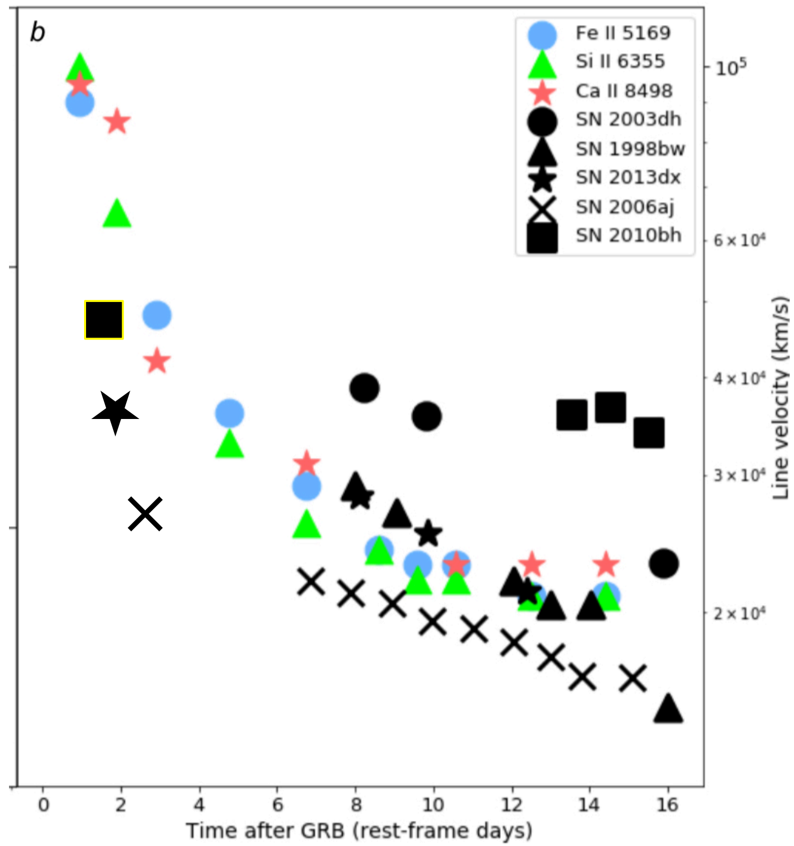
multi-wavelength photometric & spectroscopic campaign

(Swift, VLT, GTC, GROND, PST2, OSN, GOTO ...)

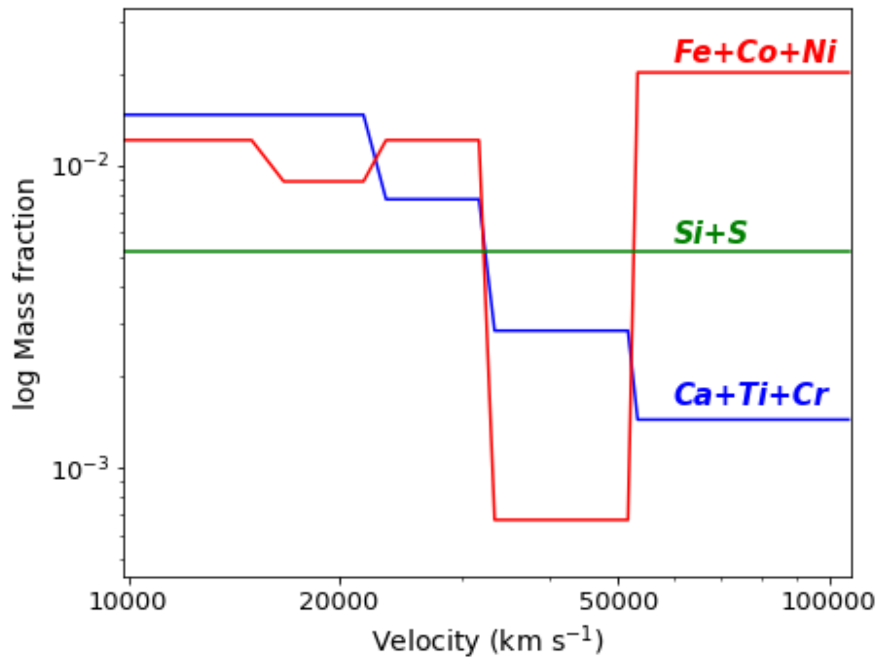


Izzo et al. Nature, 2019


SN 2017iuk evolution and modeling (Days 1-15)
1e39
L_λ + offset ($erg\,s^{-1}Å^{-1}$)
Rest-frame wavelength ($Å$)
Day 14.95
Day 10.95
Day 9.95
Day 7.00
Day 4.95
Day 3.01
Day 1.95
Day 0.97
Day 0.06
1e−16
Flux
Radial velocity (km s^{-1})
Day 1.95
Day 0.97



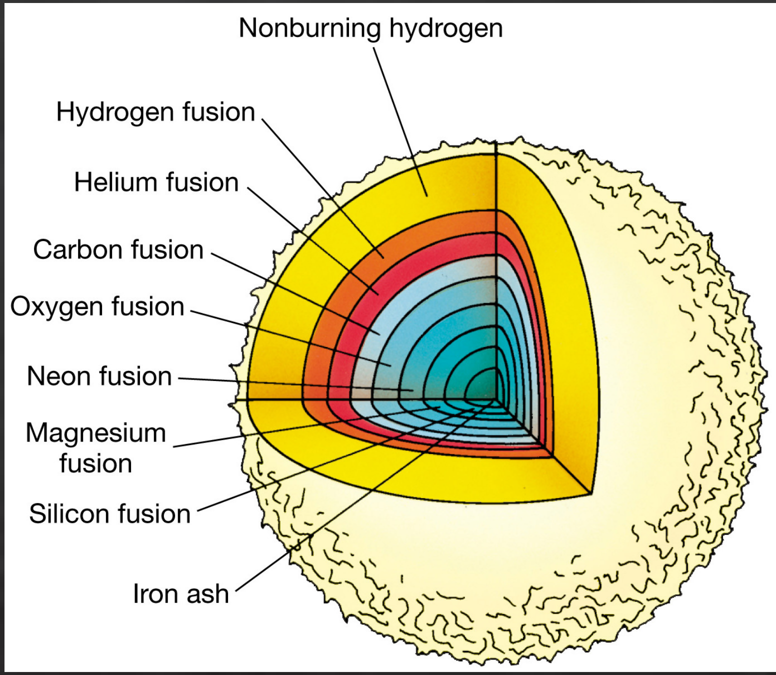
We interpret these high velocity features as signatures of a hot cocoon generated when the jet moves inside the progenitor star.



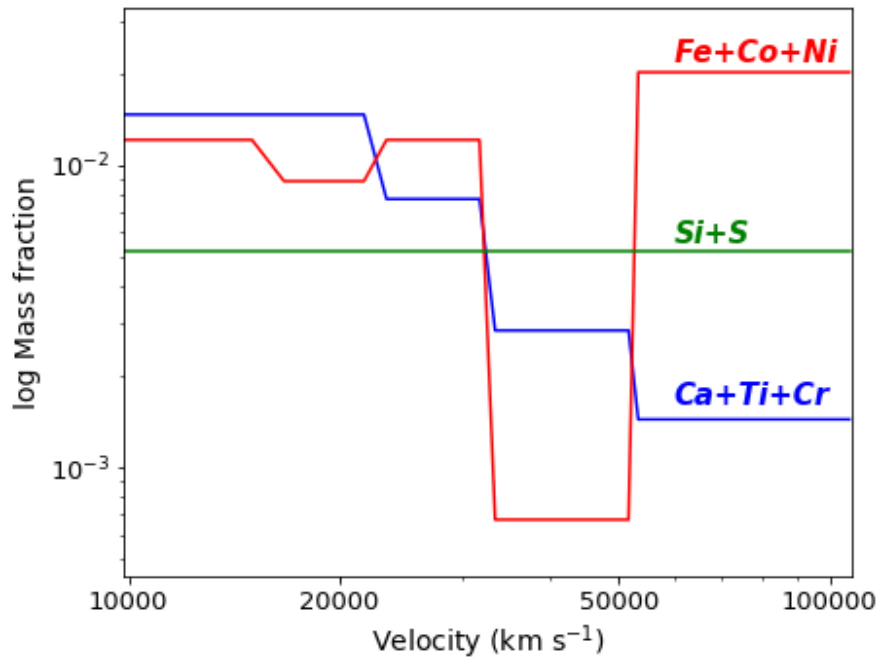
chemical composition of the high velocity (10^5 km/s) components are characterized by chemical abundances different from those observed in the SN ejecta ($\times 10^4$ km/s)

Interpreting spectra: position of elements

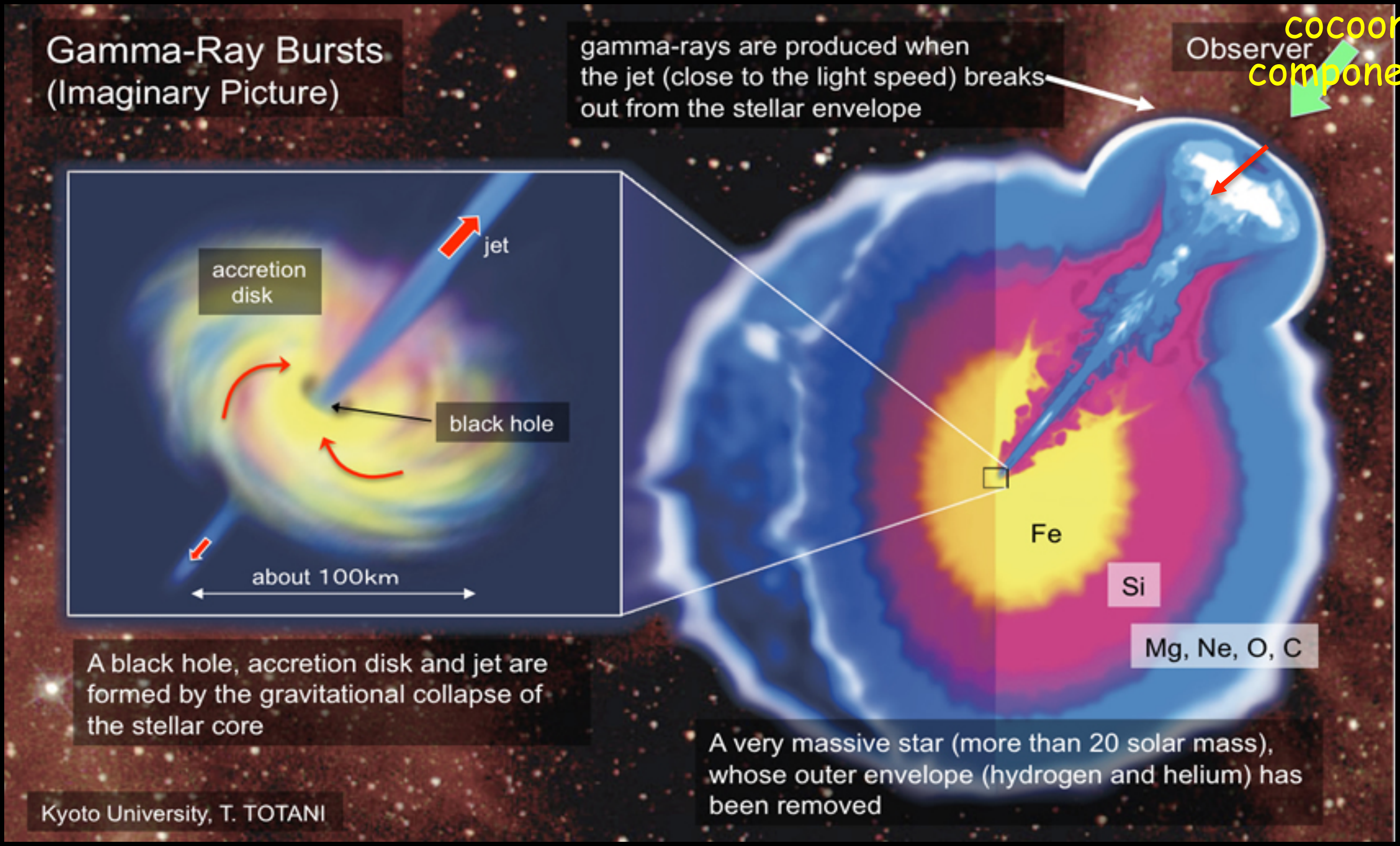
Immediately after explosion SNe go into homologous expansion → v ~ r



Relative positions of elements do not change



chemical composition of the high velocity (10^5 km/s) components are characterized by chemical abundances different from those observed in the SN ejecta ($\times 10^4$ km/s) → **consistent with substantial mixing of the explosive material induced by the jet**



Is this mechanism at play for all CC-SNe?

Murase & Ioka 2013
Murase et al. 2016
Senno et al. 2016, 2017
Denton & Tamborra 2017
He et al. 2018
Esmaili & Murase 2018

In the chocked jets protons are acceleretd to high energies and the thermal photons are produced in the jet head and propagate inside the internal shock region. This interaction produces pions which decay in high energy neutrinos

Constraining the Fraction of Core-Collapse Supernovae Harboring Choked Jets with High-energy Neutrinos

DAFNE GUETTA,[1] ROI RAHIN,[2] IMRE BARTOS,[3] AND MASSIMO DELLA VALLE[4, 5]

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(observed by IceC<ube)

N(r) total number of expected neutrinos by a SN source by integrating the neutrino fluence convoluted with the effective energy sensitivity of the detector over the energy range 1-100 TeV:

$$N(r) = \int_{1\,TeV}^{100\,TeV} \frac{dN_\nu(E(1+z))}{dE_\nu} A(E_\nu, \delta) dE_\nu$$

where r is the luminosity distance, dN/dE is the neutrino spectral fluence, A(Ev , δ) is the effective area of the neutrino detector, as a function of the neutrino energy Ev and of the source declination

We find that the fraction of SNe within distance rmax that will have a detected astrophysical high-energy neutrino counterpart is:

$$f_\nu = \frac{f_{\rm jet} f_{\rm b} \int_0^{r_{\rm max}} (1 - \mathrm{Poiss}(0, \mathrm{N(r)}))\rho(\mathrm{r}) 4\pi \mathrm{r}^2 \mathrm{dr}}{\int_0^{r_{\rm max}} \rho(r) 4\pi r^2 dr}$$

where fb is the jet beaming factor, defined as the fraction of the sky in which the jet emits high-energy neutrinos, fjet is the fraction of CCSNe that produce jets, Poiss(k, λ) is the Poisson probability of measuring k for average value λ, and rmax is the maximum luminosity distance out to which the CCSN can be detected optically.

What is the fraction of SNe-Ib/c which produces (long)GRBs ?

Rate for Ibc: 2.6×10^4 SNe-Ibc $Gpc^{-3}\ yr^{-1}$

GRB rate: 0.7 GRB $Gpc^{-3}\ yr^{-1}$

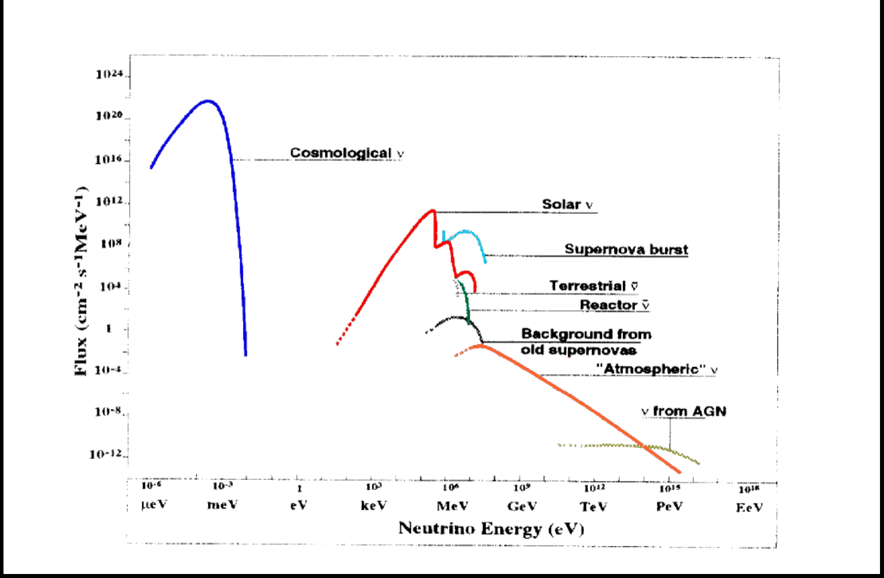
$\langle fb^{-1}\rangle \sim 500$	(Frail et al. 2001; Ghirlanda et al. 2013)	($\vartheta \sim 4°$)
$\langle fb^{-1}\rangle \sim 75$	(Guetta et al. 2004)	($\vartheta \sim 9°$)
$\langle fb^{-1}\rangle <\sim 10$	(Guetta & DellaValle 2007)	($\vartheta > 25°$) for sub-lum GRBs
$\langle fb^{-1}\rangle <\sim 7$	(Pisani et al. 2016)	($\vartheta > 30°$)

GRB/SNe-Ibc: 1.5%-0.02%

Conclusions

	ZTF	LSST
CCSN	40	10^5
SN-Ibc	200	6×10^5
Hypernova	2×10^4	2×10^7

These are the numbers of supernovae of different types, that are required for a 3σ detection above the neutrinos background.



Conclusions cont'd

Given the current SN rates, the required number of CCSN detections can be achieved in about a year by either ZTF or LSST if CCSNe (or a fraction of them) produce jets (and the adopted models are correct).

"*Our findings suggest a continuum of central engine activities in different types of CCSNe and call for rethinking of the explosion mechanism of CCSNe*"

(Piran et al. 2019)