Supernova Explosions in the Multimessenger Era

Massimo Della Valle

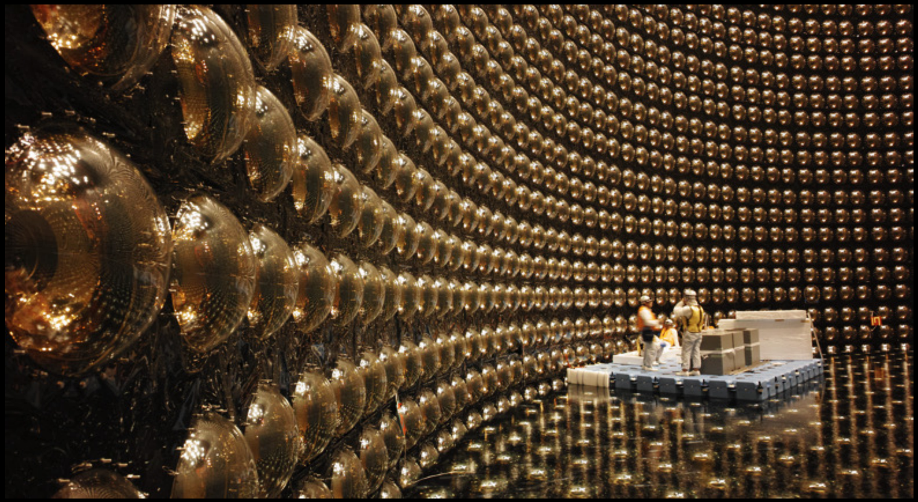
Capodimonte Observatory, INAF-Naples

Sexten 9-14 Jan 2023

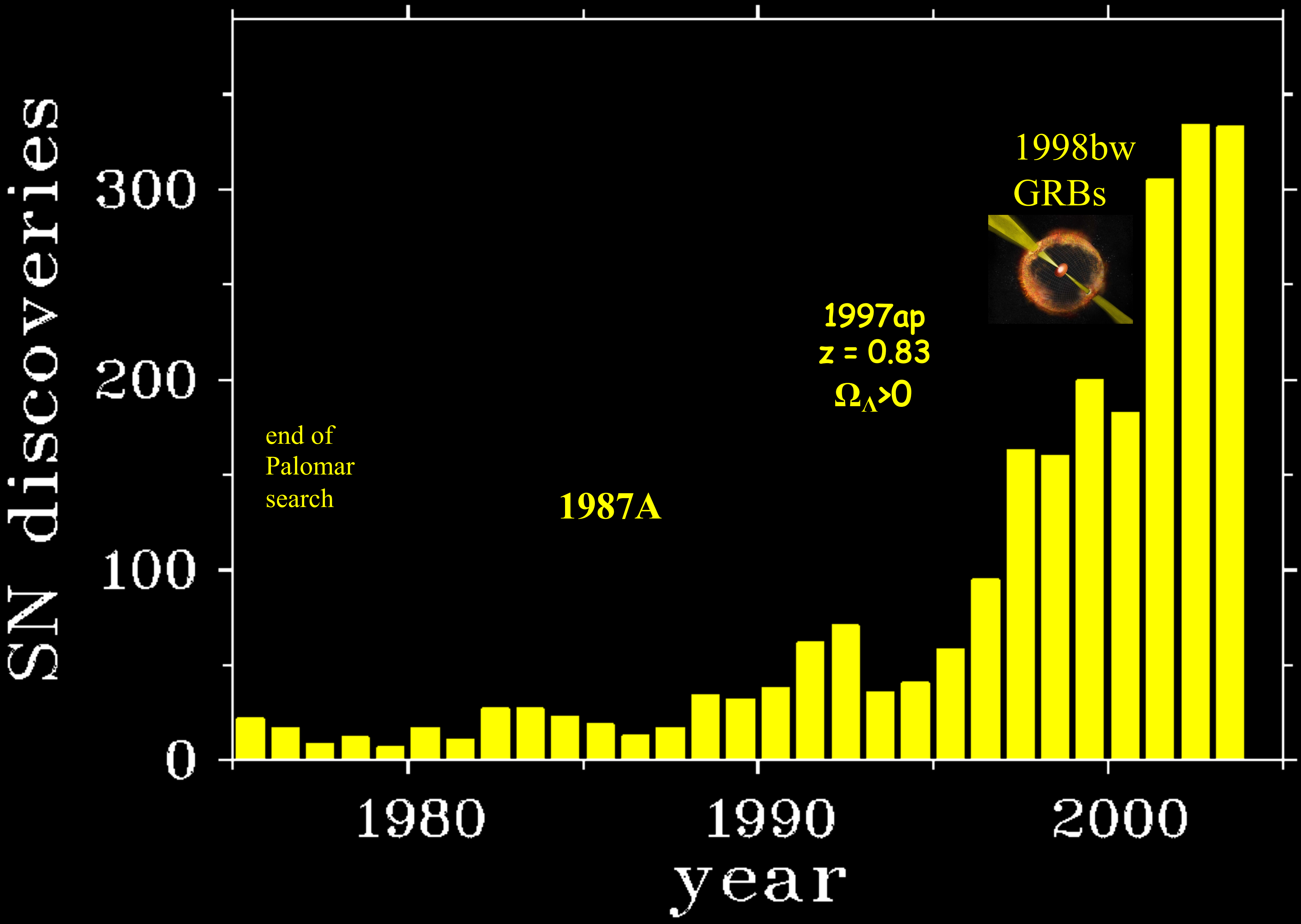
Summary:

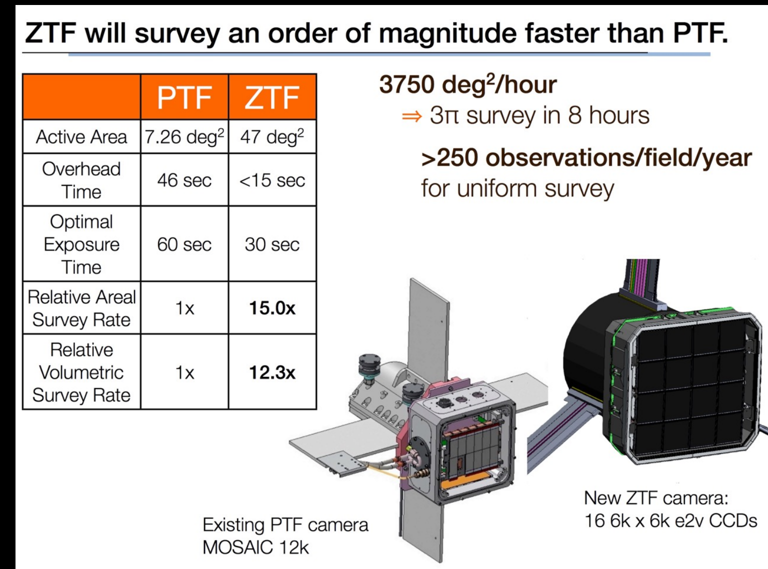
Are we prepared to observe the next nearby SN ?

Ligo, Virgo, Kagra



De Stella Nova “*in pede Serpetarii*” 1606


SN discoveries
0
100
200
300
1980
1990
2000
year
end of
Palomar
search
1987A
1997ap
z = 0.83
Ω_Λ>0
1998bw
GRBs



ZTF will survey an order of magnitude faster than PTF.

	PTF	ZTF
Active Area	7.26 deg^2	47 deg^2
Overhead Time	46 sec	<15 sec
Optimal Exposure Time	60 sec	30 sec
Relative Areal Survey Rate	1x	**15.0x**
Relative Volumetric Survey Rate	1x	**12.3x**

3750 deg^2/hour
⇒ 3π survey in 8 hours

>250 observations/field/year
for uniform survey

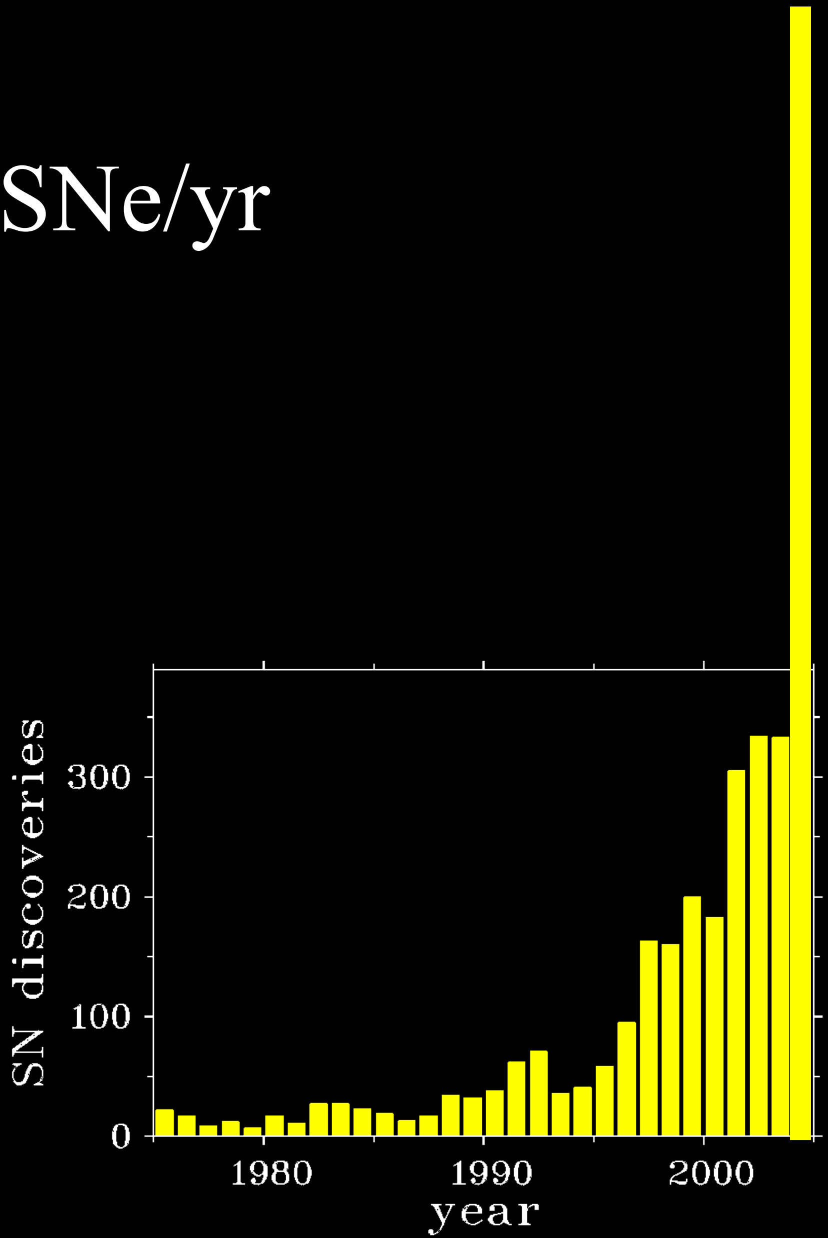
PAN-STARRS

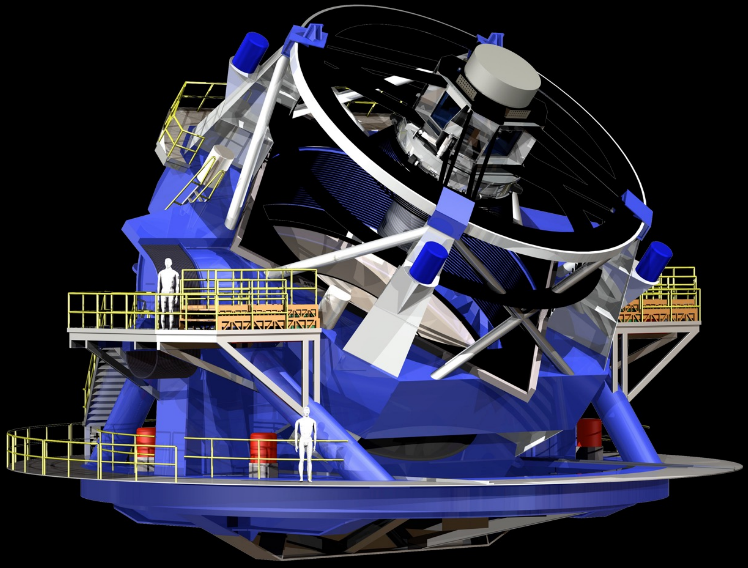
SkyMapper

ASASSN
SDSS and DES
ATLAS
ESSENCE SN survey
DLT40
SUDARE @ VST

Chile, Hawaii, Texas, South Africa

~ 1000 SNe/yr

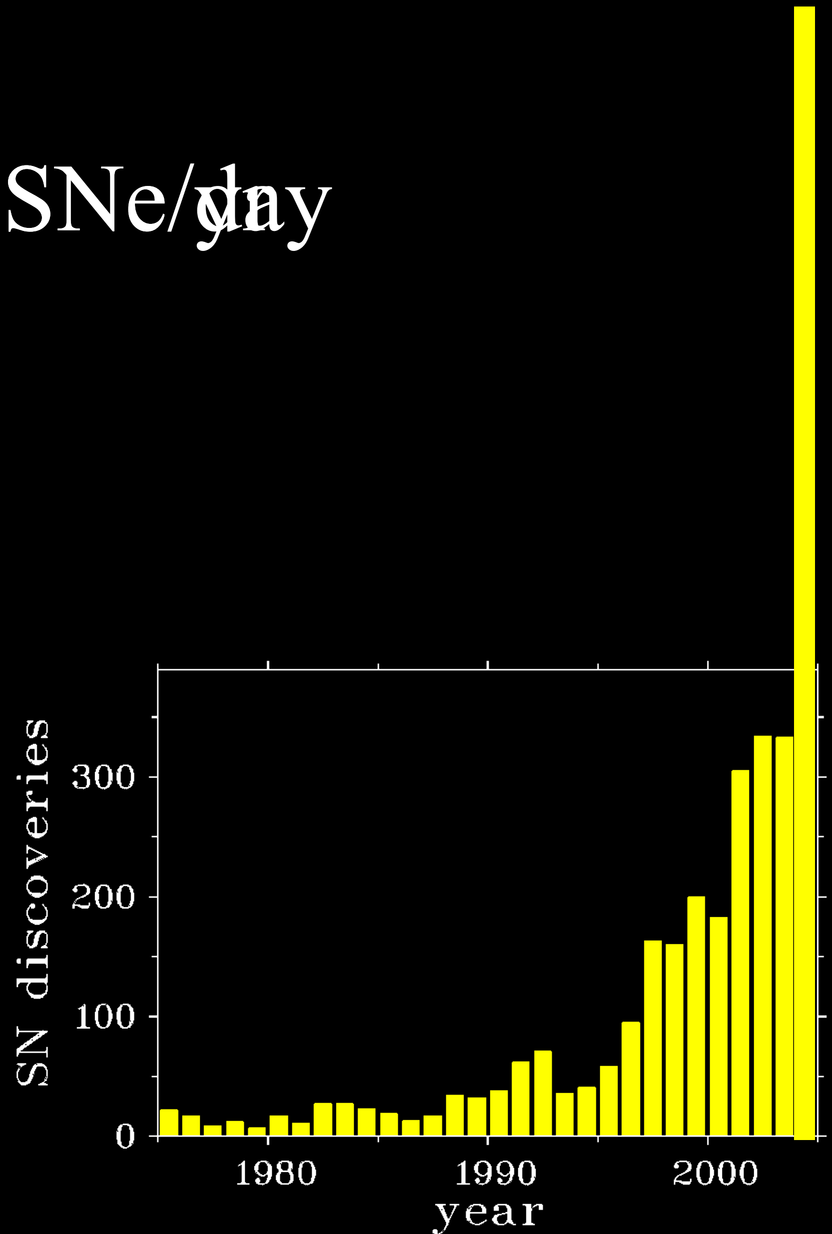




LSST

R~24.4 z~1.7 V~500 Gpc^3

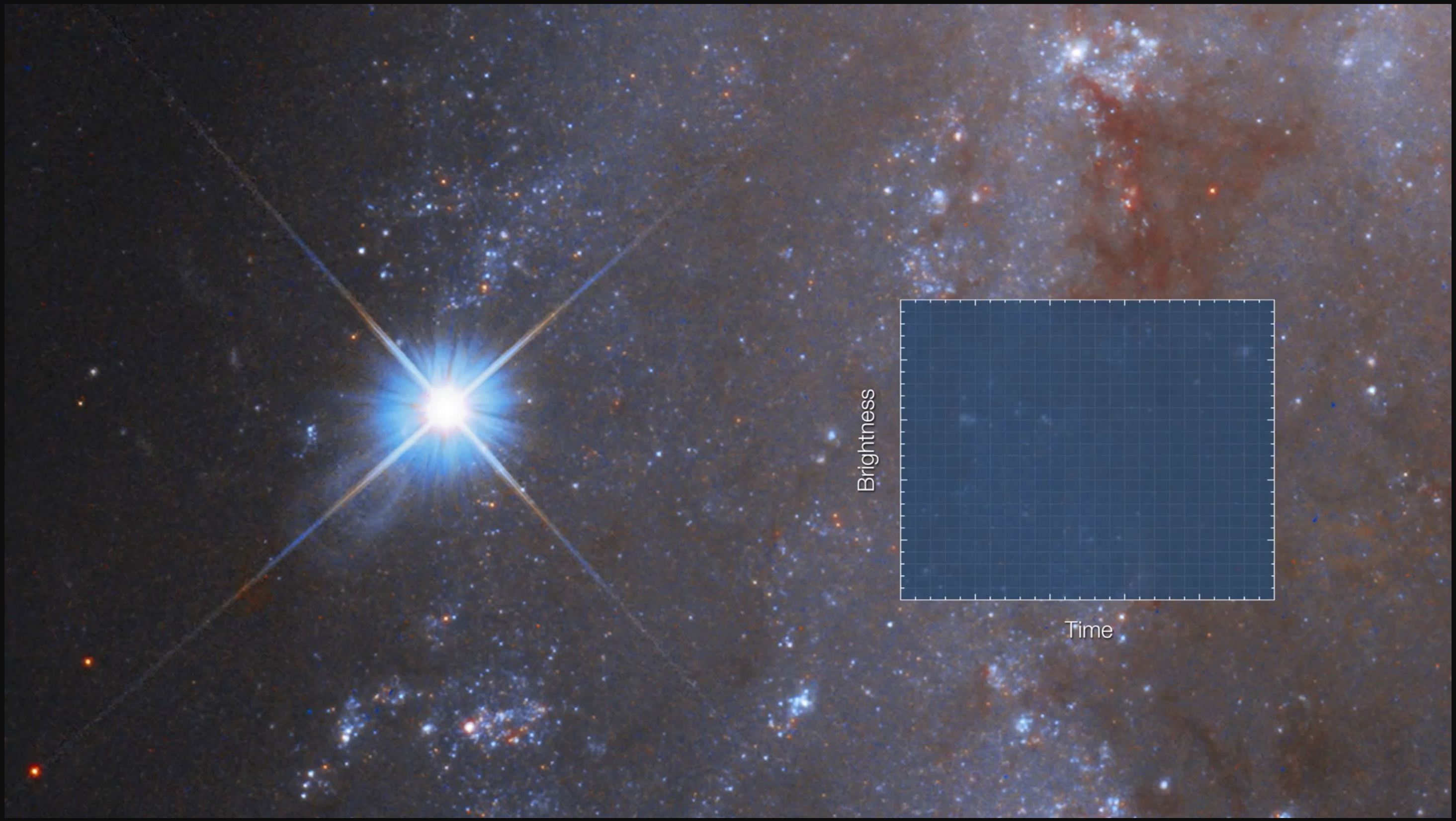
~ 1000 SNe/day



Astrophysics with Supernovae

• Explosive Death of Stars	-Physics of compact objects
• Metal Enrichment	-Galaxies Nucleosinthesis
• Energy Injection	
• Tracers of SFRs	-Evolution of stellar populations and galaxies
• Distance Indicators	
• Tracers of cosmological models	-Cosmology
• Bright Background Sources	-CBM/IGM Studies at high ***z***
• Bright Echoes	-3D Structure of ISM
• Cosmic Rays	- SN Remnants
• **Multi-Messenger**	**-Neutrinos (SN 1987A)**
	-GWs (not yet)

How many SNe do we expect to occur in the Milky Way in 400 years ?



SN rates in the Local Universe

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

Lick Survey
(Li et al. 2011)

$V_{MW} \sim 10^{-6}$ Mpc -> 2 SNe/100yr in the Milky Way

We have to find the probability that a number of events – with a known average rate- occur in a fixed time (assuming that the events are independent of the time since the last event)

CONFIDENCE LIMITS FOR SMALL NUMBERS OF EVENTS IN ASTROPHYSICAL DATA

NEIL GEHRELS
Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center
Received 1985 August 5; accepted 1985 September 30

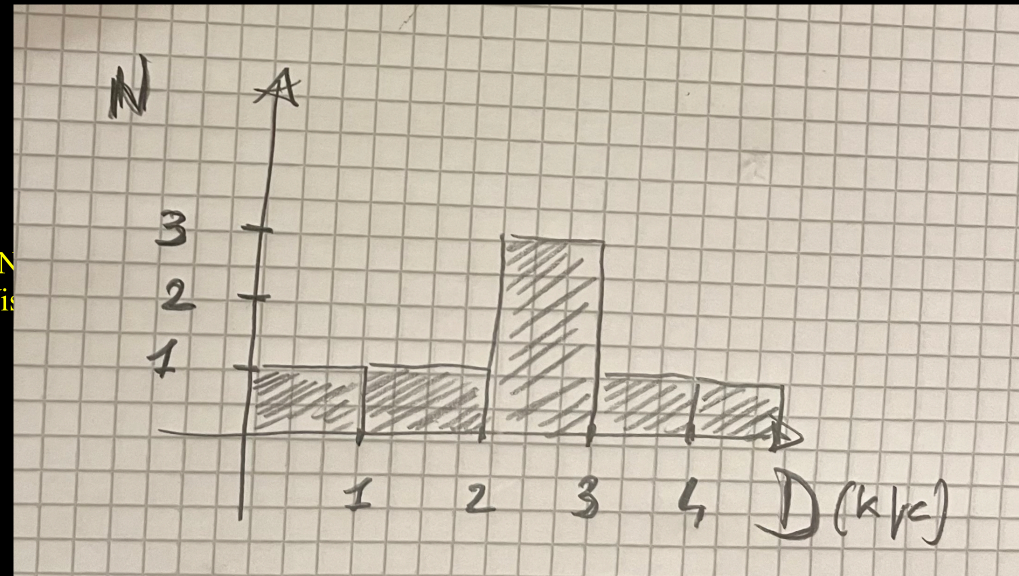
ABSTRACT

Convenient tables and approximate formulae are presented for confidence limits based on Poisson and binomial statistics. Poisson statistics apply when event rates are calculated from small numbers of observed events, and binomial statistics apply when ratios of two different event types are calculated from small numbers of observed events. The limits in the tables are given for all confidence levels commonly used in astrophysics.

0	vs.	1σ	5.2 - 12.0
0	vs.	2σ	3.4 - 15.6
0	vs.	3σ	2.0 - 20.7

Most of SNe occurring in the Galactic Disk will be missed because of the high interstellar reddening in the cone toward the Galactic Bulge

“Bright



Date (AD)	Type	m_{max}	N Vis		
185?	I?	-8			
393	?	-1			
837	?	-8?			
1006	I	-9	> 2yrs	2.2 kpc	SN 1006
1054	II	-6	~2yrs	2kpc	Crab Nebula
1181	II?	+1	0.5yrs	2kpc	3C58
1572	I	← -1	1.5 yrs	2.5-3 kpc	Tycho
1604	I	-3	1 yr	3-7 kpc	Kepler
~1690	II	+5?	missed	3.4 kpc	Cas A
1870	I	~ +6	missed	Hartwig	M31
1987	II	+2.9	~1 yr	Ian Shelton	SN1987A

The volume actually sampled was ~ 10%

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0	**vs.**	**1σ**	5.2 - 12.0
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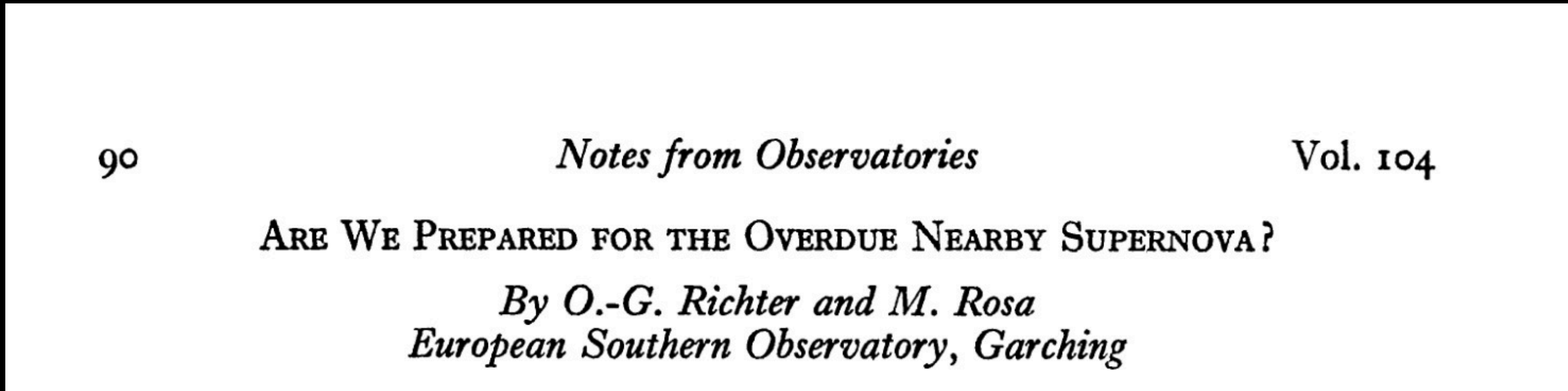
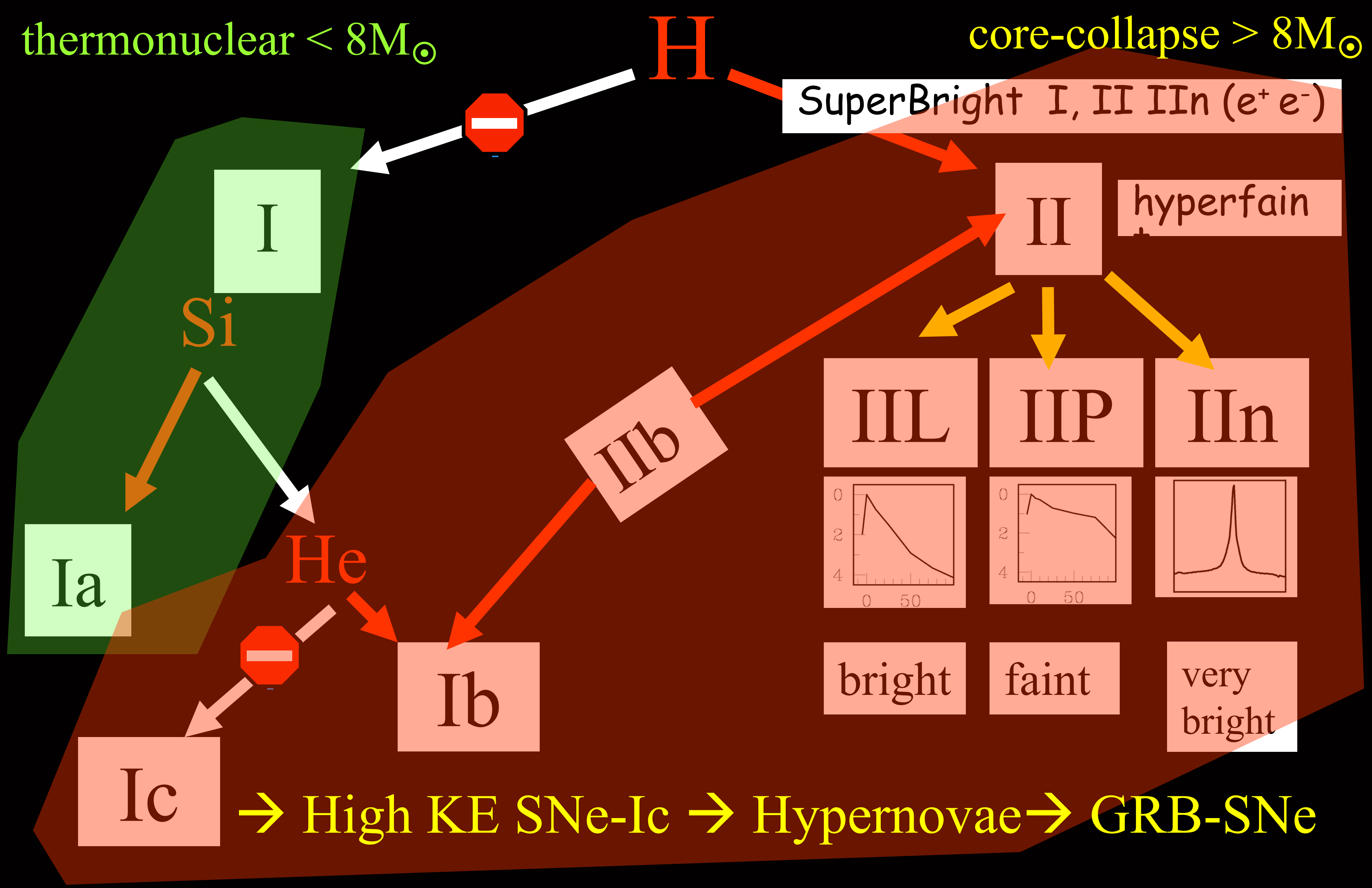
0	**vs.**	**3σ**	2.2 - 20.7


90 *Notes from Observatories* Vol. 104

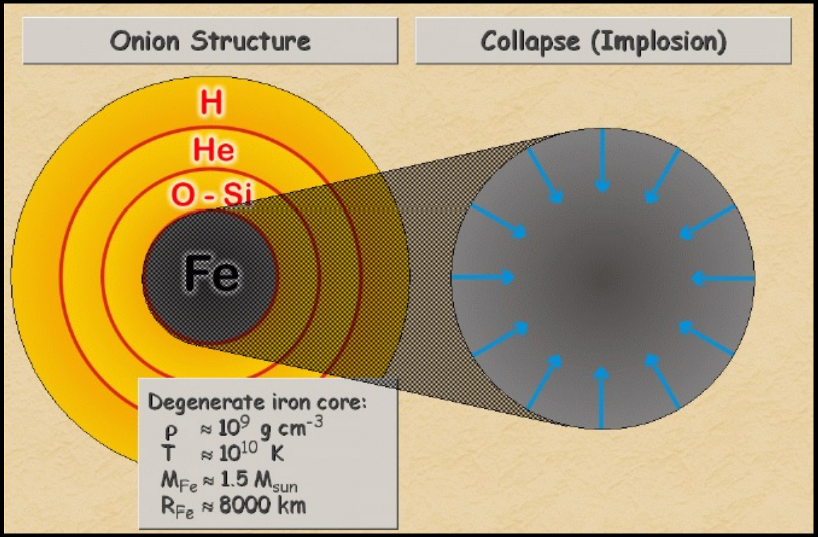
ARE WE PREPARED FOR THE OVERDUE NEARBY SUPERNOVA?

By O.-G. Richter and M. Rosa
European Southern Observatory, Garching

Supernova taxonomy



The Energy Budget of a CC-SN



>1.4 $M_\odot$ Fe Core collapses to Neutron Star R_{NS} ~ 10 Km

Gravitational binding energy:

$\Delta E_B \cong G\, M_{WD}^2 / R_{NS} - G M_{WD}^2 / R_{Fe\text{-}core} \cong 3 \times 10^{53}$ ergs

Kinetic energy of explosion ≈ 1% x ΔE_B

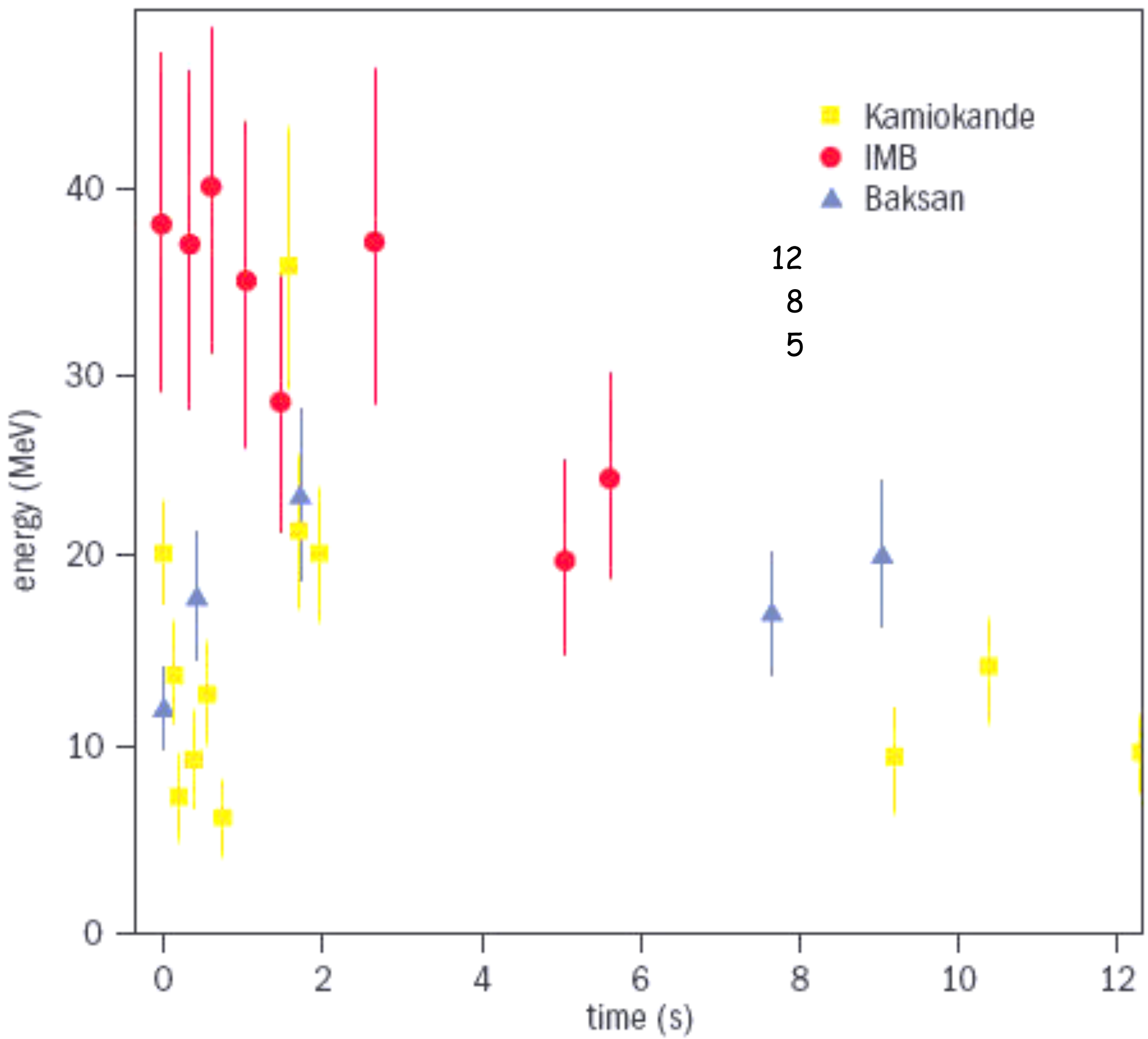
Electromagnetic radiation ≈ 0.01% x ΔE_B

Neutrinos ≈ 99% x ΔE_B

SN 1987A in the LMC

30 Dor Nebula before
SN 1987A explosion

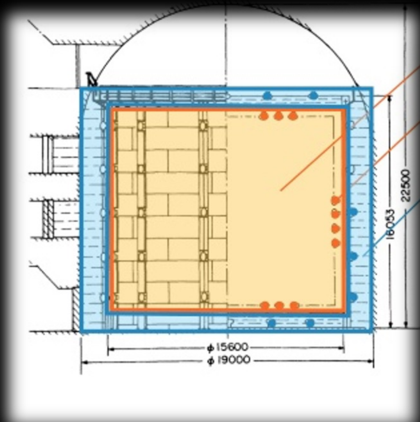
30 Dor Nebula after
SN 1987A explosion

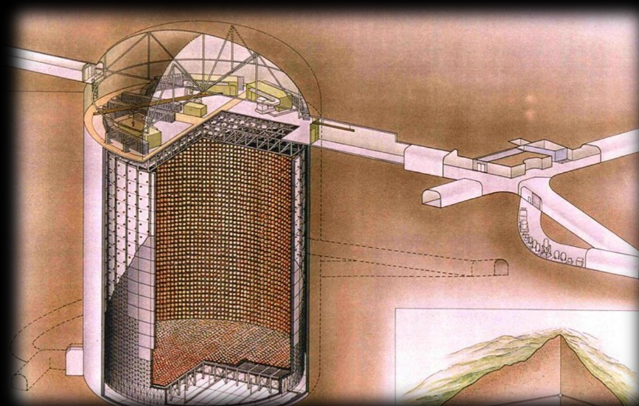


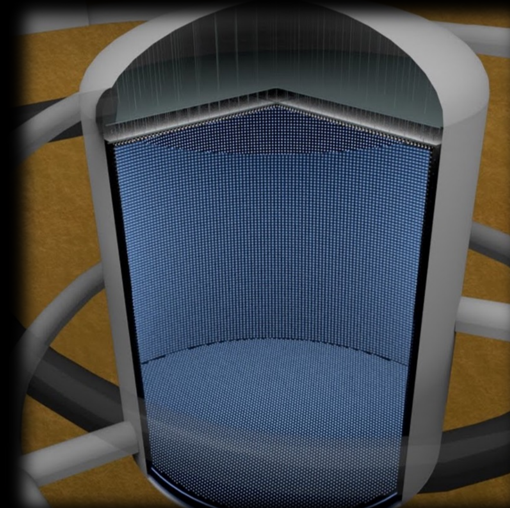
Neutrinos detection confirms that a NS is the residual of a CC SN explosion.

Kamiokande Progression

Neutrinos sensitivity







Kamiokande
1983-1996
3kton

1

Super-Kamiokande
1996-
50kton

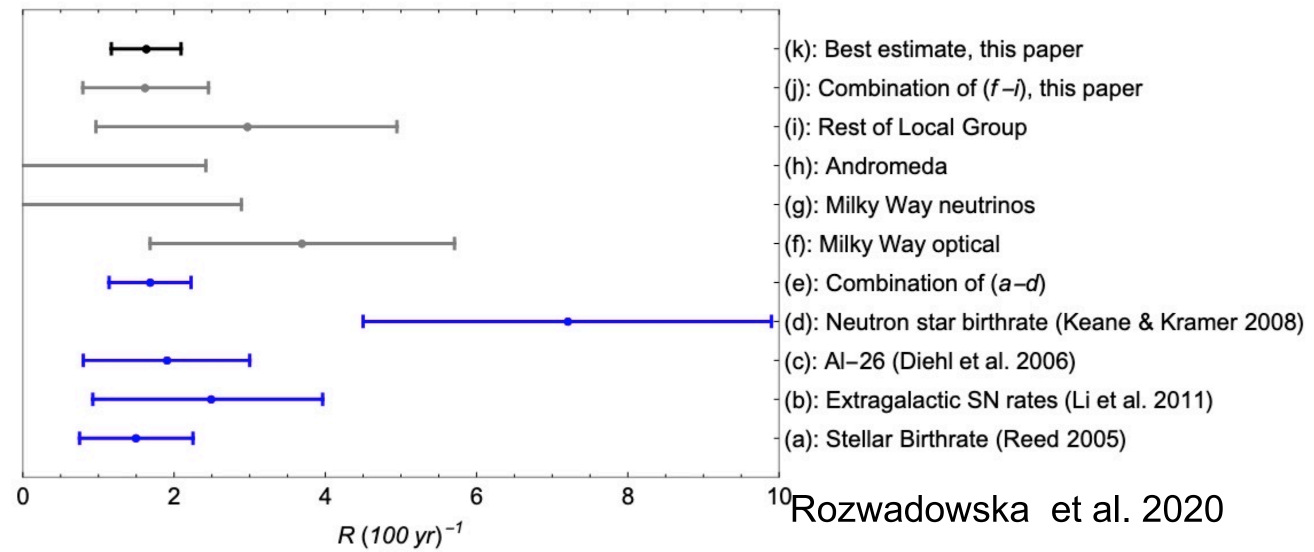
x 17

Hyper-Kamiokande
2027
0.52Mton

x 10

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 ……



Rozwadowska et al. 2020

"Bright Guest Stars"

Date (AD)	Type	m_{max}	Naked Visibility	Discovered by	Remnant
185?	I?	-8	?	Chinese	RCW86
393	?	-1	?	Chinese	
837	?	-8?	?	Chinese	IC 443
1006	I	-9	> 2yrs	Chinese/Arabs	SN 1006
1054	II	-6	~2yrs	China/Japan/ Chaco Canyon	Crab Nebula
1181	II?	+1	0.5yrs	China/Japan	3C58
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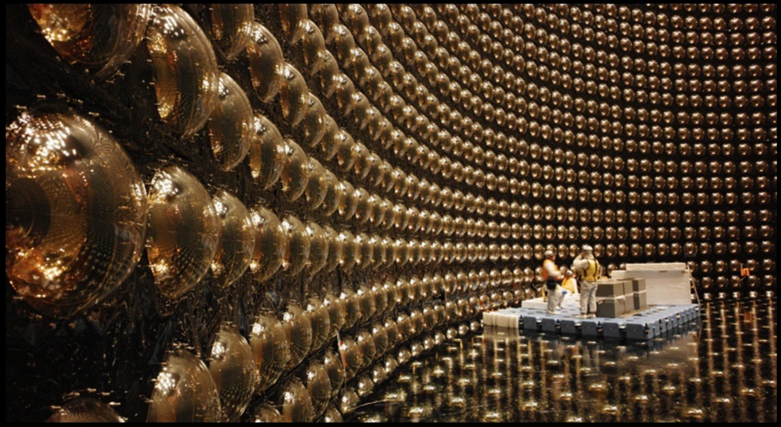
ca. 1667	II	+5?	missed	Flamsteed	Cas A
1870	I	~ +6	missed	Hartwig	M31
1987	II	+2.9	~1 yr	Ian Shelton	SN1987A

Lack of SN neutrinos detection in the last ~40 yrs



CC-SN and SN/GRB 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
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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; Cappellaro et al. 2015

ON THE RATES OF GAMMA-RAY BURSTS AND TYPE Ib/c SUPERNOVAE

DAFNE GUETTA[1] AND MASSIMO DELLA VALLE[2]

Received 2006 August 1; accepted 2006 December 5; published 2007 February 21

ABSTRACT

We measure the local rates of "low-luminosity" gamma-ray bursts (LL GRBs; i.e., $L \lesssim 10^{49}$ ergs s^{-1}) and "high-luminosity" gamma-ray bursts (HL GRBs). The values are in the range $\dot{n}_0$ = 100–1800 Gpc^{-3} yr^{-1} and $\dot{n}_0$ = 100–550 Gpc^{-3} yr^{-1}, respectively, and their ratios to Type Ibc supernovae (SNe Ibc) are ~1%–9% and 0.4%–3%, respectively. These data may suggest the existence of two physically distinct classes of GRBs in which LL GRBs are (intrinsically) more frequent events than HL GRBs. However, with the present data, we cannot exclude the possibility of a single population of GRBs that gives rise to both an isotropic low-luminous emission (LL GRBs: detectable only in nearby GRBs) and to a highly collimated high luminous emission (HL GRBs: detectable preferentially at high z). We also compute the rate of SNe Ibc characterized by broad-lined spectra (hypernovae [HNe]) and find it to be about 1.5×10^{-4} yr^{-1} per 10^{10} $L_{B,\odot}$ (i.e., less than 10% of SNe Ibc occurring in spiral galaxies). This result implies that the ratio of HL GRBs to HNe is smaller than 1, possibly in the range of 0.04–0.3. We have used the ratio between HNe and LL GRBs to constrain their beaming factor to $f_b^{-1} \sim 10$ or less.

Guetta & Della Valle 2007

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)	$0.048^{+0.006}_{-0.005}(^{+0.010}_{-0.010})$	$0.006^{+0.004}_{-0.003}(^{+0.002}_{-0.002})$	$0.003^{+0.002}_{-0.001}(^{+0.001}_{-0.001})$
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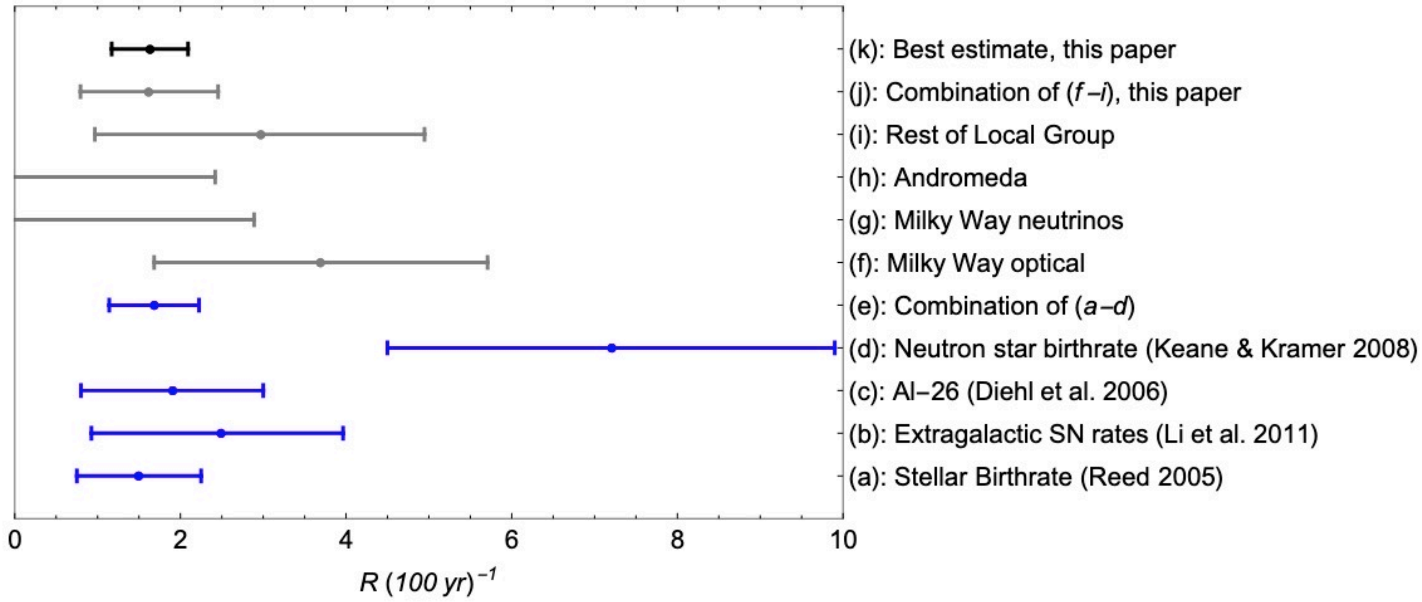
Vol-rate (10^{-4} SN Mpc^{-3} yr^{-1})	$0.301^{+0.038}_{-0.037}(^{+0.049}_{-0.049})$	$0.258^{+0.044}_{-0.042}(^{+0.058}_{-0.058})$	$0.447^{+0.068}_{-0.068}(^{+0.131}_{-0.111})$

Lick Survey Li et al. 2011

28

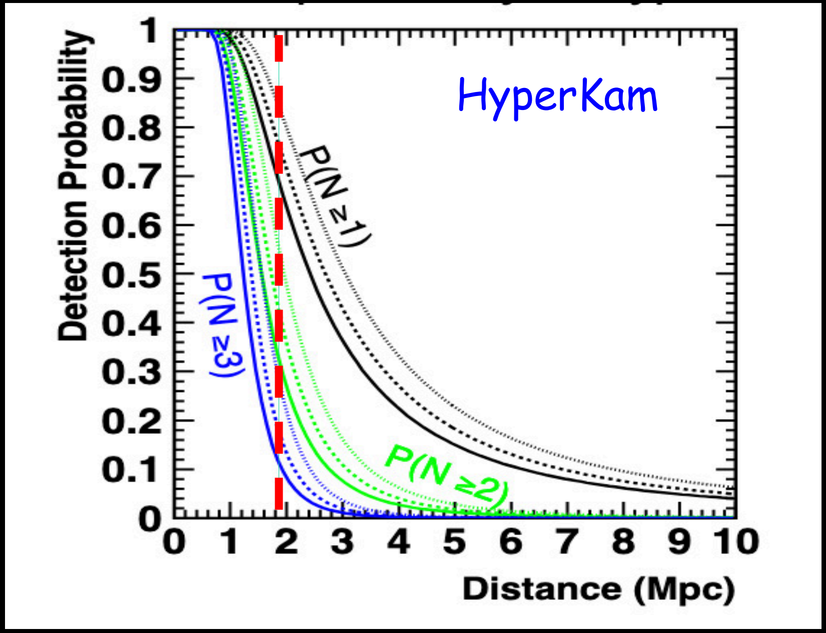


Rozwadowska et al. 2020

$$R_{\mathrm{full}} = 1.63 \pm 0.46\ (100\ \mathrm{yr})^{-1}$$

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 ~ 60 years



Within ~ LG of galaxies
~ 1 neutrino per SN
about 1 SN ~ 30 years

The CC-SN frequency of occurrence in the LG of galaxies is miserable….

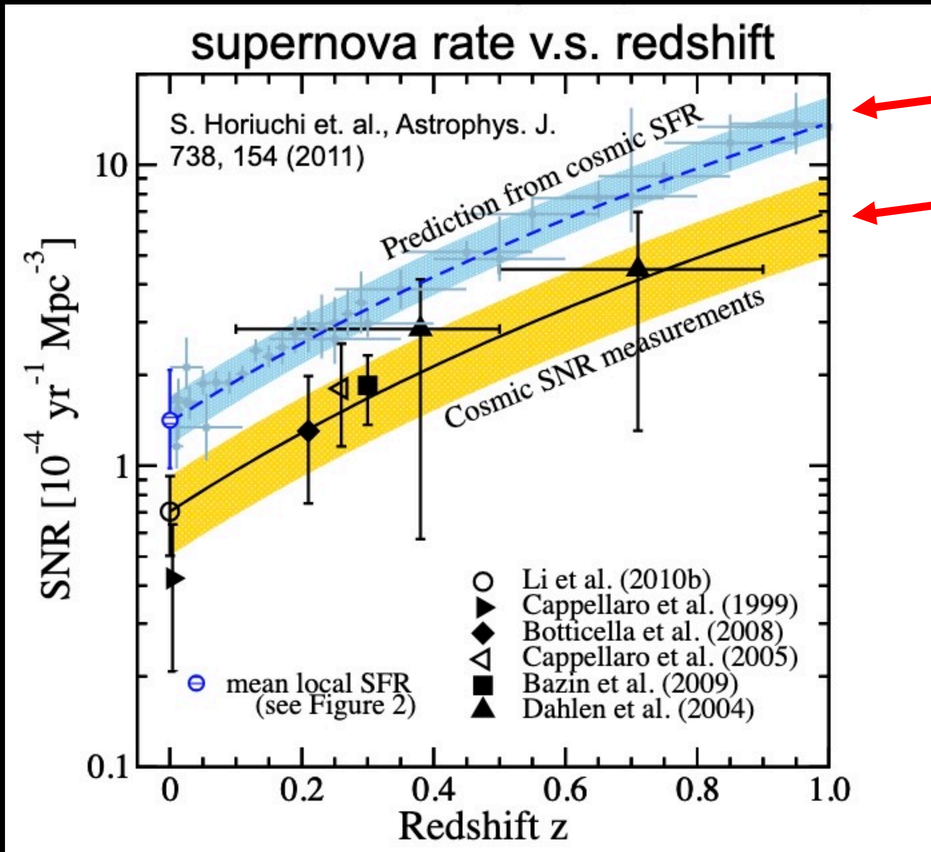
"Never underestimate desperate people. You never know how far they will go to get what they want"

(anonymous)

CC-SNe ~ Gpc: ~ 0.76 x 10^{-4} Mpc^{-3} yr^{-1} ~ 10^{5} SNe/yr

→ « 1 neutrino/yr

→ diffuse neutrino background



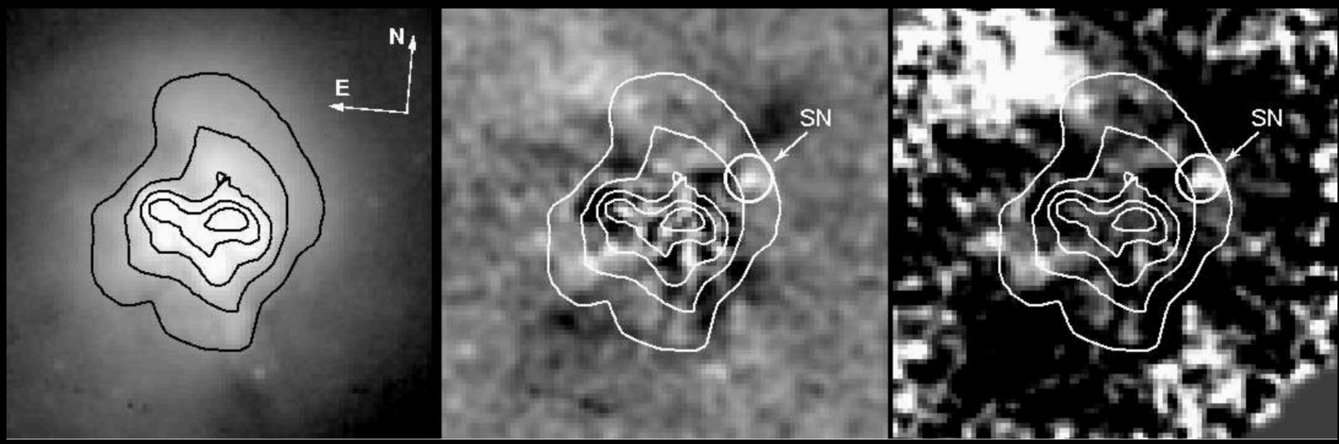
core-collapse rate

observed supernova rate is a factor ~2 smaller than the expected one

dust ? the observed near-infrared rate is still a factor 3-10 smaller than that estimated from the far-infrared luminosity of the galaxies. Among various possibilities, the most likely scenario is that dust extinction is so high (AV>30) to obscure most SNe even in the near-IR

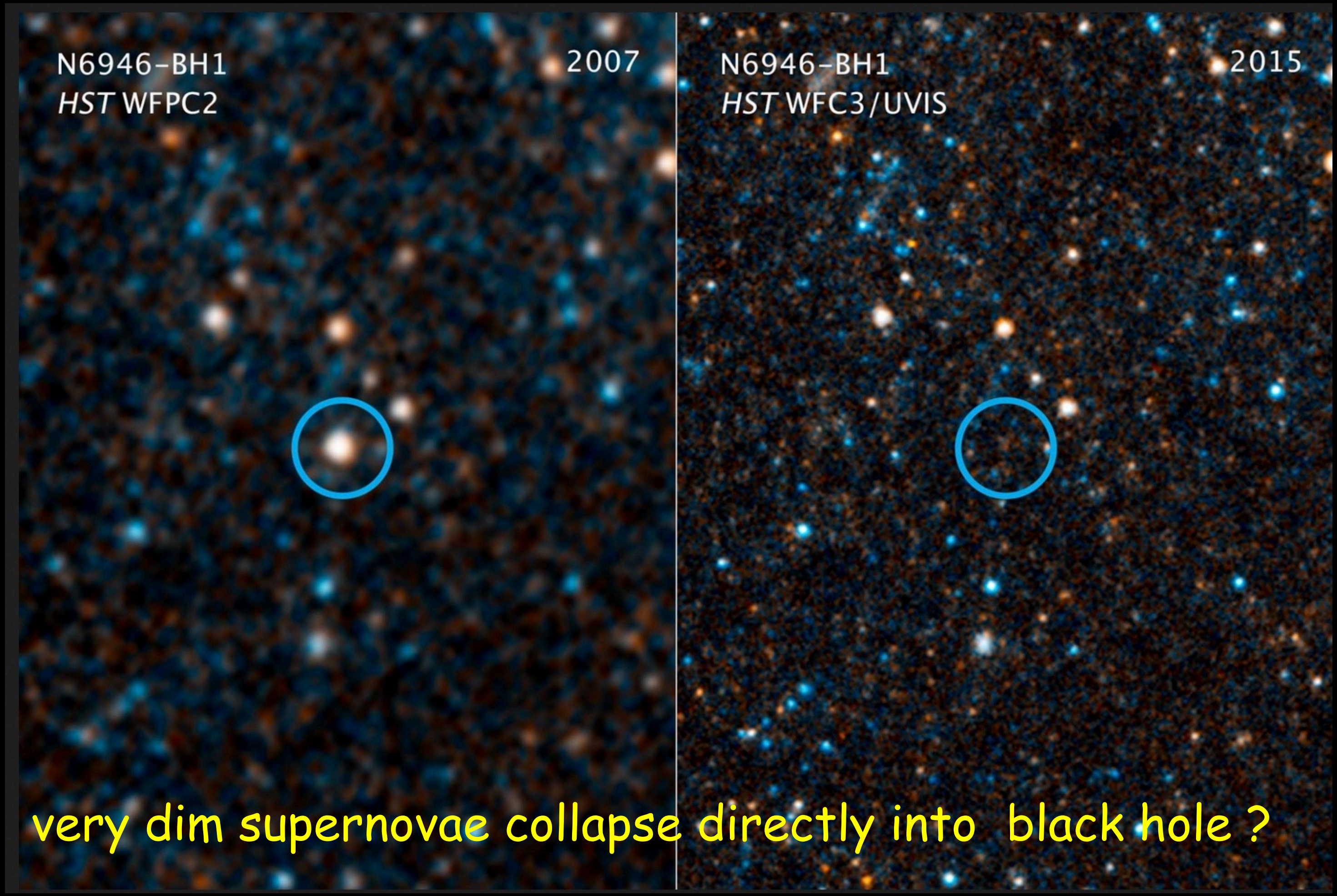
(Mannucci, DV and Panagia 2007)

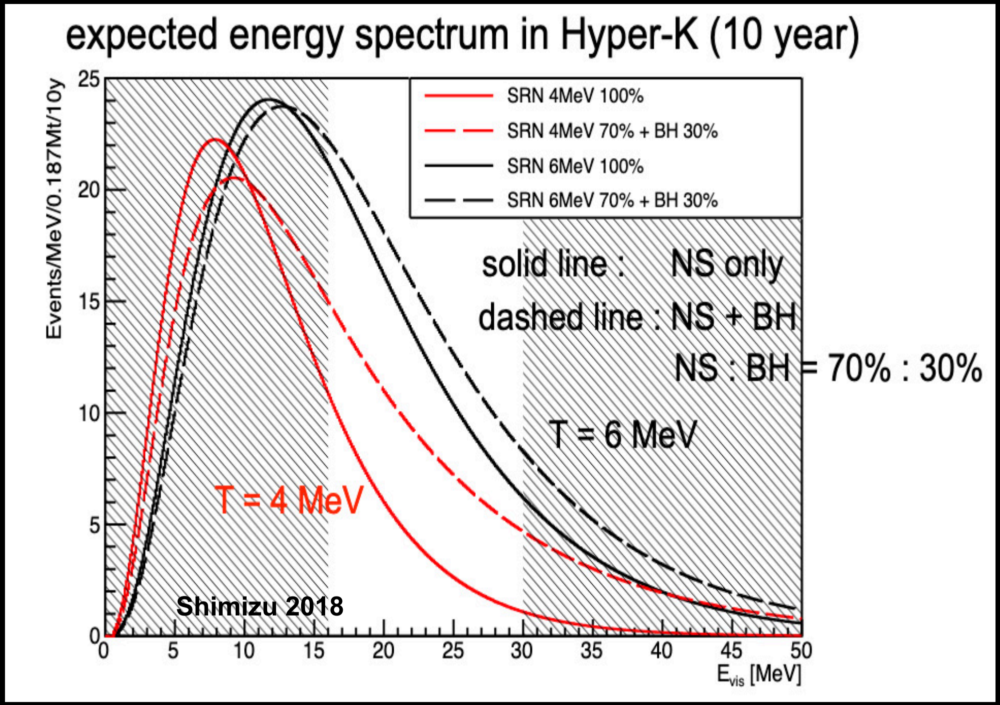
Cresci et al. 2007

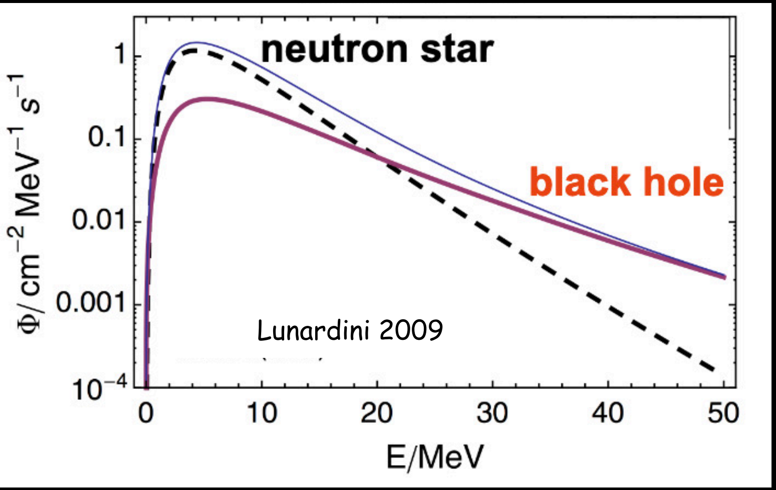


The Search for Failed Supernovae with The Large Binocular Telescope: First Candidates

J. R. Gerke[1], C. S. Kochanek[1,2], K. Z. Stanek[1,2]







Diffuse neutrinos flux from stellar collapses with direct black hole formation (failed supernovae) is more energetic than that from successful supernovae. Thus it might contribute substantially to the total diffuse flux above realistic detection thresholds energy.

Relativistic Jets in Core-collapse Supernovae

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[1] Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel
[2] Raymond and Beverly Sackler School of Physics & Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
[3] Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool L3 5RF, UK
[4] Max-Planck-Institut fur Astrophysik, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany
[5] INAF, Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna, I-40129 Bologna, Italy
[6] Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy
Received 2018 December 20; revised 2019 January 7; accepted 2019 January 17; published 2019 January 28

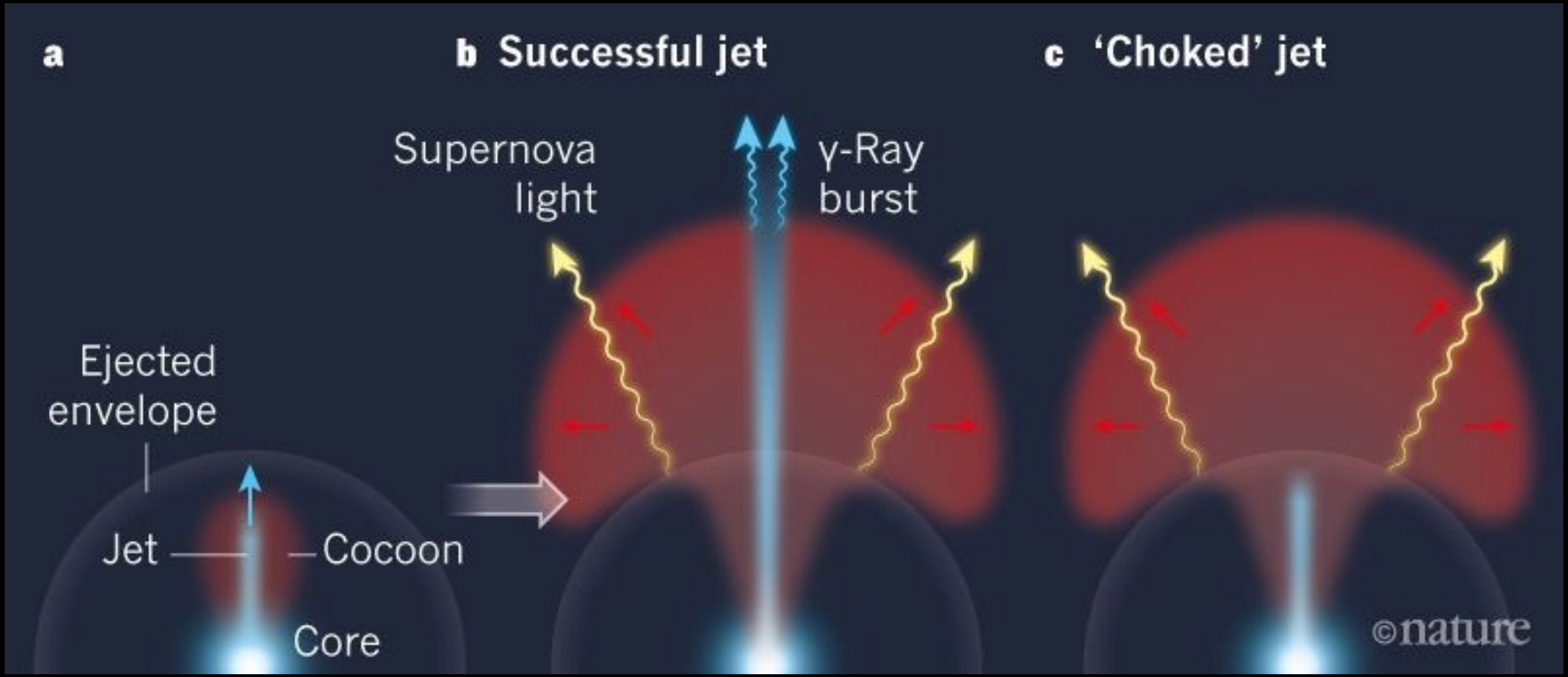
Table 1
Properties of the SNe Discussed Here

SN	Type	$E_{\rm tot}$ [a]	$M_{\rm ej}$ [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	$\gtrsim 2$	⋯	⋯	llGRB980425
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. Most times the gamma-ray bursts transfer so much of their own energy to cocoons that there's not enough left for the GRB to break through (see Nakar & Piran 2017)

Cocoon signatures

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

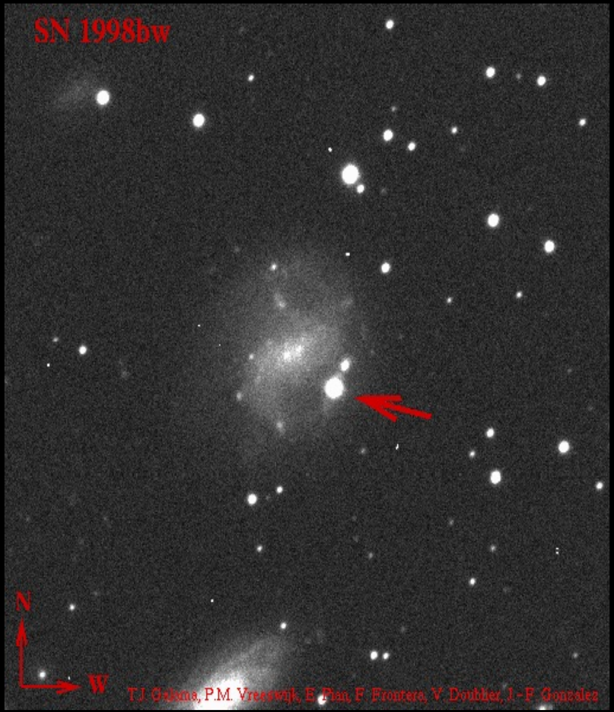


(Nakar & Piran 2018, Nakar 2019)

GRB SNe vs. Hypernovae

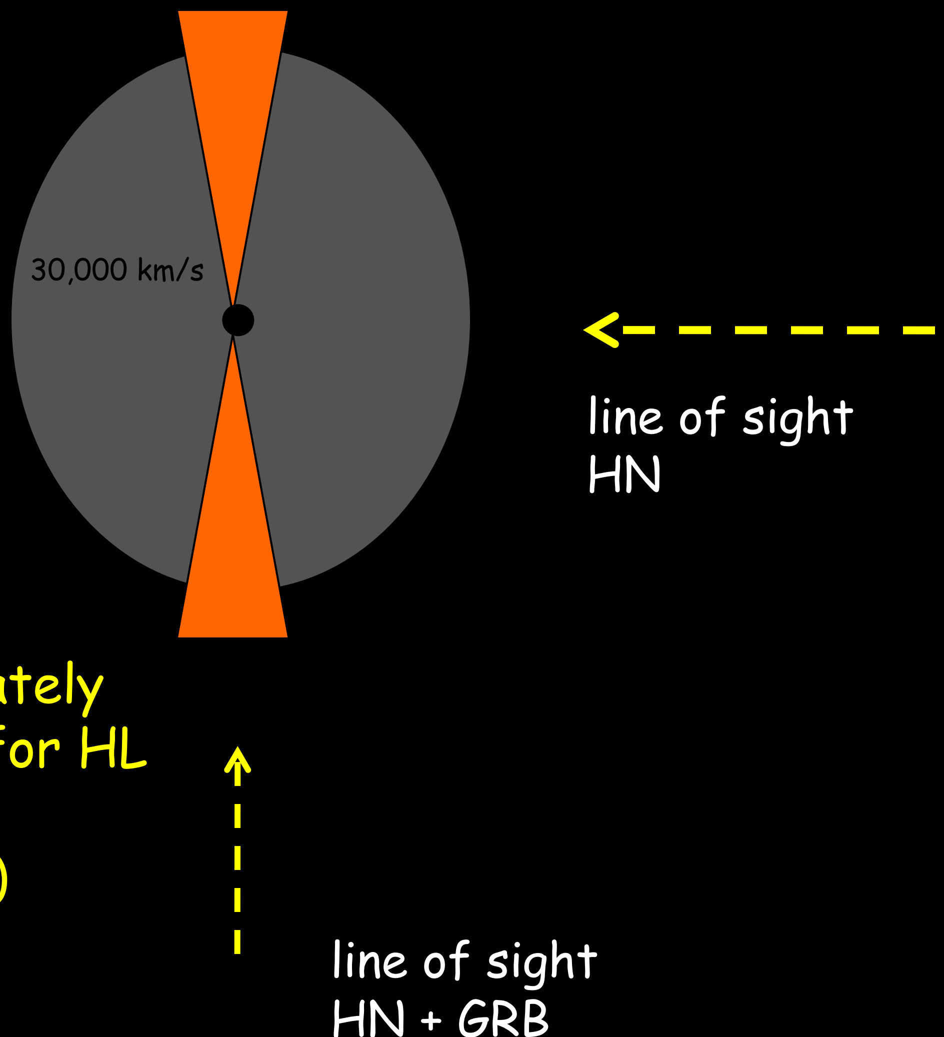
GRB/SNe-Ibc: < 1.5%

HNe/SNe-Ibc: ~ 7%



A simplified (and possibly wrong) 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}

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, $\theta_j \gtrsim 0\overset{\circ}{.}8$. (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 GRB at the 84% confidence level”

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

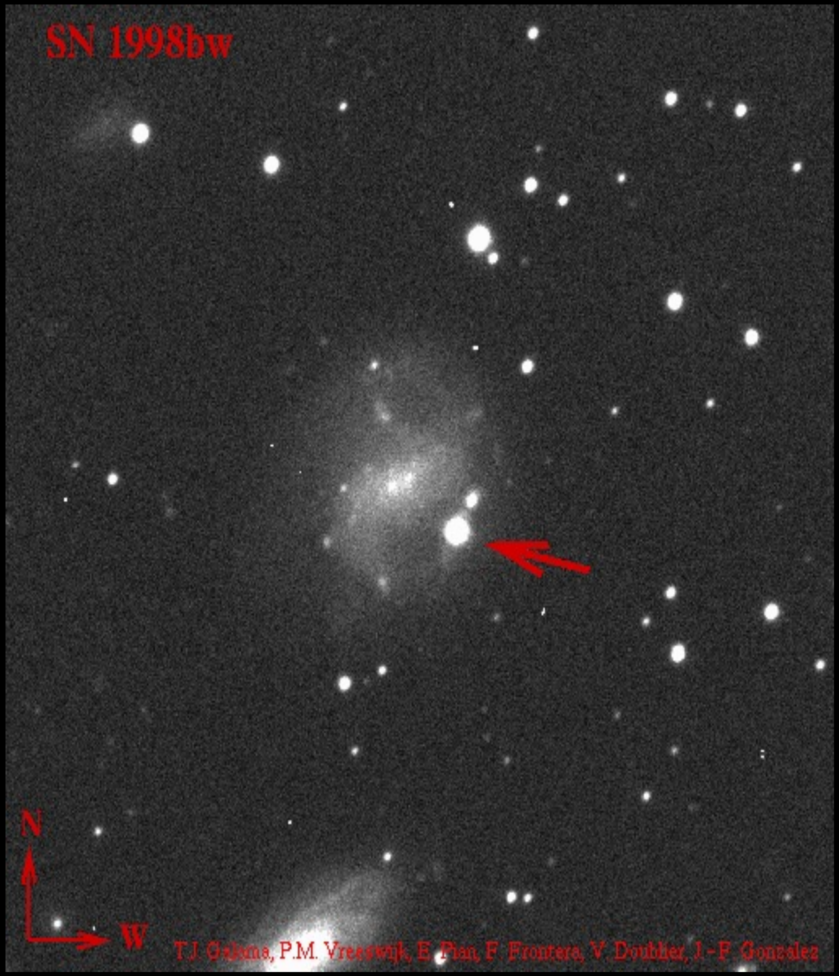
MNRAS **440**, 821–832 (2014) doi:10.1093/mnras/stu246
Advance Access publication 2014 March 14

Radio limits on off-axis GRB afterglows and VLBI observations of SN 2003gk

M. F. Bietenholz,[1,2★] F. De Colle,[3] J. Granot,[4] N. Bartel[2] and A. M. Soderberg[5]

Confirmed by Bietenholz et al. 2014

SN 1998bw



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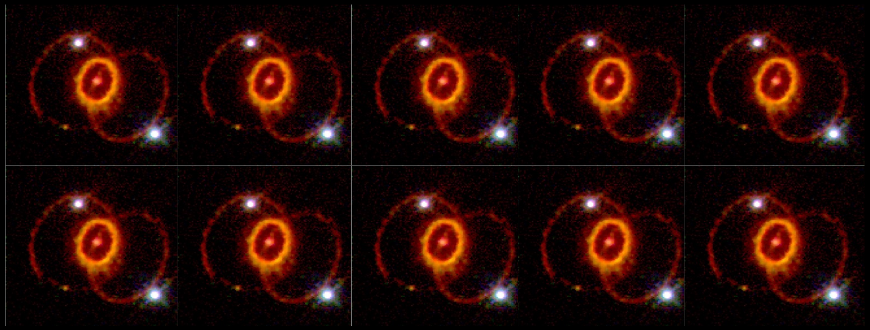
SN 1987A



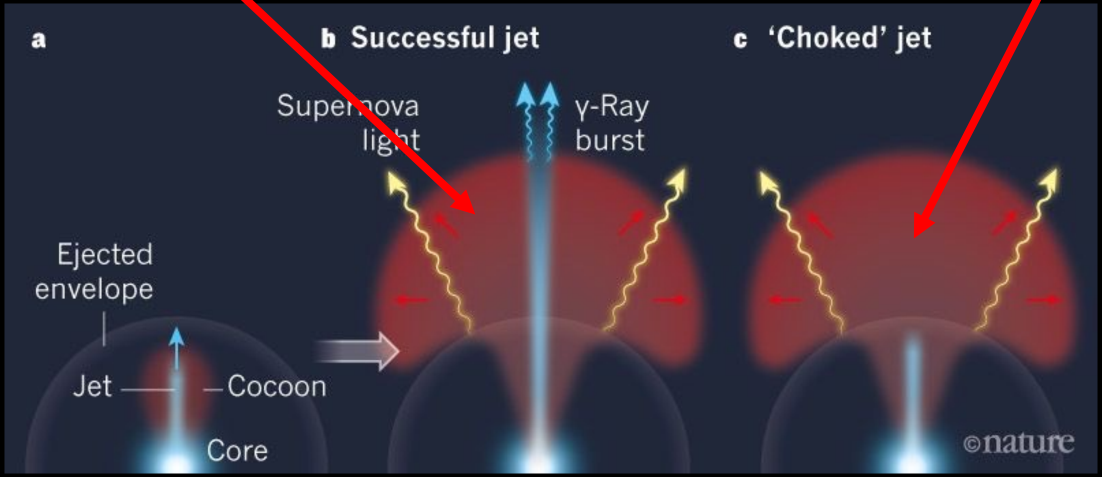
$E_K \sim 30 \times 10^{51}$ erg

$E_K \sim 1 \times 10^{51}$ erg

A simplified (and possibly fair) scheme for a GRB-SN event

HN+GRB/SNe-Ibc: < or << 1.5%

HNe/SNe-Ibc: ~ 7%



All HNe produce a GRB, most times the gamma-ray bursts transfer so much of their own energy to the stellar layers so there's not enough left for the GRB to break through -- > "choked jet" (see Nakar and Piran 2017)

Letter | Published: 16 January 2019

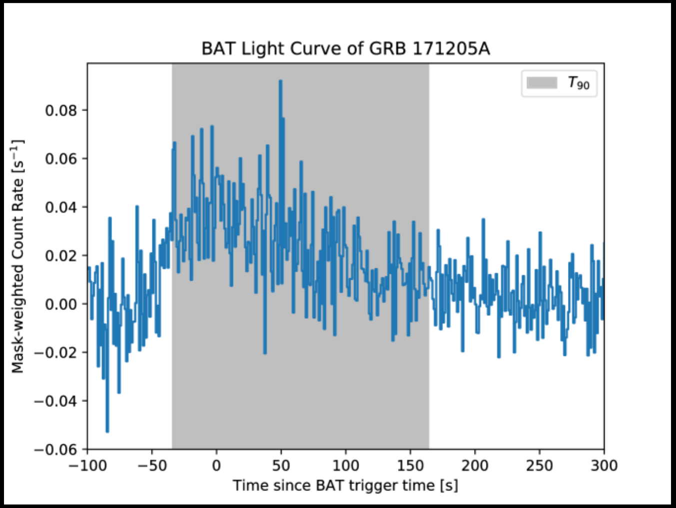
Signatures of a jet cocoon in early spectra of a supernova associated with a γ-ray burst

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

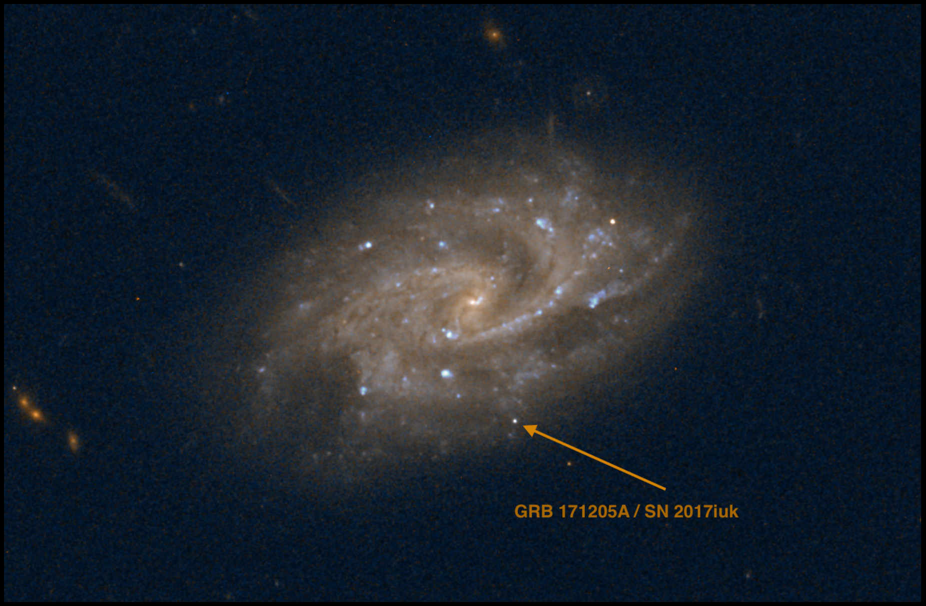
i) third closest GRB-SN z = 0.0368 (160 Mpc)
ii) low-luminous GRB $E_{iso} \sim 10^{49}$ erg
iii) grand-design spiral host galaxy

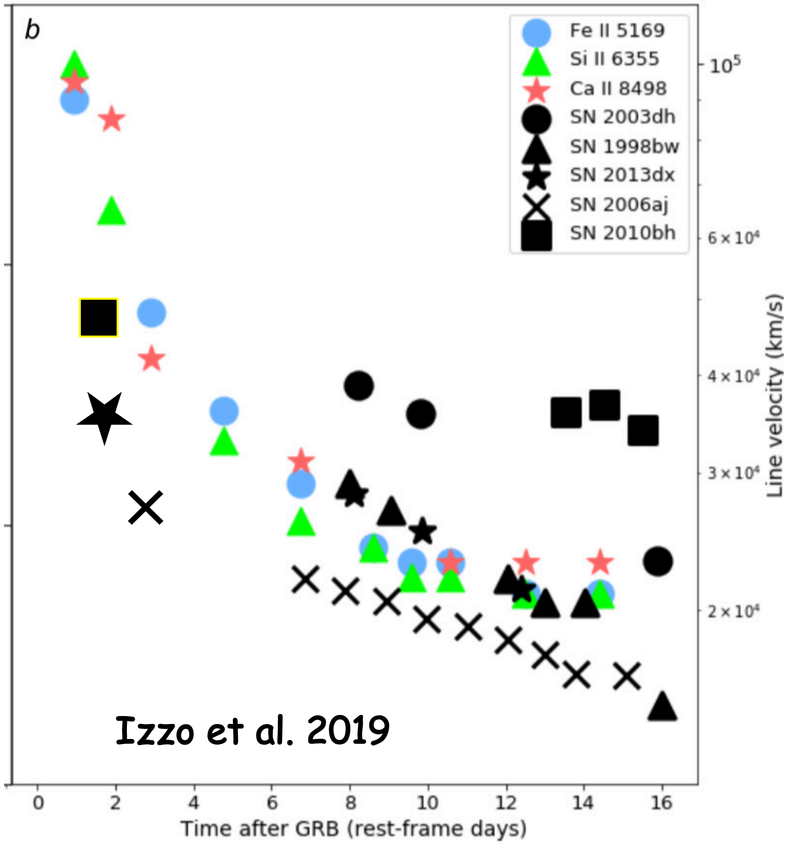


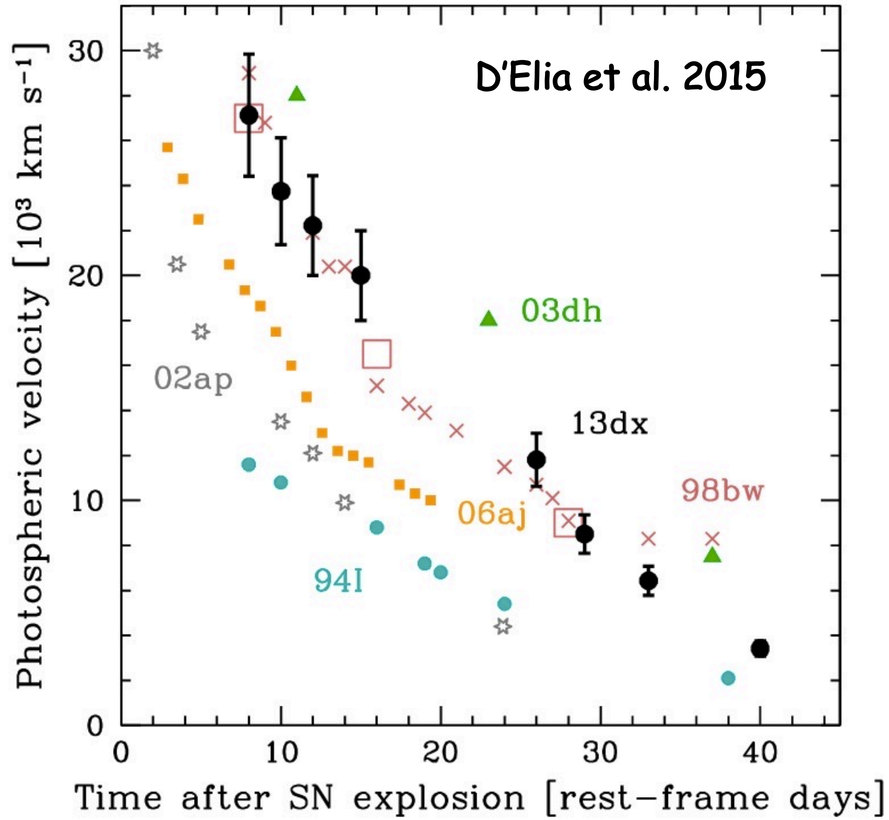
multi-wavelength photometric & spectroscopic campaign

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

Izzo et al. Nature, 2019







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

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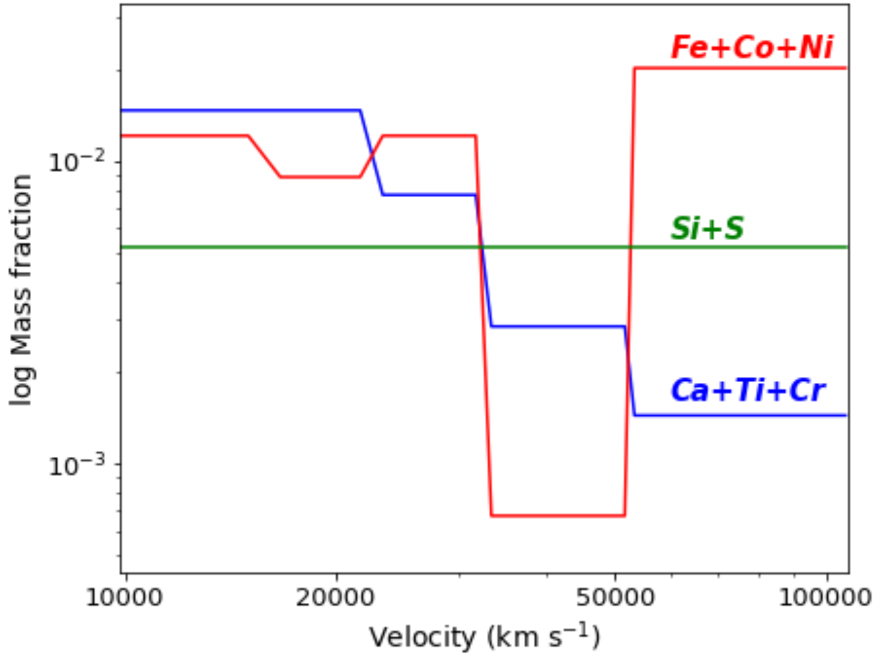
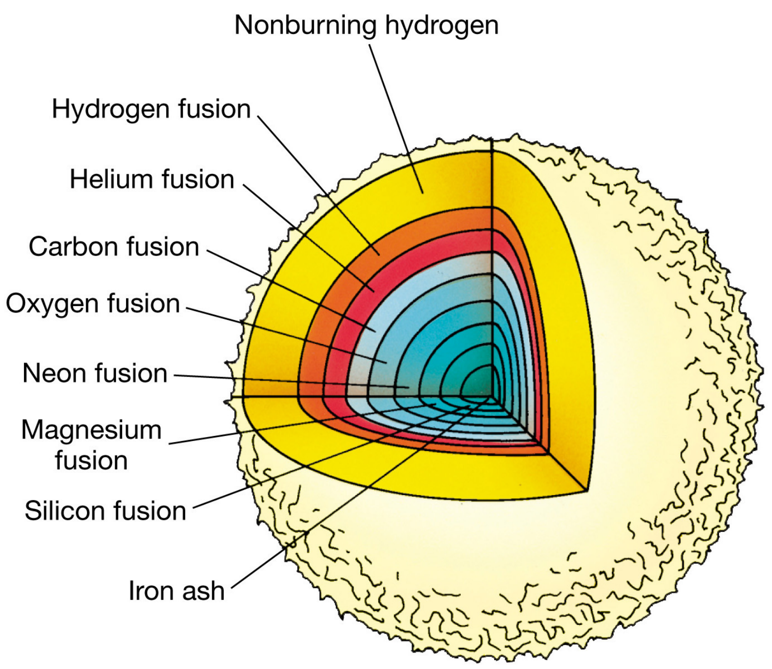


Chemical composition of the high velocity (10^5 km/s) components are characterized by chemical abundances different from those observed in the SN ejecta ($\times 10^4$ km/s)

Interpreting spectra: position of elements

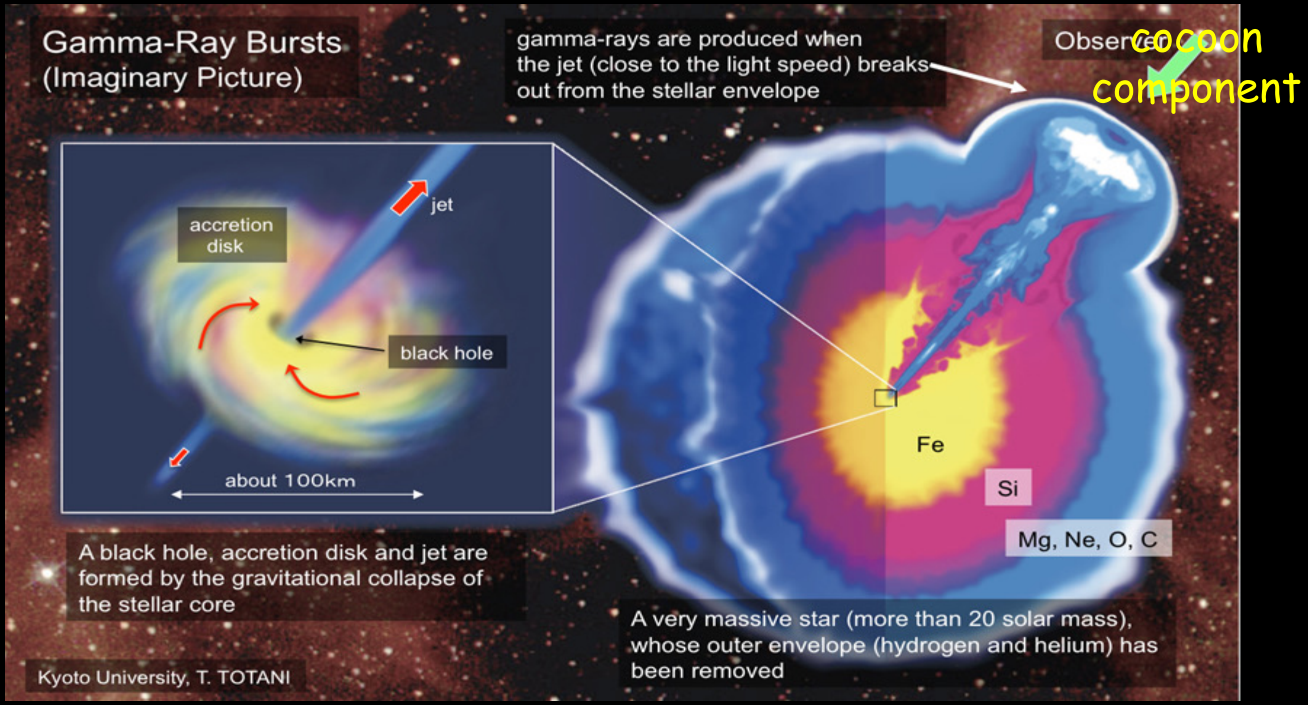
Immediately after explosion SNe go into homologous expansion → v ~ r



Relative positions of elements do not change

"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)



Is this mechanism at play for all CC-SNe?

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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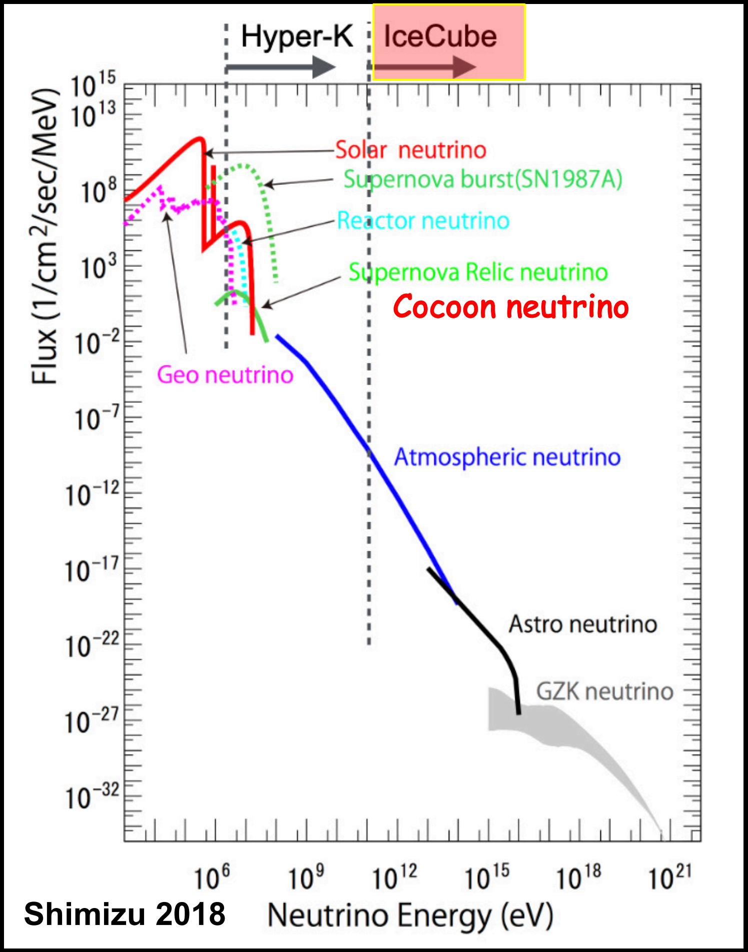
[4] *Capodimonte Observatory, INAF-Naples , Salita Moiariello 16, 80131-Naples, Italy*
[5] *European Southern Observatory, Karl-Schwarzschild-Strae 2, D-85748 Garching bei Mnchen, Germany*

$$p\gamma \rightarrow p\pi^0, n\pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

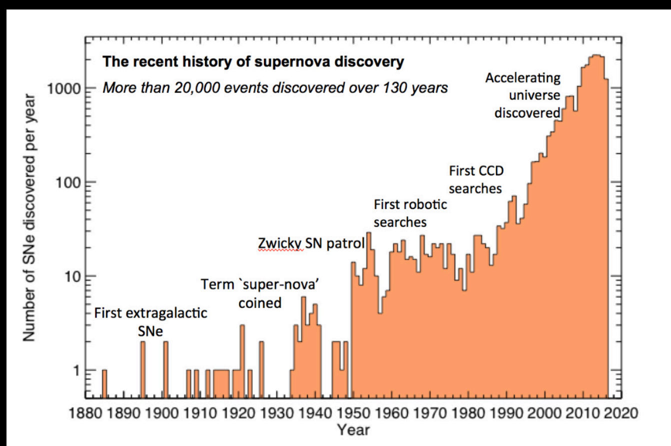
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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



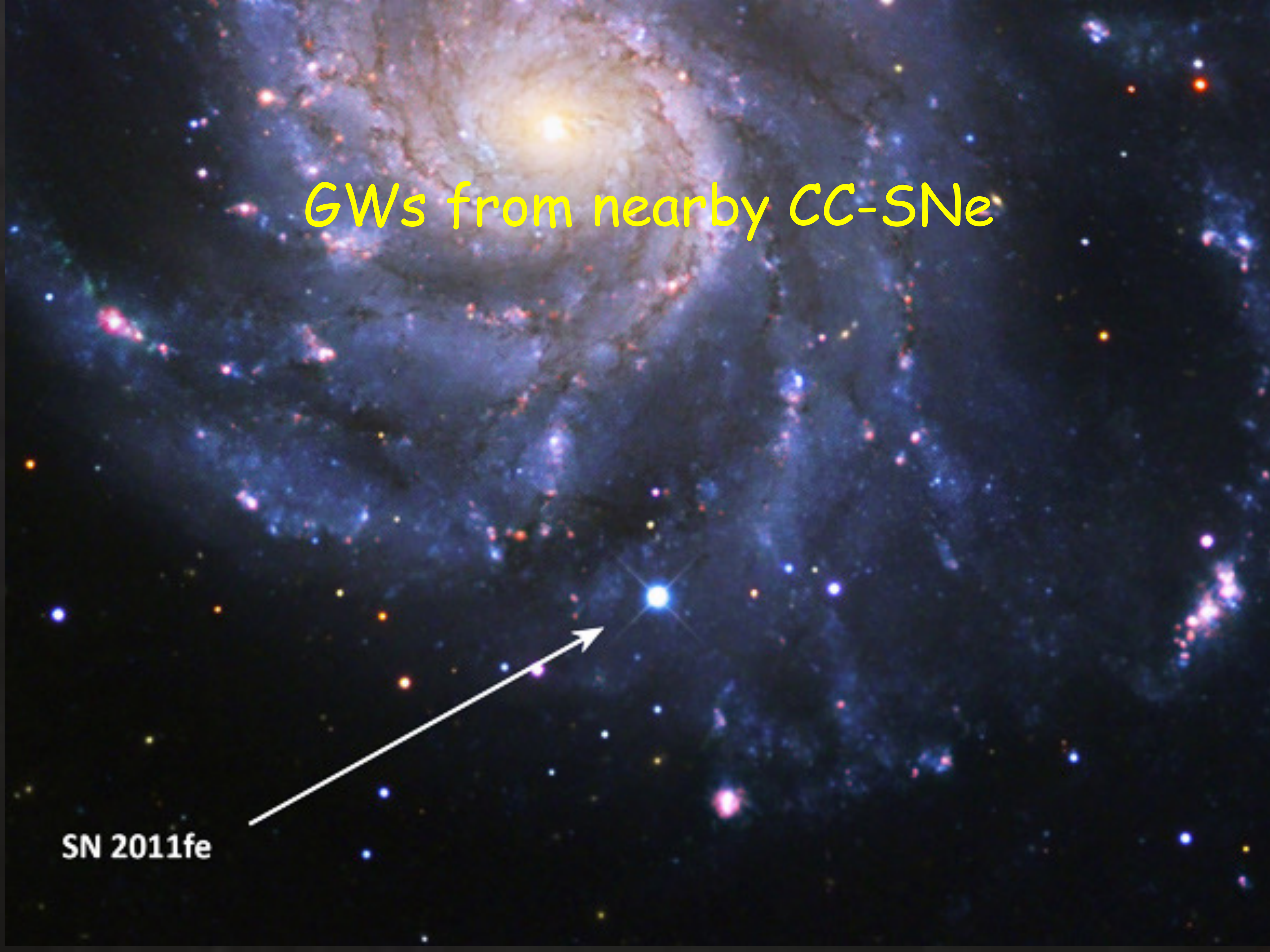
	ZTF	LSST
CCSN	40	10^5
SN-Ibc	200	6×10^5
Hypernova	2×10^4	2×10^7

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



The empirical confirmation of the chocked model requires a number of CC-SNe that can be achieved within a very few years by either ZTF or LSST if all CC-SNe (or a significant fraction of them) produce jets. It can take several years of even decades (in the worst case) if the ciocked jet scenario apply only to a small fraction of CC-SNe, such as SN-Ibc, BLs or HNe.

GWs from nearby CC-SNe



Core-Collapse SNe

SNe-II

Progenitor Mass ~ 8-20 $M_{\odot}$
Remnant → NS (1.5 $M_{\odot}$)
Radiated Energy ~ $10^{47/49}$ erg
Kinetic Energy ~ 10^{51} erg
rate ~ 0.48 x 10^{-4} Mpc^{-3} yr^{-1}

~ NS

SNe-Ibc/HNe

Progenitor Mass ~ 30-50 $M_{\odot}$
Remnant: NS or BH (3$M_{\odot}$)
Radiated Energy ~ $10^{47}/^{49}$ erg
Kinetic Energy ~ 10^{51} erg
rate ~ 0.26 x 10^{-4} Mpc^{-3} yr^{-1}
rate ~ 1.82 x 10^{-6} Mpc^{-3} yr^{-1}

~ BH

CC-SNe might have the needed ingredients for an output in gravitational radiation

i) E_ν evidences the formation of high density remnant (i.e. BHs or NSs)
ii) High angular momentum of the remnant
iii) Formation of an accretion disk around the remnant
iv) In some cases the mass/motion takes place on the Schwarzschild scale (e.g., the Innermost Stable Circular Orbit (ISCO) around a newly formed black hole

The quadrupole formula predicts (see 2019) an appreciable luminosity for standard values of non-axisymmetric mass inhomogeneities δm about a central mass $M \approx 3\ M_\odot$, $\xi = \delta m / M_D = 0.1$ as a mass perturbation in a torus or inner disk of mass $M_D \approx 0.03\ M$

$$h = 3.4 \times 10^{-23}\, M \left(\frac{\xi}{0.1}\right) \left(\frac{\sigma}{0.01}\right) \left(\frac{D}{20\,\mathrm{Mpc}}\right)^{-1} \left(\frac{f_{gw}}{600\,\mathrm{Hz}}\right)^{\frac{2}{3}}$$

CC-SNe (particularly Ibc/HNe) might have the needed ingredients for an output in gravitational radiation

i) E
re
ii) H
iii) F
re
iv) T
S

Springer Link

Review | Published: 28 October 2019

Prospects for multi-messenger extended emission from core-collapse supernovae in the Local Universe

Maurice H. P. M. van Putten, Amir Levinson, Filippo Frontera, Cristiano Guidorzi, Lorenzo Amati & Massimo Della Valle

The European Physical Journal Plus **134**, Article number: 537 (2019) | Cite this article

The quadrupole formula predicts (see 2019) an appreciable luminosity for standard values of non-axisymmetric mass inhomogeneities δm about a central mass $M \approx 3\ M_{\odot}$, $\xi = \delta m/M_D = 0.1$ as a mass perturbation in a torus or inner disk of mass $M_D \approx 0.01\ M$

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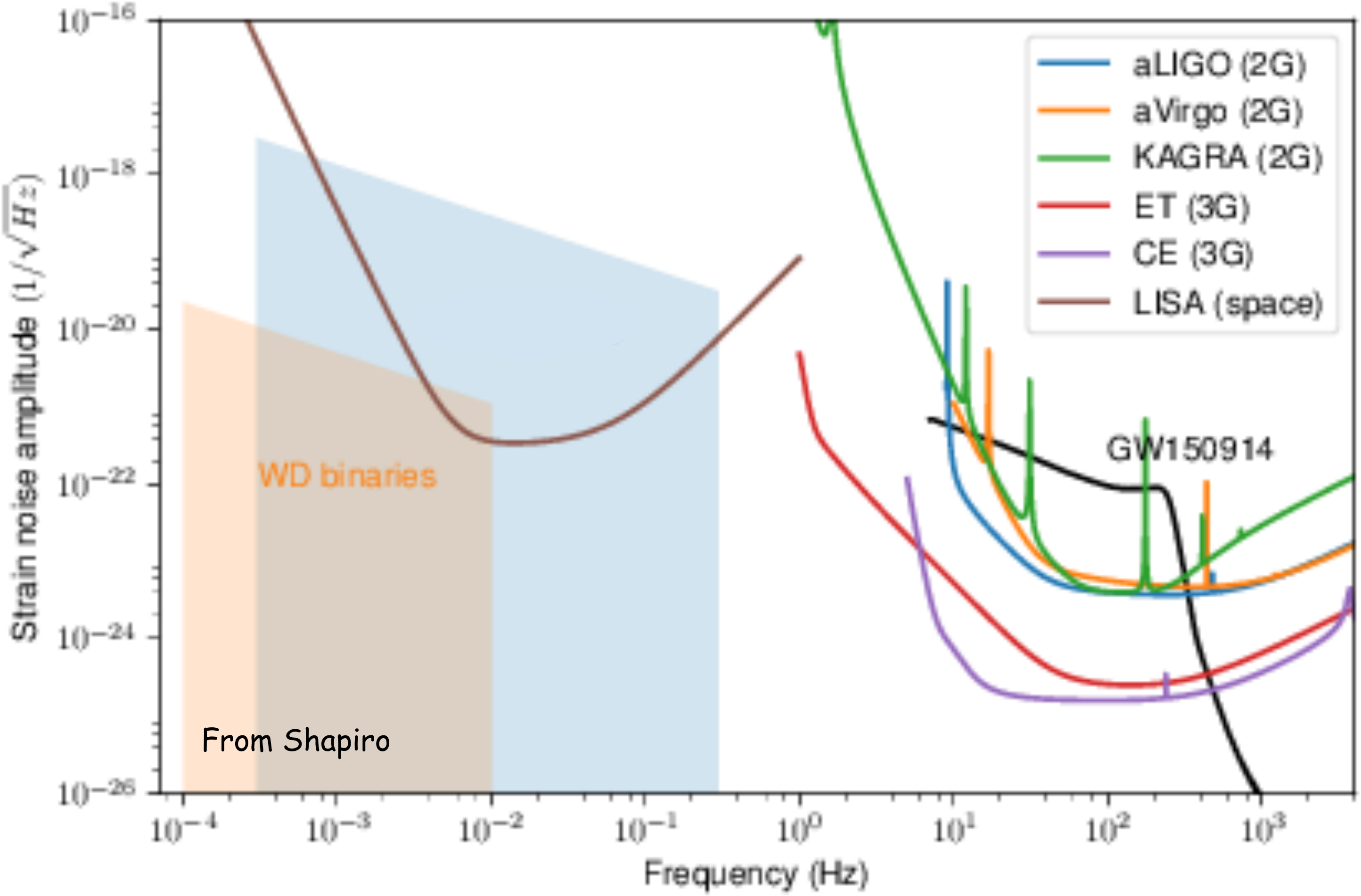


aLIGO (2G)
aVirgo (2G)
KAGRA (2G)
ET (3G)
CE (3G)
LISA (space)
GW150914
WD binaries
From Shapiro
Strain noise amplitude $(1/\sqrt{Hz})$
Frequency (Hz)
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

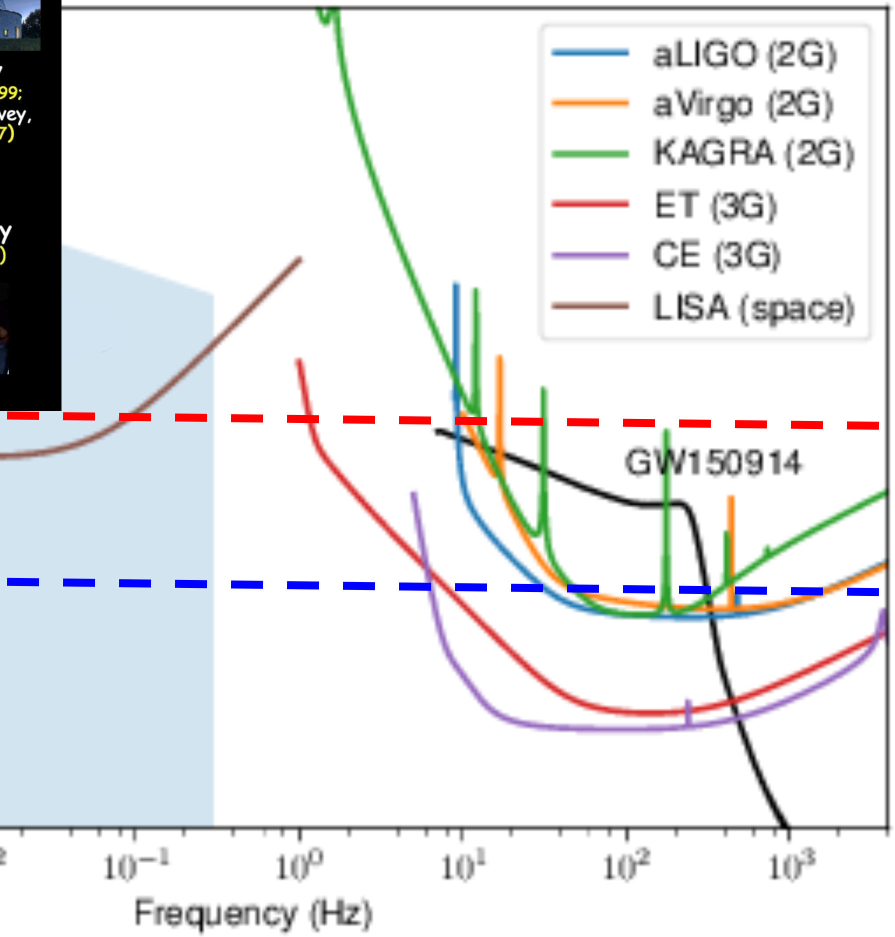
SN rates in the Local Universe

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)



~ 1 CC-SN / 60 yr in the MW

Rozwadowska, Vissani & Cappellaro 2020

~ 1 CC-SN yr^{-1} within the "Virgo Circle" (17 Mpc)

~ 0.6 SNe-II; 0.3 SNe-Ibc; 0.1 HNe yr^{-1}

SNe-Ibc within Virgo circle (D=17 Mpc)

Within Virgo Circle in the lat 10 years, we have observed:

4 SNe-II (2013gc, 2016gkg, 2019el, 2021sjt)
4 SNe-Ibc (2017ein, 2019ehk, 2019yvr, 2022fzy)
2 SNe-BL (2016coi, 2022xxf)

Conclusions

Neutrinos and GWs Observatories have the capability to detect CC SN explosions inside the Milky Way. The obvious drawback is represented by the low rate of events (~2 per century or so)

The analysis of the diffuse neutrinos background has the ability to disentangle the two scenarios: *dust vs. failed SNe*

Recent observations of ciocked jets, associated with GRBs appear a realistic possibility for neutrinos detections from SN events. Given the current estimates of SN rates, the required number of CC-SN detections **for a 3σ detection above the neutrinos background.** can be achieved on a time-frame of a few years by either ZTF or LSST if all CC-SNe (or a significant fraction of them) produce jets. Decades in the worse case (only BLs SNe do it).

Conclusions

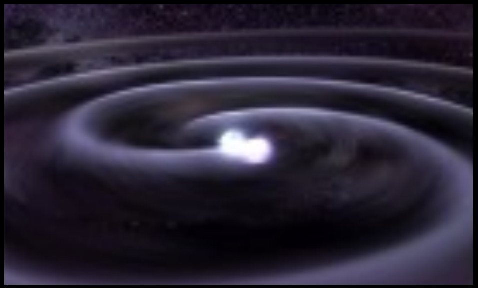
Present interferometers have the capability to detect GWs emission from CC-SNe in the MW. The obvious problem is represented by the low rate of events (~2 per century or so).

Future facilties (ET and CE) will detect GW emission from SNe occurring in the Virgo Cluster within the time-frame of 1-3 years up to about 10 yrs (only BLs).

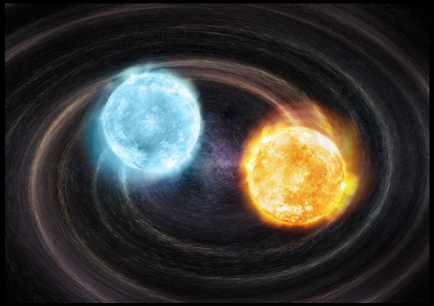
SNe-Ia

Progenitor Mass 3-7 $M_\odot$
Mass after merging ≈ 1.4 $M_\odot$
Remnant → none
Radiated Energy ~ $10^{47/49}$ erg
Kinetic Energy ~ 10^{51} erg
rate ~ 0.30 x 10^{-4} Mpc^{-3} yr^{-1}

~ 10km



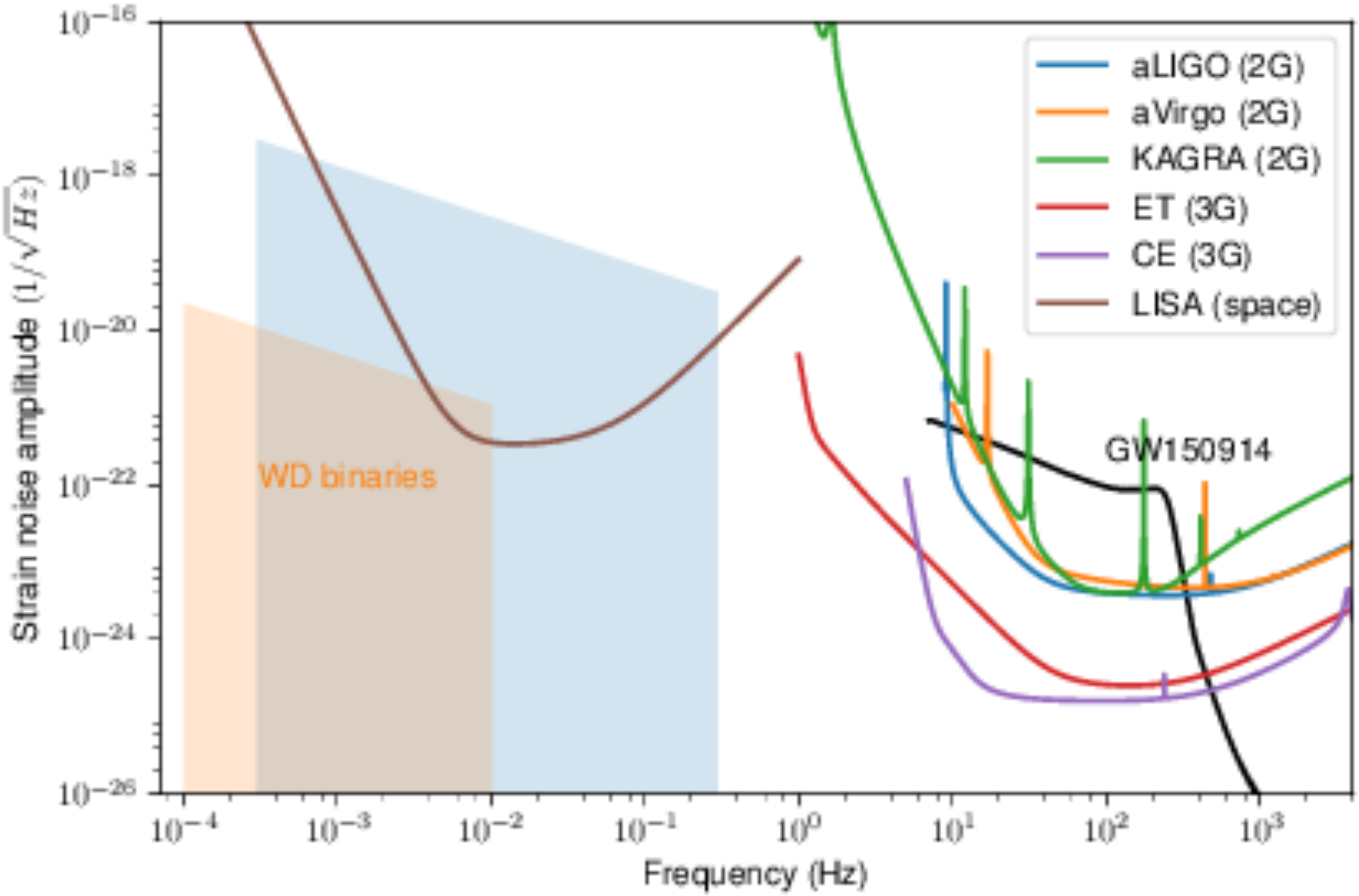
~ 10,000km



$$h = 6.3 \times 10^{-23} \left(\frac{M}{3M_\odot}\right)^{\frac{5}{3}} \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \left(\frac{f_{gw}}{1000\,\mathrm{Hz}}\right)^{\frac{2}{3}}$$

van Putten et al. 2019

Comparable final mass, size of the sysyems are different: 10,000km vs 10km, which is 1000 times wider → Kepler frequency ~ $(1/\text{separation})^{3/2}$ → the frequency lower by a factor ~ 1000 Hz/30,000 ≈ 0.03 Hz



aLIGO (2G)
aVirgo (2G)
KAGRA (2G)
ET (3G)
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LISA (space)
GW150914
WD binaries
Strain noise amplitude $(1/\sqrt{Hz})$
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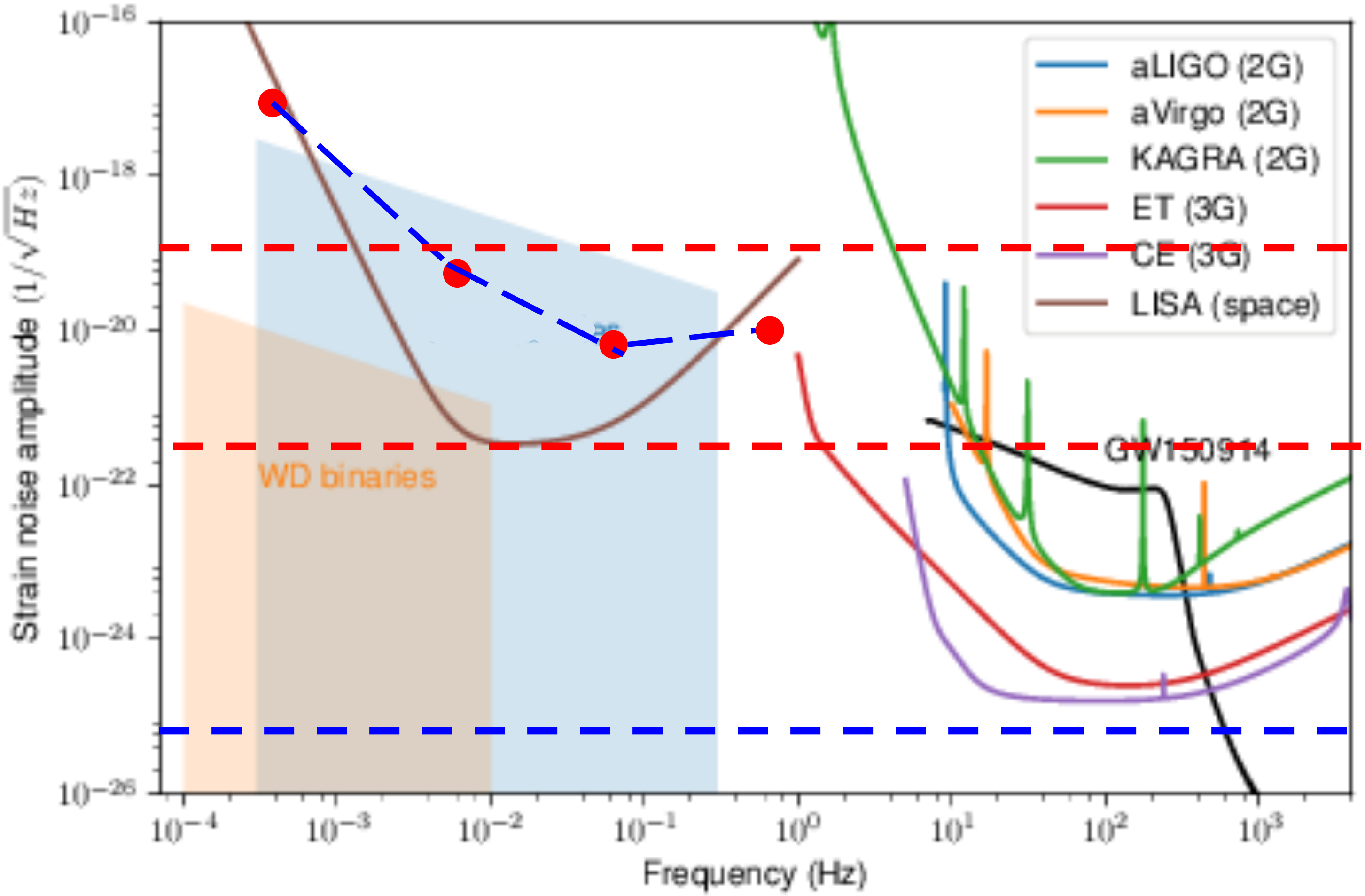
10^{-24}
10^{-26}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Lunar Gravitational Wave Antenna (Harms et al. 2021)



$10^{-19} < h < 10^{-22}$ inside the MW (100-10,000 pc)