Supernovae in the Multimessenger Era

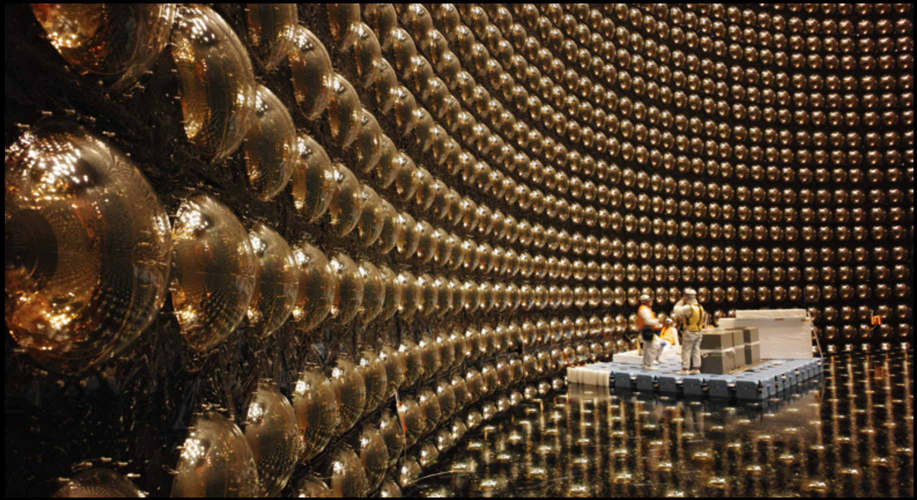
Massimo Della Valle

Capodimonte Observatory, INAF-Naples

Volterra 23-25 June 2021

Summary:
Are we prepared to observe the next SN ?

Ligo, Virgo, Kagra



CC-SN 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

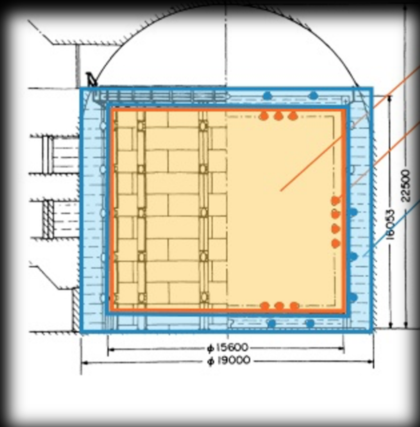
Asiago Survey
(Cappellaro et al. 1999; Cappellaro et al. 2015)

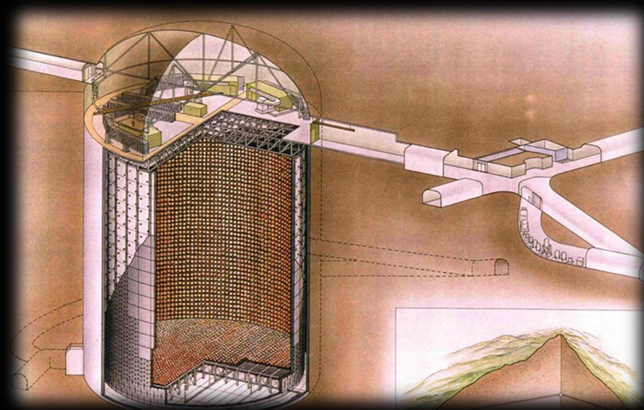
Rate	SN Ia	SN Ibc	SN II
Early(fiducial; SNuK)	$0.064^{+0.008}_{-0.007}(^{+0.013}_{-0.013})$	$0.008^{+0.006}_{-0.004}(^{+0.002}_{-0.002})$	$0.004^{+0.003}_{-0.002}(^{+0.001}_{-0.001})$
Late(fiducial; SNuK)	$0.074^{+0.006}_{-0.006}(^{+0.012}_{-0.012})$	$0.096^{+0.010}_{-0.009}(^{+0.018}_{-0.018})$	$0.172^{+0.011}_{-0.011}(^{+0.045}_{-0.036})$
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})	$0.301^{+0.038}_{-0.037}(^{+0.049}_{-0.049})$	$0.258^{+0.044}_{-0.042}(^{+0.058}_{-0.058})$	$0.447^{+0.068}_{-0.068}(^{+0.131}_{-0.111})$

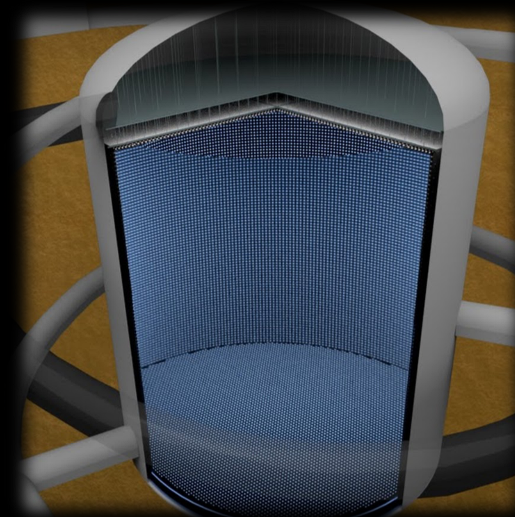
Lick Survey (Li et al. 2011)

Kamiokande Progression

Neutrinos sensitivity







Kamiokande
1983-1996
3kton

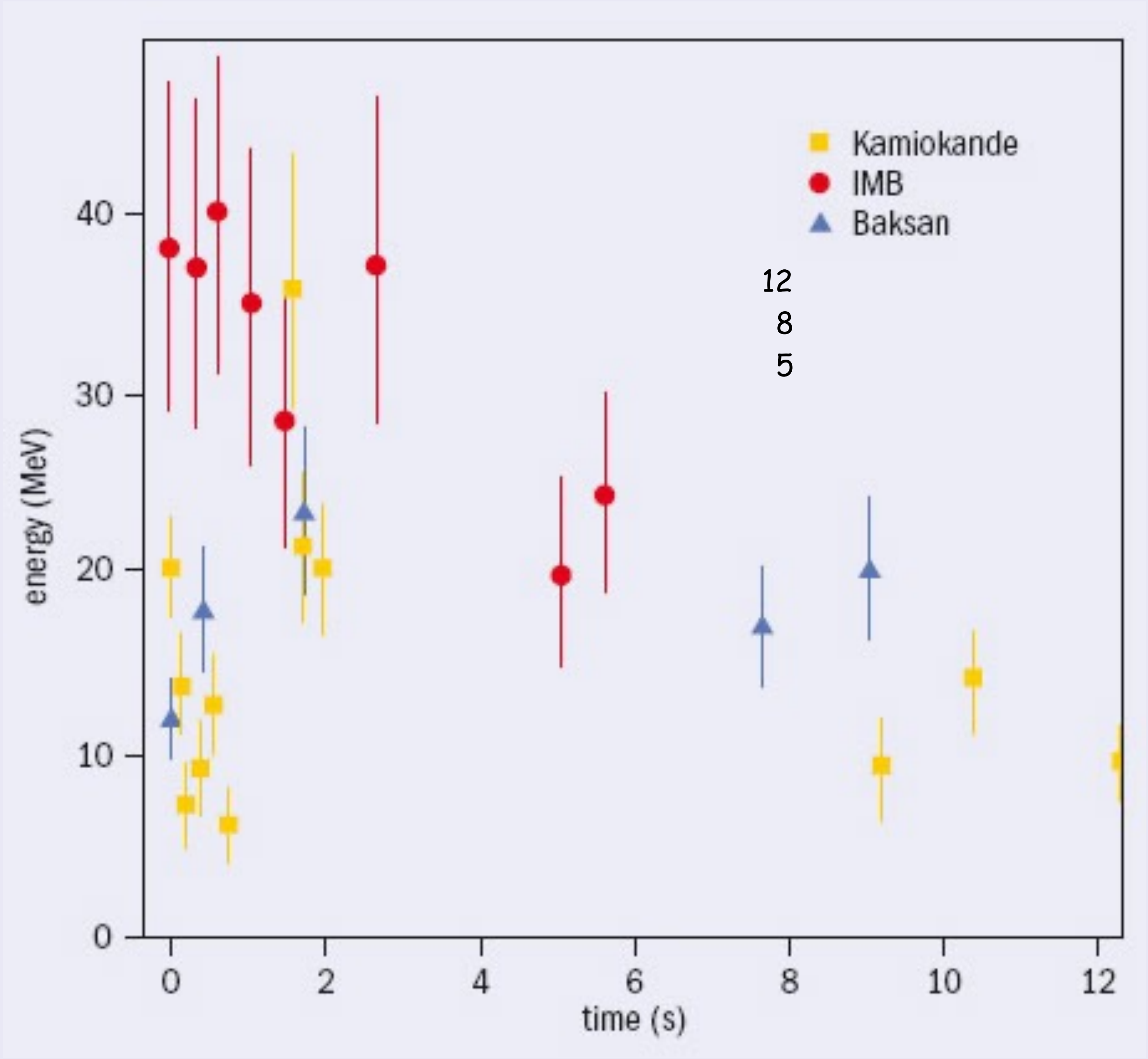
1

Super-Kamiokande
1996-
50kton

× 17

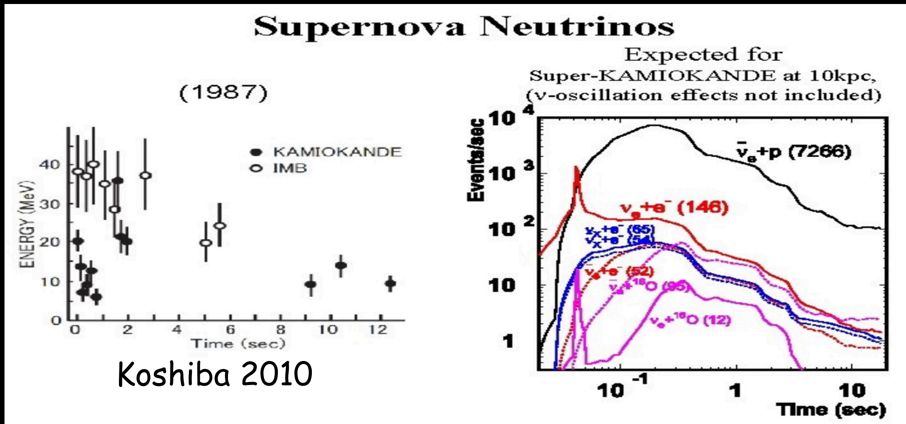
Hyper-Kamiokande
2027
0.52Mton

× 10



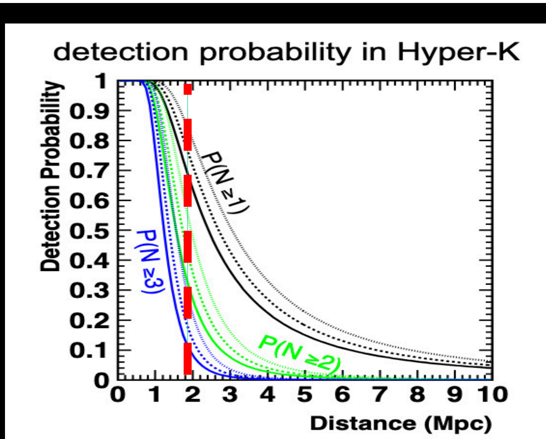
Neutrinos detection confirms that a NS is the residual of a CC SN explosion.

Expected CC-SN/Neutrino rates



Koshiba 2010

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

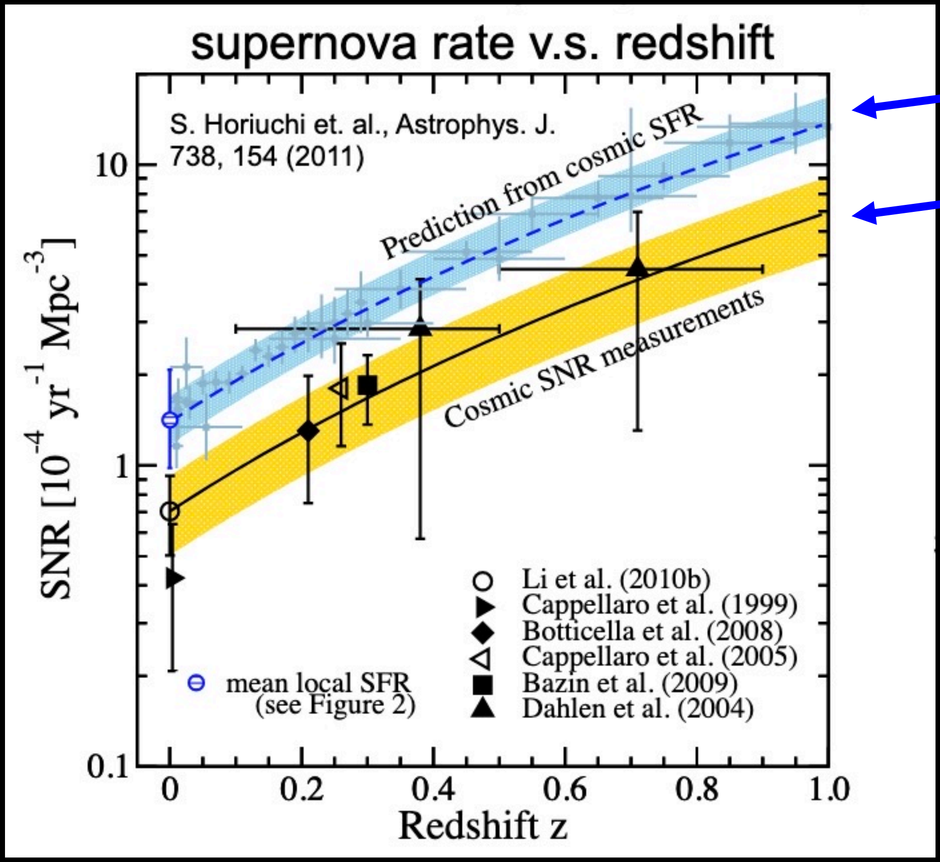


SNe within ~ LG of galaxies ~ 1 neutrino per SN and ~ 0.1 neutrinos per SN within the Virgo circle ~ 2 SN/yr

CC-SNe ~ Gpc: ~ 1×10^{-4} Mpc^{-3} yr^{-1} ~ 10^5 SNe/yr → < 1 neutrino/year → diffuse neutrino background

Conclusions

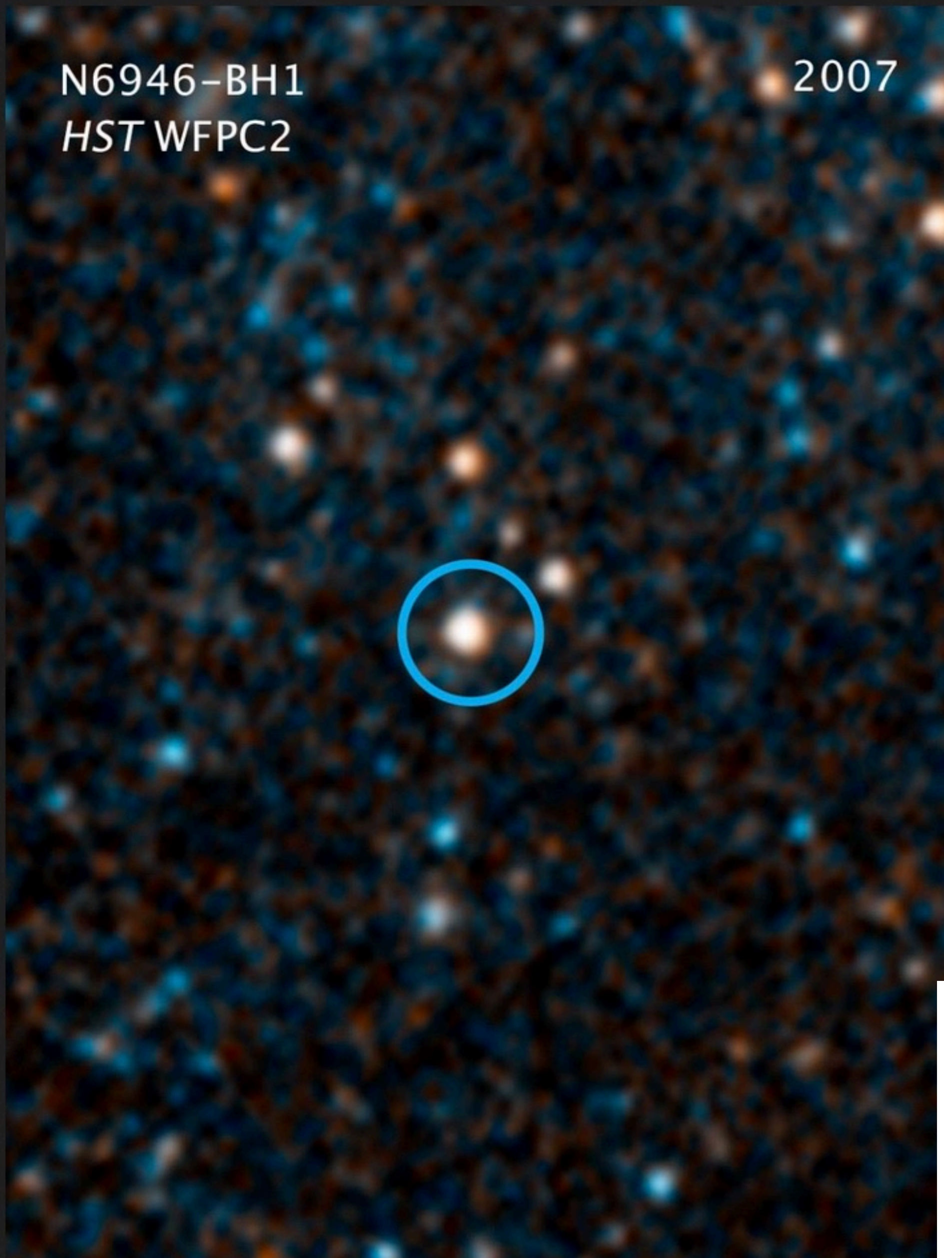
The situation looks desperate

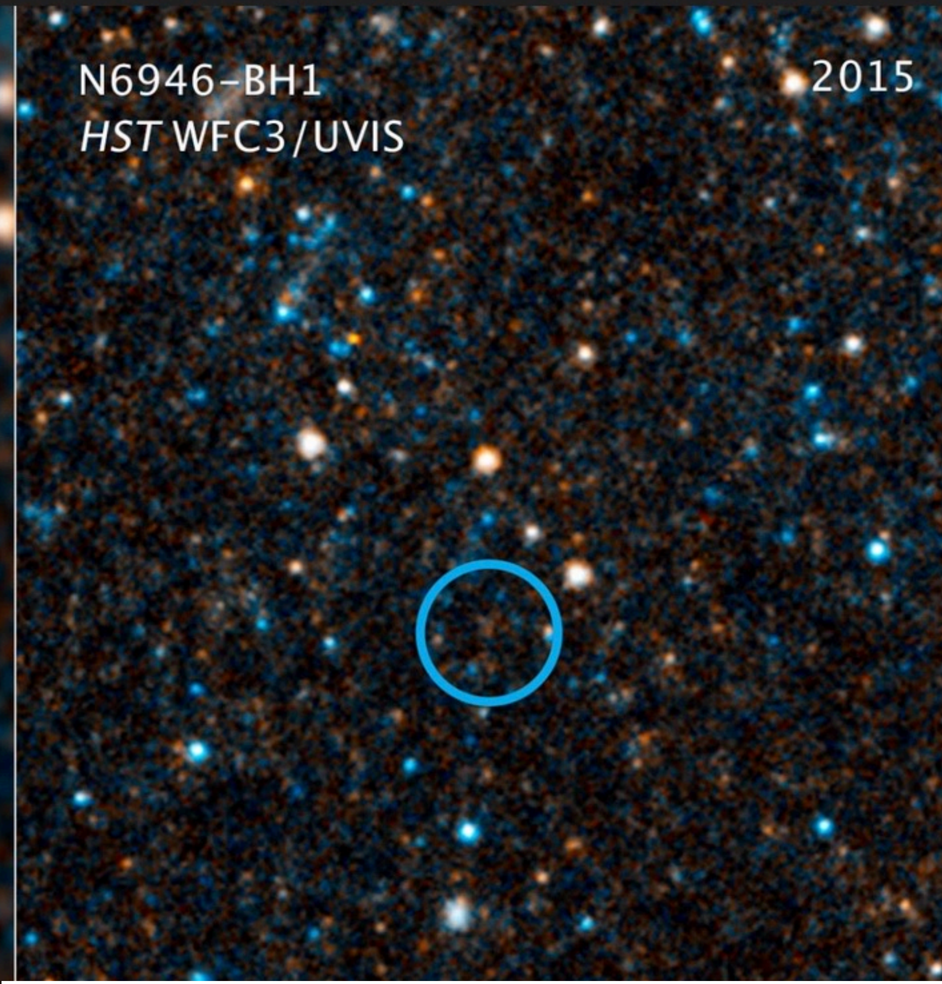


core-collapse rate

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

→ i) dust ? ii) very dim supernovae collapse directly into black hole ?

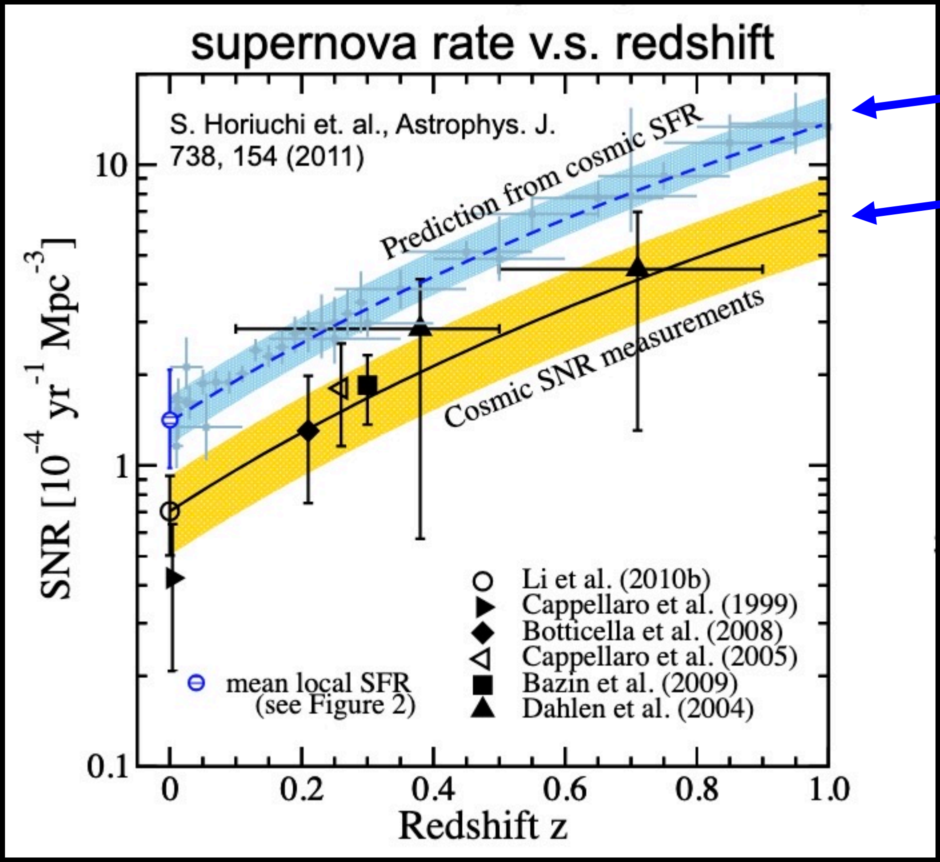




Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 10 April 2015 (MN LaTeX style file v2.2)

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

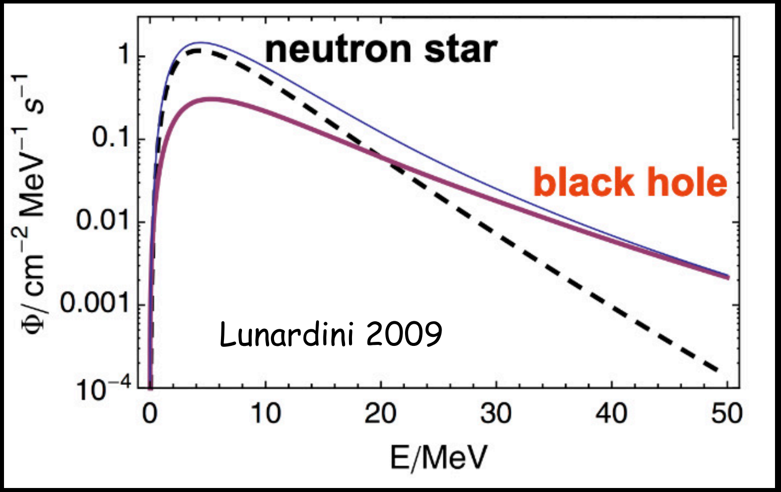
J. R. Gerke[1], C. S. Kochanek[1,2], K. Z. Stanek[1,2]
[1] *Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus OH 43210*
[2] *Center for Cosmology and AstroParticle Physics, The Ohio State University, 191 W. Woodruff Avenue, Columbus OH 43210*

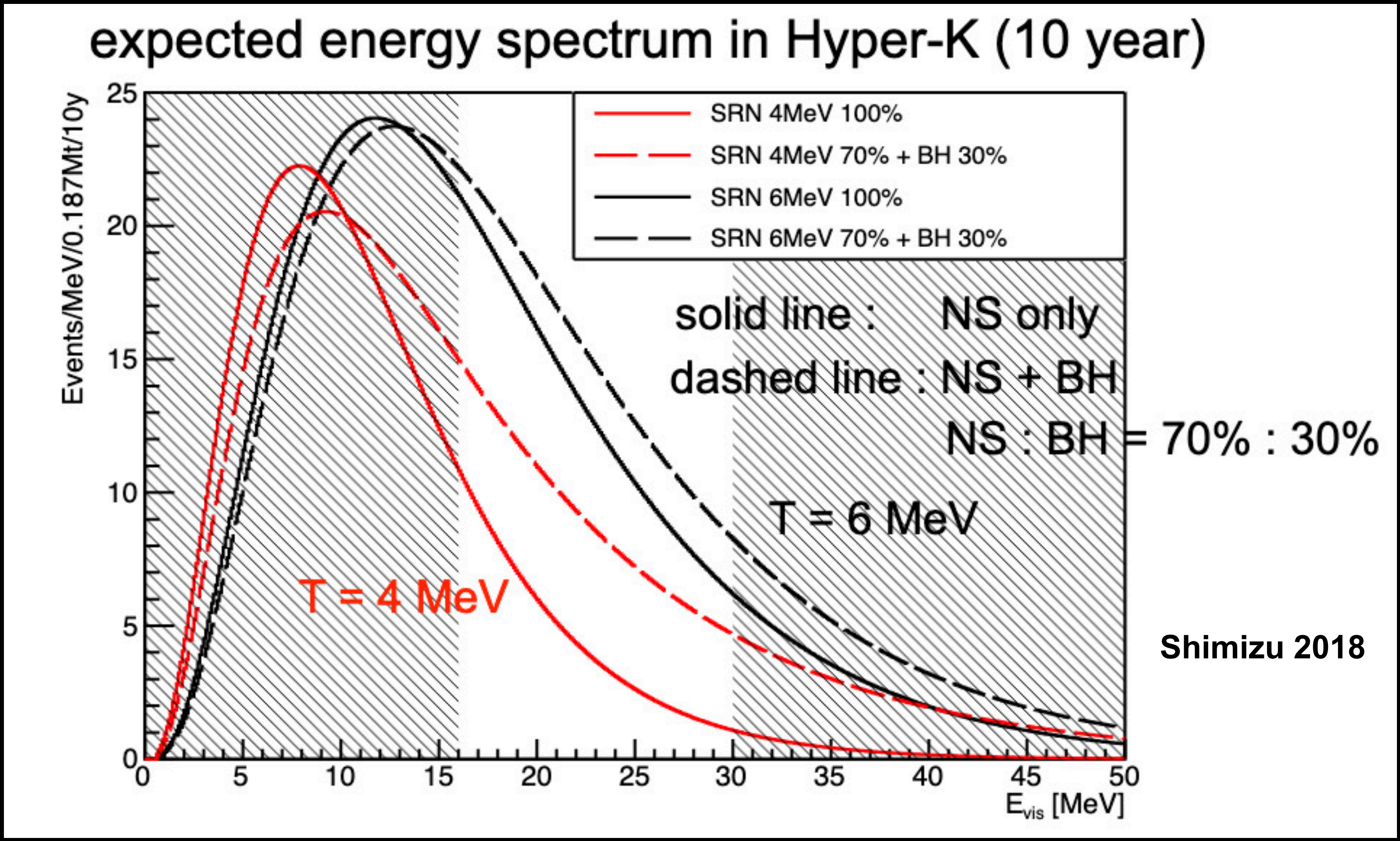


core-collapse rate

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

→ i) dust ? ii) very dim supernovae collapse directly into black hole ?





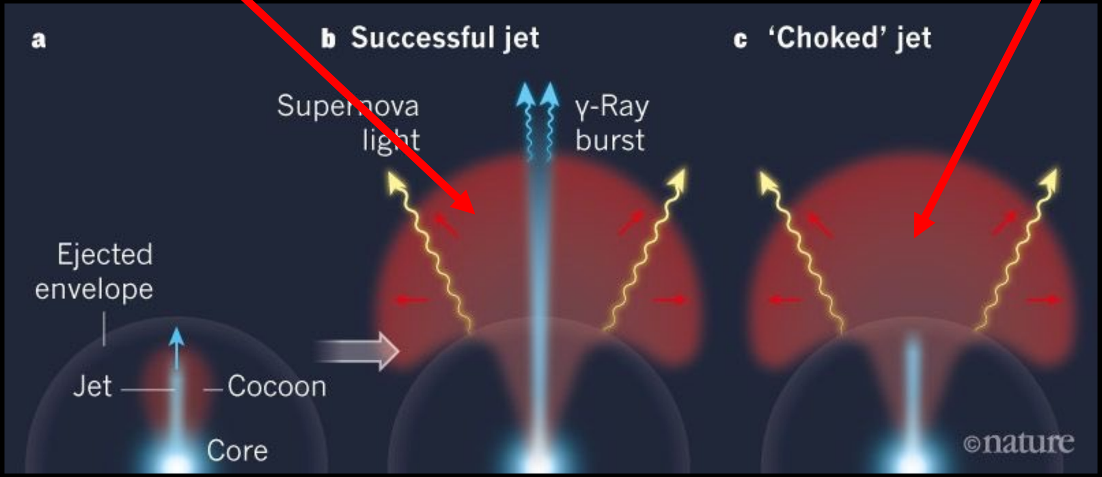
Neutrino flux is harder in BH formation

Relativistic Jets in Core-collapse Supernovae

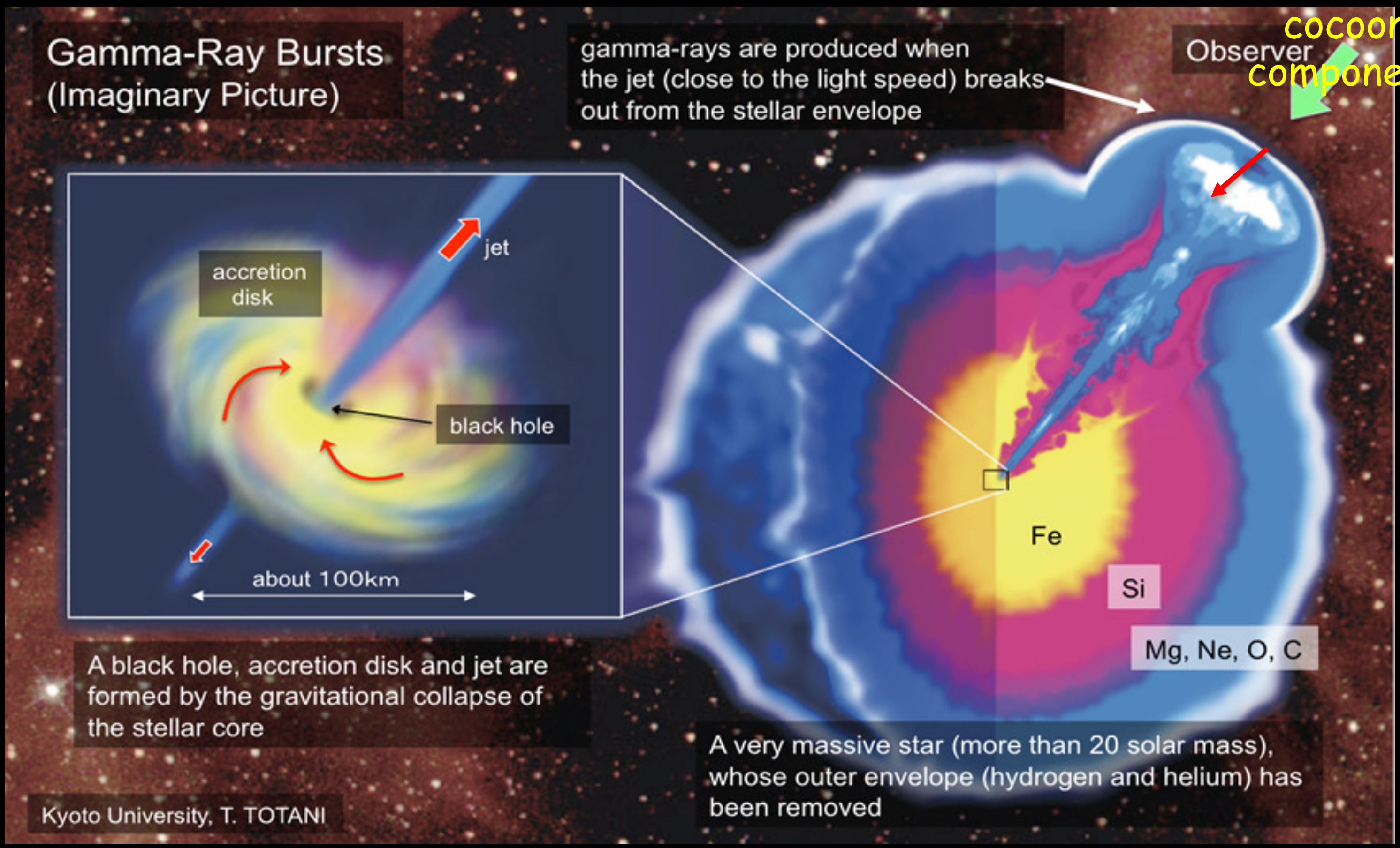
Tsvi Piran[1], Ehud Nakar[2], Paolo Mazzali[3,4], and Elena Pian[5,6]
[1] Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel
[2] Raymond and Beverly Sackler School of Physics & Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
[3] Astrophysics Research Institute, 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

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

HNe/SNe-Ibc: ~ 7%



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 the stellar layers where they are moving that there's not enough left for the GRB to break through -- > "choked jet" (see Nakar and Piran 2017)



In the chocked jets the protons are acceleretd to high energies and they interact with the thermal photons produced in the jet head and propagating inside the internal shock region.

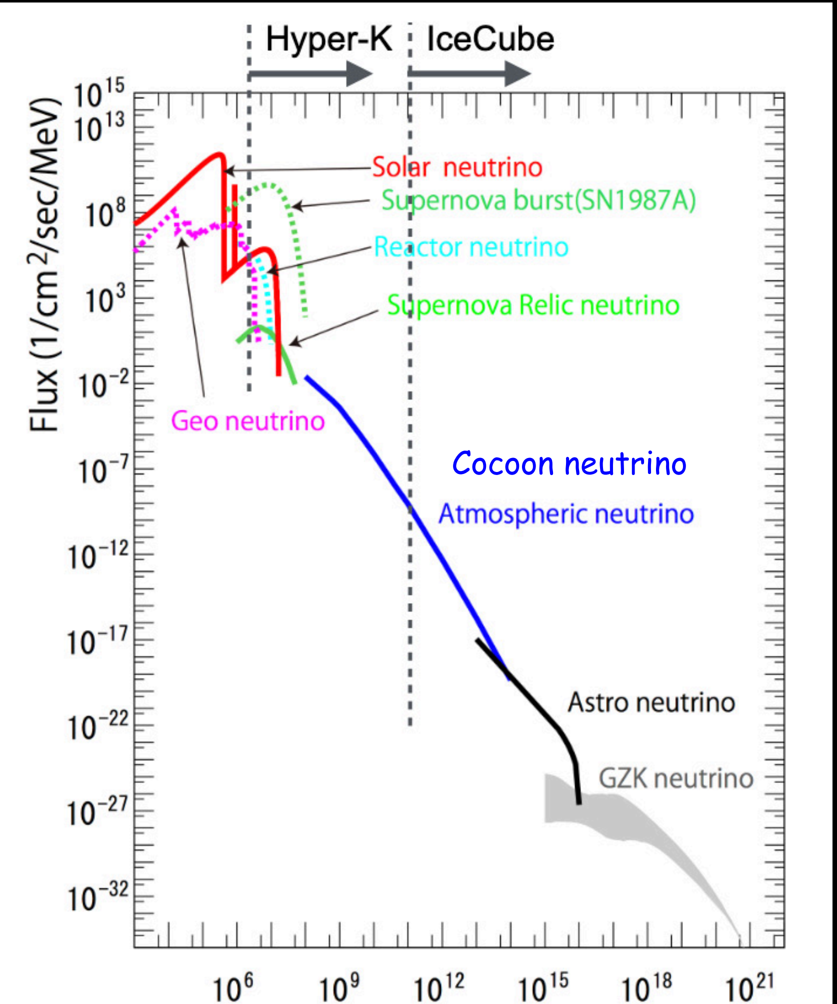
This interaction produces pions which decay in high energy (TeV/PeV) neutrinos observable by IceCube

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

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

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

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



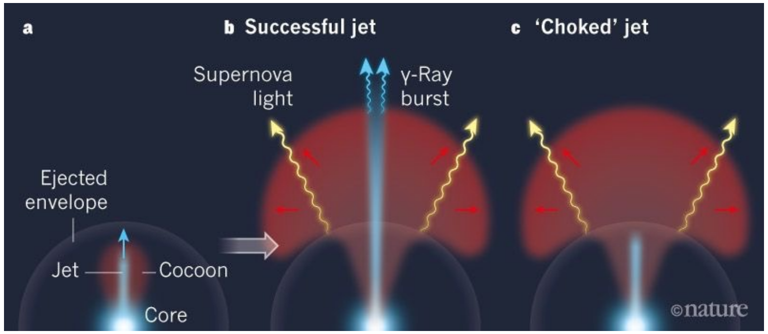
Shimizu 2018

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

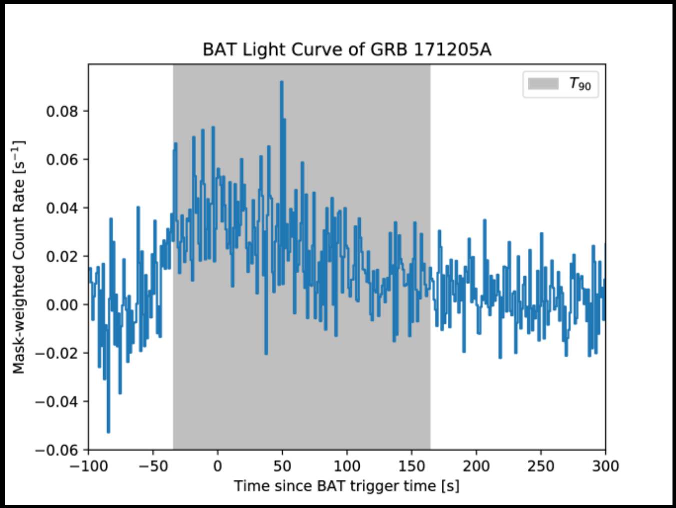


GRB 171205A

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

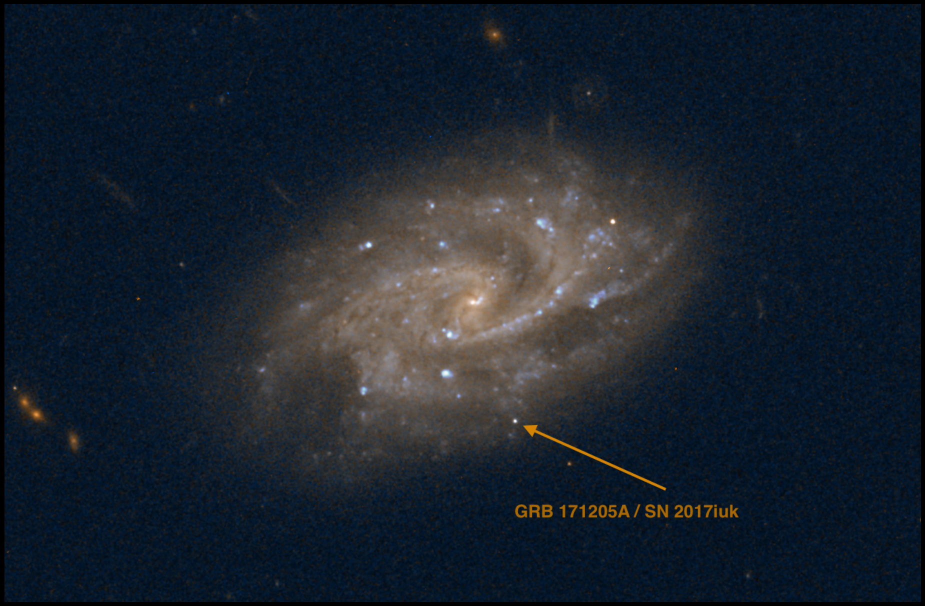
ii) low-luminous GRB $E_{iso} \sim 10^{49}$ erg

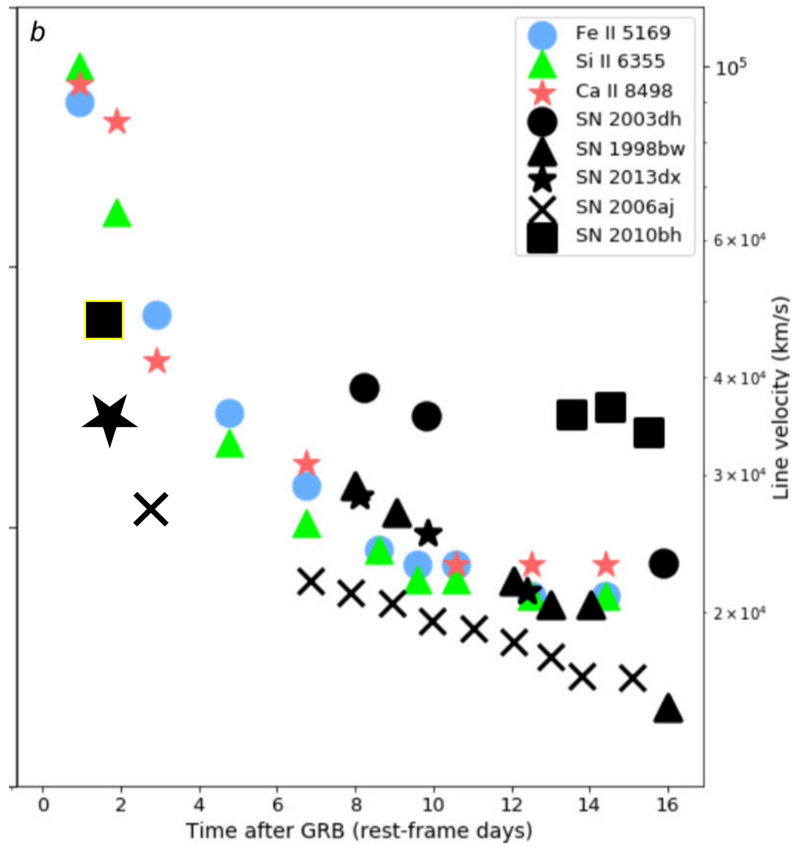
iii) grand-design spiral host galaxy



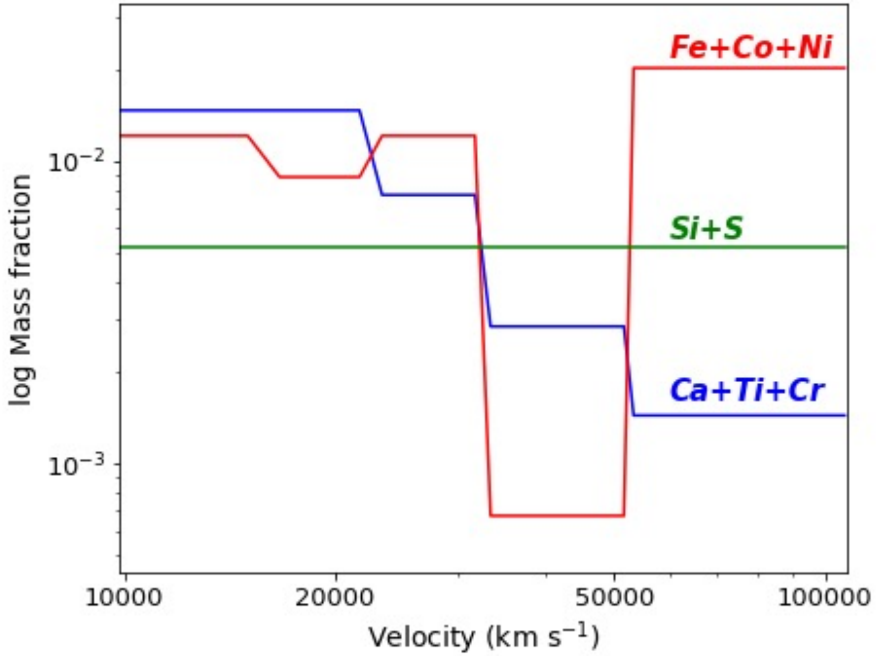
multi-wavelength photometric & spectroscopic campaign

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





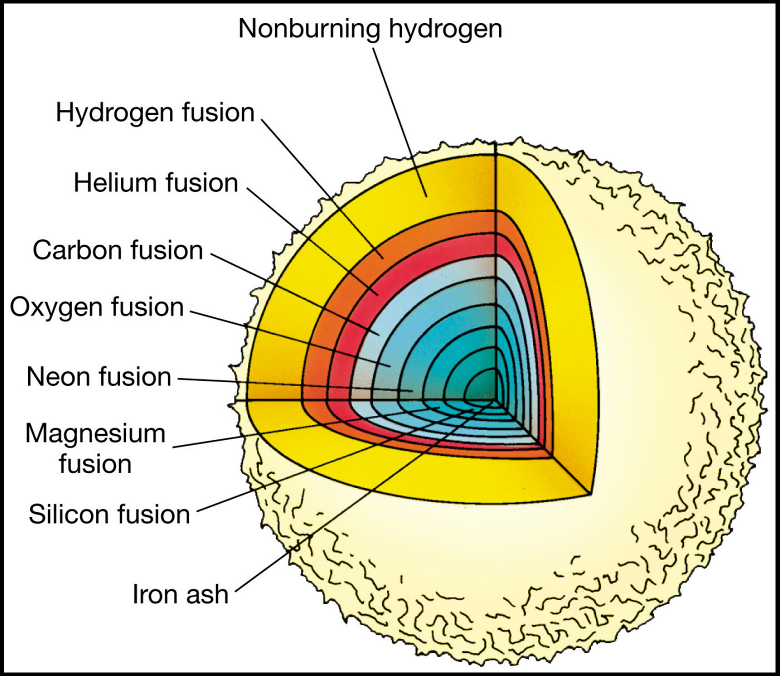
We interpret these high velocity features as signatures of a hot cocoon generated when the jet moves inside the progenitor star.



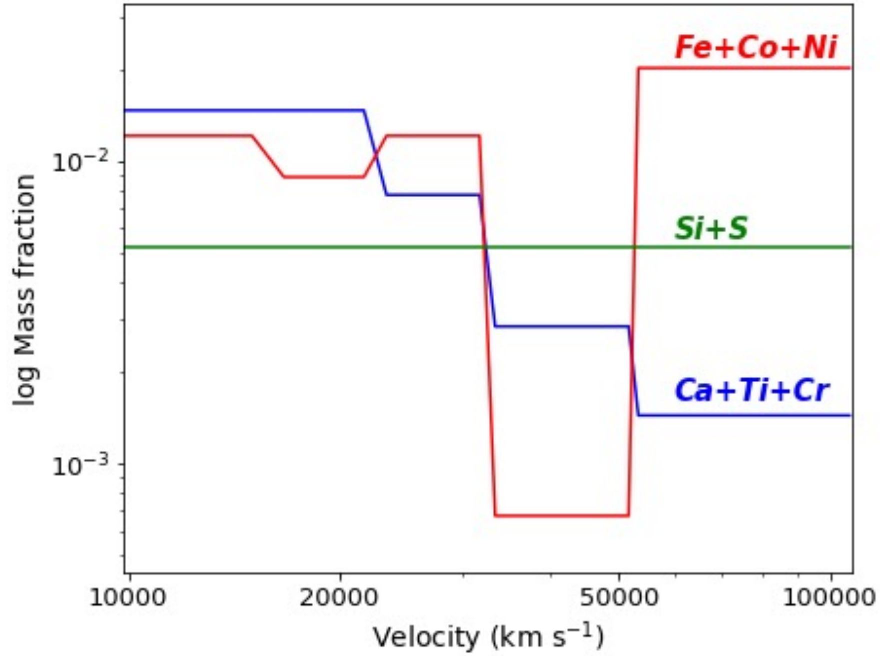
chemical composition of the high velocity (10^5 km/s) components are characterized by chemical abundances different from those observed in the SN ejecta ($x10^4$ km/s)

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 ($x10^4$ km/s)

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

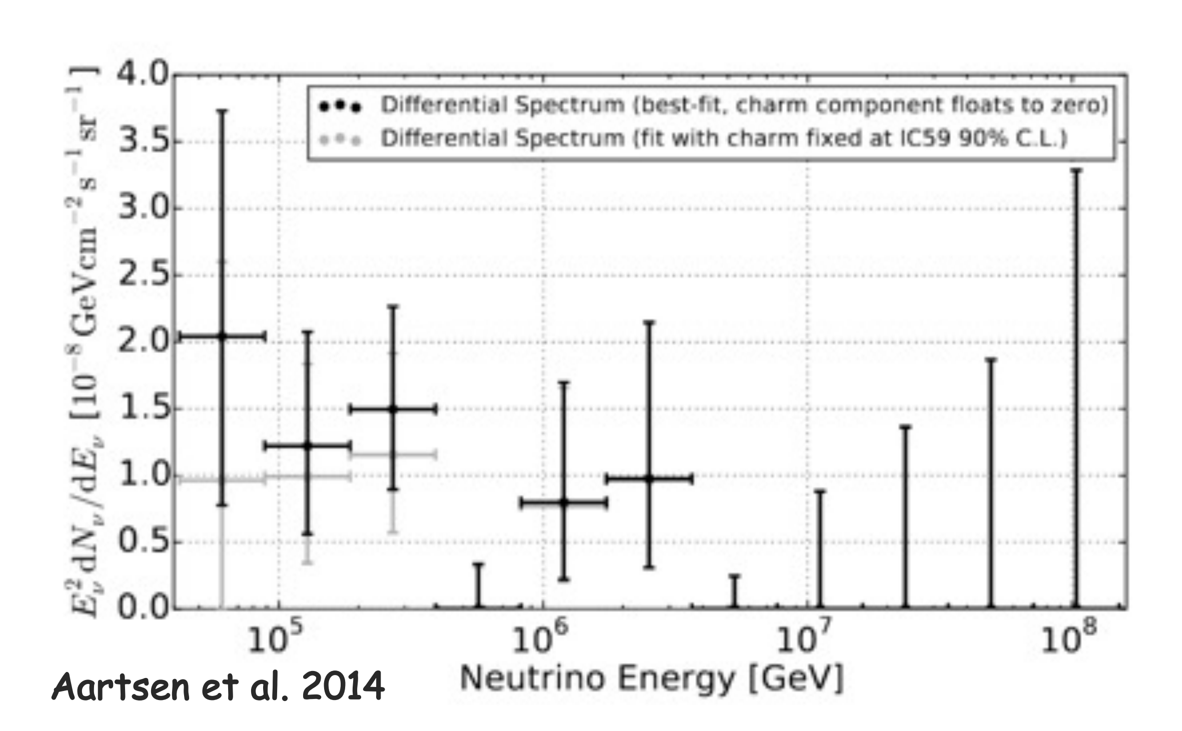
Dafne Guetta,[1] Roi Rahin,[2] Imre Bartos,[3] and Massimo Della Valle[4,5]

[1] ORT Braude, Karmiel, Israel
[2] Technion, Haifa, Israel
[3] Department of Physics, University of Florida, PO Box 118440, Gainesville, FL 32611-8440, USA
[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

	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 HE neutrinos detection above the neutrinos background

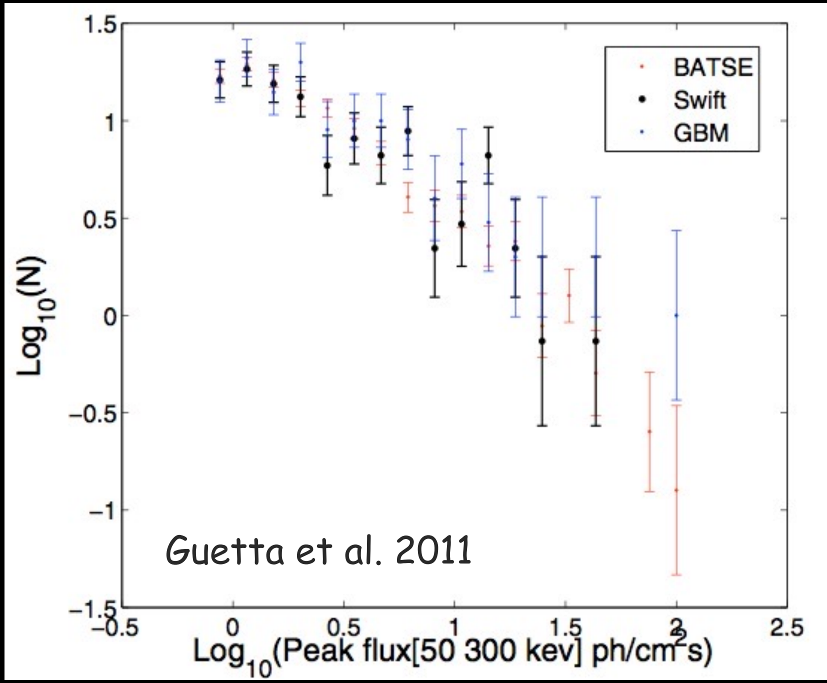
Fasano et al. 2020 find that if 10%-100% of GRB energy is channeled into protons, choked GRBs may reproduce the diffuse flux of high-energy neutrinos observed by the IceCube experiment, **if the local rate of GRBs is 0.3-3 $Gpc^{-3}\ yr^{-1}$**



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

Sample	Rate ($z = 0$)[1] $Gpc^{-3}\ yr^{-1}$	L^* [50–300] keV 10^{51} erg/s	a_1	a_2	χ^2/d.o.f.[3]
GBM	$0.5^{+0.3}_{-0.2}$	$5.5^{+1.5}_{-2}$	$0.3^{+0.1}_{-0.5}$	$2.3^{+0.6}_{-0.3}$	1.1
BATSE	$1.0^{+0.2}_{-0.4}$	$4^{+2}_{-1.5}$	$0.1^{+0.3}_{-0.1}$	$2.6^{+0.9}_{-0.5}$	1.1
Swift	$0.6^{+0.3}_{-0.1}$	$3.3^{+2.5}_{-0.5}$	$0.1^{+0.3}_{-0.1}$	$2.7^{+1}_{-0.4}$	0.95

1.5	Schmidt 1999
0.15	Schmidt 2001
0.5	Guetta et al. 2005
1.1	Guetta & Della Valle 2007
1.1	Liang et al. 2007
> 0.5	Pelangeon et al. 2008
1.3	Wanderman and Piran 2010



GWs from nearby CC- and Ia- 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}

SNe-Ibc/HNe

Progenitor Mass ~ 30-50 $M_\odot$

Remnant: NS or BH ($3M_\odot$)

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}

Core-Collapse SNe

SN

Pro 0 $M_\odot$

Rer $_\odot$)

Rad 7/49 erg

Kin rg

rat $^{-3}$ yr^{-1}

SNe-Ibc/HNe

Progenitor Mass ~ 30-50 $M_\odot$

Remnant: NS or BH ($3M_\odot$)

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}

Ibc/HNe might have the needed ingredients for an output in gravitational radiation

i) E_ν evidences the formation of high density remnant
ii) High angular momentum of the remnant
iii) Formation of an accretion disk around the remnant
iv) The mass-motion takes place on the Schwarzschild scale of the newly born BH

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 $M_D \approx 0.01\ M$

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

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 $M_D \approx 0.01\, M$

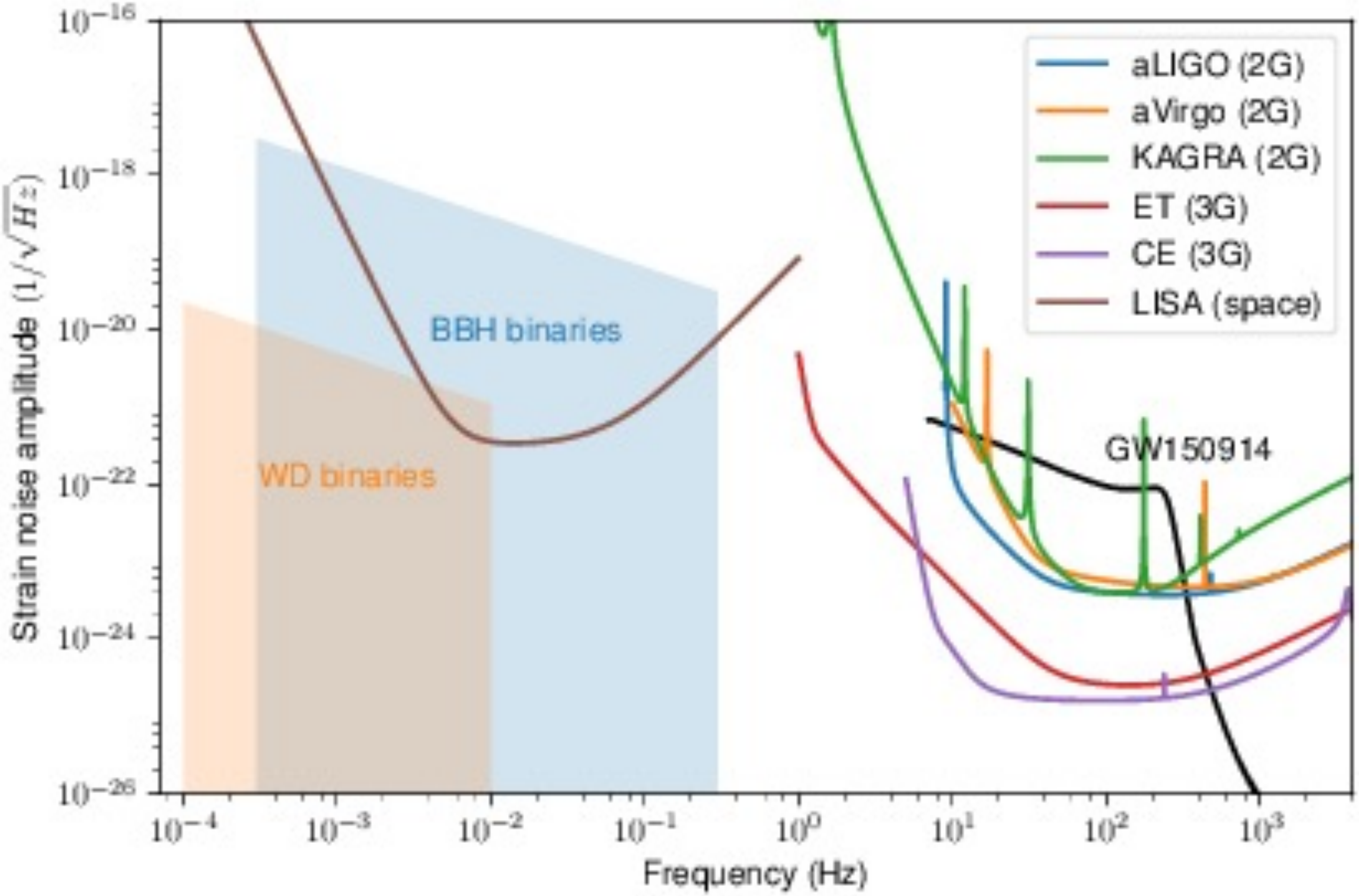
$$h = 3.4 \times 10^{-23}\, M \left(\frac{\xi}{0.1}\right)\left(\frac{\sigma}{0.01}\right)\left(\frac{D}{20\,\mathrm{Mpc}}\right)^{-1}\left(\frac{f_{gw}}{600\,\mathrm{Hz}}\right)^{\frac{2}{3}}$$

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

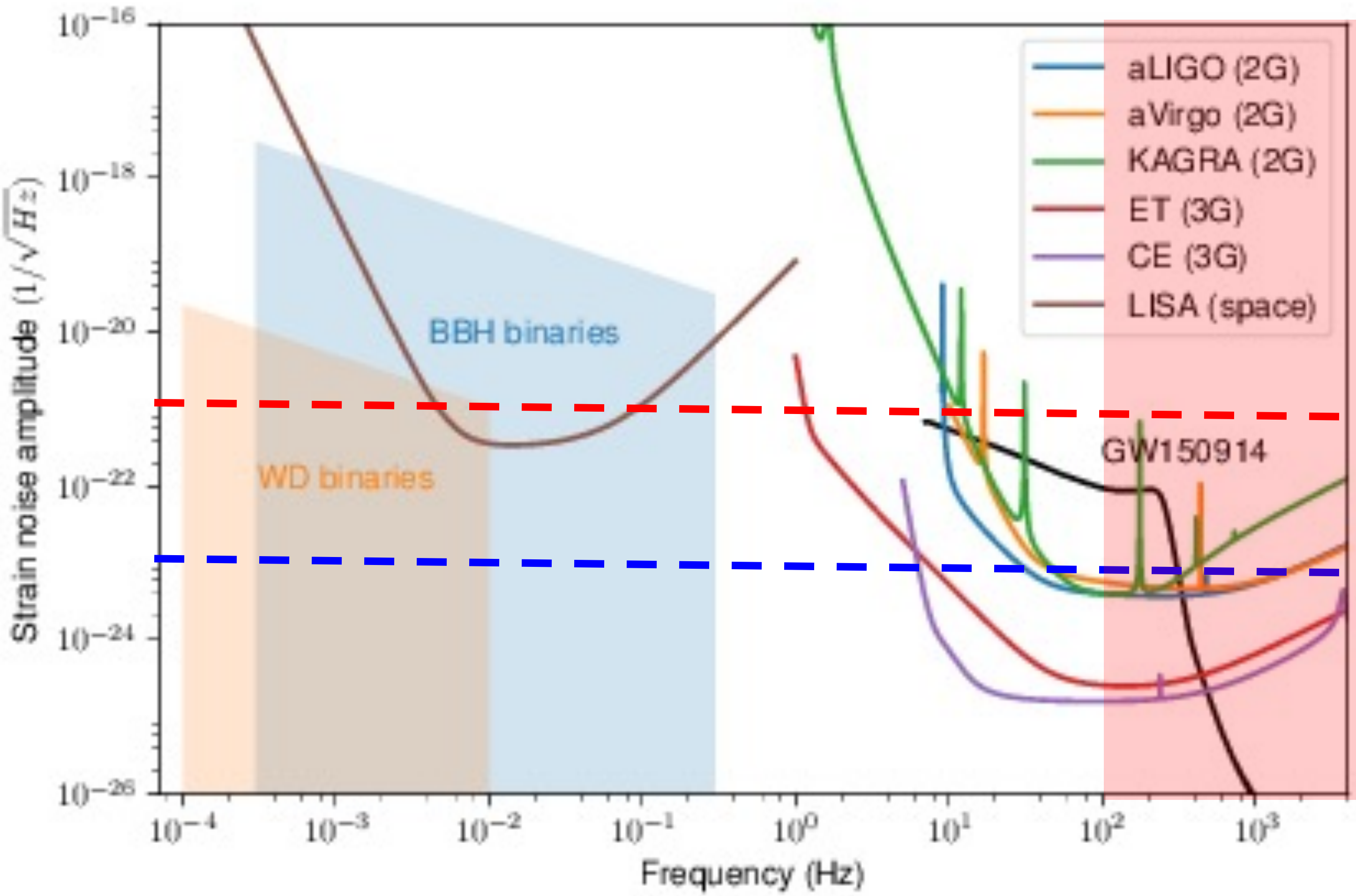
i) E_ν evidences the formation of high density remnant
ii) High angular momentum of the remnant
iii) Formation of an accretion disk around the remnant
iv) The mass-motion takes place on the Schwarzschild scale of the newly born BH

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 $M_D \approx 0.01\,M$

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



courtesy of J. Shapiro



~ 1 SN-Ibc / 50 yr in the MW

Rozwadowska, Vissani & Cappellaro 2020

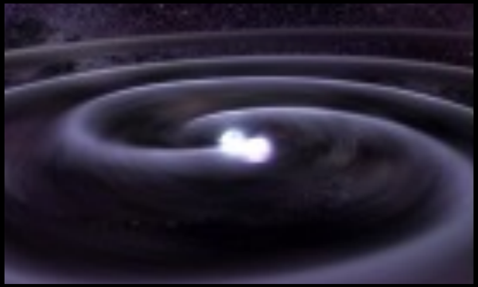
~ 0.83 yr^{-1} SN-Ibc within the "Virgo Circle" (20 Mpc)

~ 0.05 yr^{-1} HNe within the "Virgo Circle" (20 Mpc)

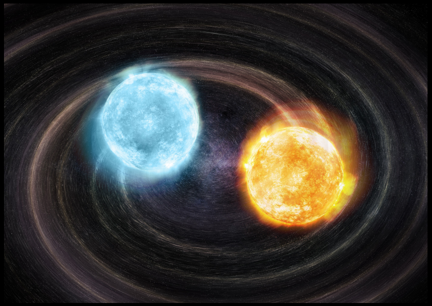
SNe-Ia

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



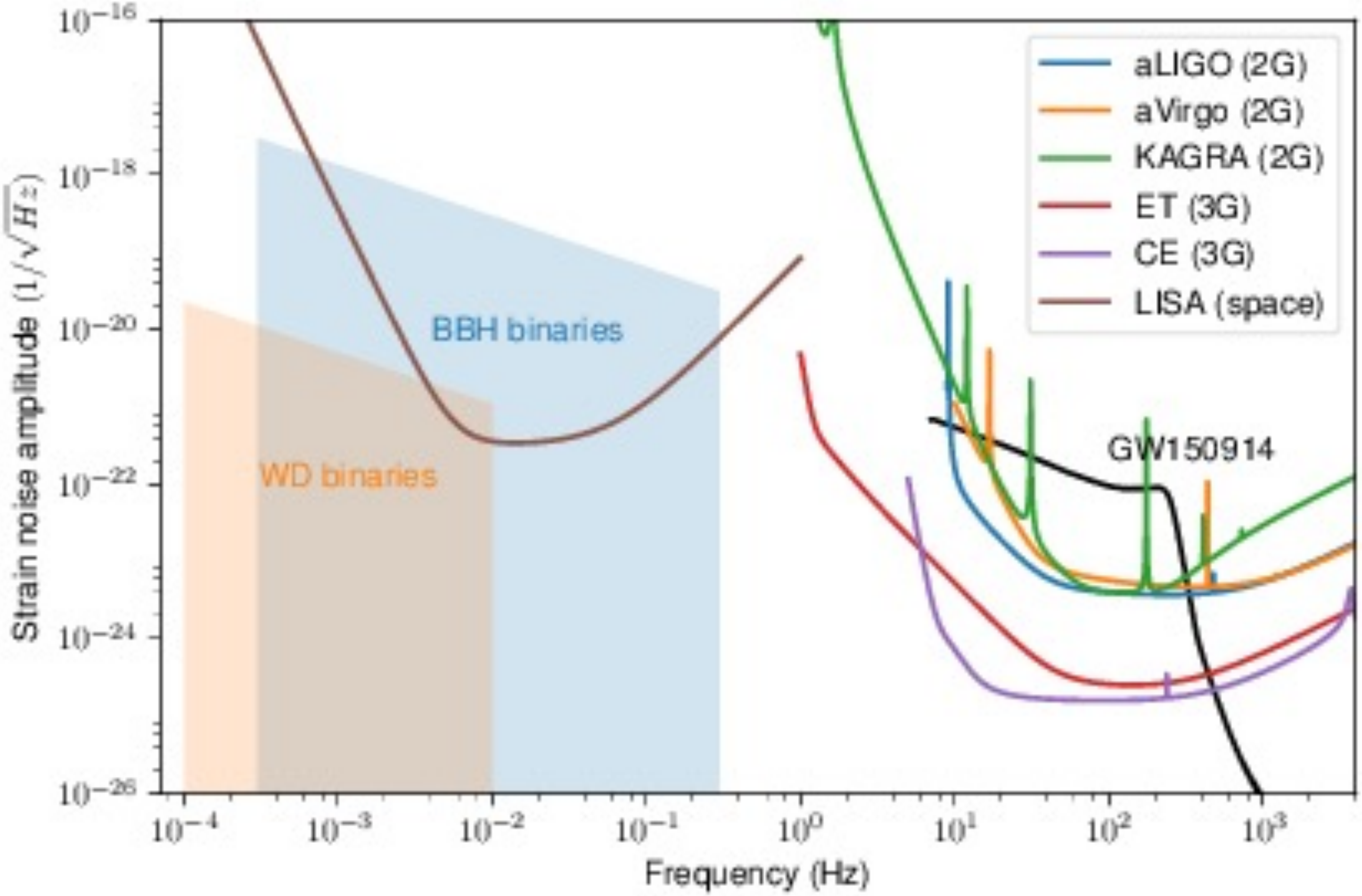
~ 10,000km



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

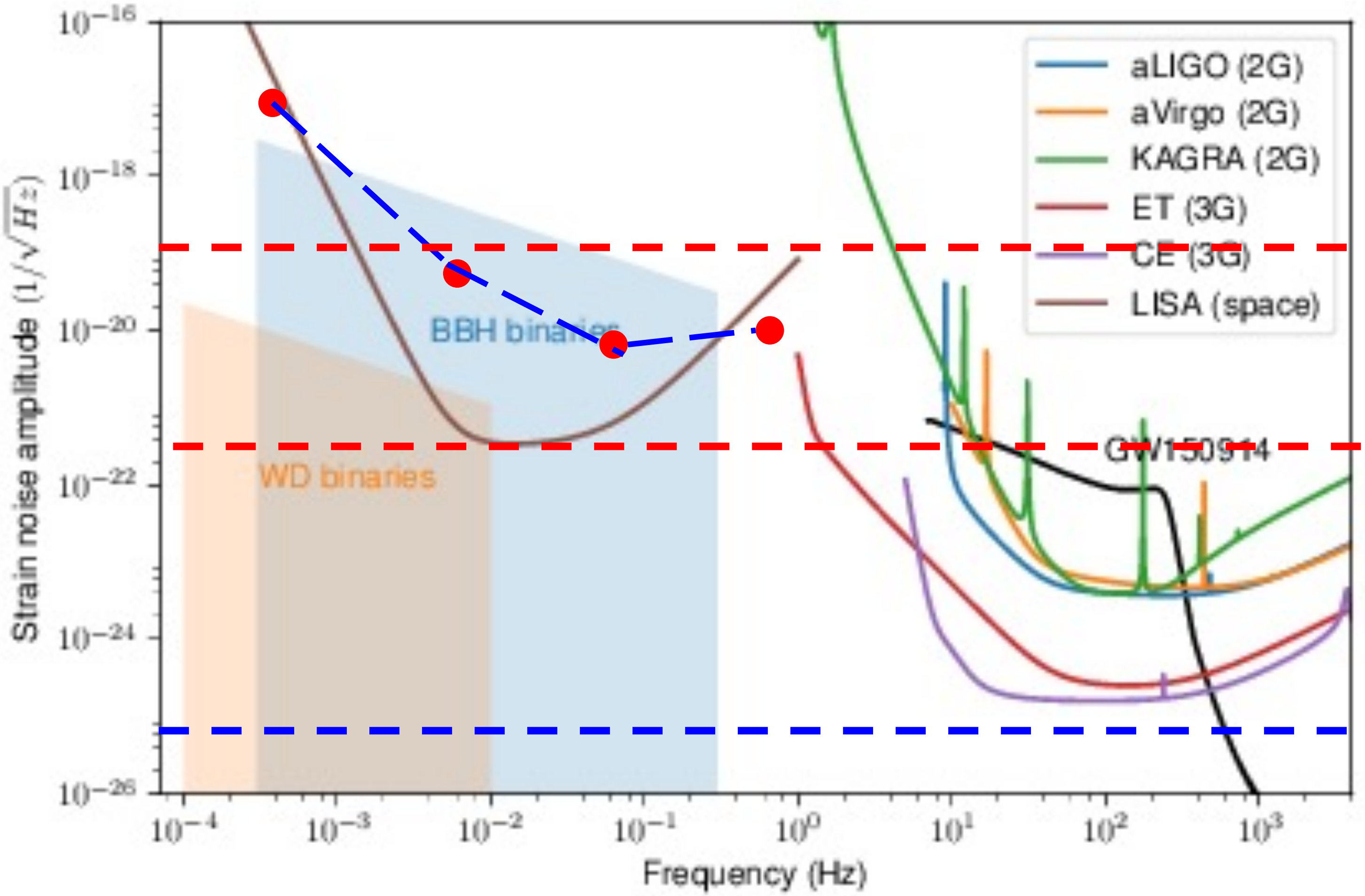
van Putten et al. 2019

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



aLIGO (2G)
aVirgo (2G)
KAGRA (2G)
ET (3G)
CE (3G)
LISA (space)
BBH binaries
WD binaries
GW150914
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}

Lunar Gravitational Wave Antenna (Harms et al. 2021)



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

Conclusions I

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 (~1-2 per century or so)

Future GWs detectors (ET and CE) can detect GWs emission from CC-SNe forming BHs occurring in the Virgo Cluster within the time-frame of a few years (most SNe-Ibc) up to ~ 20 years (only HNe)

LISA and LGWA will detect GWs emission from close WD binaries in the MW, then contributing significantly to clarify the nature of the SN-Ia progenitors.

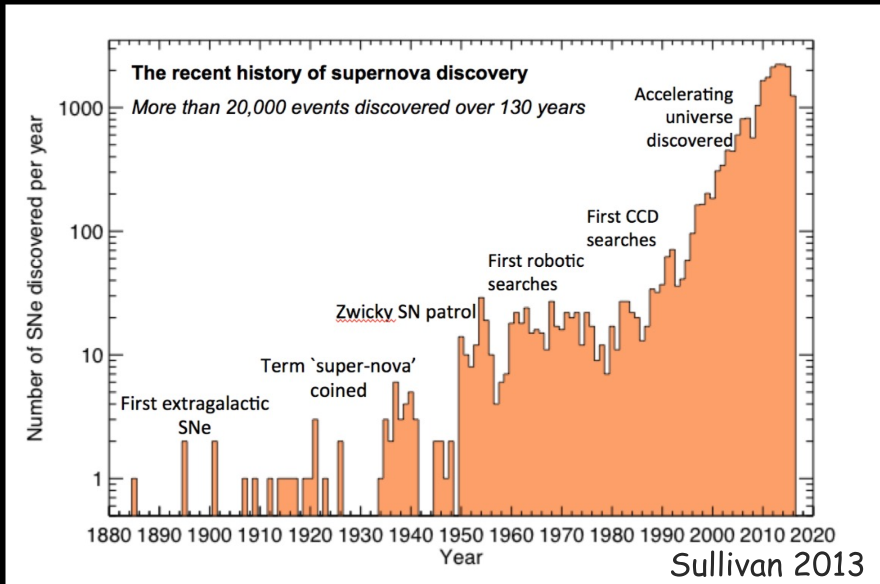
Conclusions II

Current Neutrinos Observatory have the capability to detect CC-SN events occuring in the Milky Way. Positive detections are hampered by the low frequency of SNe in the MW.

HyperKamiokande observations of neutrinos on time scale of ~ 10 yrs should solve the problem of *missing SNe* in terms of dust effect or direct collapse of massive progenitors into BHs.

Recent observations of cioked jets, associated with GRBs appear the most interesting possibility for TeV /PeV neutrinos detections via Icecube, Antares or KM3NeT.

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 in about a year by either ZTF or LSST if all CC-SNe produce jets



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

An empirical confirmation of the chocked model will take several years of even decades if the ciocked jet scenario apply only to a fraction of CC-SNe, such as SN-Ibc or HNe.