Workshop on Supernova at Hyper-Kamiokande

Diffuse supernova neutrino background

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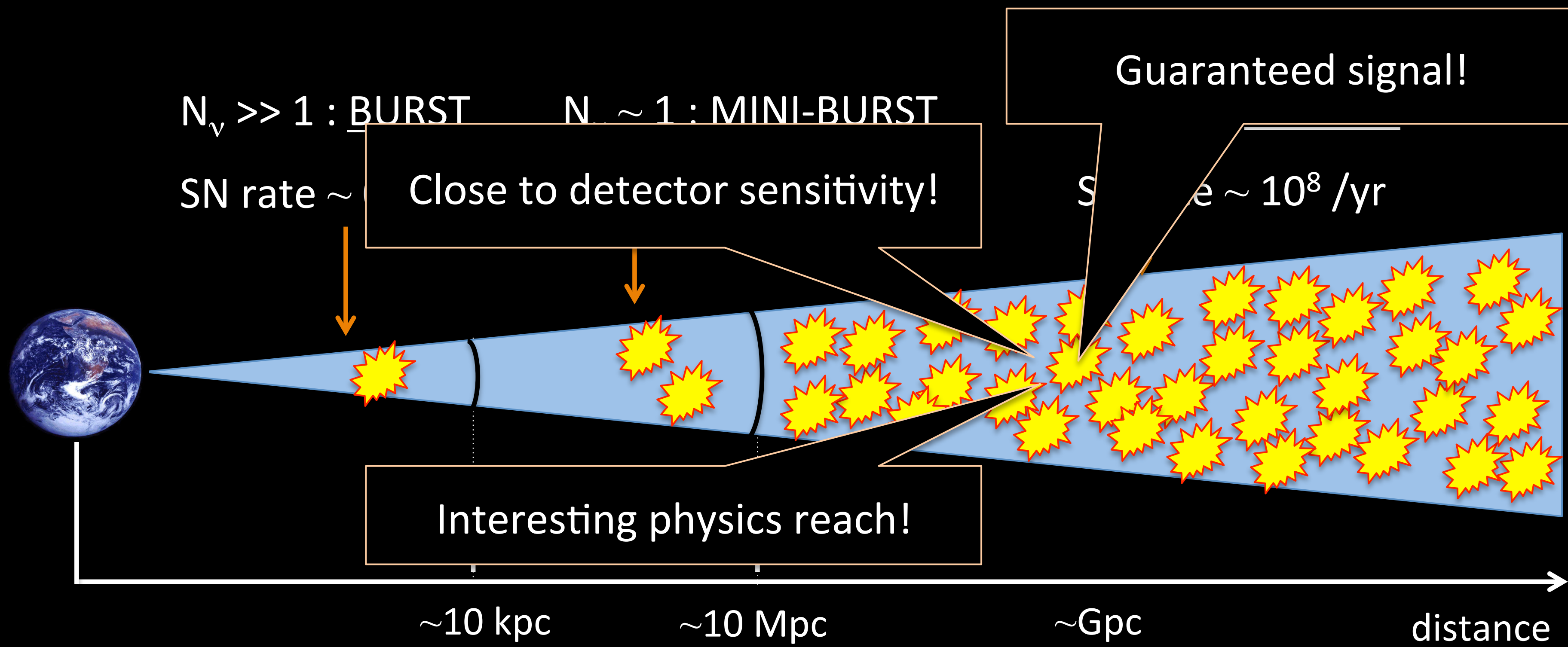
Distance scales and physics reach



(adapted from Beacom@Nu2012)

	Galactic burst	Mini-bursts	Diffuse signal
Physics reach	Explosion mechanism, astronomy	supernova variety with individual ID	Average emission, multi-populations

Diffuse Supernova Neutrino Background

Observed positron spectrum

Input 1: supernova neutrino spectrum (intensely studied by simulations, quantity *of interest*)

$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu) \int R_{\rm CCSN}(z) \left|\frac{cdt}{dz}\right| (1+z) \frac{dN_\nu}{dE_\nu}\left[E_\nu(1+z)\right] dz$$

See, e.g., reviews by Beacom (2010), Lunardini (2010)

Input 2: core-collapse rate (intensely studied by astronomers using photons, *rapidly improving*)

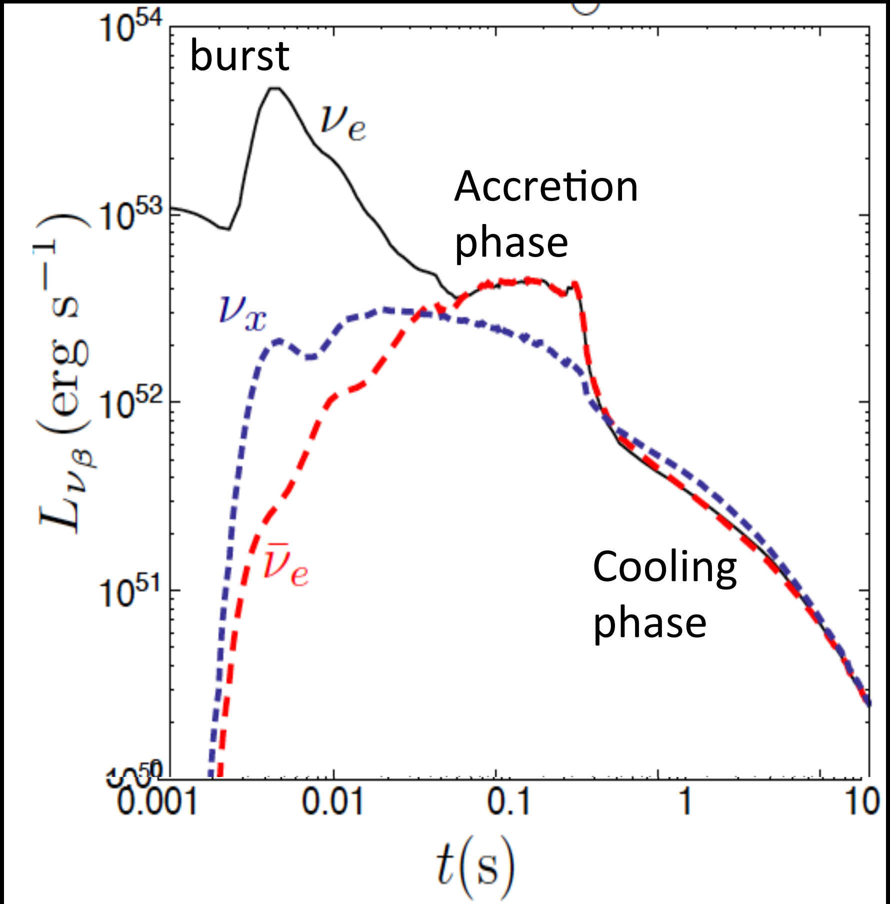
Input 3: neutrino detector capabilities (well understood for H_2O)

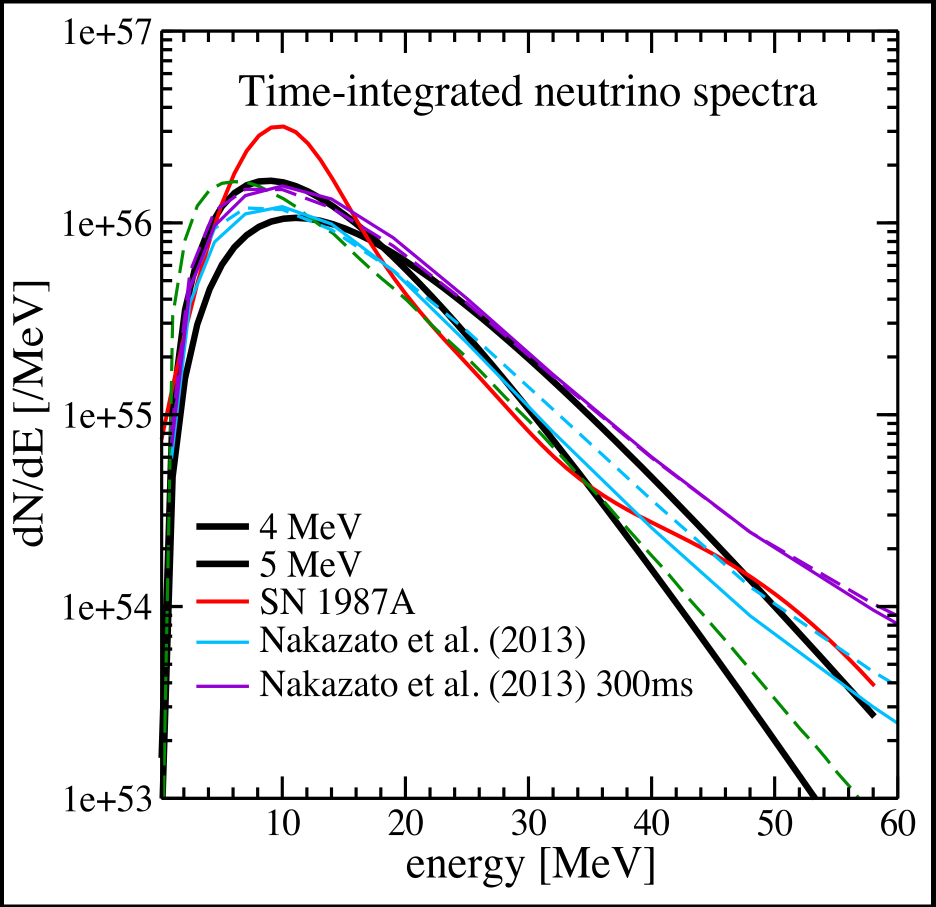
$$\bar{\nu}_e + p \to e^+ + n$$

Input 1: neutrino emission

Copious MeV neutrinos

Each core collapse releases ~ 3x10^{53} erg of neutrinos, of which ~ 6x10^{52} erg in anti-ν_e



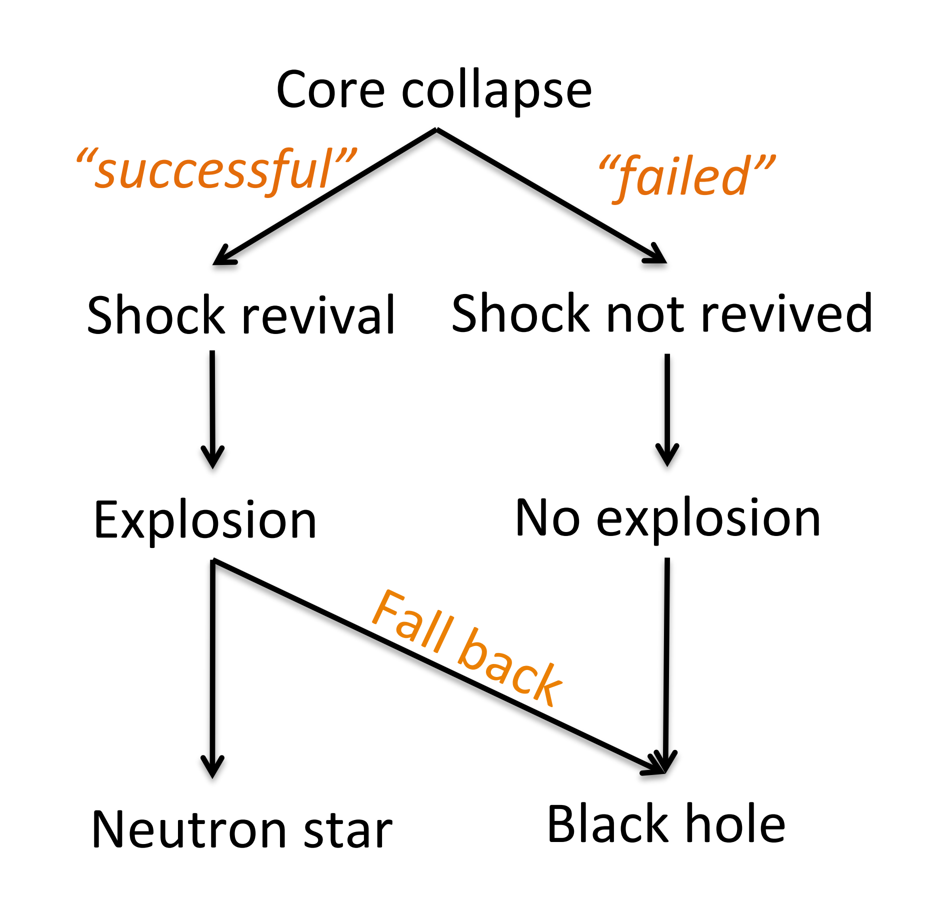


Fischer et al (2010)

…but not all core collapse may be identical!

Collapse to black hole

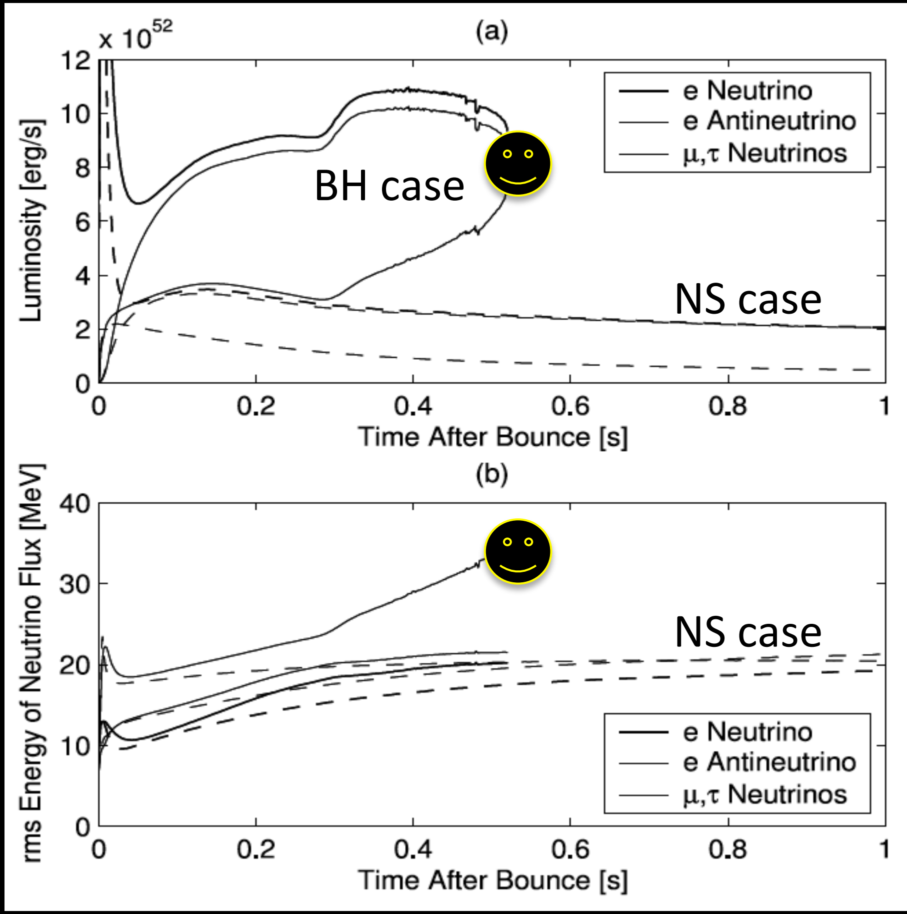
Core collapse may "fail" to generate an optical explosion, but still generate copious neutrinos

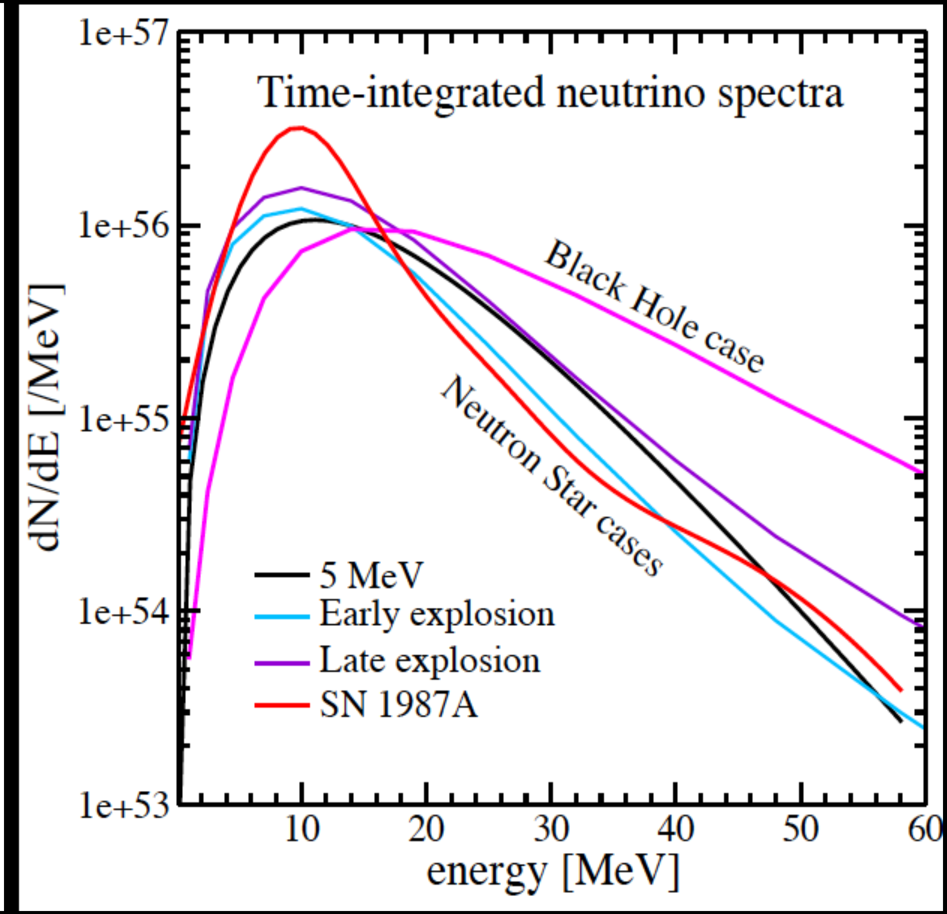


Liebendoerfer et al 2004, Fischer et al 2009, Sumiyoshi et al 06, 07, 08, 09, Nakazato et al 2008, 2010, O'Connor & Ott 2011, …

Collapse to black hole

Black hole formation necessarily goes through rapid mass accretion → ν emission gets cut off but is more luminous and hotter (quantitatively depends on EOS)





Liebendoerfer et al 2004, see also Fischer et al 2009, Sumiyoshi et al 2006, 2007, 2008, 2009, Nakazato et al 2008, 2010, O'Connor & Ott 2011, …

Collapse to black hole

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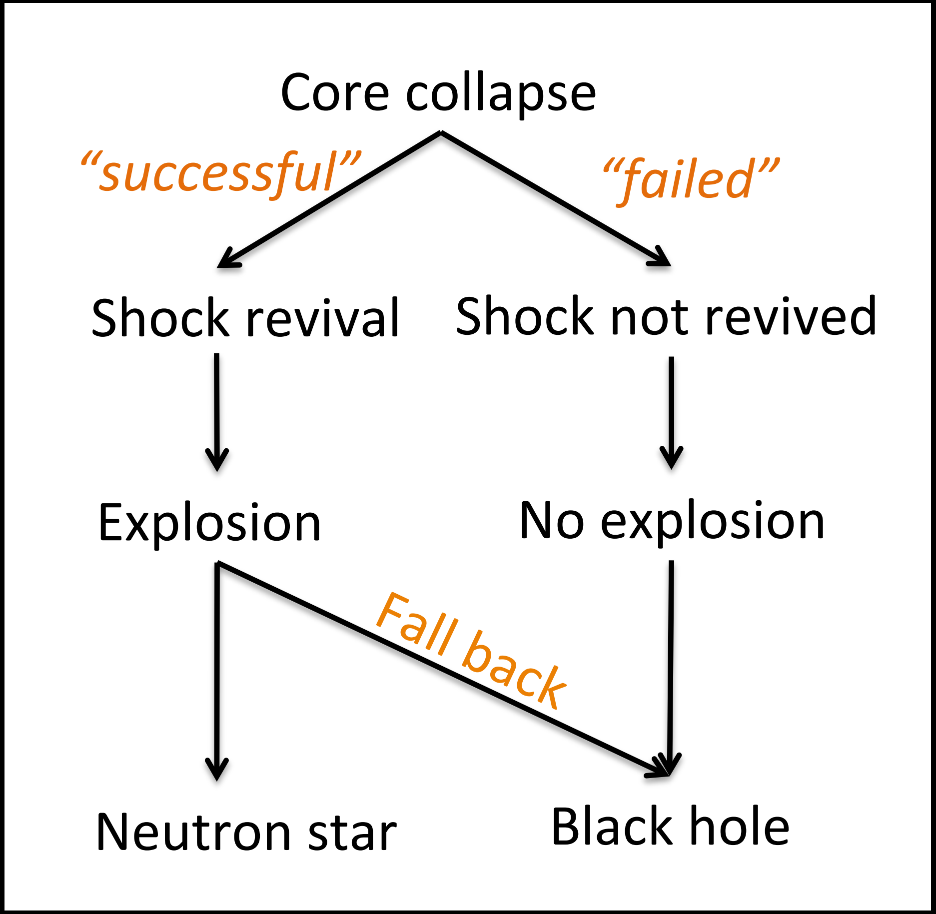


Liebendoerfer et al 2004, Fischer et al 2009, Sumiyoshi et al 06, 07, 08, 09, Nakazato et al 2008, 2010, O'Connor & Ott 2011, …

Systematic core-collapse simulations

Sophisticated simulations [no systematic studies yet]

- 3D with neutrino transport
- Few progenitor models
- Address: explosibility, neutrino and gravitational wave signals

Hanke et al (2013, 2014), Melson et al (2015), Lentz et al (2015), Takiwaki et al (2016) …

Systematic studies in spherically symmetry

- Spherically symmetric with parameterized neutrino heating
- $\sim$700 progenitor models
- GR gravity
- Address: progenitor dependence, black hole formation

Ugliano et al (2012), O'Connor & Ott (2011, 2013), Ertl et al (2015)

Systematic study in axis-symmetry

- Axis-symmetric with simplified neutrino transport (IDSA)
- $\sim$400 progenitor models
- Newtonian gravity
- Address: progenitor dependence, SASI, other observables (M_{Ni}, etc)

Nakamura et al (2014)

Progenitor compactness

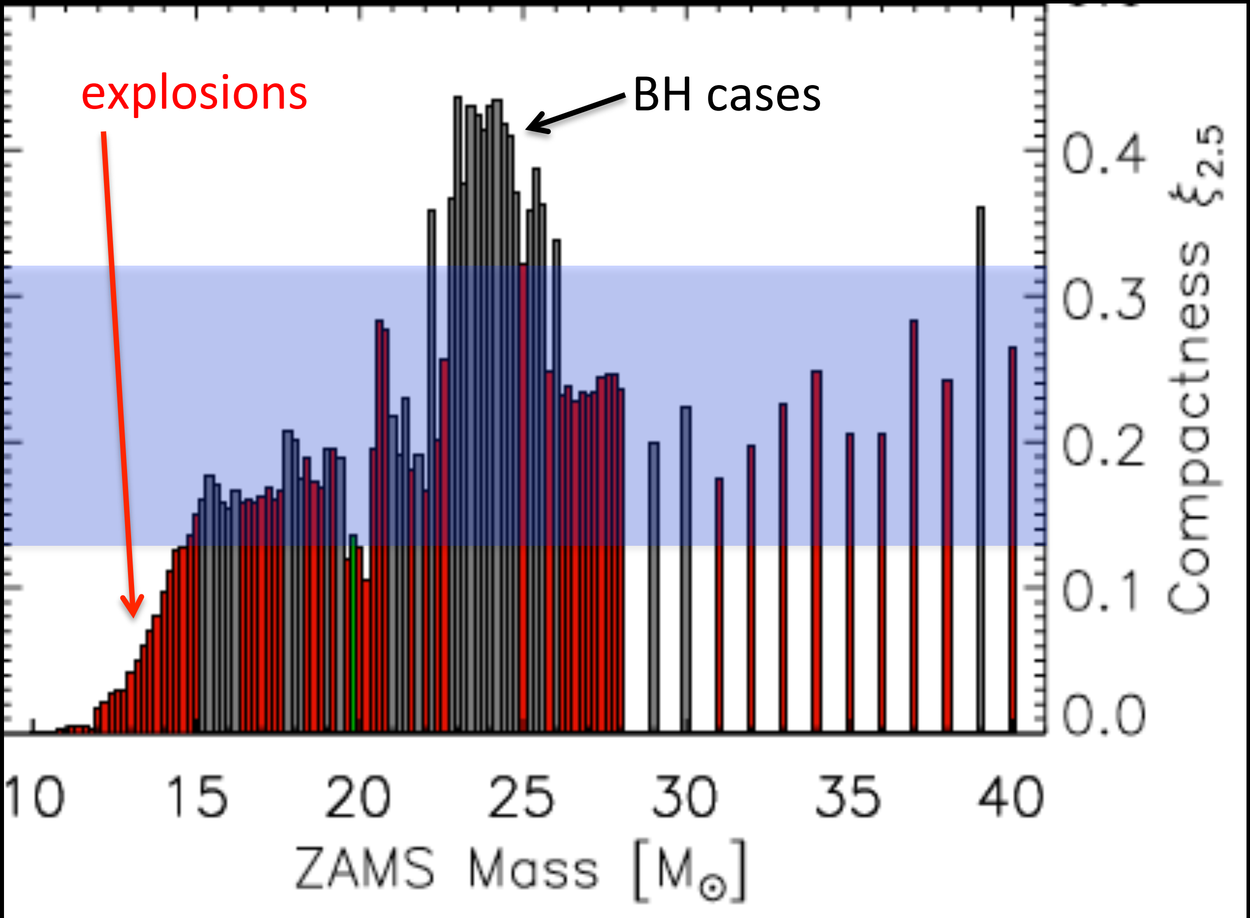
Compactness: is a useful indicator to discuss the eventual outcome of core collapse

$$\xi = \left. \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}} \right|_t$$

Successful / failed explosion threshold occurs in

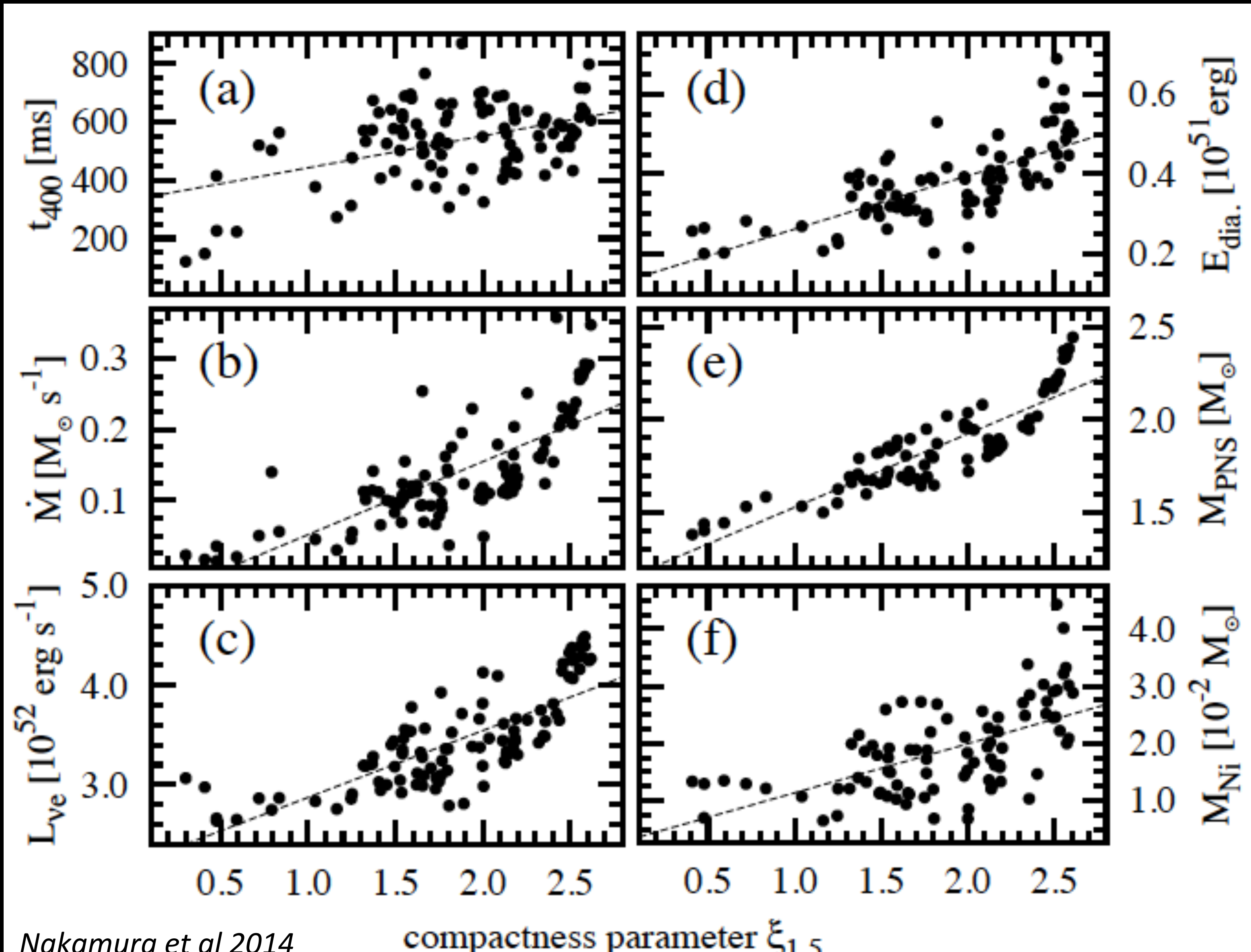
$$\xi_{2.5} \sim 0.1 - 0.35$$

but needs further studies



Ugliano et al (2012)
See also O'Connor & Ott (2011),
Horiuchi et al (2014),
Pejcha & Thompson (2015),
Ertl et al (2015)

Systematic results in 2D



Nakamura et al 2014

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Input 2: core-collapse rate (intensely studied by astronomers using photons, *rapidly improving*)

Input 3: neutrino detector capabilities (well understood for H_2O)

$$\bar{\nu}_e + p \to e^+ + n$$

Input 2: cosmic core-collapse rate

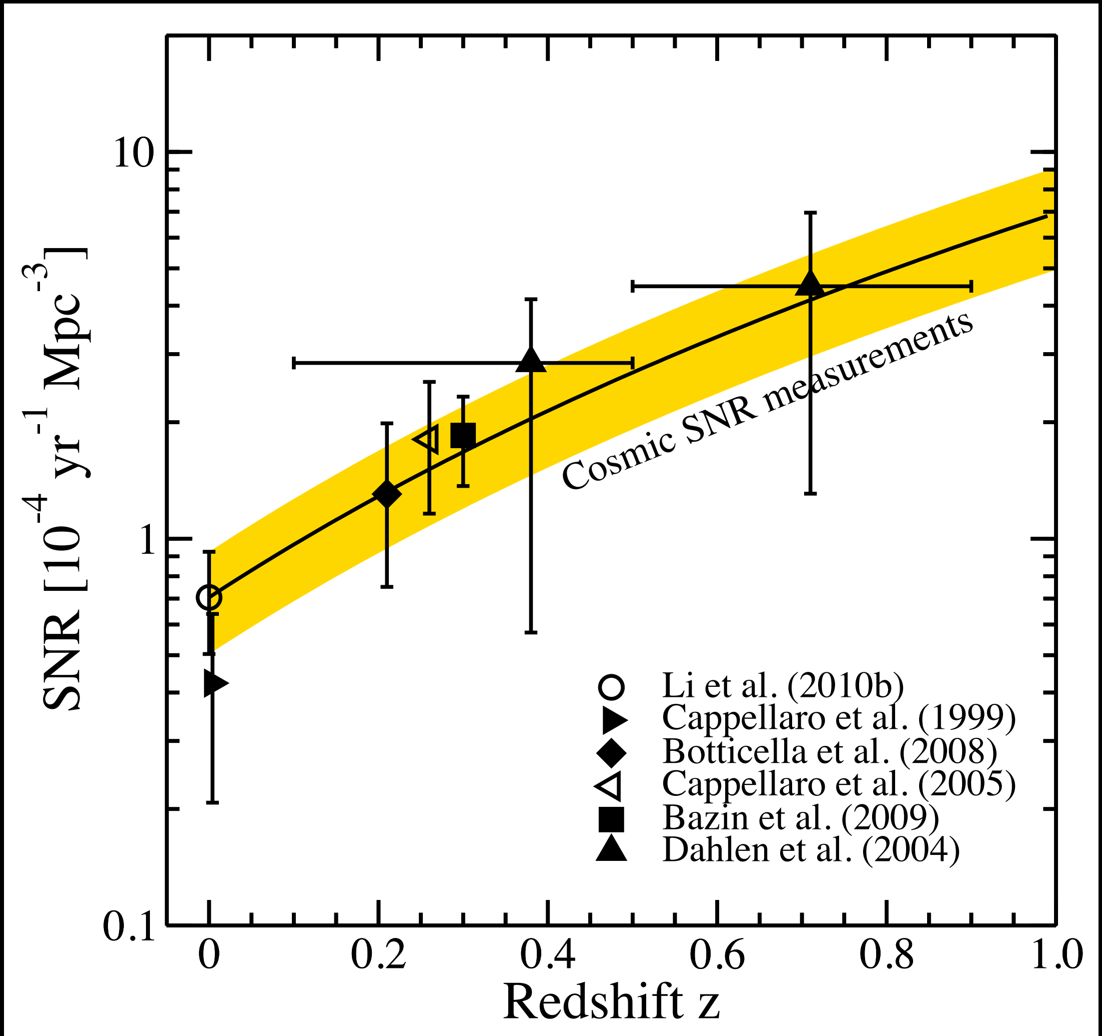
Direct measurements

Two different strategies:

- Target pre-selected galaxies, e.g., LOSS, STRESS
- Target pre-selected fields, e.g., SNLS, HST-ACS, SDSS, DES, …

Measurements converging and improving quickly

Note: at z = 0, approximately 0.01 Milky Way sized galaxy per Mpc^3 each with ~0.01 core collapse per year

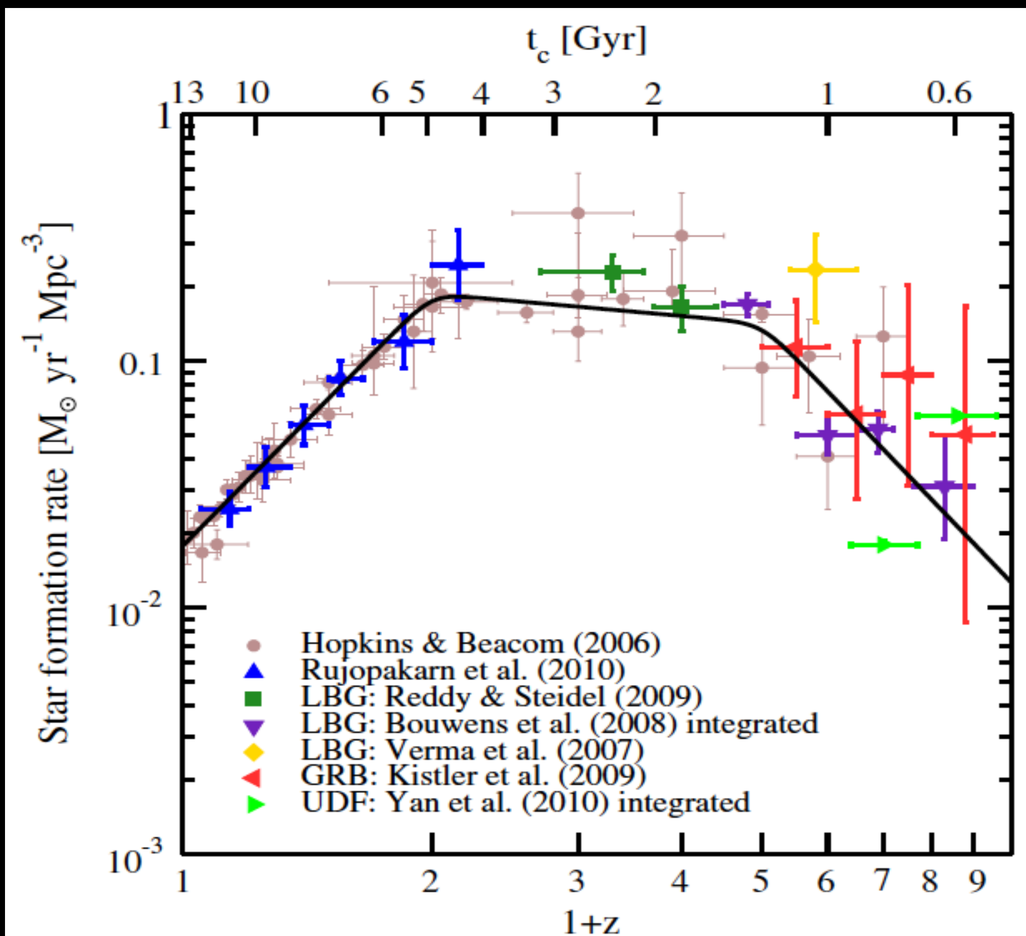


Adapted from Horiuchi et al (2010)

Birth rate of stars

Core collapse rate = Birth rate of massive stars

*because lifetime of massive stars are cosmologically short



The star formation rate

Measured by many groups using many wavebands (radio, FIR, MIR, NIR, Hα, UV, X rays) and data sets

$$SFR = (calibration) \times L_{gal}$$

Uncertainties are systematic

Mainly due to:

- dust corrections
- calibration factors
- Initial mass function

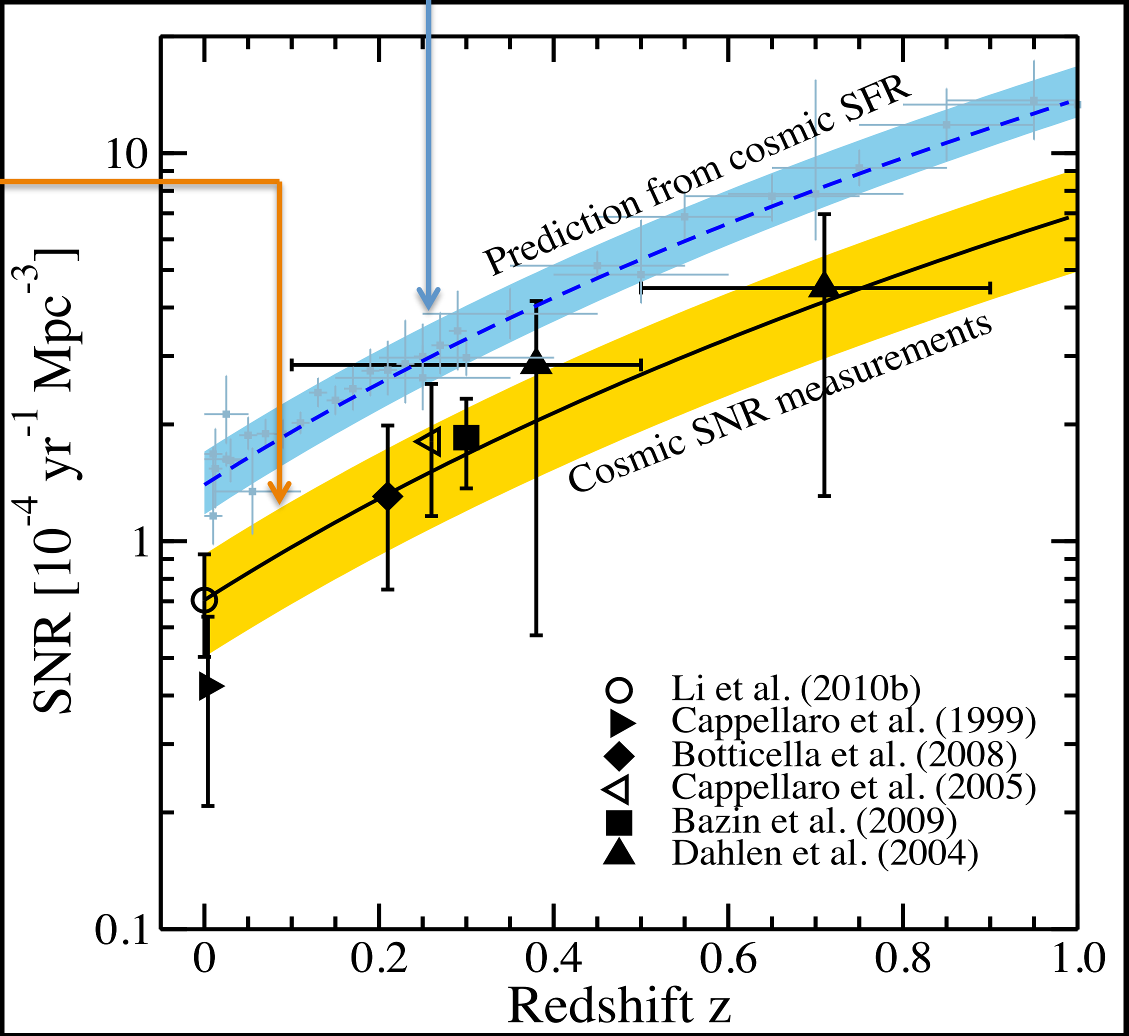
Horiuchi & Beacom (2010),
See also Hopkins & Beacom (2006),
Madau & Dickinson (2014)

Cosmic rates: estimate comparison

Birthrate of massive stars
Defined as 8 – 40 Msun stars

Observed supernova rate
Gives the observed core-collapse rate, probed by observations of _luminous_ supernovae.

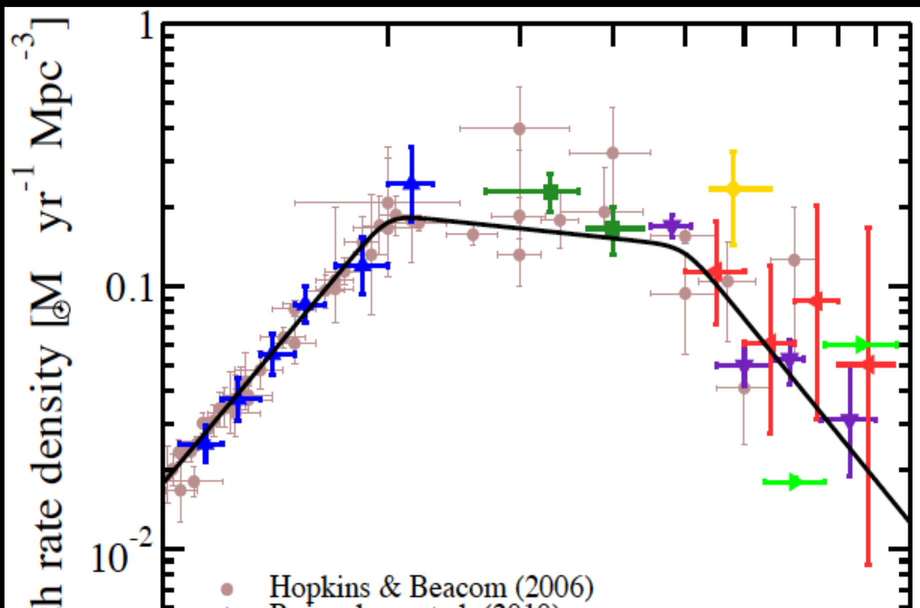
(Birth rate) – (supernova rate) = collapse to black hole?
Nominally the fraction looks to be up to 50%, but we must be careful



Horiuchi et al (2010)

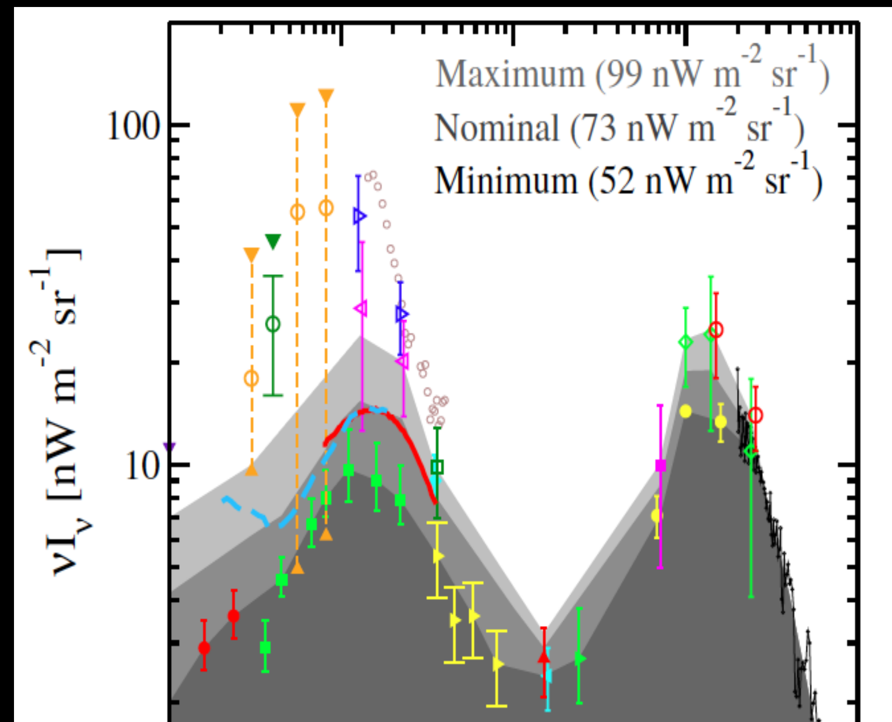
Is the birth rate artificially high?

Cosmic stellar birth rate density



IMF	Total EBL intensity	Error
Baldy-Glazebrook ‘03	78 nW m^{-2} sr^{-1}	54–109

Extragalactic background Light (EBL)



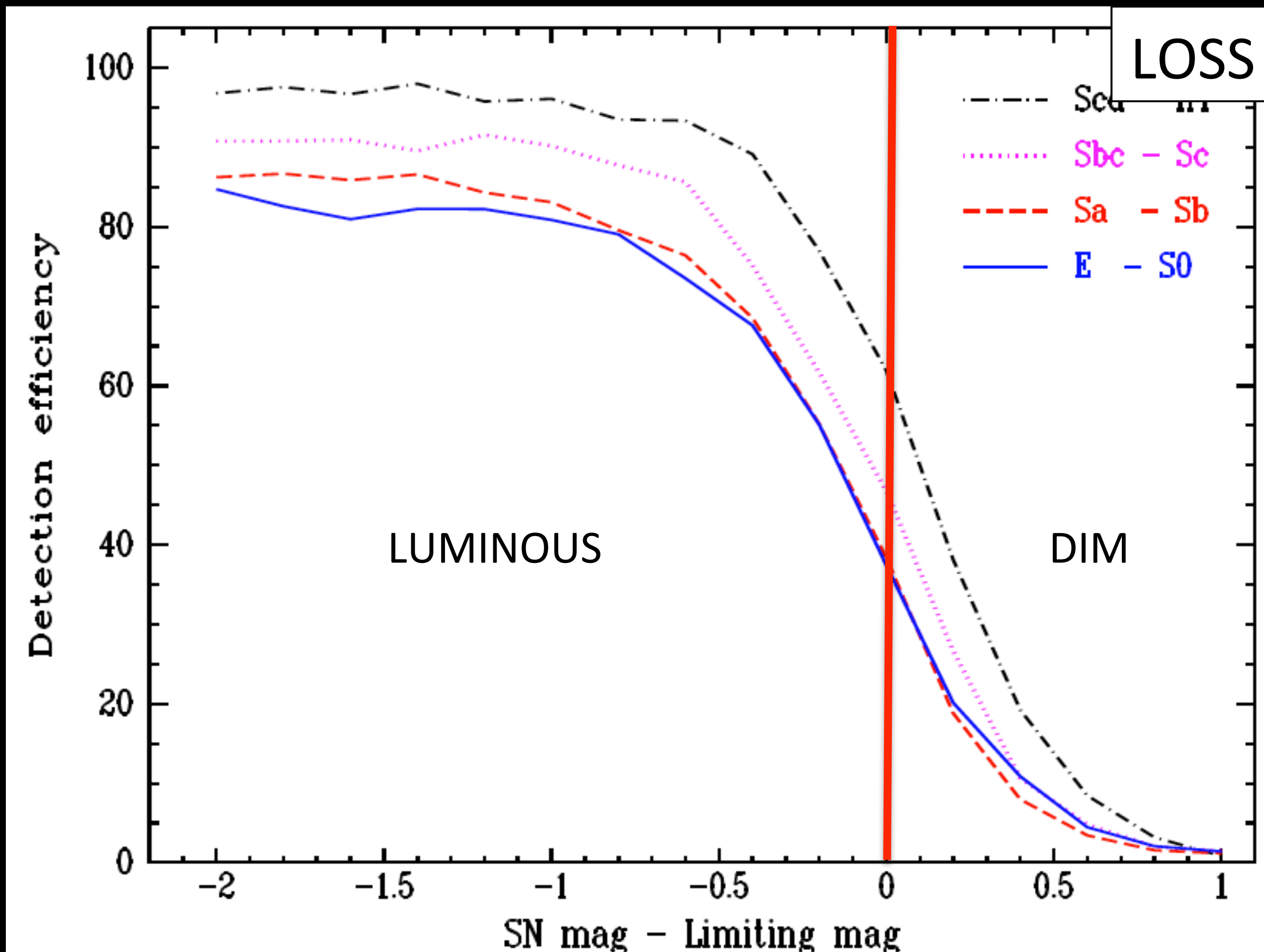
$$73^{+26}_{-21}\,\mathrm{nW\,m^{-2}\,sr^{-1}}$$

Horiuchi & Beacom (2010)
Many works, e.g., Yuksel et al (2008)
Hopkins & Beacom (2006)

Horiuchi et al (2009)
Many updates, e.g., Gilmore et al (2012)

Is the supernova rate artificially low?

Supernova rate measurements have similar rest-frame luminosity cut off sensitivities



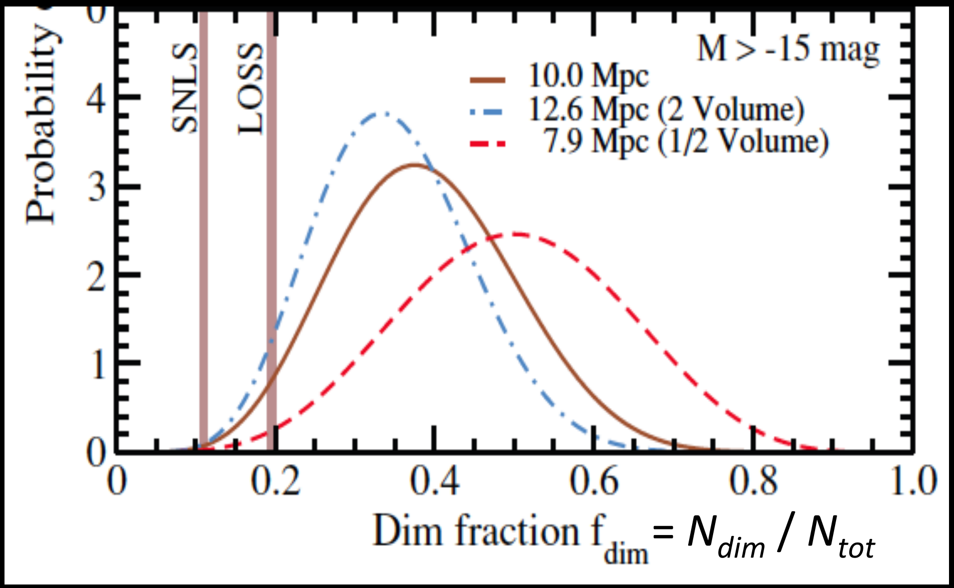
Local (within ~ 13 Mpc) supernovae

Shaded: falls below sensitivity cut of cosmic supernova rate studies

SN	Galaxy	Type	D (Mpc)	$E(B-V)$	Absolute Magnitude[a]	Discovery Phase
SN 2002bu	NGC 4242	IIn[b]	5.8	0.012	$M_R \approx -14.1$	Early
SN 2002hh	NGC 6946	IIP	5.9	0.342	$M_R \approx -14.3$	Early
SN 2002kg	NGC 2403	LBV	3.2	0.04	$M_V \approx -9$	Not CC SN
SN[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SN[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SN 2004et	NGC 6946	IIP	5.9	0.342	$M_R \approx -17.6$	Early
SN 2005af	NGC 4945	IIP	3.6	0.177	$M_R \sim -15.4$	1 month
SN 2005at	NGC 6744	Ic	7.1	0.043	$M_R \sim -15.1$	2 weeks
SN 2008bk	NGC 7793	IIP	4.1	0.019	$M_R \sim -15.5$	1 month
SN 2008iz	NGC 3034 (M82)	II?	3.5	0.159	no optical	Radio only
SN 2008S	NGC 6946	IIn[b]	5.9	0.342	$M_R \approx -13.3$	Early
NGC 300-OT	NGC 300	IIn[b]	1.9	0.013	$M_V \sim -12.3$	1 month
SN 2002ap	NGC 0628	IcPec	9.0	0.07	$M_R \approx -17.8$	Early
SN 2003gd	NGC 0628	IIP	9.0	0.07	$M_R \sim -16.7$	2 months
SN 2005cs	NGC 5194 (M51)	IIP	8.4	0.035	$M_R \approx -15.4$	1 month
SN 2007gr	NGC 1058	Ic	9.9	0.062	$M_R \approx -17.4$	Early
SN 2008ax	NGC 4490	IIb	9.6	0.022	$M_R \approx -16.6$	2 weeks
SN 2009hd	NGC 3627 (M66)	IIP	8.3	0.032	$M_R \approx -13.9$	Early
SN 2001ig	NGC 7424	IIb	11.5	0.011	$M_R \approx -17.3$	Early
SN 2003ie	NGC 4051	II	12.2	0.013	$M_R < -15.6$	Uncertain
SN 2003jg	NGC 2997	Ibc	11.3	0.109	$M_R \sim -14.1$	Few weeks
SN 2007it	NGC 5530	IIP	11.7	0.116	$M_V \approx -18.7$	Early
SN 2008eh	NGC 2997	Ibc?	11.3	0.109	$M_R \sim -15.3$	1 month
SN 2009ib	NGC 1559	IIP	12.6	0.03	$M_R \approx -15.9$	Early

Di-biased cosmic supernova rates

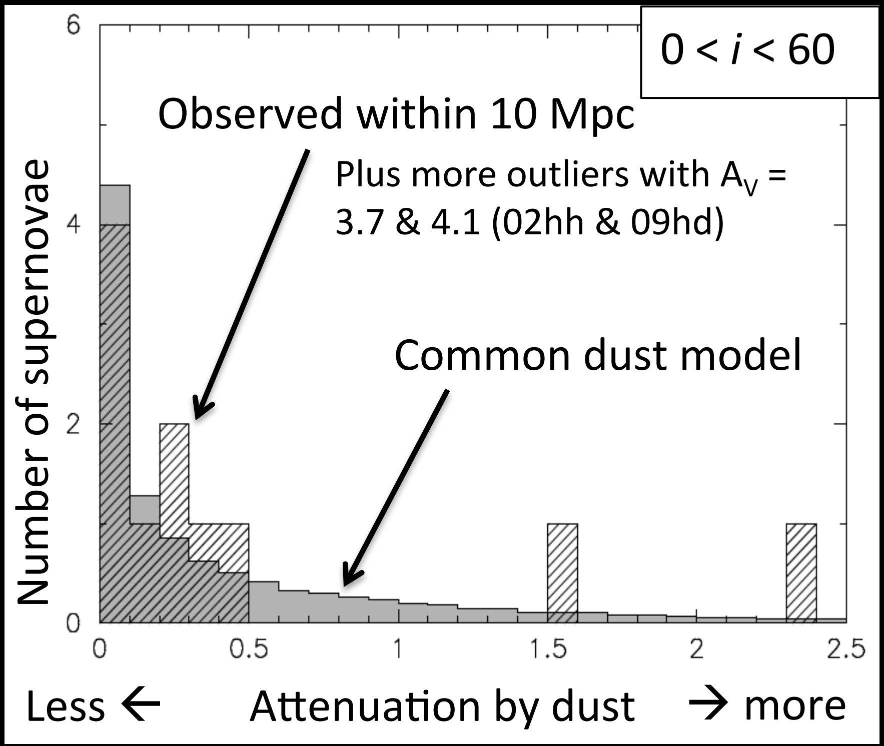
Missing dim supernovae
Such dim supernovae are typically missing from cosmic surveys



Horiuchi et al (2010)

→ *Mattila et al (2012), see also Mannucci et al (2007)*

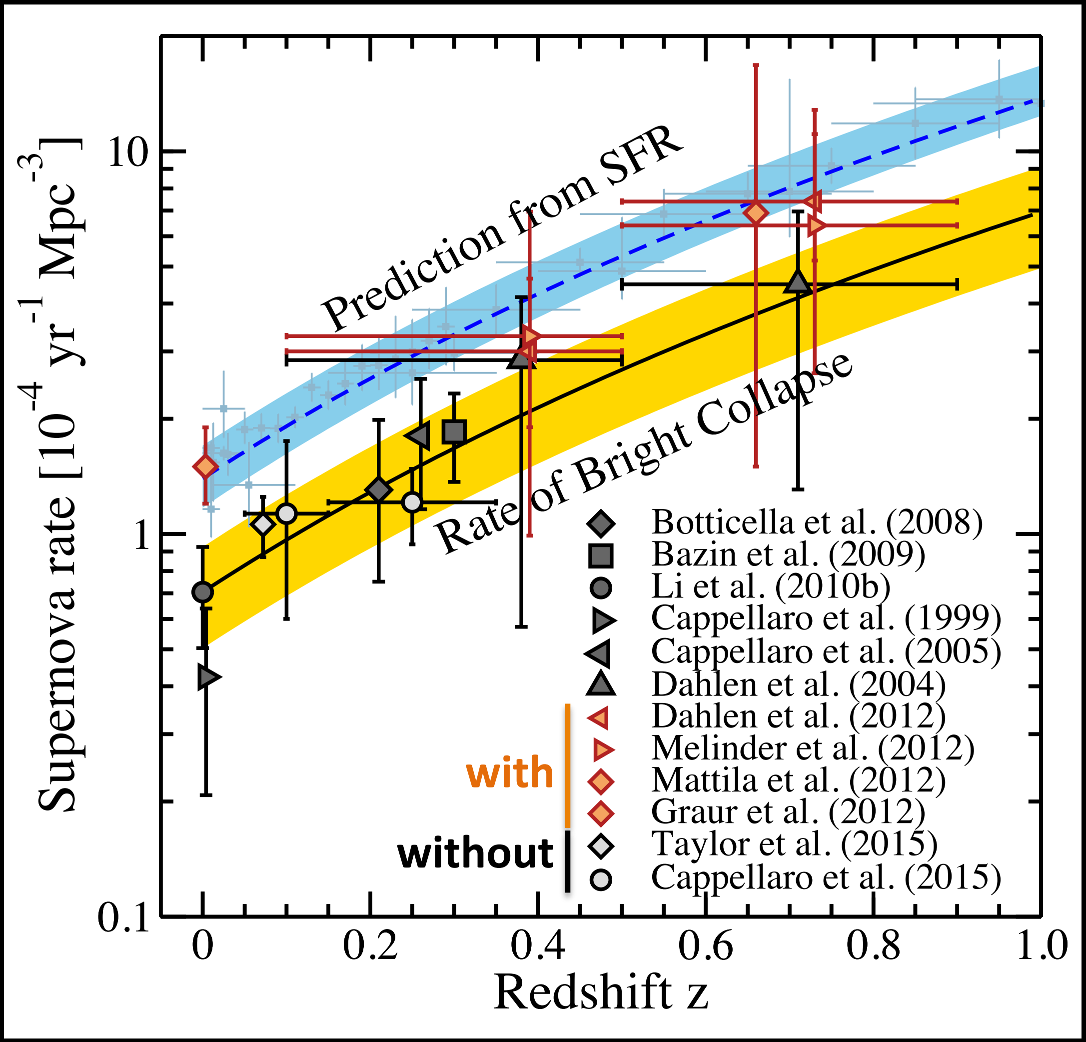
The reason:
Most of the locally dim supernovae are heavily dust attenuated objects.



➔ Cosmic rate measurements are underestimating dim supernovae

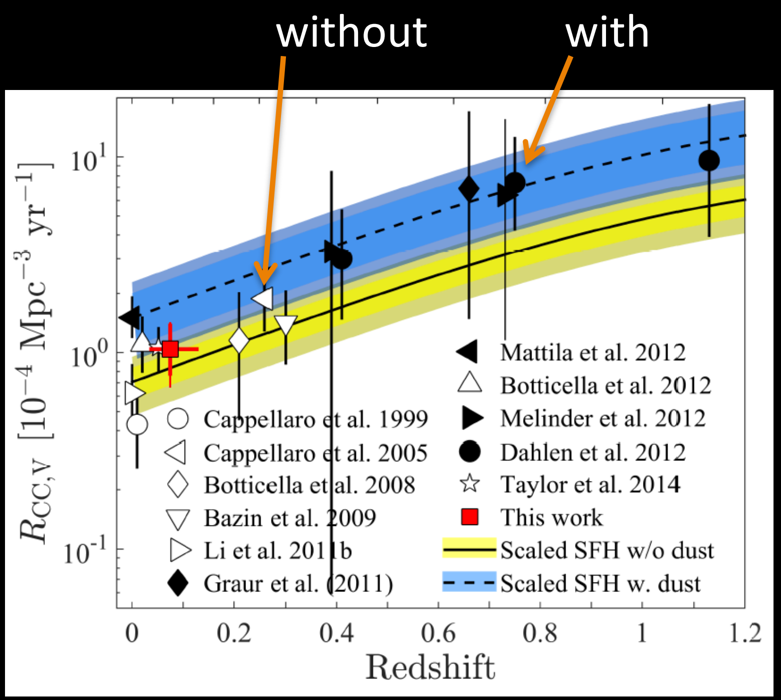
Di-biased cosmic supernova rates

Recent updates



Recent updates with and without correction for heavily dust attenuated supernovae

→ **BH fraction ~10-30%**

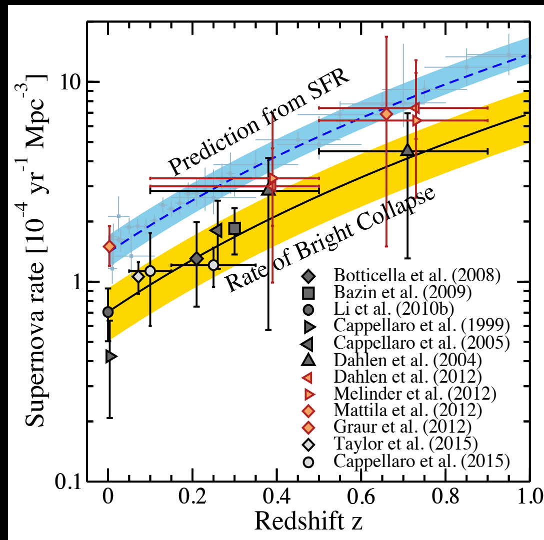


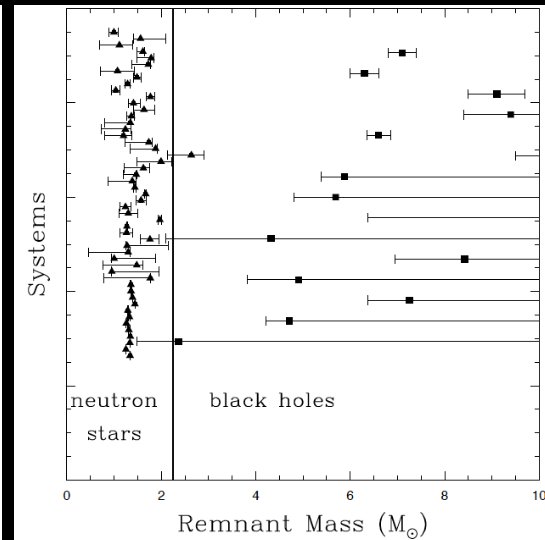
Graur et al (2015)

Input 2b: what is the black hole fraction?

Supernova rate

~10-30%





Black hole mass function

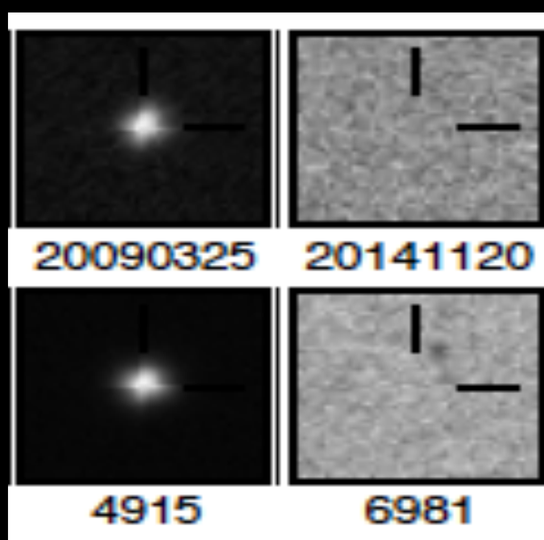
~20-30%

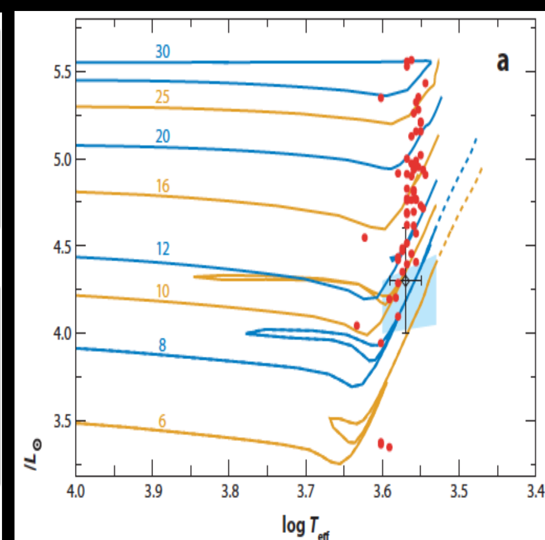
Kochanek et al (2014)

Search for failed explosion

~10-40%

Gerke et al (2014)

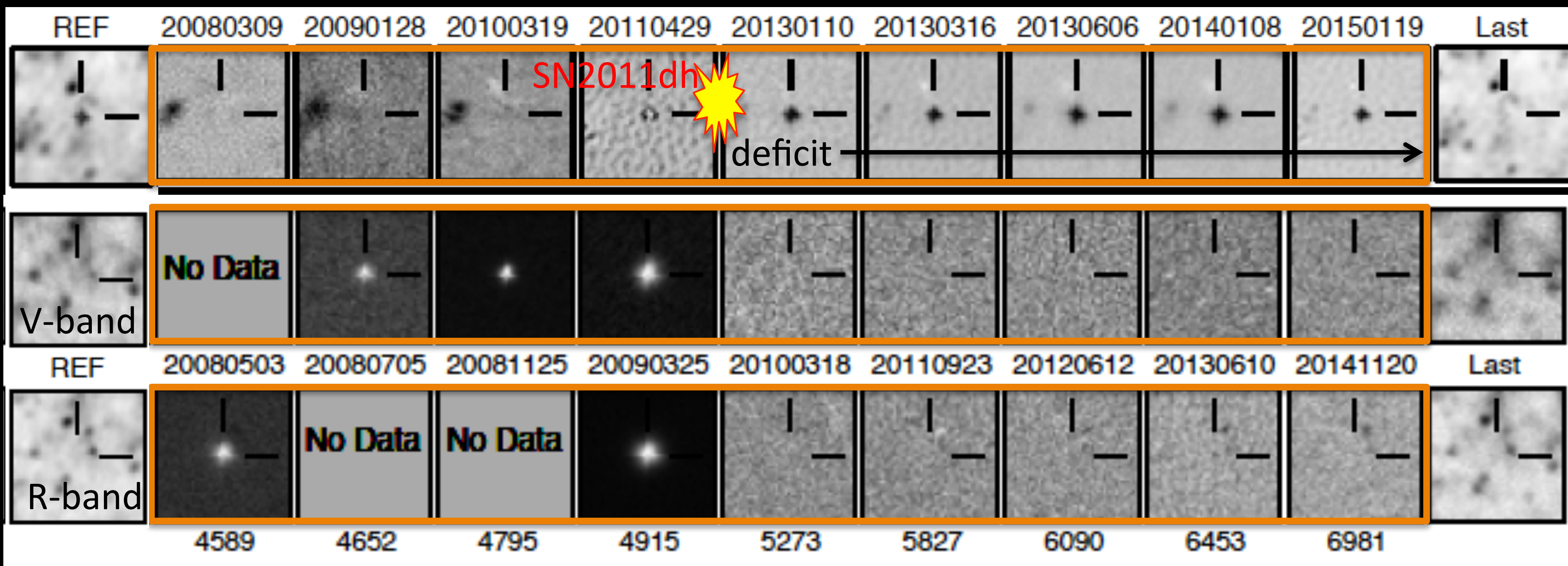




Red supergiant problem

~20-30%

Smartt et al (2009)
Horiuchi et al (2014)



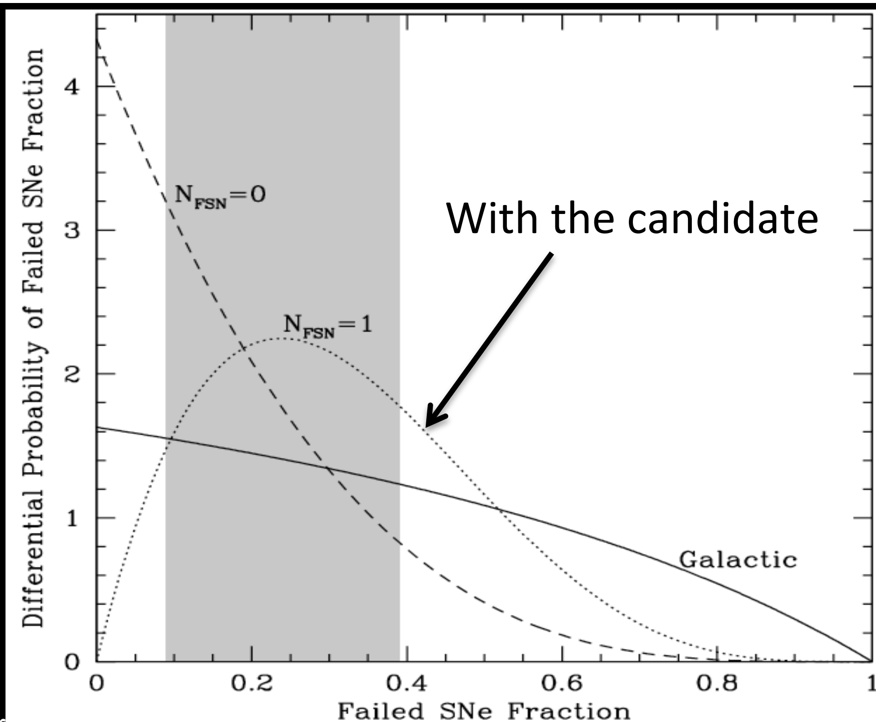
Survey about Nothing: results so far

In 4 years running,

- 3 luminous CC supernovae: SN2009dh, SN2011dh, SN2012fh
- 1 candidate failed supernova: NGC6946-BH1 (@~6Mpc)

→ **Peak failed collapse rate 10 – 40%**

Kochanek et al. (2008),, Gerke et al (2015)

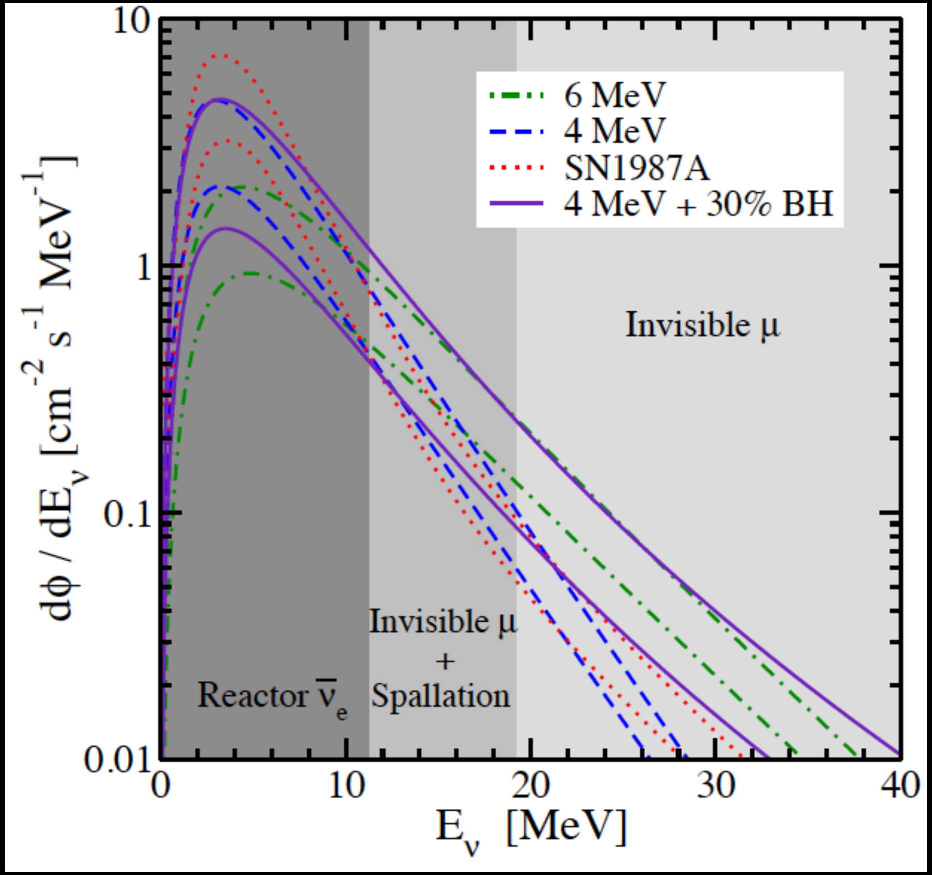


The DSNB flux

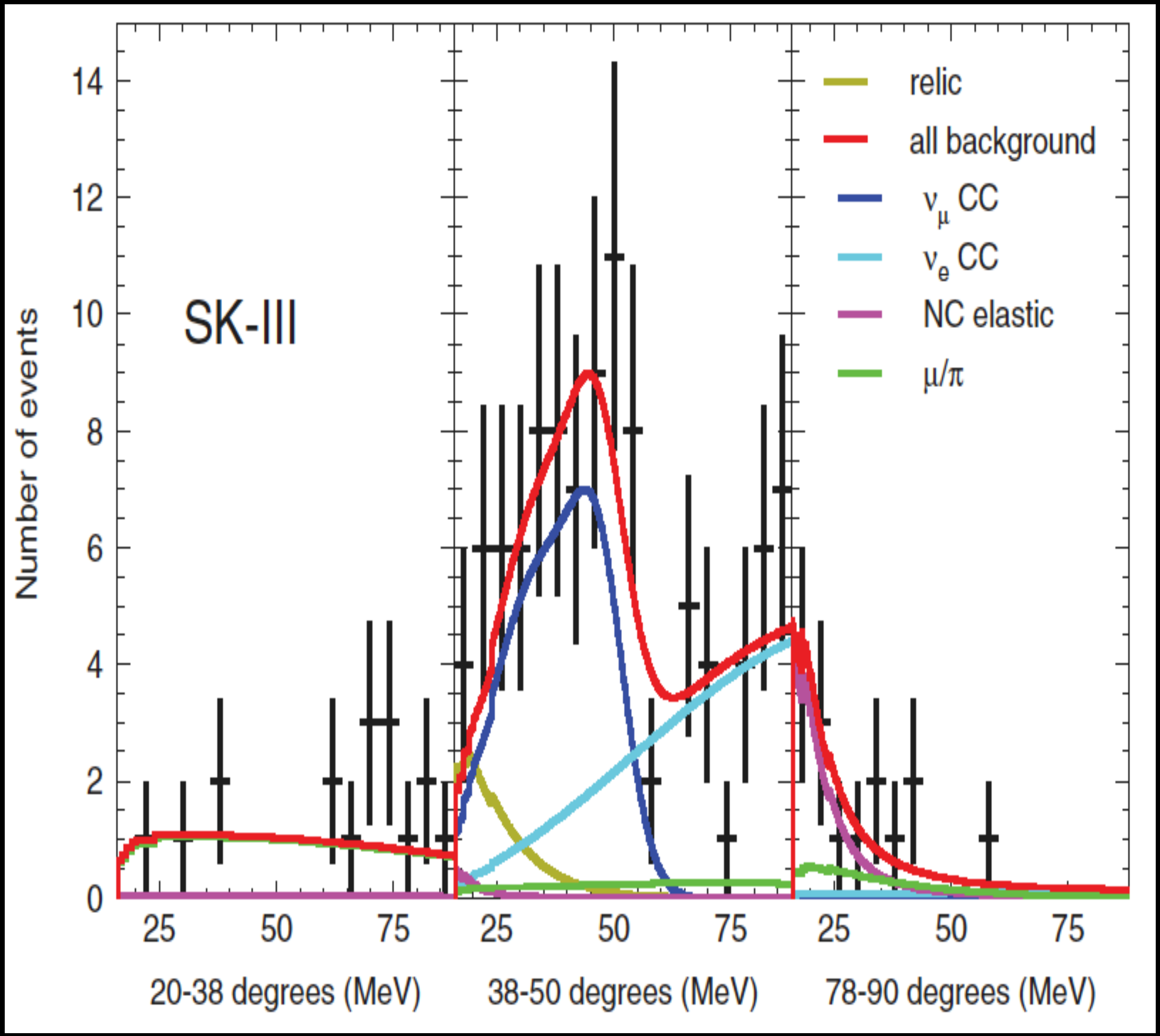
- We know there are many core collapse in the past
- We know each emits copious neutrinos
- We know both of these quantitatively

So, can we detect the neutrinos?

The DSNB flux:



Searches: backgrounds and limits



Bays et al (2012)

Kamiokande-II

Flux < 226 $cm^{-2}\ s^{-1}$

[19 – 34 MeV, 90%CL]

Zhang et al. (1988)

Super-Kamiokande (SK-I)

Flux < 1.2 $cm^{-2}\ s^{-1}$

[>19.3 MeV, 90%CL]

Malek et al. (2003)

SK-I, SK-II, and SK-III:

Flux < 2.0 $cm^{-2}\ s^{-1}$

[E_{e+} > 18 MeV, 90%CL]

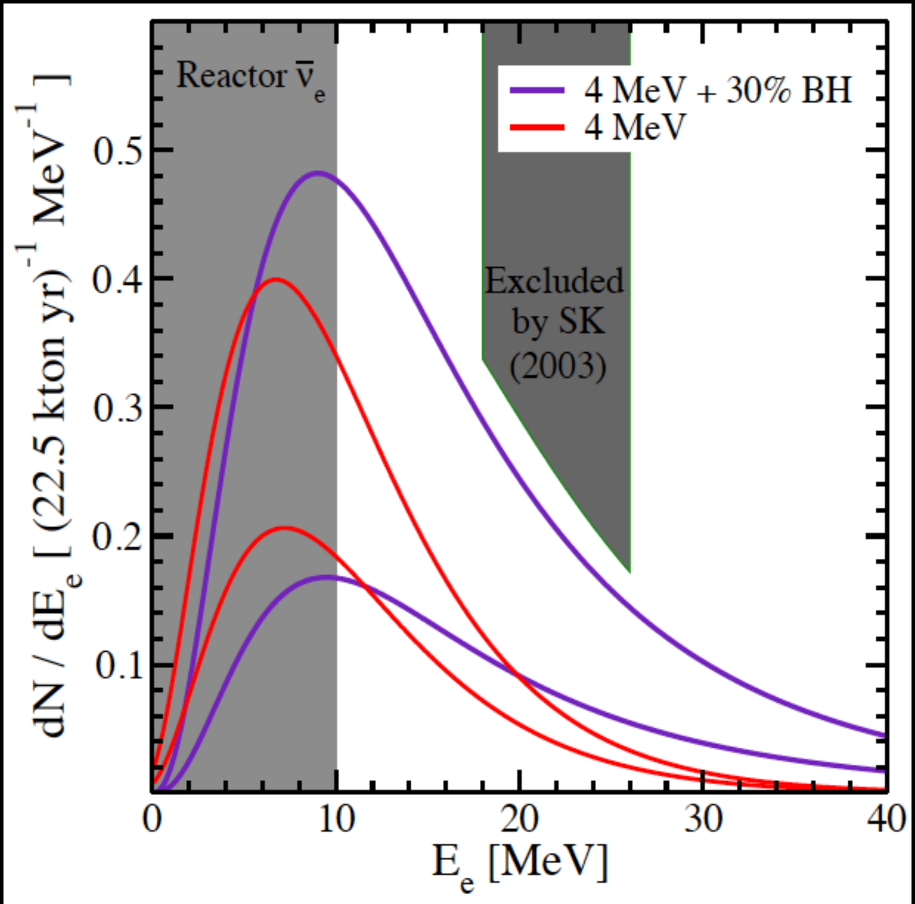
Bays et al (2012)

Low-E update, Zhang et al (2014)

DSNB event rates

Event spectrum:

Upper limits already rule out extreme neutrino emissions (e.g., T = 8 MeV).
Also, the uncertainty due to supernova rate is getting competitively small



Adapted from Horiuchi, Beacom, Dwek (2009)

Event rates [/yr] at Super-K

Spectrum	Current Super-K [/yr]
4 MeV	0.4 +/- 0.1
4M+30% BH	1.1 +/- 0.3
SN1987A	0.5 +/- 0.1

Event rates [/yr] at Hyper-K

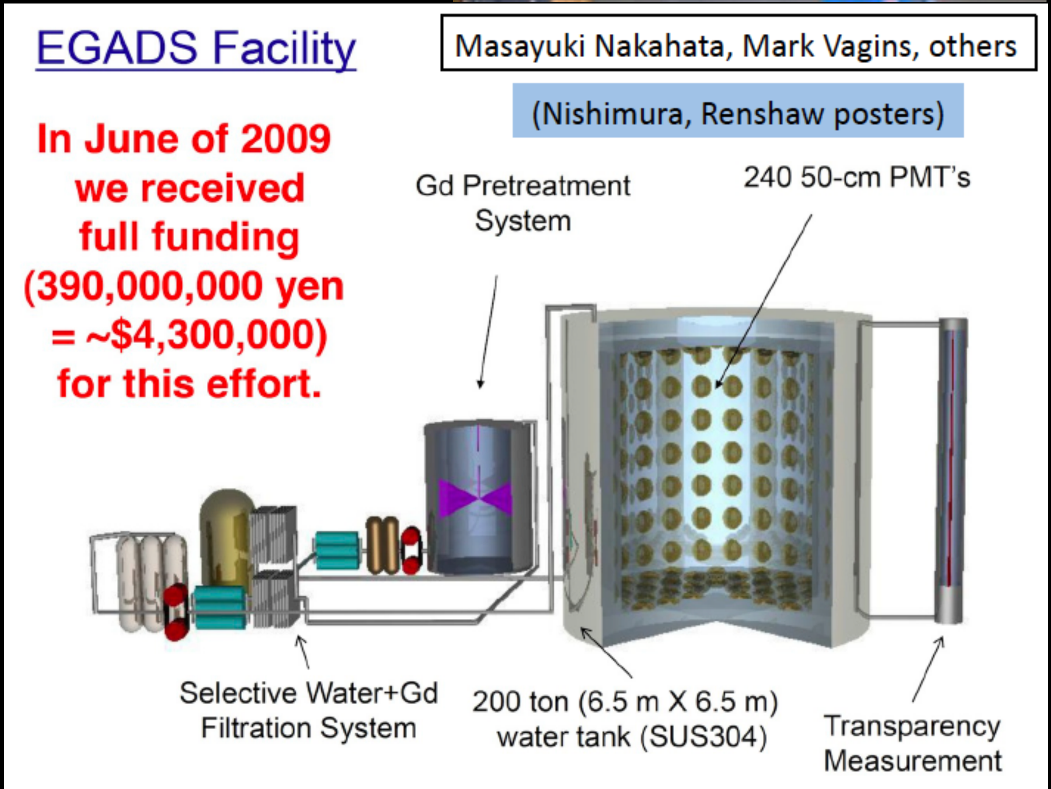
Spectrum	18 – 26 MeV [/yr]
4 MeV	7 +/- 2
4M+30% BH	18 +/- 5
SN1987A	8 +/- 2

Gd enhancement

Beacom & Vagins (2004): use dissolved Gadolinium (Gd) for effective neutron-tagging

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

H_2O	H_2O + Gd
Capture on protons, 2.2 MeV gamma (below threshold)	Capture on Gd, ~8 MeV gamma, easily detectable coincidence signal



(from Vagins)

EGADS = Evaluating Gadolinium's Action on Detector Systems

Success and refined to:
EGADS = Employing Gadolinium to Autonomously Detect Supernovas

DSNB event rates

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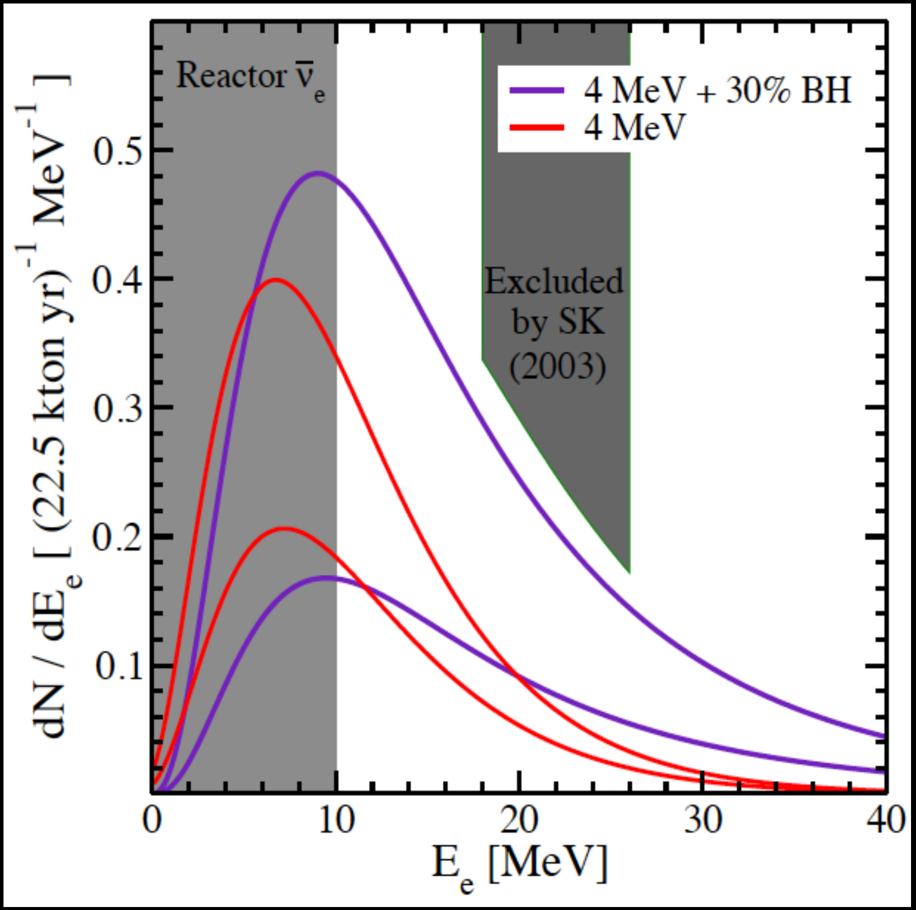


Adapted from Horiuchi, Beacom, Dwek (2009)

Event rates [/yr] at Super-K

Spectrum	Current Super-K [/yr]	With Gd upgrade [/yr]
4 MeV	0.4 +/- 0.1	1.8 +/- 0.5
4M+30% BH	1.1 +/- 0.3	3.0 +/- 1.0
SN1987A	0.5 +/- 0.1	1.7 +/- 0.5

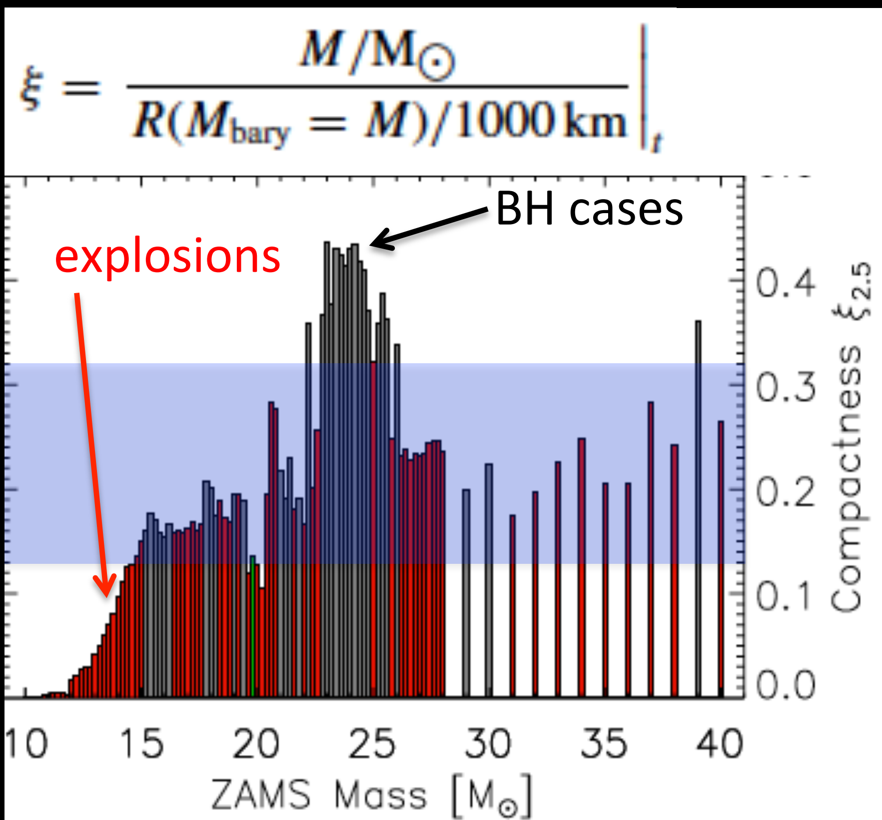
Event rates [/yr] at Hyper-K

Spectrum	18 – 26 MeV [/yr]	10 – 26 MeV [/yr]
4 MeV	7 +/- 2	30 +/- 8
4M+30% BH	18 +/- 5	50+/- 17
SN1987A	8 +/- 2	28 +/- 8

Probe of explosion / failure threshold

Critical compactness

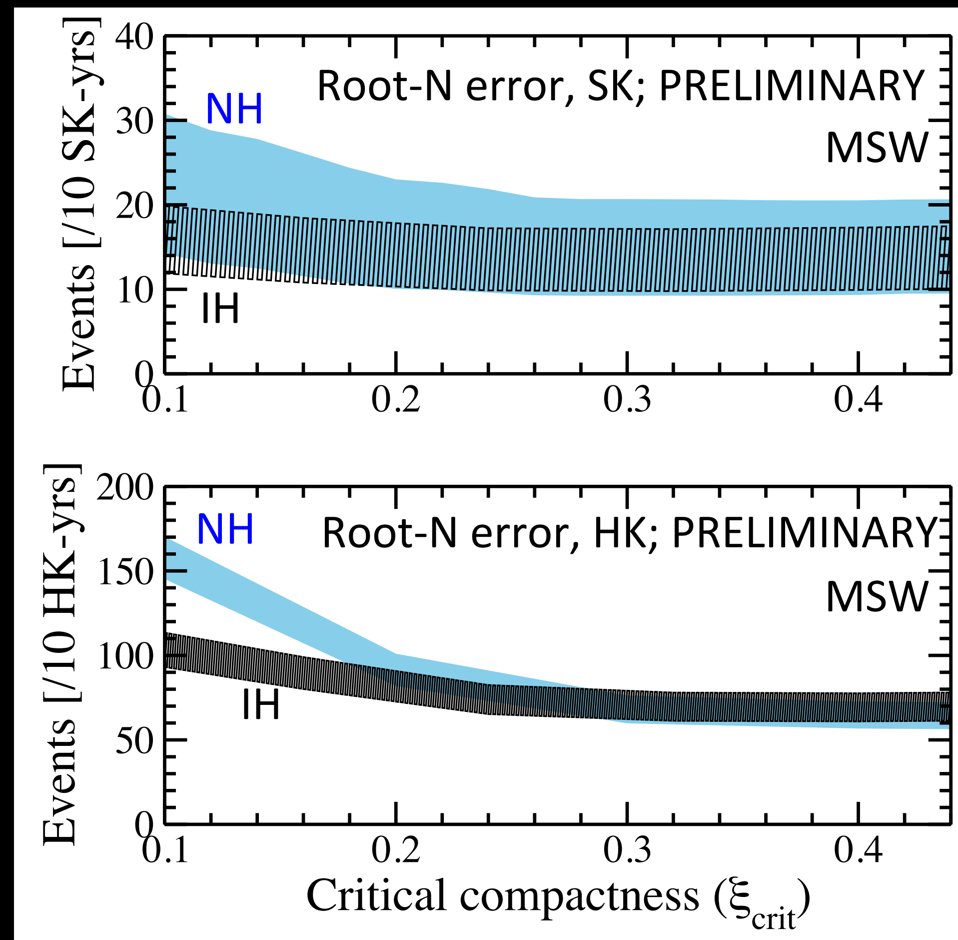
Successful / failed explosion threshold occurs between $\xi_{2.5} \sim 0.1 - 0.35$?



O'Connor & Ott (2011), Ugliano et al (2012), Horiuchi et al (2014), Pejcha & Thompson (2015), Ertl et al (2015)

DSNB probes

Event rate will be sensitive to the critical compactness



Summary

The DSNB is a guaranteed signal

- We know core collapse occur regularly: with constant updates from astronomers
- We know each emit neutrinos: from SN1987A observations, but also constant updates from theory, in particular the combination of state-of-the-art and systematic simulations

There are excellent prospects for DSNB detection

- On-going Gd upgrade at Super-K to deliver signal limited search

The DSNB holds interesting physics of explosions / black hole formation

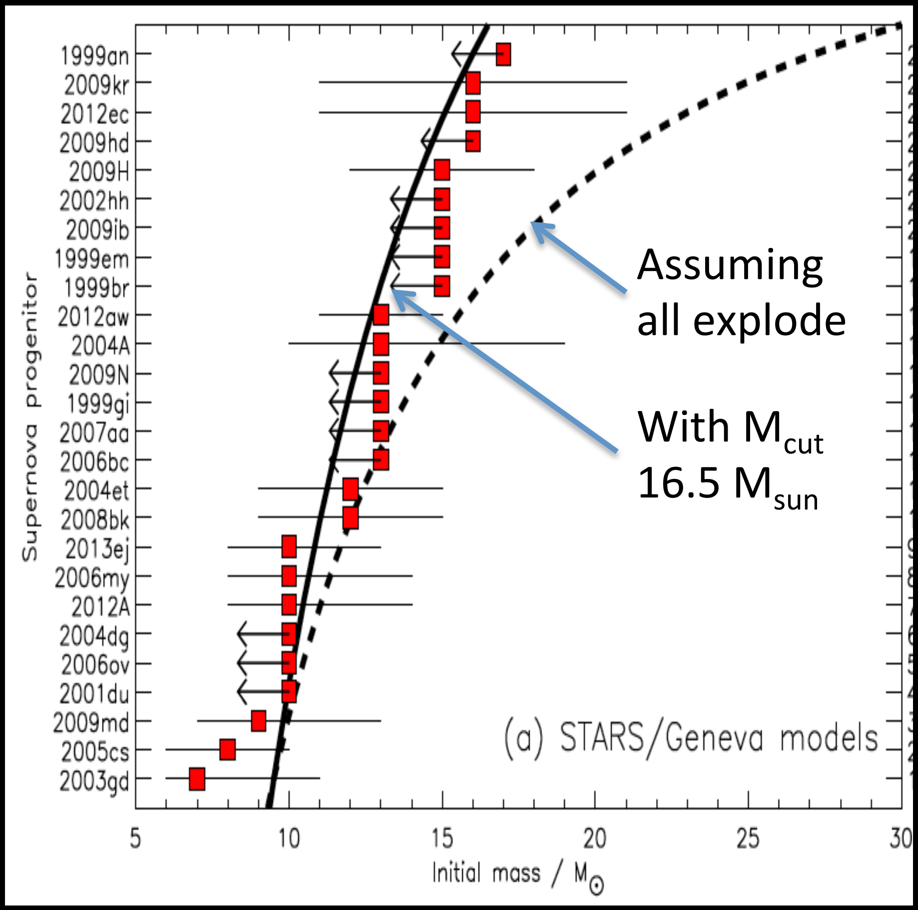
- Future high-statistics DSNB can shed light on critical compactness

BACKUP SLIDES

1. Red supergiant problem

Some stars don't explode?

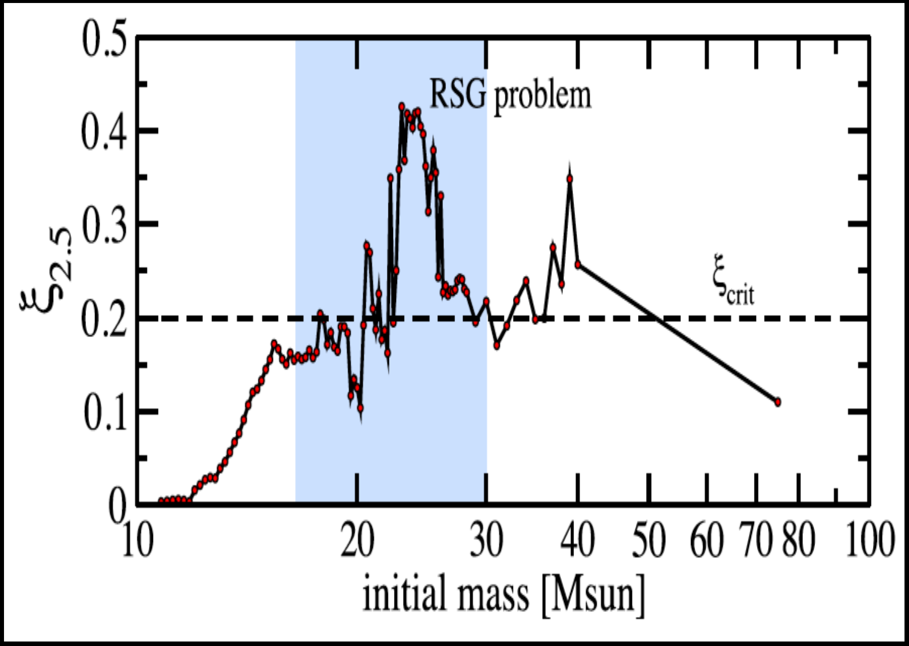
Observationally, the red supergiants with mass 16 – 25 Msun are not exploding



Smartt (2015)

This is ~20% of massive stars.

The mass range in question is an island of high compactness → theoretically more likely to form black holes.



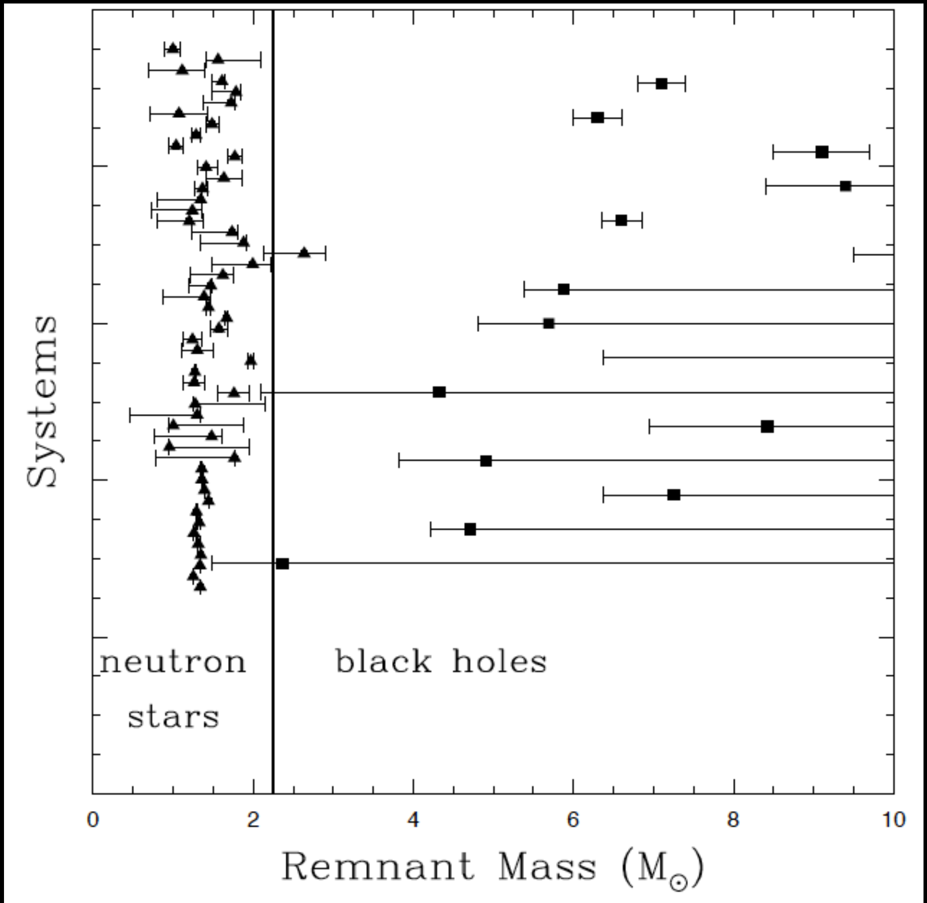
Horiuchi et al (2014); see also Kochanek (2014)

Requires low critical $\xi_{2.5}$ ~ 0.2

→ Needs testing by 3D simulations

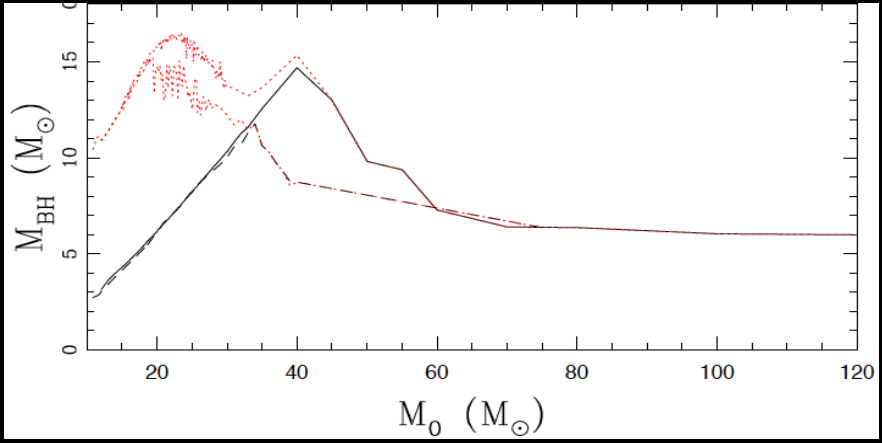
2. Black hole mass function

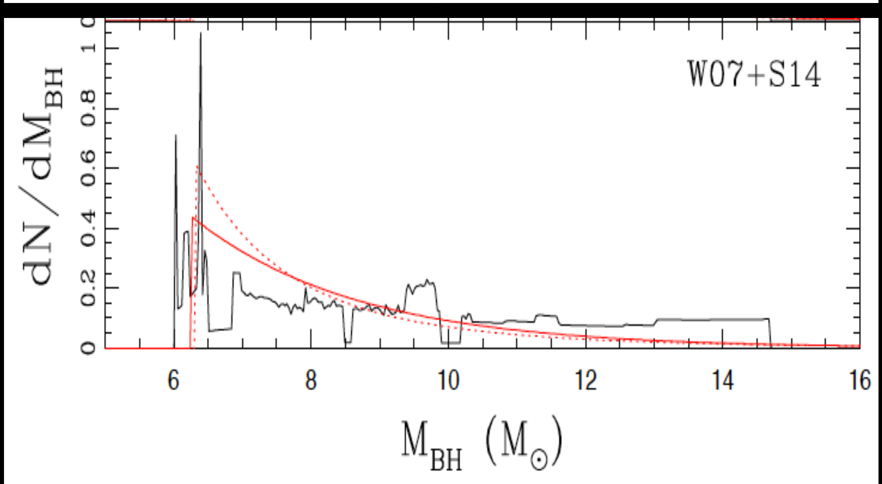
Compact object mass function:
There are hints of a dearth of compact black holes just above the NS mass range



e.g., Kreidberg et al. (2012), Kizeltan et al. (2013)

A critical compactness $\xi_{2.5}$~0.2 predicts a black hole mass function with a cutoff





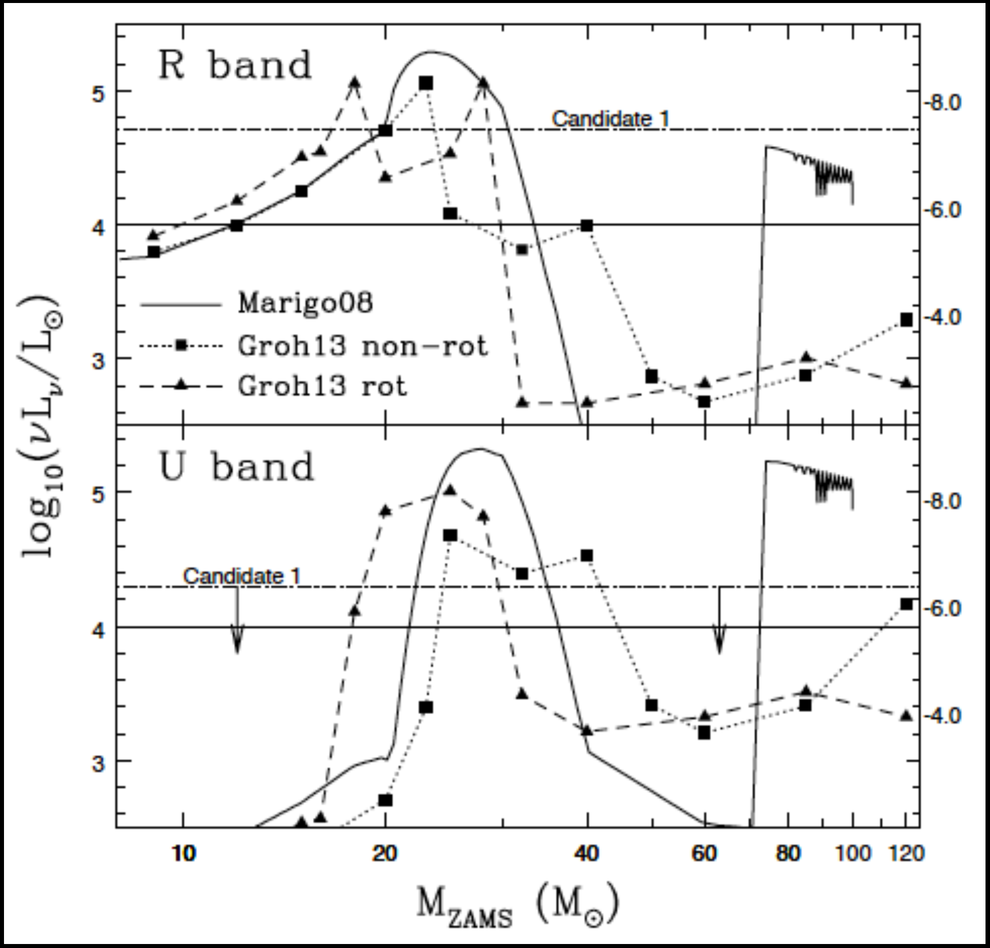
Lovegrove & Woosley 2013, Kochanek (2014)

4. Searching for failed explosions: Survey about nothing

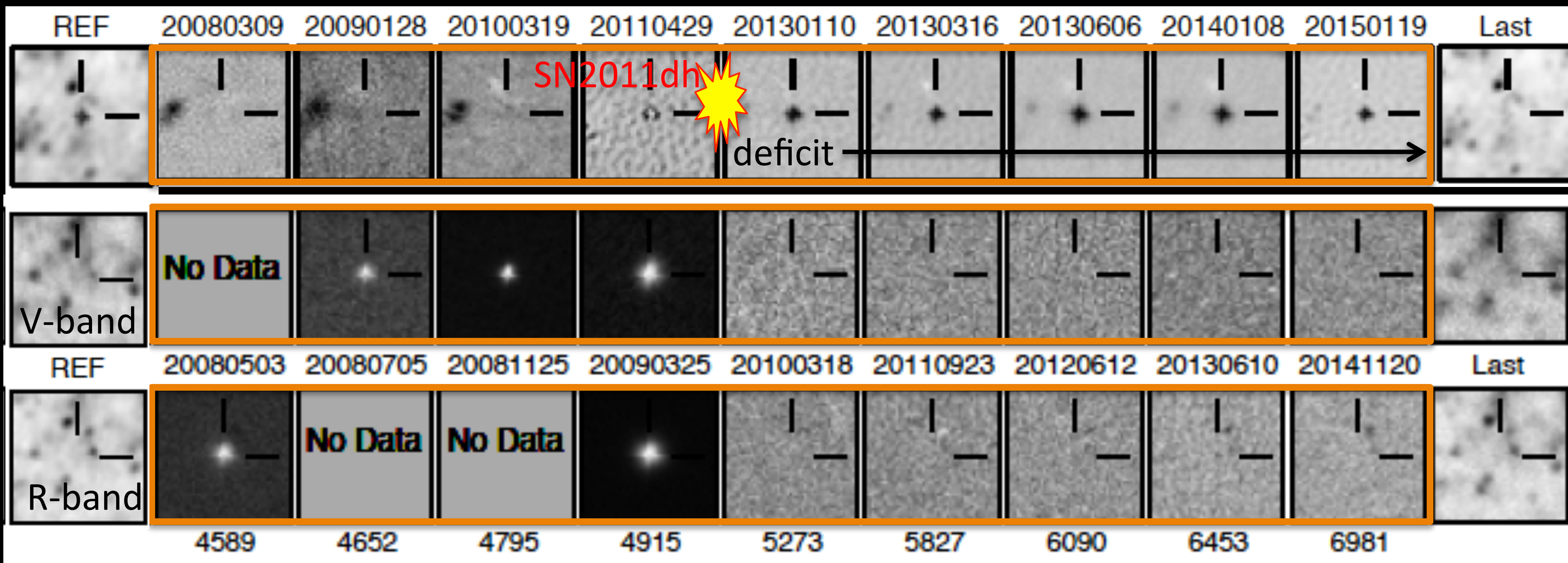
Survey About Nothing

- Look for the disappearance of red-supergiants in nearby galaxies
- Monitor 27 galaxies with the Large Binocular Telescope
  - → $\sim 10^6$ red supergiants with luminosity > 10^4 Lsun
  - → expect $\sim$1 core collapse /yr
  - → In 10 years, sensitive to 20 – 30% failed fraction at 90%CL

Kochanek et al. (2008)



Gerke et al. (2015)



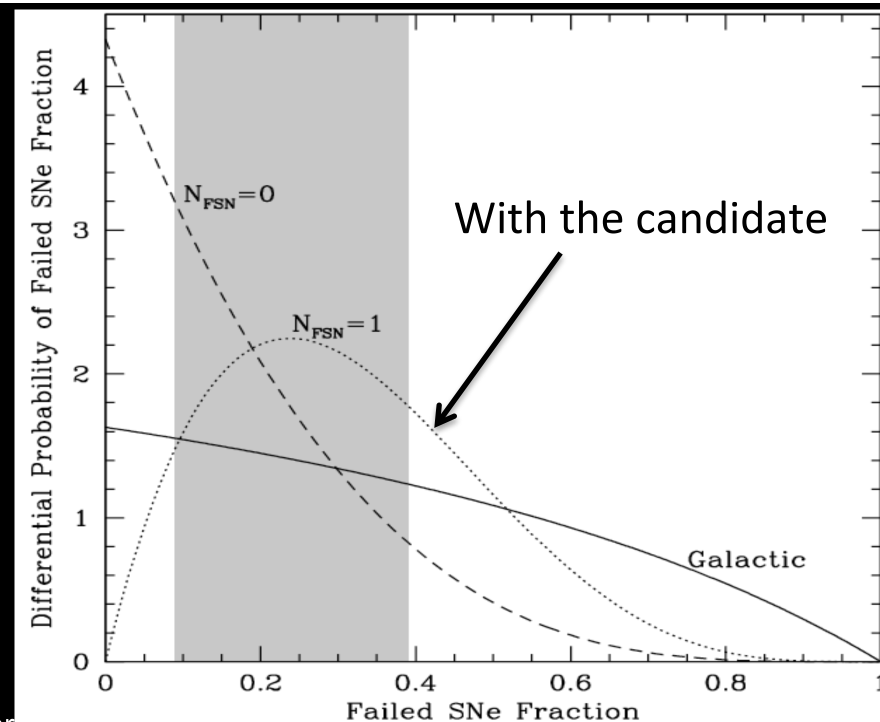
Results so far:

In 4 years running,

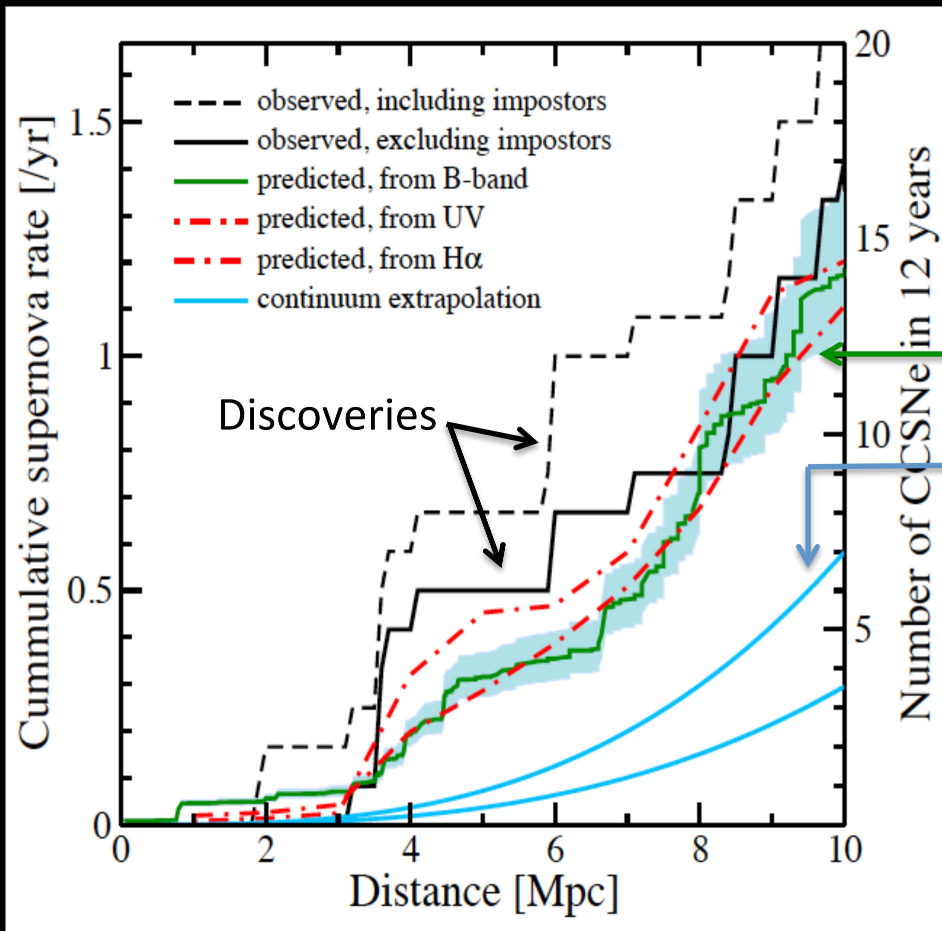
- 3 luminous CC supernovae: SN2009dh, SN2011dh, SN2012fh
- 1 Type Ia (SN2011fe)
- 1 candidate failed supernova: NGC6946-BH1 (@~6Mpc)

→ **Peak failed collapse rate 10 – 40%**

Gerke et al (2015)



Mini-bursts: reach into our neighbors



Horiuchi et al. (in prep); see also Ando et al. (2005)

High nearby supernova rates:

Both observations and predictions show that our neighborhood has an ***enhancement*** of supernovae wrt the smooth limit

Predictions

Smooth limit

Yields in Hyper-K without/with Gd:

$$N_{e^+}(18 < E_{e^+} < 30) \approx 5 \left(\frac{d}{1\,\mathrm{Mpc}}\right)^{-2}$$

$$N_{e^+}(12 < E_{e^+} < 38) \approx 9 \left(\frac{d}{1\,\mathrm{Mpc}}\right)^{-2}$$

Can probe out to a few Mpc

Mini-burst Prediction

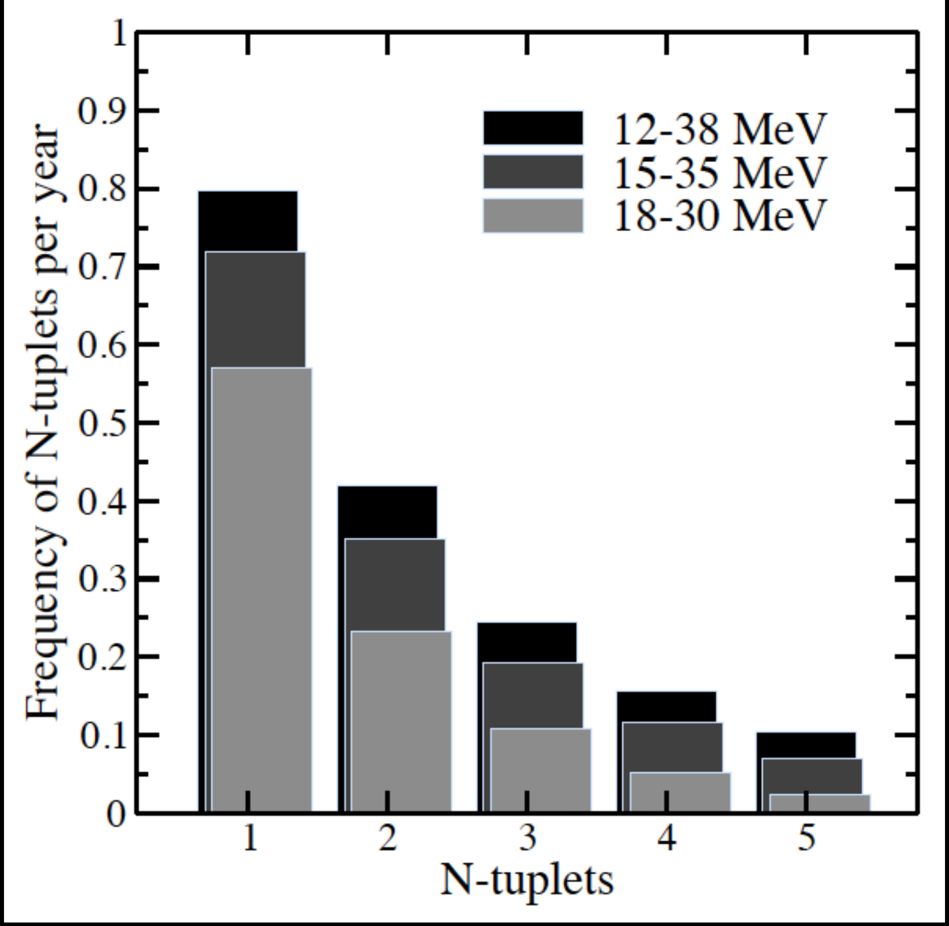
Targets:
Coincidence with nearby supernovae and also failed supernovae (Survey about Nothing)

Backgrounds:
The usual suspects: reactor and atmospheric neutrinos, spallation daughter decays, invisible muon decays

Background control:
Narrow the time window helps reduce accidental signals caused by backgrounds

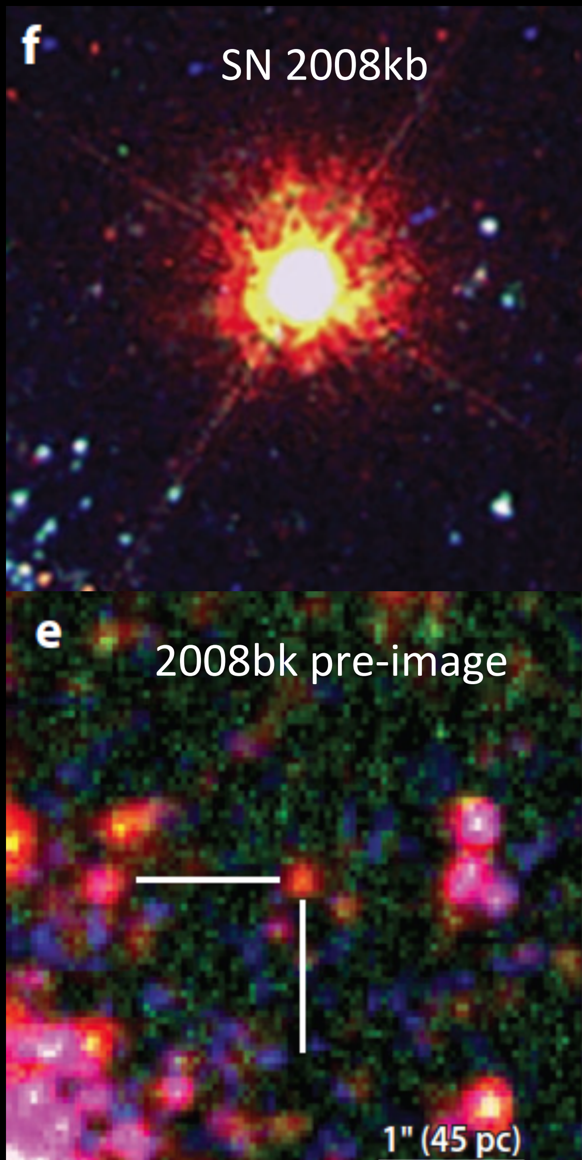
Rate of neutrinos (total):
12 – 38 MeV: 1.6 per yr
15 – 35 MeV: 1.2 per yr
18 – 30 MeV: 0.7 per yr

Adapted from *Kistler et al. (2011)*

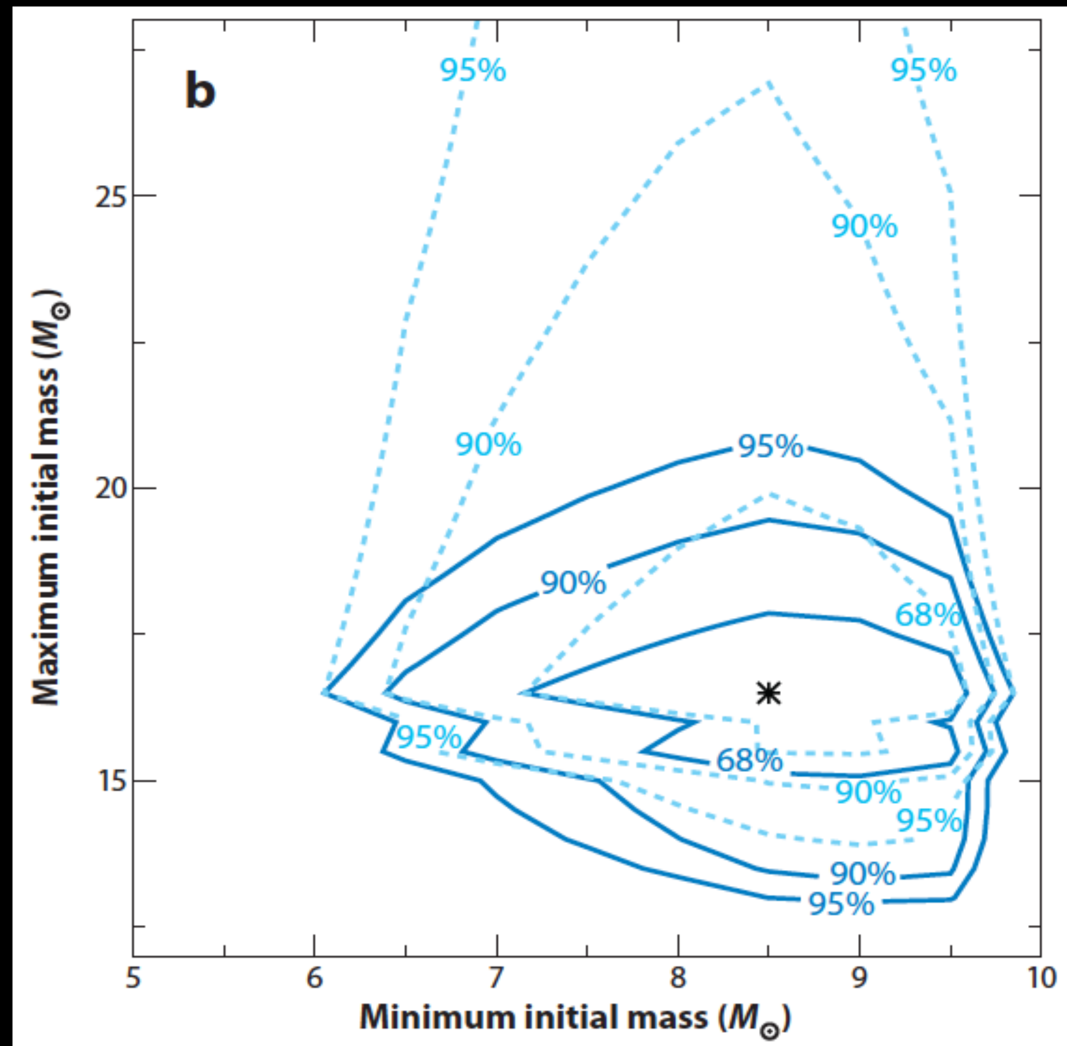


Rate of N-tuplets:
The frequency of obtaining a N-tuplet in Hyper-K, assuming the nearby supernova rate

Supernova progenitors



$M_{min} \approx 8.5^{+1}_{-1.5}$ Msun and $M_{max} \approx 16.5 \pm 1.5$ Msun



Smartt et al. (2009)