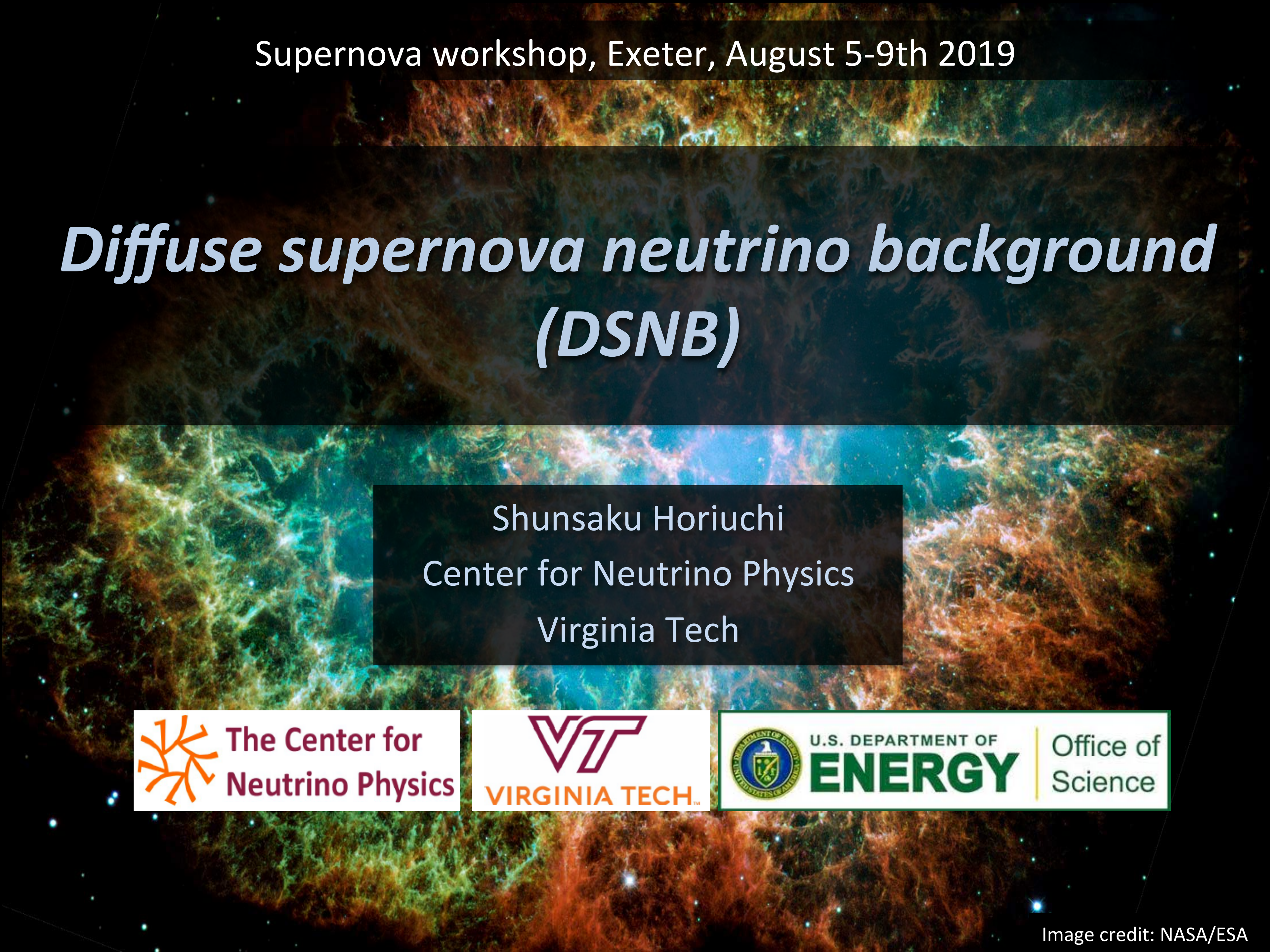
Supernova workshop, Exeter, August 5-9th 2019



Diffuse supernova neutrino background (DSNB)

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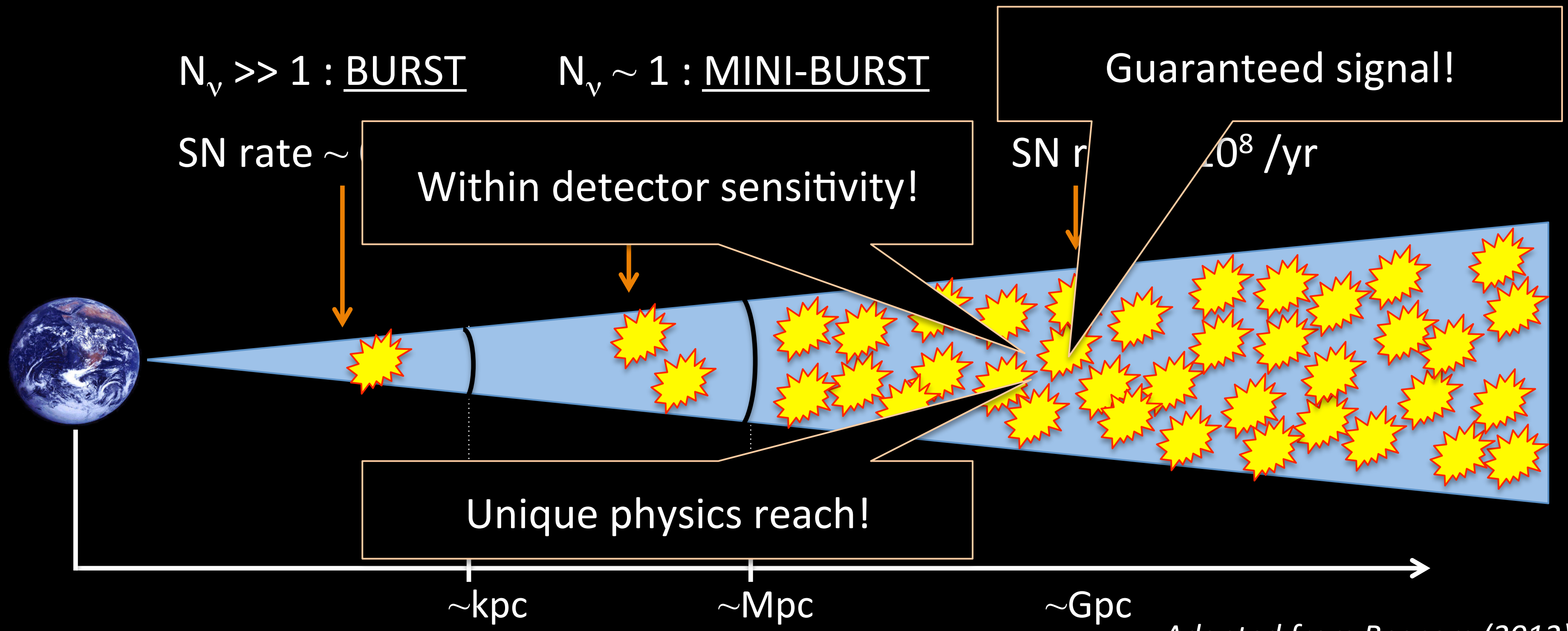
Center for Neutrino Physics
Virginia Tech

The Center for Neutrino Physics
VIRGINIA TECH
U.S. DEPARTMENT OF ENERGY | Office of Science

Image credit: NASA/ESA

Distance scales and physics outcomes



$N_\nu >> 1$: BURST

$N_\nu \sim 1$: MINI-BURST

Guaranteed signal!

SN rate ~ (

Within detector sensitivity!

SN r

0^8 /yr

Unique physics reach!

~kpc

~Mpc

~Gpc

Adapted from Beacom (2012)

	Galactic burst	Mini-bursts	Diffuse signal
Physics reach	Explosion mechanism, progenitor properties, multi-messenger astronomy, neutrino physics	supernova variety	Average emission, multi-populations (e.g., black holes)

Diffuse Supernova Neutrino Background

Observed positron spectrum

Input 1: supernova neutrino spectrum (intensely studied, 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 Ando & Sato (2004)
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)

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

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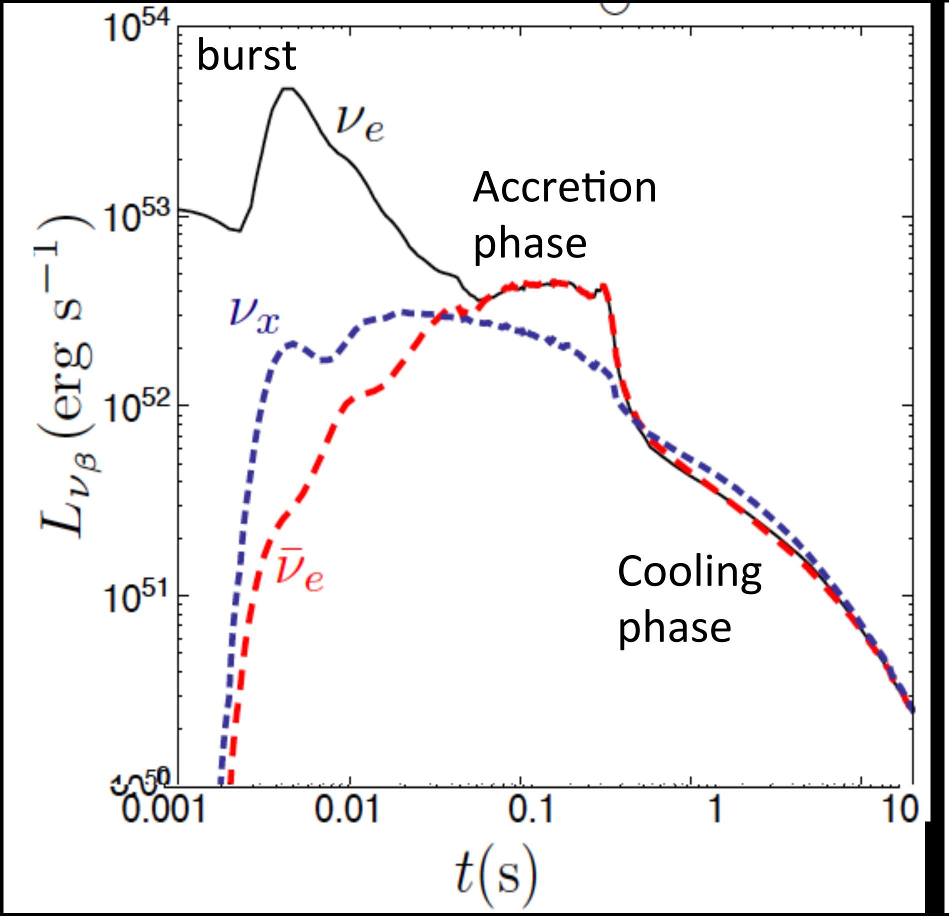
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

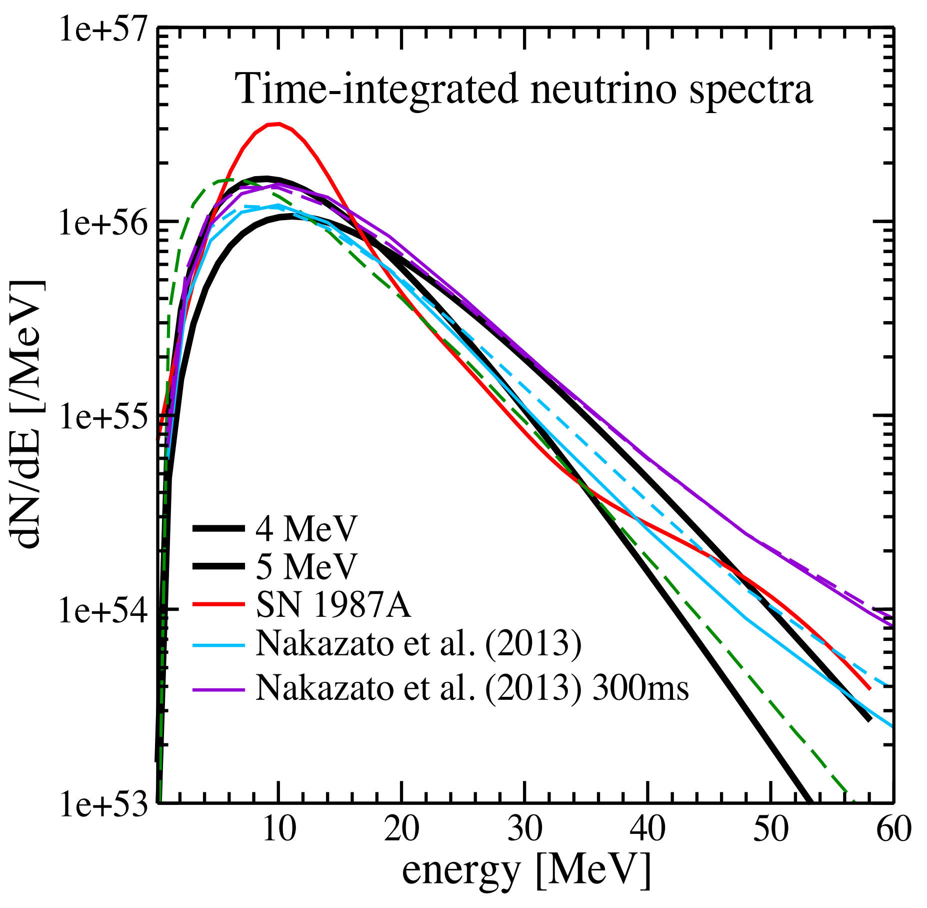
Input 1: neutrino emission

Neutrinos from core collapse

Each core collapse releases ~3x10^{53} erg of neutrinos, of which ~1/6 is in anti-ν_e

Time-integrated emission is typically T_ν = 4 – 5 MeV or so



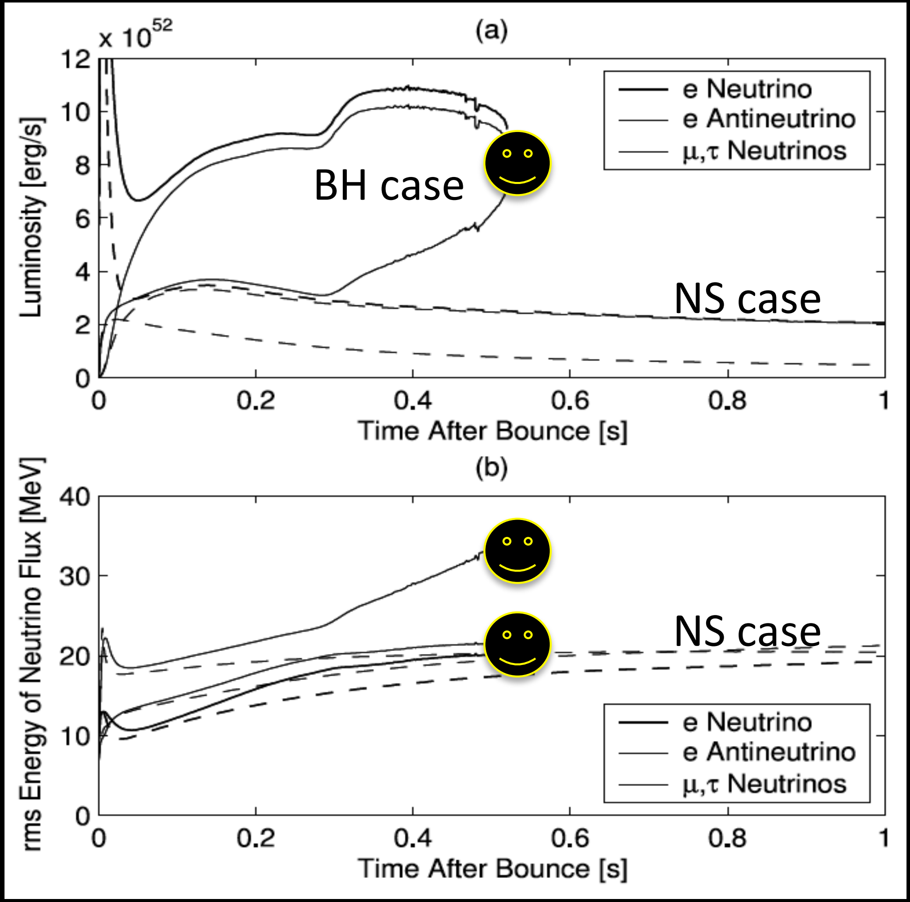


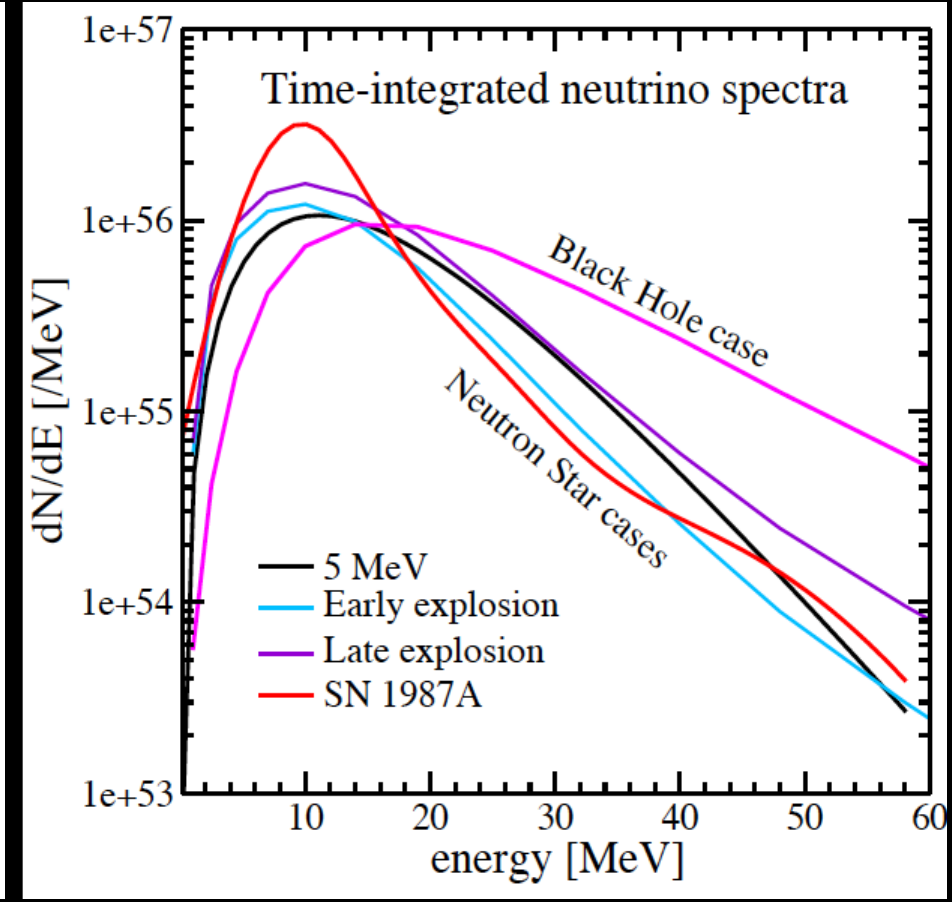
Fischer et al (2010)

Collapse to black holes

Neutrinos from collapse to black hole

Black hole formation necessarily goes through high mass accretion → ν emission is more luminous and hotter (quantitatively depends on EOS)

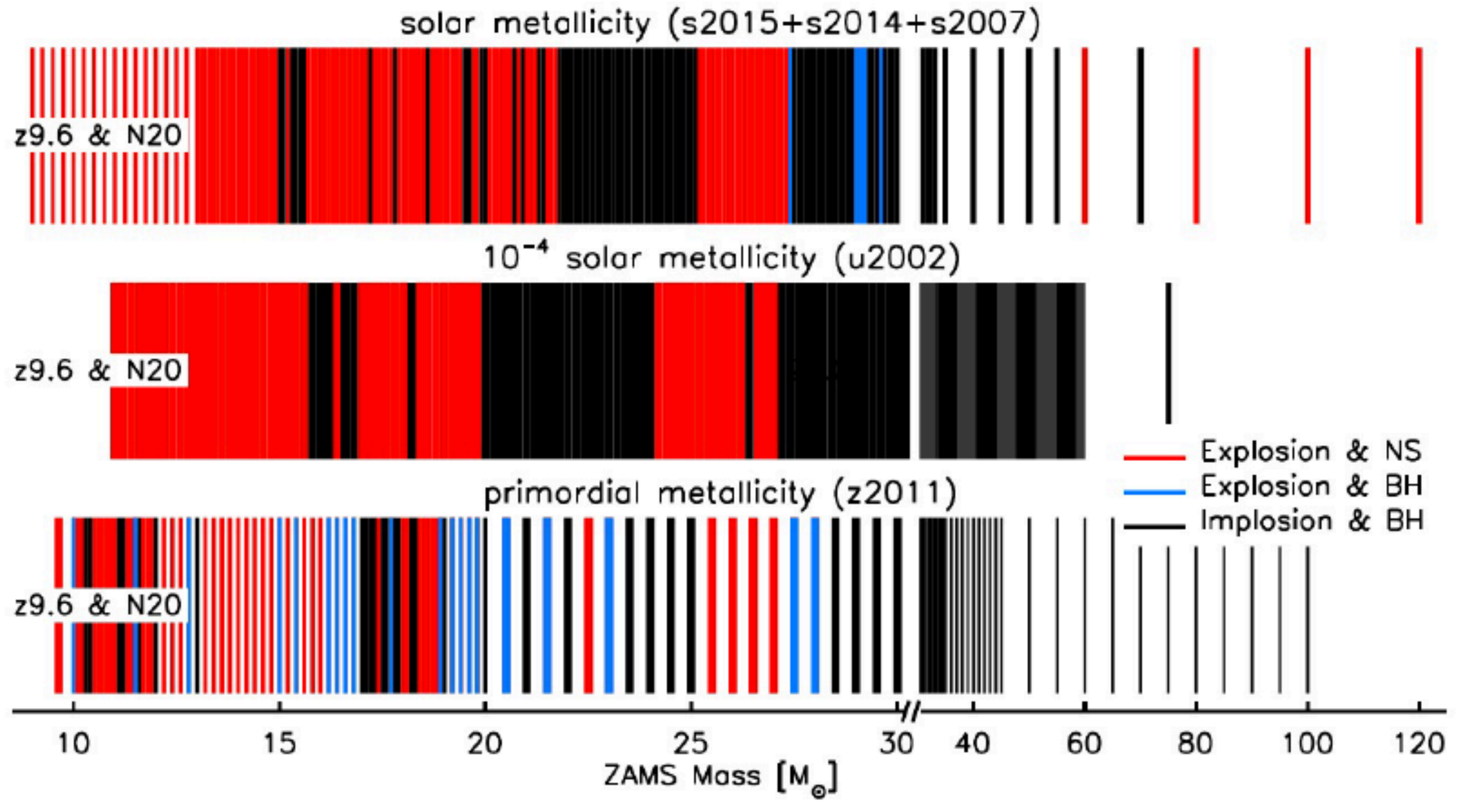




Liebendoerfer et al 2004; many studies, e.g., Fischer et al 2009, Sumiyoshi et al 2006, 2007, 2008, 2009, Nakazato et al 2008, 2010, O'Connor & Ott 2011, …

Supernova diversity

Systematic studies: thinking in mass looks incomplete



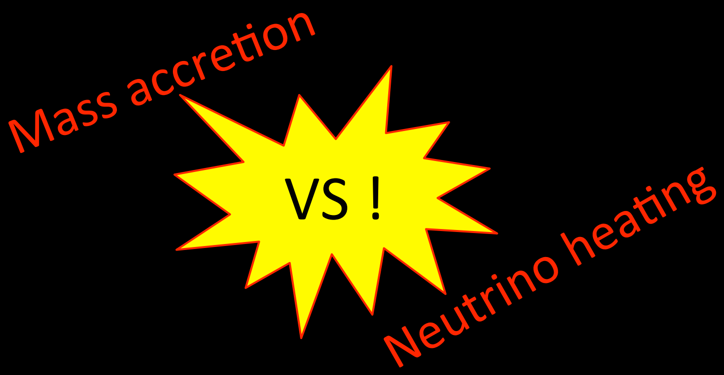
Janka 2017; see also O'Connot & Ott (2011), Pejcha & Thompson (2015), Sukhbold et al (2016), Mueller et al (2016)

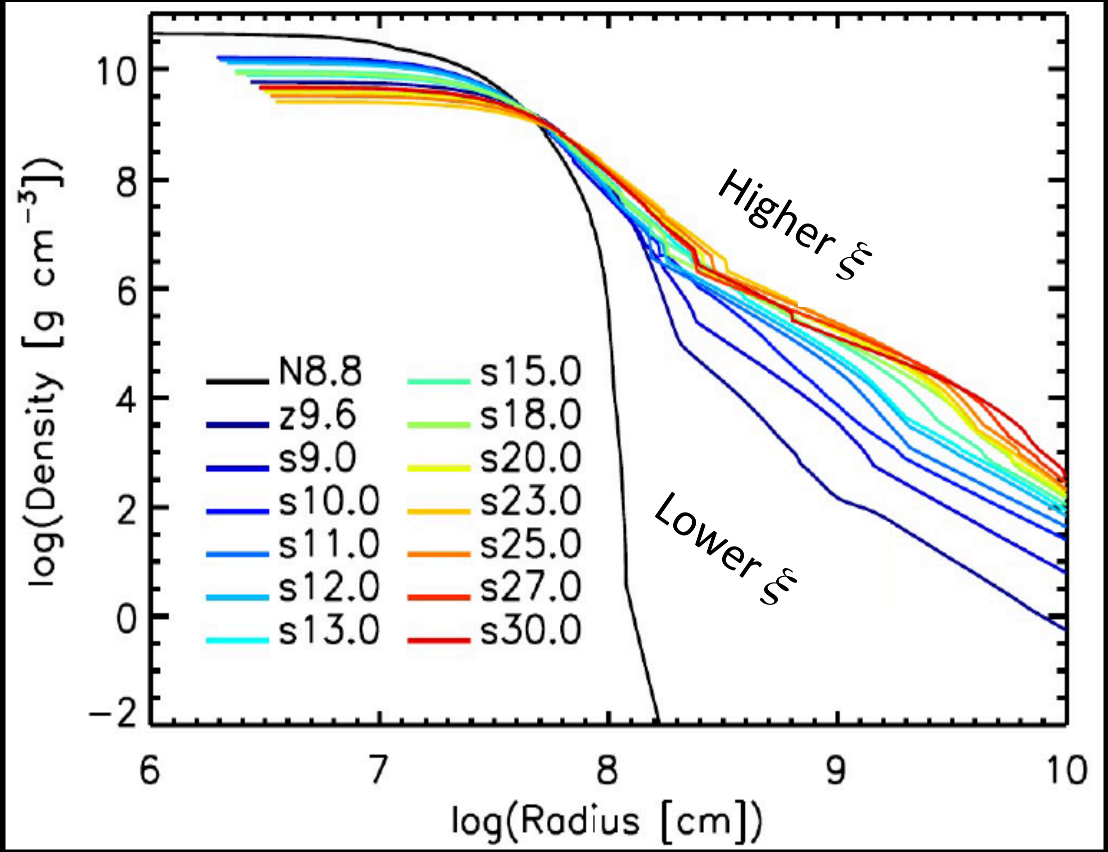
Compactness: a progenitor indicator

Compactness:
Captures the density structure of the progenitor, which impacts mass accretion evolution

O'Connor & Ott (2011)

$$\xi_M = \frac{M/M_\odot}{R(M_{\mathrm{bary}} = M)/1000\,\mathrm{km}}\Bigg|_t$$





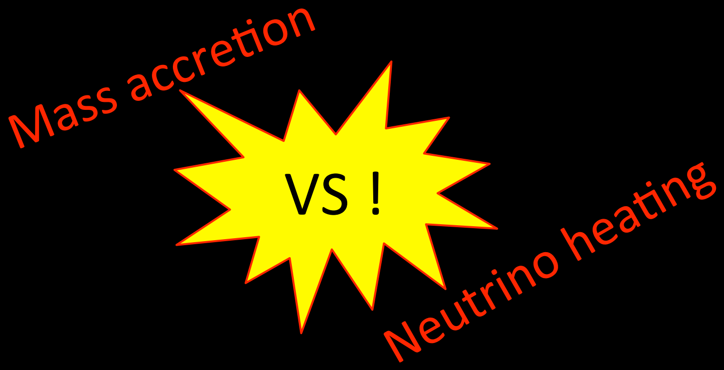
- Higher ξ → higher Mdot
- Lower ξ → lower Mdot

Compactness lv1: BH formation

Compactness:
Captures the density structure of the progenitor, which impacts mass accretion evolution

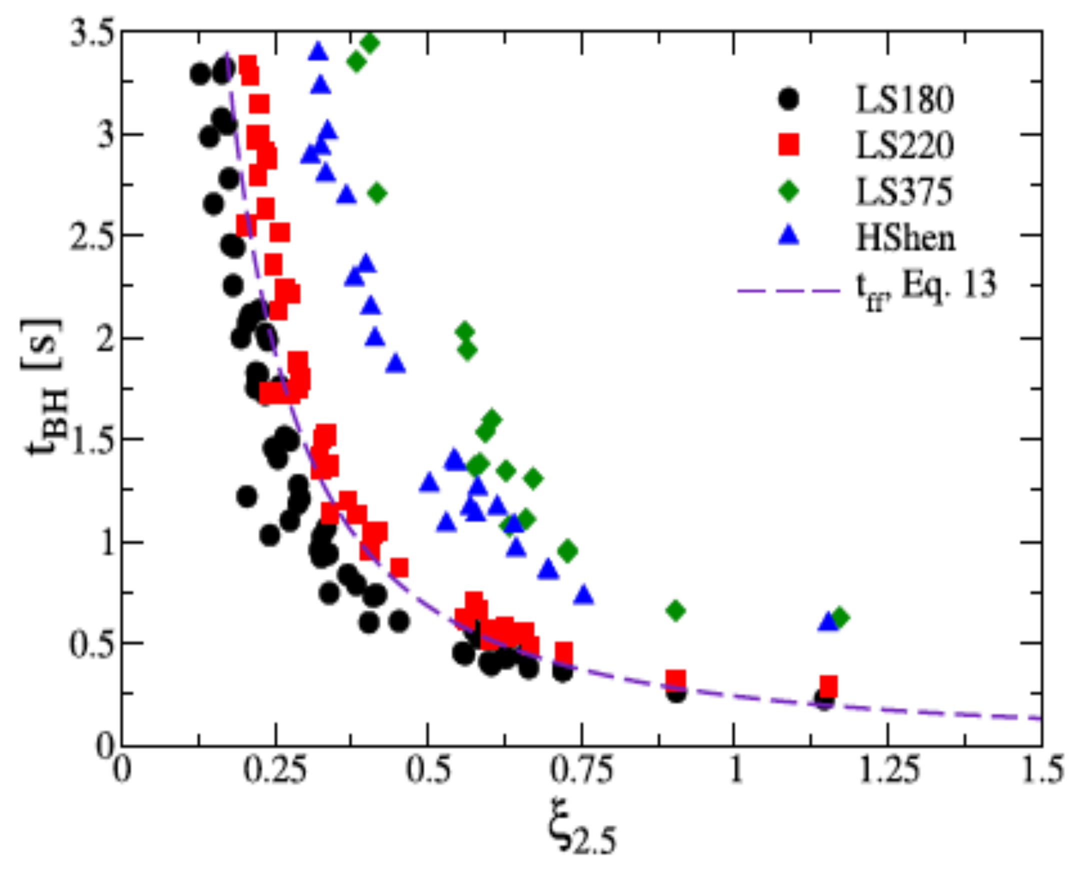
O'Connor & Ott (2011)

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


Mass accretion

VS !

Neutrino heating



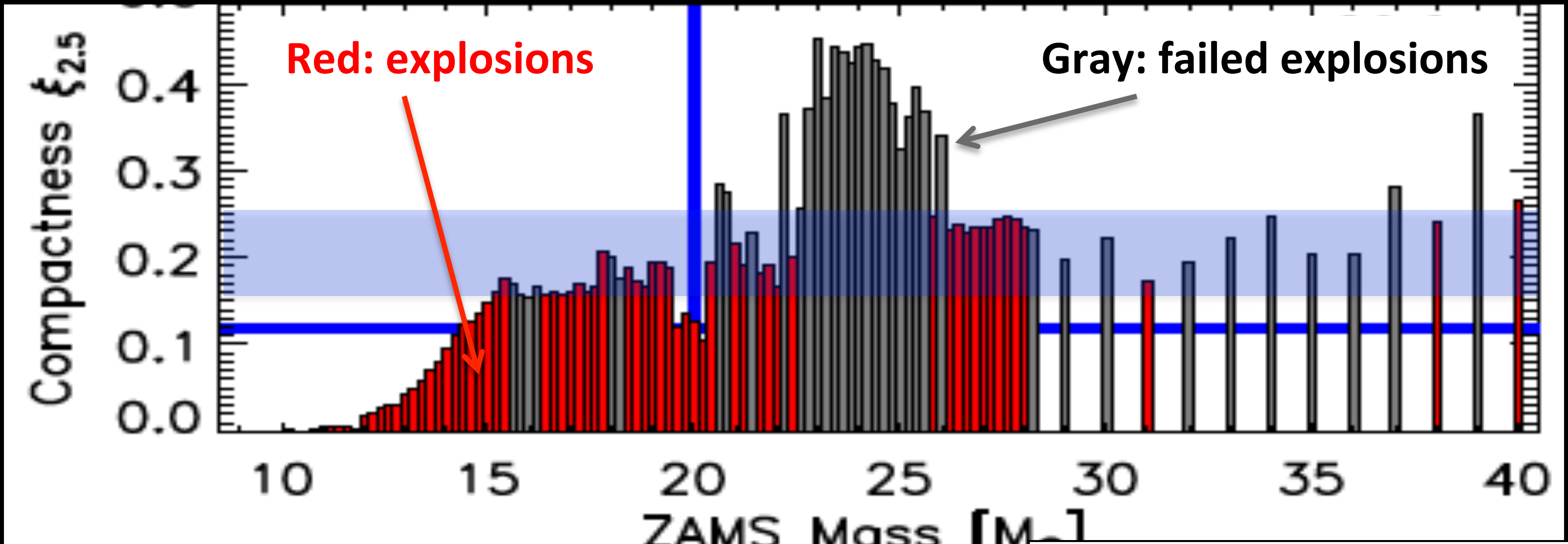
O'Connor & Ott (2011)

- Higher ξ → higher Mdot → BH forms earlier
- Lower ξ → lower Mdot → BH formation takes longer

Compactness lv2: Explodability

…beyond black hole formation time…

Compactness does a crude first job separating failed vs explosions.



Ertl et al (2016) ; see also Ugliano et al (2012)

- BH formation for $\xi_{2.5} > 0.3$
- Explosions for $\xi_{2.5} < 0.15$
- Mixture in between

Is there a critical compactness?

- 1 compactness predicts at most ~88% of cases
- 2 parameters successful in ~97% of progenitors

Pejcha & Thompson (2015)
Ertl et al (2016)

- Critical $\xi_{2.5} \sim 0.2$ consistent with 2D simulations
- TBD for 3D

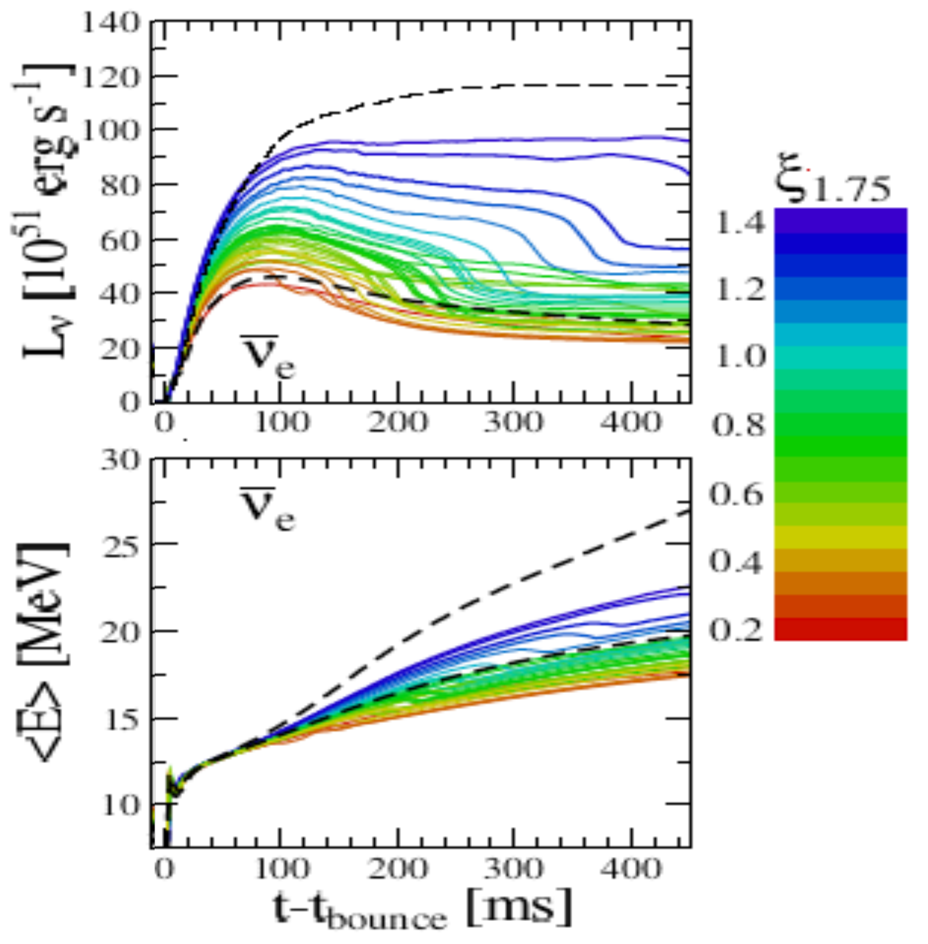
Horiuchi et al (2014)

Compactness lv3: neutrino emission

…beyond explosion/implosion…

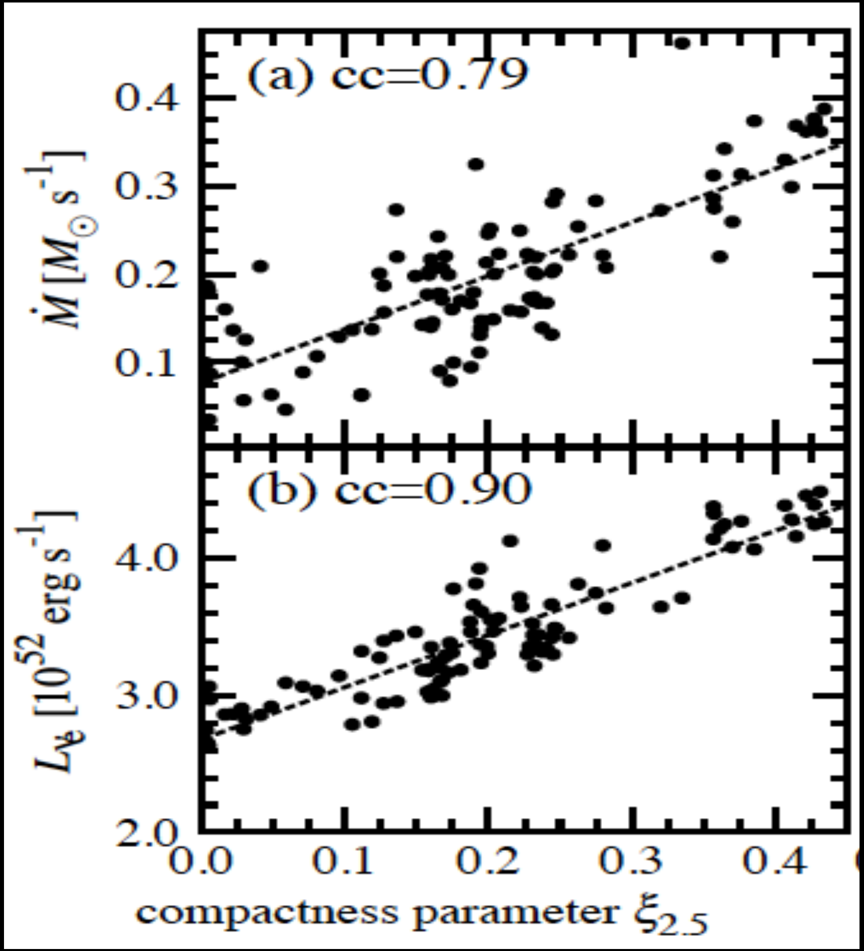
The neutrino light curve reflects the progenitor compactness

1D simulations



O'Connor & Ott (2013)

2D simulations



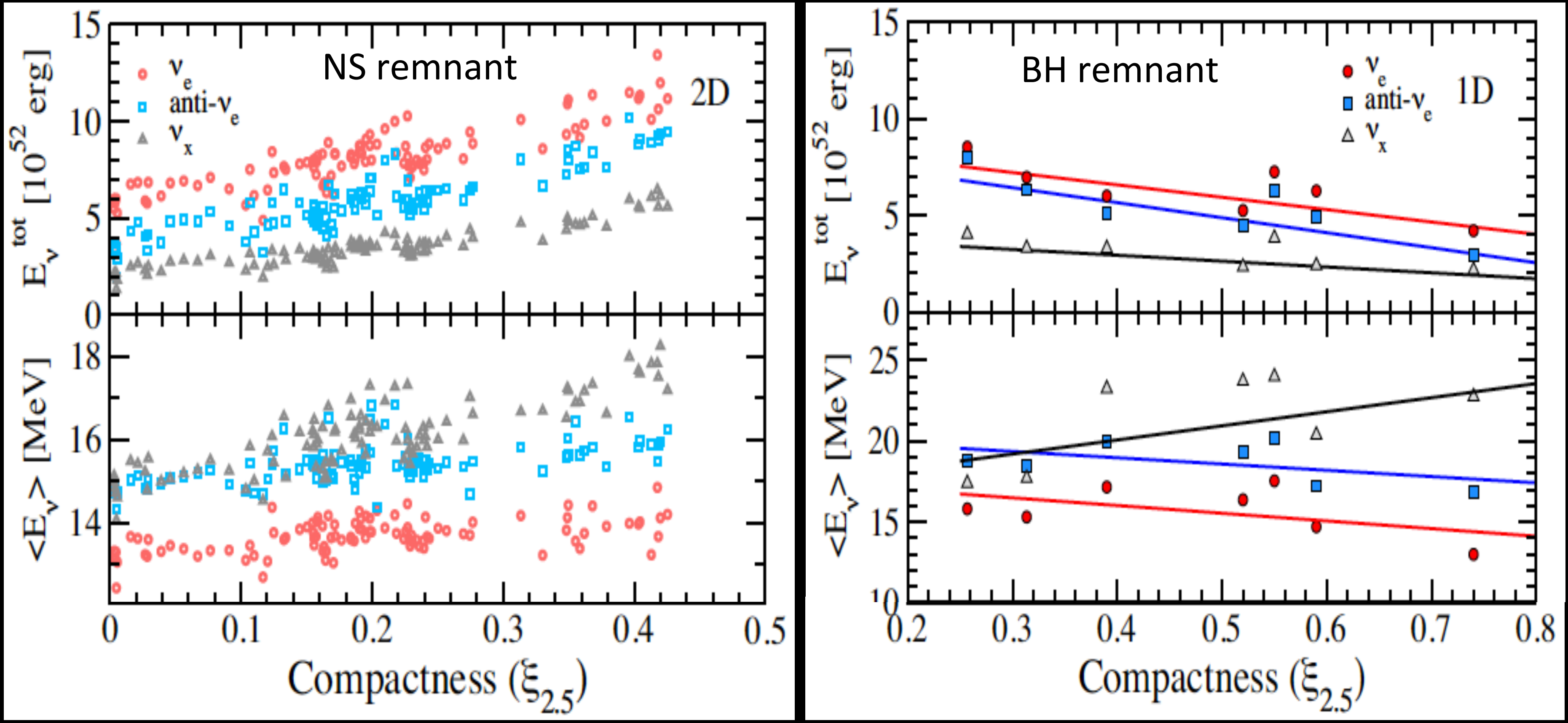
Nakamura et al (2015)

Compactness lv3: time-integrated emission

Systematic dependence on compactness

$$f_\nu(E) \propto E^\alpha e^{-(\alpha+1)E/E_{\rm av}}$$

- Spectral parameters (E_{tot}, E_{ave}, α_{pinch})
- From 100+ simulations (2D) of *Nakamura et al 2015,* 18 simulations (2D) of *Summa et al 2016*, and multiple BH simulations (1D).

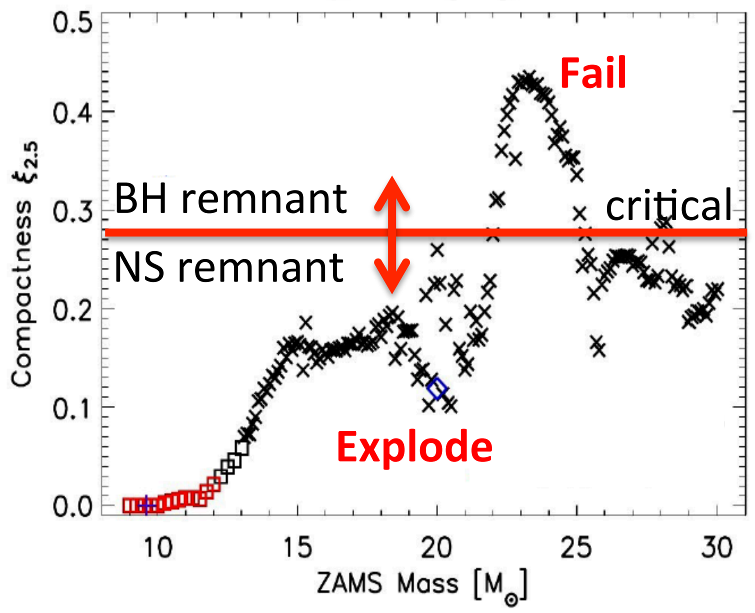


Horiuchi et al (2018)

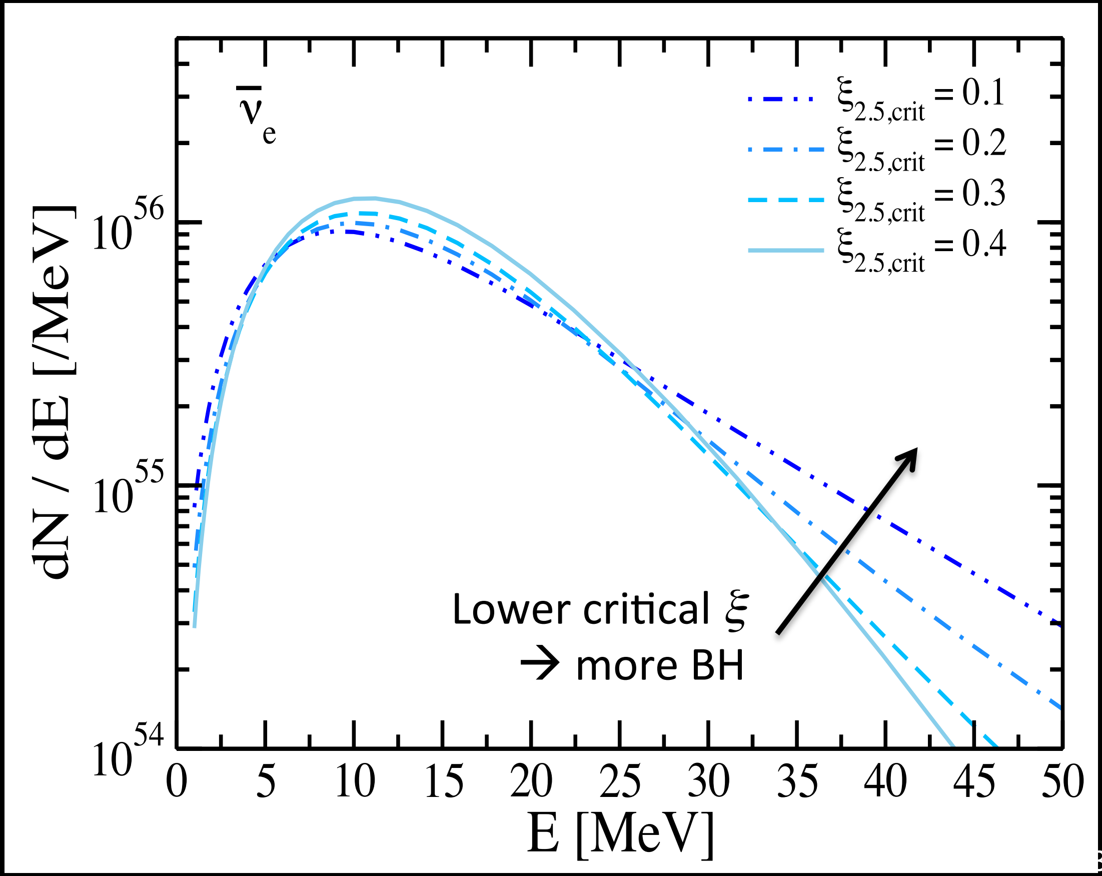
Input 1: mean neutrino emission

Mean neutrino emission per supernova

- Assume IMF
- Include distribution of stellar compactness (informed by WHW02 & WH07)
- Include scaling with progenitor compactness (informed by 100+ simulations)
- Distribute NS and BH channels (by a critical compactness parameter)



Horiuchi et al (2018)



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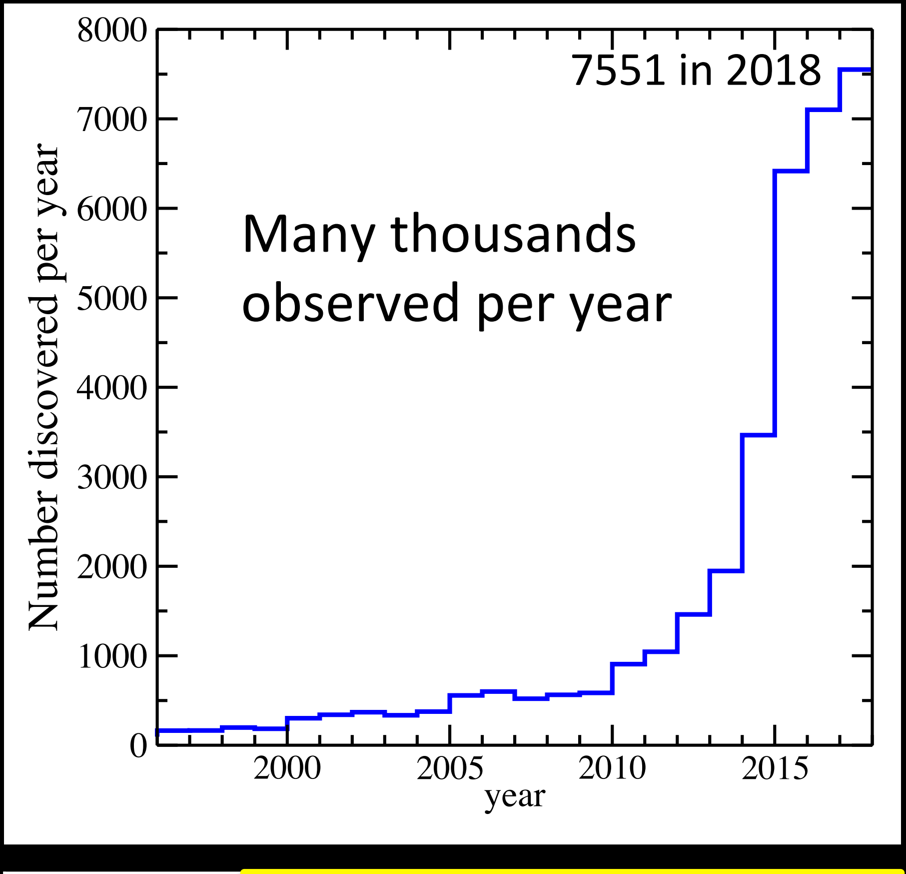
Input 2: core-collapse rate (intensely studied by astronomers using photons, *rapidly improving*)

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

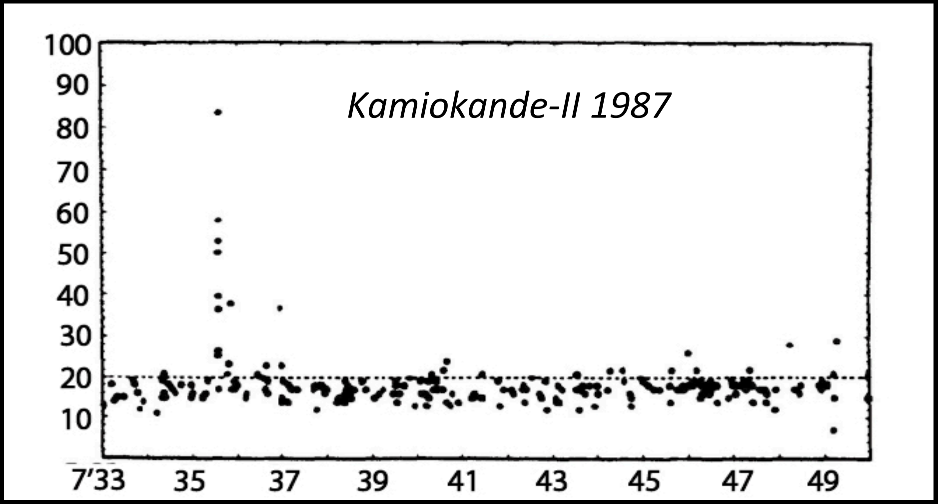
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Stars explode EVERYDAY



7551 in 2018

Many thousands observed per year



Kamiokande-II 1987

Anti-neutrinos from SN1987A

…most supernova are too far away

Ia	Ib	Ic	II
	No Hydrogen		H
Si	No Silicon		
No He	He	No He	

Measurement developments

Data was sparse

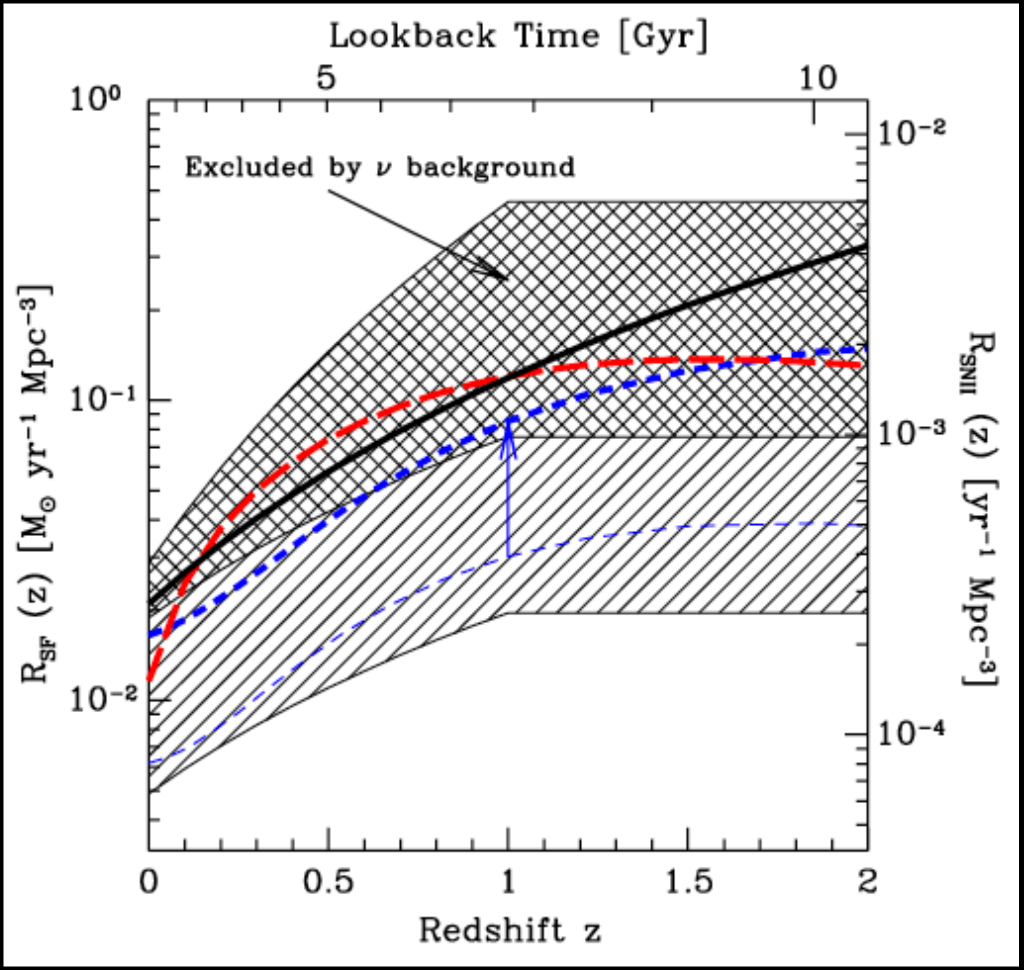
Use the DSNB to constrain the core-collapse rate and/or the star formation rate

Strigari et al (2004); Fukugita & Kawasaki (2003), Ando (2004), Hopkins & Beacom (2006), …

Developments in recent decade

Fortunately, important updates by our astronomer colleagues

- ✓ More direct measurements
- ✓ Better direct measurements
- ✓ Better systematic confirmations
- ✓ New searches of `dark' collapse



Strigari et al (2004)

Cosmic core-collapse rate

Direct measurements

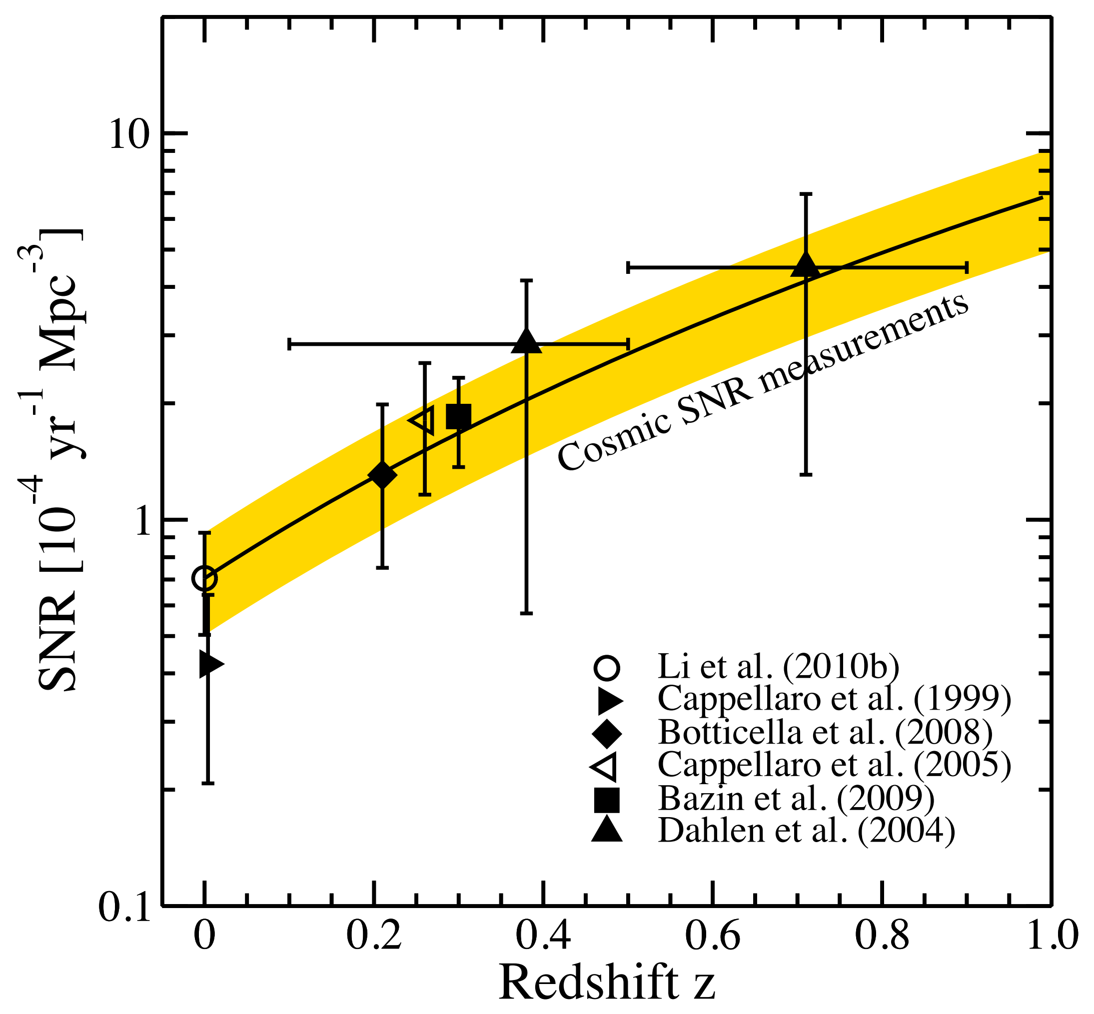
Two different strategies:

1. Efficient but Biased: target pre-selected galaxies, e.g., LOSS, STRESS
2. Unbiased but harder: target pre-selected fields, e.g., SNLS, HST-ACS, SDSS, DES, …

➔ **Measurements improving**

Future measurements coming up (ASAS-SN, DES, LSST)

e.g., Lien & Fields (2009)

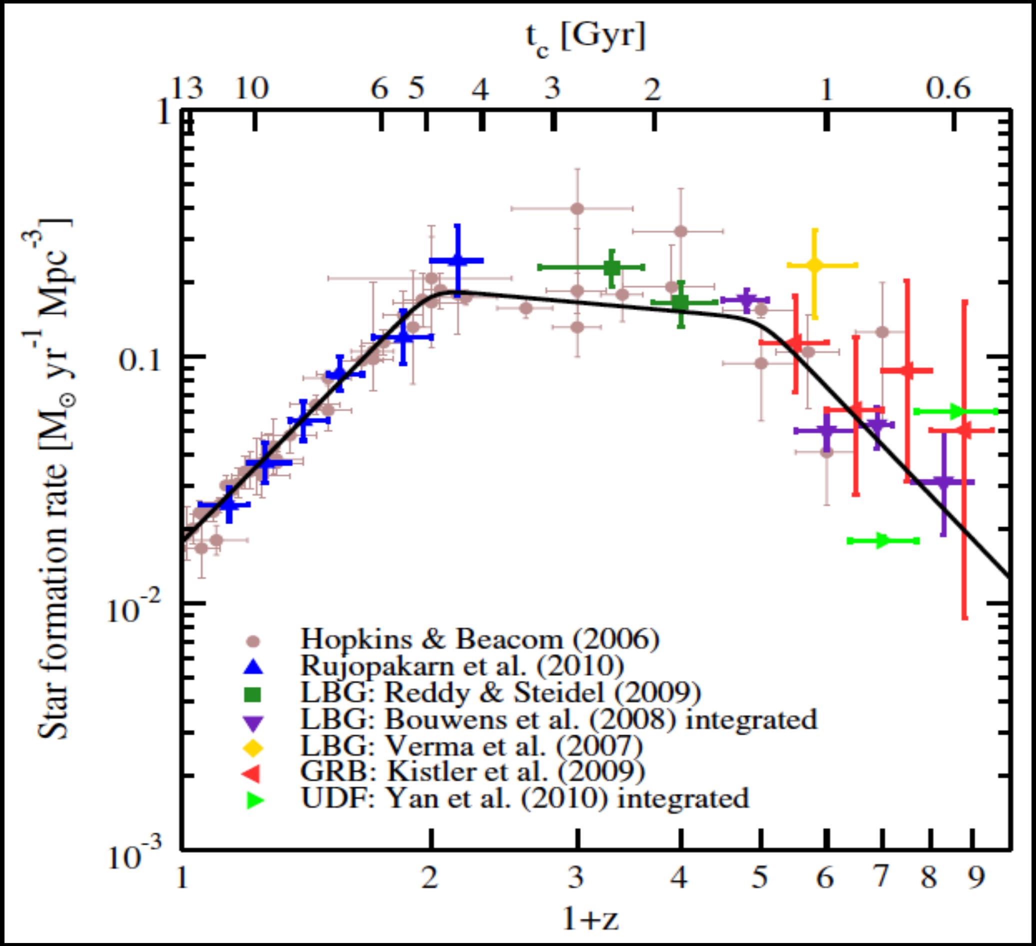


Horiuchi et al (2011)

Cosmic 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)

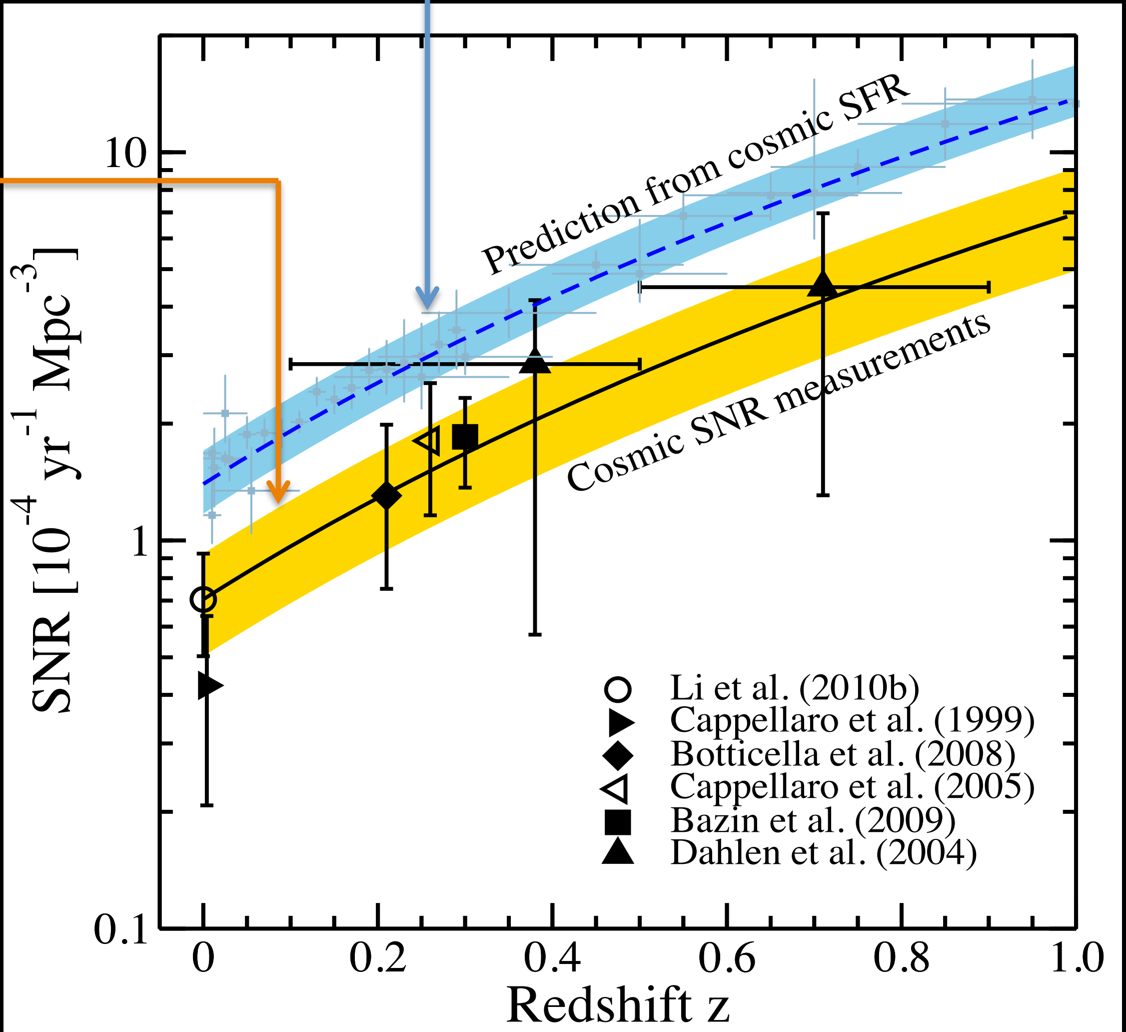
Birth & death rate comparison

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 this is ~50% (!!), indicating a critical $\xi_{2.5} \sim 0.05$

…but we must be careful



Horiuchi et al (2011)

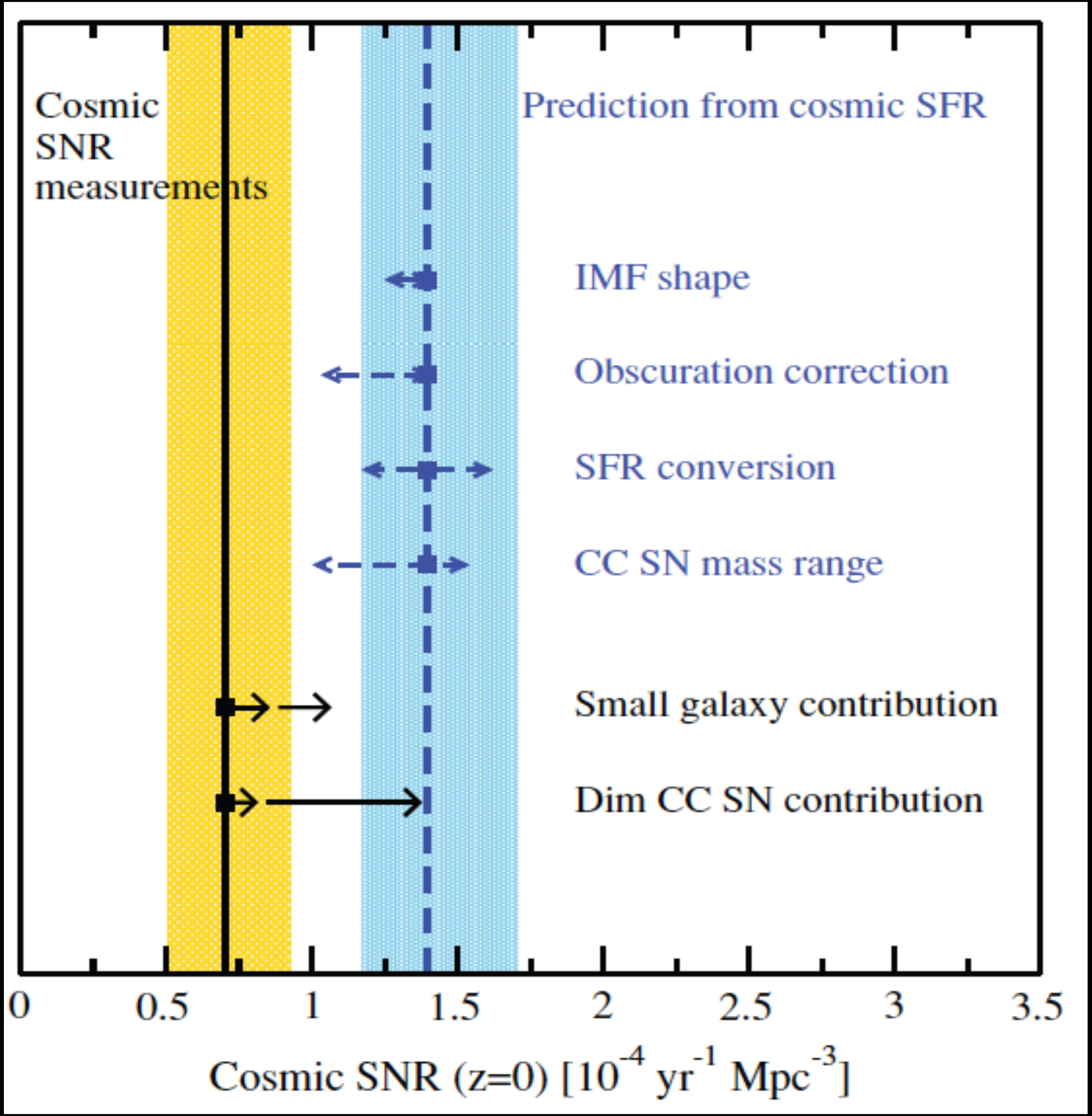
Are the rates systematically low/high?

Uncertainties

Sizable, but most are not enough to explain a factor 2 difference

Only 1 remains large enough: missing dim supernovae

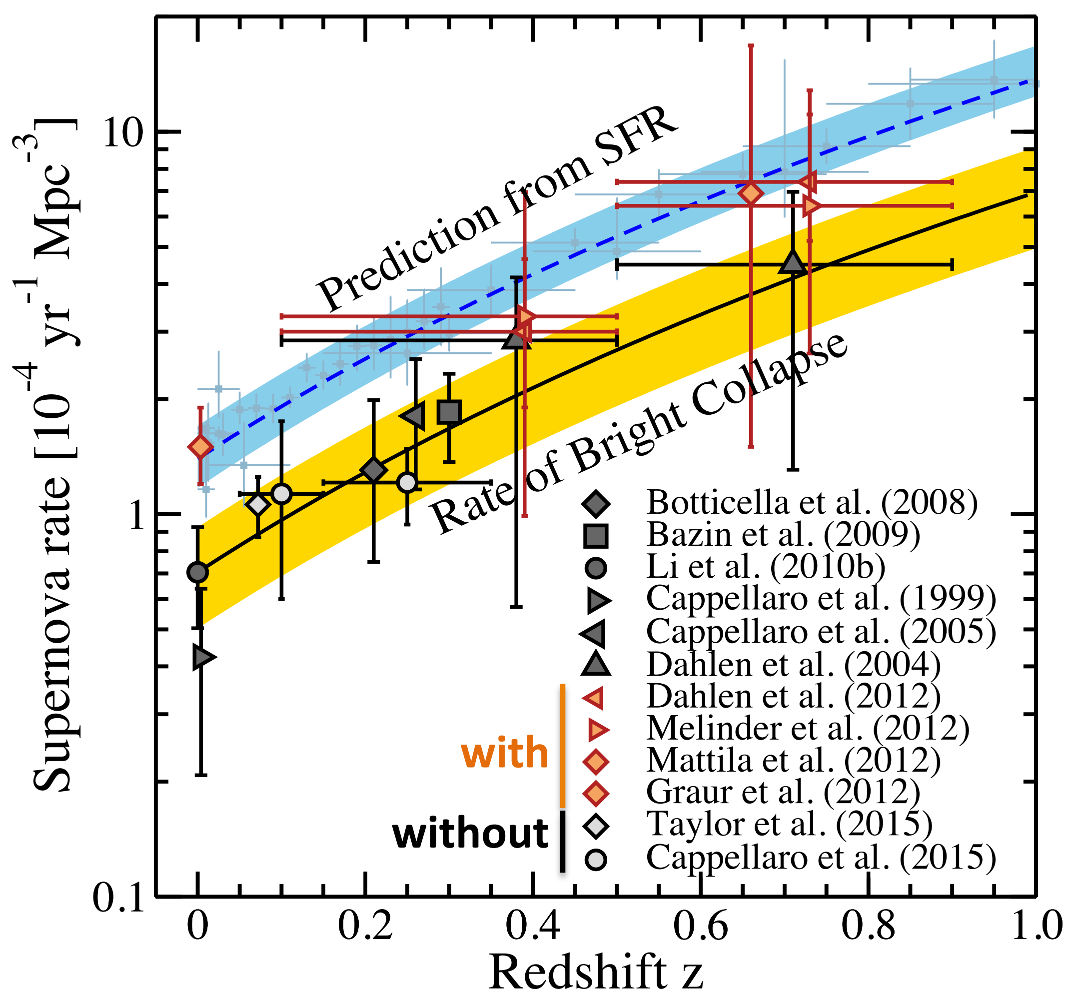
We argued these are due to highly extinguished supernovae.



Horiuchi et al (2011)

Di-biased cosmic supernova rates

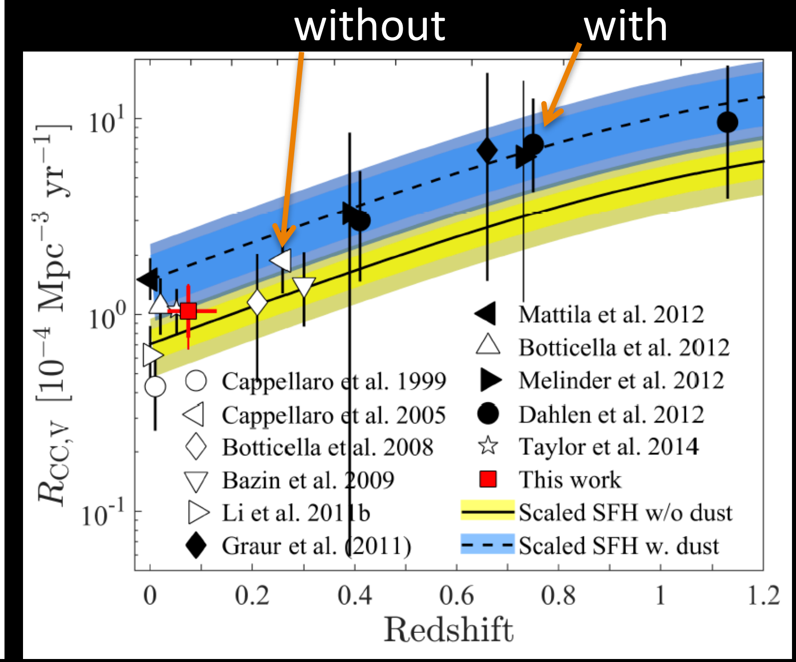
Better agreement



Updated from Horiuchi et al (2011)

← Updates with (filled symbols) and without (empty symbols) correction for heavily attenuated supernovae

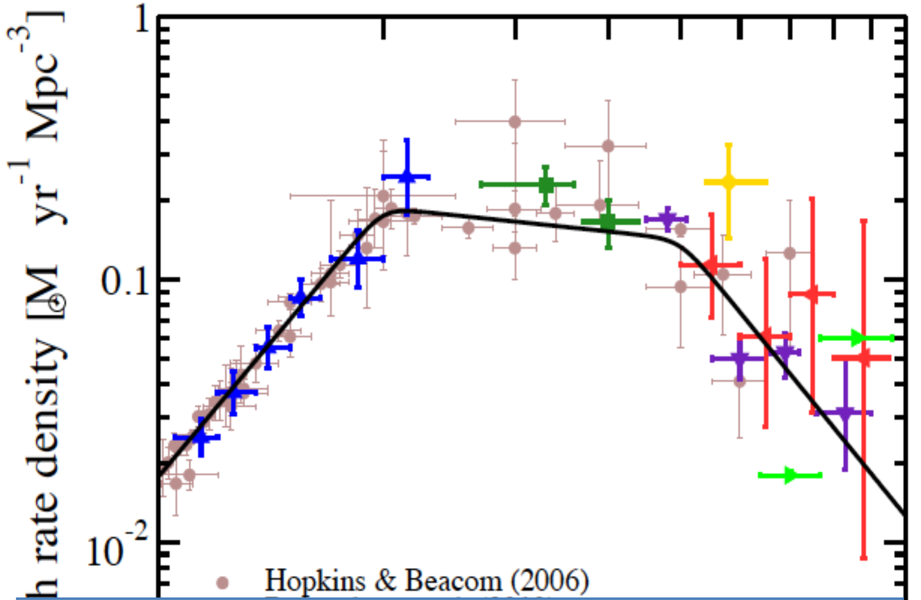
→ **BH fraction < 30% (still large errors)**



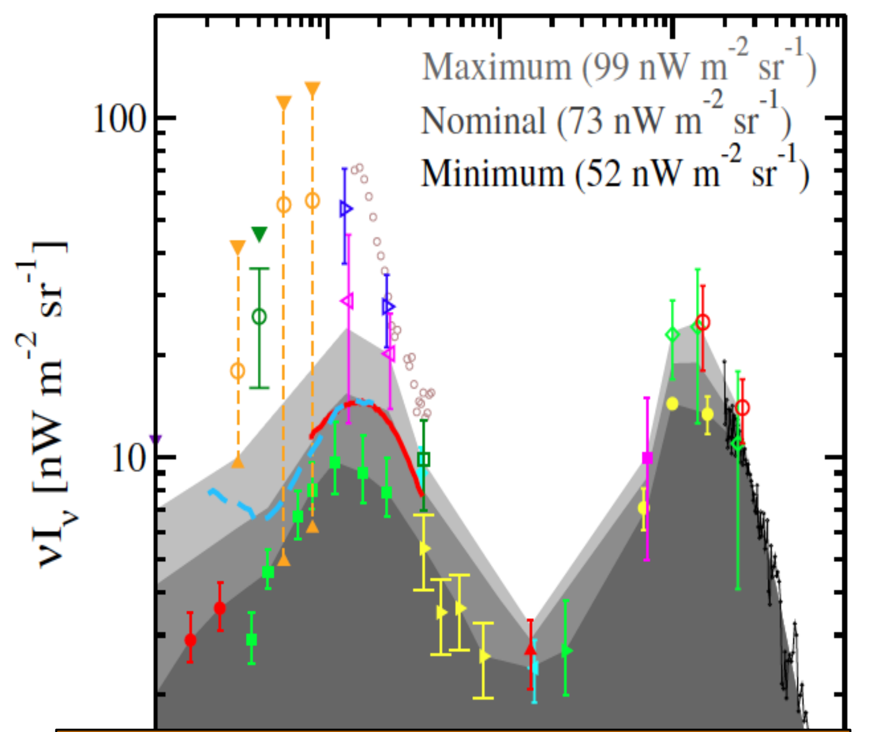
Graur et al (2015)

Is the birth rate artificially high?

Cosmic stellar birth rate density → → → → Extragalactic background Light



IMF	Total EBL intensity	Error
Baldy-Glazebrook '03	78 nW m^{-2} sr^{-1}	-24 / +31



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

Horiuchi & Beacom (2010)
Many updates, e.g., Yuksel+ (2008),
Madau & Dickinson (2014)

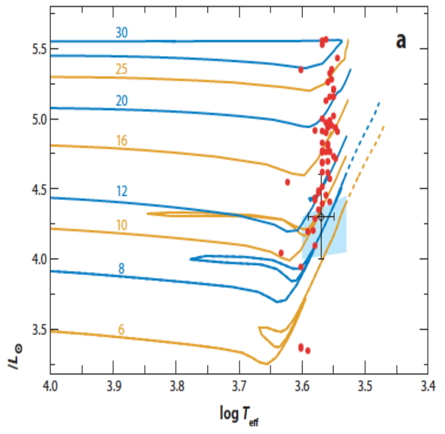
→ No evidence of birth rate being too high

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

What is the BH fraction?

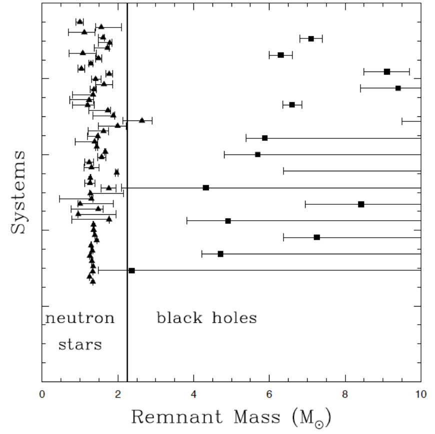
Multiple circumstantial evidence for a large fraction of failed explosions.

Red supergiant problem



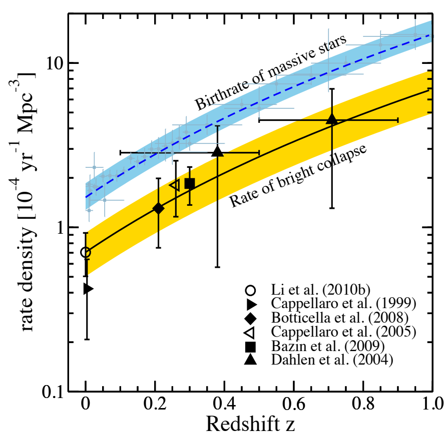
Smartt et al (2009)

Black hole mass function



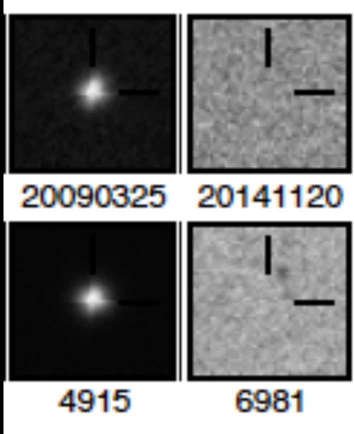
Kochanek et al (2014, 2015)

Supernova rate



Horiuchi et al (2011)

Survey about nothing



Gerke et al (2015)

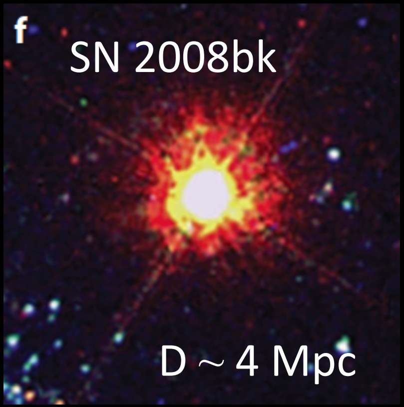
+ supernova remnants, nebular spectra

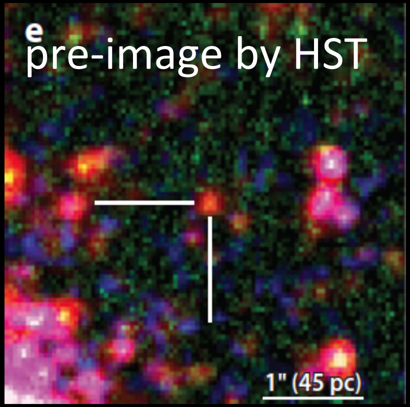
Insight for compactness:

All of these can be explained by a critical compactness $\xi_{2.5} \sim 0.2$
(i.e., explosions $\xi_{2.5} < 0.2$ and fails for $\xi_{2.5} > 0.2$)

Red supergiant problem

Pre-imaging:
Limited to nearby SNe, successful for Type II



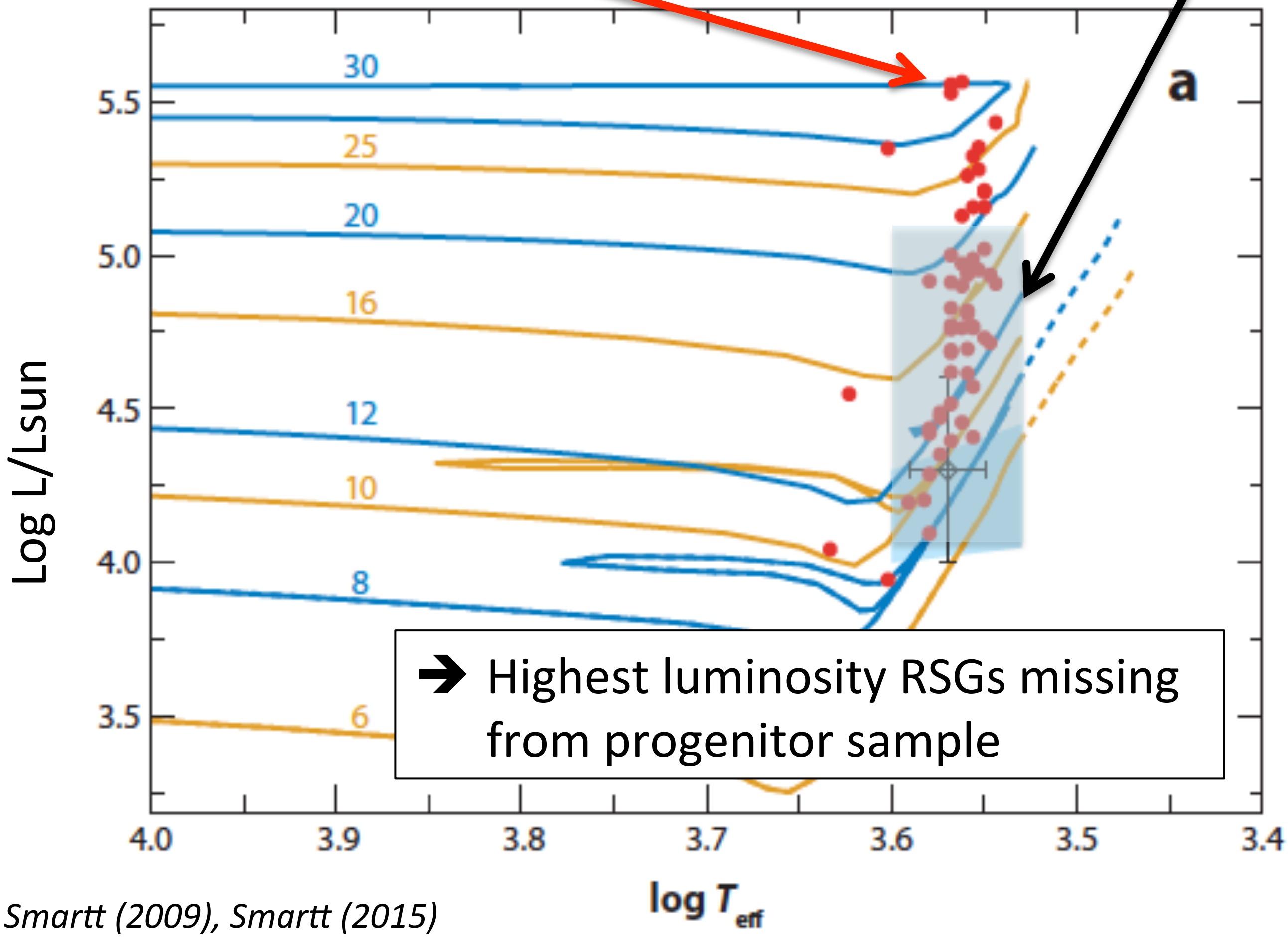


A deficit of high mass supernova progenitors *Kochanek et al (2008)*

Sample: volume limited to < 28 Mpc (V<2000 km/s)

Known red-supergiants (@MW, LMC)

Observed progenitors



➔ Highest luminosity RSGs missing from progenitor sample

Smartt (2009), Smartt (2015)

Another way to state the RSG problem

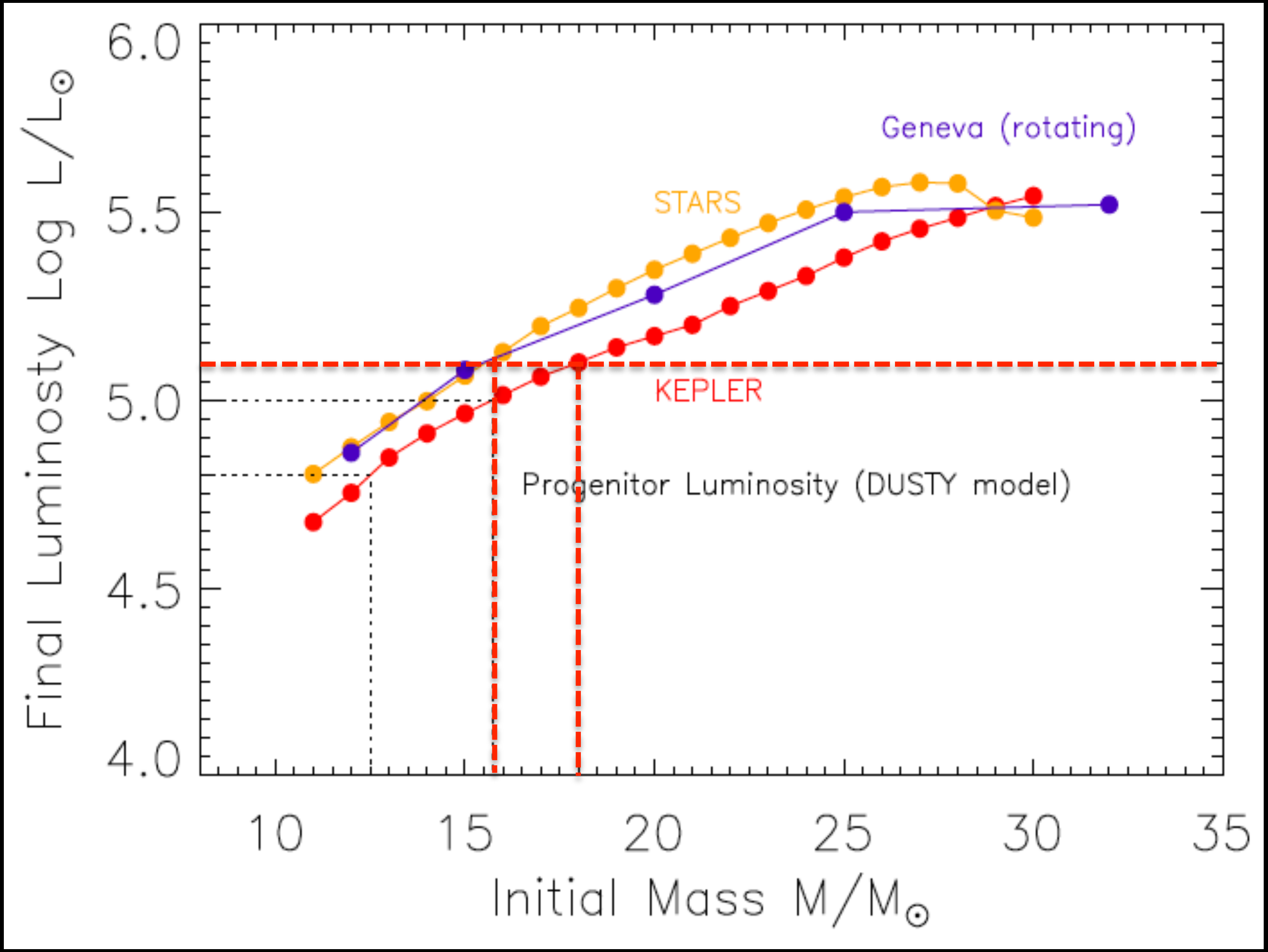
Log *L/Lsun* ~ 5.1

- → This is 16–18 Msun
- → With a Salpeter IMF, 63–69% of massive stars are below this mass
- → With 35 below this mass, we expect 16–21 stars above

What's happening to these stars?

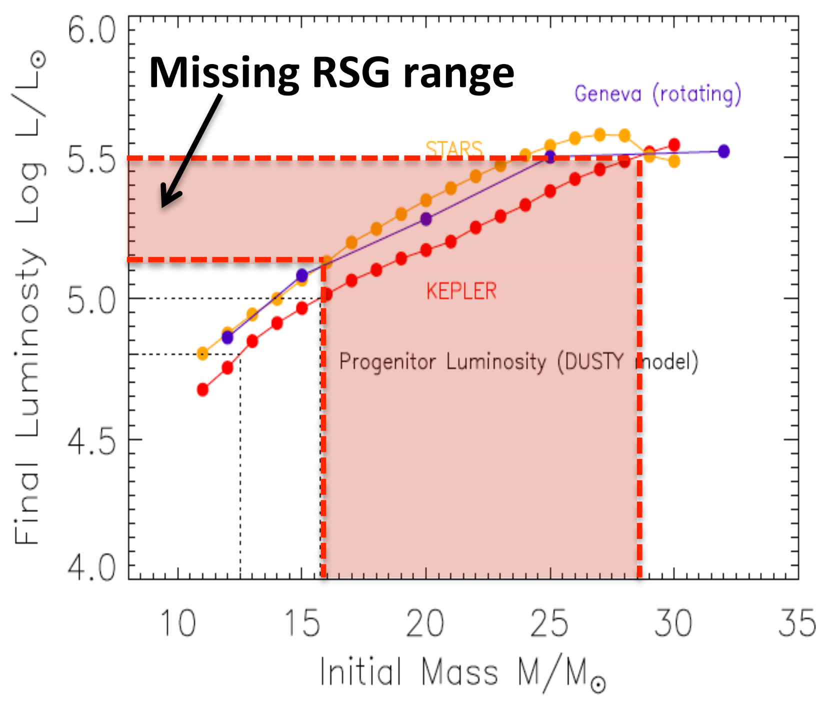
16–21 expectation rarely fluctuates to 5

→ Deficit of massive progenitors



Jerkstrand et al (2014)

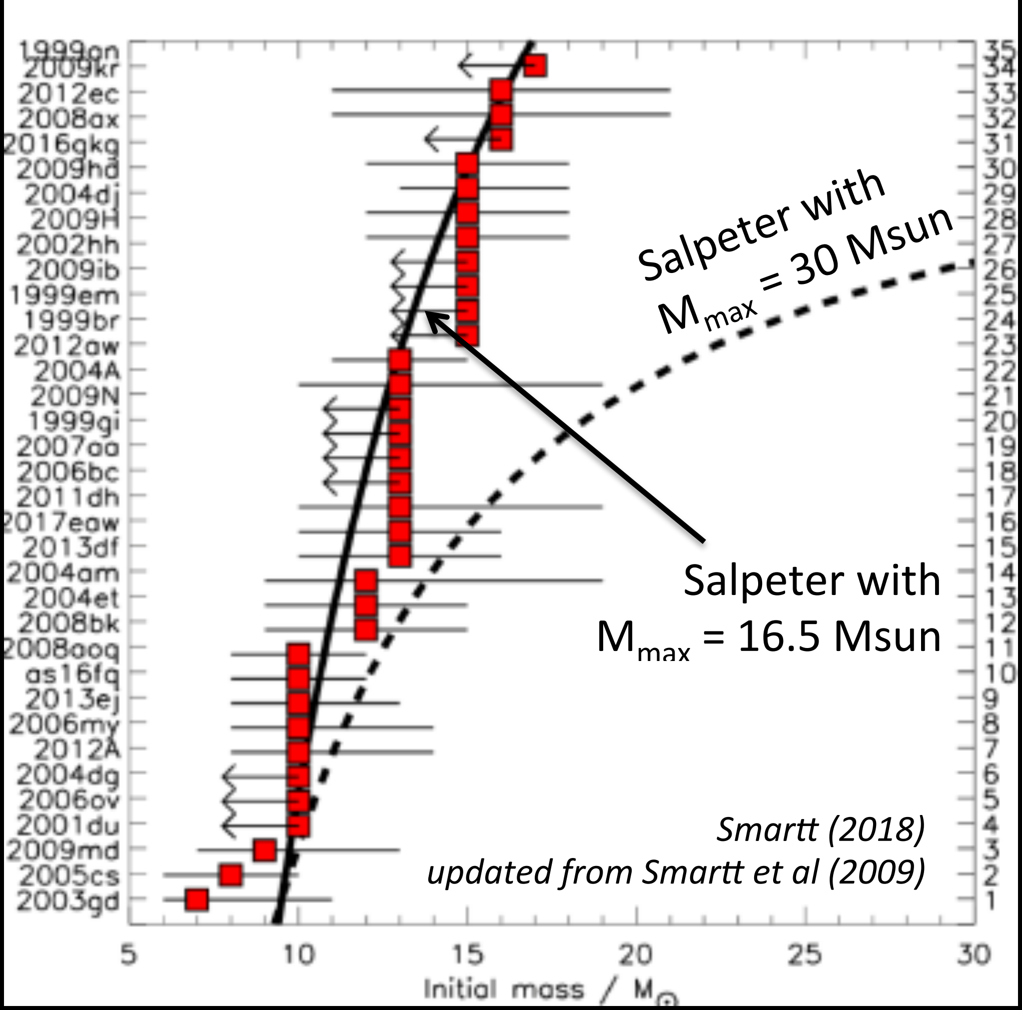
Type II progenitors



Jerkstrand et al (2014)

$$M_{\rm max} = 16.5^{+1.5}_{-1.5}\, M_\odot$$

$$M_{\rm max} < 21\, M_\odot$$ (95%)



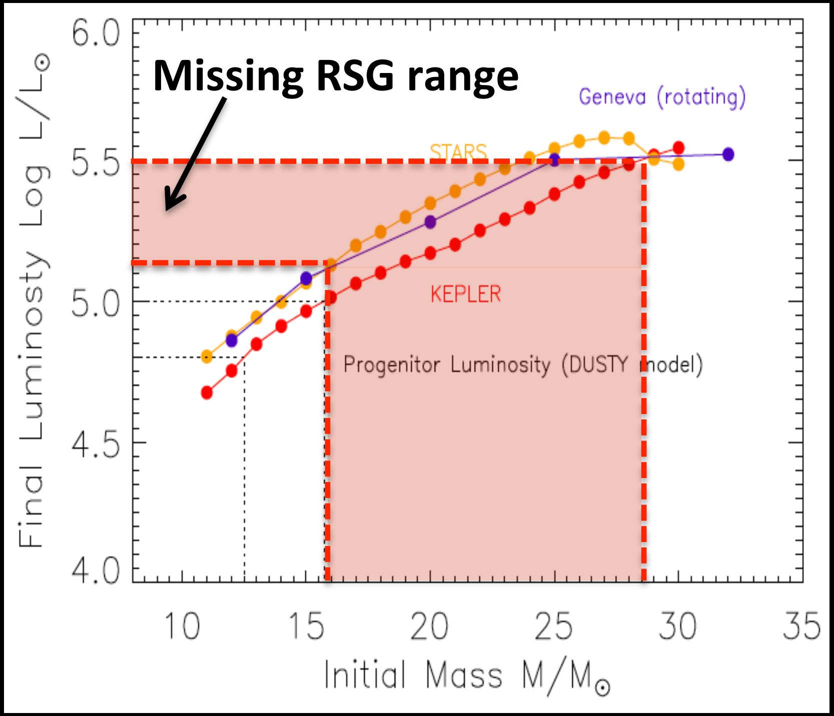
Smartt (2018)
updated from Smartt et al (2009)

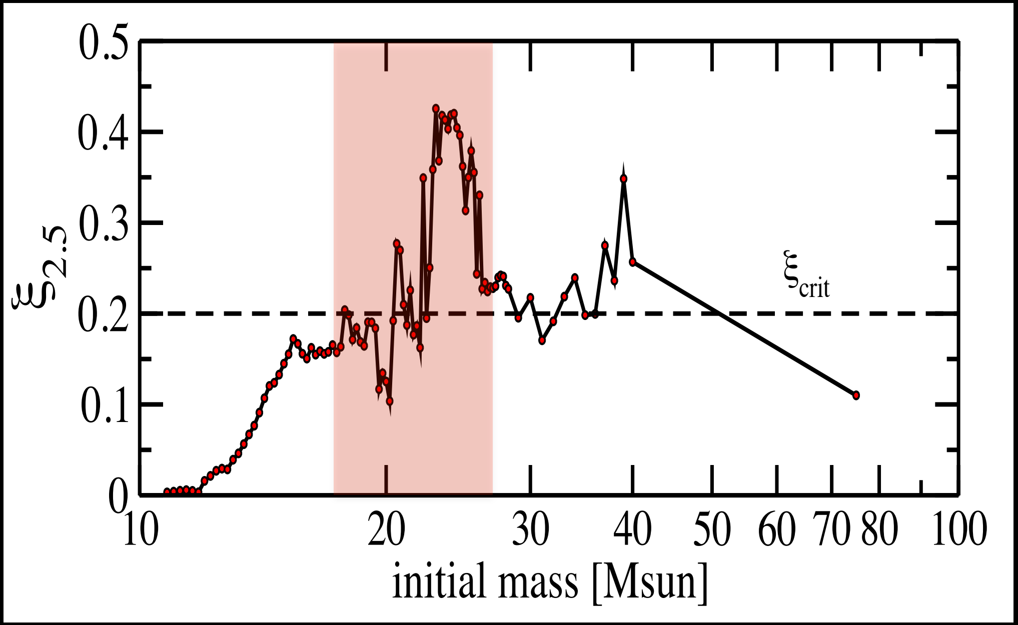
➔ 21–30 Msun missing (~11% of massive stars)

20 detection + 15 upper limits

Interpreting the RSG problem

Supergiants may not be exploding





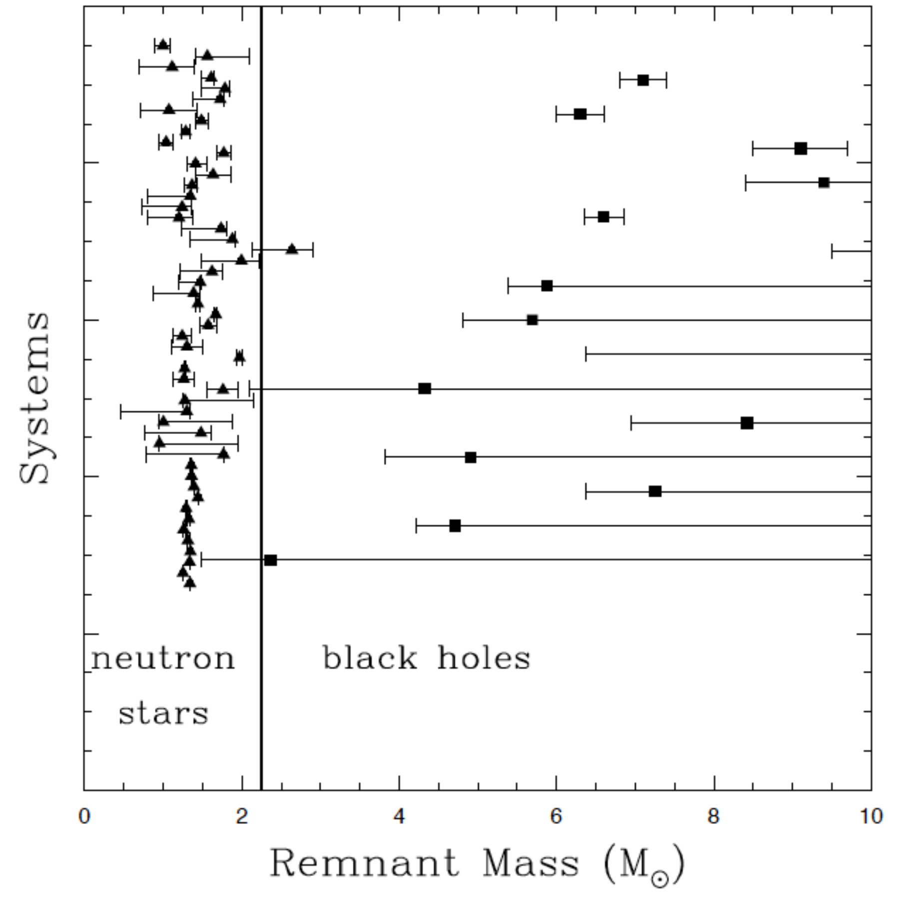
➔ Consistent with high compactness stars failing to explode

Horiuchi et al (2014), Sukhbold & Adams (2019)

(Other explanations have been explored)

BH mass function

Compact object mass function:
Indications of a dearth of black holes with mass just above the NS range



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

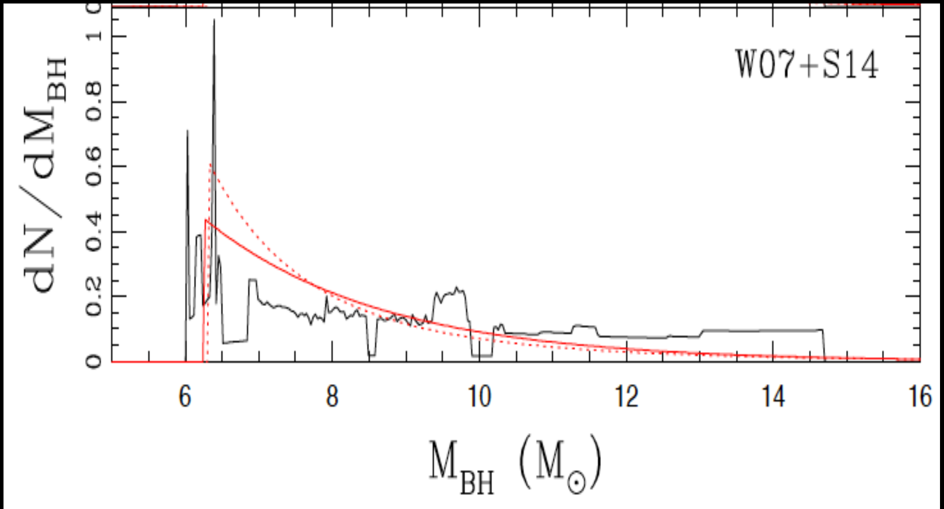
The Nadezhin mechanism:
H envelop unbound in BH formation due to neutrino mass-energy loss.

- Numerically verified

Nadezhin (1980), Lovegrove & Woosley (2013), Fernandez et al (2017), Coughlin et al (2018)

→ **Failed explosions create BHs with mass of He core (not entire star)**

→ **Creates a BH mass distribution with the observed low mass deficit**



Kochanek (2014)

Searches of failed explosions: Survey about nothing

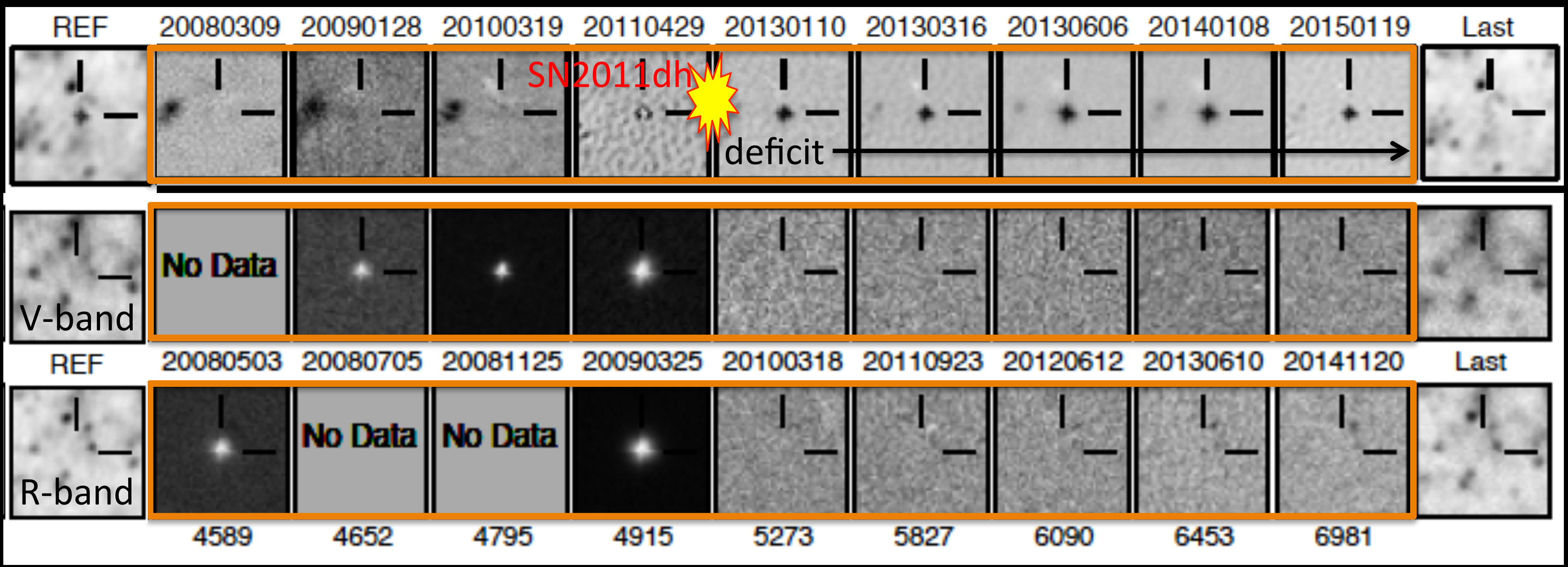
Survey About Nothing

Look for the disappearance of red-supergiants in nearby galaxies caused by core collapse to black holes

Monitor ~27 galaxies with the Large Binocular Telescope

- → Survey $\sim 10^6$ red supergiants with luminosity sensitivity > 10^4 Lsun
- → expect ~1 core collapse /yr
- → In 10 years, sensitive to 20 – 30% failed fraction at 90% CL

Kochanek et al. (2008)

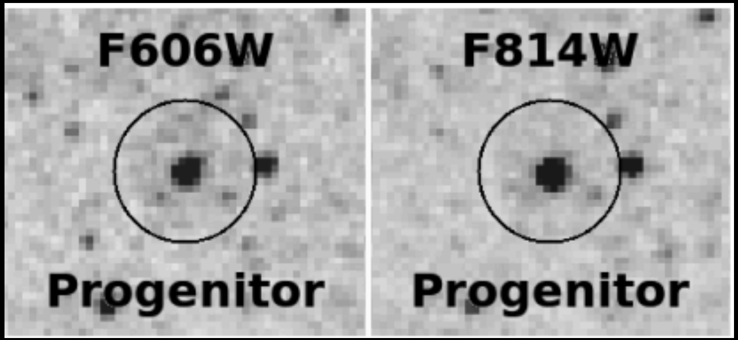


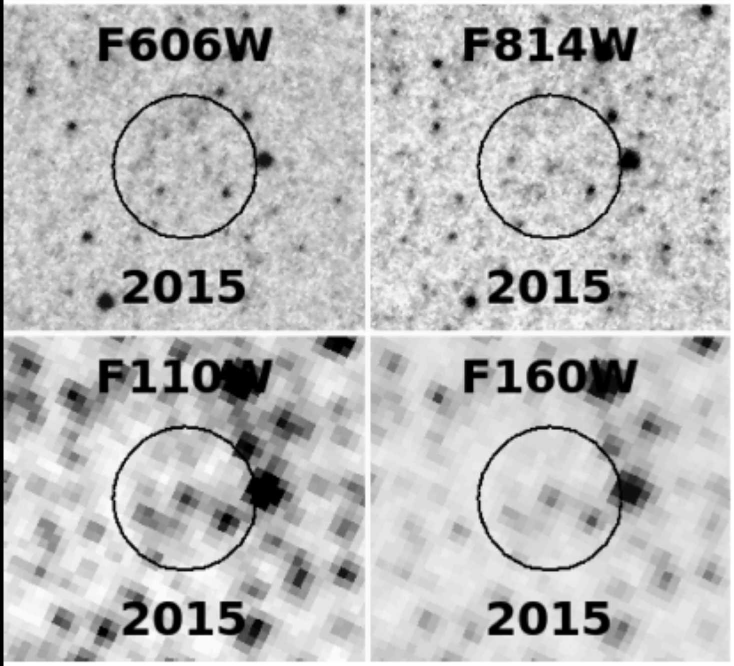
Gerke et al (2015)

So far over 7 years:

- 6 luminous CC supernovae
- 1 candidate failed supernova: NGC6946-BH1 (@~6Mpc); SED well fit by 25Msun RSG

Further HST images of NGC6946-BH1



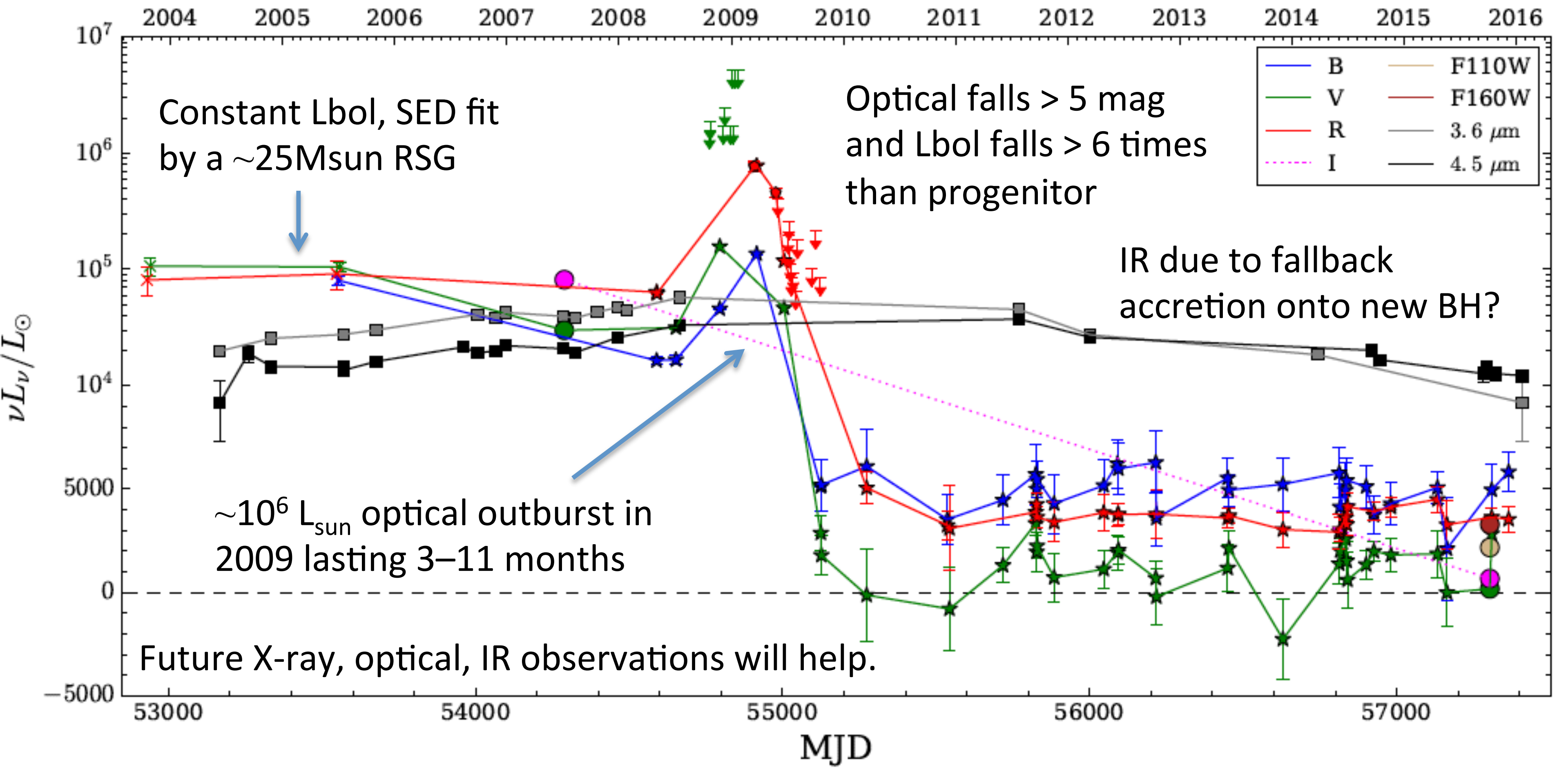


Adams et al (2017); also: Reynolds et al (2016)

Importance of NGC6946-BH1

Multi-wavelength follow-up indicative of failed event

Optical & IR detections consistent with Lovegrove & Woosley (2013) prediction + fallback accretion. Lack of other explanations.



Constant Lbol, SED fit by a ~25Msun RSG

Optical falls > 5 mag and Lbol falls > 6 times than progenitor

IR due to fallback accretion onto new BH?

~10^6 L_{sun} optical outburst in 2009 lasting 3–11 months

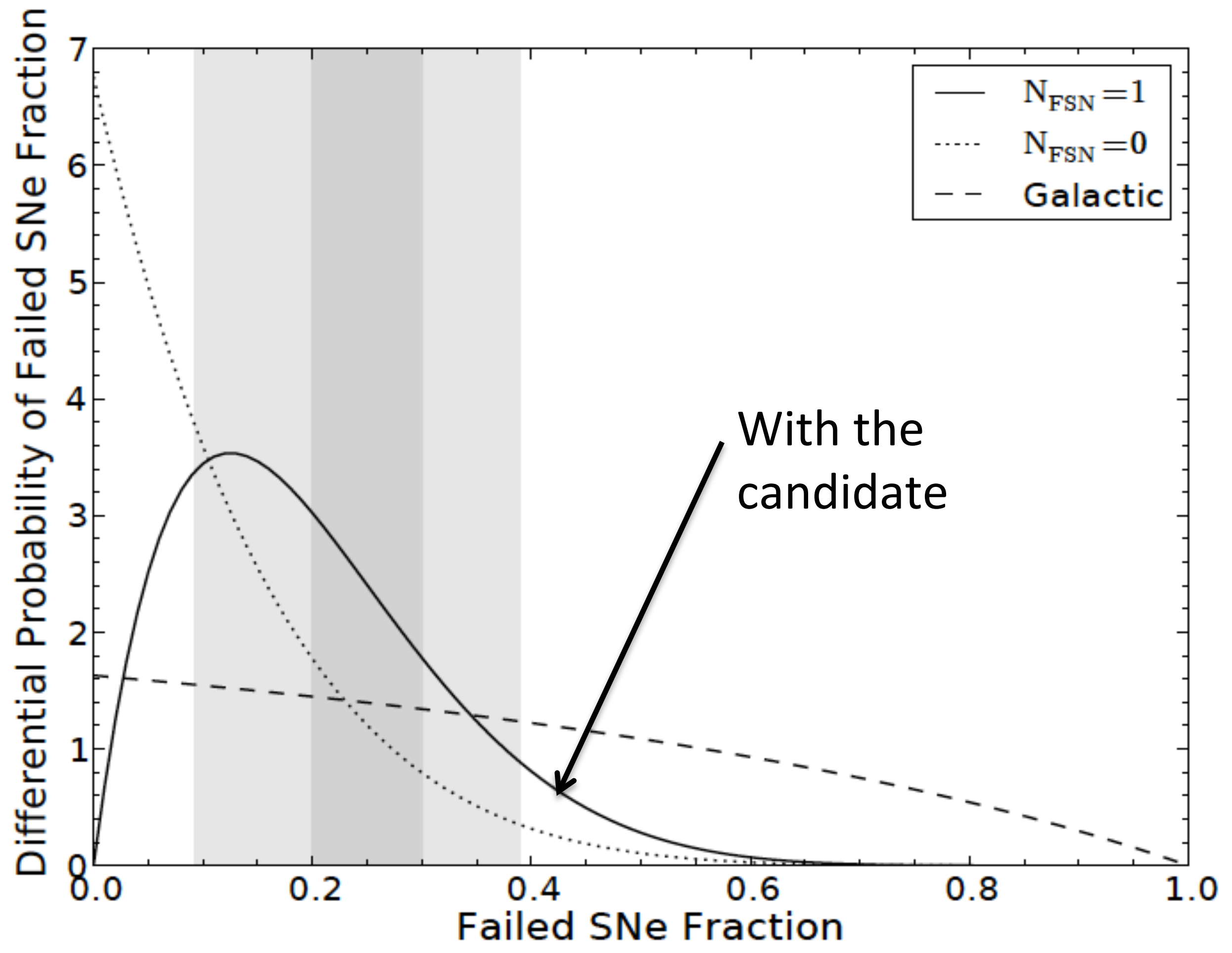
Future X-ray, optical, IR observations will help.

Adams et al (2017)

Fraction of failed explosion

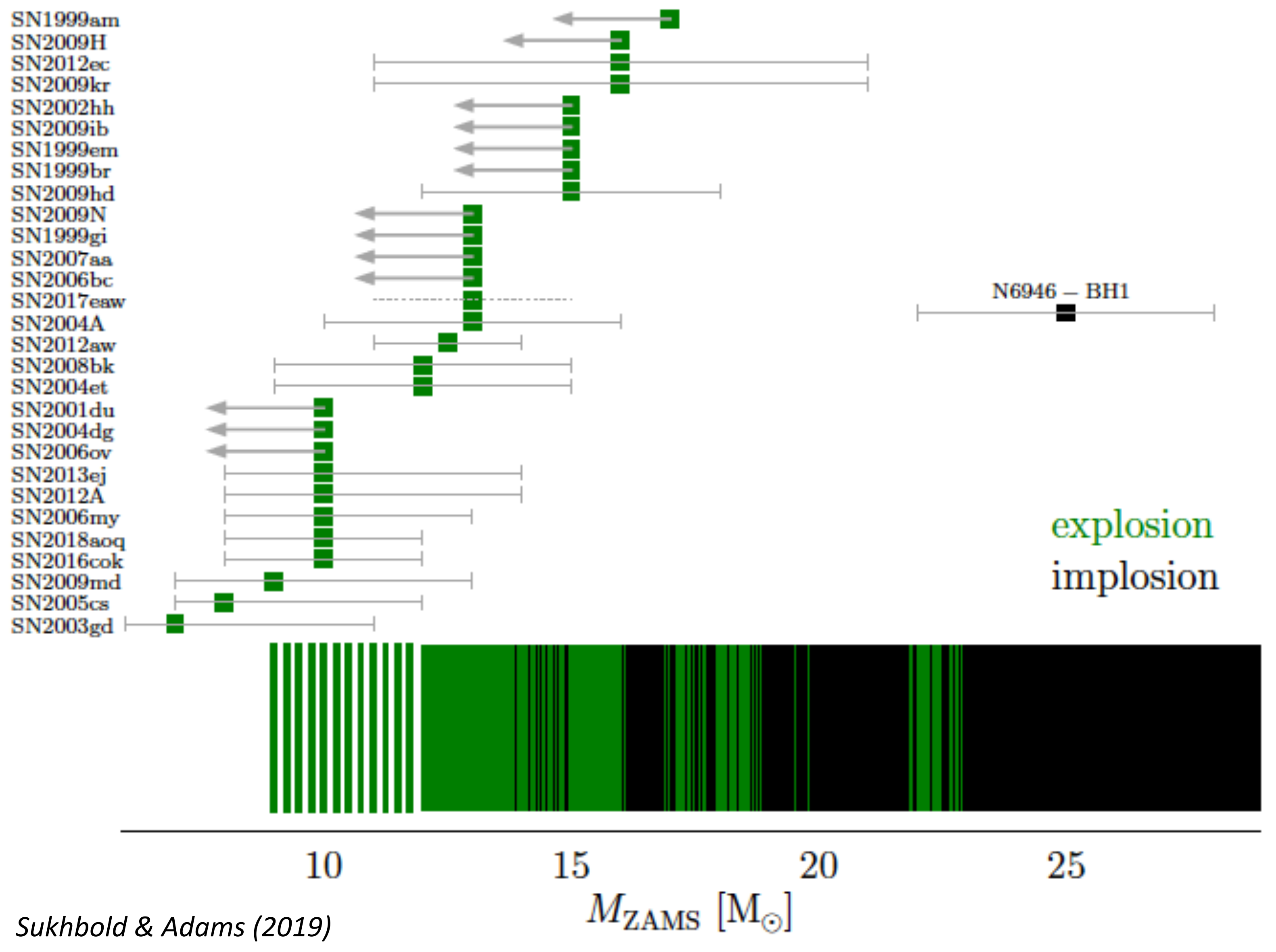
Based on observed supernovae & BH candidate

Adams et al (2016)



➔ Failed fraction $f = 0.14^{+0.33}_{-0.10}$ **(90%CL)**

Developing picture



Sukhbold & Adams (2019)

Diffuse Supernova Neutrino Background

Observed positron spectrum

Input 1: supernova neutrino spectrum (intensely studied, <u>quantity *of interest*</u>)

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

See, e.g., reviews by Ando & Sato (2004)
Beacom (2010), Lunardini (2010)

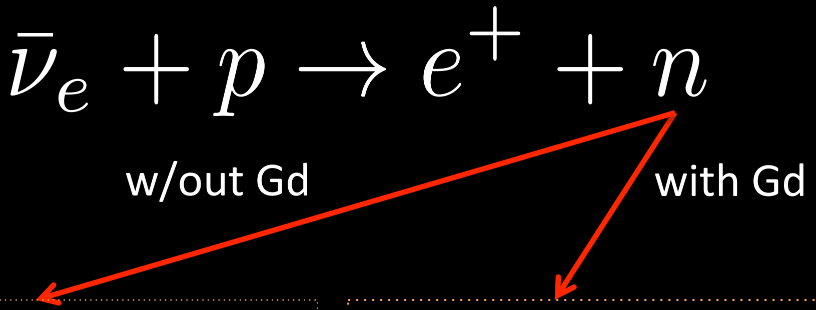
Input 2: core-collapse rate (intensely studied by astronomers using photons, <u>*rapidly improving*</u>)

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

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

Super-K with Gadolinium

Background rejection:
In water Cherenkov the signal produces a neutron, while backgrounds typically do not



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

w/out Gd

with Gd

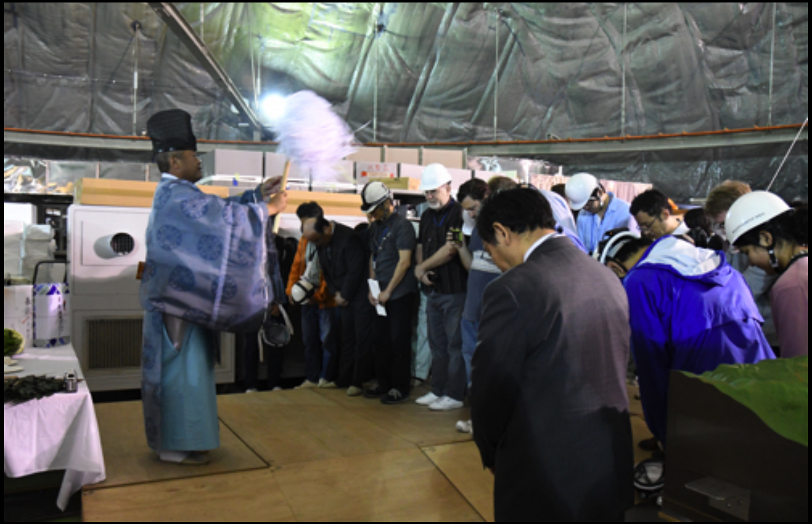
Capture on protons, signal mostly lost (~18% tagging)

Capture on Gadolinium, yields a coincidence signal (~90% tagging)

Beacom & Vagins (2004)

After many R&D & tests (EGADS), Super-K drained & refill in 2018, poised to add Gd in 2019

EGADS: Evaluating Gadolinium's Action on Detector Systems



Backgrounds and search window

Optimal search window
Dependent on the relevant backgrounds.

Neutrinos:

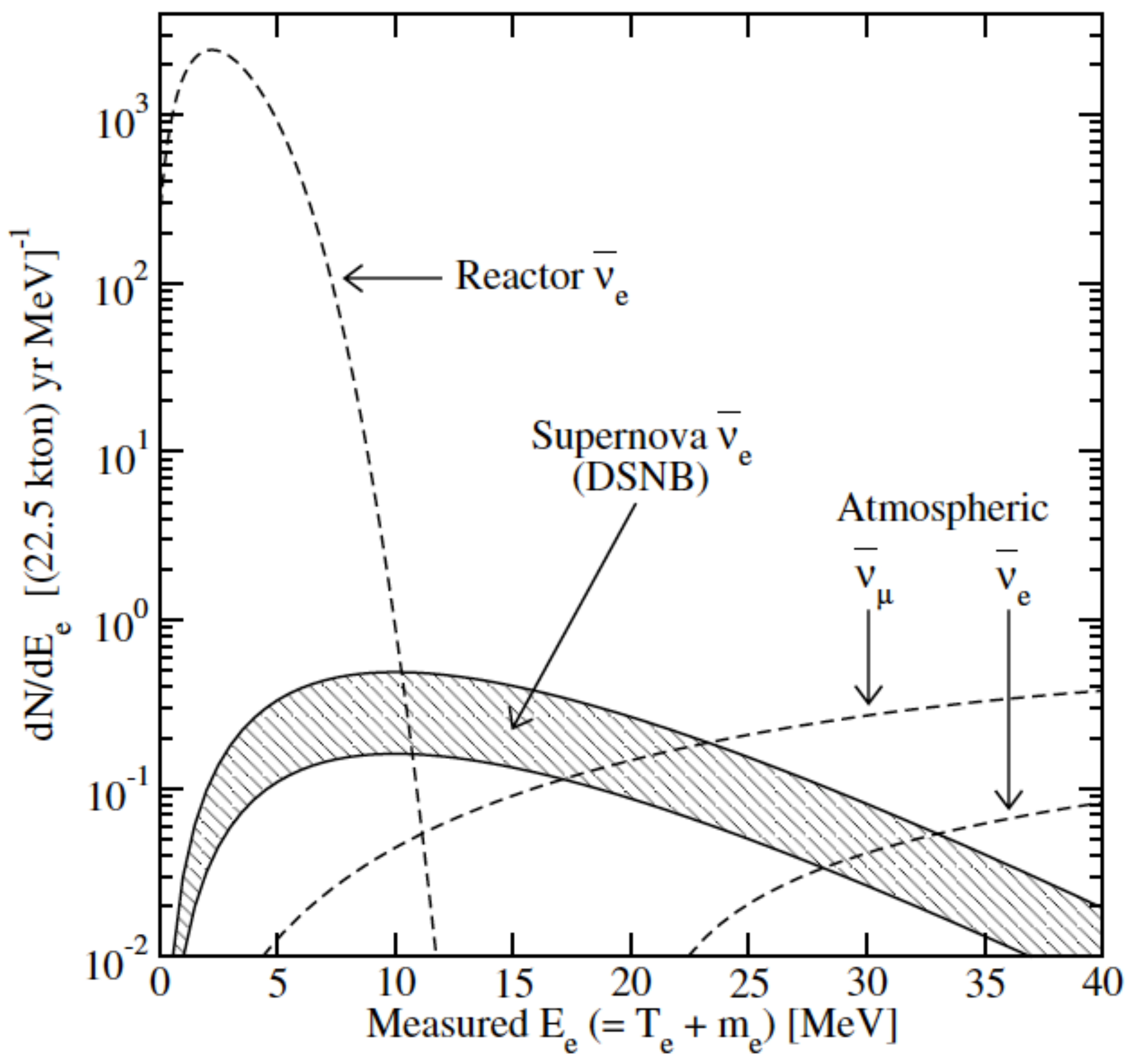
- Reactor neutrinos
- Atmospheric neutrinos

Mimicking neutrinos:

- Invisible muon decays
- Spallation products

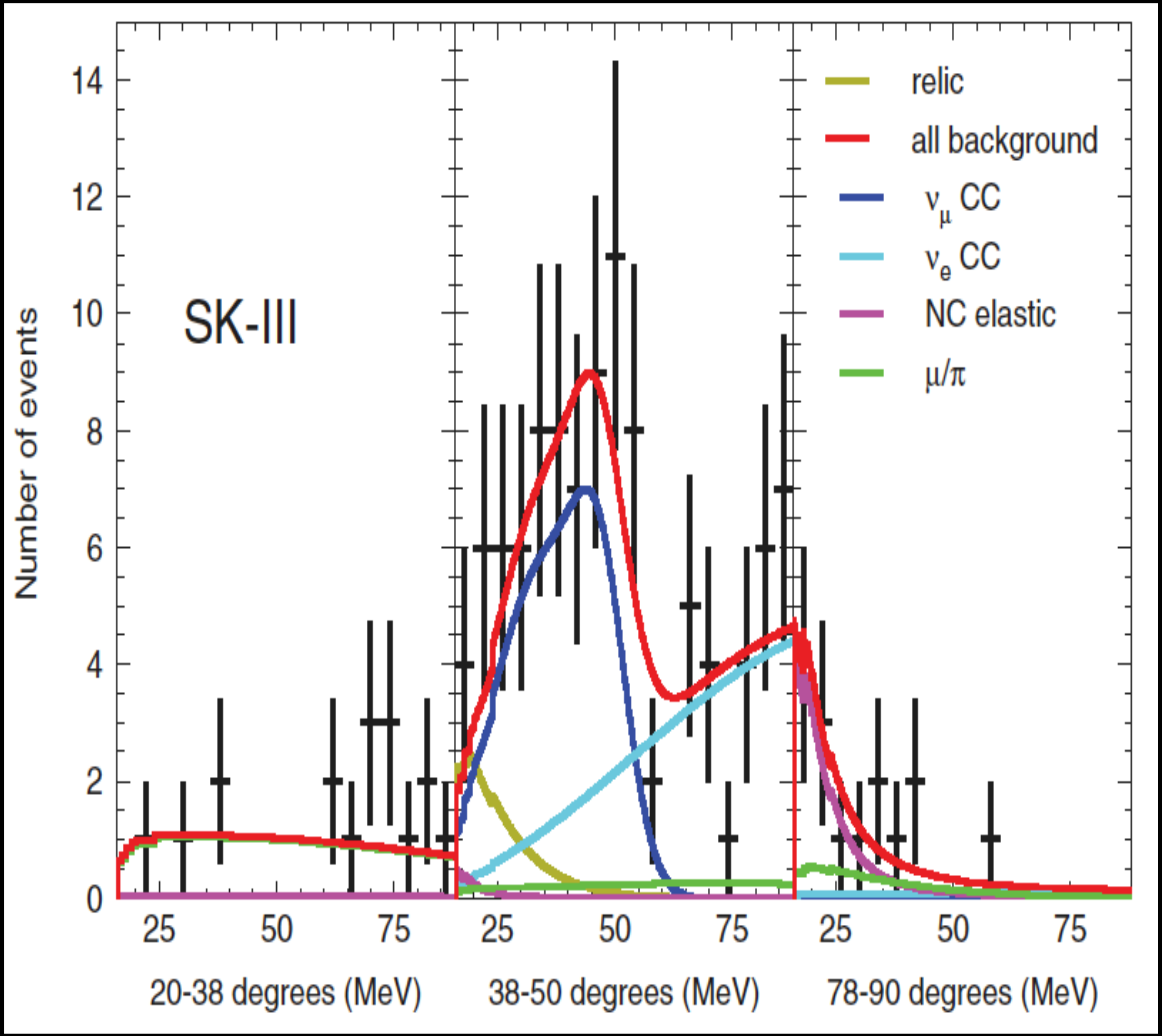
which can be reduced by Gd

➔ Window is ~10-25 MeV with Gd



Beacom & Vagins (2004)

Searches: limits



Bays et al (2012)

Kamiokande-II

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

[19 – 34 MeV, 90%CL]

Zhang et al. (1988)

Super-Kamiokande (SK-I)

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

[>19.3 MeV, 90%CL]

Malek et al. (2003)

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

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

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

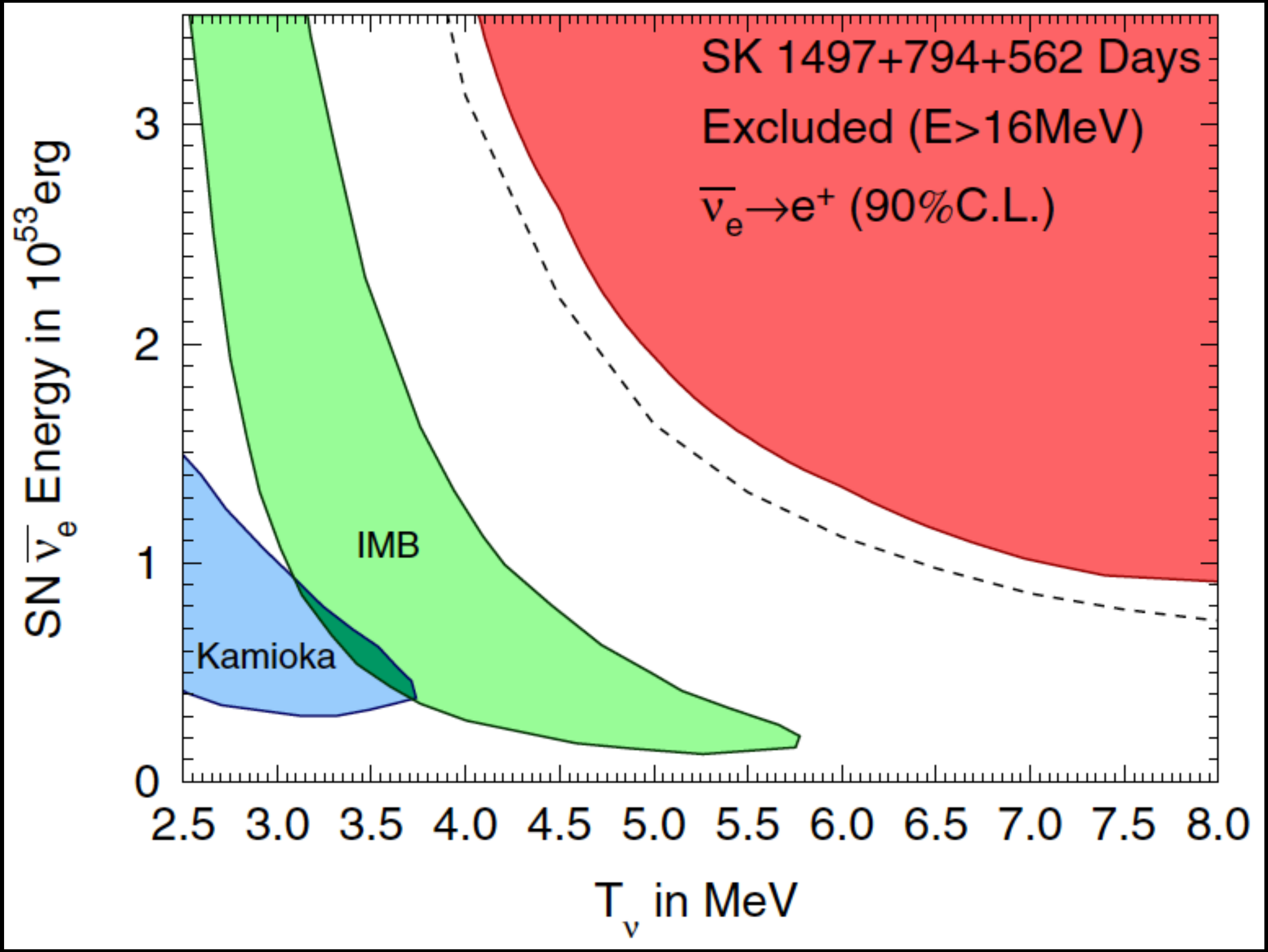
Bays et al (2012)

Low-E update, Zhang et al (2014)

Interpretation of present limits

Search with Super-Kamiokande

Already excluding large energetics & neutrino energy



Bays et al (2012)

Upcoming sensitivity

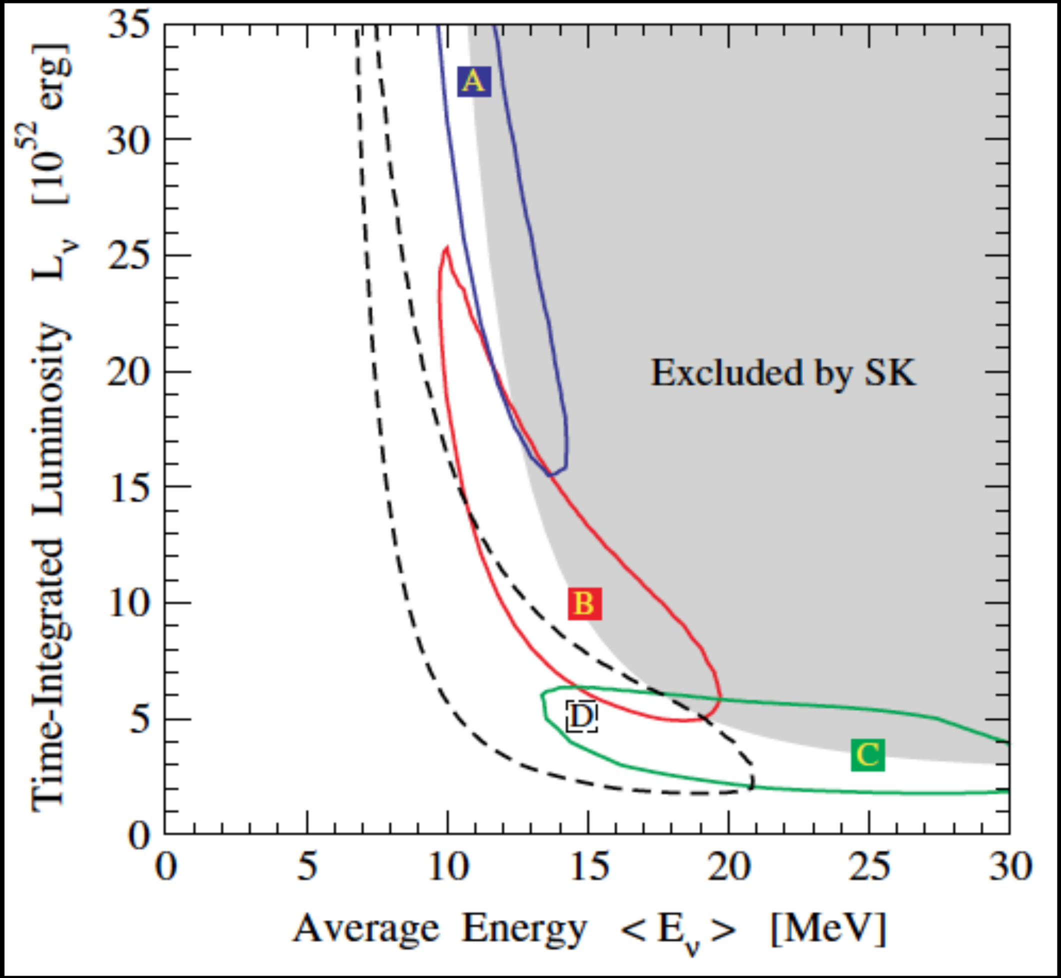
Search with Super-K + Gadolinium

Gd transforms Super-K into a signal-dominated search with a wider energy window.

Spectrum ($\xi_{2.5}$)	Water (E > 18 MeV) [/yr]
All NS	0.4 +/- 0.1
$\xi_{2.5,crit} = 0.2$	0.6 +/- 0.1
$\xi_{2.5,\,crit} = 0.1$	1.0 +/- 0.3

Spectrum ($\xi_{2.5}$)	Water + Gd (E > 10 MeV) [/yr]
All NS	1.7 +/- 0.4
$\xi_{2.5,\,crit} = 0.2$	1.9 +/- 0.5
$\xi_{2.5,\,crit} = 0.1$	2.8 +/- 0.8

10 years with Super-K + Gd



Yuksel et al (2006)

NB: "All NS" closest to D

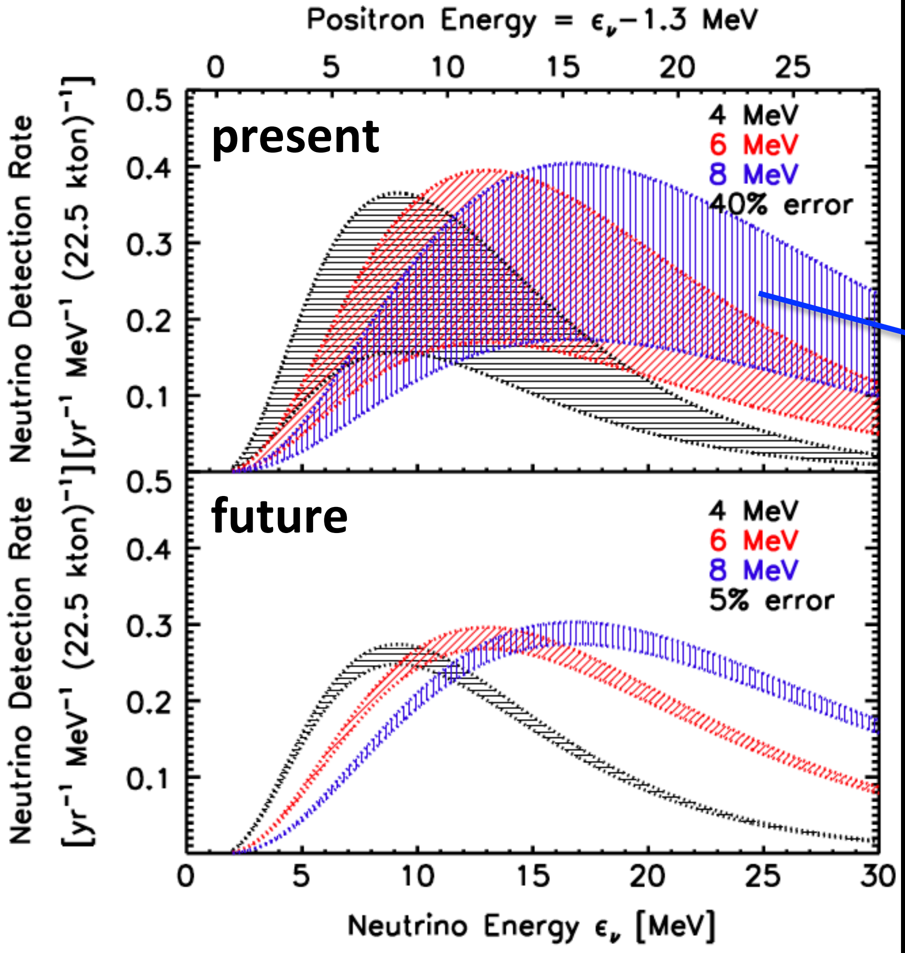
DSNB: long-term future

Supernova rate uncertainty

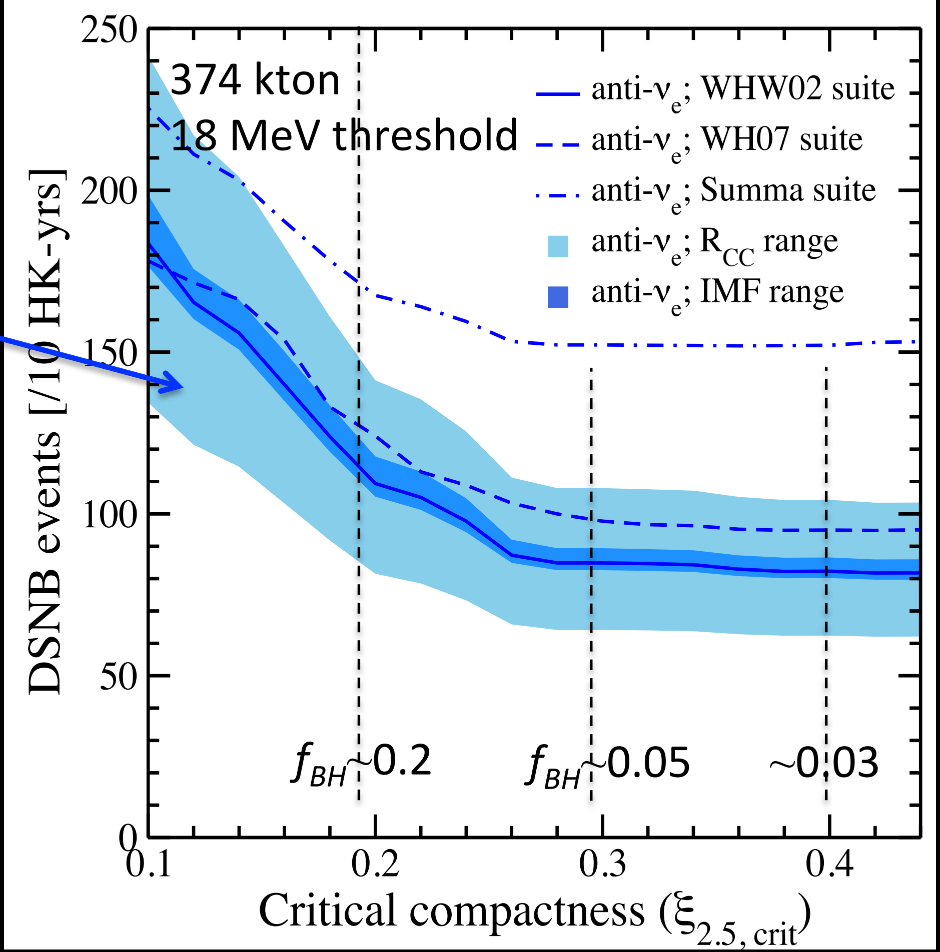
Will reduce with next-generation supernova surveys (e.g., LSST; 2023~)

Neutrino detector

Hyper-Kamiokande will increase detector volume by x10 or so



Lien et al (2010)



Horiuchi et al (2018)

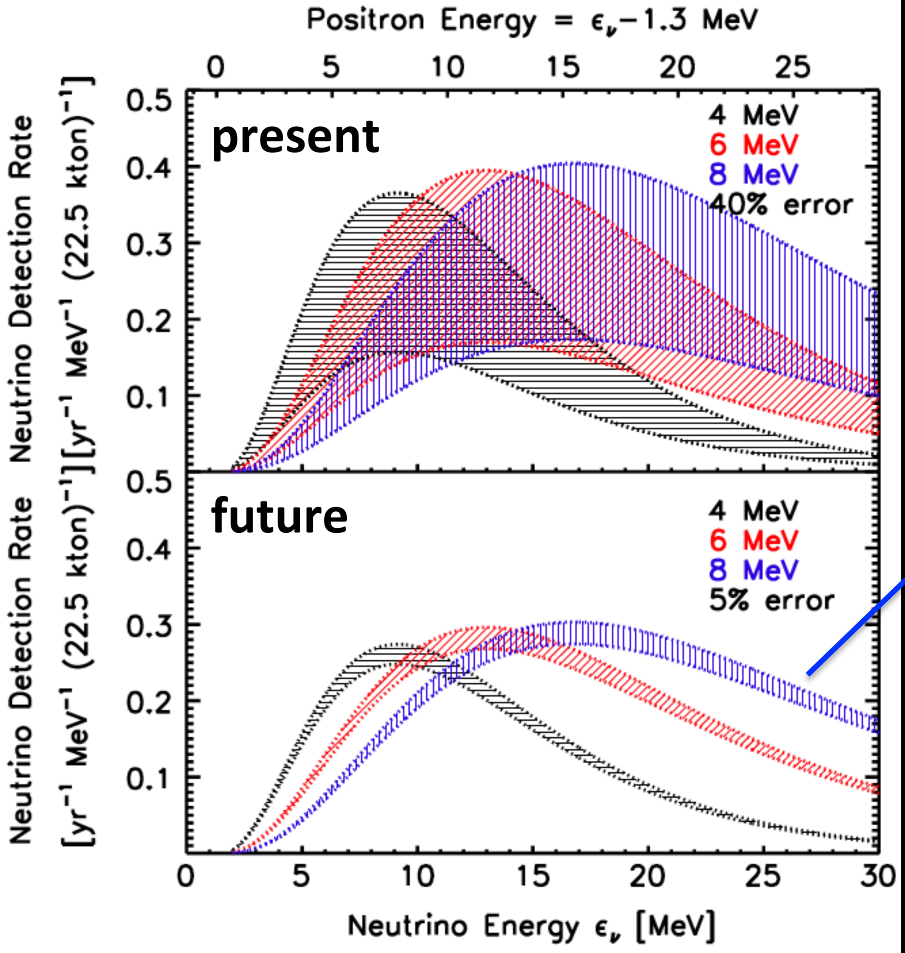
DSNB: future

Rate uncertainty

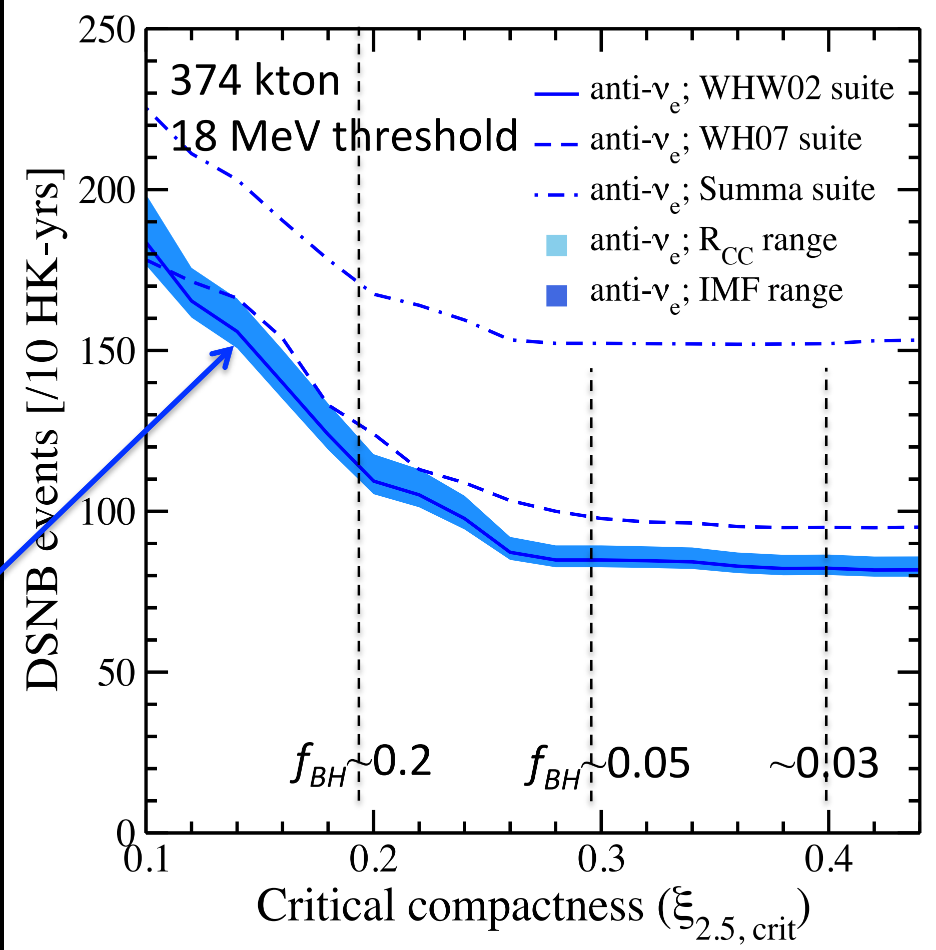
Will reduce with next-generation supernova surveys (e.g., LSST; 2023~)

Neutrino detector

Hyper-Kamiokande will increase detector volume by x10 or so



Lien et al (2010)



Horiuchi et al (2018)

Concluding remarks

Theory: supernova neutrino background is a **guaranteed signal**

- ✓ We know core collapse occur regularly in the Universe (constant updates from astronomers)
- ✓ We know core collapse emits neutrinos (by SN1987A and byconstant updates from theory)

Present: improving prospects for **detection**

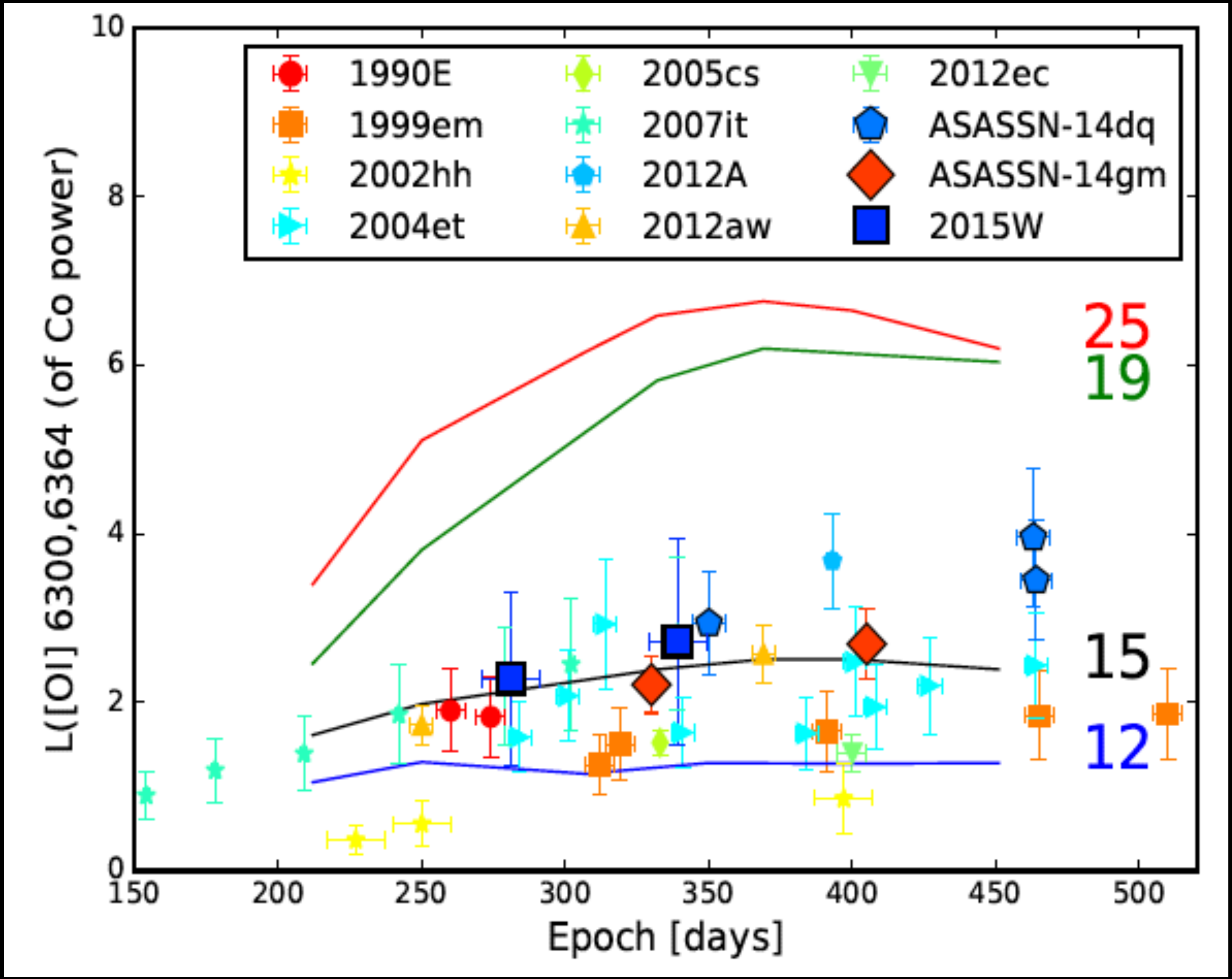
- ✓ Gd upgrade at Super-K delivers signal-limited search
- ✓ Can provide detection in 5-10 years

Future: era of new probes, e.g.

- ✓ High-statistics DSNB probes **black hole formation track**
- ✓ Benefit from ongoing new simulations, long-term simulations, core-collapse rate measurements, oscillation parameters, etc

Nebular spectra connection

Oxygen production in supernova



Nebular phase allows stellar material within CO cores to be visible. Opens independent progenitor mass estimate.

SNe (12 type II, including IIP and IIL) studied, consistent with RSG in mass range 12–16 Msun

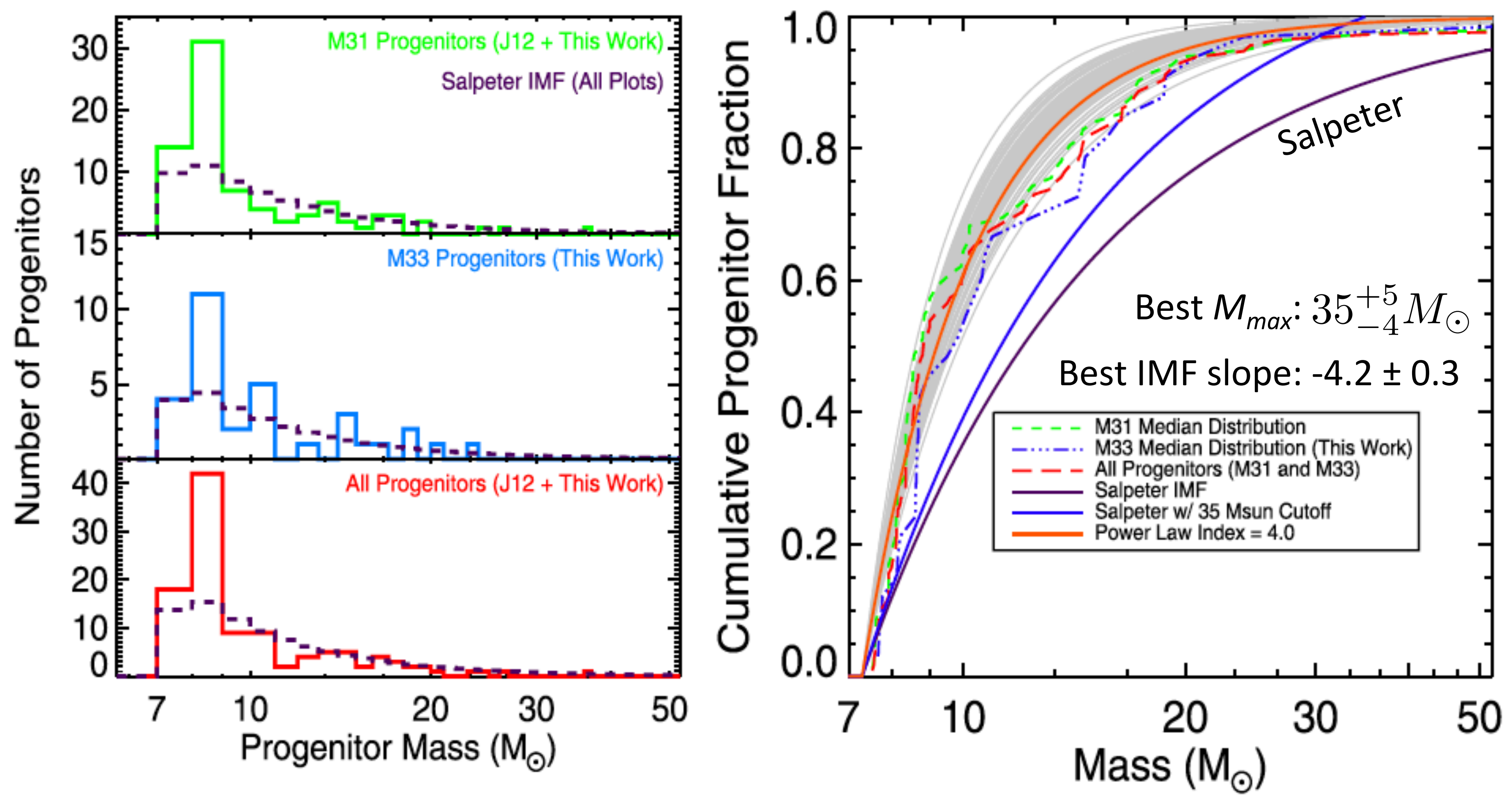
➔ Missing massive stars consistent with missing RSG

Valenti et al (2016), Jerkstrand et al (2015)

Supernova remnant connection

SNR mass distributions yield steeper IMF slope and/or presence of M_{max}

→ Massive stars tend to be lacking as SNR progenitors compared to low mass stars



Salpeter

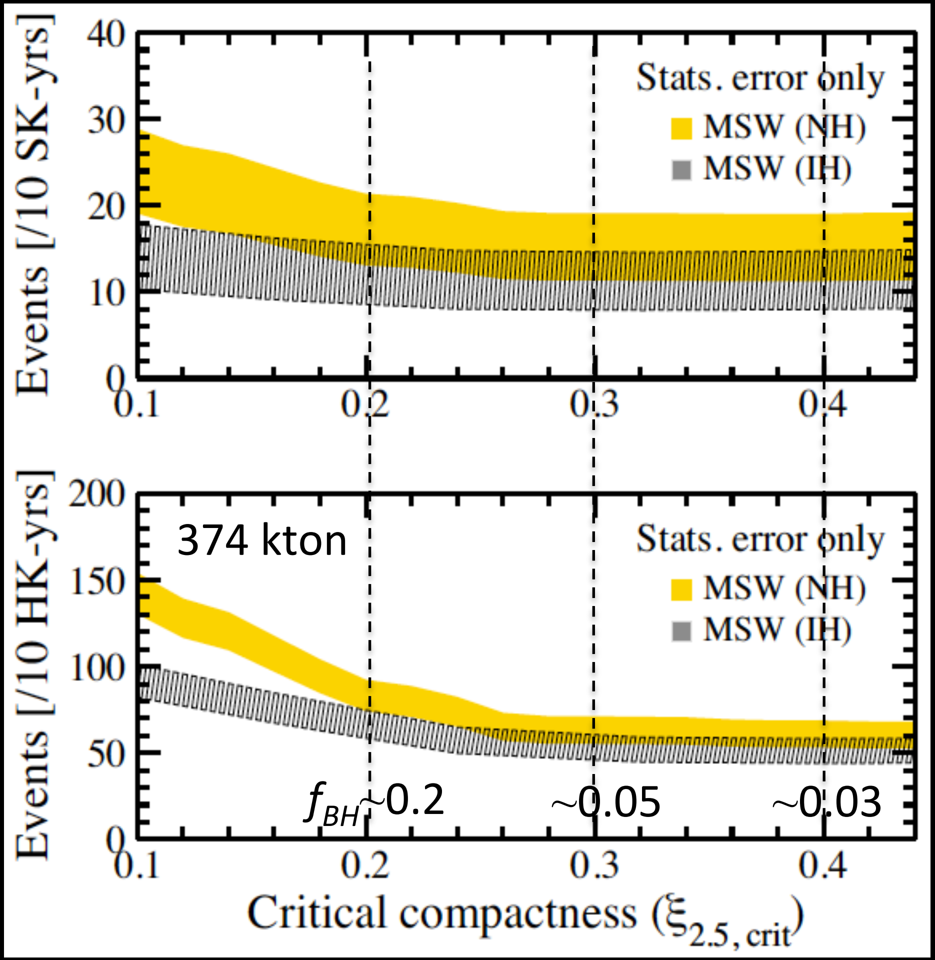
Best M_{max}: $35^{+5}_{-4} M_\odot$

Best IMF slope: -4.2 ± 0.3

Jennings et al (2012, 2014); also Diaz-Rodriguez et al (2018), but Auchtettl et al (2019)

DSNB: future

Hyper-Kamiokande



Horiuchi et al (2018); also Lunardini (2009), others

Time-integrated neutrino signal

Spectrum per core collapse

Spectral parameters from 100+ simulations: reveals systematic dependence on compactness

$$f_\nu(E) \propto E^{\alpha} e^{-(\alpha+1)E/E_{\rm av}}$$

➔ *$(E_{tot}, E_{ave}, \alpha_{pinch})$*