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Diffuse supernova neutrino background (DSNB) predictions and discovery potential

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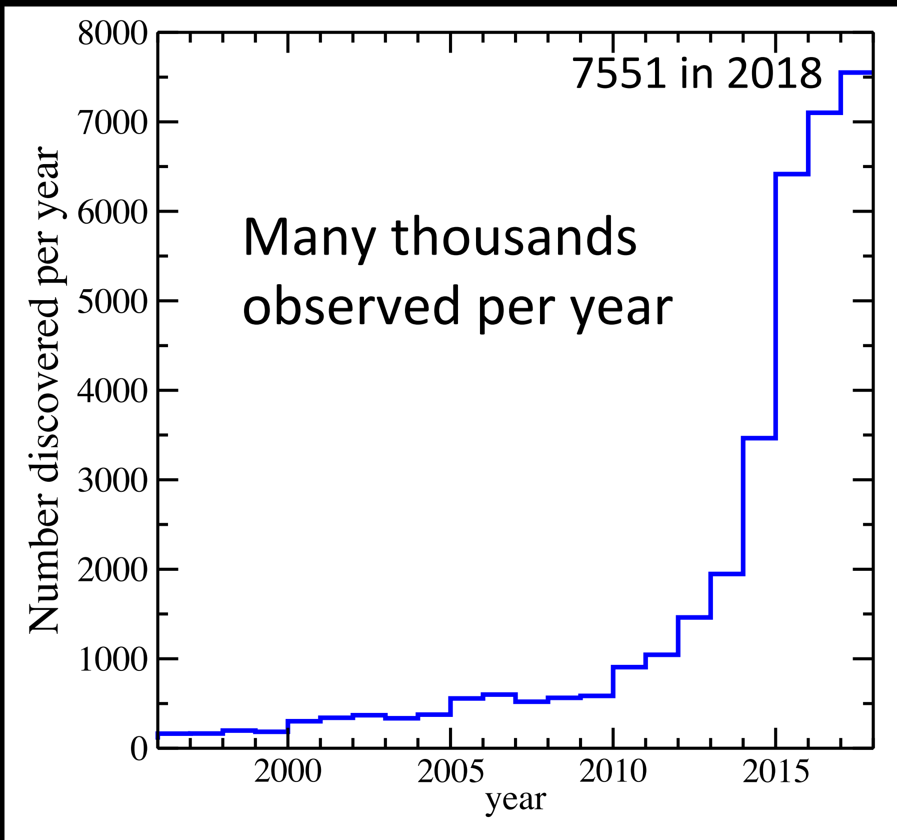
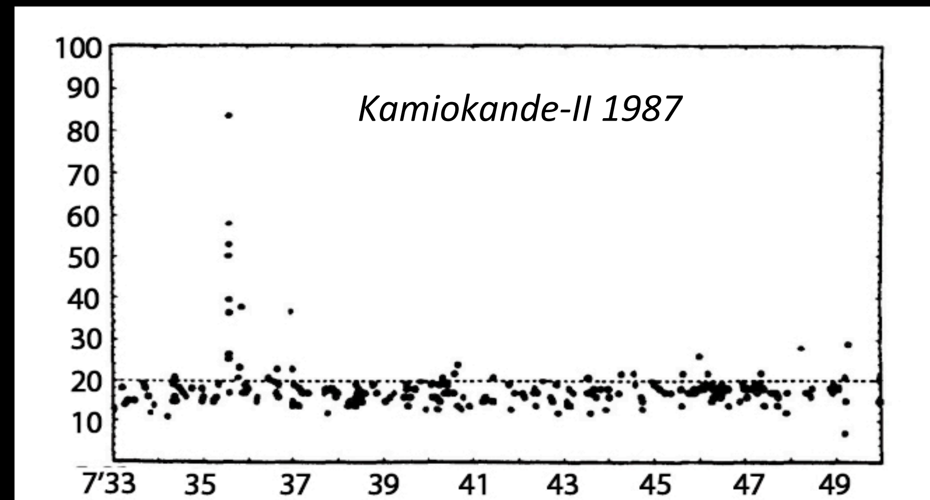
U.S. DEPARTMENT OF ENERGY | Office of Science

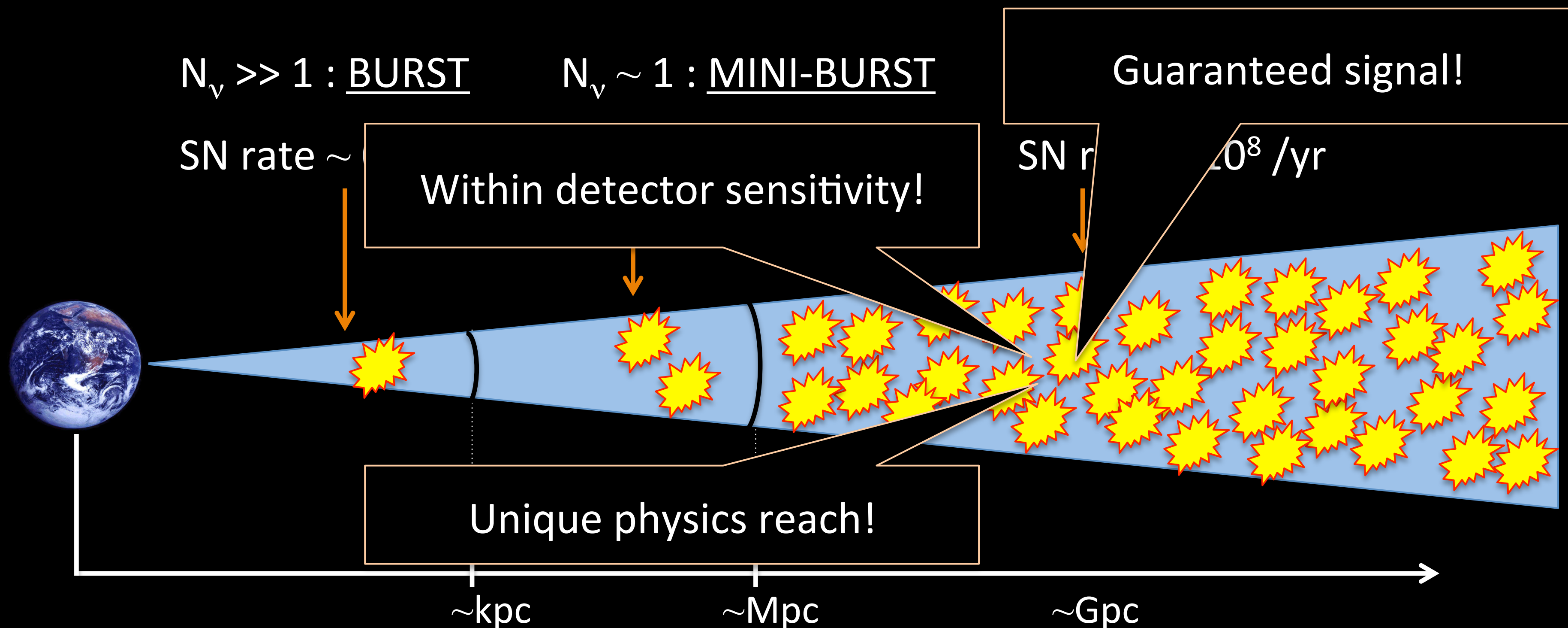
Stars explode EVERYDAY





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

Distance scales and physics outcomes



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

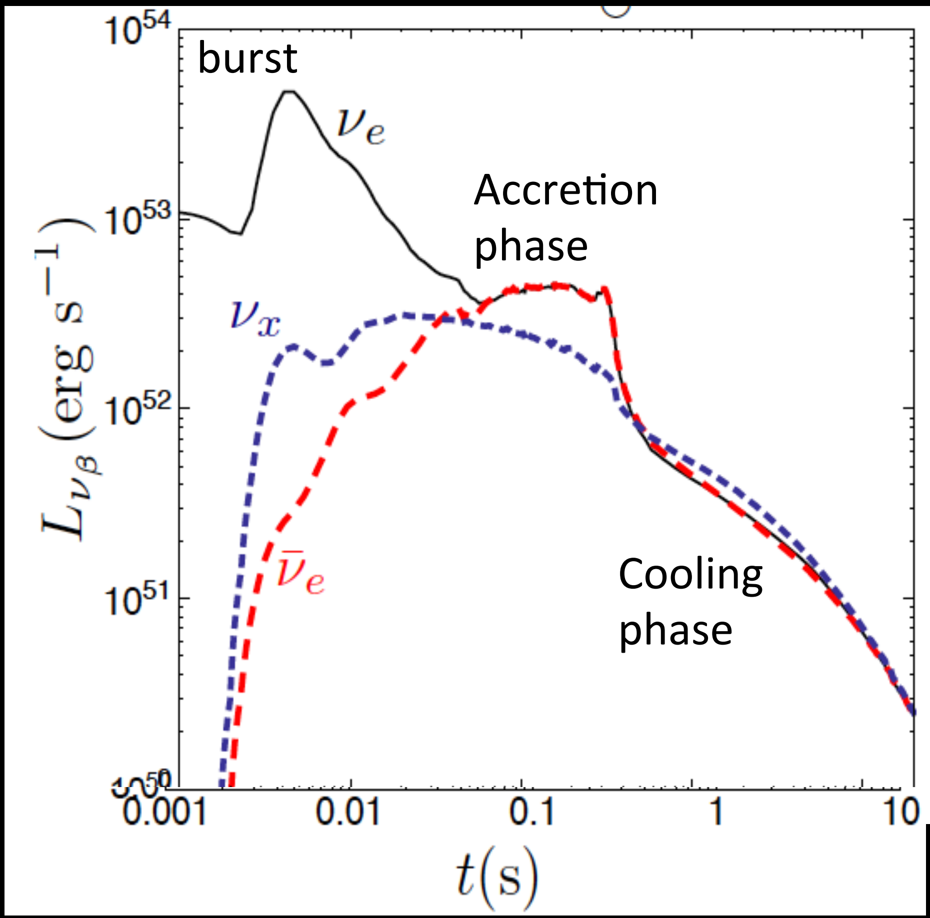
Input 1: neutrino emission

Neutrinos from core collapse

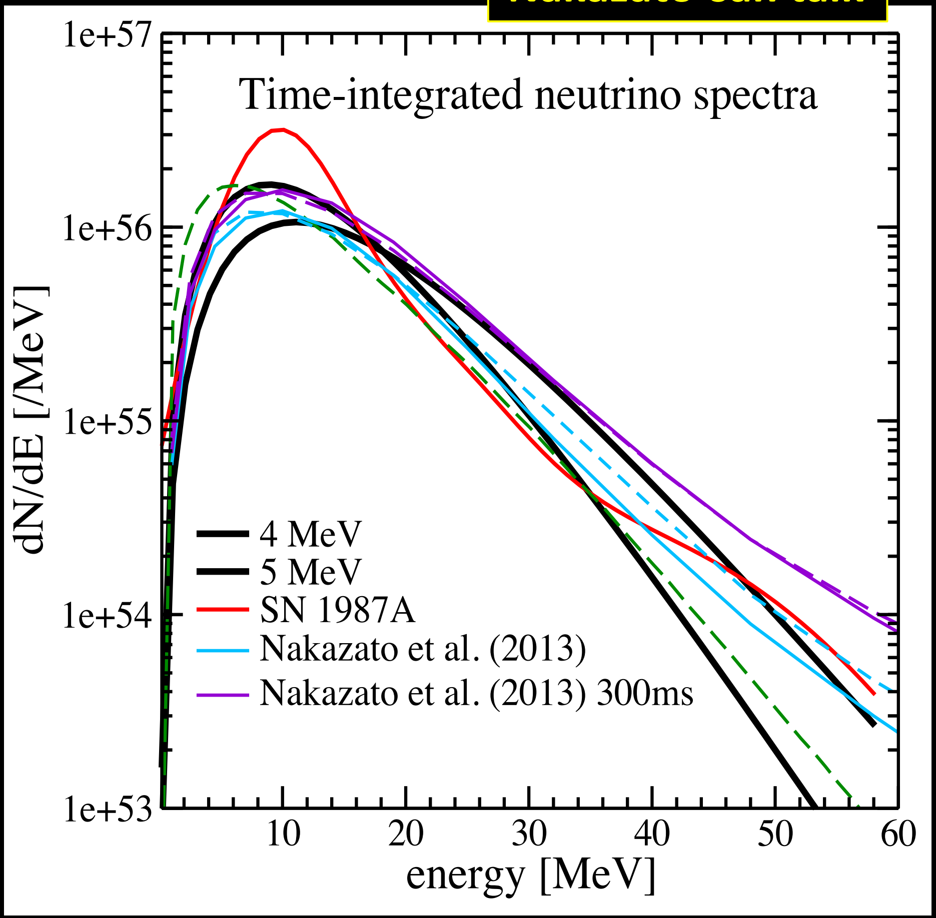
Each core collapse releases ~3x10[53] erg of neutrinos, of which ~1/6 is in anti-ν_e

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

Nakazato-san talk



Fischer et al (2010)

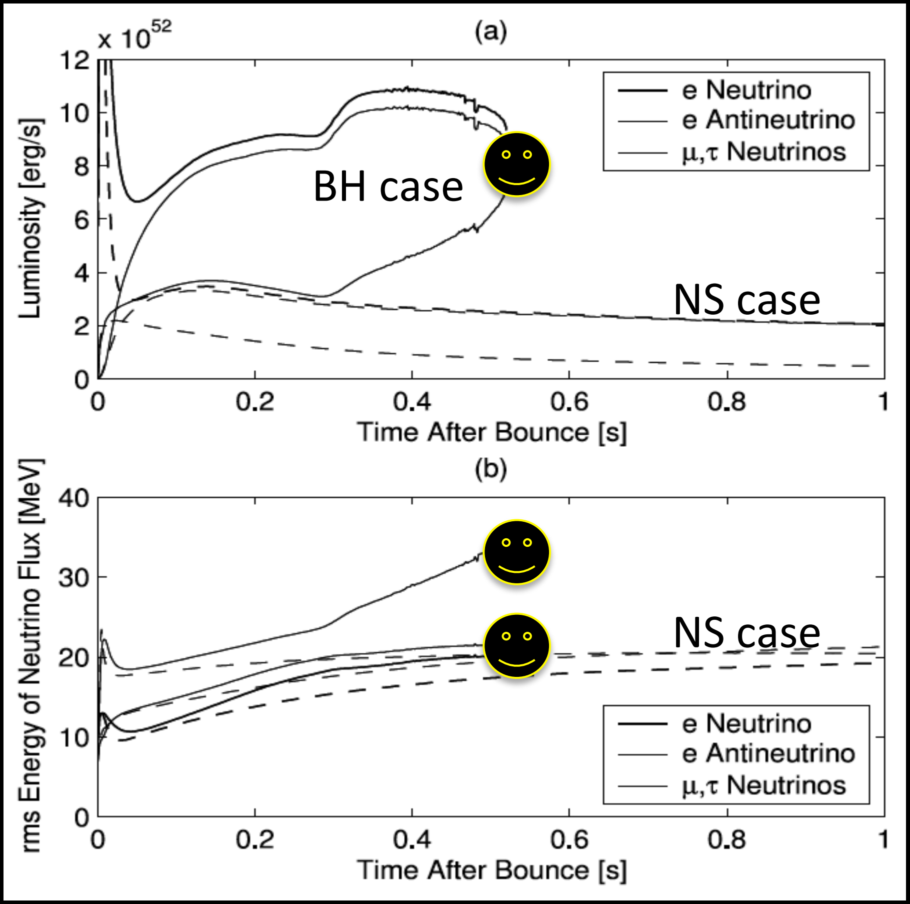


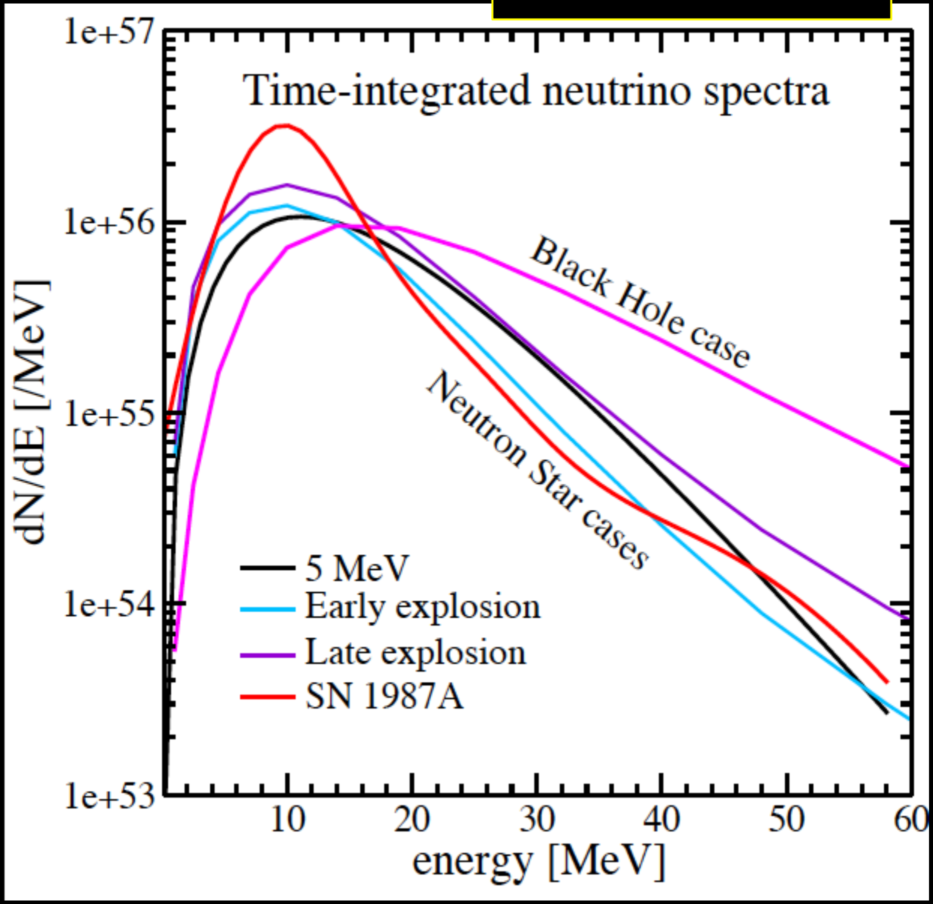
Collapse to black holes

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)

Nakazato-san talk





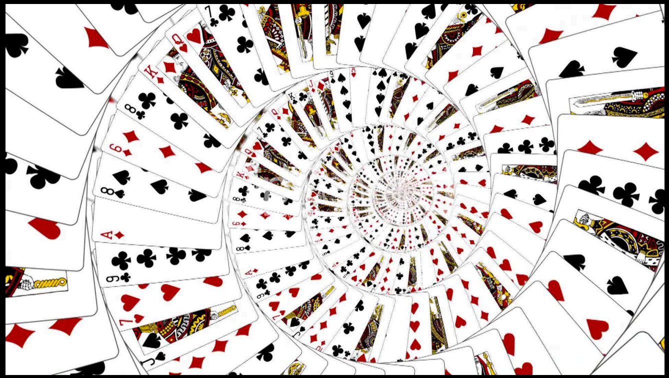
Liebendoerfer et al 2004; many studies, e.g., Fischer et al 2009, Sumiyoshi et al 2006, 2007, 2008, 2009, Nakazato et al 2008, 2010, O'Connor & Ott 2011, …

Core-collapse diversity

Sophisticated simulations [no systematic studies yet]

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

World-wide: groups in Japan, Australia, Germany, Poland, Sweden, USA, …



First systematic studies in spherically symmetry

- Spherically symmetric with parameterized neutrino heating
- ~700 models, GR gravity, varied progenitor, EOS, etc

O'Connor & Ott (2011, 2013), Ugliano et al (2012), Pejcha & Thompson (2015), Ertl et al (2015), Summa et al (2016), Sukhbold et al (2016), Mueller et al (2016), …

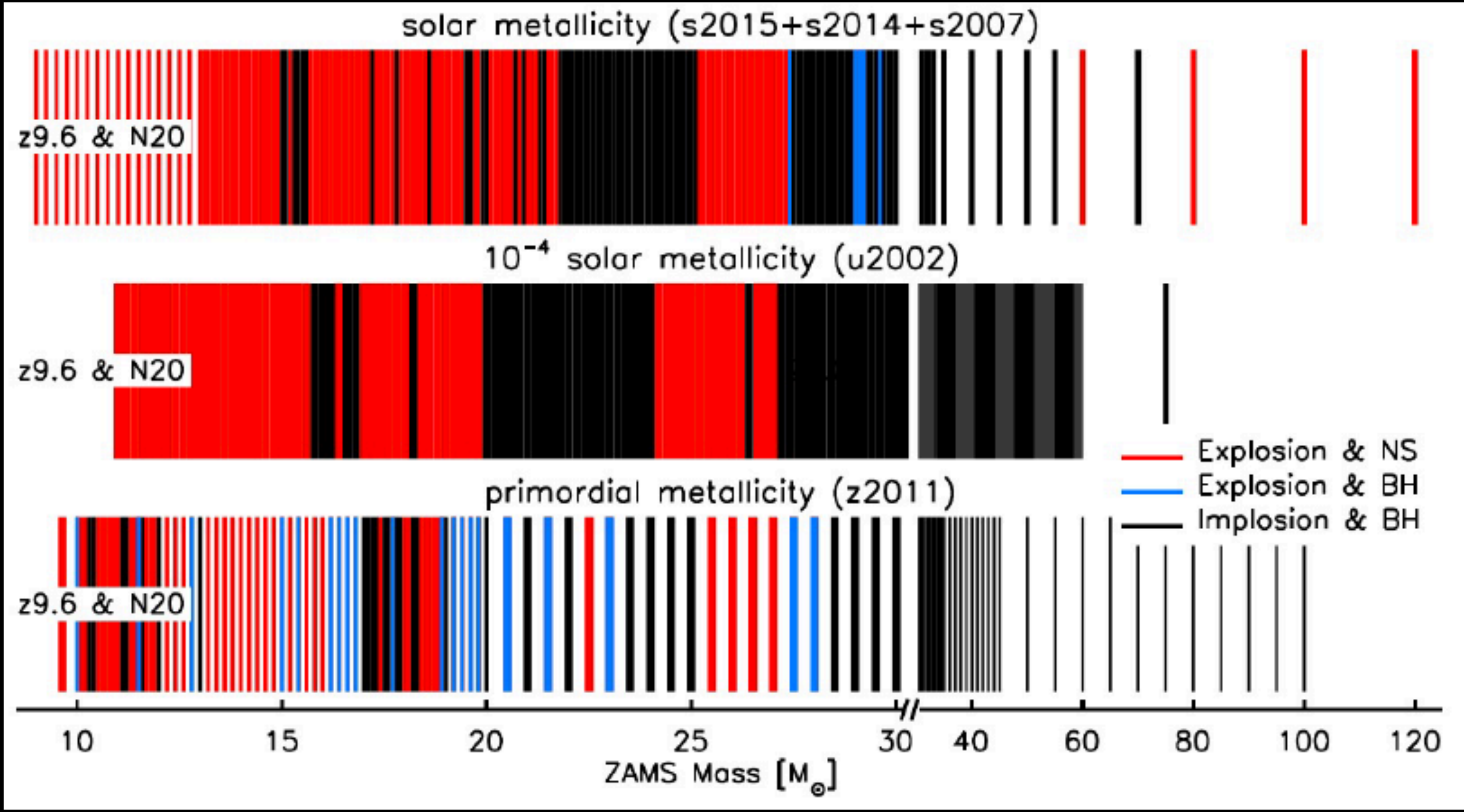
Systematic study in axis-symmetry

- Axis-symmetric with simplified neutrino transport
- ~400 progenitor models, Newtonian, single EOS

Nakamura et al (2014), Summa et al (2016)

Supernova diversity

Systematic studies: thinking in mass looks incomplete



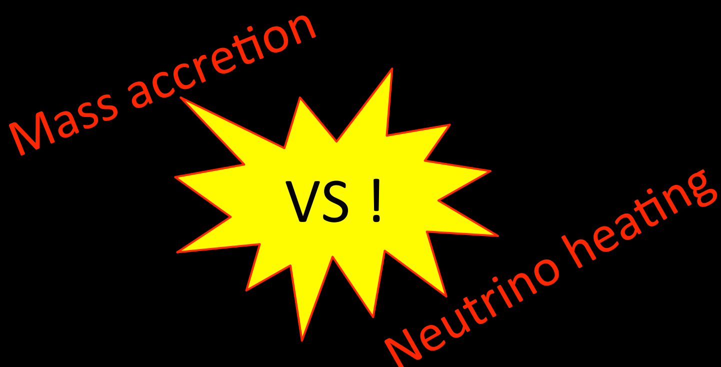
Janka 2017; see also O'Connot & Ott (2011), Pejcha & Thompson (2015), Sukhbold et al (2016), Mueller et al (2016)

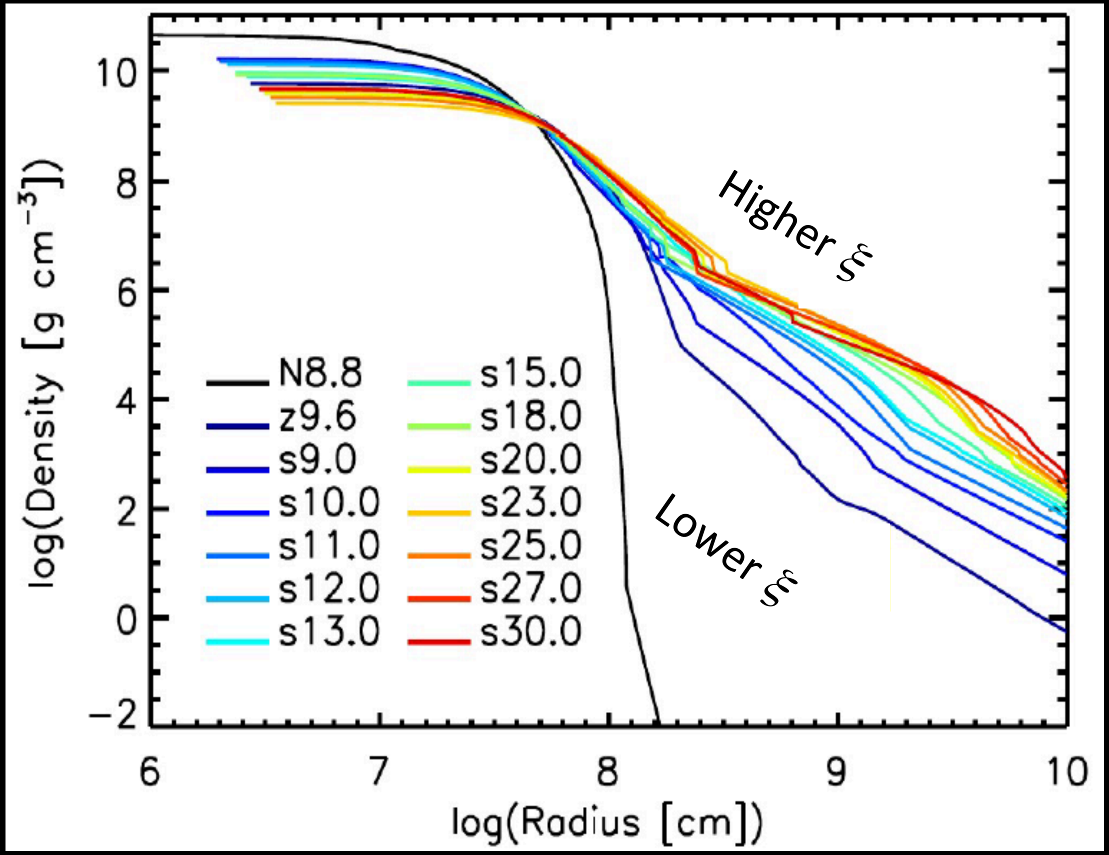
Compactness: a useful indicator

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

O'Connor & Ott (2011)

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





- Higher ξ → higher Mdot → harder to explode
- Lower ξ → lower Mdot → easier to explode

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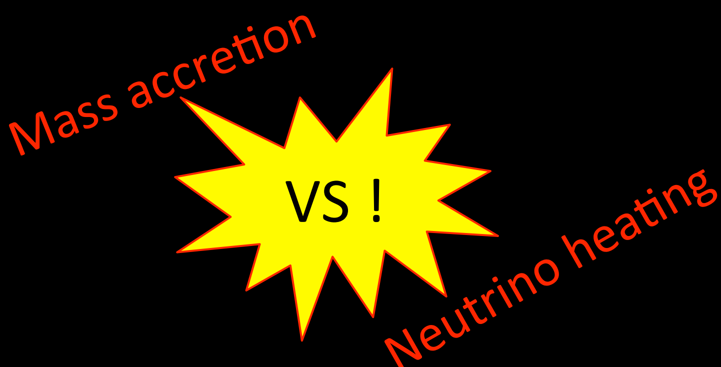
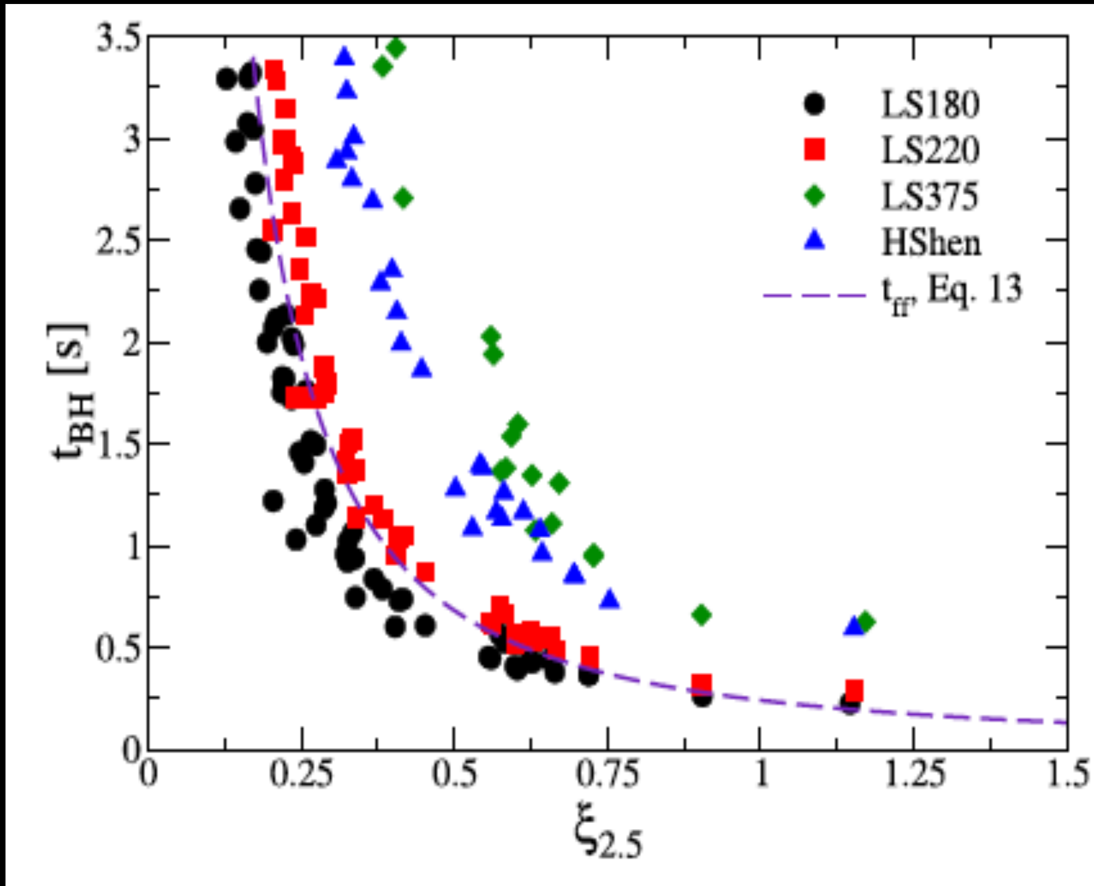


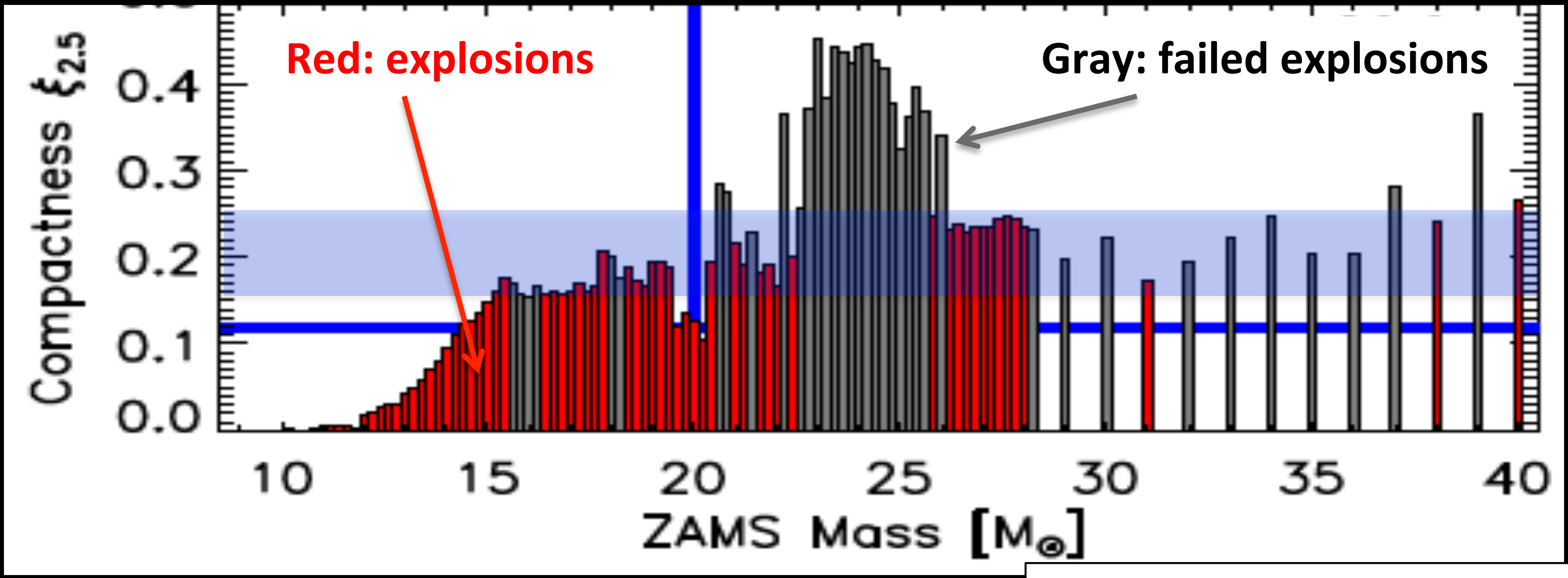


O'Connor & Ott (2011)

- Higher ξ → higher Mdot → harder to explode → fails earlier
- Lower ξ → lower Mdot → easier to explode → a little harder to fail

Islands of "un-explodability"

Failed explosions appear in islands, and correspond to stars with large compactness



Ertl et al (2015) ; see also Ugliano et al (2012)

- BH formation for $\xi_{2.5} > 0.25$
- Explosions for $\xi_{2.5} < 0.15$
- Mixture in between

A critical compactness?

- 1 compactness successful in ~88% of progenitors

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

Multi-dimensional simulations?

- Critical compactness $\xi_{2.5} \sim 0.2$ is consistent with axisymmetric simulations
- Critical compactness in 3D simulations still TBD

Horiuchi et al (2014)

Correlations in systematic 2D simulations

Axis-s

Based

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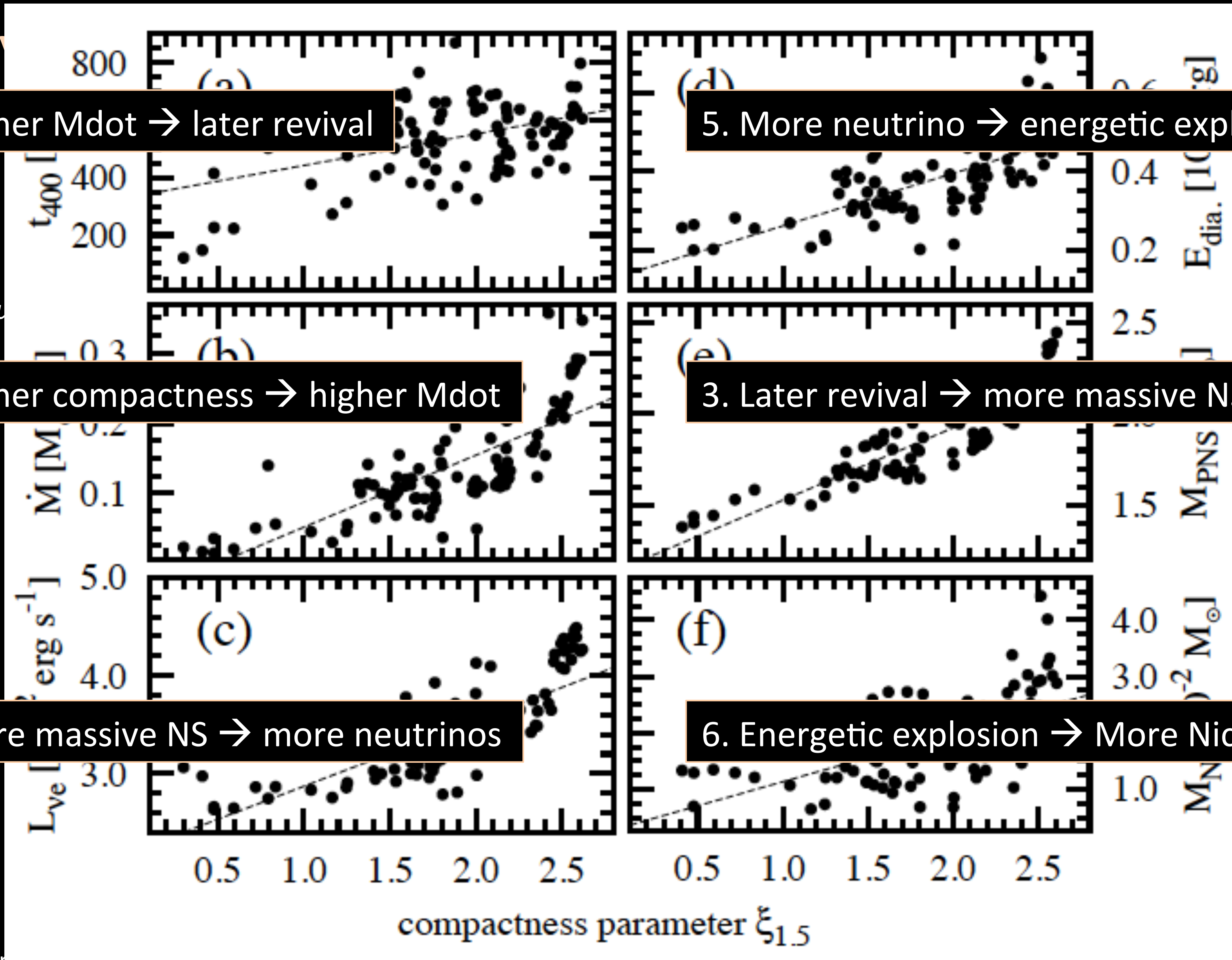
Nakamu



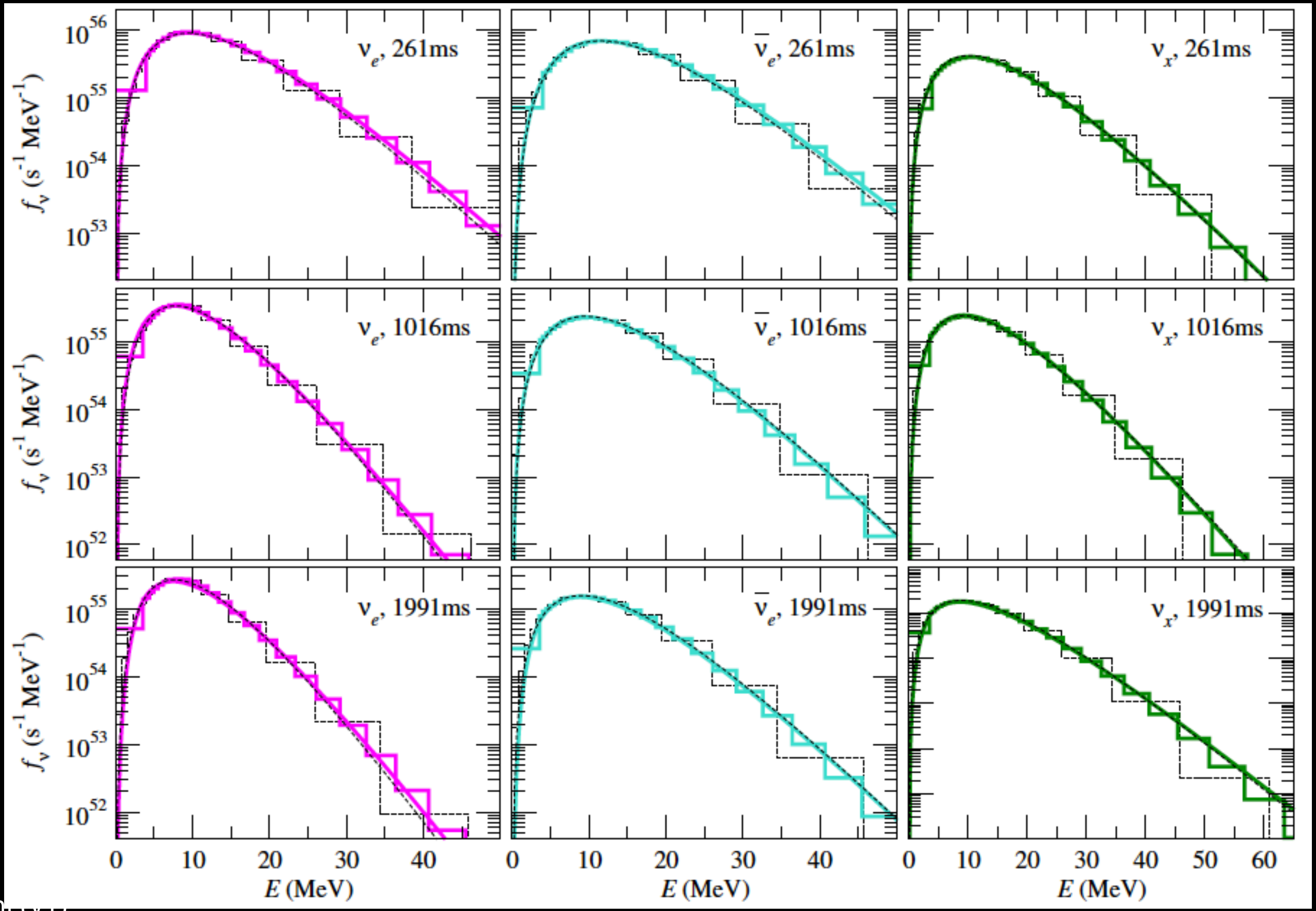
Neutrino emission spectrum

Supernova neutrino spectral area well fit by a pinched spectrum (3 parameters)

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

(E_{tot}, E_{ave}, α_{pinch})

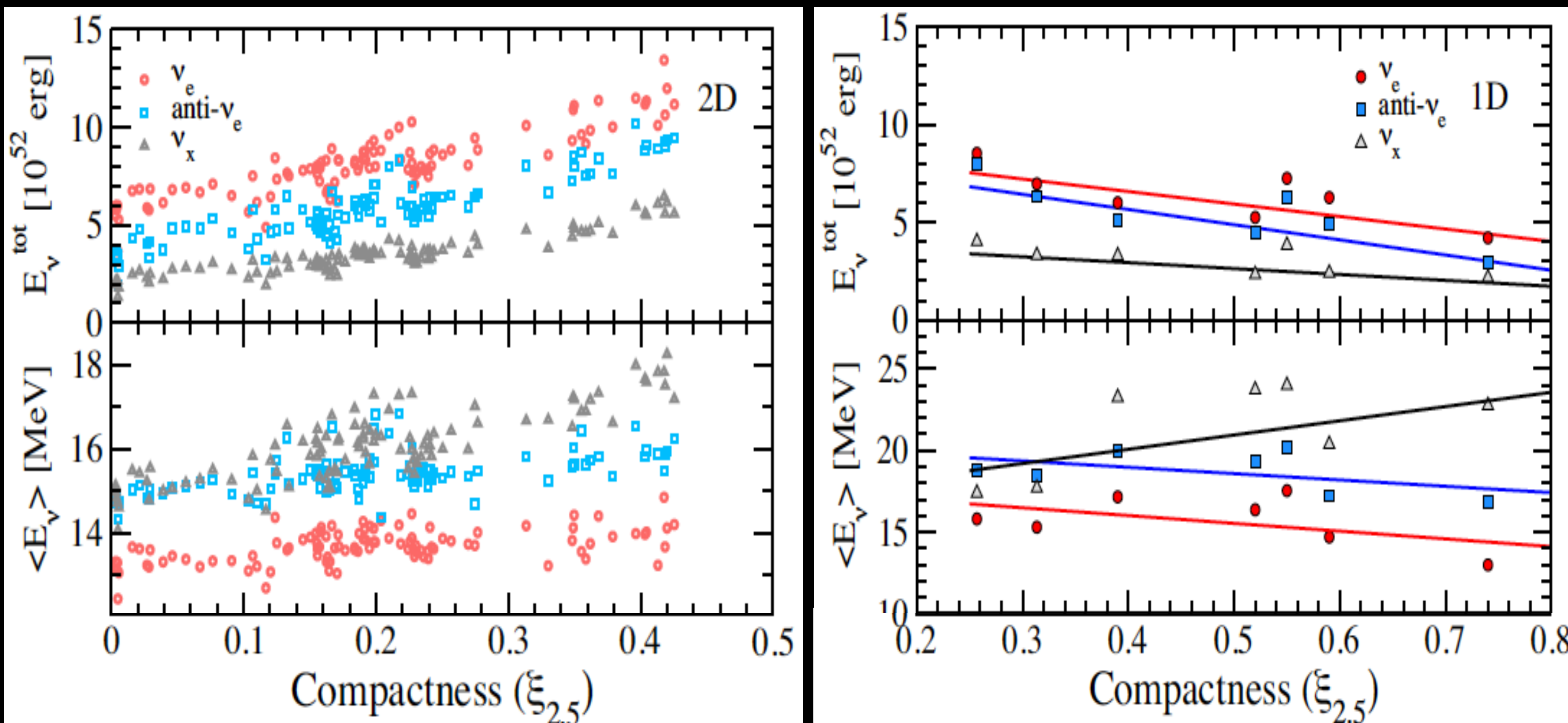
Tamborra et al (2012)



Time-integrated neutrino signal

Systematic dependence on compactness

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

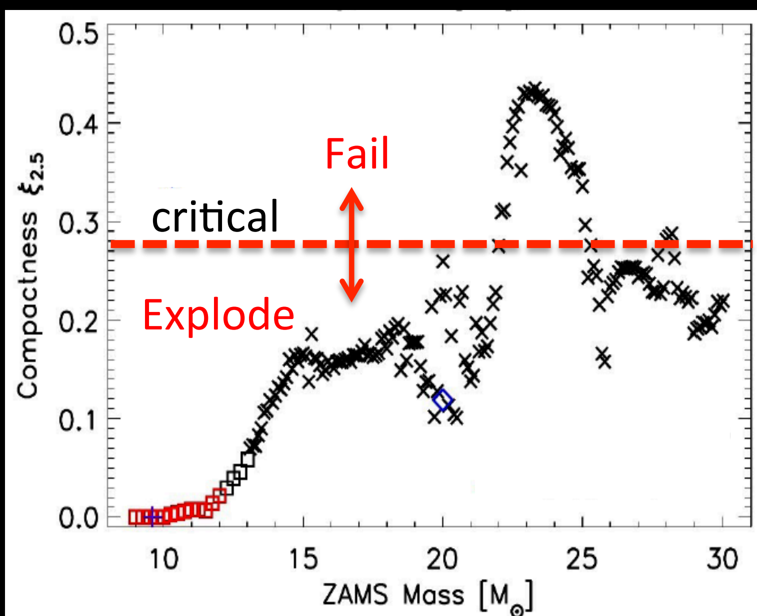


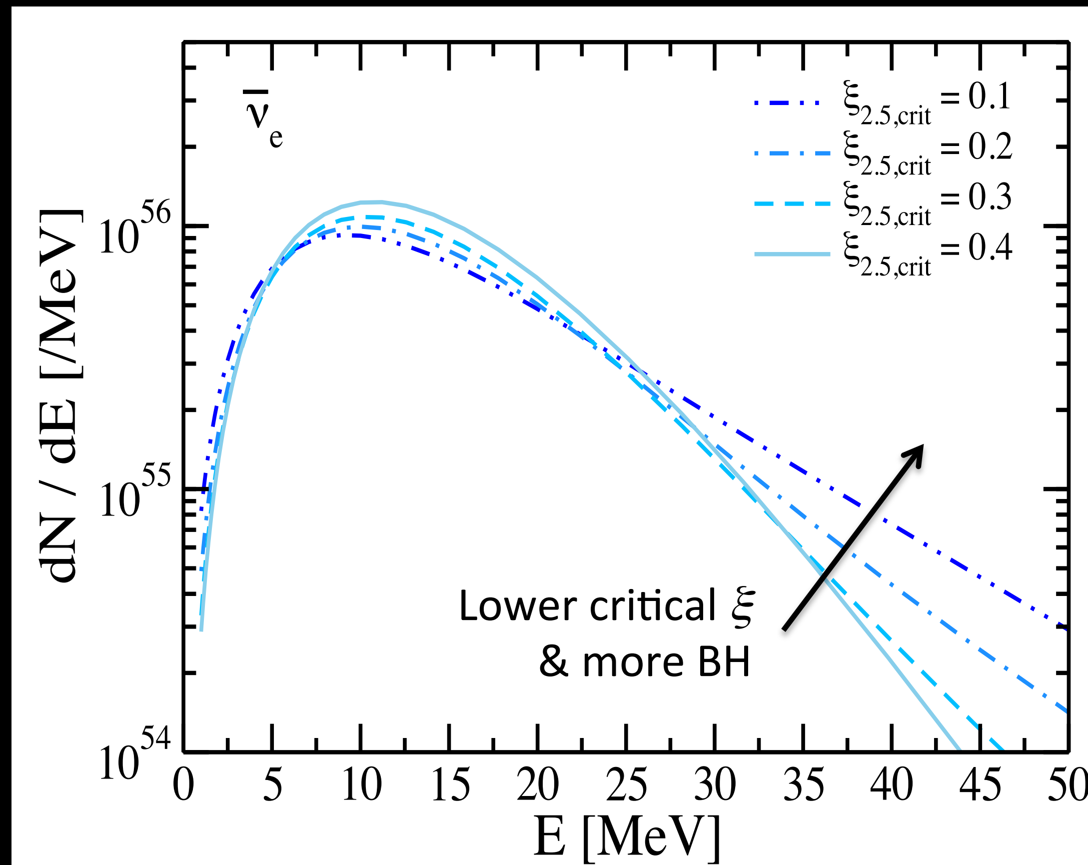
Horiuchi et al (2018)

Mean neutrino emission

Weighted mean neutrino emission

- ✓ Include diversity (by progenitor compactness)
- ✓ Include distribution of stellar properties (by initial mass function)
- ✓ Include NS and BH channels (by a critical compactness parameter)
- ✓ Include neutrino oscillations (MSW mixing; hierarchy dependent)





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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)

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

Input 2: Developments

Data sparse

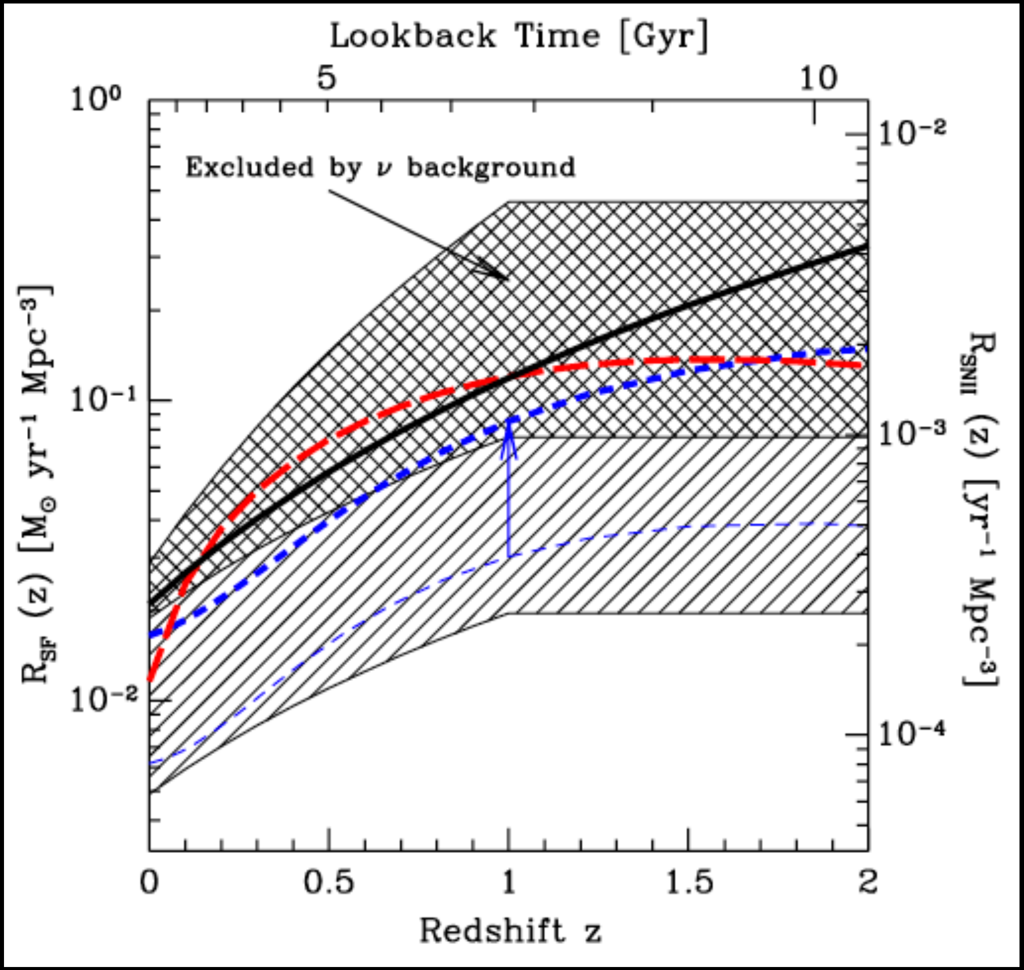
Use the DSNB to constrain the core-collapse rate and/or the star formation rate

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

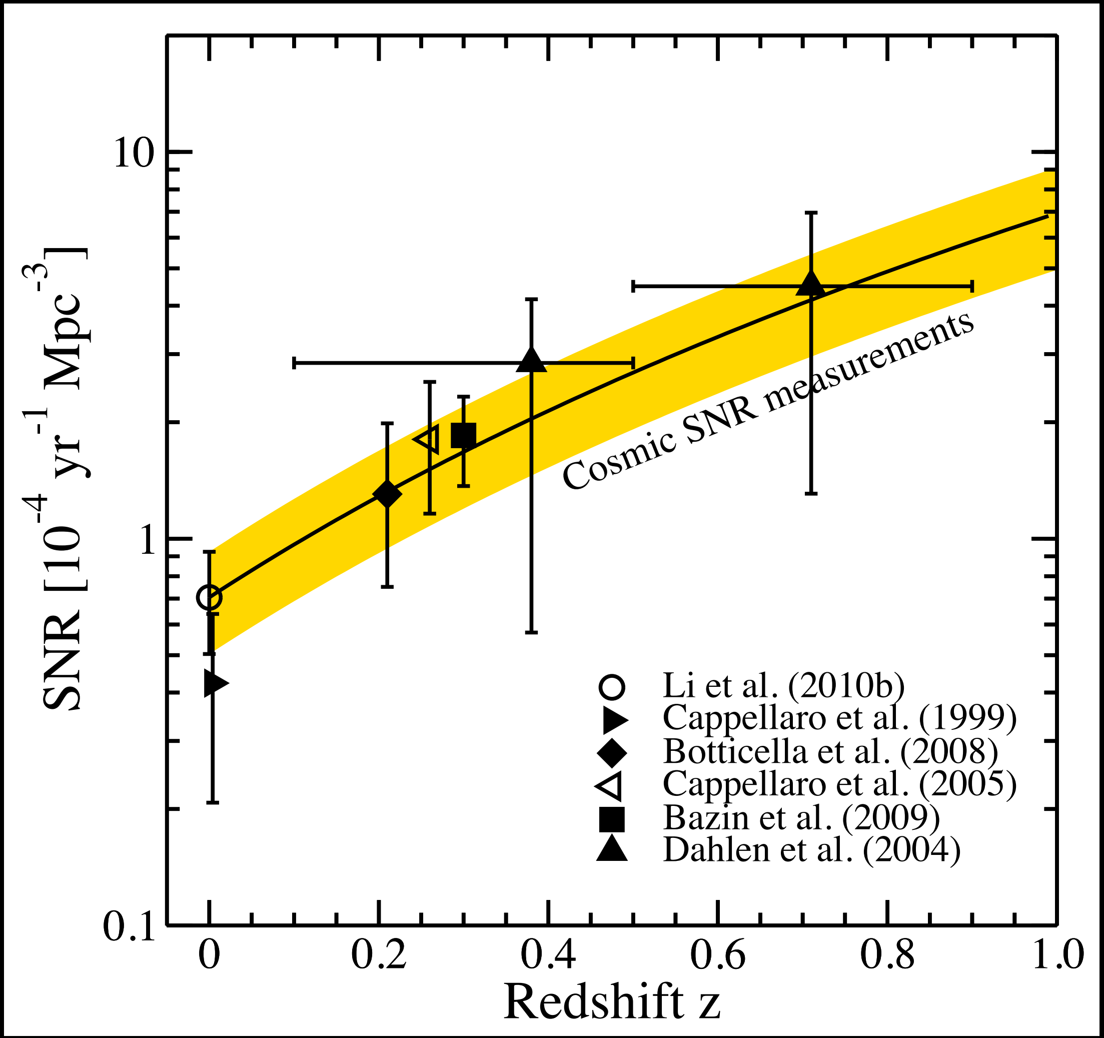
Two different strategies:

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)

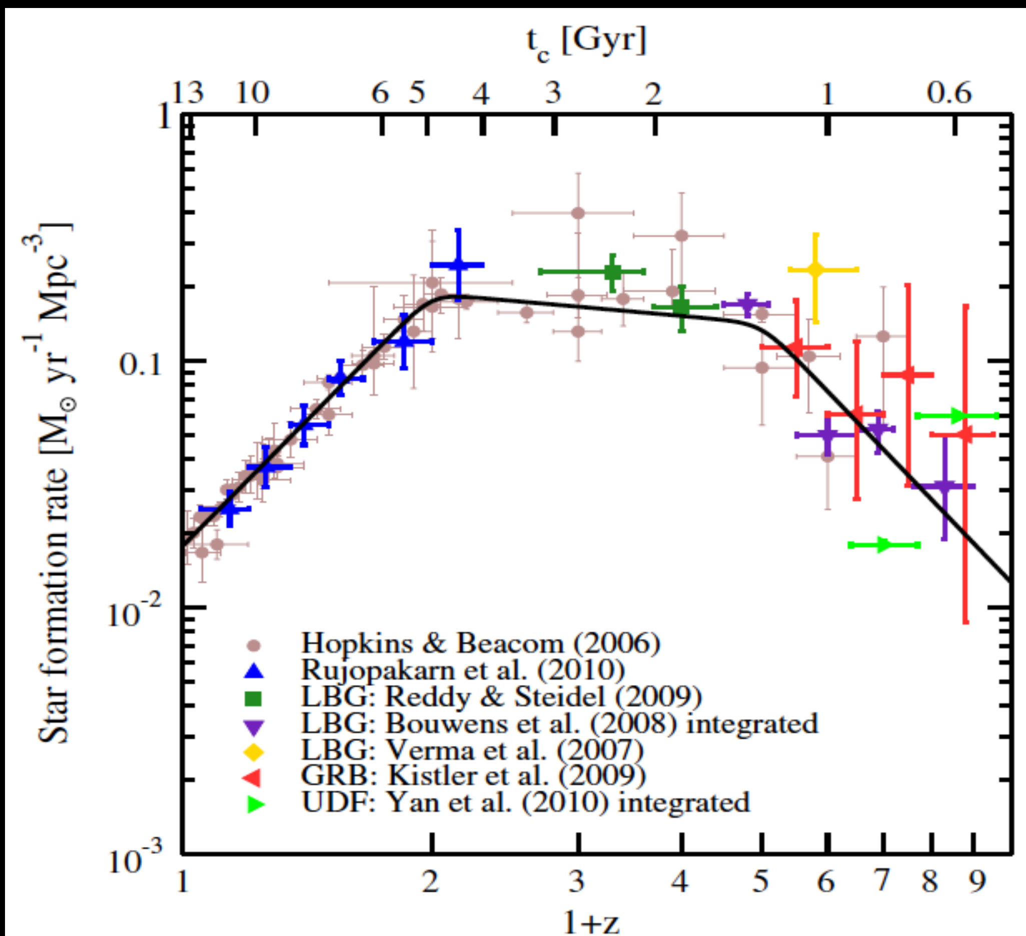


Horiuchi et al (2011)

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)

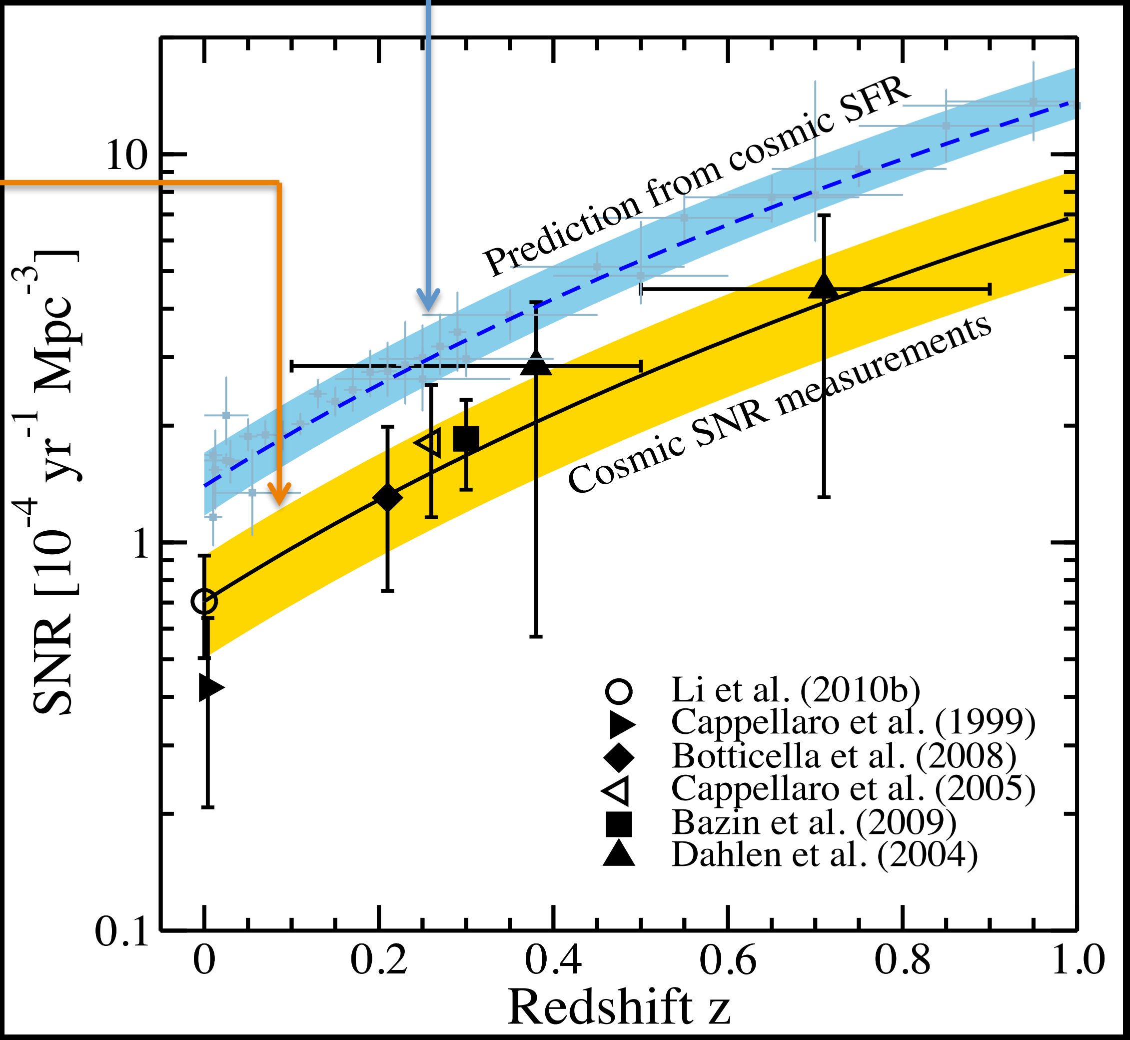
Birth & death rate comparison

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 the fraction looks to be approximately 50%

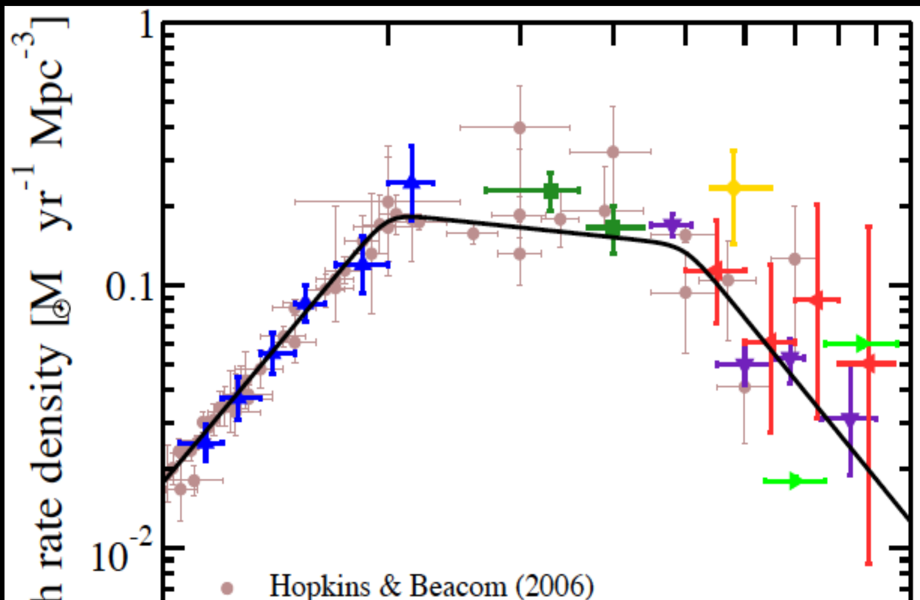
…but we must be careful



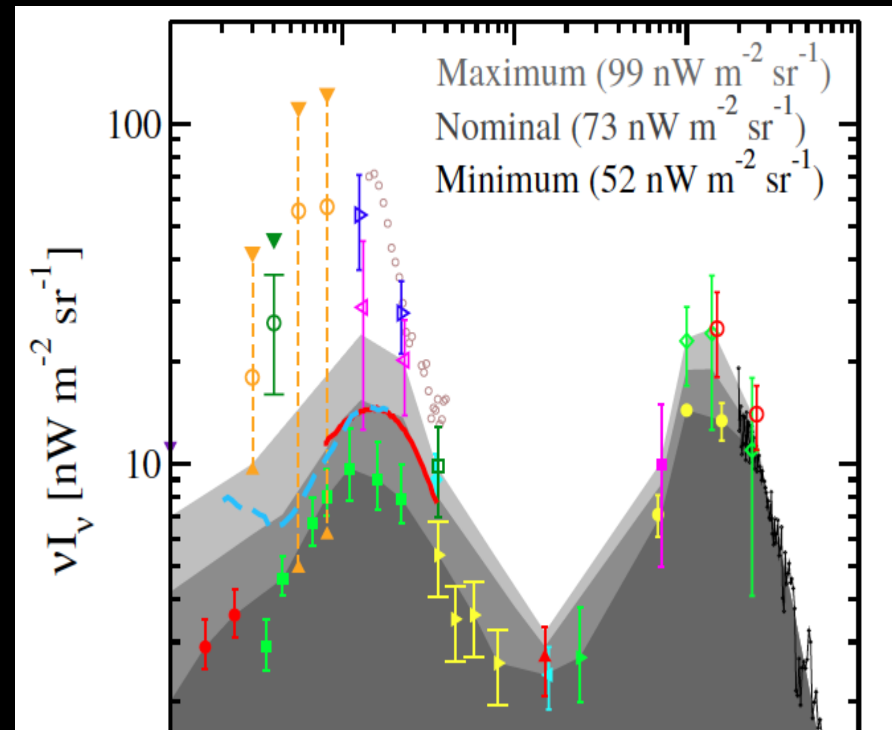
Horiuchi et al (2011)

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)

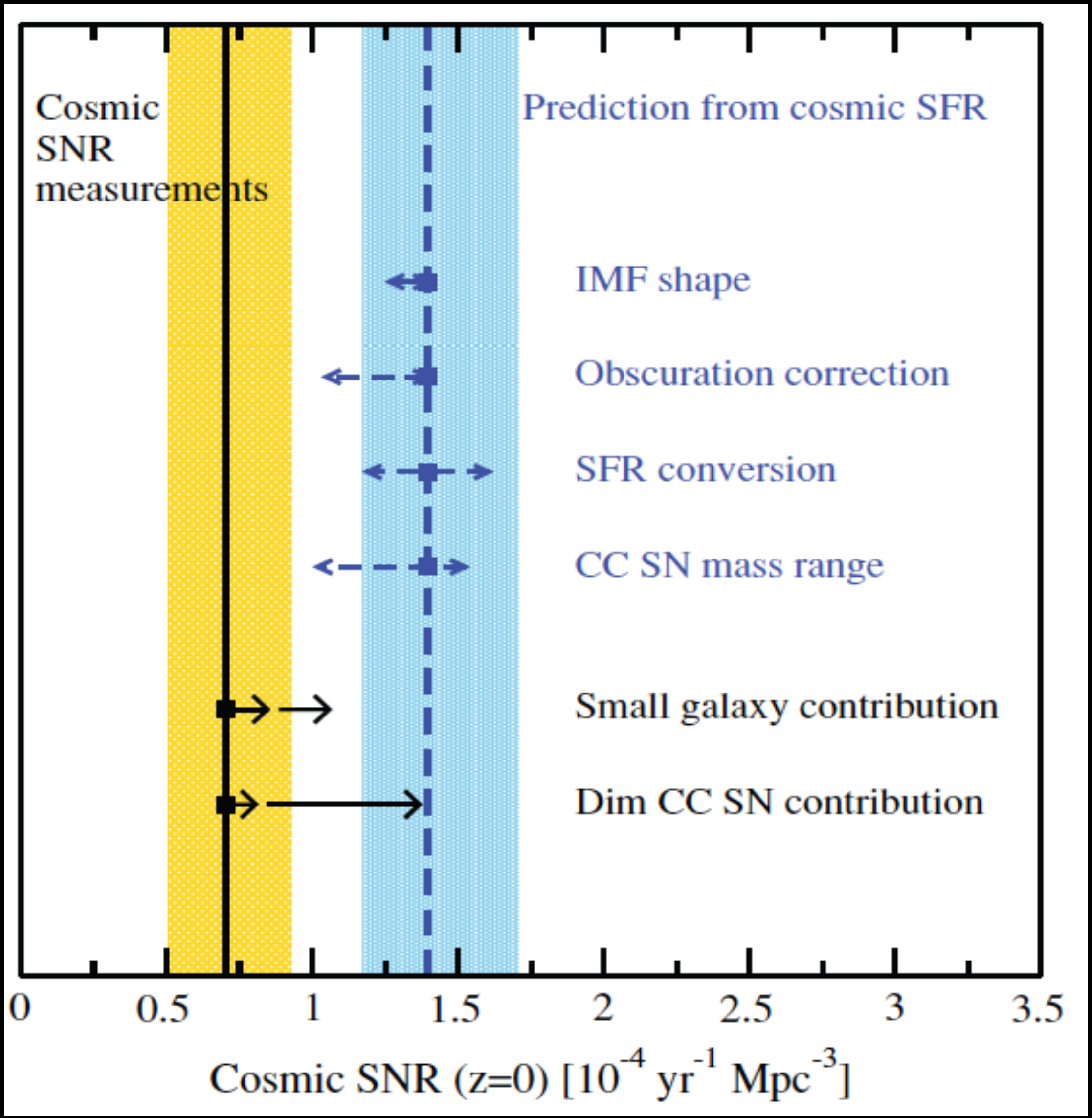
➔ **No evidence of birth rate being too high**

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

Are the rates systematically low/high?

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

Only 1 remains large enough: missing dim supernovae

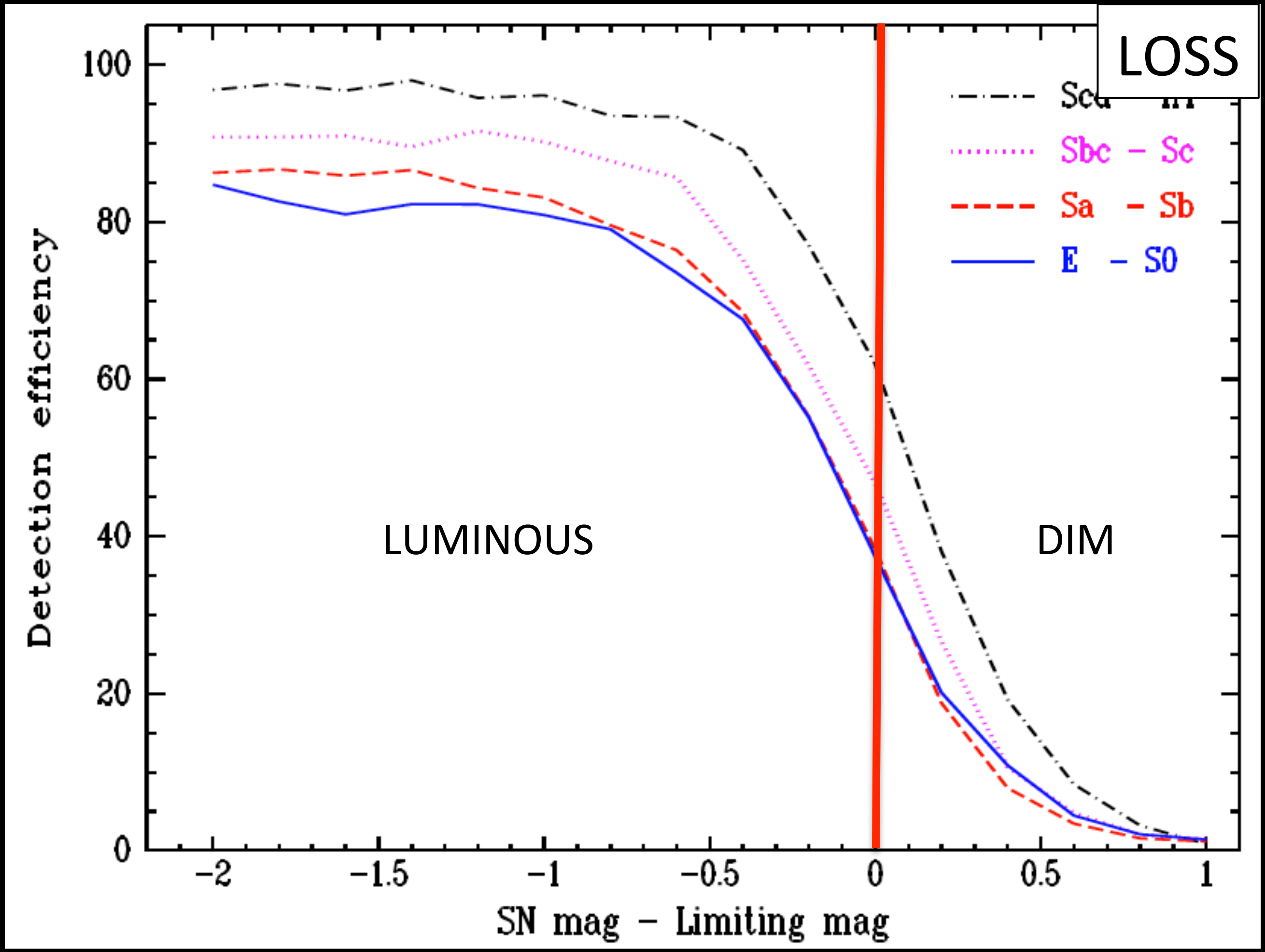


Horiuchi et al (2011)

Dim supernovae

Dim supernovae

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



Local (within ~ 13 Mpc) supernovae

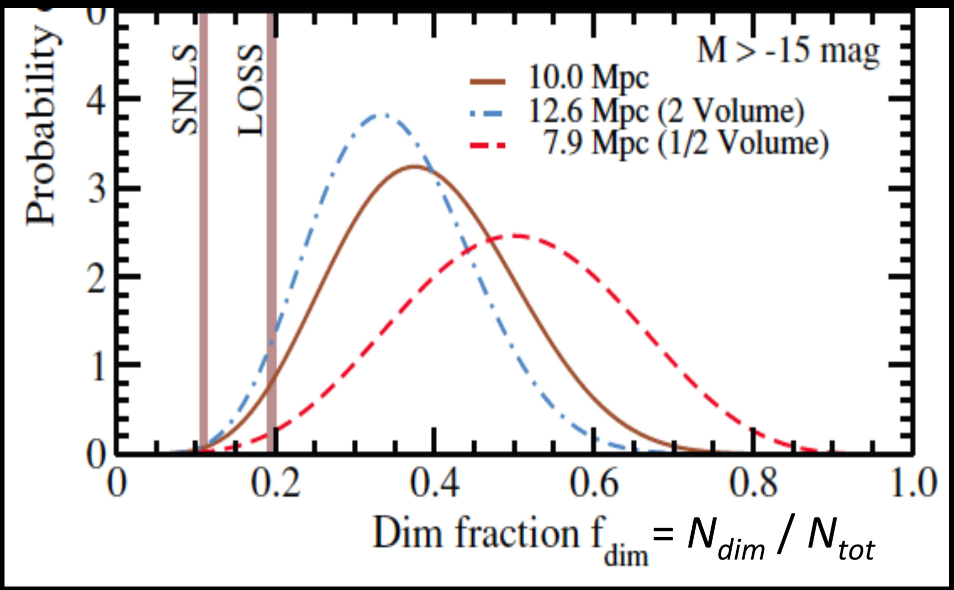
SN	Galaxy	Type	D (Mpc)	$E(B-V)$	Absolute Magnitude[a]	Discovery Phase
SN 2002bu	NGC 4242	IIn[b]	5.8	0.012	$M_R \approx -14.1$	Early
SN 2002hh	NGC 6946	IIP	5.9	0.342	$M_R \approx -14.3$	Early
SN 2002kg	NGC 2403	LBV	3.2	0.04	$M_V \approx -9$	Not CC SN
SN						
SN						
SN 2004et	NGC 6946	IIP	5.9	0.342	$M_R \approx -17.6$	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

10/21: falls below sensitivity cut of cosmic supernova rate studies

Horiuchi et al (2011)

Dim supernova

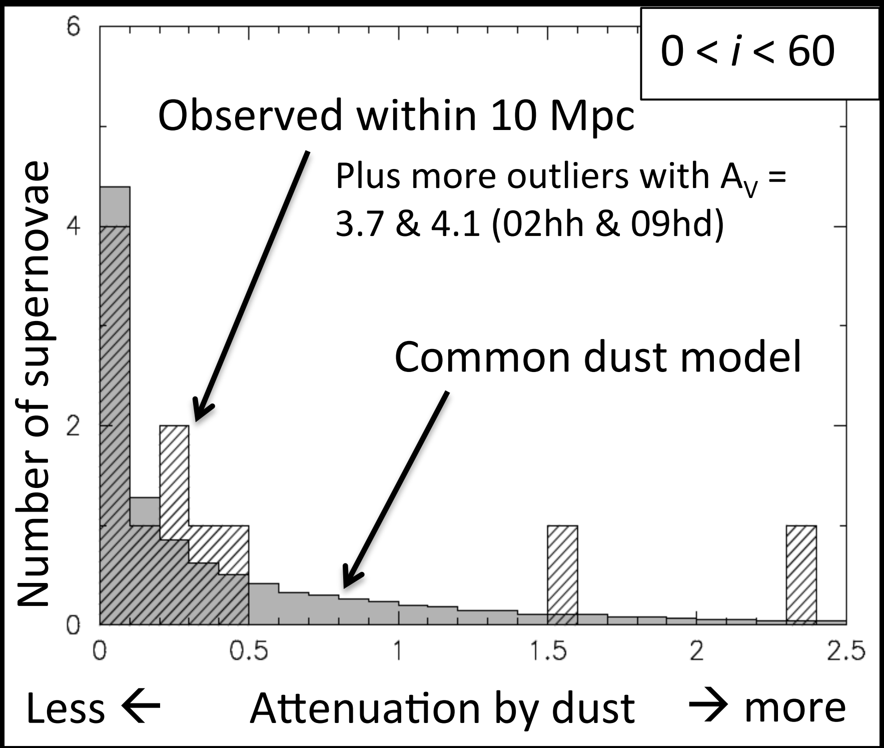
Missing dim supernovae
Fraction of dim supernovae are much smaller in surveys than they are locally



Horiuchi et al (2011)

➔ Cosmic rate measurements need further de-biasing

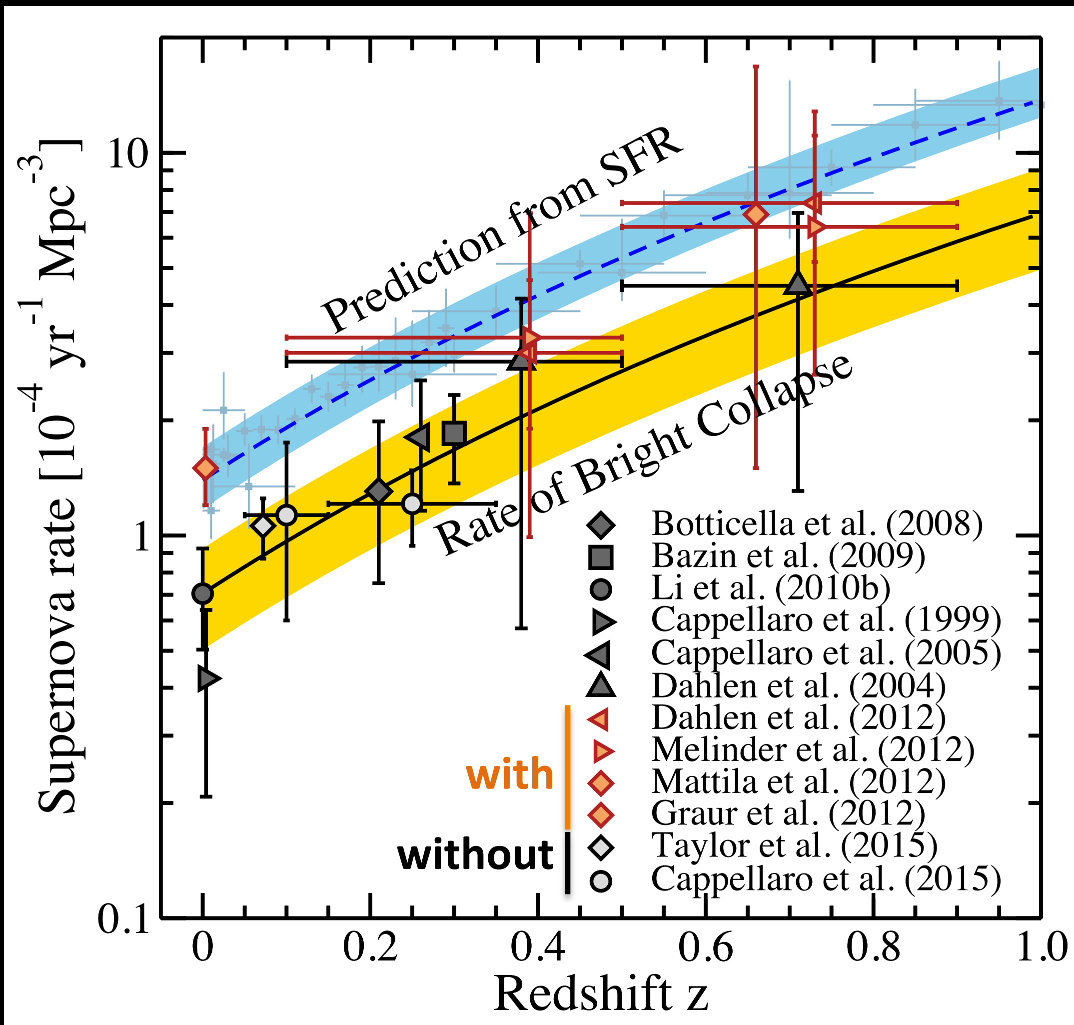
The reason:
Most of the locally dim supernovae are heavily dust attenuated objects.



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

Di-biased cosmic supernova rates

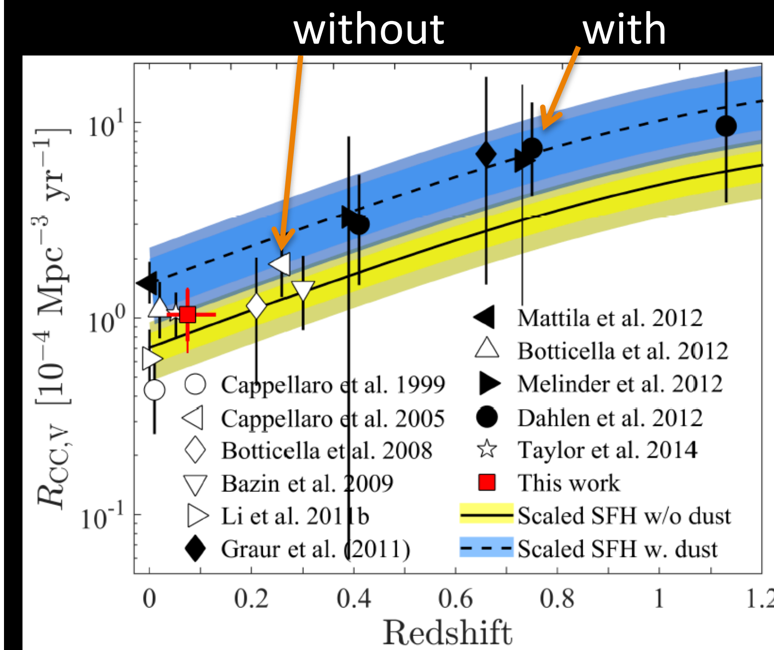
Better agreement



Updated from Horiuchi et al (2011)

← Recent updates with (filled symbols) and without (empty symbols) correction for heavily dust attenuated supernovae

➔ **BH fraction ~10-30% (still large errors)**

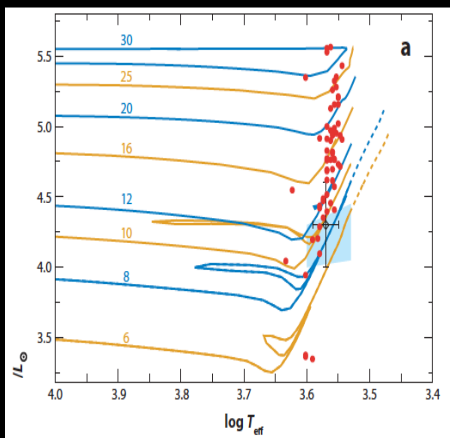


Graur et al (2015)

Failed fraction could be large

Multiple circumstantial evidence for a large fraction of failed explosions.

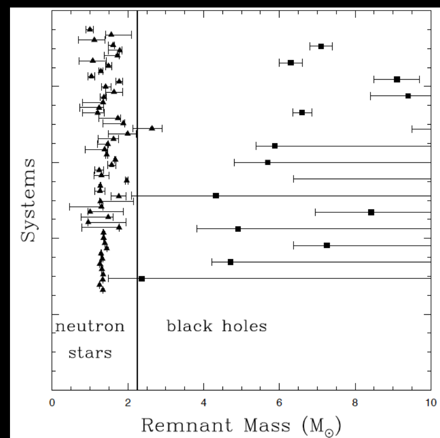
Red supergiant problem



f_{BH}~20-30%

Smartt et al (2009)

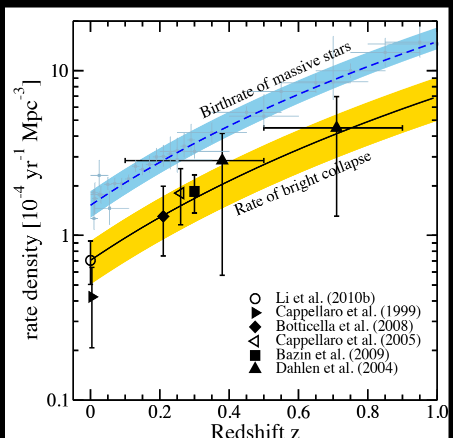
Black hole mass function



f_{BH}~10-40%

Kochanek et al (2014, 2015)

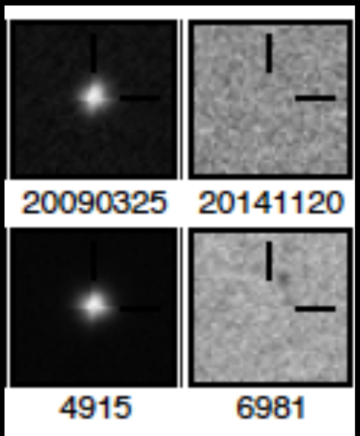
Supernova rate



f_{BH}~10-30%

Horiuchi et al (2011)

Survey about nothing



f_{BH}~4-43%

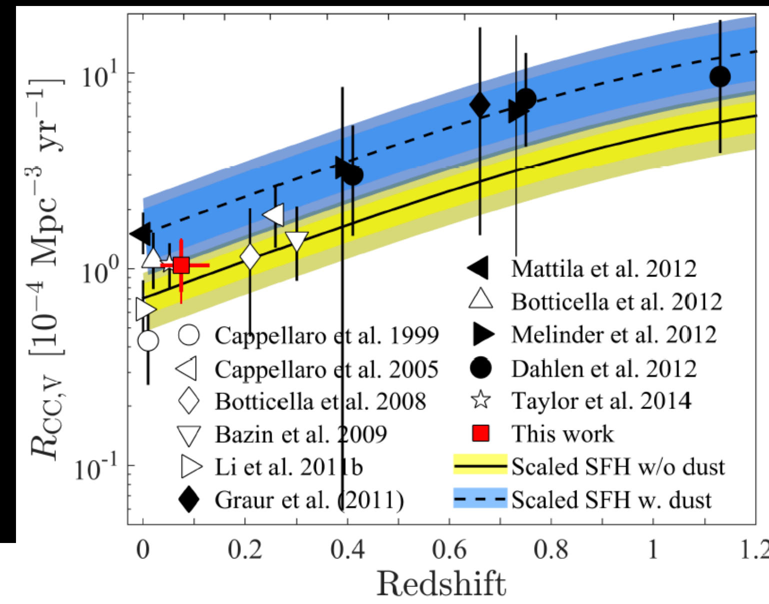
Gerke et al (2015)

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 $\xi_{2.5} > 0.2$)

#1. Cosmic supernova rates

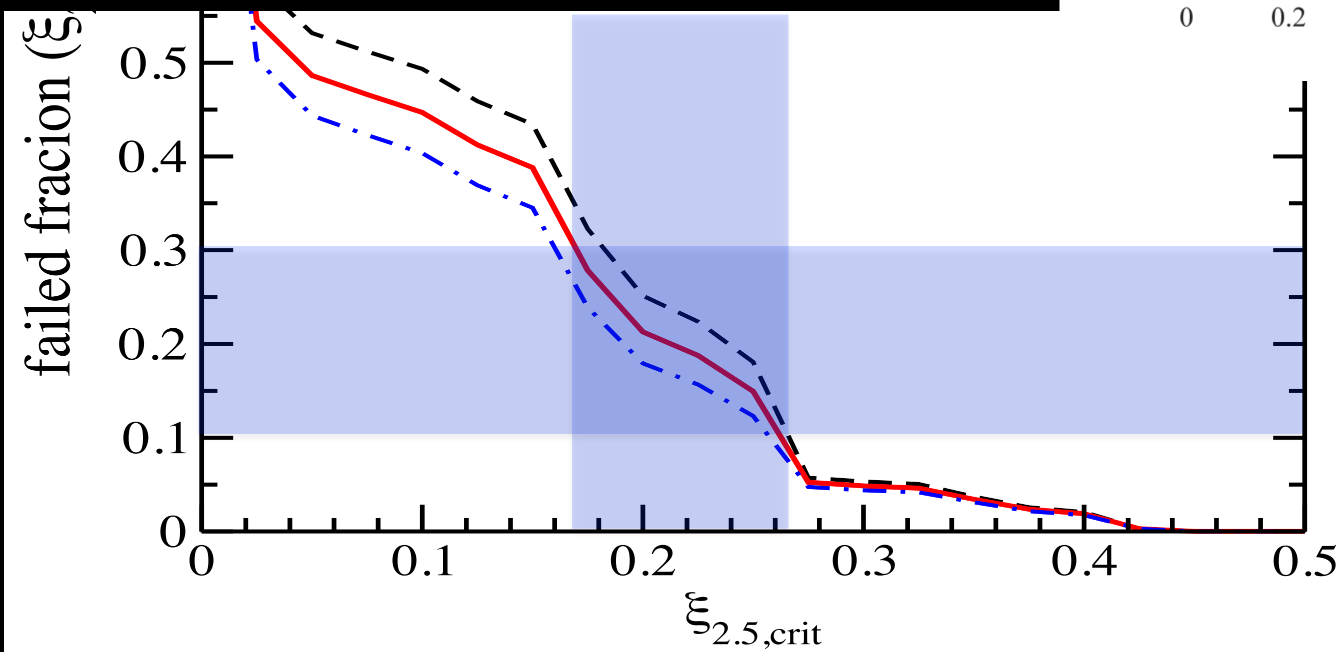
Recent updates with and without correction for heavily dust attenuated supernovae suggests BH fraction ~10-30%



Connection to compactness

This corresponds to

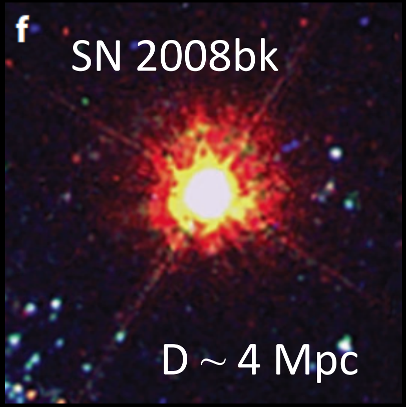
➔ **compactness $\xi_{2.5} > 0.2$ or so**

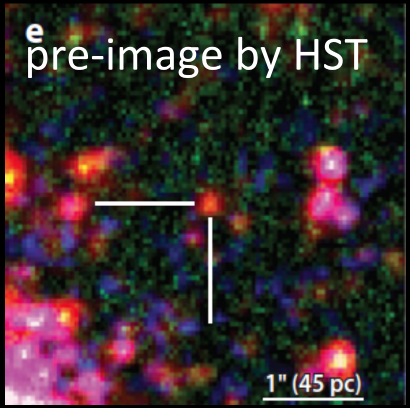


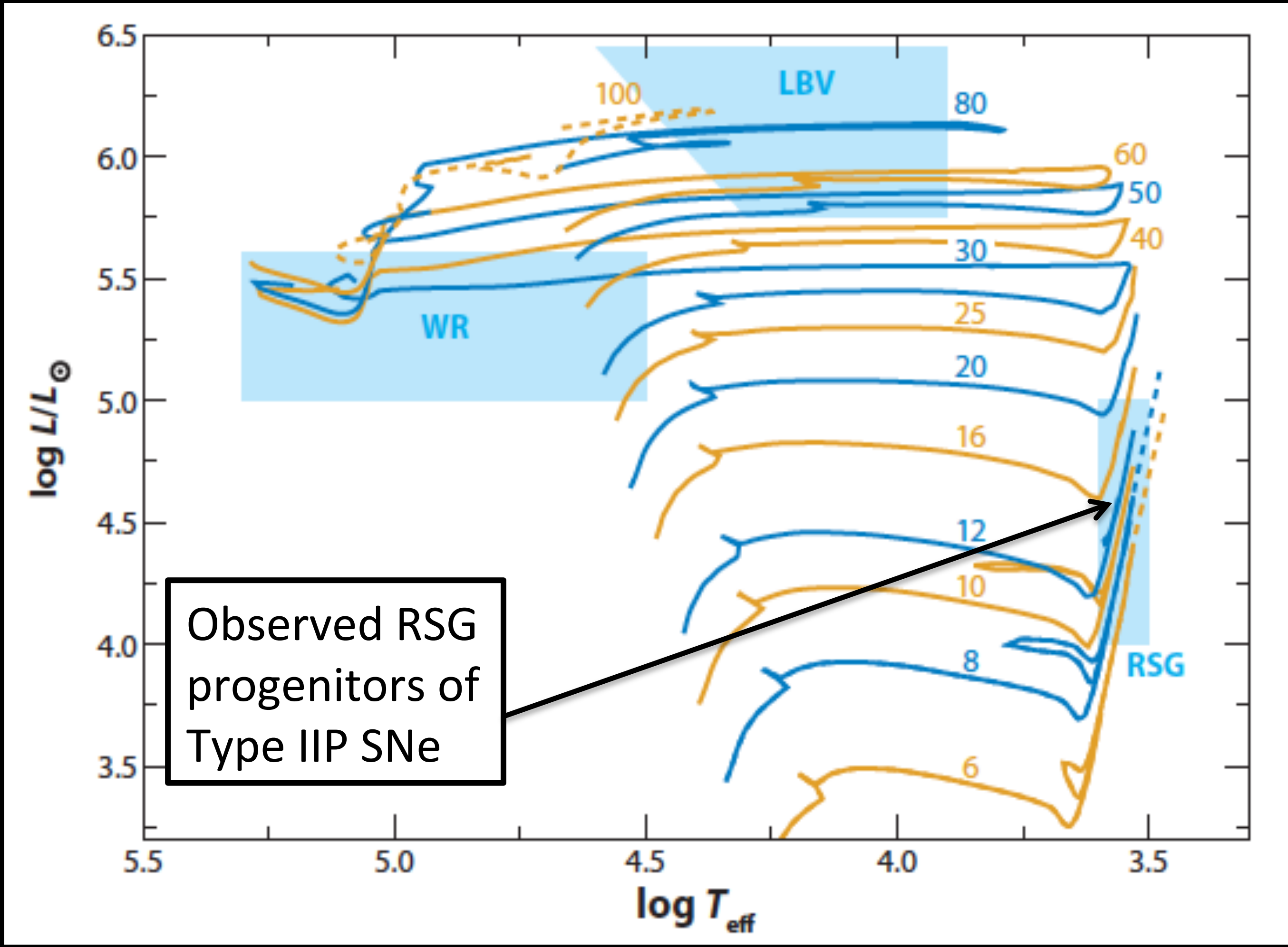
Horiuchi et al (2014)

#2. Red supergiant problem

Pre-imaging:
Very successful for Type II SNe







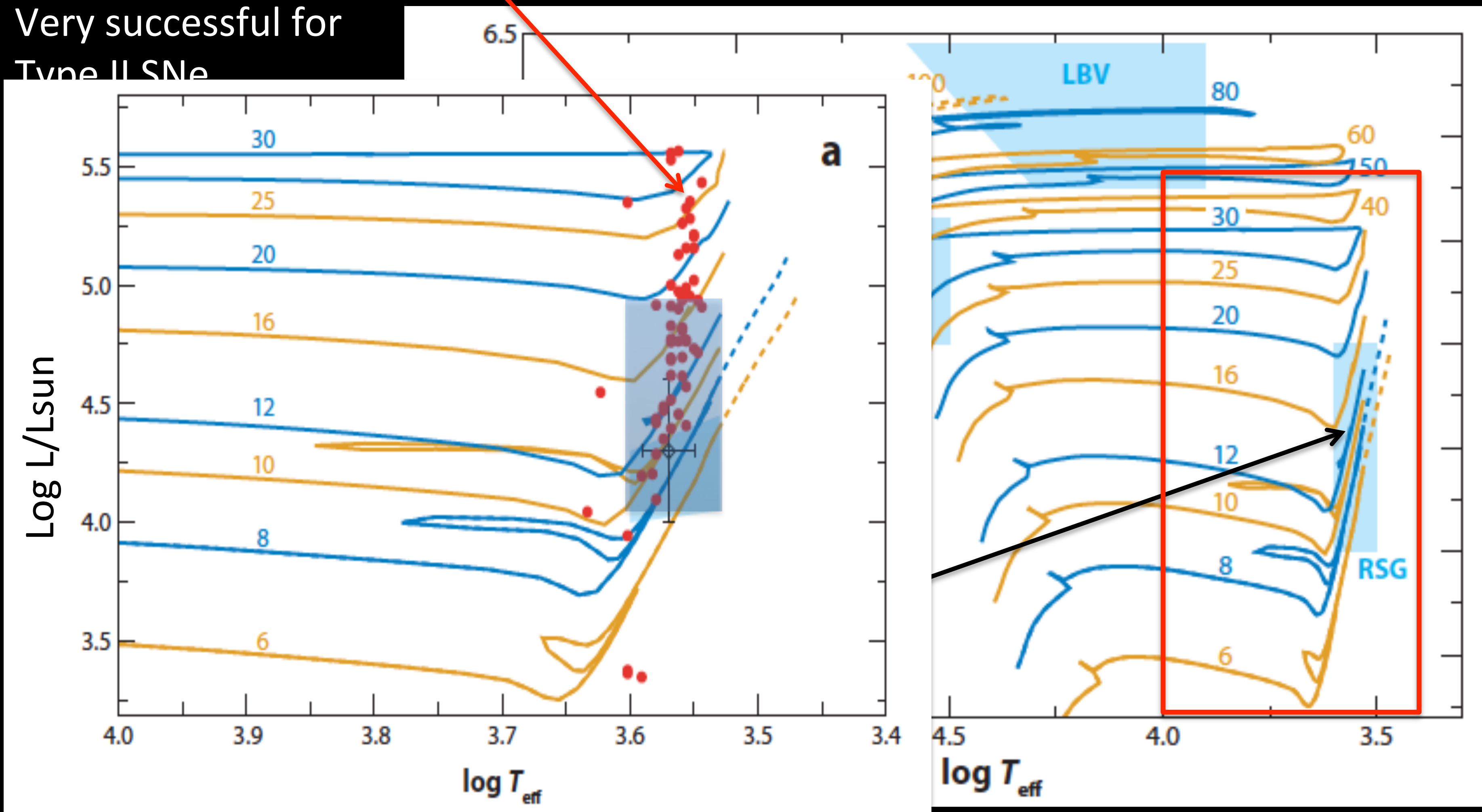
Smart et al (2001), Van Dyk et al (1999),

Smartt (2009), Smartt (2015)

#2. Red supergiant problem

Pre-imaging:
Very successful for Type II SNe

Known red-supergiants (@MW+LMC): reach ~$10^{5.5}$ Lsun



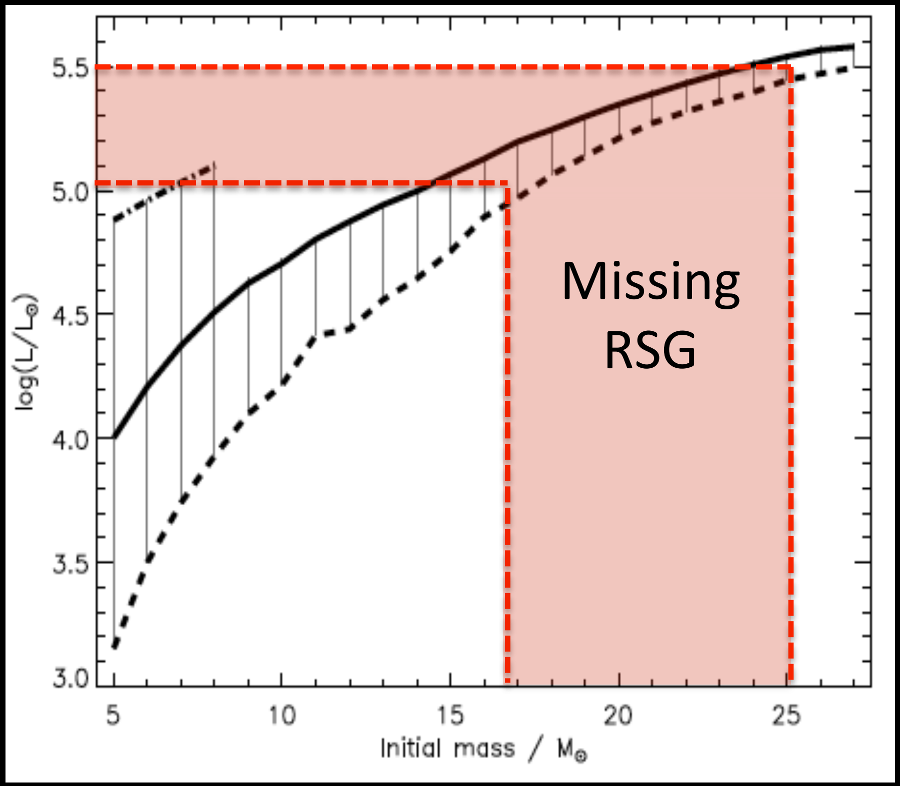
Smart et al (2001), Van Dyk et al (1999),

Smartt (2009), Smartt (2015)

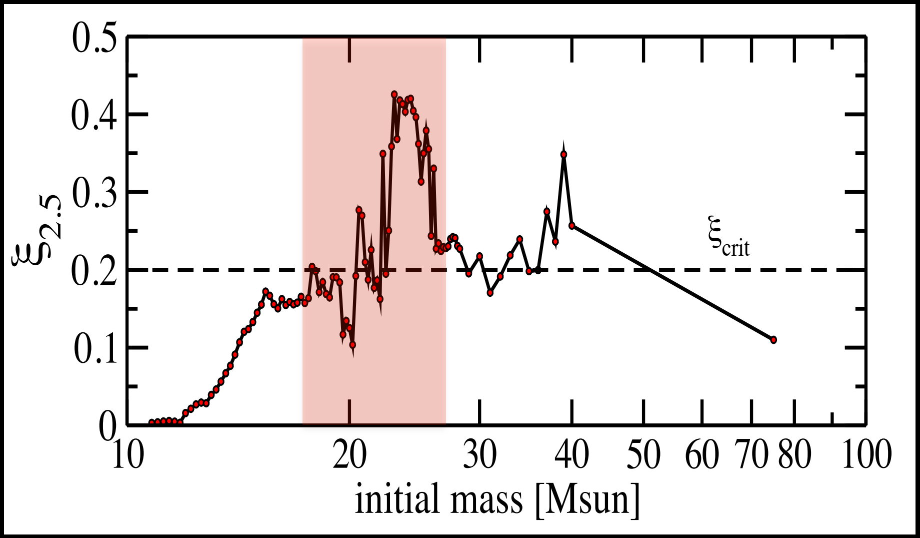
#2. Red supergiant problem

Supergiants may not be exploding

Observationally, these red supergiants have mass ~16 –25 Msun



Smartt et al (2009)



Connection to compactness

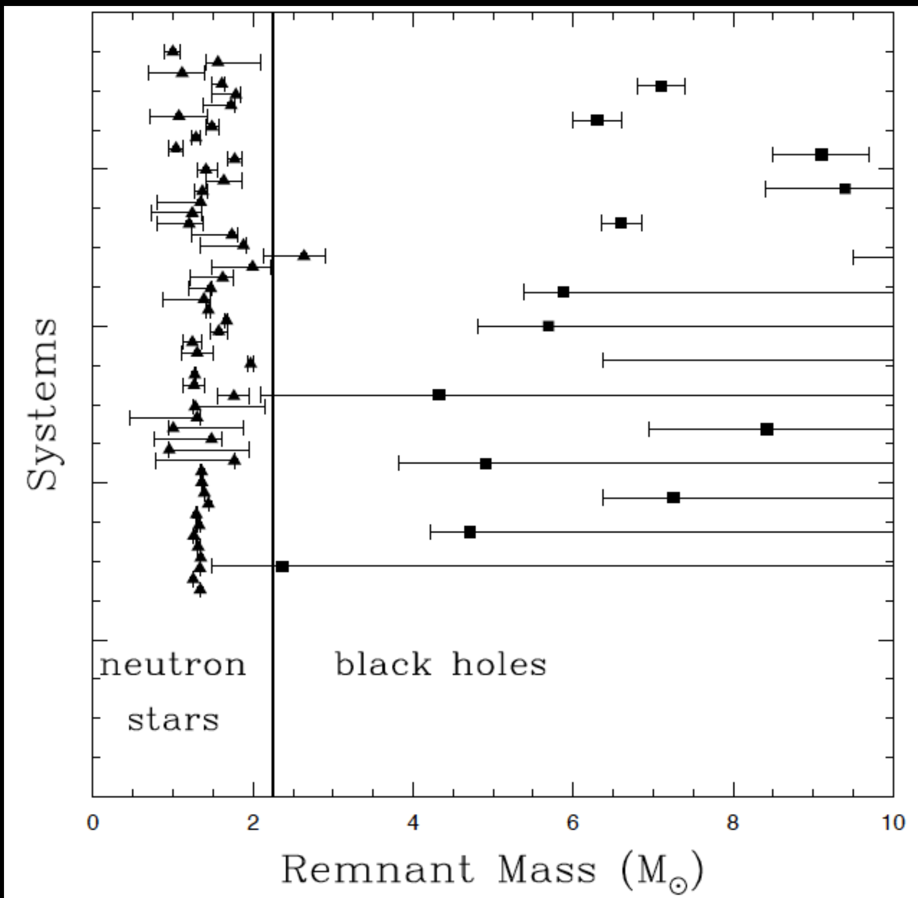
- Mass range is supergiants with the highest compactness
- **Consistent with stars with $\xi_{2.5}$ > 0.2 or so failing to explode**

Horiuchi et al (2014); Kochanek (2014)

(Other explanations have been explored)

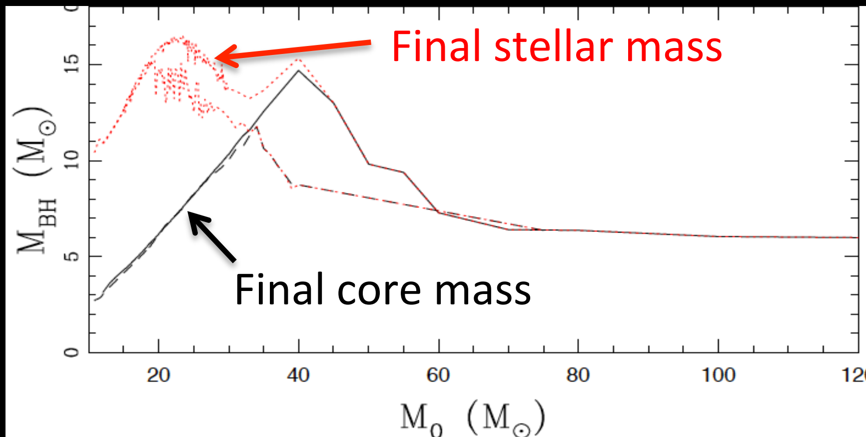
#3. Black hole mass function

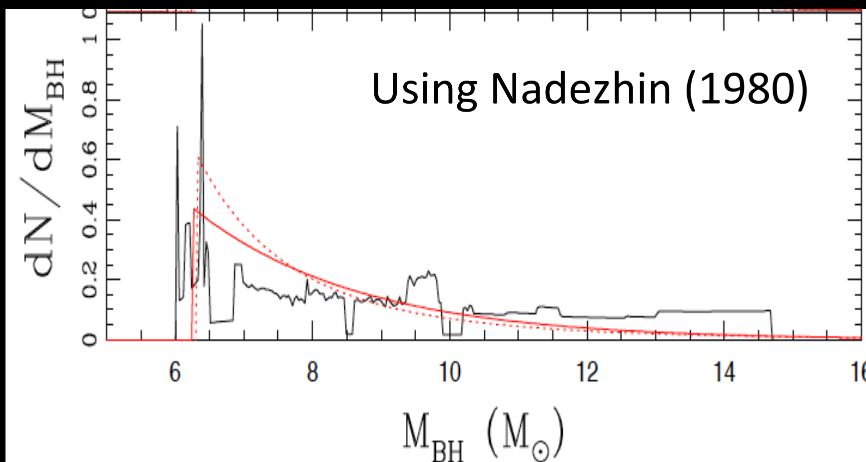
Compact object mass function:
There are hints of a dearth of stellar black holes just above the NS mass range



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

Connection to compactness
Critical compactness $\xi_{2.5}$~0.2 yields a cutoff in the black hole mass function





Kochanek (2014); also Sukhbold et al (2016), etc

#4. Searches of failed explosions: Survey about nothing

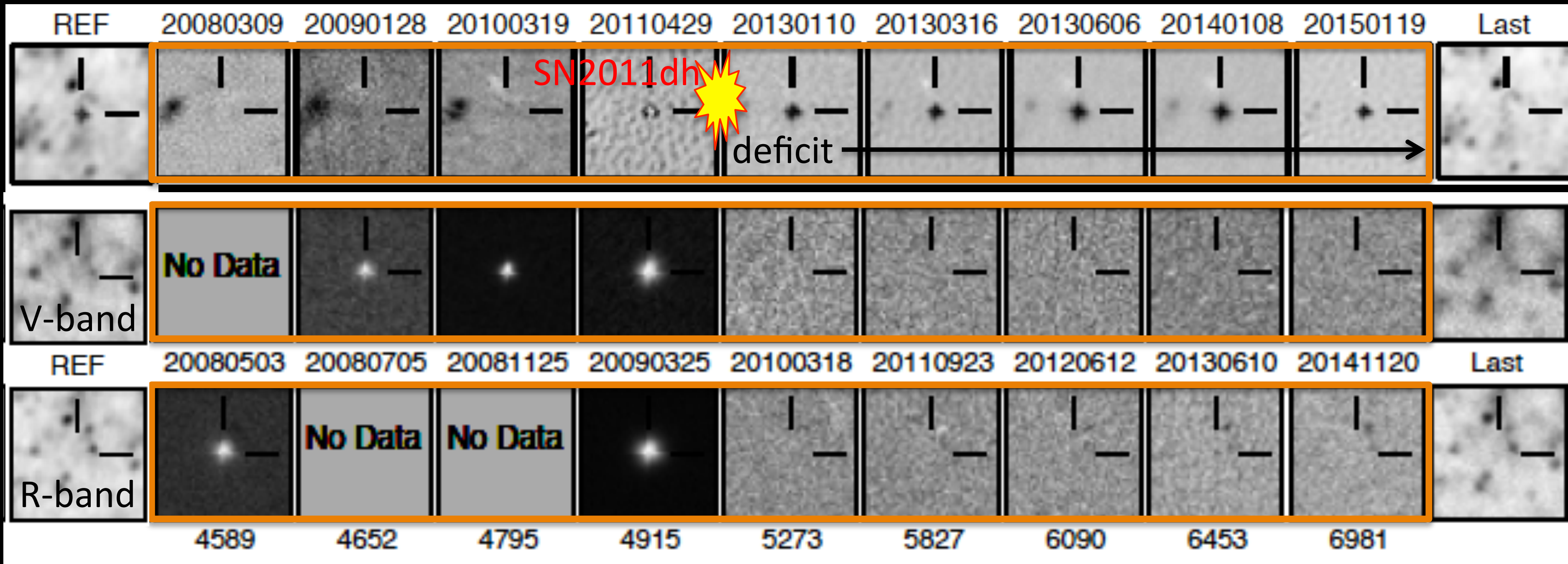
Survey About Nothing

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 ~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)



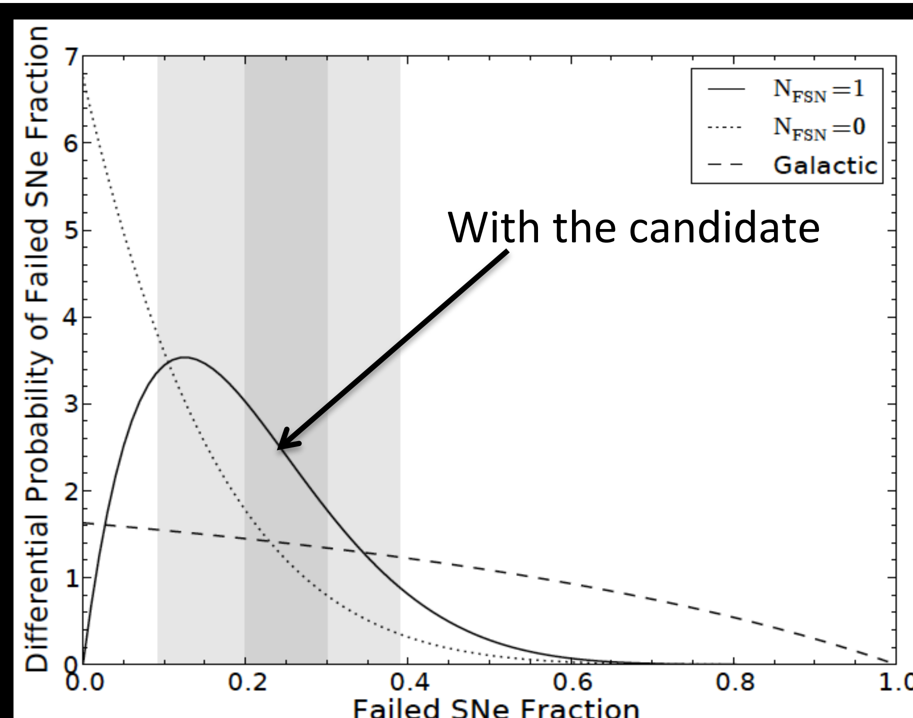
Gerke et al. (2015)

Potential failed explosion:

- 6 luminous CC supernovae (SN2009dh, SN2011dh, SN2012fh, SN2013ej, SN203em, SN2014bc)
- 1 candidate failed supernova: NGC6946-BH1 (@~6Mpc); SED well fit by 25Msun RSG

➔ Failed fraction 4 – 43% (90%CL)

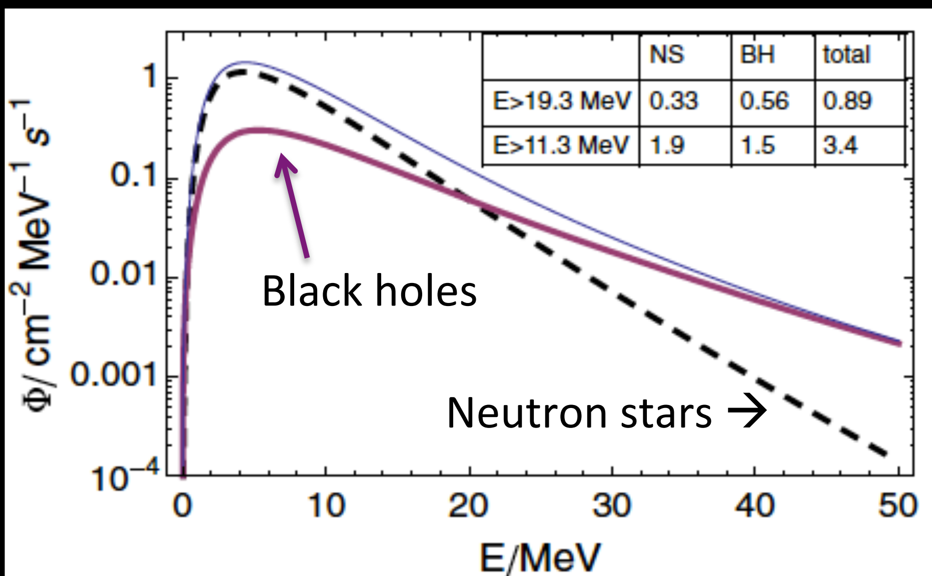
➔ Critical compactness ~0.2 – 0.3



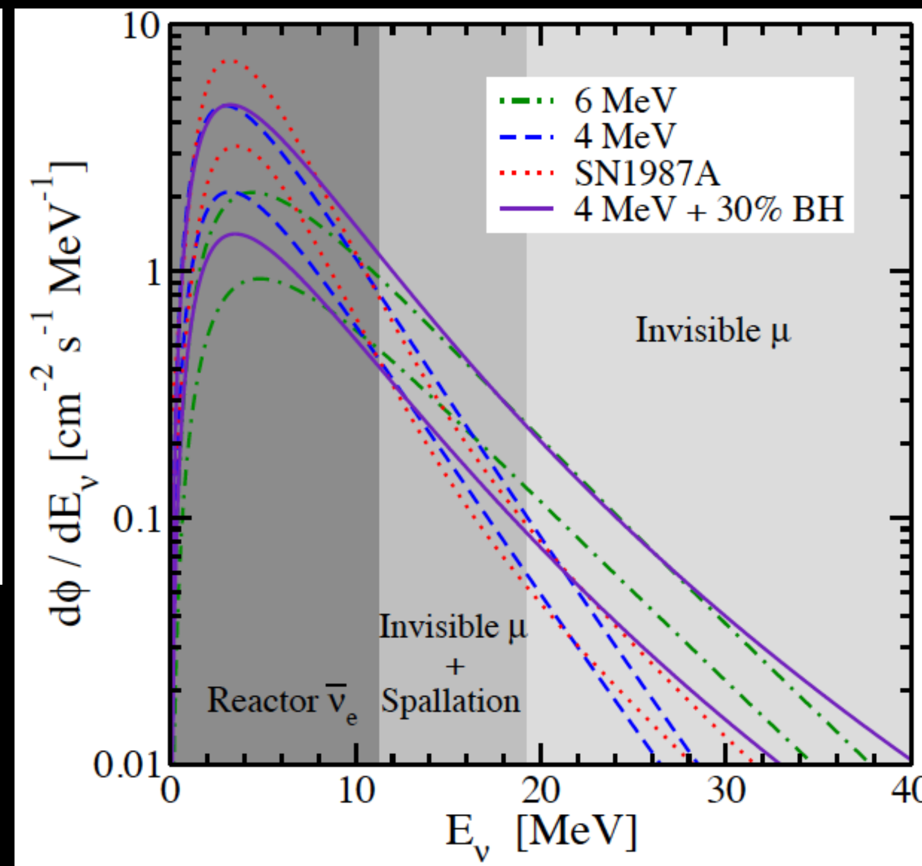
Adams et al (2017)

Flux prediction

- ✓ We know there are many core collapse in the past
- ✓ We know core collapse emits copious neutrinos
- ✓ We know both of these quantitatively
- ✓ We expect some (maybe sizable) collapse to form black holes



Lunardini (2009)



Horiuchi et al (2009)

Can we detect these neutrinos?

BH considered also in: Lien et al (2010), Keehn & Lunardini (2010), Nakazato (2013), Yuksel & Kistler (2014), Priya & Lunardini (2017), Moller et al (2018)

Diffuse Supernova Neutrino Background

Observed positron spectrum

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

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

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>)

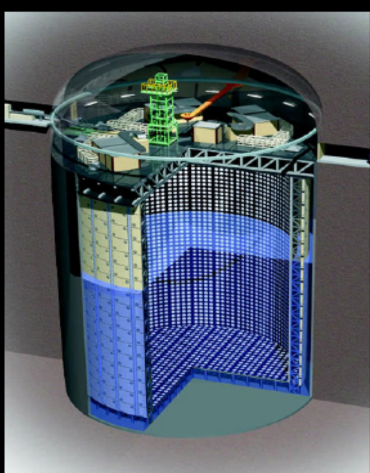
Input 3: neutrino detector capabilities (well understood for H_2O)

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

Neutrino detectors

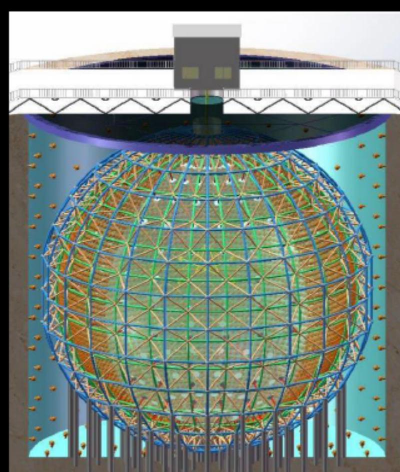
- Detector must be massive
  Optically thin -- needs large volumes
- Detector must be "quiet"
  Built with low natural radioactivity and with plenty of shielding
- Detector better to have background rejection
  Built with capabilities to distinguish between signal and background events

Super-Kamiokande



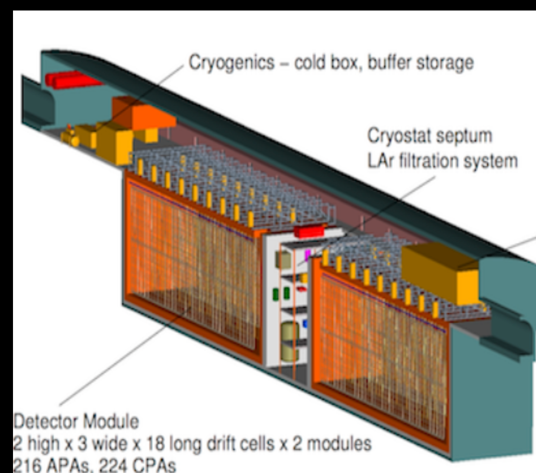
50 kton water + Gd
Upgrading

JUNO



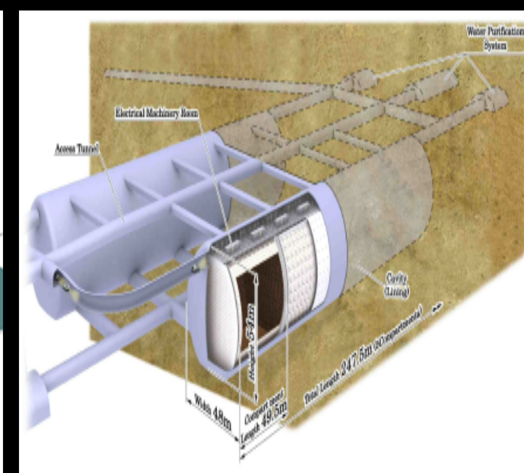
20 kton oil
Building

DUNE



40 kton liquid argon
In progress

Hyper-Kamiokande



260 kton water
In progress

Super-K with Gadolinium

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

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

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 and studies, upgrade ongoing!

EGADS: Evaluating Gadolinium's Action on Detector Systems

Backgrounds and search window

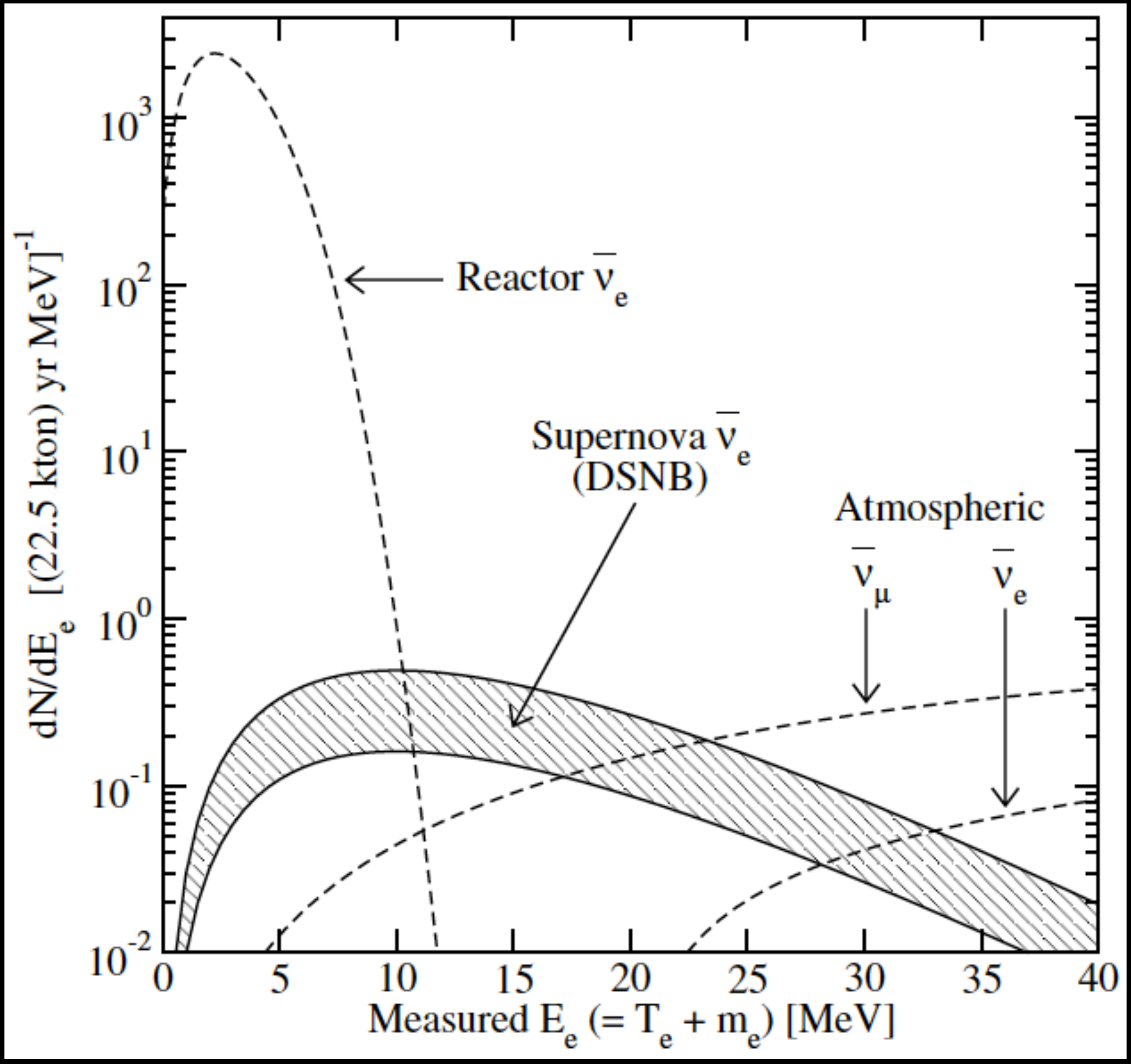
Optimal search window
Dependent on the relevant backgrounds.

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

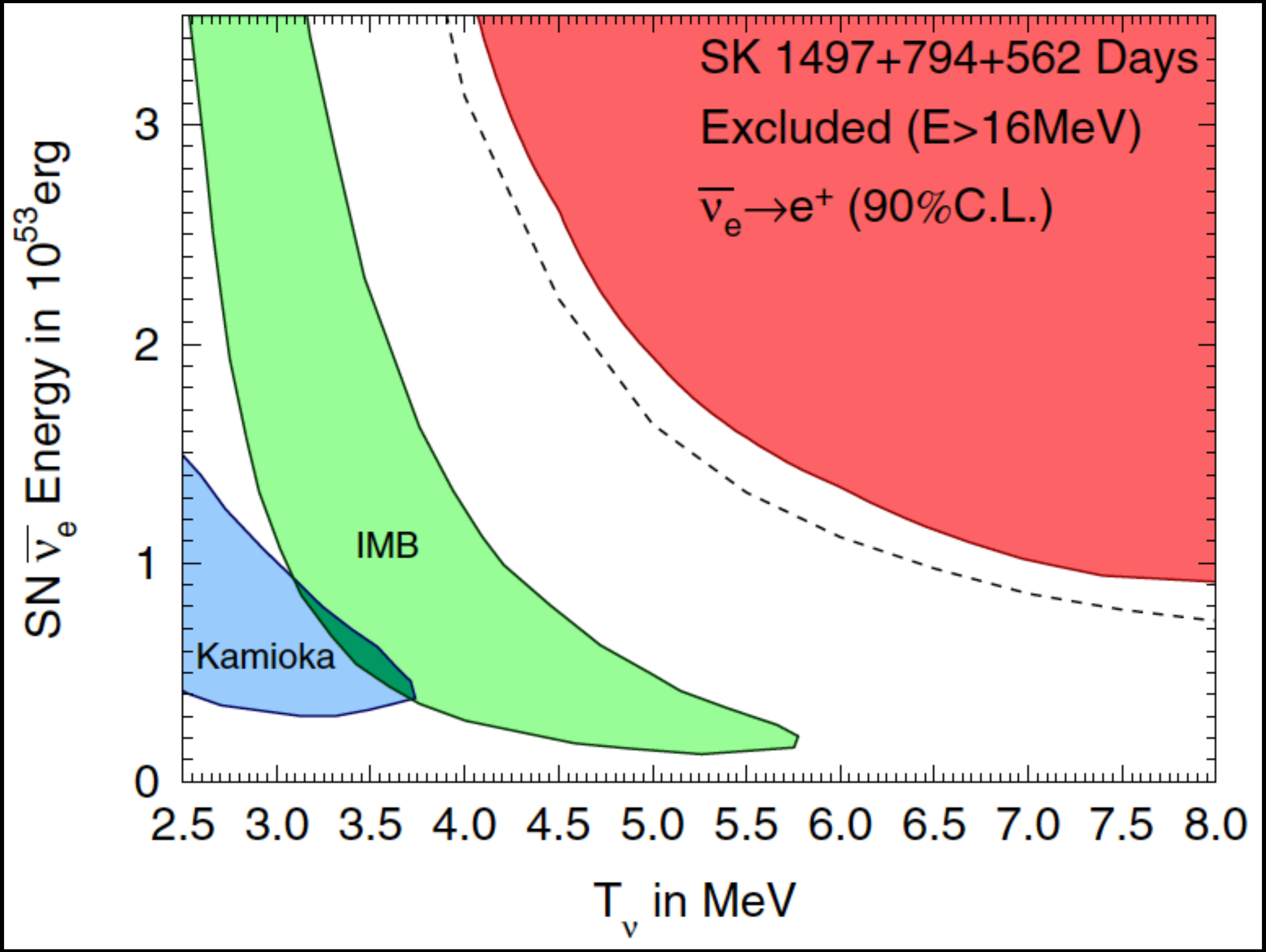


Beacom & Vagins (2004)

Present limits

Search with Super-Kamiokande

Already excluding large energetics & neutrino energy



Bays et al (2012)

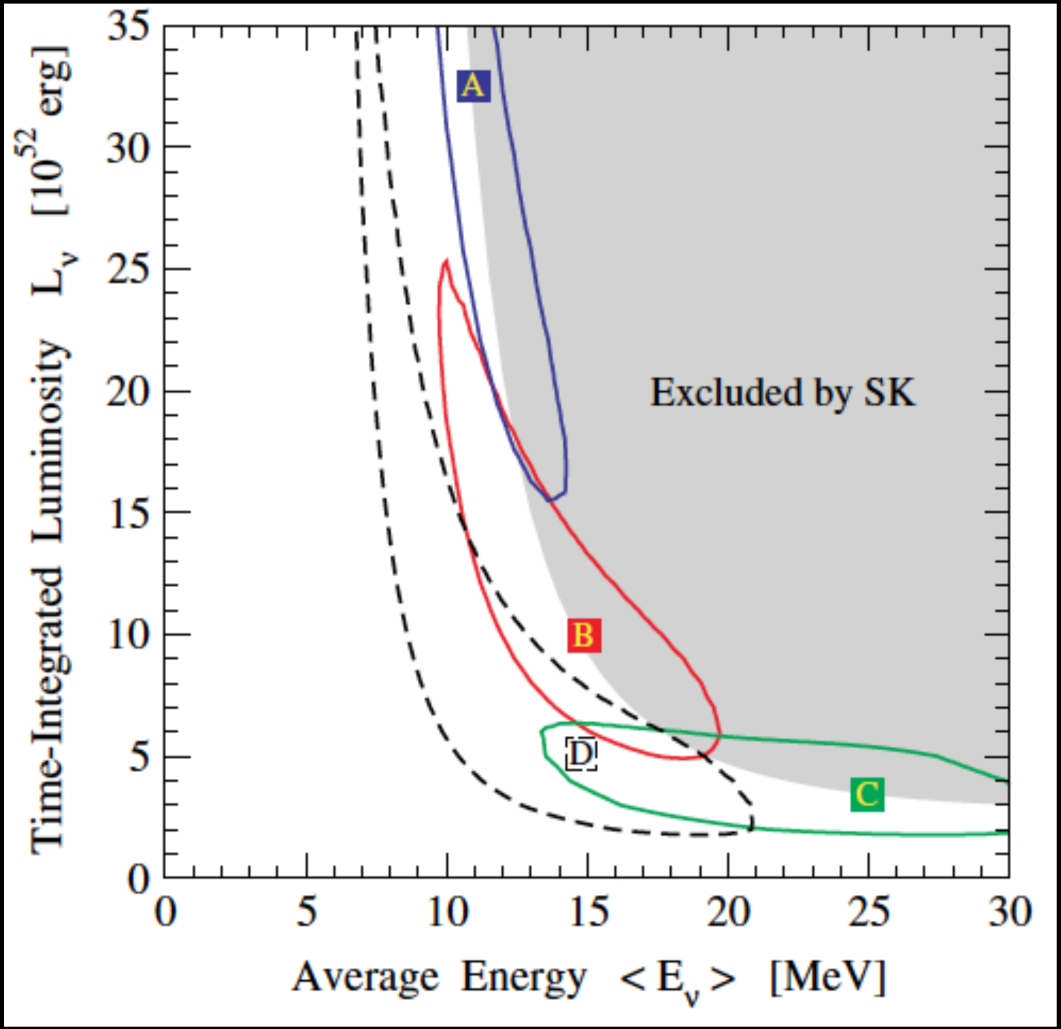
Upcoming sensitivity

Search with Super-K + Gadolinium

Transforms into signal dominated search with wider energy window. Will probe emission parameters.

Spectrum	H2O (18 MeV threshold) K [/yr]
4 MeV	0.4 +/- 0.1
4MeV +30% BH	1.1 +/- 0.3
SN1987A	0.5 +/- 0.1

Spectrum	H2O + Gd (10 MeV threshold) [/yr]
4 MeV	1.8 +/- 0.5
4MeV +30% BH	3.0 +/- 1.0
SN1987A	1.7 +/- 0.5



Yuksel et al (2006)

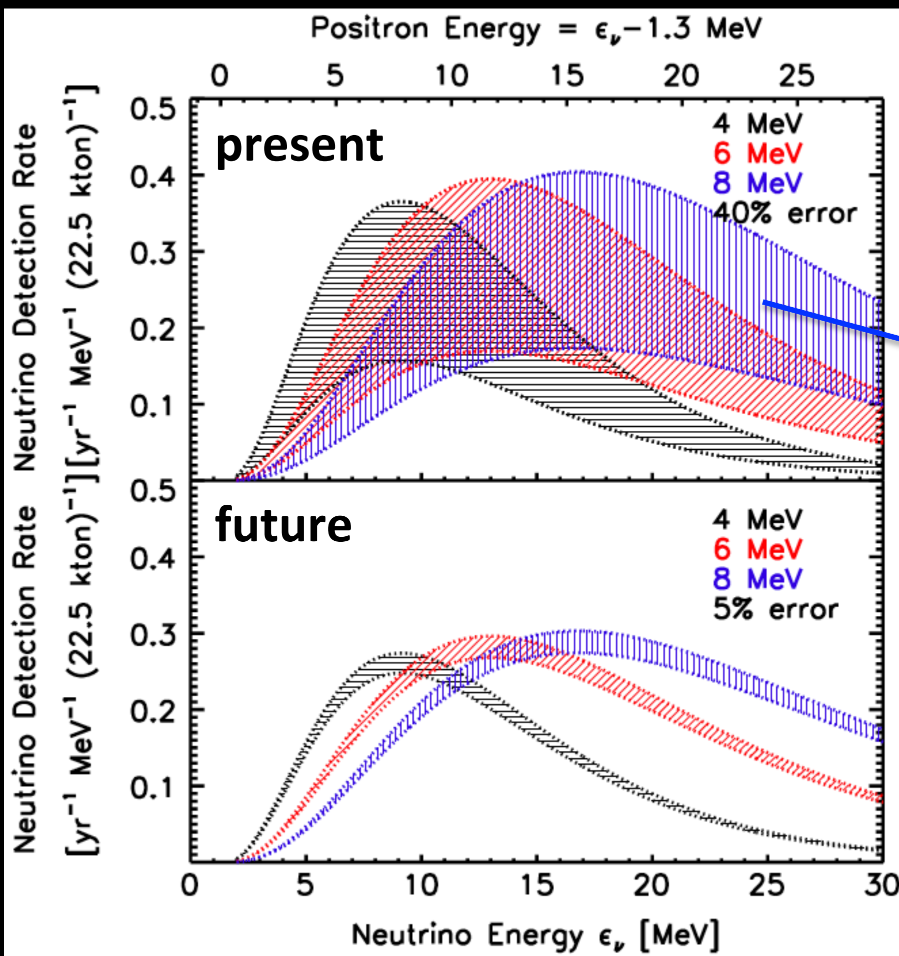
DSNB: future

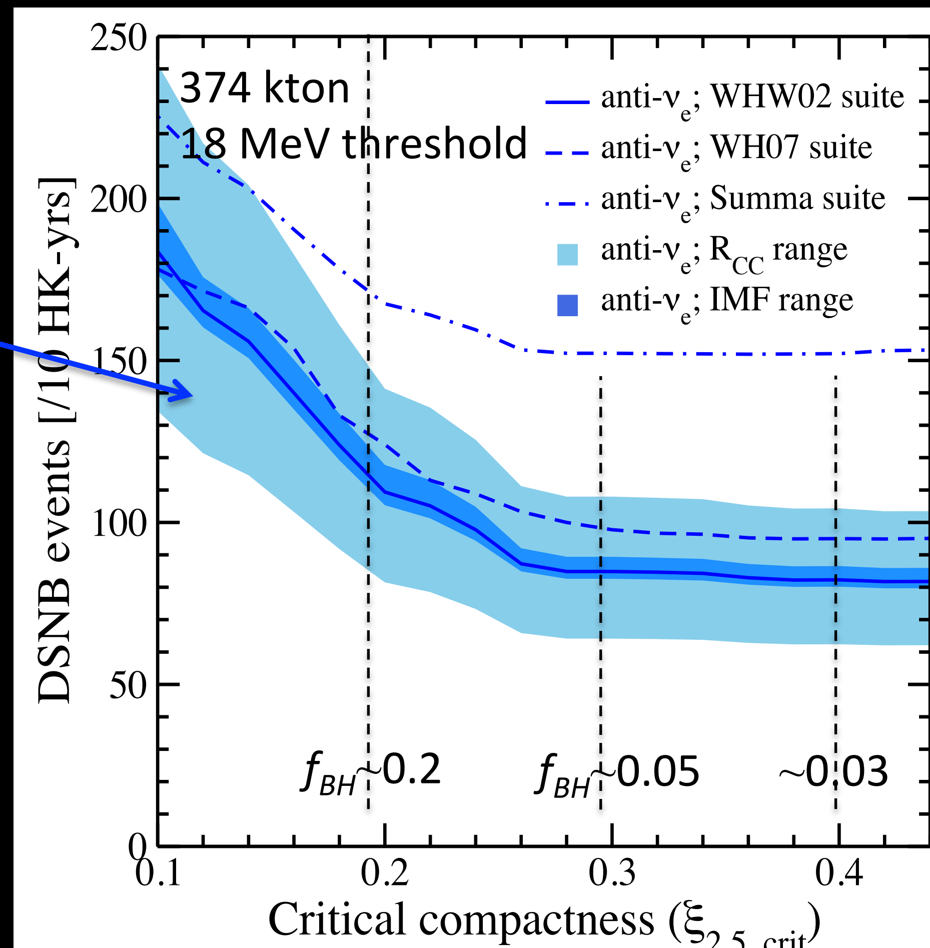
Rate uncertainty

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

Hyper-Kamiokande

Can be sensitive to small values of critical compactness, $\xi_{2.5} < 0.2$





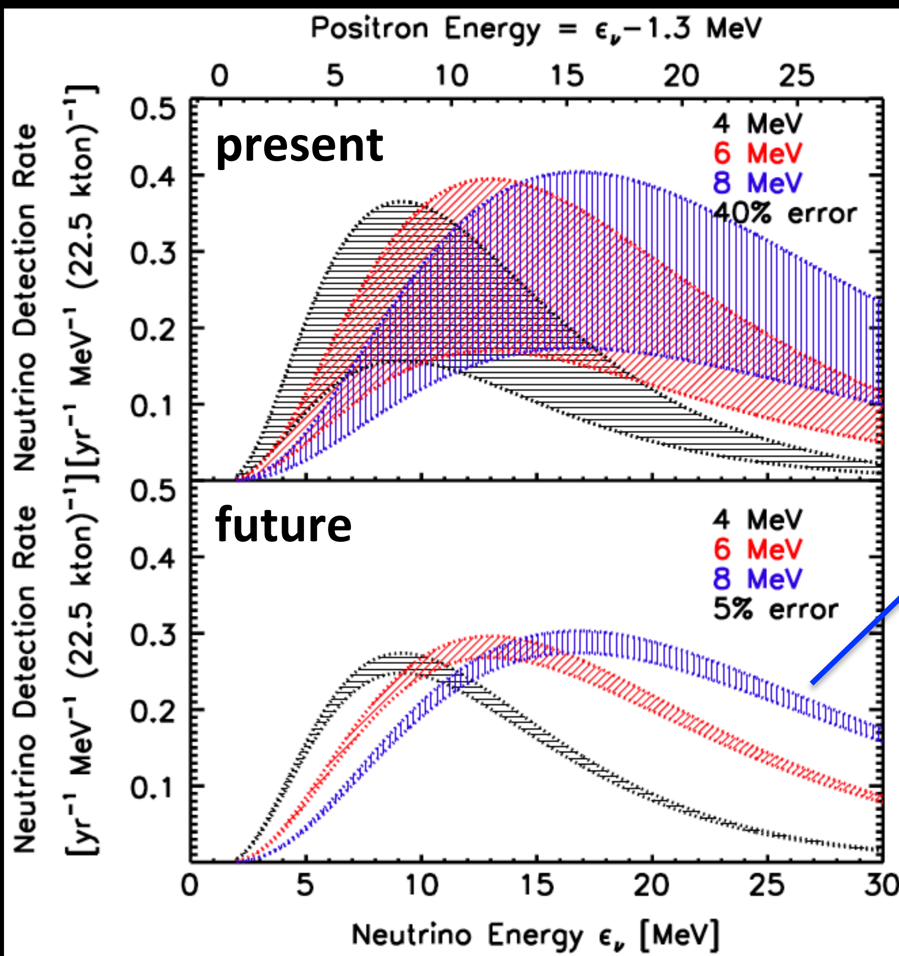
Lien et al (2010)

Horiuchi et al (2018)

DSNB: future

Rate uncertainty

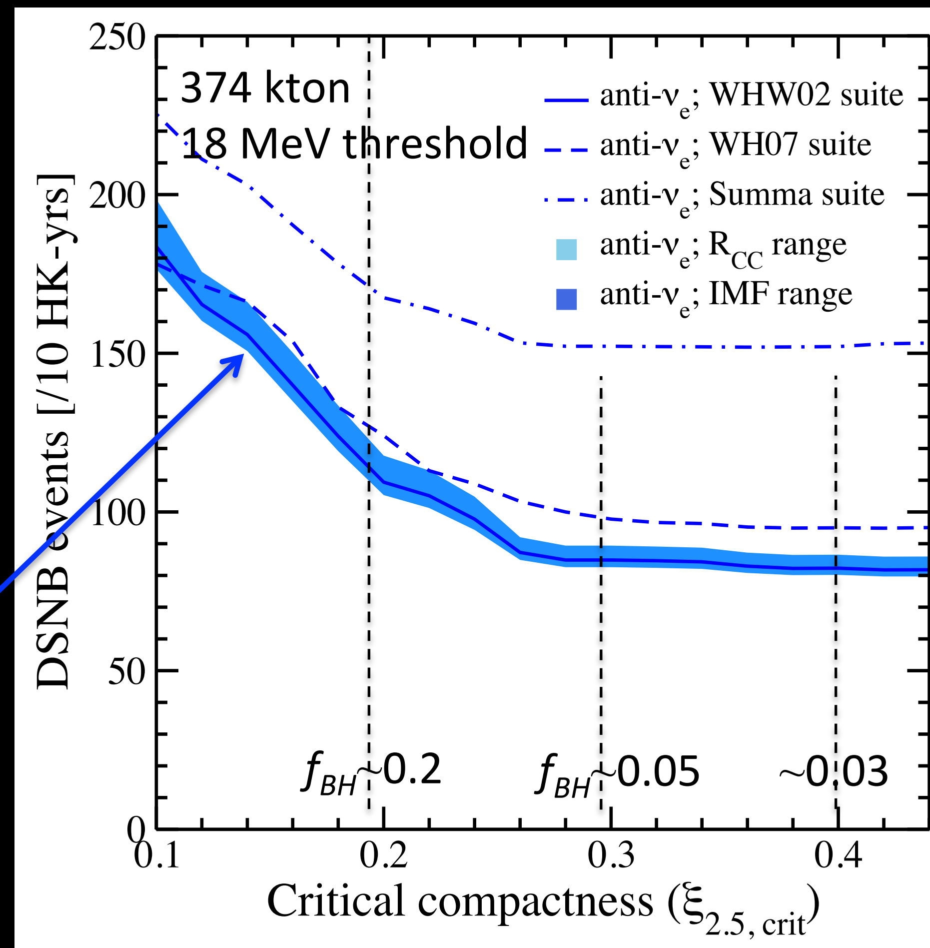
Will reduce with next-generation supernova surveys (e.g., LSST; 2023~)



Lien et al (2010)

Hyper-Kamiokande

Can be sensitive to small values of critical compactness, $\xi_{2.5} < 0.2$



Horiuchi et al (2018)

Concluding remarks

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

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

Present: excellent prospects for **detection**

- ✓ Gd upgrade at Super-K to deliver signal-limited search
- ✓ Can provide emission parameter estimates in 5-10 years

Future: signal probes new populations, e.g., **black hole formations**

- ✓ Future high-statistics DSNB probes low critical compactness
- ✓ Benefit from ongoing new simulations, long-term simulations, core-collapse rate measurements, oscillation parameters, etc

BACKUP

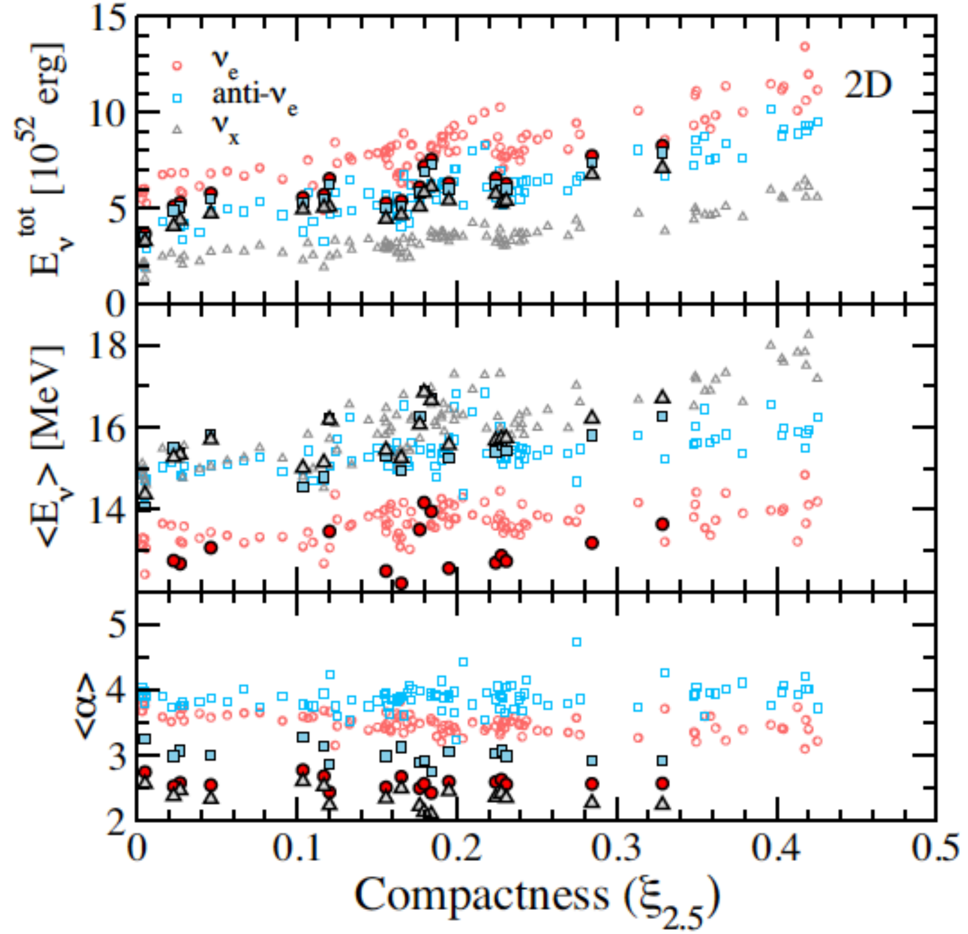
Time-integrated neutrino signal

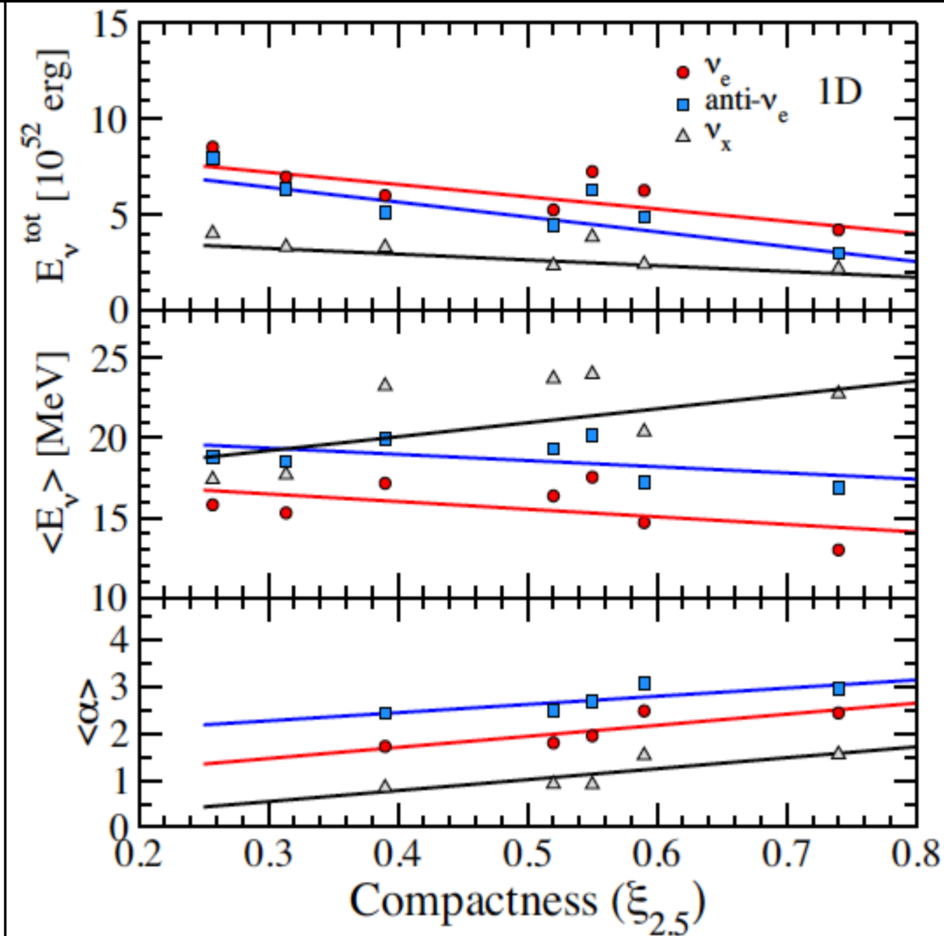
Spectrum per core collapse

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

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

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

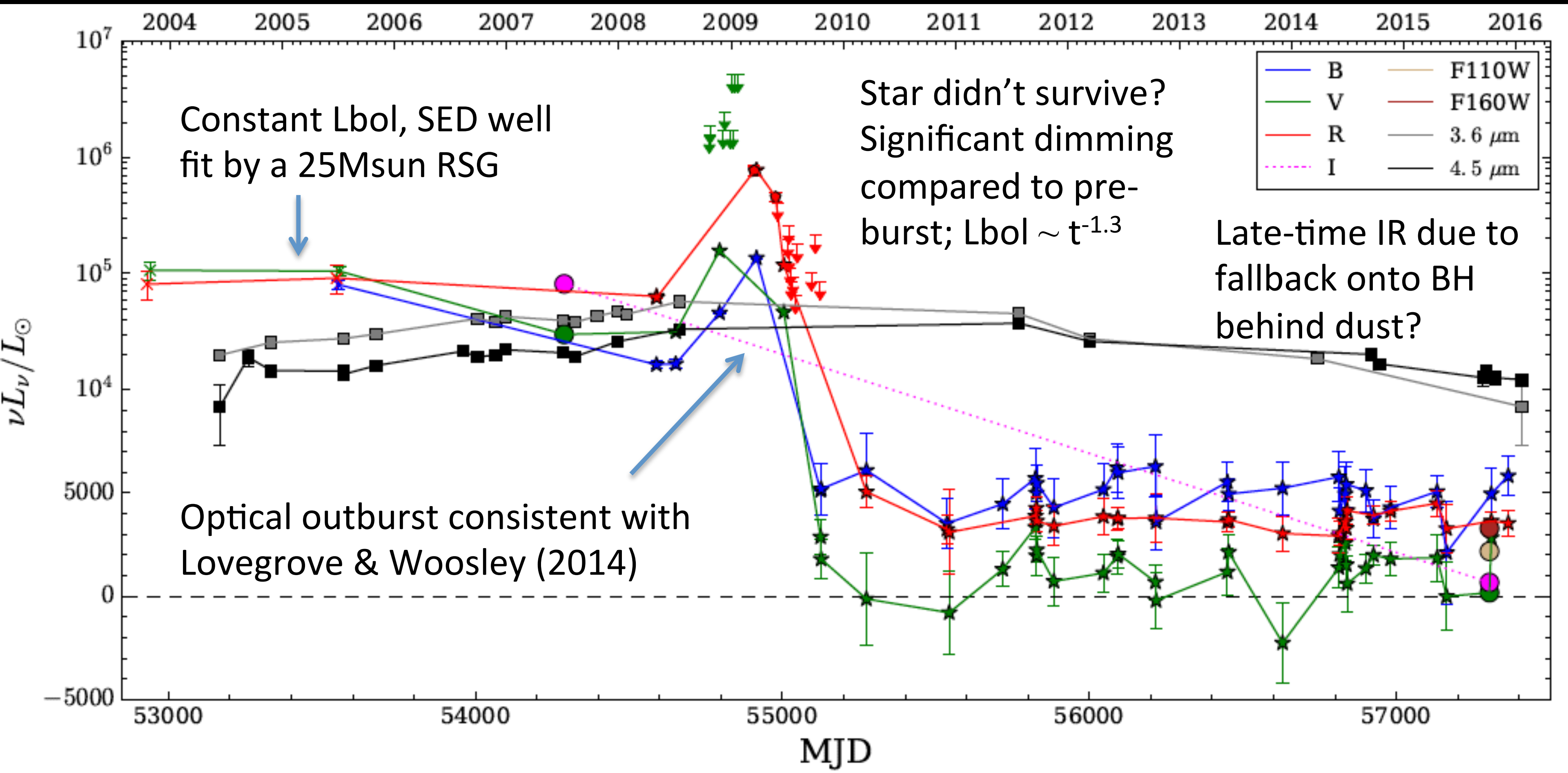




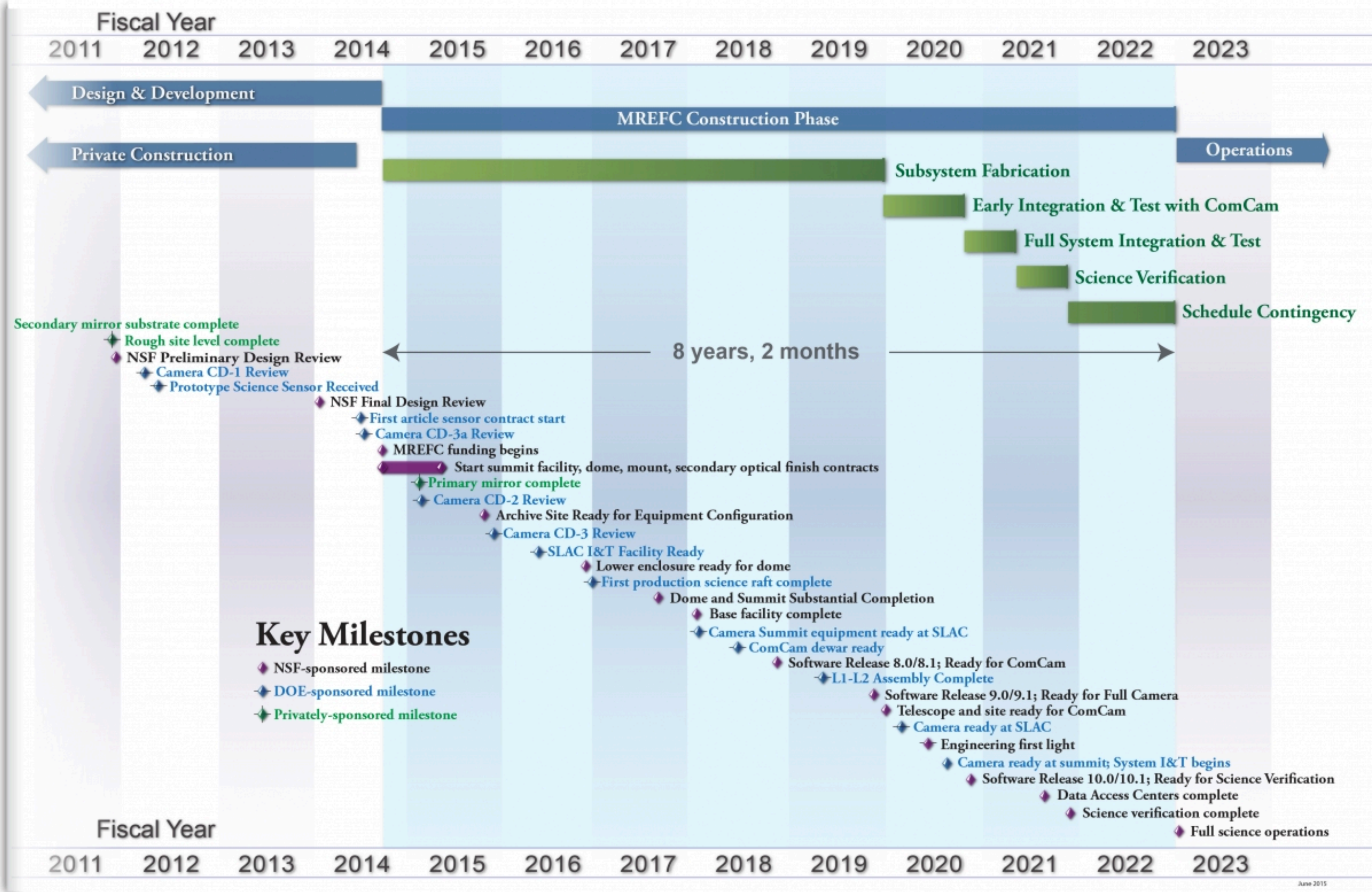
#4 The NGC6946-BH1 candidate

False positive?

New search will have new false positive → multi- wavelength follow-up is needed to vet failed SN candidates and determine whether the star survived or disappeared



Adams et al (2016)



Fiscal Year
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Design & Development
MREFC Construction Phase
Private Construction
Operations
Subsystem Fabrication
Early Integration & Test with ComCam
Full System Integration & Test
Science Verification
Schedule Contingency
8 years, 2 months
Secondary mirror substrate complete
Rough site level complete
NSF Preliminary Design Review
Camera CD-1 Review
Prototype Science Sensor Received
NSF Final Design Review
First article sensor contract start
Camera CD-3a Review
MREFC funding begins
Start summit facility, dome, mount, secondary optical finish contracts
Primary mirror complete
Camera CD-2 Review
Archive Site Ready for Equipment Configuration
Camera CD-3 Review
SLAC I&T Facility Ready
Lower enclosure ready for dome
First production science raft complete
Dome and Summit Substantial Completion
Base facility complete
Camera Summit equipment ready at SLAC
ComCam dewar ready
Software Release 8.0/8.1; Ready for ComCam
L1-L2 Assembly Complete
Software Release 9.0/9.1; Ready for Full Camera
Telescope and site ready for ComCam
Camera ready at SLAC
Engineering first light
Camera ready at summit; System I&T begins
Software Release 10.0/10.1; Ready for Science Verification
Data Access Centers complete
Science verification complete
Full science operations
Key Milestones
NSF-sponsored milestone
DOE-sponsored milestone
Privately-sponsored milestone
Fiscal Year
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
June 2015

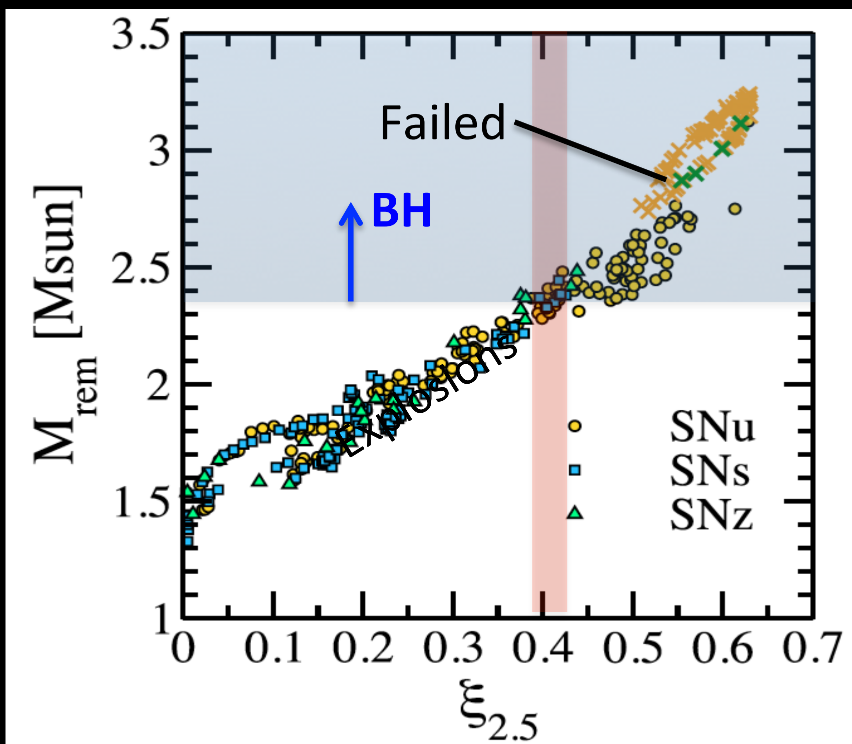
Critical compactness in 2D and 3D

Explosions in 2D

- 378 models, axis-symmetric

  Nakamura et al (2014)

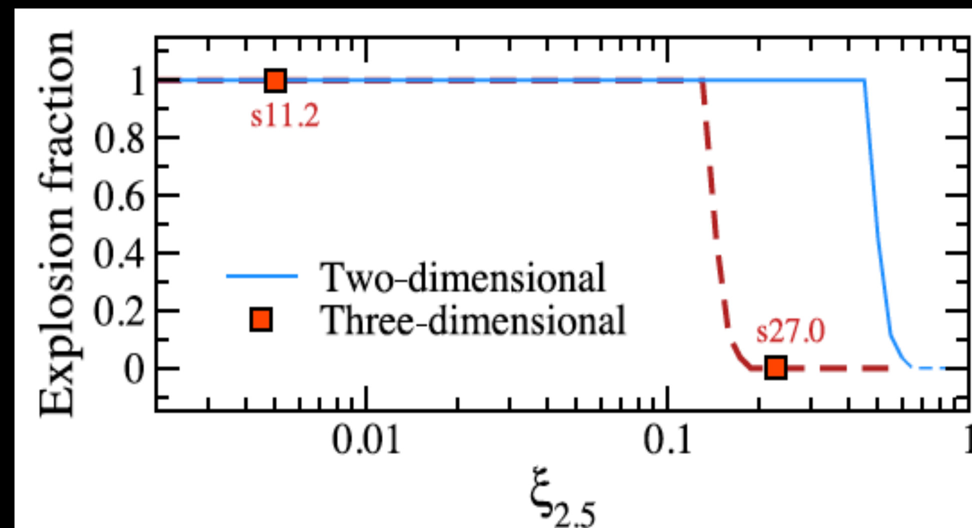
- 2D setup is conducive to explosions
- Remnants above 2.4 Msun baryonic mass not realistic and may fail



Horiuchi et al (2014)

Explosions in 3D

- No systematic simulations yet
- 3D explosions are more spherical and have later shock revival times than 2D
  - 27Msun progenitor with $\xi_{2.5}$ = 0.228 explode (late) in 2D, but not in 3D.



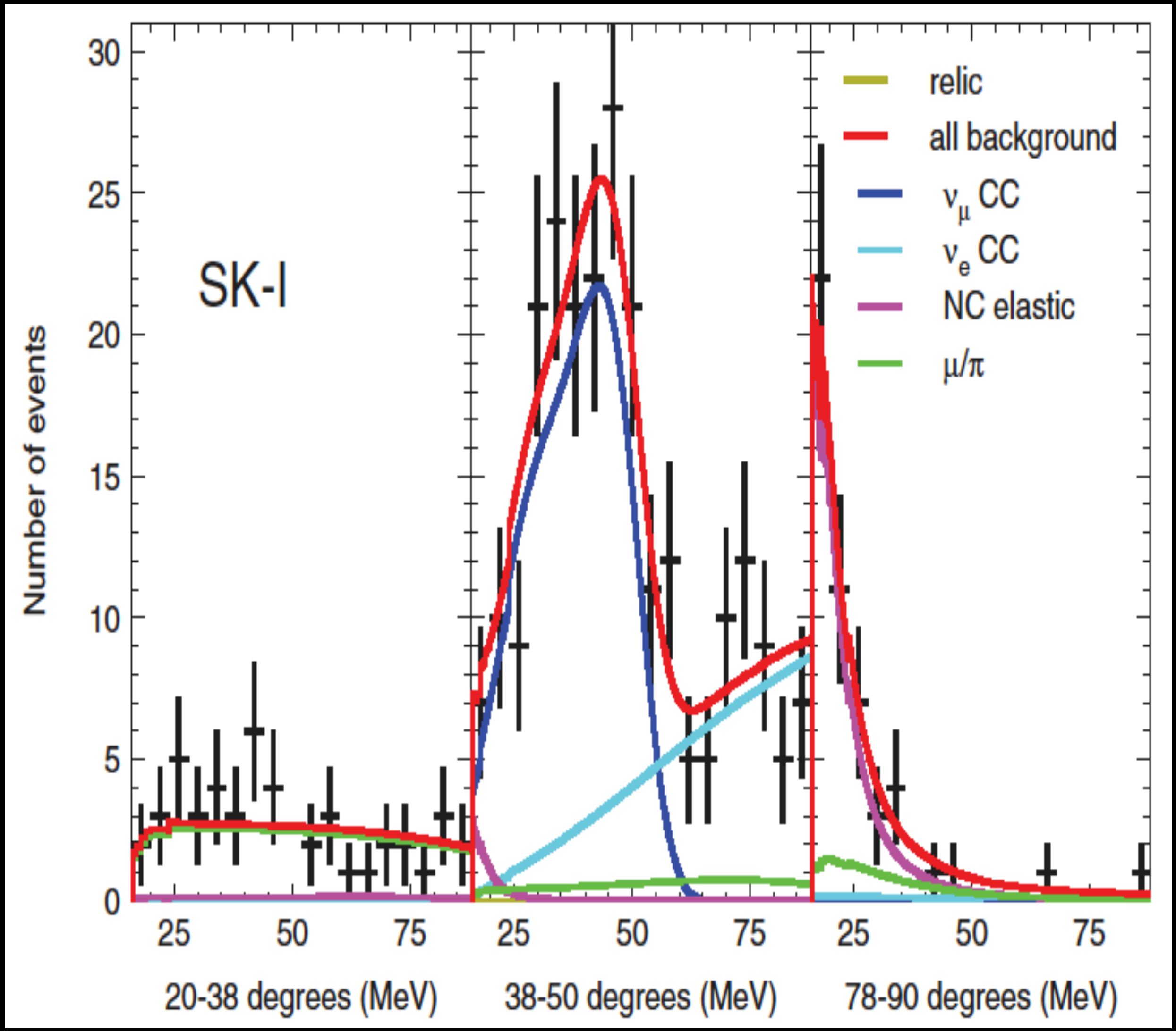
→ Critical compactness

1D: 0.15 – 0.35

2D: < 0.4

3D: < 0.2 ? Needs investigations

Searches by Super-K



Bays et al (2012)

Kamiokande-II
Flux < 226 cm^{-2} s^{-1}
[E_ν = 19 – 34 MeV, 90%CL]

Zhang et al (1988)

Super-Kamiokande (SK-I)
Flux < 1.2 cm^{-2} s^{-1}
[E_ν > 19.3 MeV, 90%CL]

Malek et al (2003)

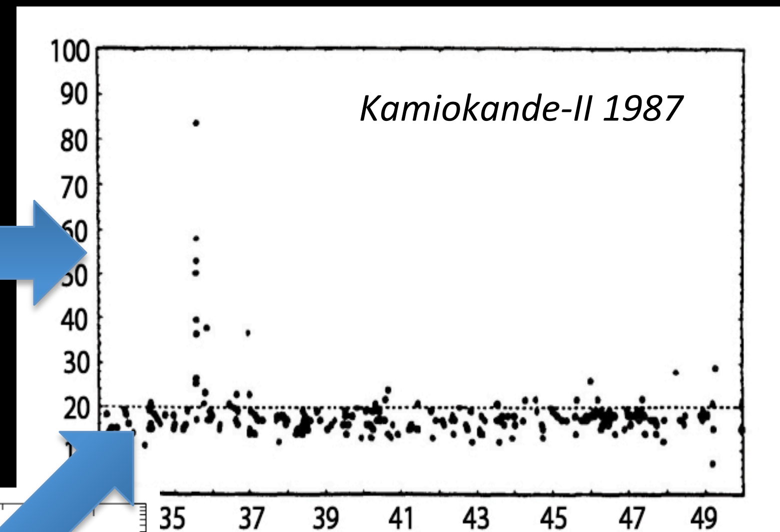
SK-I, SK-II, and SK-III:
Flux < 2.0 cm^{-2} s^{-1}
[E_{e+} > 18 MeV, 90%CL]

Bays et al (2012)
Low-E update, Zhang et al (2014)

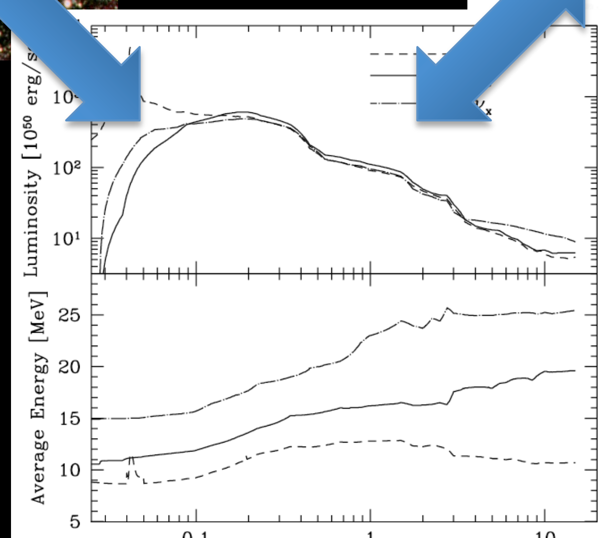
SN1987A as an example

Observation: Type II supernova associated with massive star

Observation: MeV neutrino precursor for ~10s



Theory: core collapse makes neutrinos and supernova

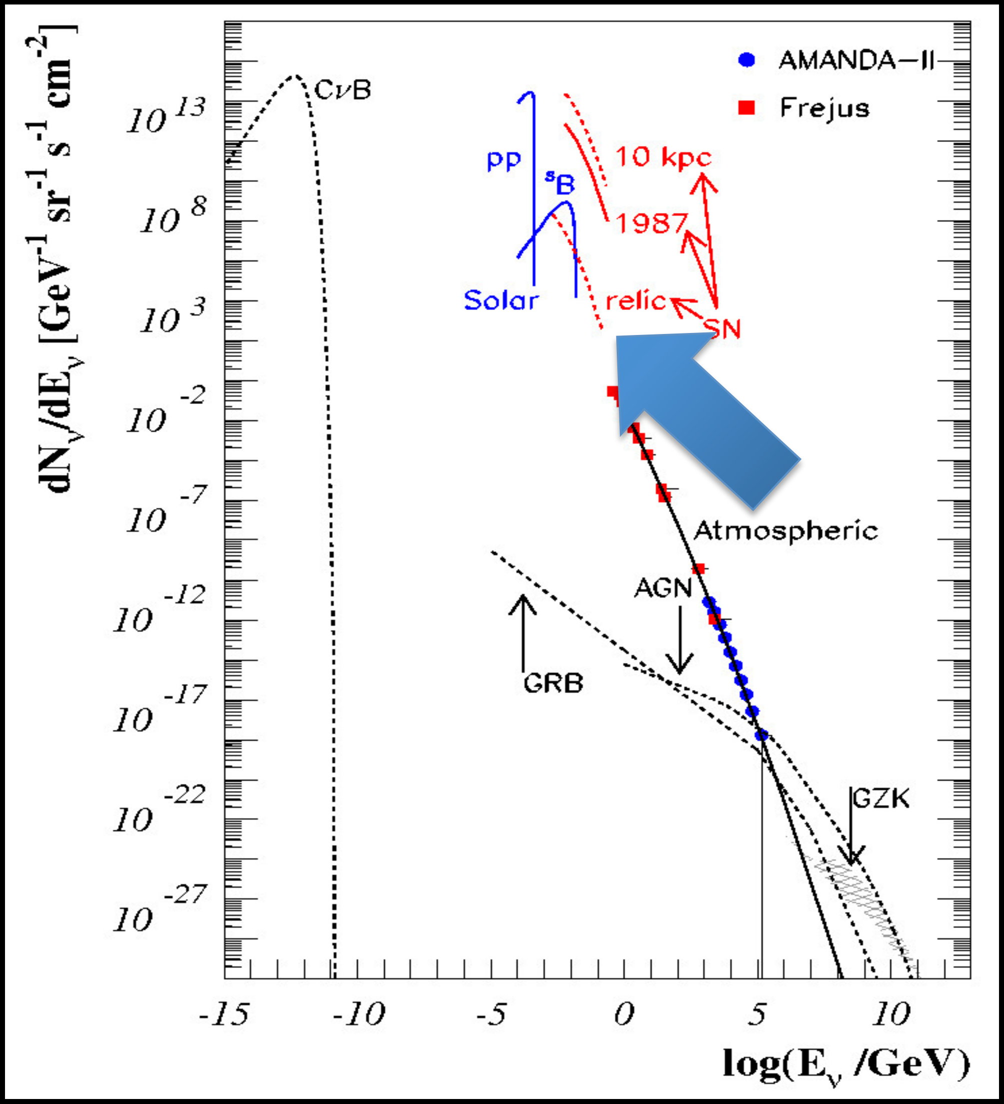


Totani et al (1998)

➔ Great insights!

1. Neutrino trapping
2. The thermal nature of neutrino spectrum
3. Total binding energy
4. Compact object form
5. Limits on axions, etc

25-orders magnitude neutrino spectrum



Extra-terrestrial Sources:

- Big bang relics (~10^{-4} eV)
- Solar neutrinos (~1 MeV)
- Core-collapse supernova neutrinos (~10 MeV)
- Gamma-ray bursts (>10 MeV)
- Active Galactic Nuclei (>1 GeV)
- Cosmogenic (~10^{15}-10^{20} eV)

Terrestrial sources

- Atmospheric neutrinos (>1 GeV)
- Geo-neutrinos (~1 MeV)