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Diffuse supernova neutrino background from extensive core-collapse simulations

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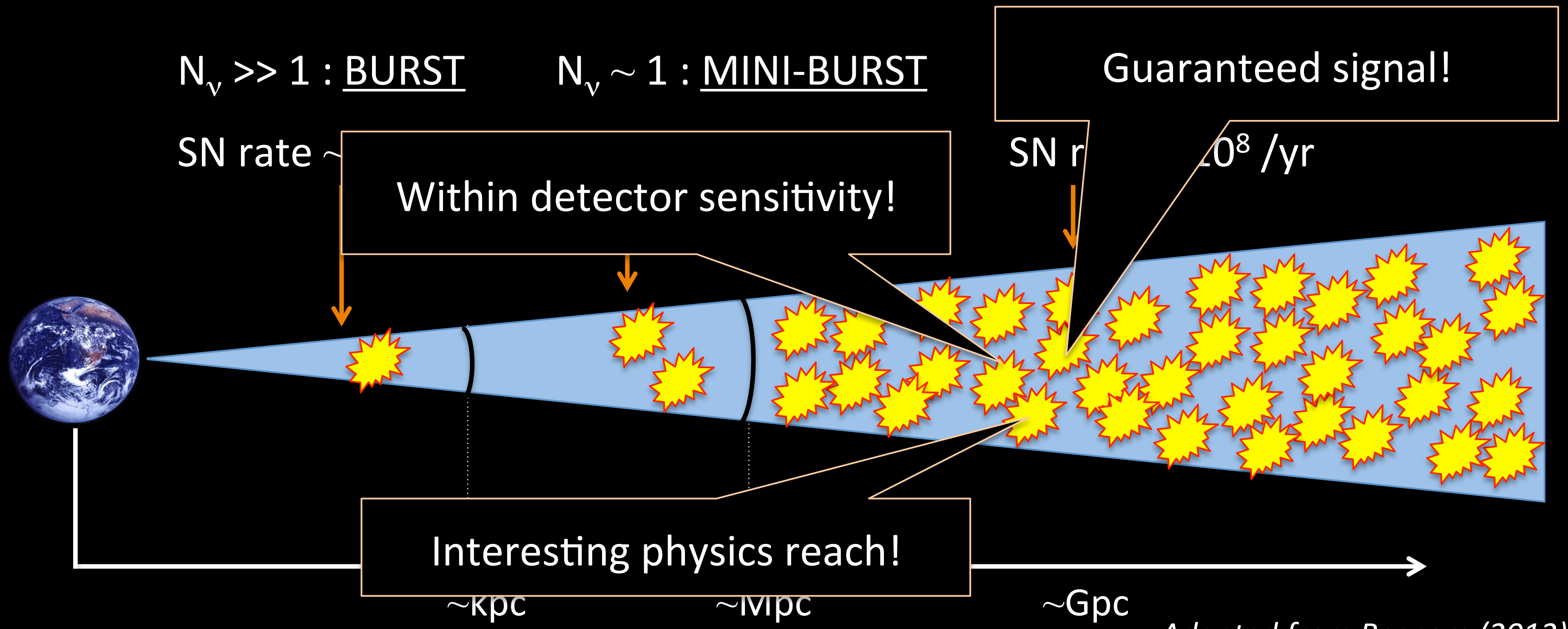
Distance scales and physics outcomes



$N_\nu >> 1$: <u>BURST</u>

$N_\nu \sim 1$: <u>MINI-BURST</u>

Guaranteed signal!

SN rate ~

SN r

10^8 /yr

Within detector sensitivity!

Interesting 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: core-collapse neutrino spectrum

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

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

Input 2: core-collapse rate

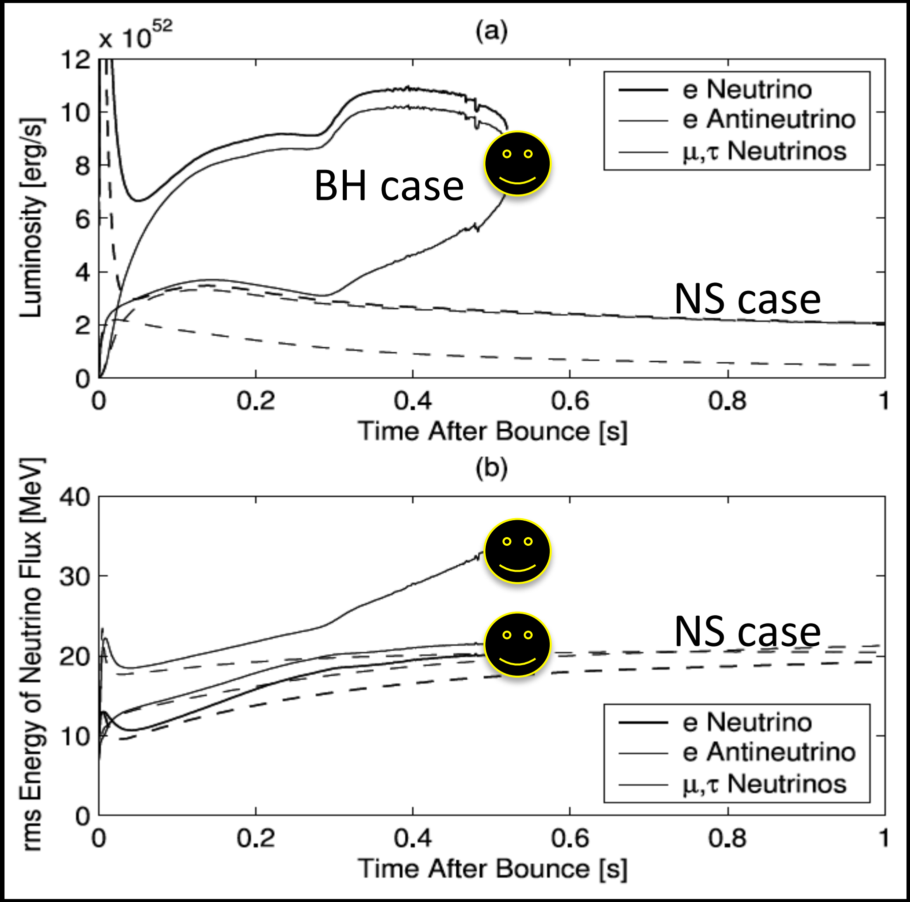
Input 3: neutrino detector capabilities

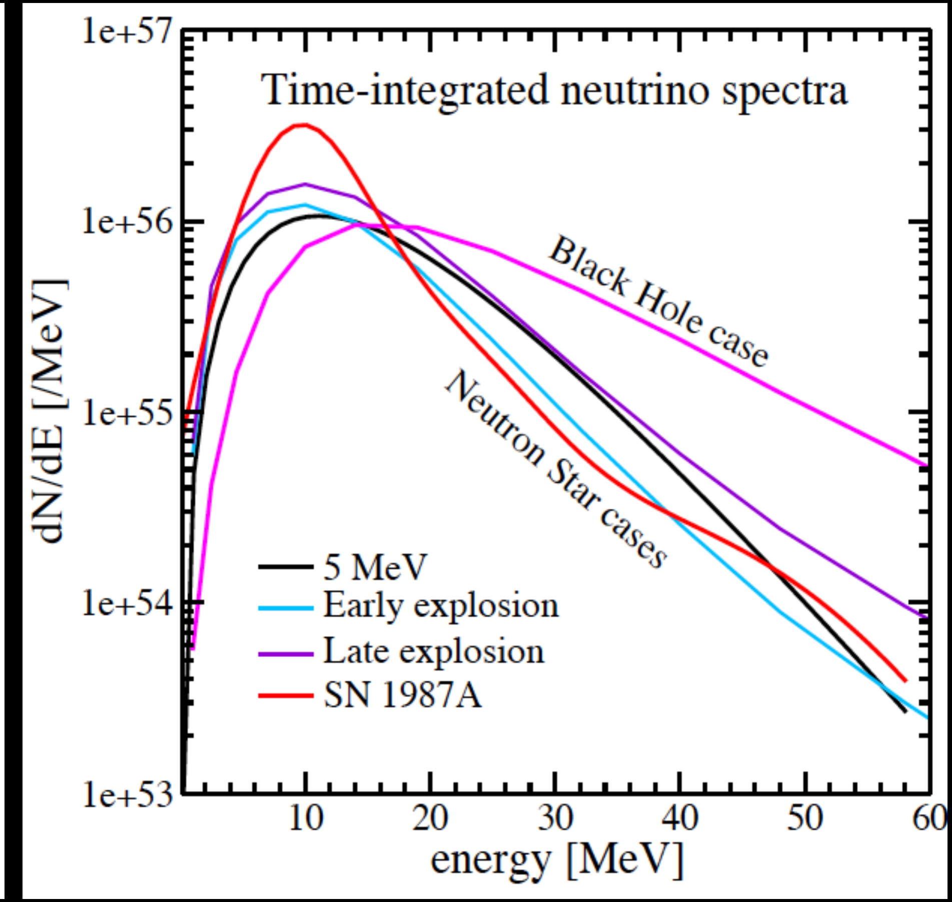
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Input 1: neutrinos from core collapse

Time-integrated neutrinos from core collapse

- Core collapse releases ~3x10^{53} erg in neutrinos, of which ~1/6 is in anti-ν_e
- BH formation goes through high mass accretion → ν spectrum hotter (EOS-dep)



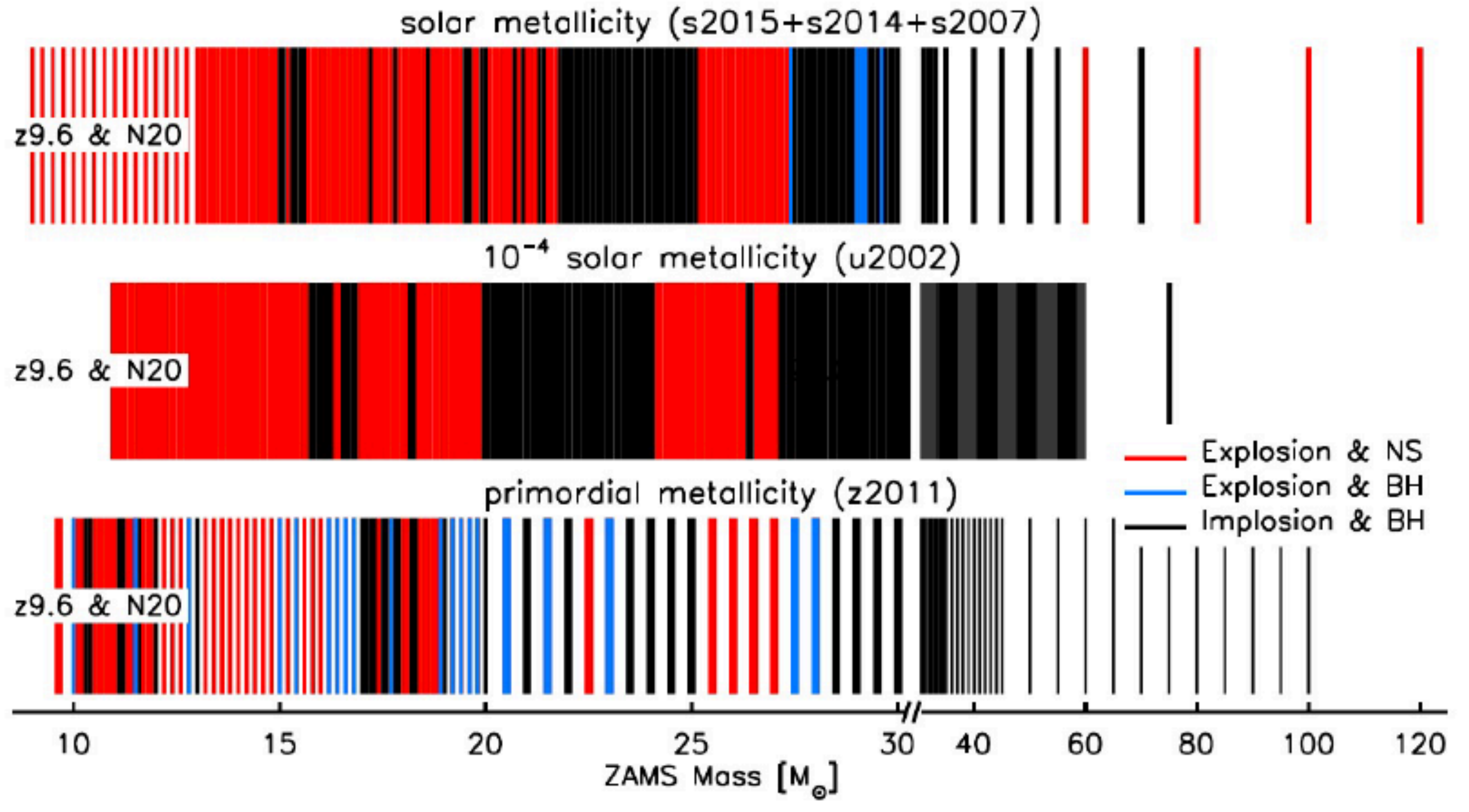


Liebendoerfer et al 2004; many studies, e.g., Fischer et al 2009, Sumiyoshi et al 2006, 2007, 2008, 2009, Nakazato et al 2008, 2010, O'Connor & Ott 2011, …

Supernova diversity

Traditionally, we think in mass

However, systematic studies are indicating that this is not complete



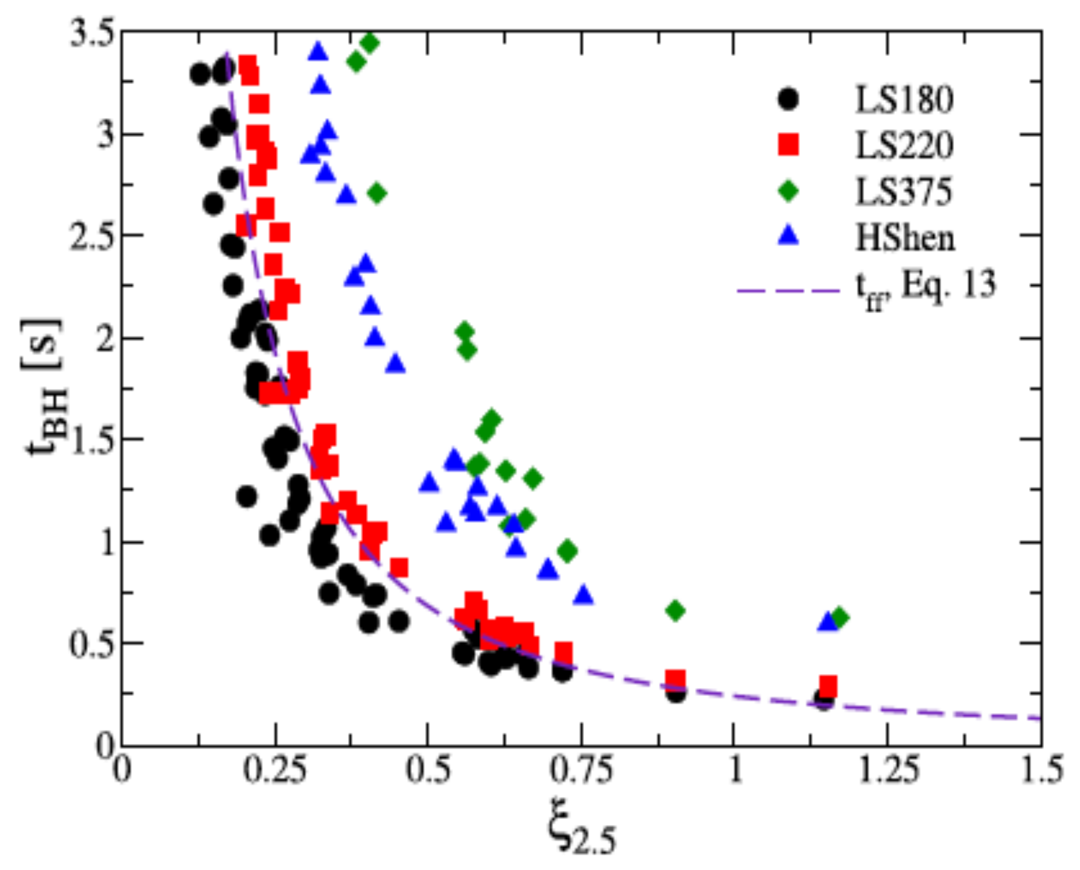
Janka 2017; based on Ertl et al (2016); see also Ugliano et al (2012), Sukhbold et al (2016), Pejcha & Thompson (2015), Mueller et al (2016)

Progenitor compactness

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

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

O'Connor & Ott (2011)



- Higher ξ → higher Mdot → BH forms earlier
- Lower ξ → lower Mdot → BH forms later

Explodability

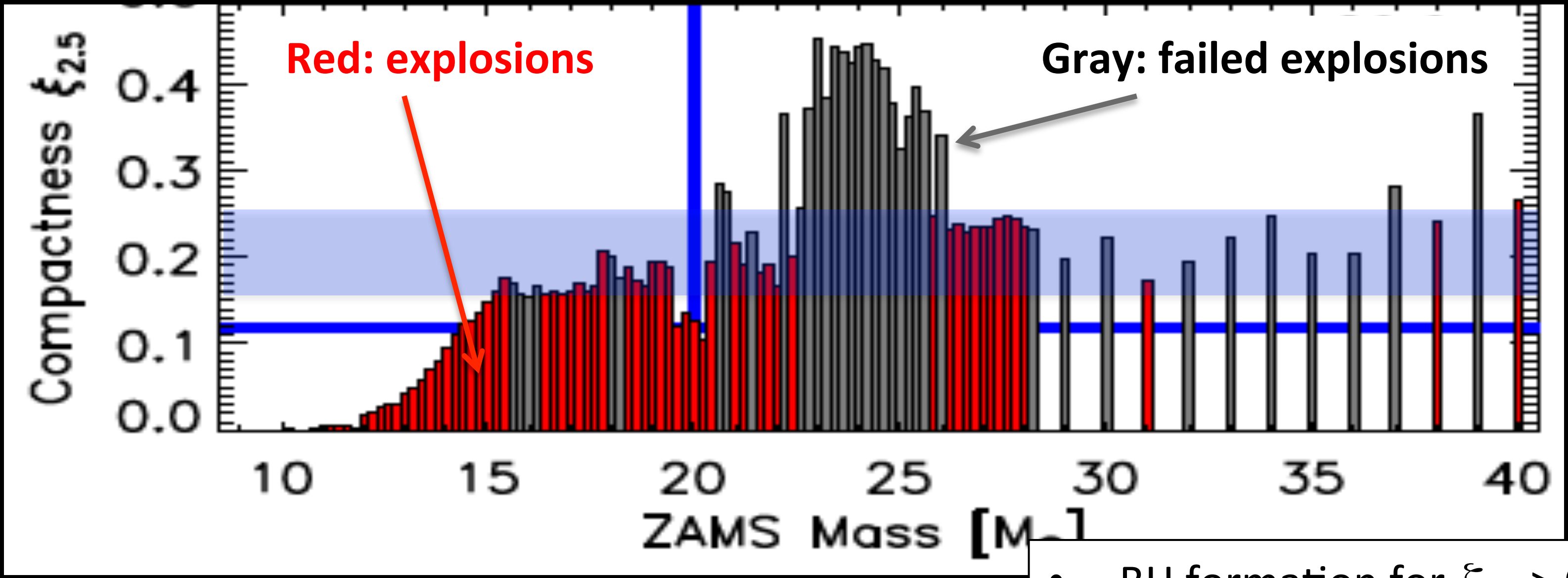
Mass accretion

VS !

Neutrino heating

Compactness: 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

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

Is there a critical compactness?

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

- Critical $\xi_{2.5} \sim 0.2$ is consistent with axisymmetric simulations
- What is the critical compactness in 3D simulations? TBD.

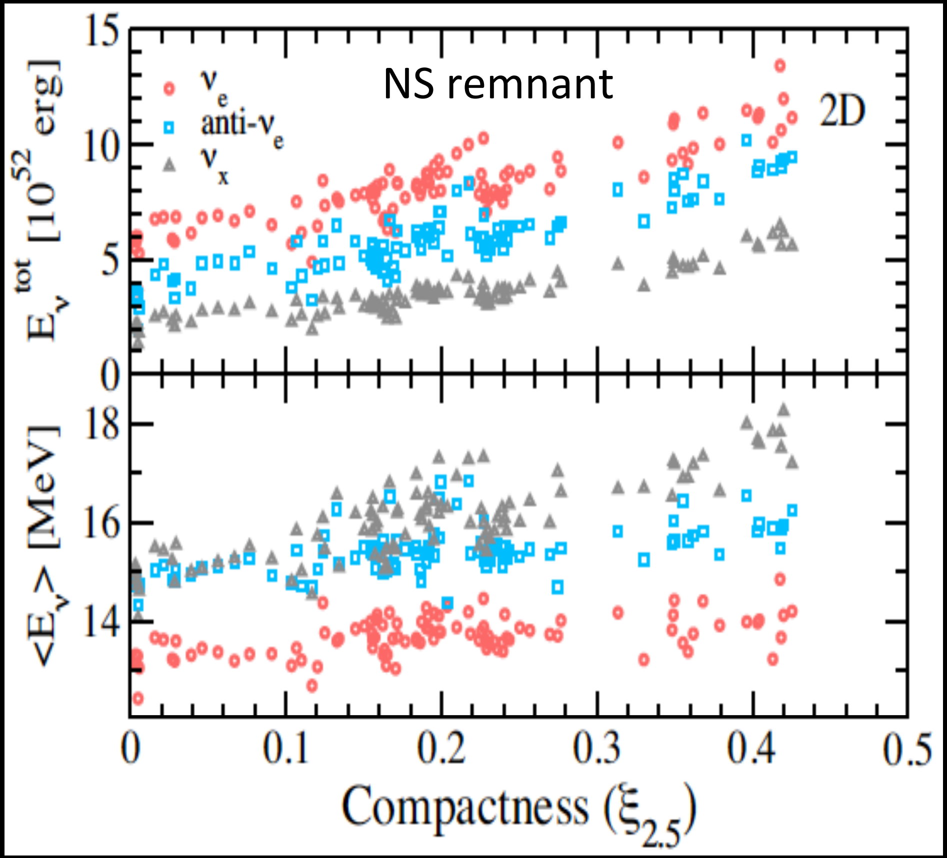
Horiuchi et al (2014)

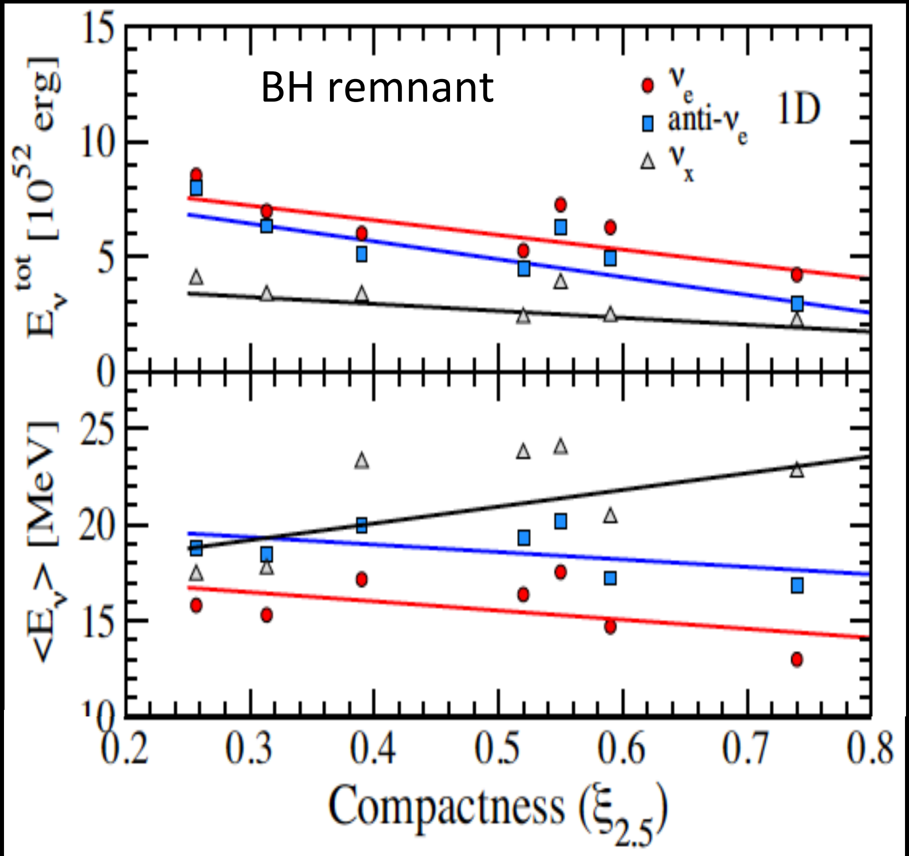
Time-integrated neutrino signal

Systematic dependence on compactness
Spectral parameters *(E_{tot}, E_{ave}, α_{pinch})* from 100+ simulations of ONeMg collapse, Fe core collapse, and collapse to BHs

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

→ *(E_{tot}, E_{ave}, α_{pinch})*



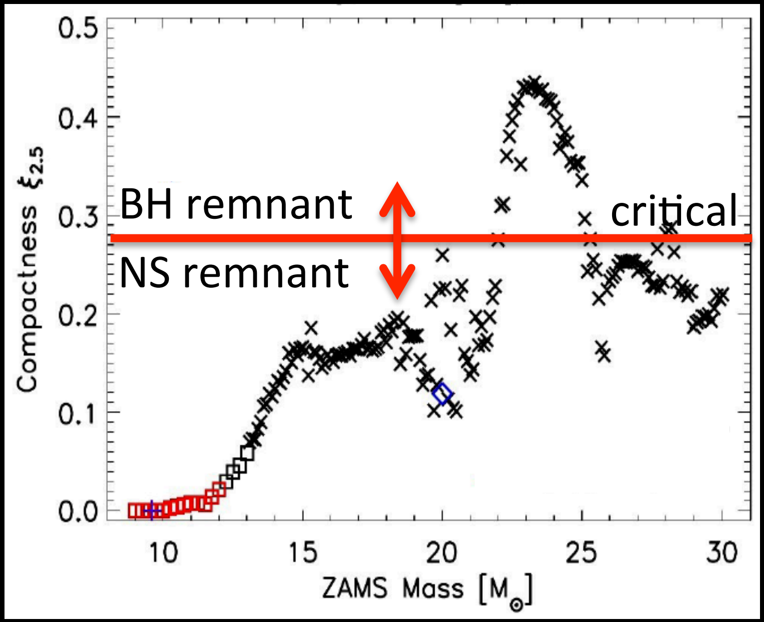


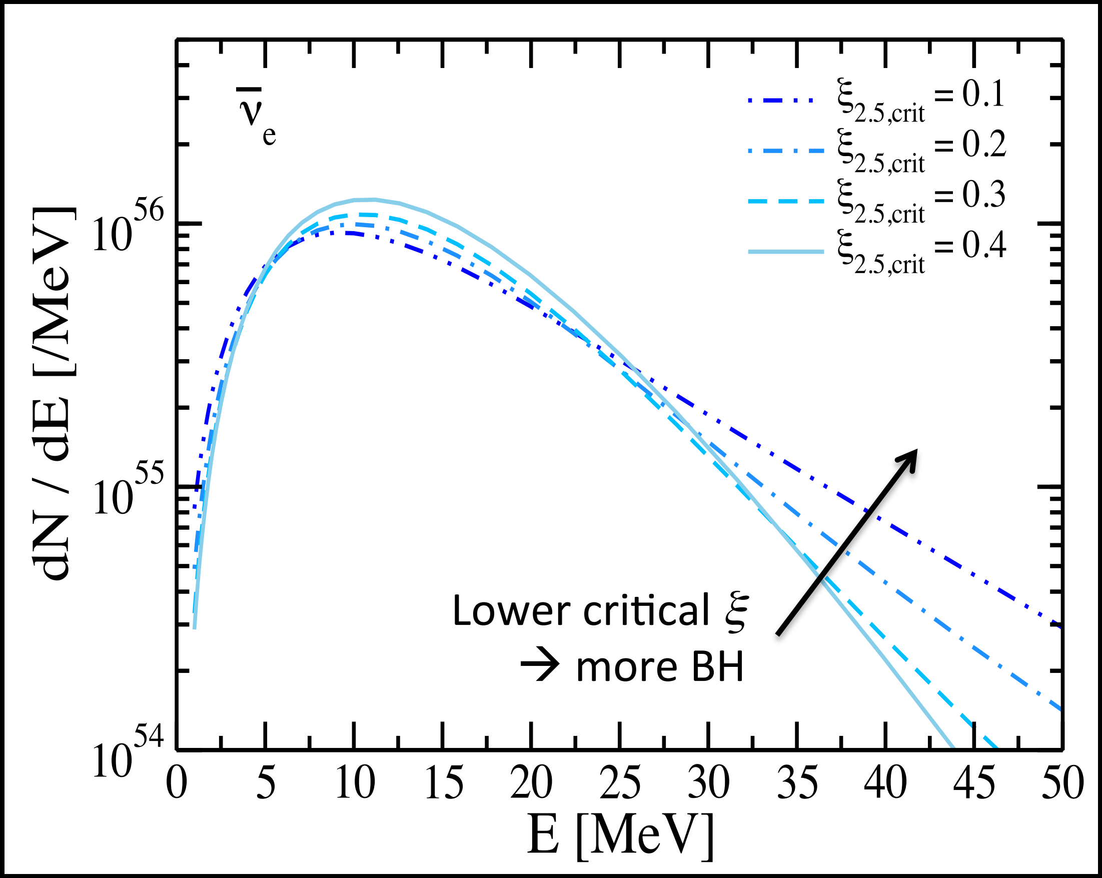
Horiuchi et al (2018); based on Hudepohl et al (2010), Nakamura et al 2015, Summa et al 2016, others

Input 1: mean neutrino emission

Mean neutrino emission per supernova

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





Horiuchi et al (2018)

Diffuse Supernova Neutrino Background

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

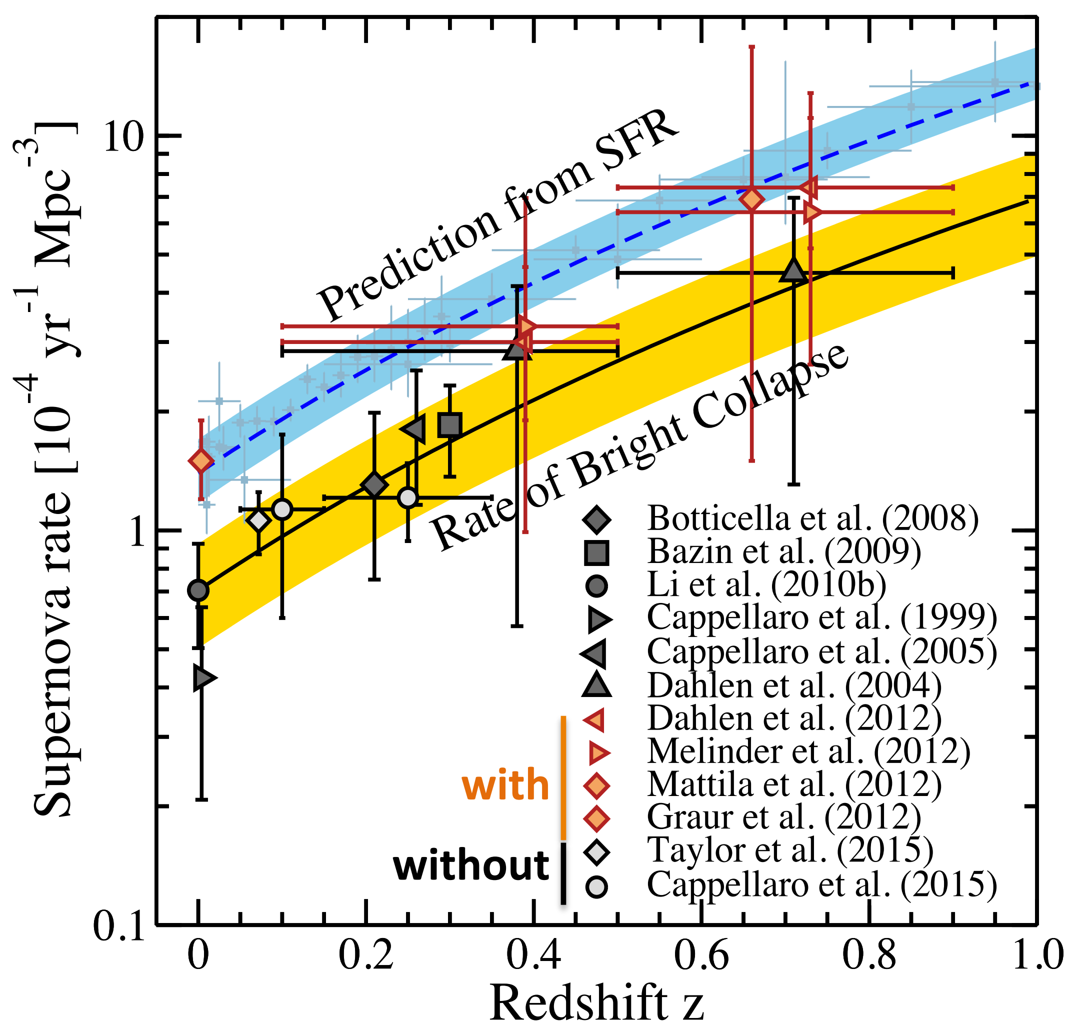
Input 2: core-collapse rate

Input 3: neutrino detector capabilities

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

Input 2: cosmic core-collapse rate

Birth rate of massive stars & supernova rate

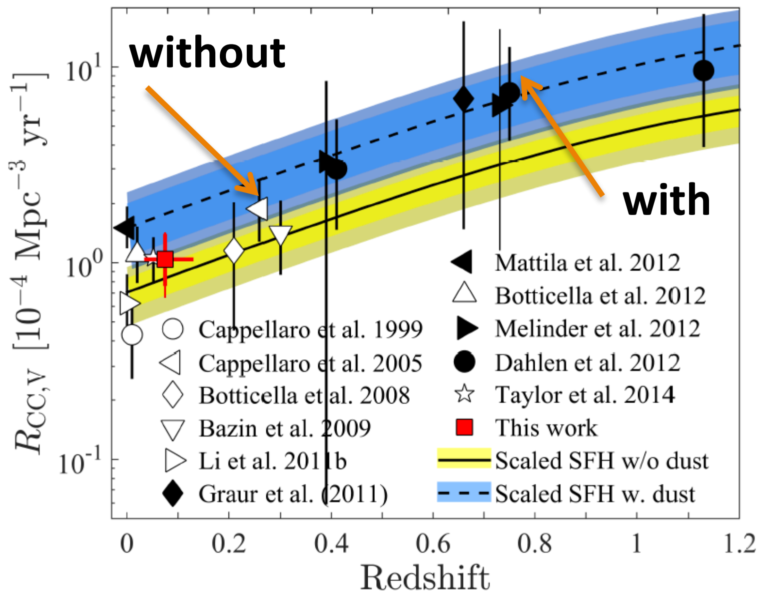


Updated from Horiuchi et al (2011)

- Cosmic supernova rates tend to be lower than birth rates: missing supernovae?

e.g., Mannucci et al (2007), Horiuchi et al (2011), Matilla et al (2012), Jencson et al (2019)

- Adopt birth rate as the total core-collapse rate, and assign "missing part" as NS or BH.



Graur et al (2015)

Input 3: Gadolinium-doped Super-K

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

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

w/out Gd

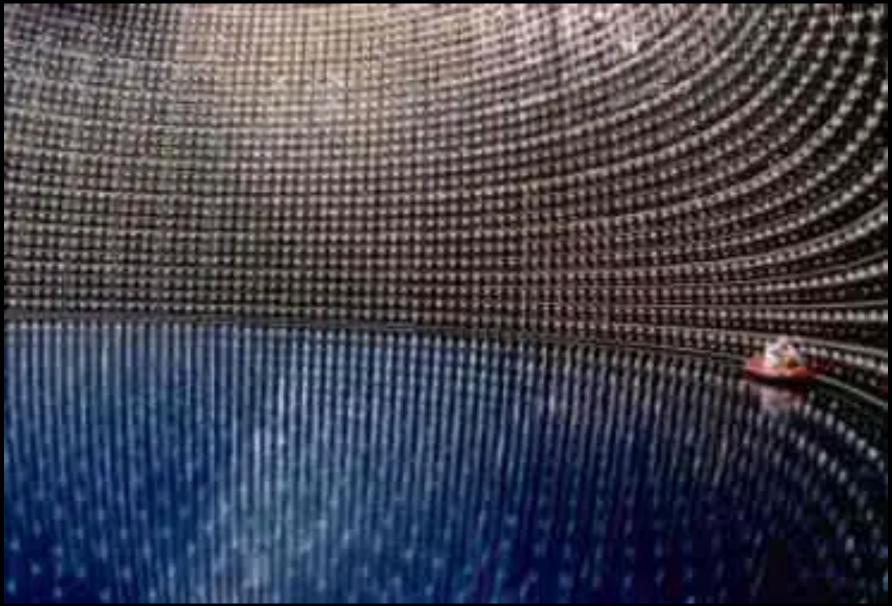
with Gd

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

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

Beacom & Vagins (2004)

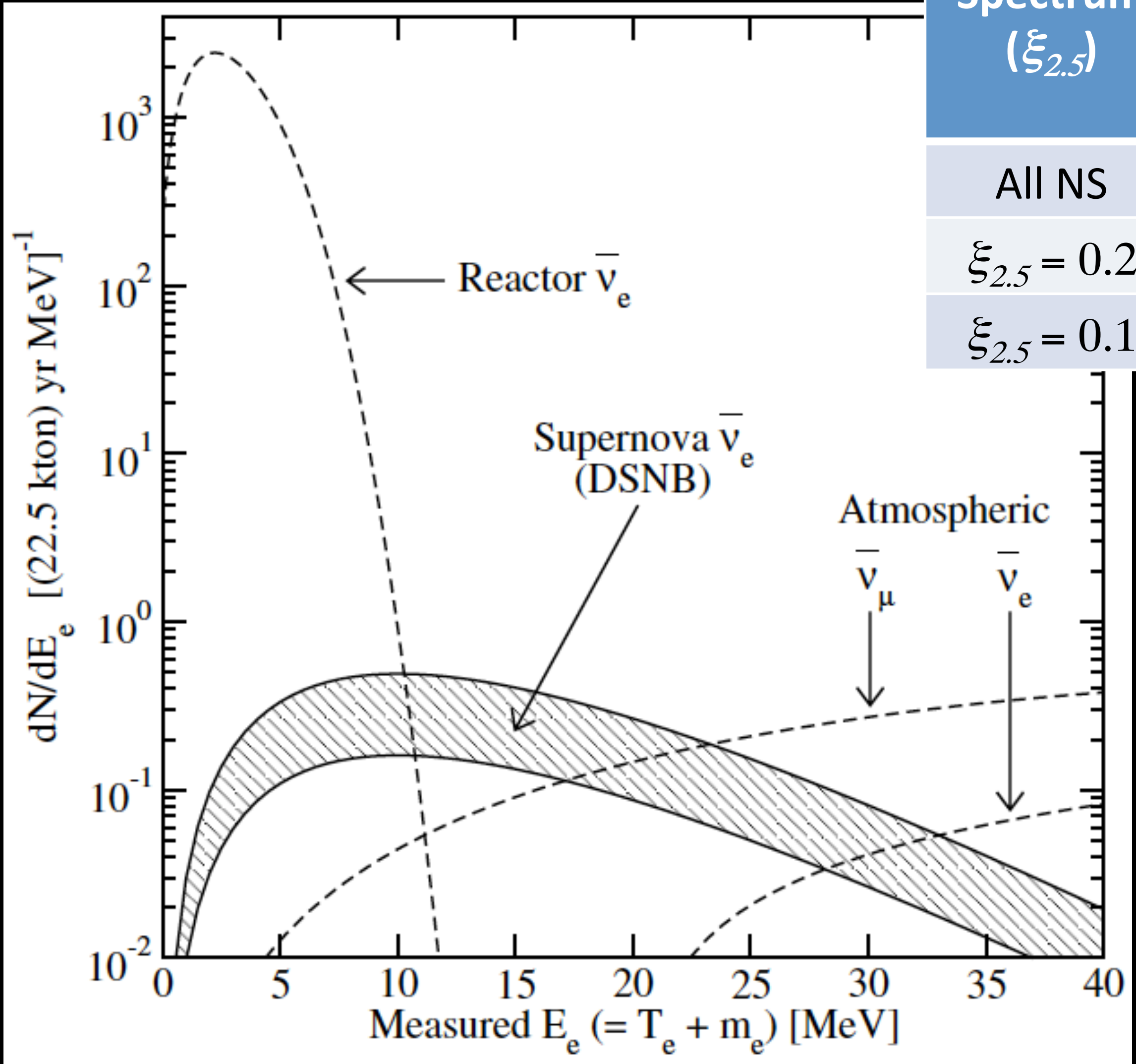
After many R&D & tests (EGADS), Super-K drained & refill in 2018, poised to add Gd in end of 2019



EGADS: Evaluating Gadolinium's Action on Detector Systems

The DSNB detection rate

DSNB search window & rates



Beacom & Vagins (2004)

Spectrum ($\xi_{2.5}$)	Water (Rate E > 18 MeV) [/yr]	Water + Gd (Rate E > 10 MeV) [/yr]
All NS	0.4 +/- 0.1	1.7 +/- 0.4
$\xi_{2.5} = 0.2$	0.6 +/- 0.1	1.9 +/- 0.5
$\xi_{2.5} = 0.1$	1.0 +/- 0.3	2.8 +/- 0.8

Horiuchi et al (2009, 2018)

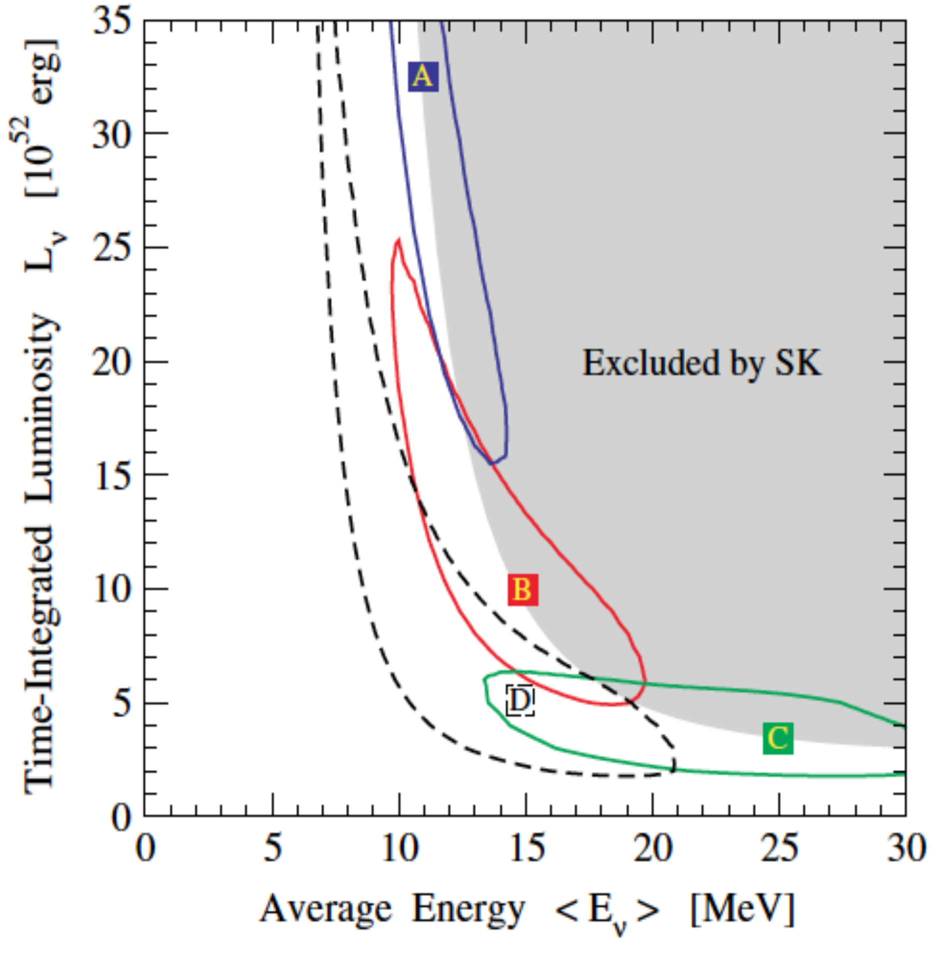
Gadolinium removes invisible muon decays and spallation products, leaving reactor neutrinos and atmospheric neutrinos.

Search energy window is ~10-20 MeV

The future

10+ years with Super-K

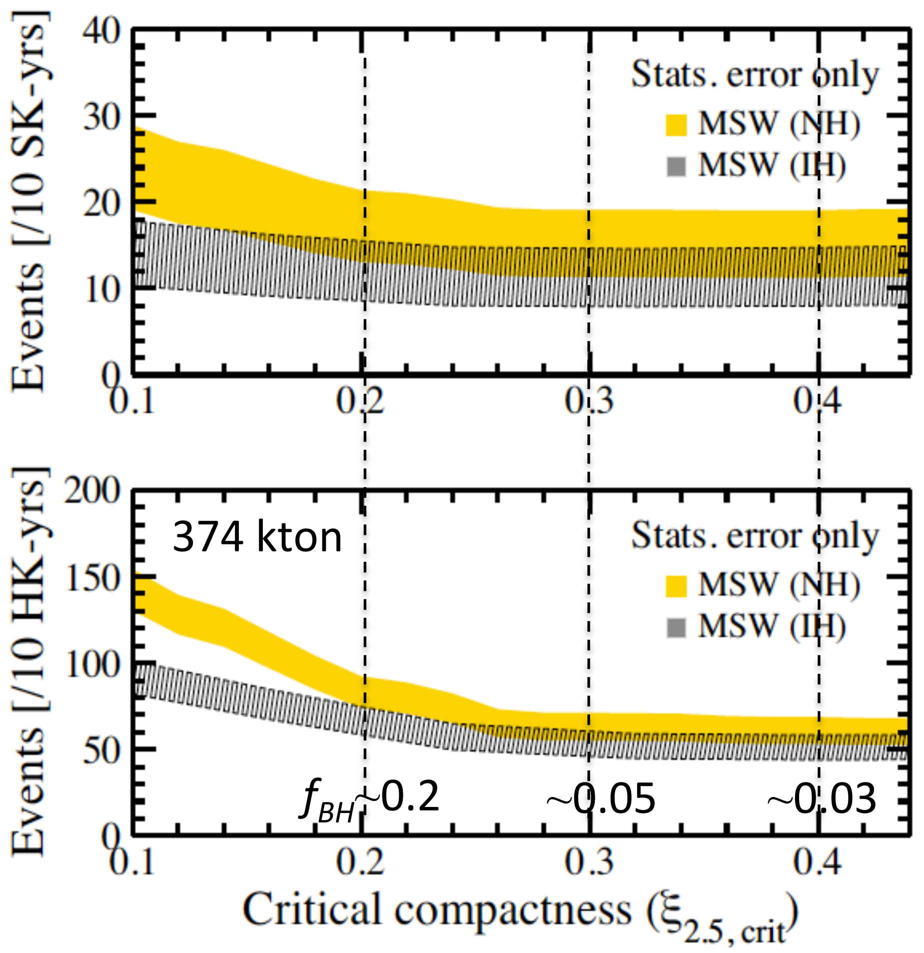
Able to eventually measure mean neutrino emission parameters



Yuksel et al (2006)

Hyper-Kamiokande

Larger volume, yields sensitivity to small values of critical compactness



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

Concluding remarks

Diffuse supernova neutrino background **predictions**

- *We now start to fold in the progenitor-dependent diversity in supernova neutrino emission*

There are improving prospects for **detection**

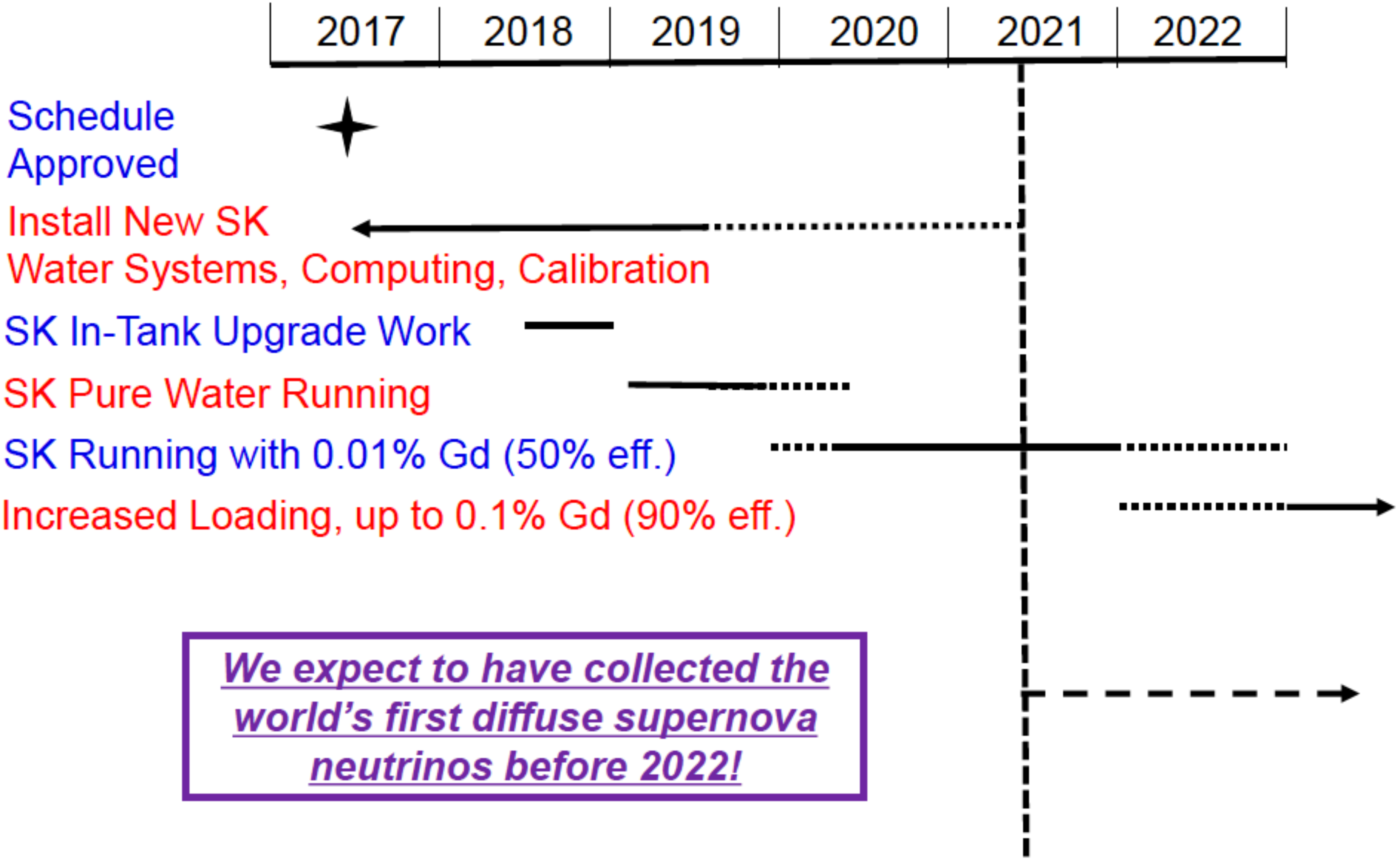
- Gd upgrade at Super-K delivers signal-limited search
- Future large volume detectors

The signal probes **explosions / black hole** formation

- Future high-statistics DSNB probes high BH formation fraction

BACKUP

Expected timeline for SK-Gd



Schedule Approved

Install New SK Water Systems, Computing, Calibration

SK In-Tank Upgrade Work

SK Pure Water Running

SK Running with 0.01% Gd (50% eff.)

Increased Loading, up to 0.1% Gd (90% eff.)

We expect to have collected the world's first diffuse supernova neutrinos before 2022!

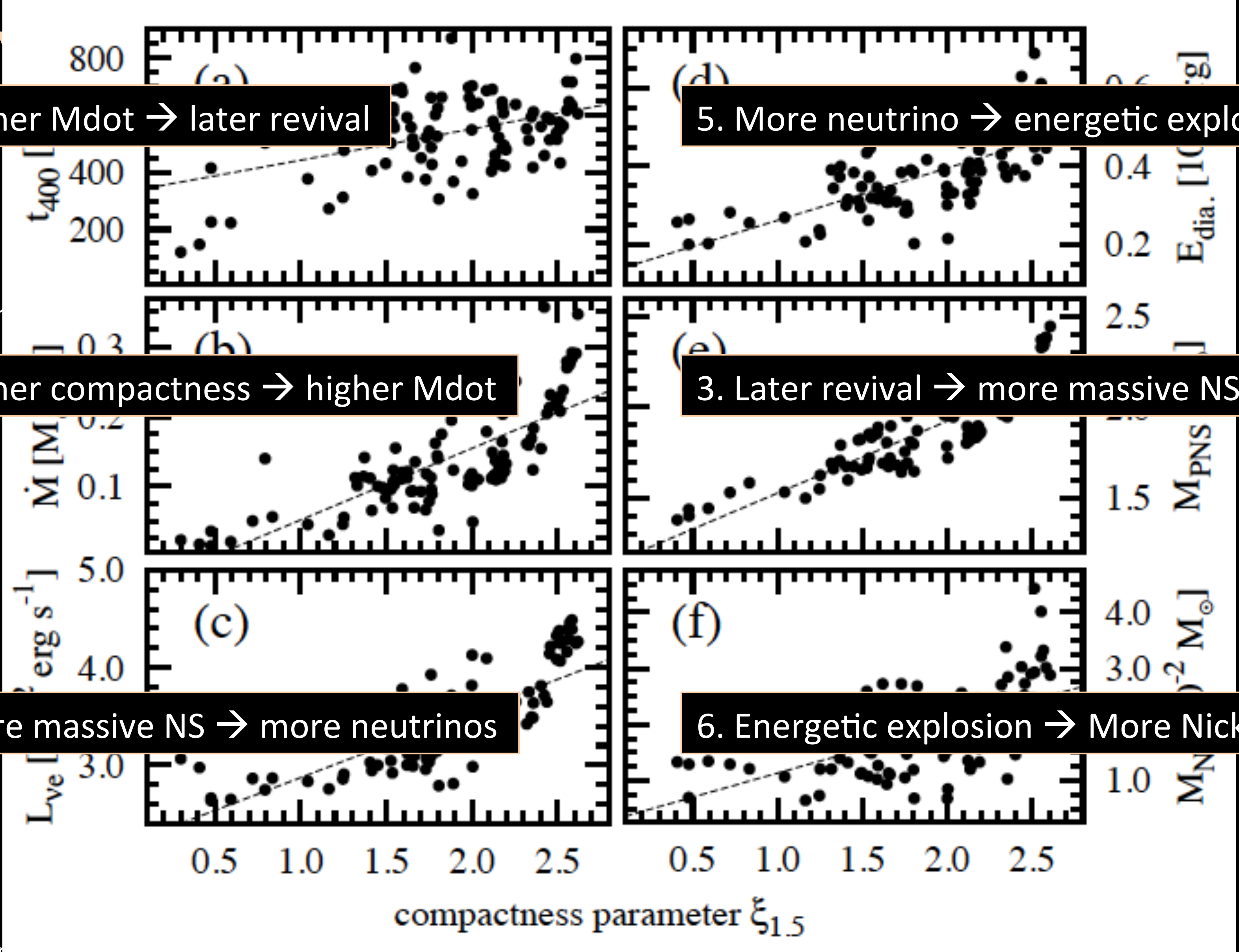
Correlations in systematic 2D simulations

Axis-sy

Based

-
-

Nakamu



2. Higher Mdot → later revival

5. More neutrino → energetic explosion

1. Higher compactness → higher Mdot

3. Later revival → more massive NS

4. More massive NS → more neutrinos

6. Energetic explosion → More Nickel

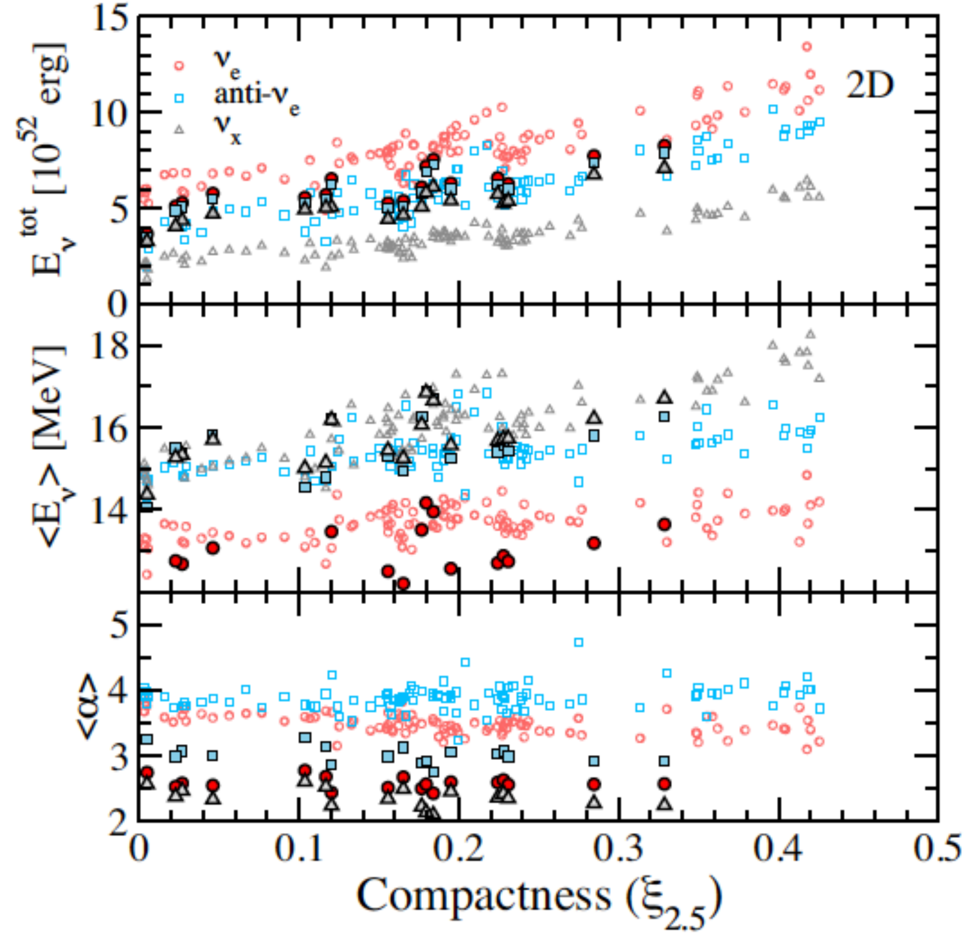
Comparison to Garching models

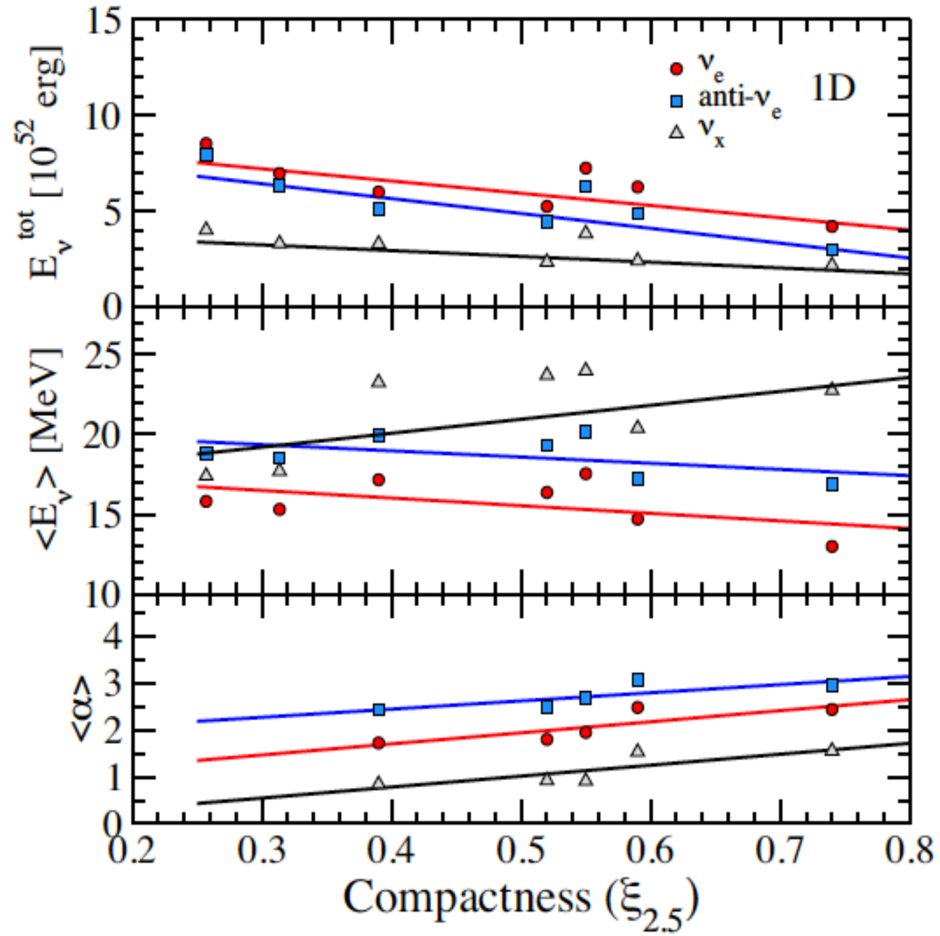
Spectrum per core collapse

Spectral parameters from 18 2D simulations from Summa et al (2016)

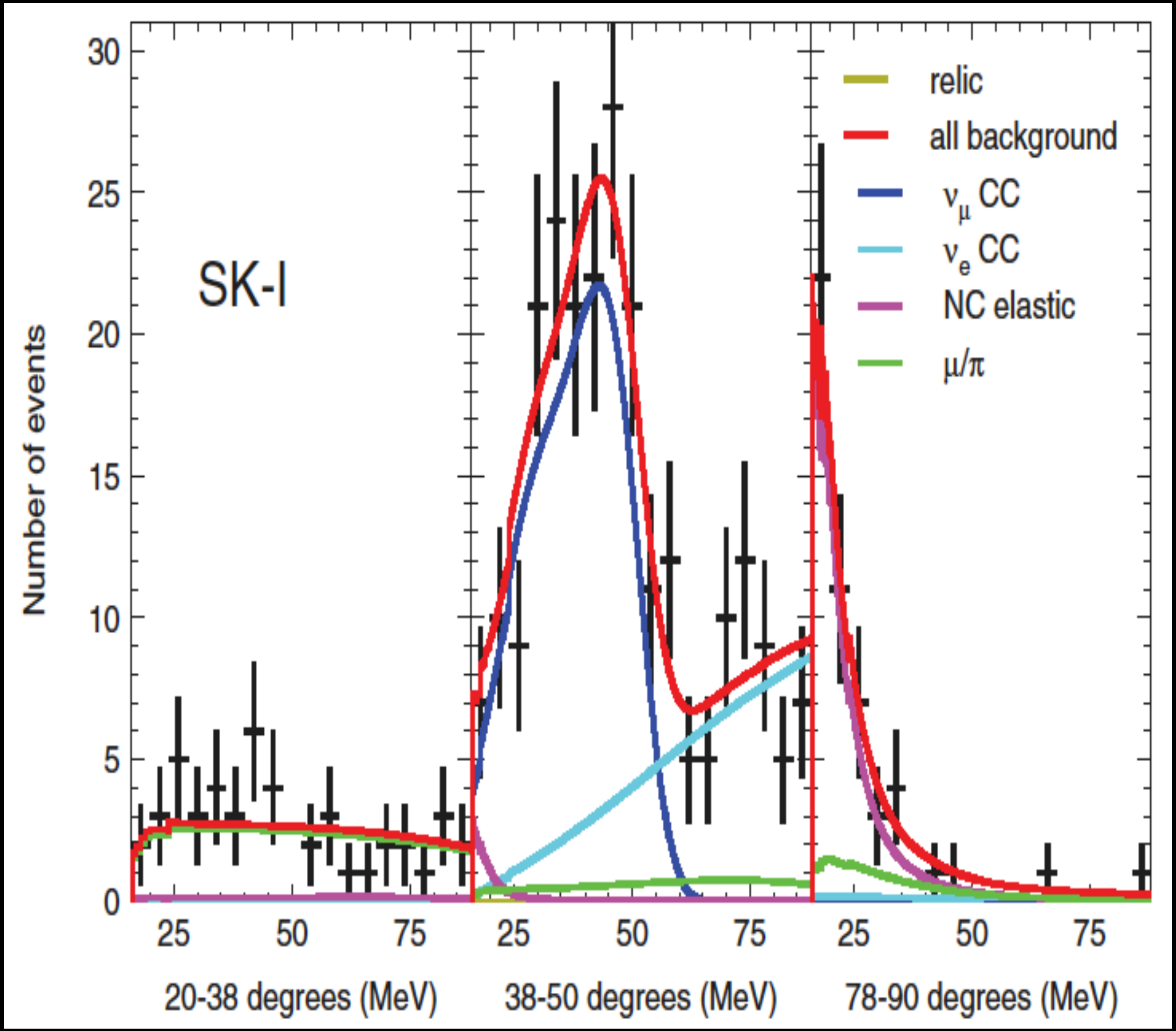
$$f_\nu(E) \propto E^\alpha e^{-(\alpha+1)E/E_{\mathrm{av}}}$$

➔ (E_{tot}, E_{ave}, α_{pinch})





Searches by Super-Kamiokande



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)

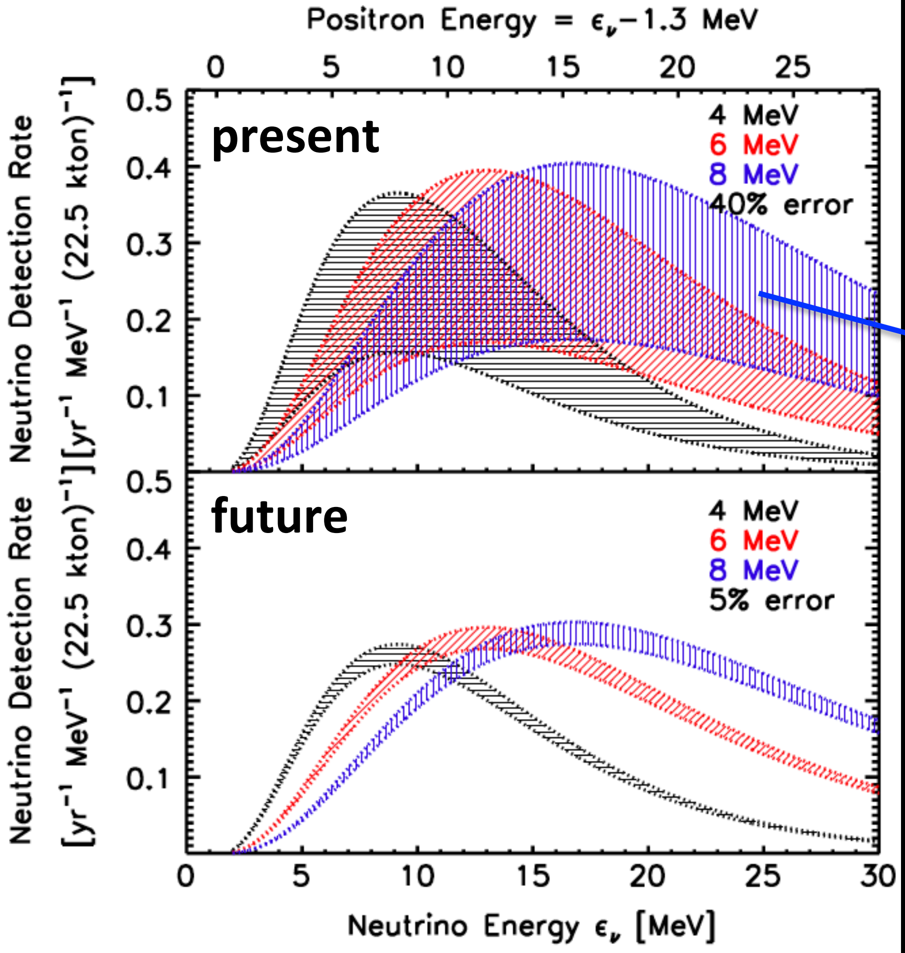
The future

Rate uncertainty

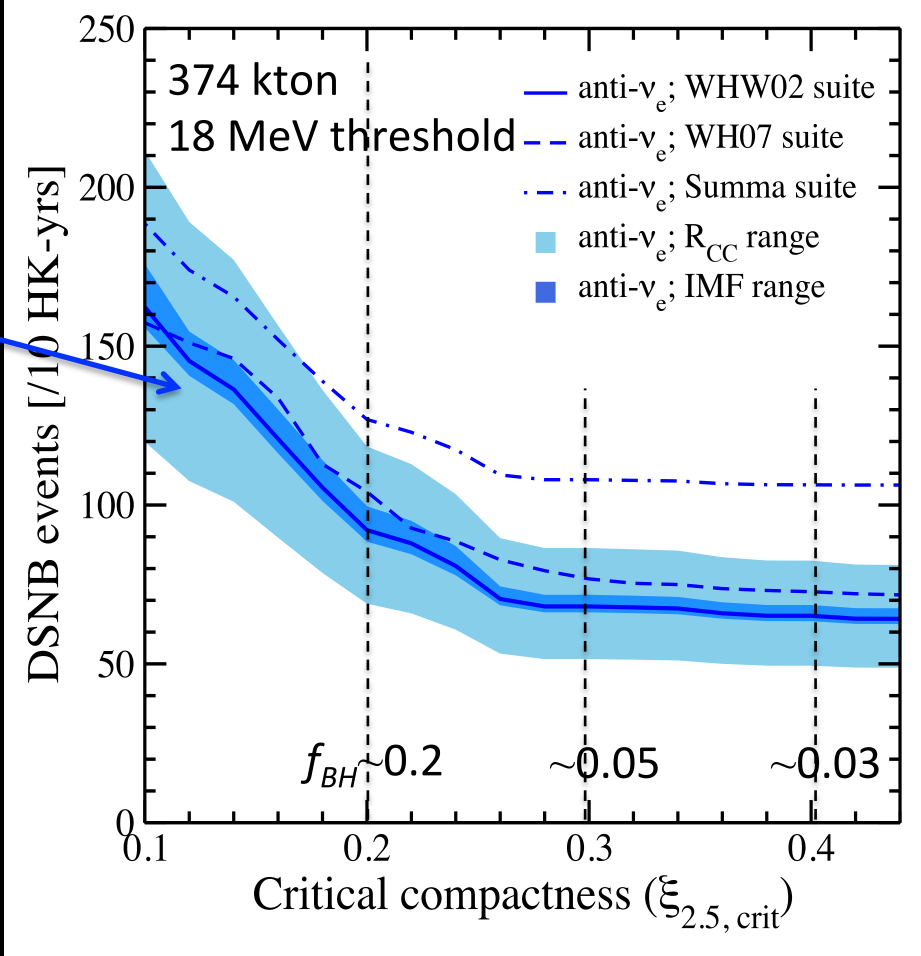
Will reduce with next-generation supernova surveys (e.g., LSST)

Hyper-Kamiokande

Sensitive to small values of critical compactness, $\xi_{2.5} < 0.2$



Lien et al (2010)



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