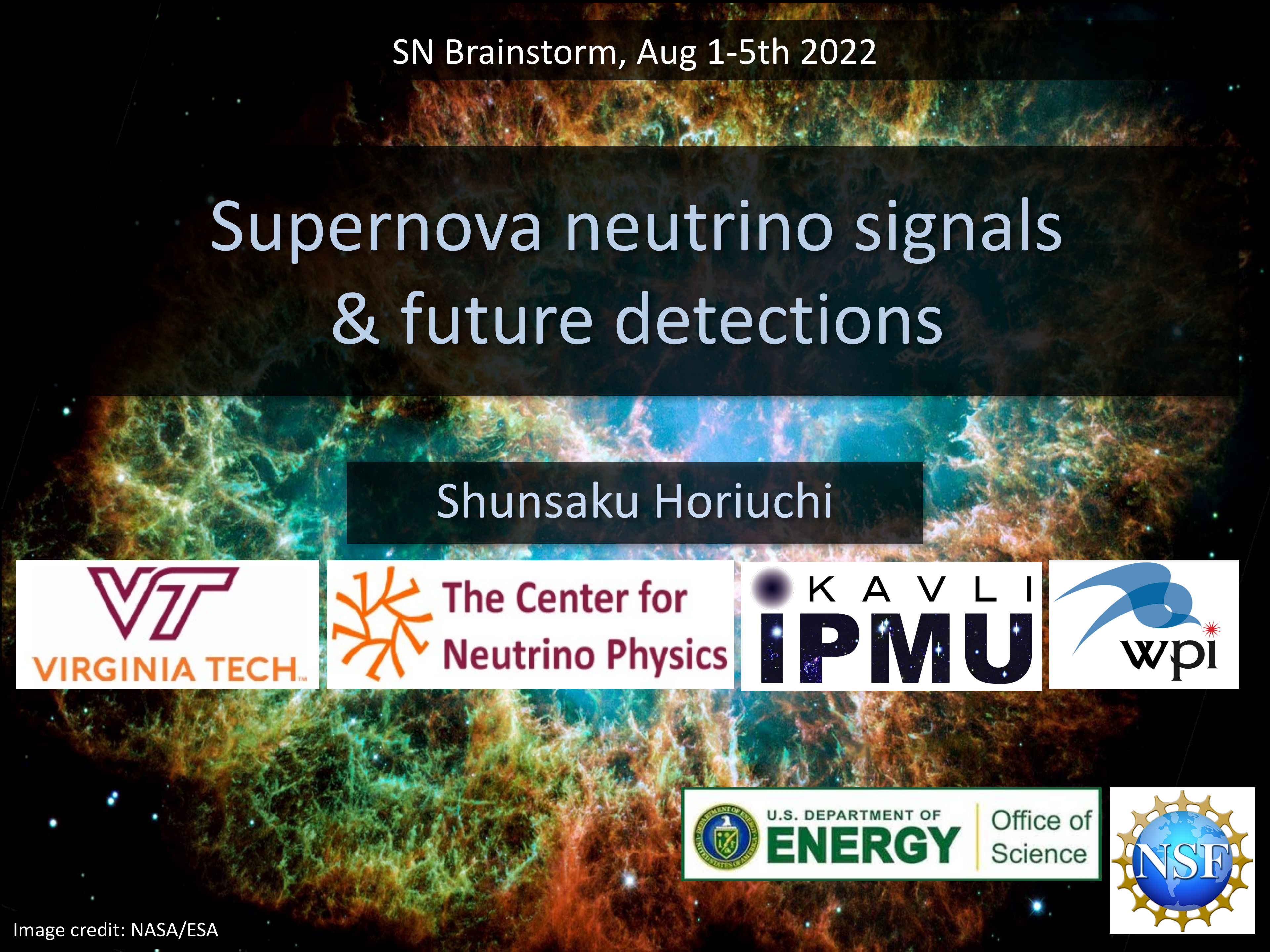


SN Brainstorm, Aug 1-5th 2022

Supernova neutrino signals & future detections

Shunsaku Horiuchi

VIRGINIA TECH

The Center for Neutrino Physics

KAVLI IPMU

wpi

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

Image credit: NASA/ESA

Contents

1. Supernova neutrinos at neutrino observatories

2. Diffuse supernova neutrinos: predicting
    - Rates
    - Neutrino emission

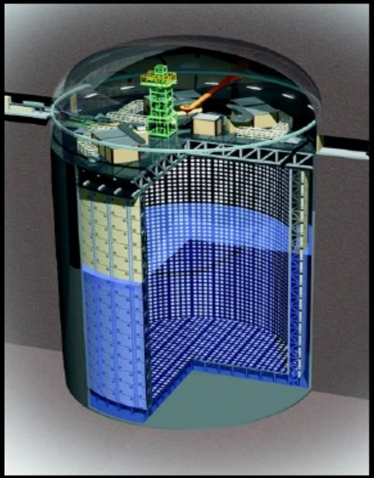
3. Diffuse supernova neutrinos: detecting
    - Present
    - Future

4. Wrap up

Neutrino detectors

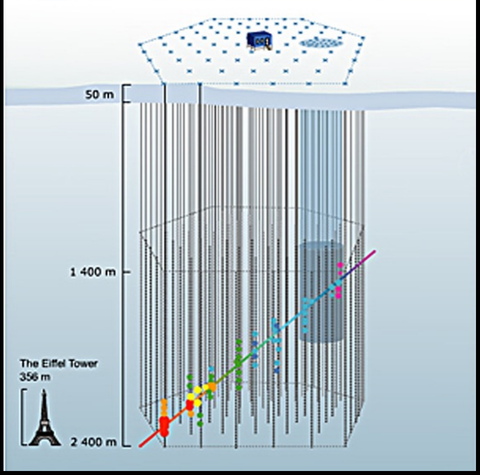
- **Detector must be massive**
  Detectors are optically thin -- need large volumes
- **Detector must be "quiet"**
  Built with low natural radioactivity and with plenty of shielding
- **Detector must have background rejection**
  Built with capabilities to distinguish between signal and background events

Super-Kamiokande



50 kton water + Gd
Running

IceCube

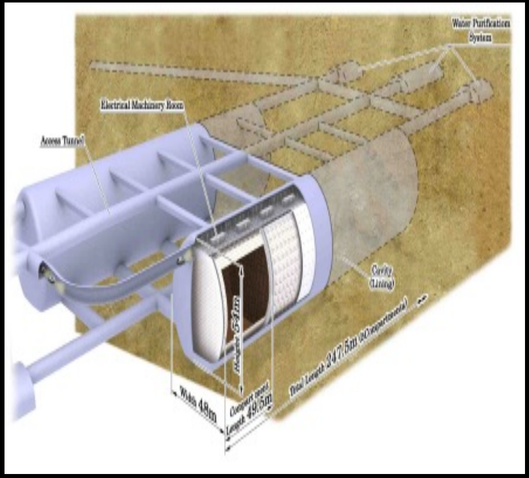


1 Gton ice
Running

DUNE

40 kton Lq Ar
Building

Hyper-Kamiokande



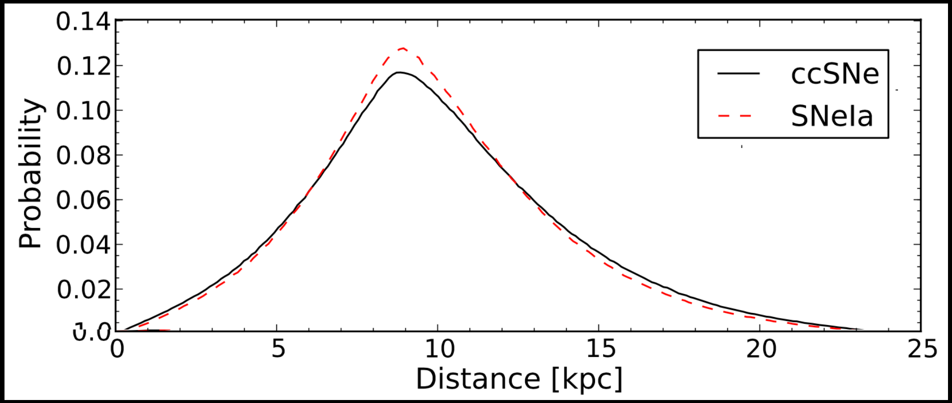
260 kton water
Building

Milky Way

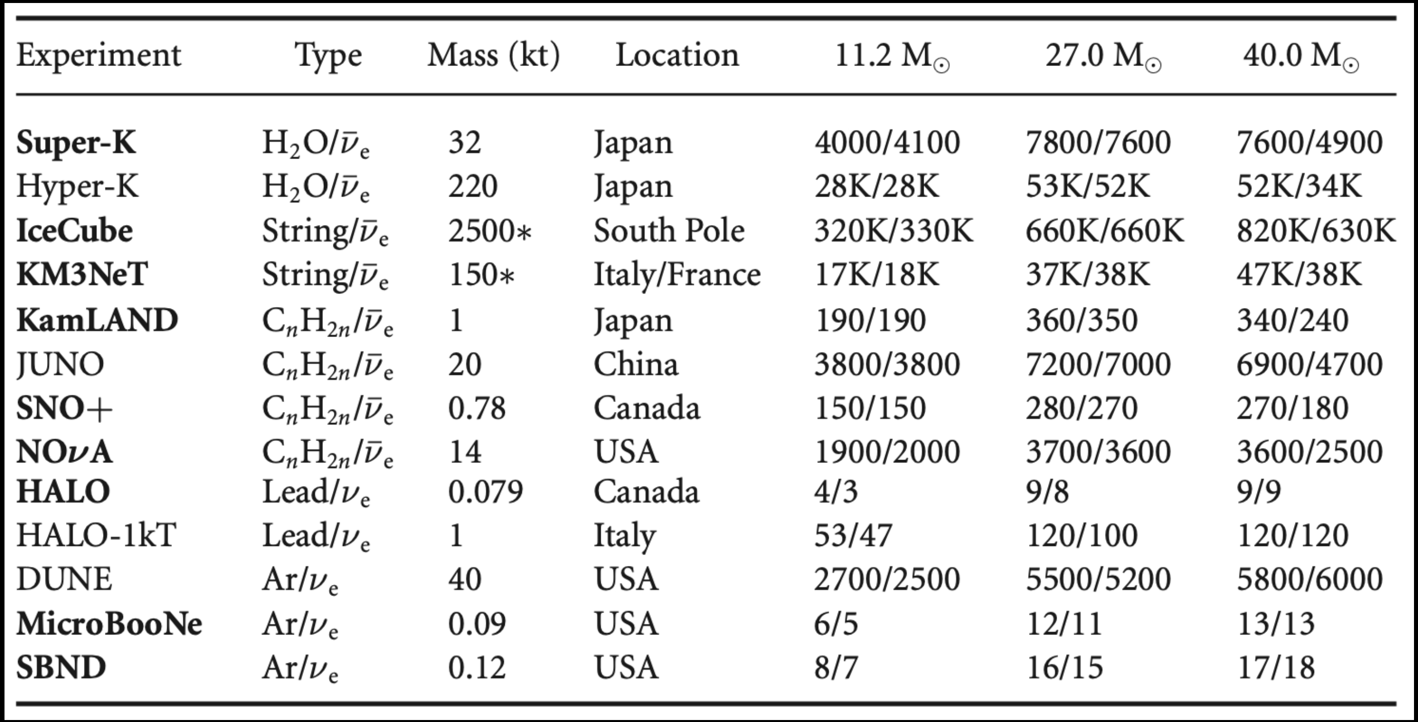
→ Typical distance is ~10 kpc

High number statistics expected from the next Galactic core collapse

We're ready!!



Adams et al (2013)



Experiment	Type	Mass (kt)	Location	$11.2\ M_\odot$	$27.0\ M_\odot$	$40.0\ M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	150*	Italy/France	17K/18K	37K/38K	47K/38K
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.78	Canada	150/150	280/270	270/180
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
HALO	Lead/ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ν_e	0.12	USA	8/7	16/15	17/18

SNEWS 2021, see also Scholberg (2012), Mirizzi et al (2015)

Flavor information?

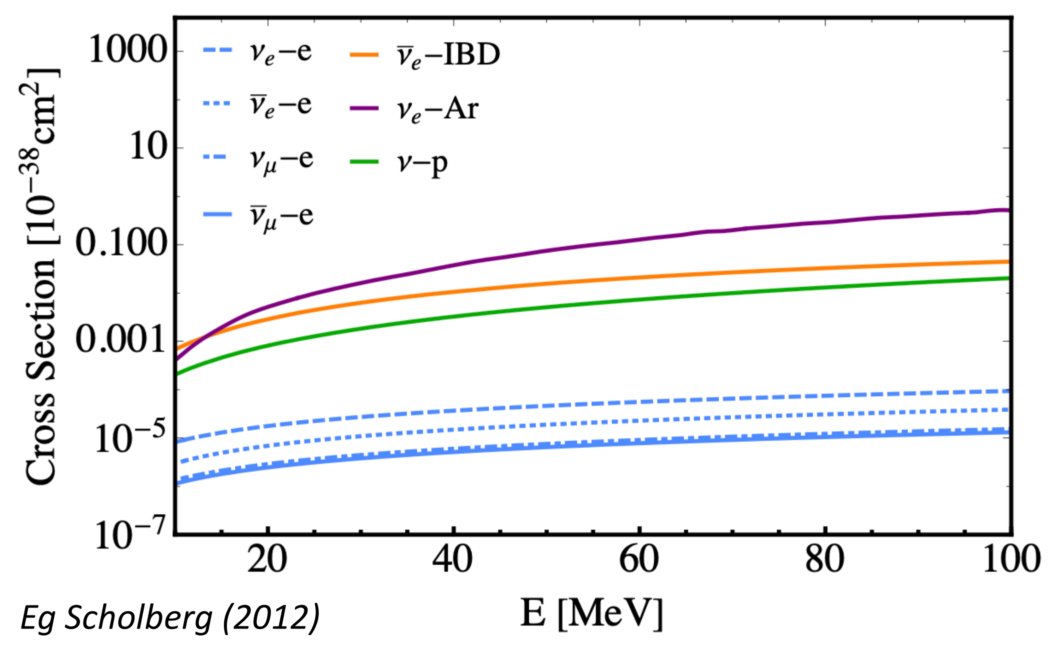
In principle, use multiple channels

In practice, issues with distinguishing eg

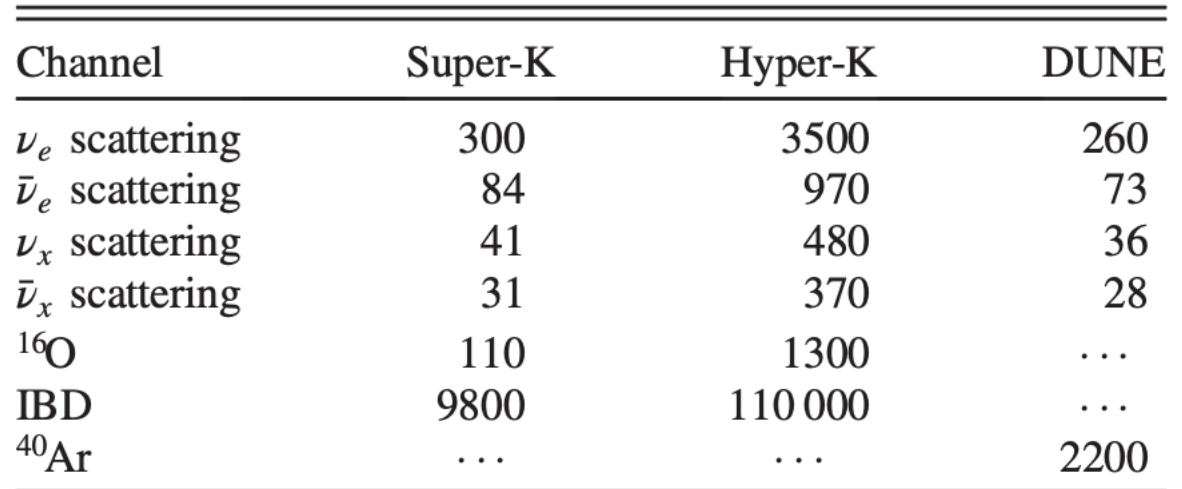
$$\bar{\nu}_e + p \rightarrow \boxed{e^+} + n$$

$$\nu + e^- \rightarrow \nu + \boxed{e^-}$$

seeing only final lepton can't distinguish them…



Eg Scholberg (2012)



Channel	Super-K	Hyper-K	DUNE
ν_e scattering	300	3500	260
$\bar{\nu}_e$ scattering	84	970	73
ν_x scattering	41	480	36
$\bar{\nu}_x$ scattering	31	370	28
^{16}O	110	1300	⋯
IBD	9800	110 000	⋯
^{40}Ar	⋯	⋯	2200

Nikrant et al (2018)

Upgrade with Gadolinium

Background rejection:
IBD produces a neutron, which could be tagged

Beacom & Vagins (2004)

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

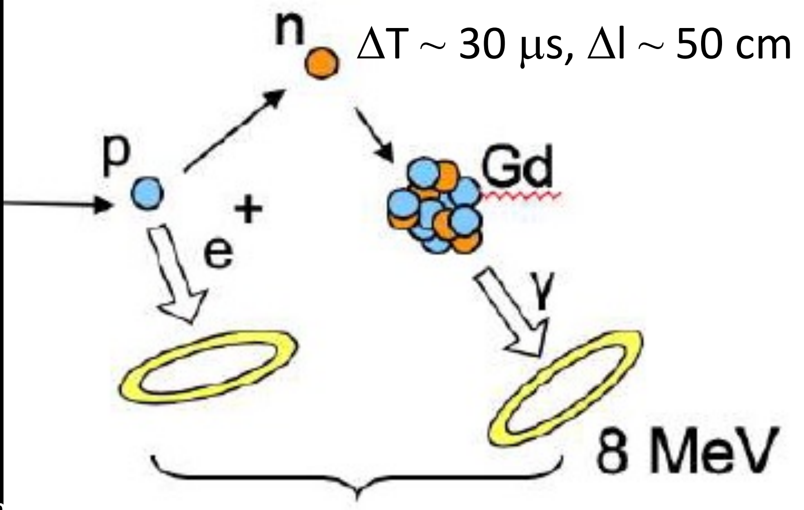
w/out Gd

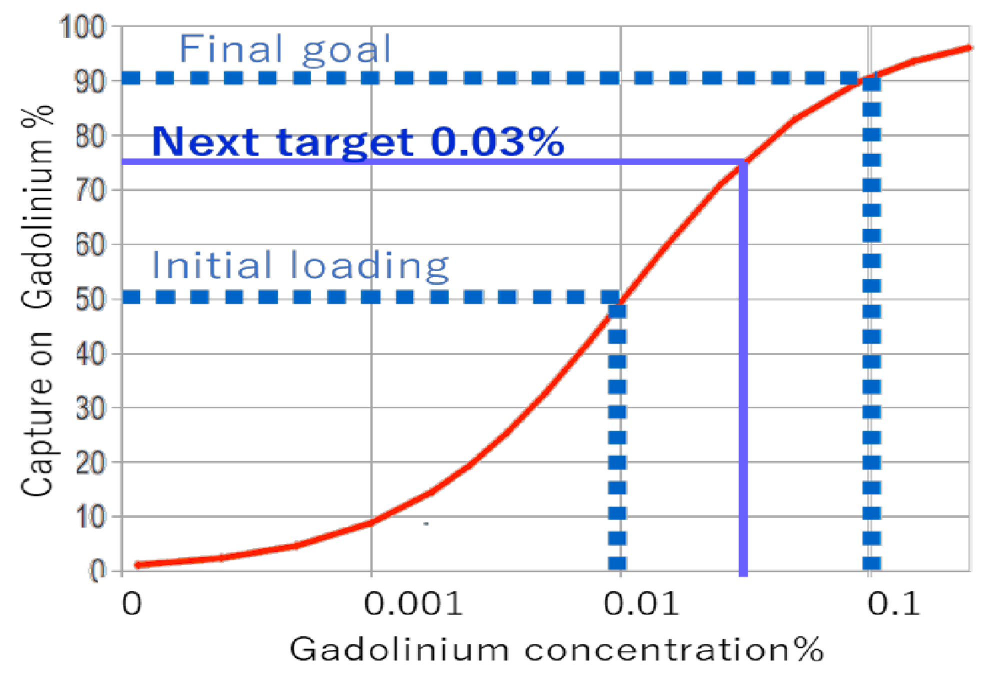
with Gd

Capture on protons, most lost (~82%)

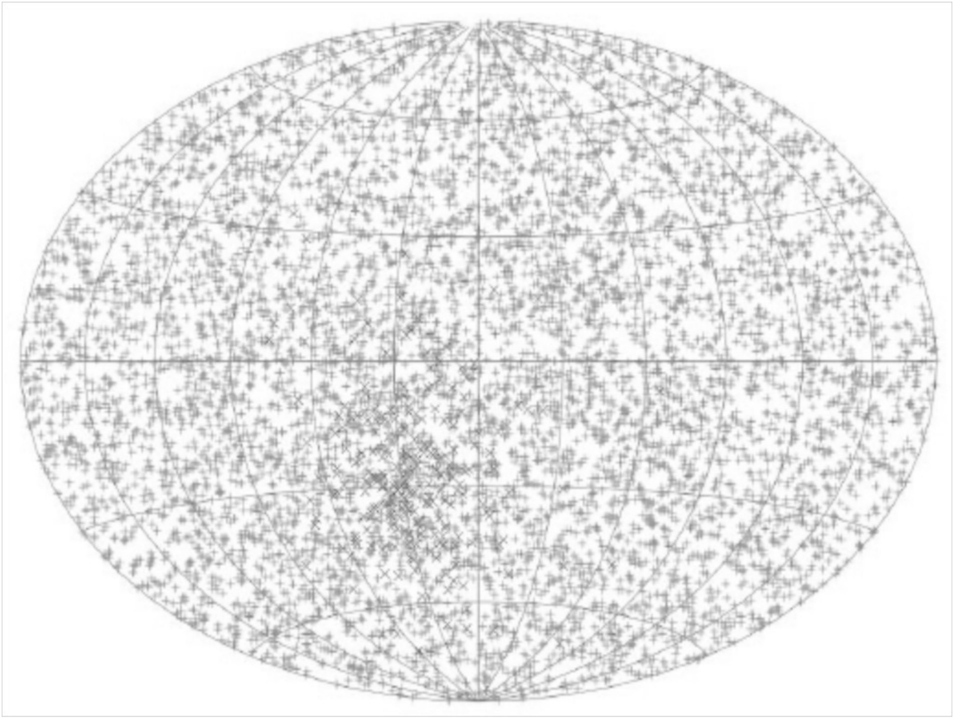
Capture on Gd, visible (~90%)

Evaluating Gadolinium's Action on Detector Systems

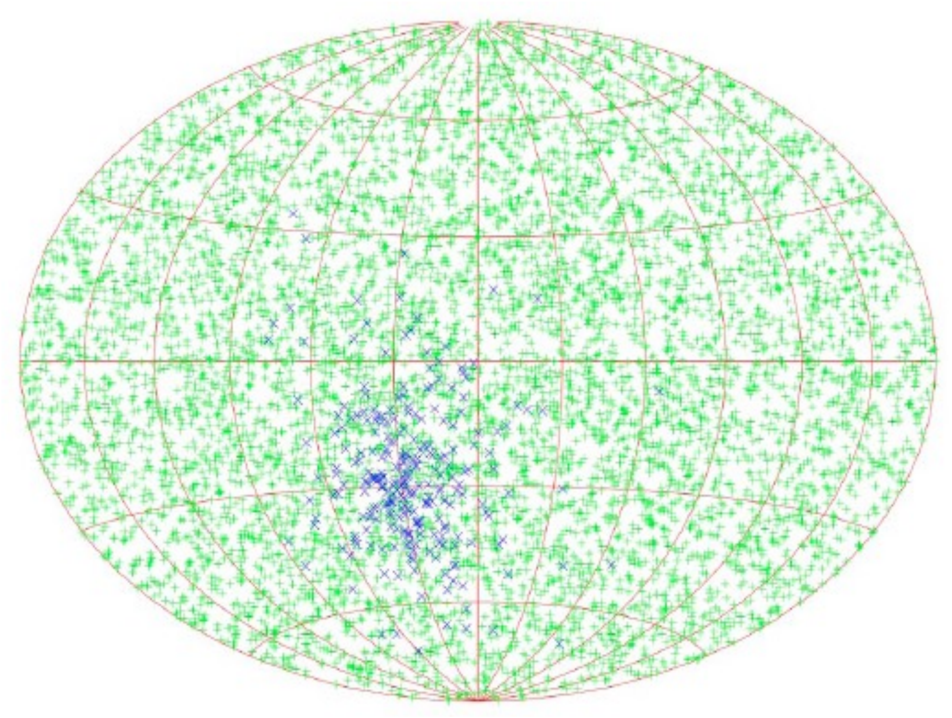

$\Delta T \sim 30\ \mu s$, $\Delta l \sim 50$ cm



Pointing



Before



With gadolinium

IBD tagged at high efficiency

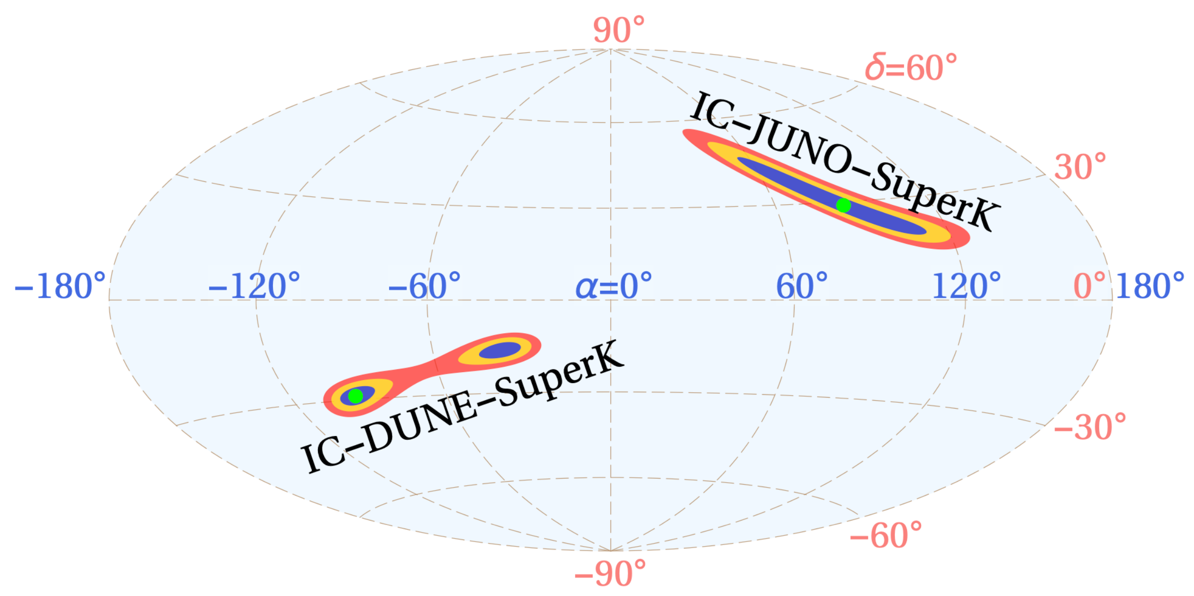
	Super-K	Hyper-K
Water only	~6 deg	~1.4 deg
Water + Gd (90% tag)	~3 deg	~0.6 deg

Beacom & Vogel (1999), Tomas et al (2003)

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

$$\nu + e^- \to \nu + \boxed{e^-}$$

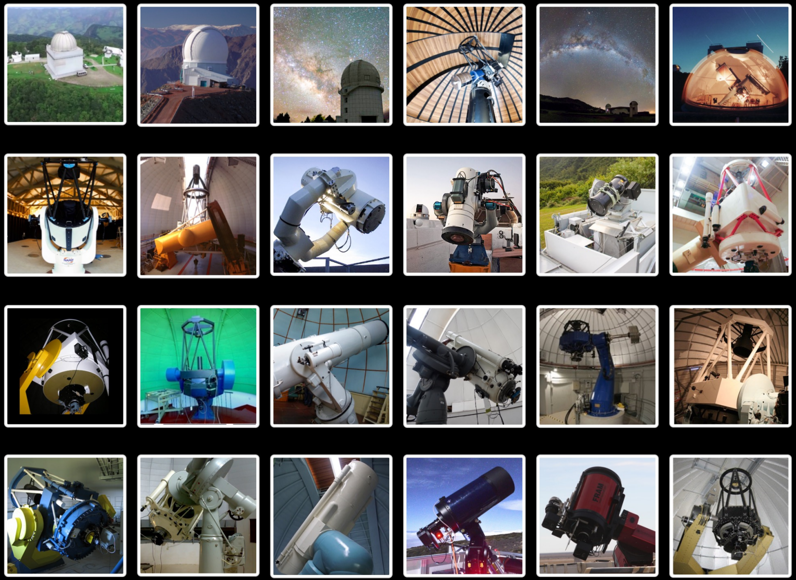
Another pointing



Coordinated pointing using triangulation

Brdar et al (2018),
See also Beacom & Vogel (1999),
Mhlbeier et al (2013),
Linzer & Scholberg (2019),

Automated follow-up



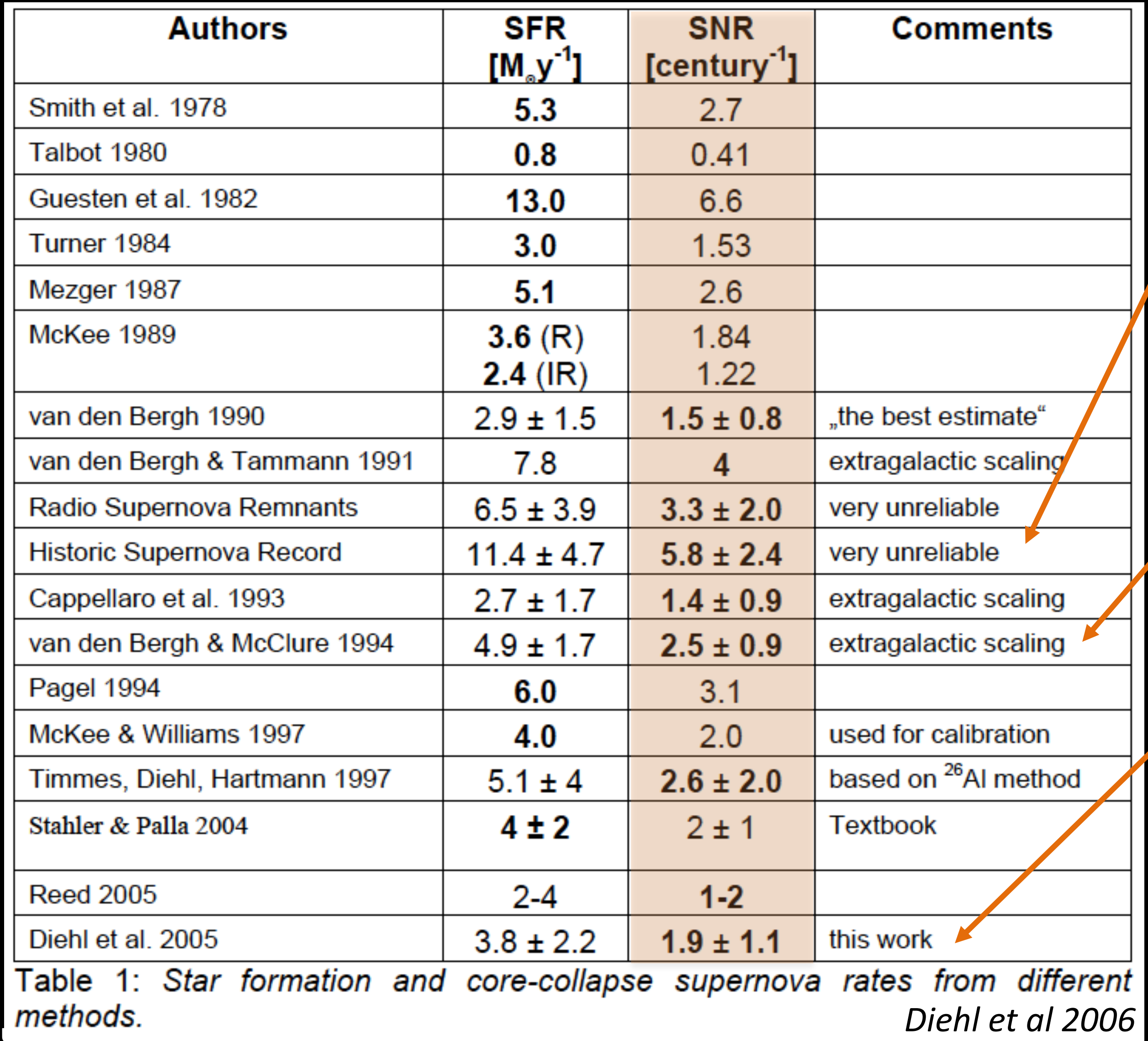
Borexino
DayaBay
HALO
IceCube
KamLAND
LVD
Super-K

Coincidence server

Shunsaku Horiuchi

Galactic supernova rate

Many methods: most probe the mean rate over Myrs, so we may be luck or unlucky



Authors	SFR $[M_{\odot} y^{-1}]$	SNR $[\mathrm{century}^{-1}]$	Comments
Smith et al. 1978	**5.3**	2.7	
Talbot 1980	**0.8**	0.41	
Guesten et al. 1982	**13.0**	6.6	
Turner 1984	**3.0**	1.53	
Mezger 1987	**5.1**	2.6	
McKee 1989	**3.6** (R) **2.4** (IR)	1.84 1.22	
van den Bergh 1990	2.9 ± 1.5	**1.5 ± 0.8**	„the best estimate“
van den Bergh & Tammann 1991	7.8	**4**	extragalactic scaling
Radio Supernova Remnants	6.5 ± 3.9	**3.3 ± 2.0**	very unreliable
Historic Supernova Record	11.4 ± 4.7	**5.8 ± 2.4**	very unreliable
Cappellaro et al. 1993	2.7 ± 1.7	**1.4 ± 0.9**	extragalactic scaling
van den Bergh & McClure 1994	4.9 ± 1.7	**2.5 ± 0.9**	extragalactic scaling
Pagel 1994	**6.0**	3.1	
McKee & Williams 1997	**4.0**	2.0	used for calibration
Timmes, Diehl, Hartmann 1997	5.1 ± 4	**2.6 ± 2.0**	based on ^{26}Al method
Stahler & Palla 2004	**4 ± 2**	2 ± 1	Textbook
Reed 2005	2-4	**1-2**	
Diehl et al. 2005	3.8 ± 2.2	**1.9 ± 1.1**	this work

Table 1: *Star formation and core-collapse supernova rates from different methods.*

Diehl et al 2006

Historical SNe: ~5.8±2.4 per century
Update with model for dust : ~3.2+7.3-2.6 per century

Adams et al (2013)

External galaxies: 2.5±0.9 per century

^{26}Al decay lines: 1.9±1.1 per century

NB: null observation of neutrino bursts: < 8 SN per century (90% CL)

Single vs diffuse

$N_\nu >> 1$: BURST

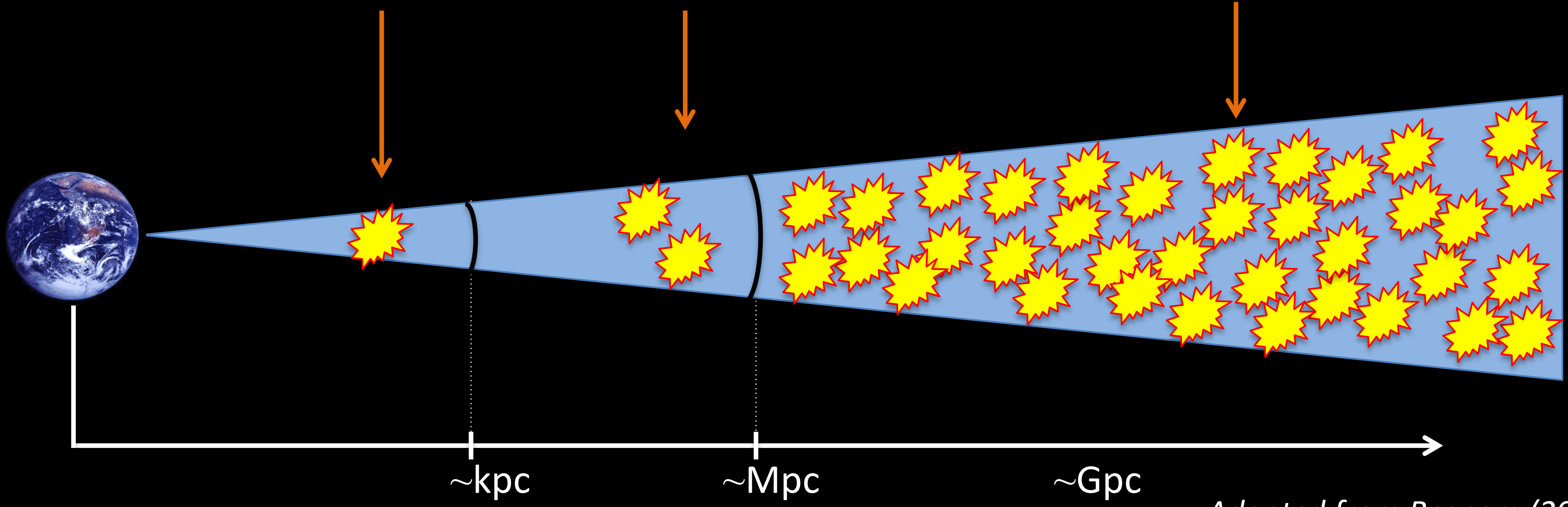
SN rate ~ 0.01 /yr

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

SN rate ~ 1 /yr

$N_\nu << 1$: DIFFUSE

SN rate ~ 10^8 /yr



Adapted from Beacom (2012)

- Rich data, multi-messenger
- Precision on 1 progenitor
- Surprises?

- No waiting
- Many progenitors, population studies
- Surprises?

Diffuse signal: ingredients

Occurrence rate of massive star core collapse

$$\frac{d\phi}{dE_\nu}(E_\nu) = \int_0^\infty [(1+z)\varphi[E_\nu(1+z)]]\,[R_{SN}(z)]\left[\left|\frac{c\,dt}{dz}\right| dz\right]$$

Averaged neutrino emission from many core collapse

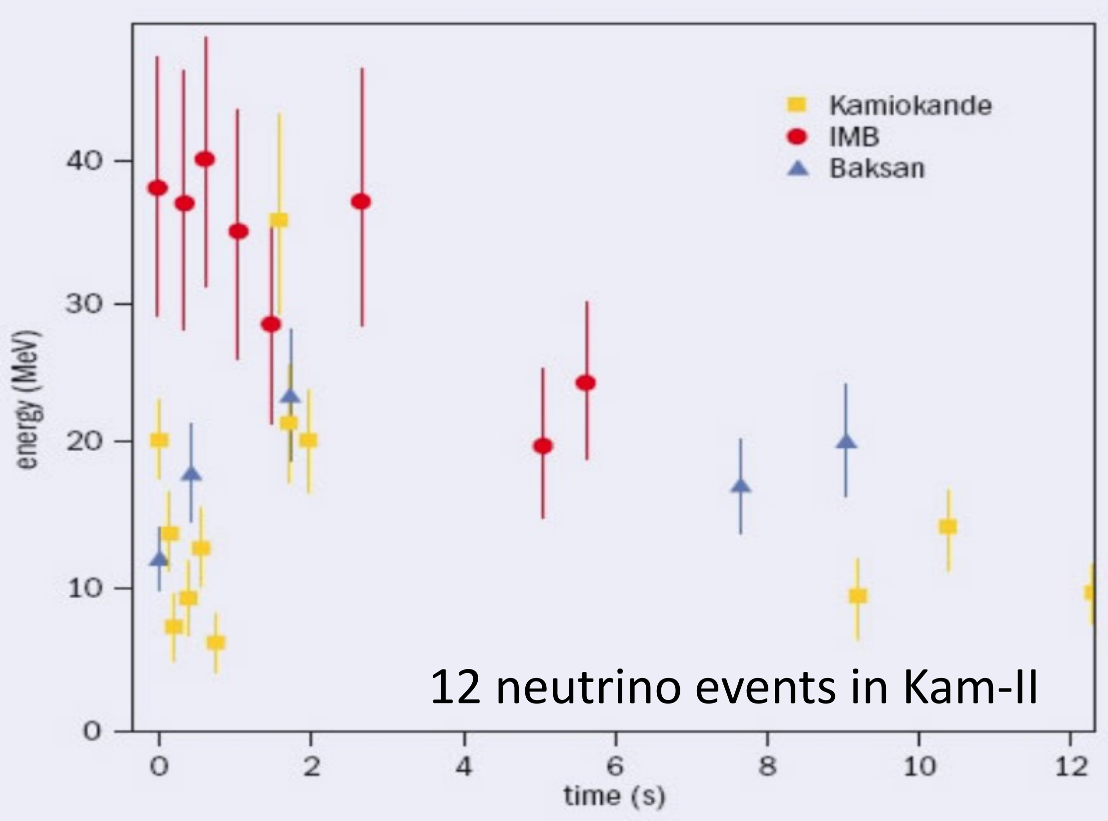
We know supernovae are occurring, and we know SN1987A emitted neutrinos

➔ Diffuse is a guaranteed signal

Order of magnitude estimate

Consider SN1987A

1 supernova @LMC 50 kpc away
~1 neutrino event per second @Kam-II



12 neutrino events in Kam-II

Hirata et al (1987)

DSNB

$$\left[\frac{N_{SN}\,M_{\rm det}}{4\pi D^2}\right]_{DSNB}$$

DSNB

100 per 10sec interval
22.5 kton
4000 Mpc (z~1)

$$\sim 10^{-7}\,\mathrm{s}^{-1} \sim 3\,\mathrm{year}^{-1},$$

Beacom 2010

Necessary ingredients

1. Occurrence rate of massive star core collapse

$$\frac{d\phi}{dE_\nu}(E_\nu) = \int_0^\infty [(1+z)\varphi[E_\nu(1+z)]]\,[R_{SN}(z)]\left[\left|\frac{c\,dt}{dz}\right| dz\right]$$

2. Averaged neutrino emission from many core collapse

Some of the challenges

1. **What is the true core-collapse rate?**
2. **What is the long-term time-integrated neutrino emission?**
3. **What is the diversity in neutrino emissions?**
4. **What is the neutrino emission from collapse to black holes? And what is its rate?**
5. **How to detect a diffuse neutrino glow?**

Cosmic core-collapse rate

Direct measurements

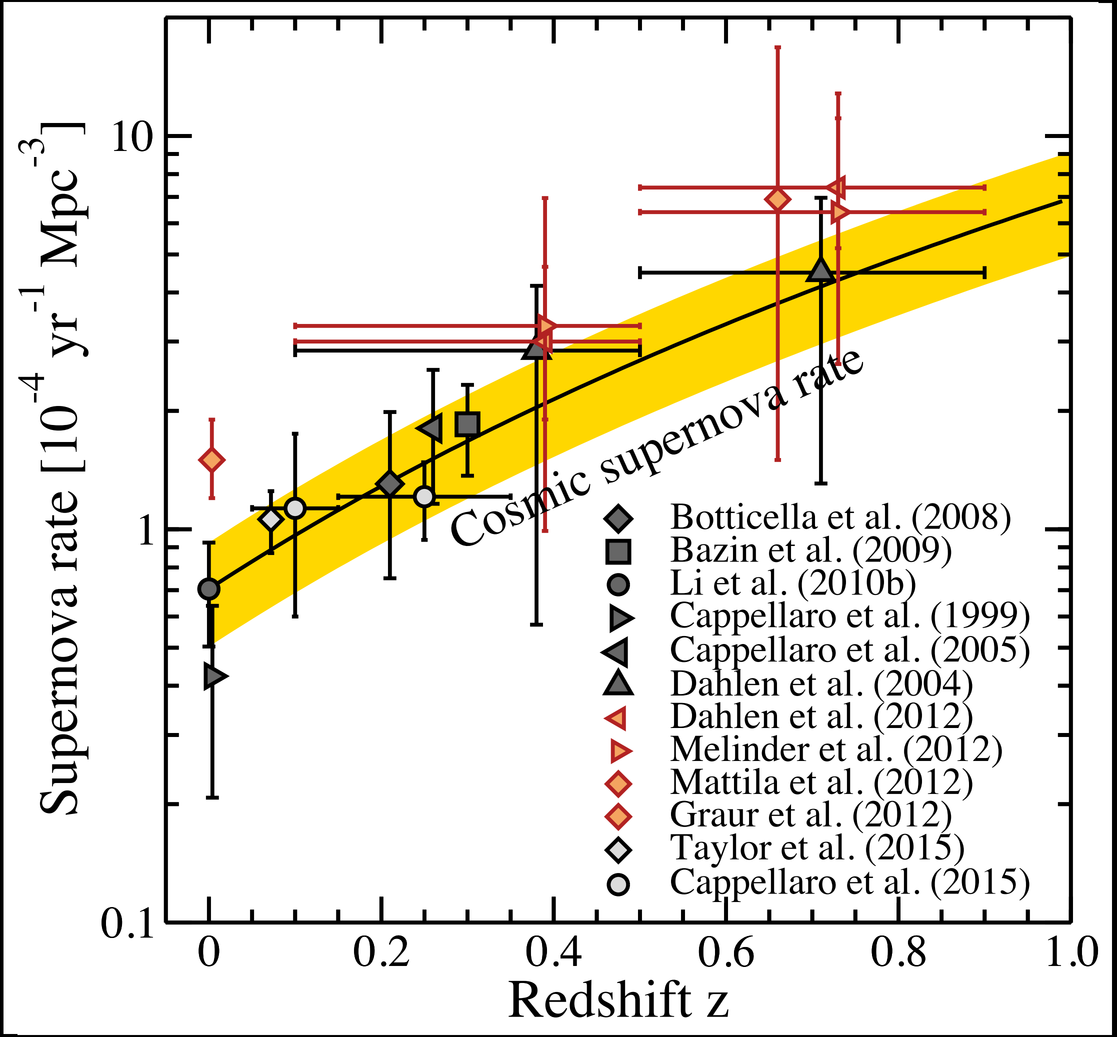
Improving quickly!

Note, two 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, DES, …

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

e.g., Lien & Fields (2009)



Updated from Horiuchi et al (2011)

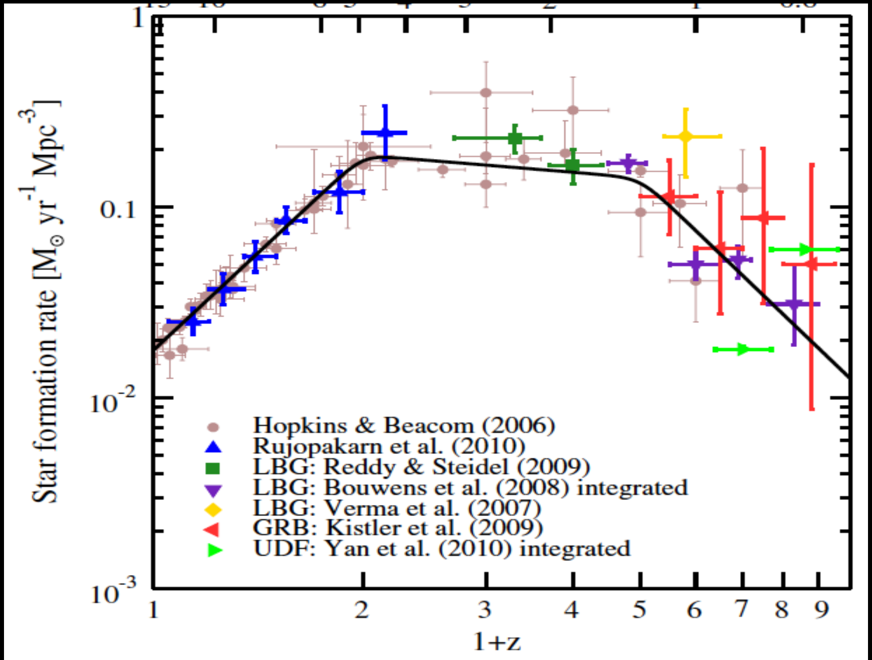
Cosmic birth rate of stars

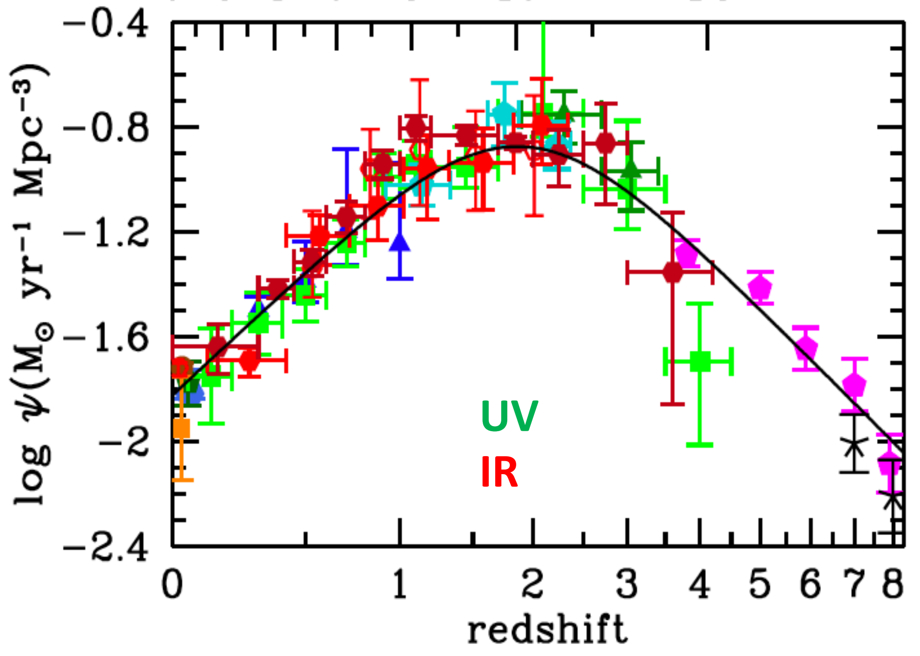
Core collapse rate = Birth rate of massive stars

*because lifetime of massive stars are cosmologically short

Star formation rate measurements

- Many groups, many wavebands, many data sets.
- Uncertainty: sample, calibration & dust





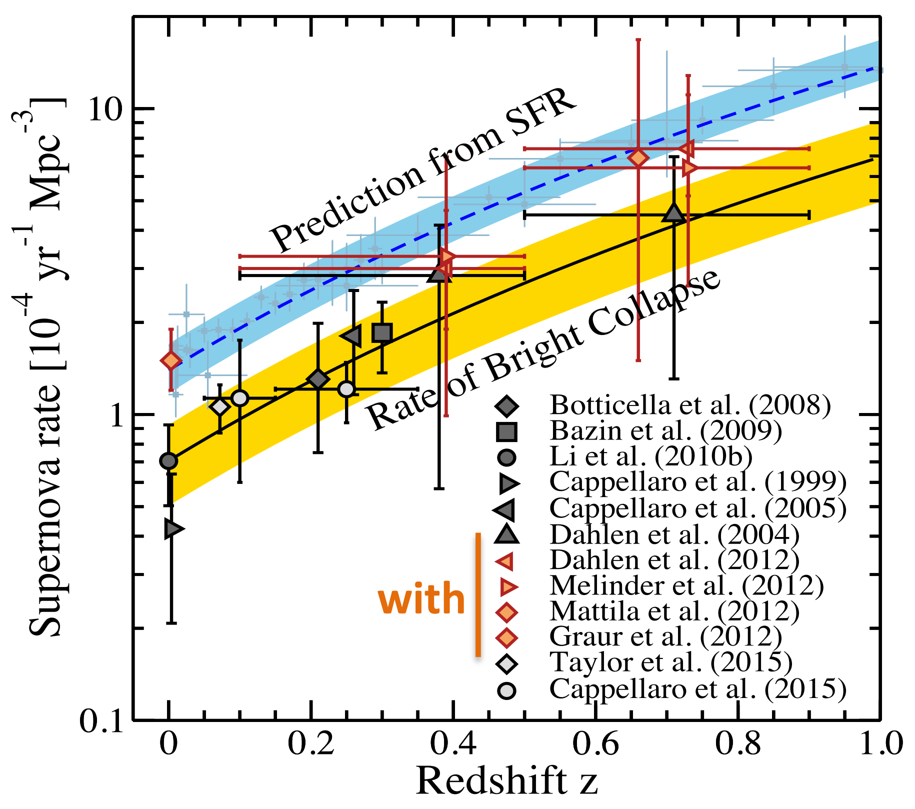
Horiuchi & Beacom (2010) *Madau & Dickinson (2014)*

Cosmic comparison

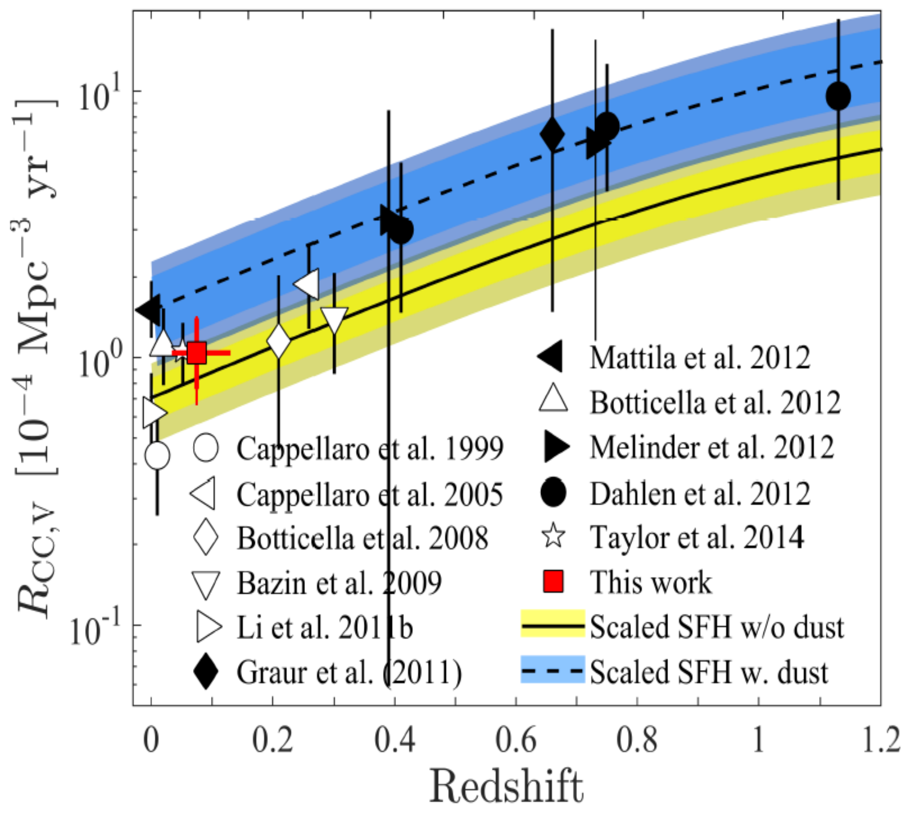
Core collapse rate = Birth rate of massive stars

*because lifetime of massive stars are cosmologically short

Importance of heavily dust-attenuated supernovae (filled symbols)

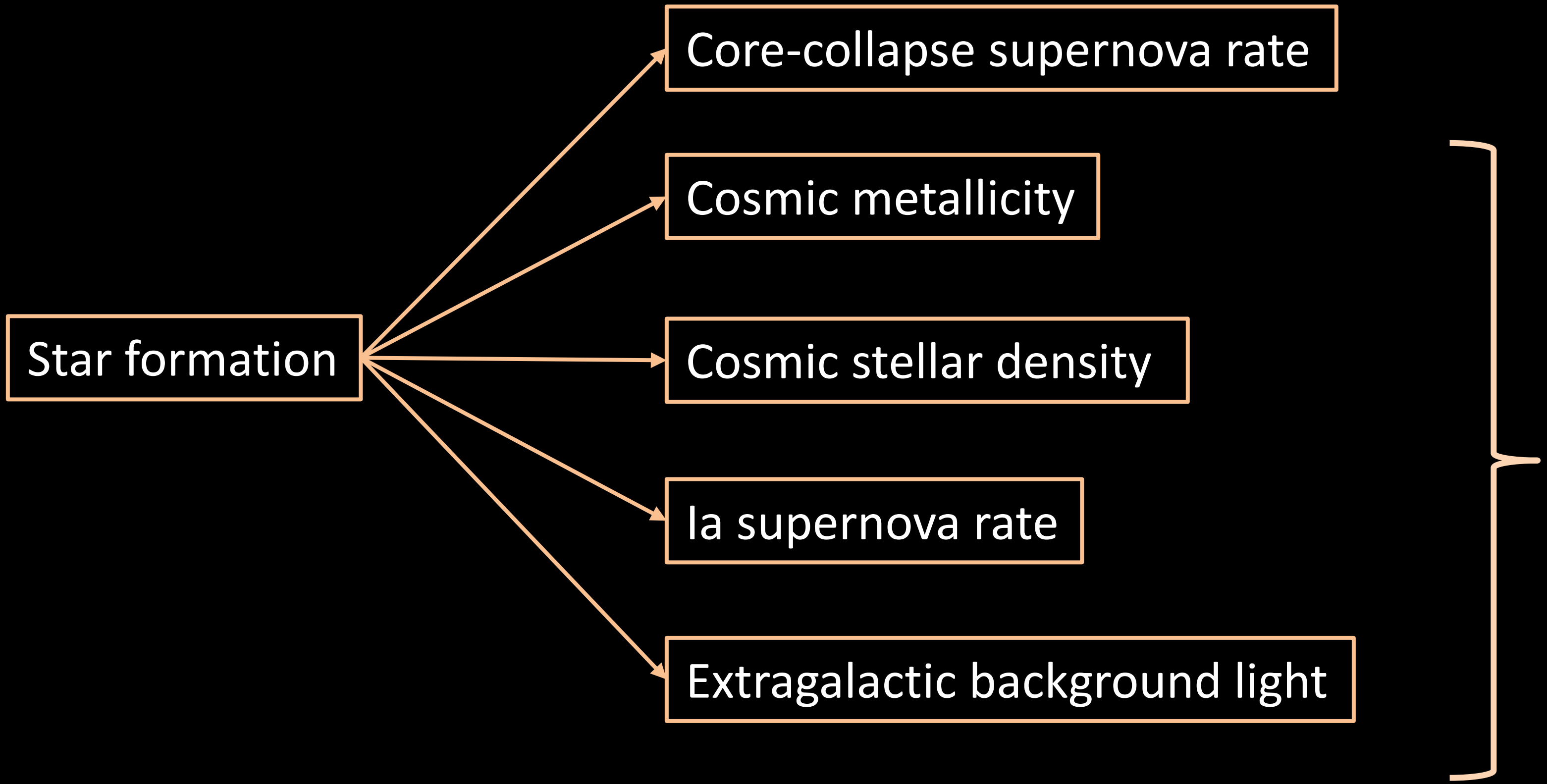


Updated from Horiuchi et al (2011)



Graur et al (2015)

Cosmic cross checks



Star formation

Core-collapse supernova rate

Cosmic metallicity

Cosmic stellar density

Ia supernova rate

Extragalactic background light

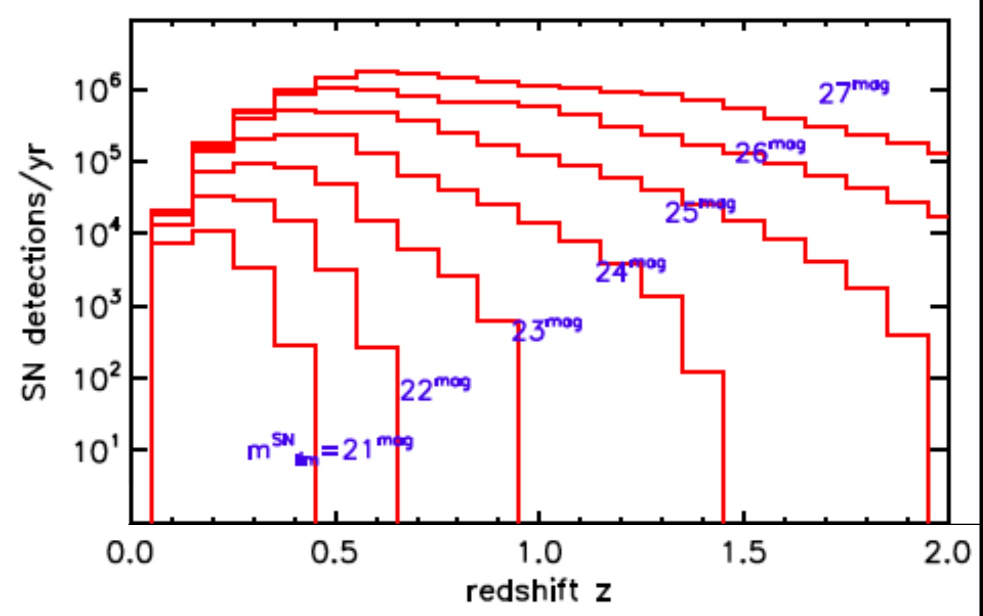
Time integrated checks

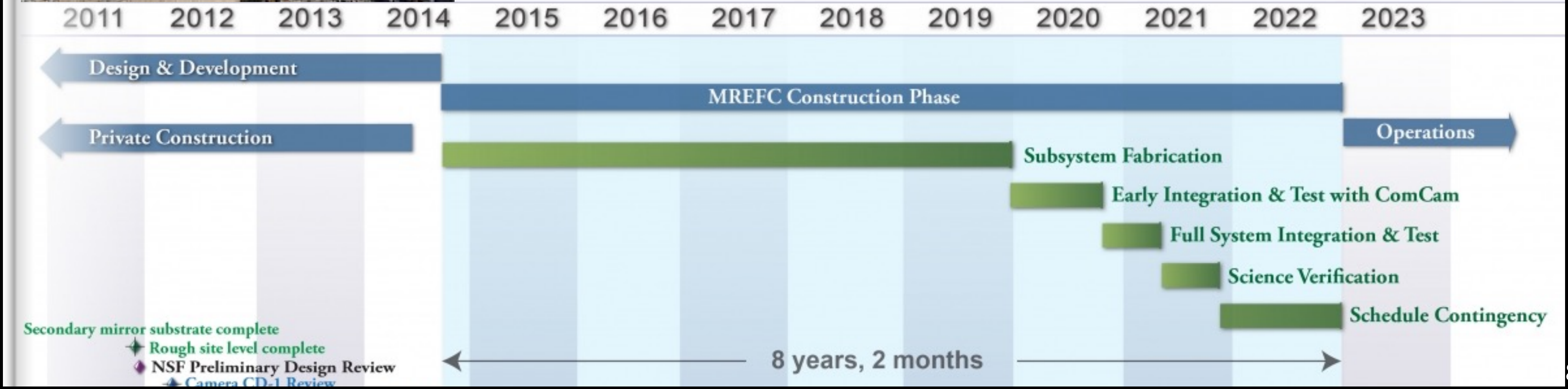
In the future

Dramatic increases in supernova discoveries

Eg, LSST: around 10^4 core-collapse supernovae at low redshifts ($z<0.1$)

Lien & Fields (2009)





First take away

Are we certain core-collapse supernovae are going off?

Yes

Are we certain about the number?

Yes, to better than factor < 2

Will we know better in the future?

Yes, improvement in discovery

Necessary ingredients

1. Occurrence rate of massive star core collapse

$$\frac{d\phi}{dE_\nu}(E_\nu) = \int_0^\infty [(1+z)\varphi[E_\nu(1+z)]]\,[R_{SN}(z)]\left[\left|\frac{c\,dt}{dz}\right|dz\right]$$

2. Averaged neutrino emission from many core collapse

Some of the challenges

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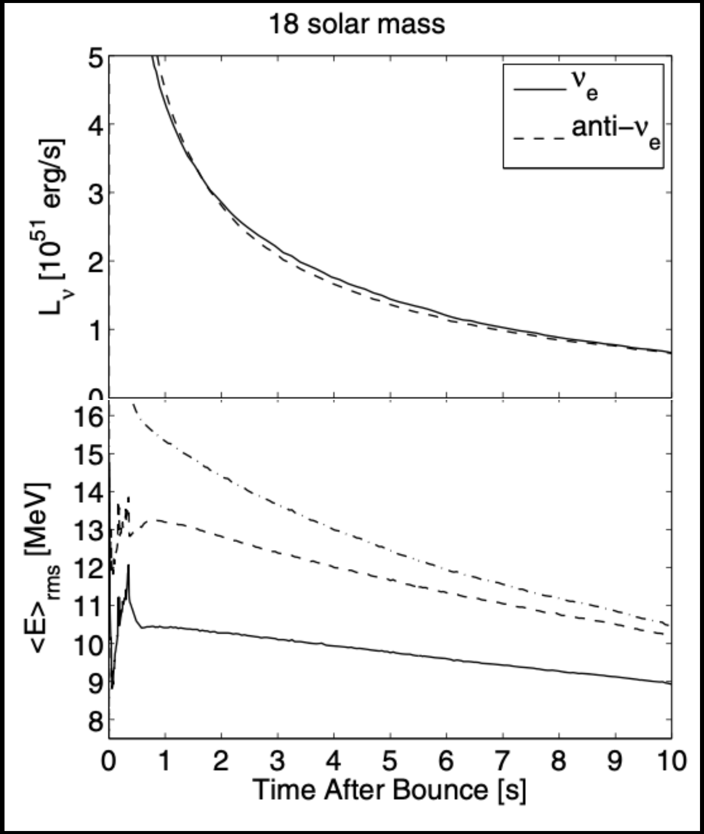
4. **What is the neutrino emission from collapse to black holes? And what is its rate?**
5. **How to detect a diffuse neutrino glow?**

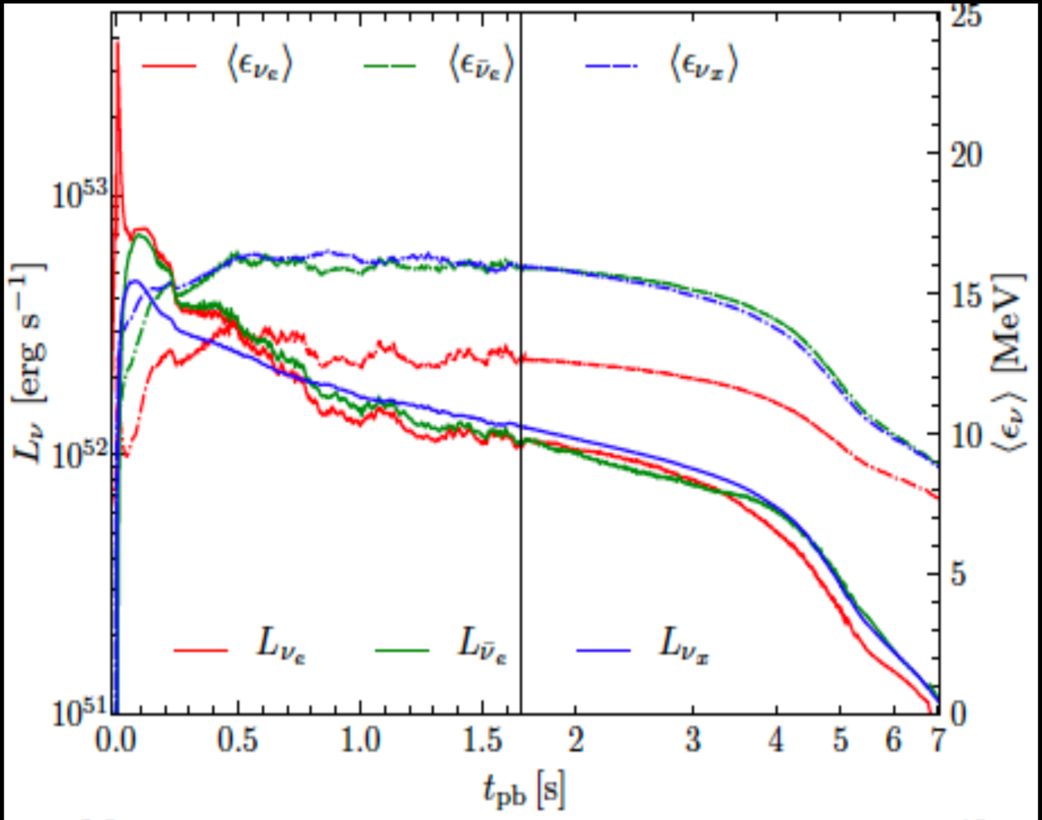
long-term simulations

Growing but need more

- Long-term (~10 sec) simulations are computationally challenging
- Becoming more available eg switching from hydro to cooling



Fischer et al (2010)

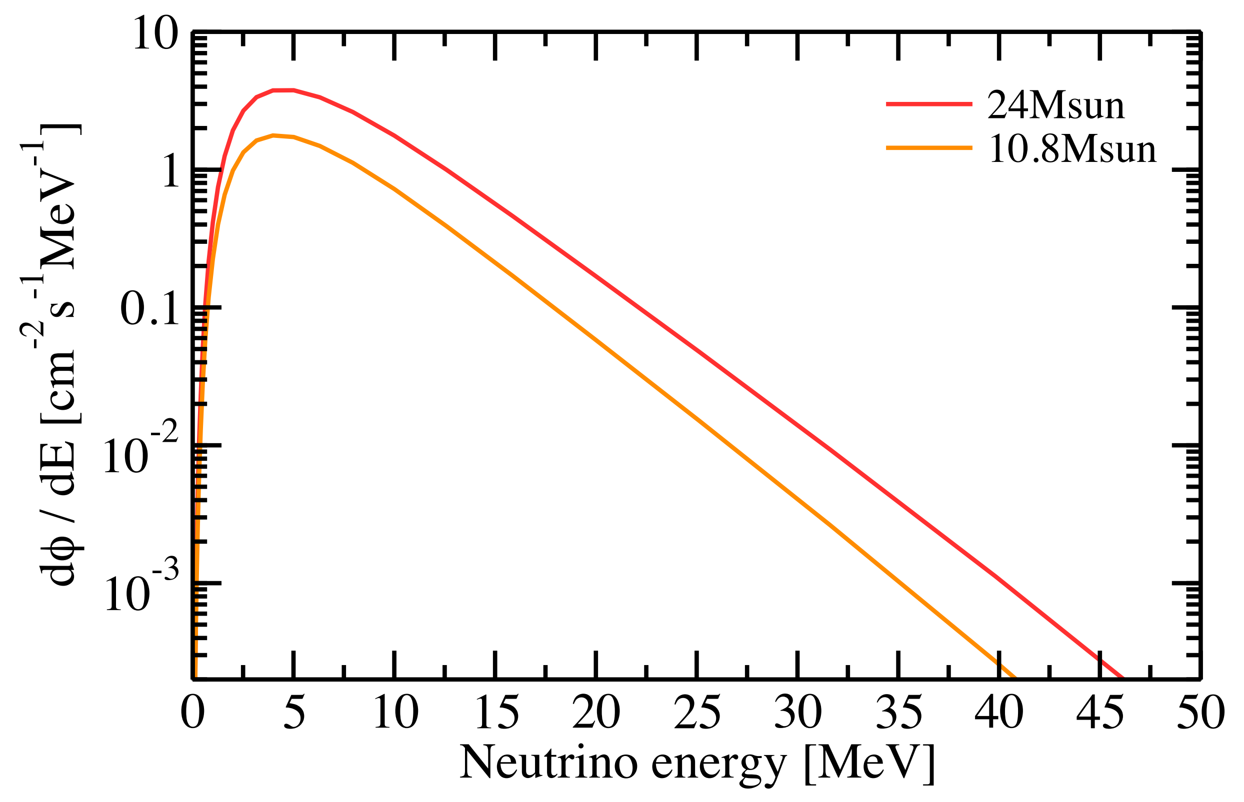


Bollig et al (2021)

Other long-term simulations, e.g.: Hudepohl et al (2010), Nakamura et al (2016), Suwa et al (2019), Sumiyoshi et al (2019), Li et al (2020), Nagakura et al (2021), Nakazato et al (2021)

Predicting the DSNB

The predicted DSNB flux spectrum, for a single neutrino emission model

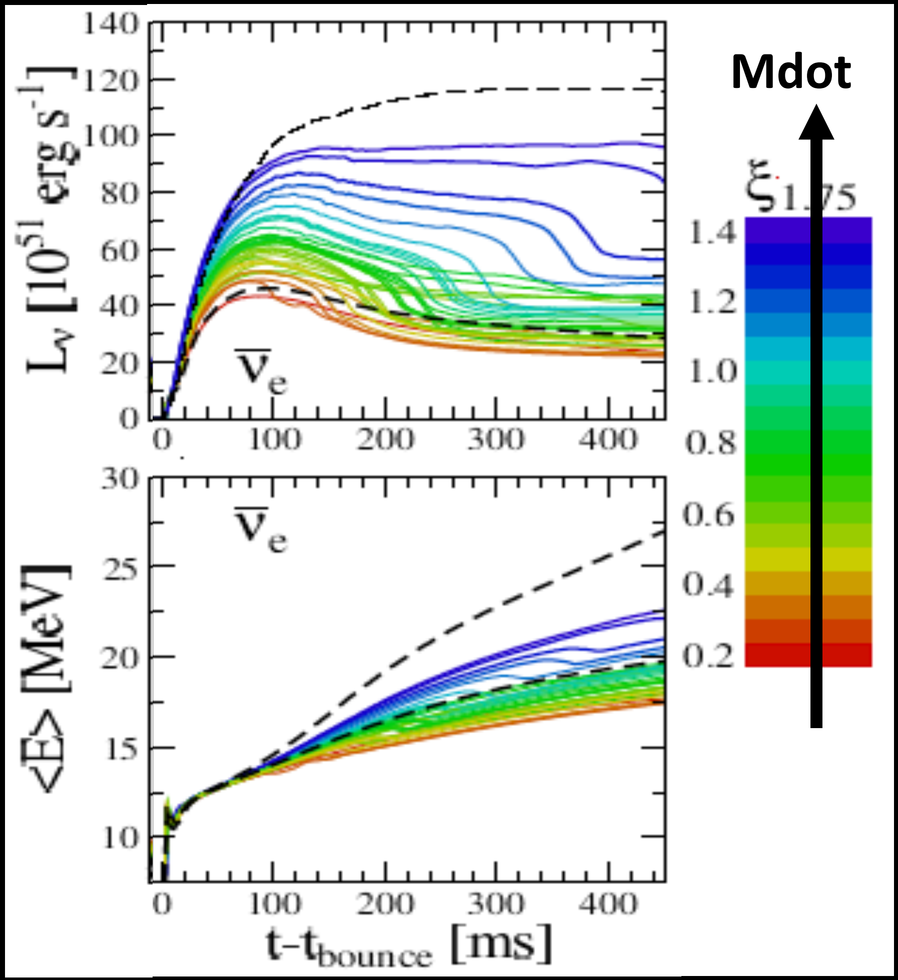


Many predictions, eg: Bisonatyi-Kogan & Seidov (1984), Krauss et al (1984), Totani et al (1996), Hartmann (1997), Kaplinghat et al (2000), Fukugita & Kawasaki (2003), Ando & Sato (2004), Strigari et al (2005), Lunardini (2006), Yuksel & Beacom (2007), Ckahraborty et al (2008), Horiuchi et al (2009), Lunardini (2009), Lien et al (2010), Yang & Lunardini (2011), Keehnn & Lunardini (2012), Nakazato (2013), Mathews et al (2014), Yuksel & Kistler (2015), Hidaka et al (2016), Priya & Lunardini (2017), Moller et al (2018), Horiuchi et al (2018), Kresse et al (2021)

Diversity in neutrino emission

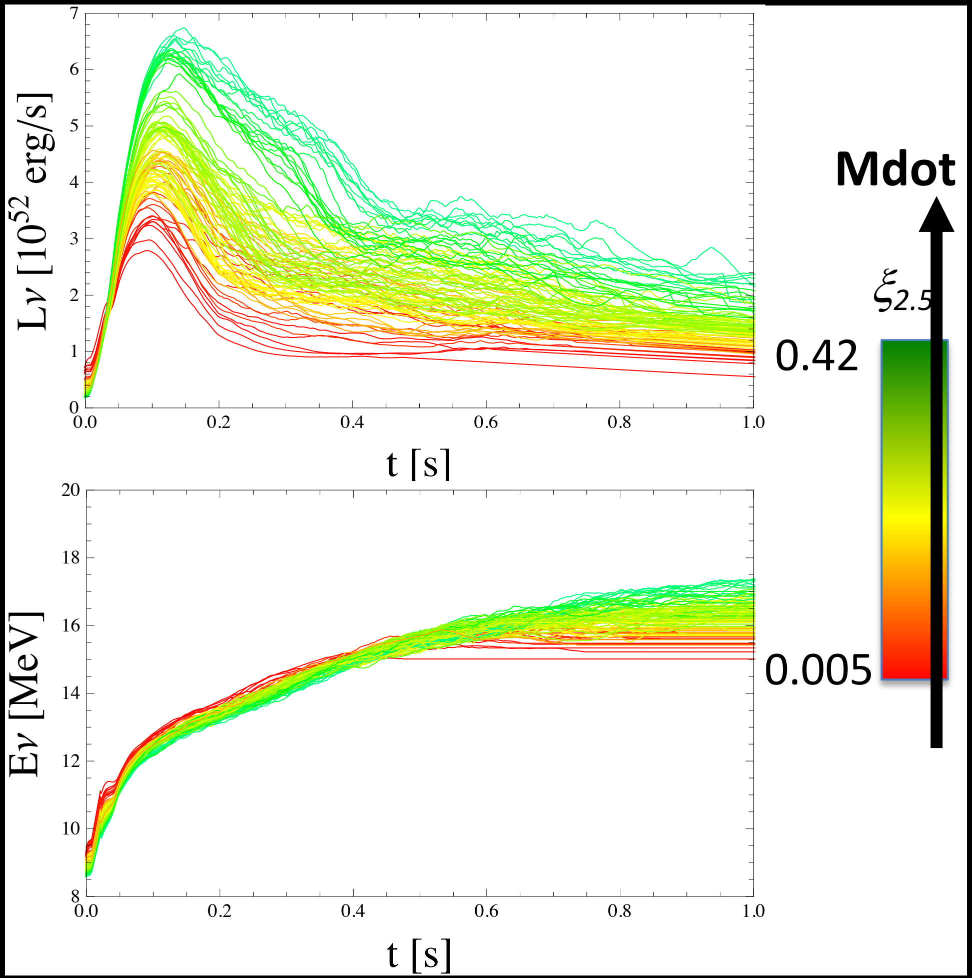
Variations: neutrino light curve reflects the progenitor's density

1D simulations



O'Connor & Ott (2013)

2D simulations



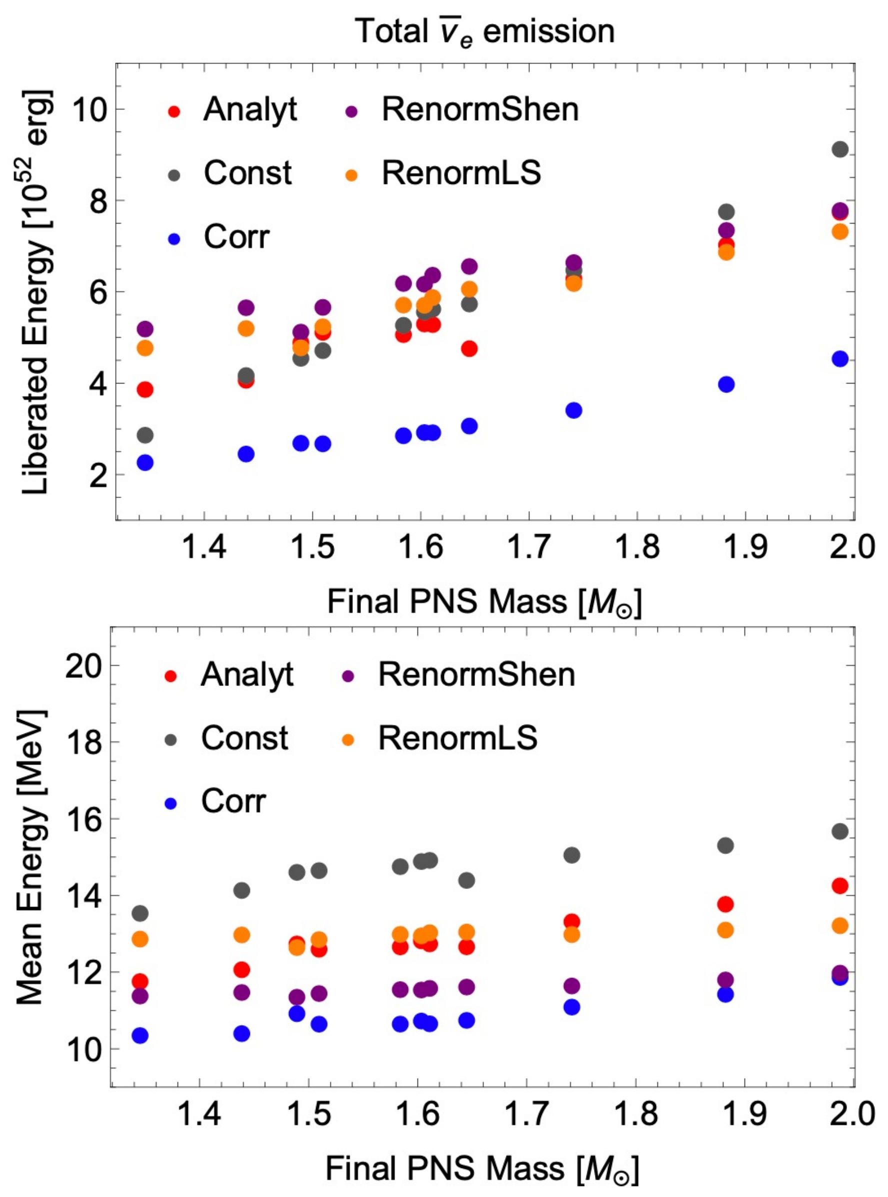
Based on Nakamura et al (2015)

Cooling phase neutrinos

Some strategies

To treat cooling phases across many stars

1. Correlation: based on Nakazato et al (2013) suite of cooling simulations
2. Renormalized versions of #1: based on suite by Hudepohl
3. Constant: no cooling phase evolution
4. Analytic treatment Suwa et al (2020)



Many things different between sims, but see at least

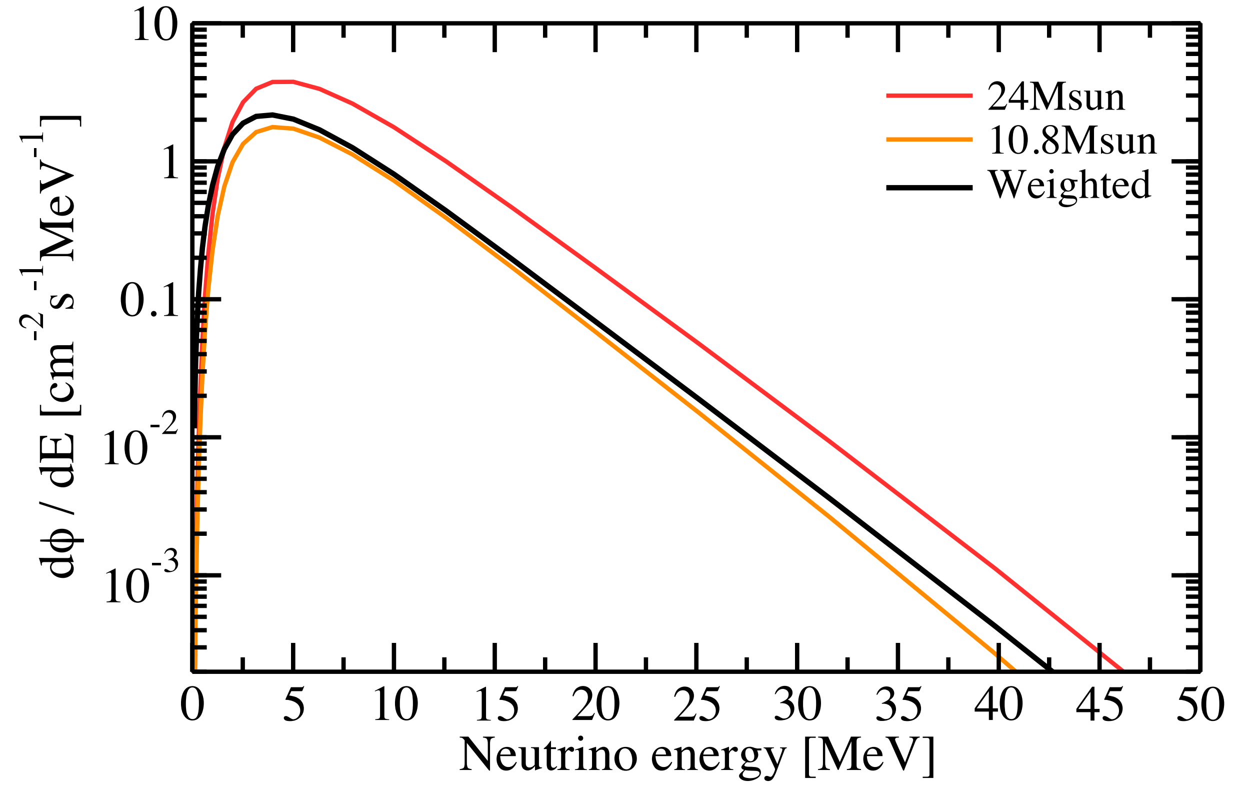
- Factor ~2 differences in liberated energy
- ~3 MeV differences in mean energy

Ekanger et al (2022)

Predicting the DSNB

The predicted DSNB flux spectrum, weighted by massive star populations

- Depends on knowledge of progenitor distribution



Assuming Salpeter IMF (initial mass function)

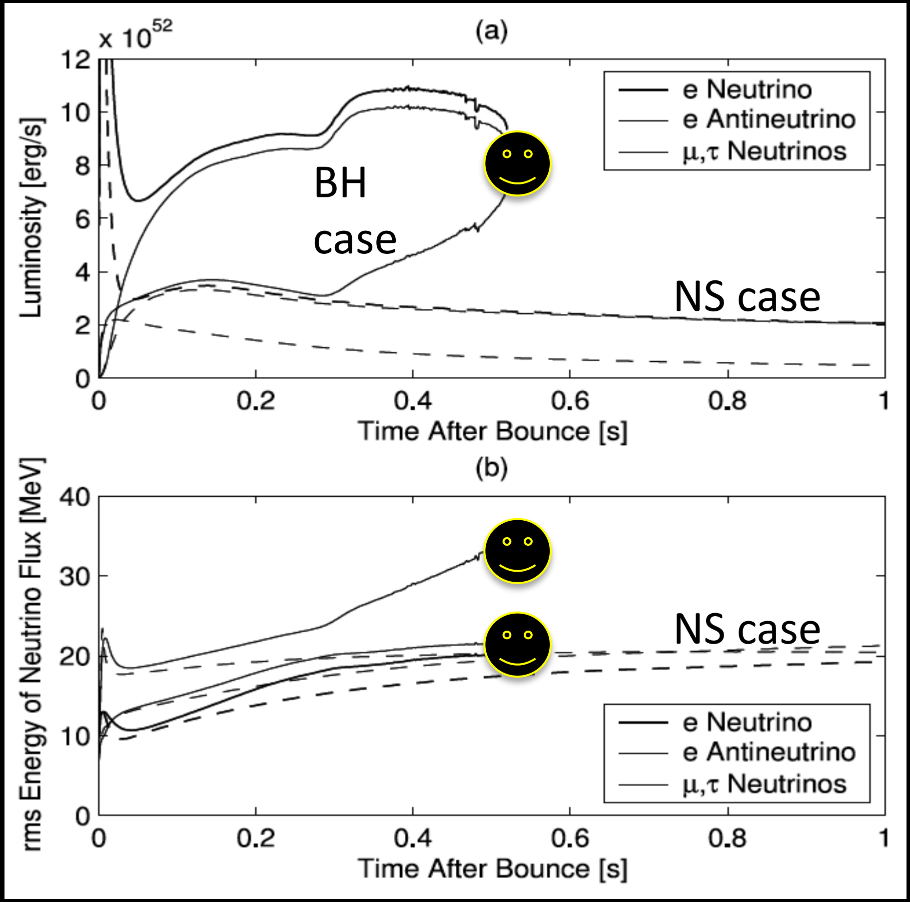
Horiuchi et al (2018); see also Kresse et al (2021)

Collapse to black holes

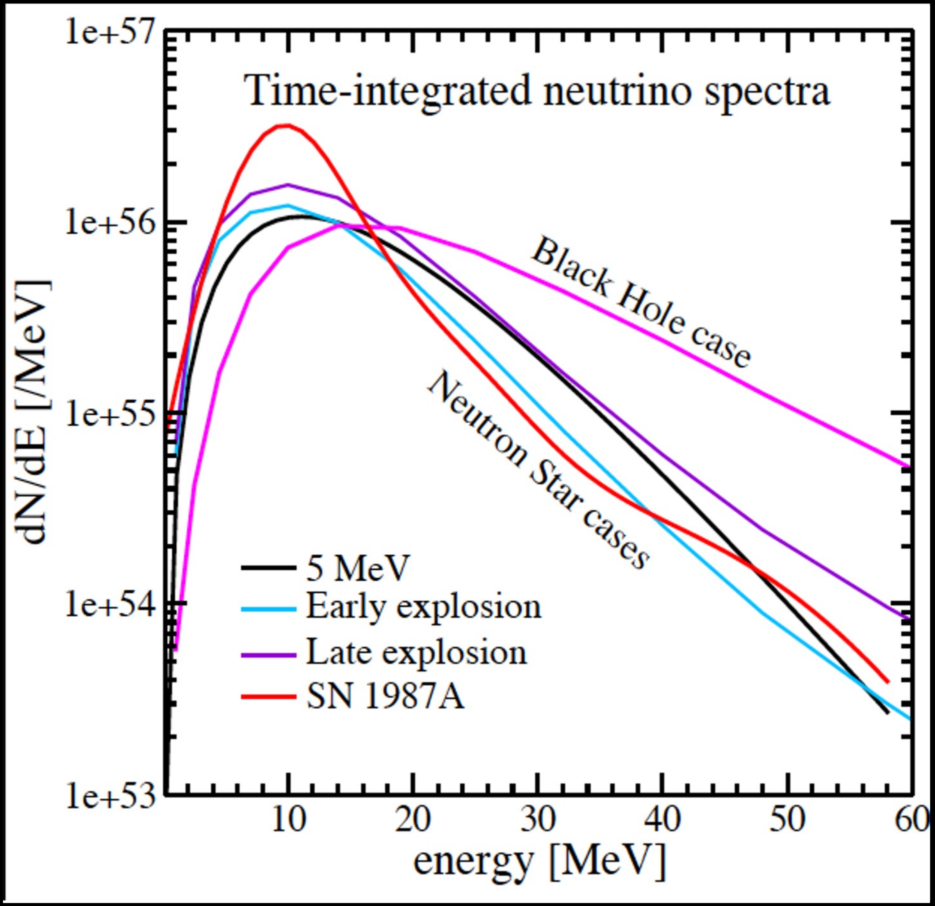
Neutrinos from collapse to black hole

Black hole formation goes through high mass accretion

→ ν emission is more luminous and hotter (depends strongly on EOS)



Liebendoerfer et al 2004

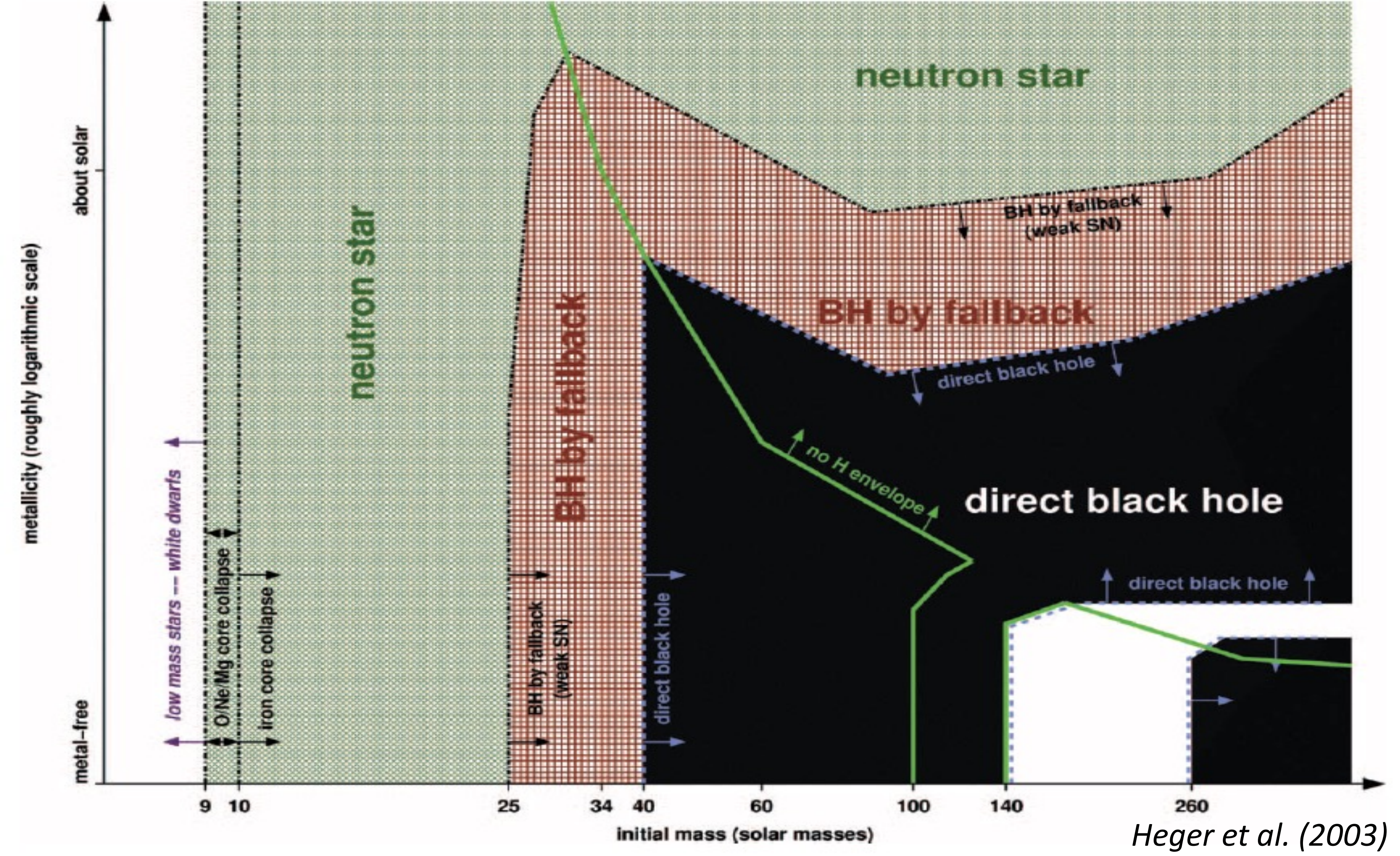


Studied by many groups, e.g., Fischer et al, Sumiyoshi et al, Nakazato et al, Ott et al, O'Connor et al, Kuroda et al.

Which stars collapse to black holes?

The expectation circa 2000:

Qualitative expectations, no binaries, no rotation, metal-driven mass loss only

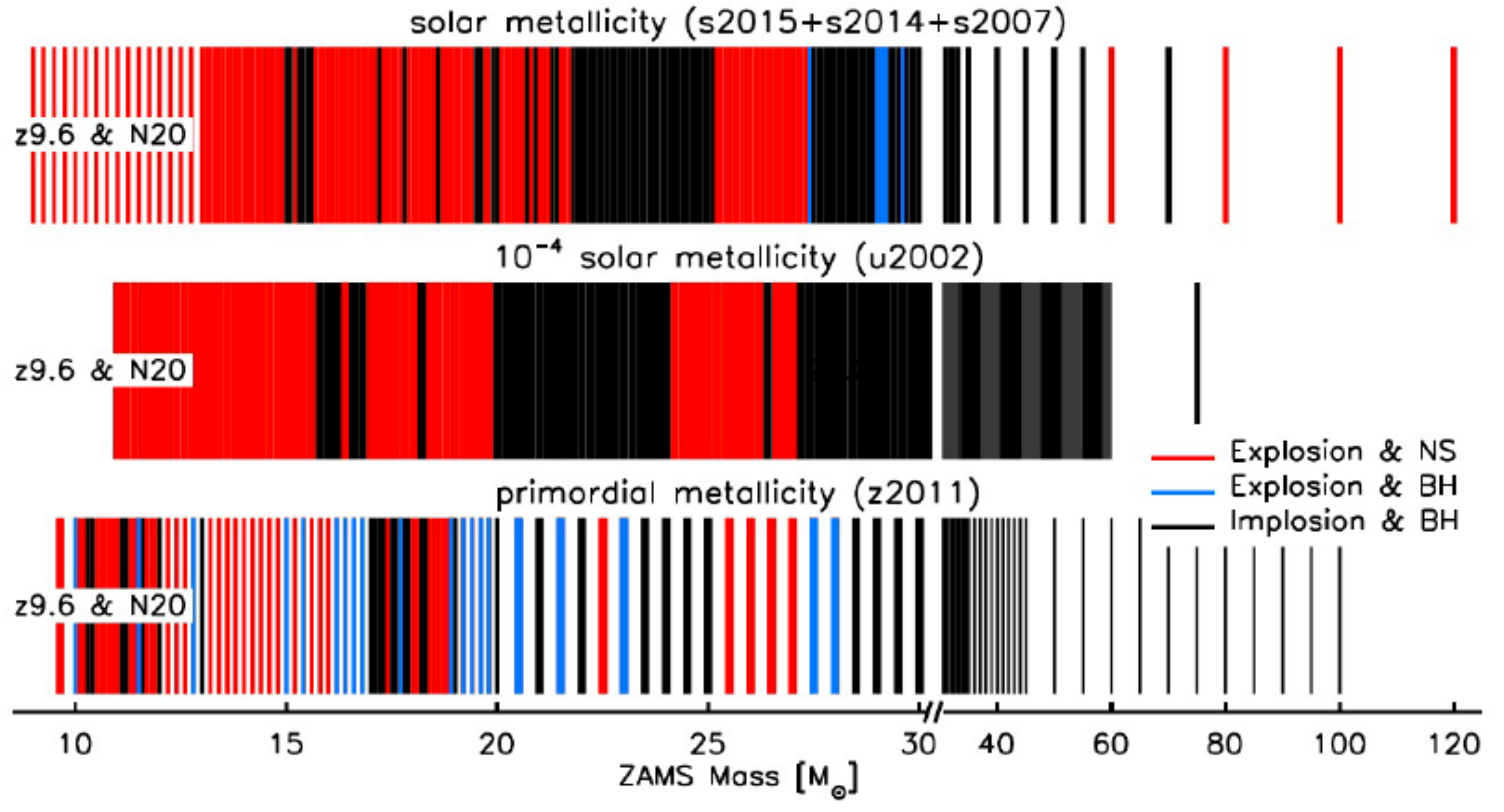


Heger et al. (2003)

Which stars collapse to black holes?

Emerging picture:

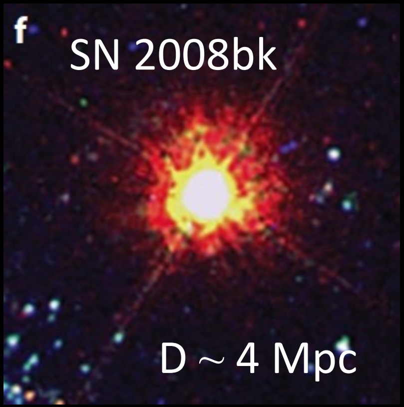
Thinking in mass looks incomplete. Trends connected to progenitor.

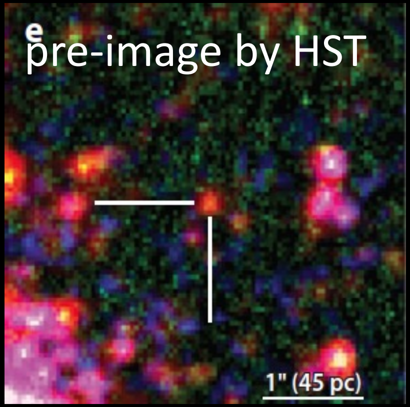


Janka 2017; see also O'Connot & Ott (2011), Ugliano et al (2012), Horiuchi et al (2014), Pejcha & Thompson (2015), Nakamura et al (2015), Ertl et al (2016), Sukhbold et al (2016), Mueller et al (2016), Kresse et al (2021)

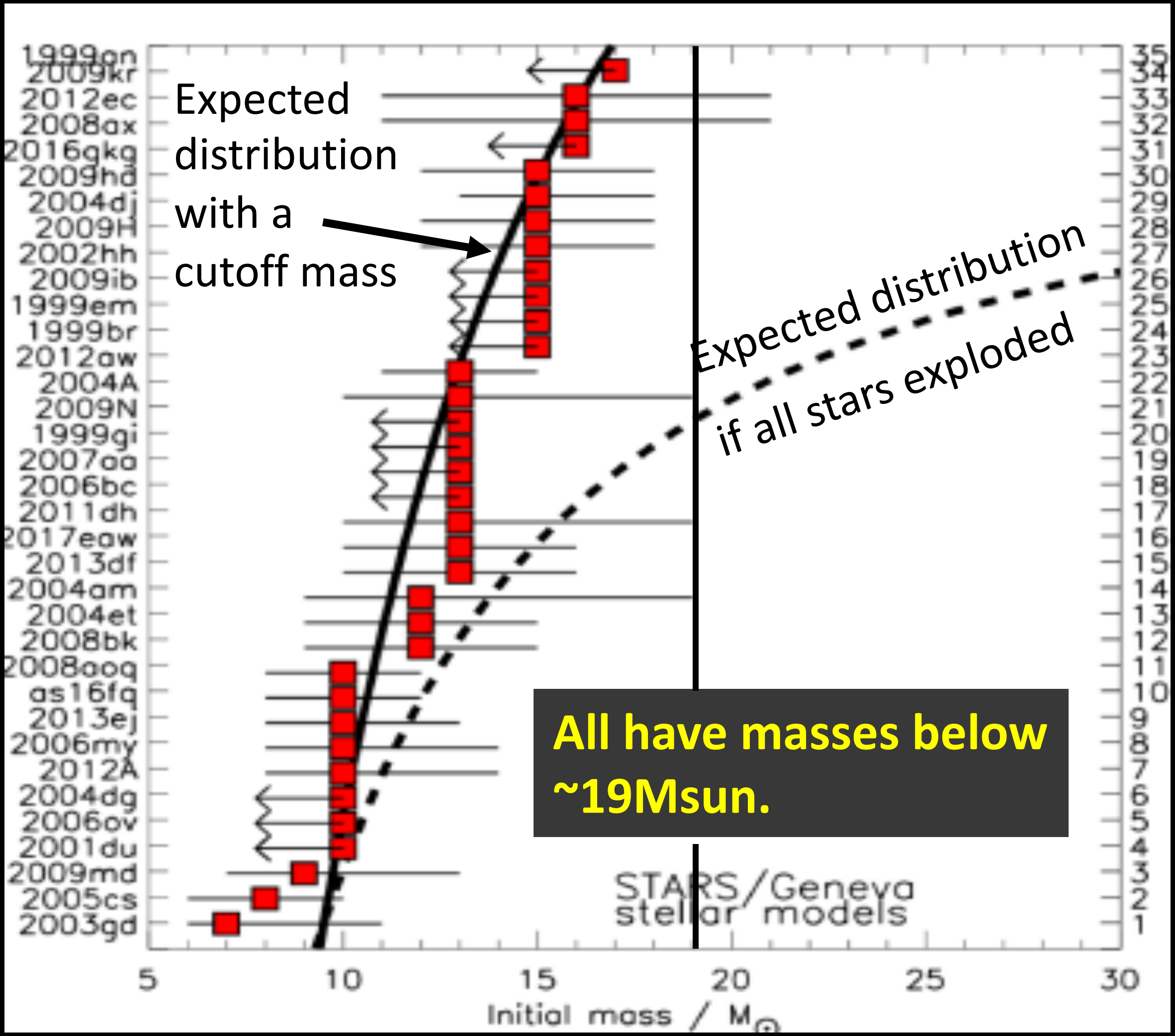
Looking for explosions

Pre-imaging:
Limited to nearby SNe, highly successful





Now: 35 supernovae (20 detections, 15 upper limits)



Expected distribution with a cutoff mass

Expected distribution if all stars exploded

All have masses below ~19Msun.

Smartt, STScI Spring Symposium (2019)

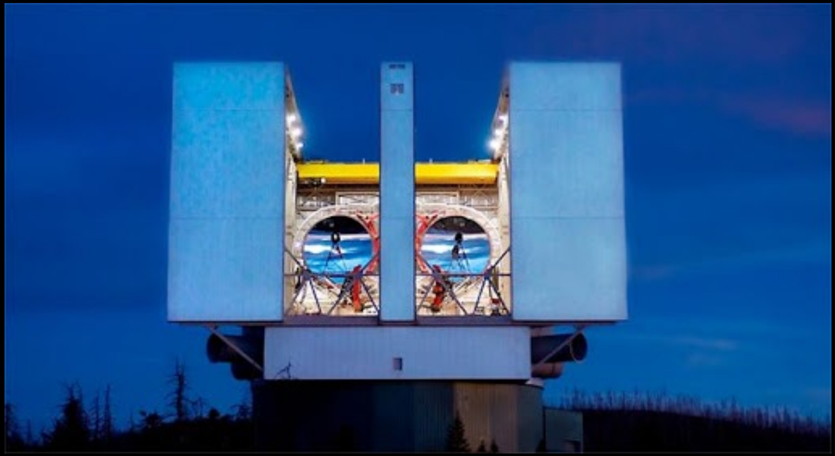
Looking for implosions

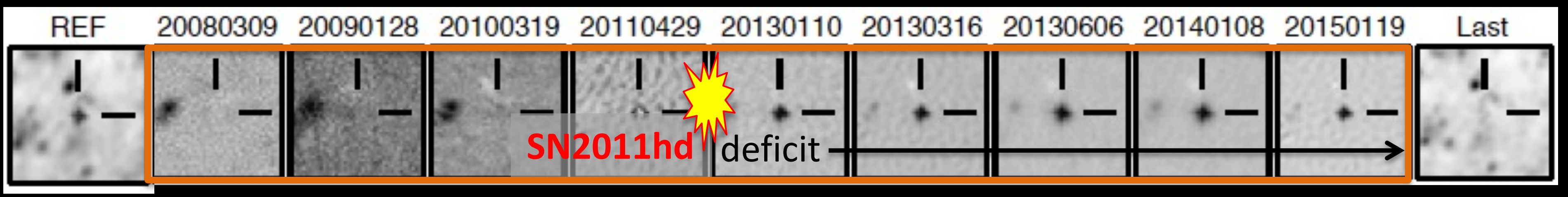
Look for disappearance of stars

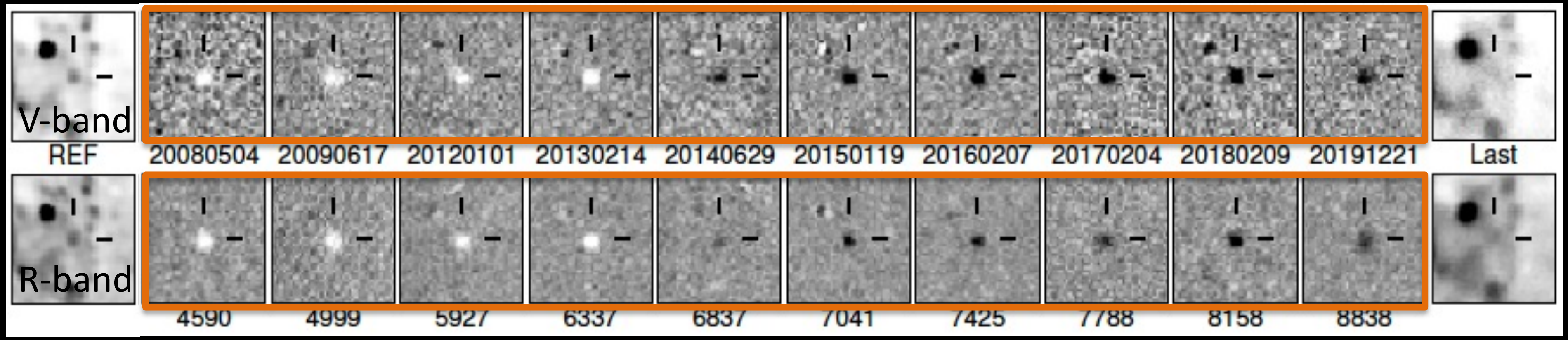
Monitor ~27 galaxies

- → Survey ~10^6 red supergiants
- → Expect ~1 core collapse /yr
- → In 10 years, sensitive to 20 – 30% failed fraction at 90% CL

Kochanek et al. (2008)





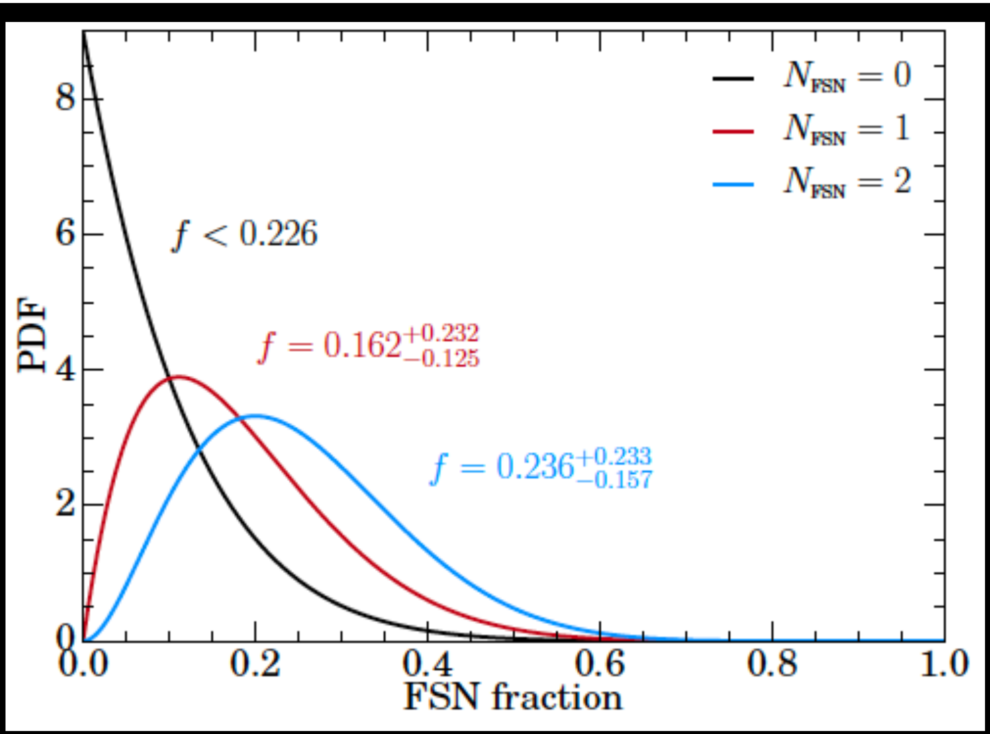


In 11 years running,

- ✓ 9 luminous CC supernovae
- ✓ 2 implosion candidates
  - NGC6946-BH1: SED well fit by ~25 Msun RSG
  - M101-OC1: follow-up ongoing

Neustadt et al (2021)

Also: Gerke et al(2015), Adams et al (2017), Reynolds et al (2016)

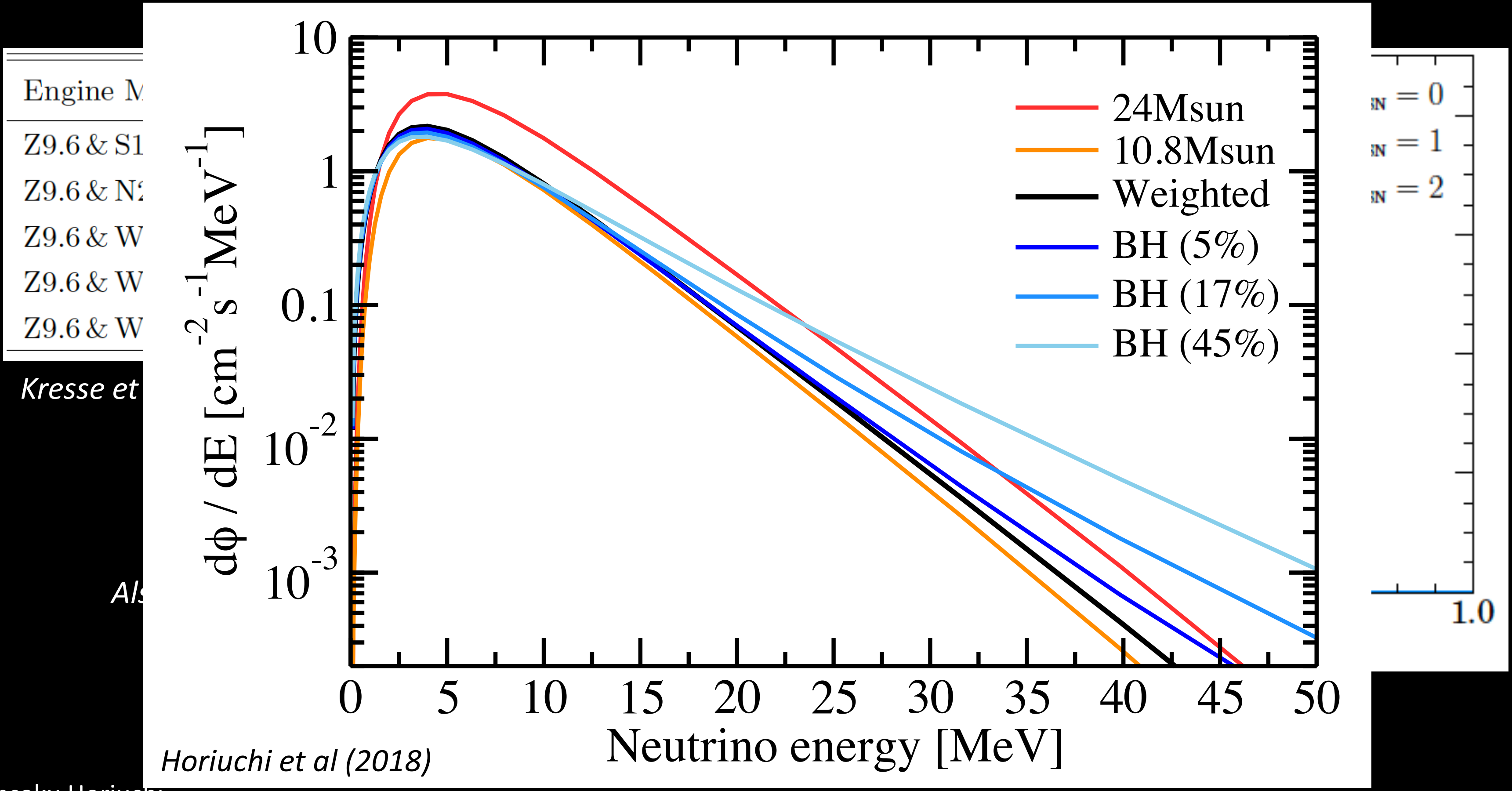


Predicting the DSNB

The predicted DSNB flux spectrum, including collapse to black holes

- Depends on BH fraction
- Depends on EOS, metallicity

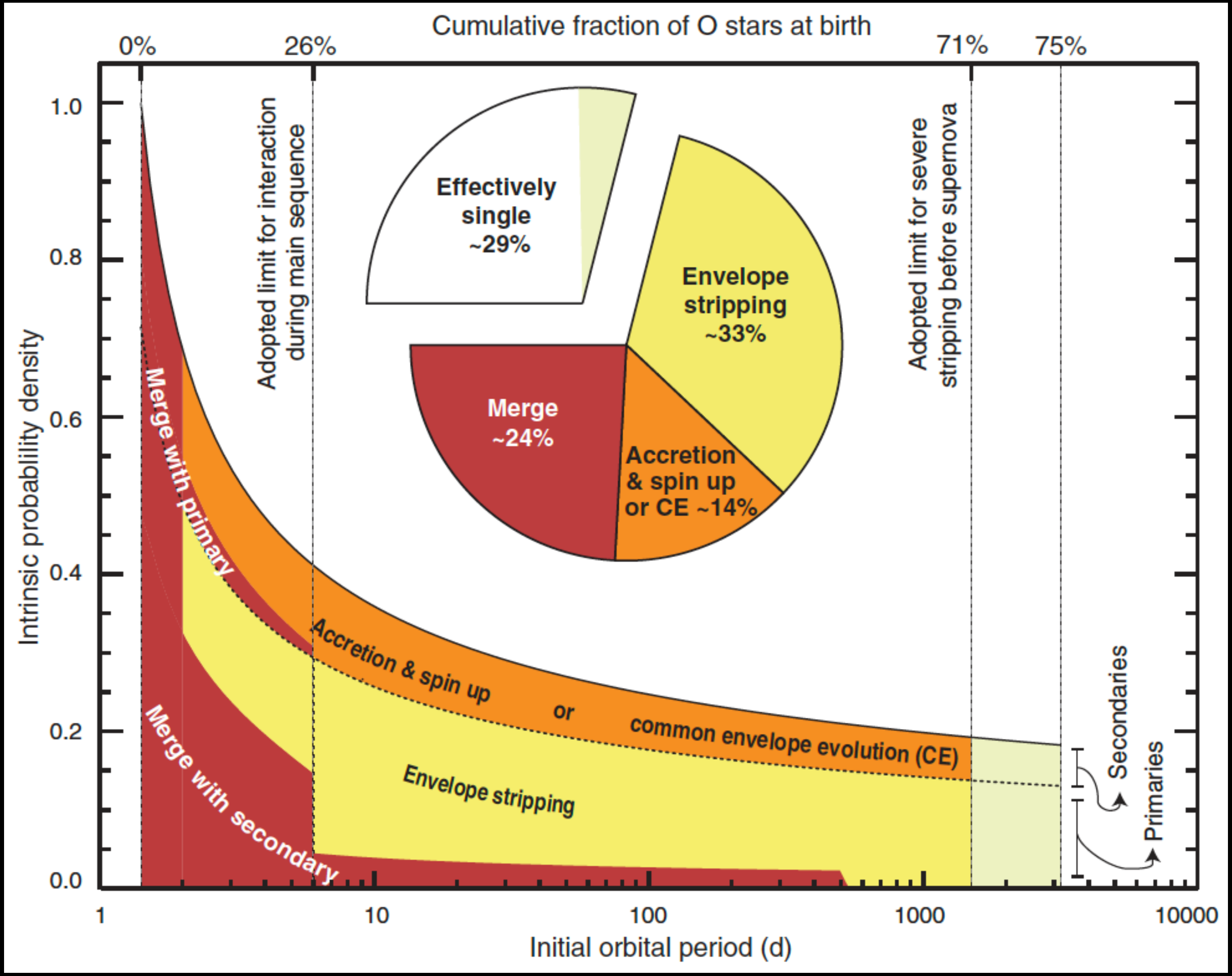
Black hole fraction dependence



Horiuchi et al (2018)

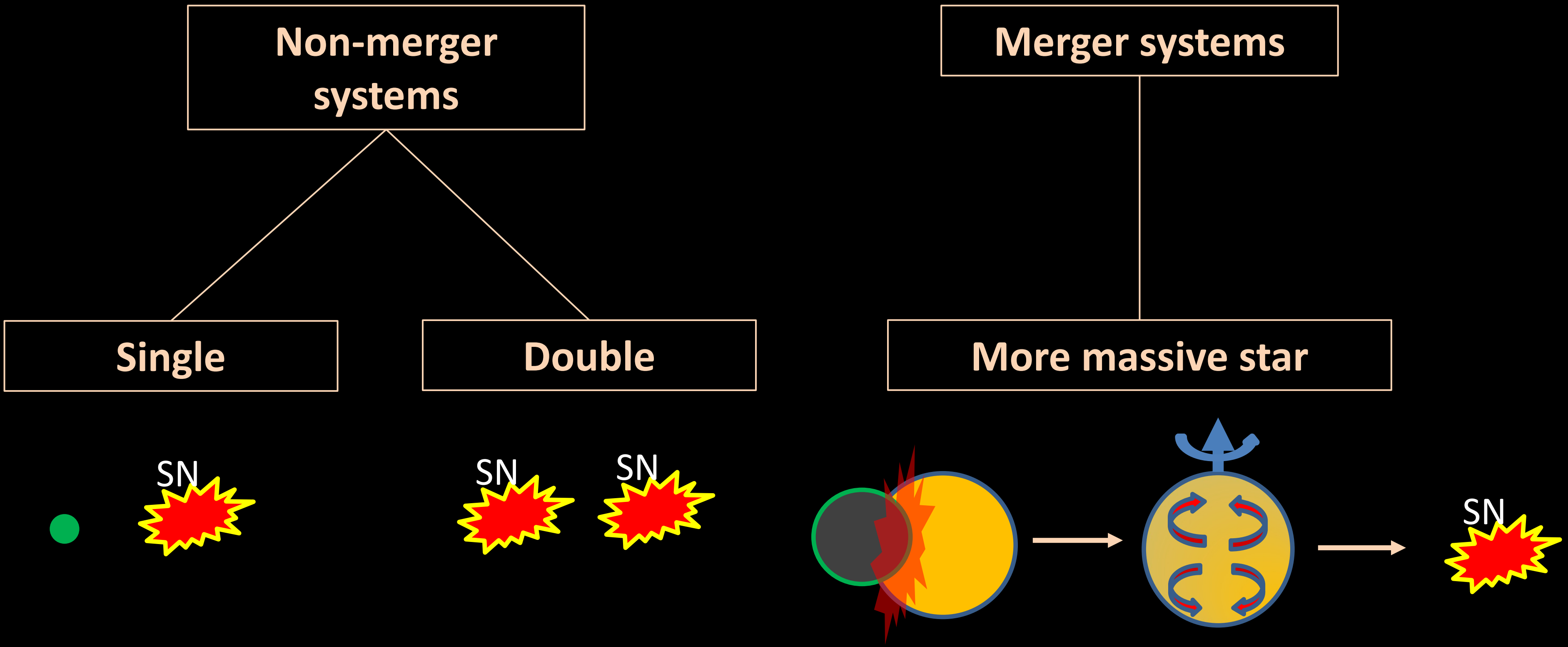
Account for binary effects

The majority of massive stars evolve in binaries



Sana et al (2012)

Binary pathways



Non-merger systems

Single

Double

Merger systems

More massive star

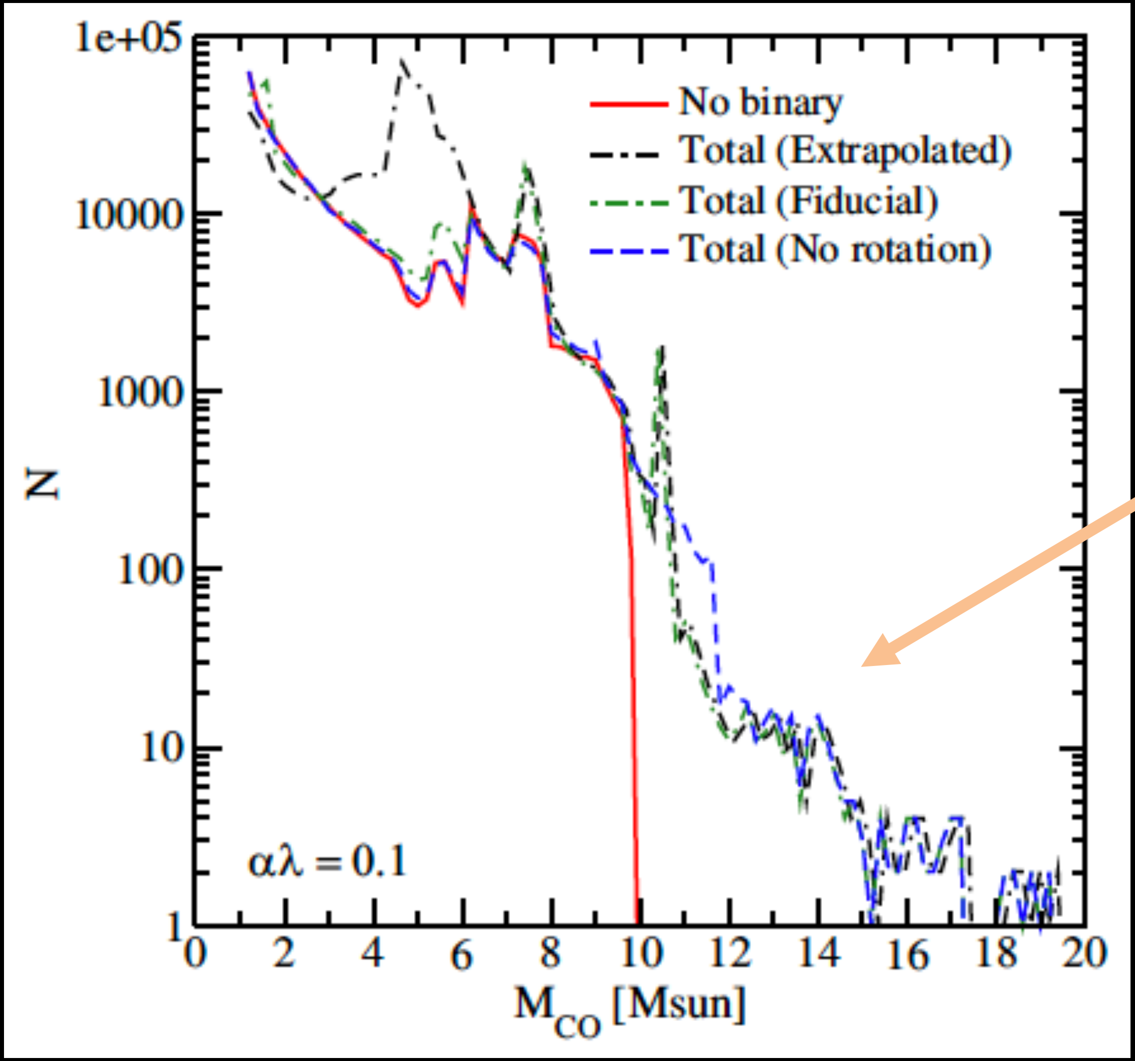
Masses of stars changed

Masses of stars changed
Number of stars changed

Visuals: thanks to Kinugawa

Effects of mergers

Effect 2: binary effect creates very massive cores for collapse

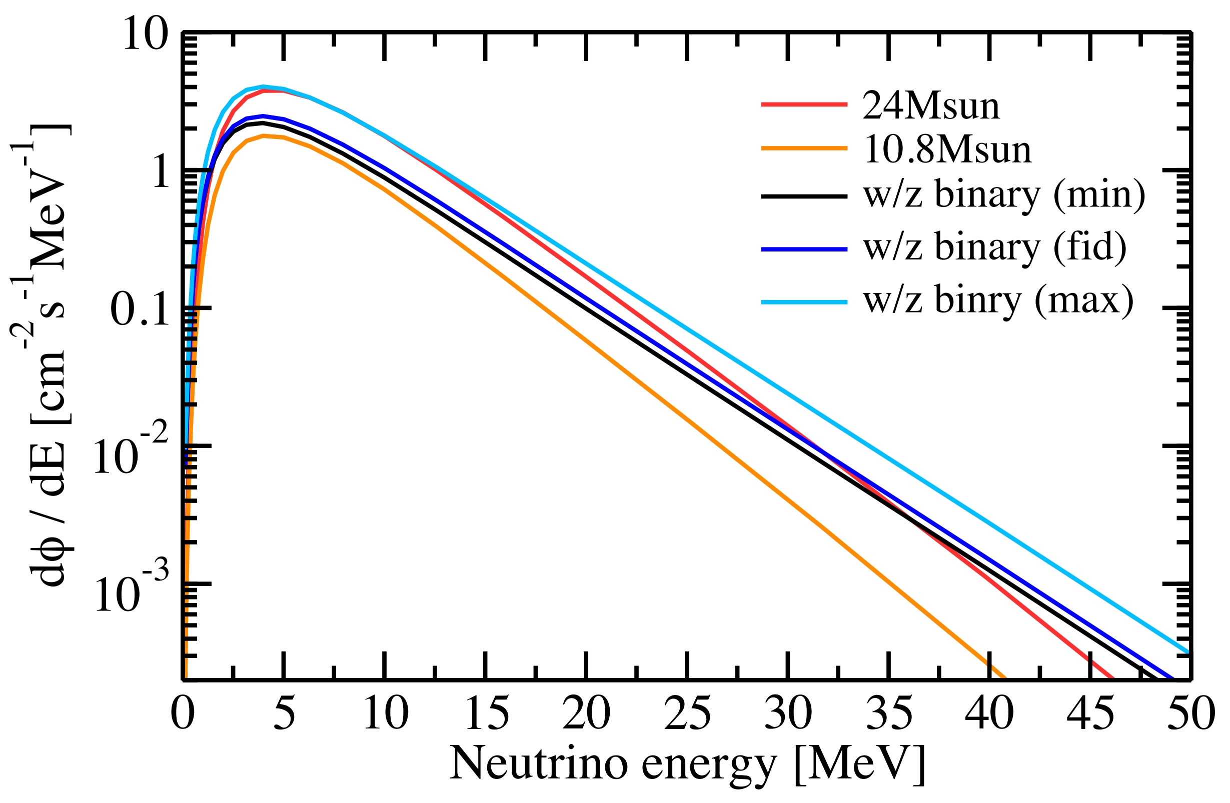


Many more high CO mass progenitors due to mass transfer & mergers

Horiuchi et al (2021)

Predicting the DSNB

The predicted DSNB flux spectrum, including binary effects



Based on Horiuchi et al (2021)

Fiducial model:
~20% increase

(Optimistic model
~75% increase)

Second take away

Are we certain core-collapse produce copious neutrinos?

Yes

What are the uncertainties?

Long-term emission over many progenitors
Black hole contribution
Binary effect

- DSNB would be good probe of populations, eg black hole forming population, others
- (hopefully don't need to use for eg supernova rates)

Detecting the DSNB

Some of the challenges

1. **What is the true core-collapse rate?**
2. **What is the long-term time-integrated neutrino emission?**
3. **What is the diversity in neutrino emissions?**
4. **What is the neutrino emission from collapse to black holes? And what is its rate?**
5. **How to detect a diffuse neutrino glow?**

Observed positron spectrum

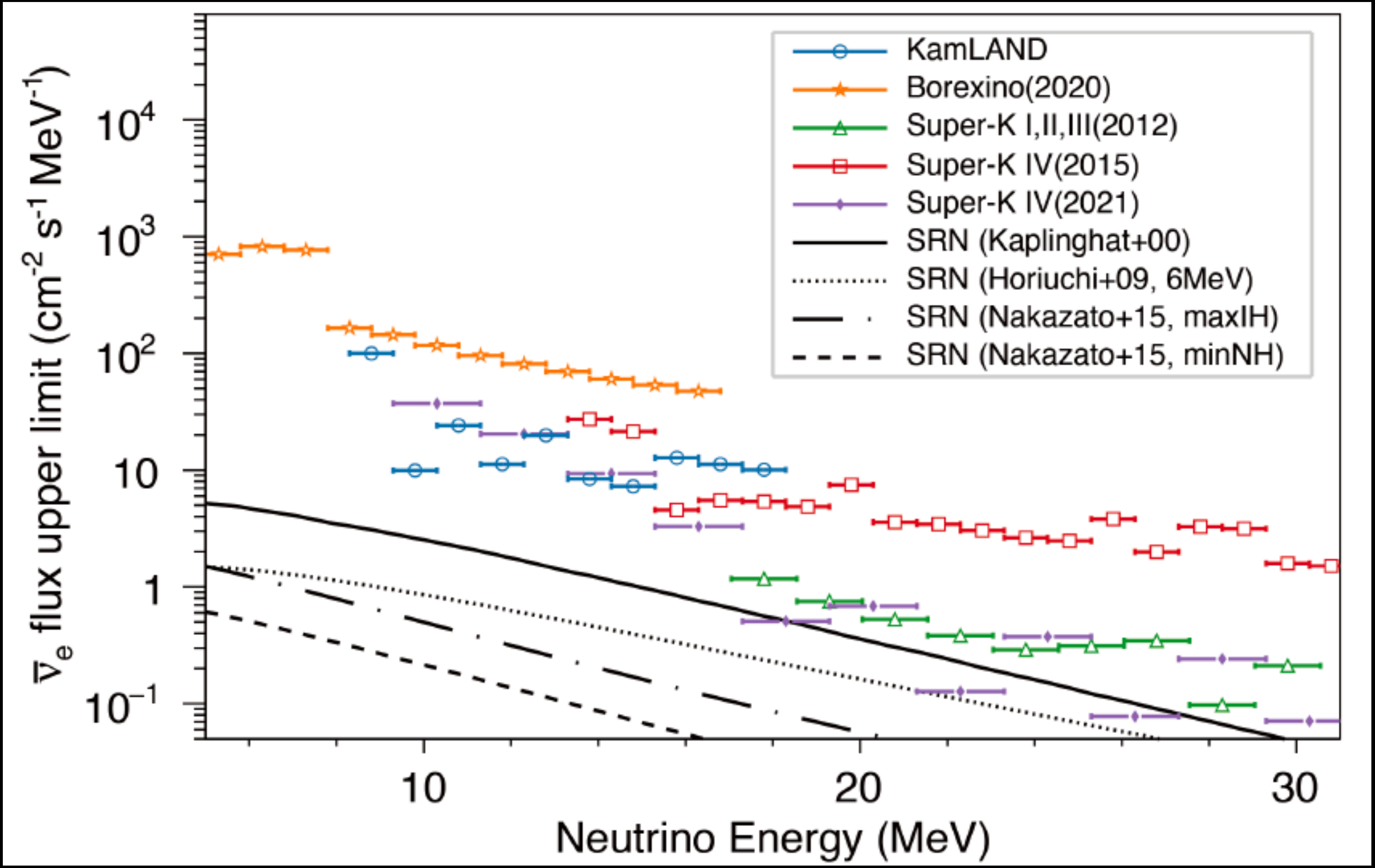
neutrino detector capabilities (well understood for H_2O)

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

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

Search limits

Nuebar limits: reaching factor of a few of theory predictions



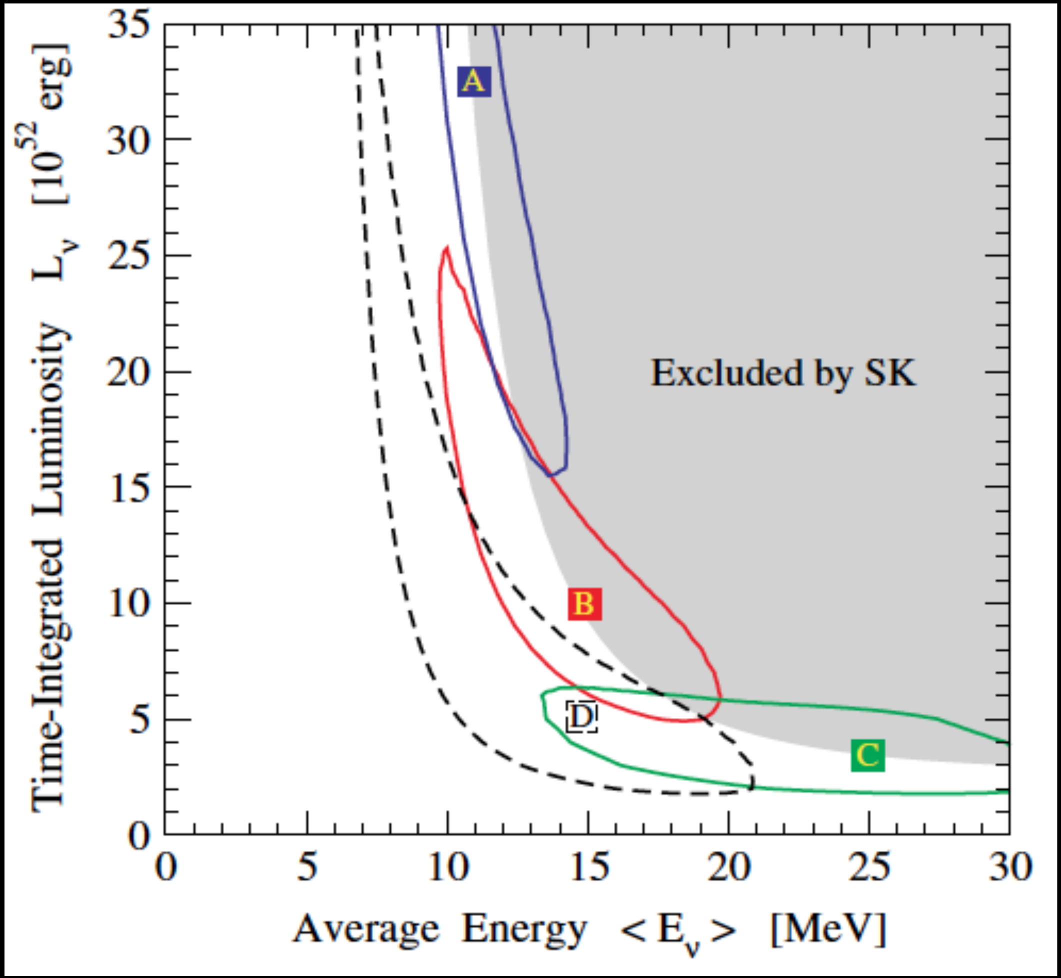
Discovery sensitivity

Gadolinium
Transforms Super-K into a signal-dominated search

Spectrum	Water (E > 18 MeV) [/yr]
All NS	0.4 +/- 0.1
5% BHs	0.6 +/- 0.1
17% BHs	1.0 +/- 0.3

Spectrum	Water + Gd (E > 10 MeV) [/yr]
All NS	1.7 +/- 0.4
5% BHs	1.9 +/- 0.5
17% BHs	2.8 +/- 0.8

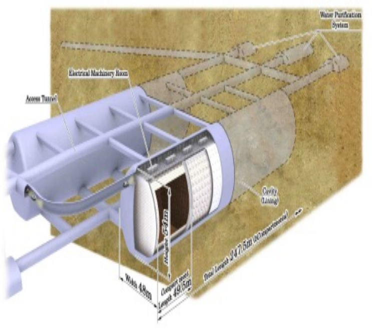
10 years with Super-K + Gd



Yuksel et al (2006)

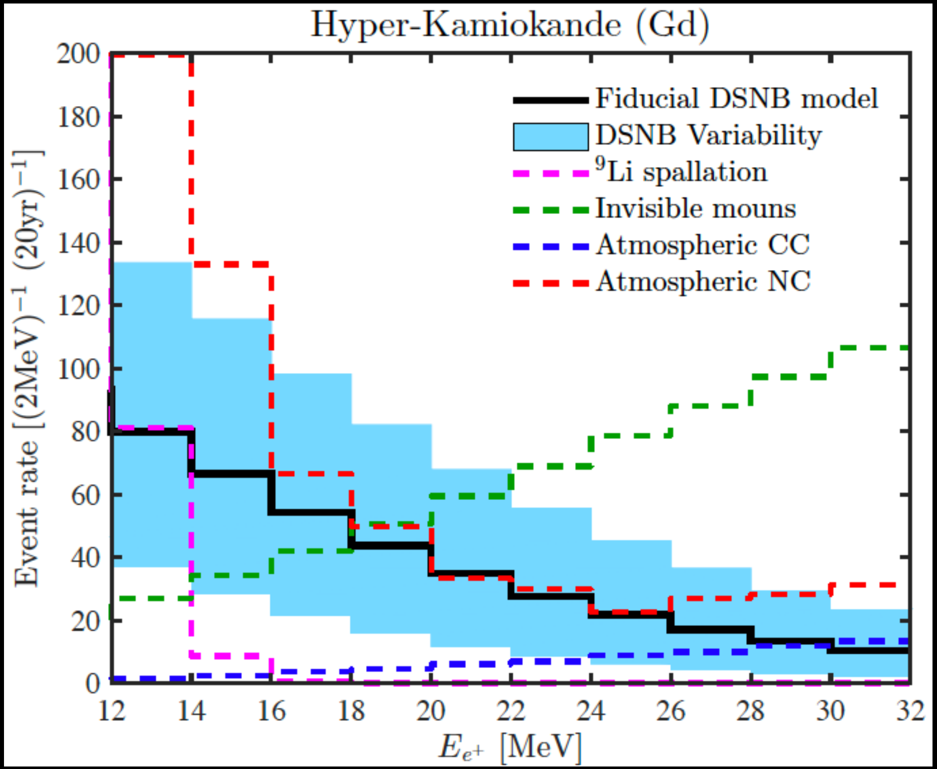
NB: "All NS" closest to D

Future detectors

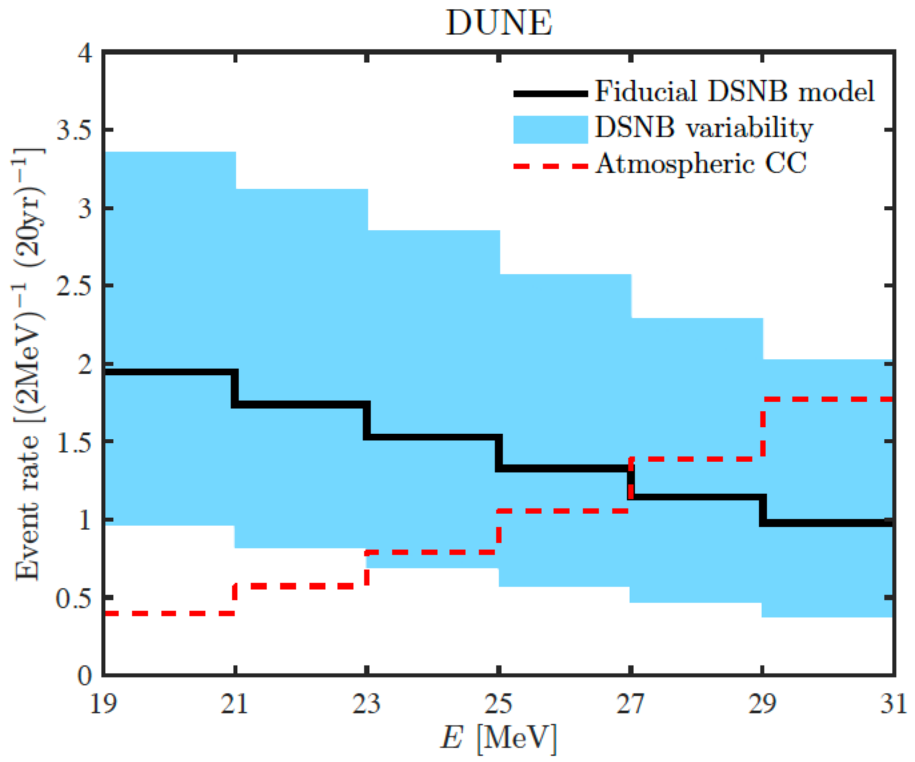


Hyper-Kamiokande
- 260k ton water
- Maybe +Gd?
- CC int. for nuebar

DUNE
- 40k ton lq Ar
- Signal & bkg studies ongoing
- CC int. for nue



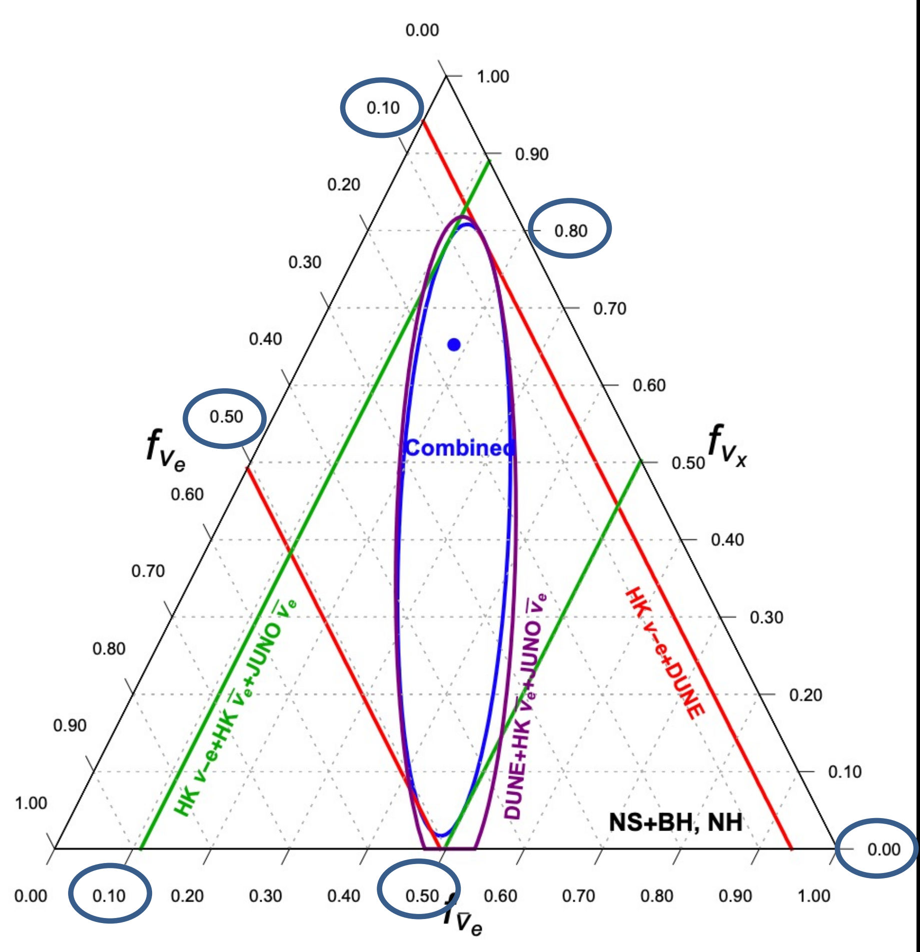
Moller et al (2018)



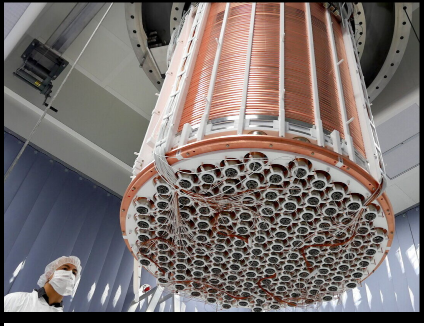
Moller et al (2018)

Future detectors

…measuring heavy lepton flavor will be challenging…

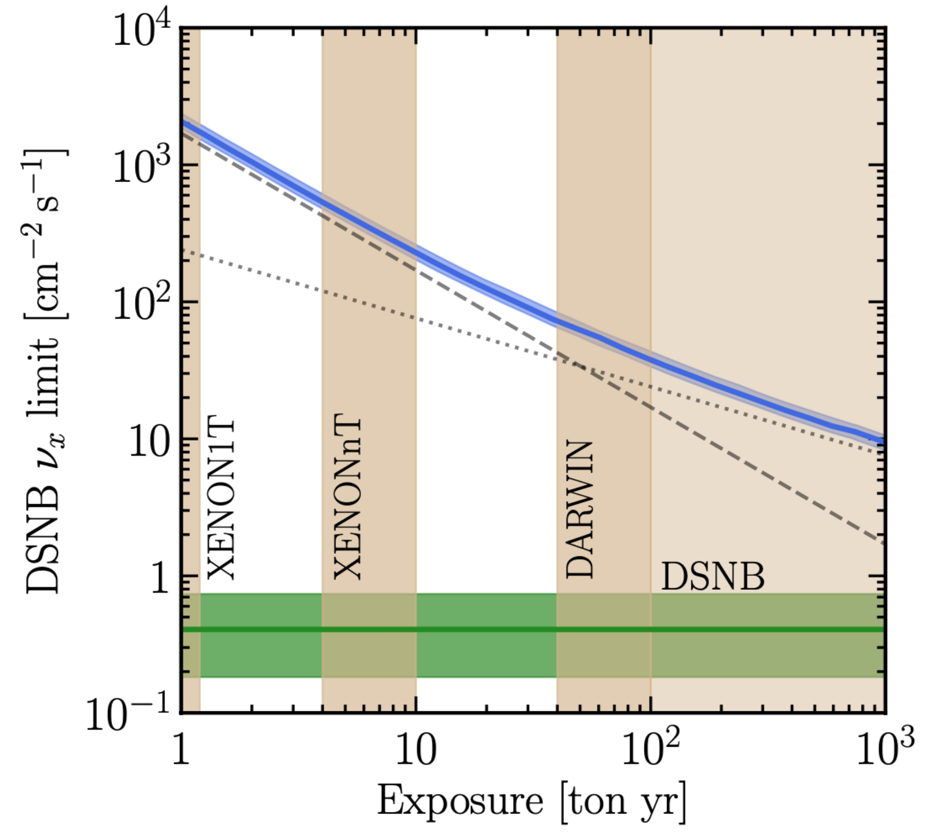


Tabrizi & Horiuchi (2021)



Direct DM detector

- Xe or Ar targets
- Solar & atm. bkgs
- CEνNS for all flavor

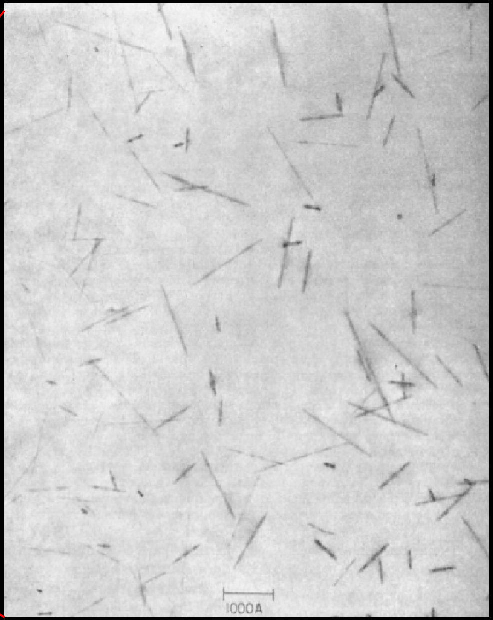


Suliga et al (2022)

Use old rocks ?

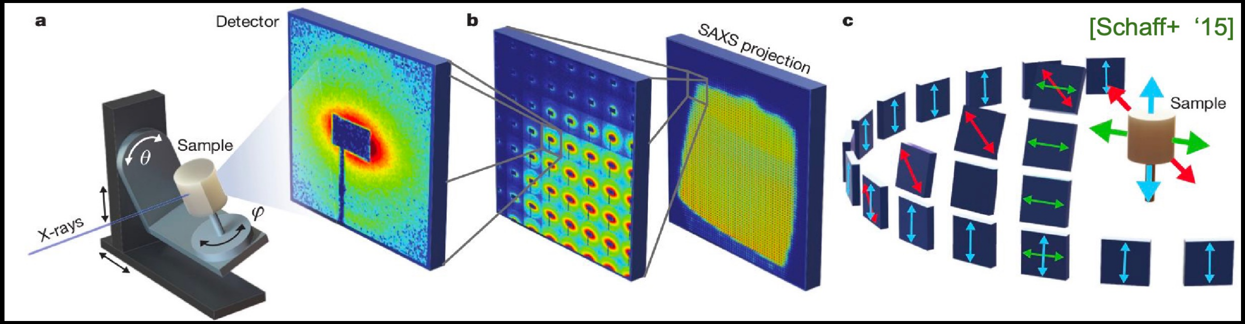
Recently revived as direct dark matter probes *Drukier et al (2019), Edwards et al (2019)*

Natural minerals as old as 10^9 years



Permanent damage tracks carry information about recoils
= solid state nuclear track detectors

Microscopy: small angle X-ray scattering + computer tomography



[Schaff+ '15]

Modern readout technologies allow fast nm-resolution mapping of structures in macroscopic samples

Advantages

Competitive exposure

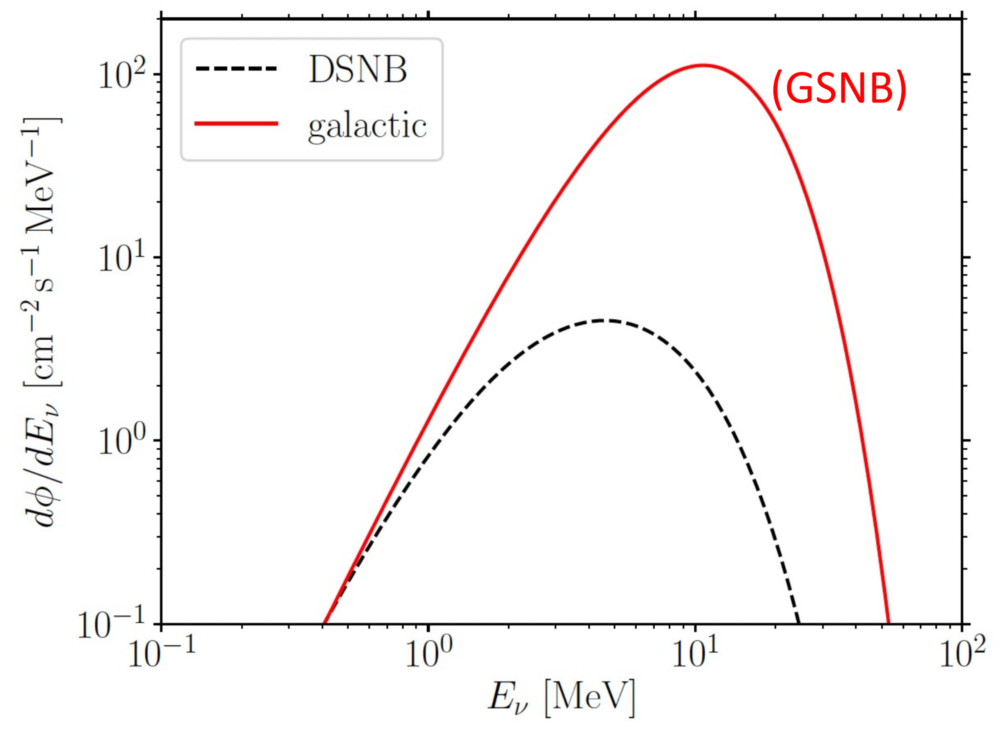
- 100 grams over 10^9 years = 10^5 t year

All flavors

- CEνNS most relevant for MeV neutrinos

"sees" thousands of Galactic core collapse

- Duration >> inverse of Galactic supernova rate



Baum et al (2020)

Backgrounds, backgrounds, backgrounds…

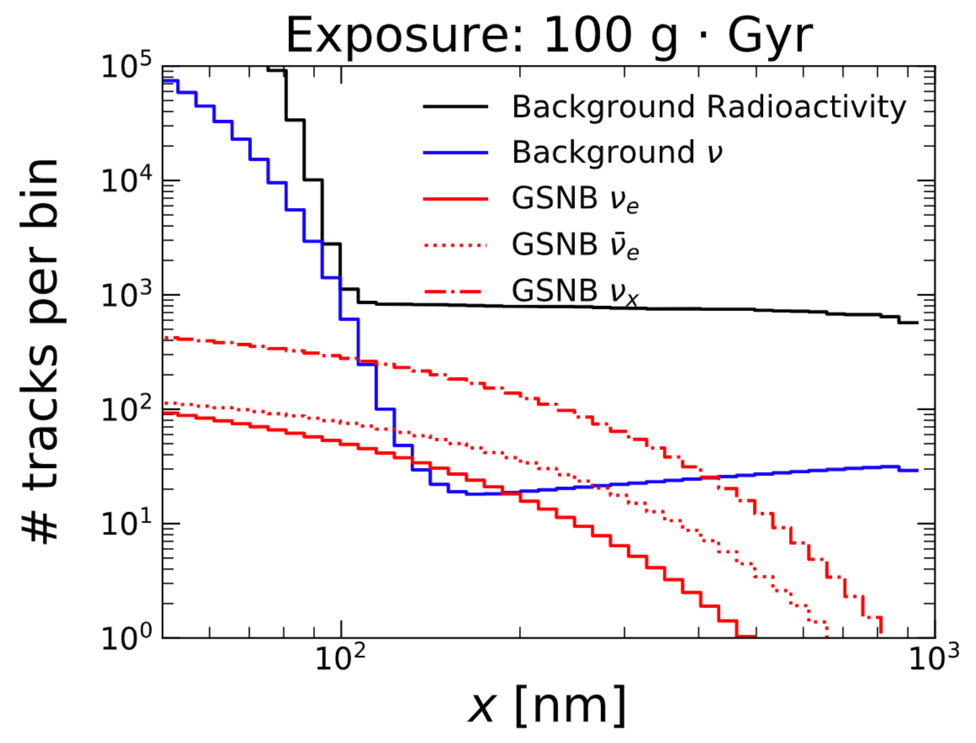
Natural defects
- Single sites or stretches across sample → easy to distinguish

Cosmogenic:
- Muons negligible by ~5 km → sample from deep boreholes

Radiogenic: ^{238}U chain, spontaneous fission
- Large background → Find radiopure sample, 0.01 ppb possible

Neutrinos: atmospheric, solar
- Has different spectrum
  → use spectral analysis

$$\text{Epsomite}\ \left[\mathrm{Mg(SO_4)\cdot 7(H_2O)}\right]$$

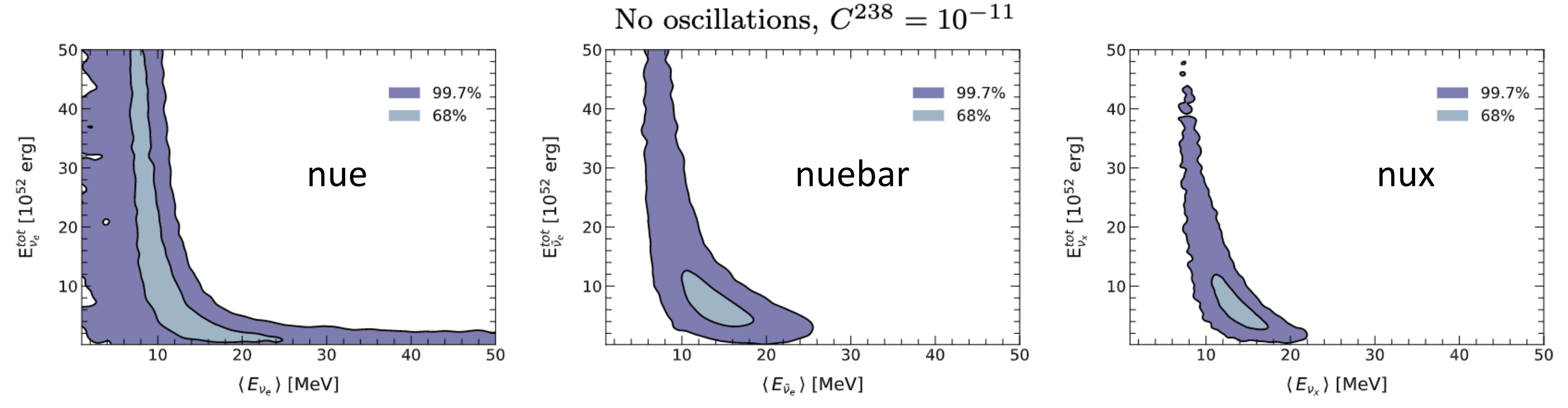


Baum et al (2022)

Idealized analysis

Fit the paleo track spectrum → All flavor information

Combine with DSNB nuebar from HyperK and DSNB nue from DUNE → residual νx



Baum et al (2022)

(100g of epsomite with 1 Gyr age, 15nm track resolution)
(100% uncertainty on radiogenic & neutrino backgrounds)
(20% uncertainty on HK & DUNE backgrounds)
(10% uncertainty on DSNB flux & galactic rate)

→ A possible new way to reveal the mean nux flux from many core collapses

Concluding thoughts

We're ready for the next Milky Way core collapse

In parallel, the diffuse supernova neutrinos is guaranteed

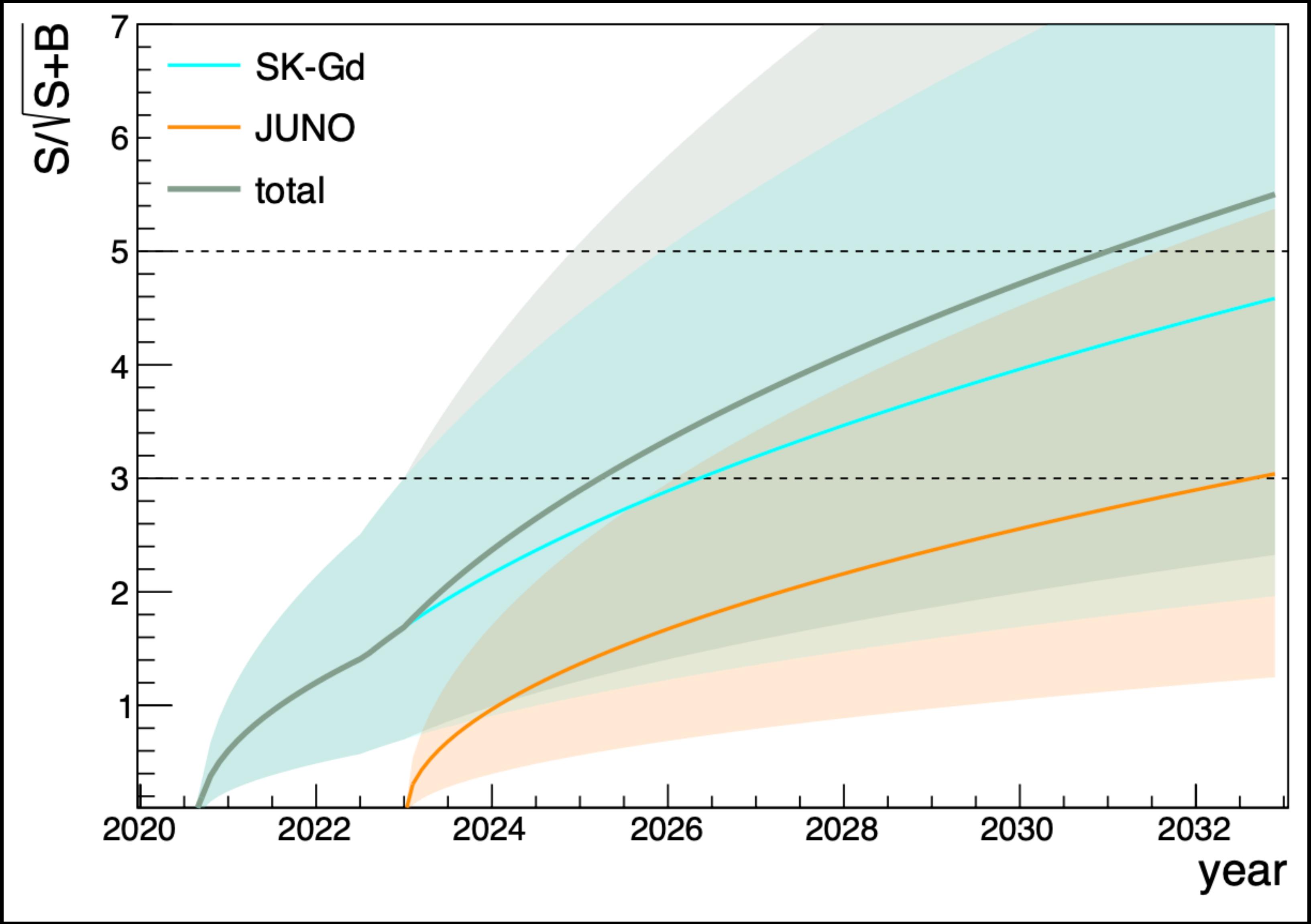
- ✓ We know core collapse occur frequently (direct observations + cross checks)
- ✓ We know core collapses emit neutrinos (SN1987A + simulations)

We have exciting sensitivity with the Gadolinium upgrade at Super-Kamiokande

Long-term evolution, progenitor dependence, black hole treatment, EOS, binary effects… all interesting physics

Thank you!

PREP



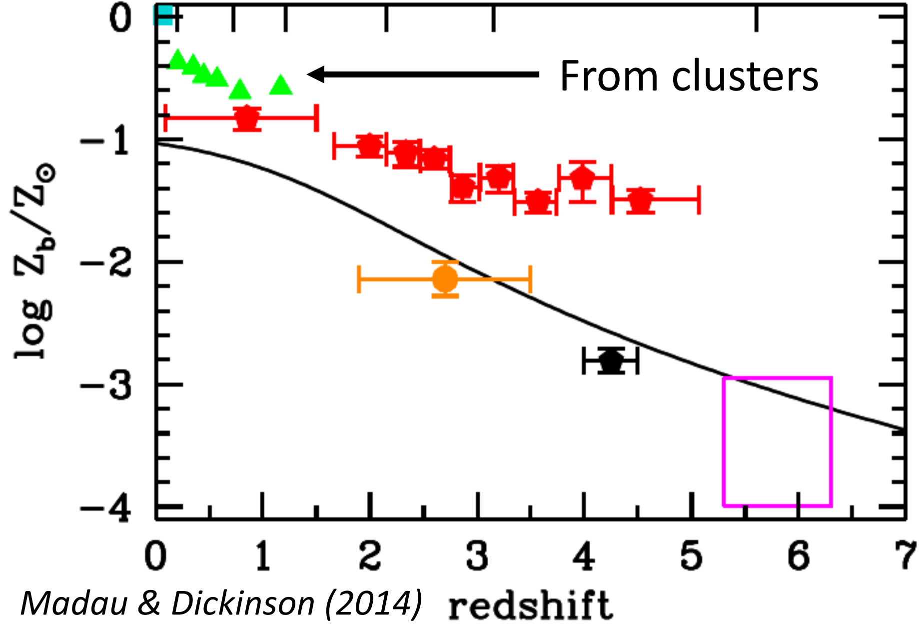
Li & Vagins (2022)

Integrated cross checks

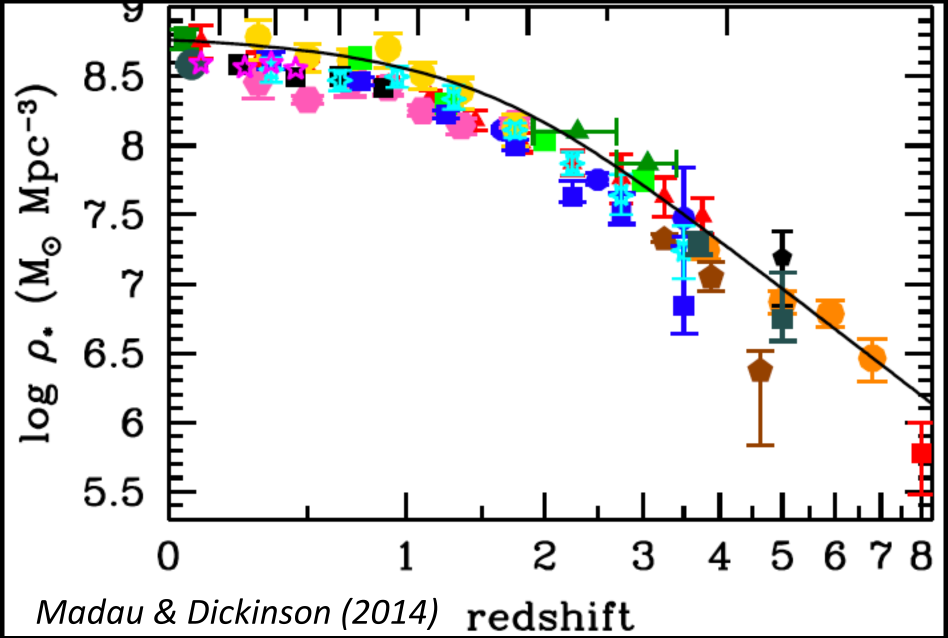
Star formation

Cosmic metallicity
*measurement systematics

Cosmic stellar density
*Sensitive to cosmic initial mass function



Madau & Dickinson (2014)



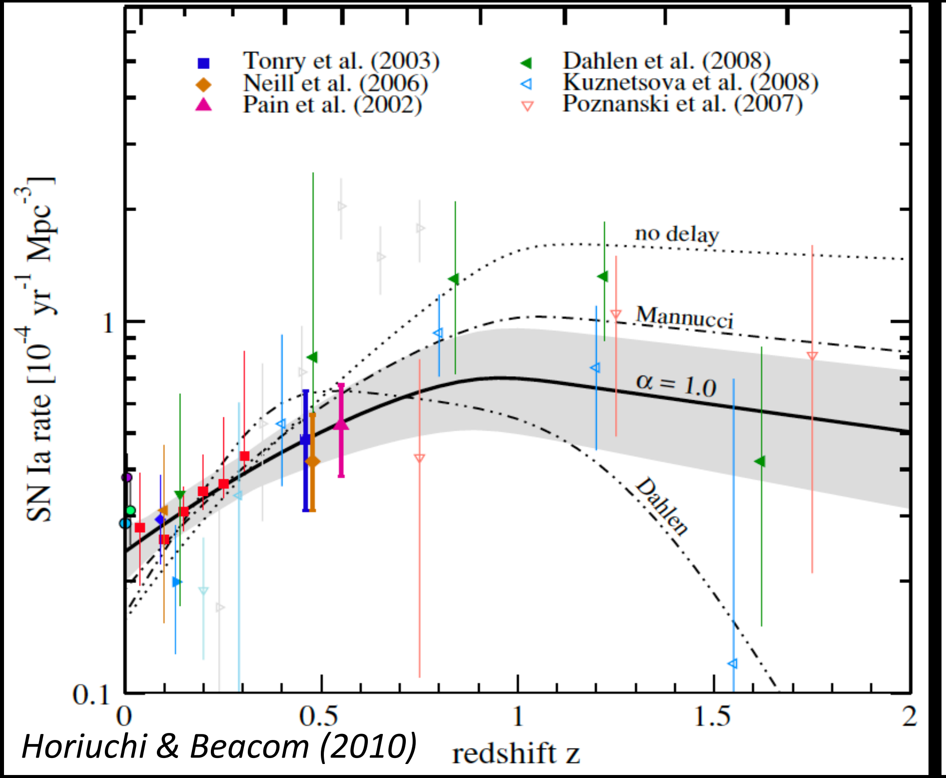
Madau & Dickinson (2014)

Integrated cross checks

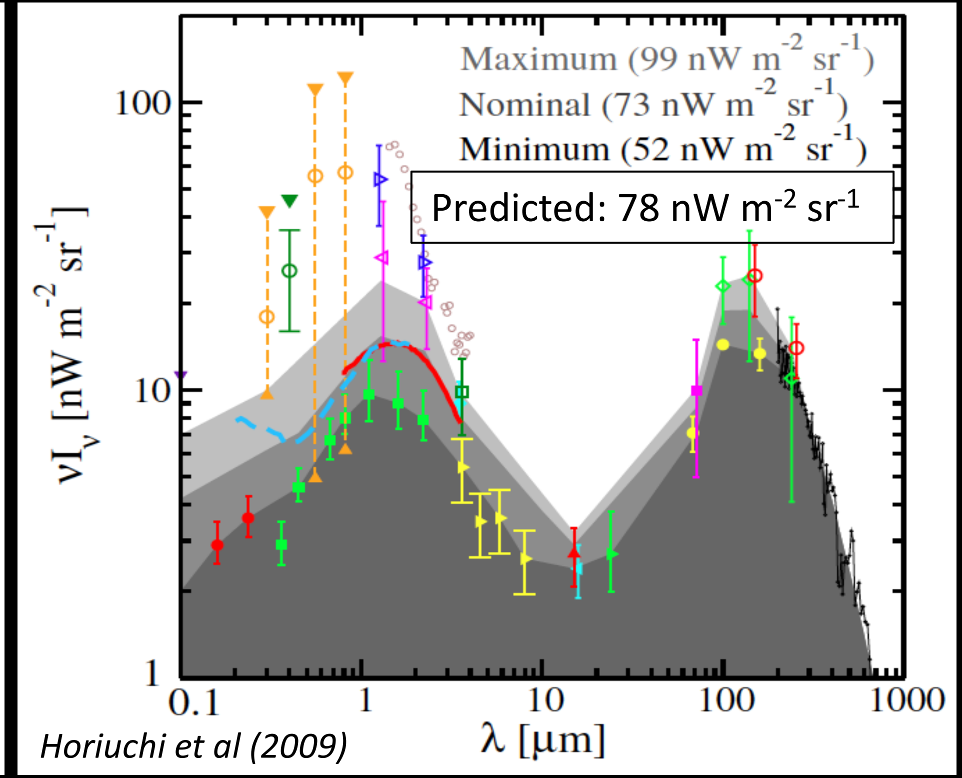
Star formation

Ia supernova rate
*Needs delay-time distribution

Extragalactic background light
*Measurement systematics



Horiuchi & Beacom (2010)



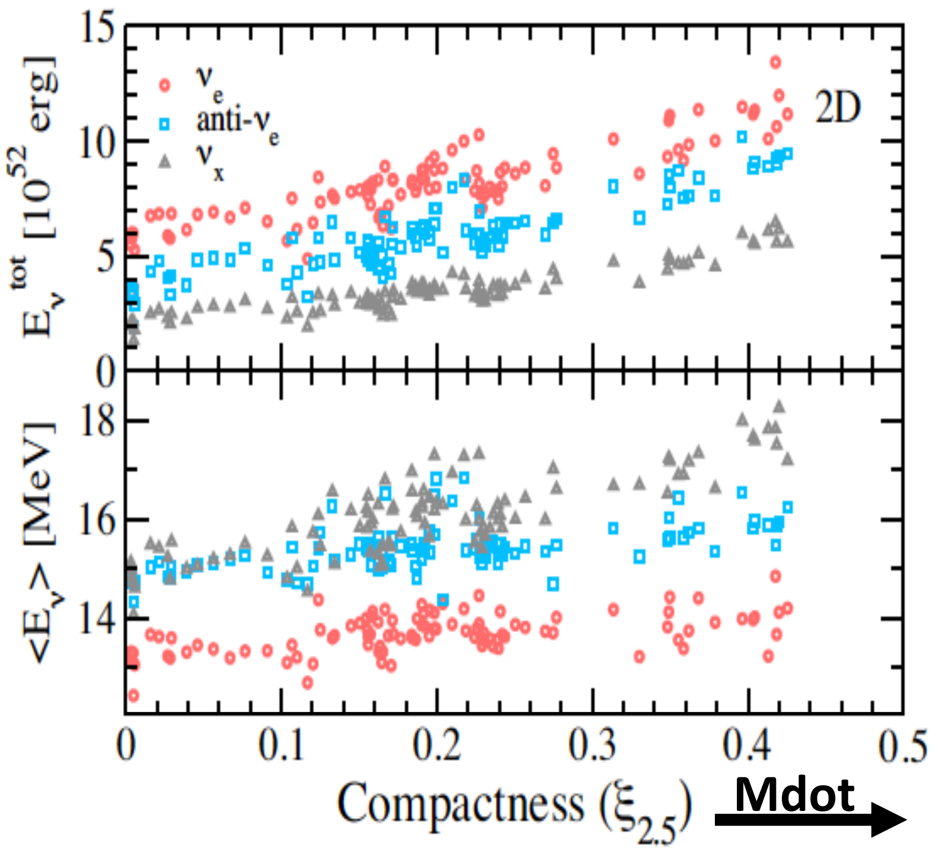
Horiuchi et al (2009)

Time-integrated neutrino emission

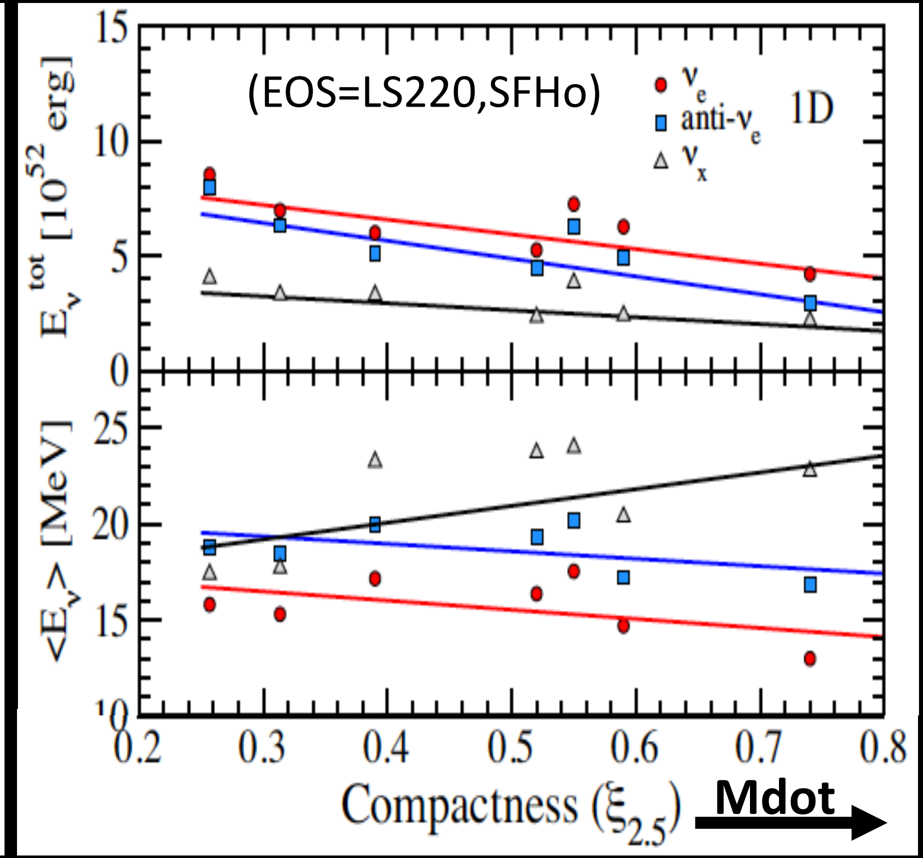
Systematic dependence on progenitor

Based on 100+ simulations (2D) of *Nakamura et al 2015,* 18 simulations (2D) of *Summa et al 2016,* and multiple BH simulations (1D).

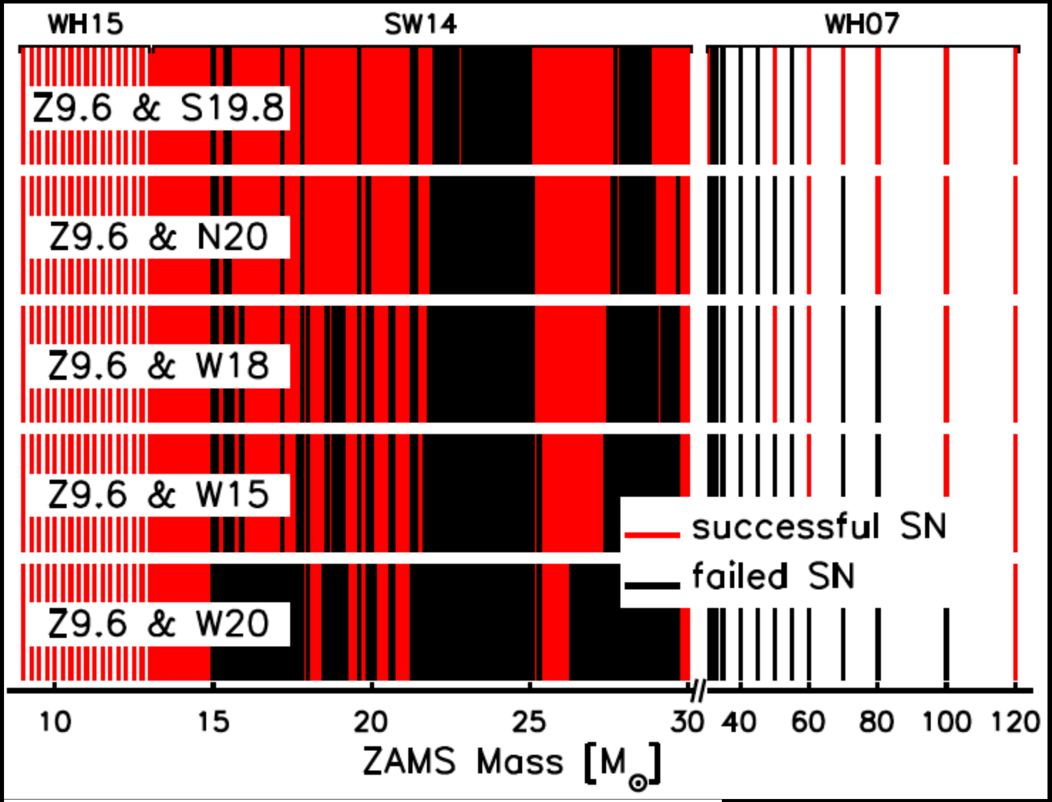
Collapse to neutron stars

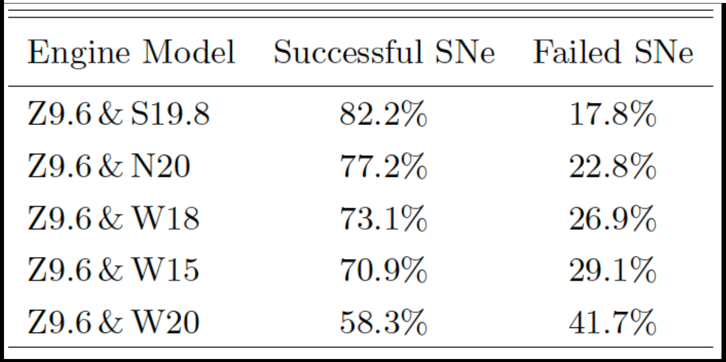


Collapse to black holes

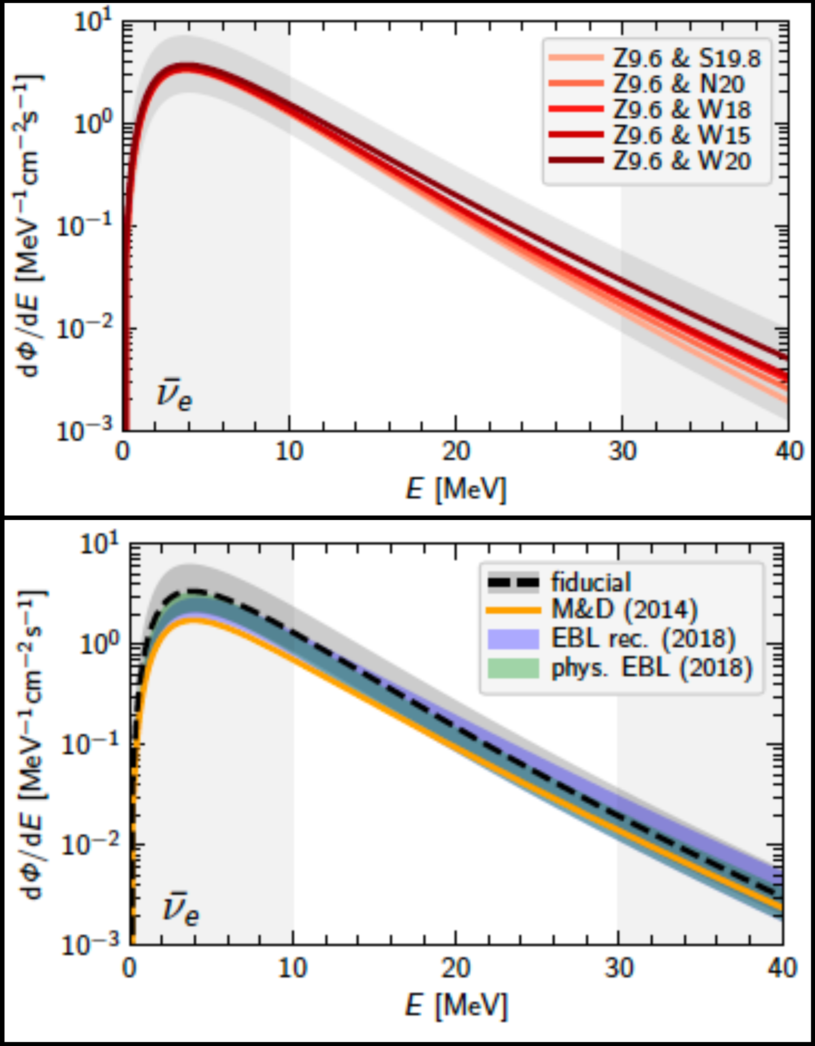


Horiuchi et al (2018)





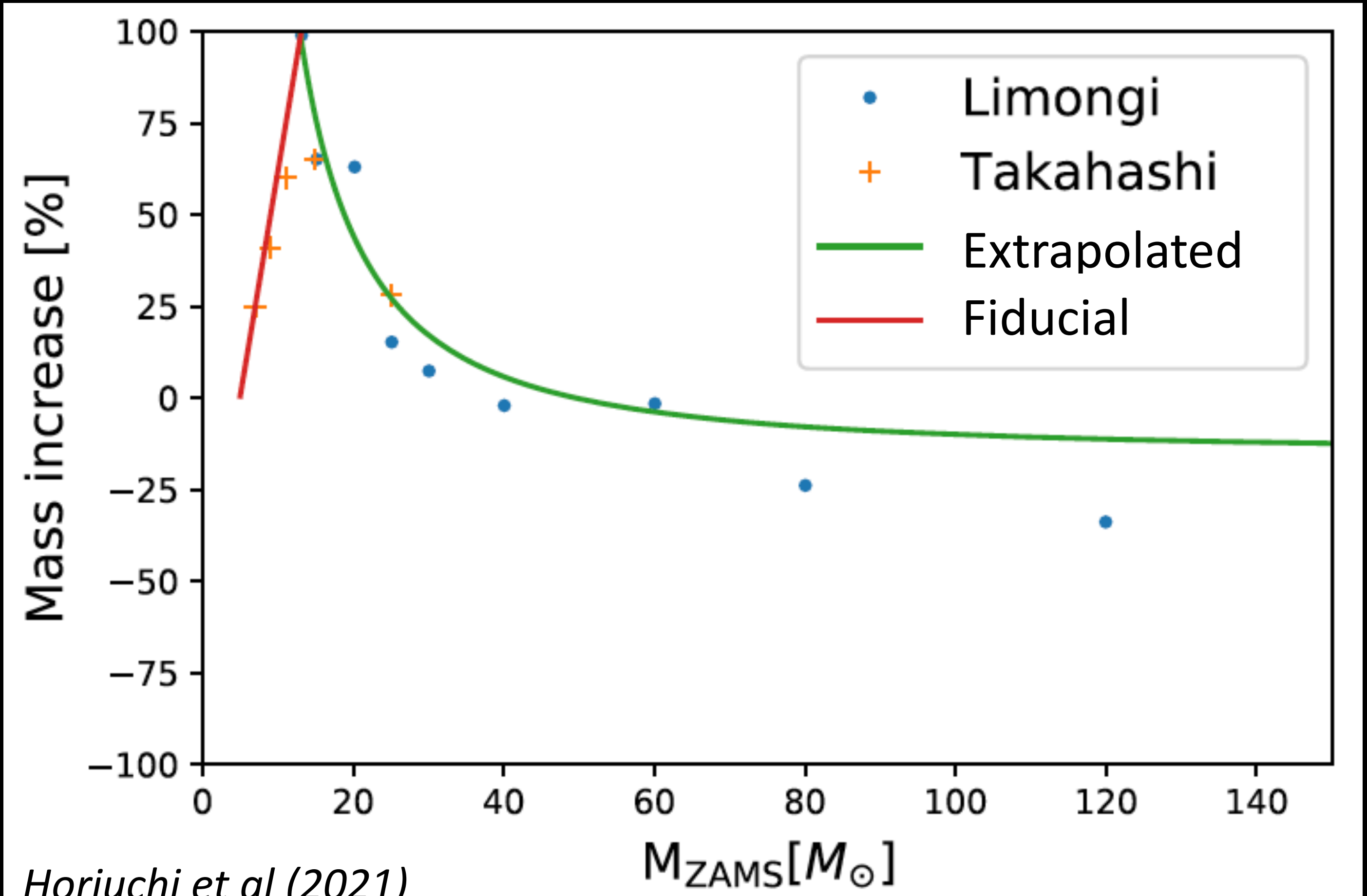
Engine Model	Successful SNe	Failed SNe
Z9.6 & S19.8	82.2%	17.8%
Z9.6 & N20	77.2%	22.8%
Z9.6 & W18	73.1%	26.9%
Z9.6 & W15	70.9%	29.1%
Z9.6 & W20	58.3%	41.7%



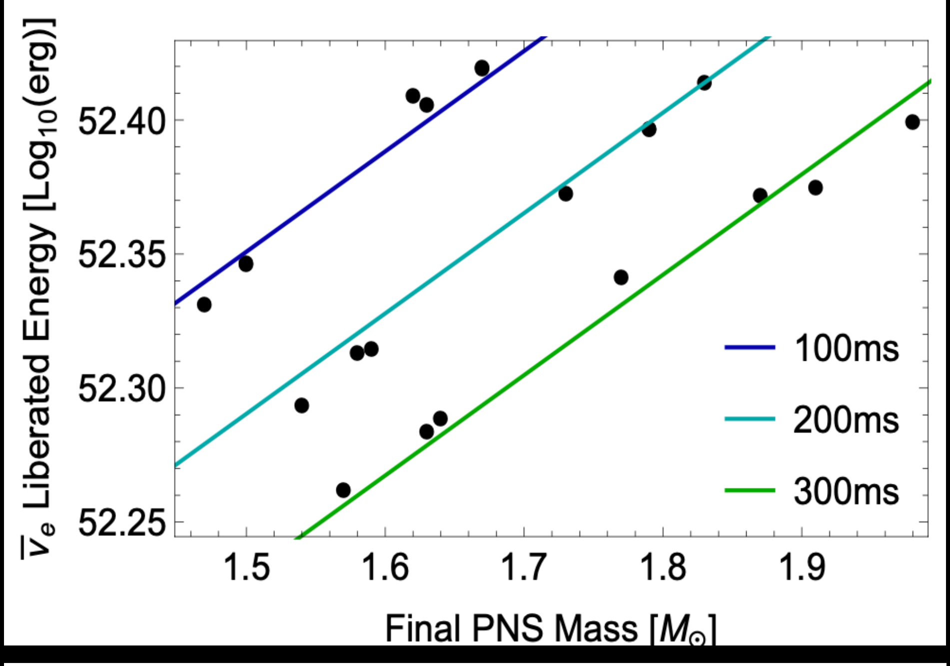
Kresse et al (2021)

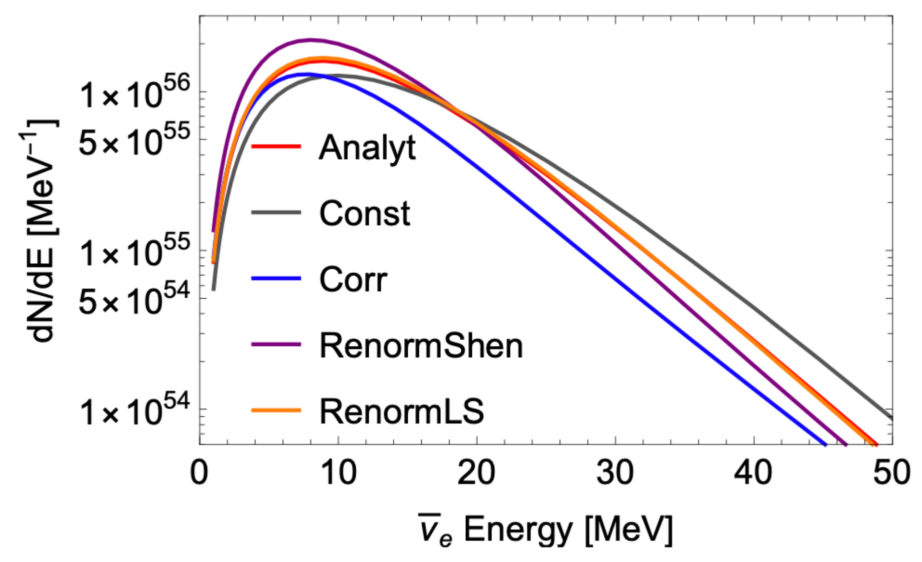
Core mass growth

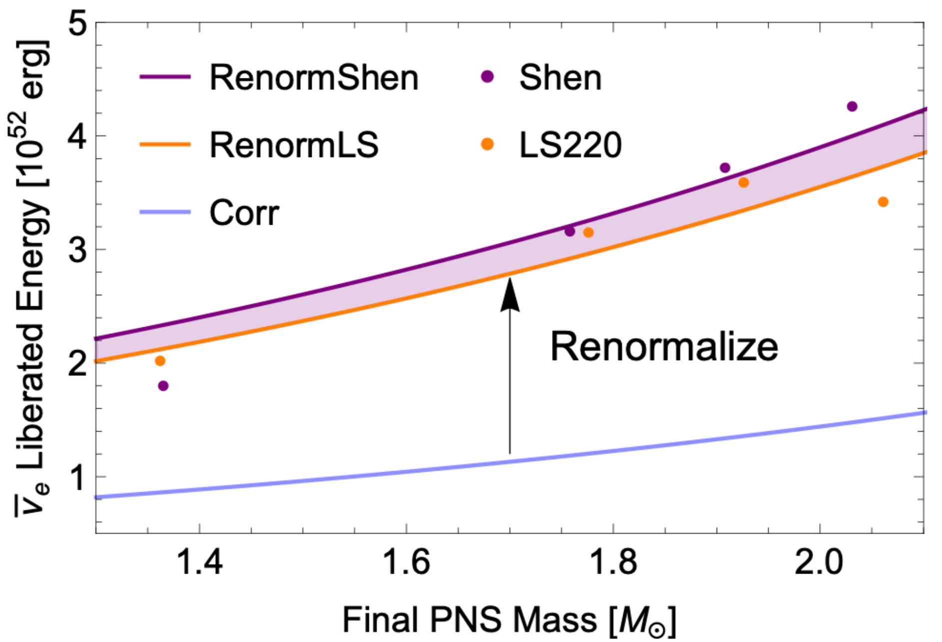
1. Extrapolated: Simple extrapolation
2. Fiducial: Numerical modeling
3. No rotation: Ignoring core mass growth (very conservative)



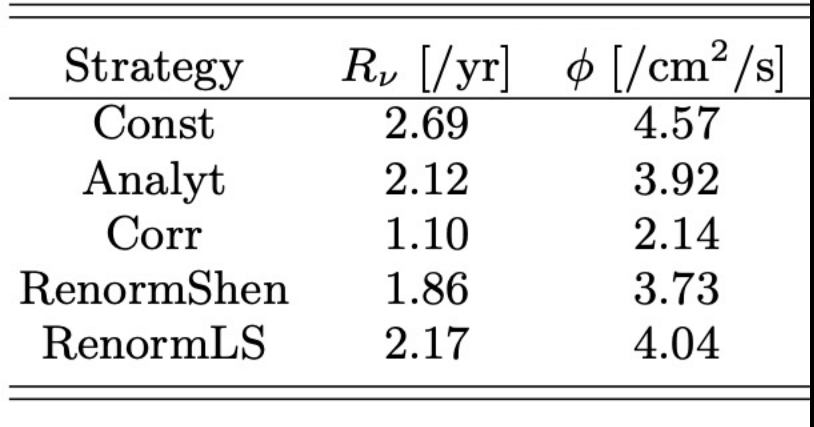
Horiuchi et al (2021)







DSNB fluxes and event rates



Strategy	R_ν [/yr]	ϕ [/cm^2/s]
Const	2.69	4.57
Analyt	2.12	3.92
Corr	1.10	2.14
RenormShen	1.86	3.73
RenormLS	2.17	4.04