

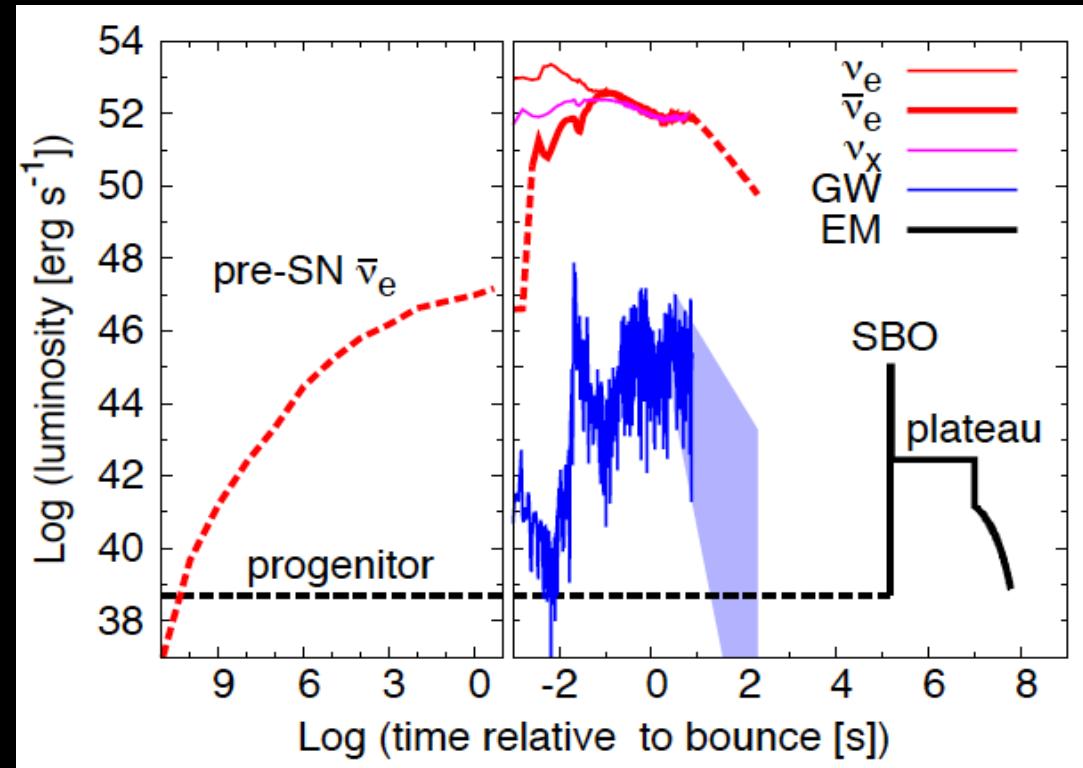
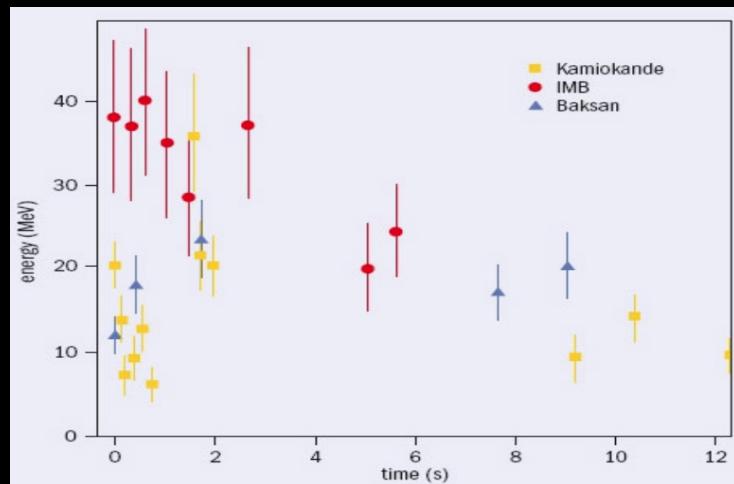
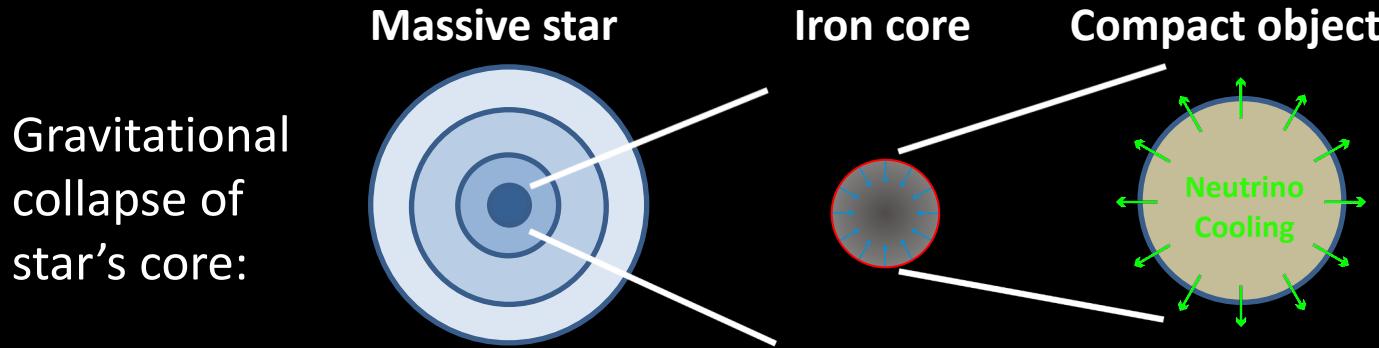
KITP, March 23rd 2022

# *Diffuse supernova neutrinos*

Shunsaku Horiuchi



# Core-collapse supernova



# *Importance of the neutrinos*

## **Energetically dominant component**

Neutrinos dominate the energetics of a core collapse

## **Explosion mechanism**

Neutrinos affect the dynamics, very likely also whether stars explode or not

## **Nucleosynthesis**

Neutrinos irradiate outgoing matter, affecting p/n ratios for nucleosynthesis

## **Birth of compact objects**

Collapse leaves behind neutron stars and stellar-mass black holes

## **Neutrino mixing**

Sites of interesting oscillation phenomena

## **BSM physics**

Neutrinos are a window for unique tests

# *Single vs multi events*

$N_v \gg 1$  : BURST

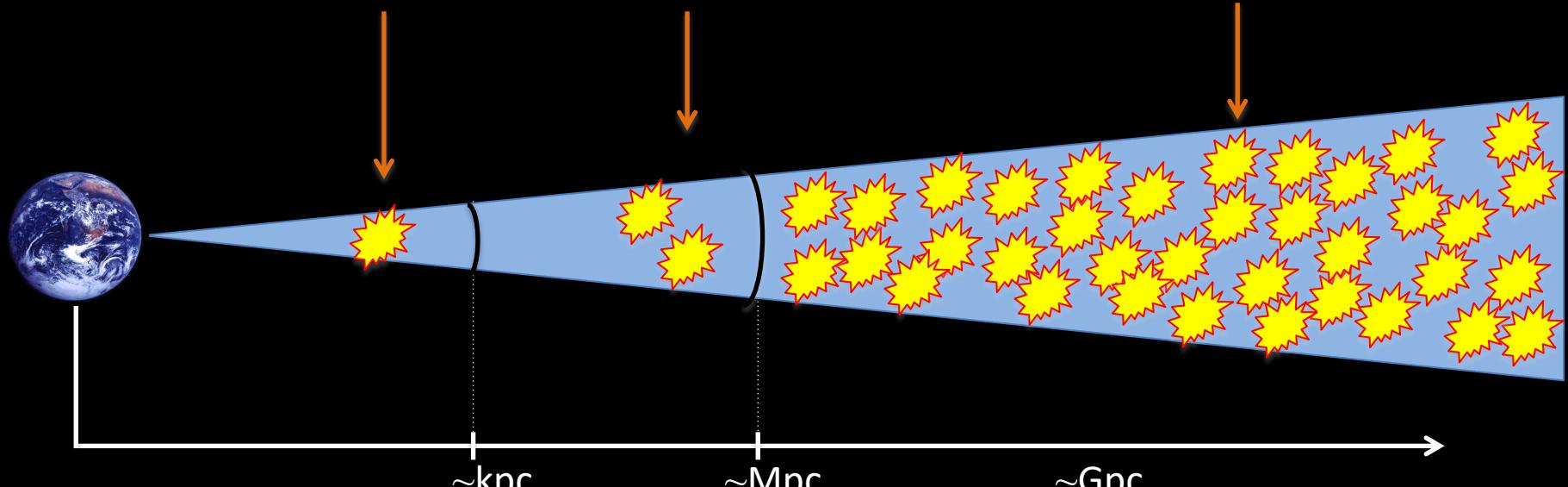
SN rate  $\sim 0.01$  /yr

$N_v \sim 1$  : MINI-BURST

SN rate  $\sim 1$  /yr

$N_v \ll 1$  : DIFFUSE

SN rate  $\sim 10^8$  /yr



*Adapted from Beacom (2012)*

- Rich data, multi-messenger
  - Precision on 1 progenitor
  - Surprises?
- No waiting
  - Many progenitors, population studies
  - Surprises?

# *Diffuse signal: ingredients*

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

Rate of massive star core collapse

Averaged neutrino emission from many core collapse

We know supernovae are occurring, and we know SN1987A emitted neutrinos  
→ Diffuse is a guaranteed signal

But, there are some 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 their rates?**
5. **How to detect a faint constant isotropic neutrino glow?**

# *What's the true core-collapse rate*

## **Supernova measurements**

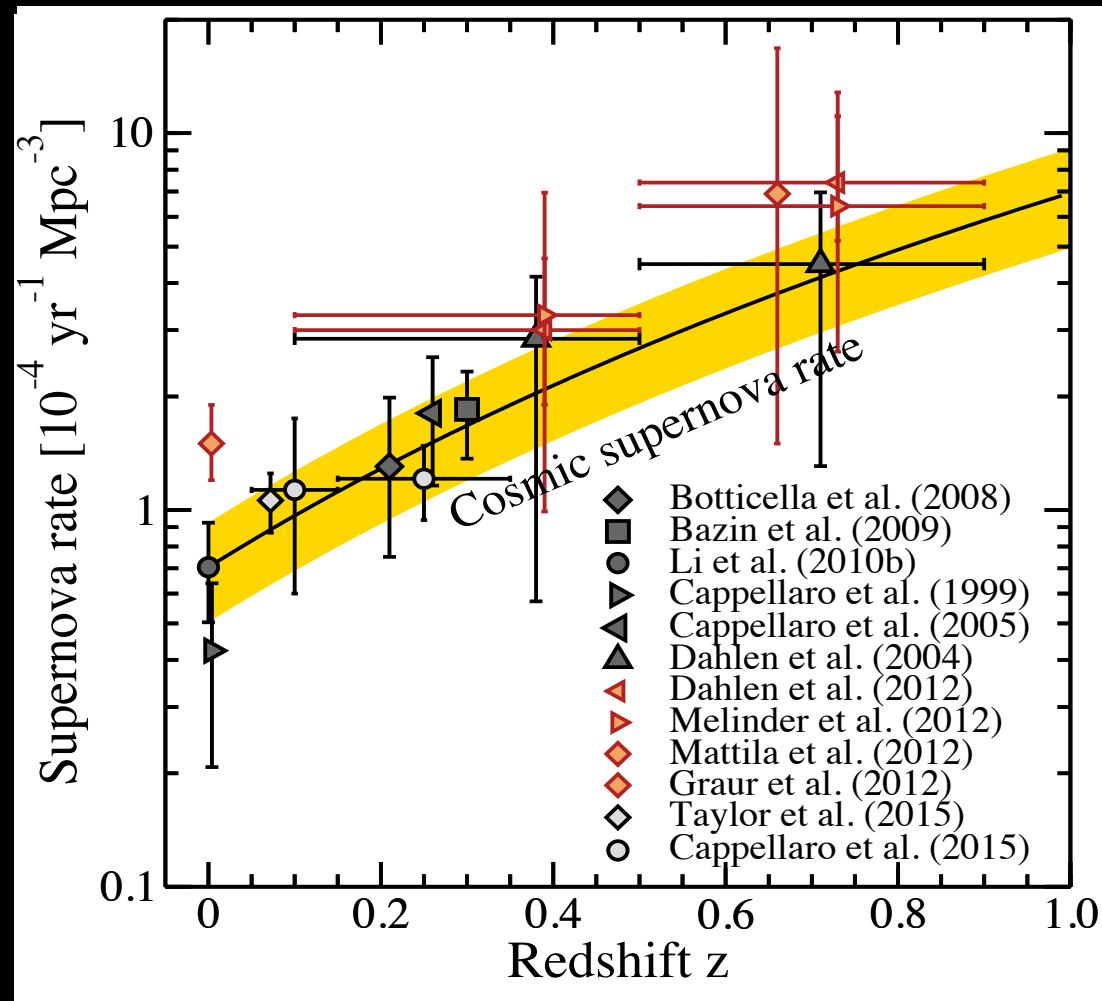
Improving quickly!

Note, two strategies:

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

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

e.g., Lien & Fields (2009)

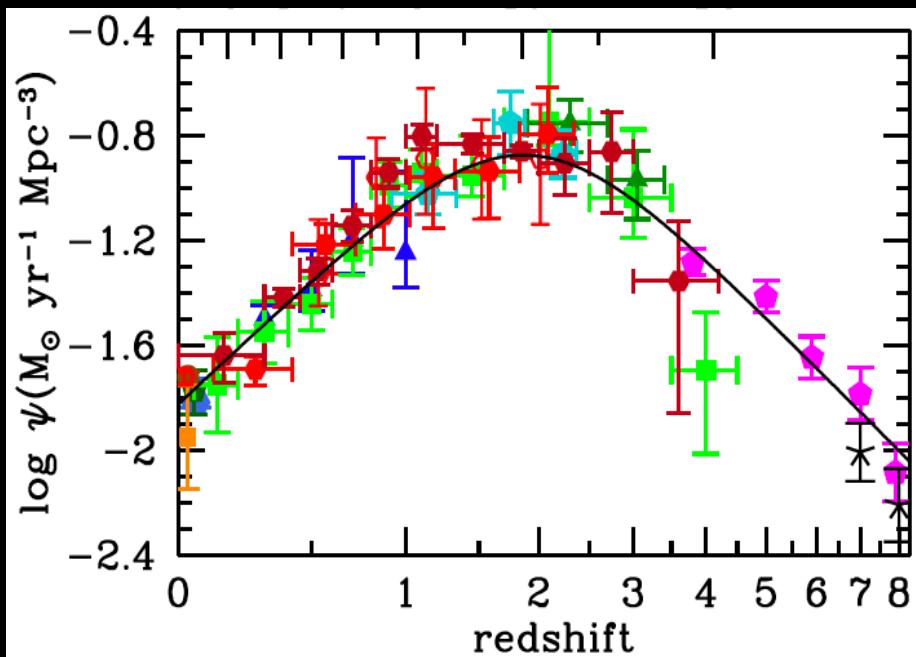


*Updated from Horiuchi et al (2011)*

# Star-formation rate gives us confidence

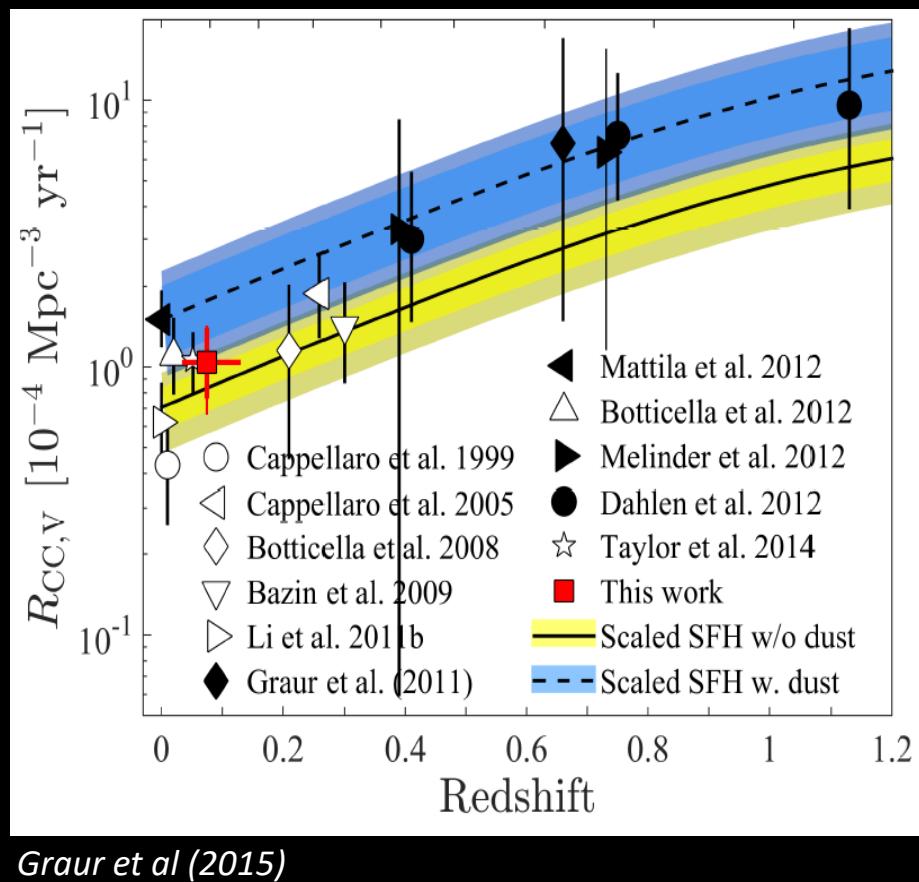


Formation rate of stars: many groups, many wavebands, many data sets

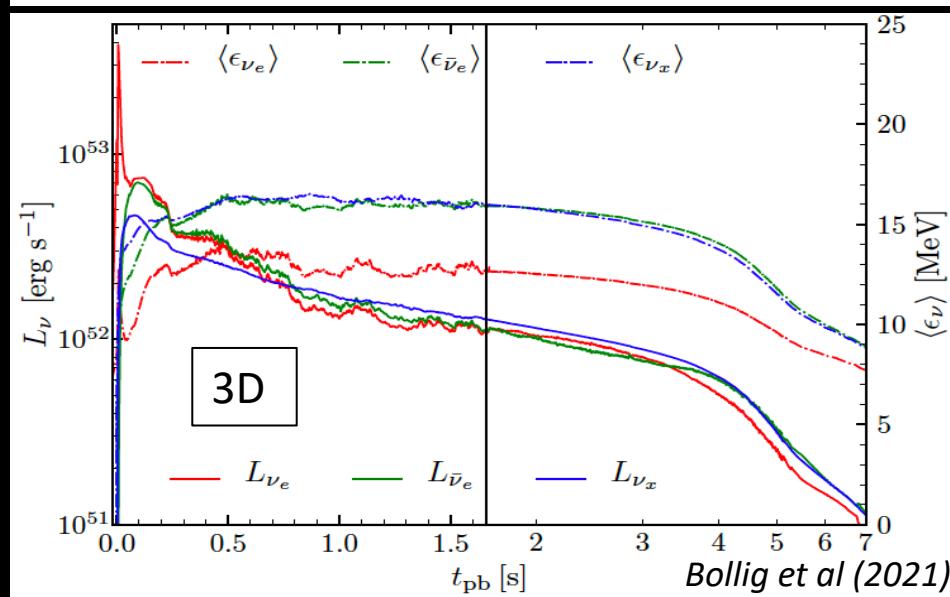
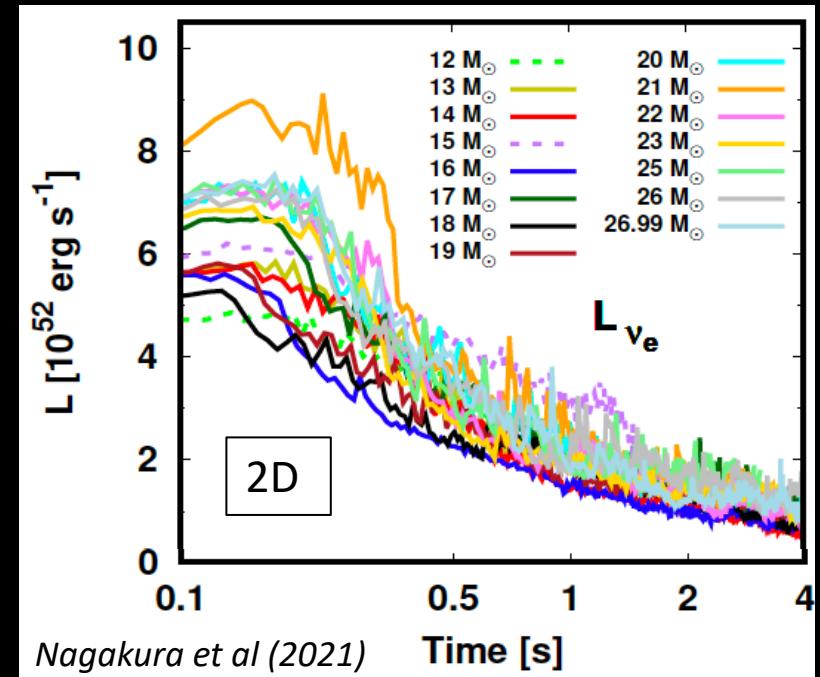
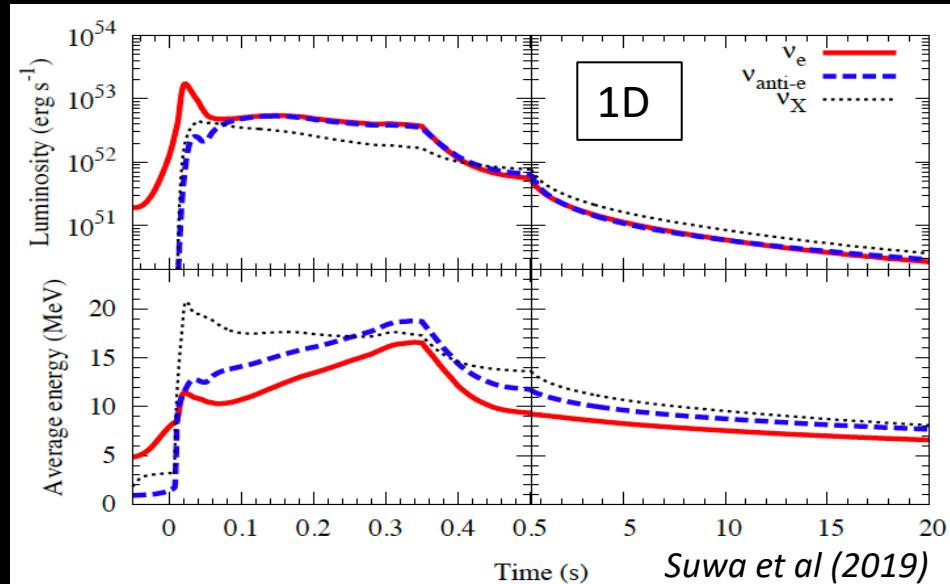


Madau & Dickinson (2014); see also Hopkins & Beacom (2006), Horiuchi et al (2011)

Comparison:



# Long-term simulations

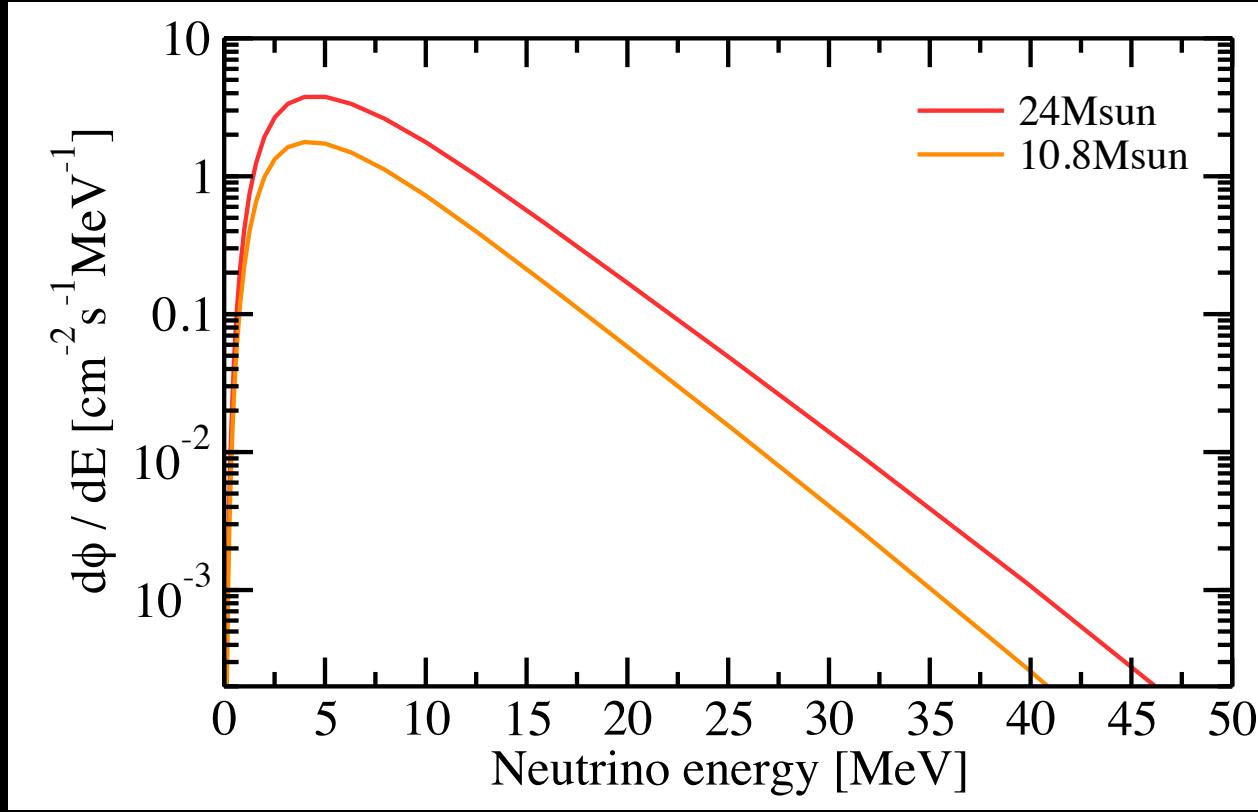


Growing availability of long-term (~10) sec simulations

See also: Fischer et al (2009), Hudepohl et al (2010), Nakazato et al (2013), Nakamura et al (2016), Sumiyoshi et al (2019), Li et al (2020)

# *Predicting the DSNB*

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

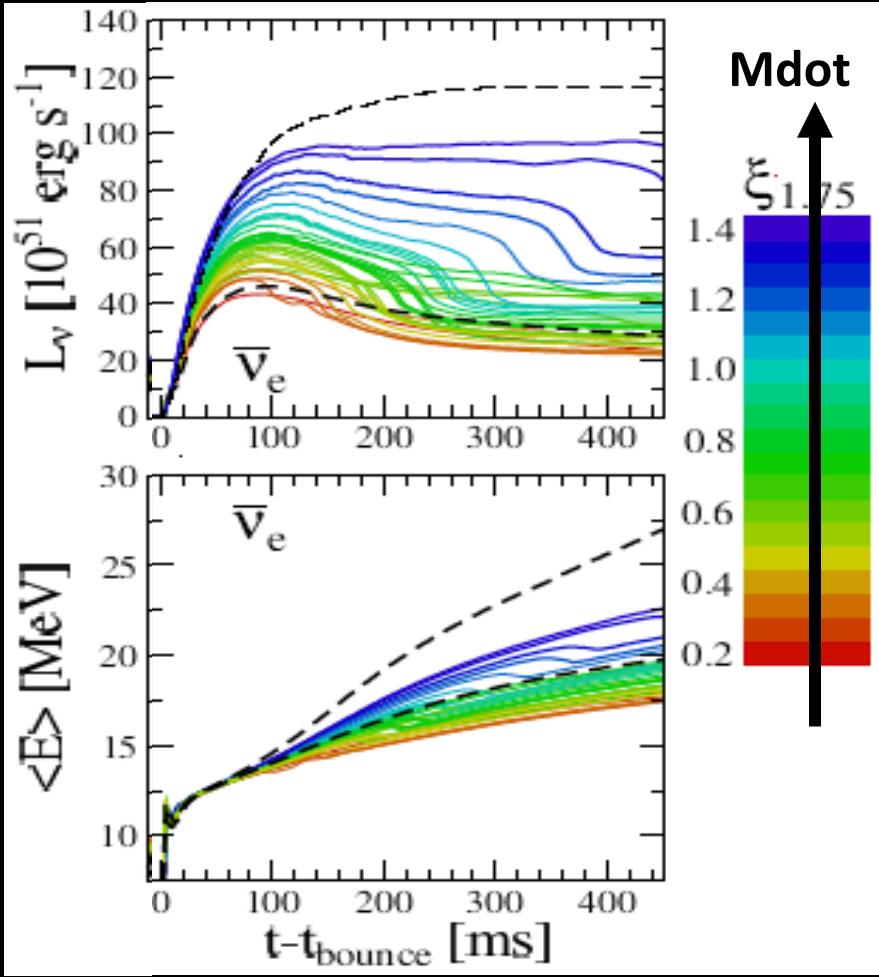


Many predictions, eg: Bisonatyi-Kogan & Seidov (1984), Krauss et al (1984), Totani et al (1996), Hartmann (1997), Kaplinghat et al (2000), Fukugita & Kawasaki (2003), Ando & Sato (2004), Strigari et al (2005), Lunardini (2006), Yuksel & Beacom (2007), Ckahrabarty et al (2008), Horiuchi et al (2009),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

# Diversity in neutrino emission

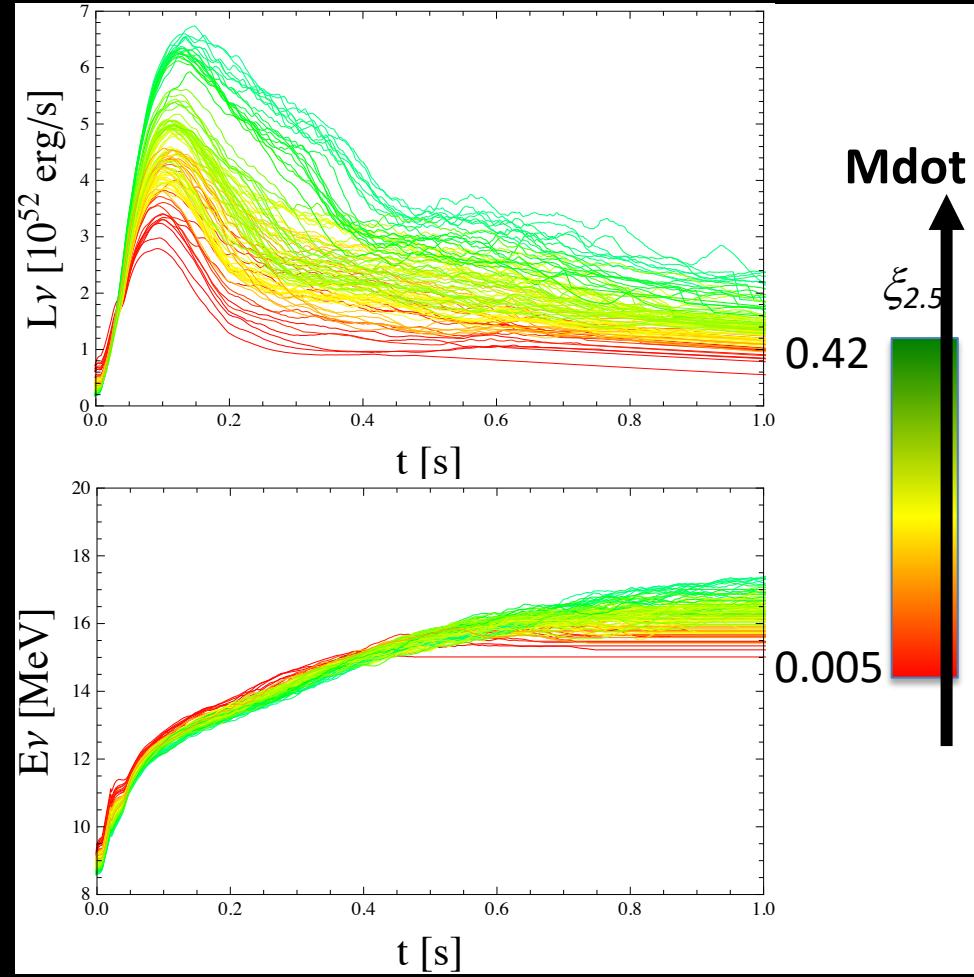
Variations: neutrino light curve reflects the progenitor's properties (density)

1D simulations



O'Connor & Ott (2013)

2D simulations

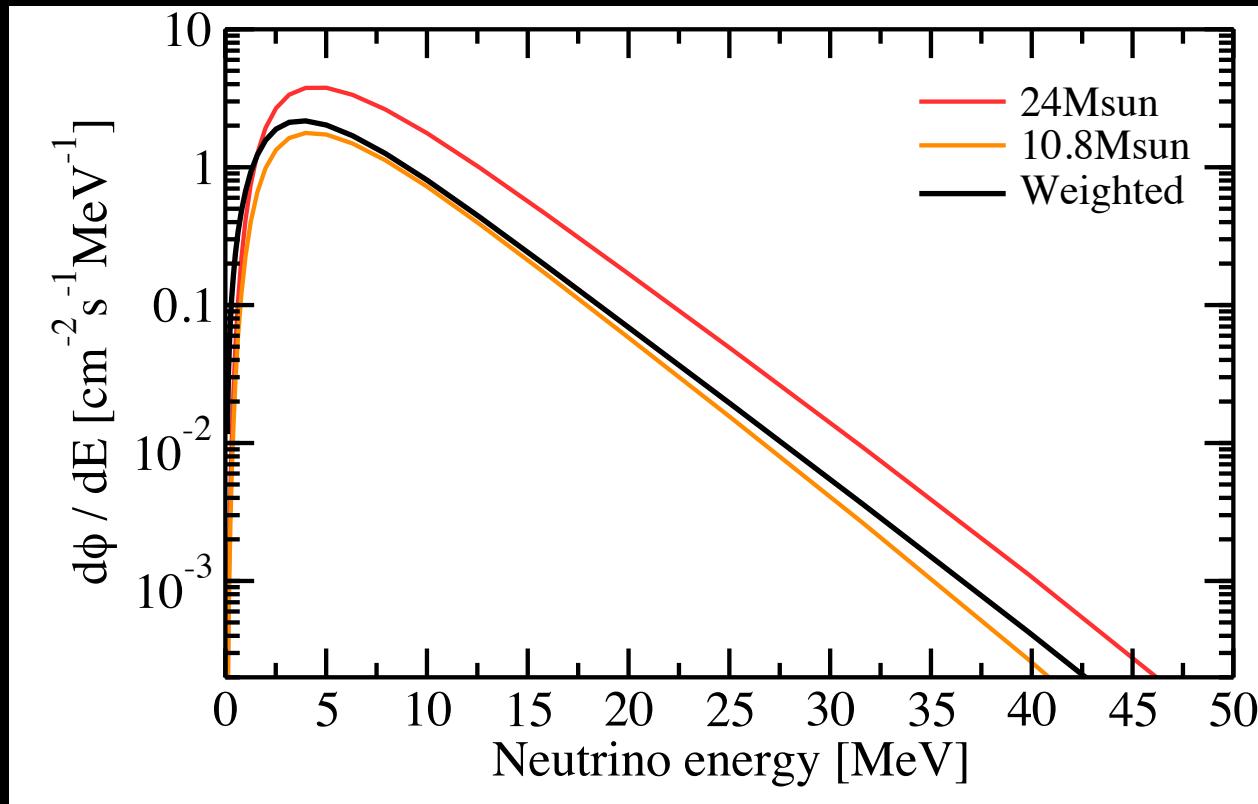


Horiuchi et al (2017) based on Nakamura et al (2015)

# *Predicting the DSNB*

The predicted DSNB flux spectrum, weighted by massive star populations

- For a Salpeter initial mass function



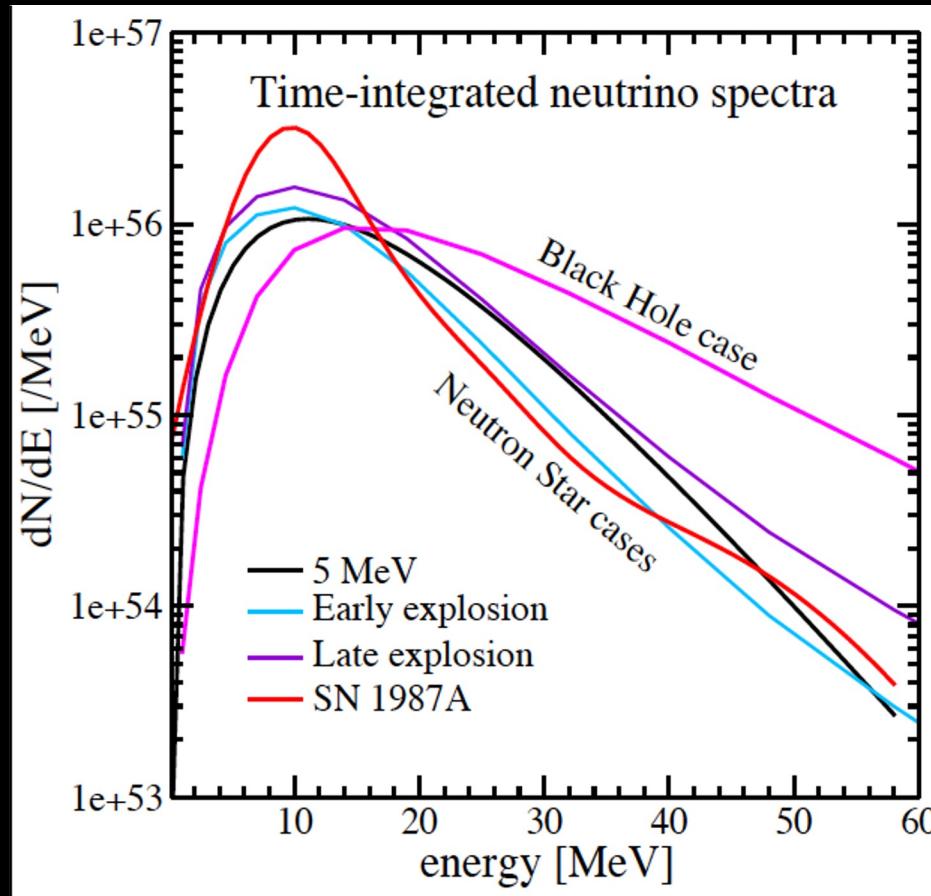
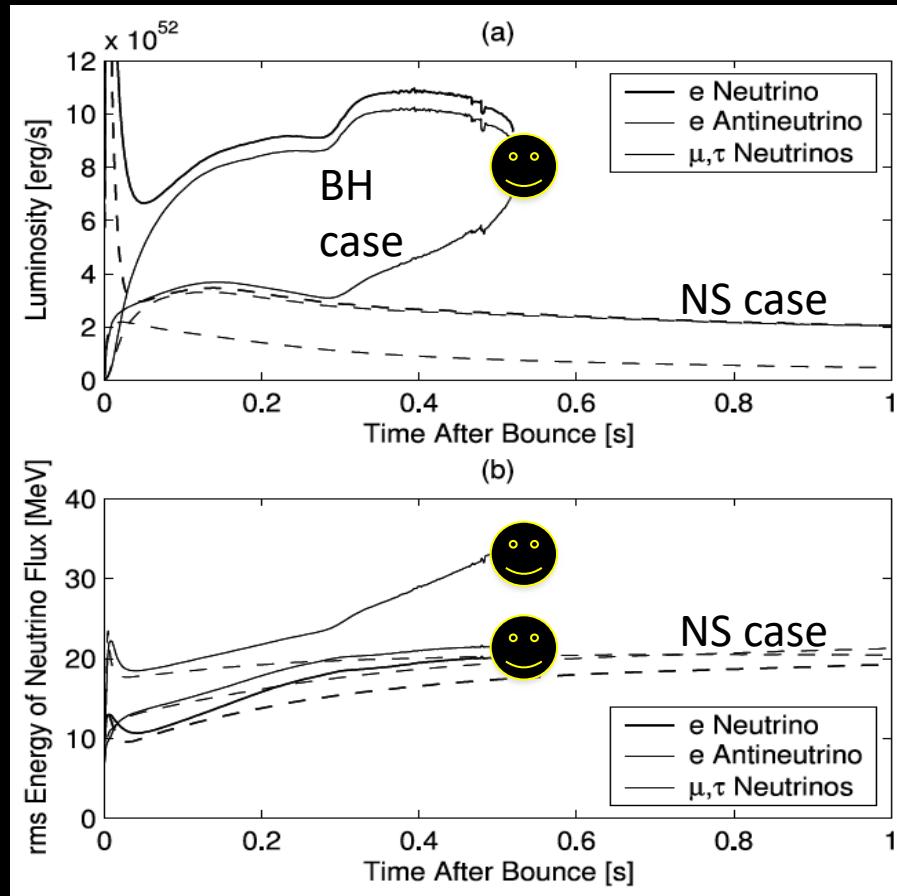
*Horiuchi et al (2018); see also Kresse et al (2021)*

# Neutrinos from BH channel

## Neutrinos from collapse to black hole

Black hole formation goes through high mass accretion

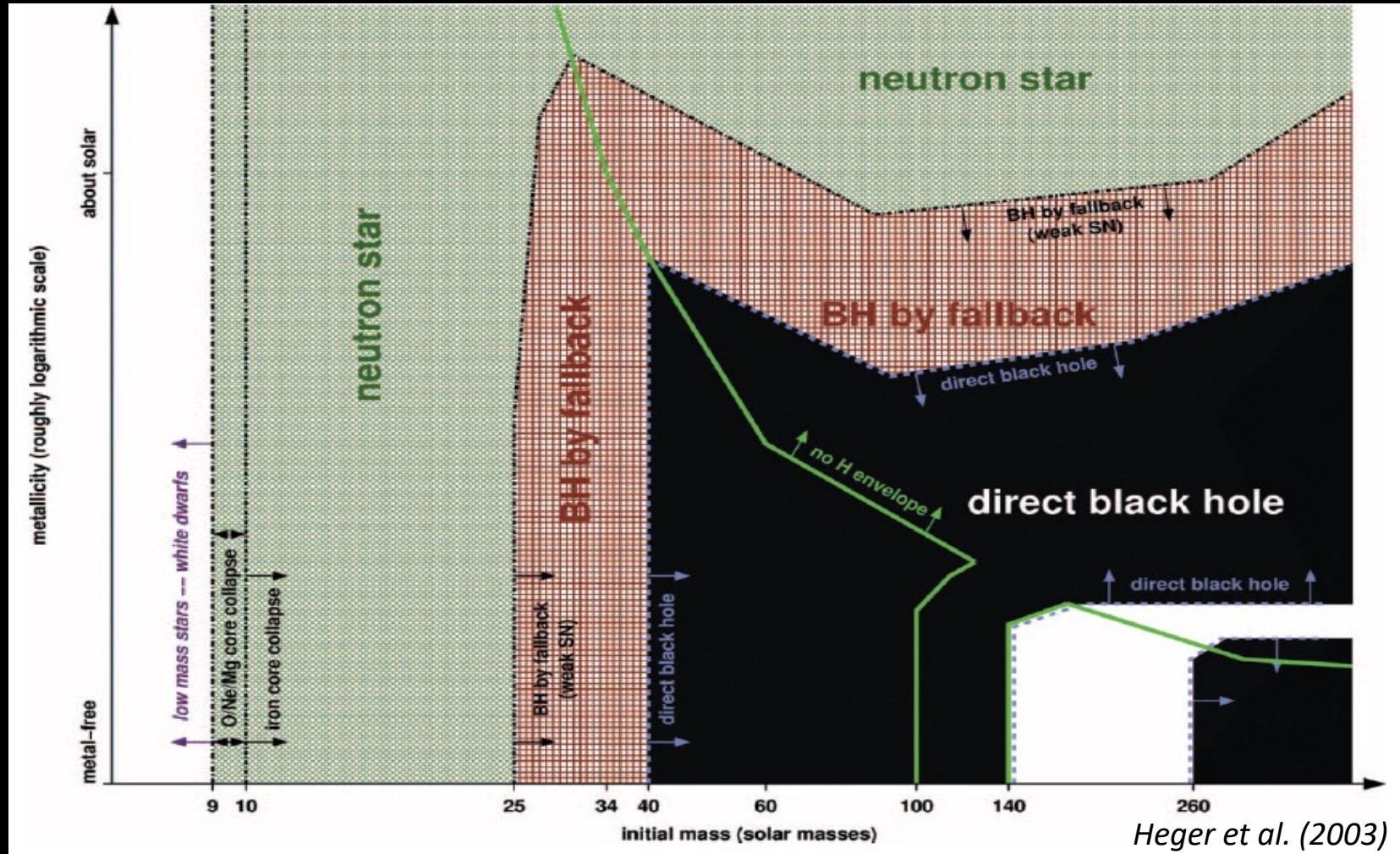
→ ν emission is more luminous and hotter (quantitatively EOS dependent)



# Which stars collapse to black holes?

The expectation circa 2000:

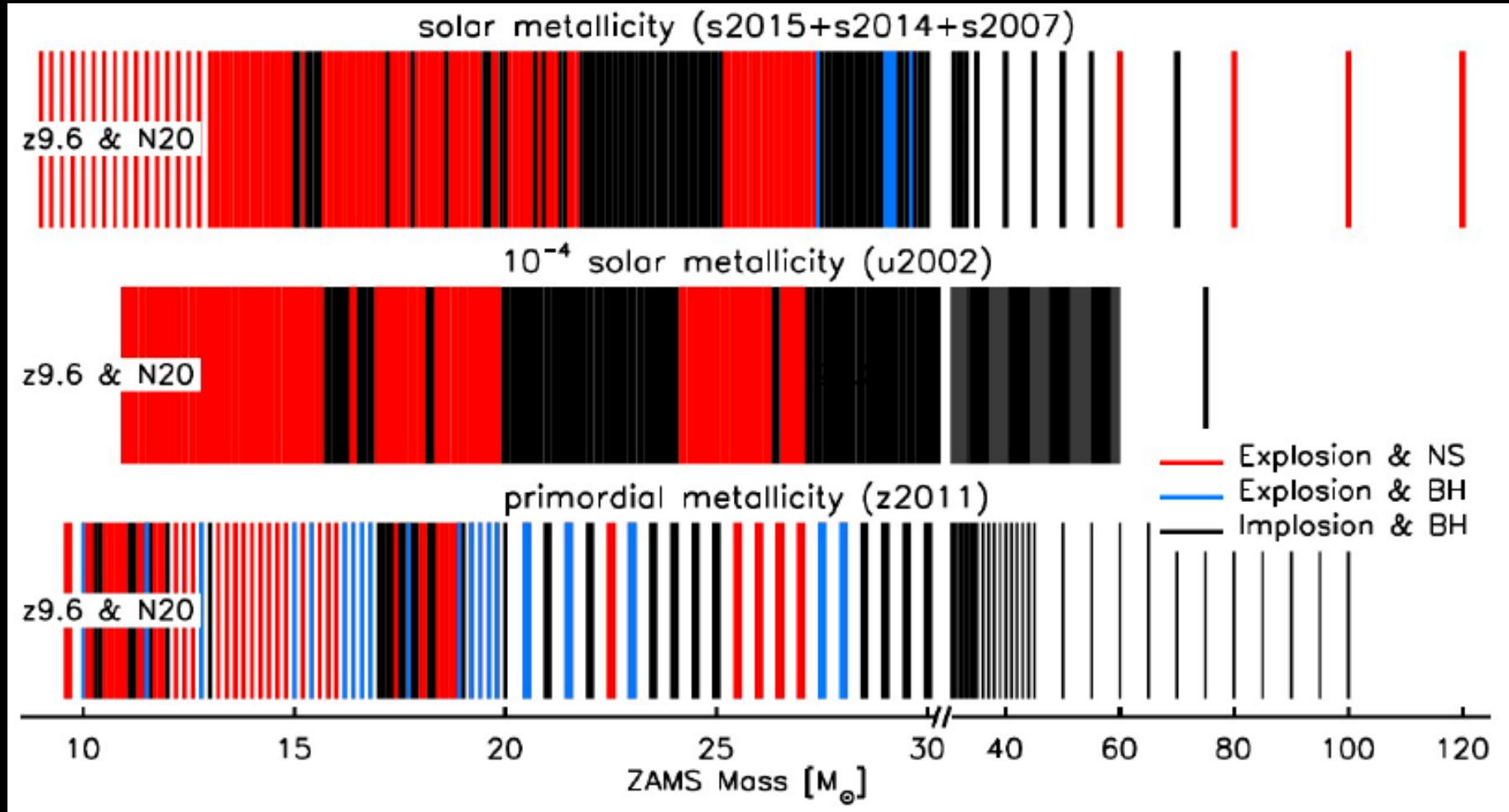
Qualitative expectations, no binaries, no rotation, metal-driven mass loss only



# Which stars collapse to black holes?

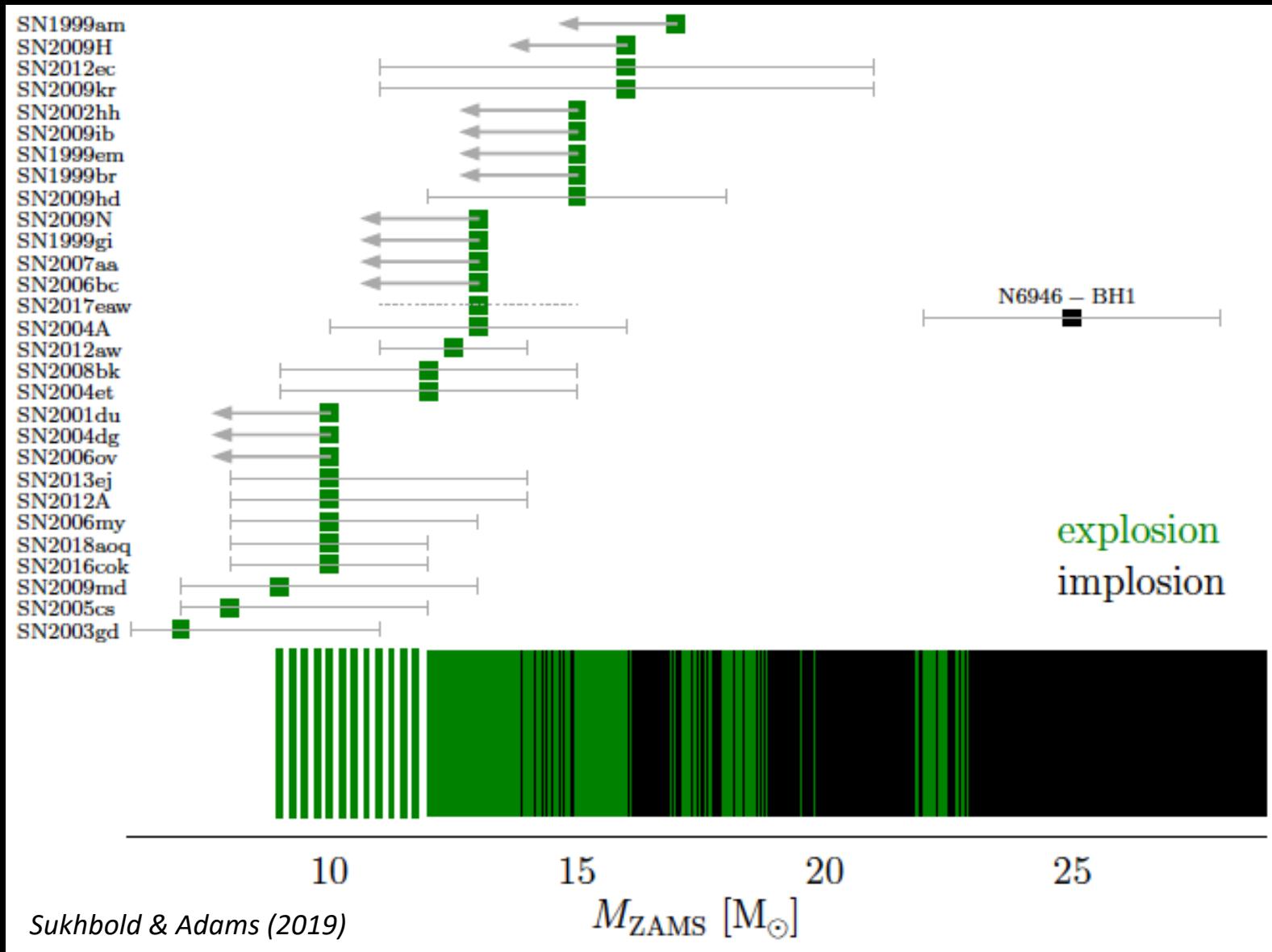
Emerging picture:

Thinking in mass looks incomplete. Trends are deeply connected to progenitor.



Janka 2017; see also O'Conno & Ott (2011), Ugliano et al (2012), Horiuchi et al (2014), Pejcha & Thompson (2015), Shunsaku Horiuchi Nakamura et al (2015), Ertl et al (2016), Sukhbold et al (2016), Mueller et al (2016), Kresse et al (2021) 14

# *Observational landscape*

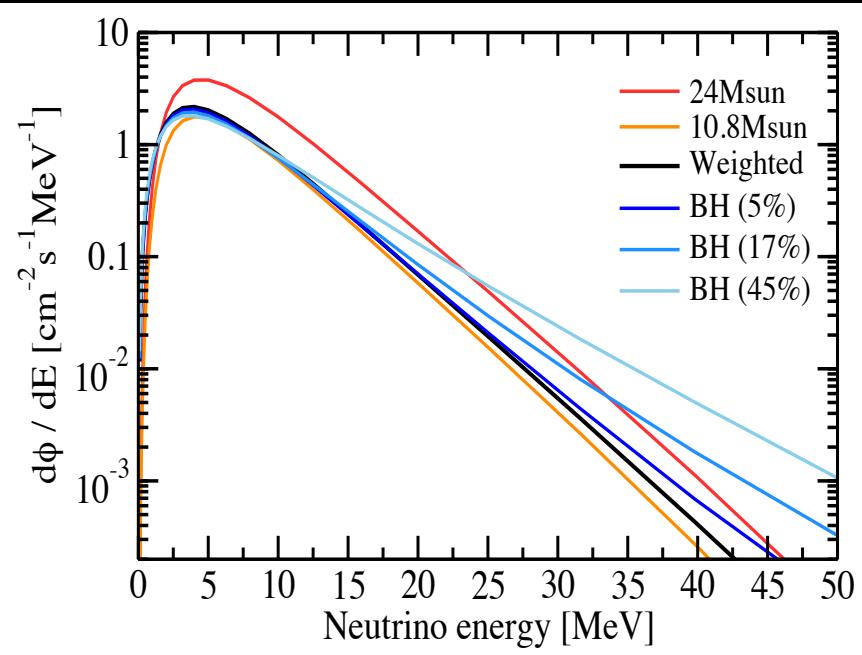


# Predicting the DSNB

The predicted DSNB flux spectrum, including collapse to black holes

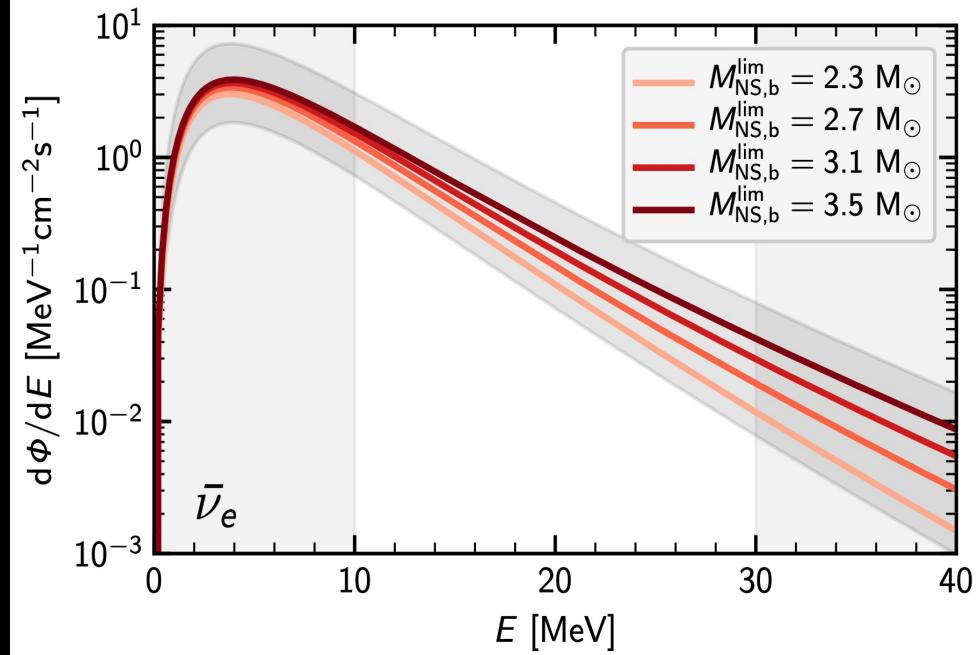
- Depends on BH fraction
- But also, EOS

BH fraction dependence



Horiuchi et al (2018)

EOS dependence



Kresse et al (2021)

# *Account for binary effects*

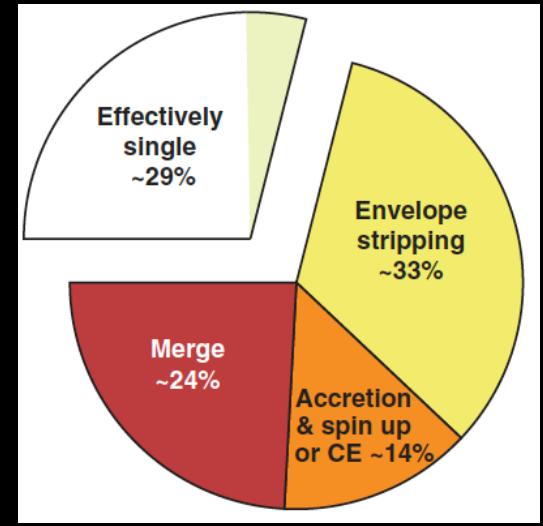
The majority of massive stars evolve in binaries

**Non-merger  
systems**

**Merger systems**

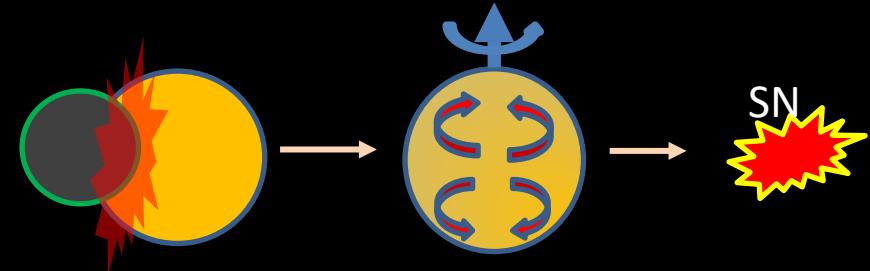
Single

Double



Sana et al (2012)

Spinning massive star

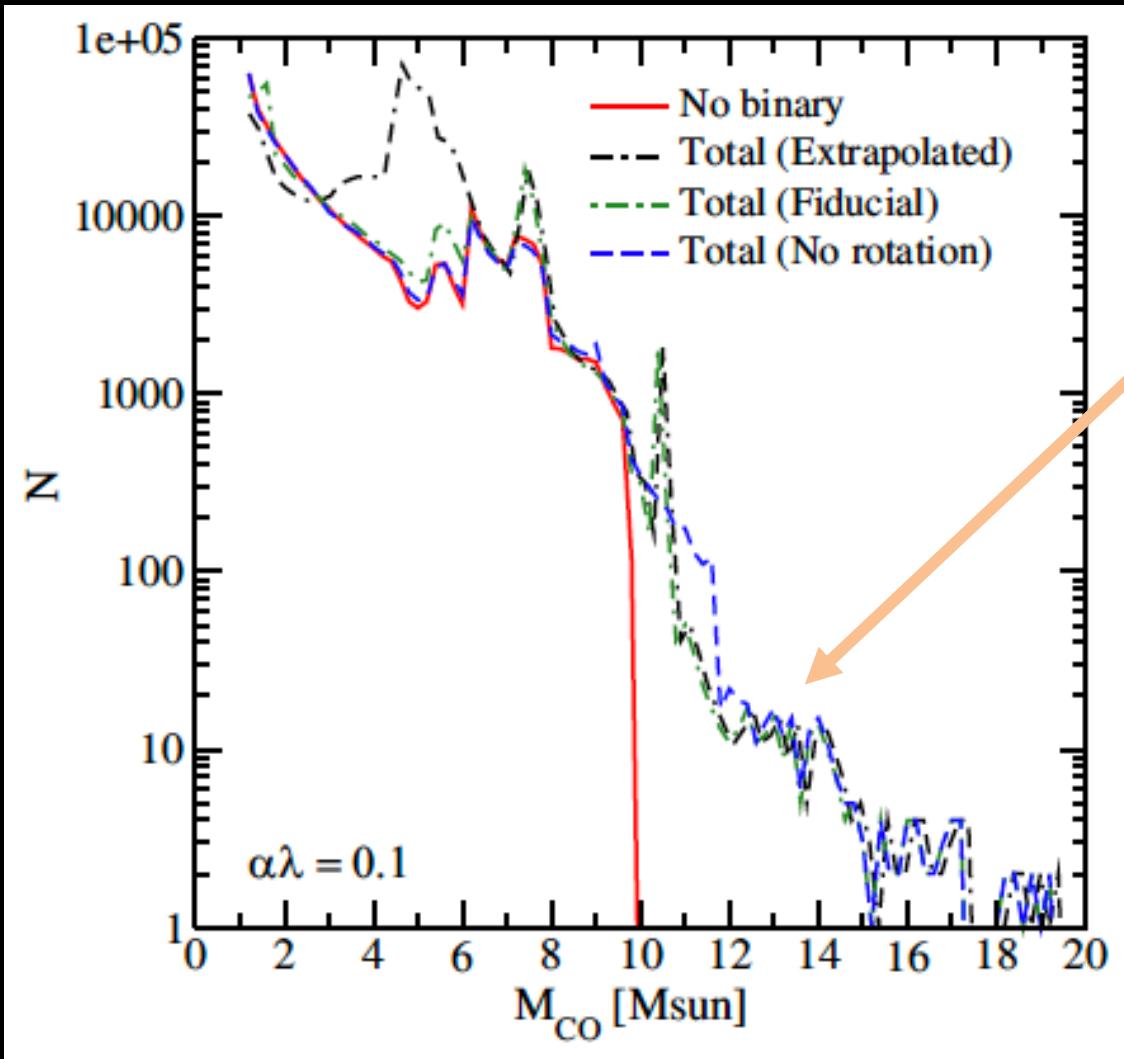


→ Masses of stars changed

→ Masses of stars changed &  
number of stars changed

# *Impact on stellar populations*

## Distribution of stellar core masses



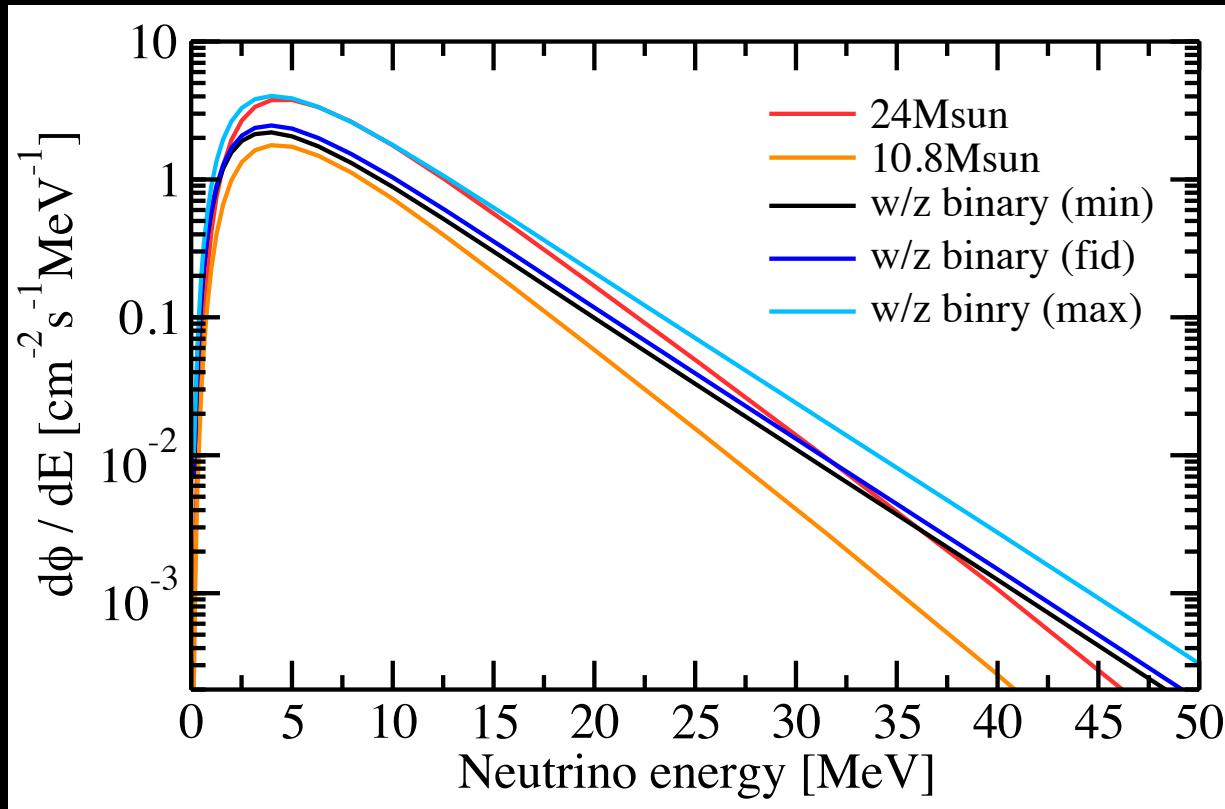
Many more high CO mass progenitors due to mass transfer & mergers

Summing over masses, we see increase in numbers too:

- Extrapolated: +75%
- Fiducial: +25%
- No rotation: +few %

# *Predicting the DSNB*

The predicted DSNB flux spectrum, including binary effects



*Based on Horiuchi et al (2021)*

# *Predictions: bottom line*

**Standard physics guarantees a diffuse signal**

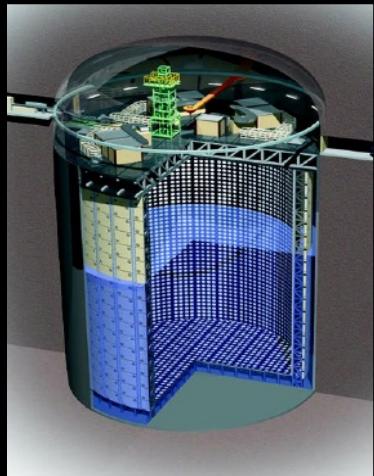
- Supernovae going off regularly in Universe
- Neutrinos observed in SN1987A
- Flux is a few  $\text{cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$

**Many uncertainties, each contributing at the tens % level, each improving rapidly**

- The true core-collapse rate
- Neutrino emission model
- Black hole occurrence and modeling
- Binary effects

# *Diffuse signal detection 202x*

Super-Kamiokande



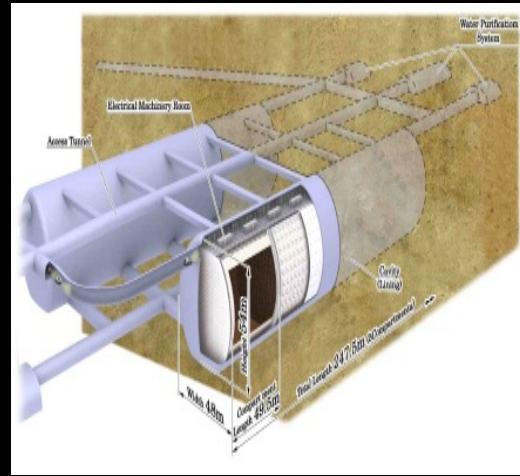
50 kton water  
*Running*

DUNE



40 kton Lq Ar  
*Building*

Hyper-Kamiokande



260 kton water  
*Building*

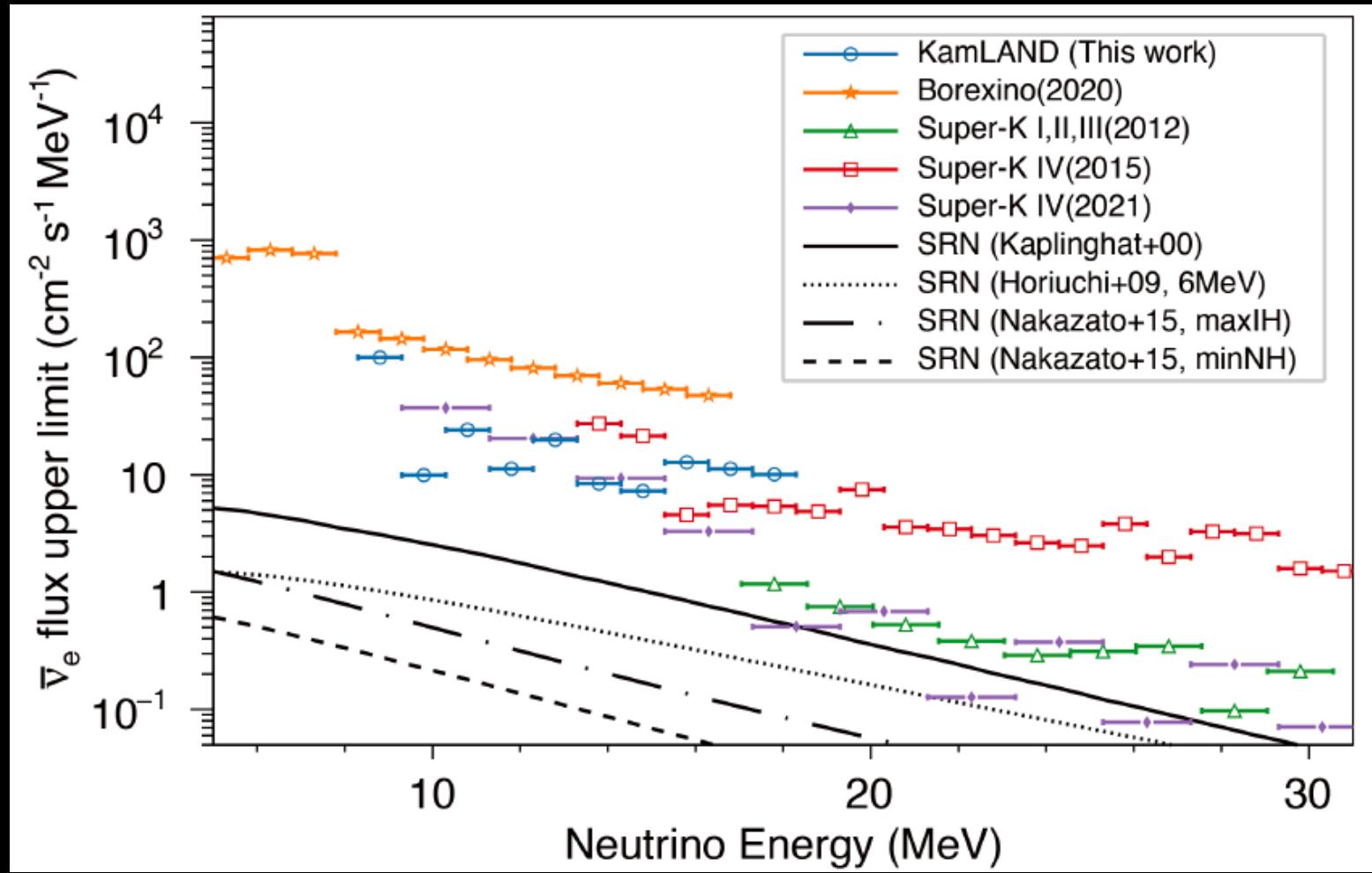
Rock minerals



< 1 gram rock  
*R & D*

# Search limits

Nuebar limits: reaching factor of a few from theory predictions

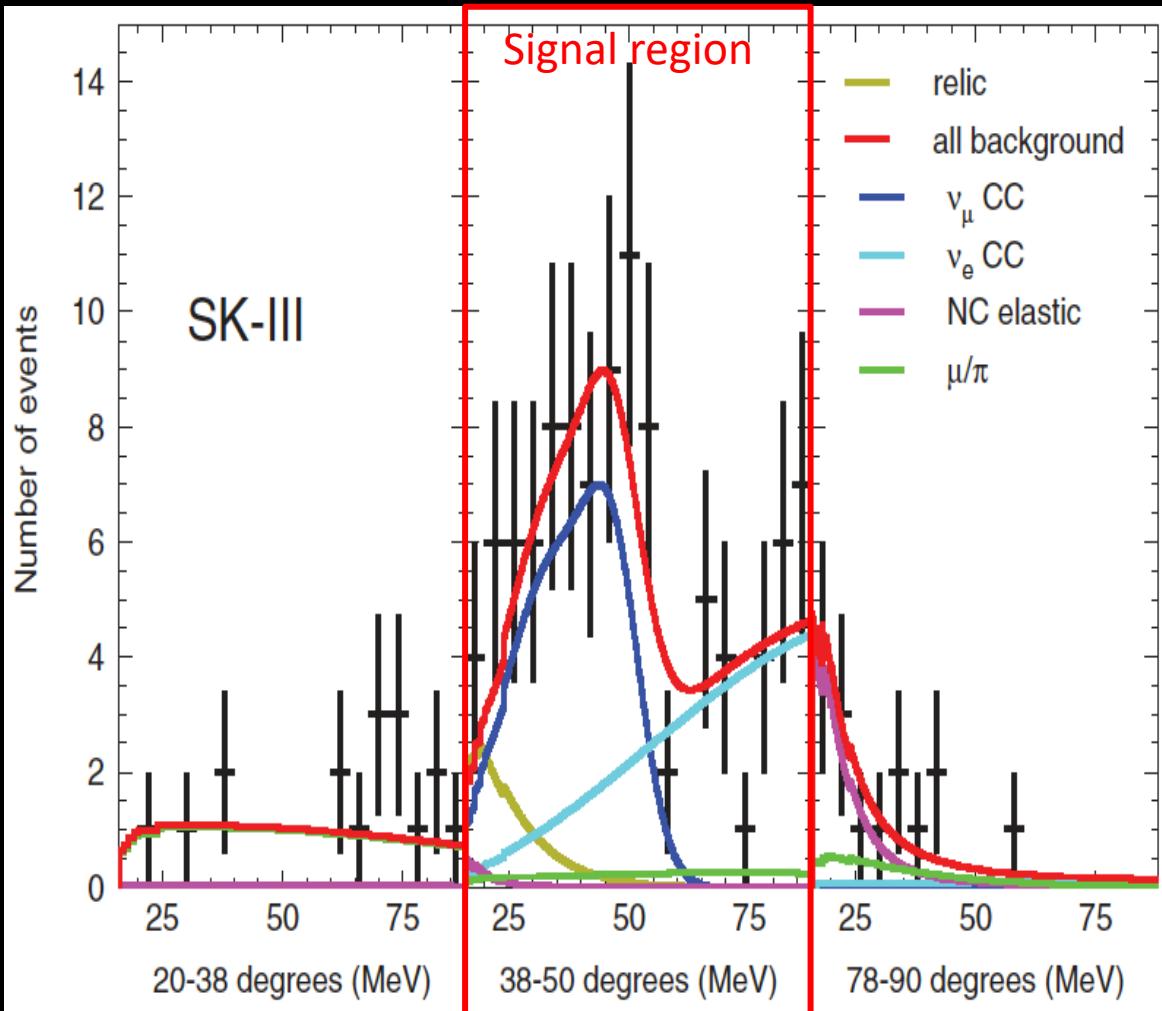


Super-K, KamLAND (2021)

# Backgrounds

Main background is invisible muons

$$\mu^\pm \rightarrow e^\pm + \nu_e + \nu_\mu \quad \bar{\nu}_e + p \rightarrow e^+ + n$$



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

[19 – 34 MeV, 90%CL]

*Zhang et al (1988)*

Super-K (SK-I)  
Flux  $< 1.2 \text{ cm}^{-2} \text{ s}^{-1}$

[>19.3 MeV, 90%CL]

*Malek et al (2003)*

SK-I, II & III:  
Flux  $< 3.1 \text{ cm}^{-2} \text{ s}^{-1}$

[> 17.3 MeV, 90%CL]

*Bays et al (2012)*

*Low-E update, Zhang et al (2015)*

SK-I to IV:  
Flux  $< 2.7 \text{ cm}^{-2} \text{ s}^{-1}$

[> 17.3 MeV, 90%CL]

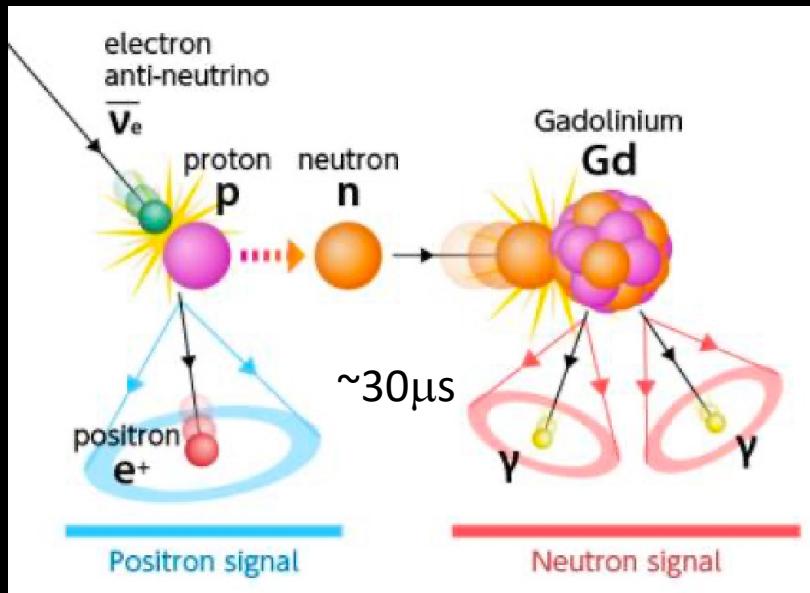
*Abe et al (2021)*

*Bays et al (2012)*

# *Into the era of gadolinium*

Transforms into a signal limited search

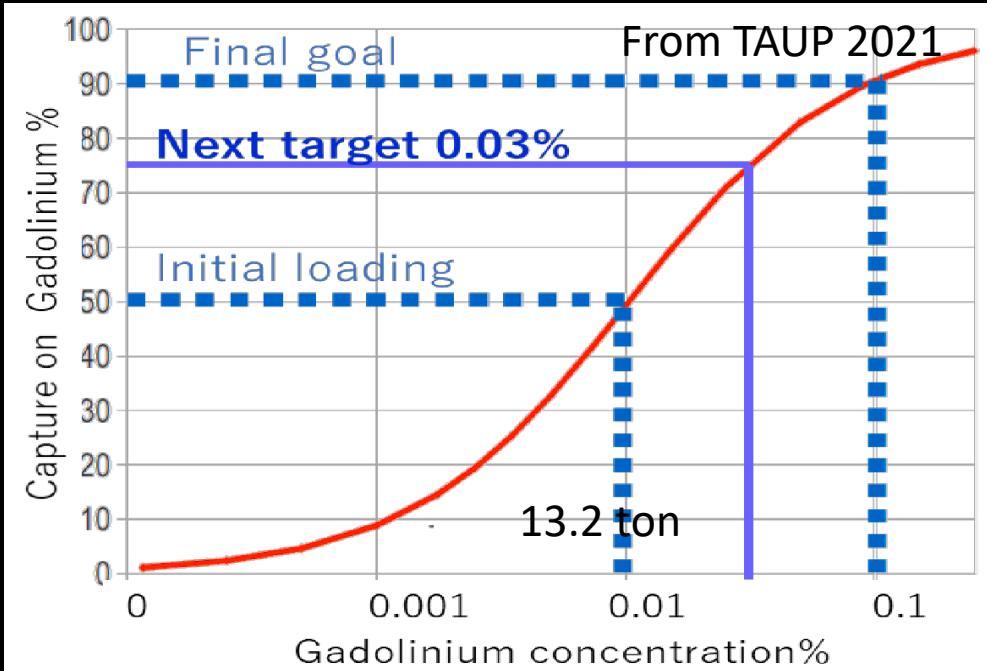
The neutrino “heartbeat” IDs IBD events



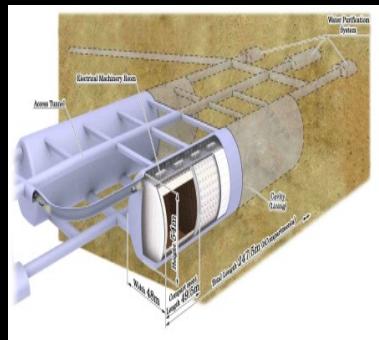
Typical DSNB rates at SK+Gd

Model	Events [/yr]
All NS	1.7
5% BHs	1.9
17% BHs	2.8

Evaluating  
Gadolinium's  
Action on  
Detector  
Systems



# Future detectors



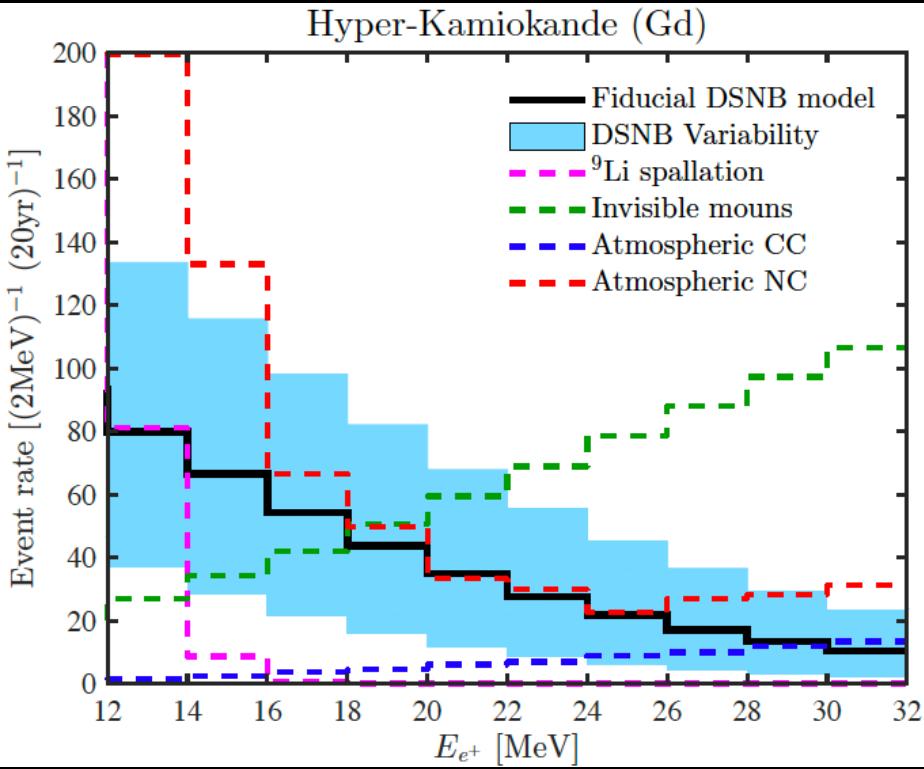
Hyper-Kamiokande

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



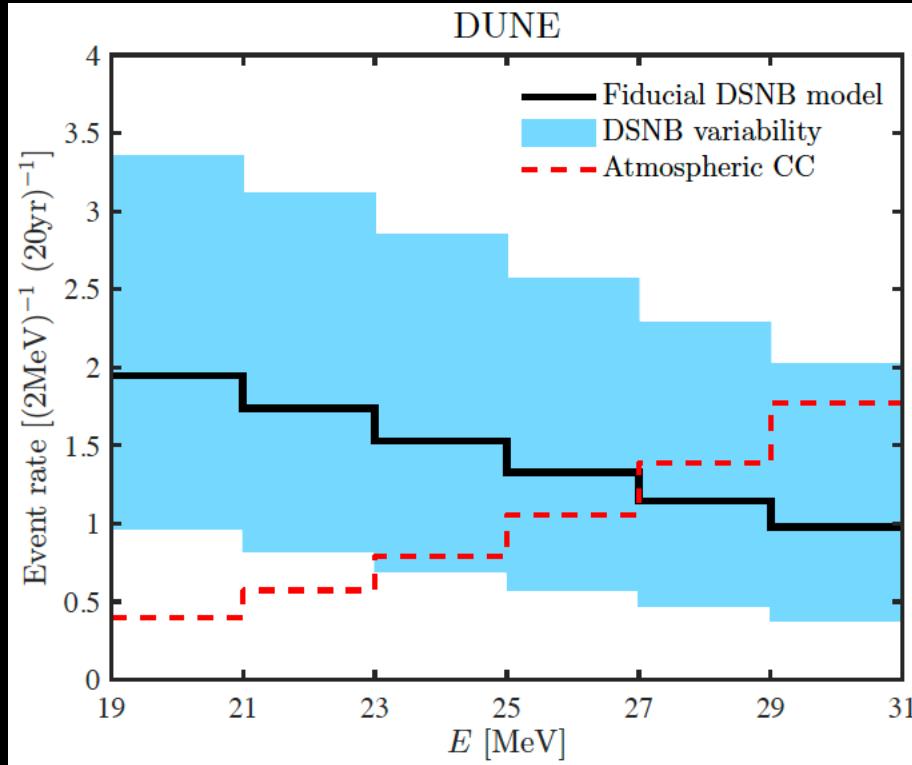
DUNE

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



Moller et al (2018)

Shunsaku Horiuchi



Moller et al (2018)

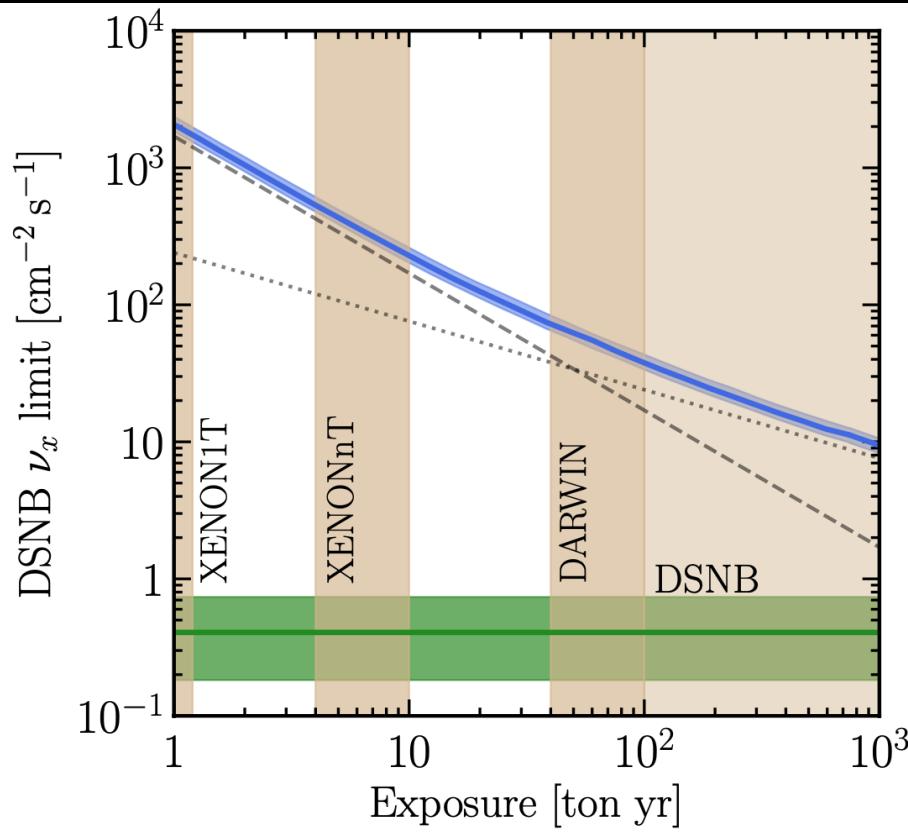
# Future detectors



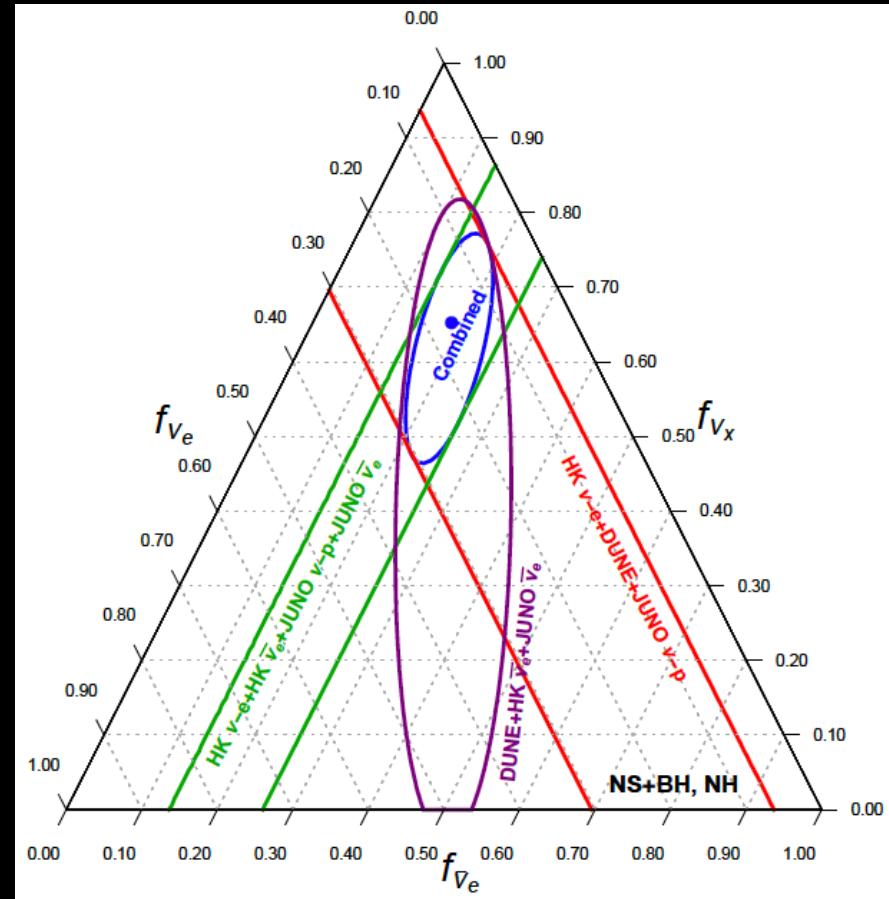
Direct DM detector

- Solar & atm. bkgns
- CEvNS for all flavor
- Limits on  $\nu_x$

...measuring heavy lepton flavor is challenging...



Suliga et al (2021)



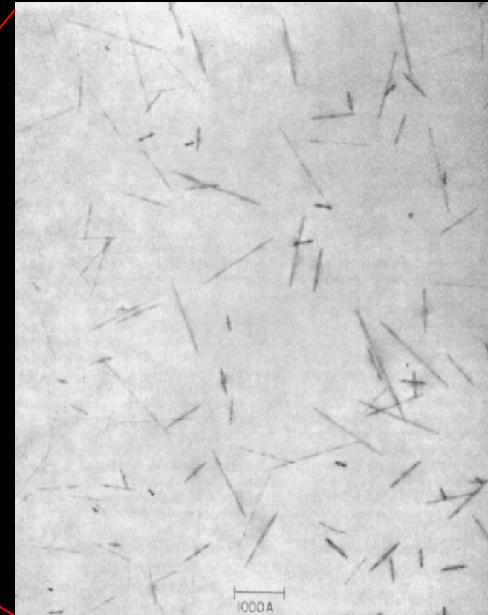
Tabrizi & Horiuchi (2021)

# Use old rocks ?

Recently revived as direct dark matter probes

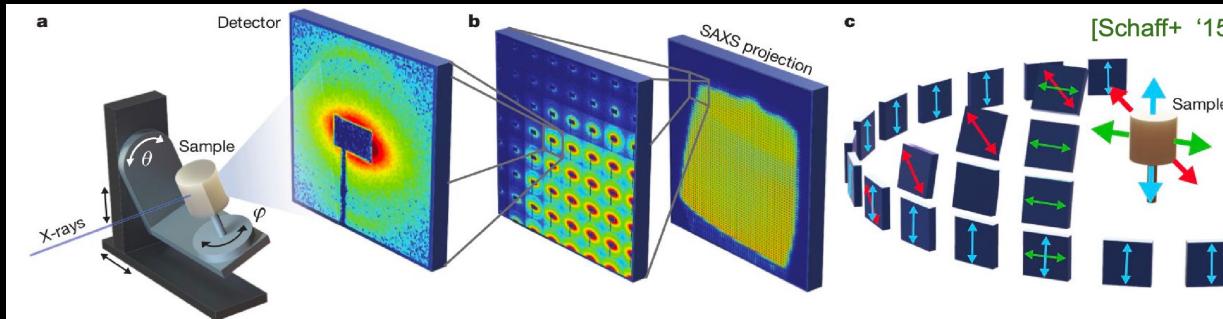
Drukier et al (2019), Edwards et al (2019)

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



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

# *Advantages*

## Competitive exposure

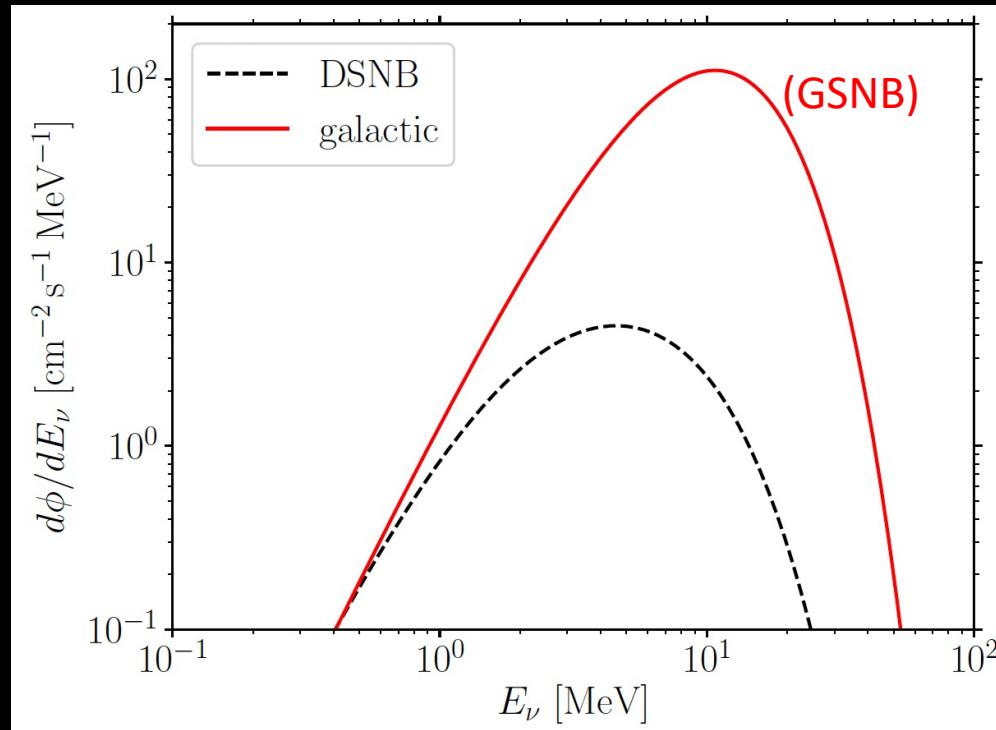
- 100 grams over  $10^9$  years =  $10^5$  t year

## All flavors

- CEvNS most important interaction for SN neutrino energies

## "sees" thousands of Galactic supernovae

- 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: $^{238}\text{U}$ chain, spontaneous fission

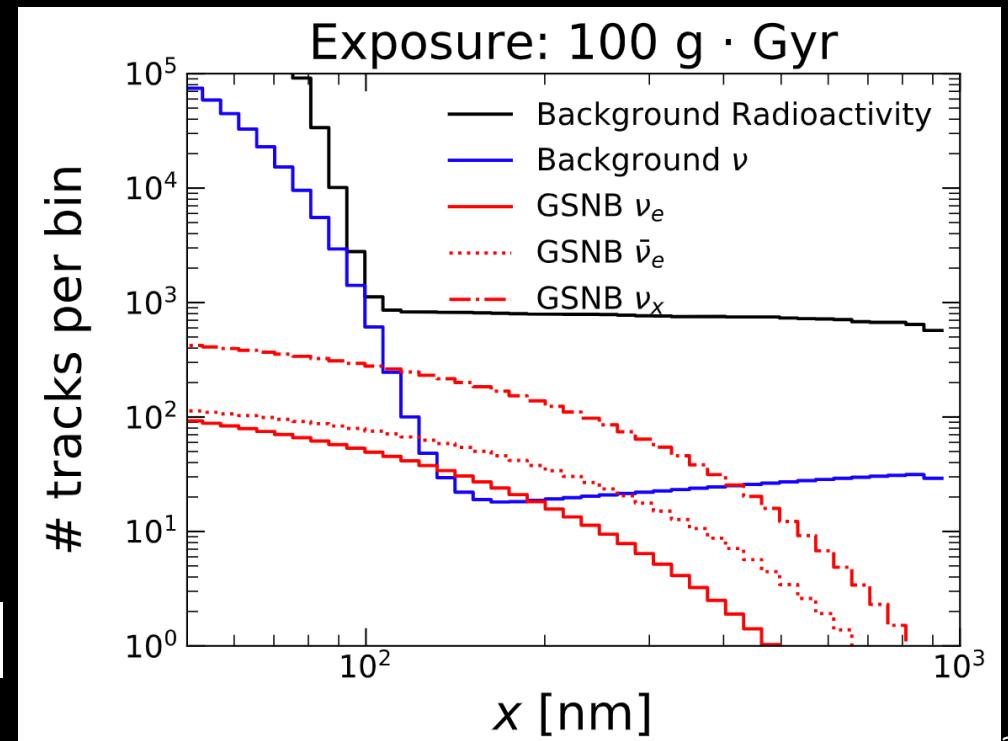
- Find radiopure sample, 0.01 ppb possible

## Neutrinos: atmospheric, solar

- Use spectral analysis

Epsomite  $[\text{Mg}(\text{SO}_4) \cdot 7(\text{H}_2\text{O})]$

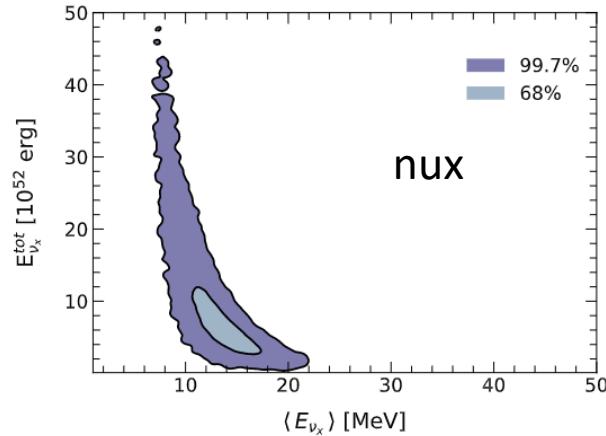
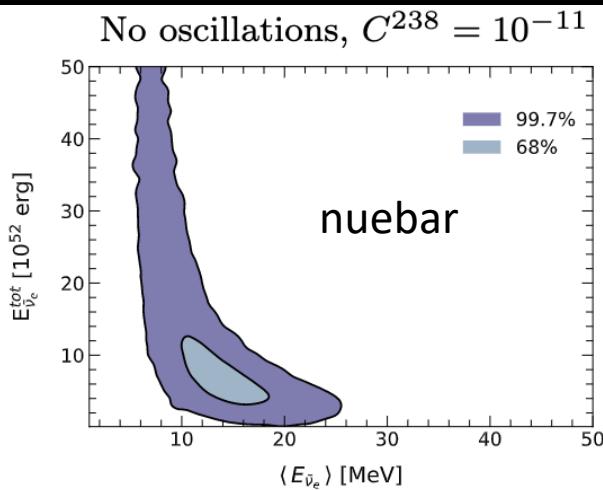
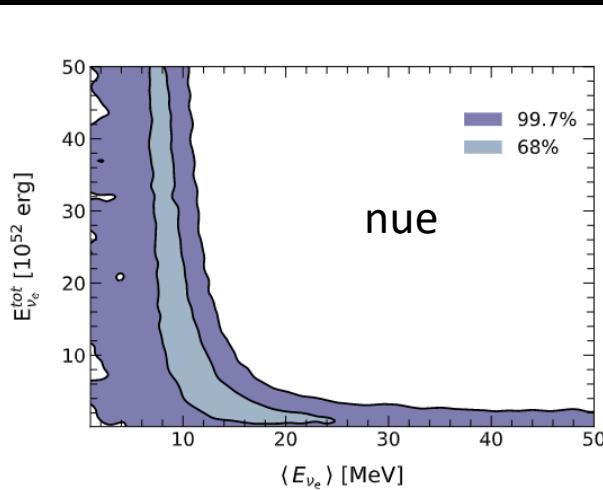
Baum *et al* (*in prep*)



# *Idealized analysis*

Fit the paleo track spectrum → All flavor information

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



Baum *et al* (in prep)

(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 remarks*

## *Diffuse supernova neutrinos*

Guaranteed by SN1987A & observation of supernova occurrence

## *Uncertainties*

Various, all several tens of percent on final event rates

- Core-collapse rate
- Simulations of core collapse (and progenitors)
- Black hole contribution
- Binary impact

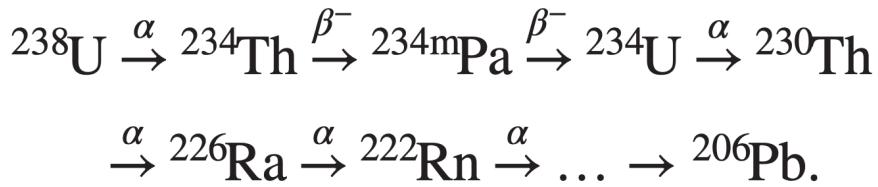
## *Detection prospects*

- Nuebar: SK+Gd opens detection era, Hyper-K opens spectral era
- Nue: DUNE promising, more studies
- Nux: needs new strategies, maybe paleo detectors

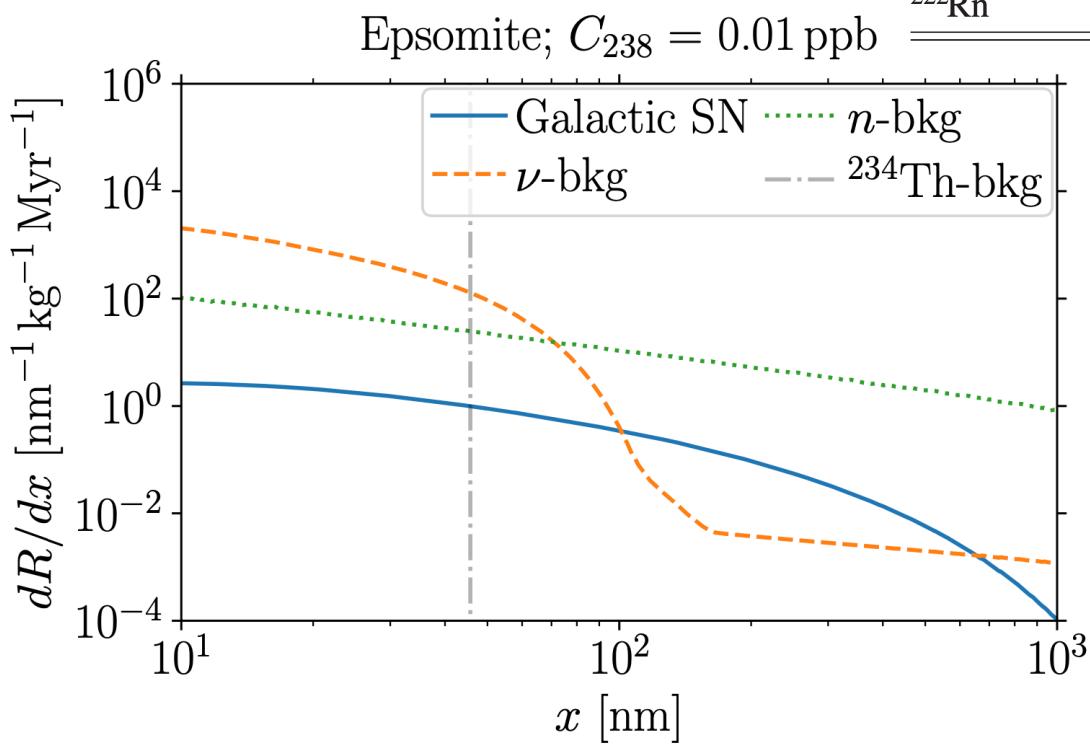
*Thank you!*

# *OTHERS*

# Paleo backgrounds



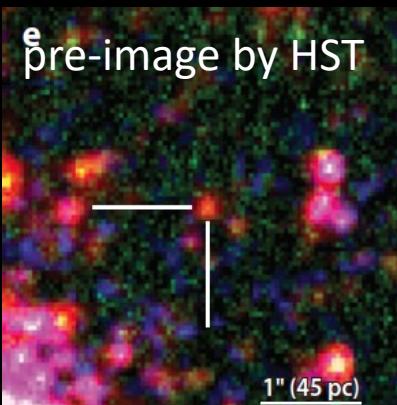
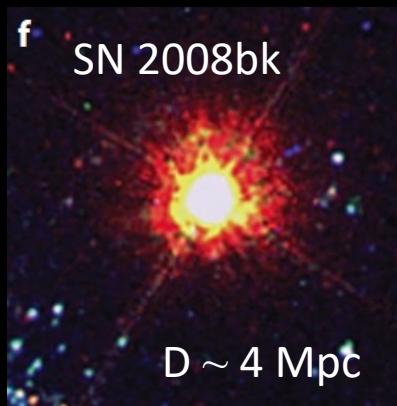
Nucleus	Decay mode	$T_{1/2}$
${}^{238}\text{U}$	$\alpha$	$4.468 \times 10^9$ yr
${}^{234}\text{Th}$	SF	$8.2 \times 10^{15}$ yr
${}^{234m}\text{Pa}$	$\beta^-$	24.10 d
	$\beta^-$ (99.84%)	1.159 min
	IT (0.16%)	
${}^{234}\text{Pa}$	$\beta^-$	6.70 d
${}^{234}\text{U}$	$\alpha$	$2.455 \times 10^5$ yr
${}^{230}\text{Th}$	$\alpha$	$7.54 \times 10^4$ yr
${}^{226}\text{Ra}$	$\alpha$	1600 yr
${}^{222}\text{Rn}$	$\alpha$	3.8325 d



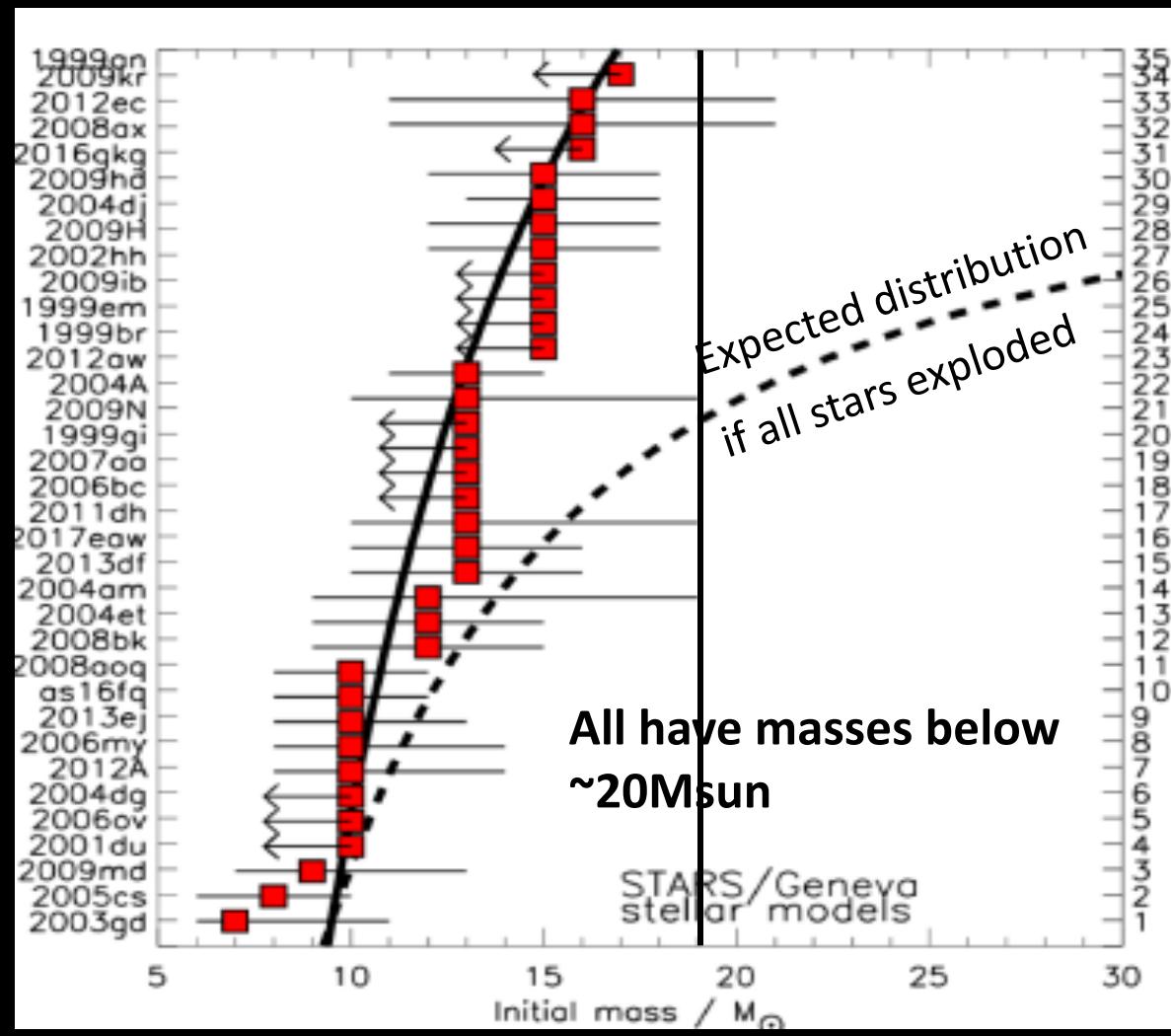
# Looking for explosions

## Pre-imaging:

Limited to nearby  
SNe, highly  
successful



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



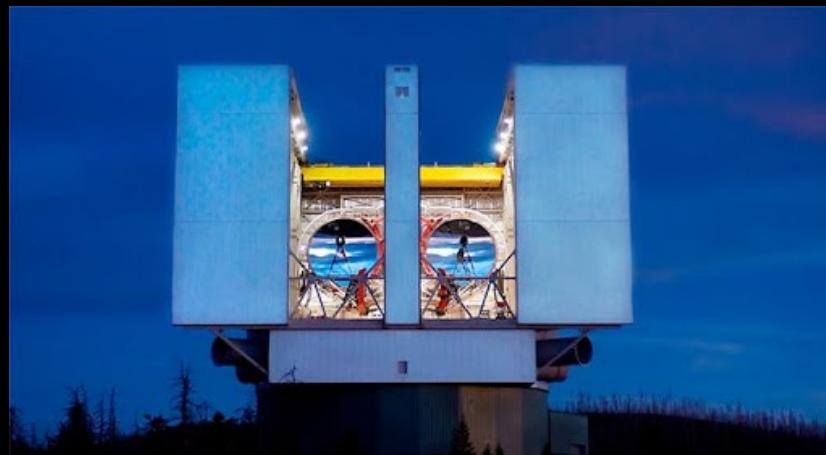
# *Looking for implosions*

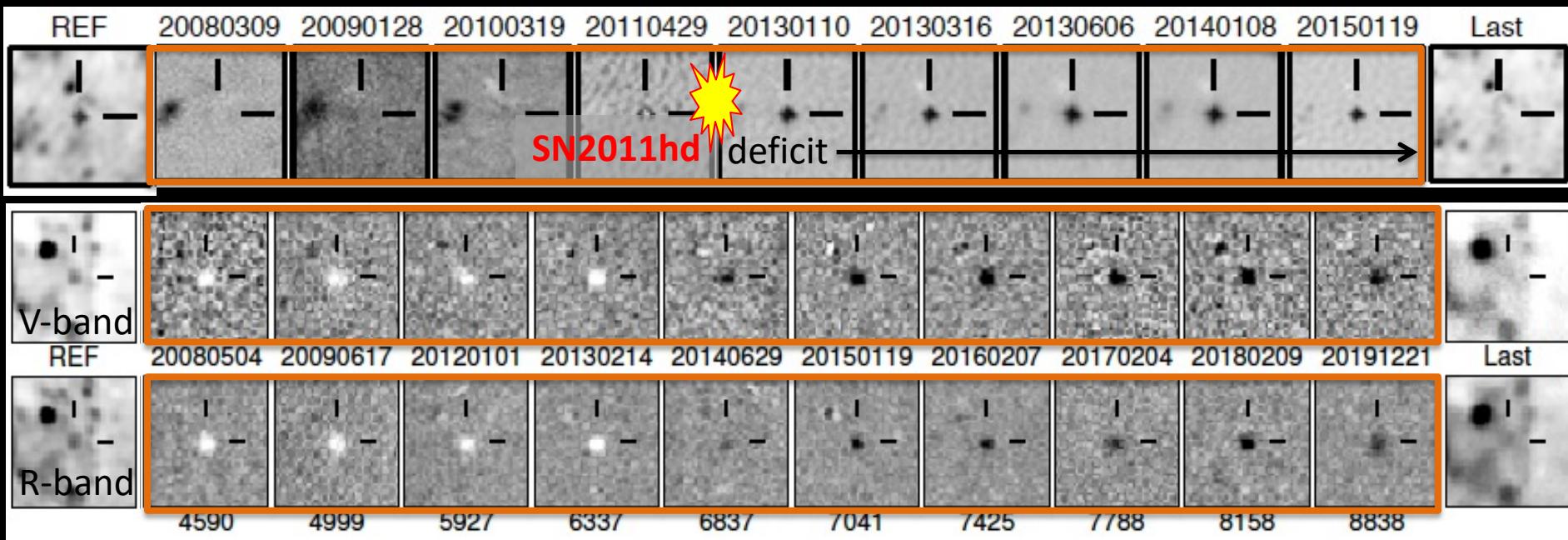
**Look for disappearance of stars**

Monitor ~27 galaxies with the Large Binocular Telescope

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

*Kochanek et al. (2008)*



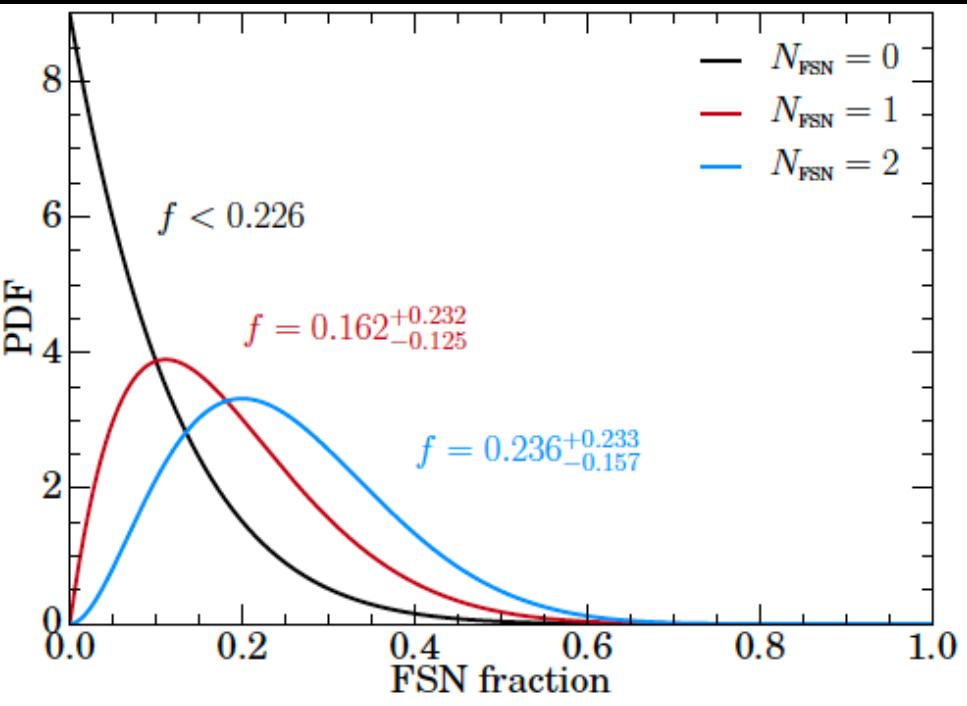


In 11 years running,

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

*Neustadt et al (2021)*

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



# Binary effects: supernova progenitors

## Effect 1: binary effect increases number of supernova progenitors

	Merger		Non-merger		Ratio wrt no binary, $f_b$
	(Rotation)		Double	Single	
No binary evolution	0	0	122,600	171,002	1
Binary $\alpha\lambda = 0.1$ Extrapolated	155,235	315,722	75,723	109,276	1.76
Binary $\alpha\lambda = 0.1$ Fiducial	155,235	50,102	75,723	109,276	1.24
Binary $\alpha\lambda = 0.1$ No rotation	155,235	0	75,723	109,276	1.00
Binary $\alpha\lambda = 1$ Extrapolated	140,467	196,983	83,070	131,679	1.53
Binary $\alpha\lambda = 1$ Fiducial	140,467	39,869	83,070	131,679	1.24
Binary $\alpha\lambda = 1$ No rotation	140,467	0	83,070	131,679	1.05

Horiuchi et al (2021)

The increase depends on the treatment of post-merger rotation

- In our fiducial model, ~25% increase
- Up to +75%

(Note: Kresse et al 2021 reports reduction but neglects mass gain and mergers)

# *Detection of Milky Way source*

High number statistics expected from a Galactic core collapse

Detector	Type	Mass (kt)	Location	Events	Flavors
Super-Kamiokande	H <sub>2</sub> O	32	Japan	7,000	$\bar{\nu}_e$
LVD	C <sub>n</sub> H <sub>2n</sub>	1	Italy	300	$\bar{\nu}_e$
KamLAND	C <sub>n</sub> H <sub>2n</sub>	1	Japan	300	$\bar{\nu}_e$
Borexino	C <sub>n</sub> H <sub>2n</sub>	0.3	Italy	100	$\bar{\nu}_e$
IceCube	Long string	(600)	South Pole	(10 <sup>6</sup> )	$\bar{\nu}_e$
Baksan	C <sub>n</sub> H <sub>2n</sub>	0.33	Russia	50	$\bar{\nu}_e$
MiniBooNE*	C <sub>n</sub> H <sub>2n</sub>	0.7	USA	200	$\bar{\nu}_e$
HALO	Pb	0.08	Canada	30	$\nu_e, \nu_x$
Daya Bay	C <sub>n</sub> H <sub>2n</sub>	0.33	China	100	$\bar{\nu}_e$
NO $\nu$ A*	C <sub>n</sub> H <sub>2n</sub>	15	USA	4,000	$\bar{\nu}_e$
SNO+	C <sub>n</sub> H <sub>2n</sub>	0.8	Canada	300	$\bar{\nu}_e$
MicroBooNE*	Ar	0.17	USA	17	$\nu_e$
DUNE	Ar	34	USA	3,000	$\nu_e$
Hyper-Kamiokande	H <sub>2</sub> O	560	Japan	110,000	$\bar{\nu}_e$
JUNO	C <sub>n</sub> H <sub>2n</sub>	20	China	6000	$\bar{\nu}_e$
RENO-50	C <sub>n</sub> H <sub>2n</sub>	18	Korea	5400	$\bar{\nu}_e$
LENA	C <sub>n</sub> H <sub>2n</sub>	50	Europe	15,000	$\bar{\nu}_e$
PINGU	Long string	(600)	South Pole	(10 <sup>6</sup> )	$\bar{\nu}_e$