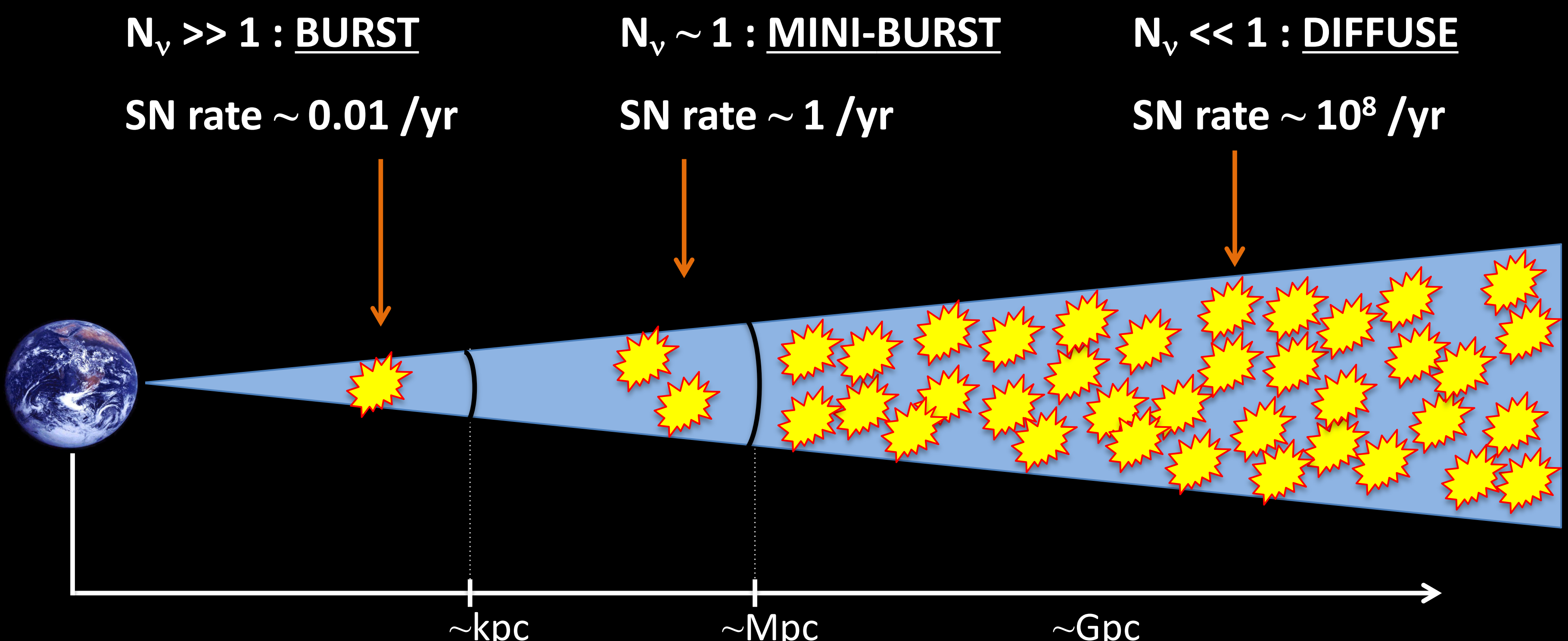
International Conference on Supernova Neutrino Detection
Gran Sasso National Laboratory, May 31st 2023

Diffuse supernova neutrino background

Shunsaku Horiuchi

DSNB in context



From Beacom (2011)

Features:
- Rich multi-messenger data
- Precision on 1 progenitor
- Surprises?

Features:
- Many progenitors, population studies
- Cosmological baseline
- Guaranteed signal
- Surprises?

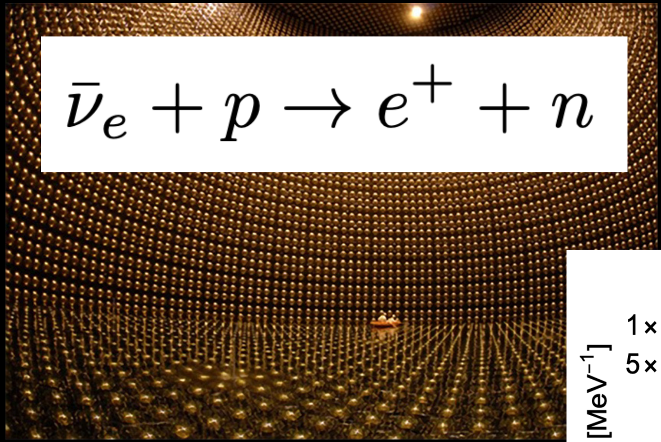
DSNB: ingredients

$$R = N_t \int dE\, \sigma_{\mathrm{IBD}} \int dz\, c \frac{dN}{dE'} (1+z) R_{CC}(z) \left| \frac{dt}{dz} \right|$$

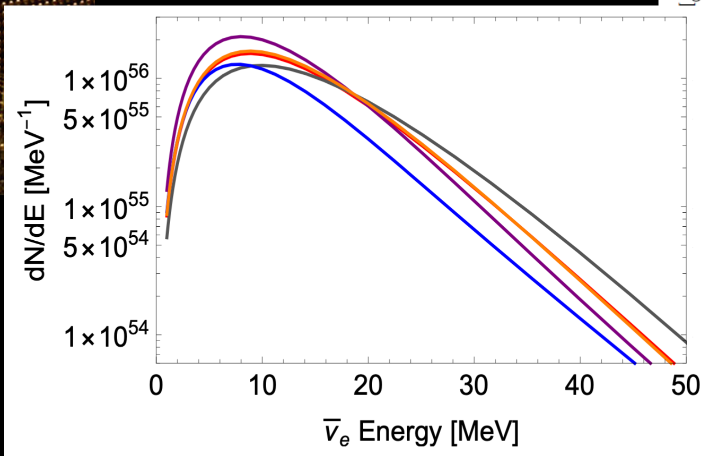
Neutrino detector capabilities

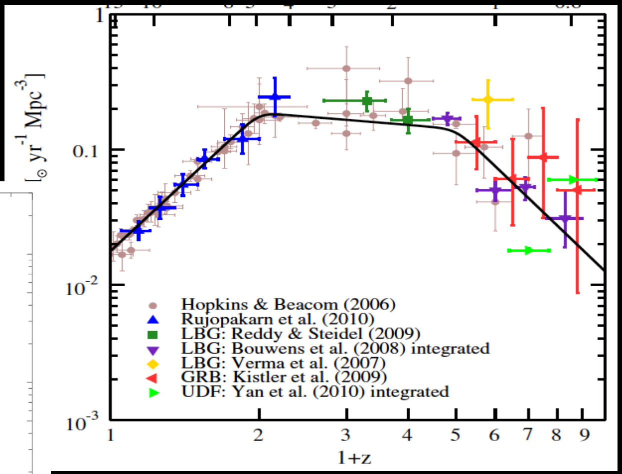
Time-integrated neutrino emission

Rate of massive star core collapse



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





DSNB challenges

$$R = N_t \int dE\, \sigma_{\rm IBD} \int dz\, c \frac{dN}{dE'}(1+z) R_{CC}(z) \left|\frac{dt}{dz}\right|$$

1. **What is the true core-collapse rate?**

2. **What is the time-integrated neutrino emission?**
   - **For exploding Fe core collapses**
   - **Diversity in neutrino emissions**
   - **Other effects**

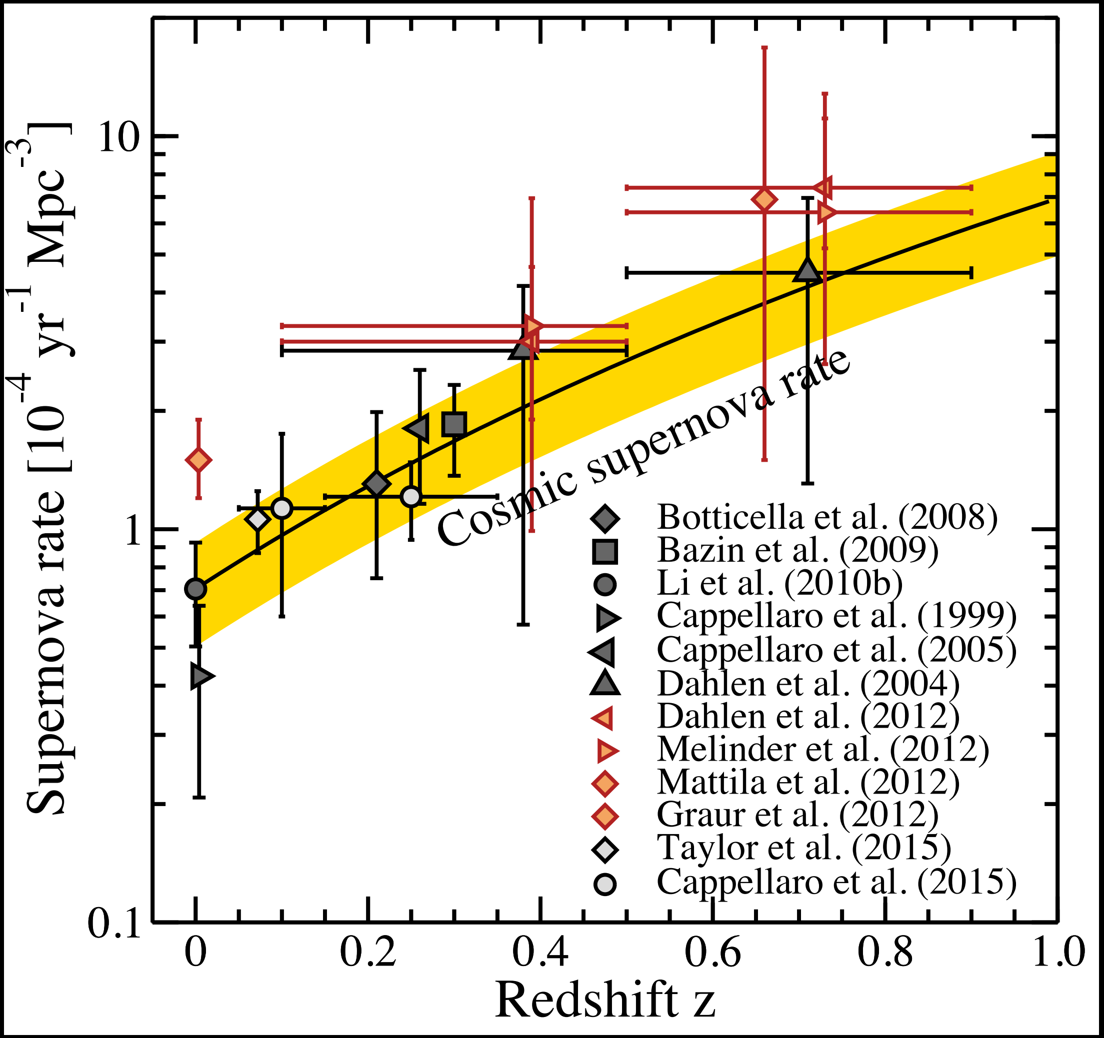
3. **Rates & detections (backgrounds)**

Cosmic core-collapse supernova rate

Direct measurements

- Important redshift range is observed by surveys
- Uncertainty: factor ~3
  - Different survey strategy, sample size, dust correction, supernova luminosity function

But: supernova rate only gives the successful core collapse rate!

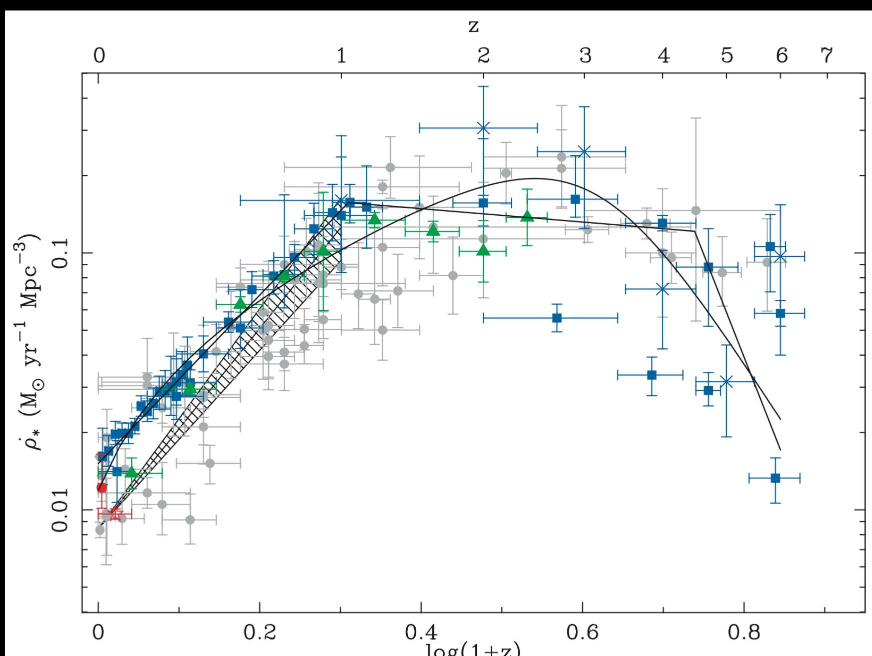


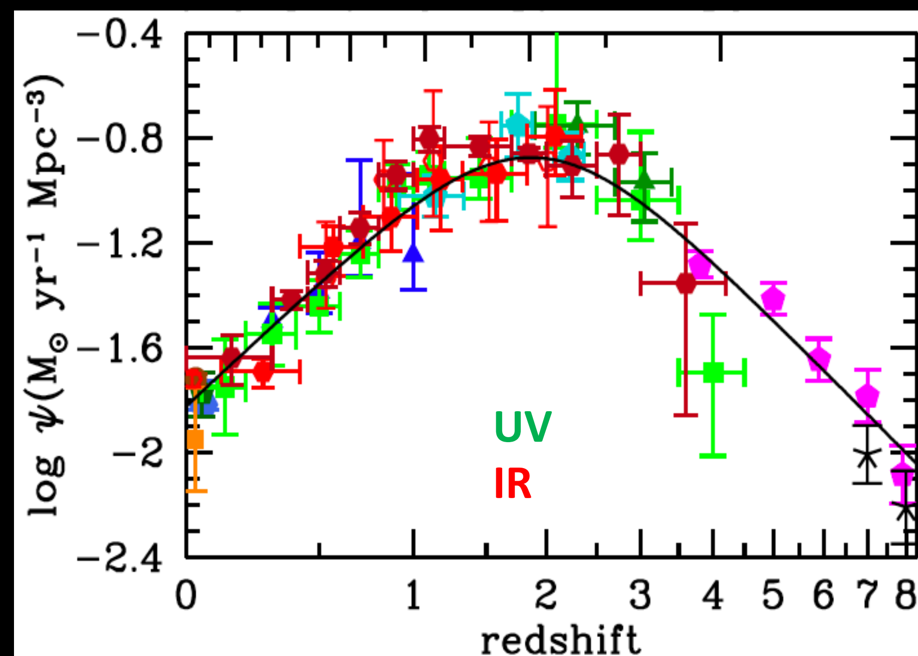
Updated from Horiuchi et al (2011)

Cosmic star-formation rate

Proxy for core-collapse rate

- Since massive stars' lives are cosmologically short
- Measured by many groups, many wavebands, many data sets
  - Important redshift range (z<1) directly observed
- Uncertainty: factor ~2 (z<1)
  - Dust correction, sample selection, initial mass function





Hopkins & Beacom (2006) *Madau & Dickinson (2014)*

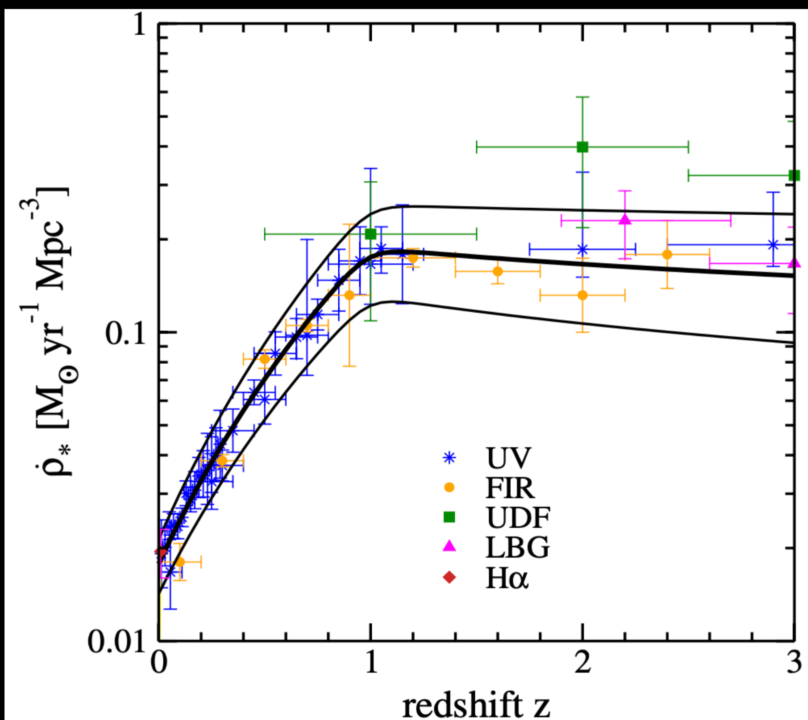
Fits versus data

Fits are handy

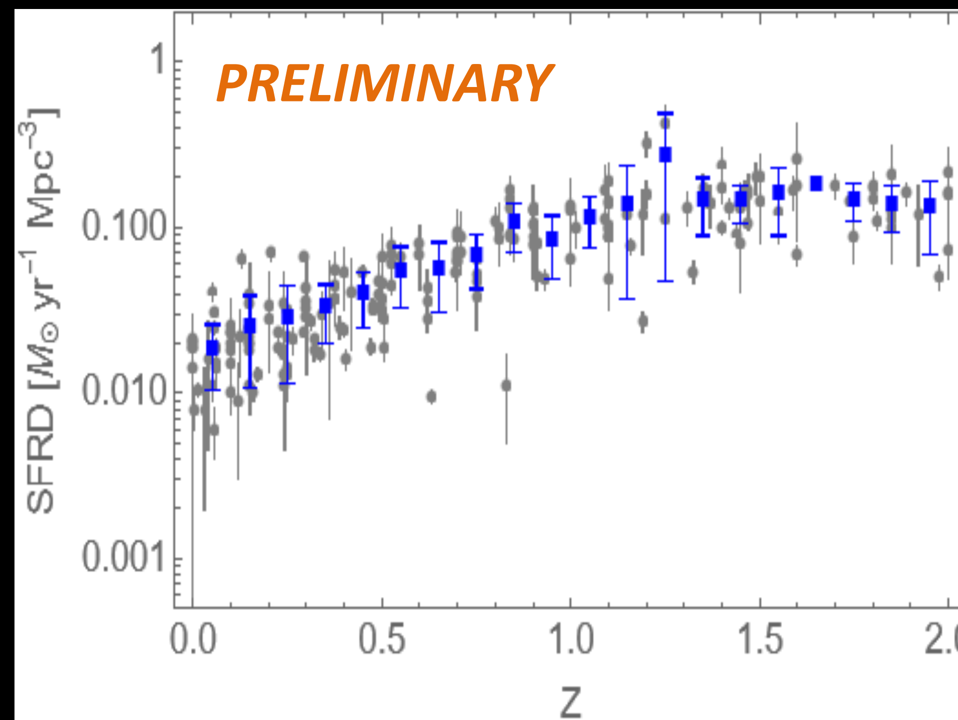
Standard practice has been to use functional fits to data with parameter estimation & errors

Data driven

Large dataset allows more direct estimates of rates & errors in redshift space



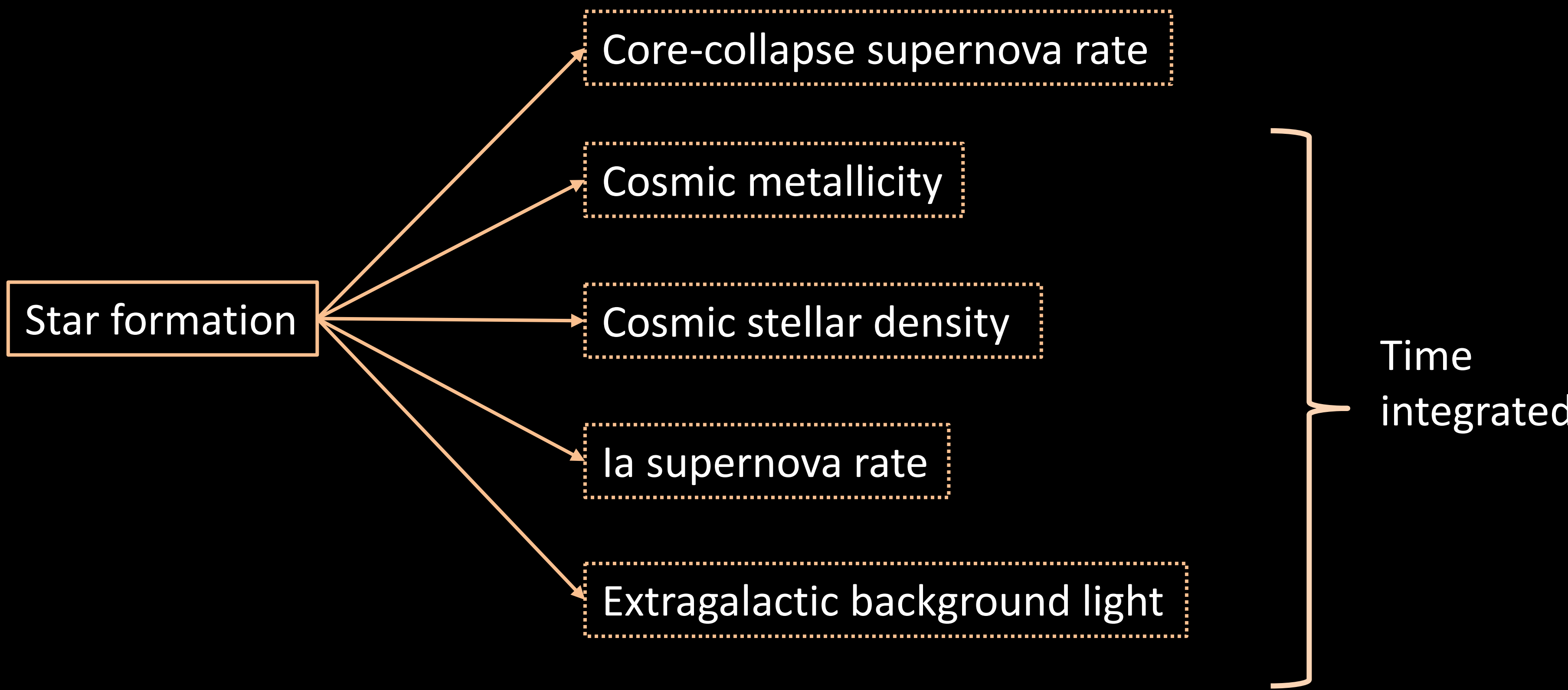
Horiuchi et al (2009), following Hopkins & Beacom (2006) and Yuksel et al (2008)



Ekanger et al (in prep)

Multiple cross checks

Cross checks: towards consensus, which gives us additional confidence

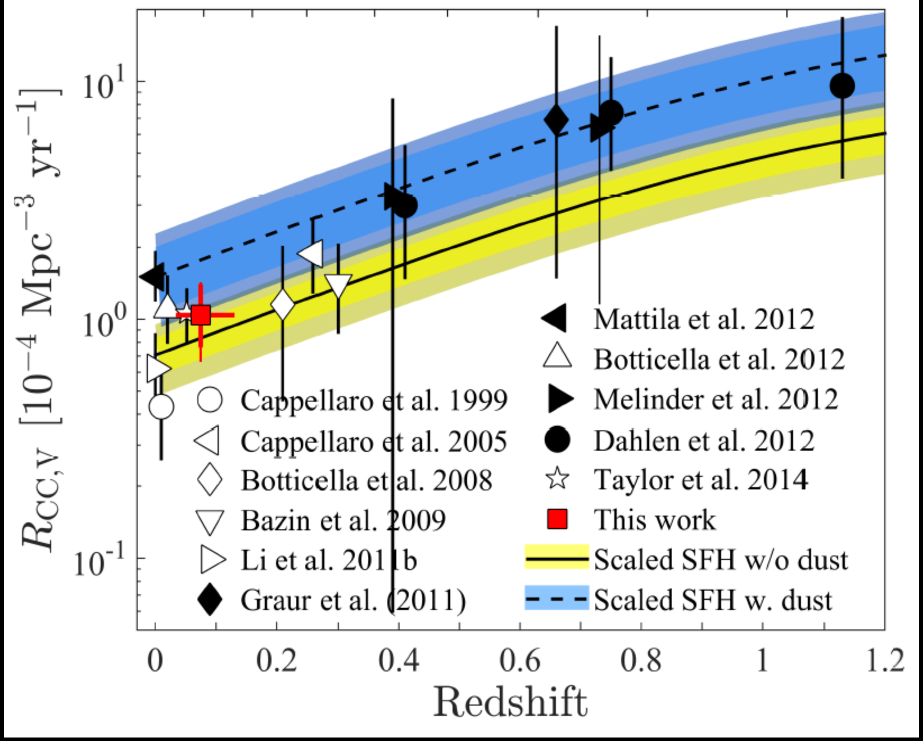


Cross checks

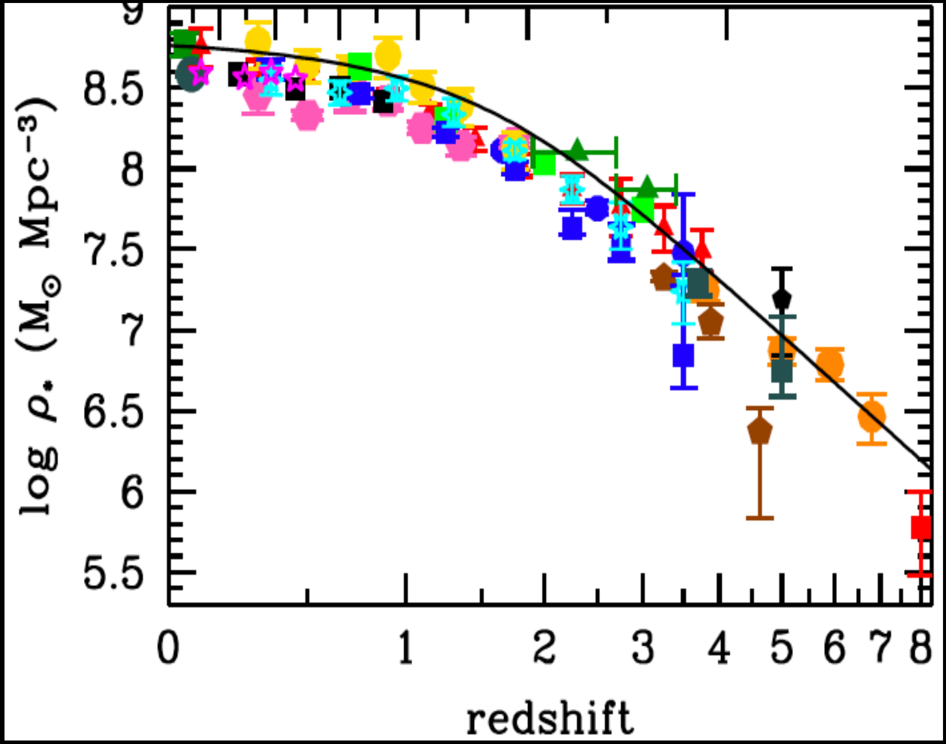
Star formation

Cosmic core-collapse supernova rate
 *Sensitive to dust

Cosmic stellar density
 *Sensitive to initial mass function



Graur et al (2015); see also Horiuchi et al (2011), Mathews et al (2014)



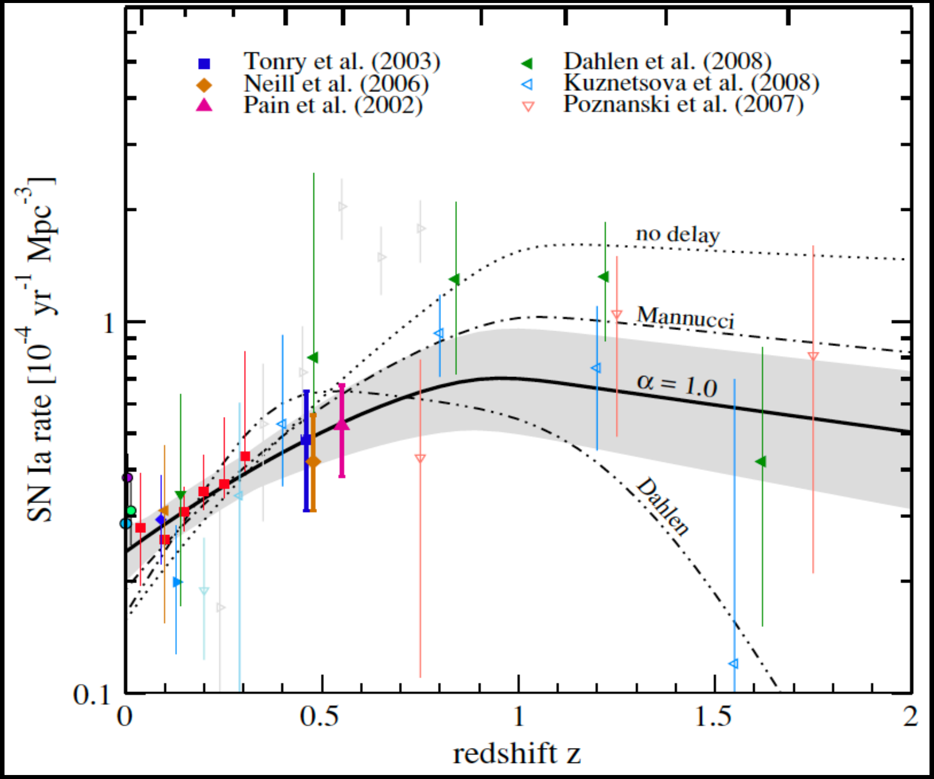
Madau & Dickinson (2014); see also Wilkins et al (2008)

Cross checks

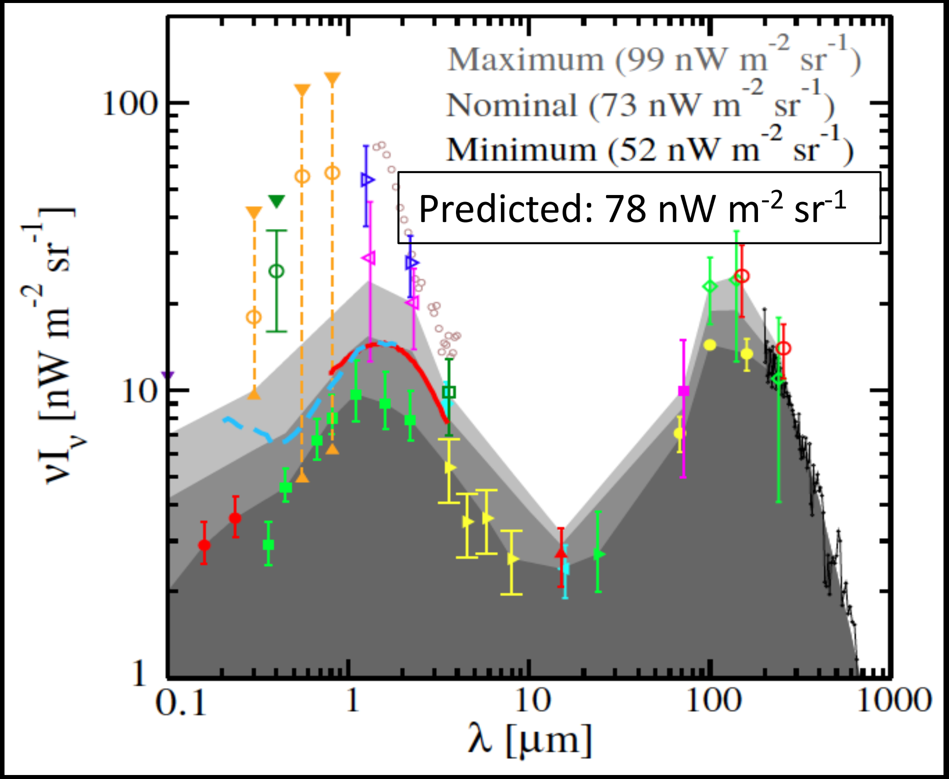
Star formation

Cosmic Ia supernova rate
*Sensitive to delay-time distribution

Extragalactic background light
*Measurement systematics



Horiuchi & Beacom (2010)

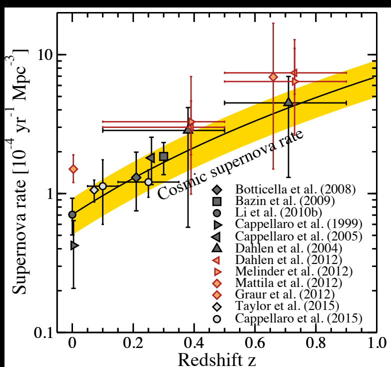


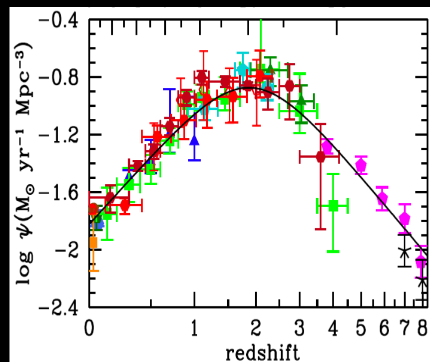
Horiuchi et al (2009)

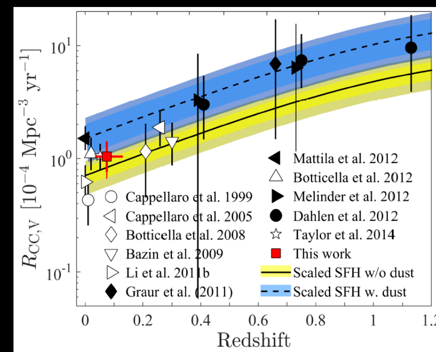
First take away

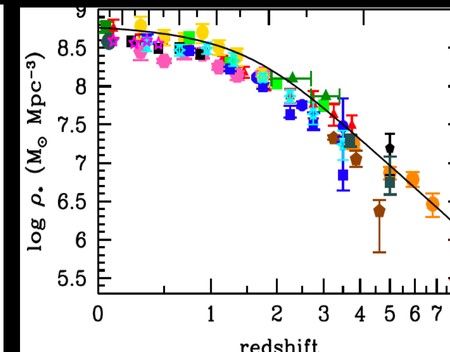
Are we confident core collapses are occurring? **Yes**

How certain are we about the rate? **To factor ~2**

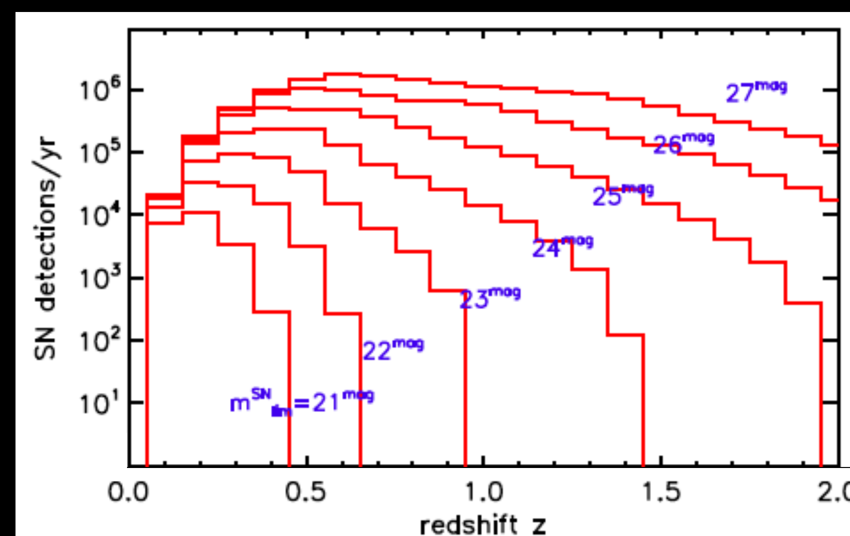








Plus, orders of magnitude more core-collapse supernovae expected by LSST (2025~).



Lien & Fields (2009)

DSNB challenges

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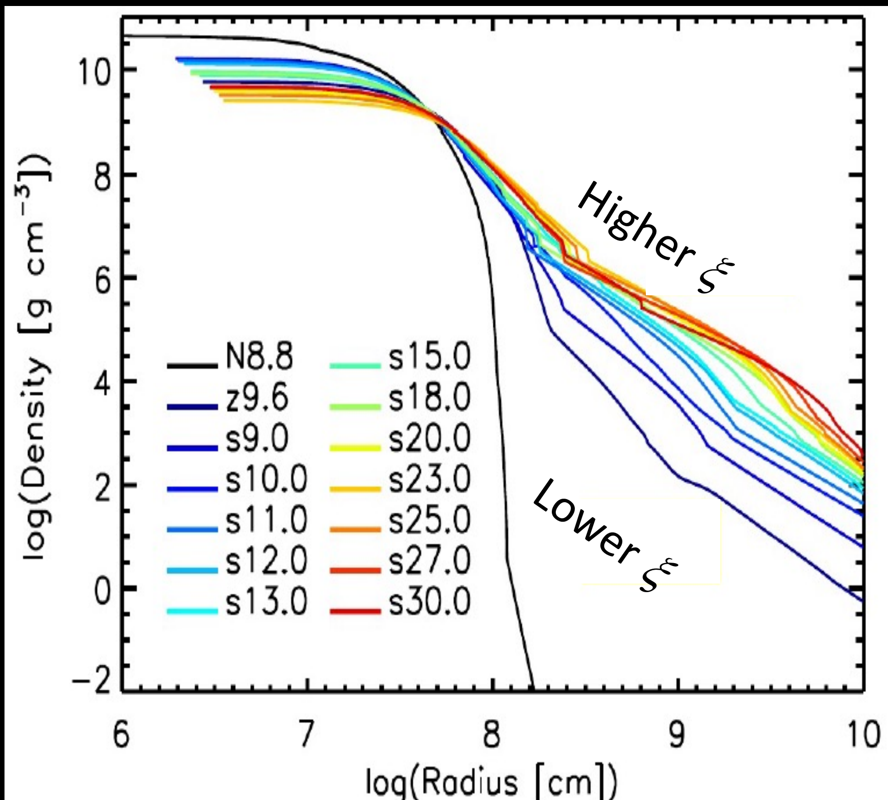
1. **What is the true core-collapse rate?**

2. **What is the time-integrated neutrino emission?**
   - **For exploding Fe core collapses**
   - **Diversity in neutrino emissions**
   - **Other effects**

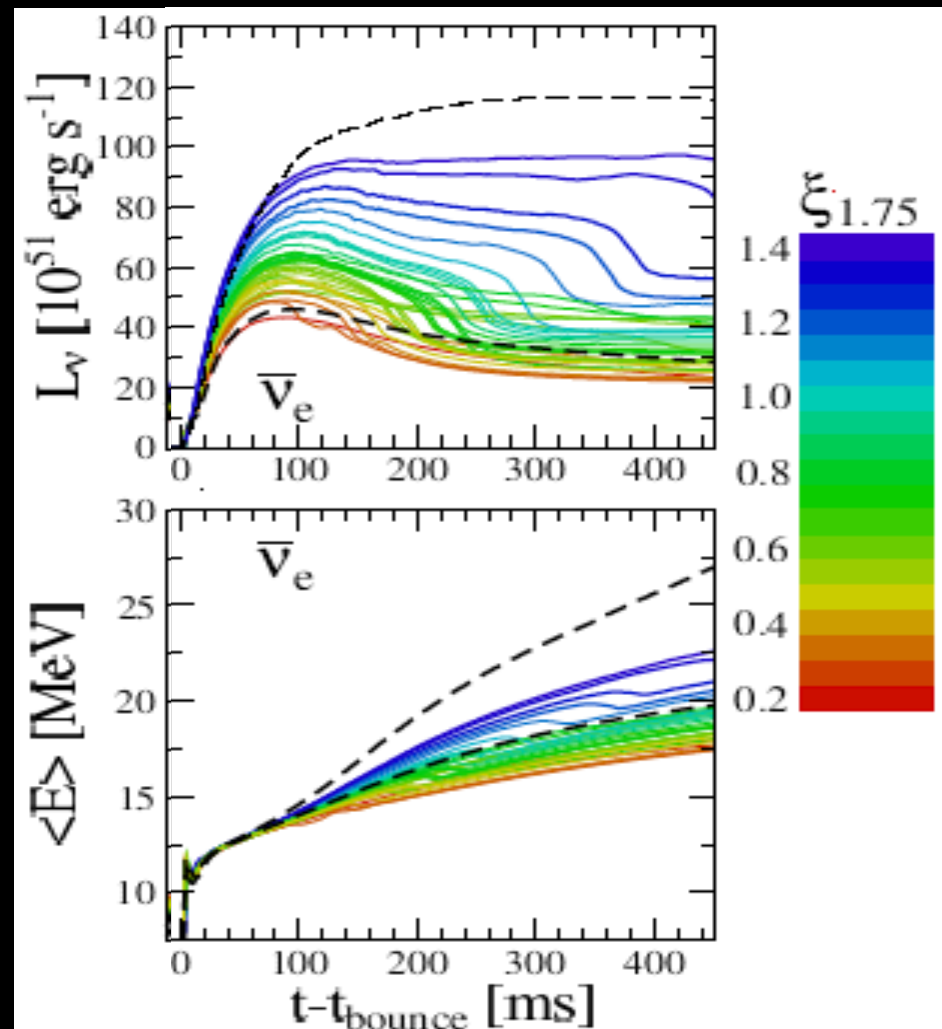
3. **Rates & detections (backgrounds)**

Not standard candles

Look to simulations for guidance: neutrino emission reflects the progenitor



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

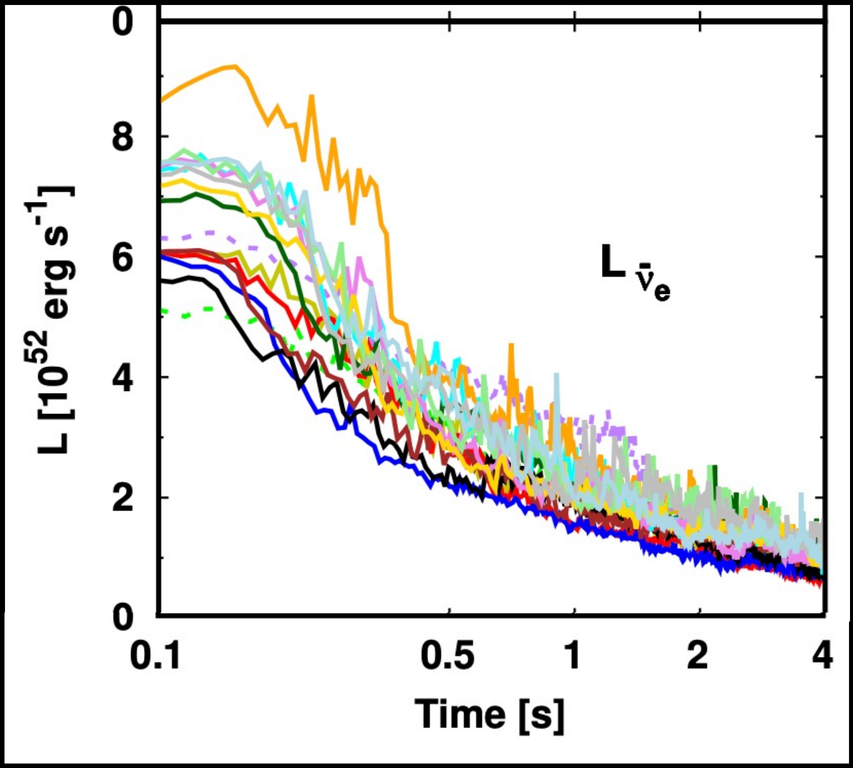


O'Connor & Ott (2013)

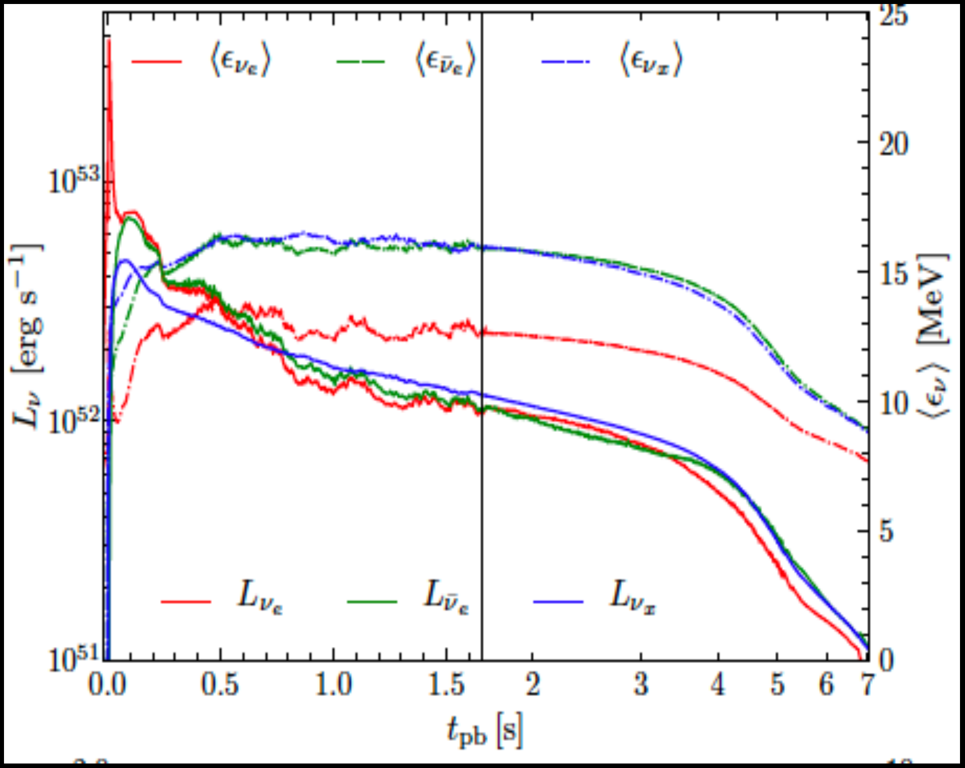
Neutrino emission out to cooling phase

Challenge is long-term (~10 sec) simulations for multiple progenitors

- Multi-D are computationally expensive, large sets becoming available



Nagakura et al (2021)

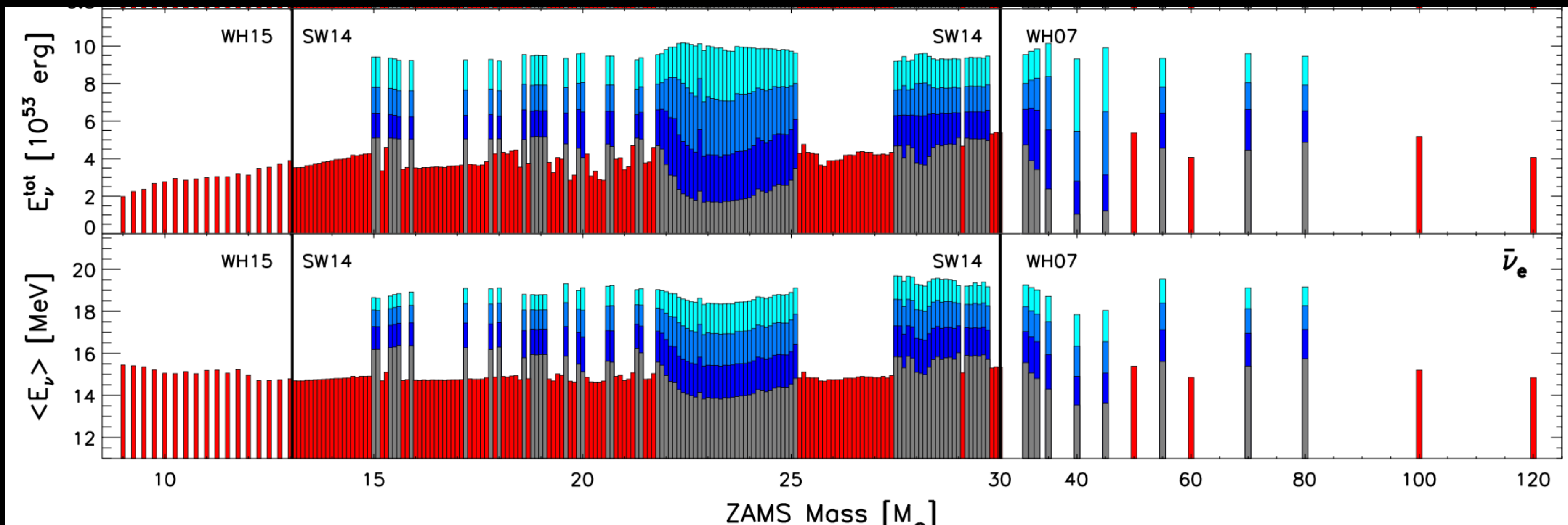


Bollig et al (2021)

Neutrino emission out to cooling phase

Challenge is long-term (~10 sec) simulations for multiple progenitors

- Multi-D are computationally expensive, large sets becoming available
- With 1D "calibrated central neutrino engines"



Kresse et al (2021)

Neutrino emission out to cooling phase

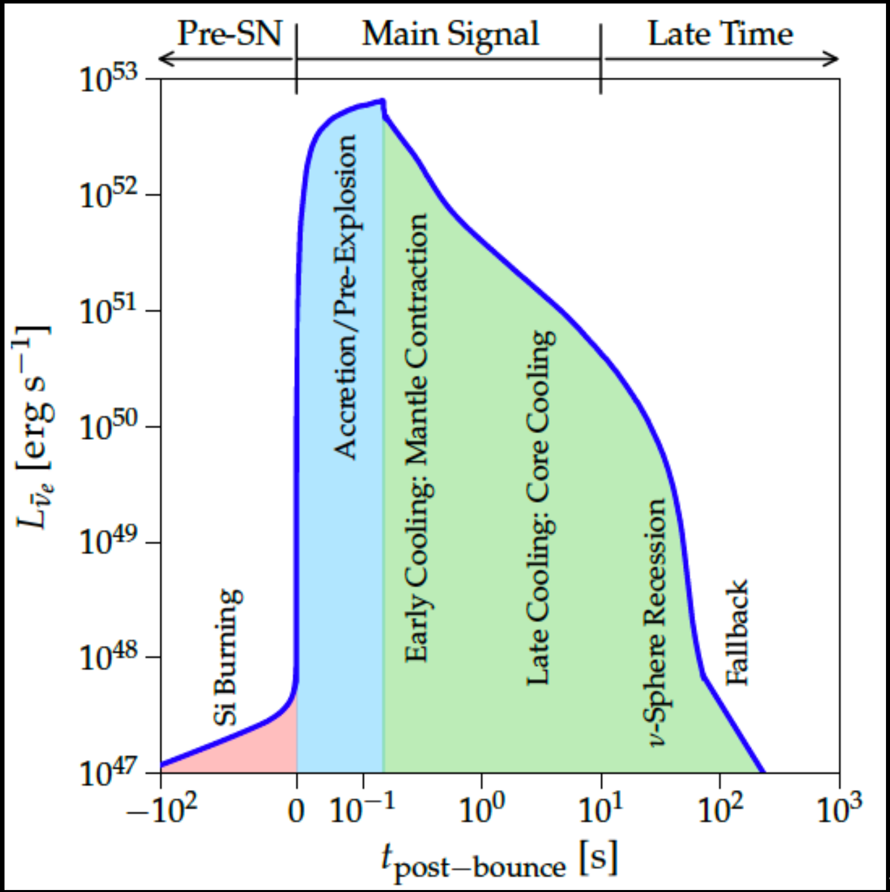
Challenge is long-term (~10 sec) simulations for multiple progenitors

- Multi-D are computationally expensive, large sets becoming available
- With 1D "calibrated central neutrino engines"
- Simple estimates for the cooling phase

Split into two phases:

1. Early: approximately until shock revival, studied by core-collapse hydo sims
2. Late: post shock revival, as central PNS cools by neutrino emission, make simple models

Total = early + late phases



Li et al (2020)

Late phase: parameterized

Simple late estimate

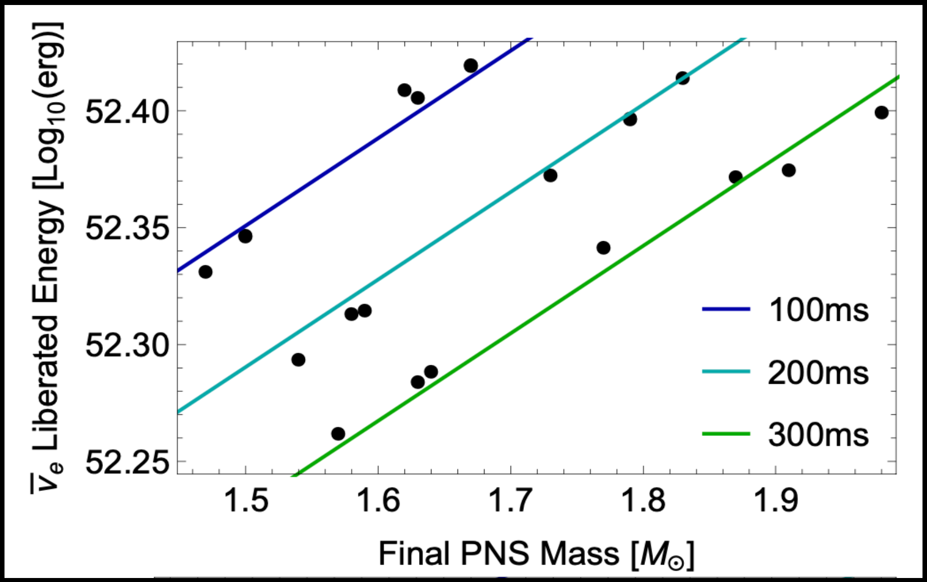
Describe the time-integrated late phase emission using two parameters:

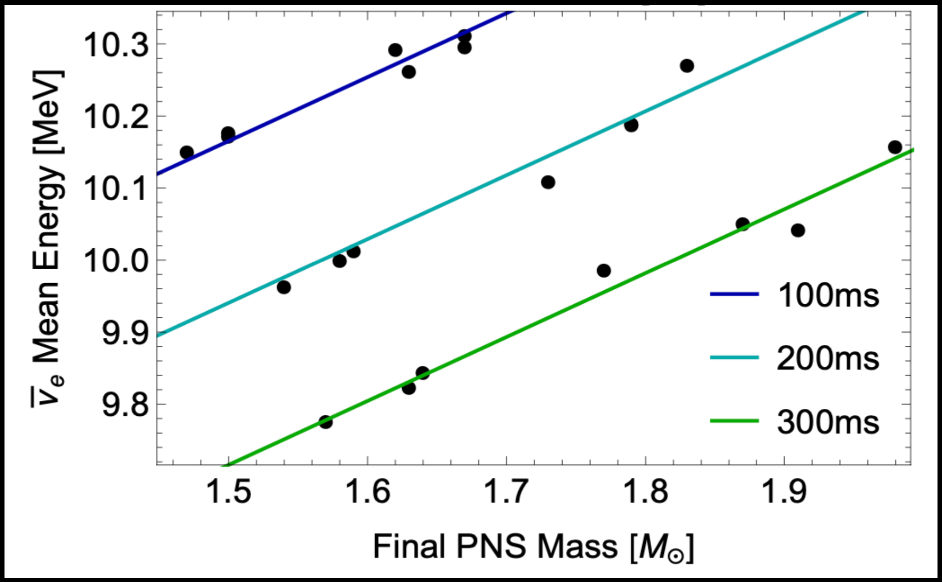
1. Final PNS mass
2. Shock revival time

$$\mathrm{Log}_{10}(E_i) = \alpha_i^{(E)} M_{\mathrm{fin}} + \beta_i^{(E)} t_{\mathrm{rev}} + \gamma_i^{(E)},$$
$$\epsilon_i = \alpha_i^{(\epsilon)} M_{\mathrm{fin}} + \beta_i^{(\epsilon)} t_{\mathrm{rev}} + \gamma_i^{(\epsilon)},$$

Quantify with suites of 1D long-term simulations

Nakazato et al (2012), Hudepohl et al (2014)





Ekanger et al (2022)

Late phase: analytic model

Polytrope PNS & neutrino diffusion: treatment has model parameters

- Final PNS mass & radius
- Structure parameter (g), opacity boost factor (β)

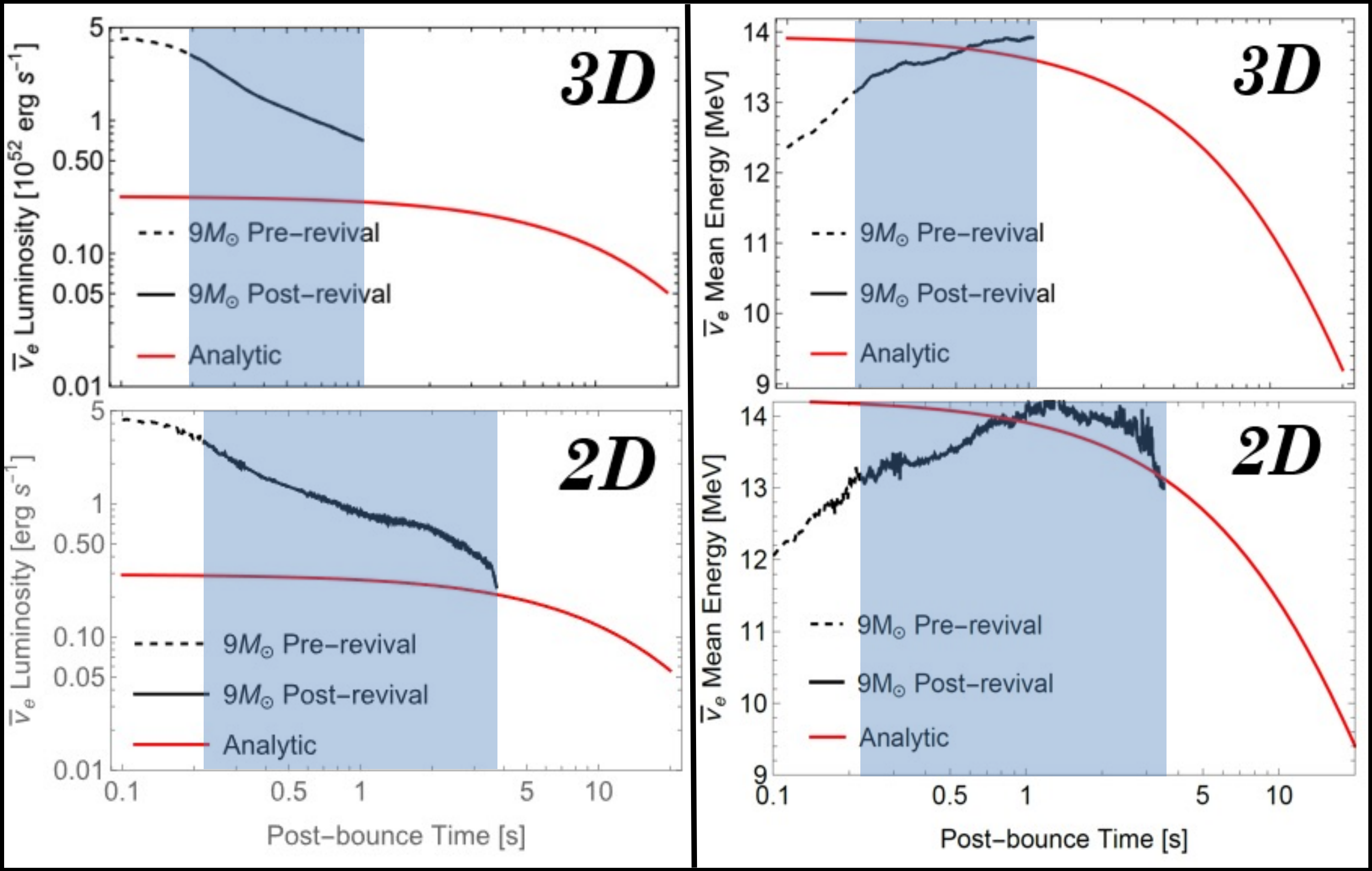
Suwa et al (2021)

Tune (g, β) to *FORNAX* post-shock revival part

Burrows et al (2019)
Nagakura et al (2021)

Best confidence when done over several seconds

Ekanger et al (2022)



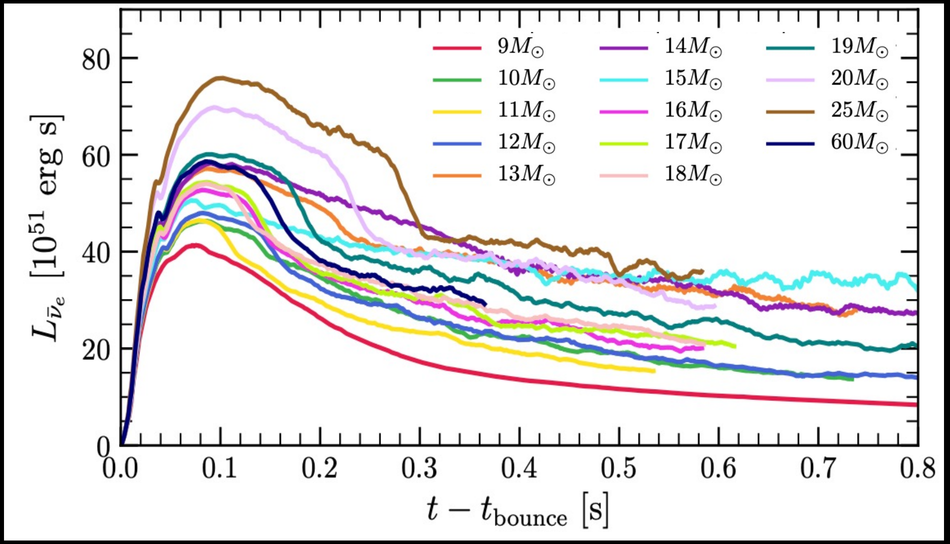
Shunsaku Horiuchi

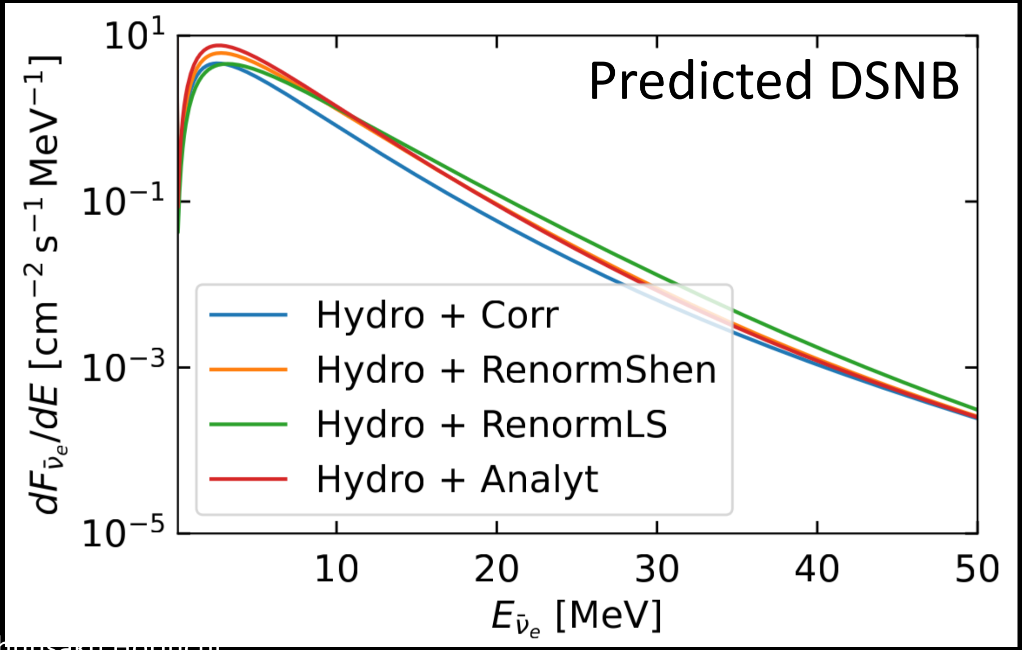
Estimate the DSNB

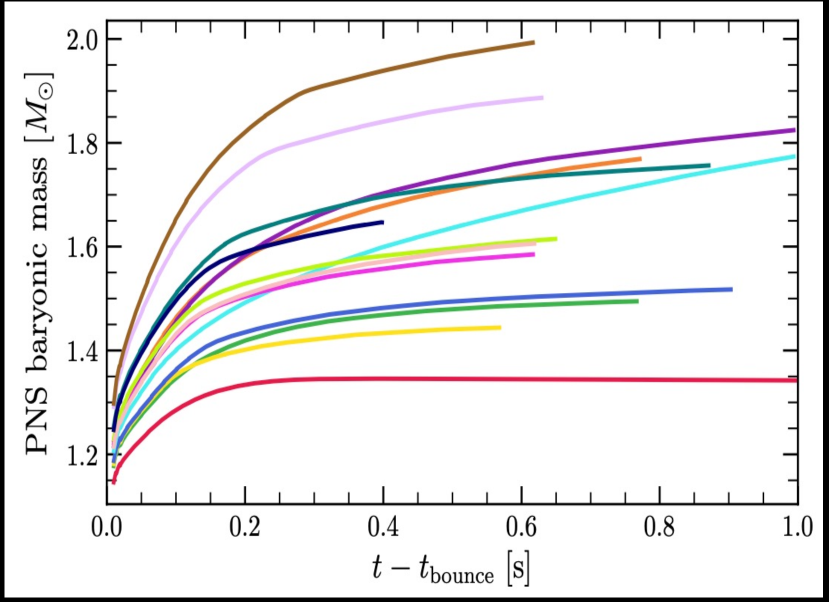
Total = early + late phases

1. <u>Early</u>: suites of *FORNAX* simulations (2D, 3D)
2. <u>Late</u>: estimate using final PNS properties

Dependences on progenitor set, CC simulation, late-time treatment, …





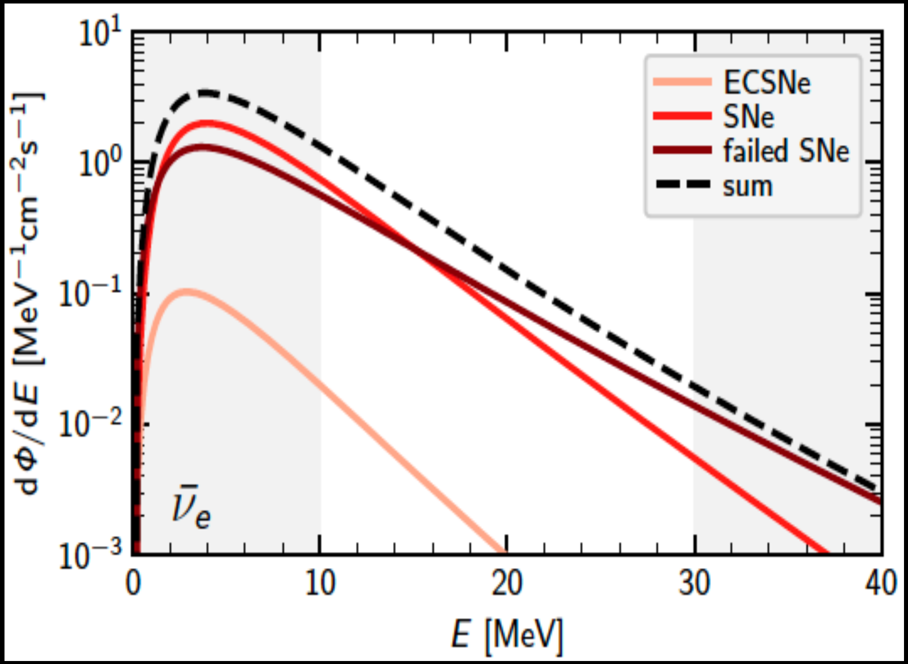


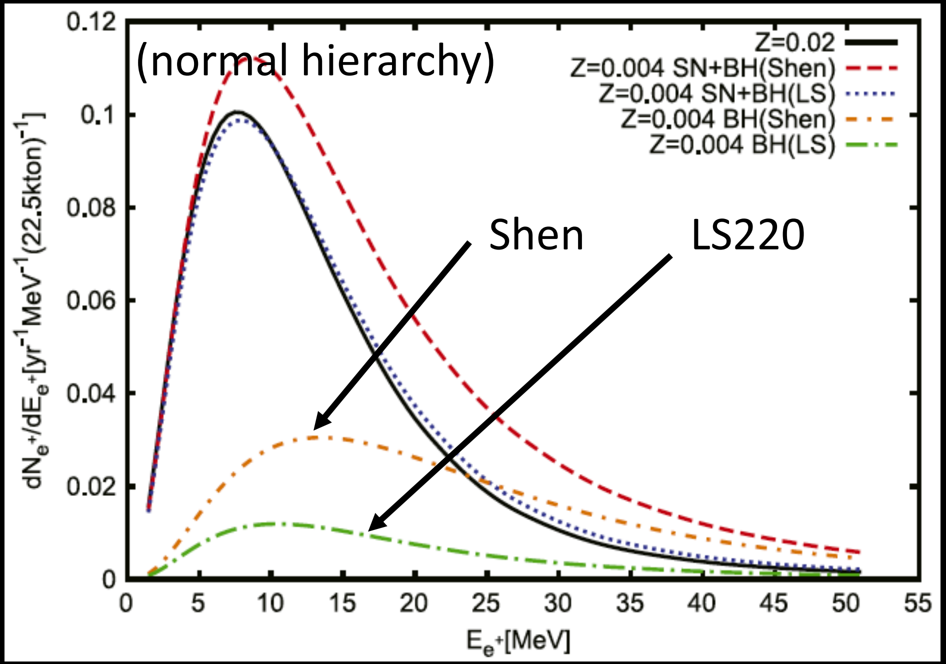
Burrows et al (2019)

Diversity in neutrino emission

Systematically different contributions can occur

- Electron-capture in ONeMg core: how frequent?
- Black hole formation: depends on progenitor, EOS, frequency





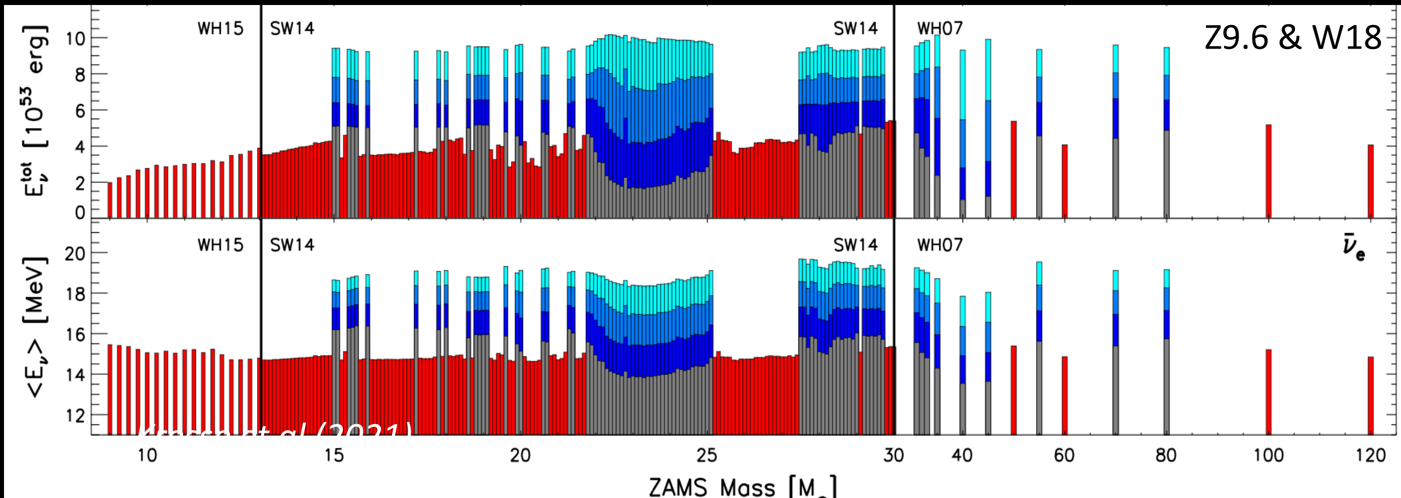
Kresse et al (2021)

Nakazato et al (2015)

See also: 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)

BH: neutrino emission & frequency

1) What are the neutrino emissions? Vary $M_{NS,b}$ (over 2.3–3.5Msun)



← Varies by factor ~2—5

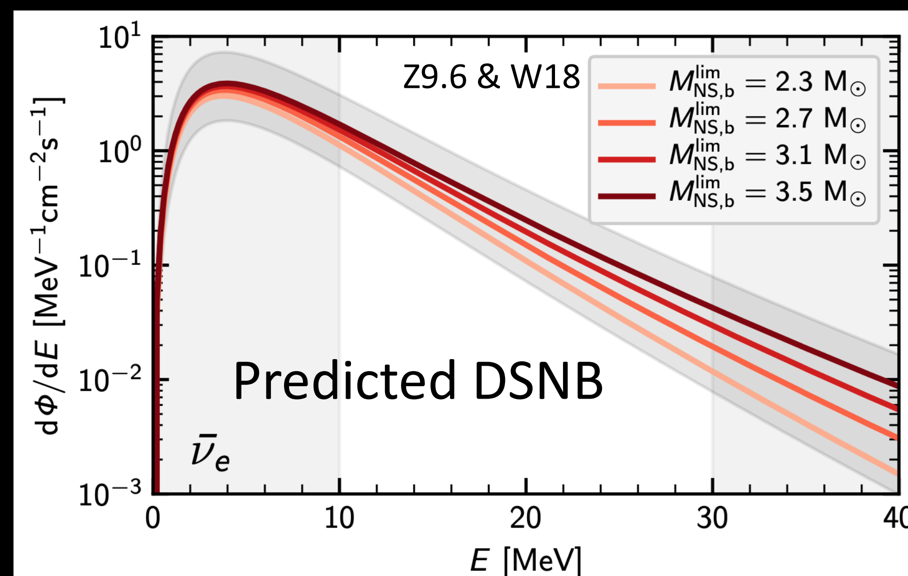
← Varies by ~4 MeV

Kresse et al (2021)

2) How frequently do they occur?

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%

Progenitor, calibration dependent



Finding collapse to black holes

Look for <u>disappearance</u> of stars

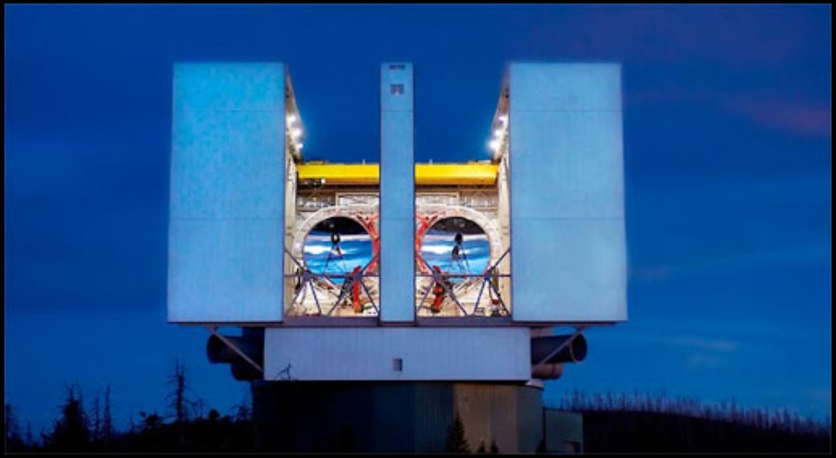
Monitor ~27 galaxies

→ 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)



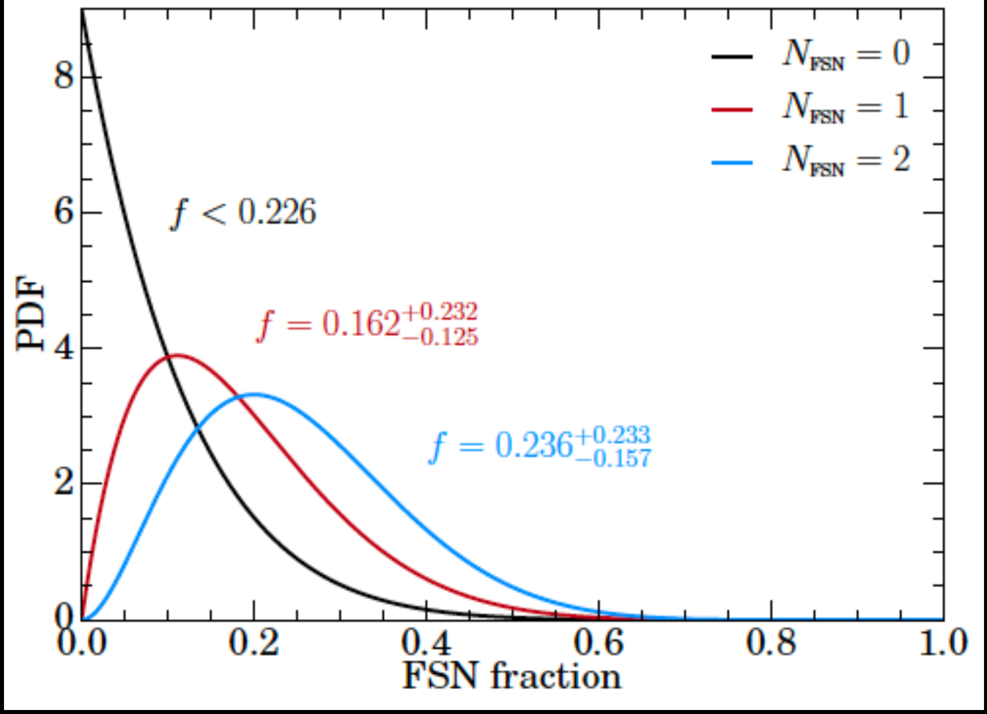
Looking for disappearing stars

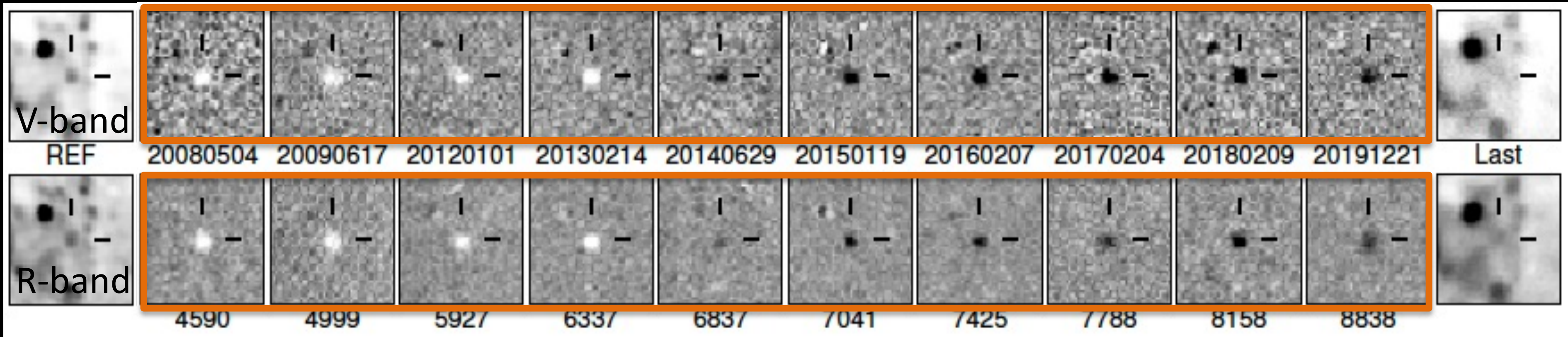
In 11 years survey

- ✓ 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)

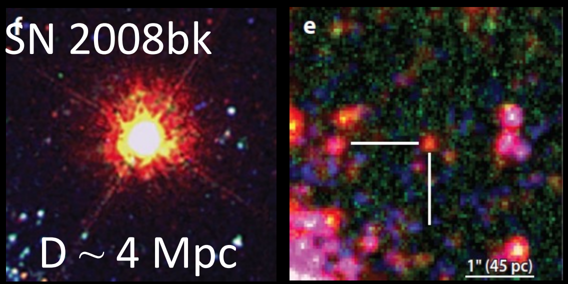




Missing red supergiants

Progenitors:

Progenitors of nearby Type IIP SNe in pre-images

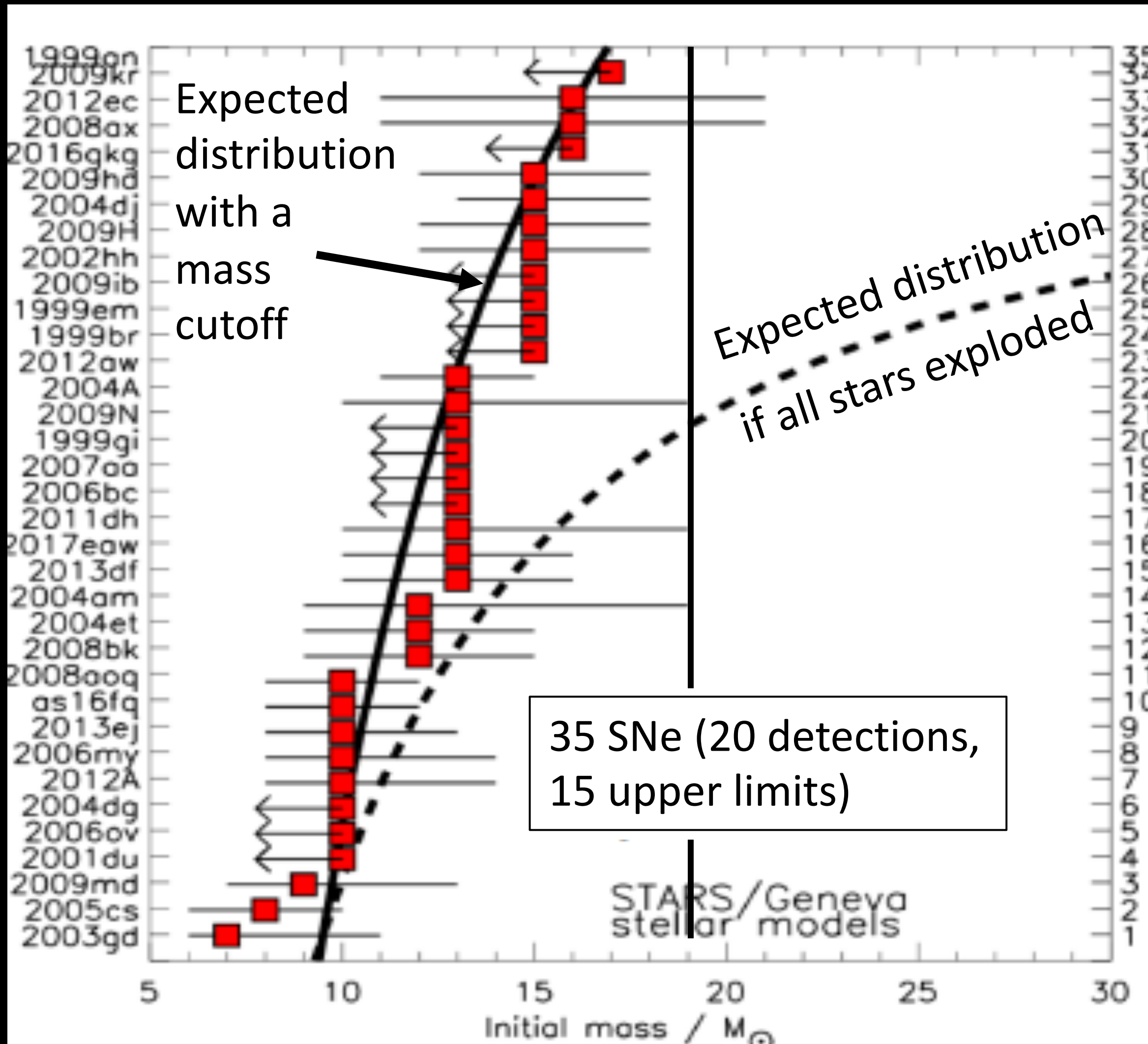


pre-image by HST

But none have mass above ~20Msun

→ Could be BH formation (but many other ideas explored)

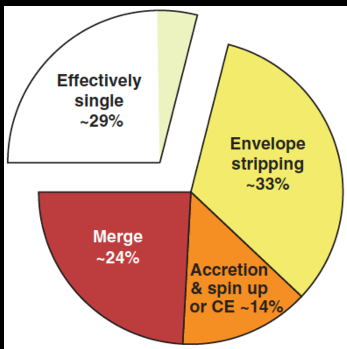
Horiuchi et al (2014), Kochanek (2014), Davies et al (2013), Walmswell & Eldridge (2012), Beasor & Davies (2016)



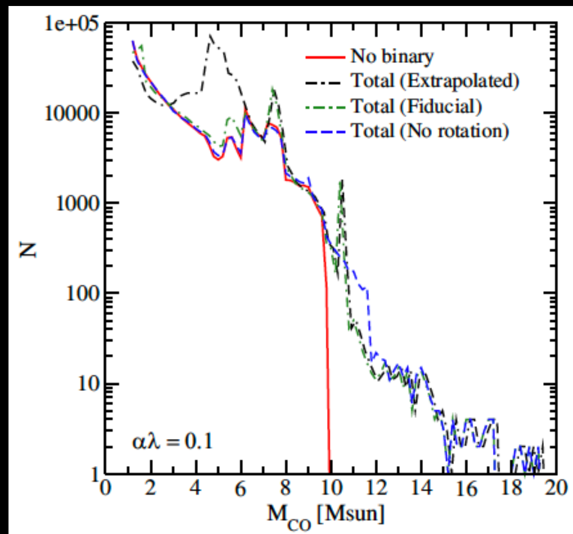
Smartt, STScI Spring Symposium (2019)

Select other effects

Binaries: are common and can enhance progenitor numbers

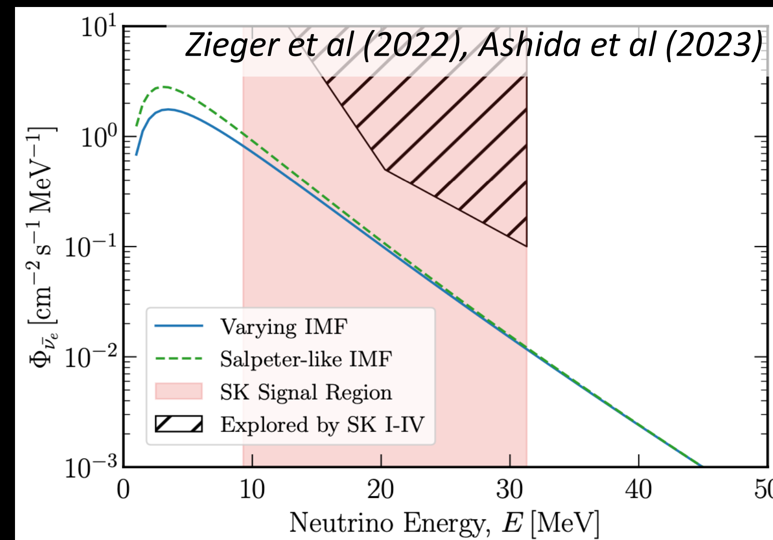


Sana et al (2012)



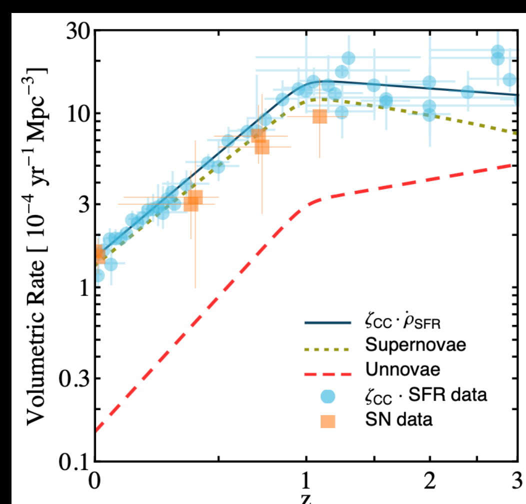
Horiuchi et al (2021)

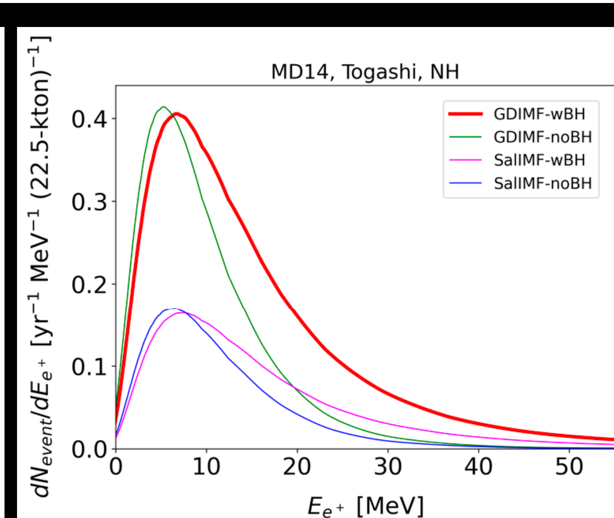
Non-Universal IMF: may be environmentally dependent



Variable BH fraction: may be more common at high redshifts

Eg Yuksel & Kistler (2014)





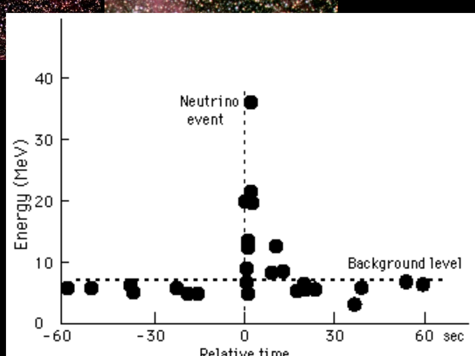
Various BSM physics

Eg de Gouvea et al (2019)

Second take away

Are we confident core collapses are emitting neutrinos?

Yes



Are we certain about the time-integrated neutrino signal?

Still many dependences to study, eg, progenitors

CC & explosion details

cooling phase treatments

BH contribution

Other effects…

These are what we want to test with the DSNB

DSNB challenges

$$R = N_t \int dE\, \sigma_{\rm IBD} \int dz\, c \frac{dN}{dE'} (1+z) R_{CC}(z) \left| \frac{dt}{dz} \right|$$

1. **What is the true core-collapse rate?**
2. **What is the time-integrated neutrino emission?**
   - **For exploding Fe core collapses**
   - **Diversity in neutrino emissions**
   - **Other effects**
3. **Rates & detections (backgrounds)**

DSNB: predicted rates

Setup

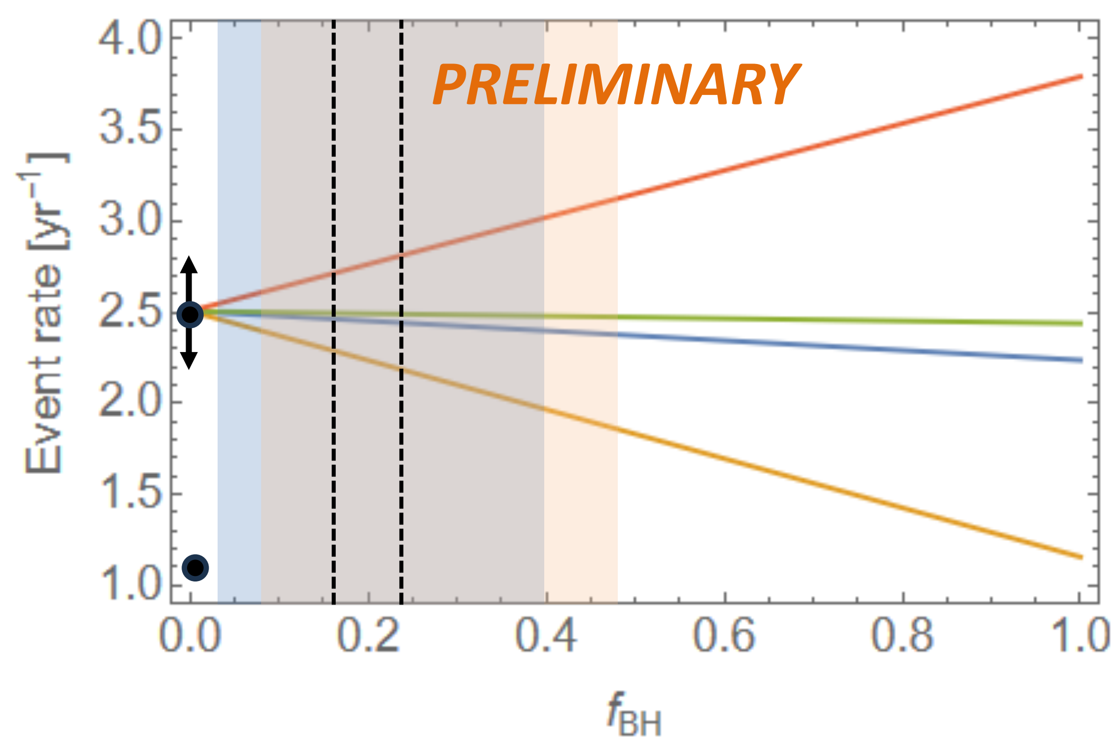
- Binned star formation rate data
- FORNAX 2D hydro + simple late-phase
- Salpeter IMF
- Normal mass ordering
- SuperK + Gd

Analytic

$$R = 2.5^{+0.27}_{-0.27}\ /\text{yr}$$

Correlation

$$R = 1.1^{+0.13}_{-0.13}\ /\text{yr}$$



Ekanger et al (in prep)

PyDSNB

Publicly available code built on SNEWPY, to model DSNB fluxes & events: *coming soon!*

Choice inputs

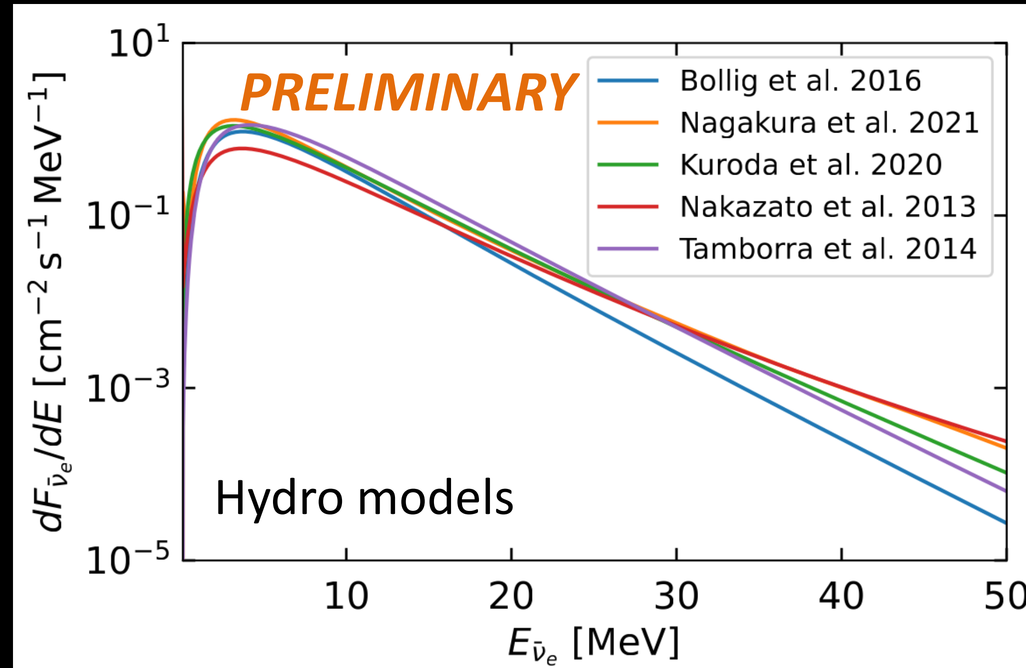
- Hydro model
- Late-time estimate method
- Initial mass function
- Failed (implosion) fraction
- BH model
- Neutrino mass hierarchy

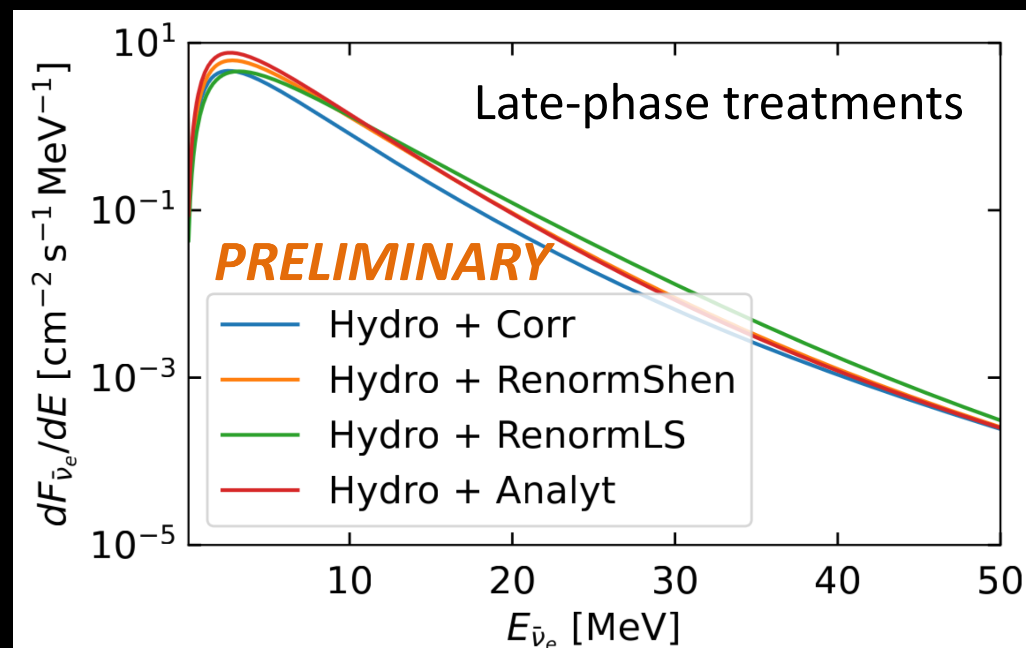
Normal:

$$F_{\bar{\nu}_e}^{\text{obs}} \simeq \cos^2\theta_{12} F_{\bar{\nu}_e} + \sin^2\theta_{12} F_{\nu_x}$$

Inverted:

$$F_{\bar{\nu}_e}^{\text{obs}} \simeq F_{\nu_x}$$





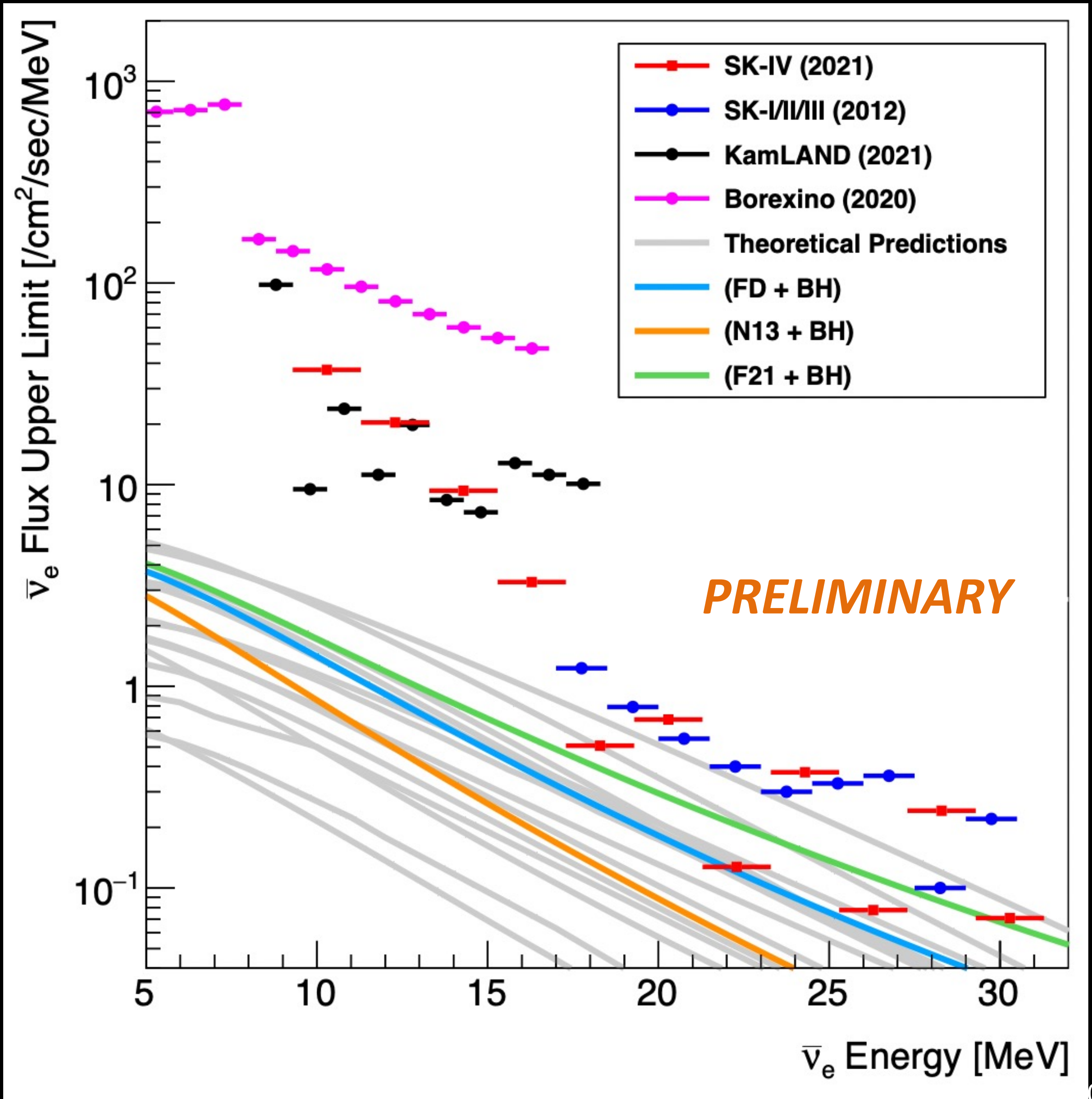
Ando, Ekanger, Horiuchi, Koshio (in prep)

DSNB search limits

Existing limits are reaching into theory predictions

Predictions by *pyDSNB*:

- Three spectra
  1. 4.1 MeV Thermal
  2. Nakazato 1D
  3. Fornax 2D
- BH Fraction 23.6%
- Nakazato 30M Shen
- Kroupa IMF

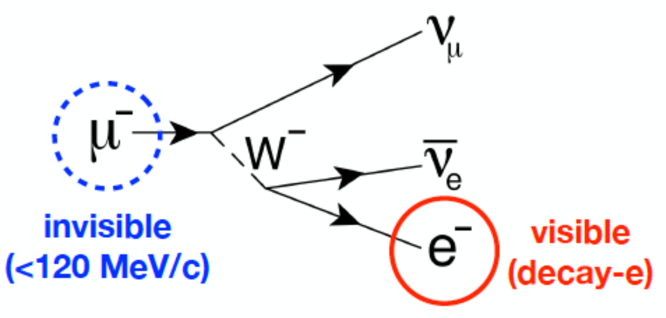


Ando, Ekanger, Horiuchi, Koshio (in prep)

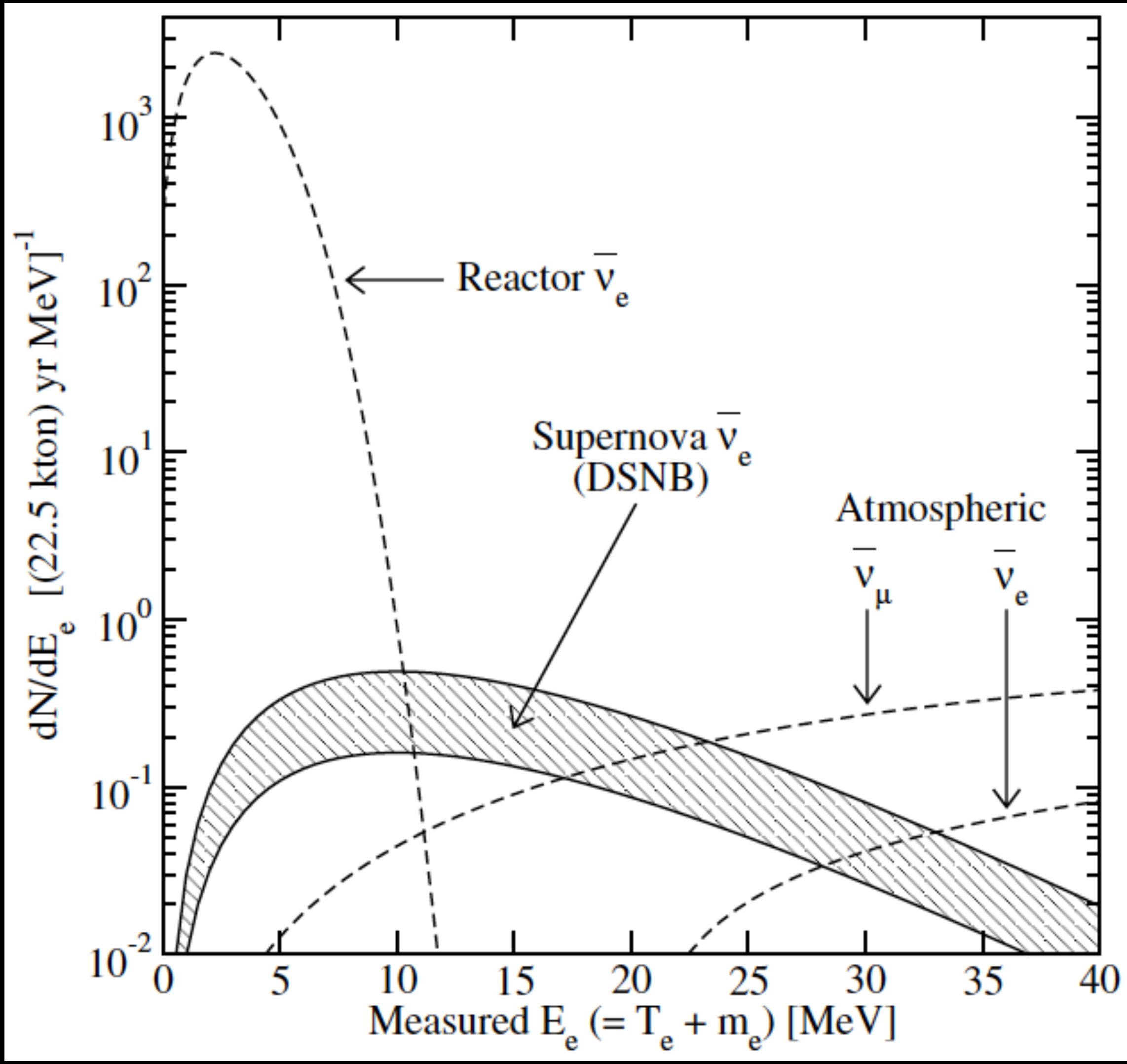
Relevant backgrounds

1. Neutrinos
- Reactor neutrinos
- Atmospheric neutrinos

2. Non-neutrinos
- Invisible muon decays



- CR μ spallation products
- Atmospheric neutrino related



Beacom & Vagins (2004)

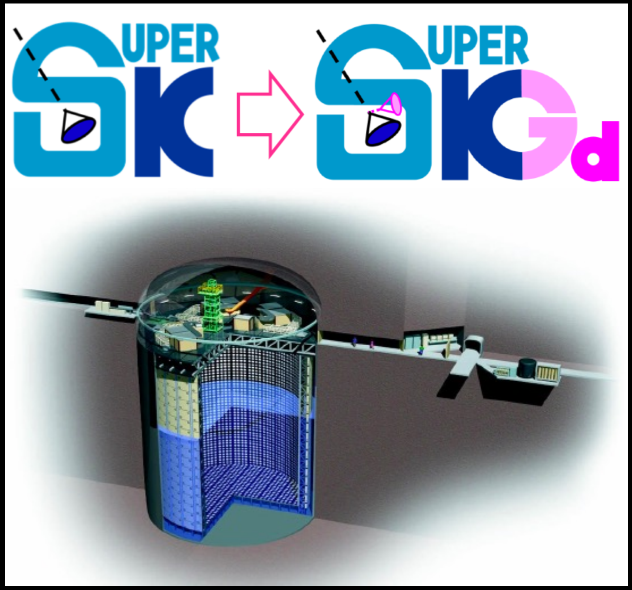
SK-Gd: world's best DSNB detector

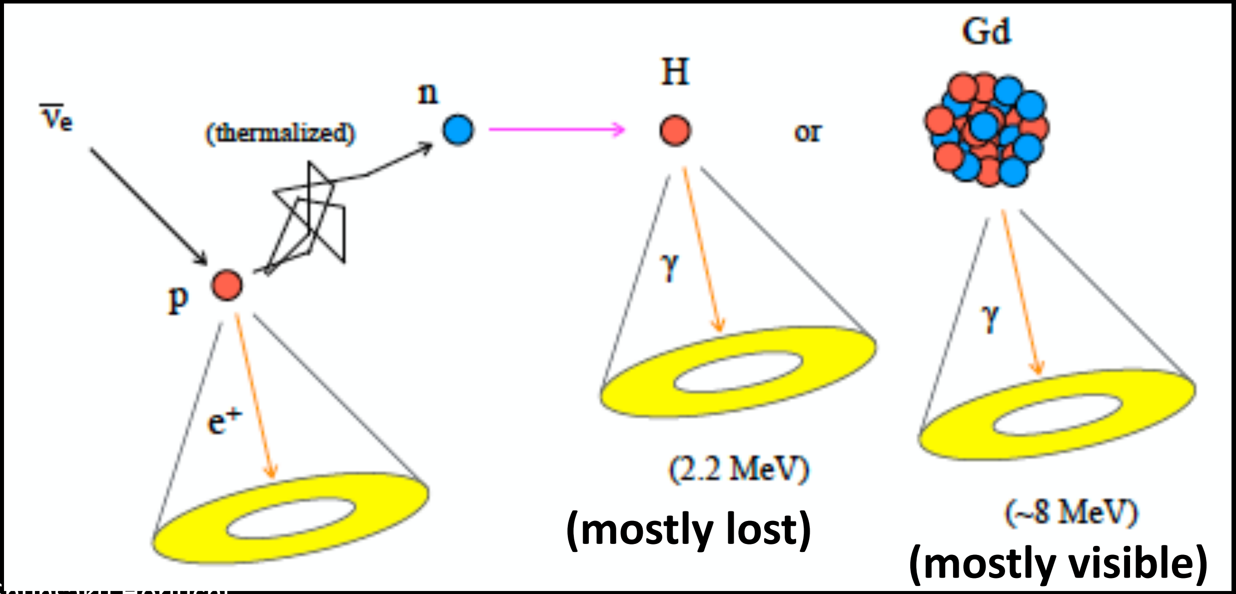
Gadolinium tags IBD

Proposed in 2003, after many R&D & tests (EGADS), Super-K was drained in 2018, refurbished, and started adding Gd in 2020

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

Beacom & Vagins (2004), SK 2021 (arXiv:2109.00360)





Evaluating
Gadolinium's
Action on
Detector
Systems

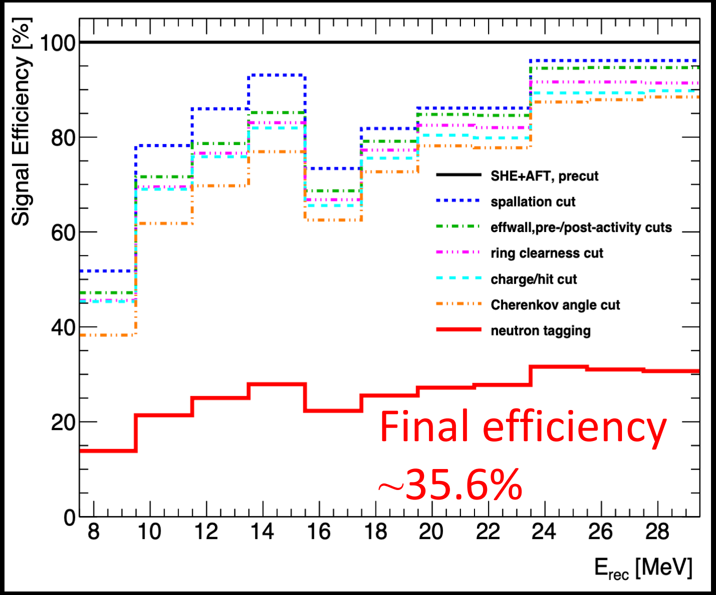
SK-VI: successful Gd performance

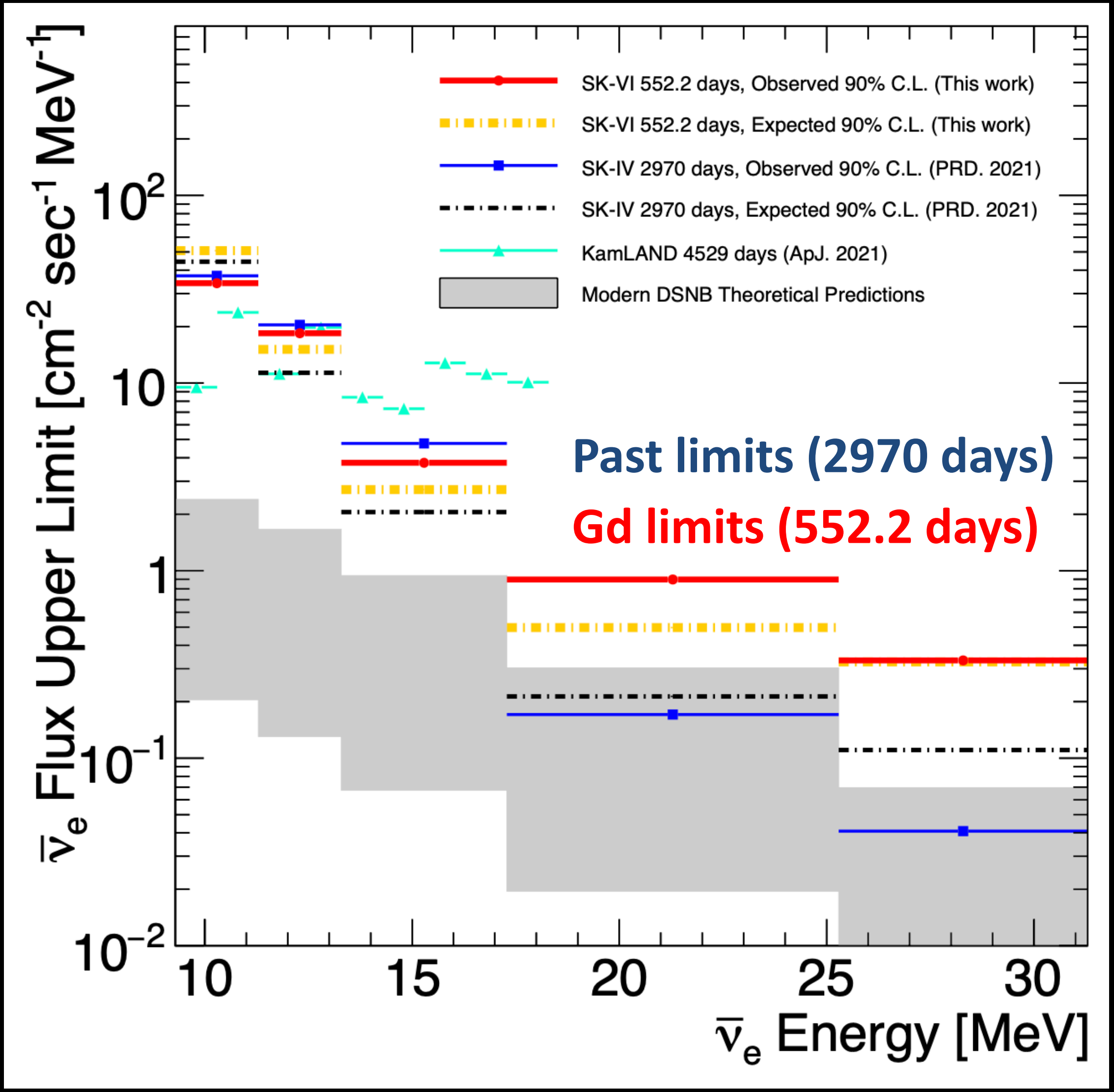
Already comparable with ~10 years of pre-Gd result!

SuperK most recently ran with ~0.01% Gd by mass

→ ~50% captures on Gd

→ Neutron tag efficiency approx doubled cf pre-Gd



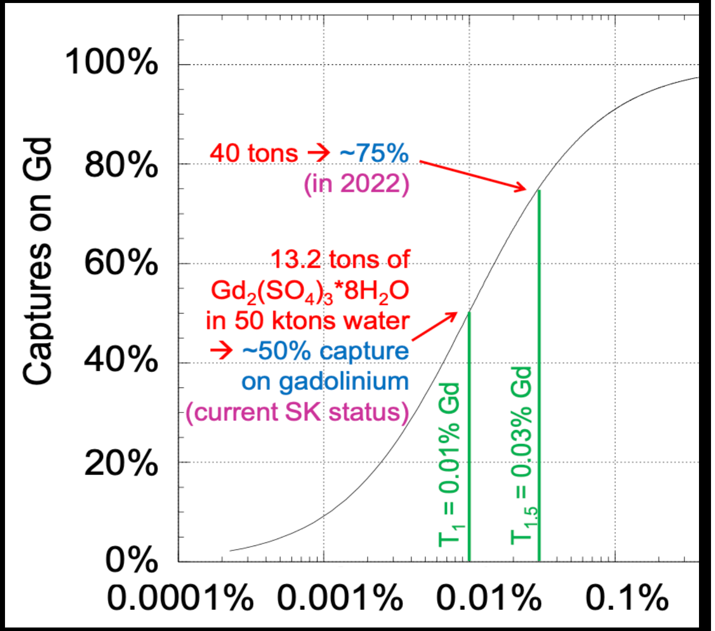


SuperK (Harada et al 2023)

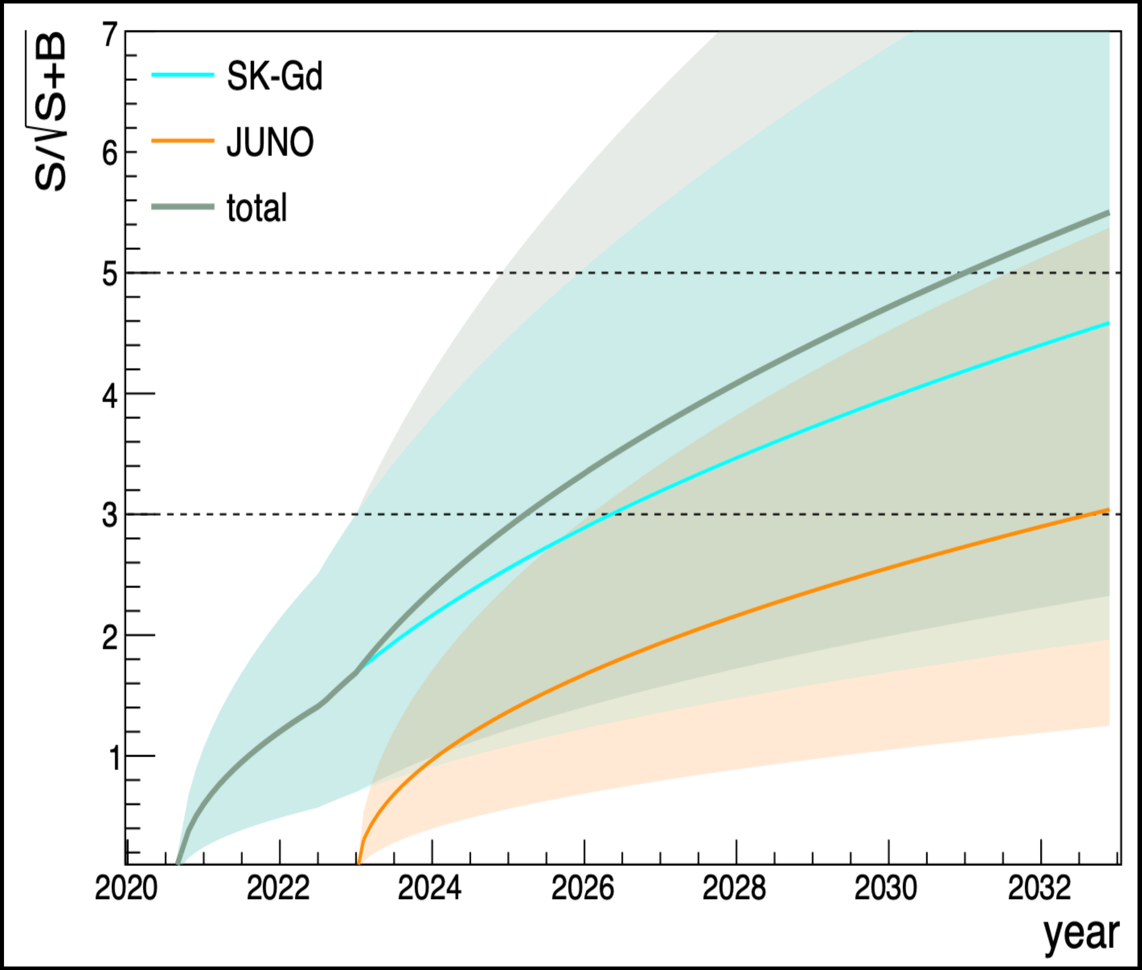
SK-VII: discovery potential

Prospect: SKGd + JUNO reaches ~5σ for central predictions by ~2030

Now running (SK-VII) with ~0.03% Gd by mass
→ ~75% captures on Gd
→ signal : bkg ~ 2



Gd by mass percentage



Li, Vagins, Wurm (2022)

Conclusions

The diffuse supernova neutrino background is *guaranteed*

- ✓ **Core collapse occur frequently (measurements + cross checks)**
- ✓ **Core collapses emit neutrinos (but many details to study)**

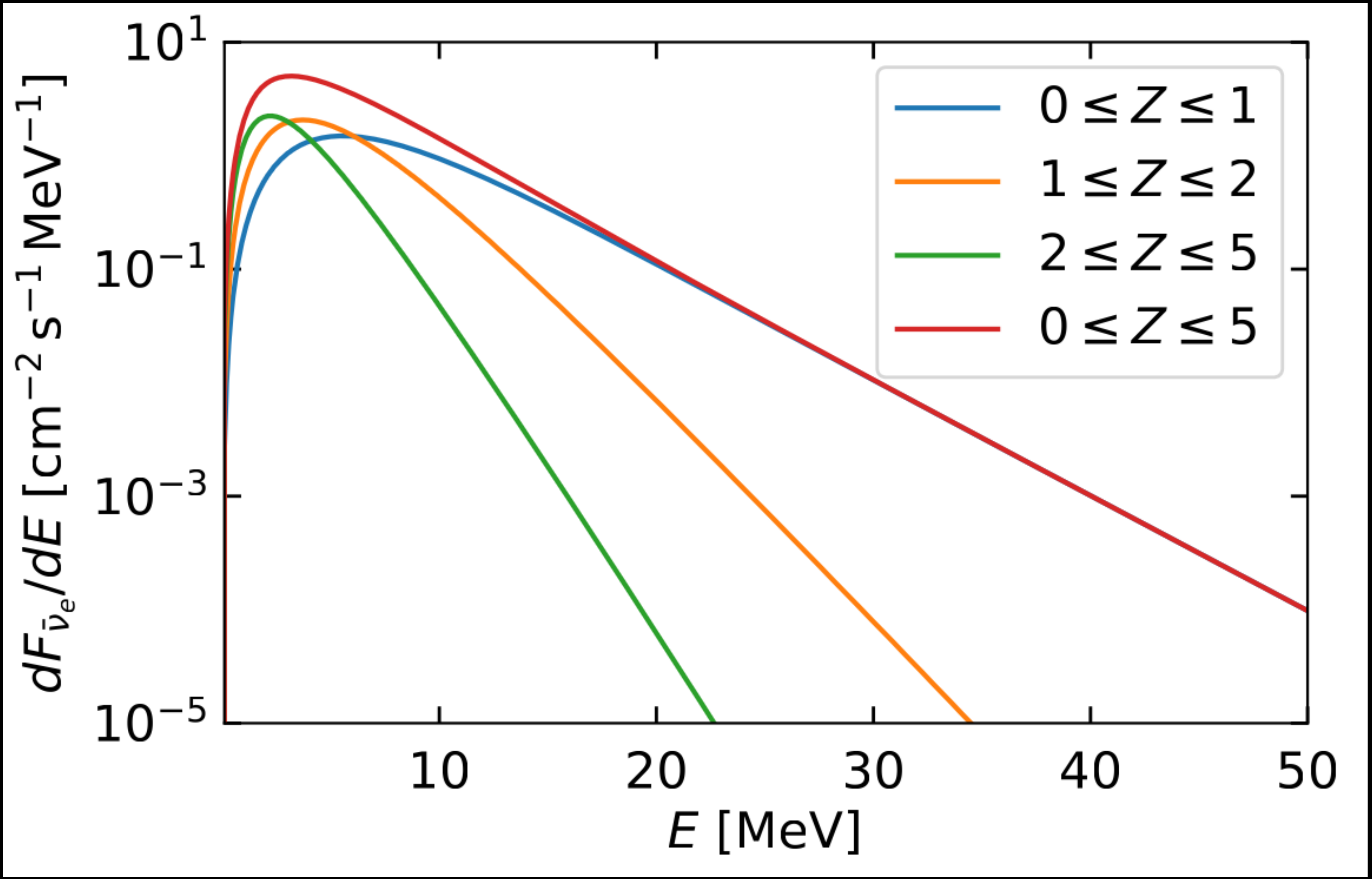
Interesting inputs: **time-integrated neutrino emission, black hole contribution, EOS, binary effects, BSM physics, so on. Testing these will need a well-measured core-collapse rate, which is improving.**

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

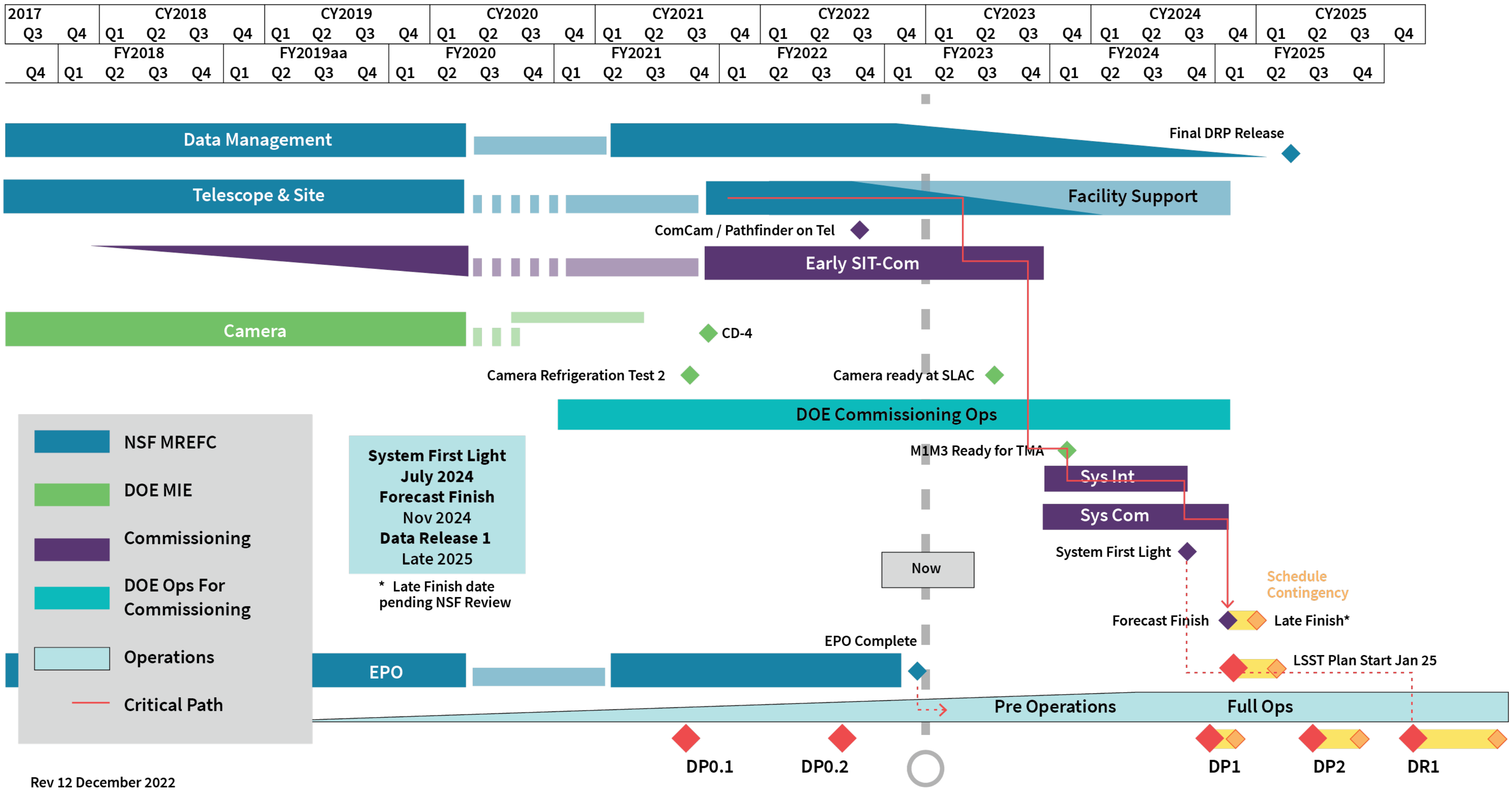
Thank you!

BACKUP

Redshift range



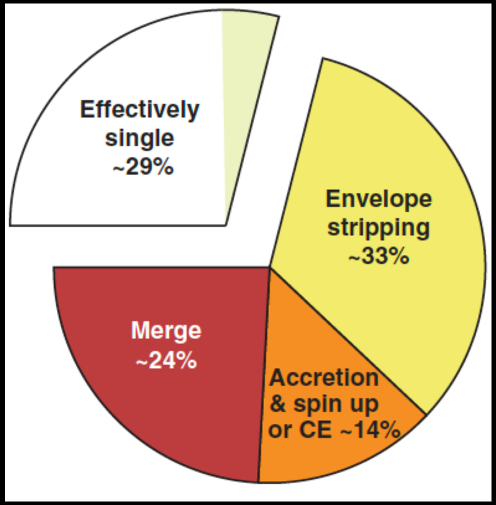
LSST operations 2025~



Importance of binaries

The majority of massive stars evolve in binaries

e.g., Sana et al (2012)

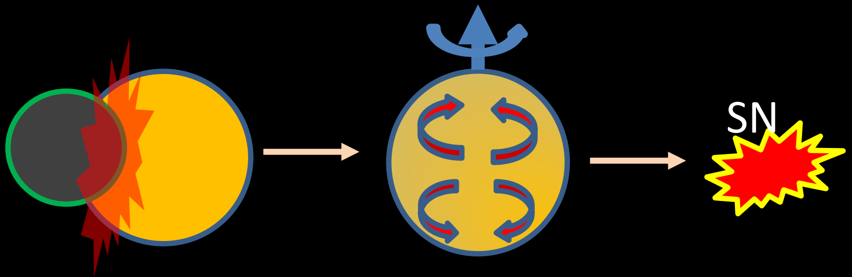


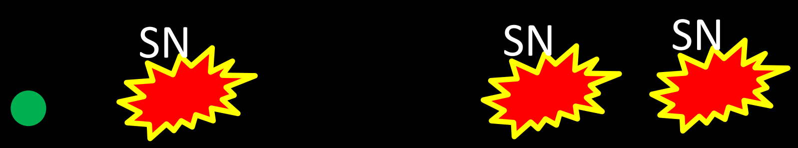
For core-collapse supernovae:

➔ **Number of progenitors changed**
➔ **Masses of progenitors changed**

Merger case → **More massive progenitor**

Non-merger → **Single** / **Double**

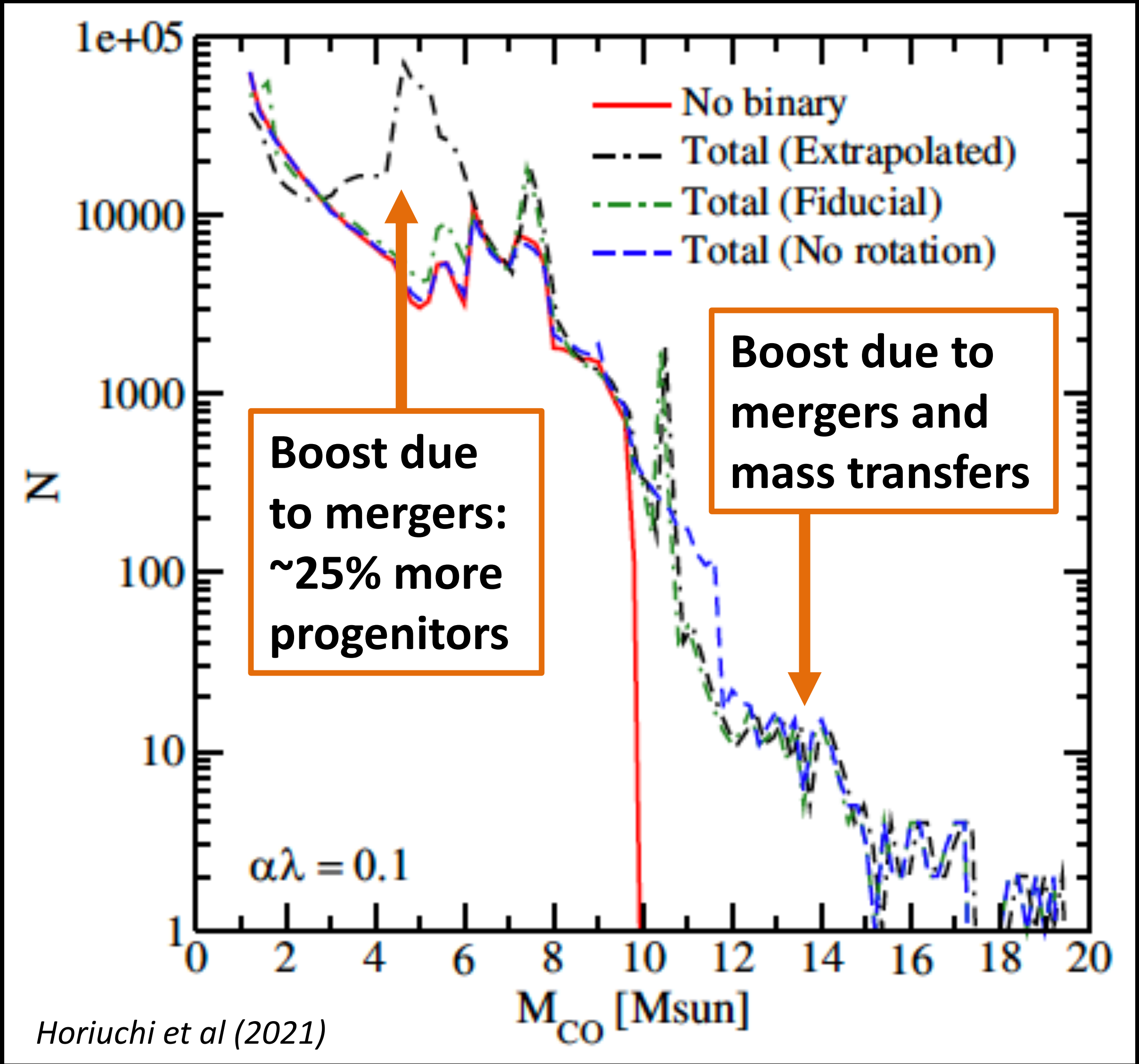




Visuals: thanks to T. Kinugawa

Population synthesis results

Results of binary population syntheses:



Horiuchi et al (2021)

Population synthesis

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%

DSNB searches

Currently background dominated

SuperK (2023)