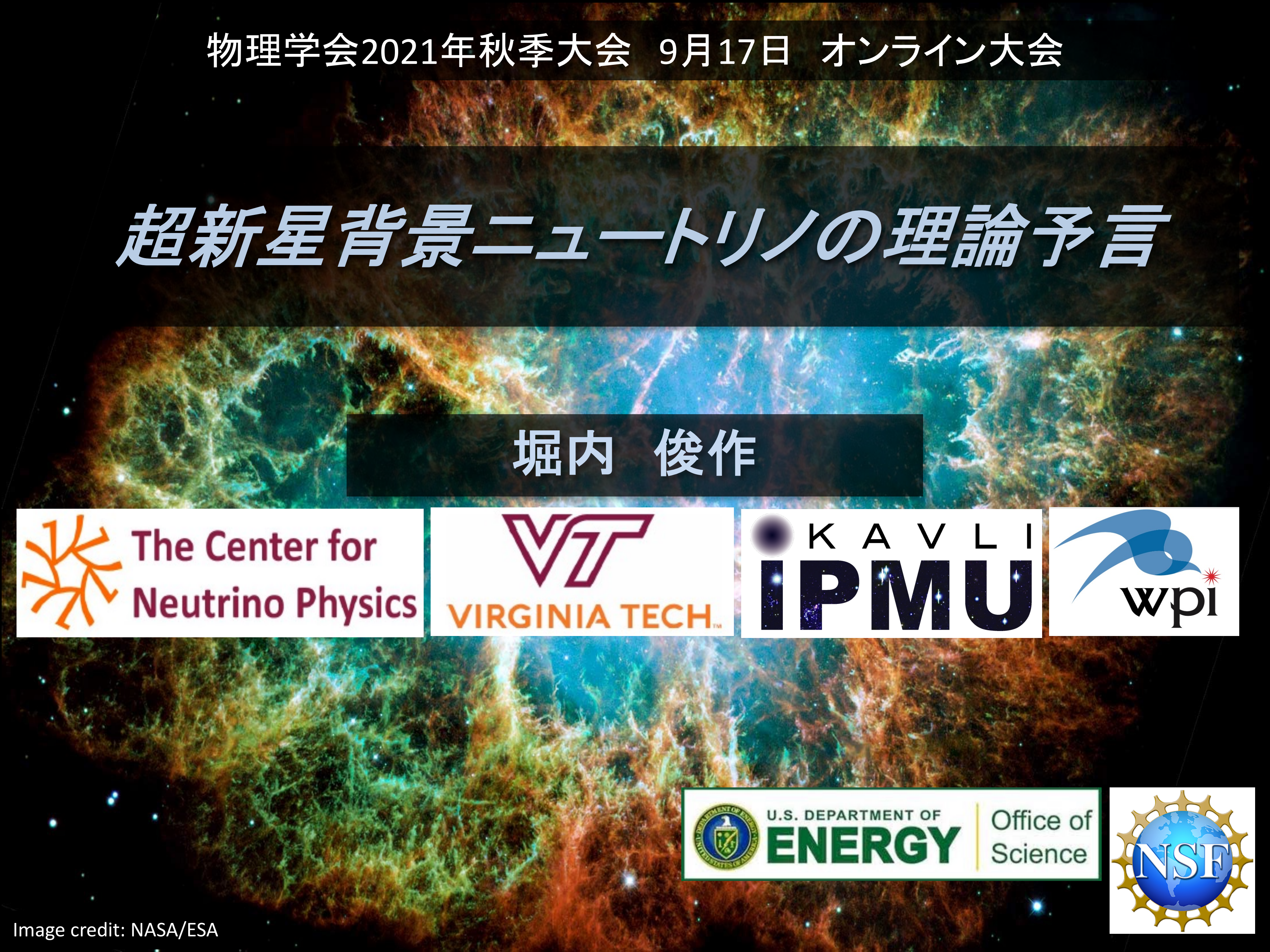


物理学会2021年秋季大会　9月17日　オンライン大会

超新星背景ニュートリノの理論予言

堀内　俊作

The Center for Neutrino Physics

VIRGINIA TECH

KAVLI IPMU

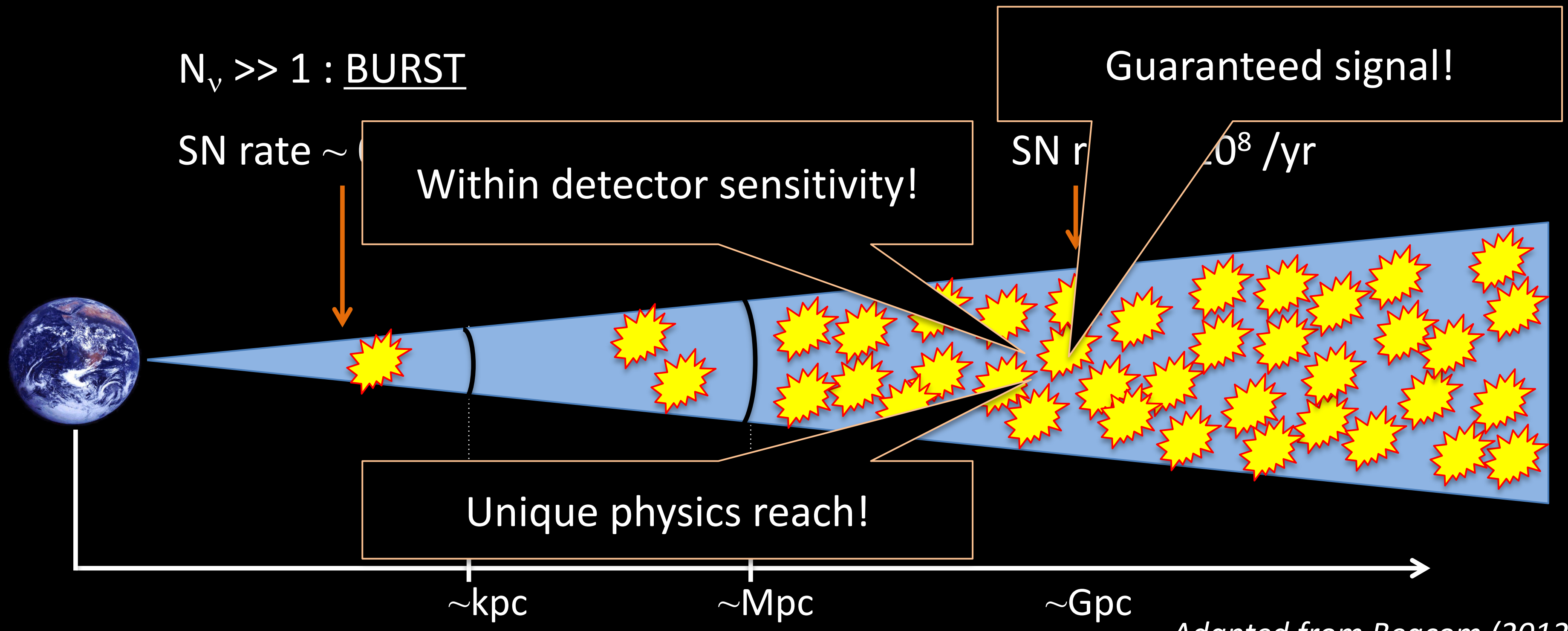
wpi

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

Image credit: NASA/ESA

Distance scales and physics outcomes



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

SN rate ~ (

Within detector sensitivity!

Guaranteed signal!

SN r 0^8 /yr

Unique physics reach!

~kpc

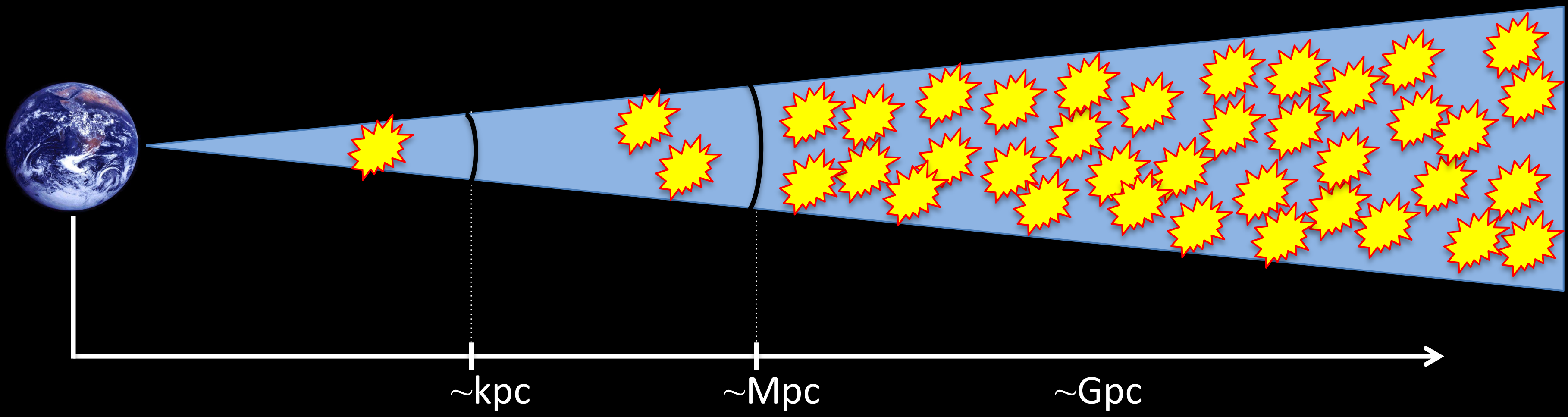
~Mpc

~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) Multi explosion mechanisms Neutrino physics

Necessary ingredients



1. Rate of massive star core collapse

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

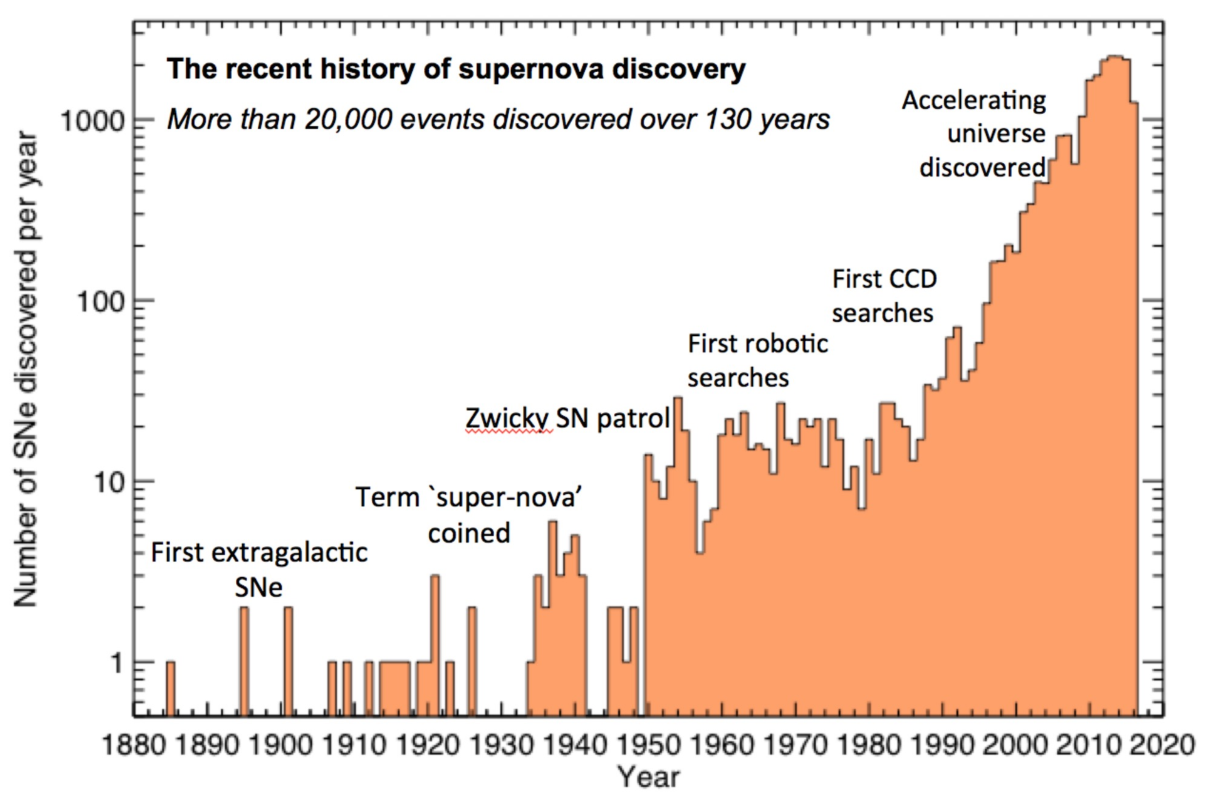
2. Averaged neutrino emission from many core collapse

Stars explode EVERYDAY

➜ In the LMC

SN 1987A

➜ But in the universe, supernovae are not rare



1801.06643

Cosmic core-collapse rate

Direct measurements

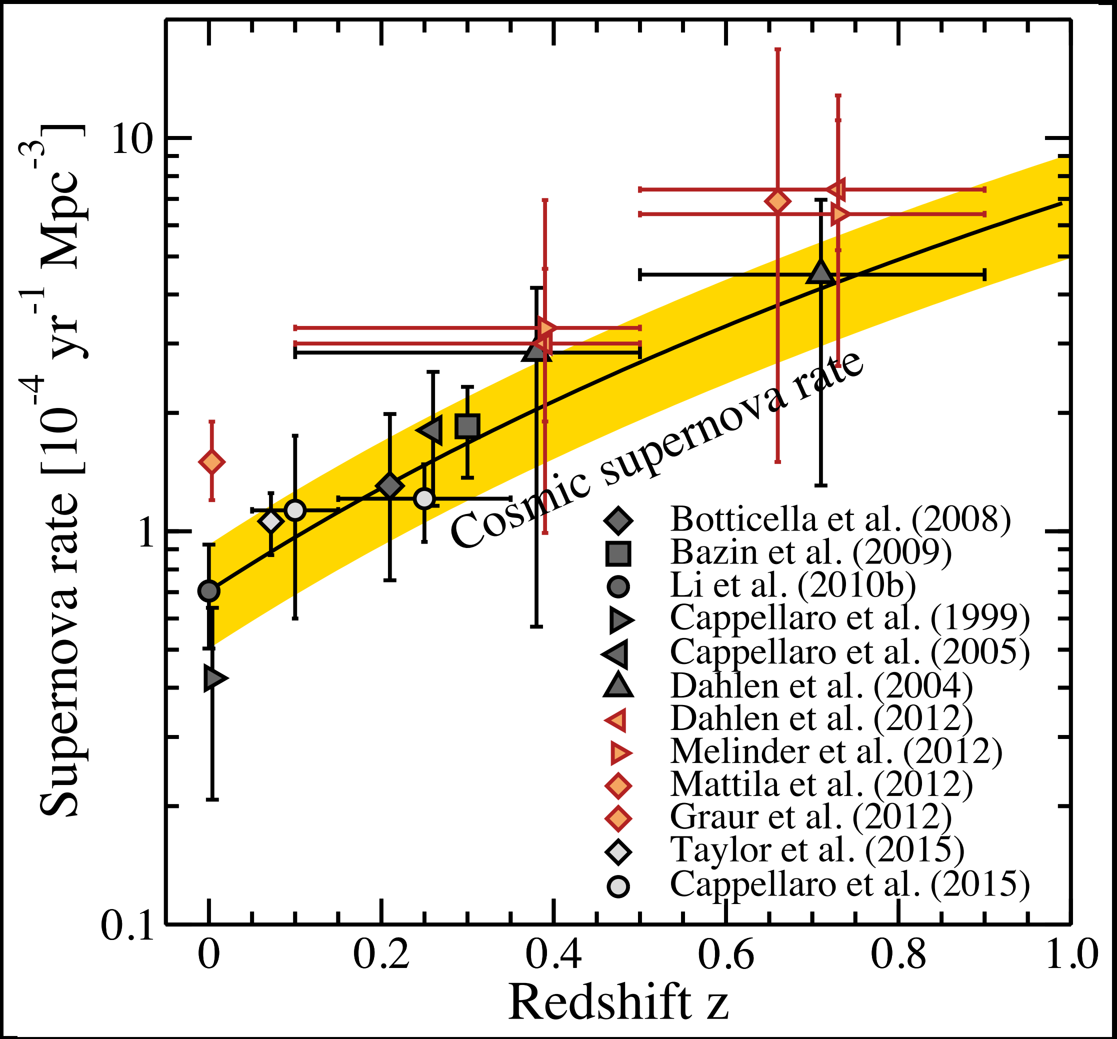
Improving quickly!

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)

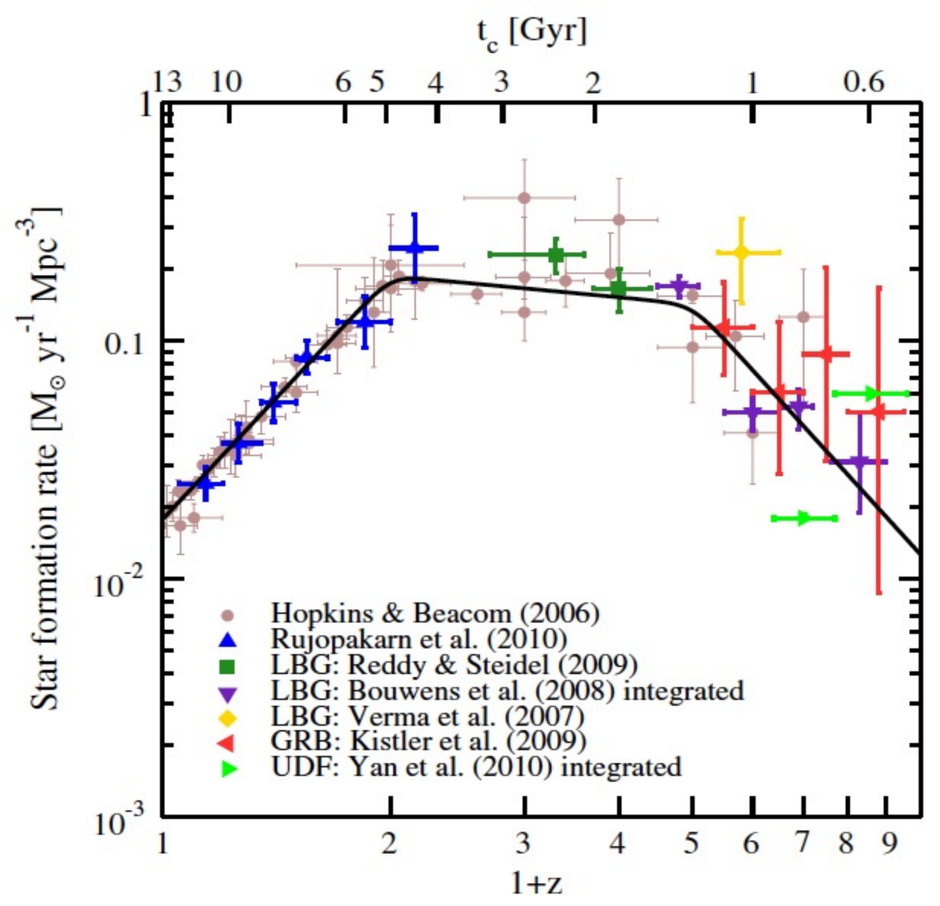


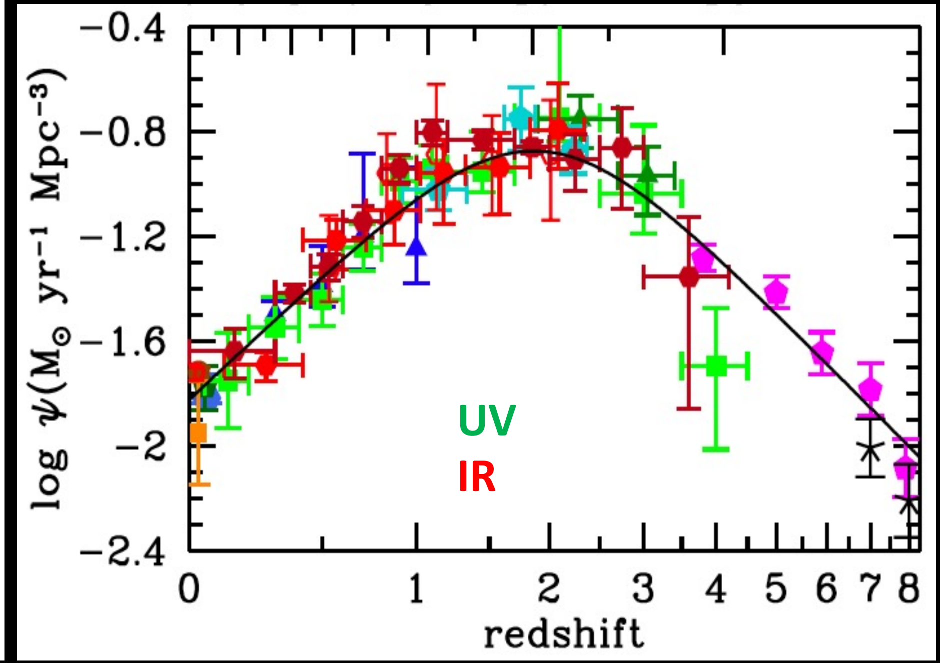
Updated from Horiuchi et al (2011)

Cosmic birth rate of stars

Useful comparison point:

- Many groups, many wavebands, many data sets.
- Dust correction is main difficulty





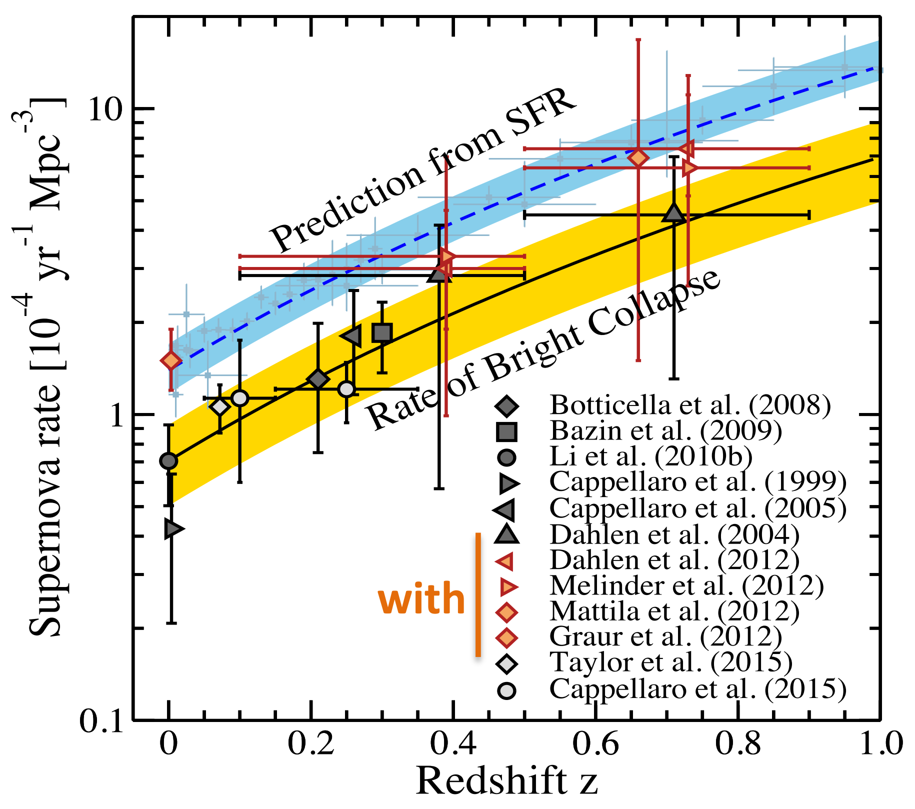
Horiuchi & Beacom (2010)   Madau & Dickinson (2014)

Cosmic comparison

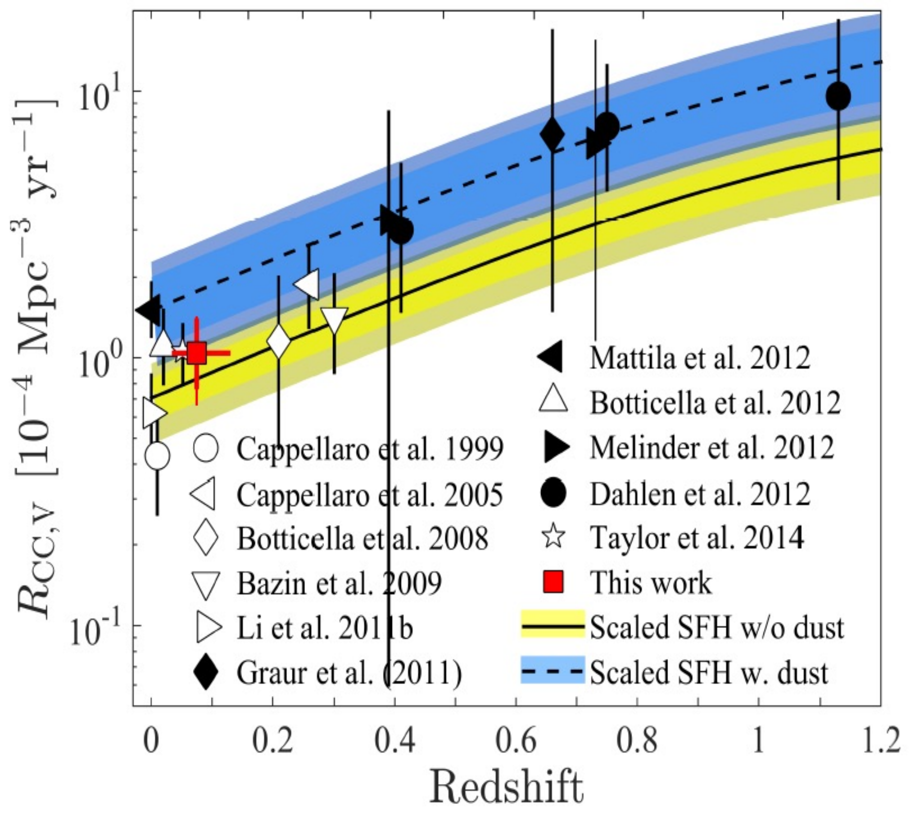
Core collapse rate = Birth rate of massive stars

*because lifetime of massive stars are cosmologically short

Correct for especially heavy attenuation by dust (filled symbols)

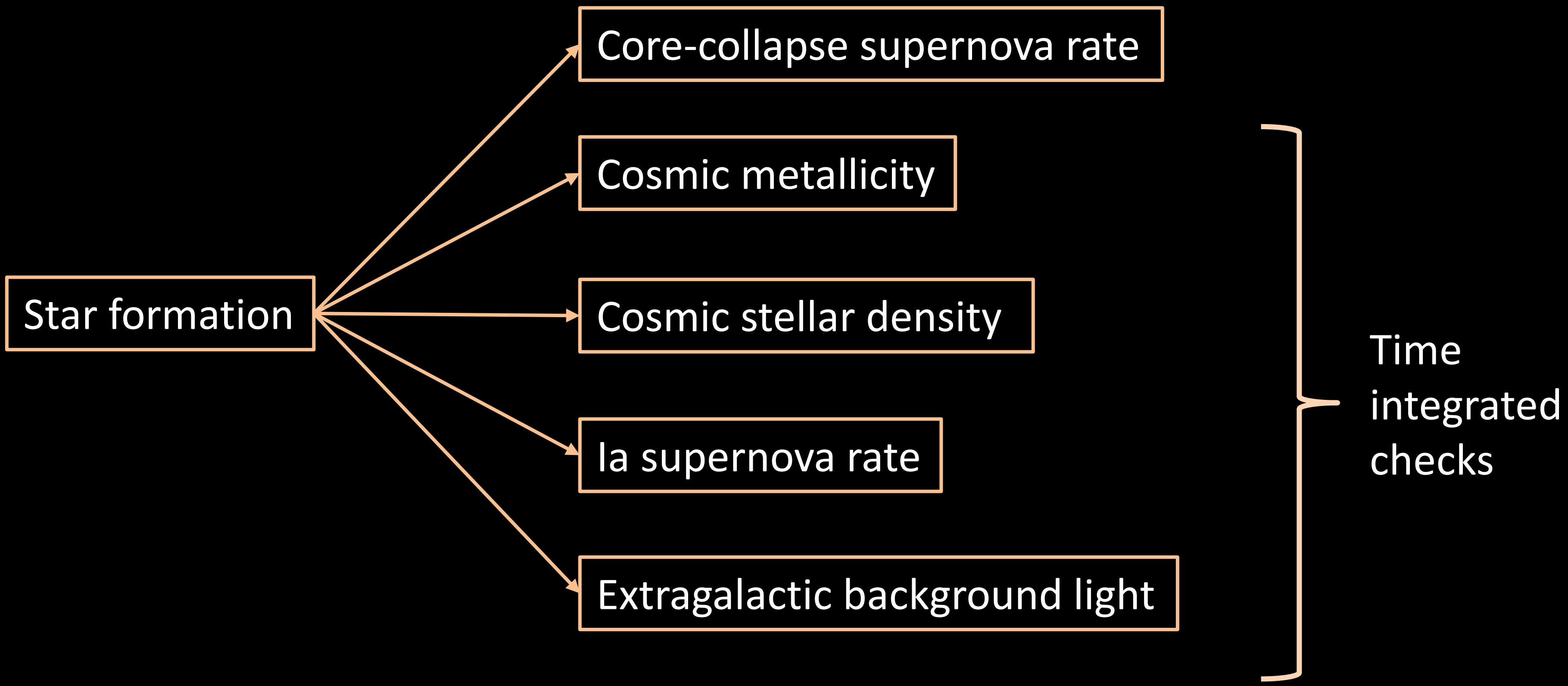


Updated from Horiuchi et al (2011)



Graur et al (2015)

Examples of cosmic cross checks



Star formation

Core-collapse supernova rate

Cosmic metallicity

Cosmic stellar density

Ia supernova rate

Extragalactic background light

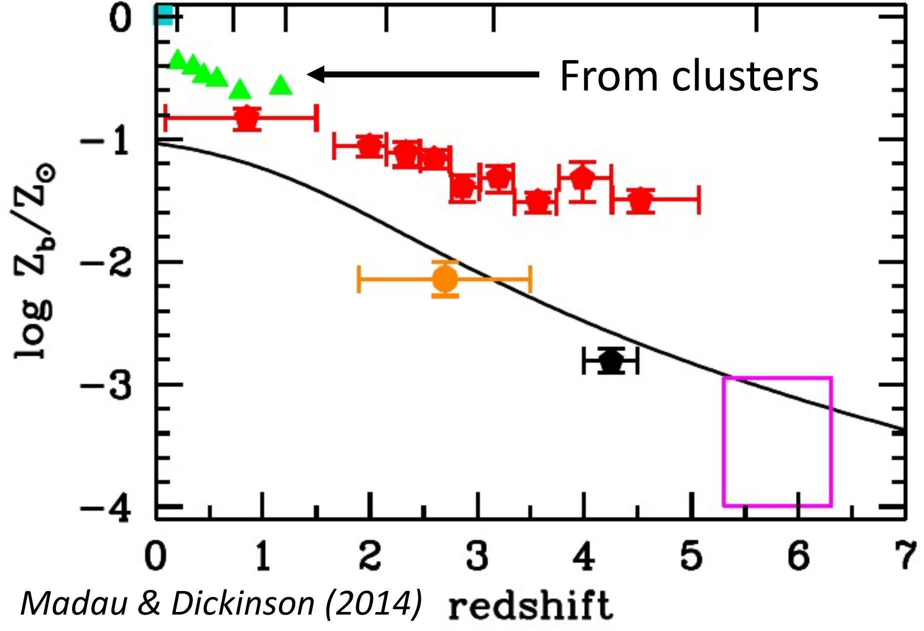
Time integrated checks

Integrated cross checks

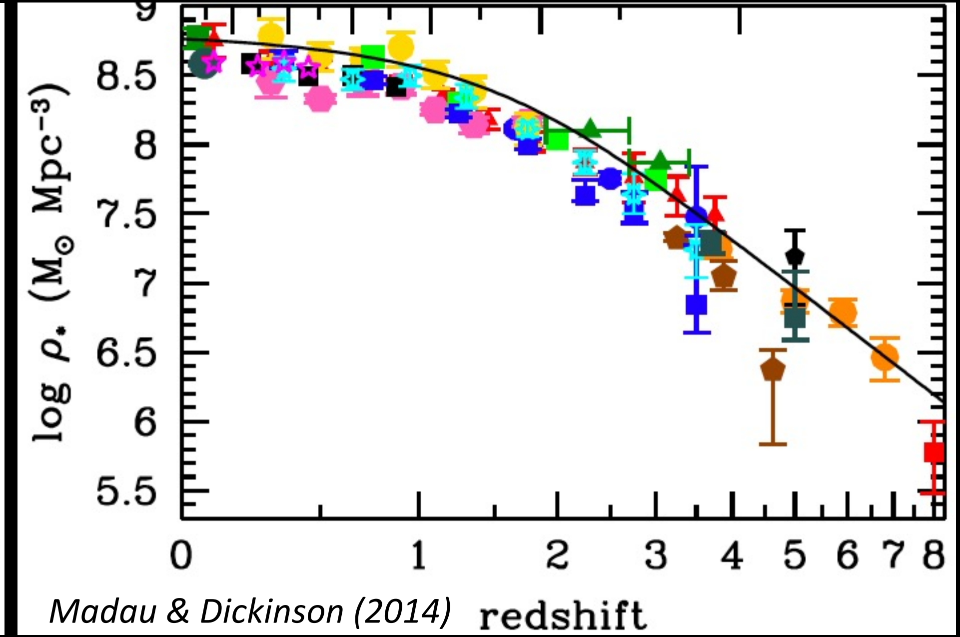
Star formation

Cosmic metallicity
*measurement systematics

Cosmic stellar density
*Sensitive to cosmic initial mass function

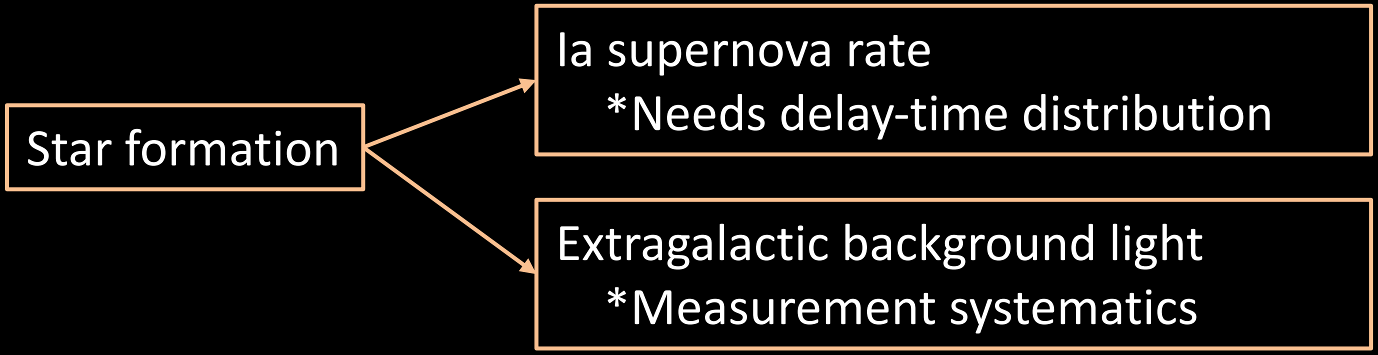


Madau & Dickinson (2014)



Madau & Dickinson (2014)

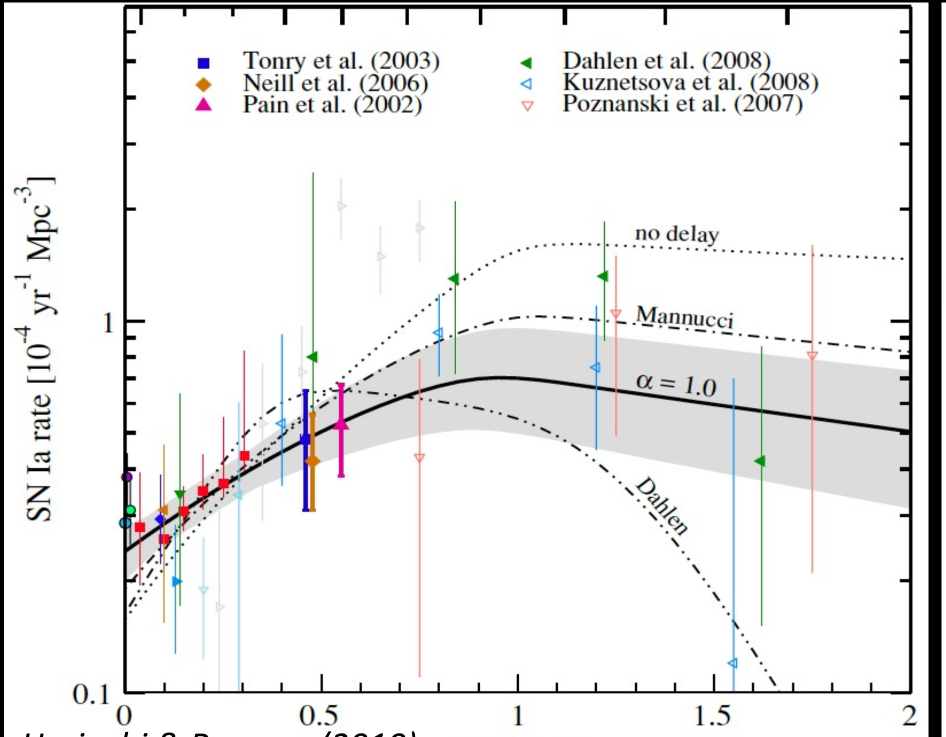
Integrated cross checks



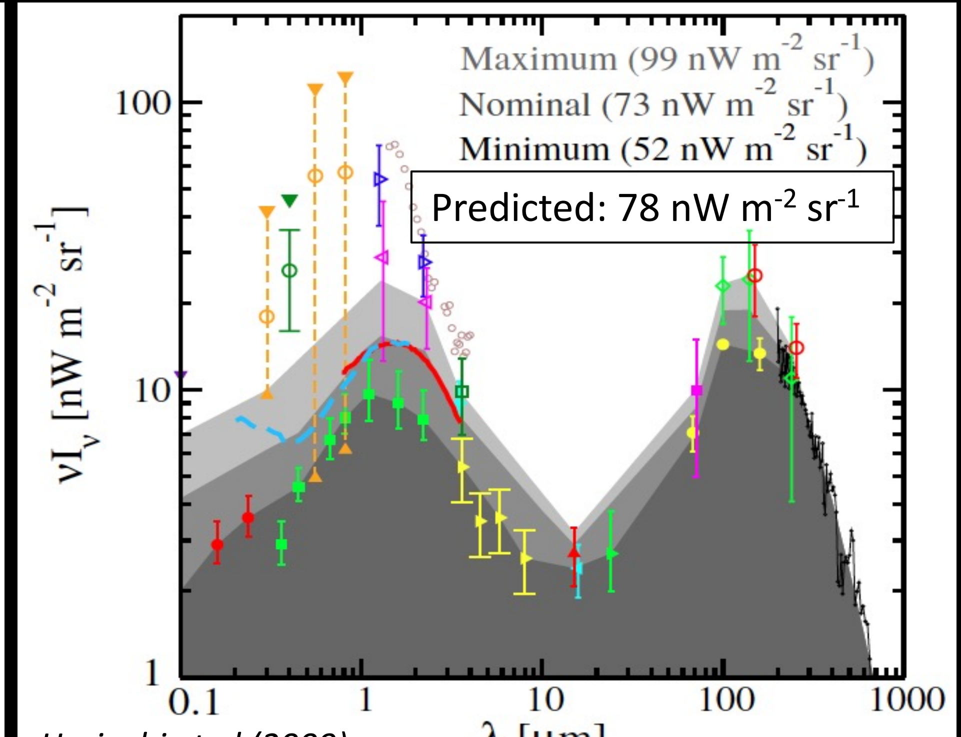
Star formation

Ia supernova rate
*Needs delay-time distribution

Extragalactic background light
*Measurement systematics



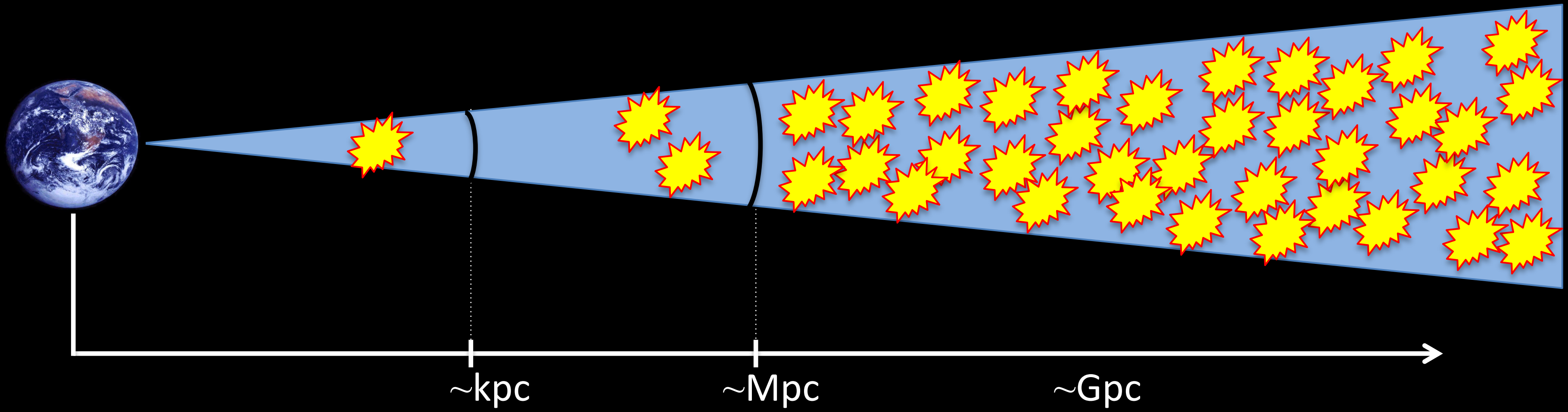
Horiuchi & Beacom (2010)



Predicted: 78 nW m^{-2} sr^{-1}

Horiuchi et al (2009)

Necessary ingredients



1. Rate of massive star core collapse

2. Averaged neutrino emission from many core collapse

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

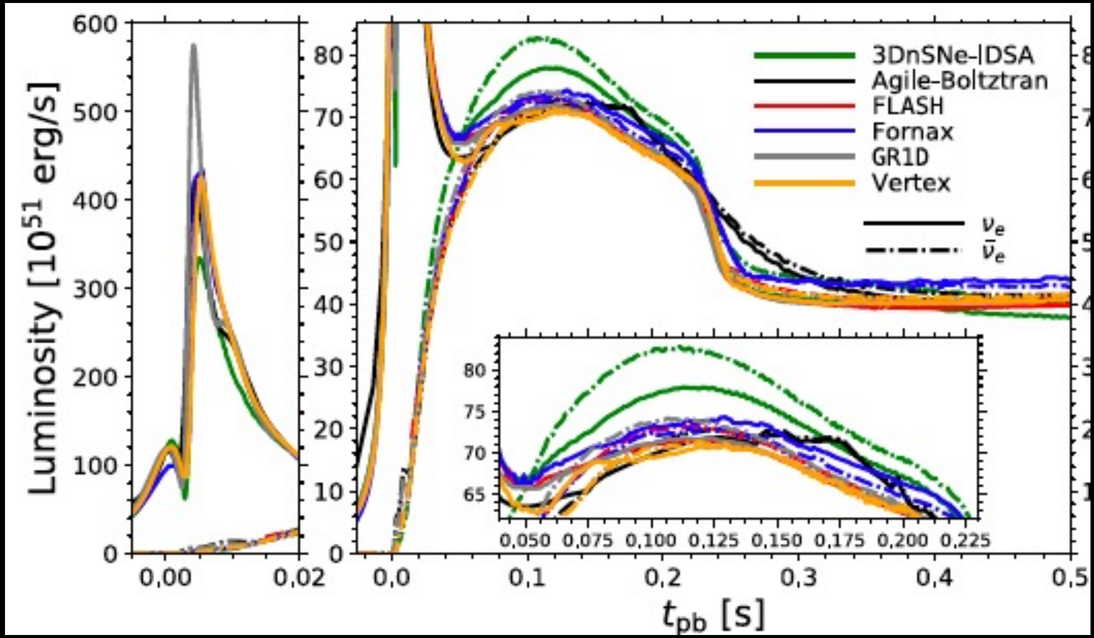
Cross sections, detector capabilities

Neutrino emission

Much progress on numerical studies of core-collapse neutrino emission

- ✓ Three-dimensional simulations
- ✓ Input microphysics
- ✓ Systematic code comparison
- ✓ Oscillation likely get averaged out to MSW

Lunardini & Tamborra (2012)



O'Connor et al (2018)

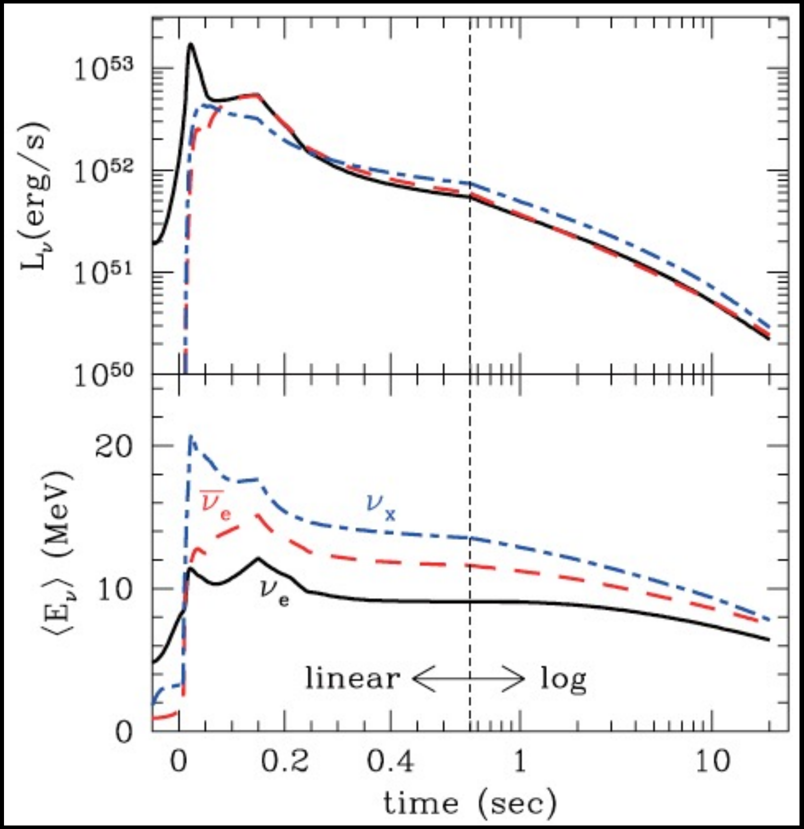
However, there are some unique challenges for the DSNB:

1. What is the long-term time-integrated neutrino emission?
2. What is the diversity in neutrino emissions?
3. How to account for collapse to black holes?
4. How to account for stellar binary effects?

1. long-term simulations

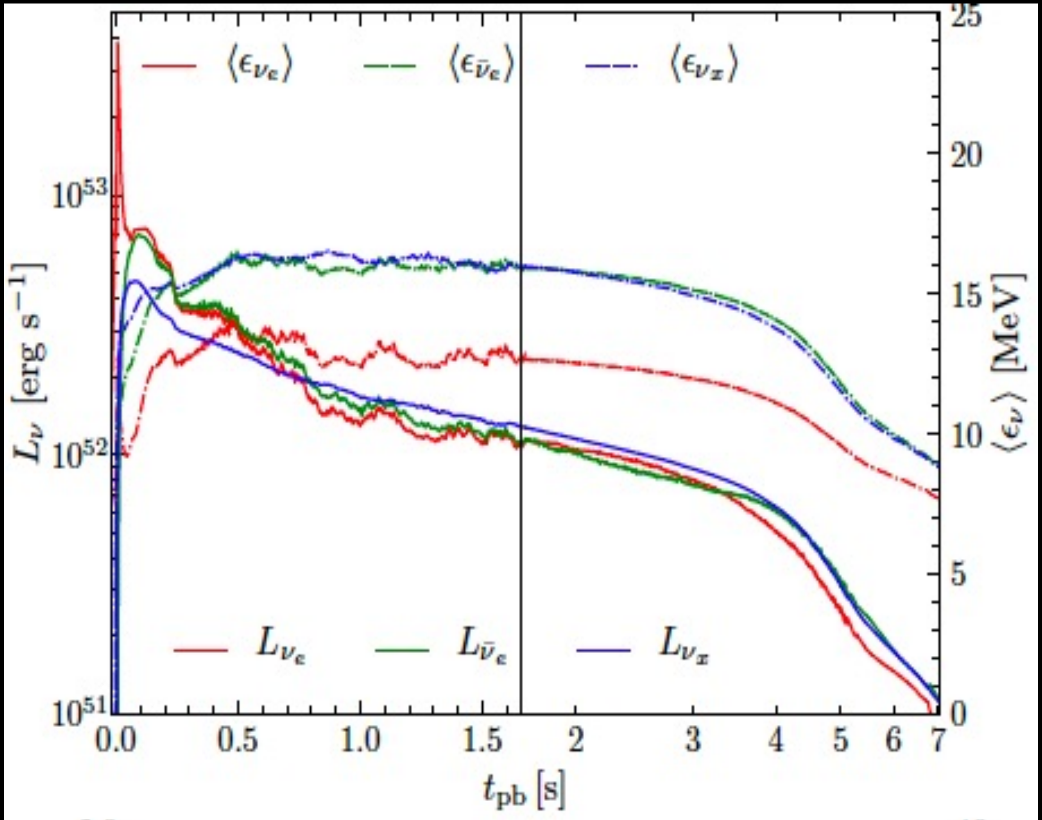
Growing availability: Long-term (~10 sec) simulations are feasible by switching from hydro to cooling after shock expansion

With 1D hydro, systematic sample



Nakazato et al (2013)

With 3D hydro, single progenitor



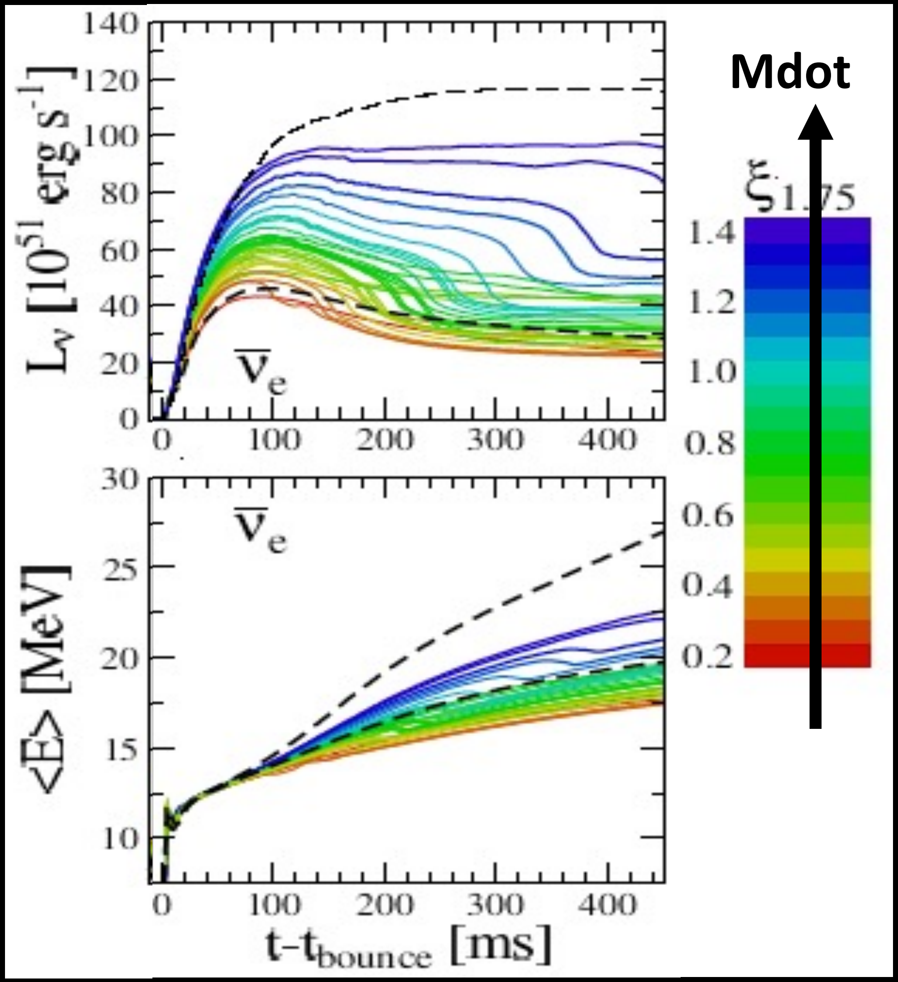
Bollig et al (2021)

Other long-term simulations, e.g.:
Fischer et al (2009), 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)

2. Diversity in neutrino emission

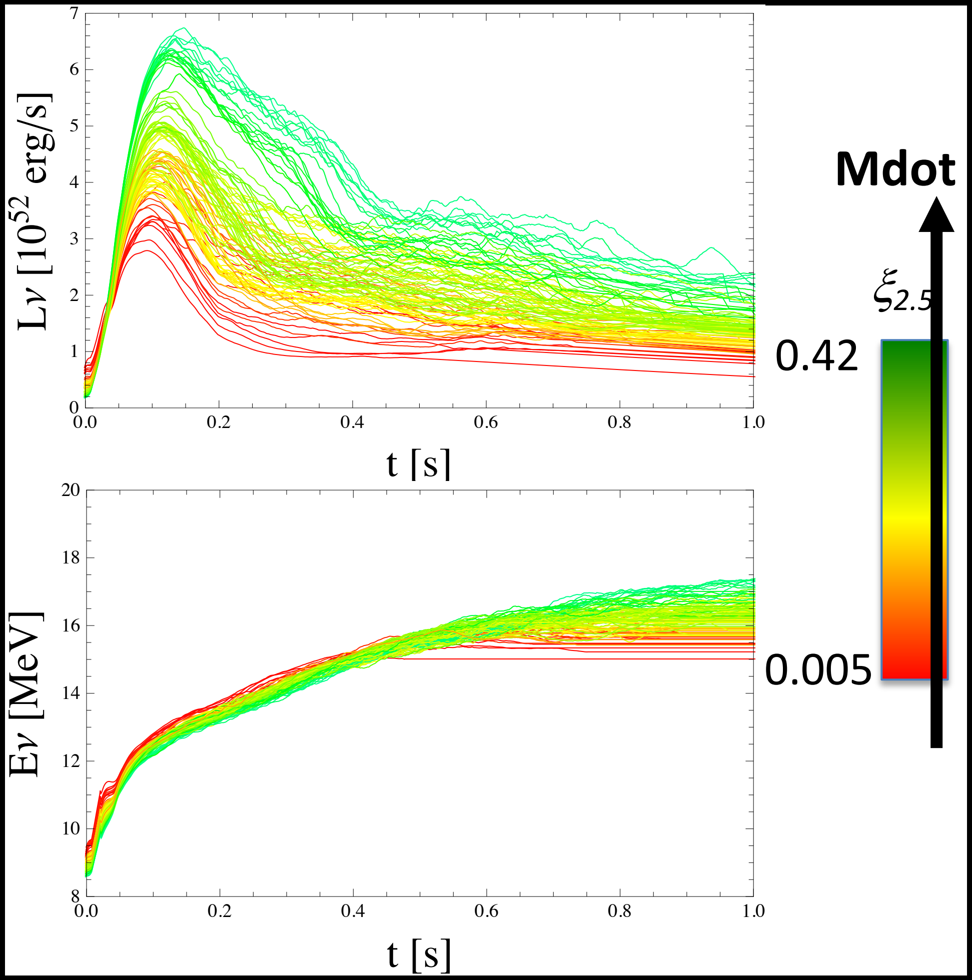
Strong variations: neutrino light curve reflects the progenitor’s density profile

1D simulations



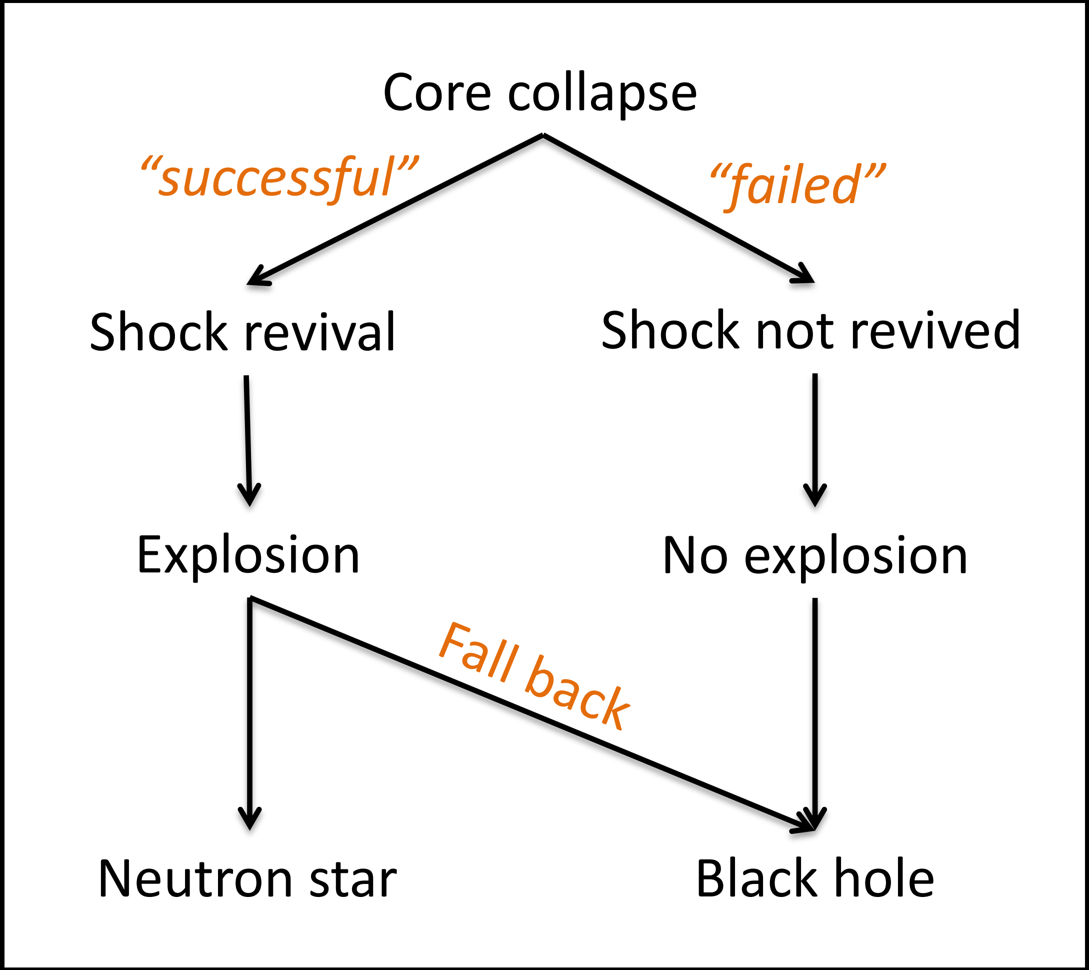
O’Connor & Ott (2013)

2D simulations



Based on Nakamura et al (2015)

3. Account for collapse to black holes



Core collapse

“successful”

“failed”

Shock revival

Shock not revived

Explosion

No explosion

Fall back

Neutron star

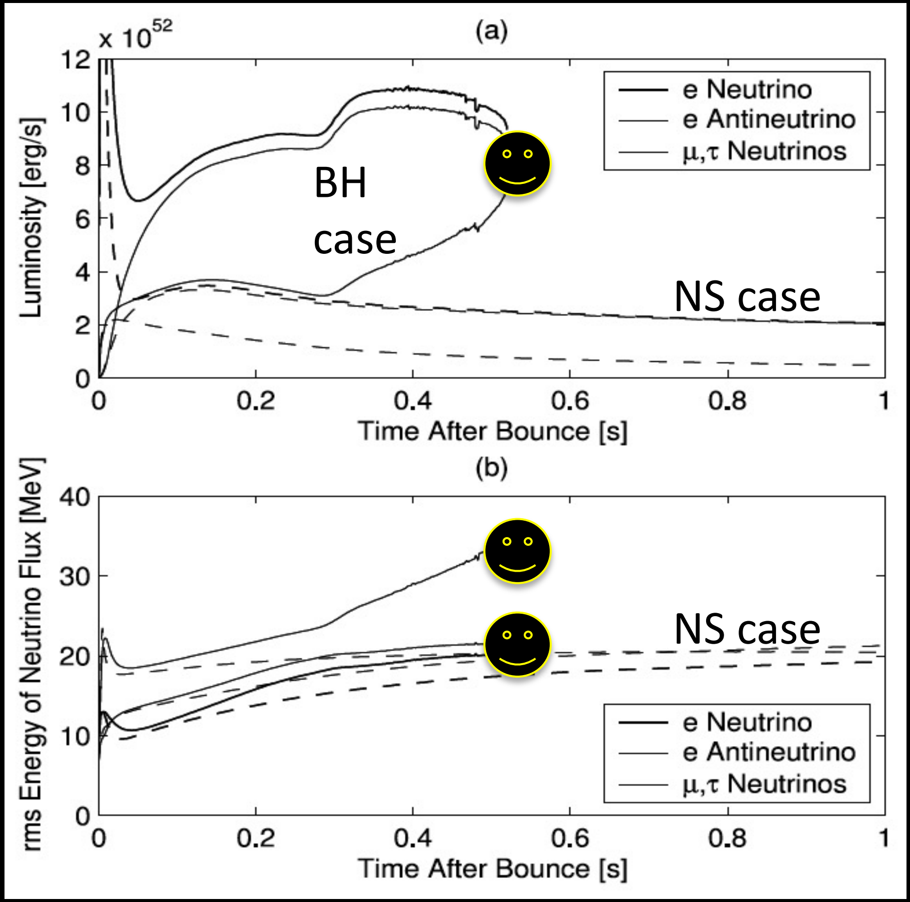
Black hole

Collapse to black holes

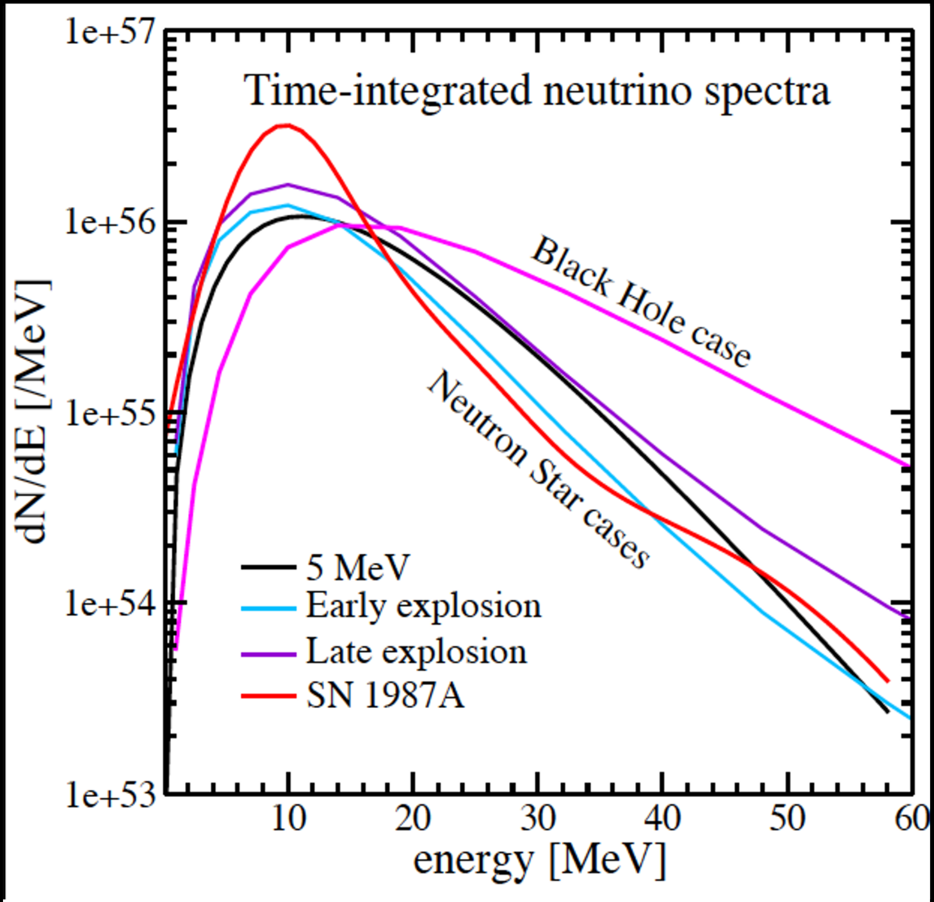
Neutrinos from collapse to black hole

Black hole formation goes through high mass accretion

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



Liebendoerfer et al 2004



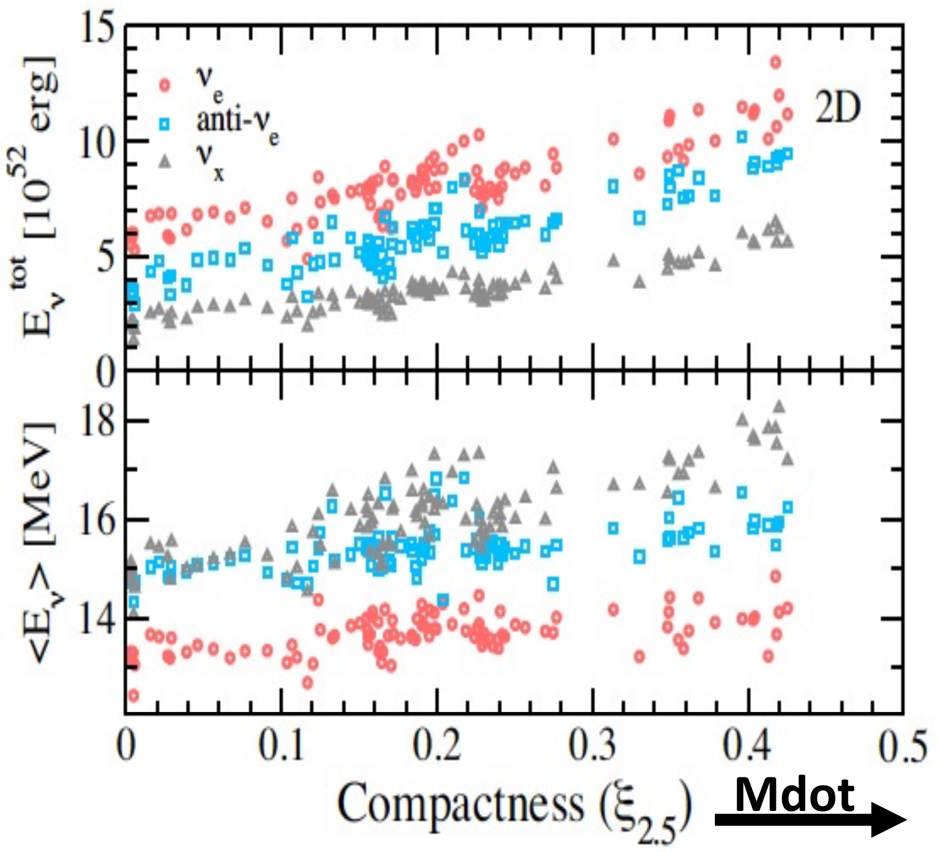
Studied by many groups, e.g., Fischer et al, Sumiyoshi et al, Nakazato et al, Ott et al, O'Connor et al, Kuroda et al.

Time-integrated neutrino emission

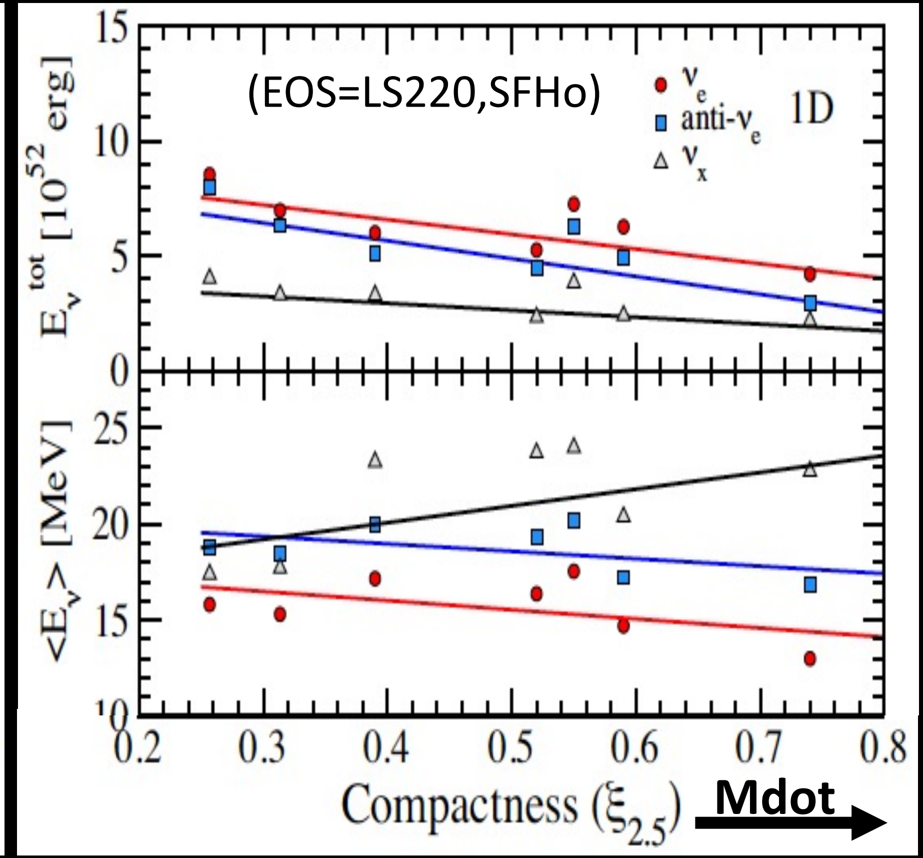
Systematic dependence on progenitor

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

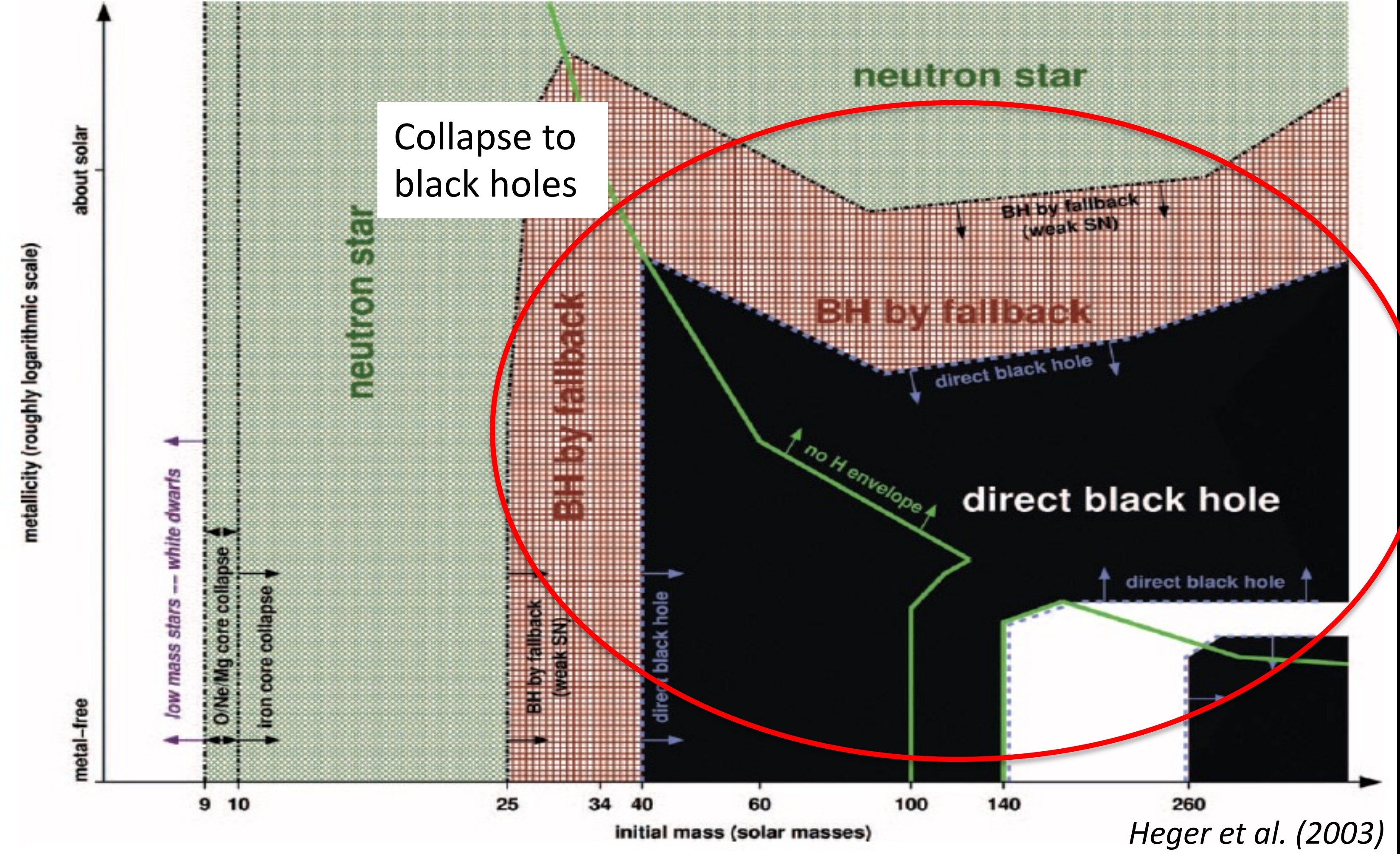

(EOS=LS220,SFHo)

Horiuchi et al (2018)

Which stars collapse to black holes?

The expectation circa 2000:

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



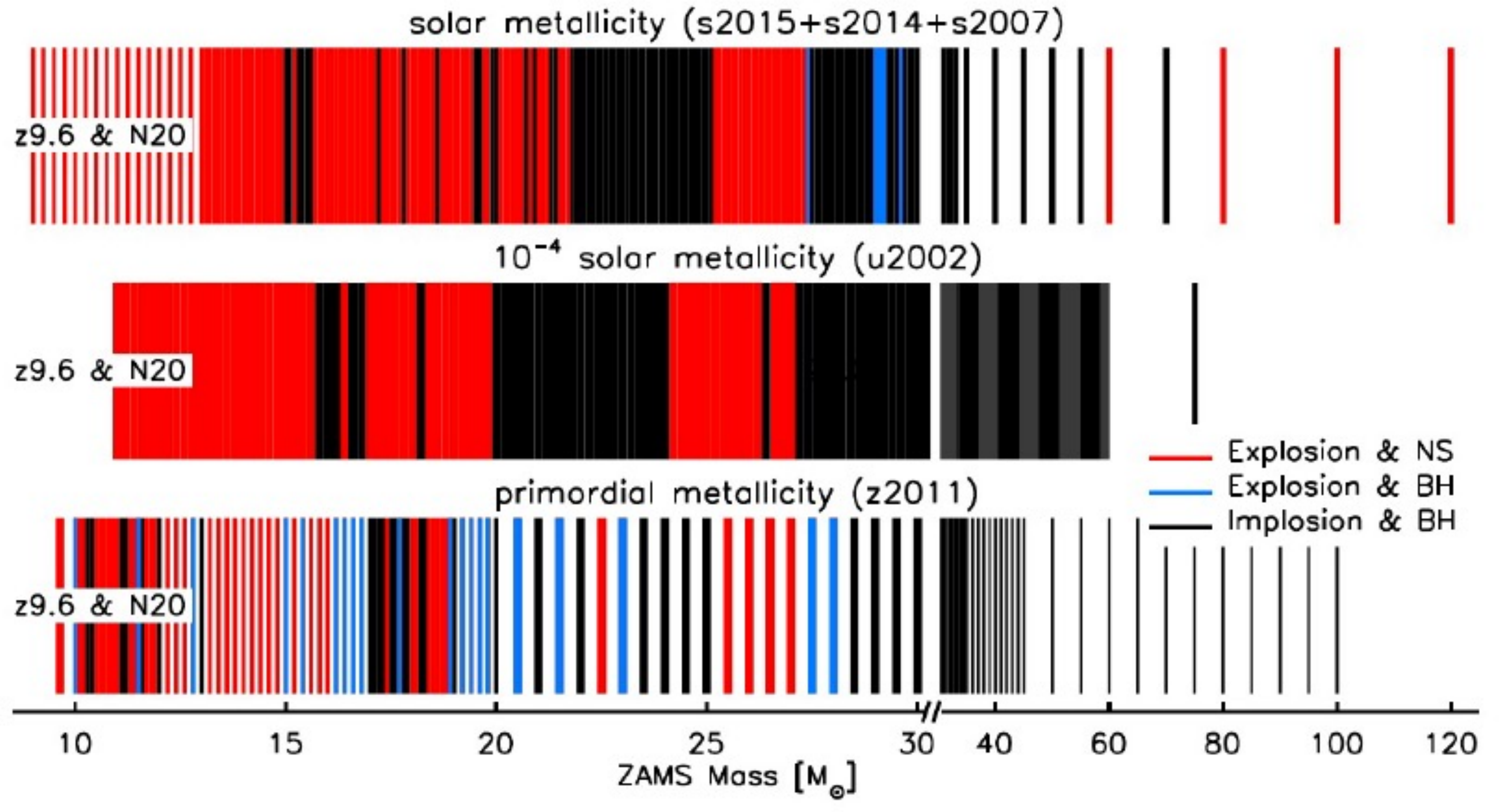
Collapse to black holes

Heger et al. (2003)

Which stars collapse to black holes?

Emerging picture:

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

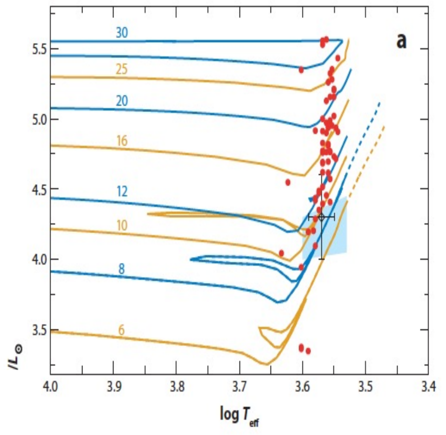


Janka 2017; see also O'Connot & Ott (2011), Ugliano et al (2012), Horiuchi et al (2014), Pejcha & Thompson (2015), Nakamura et al (2015), Ertl et al (2016), Sukhbold et al (2016), Mueller et al (2016), Kresse et al (2021)

How many black holes?

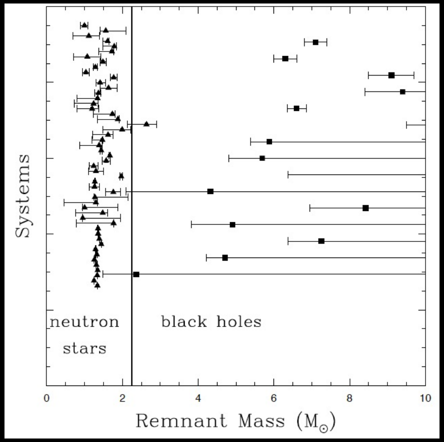
Growing evidence for a large fraction (~20%) of implosions

Red supergiant problem



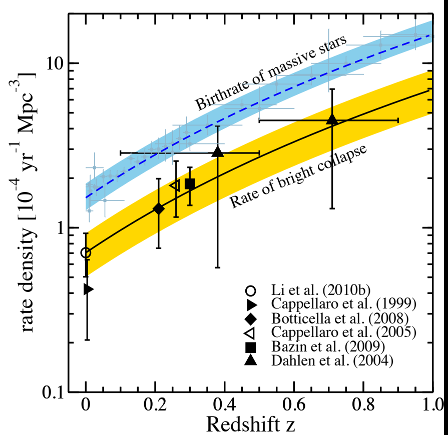
Smartt et al (2009)
Jerkstrand et al (2015)
Smartt et al (2015)

Black hole mass function



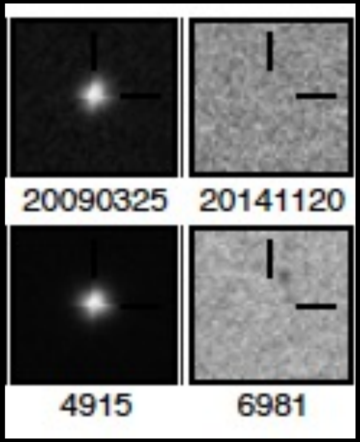
Kochanek (2014, 2015)

Supernova rate



Horiuchi et al (2011)
Yuksel & Kistler (2014)
Graur et al (2015)

Survey about nothing



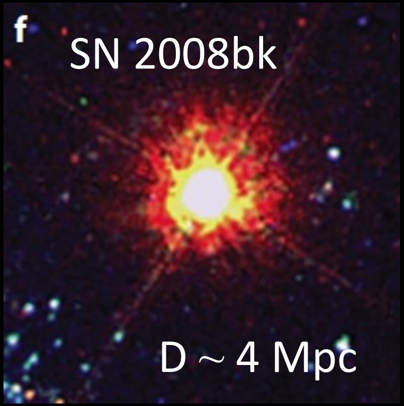
Kochanek et al (2008)
Gerke et al (2015)
Neustadt et al (2021)

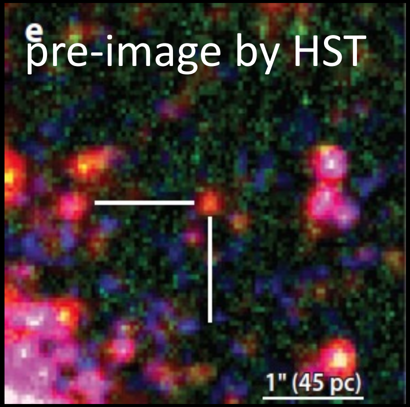
+ supernova remnants, nebular spectra

See, eg, Jennings et al (2012, 2014); also Diaz-Rodriguez et al (2018), but Auchtettl et al (2019)
Also, Valenti et al (2016), Jerkstrand et al (2015)

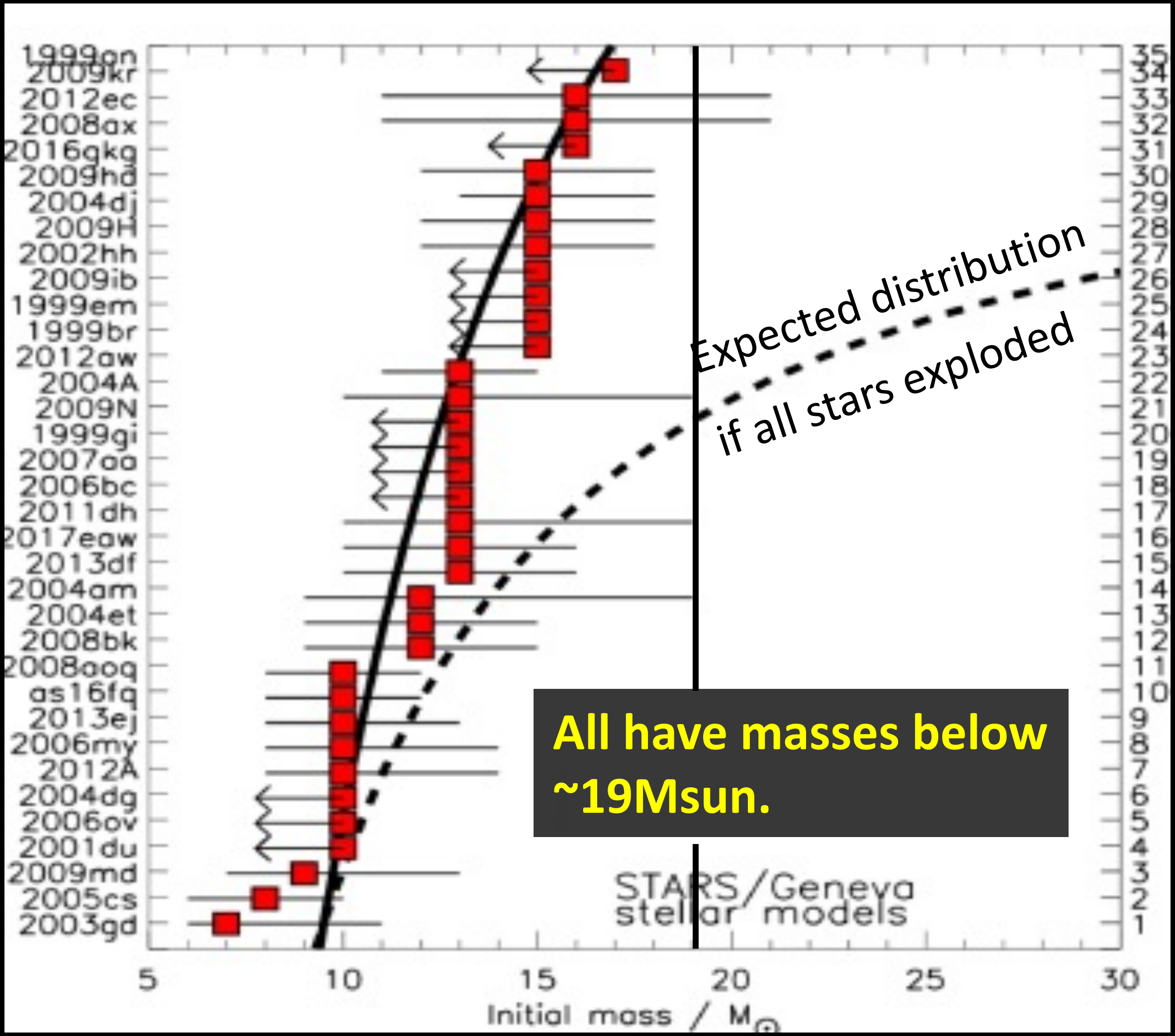
Looking for explosions

Pre-imaging: Limited to nearby SNe, highly successful





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



All have masses below ~19Msun.

Smartt, STScI Spring Symposium (2019)

Looking for implosions

Look for disappearance of stars

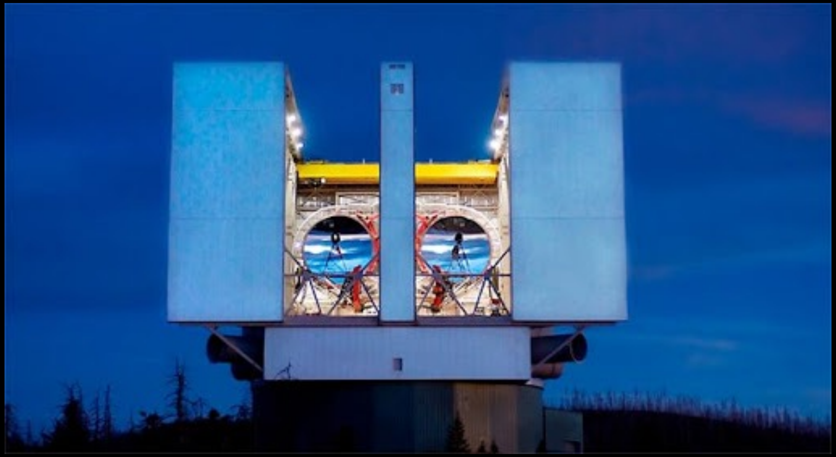
Monitor ~27 galaxies

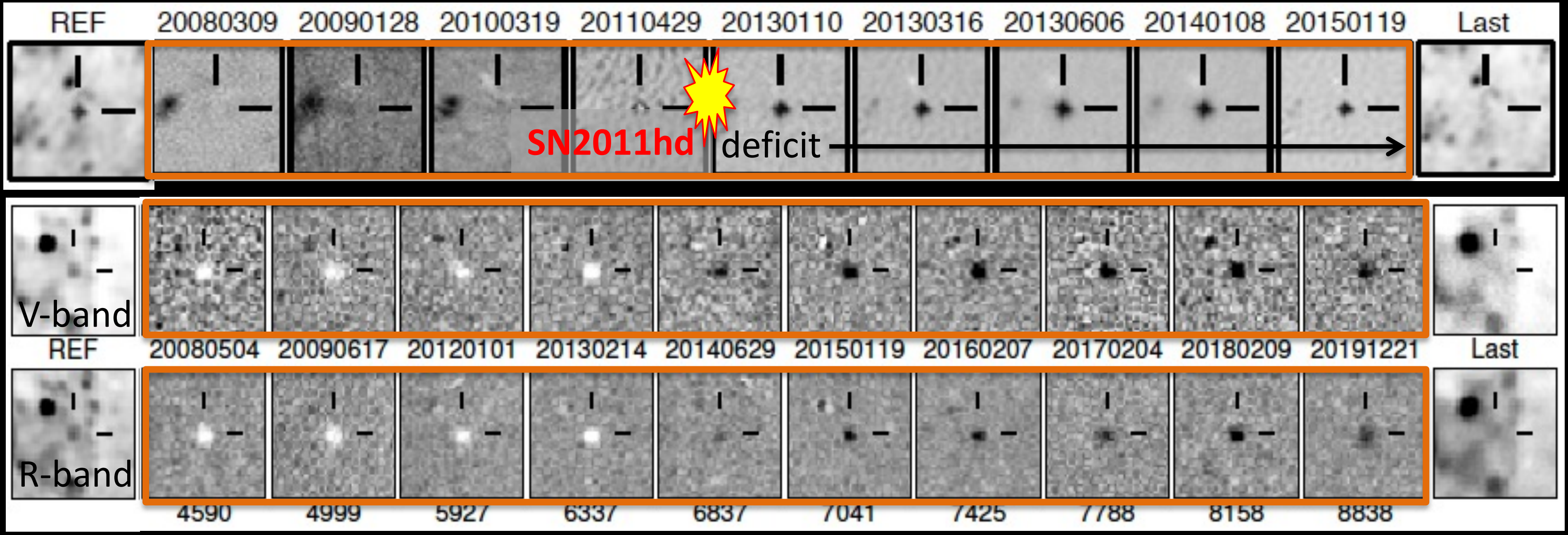
→ Survey ~10^6 red supergiants

→ Expect ~1 core collapse /yr

→ In 10 years, sensitive to 20 – 30% failed fraction at 90% CL

Kochanek et al. (2008)



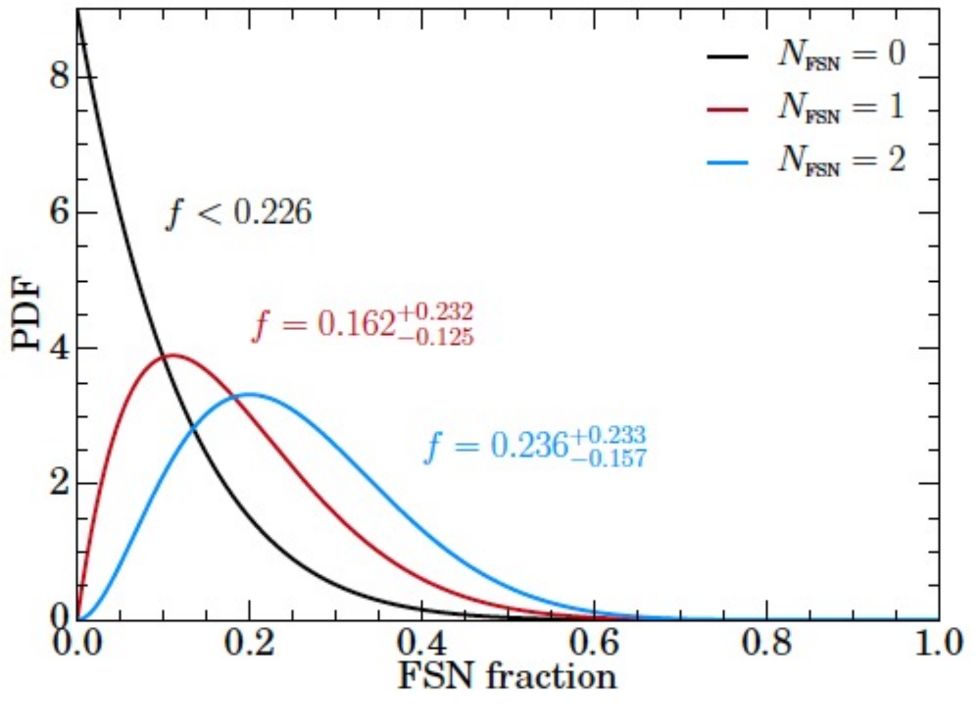


In 11 years running,

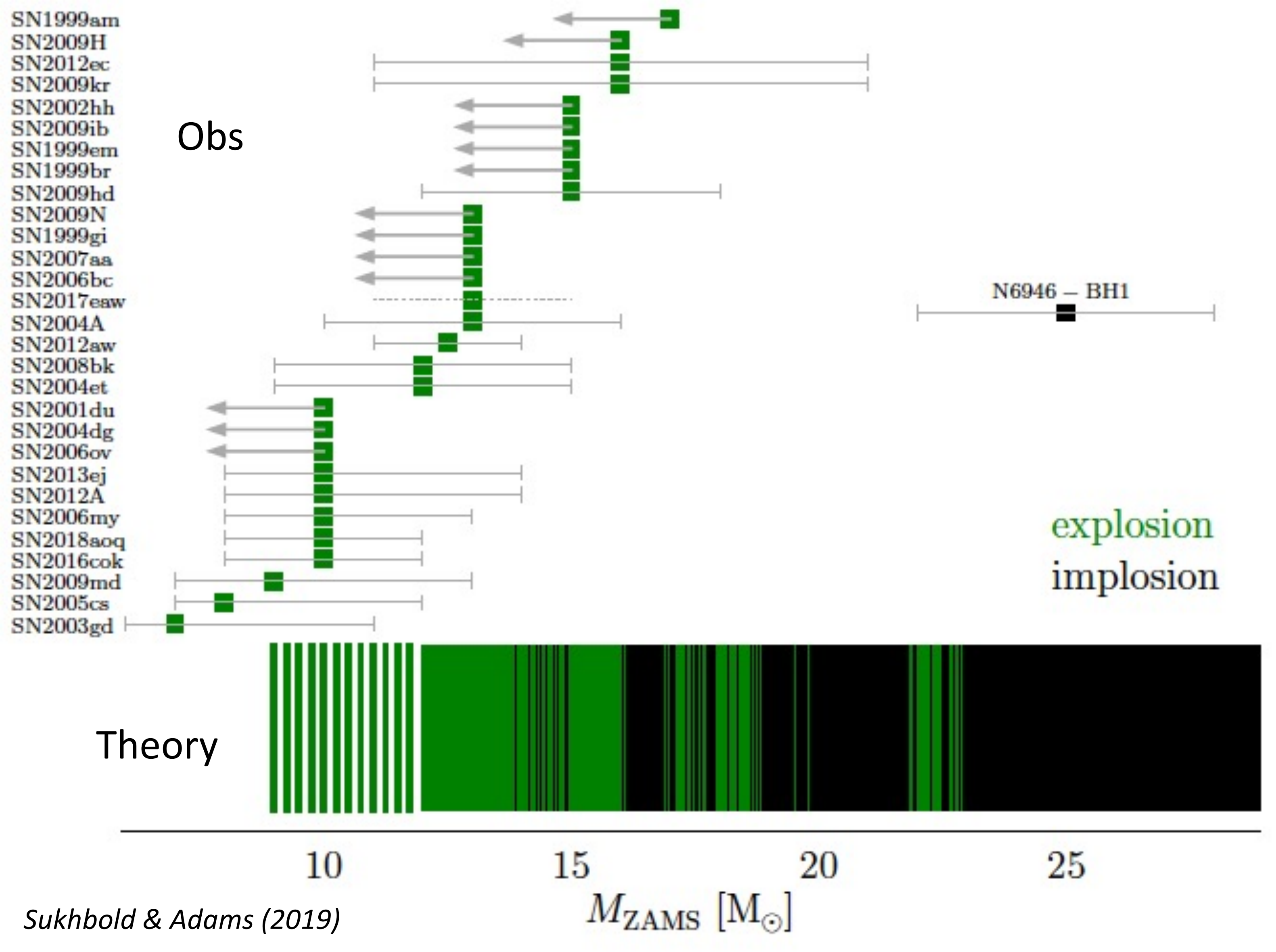
- ✓ 9 luminous CC supernovae
- ✓ 2 implosion candidates
  - NGC6946-BH1: SED well fit by ~25 Msun RSG
  - M101-OC1: follow-up ongoing

Neustadt et al (2021)

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



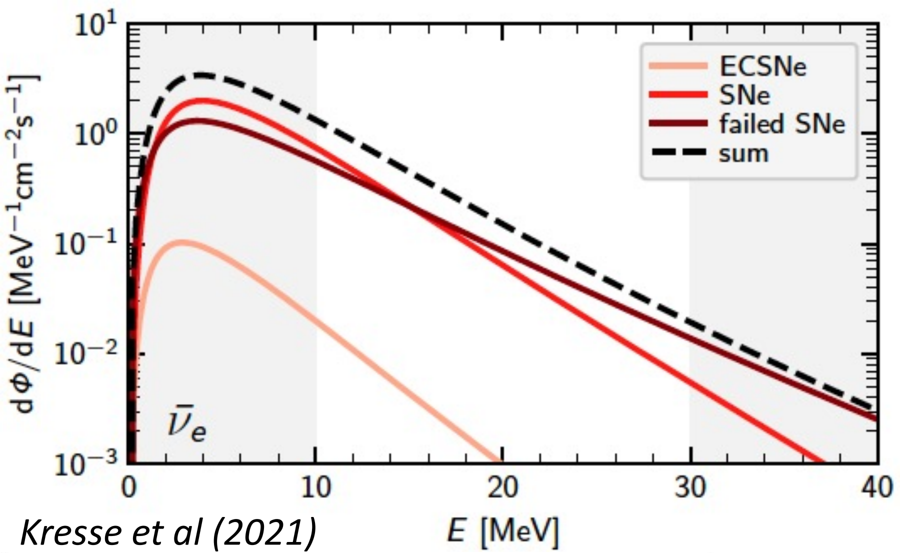
The emerging picture



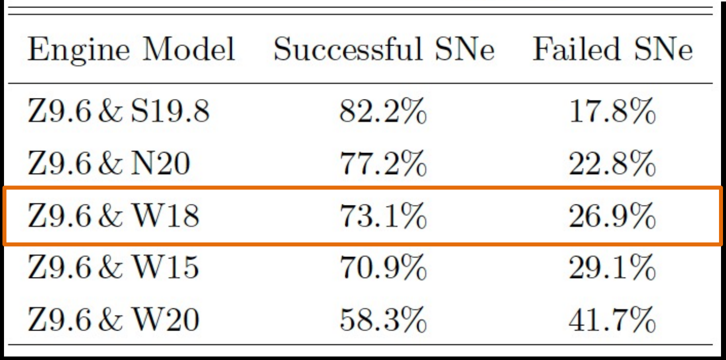
Sukhbold & Adams (2019)

Impacts on diffuse supernova neutrinos

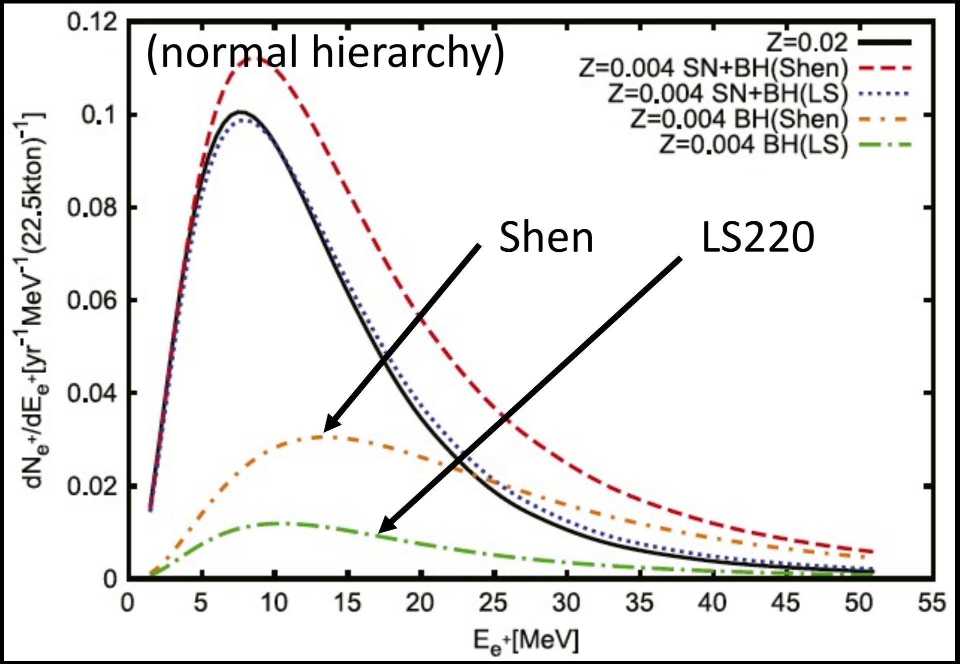
- Collapse to black holes → larger high-energy flux → more events
- Increase is about ~15% (for 17% BH fraction) but can be higher
- Depends on EOS, metallicity, neutrino hierarchy



Kresse et al (2021)



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%

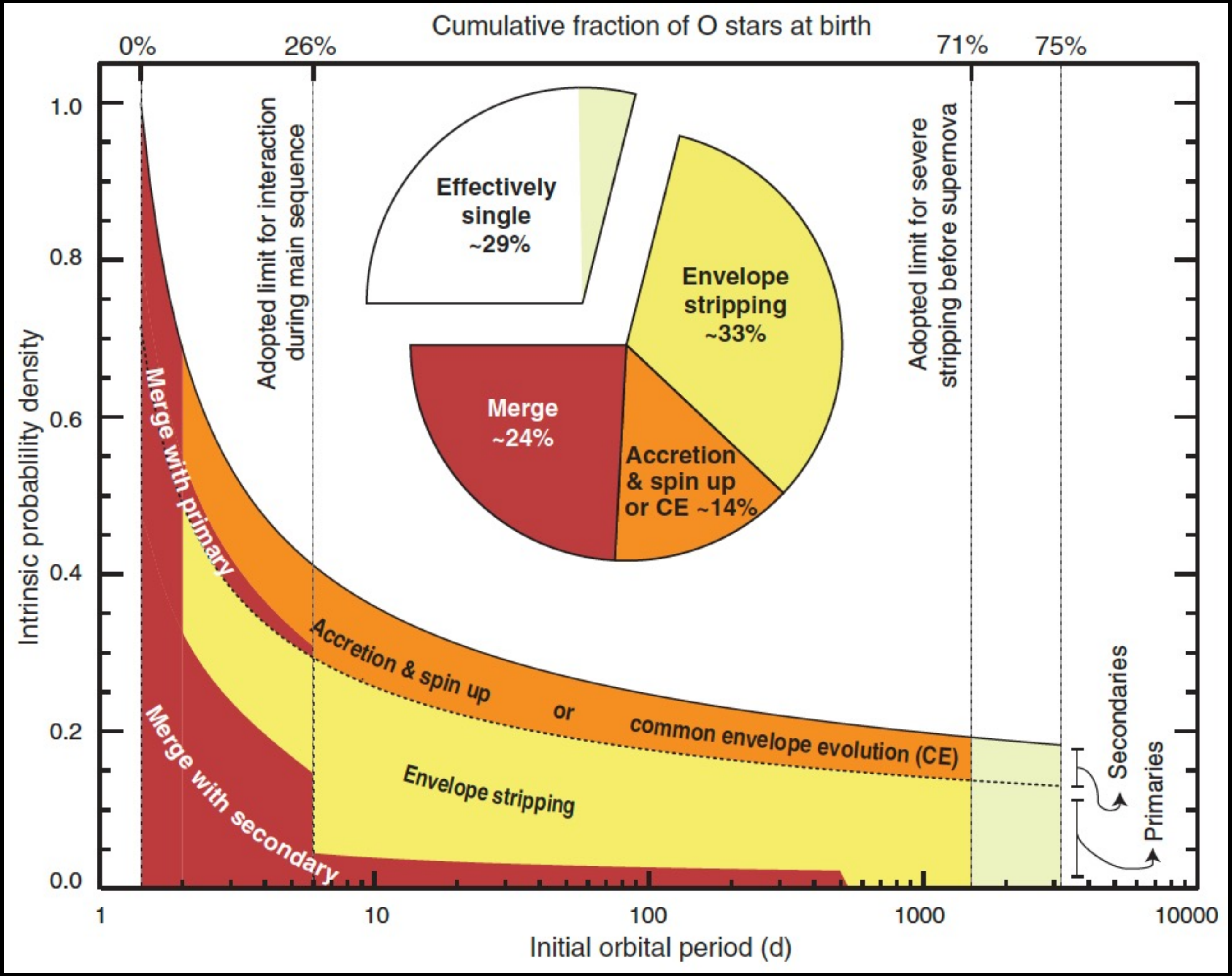


Nakazato et al (2015)

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)

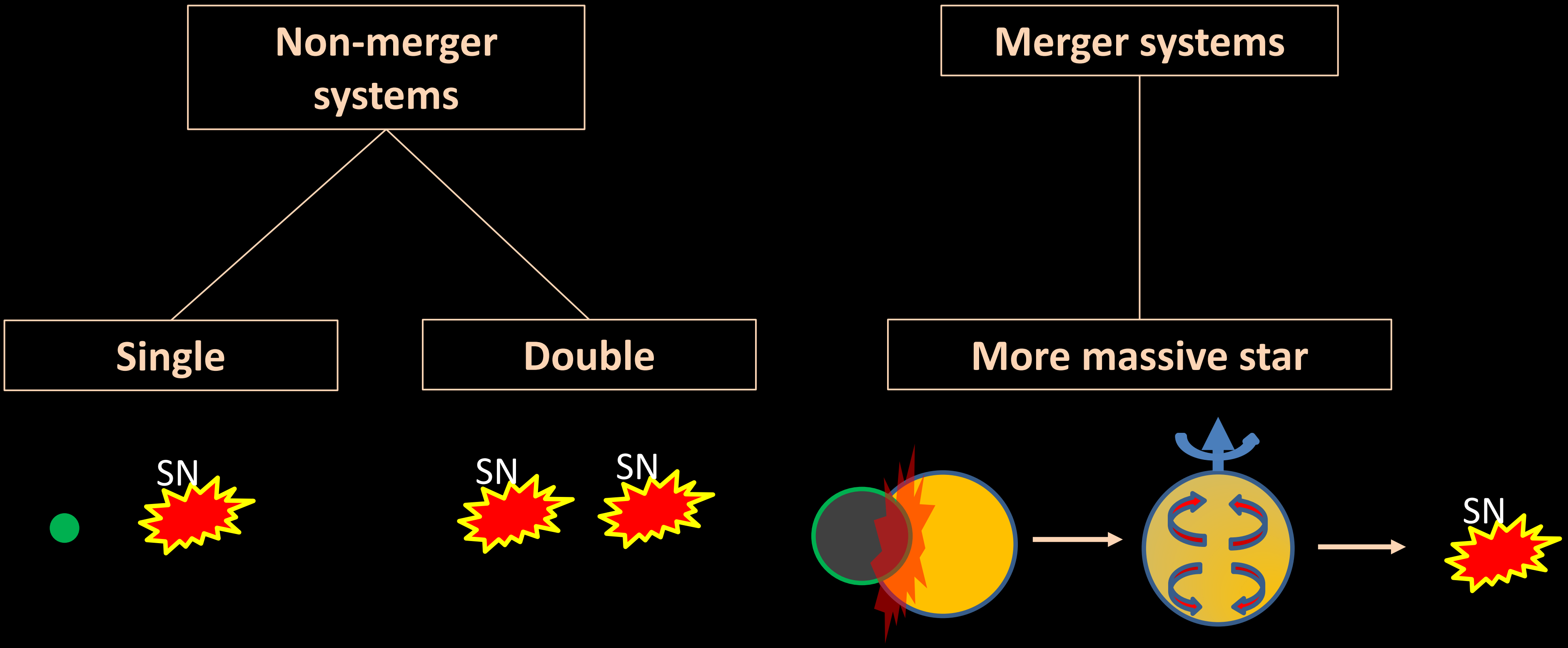
4. Binary effects

The majority of massive stars evolve in binaries



Sana et al (2012)

Binary outcomes



Non-merger systems

Merger systems

Single

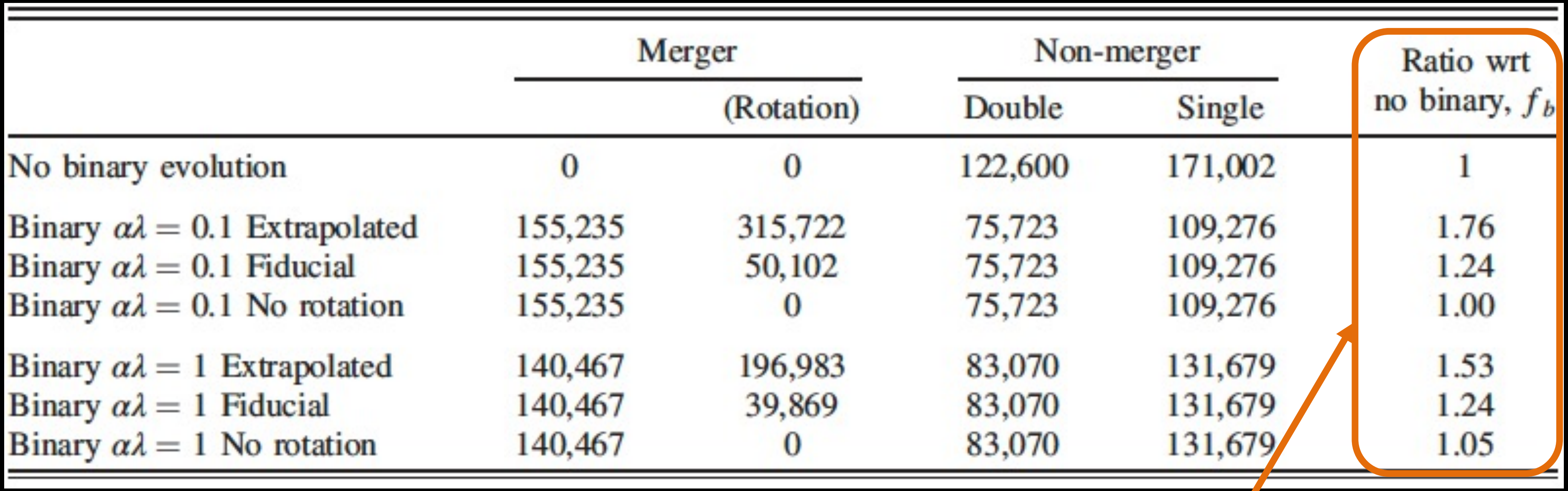
Double

More massive star

Visuals: thanks to Kinugawa

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

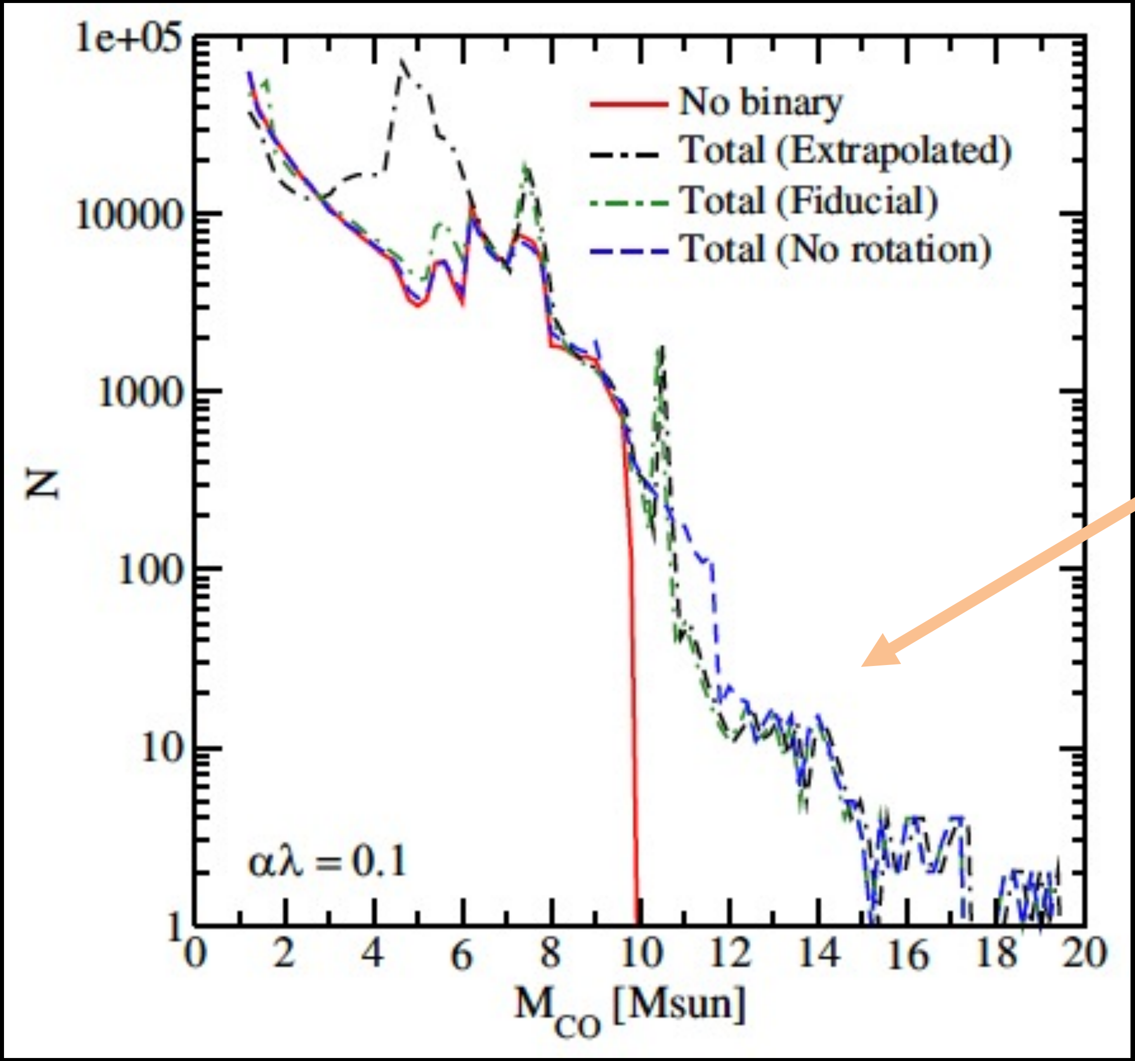
- In our fiducial model, ~25% increase
- Up to +75%

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

**Note: $\alpha\lambda$ are common envelop modeling parameters

Binary effects: supernova progenitors

Effect 2: binary effect creates very massive cores for collapse

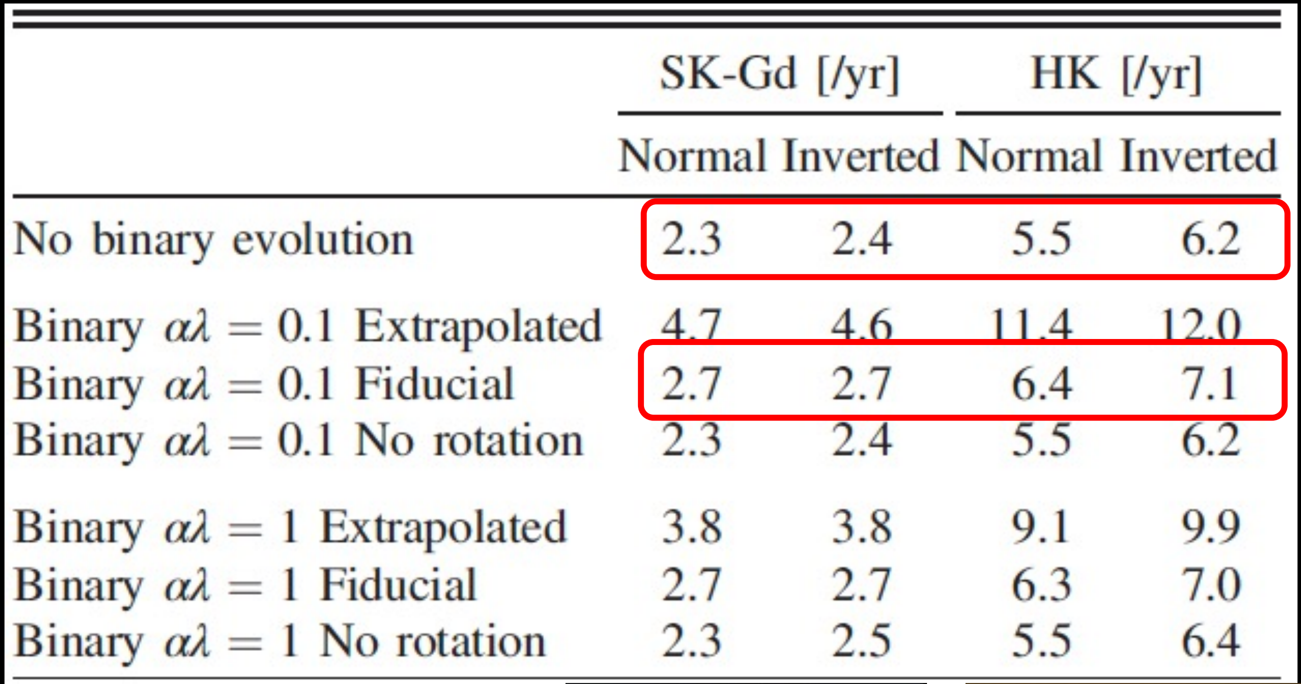


Many more high CO mass progenitors due to mass transfer & mergers

Horiuchi et al (2021)

Impacts on diffuse supernova neutrinos

More realistic binary treatment leads to improved detection prospects

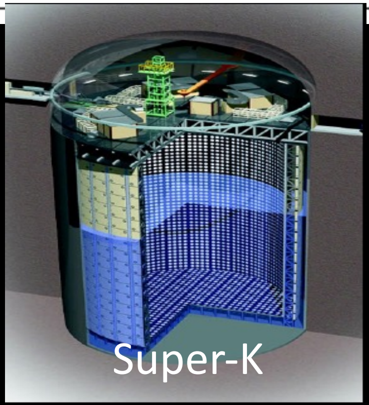


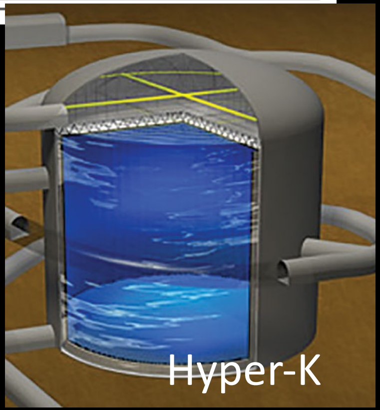
	SK-Gd [/yr]		HK [/yr]	
	Normal	Inverted	Normal	Inverted
No binary evolution	2.3	2.4	5.5	6.2
Binary $\alpha\lambda = 0.1$ Extrapolated	4.7	4.6	11.4	12.0
Binary $\alpha\lambda = 0.1$ Fiducial	2.7	2.7	6.4	7.1
Binary $\alpha\lambda = 0.1$ No rotation	2.3	2.4	5.5	6.2
Binary $\alpha\lambda = 1$ Extrapolated	3.8	3.8	9.1	9.9
Binary $\alpha\lambda = 1$ Fiducial	2.7	2.7	6.3	7.0
Binary $\alpha\lambda = 1$ No rotation	2.3	2.5	5.5	6.4

Horiuchi et al (2021)

Fiducial model: ~20% increase

**Important: black hole contributions are not included here, real rates can be even higher





Concluding remarks

Summary: the diffuse supernova neutrino background is *guaranteed*

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

➔ **Must look and find the diffuse signal!**

Various predictions:

- ✓ Differences in: supernova rate star formation rate, dust
- ✓ Differences in: progenitor, simulations, black hole treatment, EOS, …

Future connections:

- ✓ Star formation, stellar density, metallicity evolutions
- ✓ Long-term simulations, treatments of black holes
- ✓ Binary interactions

Thank you!

Compactness: a progenitor indicator

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

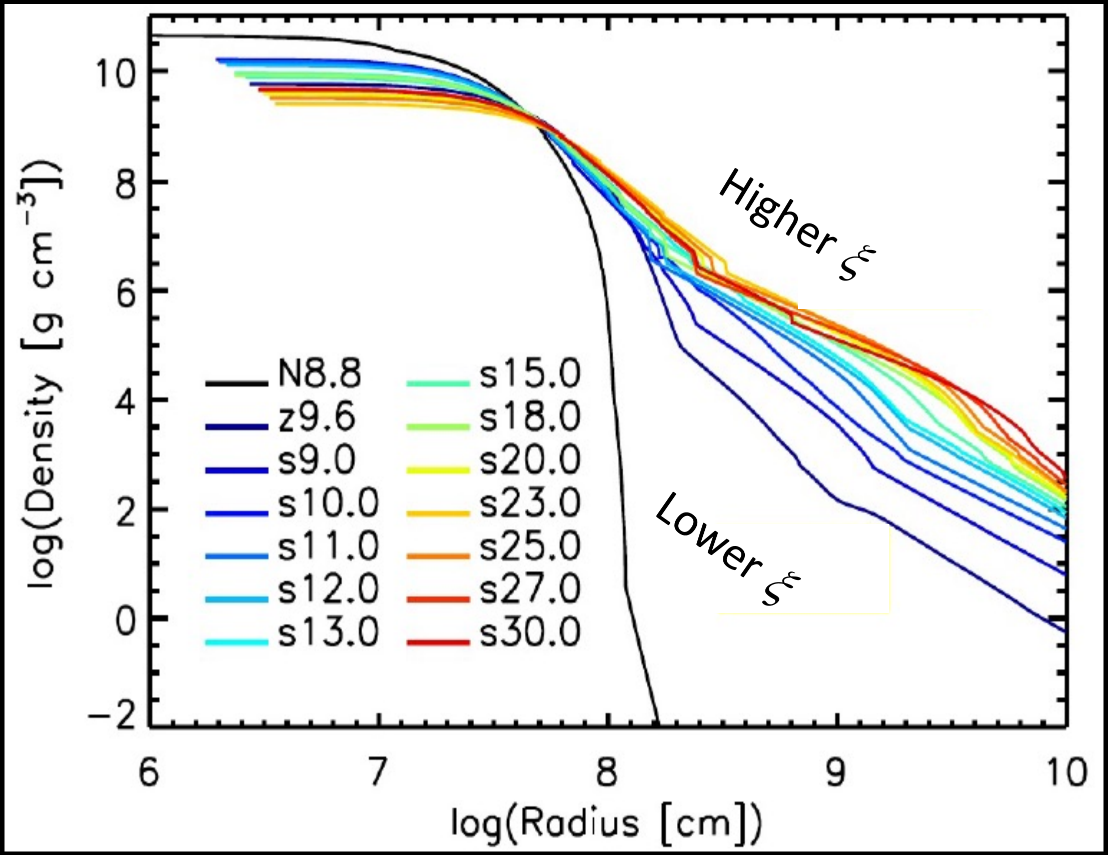
$$\xi_M = \left.\frac{M/M_\odot}{R(M_{\mathrm{bary}} = M)/1000\,\mathrm{km}}\right|_t$$

O'Connor & Ott (2011)

Mass accretion

VS !

Neutrino heating



- Higher ξ → higher Mdot
- Lower ξ → lower Mdot

Compactness: BH formation

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

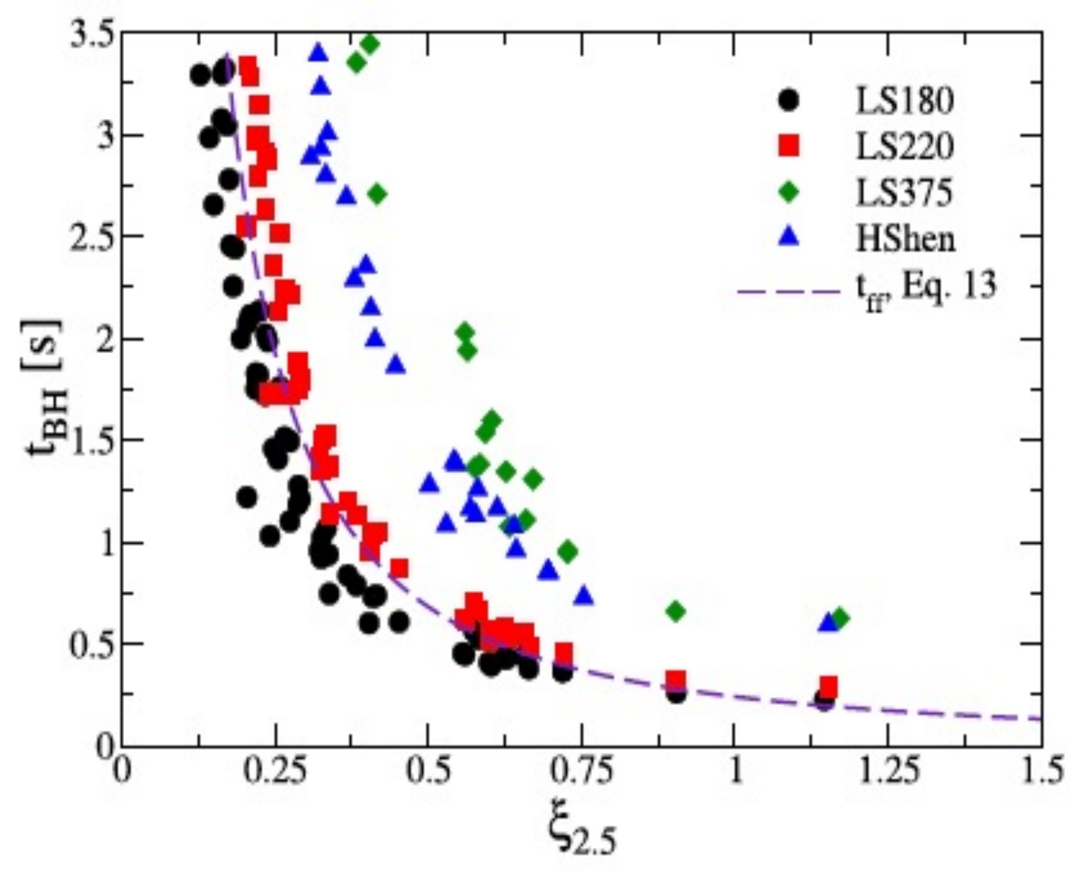
O'Connor & Ott (2011)

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

Mass accretion

VS !

Neutrino heating



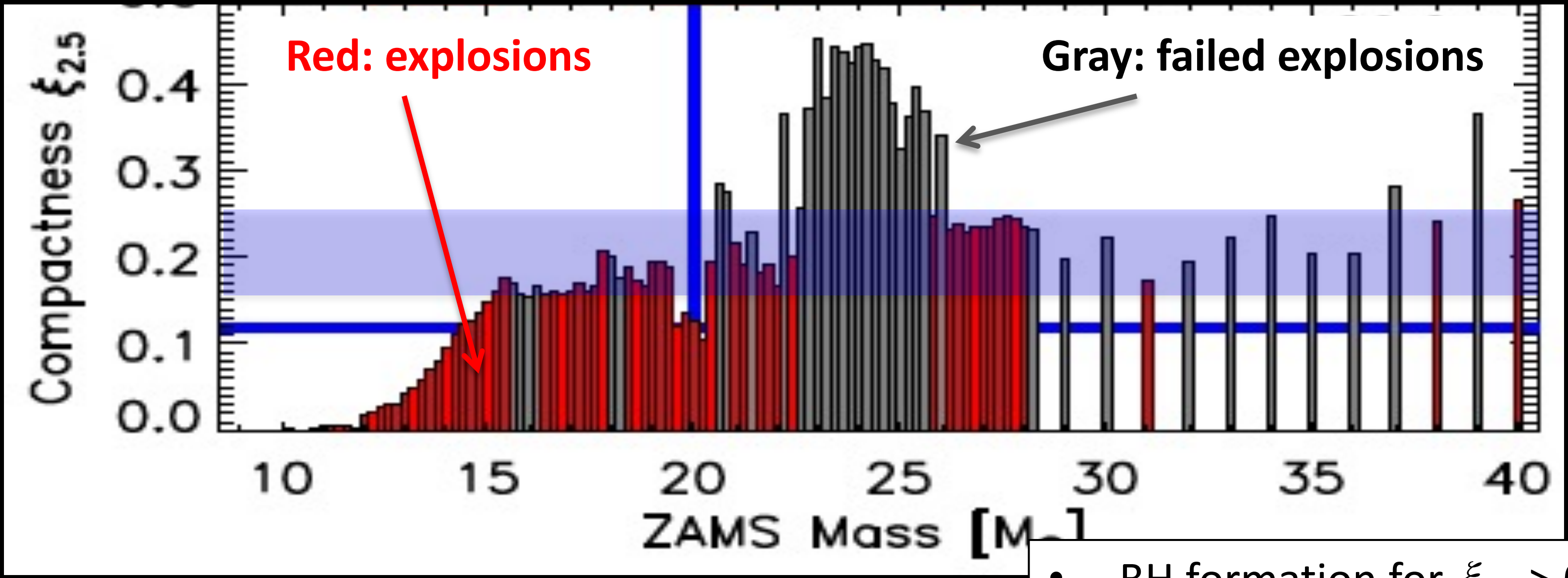
- Higher ξ → higher Mdot → BH forms earlier
- Lower ξ → lower Mdot → BH formation takes longer

O'Connor & Ott (2011)

Compactness: Explodability

…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

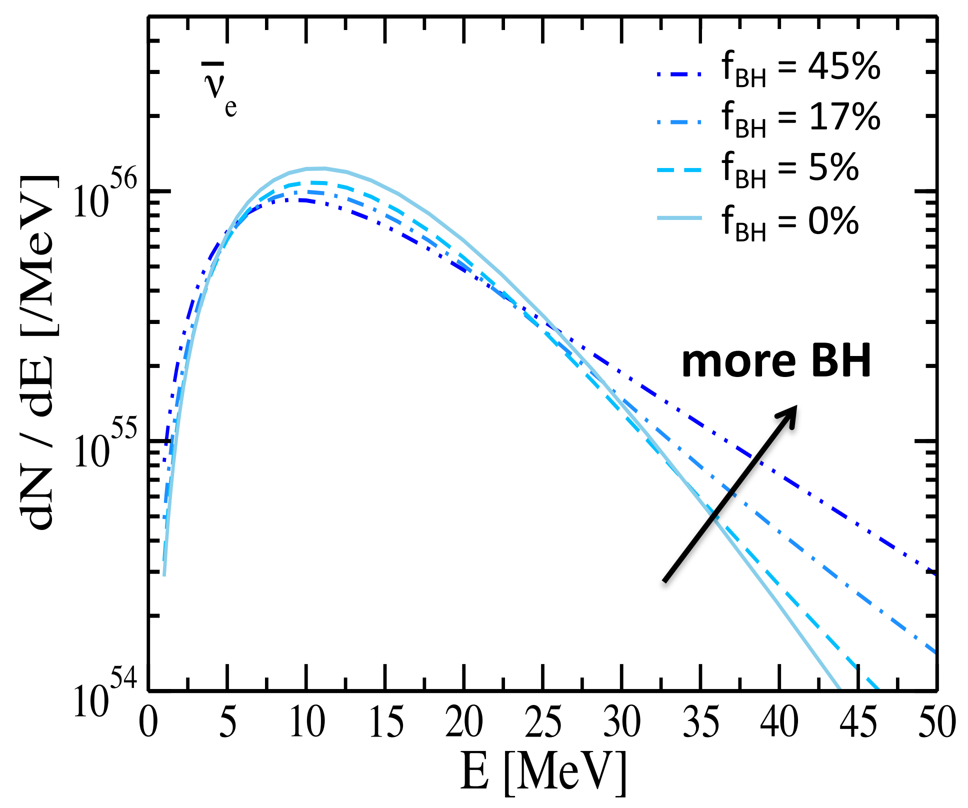
Is there a critical compactness?

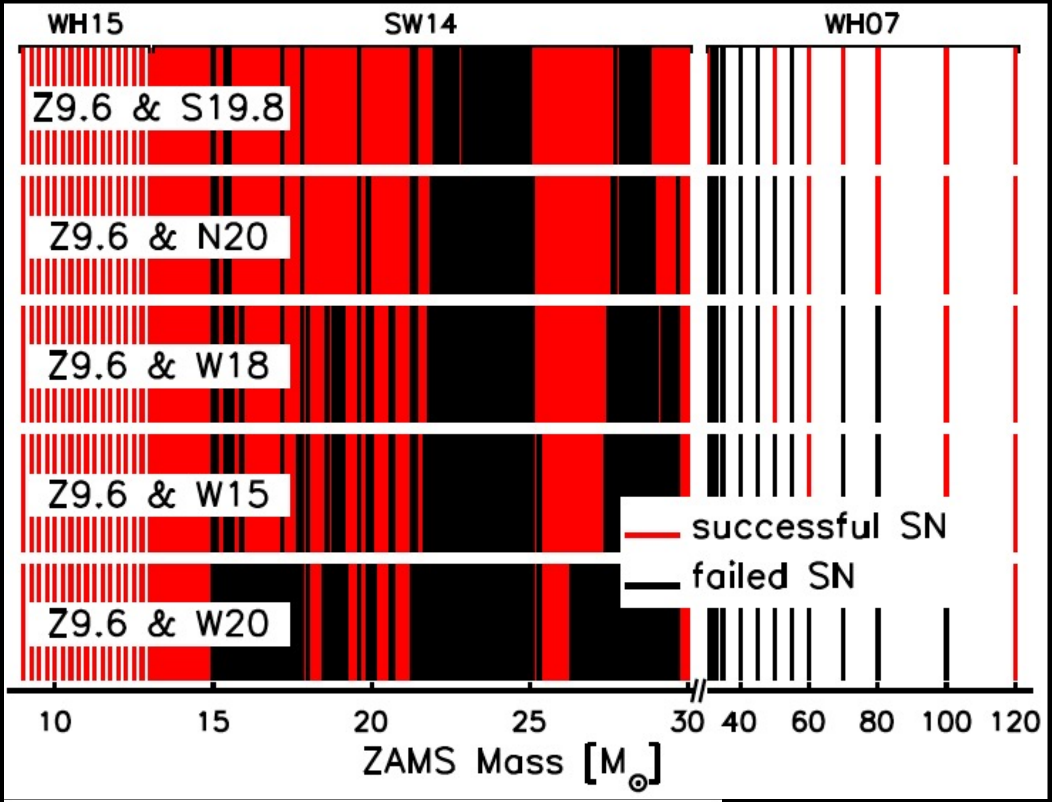
- 1 compactness predicts at most ~88% of cases
- 2 parameters successful in ~97% of progenitors

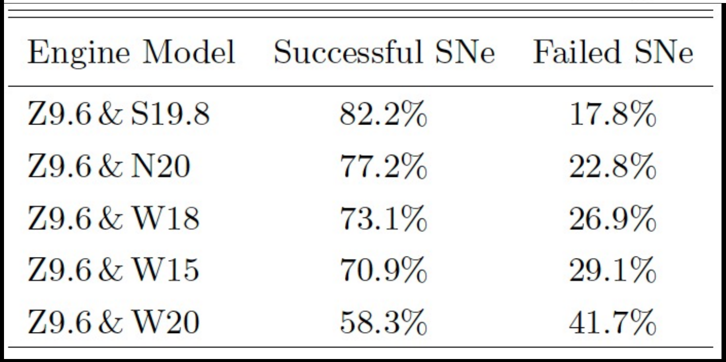
Pejcha & Thompson (2015)
Ertl et al (2016)

- Critical $\xi_{2.5} \sim 0.2$ consistent with 2D simulations
- TBD for 3D

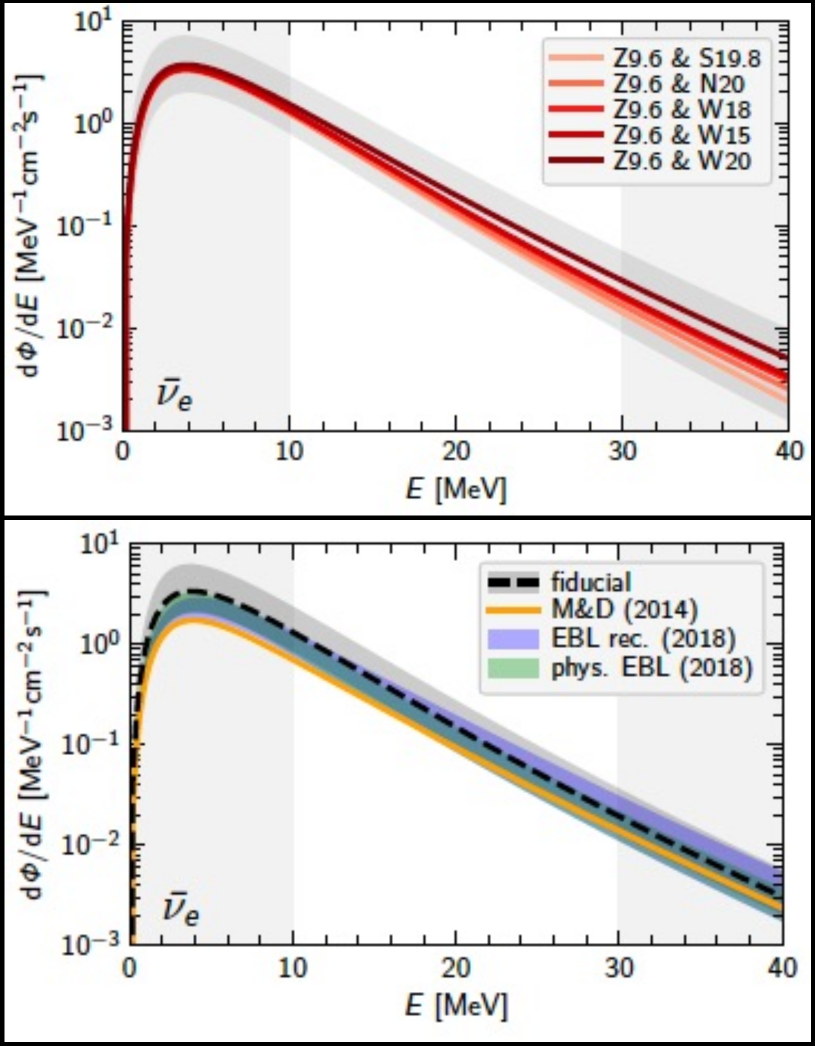
Horiuchi et al (2014)


$\bar{\nu}_e$
f_{BH} = 45%
f_{BH} = 17%
f_{BH} = 5%
f_{BH} = 0%
more BH
dN / dE [/MeV]
10^{56}
10^{55}
10^{54}
0
5
10
15
20
25
30
35
40
45
50
E [MeV]



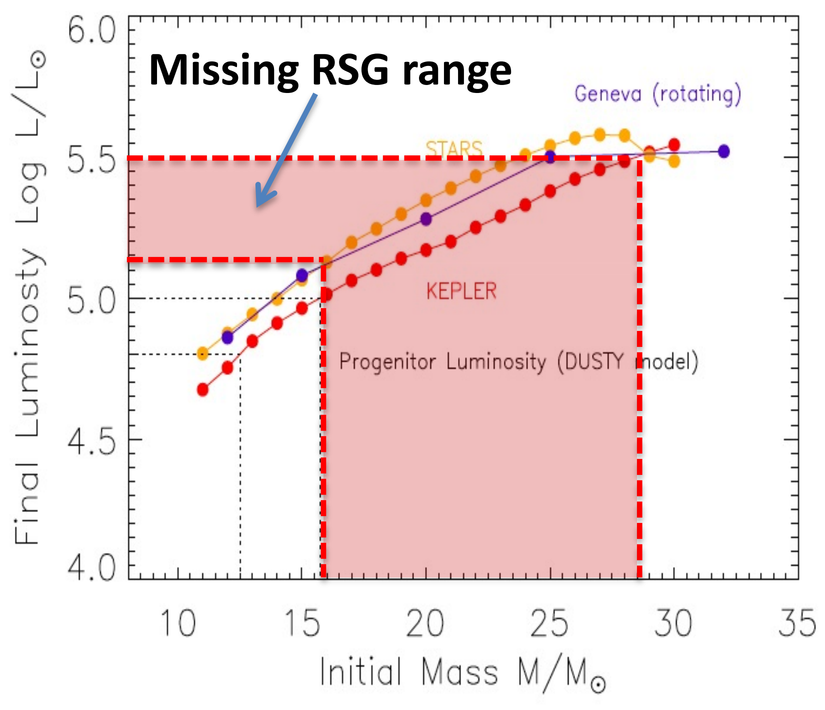


Engine Model	Successful SNe	Failed SNe
Z9.6 & S19.8	82.2%	17.8%
Z9.6 & N20	77.2%	22.8%
Z9.6 & W18	73.1%	26.9%
Z9.6 & W15	70.9%	29.1%
Z9.6 & W20	58.3%	41.7%



Kresse et al (2021)

Type II progenitors

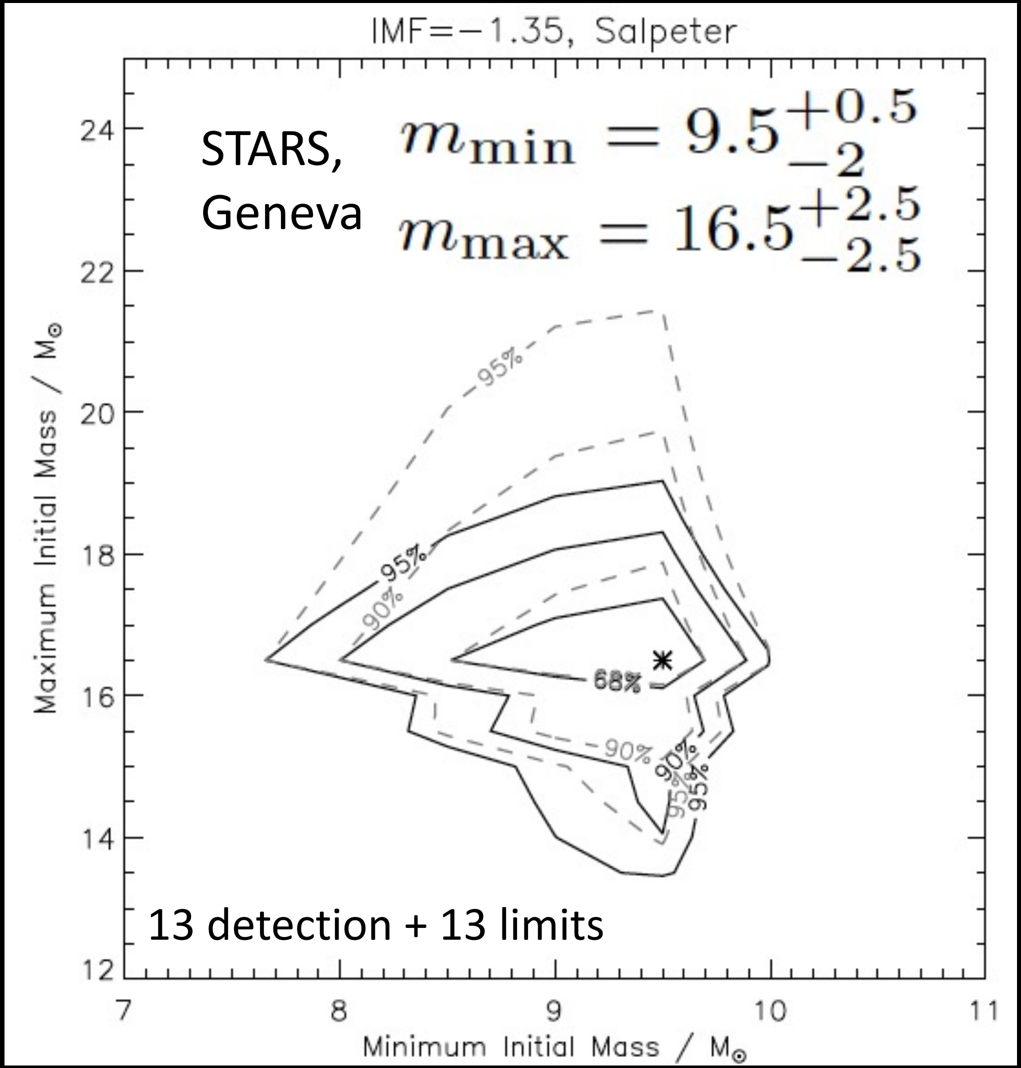


Jerkstrand et al (2014)

Systematic uncertainty in mass estimating: +2Msun with KEPLER

With KEPLER:

$$m_{\min} = 10^{+0.5}_{-1.5}$$
$$m_{\max} = 18.5^{+3}_{-4}$$



STARS, Geneva

$$m_{\min} = 9.5^{+0.5}_{-2}$$
$$m_{\max} = 16.5^{+2.5}_{-2.5}$$

13 detection + 13 limits

Smartt (2015), updated from Smartt et al (2009)

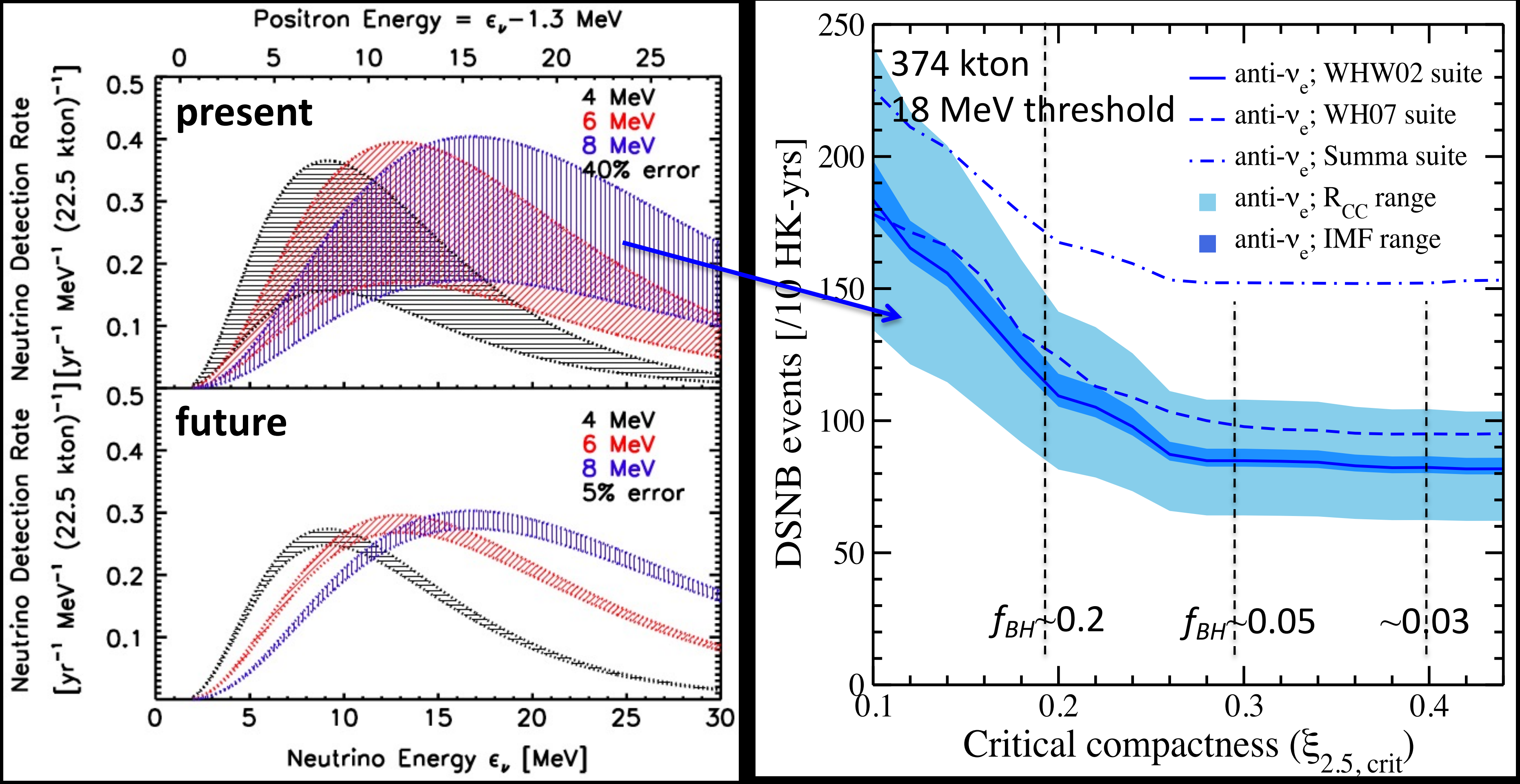
DSNB: long-term future

Supernova rate uncertainty

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

Neutrino detector

Hyper-Kamiokande will increase detector volume by x10 or so

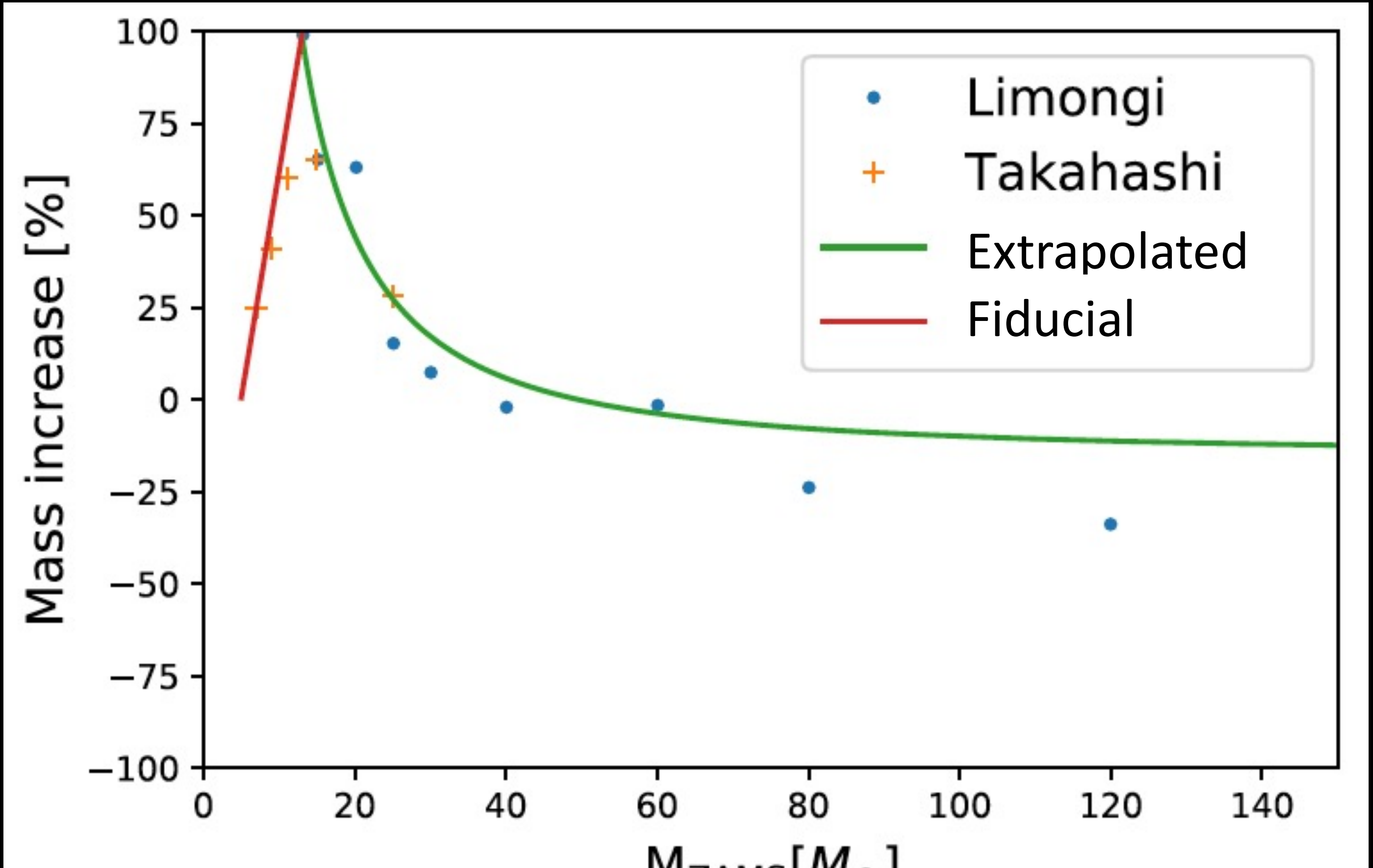


Lien et al (2010)

Horiuchi et al (2018)

Core mass growth

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



Horiuchi et al (2021)