
The Gd Father is Reborn, April 24th 2025

# Diffuse supernova neutrino background is detectable in SK

Shunsaku Horiuchi
(Science Tokyo, Virginia Tech)

Image credit: NASA/ESA

# *When I started…*

PHYSICAL REVIEW D **79,** 083013 (2009)

**Diffuse supernova neutrino background is detectable in Super-Kamiokande**

Shunsaku Horiuchi,[1,2,3] John F. Beacom,[2,3,4] and Eli Dwek[5]

- Graduate student project
- With John Beacom while visiting


**ACKNOWLEDGMENTS**

We thank Shin'ichiro Ando, Maria Terese Botticella, Thomas Dahlen, Andrew Hopkins, Cecilia Lunardini, Katsuhiko Sato, Stephen Smartt, Todd Thompson, Stephen Wilkins, and Mark Vagins for helpful discussions;

Furthermore, detection prospects would be dramatically improved with a gadolinium-enhanced Super-Kamiokande: the backgrounds would be significantly reduced, the fluxes and uncertainties converge at the lower threshold energy, and the predicted event rate is 1.2–5.6 events $yr^{-1}$ in the energy range 10–26 MeV. These results demonstrate the imminent detection of the DSNB by Super-Kamiokande and its exciting prospects for studying stellar and neutrino physics.

# *When I started…*

**Diffuse supernova n**

Shunsak

- Graduate studen
- With John Beaco
- Mark: gave me m
  support

**Mark Vagins** <vagins@hep.ps.uci.edu>
to Shunsaku

Dear Shunsaku,

Yes, of course I remember you from the November 2008 RESCEU symposium!

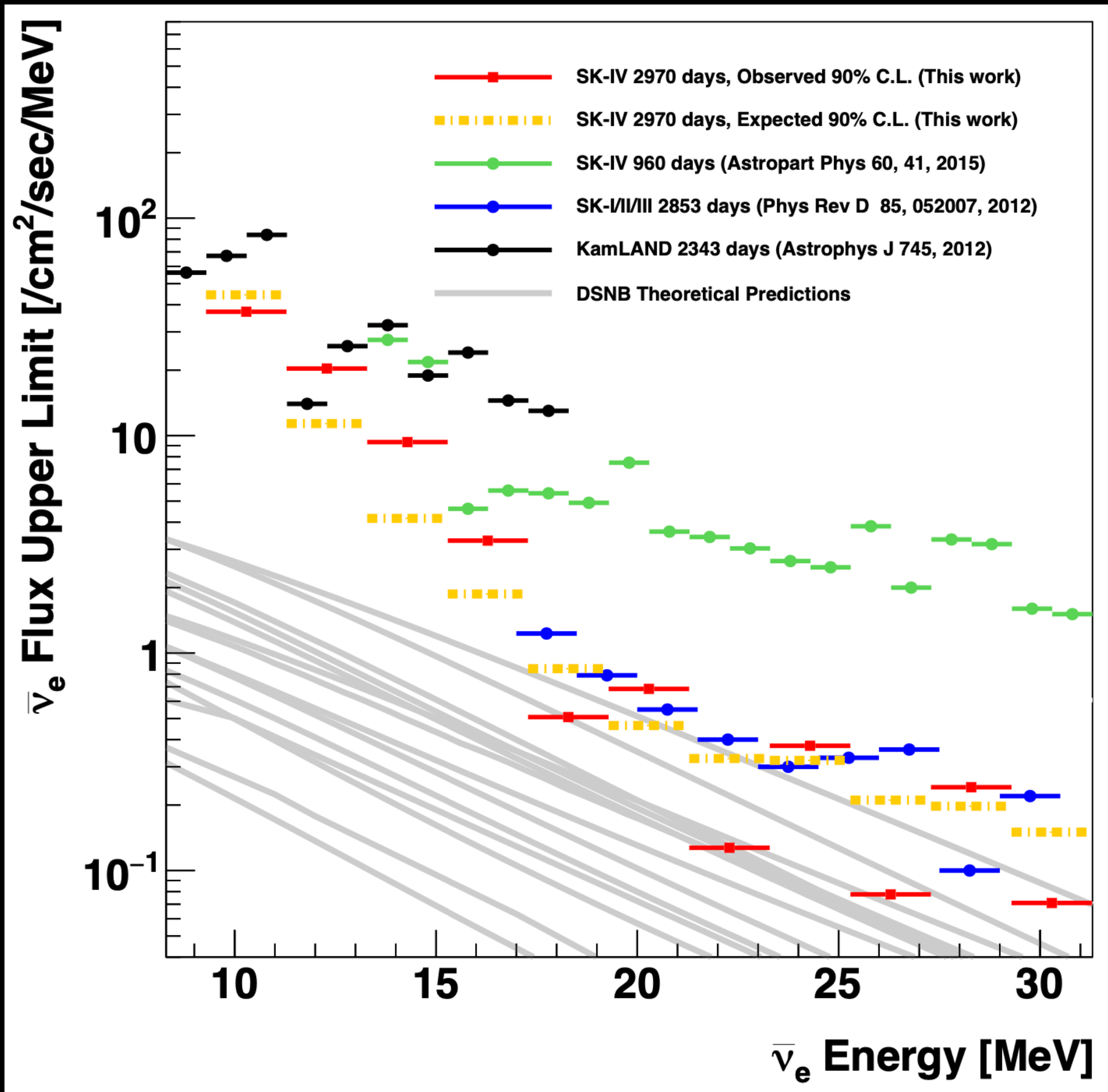
Thanks for calling my attention to this important preprint. It is a very nice piece of work, and hopefully will provide even more incentive for the Super-Kamiokande Collaboration to move forward in adding Gd to the detector. Naturally, I'm doing what I can experimentally to convince everyone, but strong theoretical support such as this paper can be quite critical in getting group decisions made in a timely fashion.

Here's hoping the editors and reviewers treat you kindly in this new year!

Sincerely,
-Mark

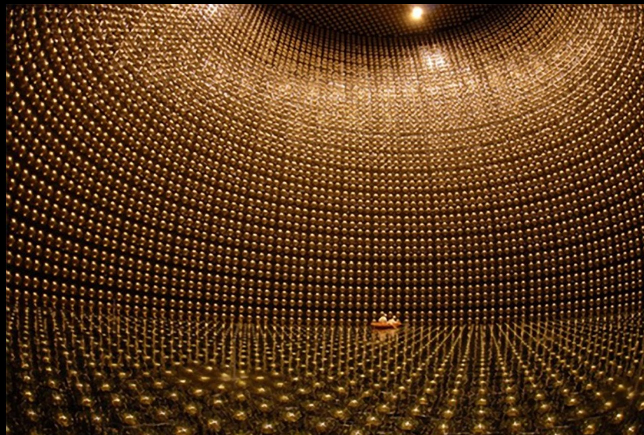
# *Progress since*

**Searches reaching into many predictions**




Looking for the positron:

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



Red: SK-IV 2970 days

*SuperK (Abe et al 2021)*

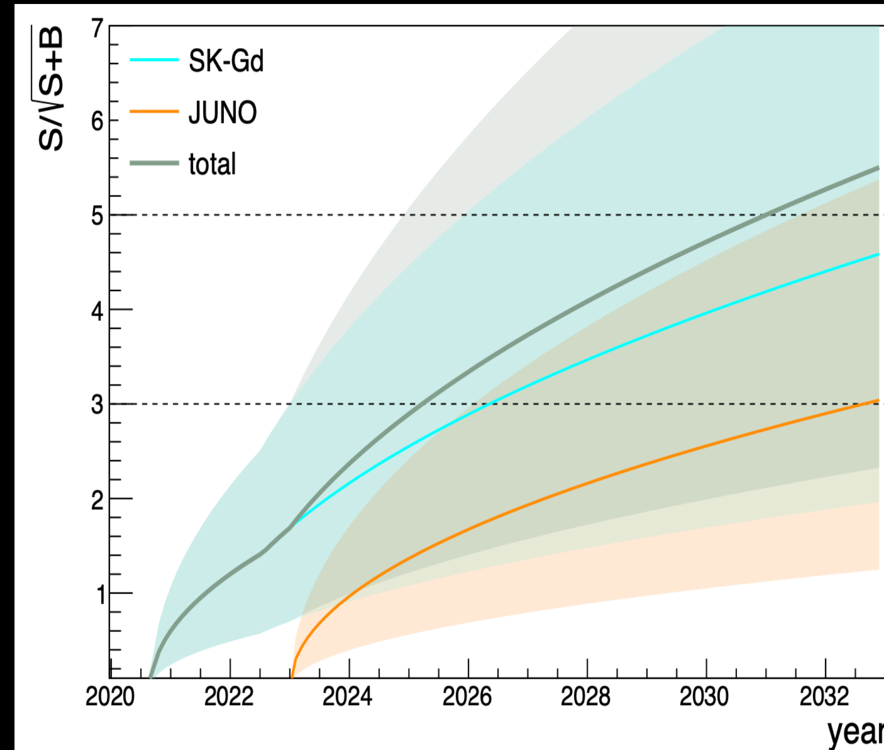
# *Where we're headed*

**Gd tags the n to reduce e backgrounds**
**→ DSNB discovery**

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


*Beacom & Vagins (2004)*

**Gd in Super-K working superbly**




**SKGd + JUNO figure of merit vs year**

*Li, Vagins, Wurm (2022)*

**Highlight:**

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is $\mathbf{1.4^{+0.8}_{-0.6}}$ $\mathbf{cm^{-2}\,s^{-1}}$ for $E_\nu > 17.3$ MeV

➡ **exhibit ~2.3 σ excess!!**

*Harada (Neutrino 2024)*

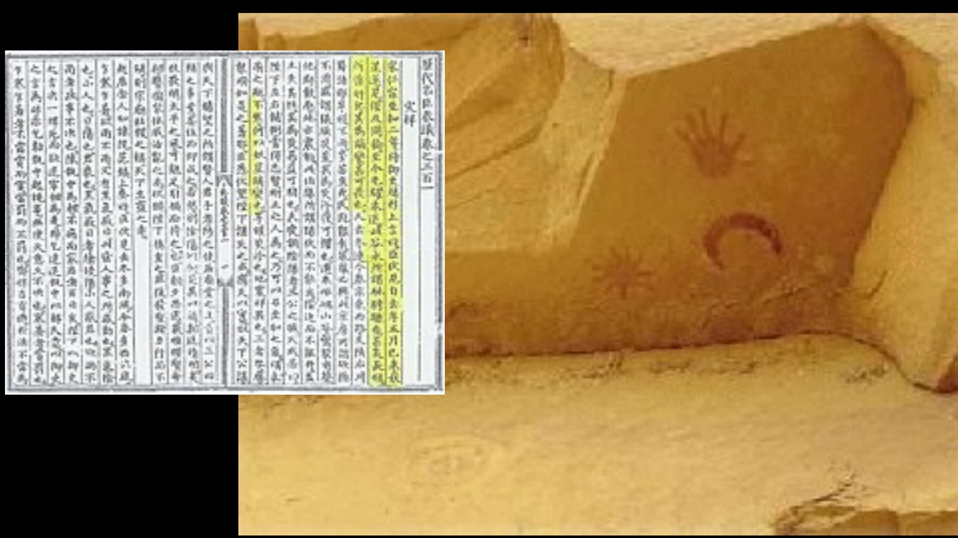
# *Core-collapse Supernovae*

$\sim\sim$

Typical supernova, L $\sim 10^{35\text{-}36}$ watts
Shines for a few months
➔ $\sim 10^{50}$ erg total*
(*still only tip of the iceberg)

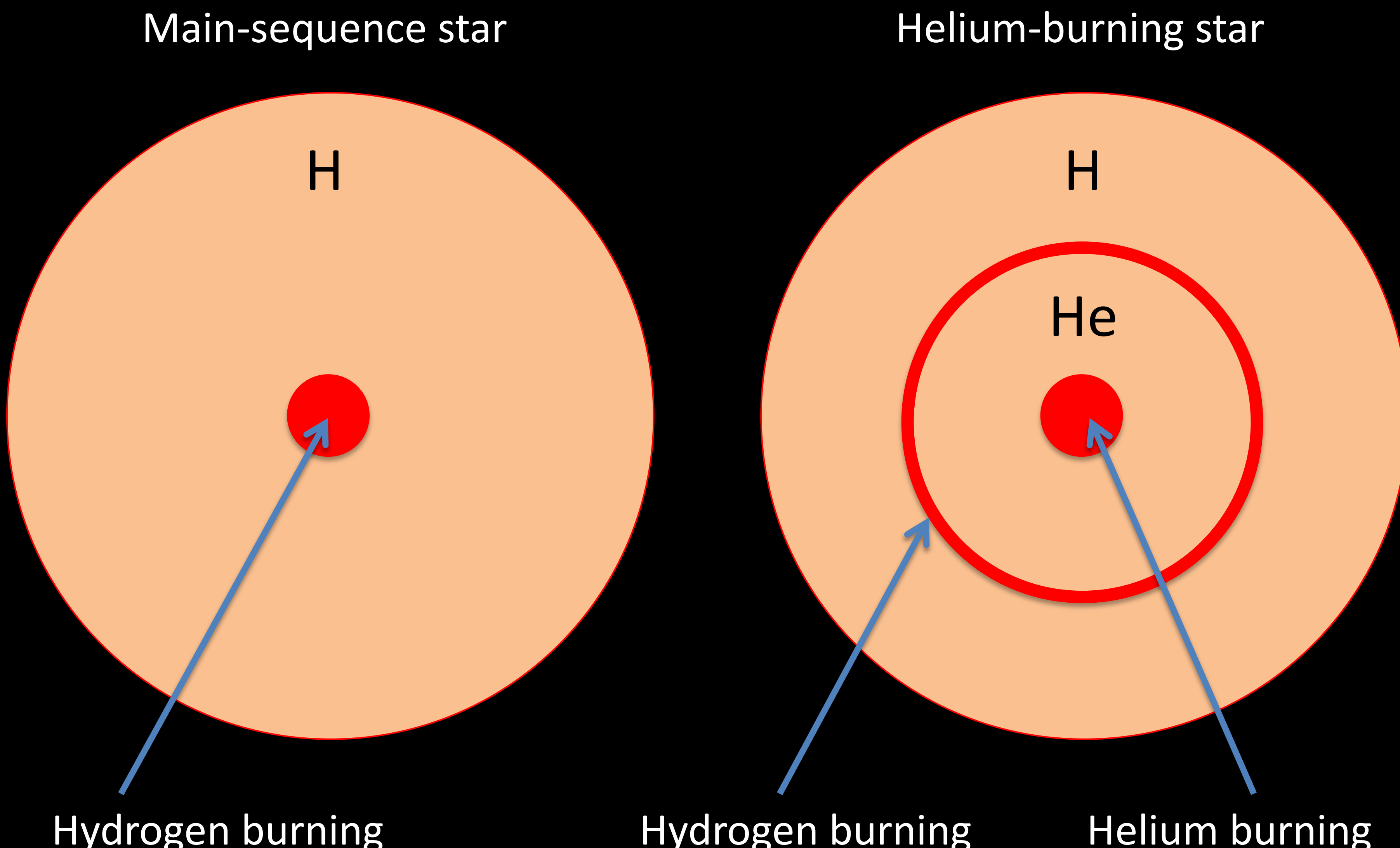
Our sun, L $\sim 10^{26}$ watts
Over 1 billion years old
➔ $\sim 10^{50}$ erg total

**SN1054**



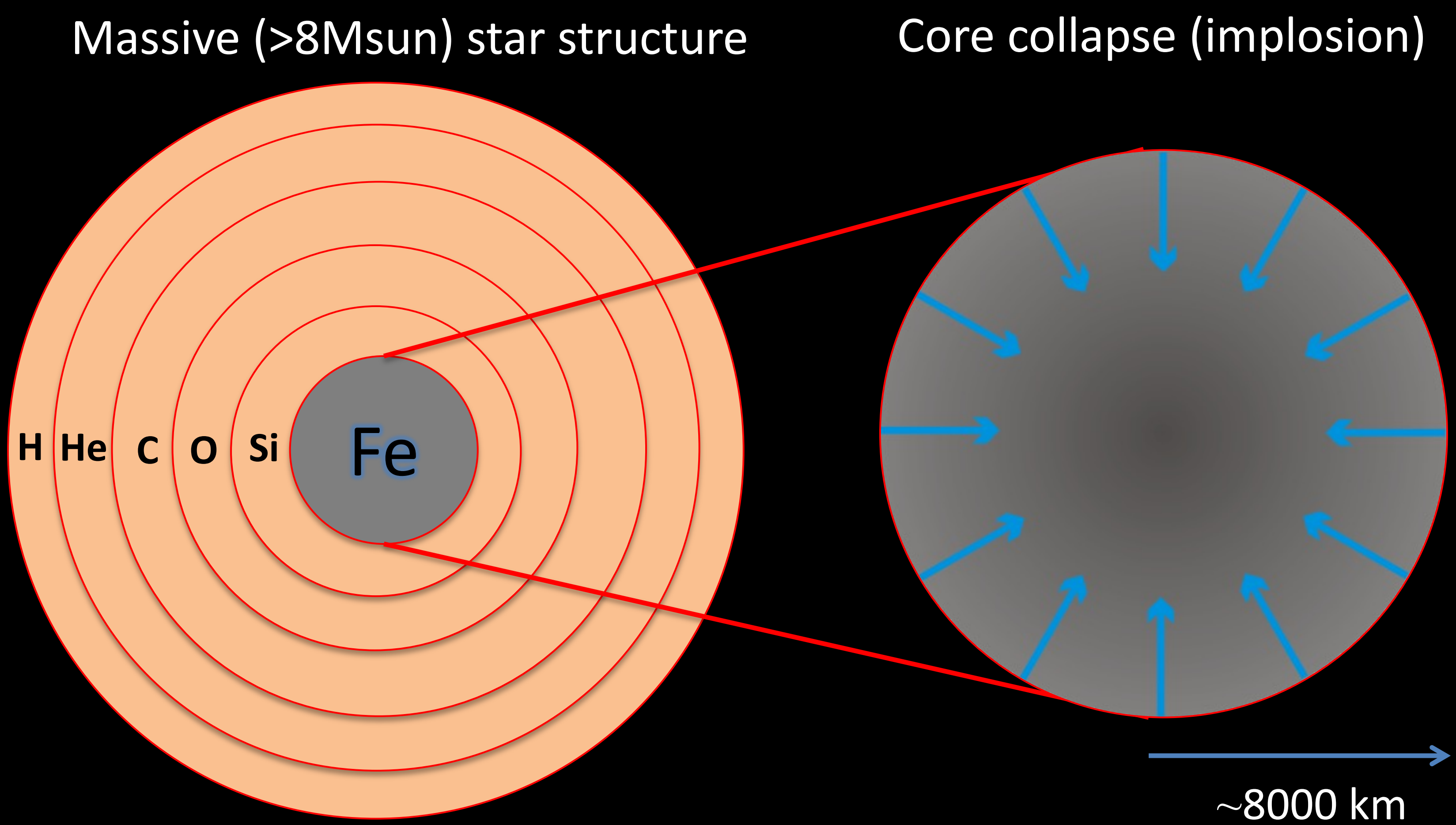
**Crab pulsar**

# *Core collapse = neutrino burst*



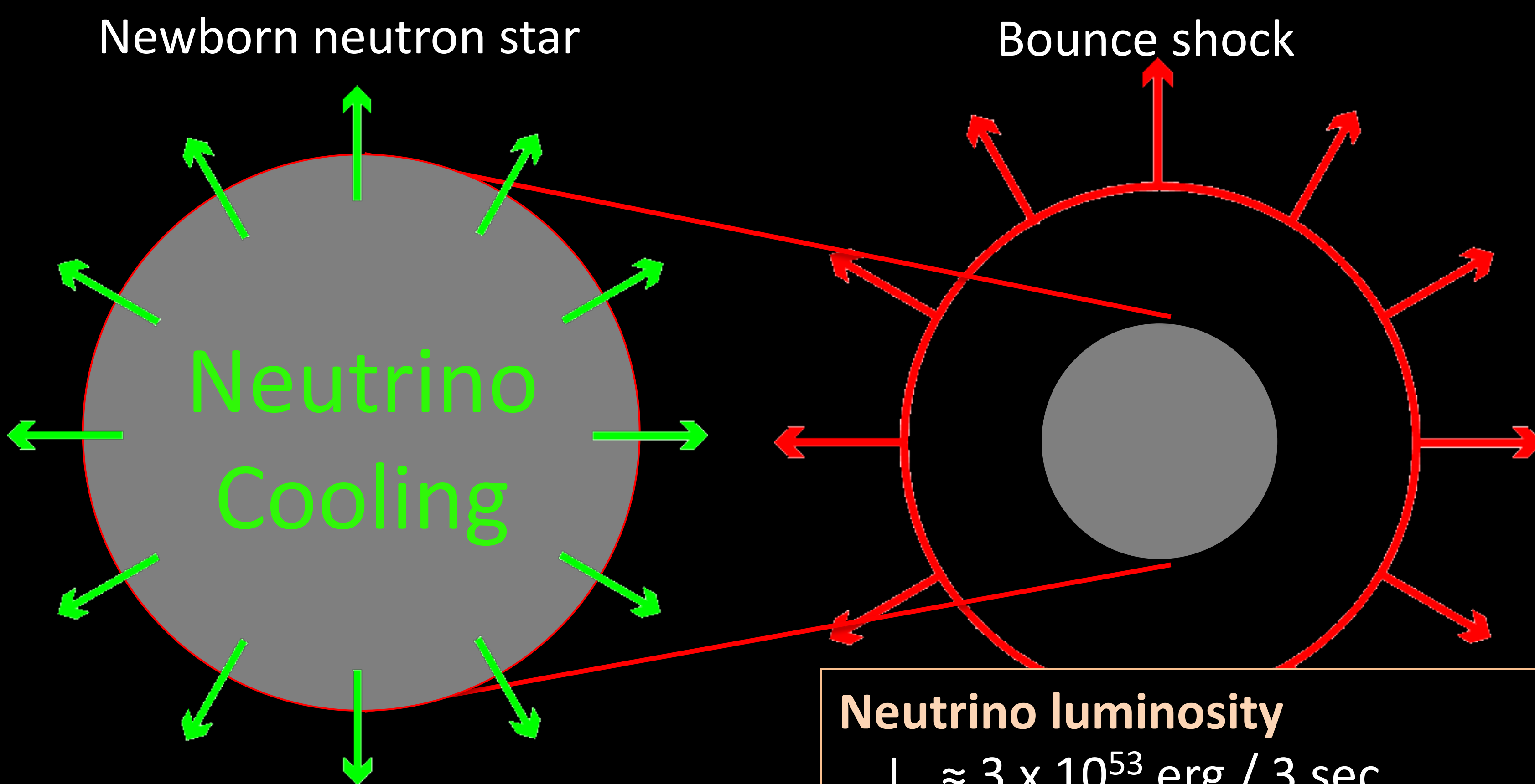

*(adapted from G. Raffelt's slides)*

# *Core collapse = neutrino burst*




*(adapted from G. Raffelt's slides)*

# *Core collapse = neutrino burst*




Energy budget ~ 3 x $10^{53}$ erg
99% into neutrinos
(~0.01% into photons)

**Neutrino luminosity**

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec
$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, it outshines the entire visible Universe

*(adapted from G. Raffelt's slides)*

# *Supernovae occur EVERYDAY*

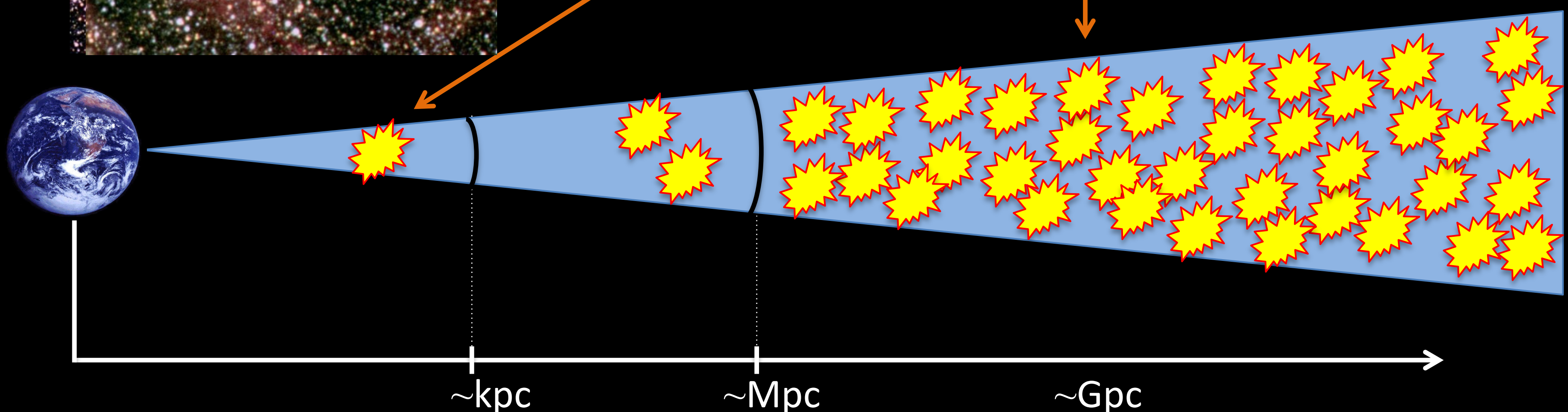
SN 1987A
Occurred in the Large Magellanic Cloud (LMC), 50 kpc away

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

SN rate ~ 0.01 /yr

$N_\nu$ << 1 : <u>DIFFUSE regime</u>

SN rate ~ 1-10 per second



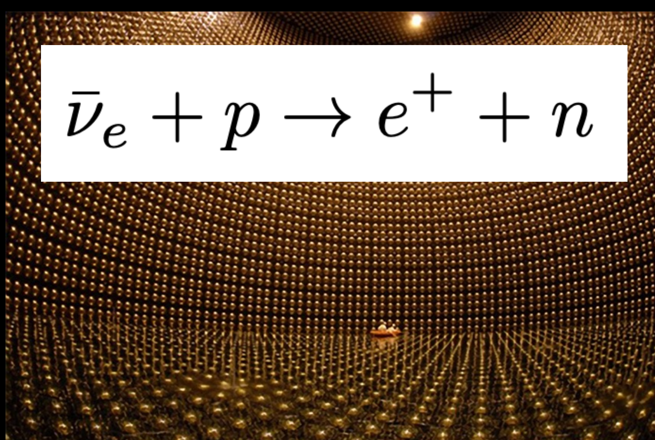

*Adapted from Beacom (2012)*

# DSNB: model prediction

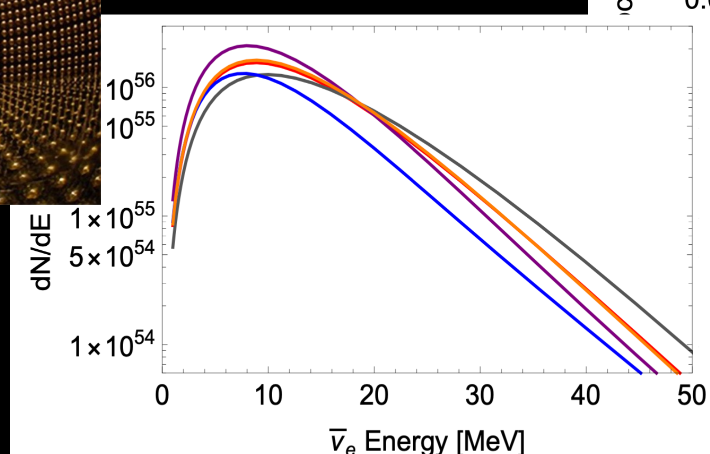
Merging of astronomy, astrophysics, and neutrino experiment

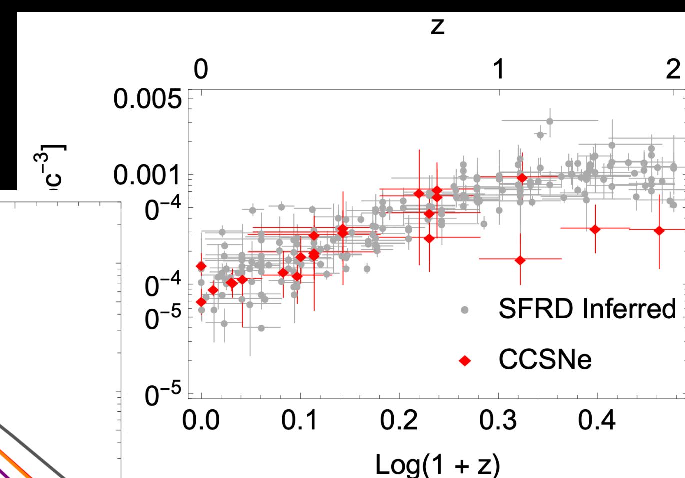
$$R = N_t \int dE\, \sigma_{\mathrm{IBD}} \int dz\, c \frac{dN}{dE'}(1+z) R_{CC}(z) \left|\frac{dt}{dz}\right|$$

- Neutrino detector capabilities
- Time-integrated neutrino emission
- Rate of massive star core collapse



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



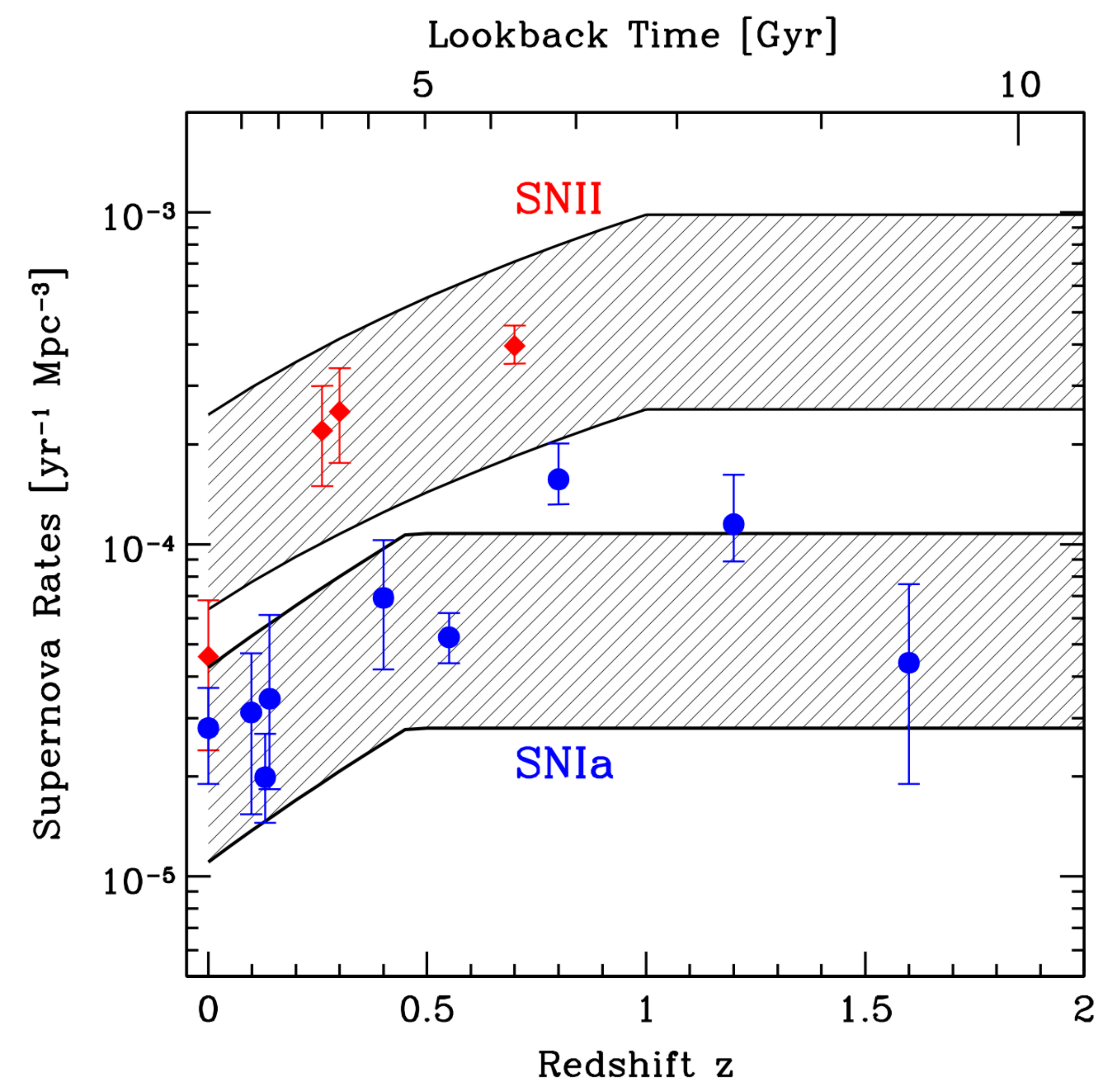



# Importance of supernova rates

**Directly measurements**
Measurements of cosmic supernova rate densities were not so great O(20) years ago…


*Beacom & Vagins (2004)*

They impact DSNB predictions ~linearly, so these uncertainties better go down.




*Strigari et al (2005)*

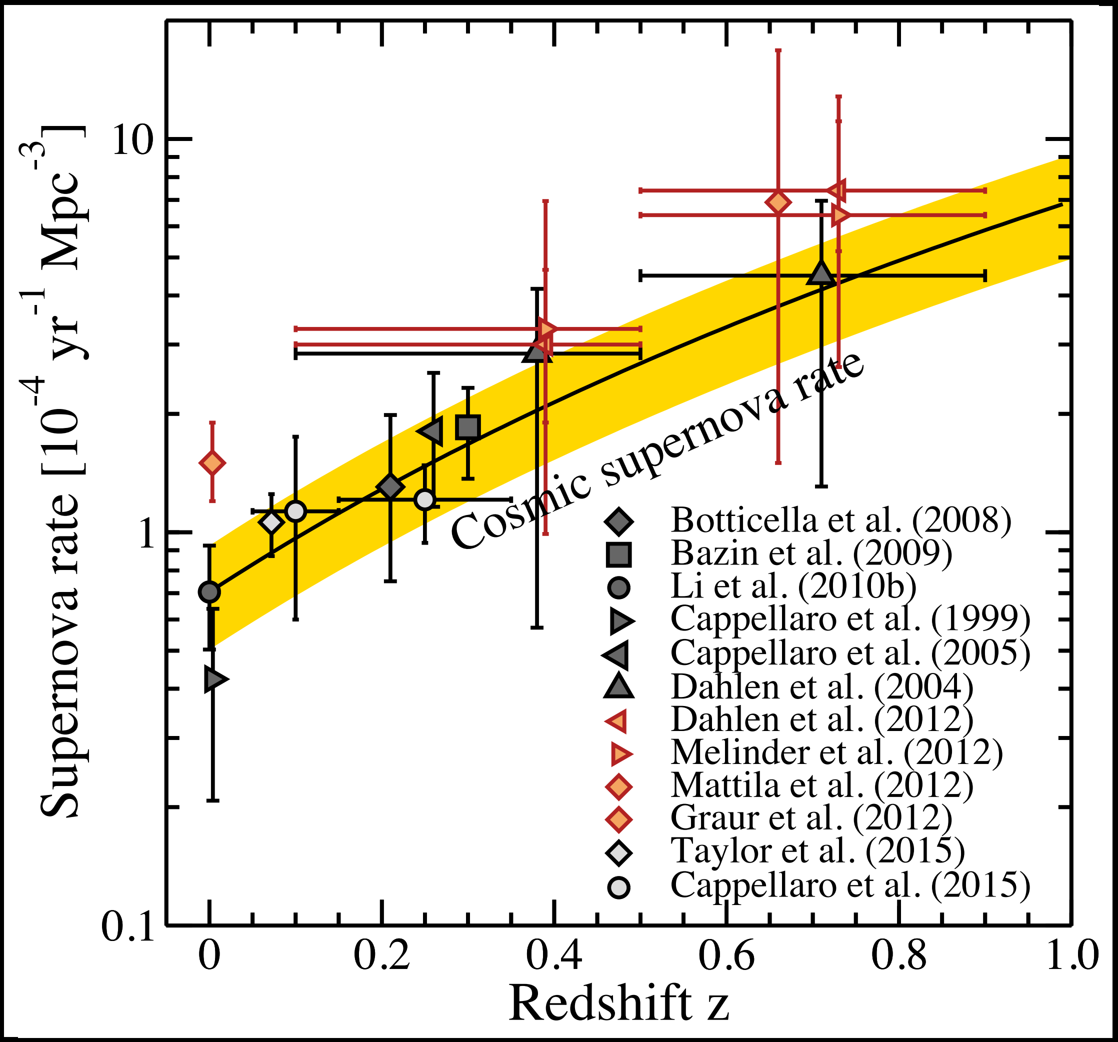
# Cosmic supernova rates

**Direct measurements**
Improved dramatically

Broadly 2 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)

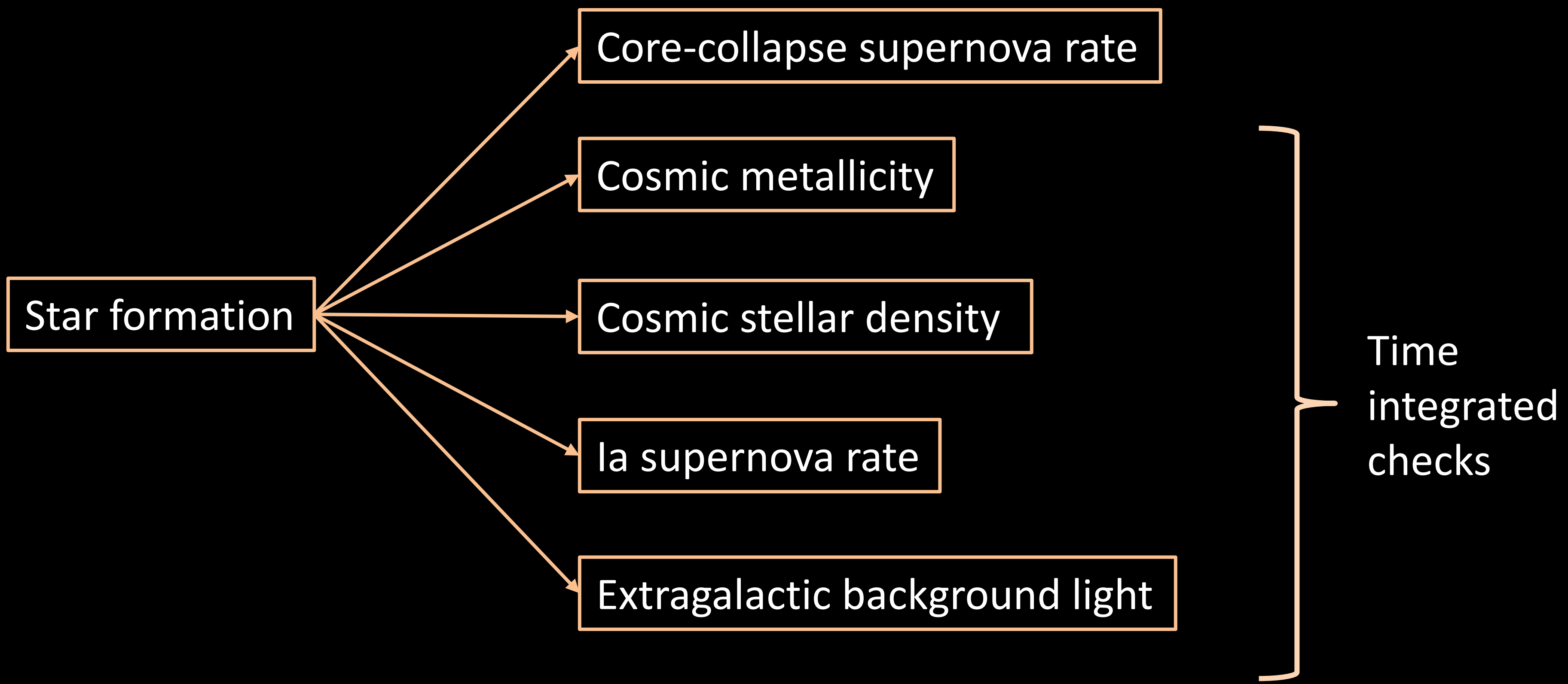
*e.g., Forecasts in Lien & Fields (2009)*




*Updated from Horiuchi et al (2011)*

# *Cosmic cross checks*

Many cross checks have been performed, which give further support:

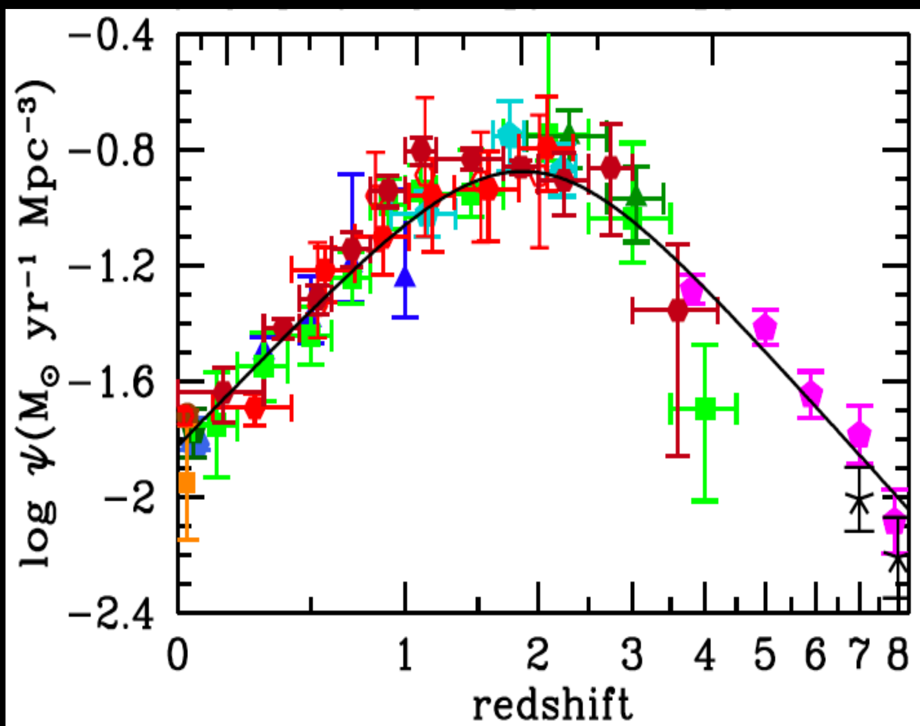


# Cosmic cross checks

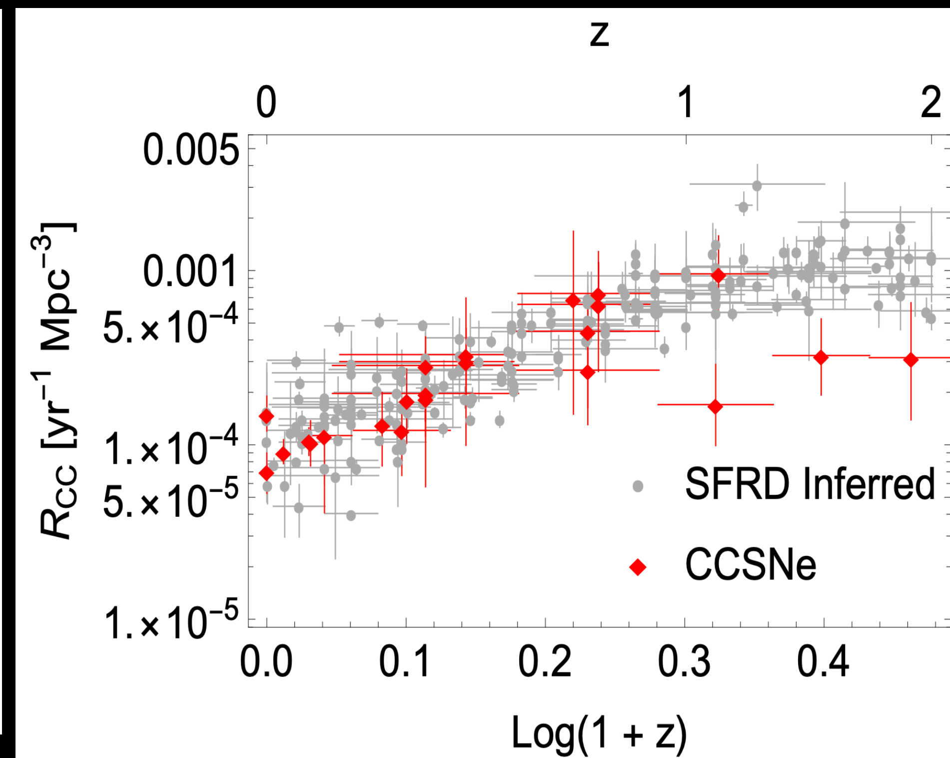
because lifetime of massive stars are cosmologically short

Birth rate of massive stars = Core collapse rate

Note: includes collapse to black holes




*Madau & Dickinson (2014);*
*see also Hopkins & Beacom (2006), Horiuchi & Beacom (2010), etc*

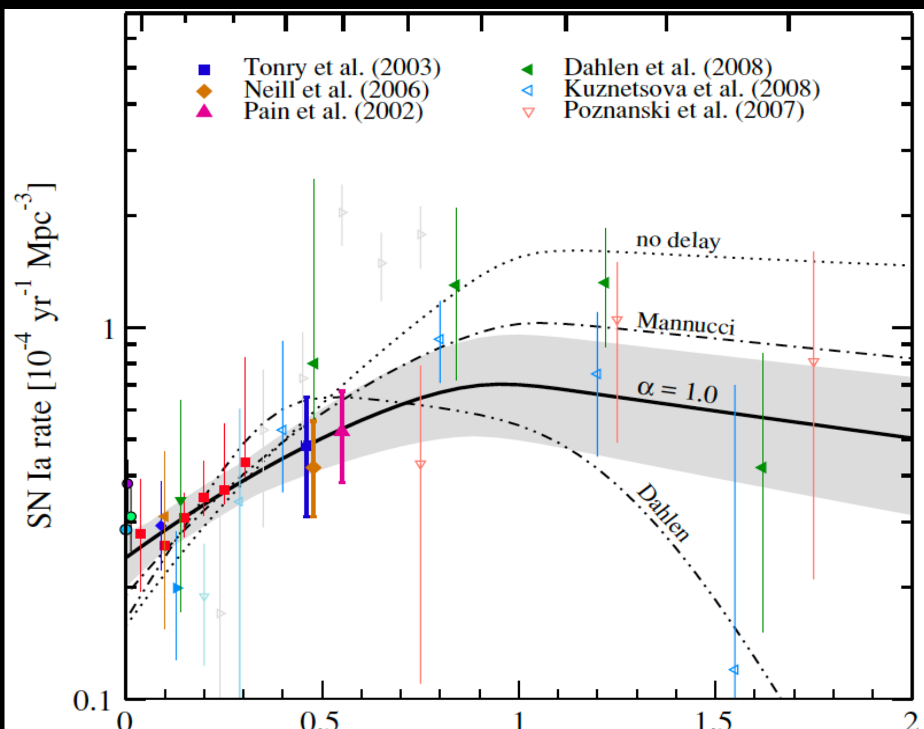



*Ekanger et al (2023);*
*see also Horiuchi et al (2011), Graur et al (2015), etc*

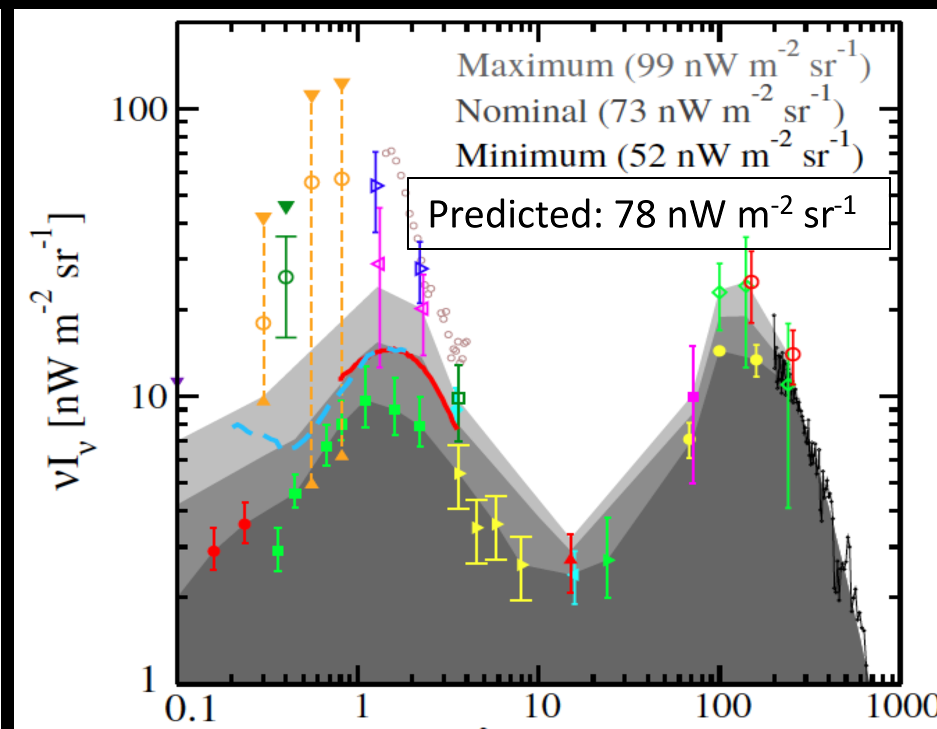
# *Integrated cross checks*

Star formation → Ia supernova rate
*Needs delay-time distribution

Star formation → Extragalactic background light
*Measurement systematics




*Horiuchi & Beacom (2010)*



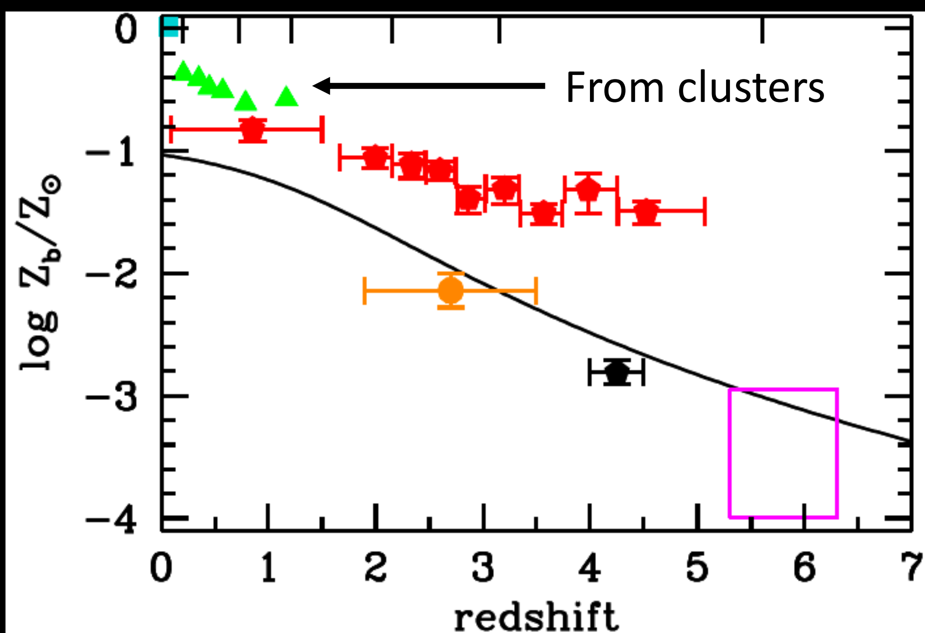

*Horiuchi et al (2009)*

# *Integrated cross checks*

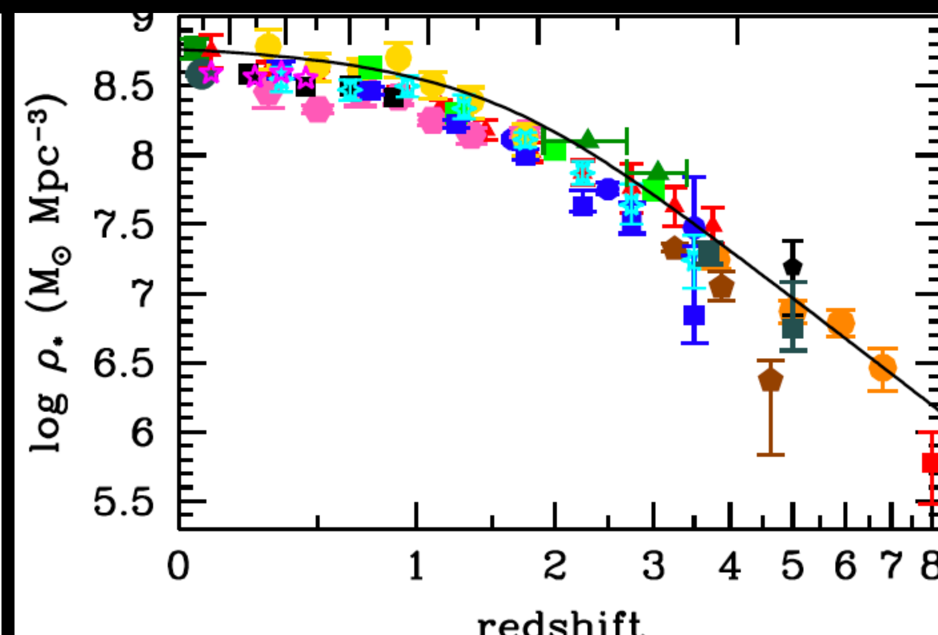
Star formation

Cosmic metallicity
*measurement systematics

Cosmic stellar density
*Sensitive to cosmic initial mass function




*Madau & Dickinson (2014)*




*Madau & Dickinson (2014)*

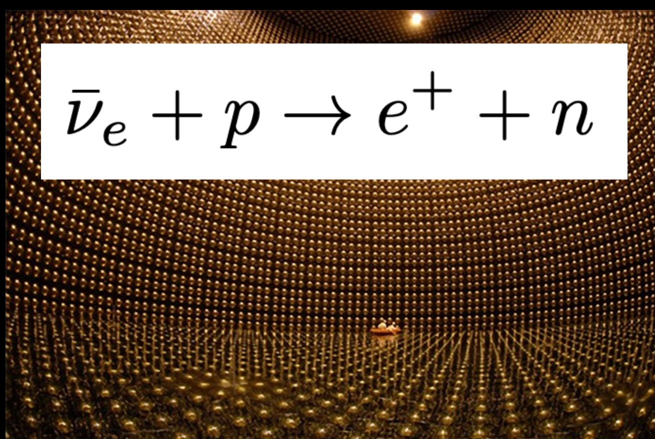
# DSNB: model prediction

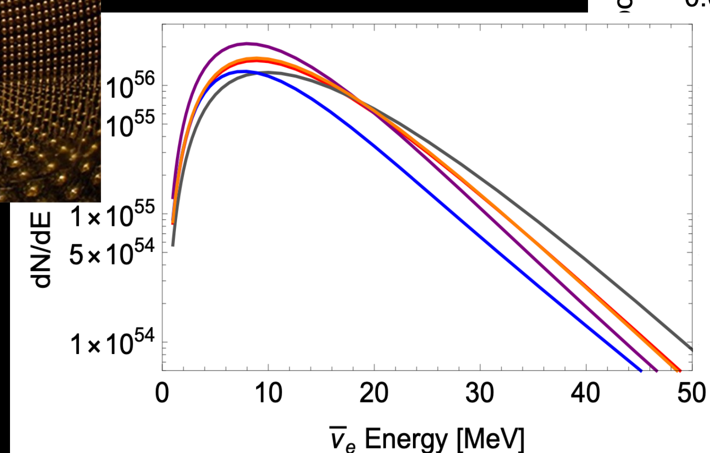
$$R = N_t \int dE\, \sigma_{\rm IBD} \int dz\, c \frac{dN}{dE'}(1+z) R_{CC}(z) \left| \frac{dt}{dz} \right|$$

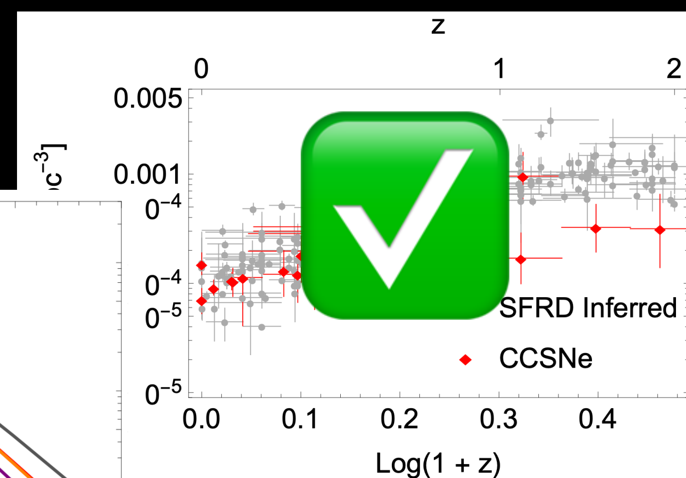
Neutrino detector capabilities

Time-integrated neutrino emission

Rate of massive star core collapse



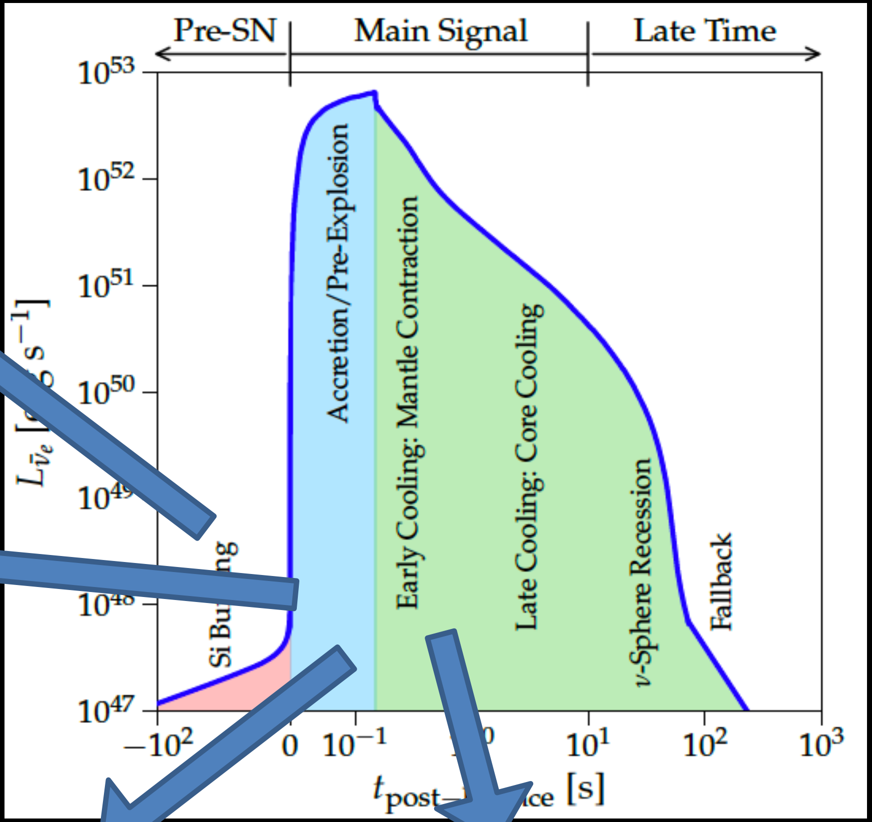



# Neutrino emission evolution

**Si burning**
- Stellar evolution
- Important IC for core collapse

**Neutronization**
- Burst of nue from freed p capturing electrons
- Small uncertainties



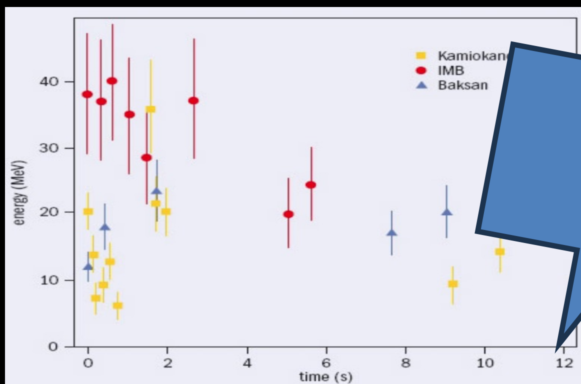

*Li et al (2020)*

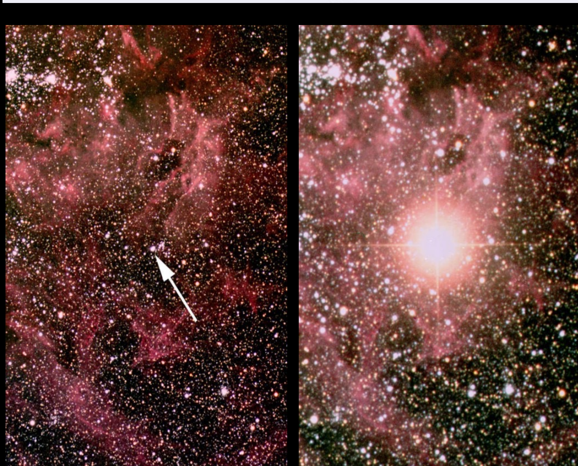
**Accretion**
- Powered by matter accretion
- Most model dependent (explosion mechanism, dimensions, instabilities, oscillation, etc)

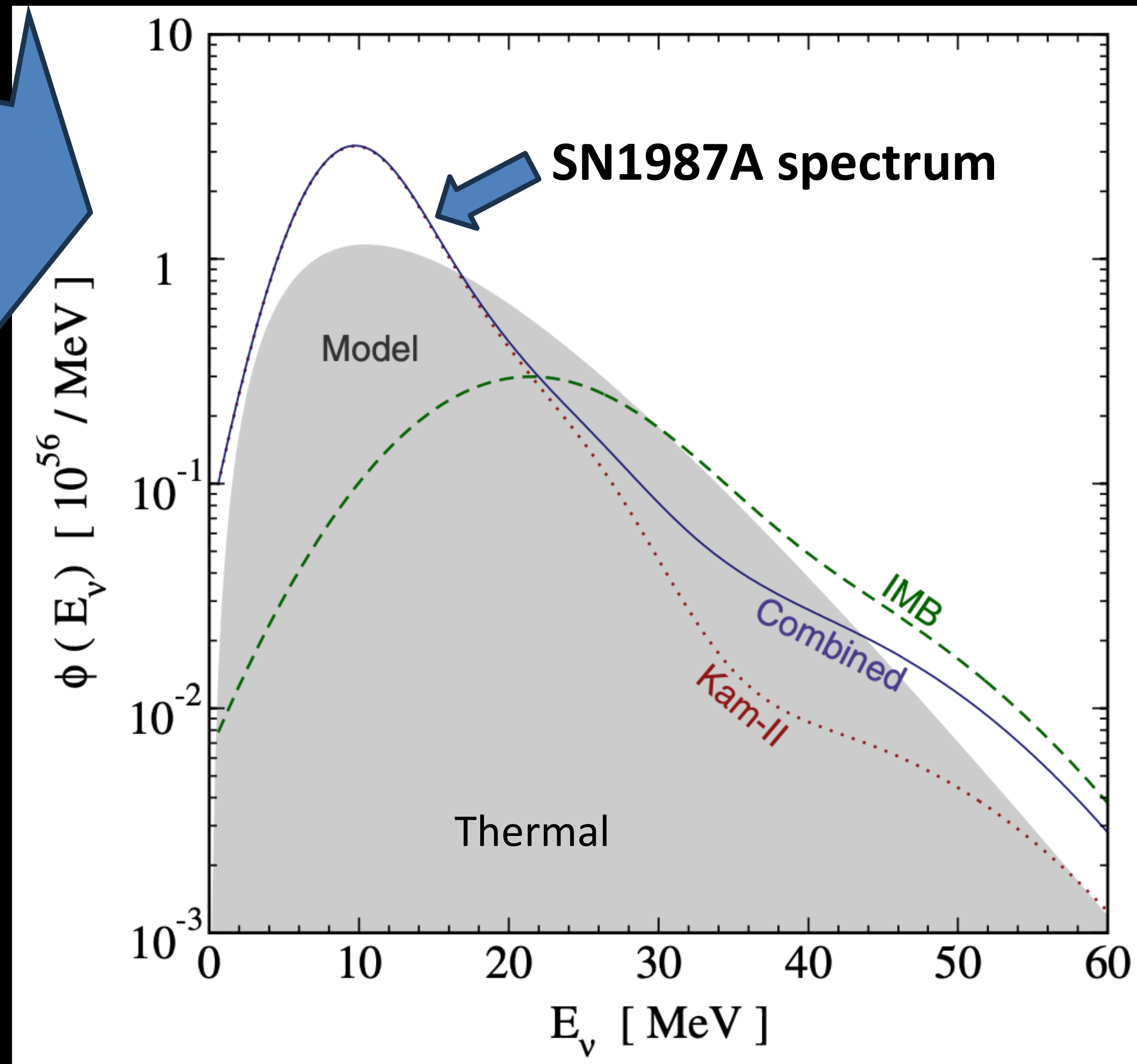
**Cooling**
- PNS cooling on diffusion time scale
- Less uncertain (EOS, remnant mass)

# *Guidance from SN1987A*

**Look to SN1987A for guidance:**



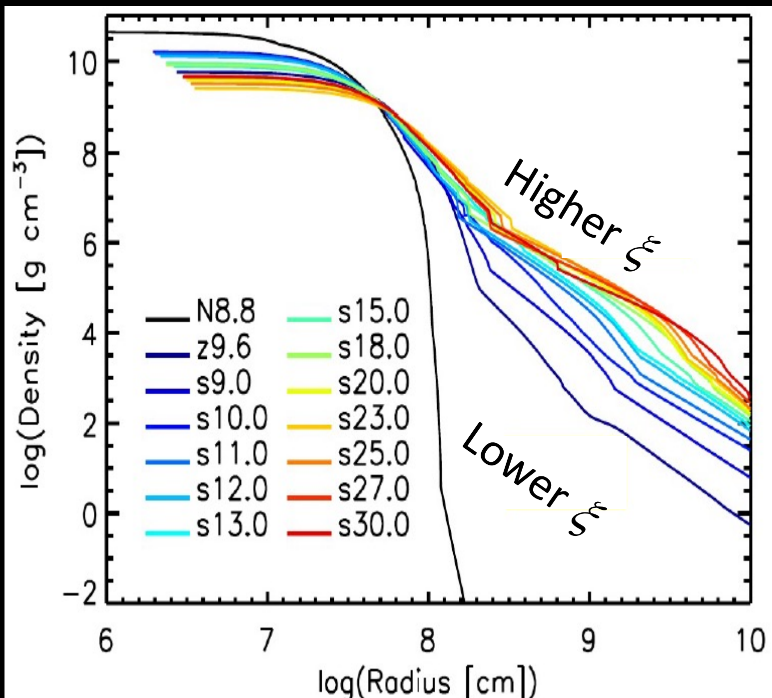





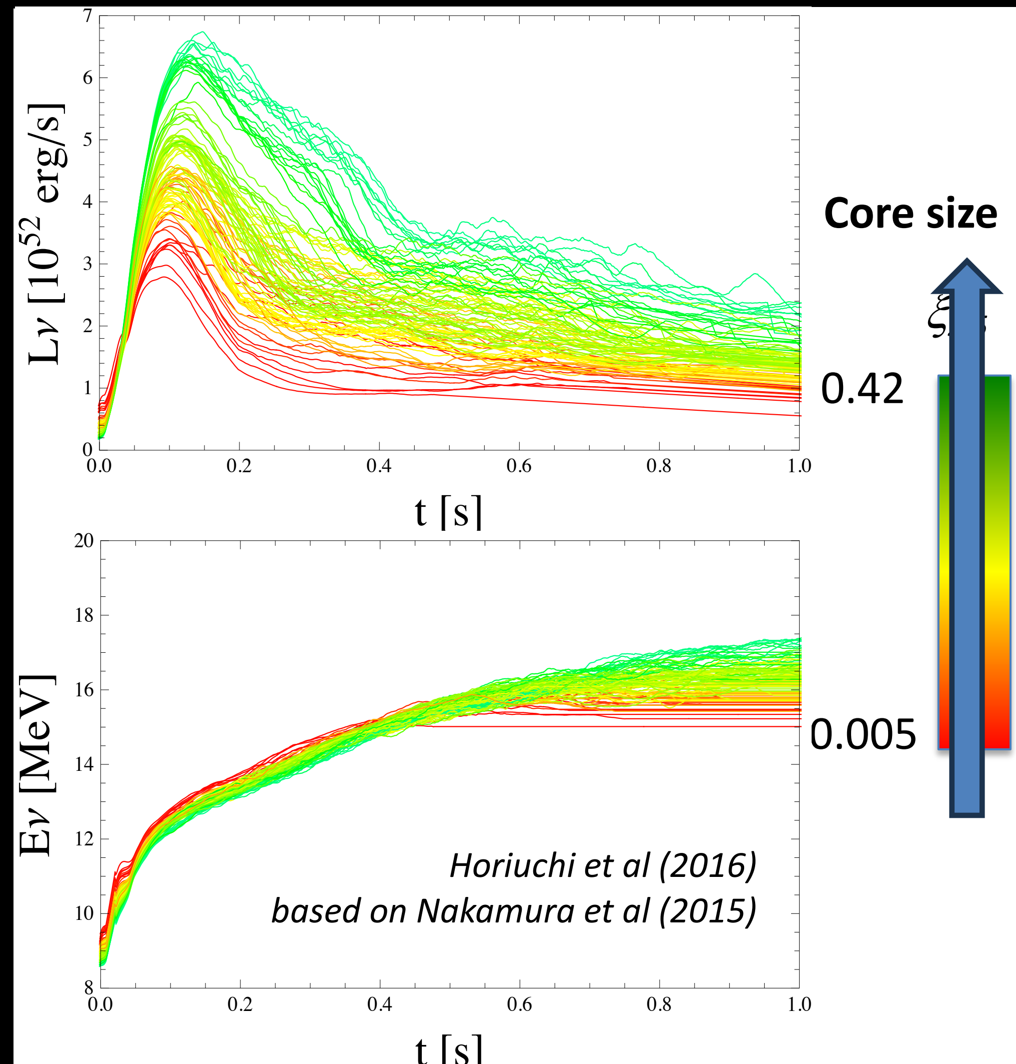

*Yuksel & Beacom (2007);*
*also Krauss (1987), Bahcall (1987),*
*Vissani (2015), others*

# *Not standard candles*

**Look to simulations for guidance: neutrino emission reflects the progenitor**




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



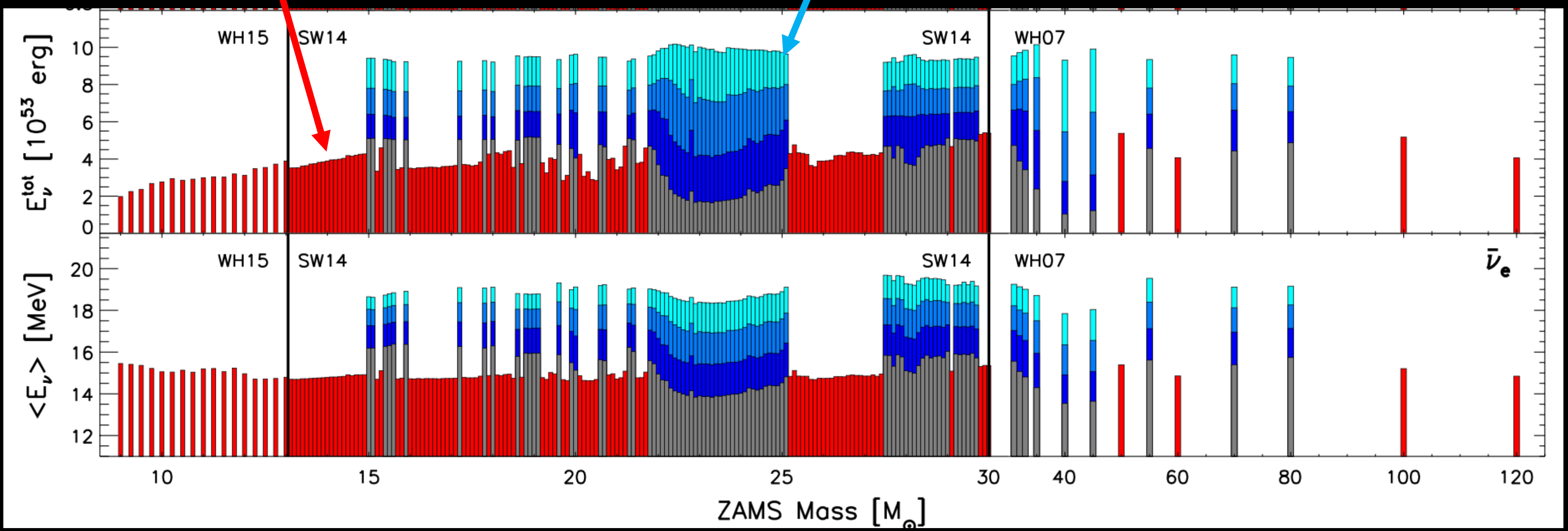
# *Neutrino emission synthesis*

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

1. Multi-D are computationally expensive, although large sets are becoming available
2. Useful are 1D “calibrated central neutrino engines”

Exploding cores

non-exploding cores (more later)




*Kresse et al (2021)*

# *Making sense of neutrino emission*

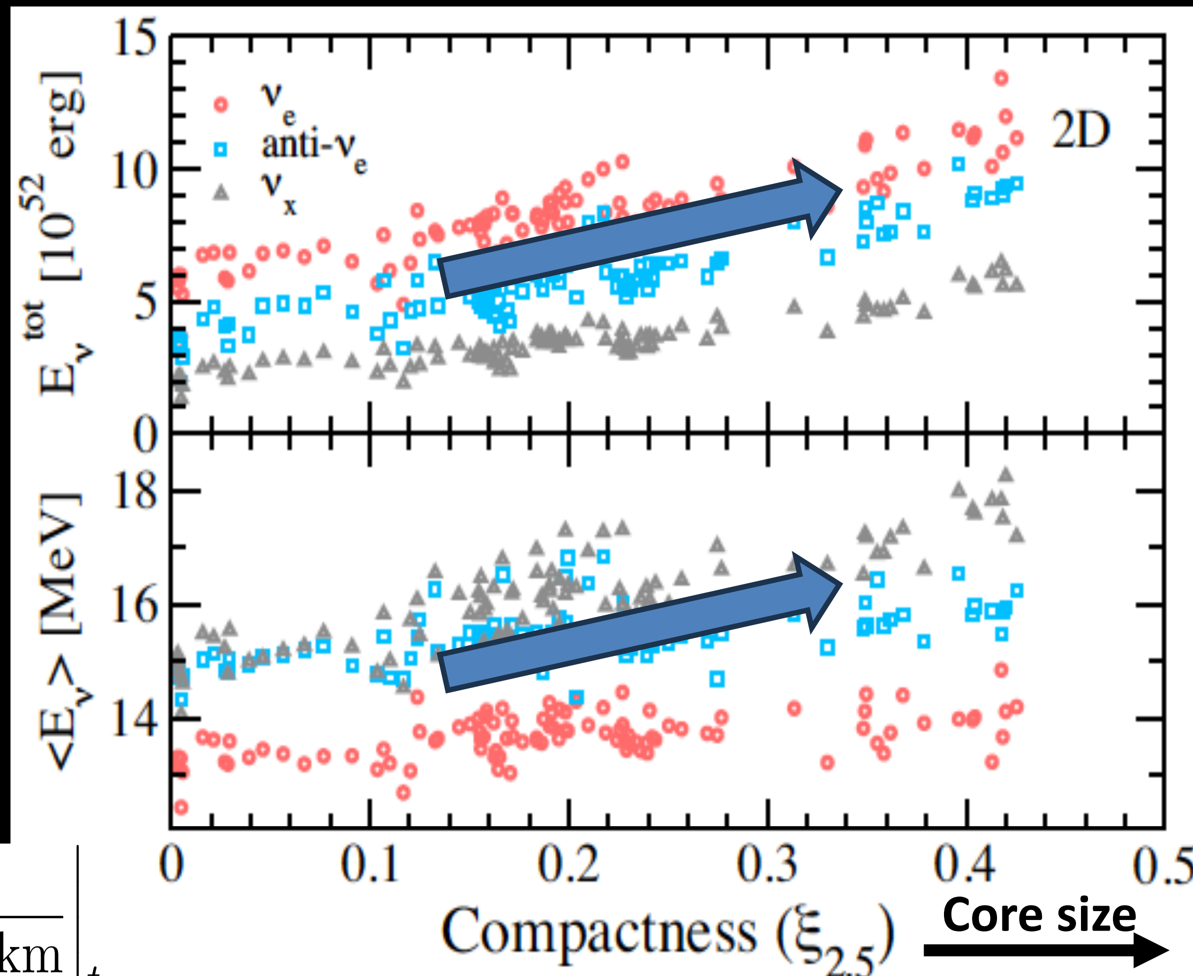
**Systematic dependence on progenitor**

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

Higher mass accretion
→ More binding energy released
→ More neutrinos

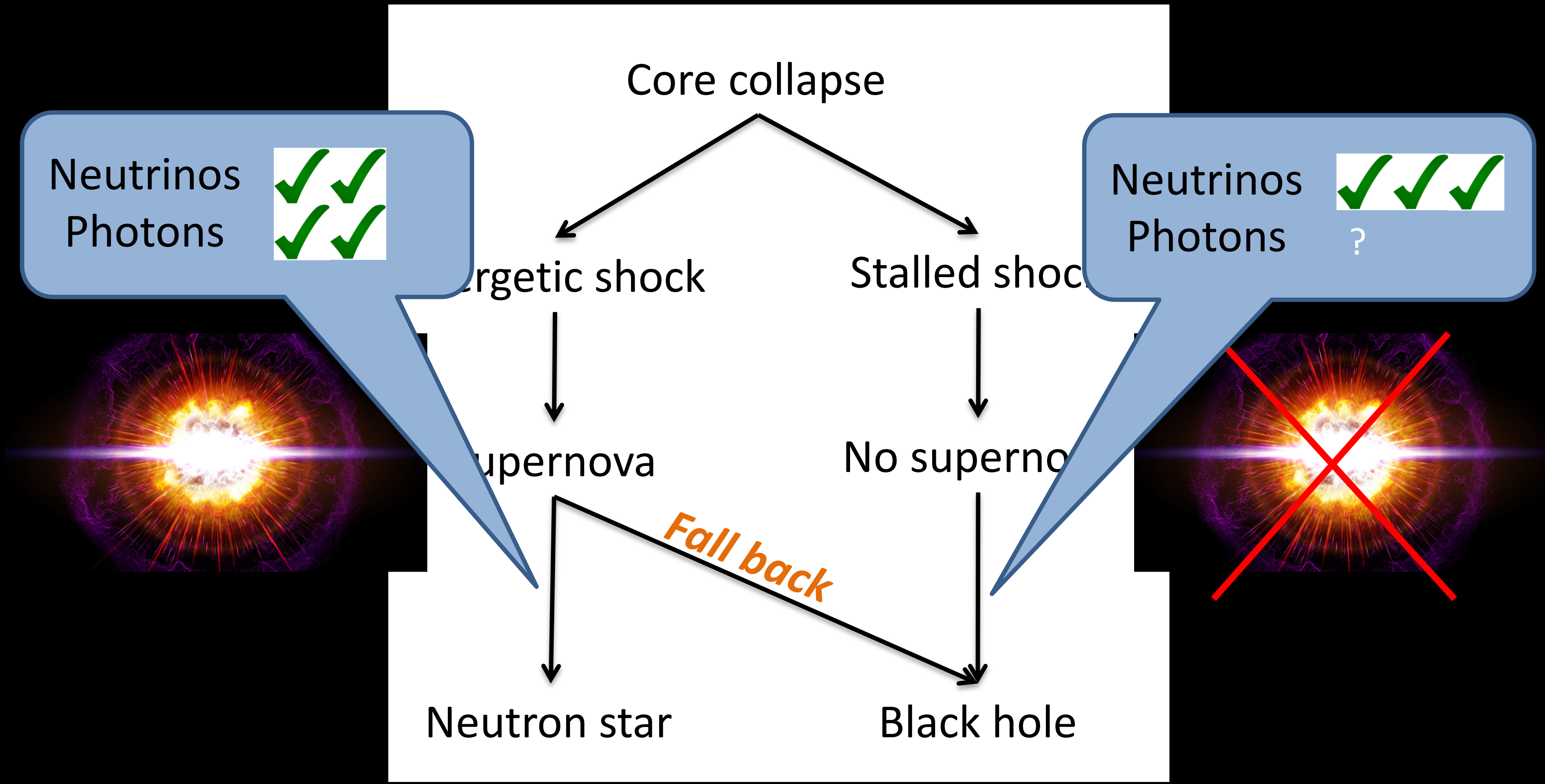
Compactness $\xi$:

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




*Horiuchi et al (2018)*

# *Extreme: collapse to black holes*



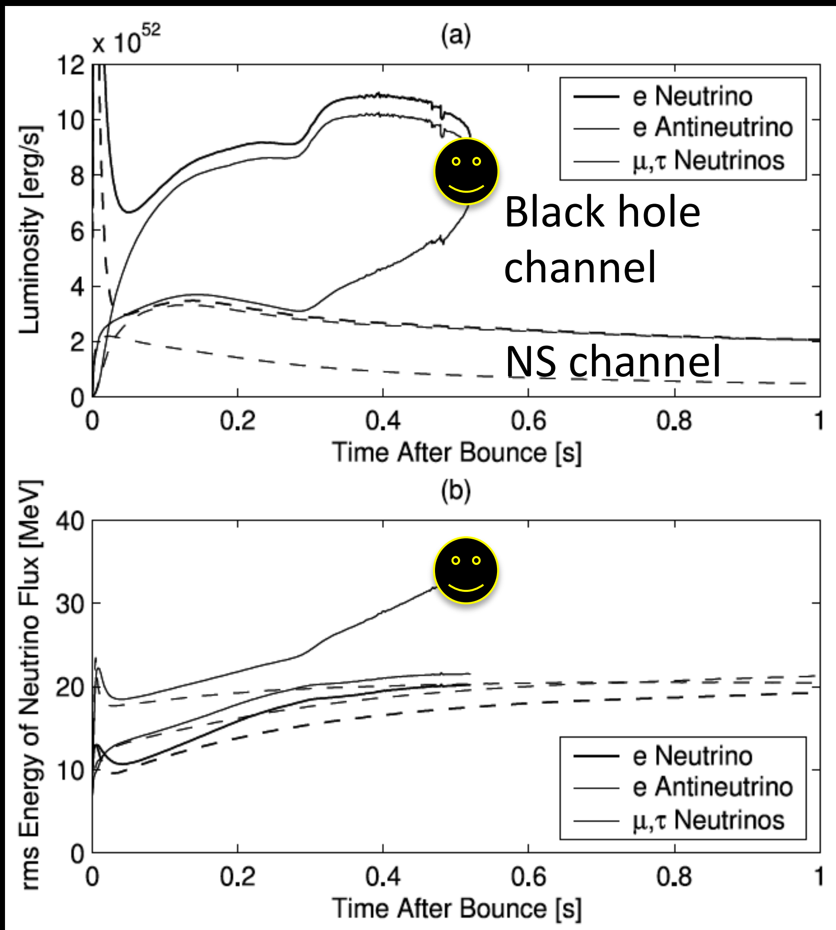
# Black hole channel: simulations

**Look to simulations for guidance:** collapse to black hole are different

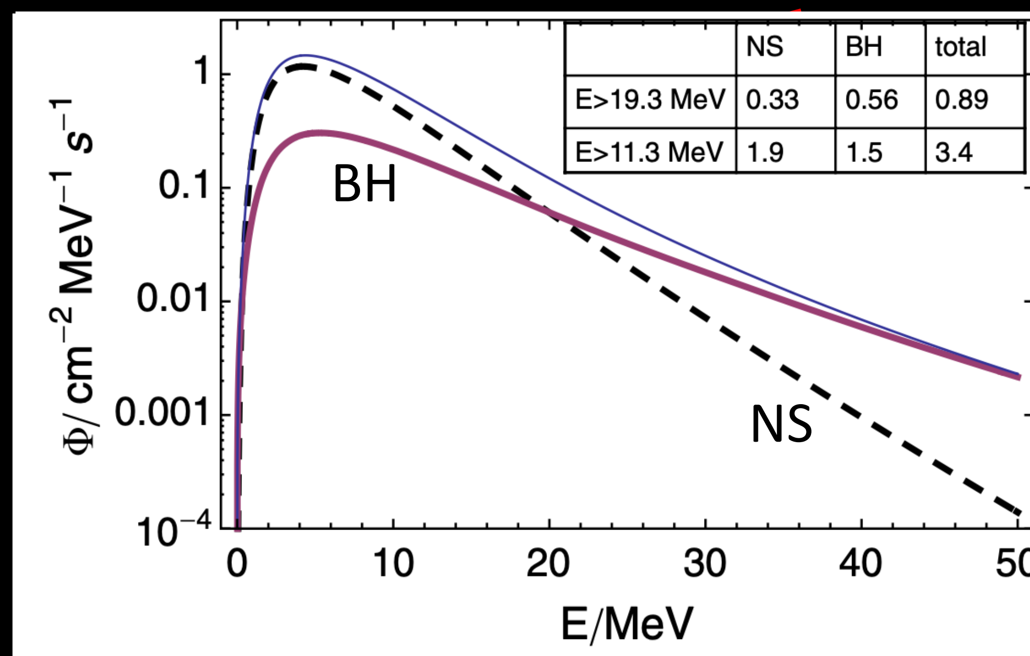
- Neutrino luminosities all rise quickly ☺
- Some neutrino energies rise ☺
- Then abruptly terminate ☹

➔ **When time-integrated, shows a systematically higher-energy spectrum**

**So, important for the DSNB!**




*Liebendoerfer et al (2004); many others*




| | NS | BH | total |
|---|---|---|---|
| E>19.3 MeV | 0.33 | 0.56 | 0.89 |
| E>11.3 MeV | 1.9 | 1.5 | 3.4 |

*Ando, Ekanger, Horiuchi, Koshio (2023)*

*Lunardini (2009)*

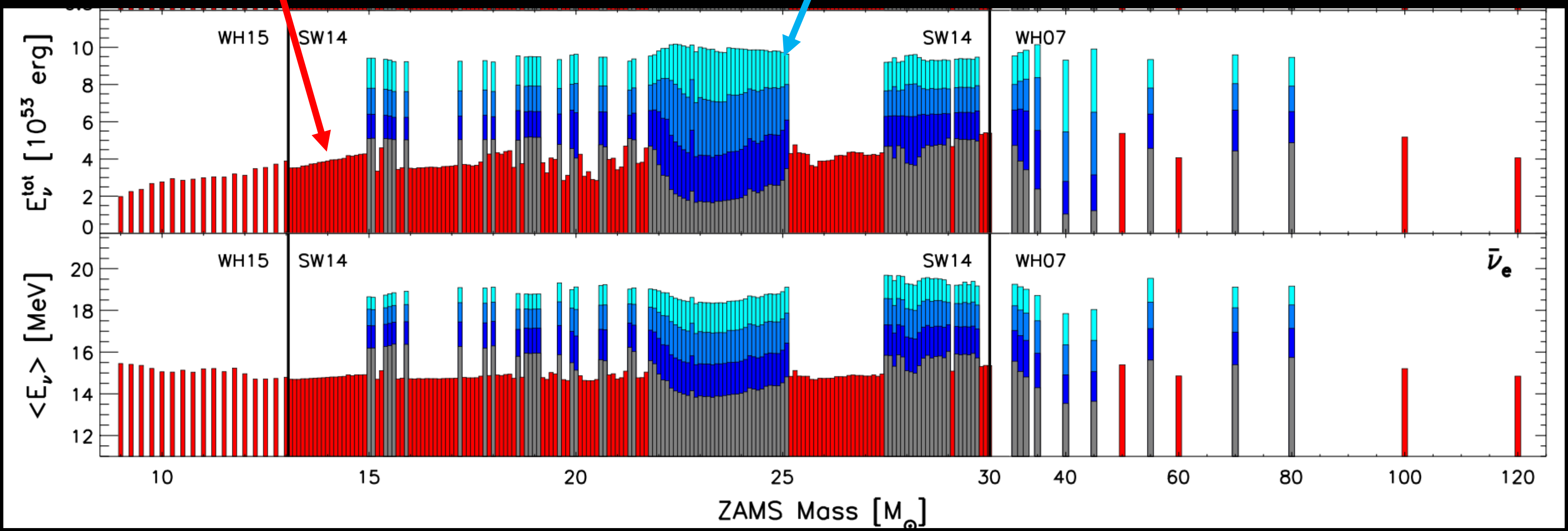
# Neutrino emission synthesis II

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

1. Multi-D are computationally expensive, although large sets are becoming available
2. Useful are 1D "calibrated central neutrino engines"

Exploding cores

non-exploding cores: a lot more neutrinos (depending)




*Kresse et al (2021)*

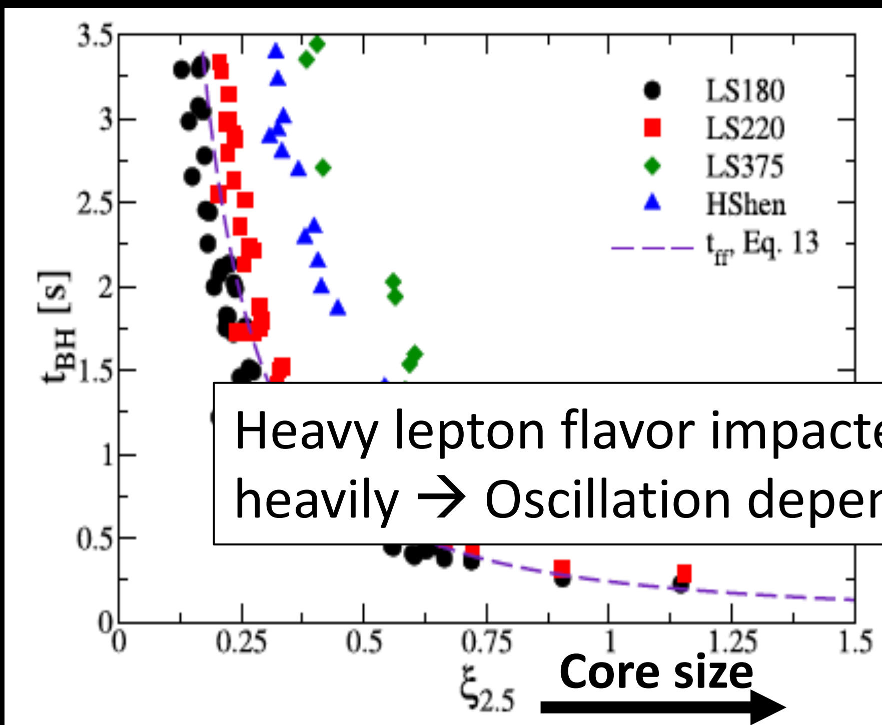
# Making sense of neutrino emission II

**Duration**

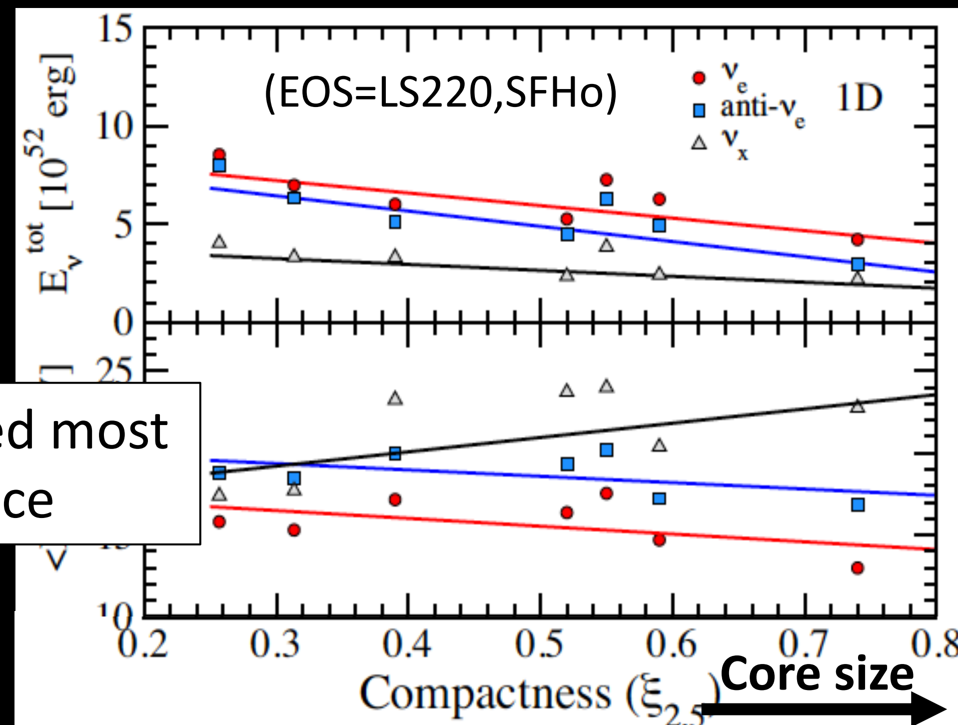
Larger cores (=compactness)
→ higher mass accretion
→ earlier black hole formation

**Time-integrated**

Larger cores (=compactness)
→ higher $L_\nu$ but shorter duration
→ net decline (except $\nu_x$ energy)




Heavy lepton flavor impacted most heavily → Oscillation depence



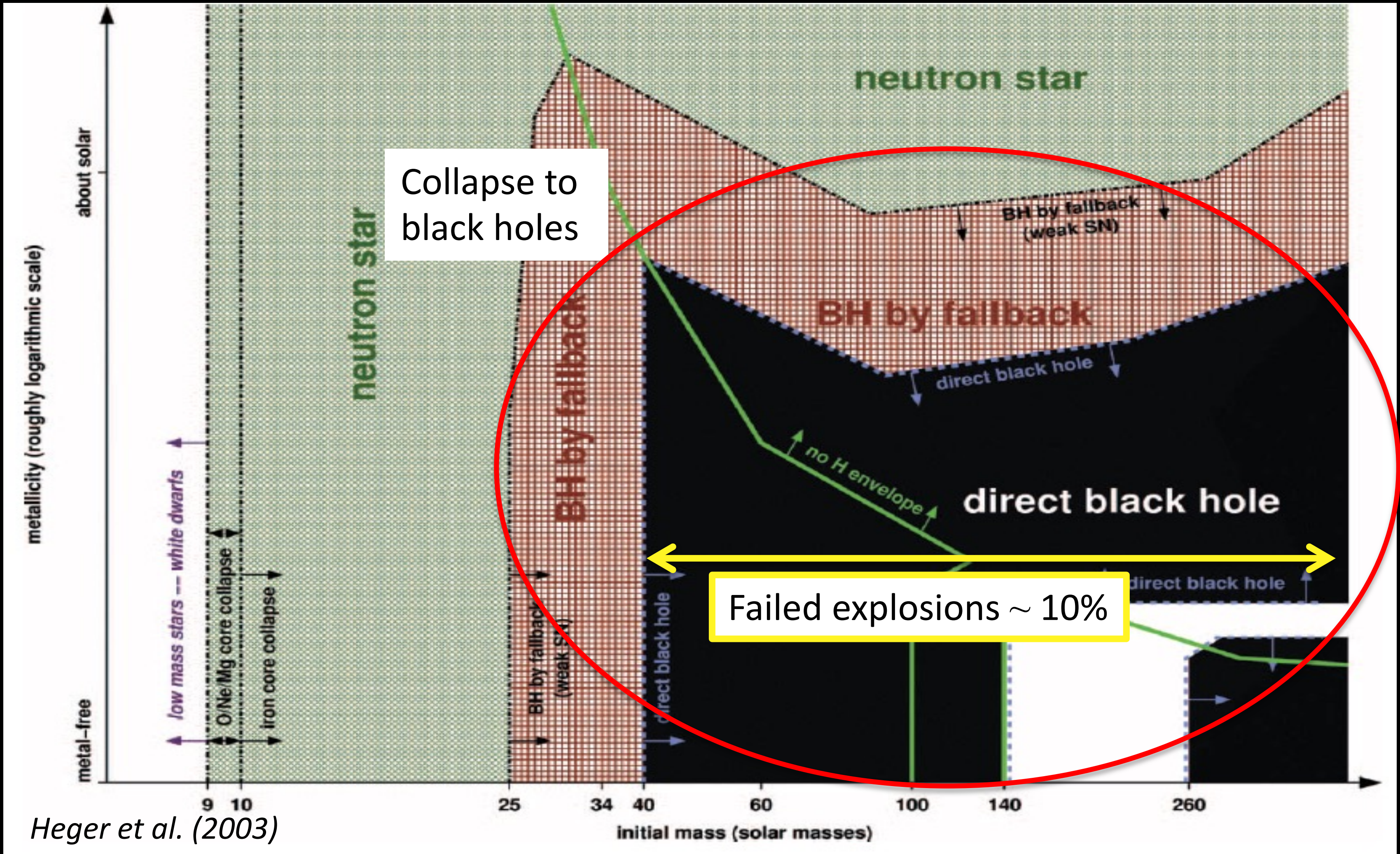

*O'Connor & Ott (2011)*

*Horiuchi et al (2018)*

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

# Black hole prediction circa 2000

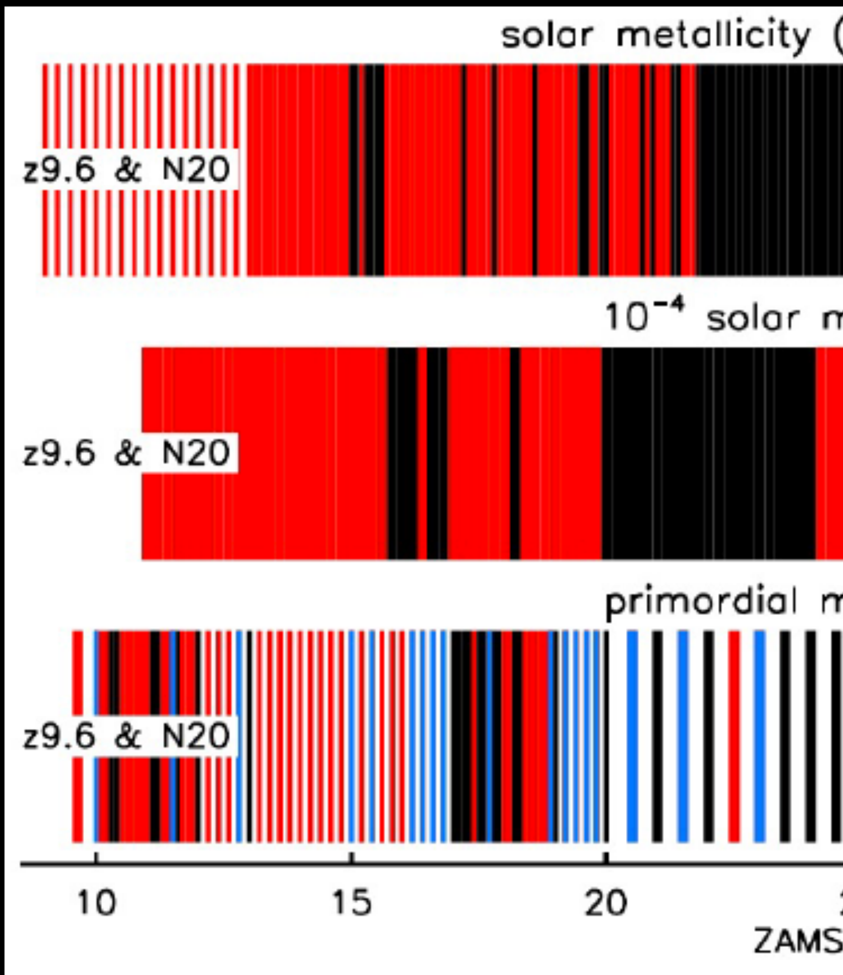
**Based on simple stellar & neutrino mechanism**




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

# *Black hole prediction updates*

**Neutrino mechanism predicts islands of successful explosions & implosions**
(exact mass ranges subject to large uncertainties – more work ongoing)




| 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% |

*Janka 2017; based on Ertl et al (2016); see also Ugliano et al (2012), Sukhbold et al (2016), Pejcha & Thompson (2015), Mueller et al (2016), Sukhbold & Adams (2019), Kresse et al (2021)*

# *Finding collapse to black holes*

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

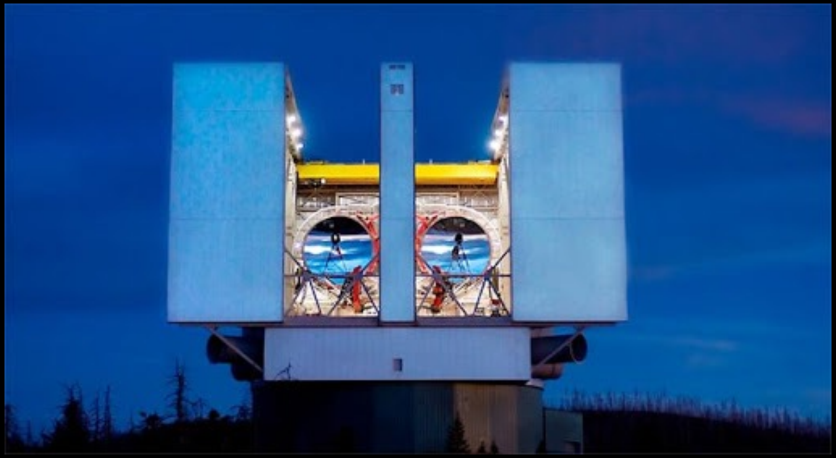
Monitor ~27 galaxies

→ Survey ~$10^6$ progenitor stars

→ Expect ~1 core collapse /yr

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

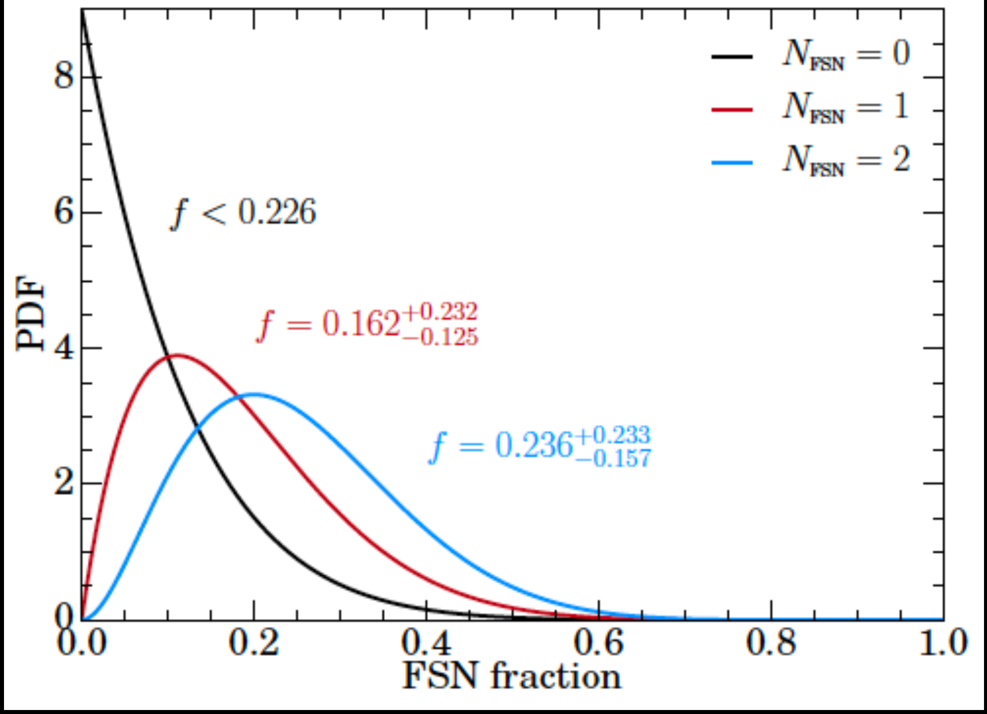
*Kochanek et al. (2008)*



# Looking for disappearing stars

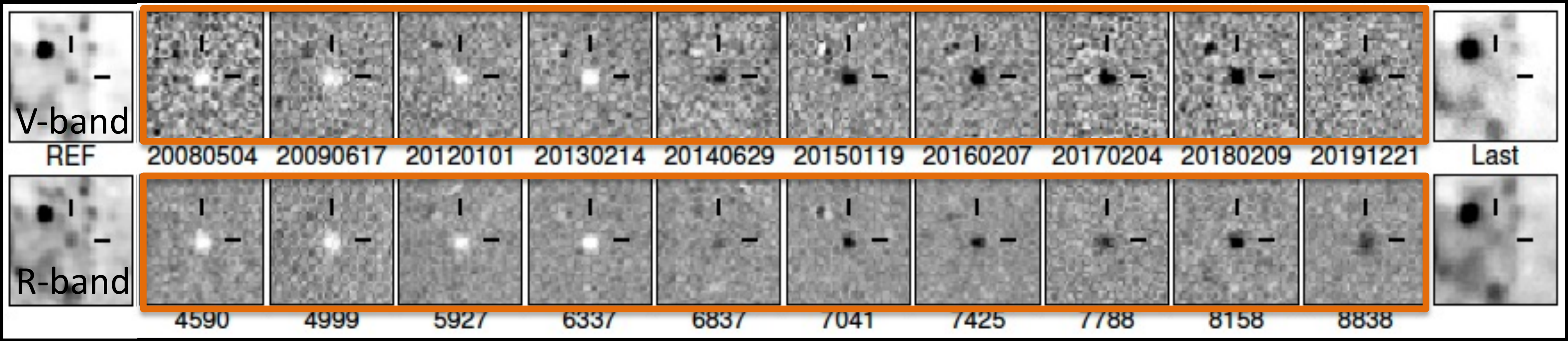
**In 11 years survey**

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



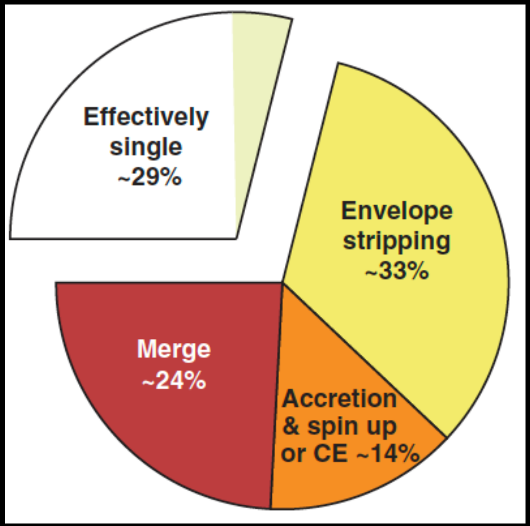

*Neustadt et al (2021)*

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



# More stellar diversity: binaries

**Majority of massive stars evolve in binaries…**



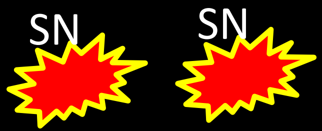

*Sana et al (2012)*

**Non-merger systems**

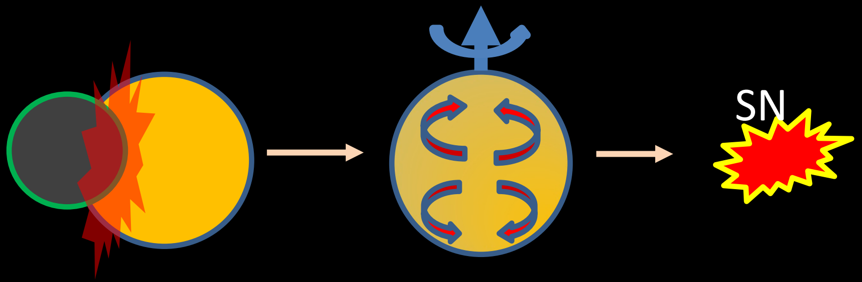
**Merger systems**

**Single**


**Double**




**Spinning massive star**




→ Masses of stars changed!

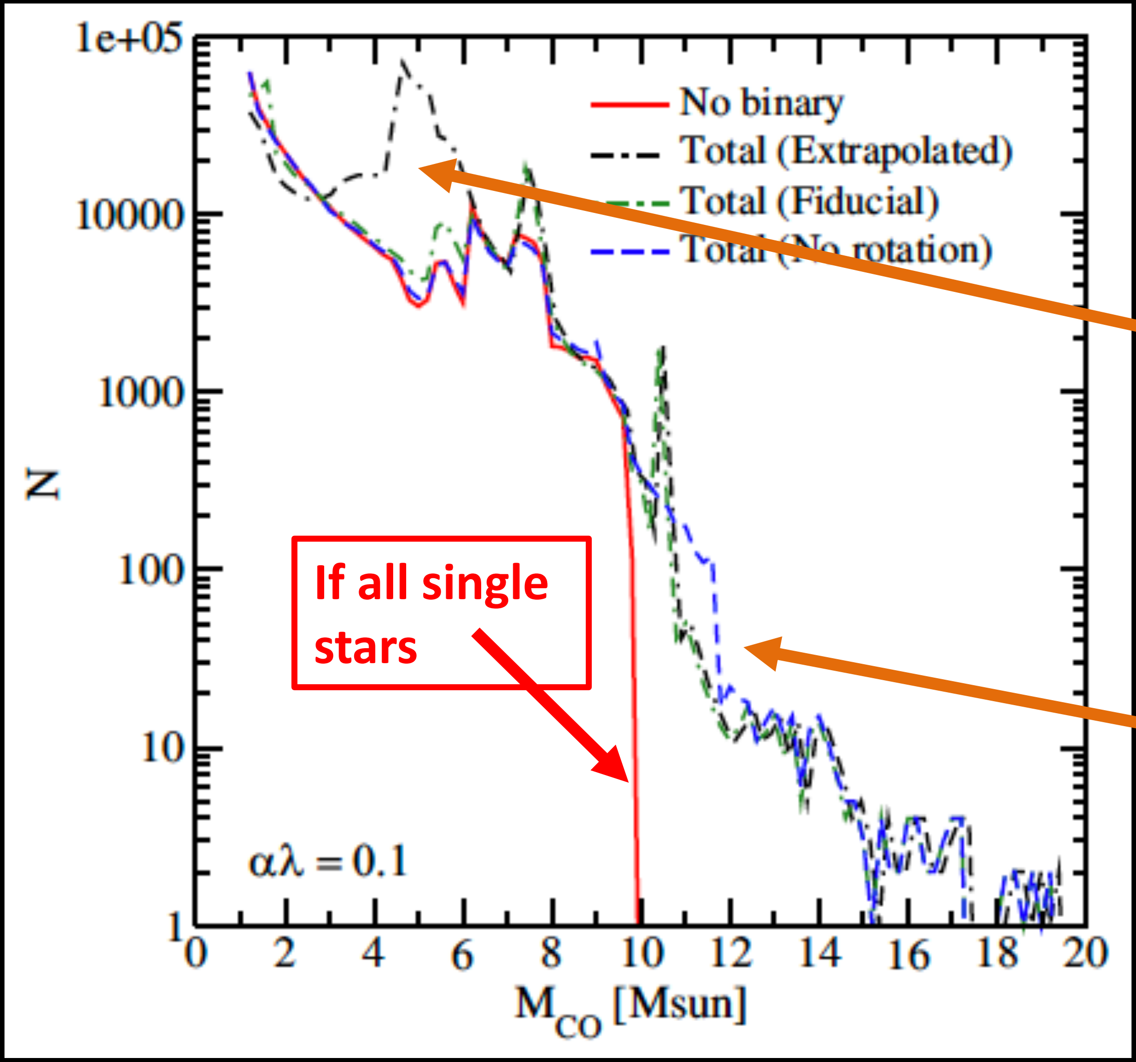
→ Masses of stars changed!
number of stars changed!

Shunsaku Horiuchi

*Visuals: thanks to Kinugawa-san*

# *Binary effects: progenitors*

**binary effect creates more and higher mass cores for collapse**




**Boost to number of progenitors due to mergers: ~25% more progenitors**

**Boost to masses of progenitors due to mergers and mass transfers (at the expense of donor's mass)**

**More realizations ongoing

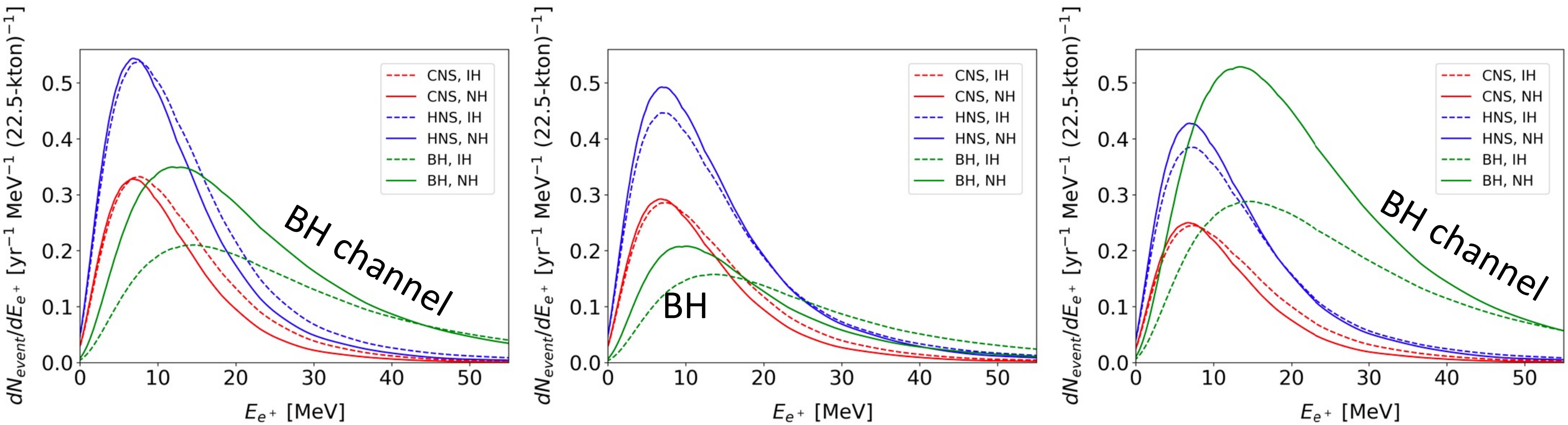
*Horiuchi et al (2021)*

# *Black hole contribution can be big*

- Strong EOS dependence
- Can be driven by late-time accretion

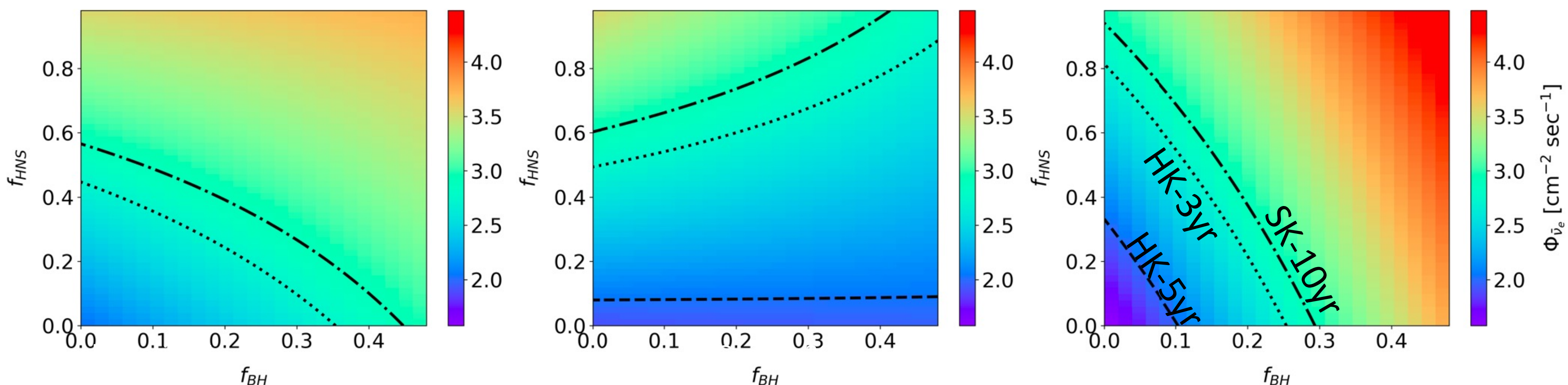
*Nakazato et al (2024)*

*Ashida & Nakazato (2022)*




(a) Togashi EOS (b) LS220 EOS (c) Shen EOS

stiffer



# *So where to now?*

This is just my contribution to a much wider active field:

PHYSICAL REVIEW D **79**, 083013 (2009)

**Diffuse supernova neutrino background is detectable in Super-Kamiokande**

Shunsaku Horiuchi,[1,2,3] John F. Beacom,[2,3,4] and Eli Dwek[5]

- Spherical symmetric simulations
- Thermal neutrino spectra
- No black hole considerations
- Core-collapse rate sysmatics

PHYSICAL REVIEW D **109**, 023024 (2024)

**Diffuse supernova neutrino background with up-to-date star formation rate measurements and long-term multidimensional supernova simulations**

Nick Ekanger,[1,*] Shunsaku Horiuchi,[1,2,†] Hiroki Nagakura,[3] and Samantha Reitz[1,4]

- Multi-dimentional long-term simulation sets
- Accounting for stellar & collapse diversity
- Black hole considerations (but still rich!)
- Core-collapse rate well established and cross checked

# So where to now?

An attempt at the error budget:

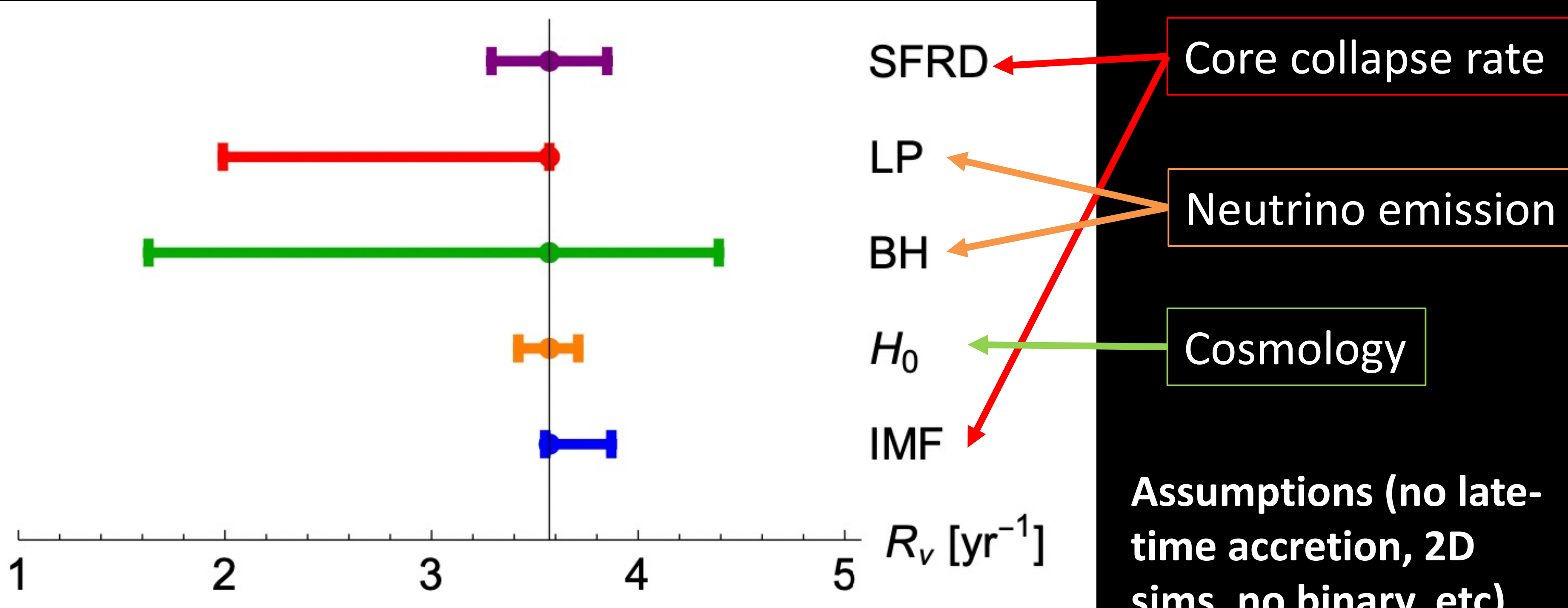



FIG. 6. Estimated errors of DSNB event rates for normal ordering at SK-Gd from SFRD measurements ('SFRD'), late-phase treatment ('LP,' Analytic or RenormLS), failed supernova modeling ('BH,' see Fig. 7), $H_0$, and IMF assumption ('IMF,' Chabrier, Salpeter A, or Baldry-Glazebrook). Quantitative values are given in Table II.

**Assumptions (no late-time accretion, 2D sims, no binary, etc)**
**➔ Nevertheless, showcases the exciting prospects of studying core collapse & neutrino physics**


*Ekanger et al (2024)*

# *Happy birthday, Mark*

**Thank you, Mark, for you and your team making the Gd dream.**

**As a theorist, I felt confident DSNB models will be tested, with you at the helm.**

- **The DSNB is a guaranteed signal with a well-established canonical flux (and we continue to make it richer).**
- **DSNB neutrinos are there, in the data set! The Gd upgrade will allow it to be discovered.**
- **When discovered, these will be the first confirmed MeV neutrinos crossing cosmological distances, opening new windows into core collapse, neutrinos, and BSM physics.**