Max-Planck-Institut für Astrophysik

LMU TUM ORIGINS Excellence Cluster

SFB 1258 Neutrinos Dark Matter Messengers

NuPhys2019: Prospects in Neutrino Physics
Cavendish Conference Centre, London, UK; 16-18 December 2019

Supernova Neutrinos

From Current 3D Explosion Models to DSNB Predictions

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MPI for Astrophysics

COCO2CASA

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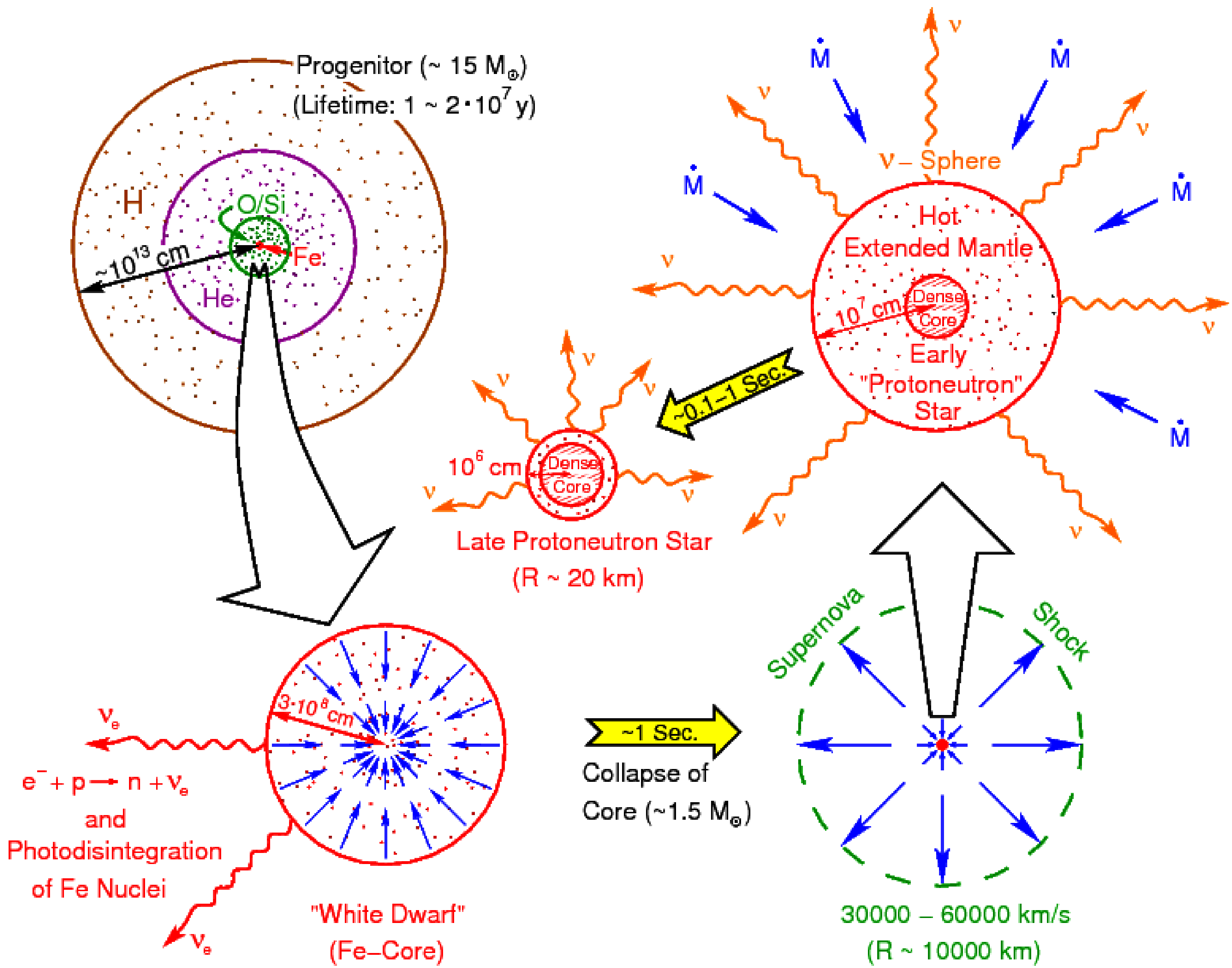
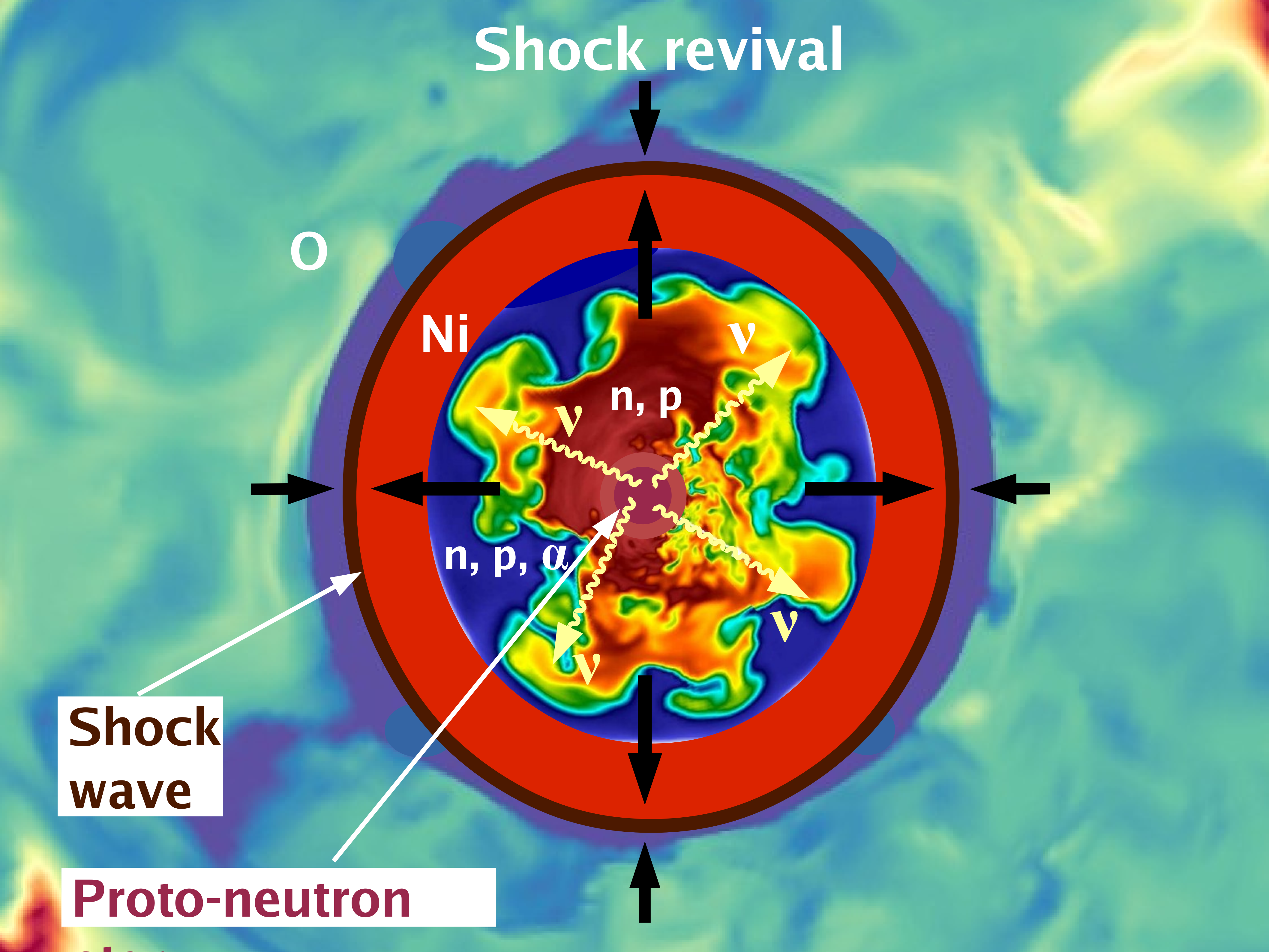
4. New predictions of the Diffuse Supernova Neutrino
   Background (DSNB)

Stellar Collapse and Supernova Stages



adapted from A. Burrows (1990)


Shock revival
O
Ni
n, p
ν
ν
n, p, α
ν
ν
Shock wave
Proto-neutron

Status of Neutrino-driven Mechanism in 3D Supernova Models

- 3D modeling has reached mature stage.
- 3D differs from 2D in many aspects, explosions more difficult than in 2D.

- Neutrino-driven 3D explosions for progenitors between 9 and 60 M_{sun}
  (with rotation, 3D progenitor perturbations, or slightly modified neutrino opacities)

3D Core-Collapse SN Explosion Models

Oak Ridge (Lentz+ ApJL 2015): 15 M_{sun} nonrotating progenitor (Woosley & Heger 2007)

Tokyo/Fukuoka (Takiwaki+ ApJ 2014): 11.2 M_{sun} nonrotating progenitor (Woosley et al. 2002)

Caltech/NCSU/LSU/Perimeter (Roberts+ ApJ 2016; Ott+ ApJL 2018):
27 M_{sun} nonrotating progenitor (Woosley et al. 2002),
15, 20, 40 M_{sun} nonrotating progenitors (Woosley & Heger 2007)

Princeton (Vartanyan+ MNRAS 2019a, Burrows+ MNRAS 2019, Nagakura+ arXiv:1912.07615):
9–60 M_{sun} suite of nonrot. progenitors (Woosley & Heger 2007, Sukhbold+2016)

3D Core-Collapse SN Explosion Models

Garching/QUB/Monash (Melson+ ApJL 2015a,b; Müller 2016; Janka+ ARNPS 2016, Müller+ MNRAS 2017, Summa+ ApJ 2018, Glas+ ApJ 2019):

- 9.6, 20 M_{sun} nonrotating progenitors (Heger 2012; Woosley & Heger 2007)
- 18 M_{sun} nonrotating progenitor (Heger 2015)
- 15 M_{sun} rotating progenitor (Heger, Woosley & Spuit 2005, modified rotation)
- 9.0 M_{sun} nonrotating progenitor (Woosley & Heger 2015)
- ~19.0 M_{sun} nonrotating progenitor (Sukhbold, Woosley, Heger 2018)

Monash/QUB (Müller+ MNRAS 2018, Müller+MNRAS 2019):

- z9.6, s11.8, z12, s12.5 M_{sun} nonrotating progenitors (Heger 2012),
- he2,8, he3.0, he3.5 M_{sun} He binary stars, ultrastripped SN progenitors (Tauris 2017)

Modeling inputs and results differ in various aspects.
3D code comparison is missing and desirable

Status of Neutrino-driven Mechanism in 3D Supernova Models

- **3D modeling has reached mature stage.**
- **3D differs from 2D in many aspects, explosions more difficult than in 2D.**

- **Neutrino-driven 3D explosions for progenitors between 9 and 40 M_{sun}**
  (with rotation, 3D progenitor perturbations, or slightly modified neutrino opacities)
- **Explosion energy can take many seconds to saturate! 10^{51} erg possible?**

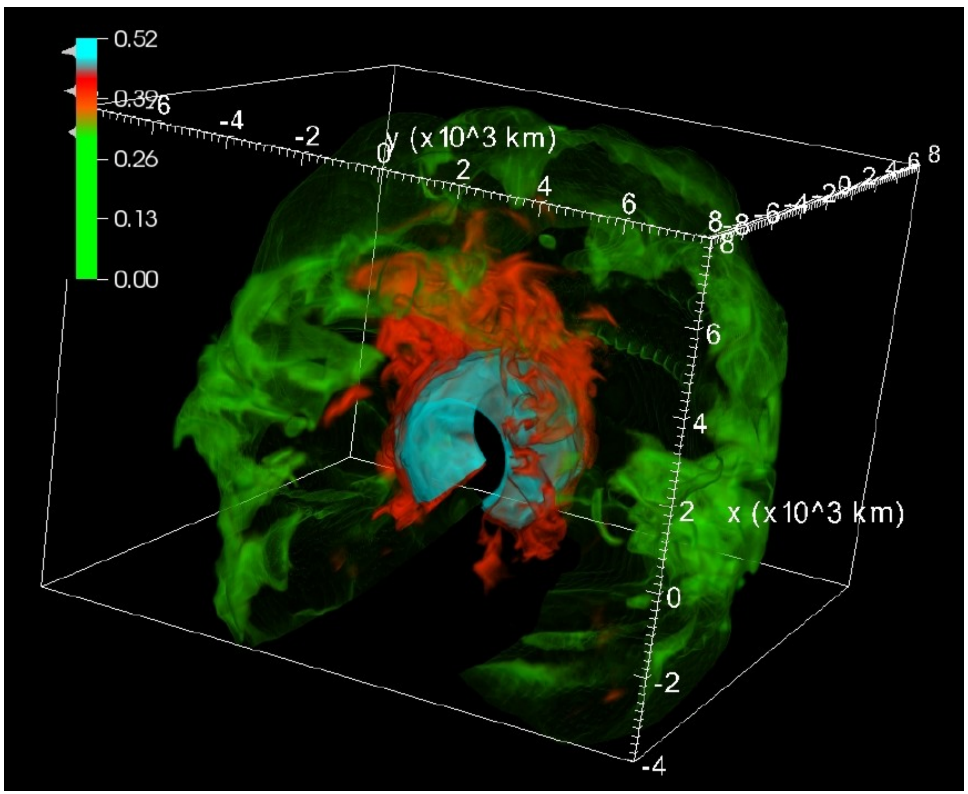
- **Progenitors are 1D**, but composition-shell structure and initial progenitor-core asymmetries can affect onset of explosion.
- 3D simulations may **still need higher resolution** for convergence.
- **Full multi-D neutrino transport** versus **"ray-by-ray" approximation.**
- **Uncertain/missing physics?**
  Dense-matter nuclear EOS and neutrino physics?
  Neutrino flavor oscillations?

Pre-collapse 3D Asymmetries in Progenitors

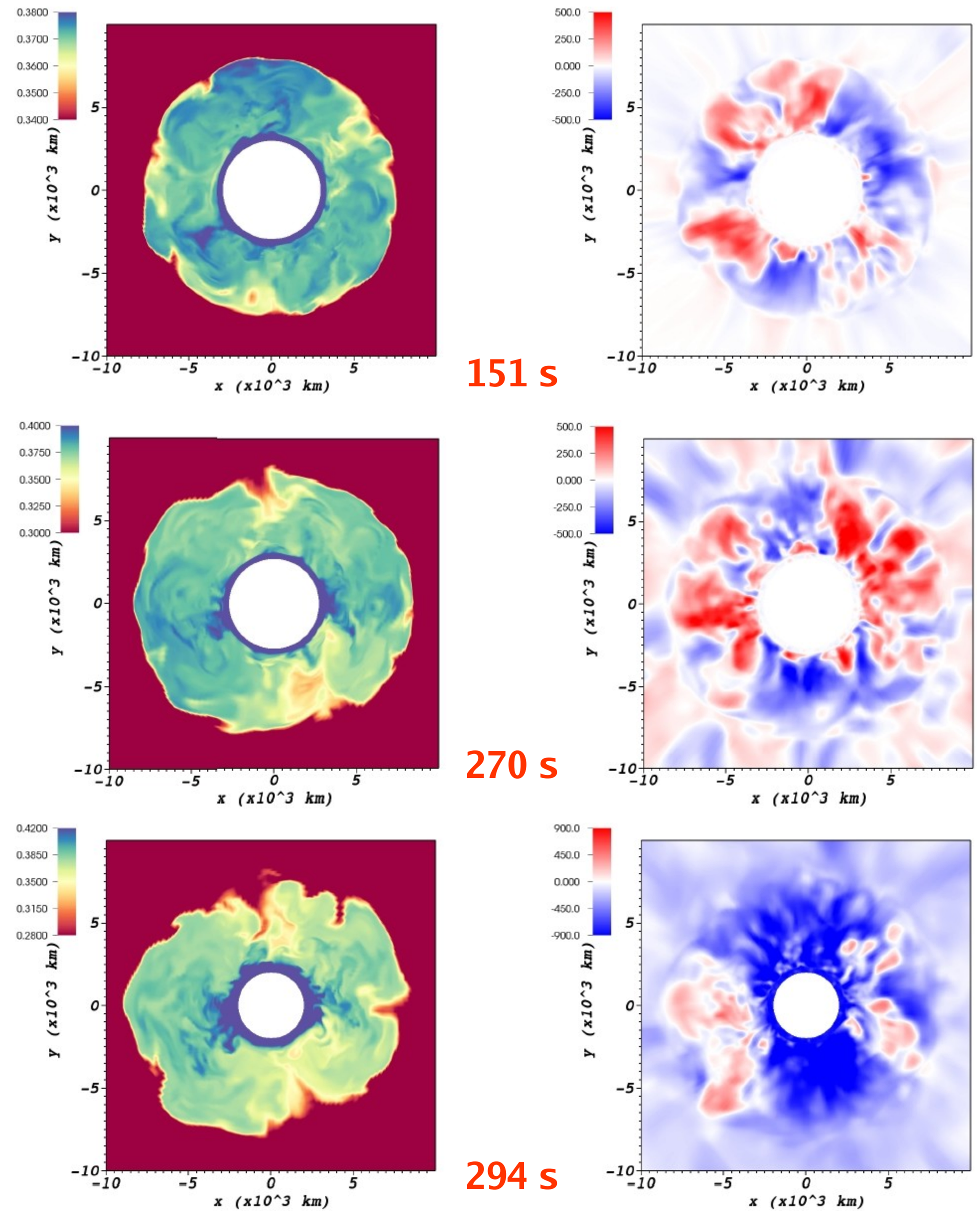
3D Core-Collapse SN Progenitor Model

18 M_{sun} (solar-metallicity) progenitor (Heger 2015)

3D simulation of last 5 minutes of O-shell burning. During accelerating core contraction a quadrupolar (l=2) mode develops with convective Mach number of about 0.1.



B. Müller, Viallet, Heger, & THJ, ApJ 833, 124 (2016)

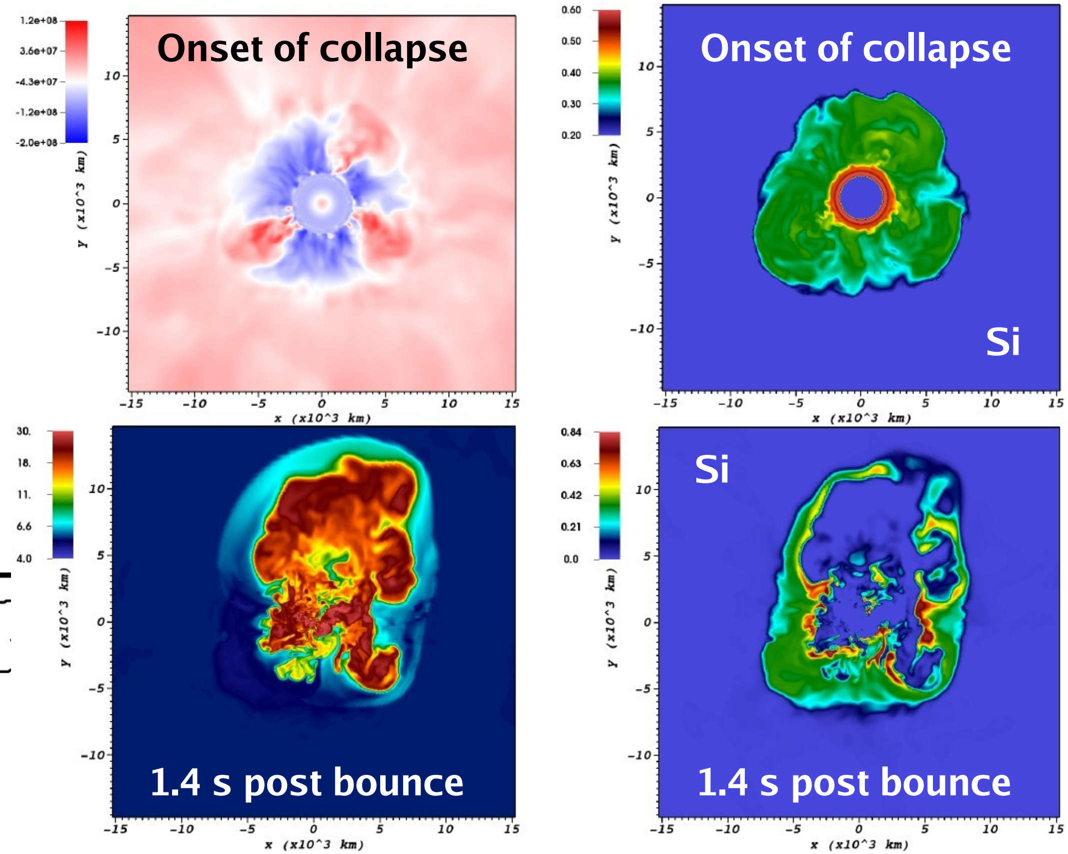


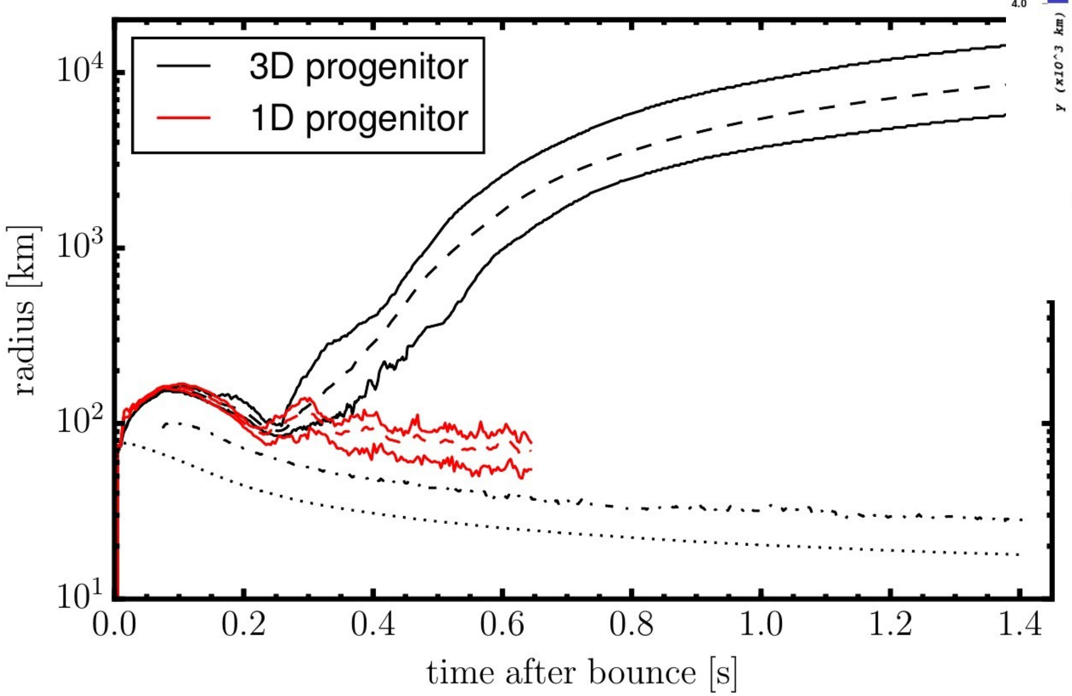
3D Core-Collapse SN Explosion Model

18 M_{sun} (solar-metallicity) progenitor (Heger 2015)

3D simulation of last 5 minutes of O-shell burning. During accelerating core contraction a quadrupolar (l=2) mode develops with convective Mach number of about 0.1.

This fosters strong postshock convection and could thus reduces the criticial neutrino luminosity for explosion.





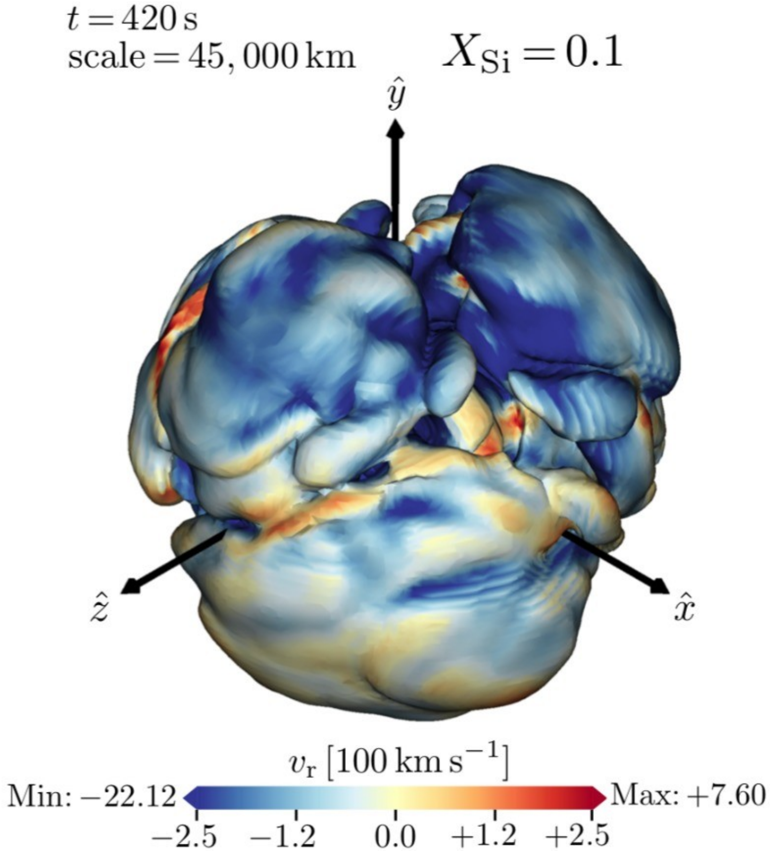
$\delta\rho/\rho \sim \mathrm{Ma}_{conv}$

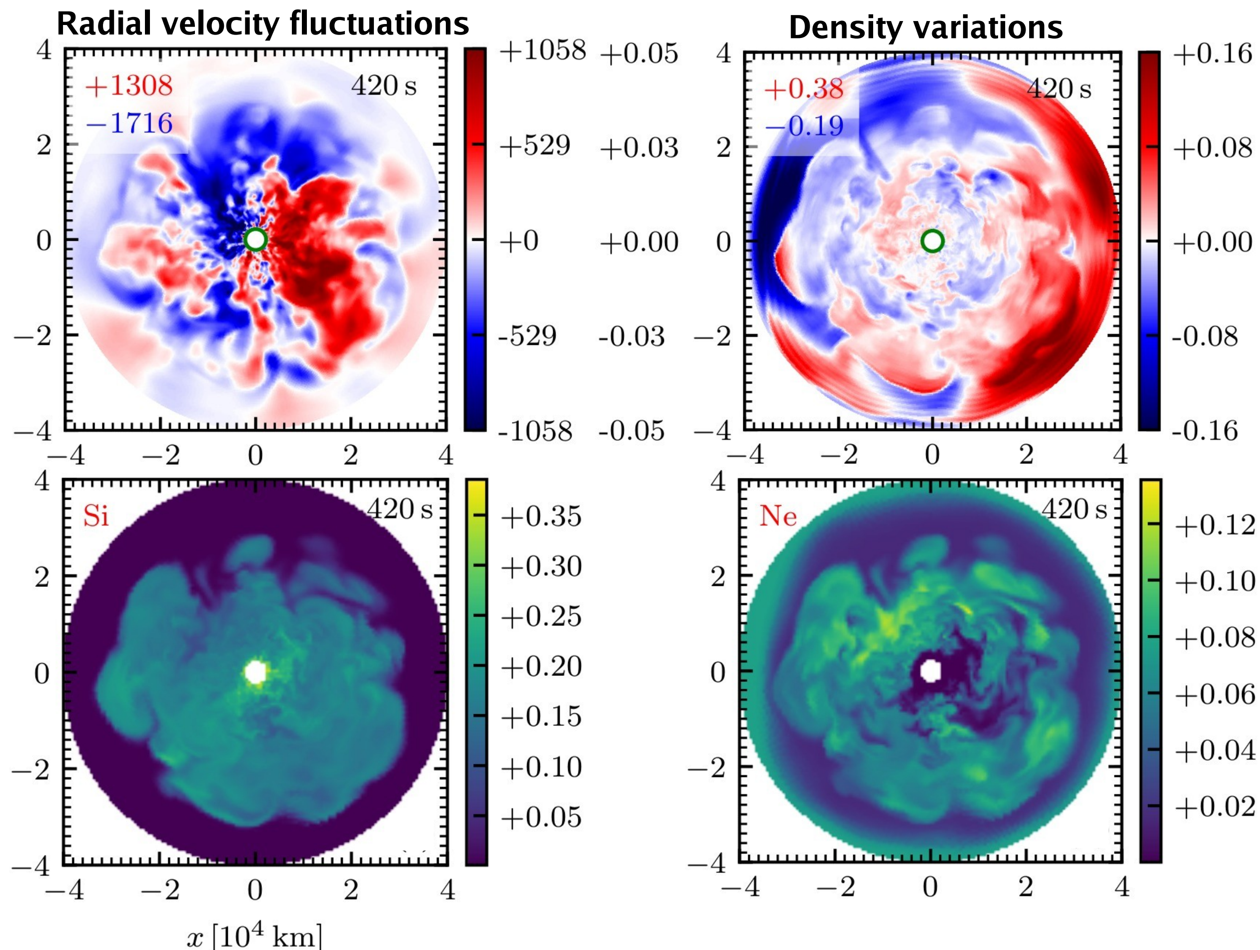
$$(L_\nu E_\nu^2)_{\mathrm{crit,pert}} \approx (L_\nu E_\nu^2)_{\mathrm{crit,3D}} \left(1 - 0.47 \frac{\mathrm{Ma}_{\mathrm{conv}}}{\ell \eta_{\mathrm{acc}} \eta_{\mathrm{heat}}}\right)$$

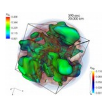
B. Müller, PASA 33, 48 (2016);
Müller, Melson, Heger & THJ, MNRAS 472, 491 (2017)

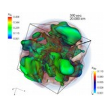
Neon-oxygen-shell Merger in a 3D Pre-collapse Star of ~19 M_{sun}

Flash of Ne+O burning creates large-scale asymmetries in density, velocity, Si/Ne composition



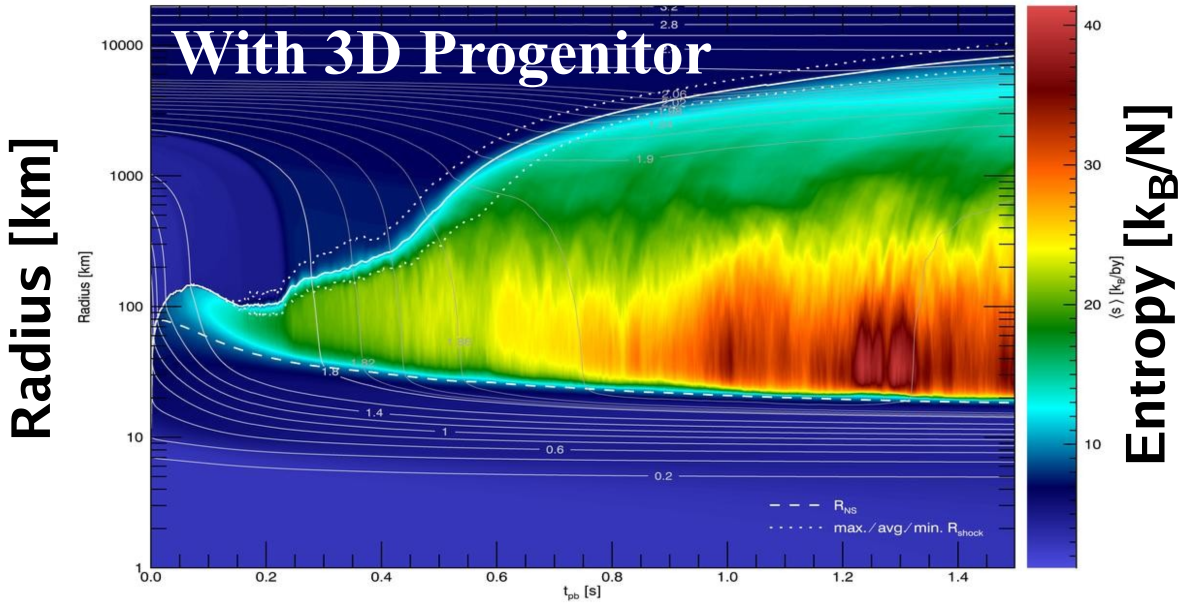


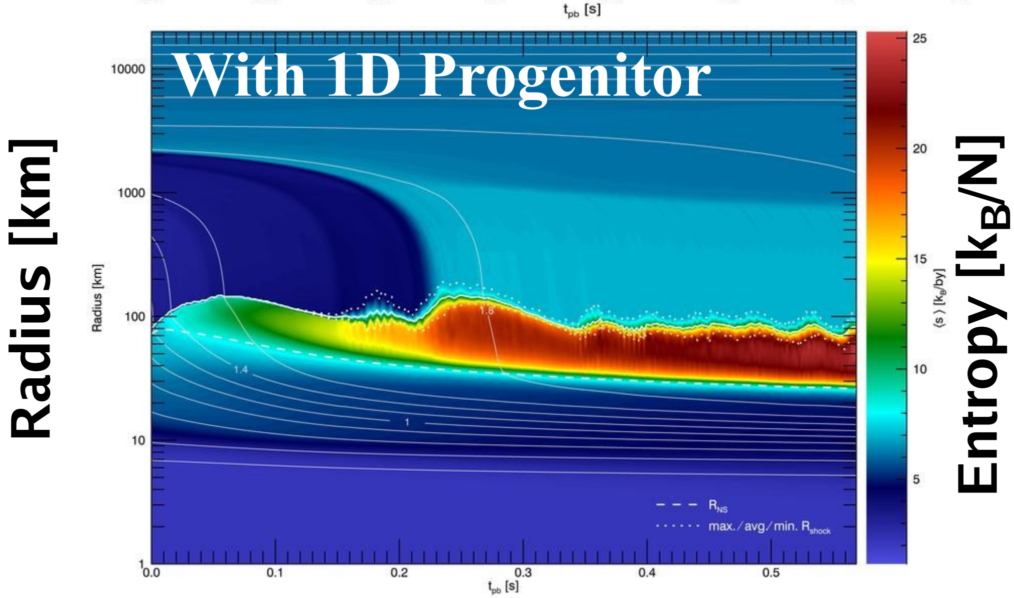




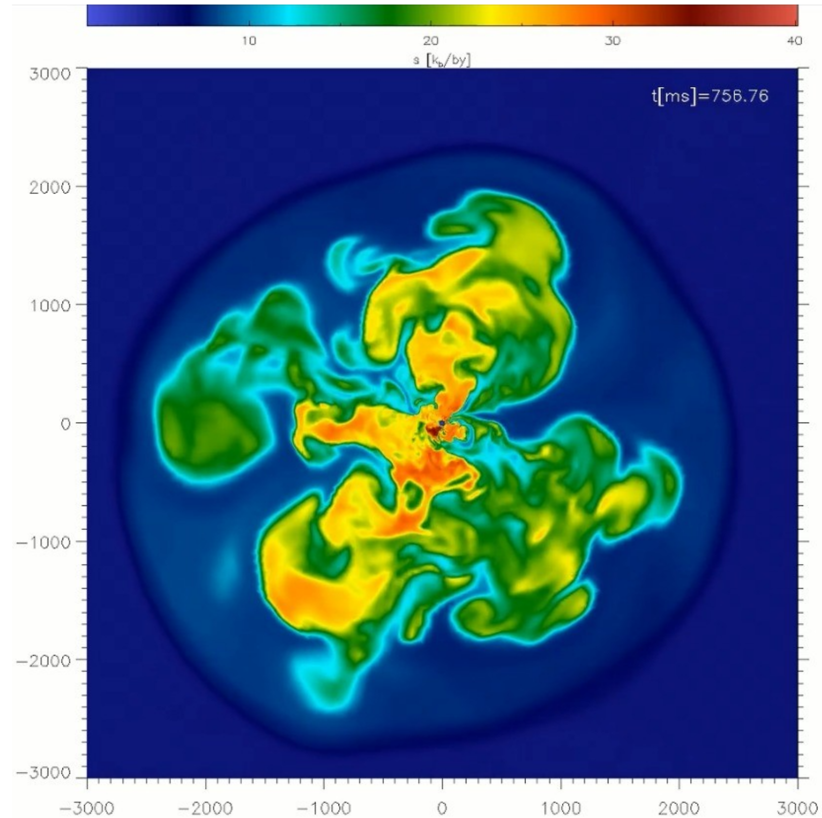
Yadav, Müller et al., arXiv:1905.04378

3D Explosion of ~19 M_{sun} Star after Neon-oxygen-shell Merger





Post-bounce Time [sec]

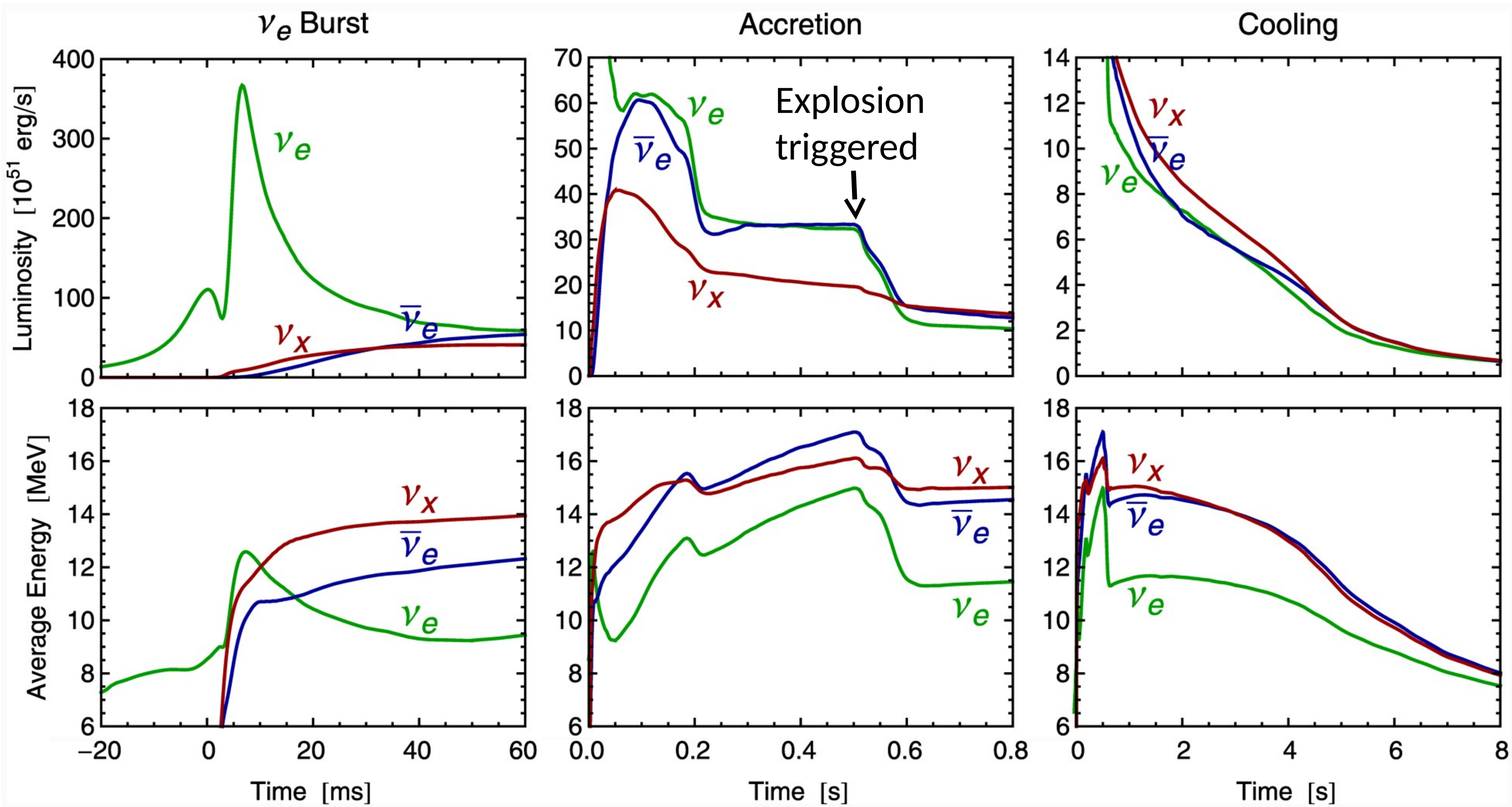


Pre-collapse perturbations in convectively burning O-shell aid explosion because it stirs strong postshock convection.

R. Bollig et al., in preparation

Neutrino Signals

Three Phases of Neutrino Emission



- Shock breakout
- Deleptonization of outer core layers

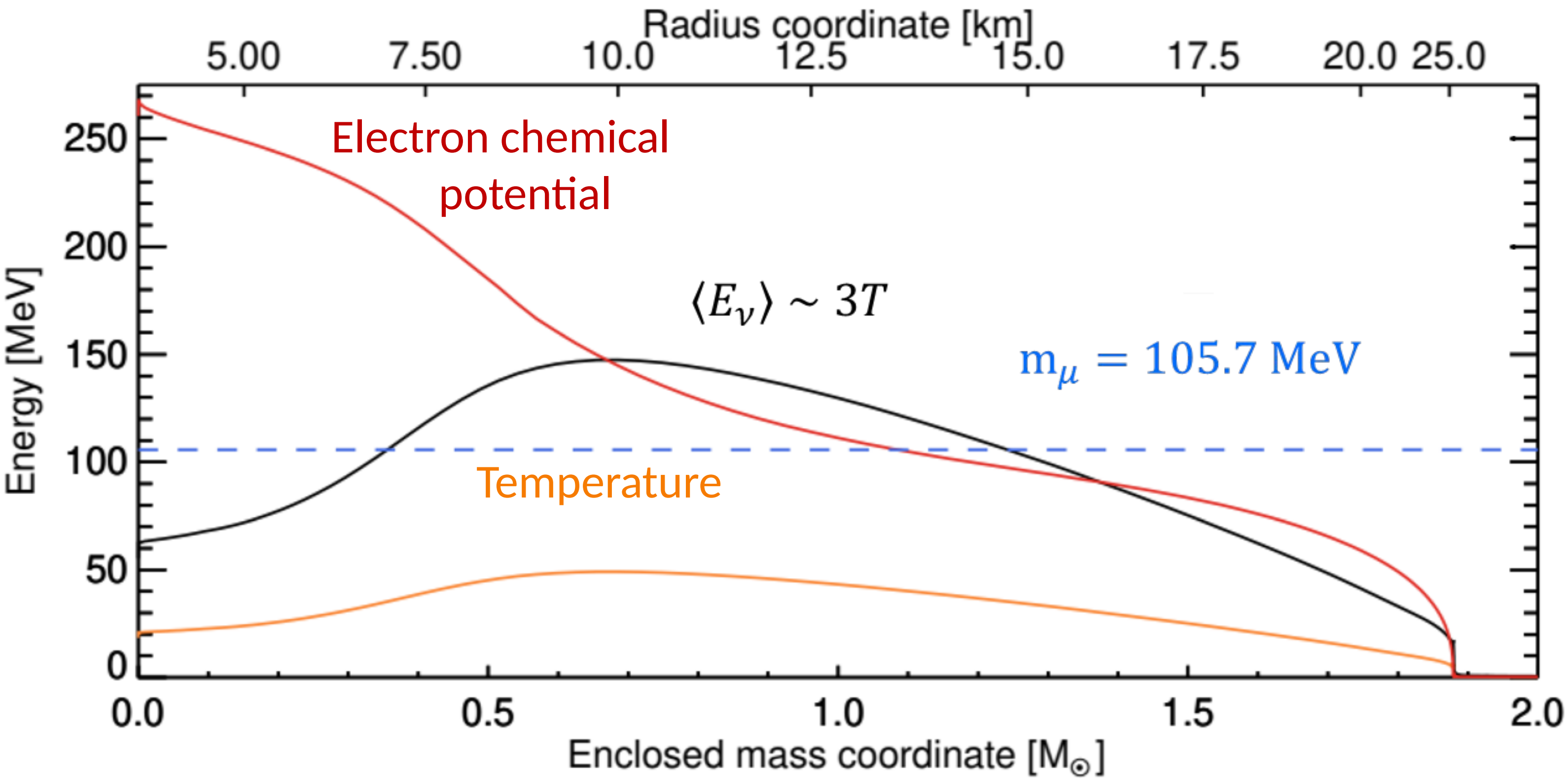
- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling of new-born neutron star on neutrino diffusion time scale

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

Muonisation of Supernova Core

- Muon production energetically favored $(m_\mu = 105.7\ \mathrm{MeV})$
- Local e-μ conversion prevented by large matter effect for ν oscillations (but BSM processes?)
- Emission of excess $\overline{\nu}_\mu$ flux builds up transient muon number density
- Emission of excess ν_e flux runs down electron lepton number (ELN)
- Requires six-species neutrino transport and muonic reactions (Robert Bollig's PhD)



Proto neutron star (PNS) profile 350 ms postbounce

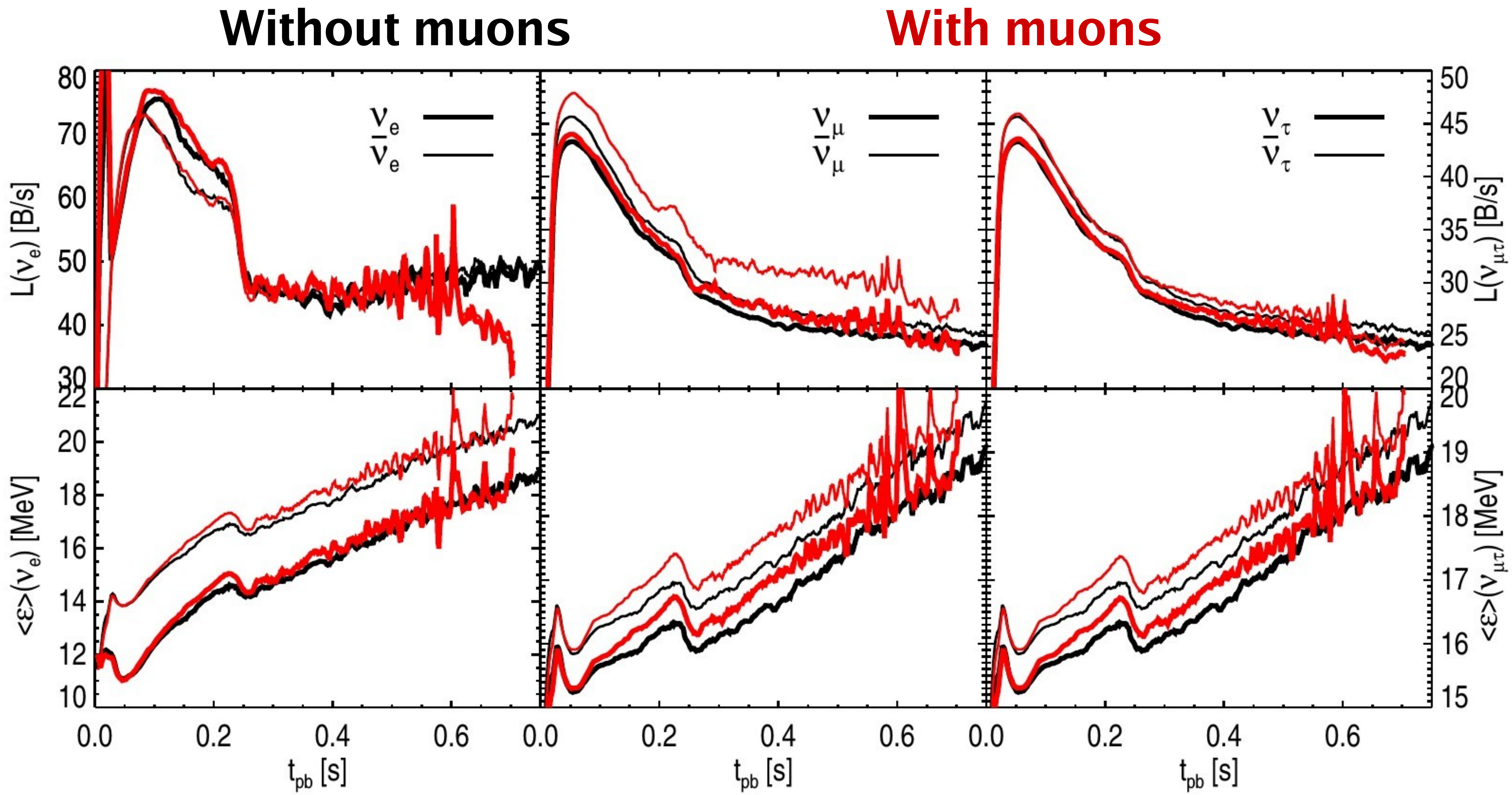
Muons in Hot Neutron-Star Medium

Additional reactions of neutrinos with electrons produce muons and couple neutrinos of different flavors:

TABLE I. Neutrino reactions with muons.

$\nu + \mu^- \leftrightharpoons \nu' + \mu^{-\prime}$	$\nu + \mu^+ \leftrightharpoons \nu' + \mu^{+\prime}$
$\nu_\mu + e^- \leftrightharpoons \nu_e + \mu^-$	$\overline{\nu}_\mu + e^+ \leftrightharpoons \overline{\nu}_e + \mu^+$
$\nu_\mu + \overline{\nu}_e + e^- \leftrightharpoons \mu^-$	$\overline{\nu}_\mu + \nu_e + e^+ \leftrightharpoons \mu^+$
$\overline{\nu}_e + e^- \leftrightharpoons \overline{\nu}_\mu + \mu^-$	$\nu_e + e^+ \leftrightharpoons \nu_\mu + \mu^+$
$\nu_\mu + n \leftrightharpoons p + \mu^-$	$\overline{\nu}_\mu + p \leftrightharpoons n + \mu^+$

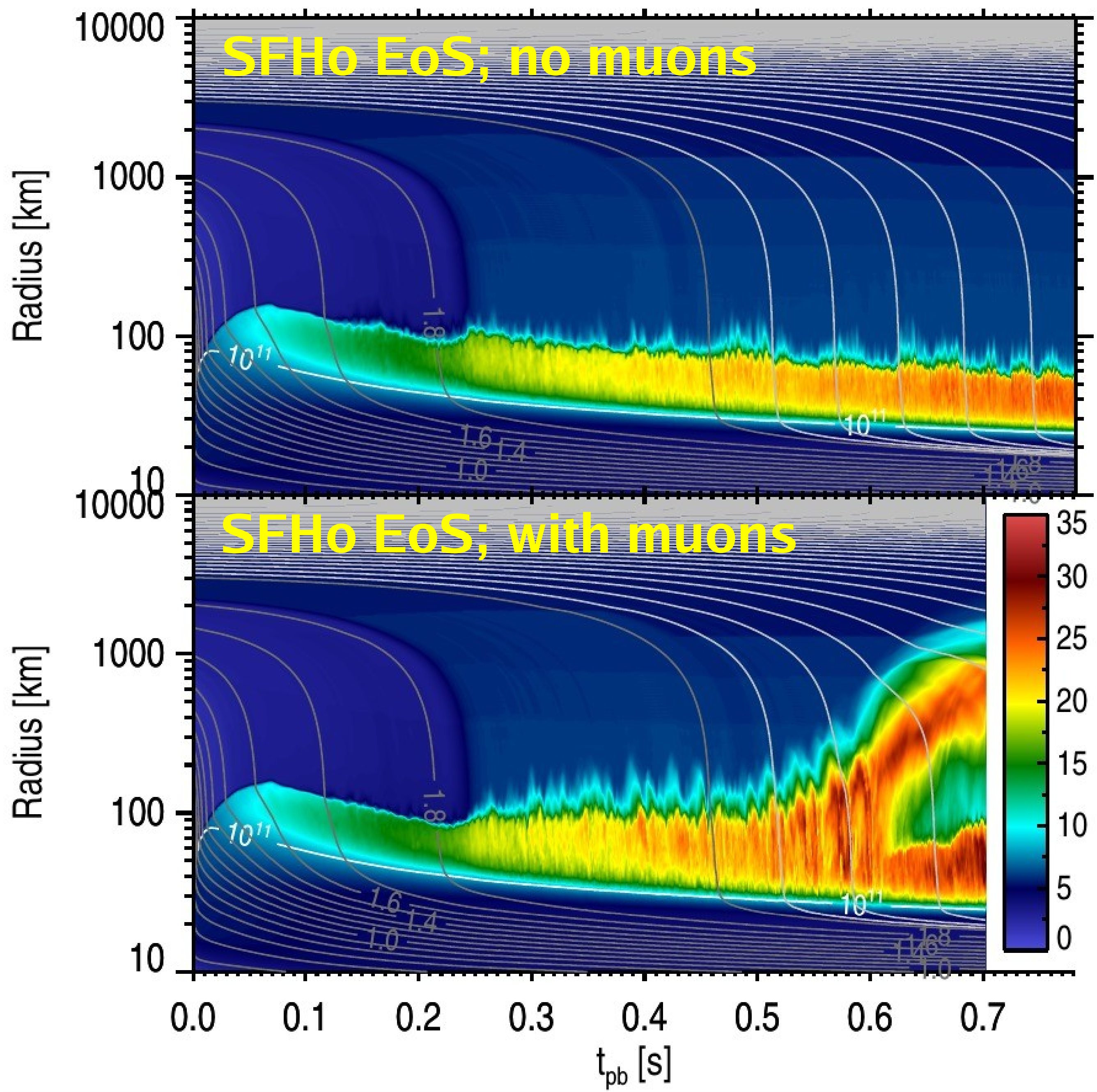
Muons in Hot Neutron-Star Medium



Muon formation softens EoS and NS radius shrinks: Therefore also electron neutrino and antineutrino luminosities and neutrino heating is enhanced, can trigger SN explosion.

Muons in Hot Neutron-Star Medium

2D simulations of 20 Msun non-rotating progenitor

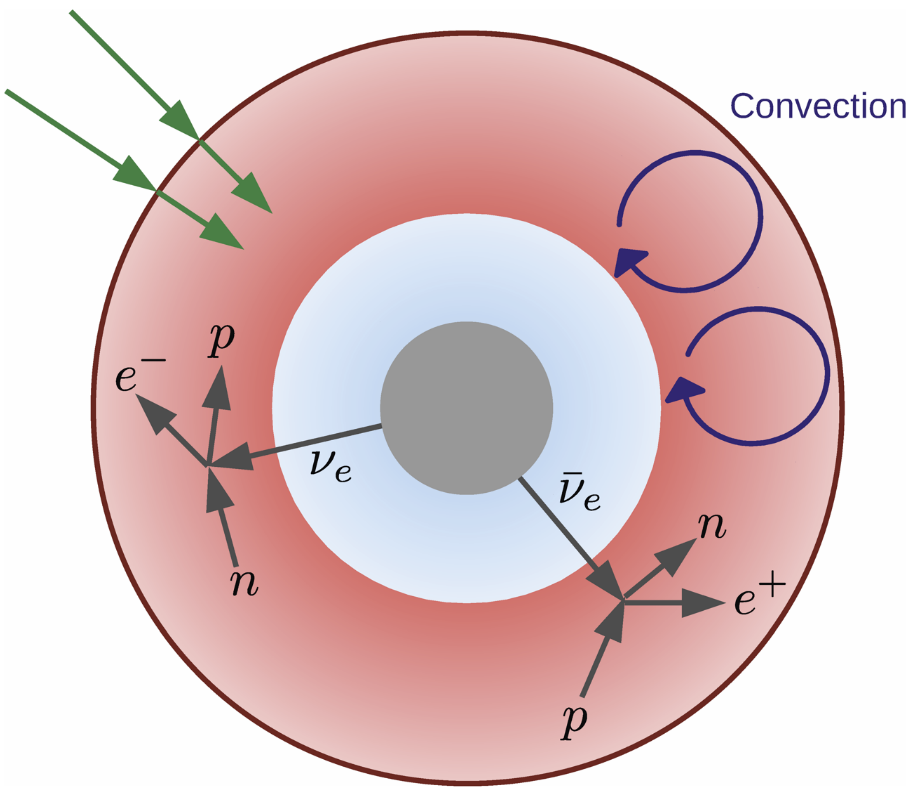


Neutrino-driven supernova explosions are favored by appearance of muons!

Neutrino-emission Features From Multi-D Flows

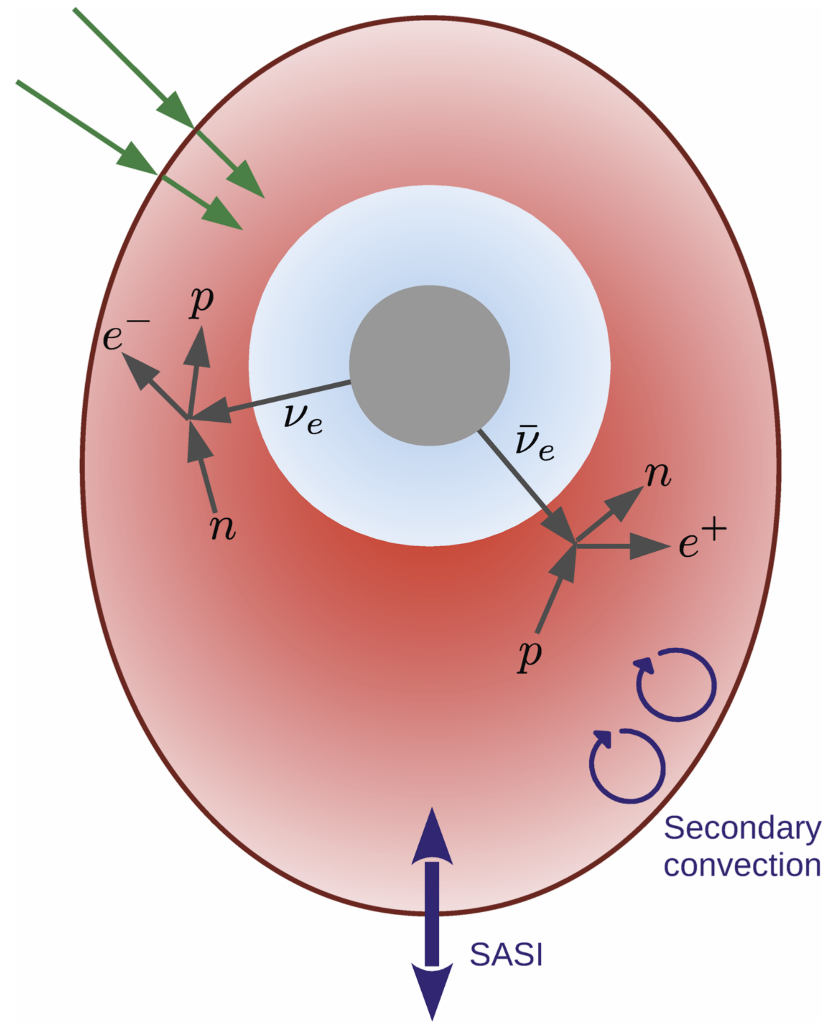
Hydrodynamic Instabilities (3D Simulations)

Convection



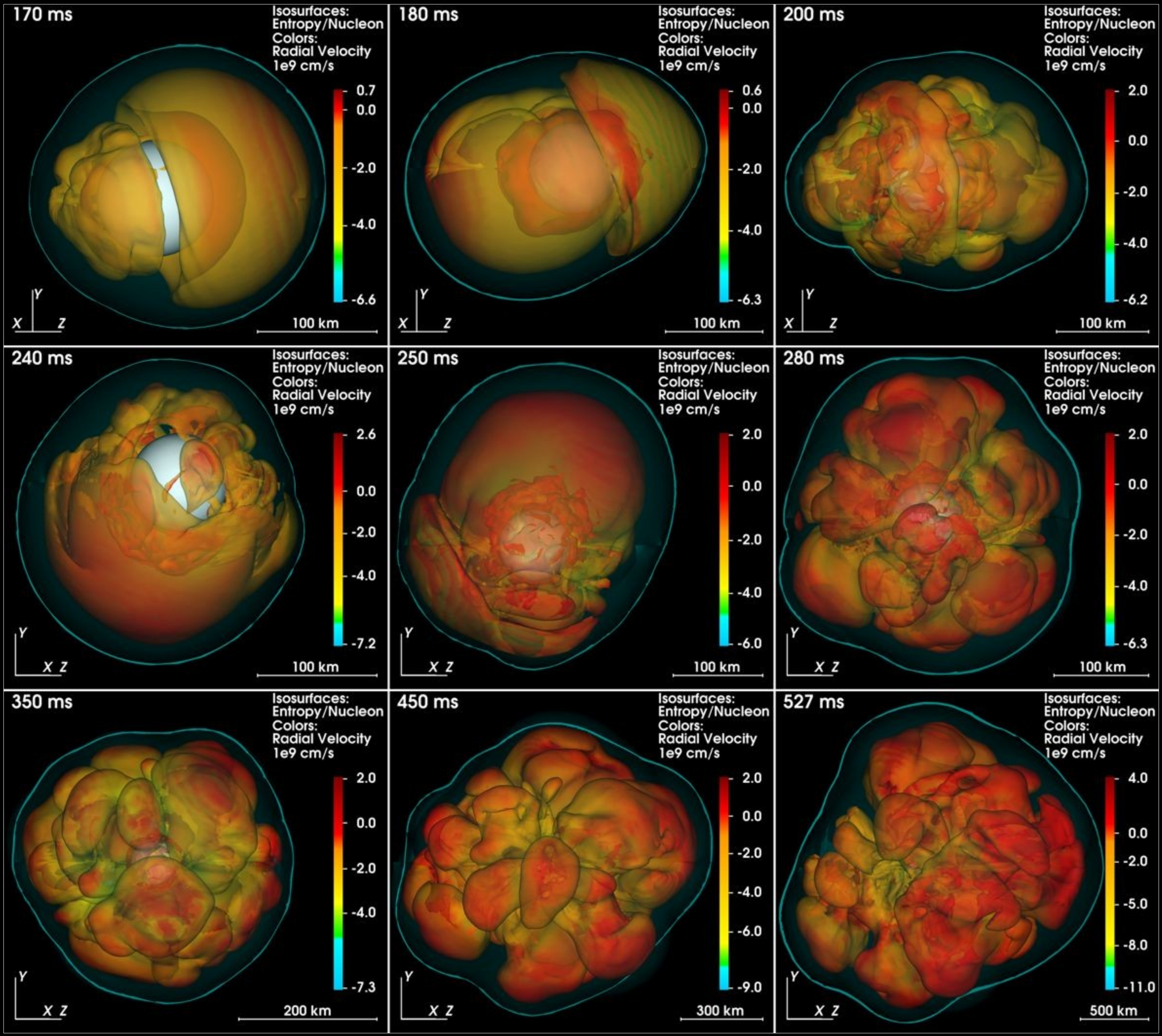
SASI

Standing accretion shock instability



Images: Tobias Melson

Breaking Spherical Symmetry (3D Effects)

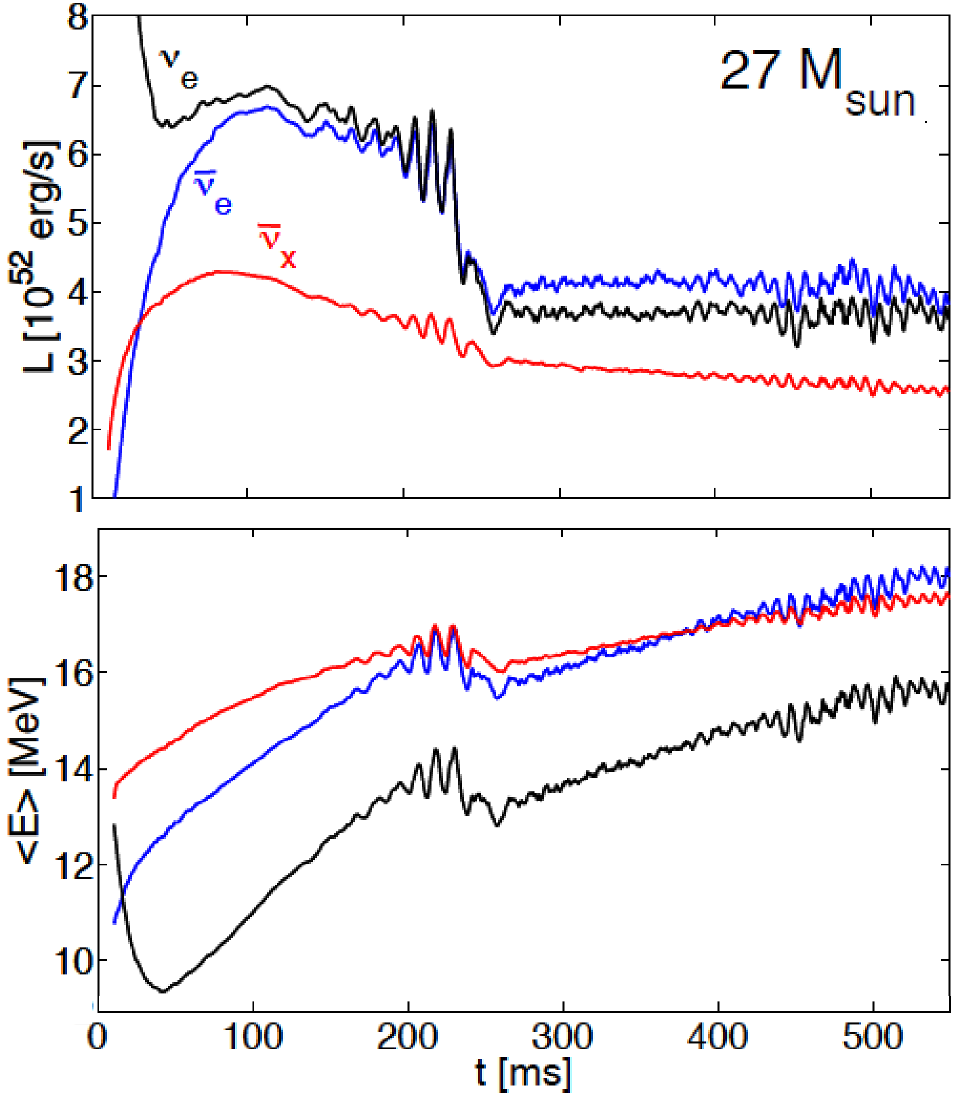


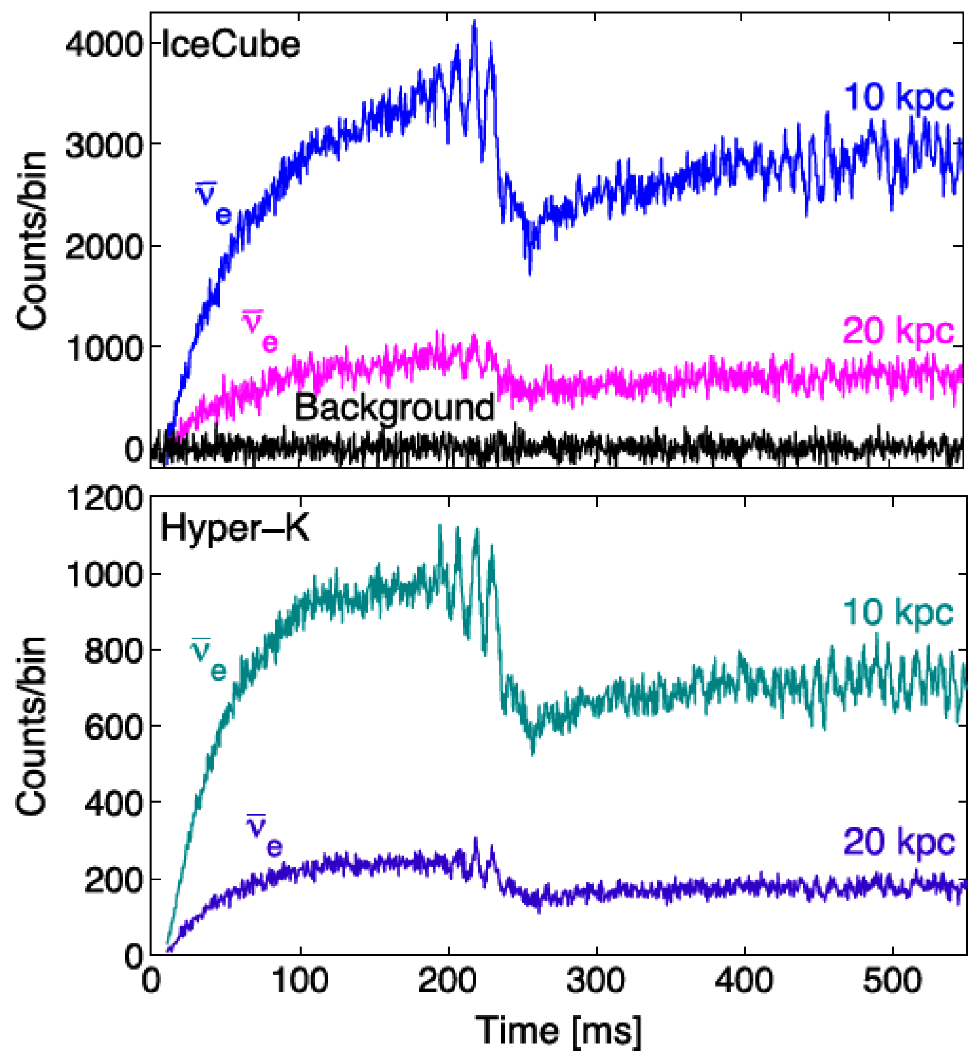
Melson et al, ApJL 808, L42 (2015)

3D Core-Collapse Models: Neutrino Signals

11.2, 20, 27 M_{sun} progenitors (WHW 2002)

SASI produces modulations of neutrino emission (and gravitational-wave signal).





(Tamborra et al., PRL 111, 121104 (2013); arXiv:1307.7936)

3D Core-Collapse Models: Neutrino Signals

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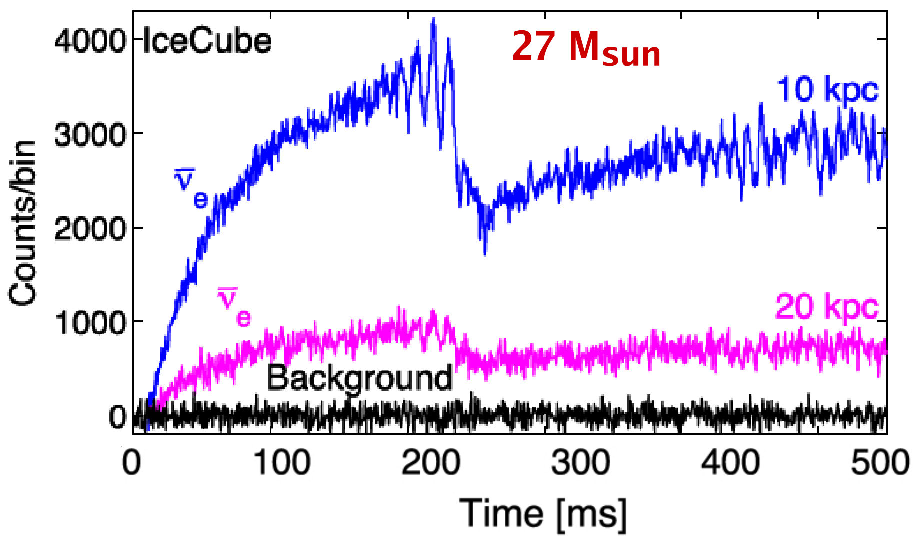
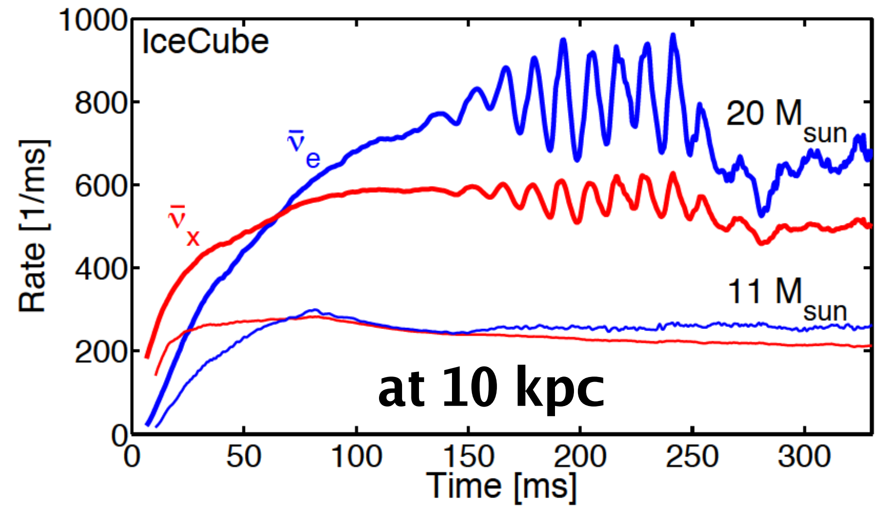
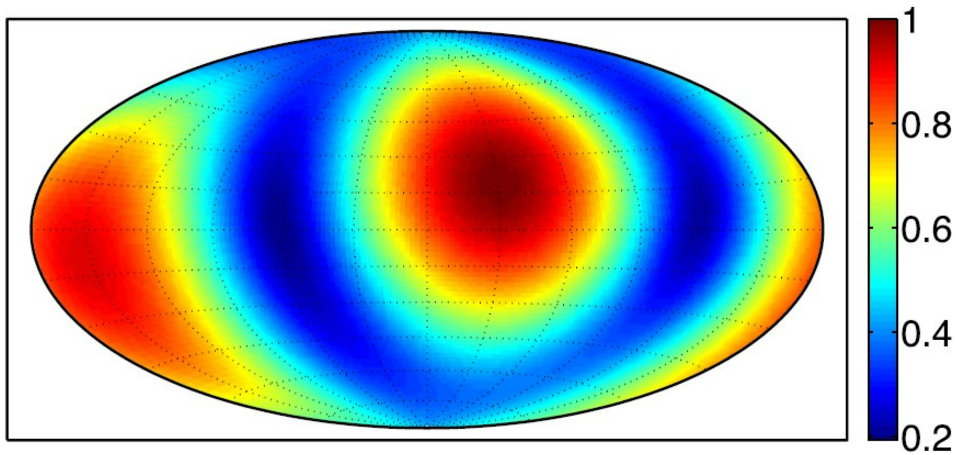
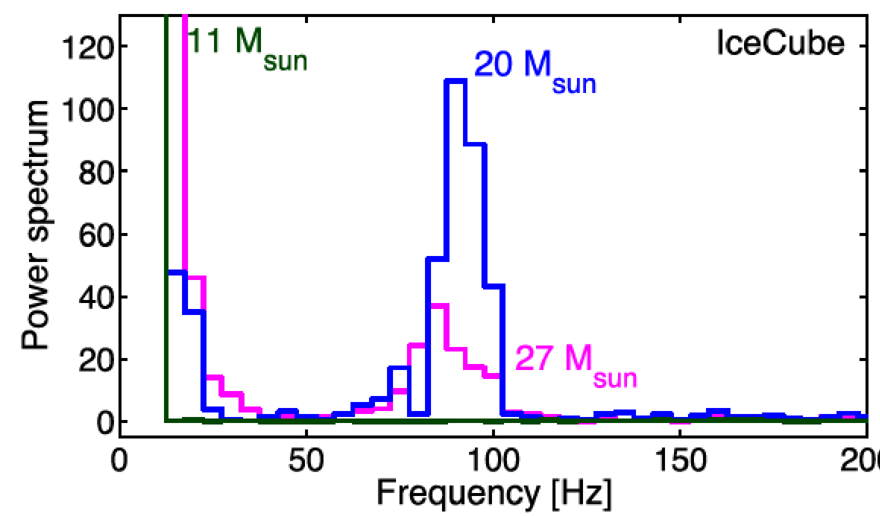




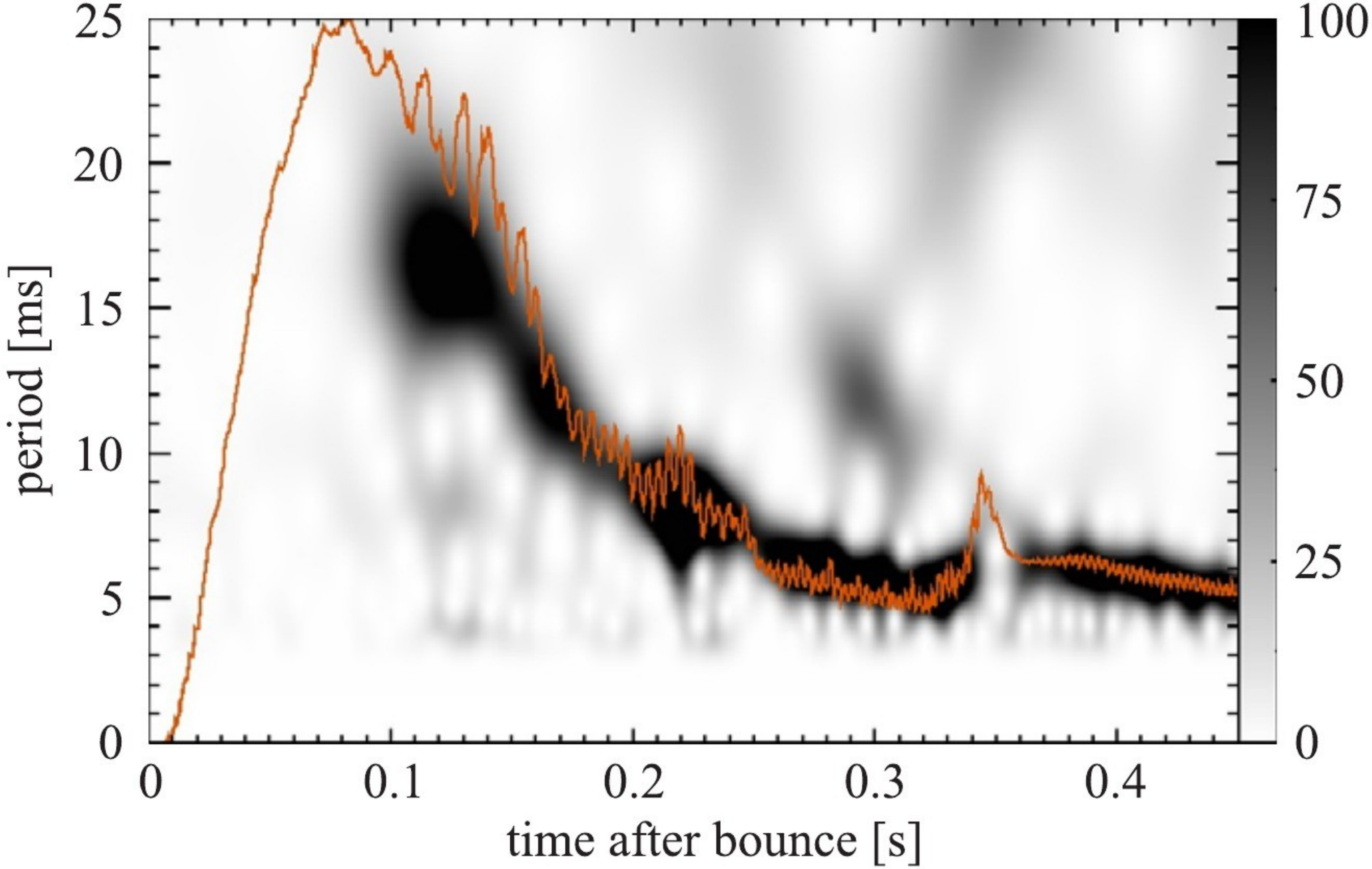




Tamborra et al., PRL 111, 121104 (2013); PRD 90, 045032 (2014)

$$f_{\mathrm{SASI}}^{-1} \sim \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{|v|} + \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{c_{\mathrm{s}} - |v|}$$

SASI Period Measures Shock Radius Evolution



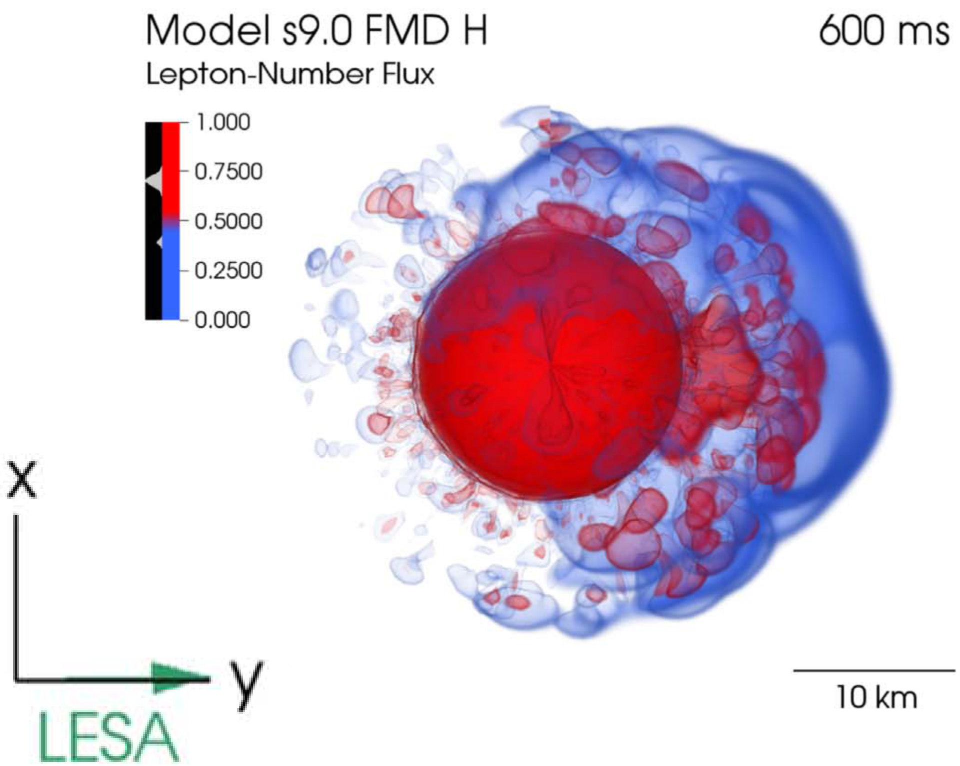
Müller & THJ, ApJ 788 (2014) 82

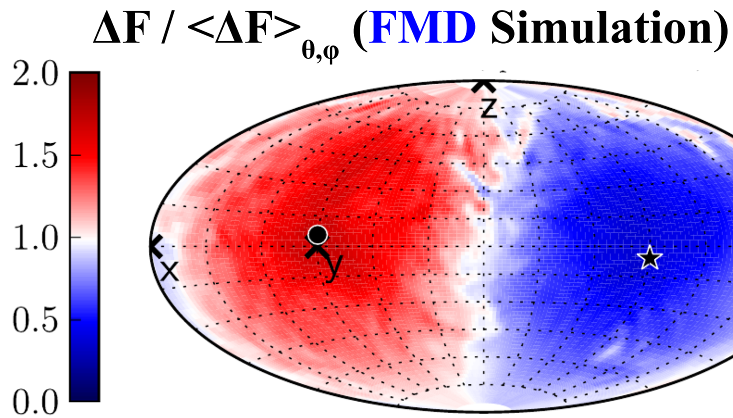
$$T_{\mathrm{SASI}} = 19\,\mathrm{ms}\left(\frac{r_{\mathrm{sh}}}{100\,\mathrm{km}}\right)^{3/2} \ln\left(\frac{r_{\mathrm{sh}}}{r_{\mathrm{PNS}}}\right)$$

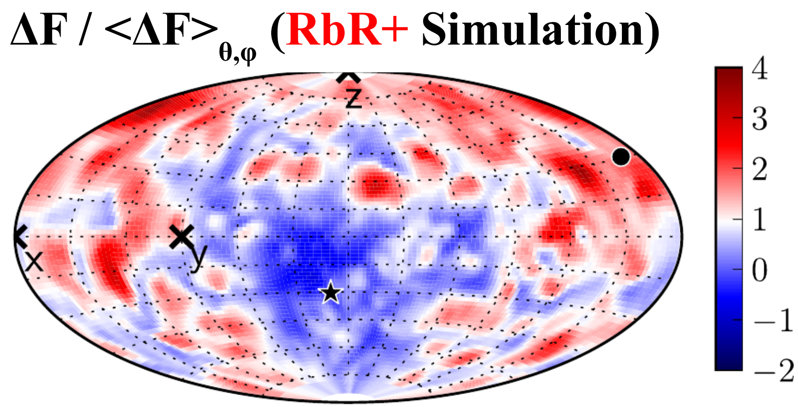
LESA

Lepton-number Emission Self-sustained Asymmetry

LESA in all 3D Models with FMD and RbR+ Neutrino Transport







Glas et al. 2019, ApJ, 881, 36

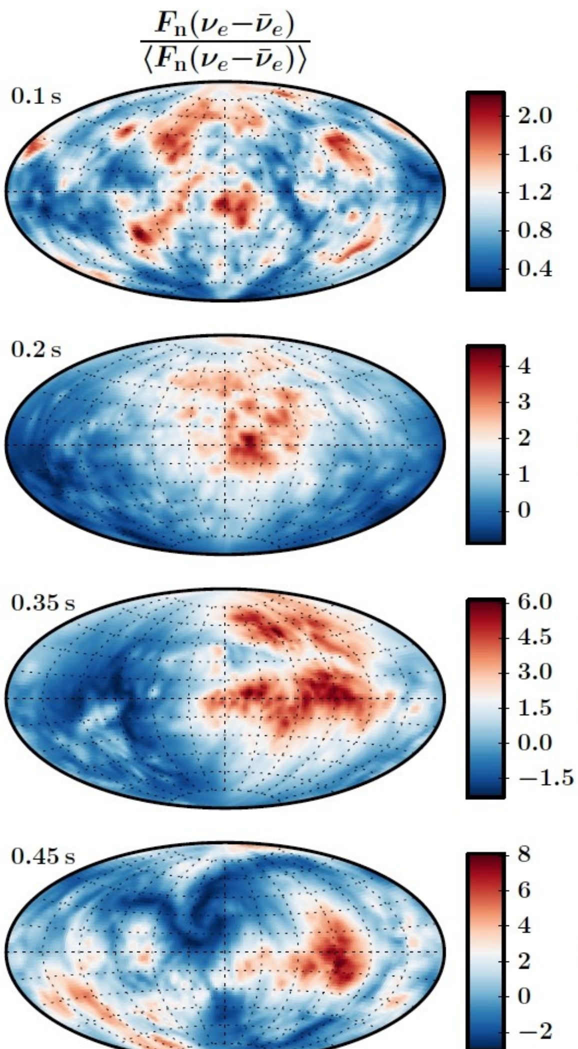
- LESA: Lepton-number Emission Self-sustained Asymmetry
- Large-scale asymmetry with dominant dipole mode of lepton-number flux: F (ν_e) - F$(\bar{\nu}_e)$

LESA: A New Nonradial 3D Instability

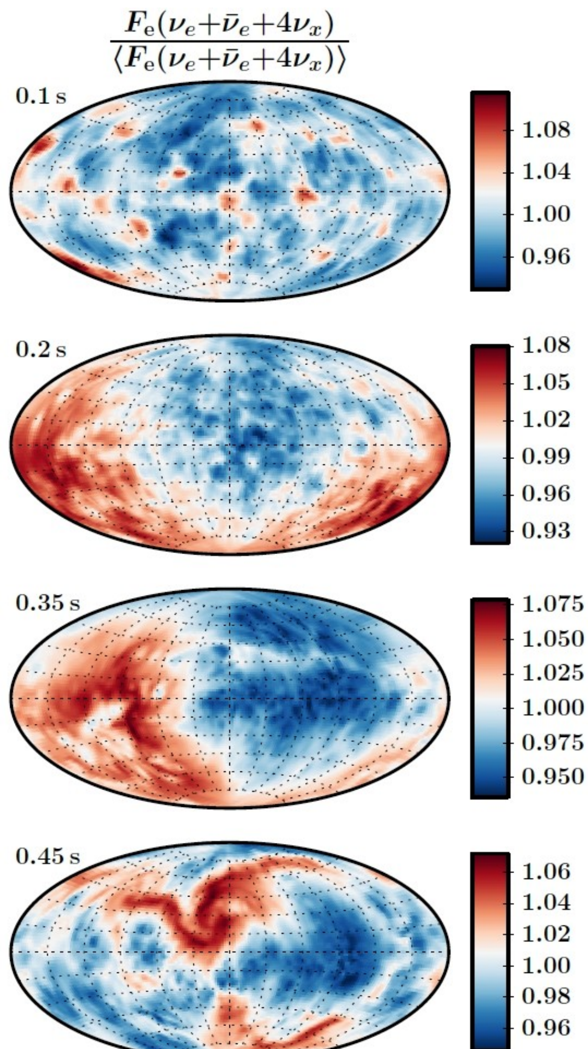
Dipole asymmetry of lepton-number emission (LESA) from hot neutron stars

Lepton number flux:
ν_e minus anti-ν_e

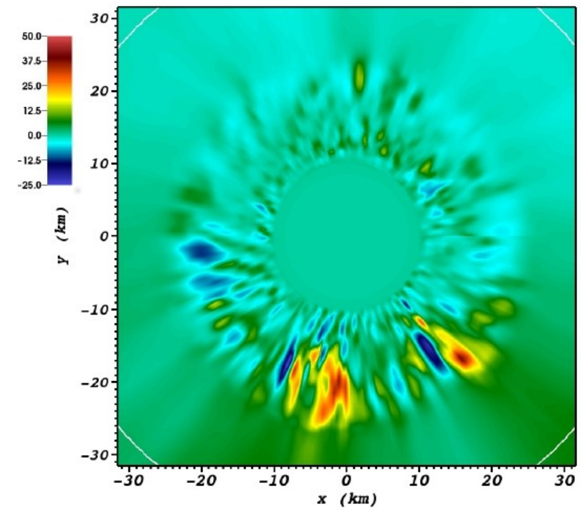
$$(F_{\nu_e} - F_{\bar{\nu}_e})/\langle F_{\nu_e} - F_{\bar{\nu}_e} \rangle$$

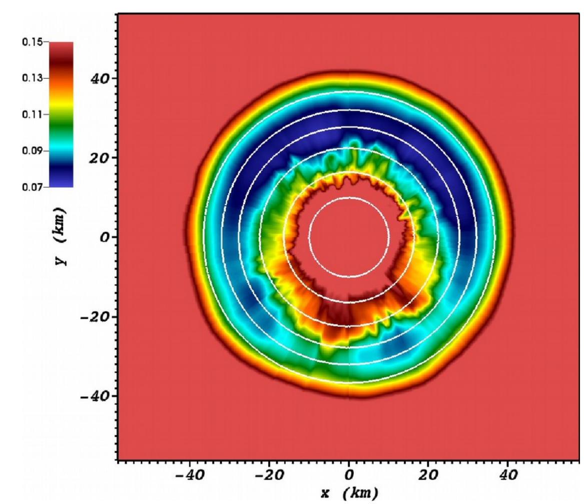


Total energy flux:
ν_e plus anti-ν_e plus heavy-lepton neutrinos



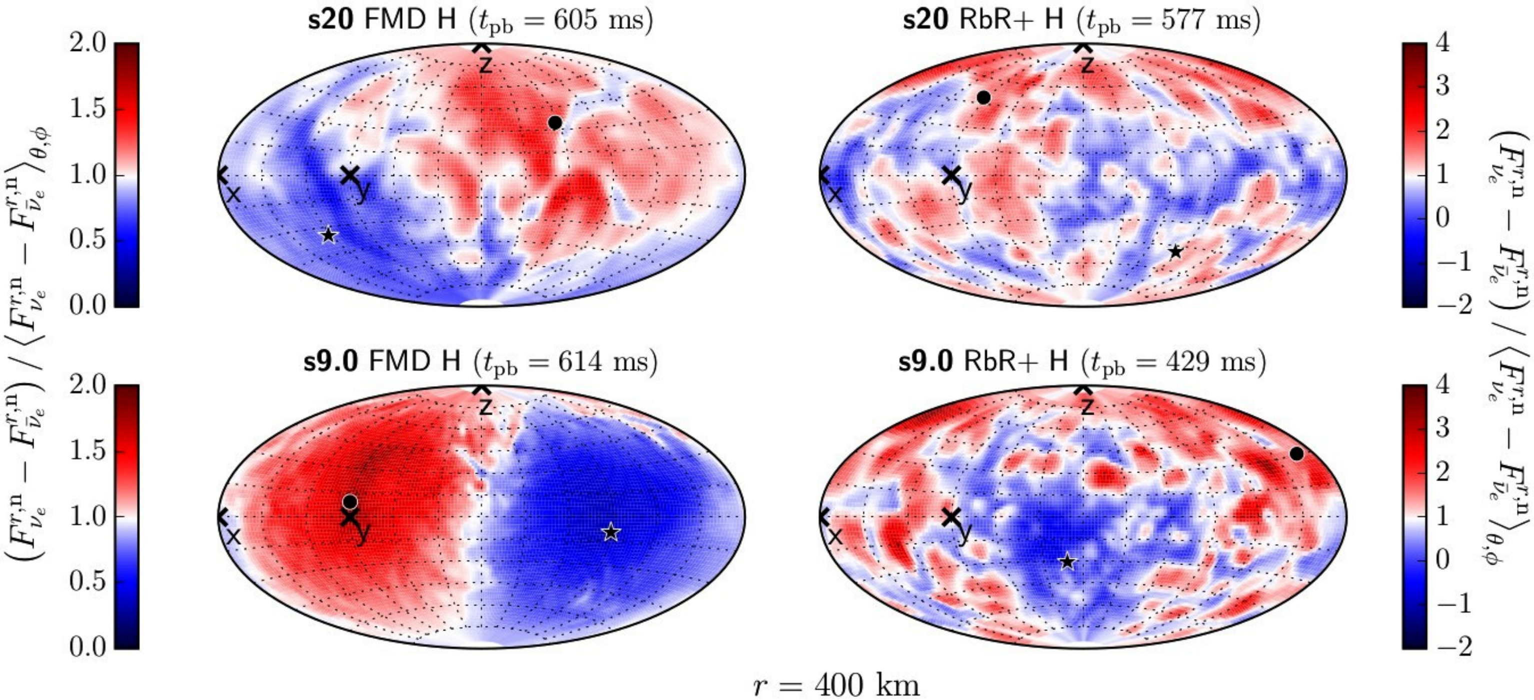
Anisotropic convection inside the proto-neutron star



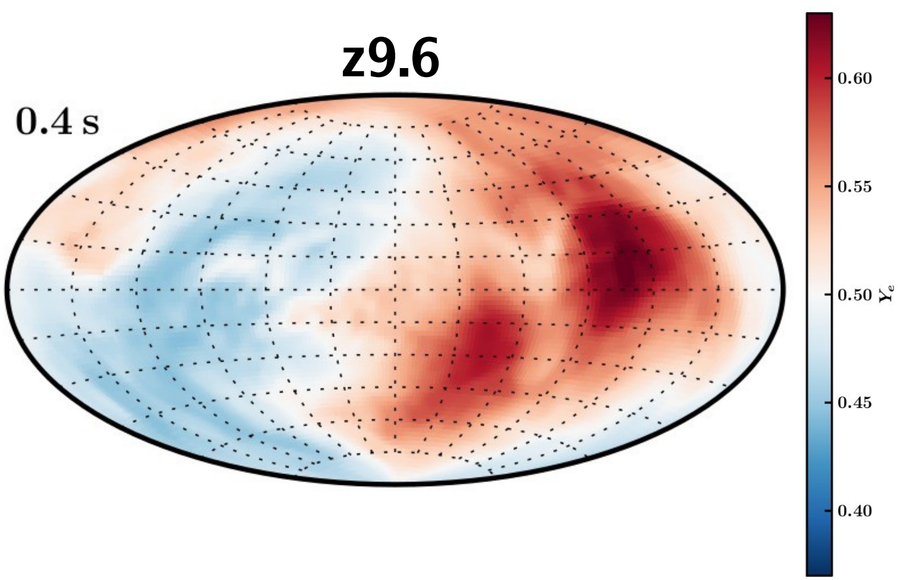


Tamborra, Hanke, THJ, et al., ApJ 792, 96 (2014);
THJ et al., ARNPS 66 (2016)

LESA with RbR+ and M1 Neutrino Transport



Glas, THJ, Just, Melson, & Stockinger, 2019, ApJ, 881, 36; arXiv:1809:10150



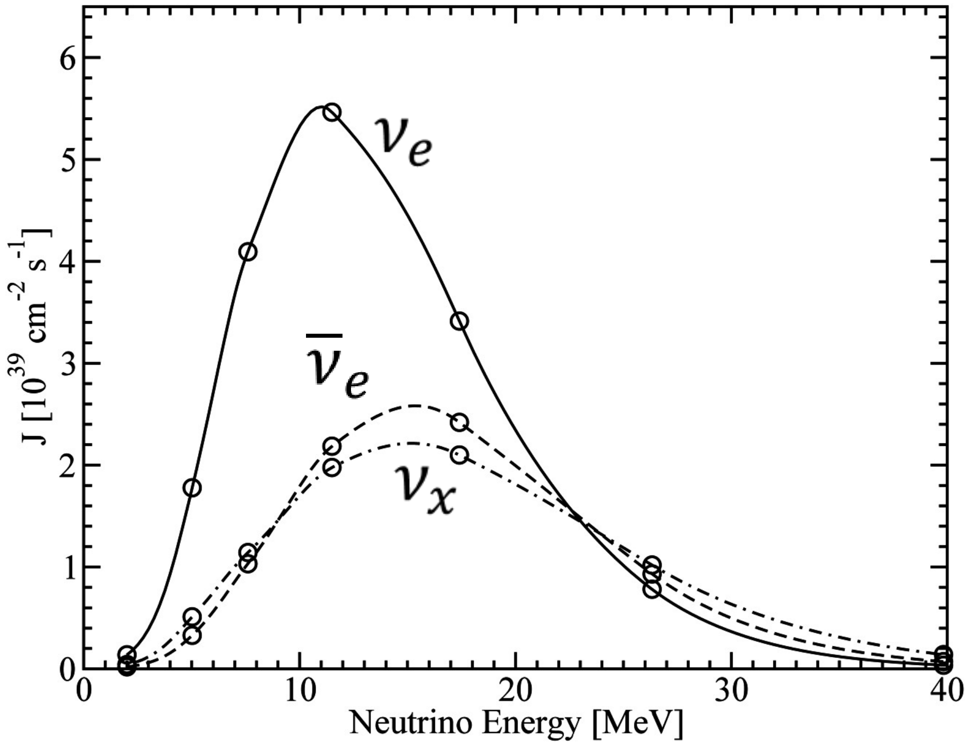
Consequences of LESA:

- Neutron-star kicks (~10–100 km/s)
- Supernova nucleosynthesis in ν-heated ejecta is direction dependent
- Viewing-angle dependent neutrino spectra
- Neutrino-flavor oscillations are direction dependent

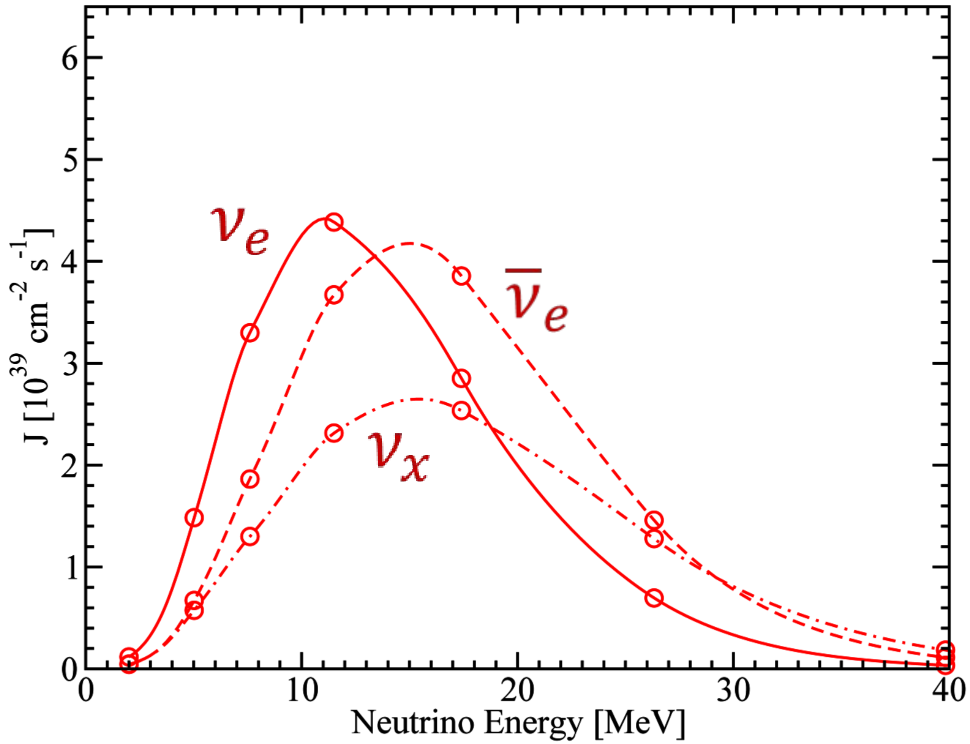
Spectra in the Two Hemispheres

Neutrino flux spectra (11.2 M_{SUN} model at 210 ms) in opposite LESA directions

Direction of
maximum lepton-number flux

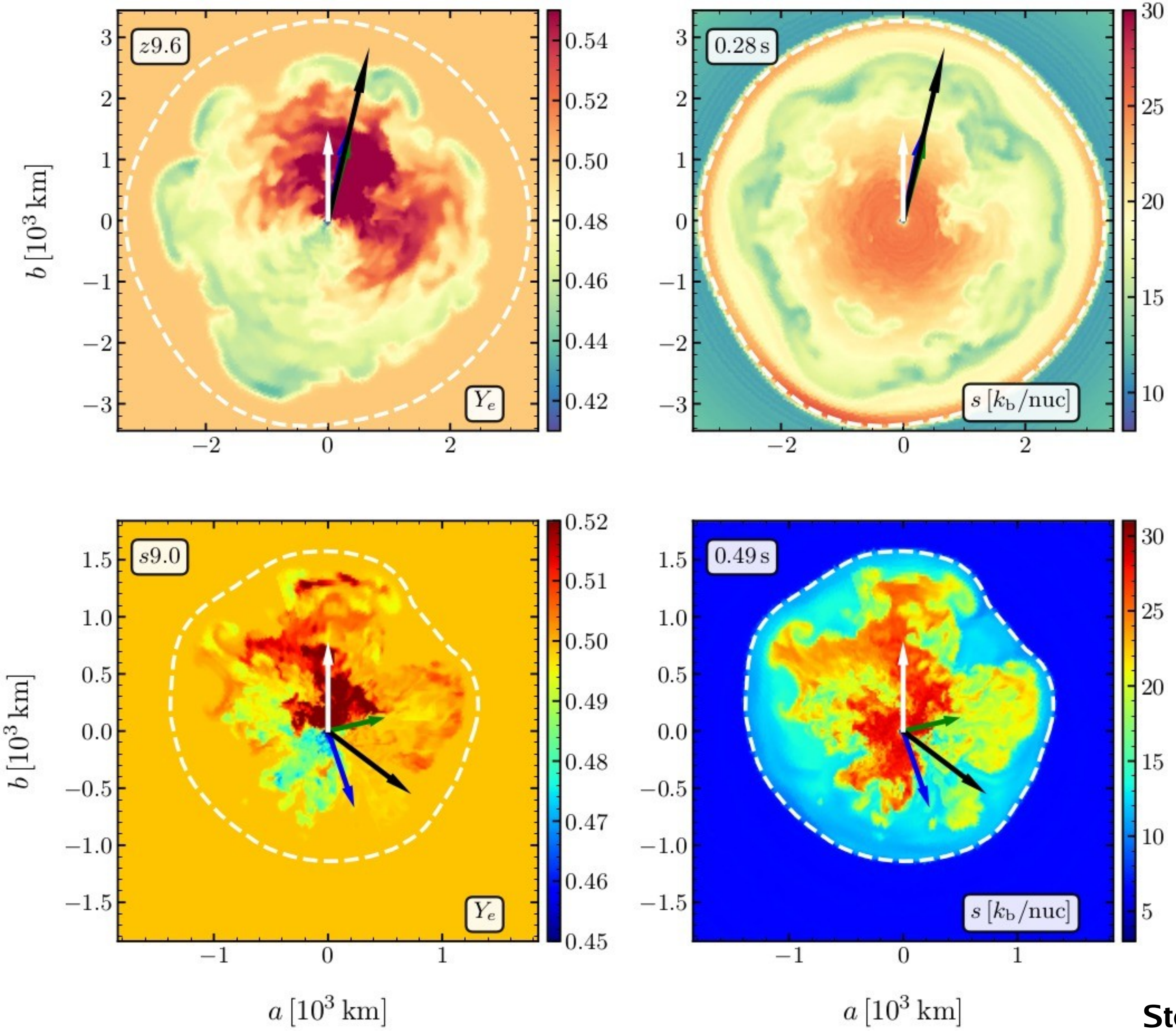


Direction of
minimum lepton-number flux



During accretion and LESA phases, flavor-dependent fluxes can vary strongly with observer direction!

Neutron Star Kicks by LESA Neutrino Emission



9.6 M_{sun} star

v_{NS}(LESA) > 25 km/s

White: LESA
Blue: hydro NS kick
Green: neutrino NS kick
Black: total NS kick

9.0 M_{sun} star

v_{NS}(LESA) > 22 km/s

Stockinger+, in preparation

Neutrino-emission Features From 3D Flows

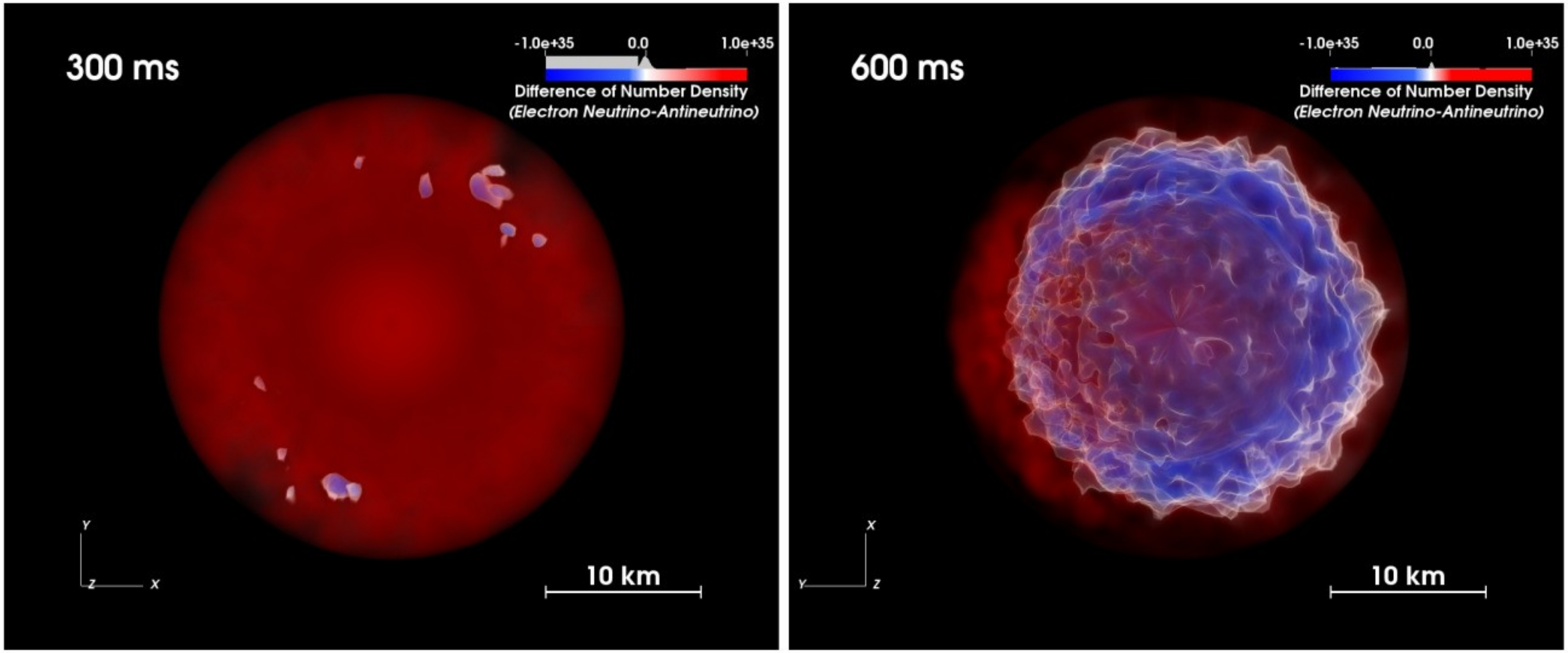
- **SASI:**
  - induces quasi-periodic modulations of neutrino luminosities and mean energies
  - direction highly time-dependent
  - neutrinos and antineutrinos are correlated

- **LESA:**
  - dipolar asymmetry of lepton-number emission
  - direction stable in time or slowly changing
  - electron neutrinos and antineutrinos anti-correlated

Fast Flavor Conversion in Dense Neutrinos?

- Neutrino flavor conversion *not included* in traditional transport simulations (of core-collapse SNe, neutron star mergers)
- Potentially relevant for energy transfer (explosion mechanism), nucleosynthesis in neutrino-driven outflows, and for SN neutrino signal
- Large matter effect suppresses usual flavor conversion in deep layers, MSW conversion at hundreds km studied by post-processing
- However, interacting dense neutrino gas supports collective flavor modes
- Nontrivial angle-distributions of ν_e vs $\overline{\nu}_e$ enable "fast flavor modes" with instabilities on scales of meters
- Amounts to pair annihilation $\nu_e + \overline{\nu}_e \rightarrow \nu_x + \overline{\nu}_x$ on refractive level (order G_F)
- Relevant conditions fulfilled in realistic simulations?
  (Recently a preprint nearly every week on this subject by different groups worldwide)
- Do we have the right criteria?
- If effect is real, how does unstable neutrino field develop and what is the practical impact on core-collapse physics?

Evidence for Fast Flavor Instability in 3D Supernova Models



Glas et al., arXiv:1912.00274

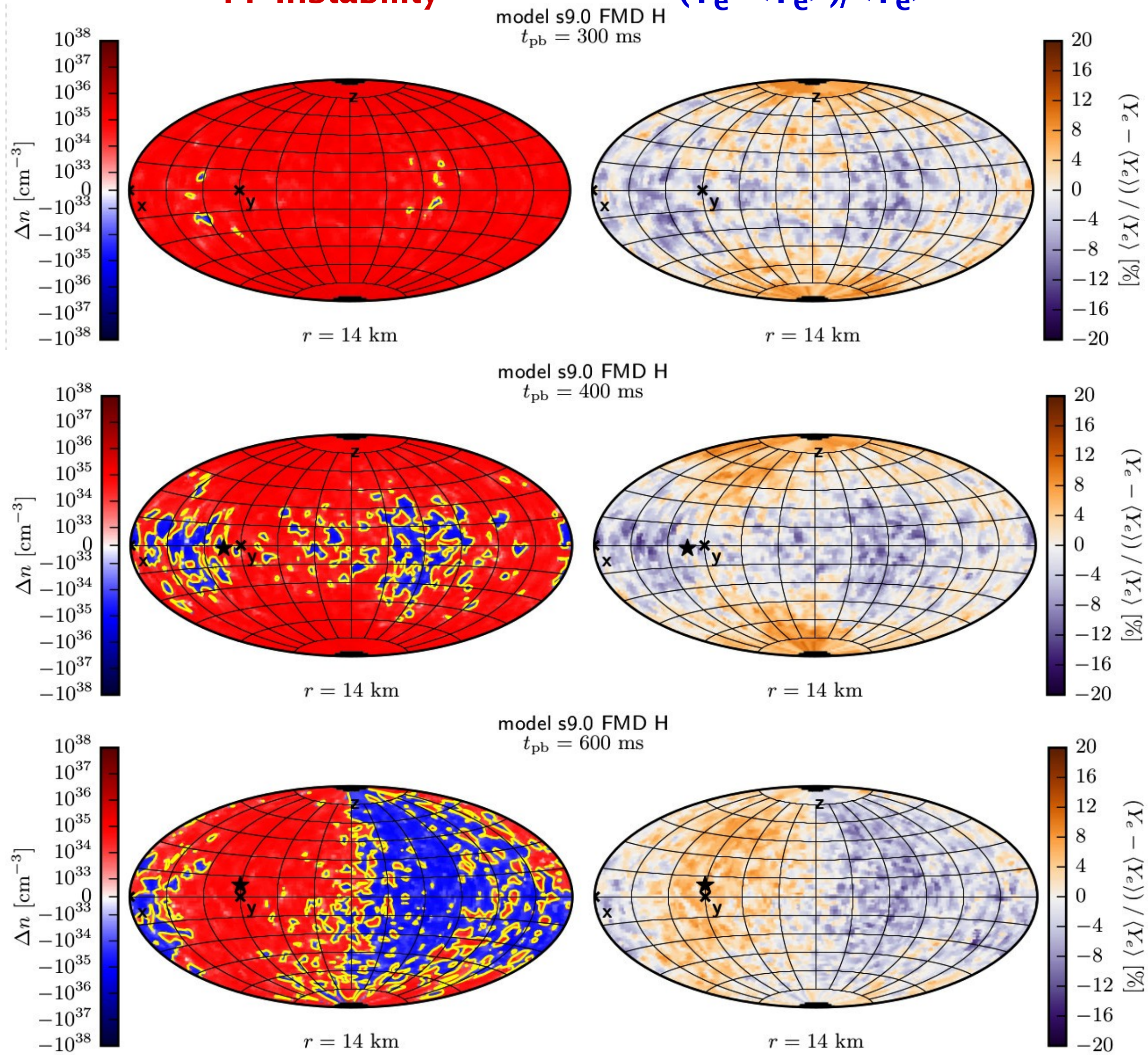
- Fast flavor instability is diagnosed inside of newly formed neutron stars (NSs).
- Instability regions are thin boundary layers of volumes where n($\bar{\nu}_e$) > n(ν_e)
- Regions grow with time in convective shell of the NS, favored by decreasing electron fraction and high temperatures.

Evolution of Fast Flavor Instability inside Neutron Stars

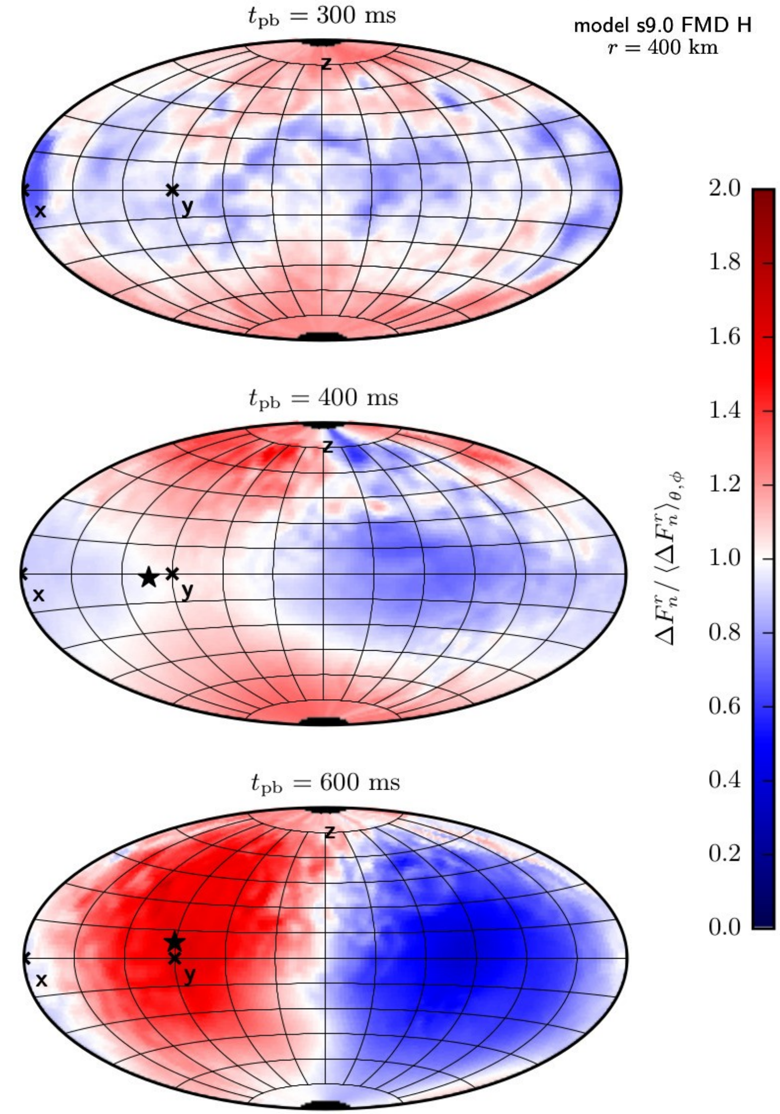
Instability regions (yellow) show anti-correlation with growth of LESA

FF Instability

$(Y_e - \langle Y_e \rangle)/\langle Y_e \rangle$



LESA



Glas et al., arXiv:1912.00274

Earth is exposed to a bath of relic neutrinos from all past supernovae

DSNB Neutrinos:

$\sim 34_{-17}^{+30}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

DSNB Spectrum and Backgrounds

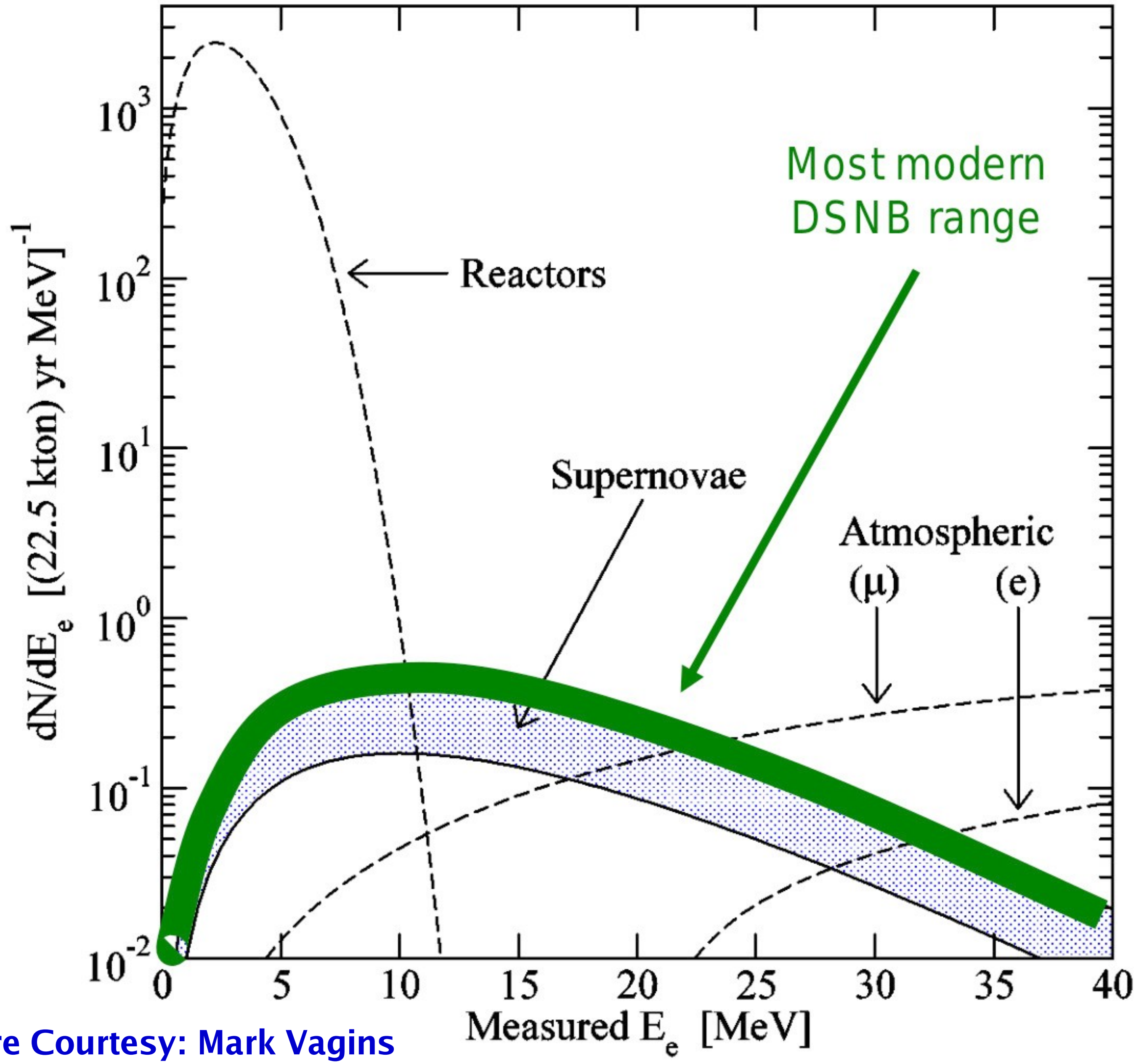


Figure Courtesy: Mark Vagins

Expected Numbers of Detected Events

in SuperKamiokande-Gd, Hyper-Kamiokande, JUNO

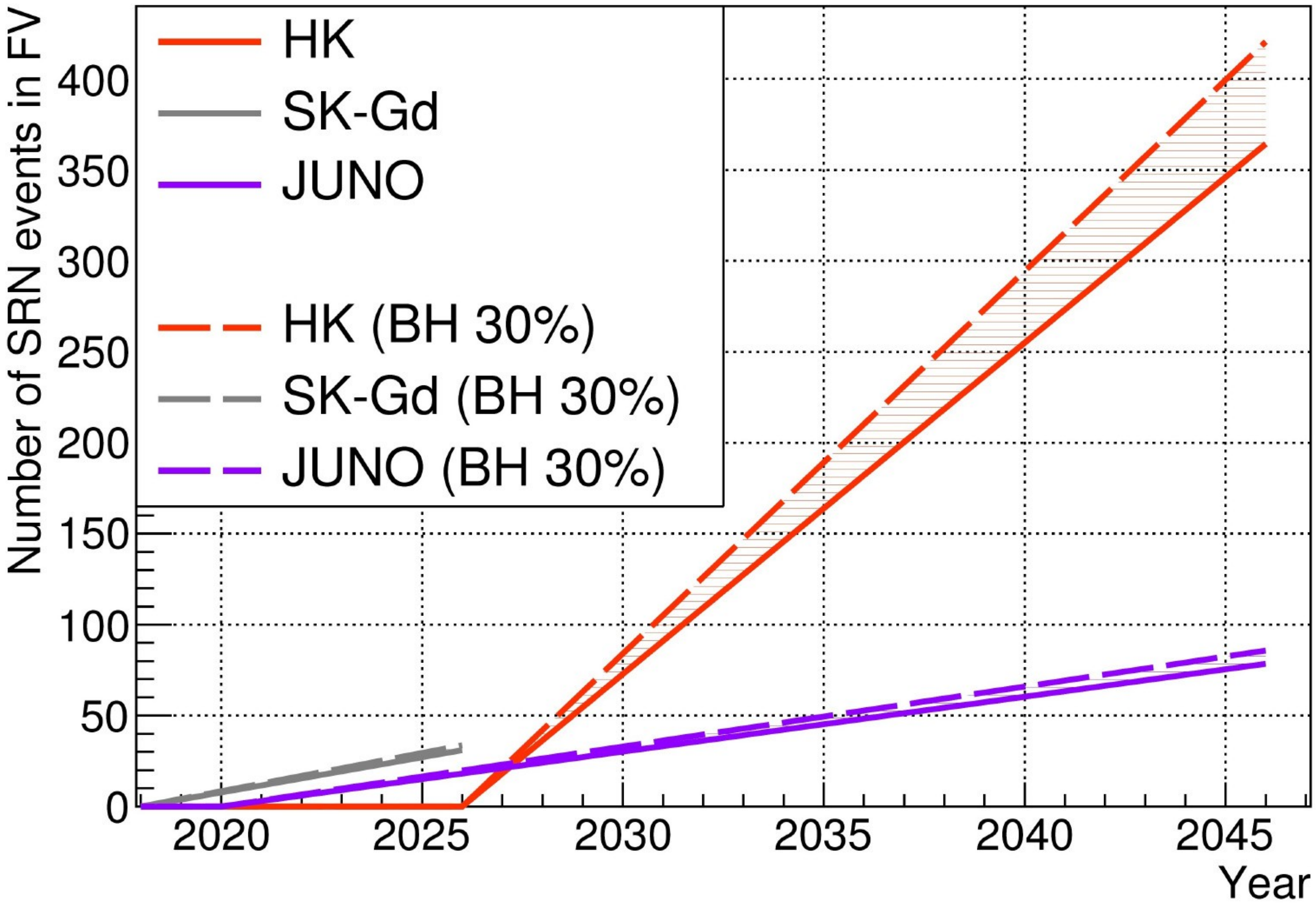
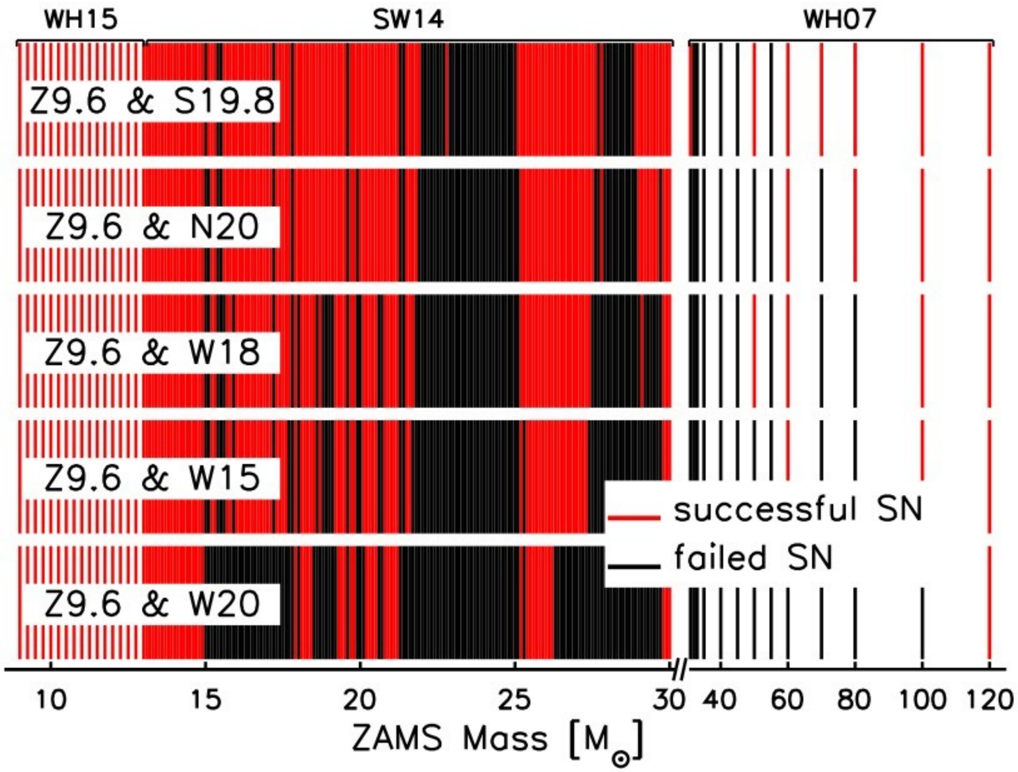


Figure Courtesy: Mark Vagins

Neutron-star vs. Black-hole Formation in Stellar Core-collapse Events



Calibration	succ. SNe	failed SNe
Z9.6 & S19.8	81.9 %	18.1 %
Z9.6 & N20	76.9 %	23.1 %
Z9.6 & W18	72.7 %	27.3 %
Z9.6 & W15	70.4 %	29.6 %
Z9.6 & W20	57.6 %	42.4 %

Kresse, Ertl, THJ, in preparation

(Original source: Sukhbold, Ertl, Woosley, Brown & THJ, ApJ 821 (2016) 38)

Neutrino Emission From Core-Collapse Supernovae

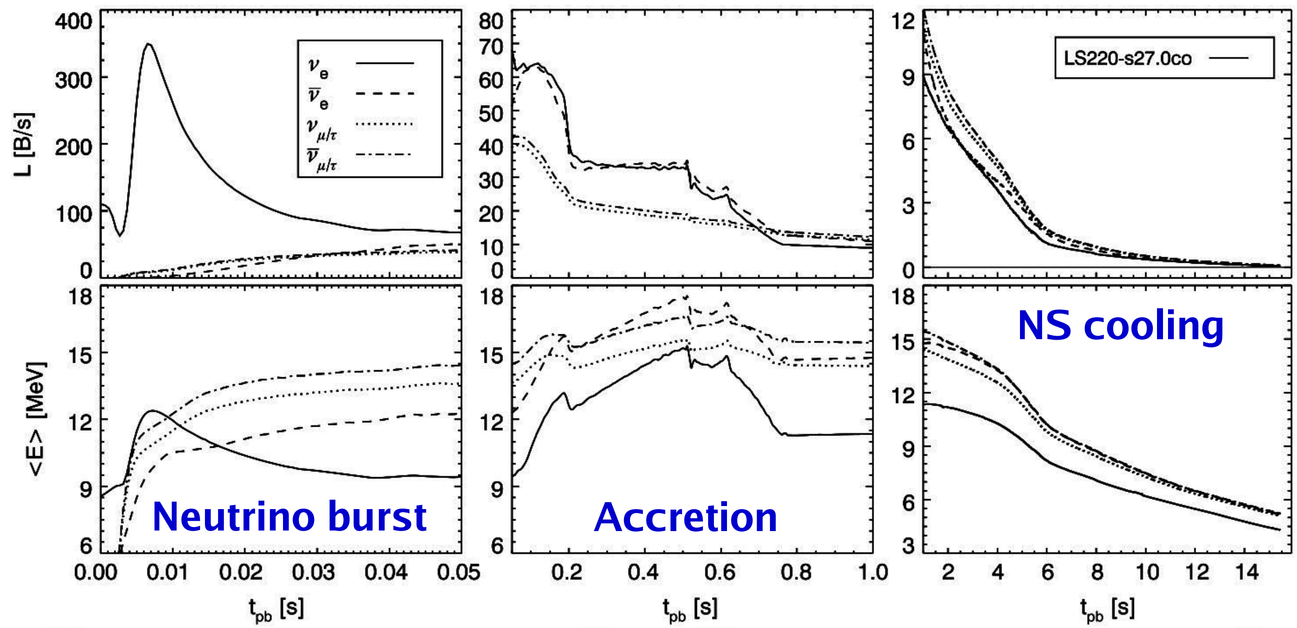
Neutrino energy release from SNe

$$E_b \sim E_g \approx \frac{3}{5}\frac{GM_{ns}^2}{R_{ns}}$$

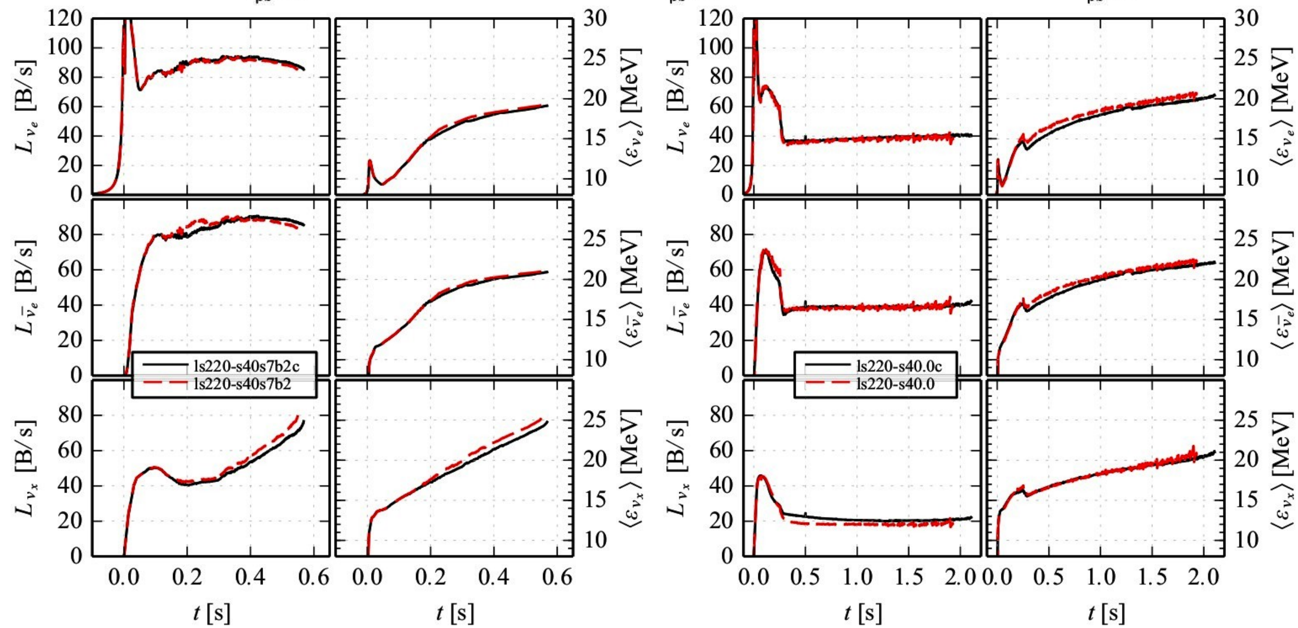
$$\approx 3.6 \times 10^{53} \left(\frac{M_{ns}}{1.5\,M_\odot}\right)^2 \left(\frac{R_{ns}}{10\,\mathrm{km}}\right)^{-1} \mathrm{erg}$$

Mirizzi, Tamborra, Janka, et al. (2016)

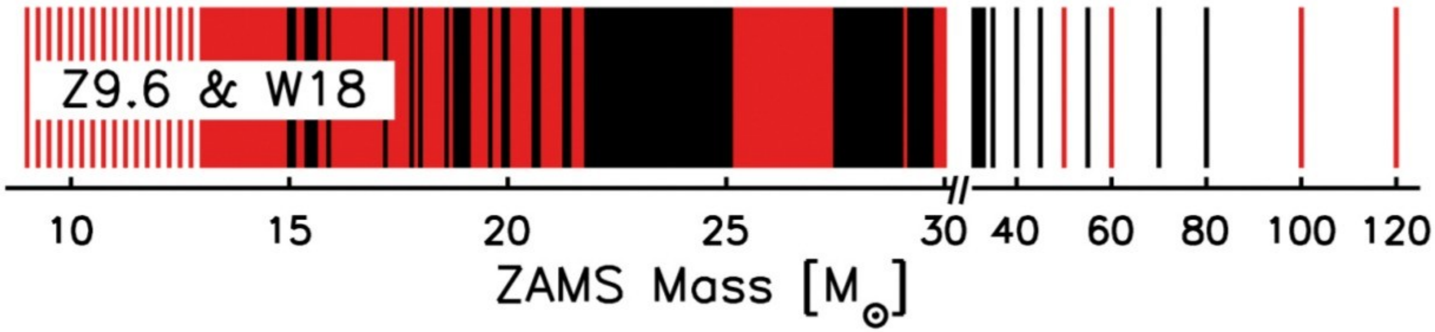
NS formation

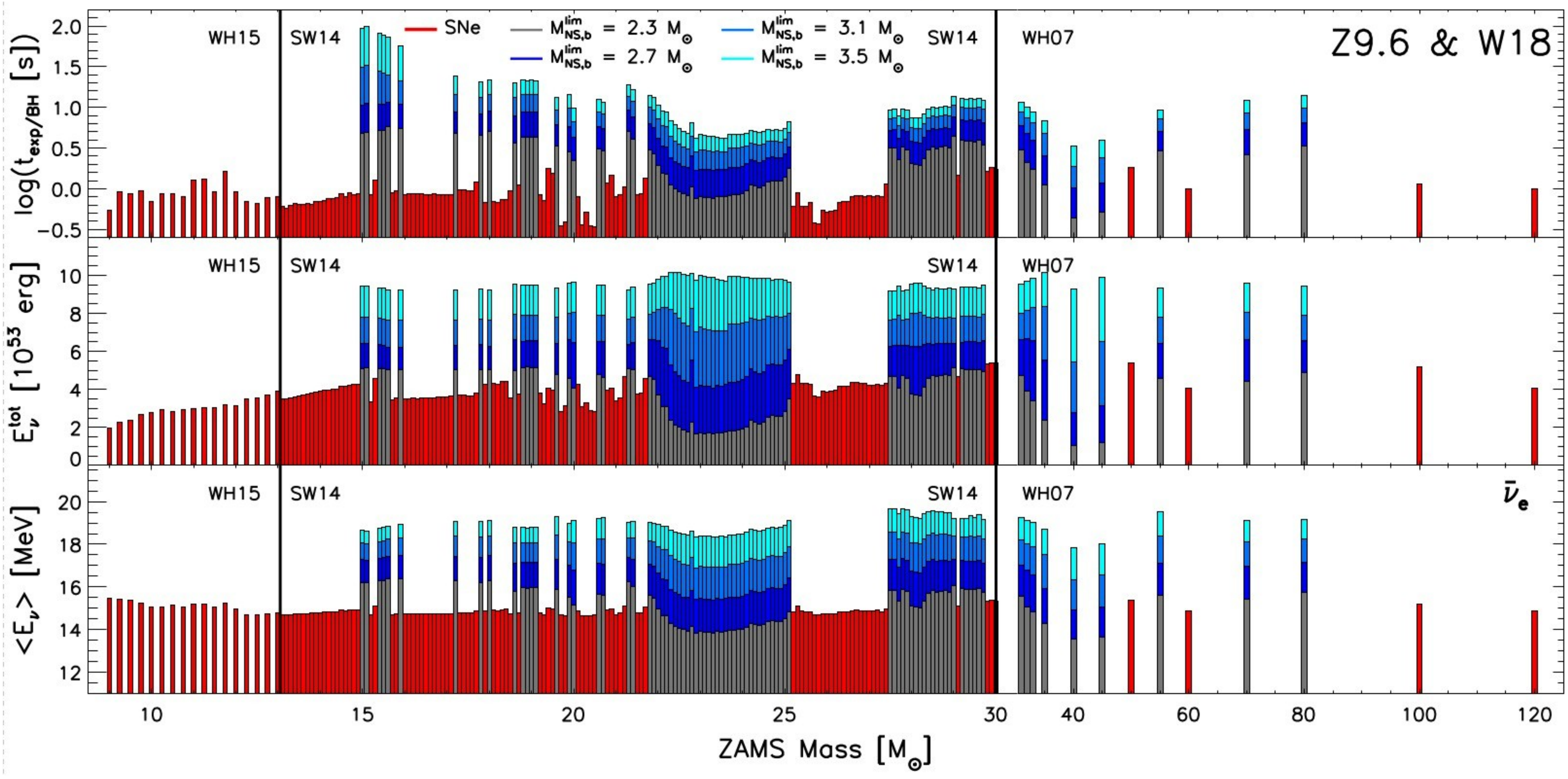


BH formation



Neutrino Emission Across the "Landscape" of Progenitors





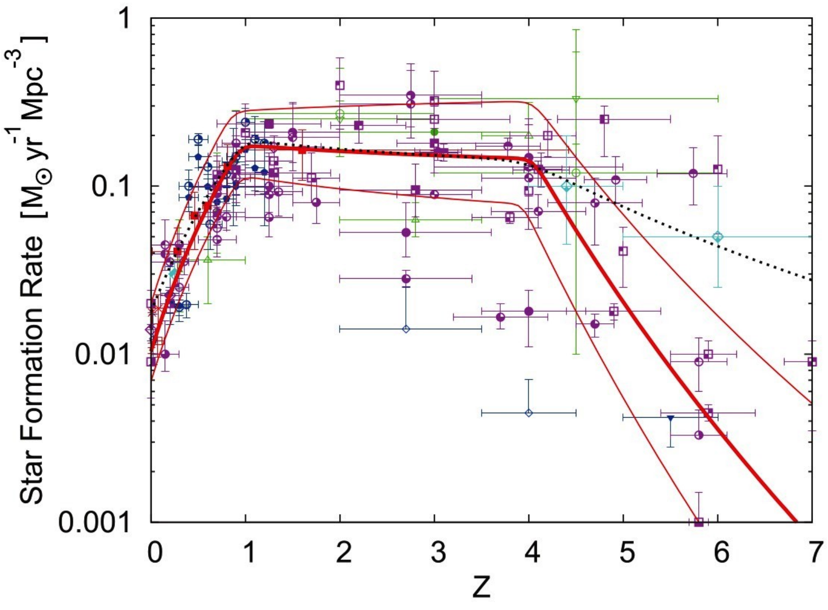
Kresse, Ertl, THJ, in preparation

Computation of DSNB Spectrum

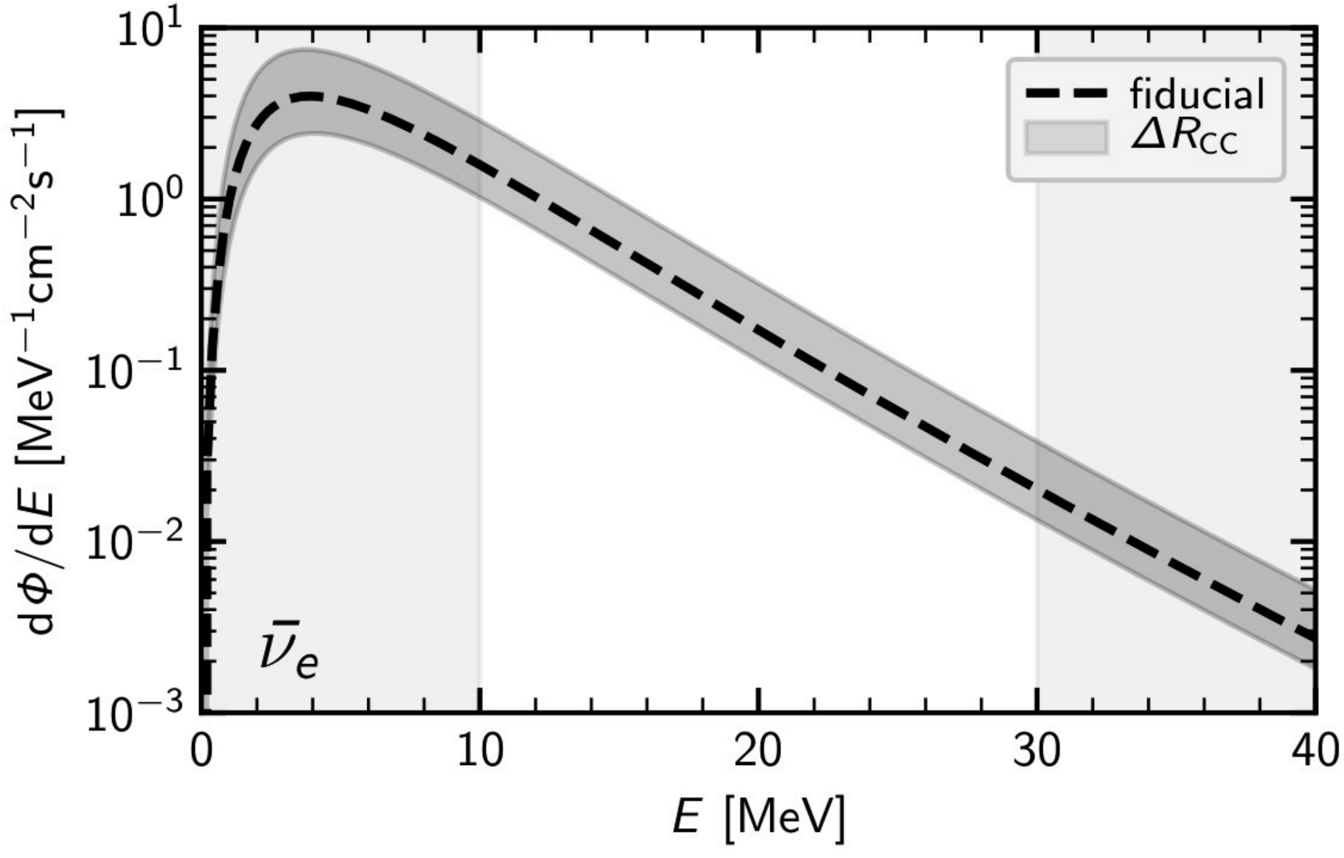
differential number flux [$\mathrm{MeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] of (anti-)neutrinos arriving on Earth with energy E:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = c \int \frac{\mathrm{d}N_{\mathrm{CC}}}{\mathrm{d}E'} \frac{\mathrm{d}E'}{\mathrm{d}E} R_{\mathrm{CC}}(z) \left| \frac{\mathrm{d}t}{\mathrm{d}z} \right| \mathrm{d}z$$

- Supernova neutrino number spectrum [MeV^{-1}], time-integrated and IMF-folded; cosmological redshift $E' = (1+z)E$
- Cosmic core-collapse rate density [$\mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$]
- Cosmological volume factor
- 1st and 2nd factor contain large uncertainties

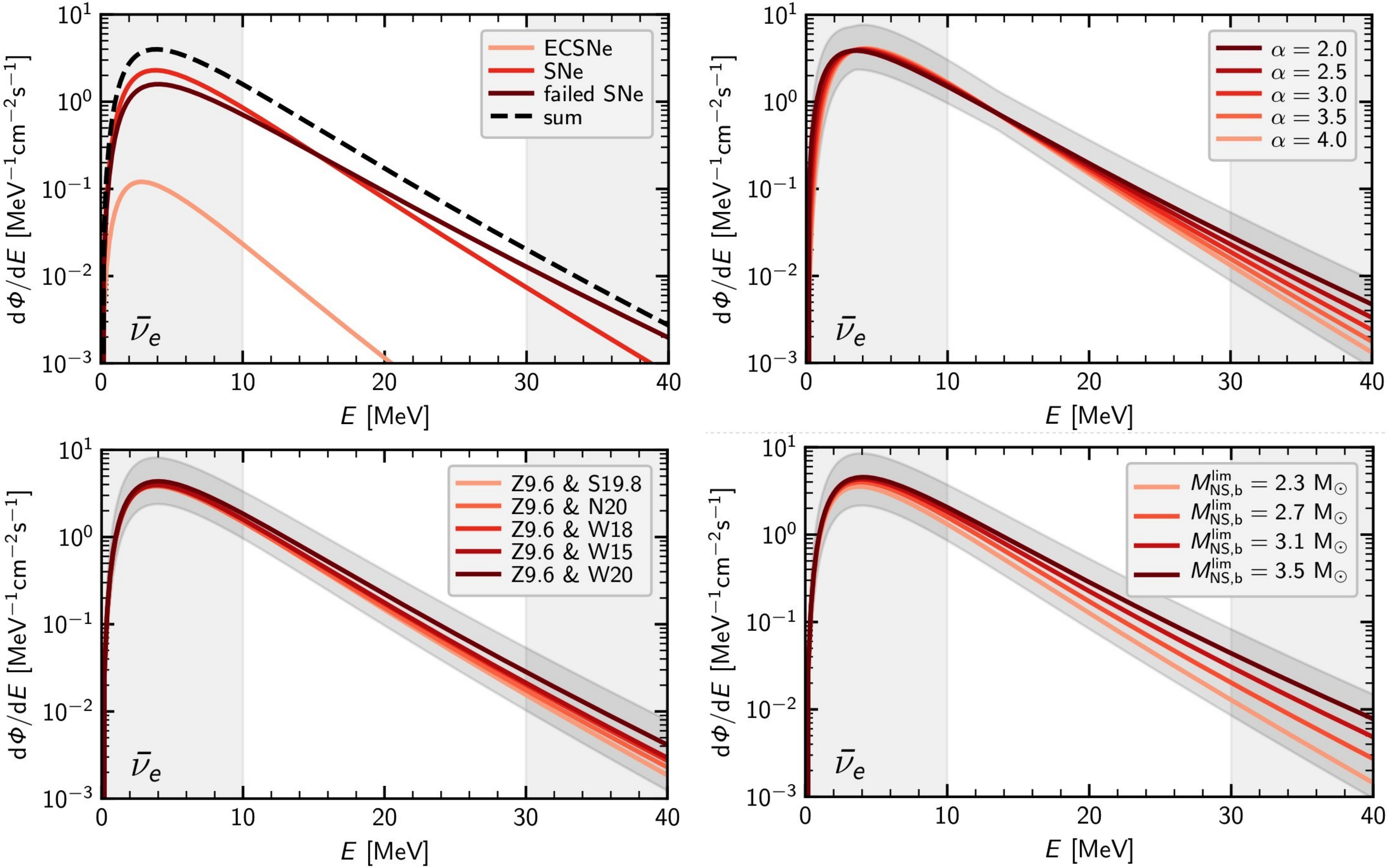


DSNB Spectrum: Fiducial Case

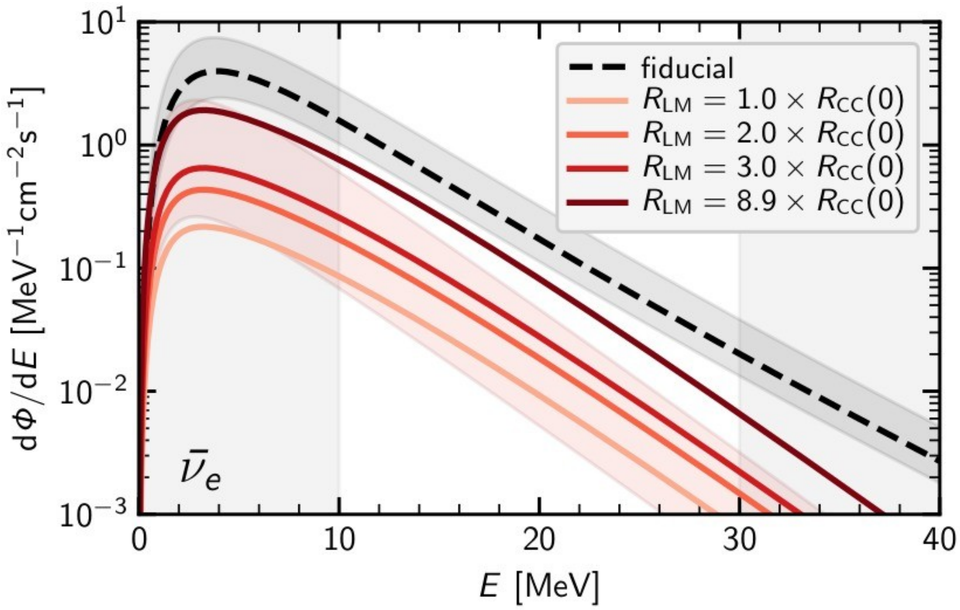


D. Kresse et al., in prep.

DSNB Spectrum With Uncertainties

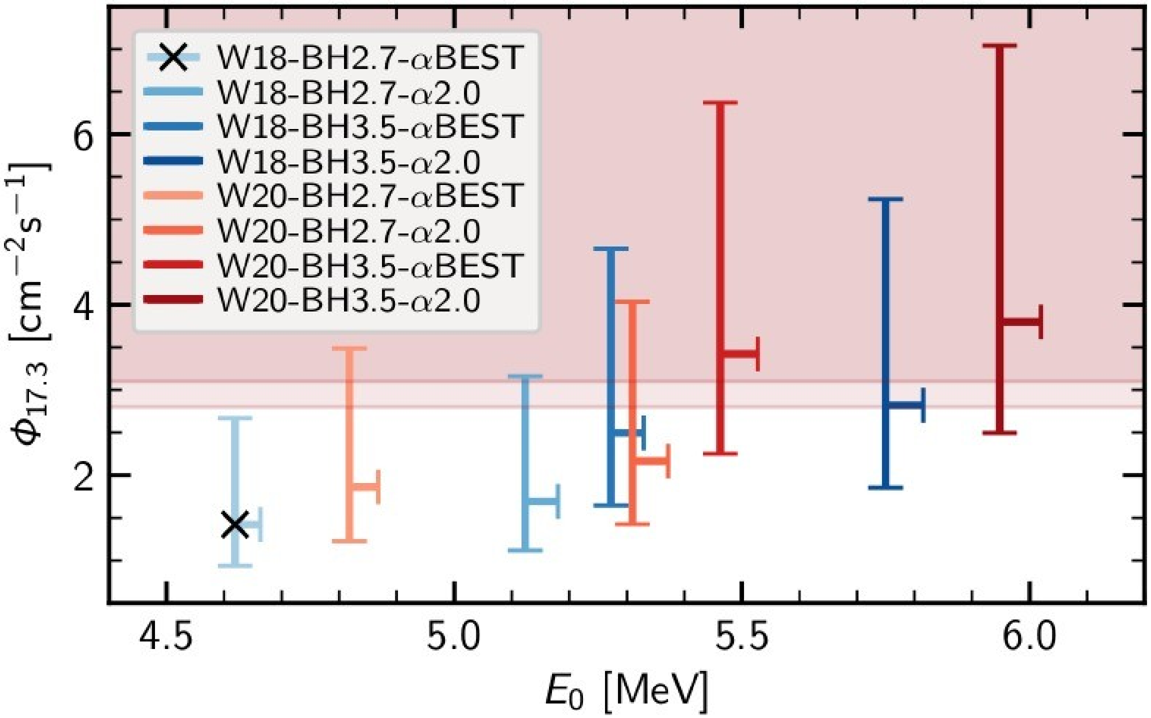


D. Kresse et al., in prep.

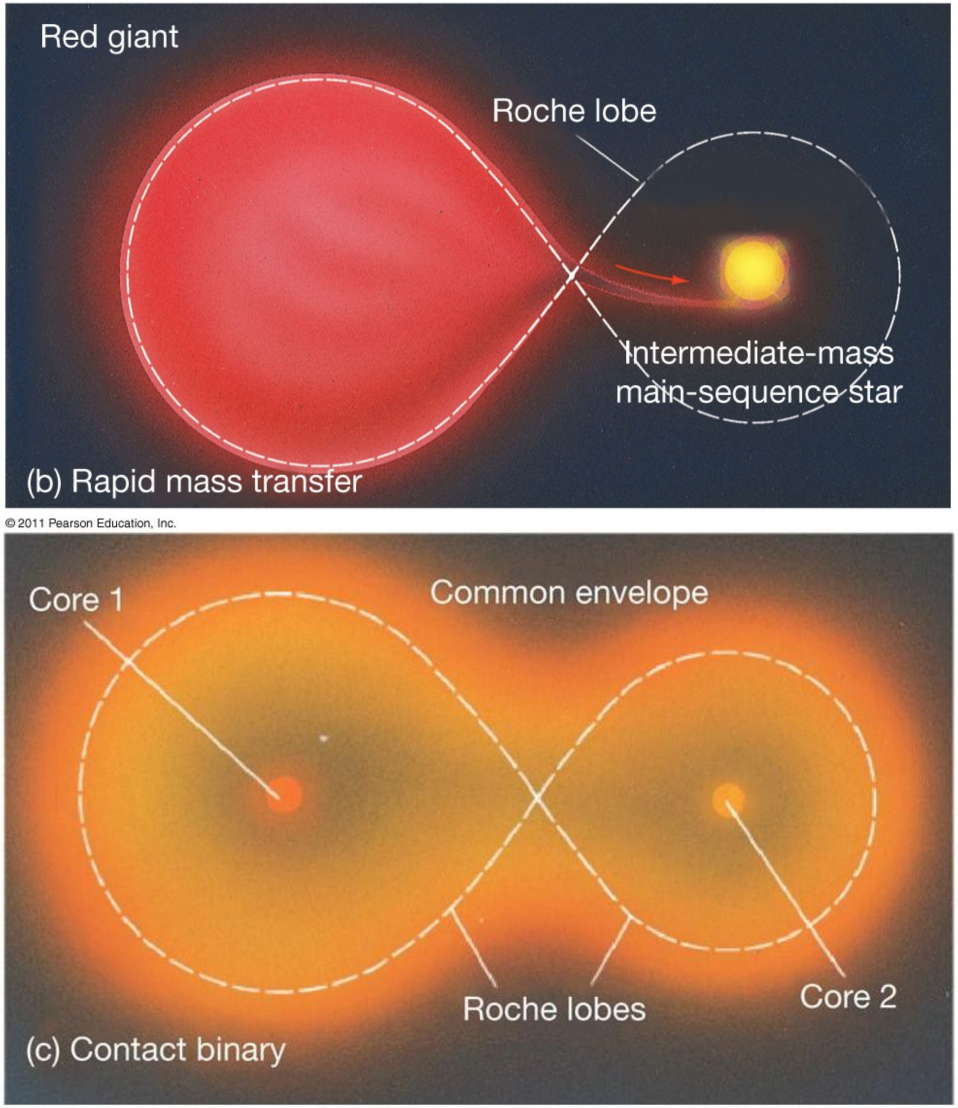


Contribution from add. low-mass (AIC, ultrastripped SNe) CC sources

SK-limit already constrains model possibilities



Binary Evolution of Progenitors of Core-Collapse Supernovae



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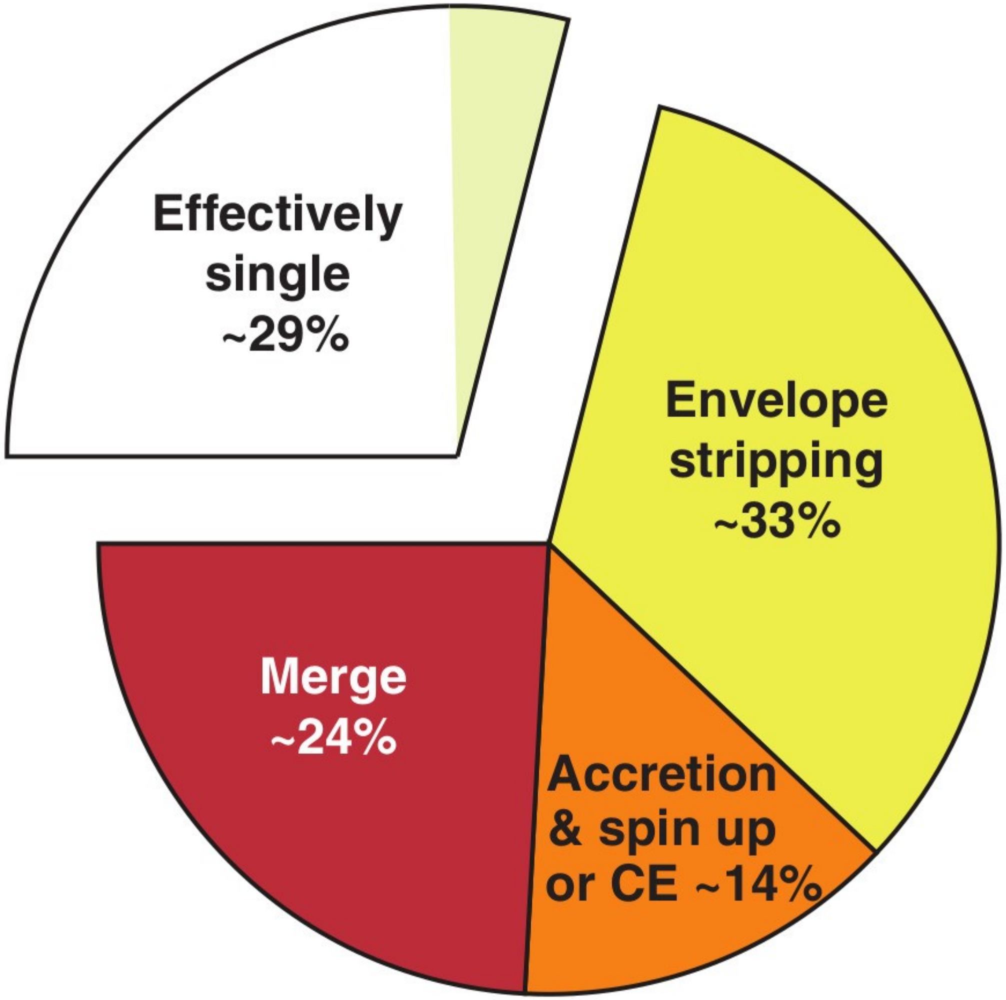
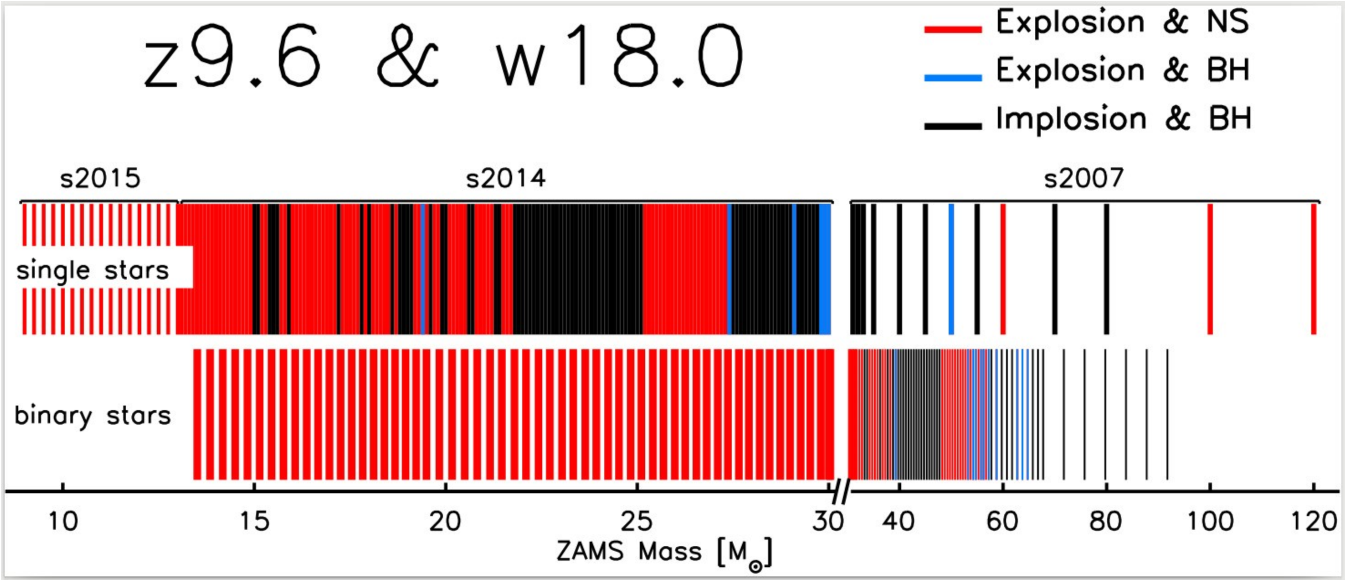


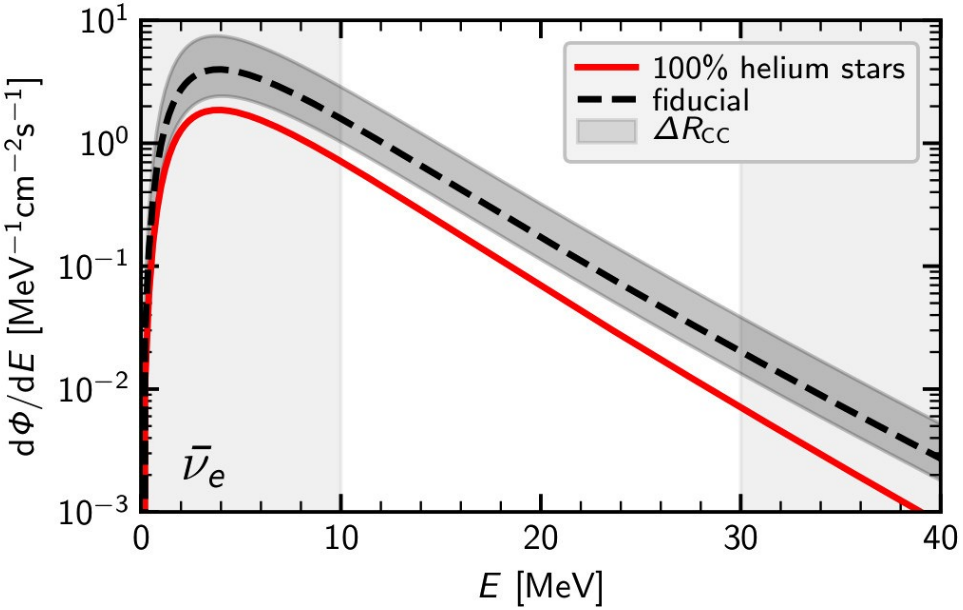
Sana, de Mink, de Koter, et al., Science (2012)

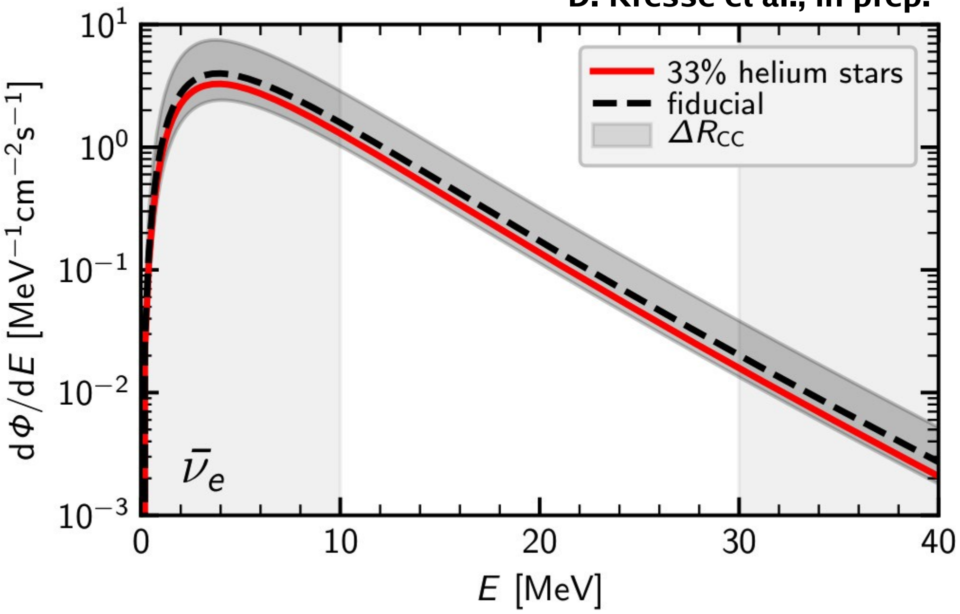
DSNB Spectrum Including Binary Progenitors of CC Supernovae



T. Ert et al., arXiv:1910.01641

D. Kresse et al., in prep.





DSNB Events Expected in JUNO

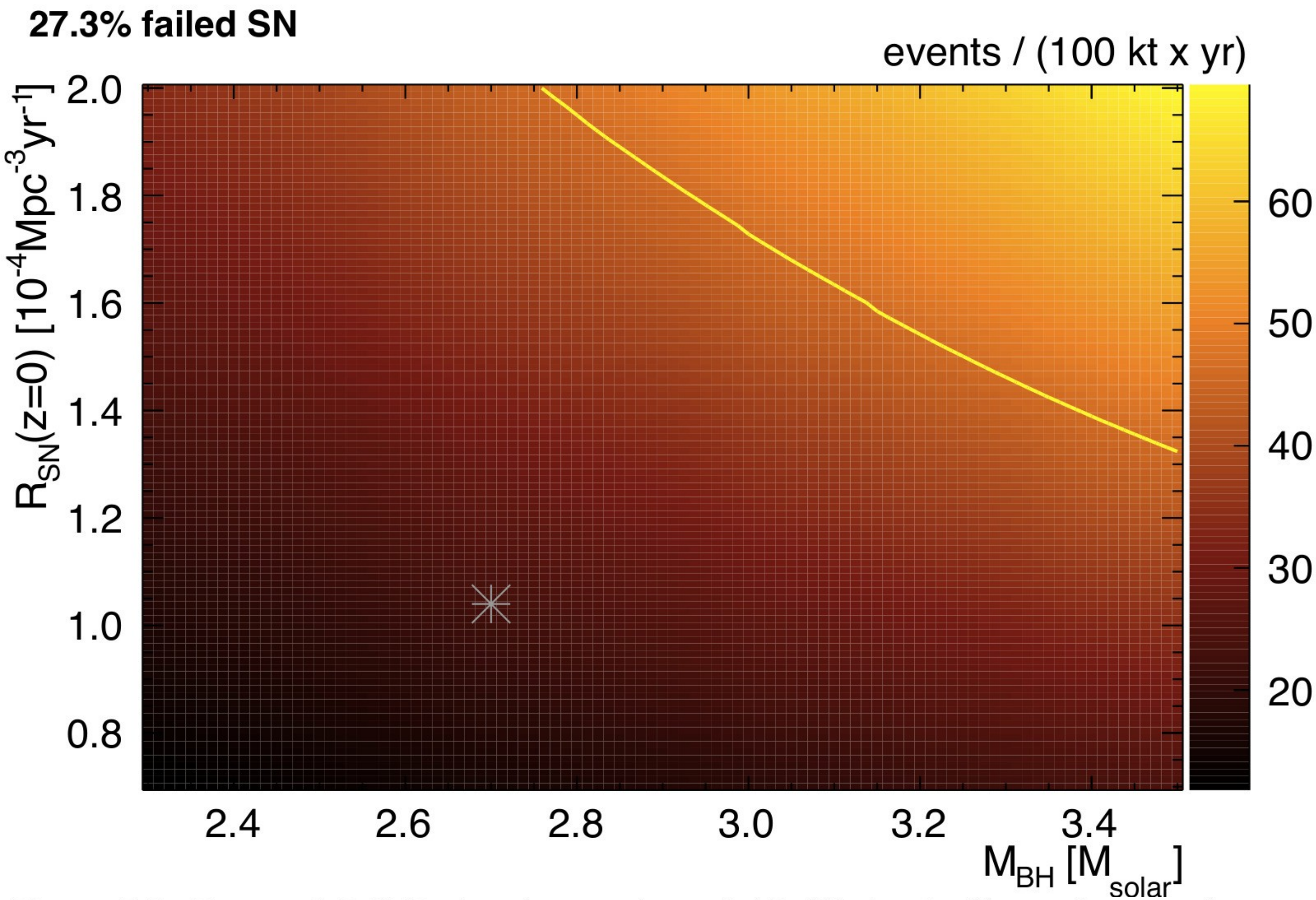


Figure 5.7: *Expected DSNB signal rates for a LAB filled scintillator detector, between* $11 - 30\,\mathrm{MeV}$*. The number of events is displayed with a color scheme, where light colors represents more events than dark colors. The amount of failed SN is fixed to* 27.3%*, and the CCSN rate* R_{SN} *and the minimum mass for BH formation are varied. The grey star represents our fiducial flux model and the yellow line, the current SuperK upper limit [28].*

J. Sawatzki & L. Oberauer (TUM)

Thank You!