From supernovae to neutron stars

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YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Contents

* Supernova
* Neutrino transfer
* Equation of state for supernova simulations
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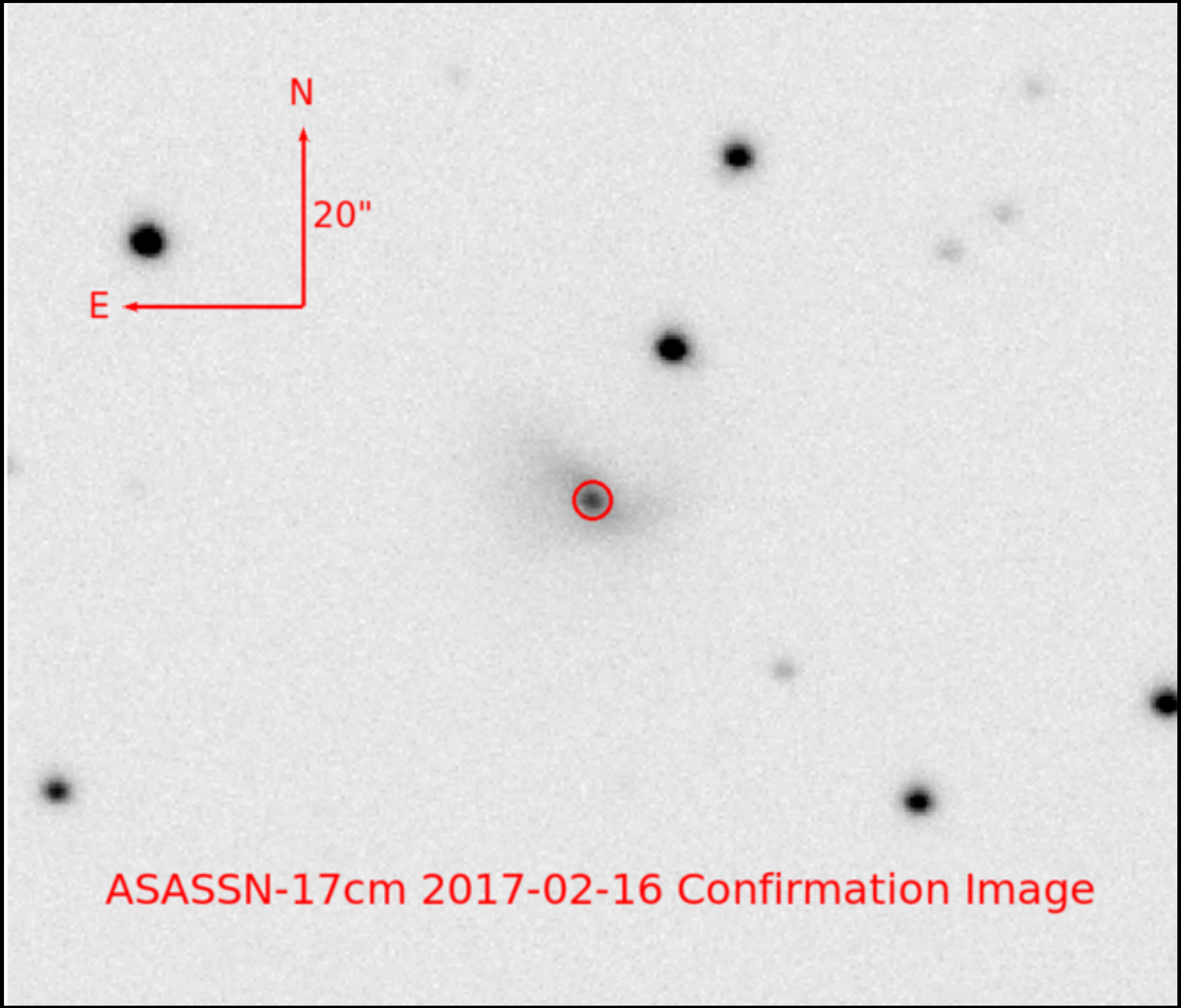
A supernova



(c)ASAS-SN project

Supernovae are made by neutron star formation

Remarks on Super-Novae and Cosmic Rays

5. *The super-nova process*

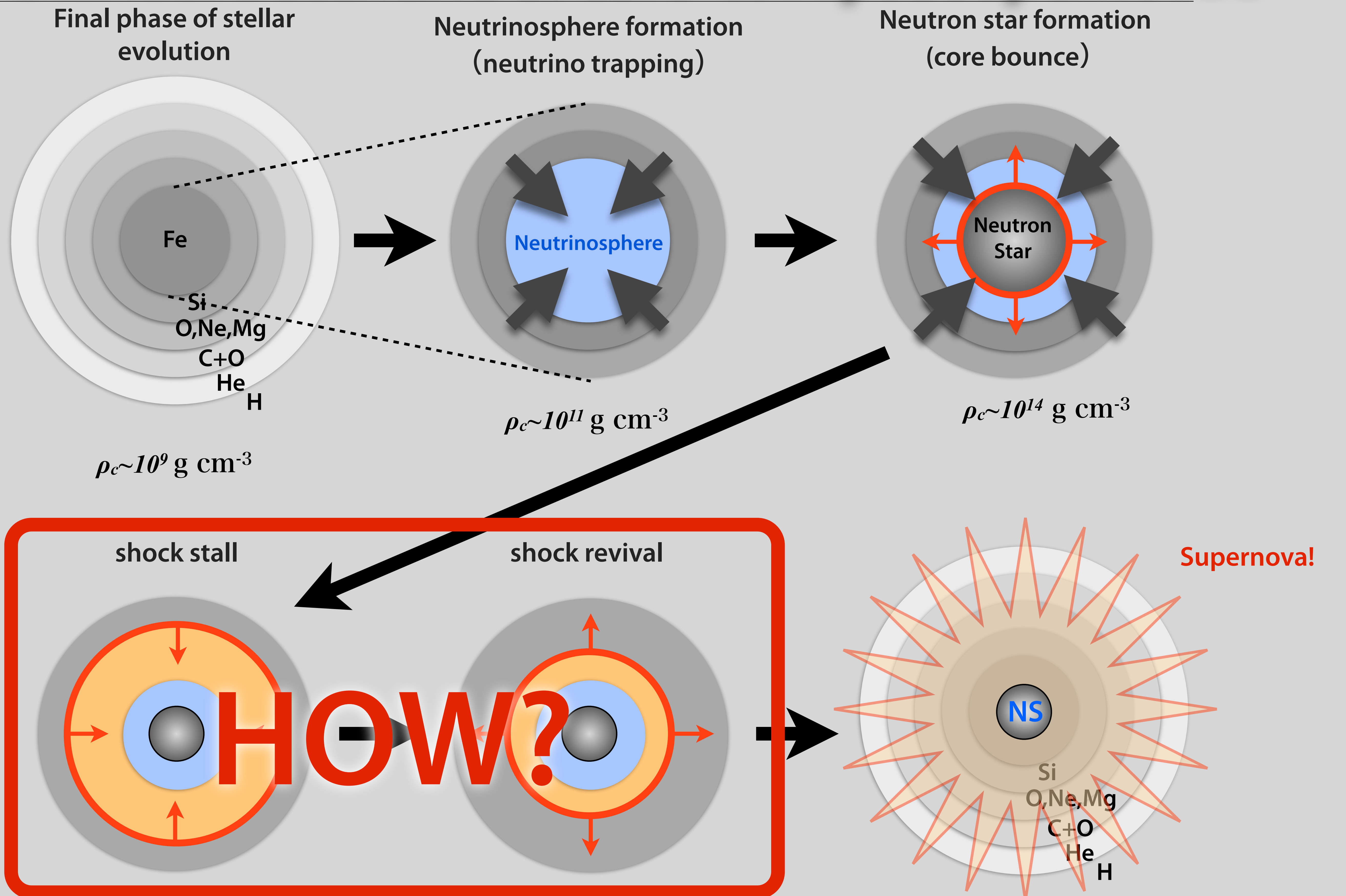
We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. Baade
F. Zwicky

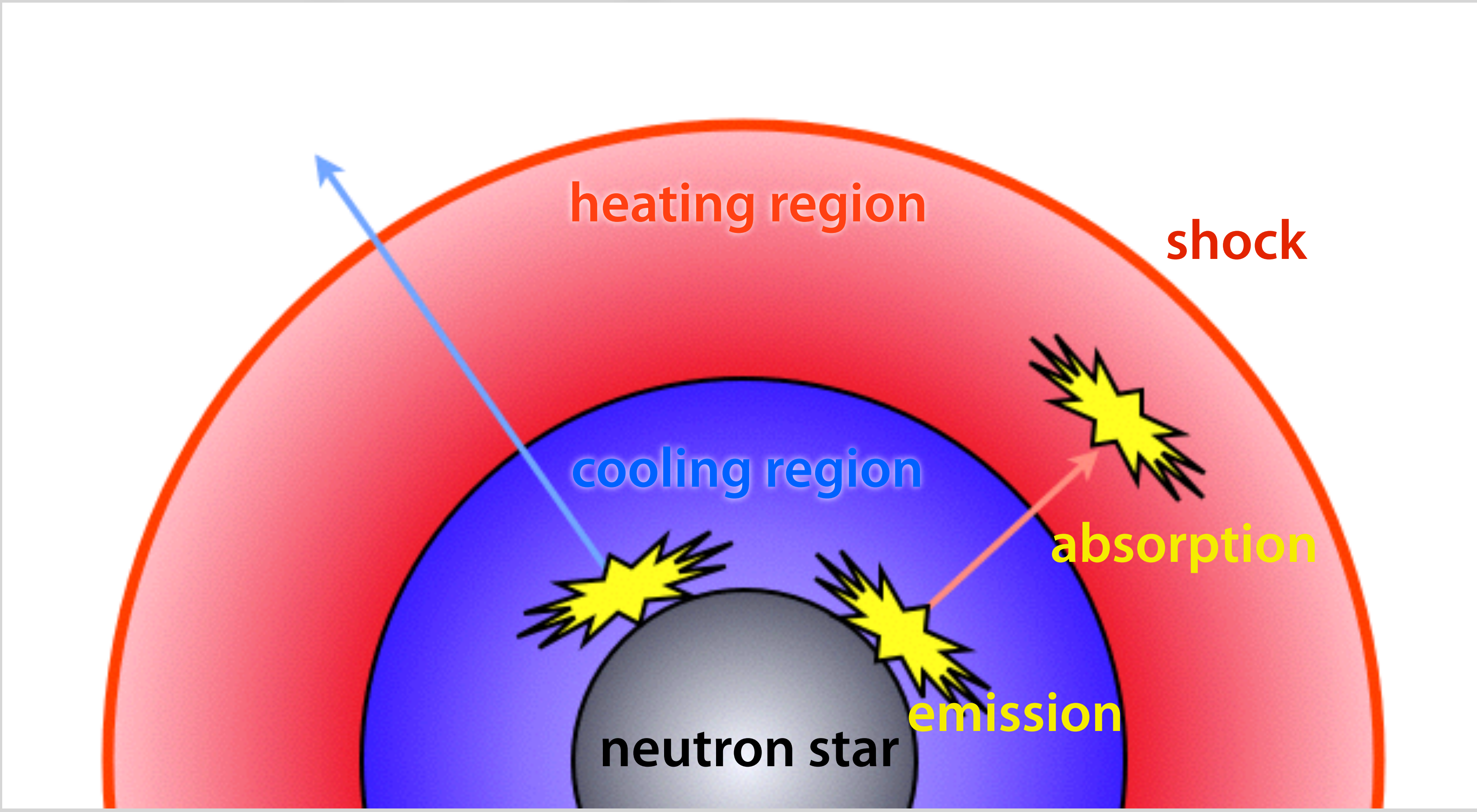
Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

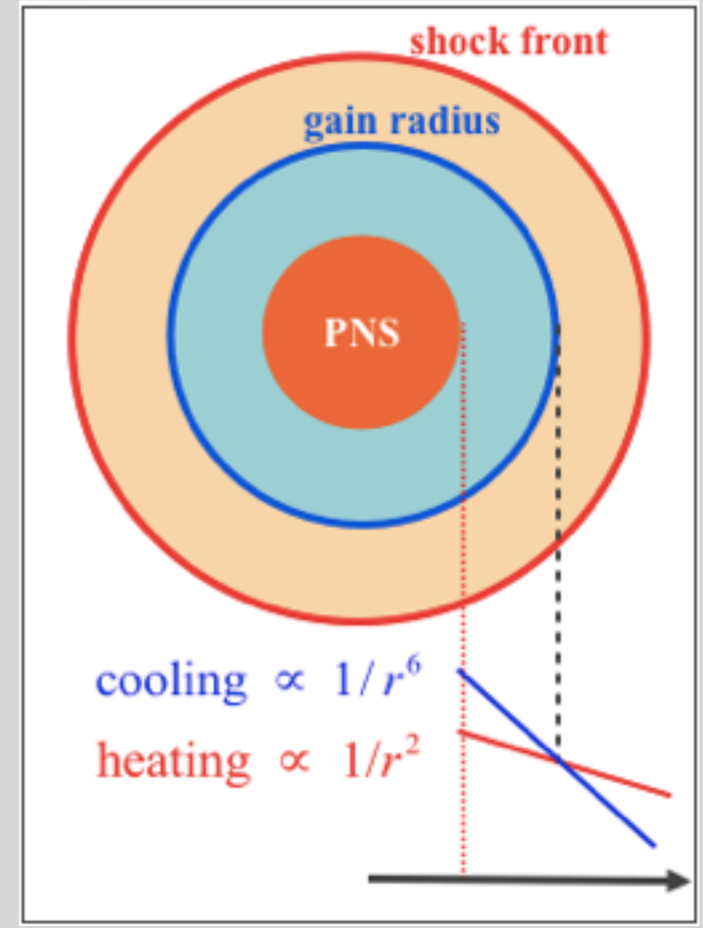
Baade & Zwicky 1934

Standard scenario of core-collapse supernovae



Current paradigm: neutrino-heating mechanism





- A CCSN emits $O(10^{58})$ of neutrinos with $O(10)$ MeV.
- Neutrinos transfer energy
  - Most of them are just escaping from the system (cooling)
  - Part of them are absorbed in outer layer (heating)
- Heating overwhelms cooling in heating (*gain*) region

What do simulations solve?

Numerical Simulations

Hydrodynamics equations

$$\frac{d\rho}{dt} + \rho\nabla\cdot\mathbf{v} = 0,$$

$$\rho\frac{d\mathbf{v}}{dt} = -\nabla P - \rho\nabla\Phi,$$

$$\frac{de^*}{dt} + \nabla\cdot\left[\left(e^* + P\right)\mathbf{v}\right] = -\rho\mathbf{v}\cdot\nabla\Phi + Q_E,$$

$$\frac{dY_e}{dt} = Q_N,$$

$$\triangle\Phi = 4\pi G\rho,$$

Solve simultaneously

Neutrino Boltzmann equation

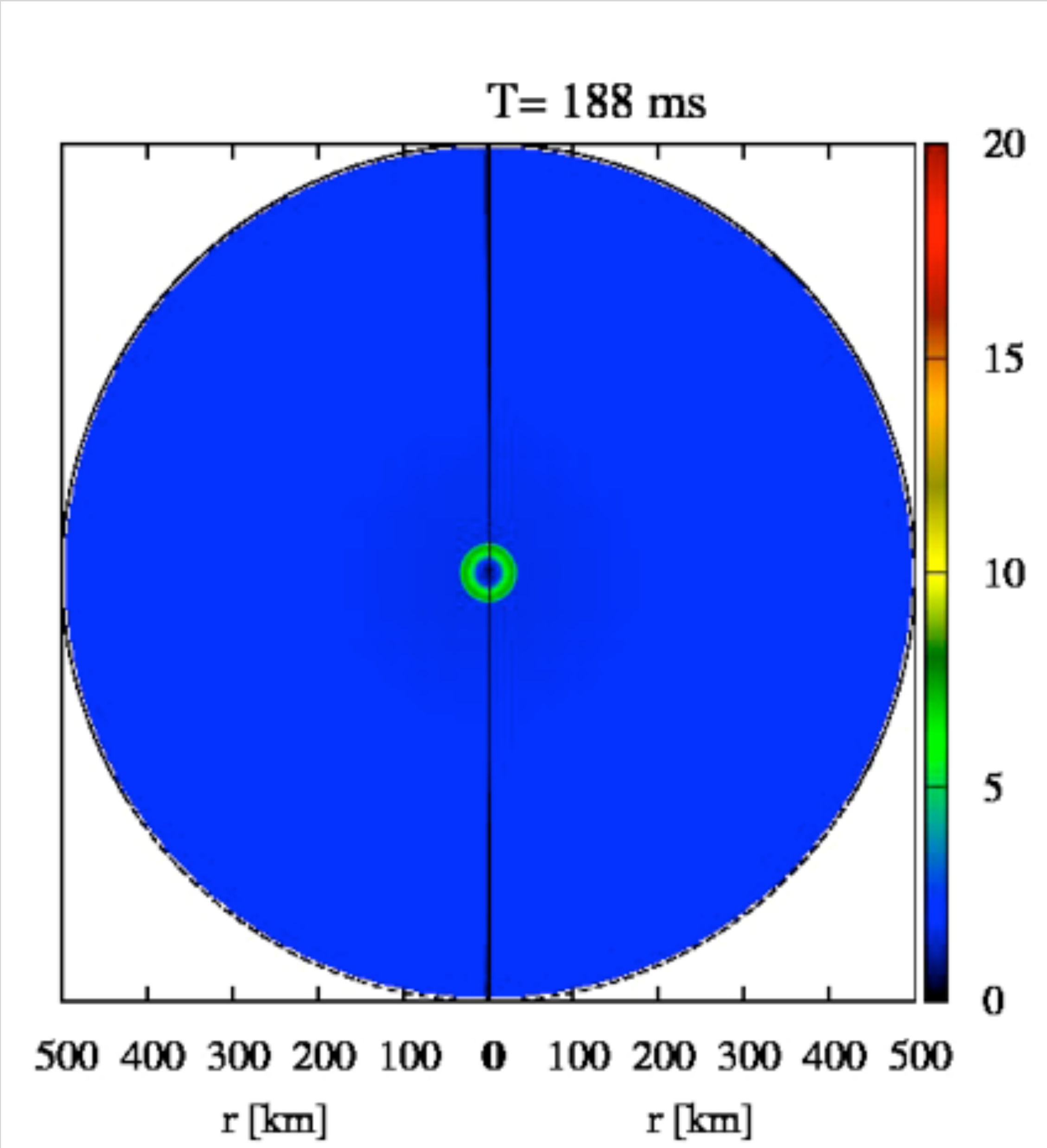
$$\frac{df}{cdt} + \mu\frac{\partial f}{\partial r} + \left[\mu\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) + \frac{1}{r}\right]\left(1-\mu^2\right)\frac{\partial f}{\partial\mu}$$
$$+ \left[\mu^2\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right]E\frac{\partial f}{\partial E}$$
$$= j\left(1-f\right) - \chi f + \frac{E^2}{c\left(hc\right)^3}$$
$$\times\left[\left(1-f\right)\int Rf'd\mu' - f\int R\left(1-f'\right)d\mu'\right].$$

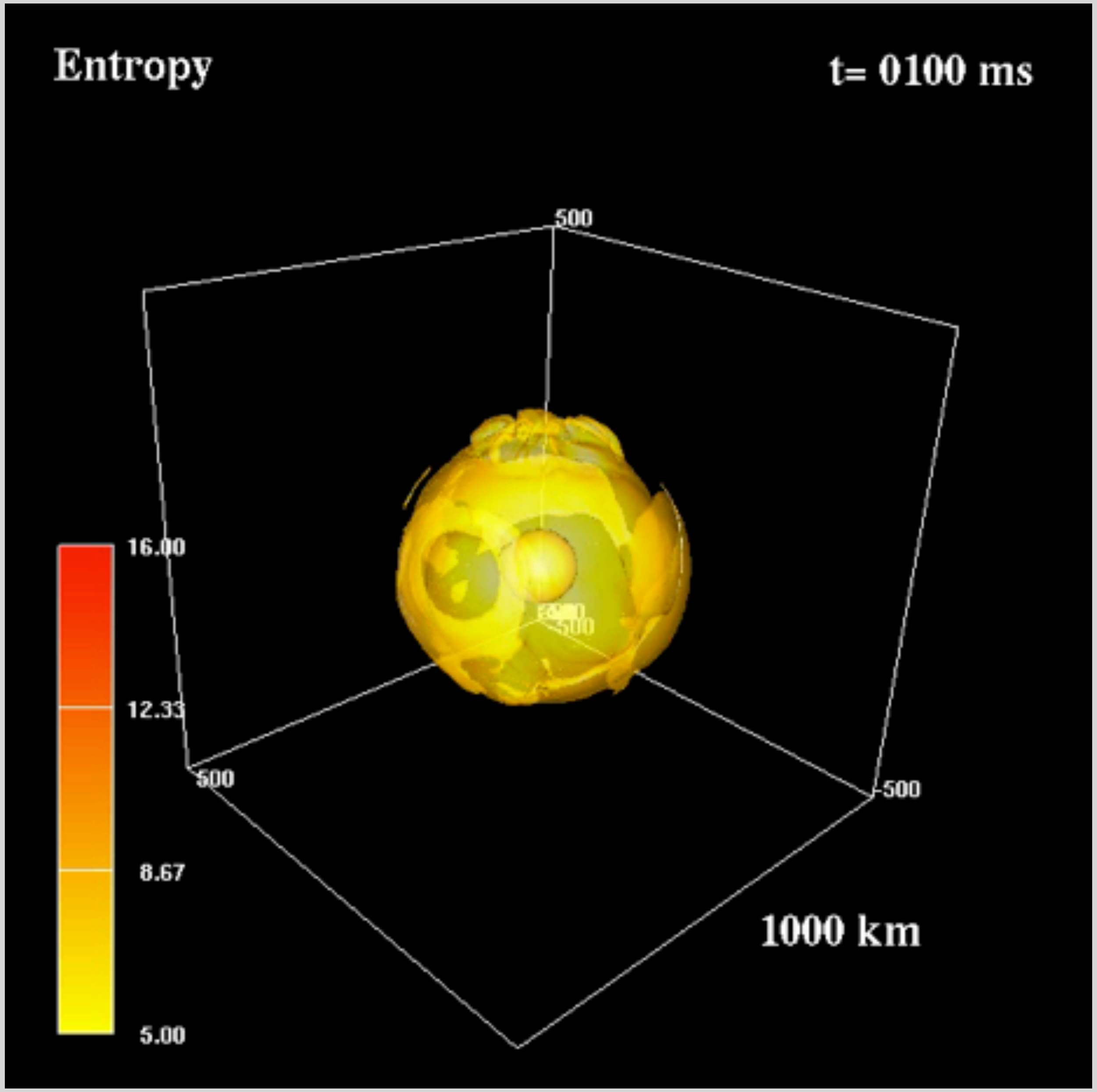
ρ: density, $\boldsymbol{v}$: velocity, P: pressure, Φ: grav. potential, e^*: total energy, Y_e: elect. frac., Q: neutrino terms

f: neut. dist. func, μ: $\cos\theta$, E: neut. energy, j: emissivity, χ: absorptivity, R: scatt. kernel

Neutrino-driven explosion in multi-D simulation

Exploding models driven by neutrino heating with 2D/3D simulations





see also, e.g.,
Marek & Janka (2009), Müller+ (2012), Bruenn+ (2013), Pan+ (2016), O'Connor & Couch (2015)

Suwa+ (2D)

PASJ, **62**, L49 (2010)
ApJ, **738**, 165 (2011)
ApJ, **764**, 99 (2013)
PASJ, **66**, L1 (2014)
MNRAS, **454**, 3073 (2015)
ApJ, **816**, 43 (2016)

Takiwaki+ (3D)

ApJ, **749**, 98 (2012)
ApJ, **786**, 83 (2014)
MNRAS, **461**, L112 (2016)

see also, e.g.,
Hanke+ (2013), Lentz+ (2015), Melson+ (2015), Müller (2015)

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Why is neutrino transfer so important?

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$$+ \left[\mu^2\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right]E\frac{\partial f}{\partial E}$$
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f: neut. dist. func, μ: $\cos\theta$, E: neut. energy, j: emissivity, χ: absorptivity, R: scatt. kernel

Boltzmann equation

Sumiyoshi & Yamada (2012); in inertial frame

$$\frac{1}{c}\frac{\partial f^{\mathrm{in}}}{\partial t} + \frac{\mu_\nu}{r^2}\frac{\partial}{\partial r}(r^2 f^{\mathrm{in}}) + \frac{\sqrt{1-\mu_\nu^2}\cos\phi_\nu}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta f^{\mathrm{in}})$$
$$+ \frac{\sqrt{1-\mu_\nu^2}\sin\phi_\nu}{r\sin\theta}\frac{\partial f^{\mathrm{in}}}{\partial\phi} + \frac{1}{r}\frac{\partial}{\partial\mu_\nu}\left[(1-\mu_\nu^2) f^{\mathrm{in}}\right]$$
$$- \frac{\sqrt{1-\mu_\nu^2}}{r}\frac{\cos\theta}{\sin\theta}\frac{\partial}{\partial\phi_\nu}(\sin\phi_\nu f^{\mathrm{in}}) = \left[\frac{1}{c}\frac{\delta f^{\mathrm{in}}}{\delta t}\right]_{\mathrm{collision}}$$

$$f^{\mathrm{in}}(r, \theta, \phi, t; \mu_\nu, \phi_\nu, \varepsilon^{\mathrm{in}})$$

3D in real space

3D in momentum space

7D in total

$$\left[\frac{1}{c}\frac{\delta f}{\delta t}\right]_{\text{emis-abs}} = -R_{\mathrm{abs}}(\varepsilon,\Omega) f(\varepsilon,\Omega) + R_{\mathrm{emis}}(\varepsilon,\Omega)[1-f(\varepsilon,\Omega)]$$

$$\left[\frac{1}{c}\frac{\delta f}{\delta t}\right]_{\mathrm{scat}} = -\int\frac{d\varepsilon'\varepsilon'^2}{(2\pi)^3}\int d\Omega' R_{\mathrm{scat}}(\varepsilon,\Omega;\varepsilon',\Omega') f(\varepsilon,\Omega) \times [1-f(\varepsilon',\Omega')] + \int\frac{d\varepsilon'\varepsilon'^2}{(2\pi)^3}\int d\Omega' R_{\mathrm{scat}}(\varepsilon',\Omega';\varepsilon,\Omega) \times f(\varepsilon',\Omega')[1-f(\varepsilon,\Omega)],$$

$$\left[\frac{1}{c}\frac{\delta f}{\delta t}\right]_{\mathrm{pair}} = -\int\frac{d\varepsilon'\varepsilon'^2}{(2\pi)^3}\int d\Omega' R_{\text{pair-anni}}(\varepsilon,\Omega;\varepsilon',\Omega') \times f(\varepsilon,\Omega)\overline{f}(\varepsilon',\Omega') + \int\frac{d\varepsilon'\varepsilon'^2}{(2\pi)^3}\int d\Omega' R_{\text{pair-emis}}(\varepsilon,\Omega;\varepsilon',\Omega') \times [1-f(\varepsilon,\Omega)][1-\overline{f}(\varepsilon',\Omega')],$$

7D integro-diffrential eq.
so complex…

Methods to solve Boltzmann eq.

Direct integration of Boltzmann eq. with discrete-ordinate method
=> S_N method
It's too costly, though.

By taking angular moments of radiation fields

$$\{E, F^i, P^{ij}\} \propto \int d\Omega f \{1, \ell^i, \ell^i \ell^j\}$$

Moment equations;

$$\partial_t E + \partial_i F^i = S_0$$
$$\partial_t F^i + \partial_j P^{ij} = S_1$$
$$\dots$$

To close the system, we need additional equation
(the same as equation of state in hydrodynamics equation)

Methods to solve Boltzmann eq. (cont.)

The simplest way; only cooling terms are taken into account
=> leakage scheme (no transport; $\partial_t e_{matter} = -\partial_t E$)

Next is diffusion assumption, $F \propto \nabla E$, but is wrong in optically thin regime. To take into account both optically thick and thin regime, modification is needed
=> Flux limited diffusion (FLD) F is given by E and ∇E
Isotropic diffusion source approximation (IDSA) F is given by the distance from last-scattering surface

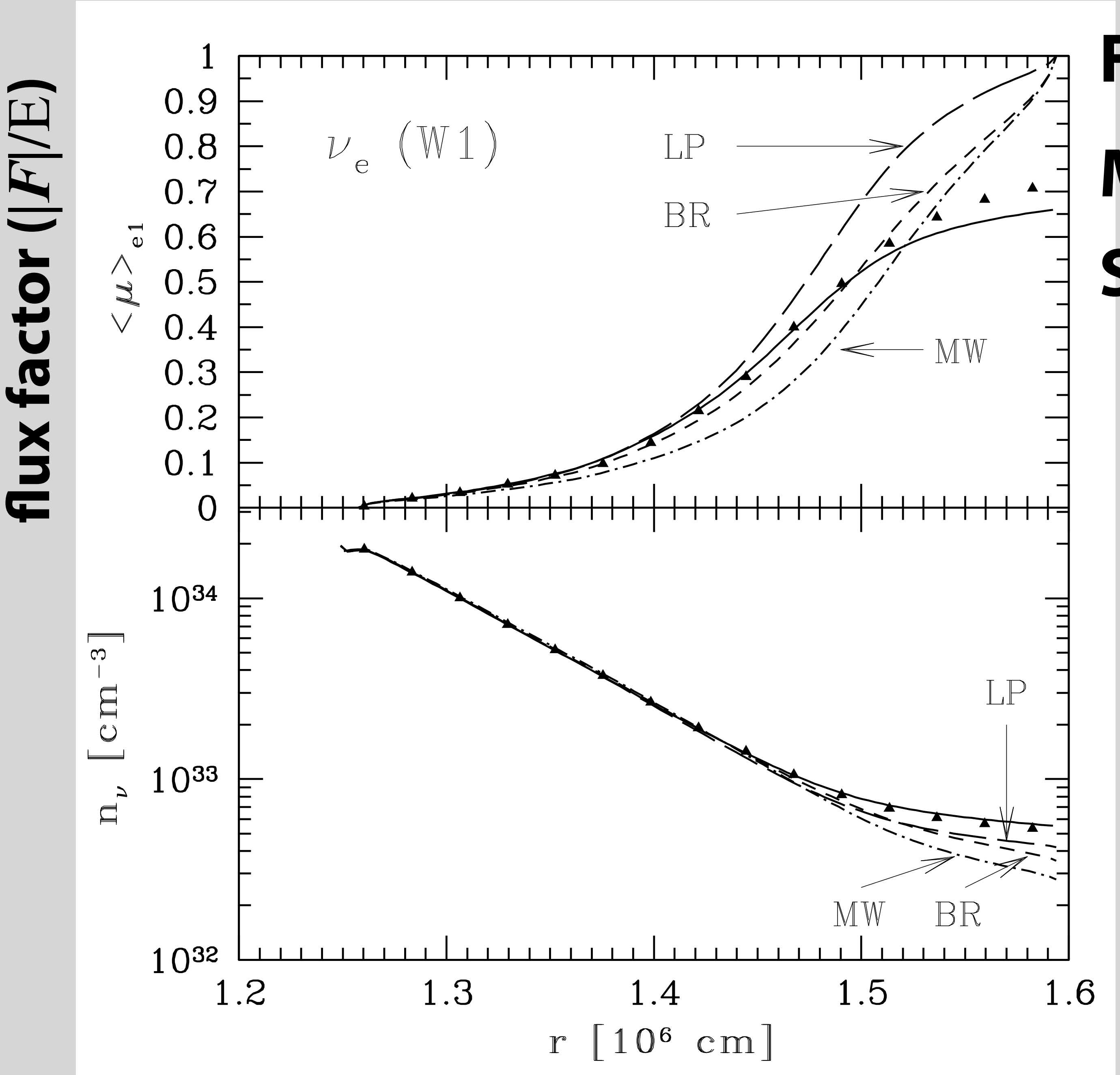
Higher moment (P) is helpful to obtain more precise solution.
=> M_1 closure P is given by E and F
Variable Eddington factor (VE) P is given by solving simpler Boltzmann eq.

S_N > VE > M_1> FLD, IDSA > leakage

← **ab initio** **higher cost** | **→** **approximate** **lower cost**

Comparison of methods

Yamada+ (1999)



FLD (dashed lines)

Monte-Carlo (▲)

S_N (solid line)

Comparison of IDSA and S_N is given in Liebendörfer+ (2009) and Berninger+ (2013)

Methods to solve Boltzmann eq. (cont.)

Methods used in supernova community

S_N

Ott+ (2008); Sumiyoshi & Yamada (2012); Nagakura+ (2017)

VE

Buras+ (2006); Müller+ (2010); Hanke+ (2013)

M_1

Obergaulinger+ (2014); O'Connor & Couch (2015); Skinner+ (2016)

FLD

Burrows+ (2006); Bruenn+ (2013)

IDSA

Suwa+ (2010); Takiwaki+ (2012); Pan+ (2016)

and many others

Questions

* **How is nuclear physics related to supernova explosion?**
* **How can we investigate nuclear physics via supernova observations?**

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List of SN EOS

Oertel et al. (2016)

Model	Nuclear Interaction	Degrees of Freedom	M_{max} ($M_\odot$)	$R_{1.4M_\odot}$ (km)	Ξ	publ. avail.	References
H&W	SKa	$n, p, \alpha, \{(A_i, Z_i)\}$	2.21[a]	13.9 [a]		n	El Eid and Hillebrandt (1980); Hillebrandt *et al.* (1984)
LS180	LS180	$n, p, \alpha, (A, Z)$	1.84	12.2	0.27	y	Lattimer and Swesty (1991)
LS220	LS220	$n, p, \alpha, (A, Z)$	2.06	12.7	0.28	y	Lattimer and Swesty (1991)
LS375	LS375	$n, p, \alpha, (A, Z)$	2.72	14.5	0.32	y	Lattimer and Swesty (1991)
STOS	TM1	$n, p, \alpha, (A, Z)$	2.23	14.5	0.26	y	Shen *et al.* (1998); Shen *et al.* (1998, 2011)
FYSS	TM1	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.22	14.4	0.26	n	Furusawa *et al.* (2013b)
HS(TM1)	TM1*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.21	14.5	0.26	y	Hempel and Schaffner-Bielich (2010); Hempel *et al.* (2012)
HS(TMA)	TMA*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.02	13.9	0.25	y	Hempel and Schaffner-Bielich (2010)
HS(FSU)	FSUgold*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	1.74	12.6	0.23	y	Hempel and Schaffner-Bielich (2010); Hempel *et al.* (2012)
HS(NL3)	NL3*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.79	14.8	0.31	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
HS(DD2)	DD2	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.42	13.2	0.30	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
HS(IUFSU)	IUFSU*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	1.95	12.7	0.25	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
SFHo	SFHo	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.06	11.9	0.30	y	Steiner *et al.* (2013a)
SFHx	SFHx	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.13	12.0	0.29	y	Steiner *et al.* (2013a)
SHT(NL3)	NL3	$n, p, \alpha, \{(A_i, Z_i)\}$	2.78	14.9	0.31	y	Shen *et al.* (2011b)
SHO(FSU)	FSUgold	$n, p, \alpha, \{(A_i, Z_i)\}$	1.75	12.8	0.23	y	Shen *et al.* (2011a)
SHO(FSU2.1)	FSUgold2.1	$n, p, \alpha, \{(A_i, Z_i)\}$	2.12	13.6	0.26	y	Shen *et al.* (2011a)

List of SN EOS (cont.)

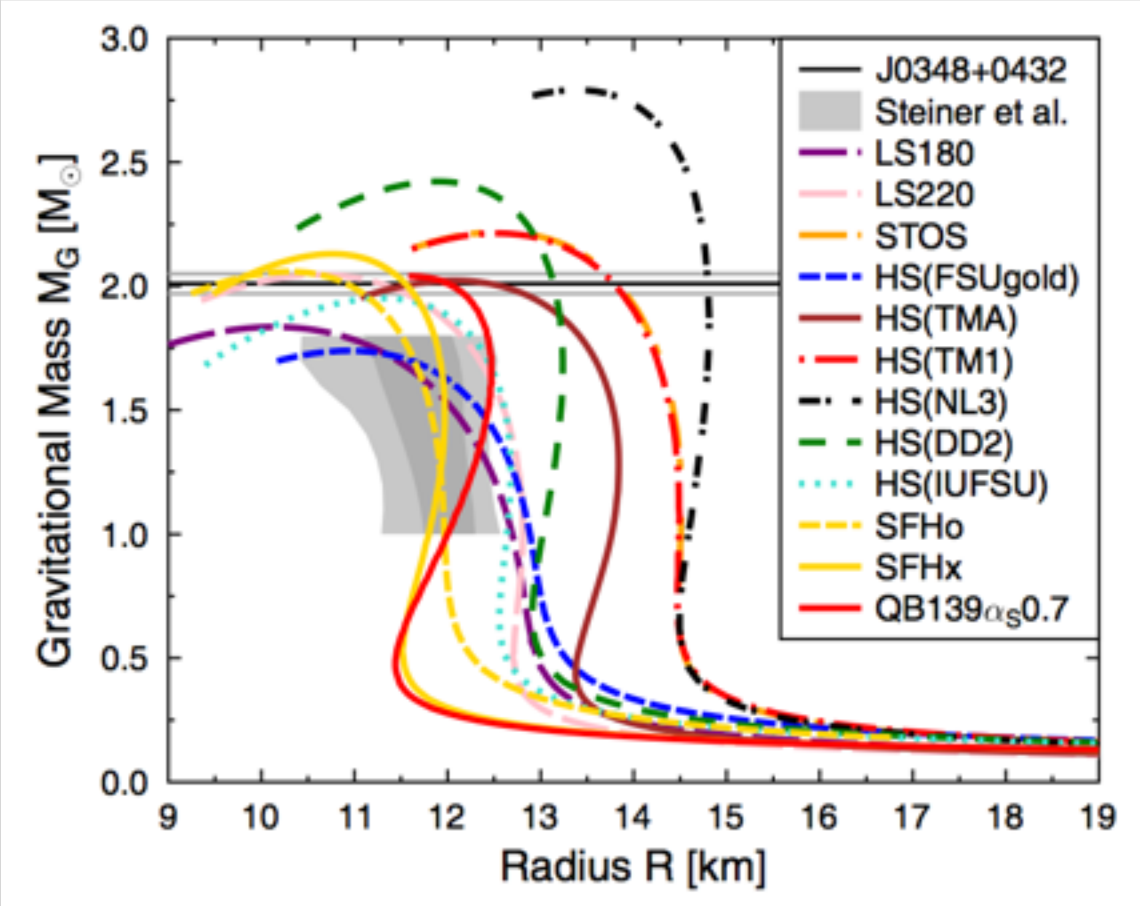
Oertel et al. (2016)

LS220Λ	LS220	$n, p, \alpha, (A, Z), \Lambda$	1.91	12.4	0.29	y	Oertel *et al.* (2012); Gulminelli *et al.* (2013)
LS220π	LS220	$n, p, \alpha, (A, Z), \pi$	1.95	12.2	0.29	n	Oertel *et al.* (2012); Peres *et al.* (2013)
BHBΛ	DD2	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}, \Lambda$	1.96	13.2	0.25	y	Banik *et al.* (2014)
BHBΛϕ	DD2	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}, \Lambda$	2.11	13.2	0.27	y	Banik *et al.* (2014)
STOSΛ	TM1	$n, p, \alpha, (A, Z), \Lambda$	1.90	14.4	0.23	y	Shen *et al.* (2011)
STOSYA30	TM1	$n, p, \alpha, (A, Z), Y$	1.59	14.6	0.17	y	Ishizuka *et al.* (2008)
STOSYA30π	TM1	$n, p, \alpha, (A, Z), Y, \pi$	1.62	13.7	0.19	y	Ishizuka *et al.* (2008)
STOSY0	TM1	$n, p, \alpha, (A, Z), Y$	1.64	14.6	0.18	y	Ishizuka *et al.* (2008)
STOSY0π	TM1	$n, p, \alpha, (A, Z), Y, \pi$	1.67	13.7	0.19	y	Ishizuka *et al.* (2008)
STOSY30	TM1	$n, p, \alpha, (A, Z), Y$	1.65	14.6	0.18	y	Ishizuka *et al.* (2008)
STOSY30π	TM1	$n, p, \alpha, (A, Z), Y, \pi$	1.67	13.7	0.19	y	Ishizuka *et al.* (2008)
STOSY90	TM1	$n, p, \alpha, (A, Z), Y$	1.65	14.6	0.18	y	Ishizuka *et al.* (2008)
STOSY90π	TM1	$n, p, \alpha, (A, Z), Y, \pi$	1.67	13.7	0.19	y	Ishizuka *et al.* (2008)
STOSπ	TM1	$n, p, \alpha, (A, Z), \pi$	2.06	13.6	0.26	n	Nakazato *et al.* (2008)
STOSQ209nπ	TM1	$n, p, \alpha, (A, Z), \pi, q$	1.85	13.6	0.21	n	Nakazato *et al.* (2008)
STOSQ162n	TM1	$n, p, \alpha, (A, Z), q$	1.54			n	Nakazato *et al.* (2013)
STOSQ184n	TM1	$n, p, \alpha, (A, Z), q$	1.36	—[b]		n	Nakazato *et al.* (2013)
STOSQ209n	TM1	$n, p, \alpha, (A, Z), q$	1.81	14.4	0.20	n	Nakazato *et al.* (2008, 2013)
STOSQ139s	TM1	$n, p, \alpha, (A, Z), q$	2.08	12.6	0.26	y	Sagert *et al.* (2012a); Fischer *et al.* (2014b)
STOSQ145s	TM1	$n, p, \alpha, (A, Z), q$	2.01	13.0	0.25	y	Sagert *et al.* (2012a)
STOSQ155s	TM1	$n, p, \alpha, (A, Z), q$	1.70	9.93	0.25	y	Fischer *et al.* (2011)
STOSQ162s	TM1	$n, p, \alpha, (A, Z), q$	1.57	8.94	0.26	y	Sagert *et al.* (2009)
STOSQ165s	TM1	$n, p, \alpha, (A, Z), q$	1.51	8.86	0.25	y	Sagert *et al.* (2009)

Nuclear matter properties and NS properties

Oertel et al. (2016)

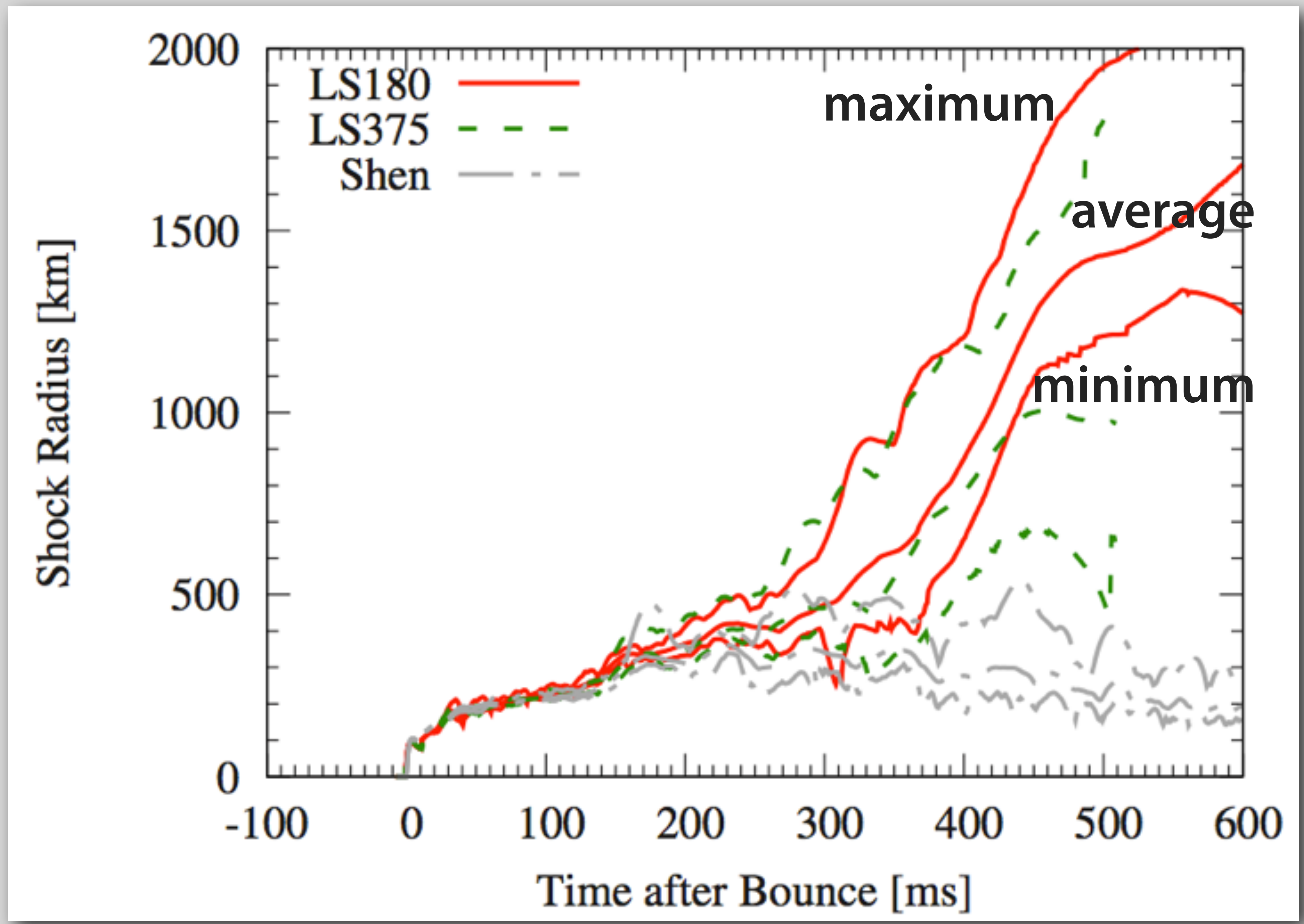
Nuclear Interaction	n_{sat} (fm^{-3})	B_{sat} (MeV)	K (MeV)	Q (MeV)	J (MeV)	L (MeV)
SKa	0.155	16.0	263	-300	32.9	74.6
LS180	0.155	16.0	180	-451	28.6[a]	73.8
LS220	0.155	16.0	220	-411	28.6[a]	73.8
LS375	0.155	16.0	375	176	28.6[a]	73.8
TM1	0.145	16.3	281	-285	36.9	110.8
TMA	0.147	16.0	318	-572	30.7	90.1
NL3	0.148	16.2	272	203	37.3	118.2
FSUgold	0.148	16.3	230	-524	32.6	60.5
FSUgold2.1	0.148	16.3	230	-524	32.6	60.5
IUFSU	0.155	16.4	231	-290	31.3	47.2
DD2	0.149	16.0	243	169	31.7	55.0
SFHo	0.158	16.2	245	-468	31.6	47.1
SFHx	0.160	16.2	239	-457	28.7	23.2



[Fischer, Hempel, Sagert, Suwa, Schaffner-Bielich, EPJA, **50**, 46 (2014)]

Shock radius evolution depending on EOS

[Suwa, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ, **764**, 99 (2013)]; 15$M_\odot$

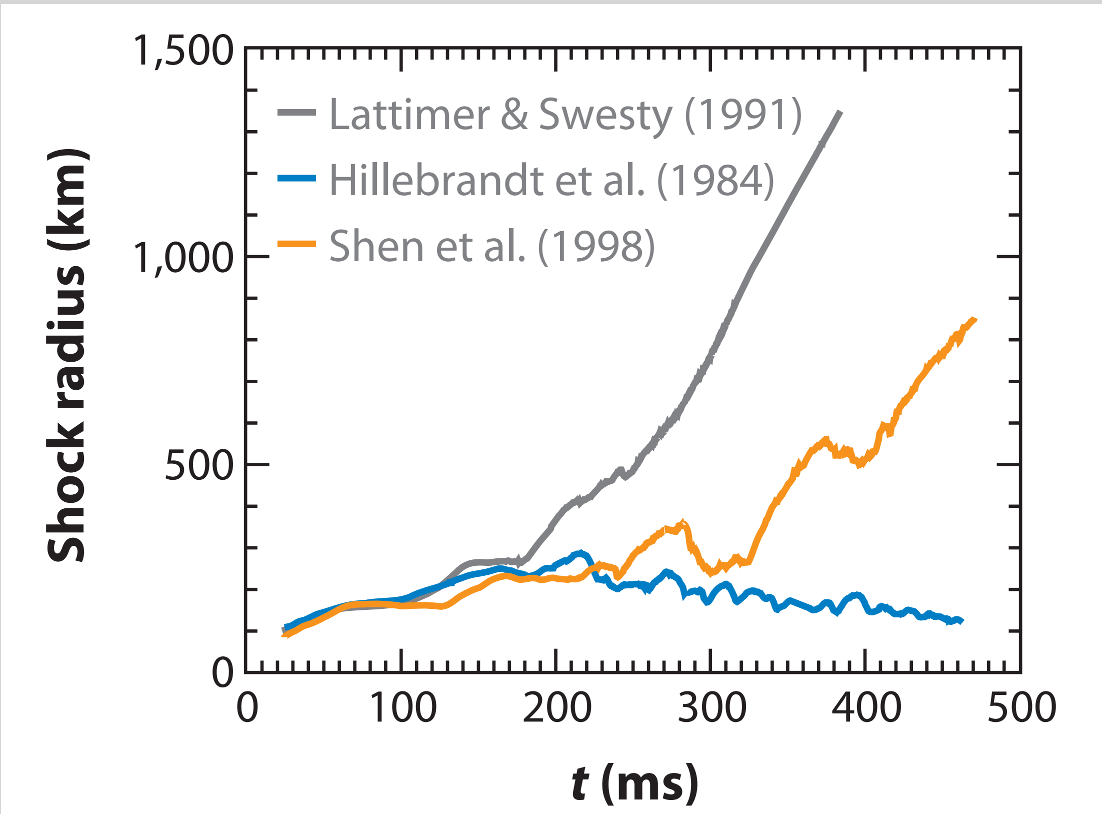


LS180 and LS375 succeed the explosion

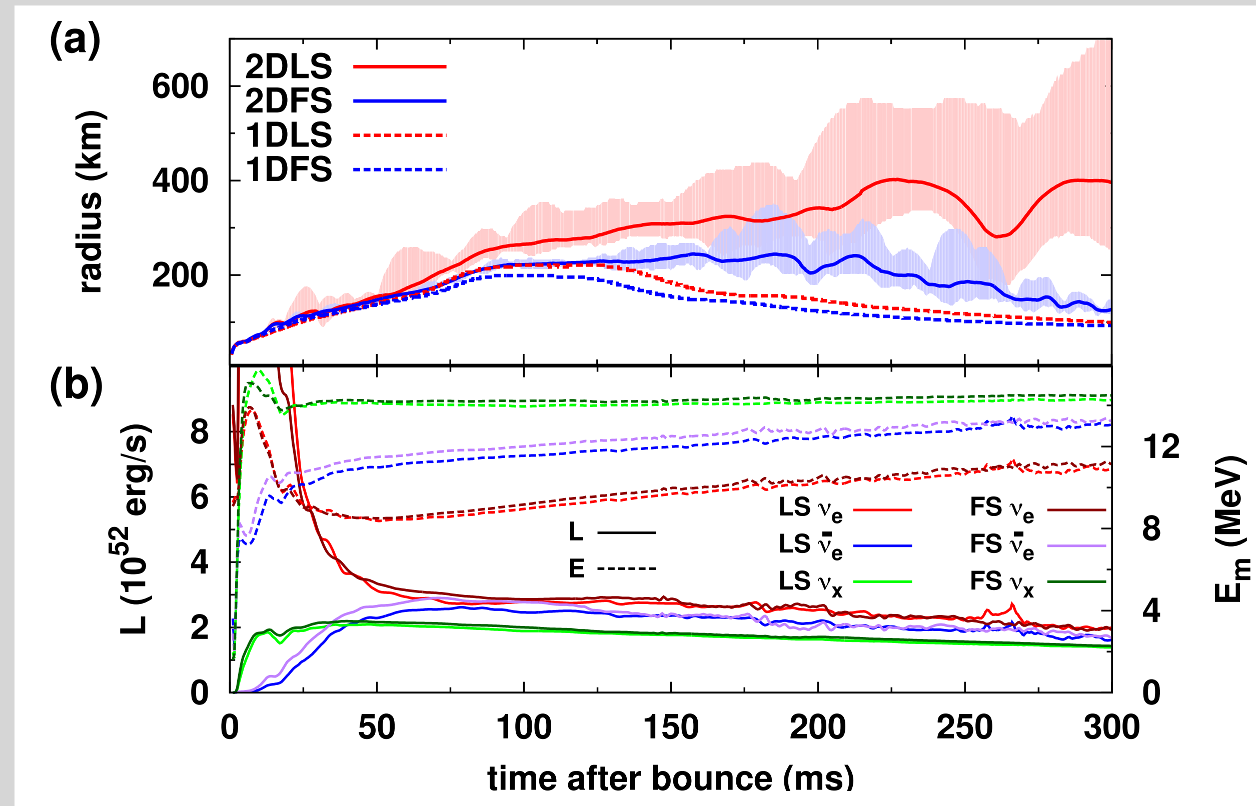
HShen (TM1) EOS fails

Other works

Janka (2012); M_{ZAMS}=11.2$M_\odot$



Nagakura et al. (2017); M_{ZAMS}=11.2$M_\odot$



Softer EOS (i.e. smaller M_{max}) is better for the explosion

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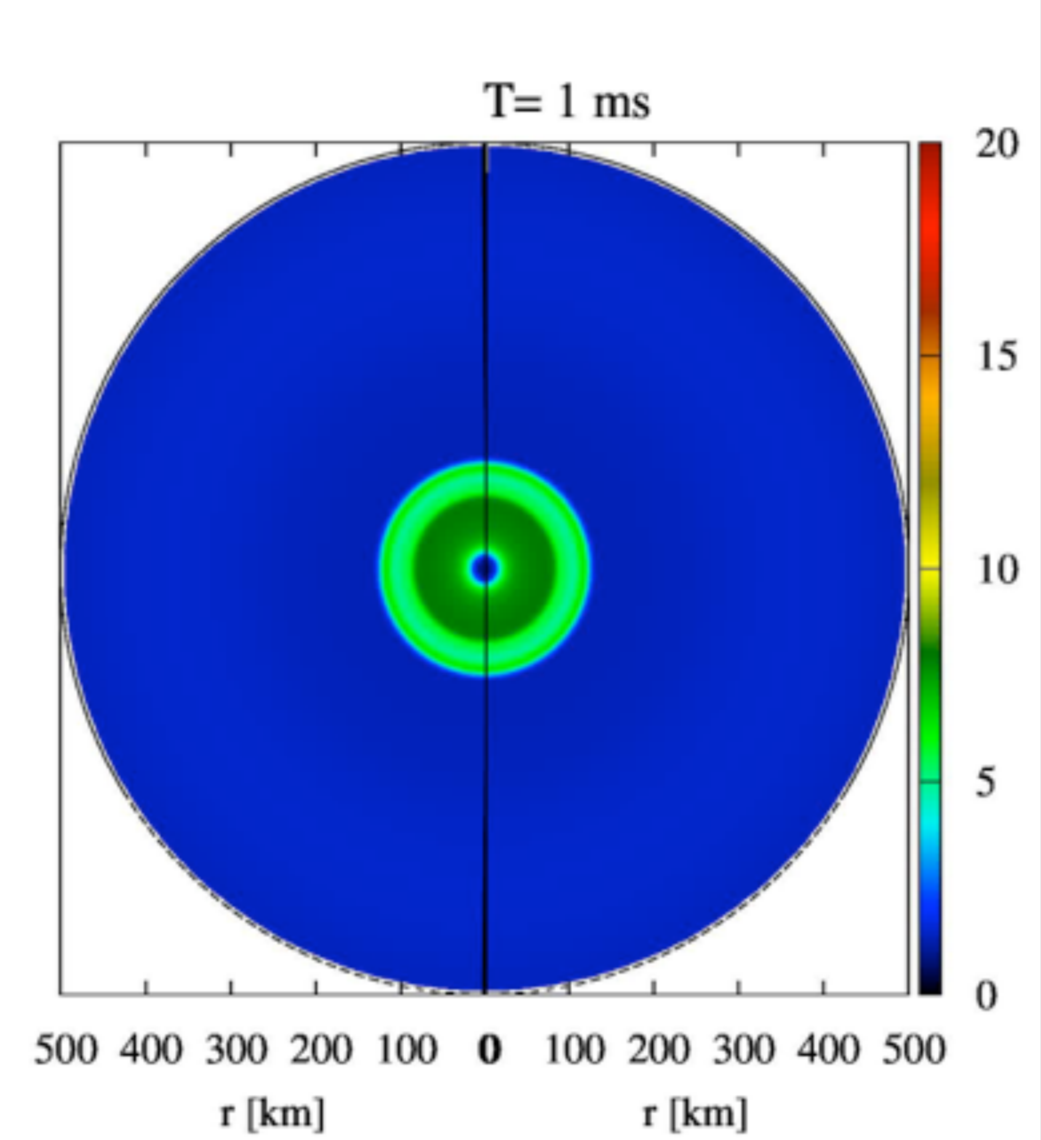
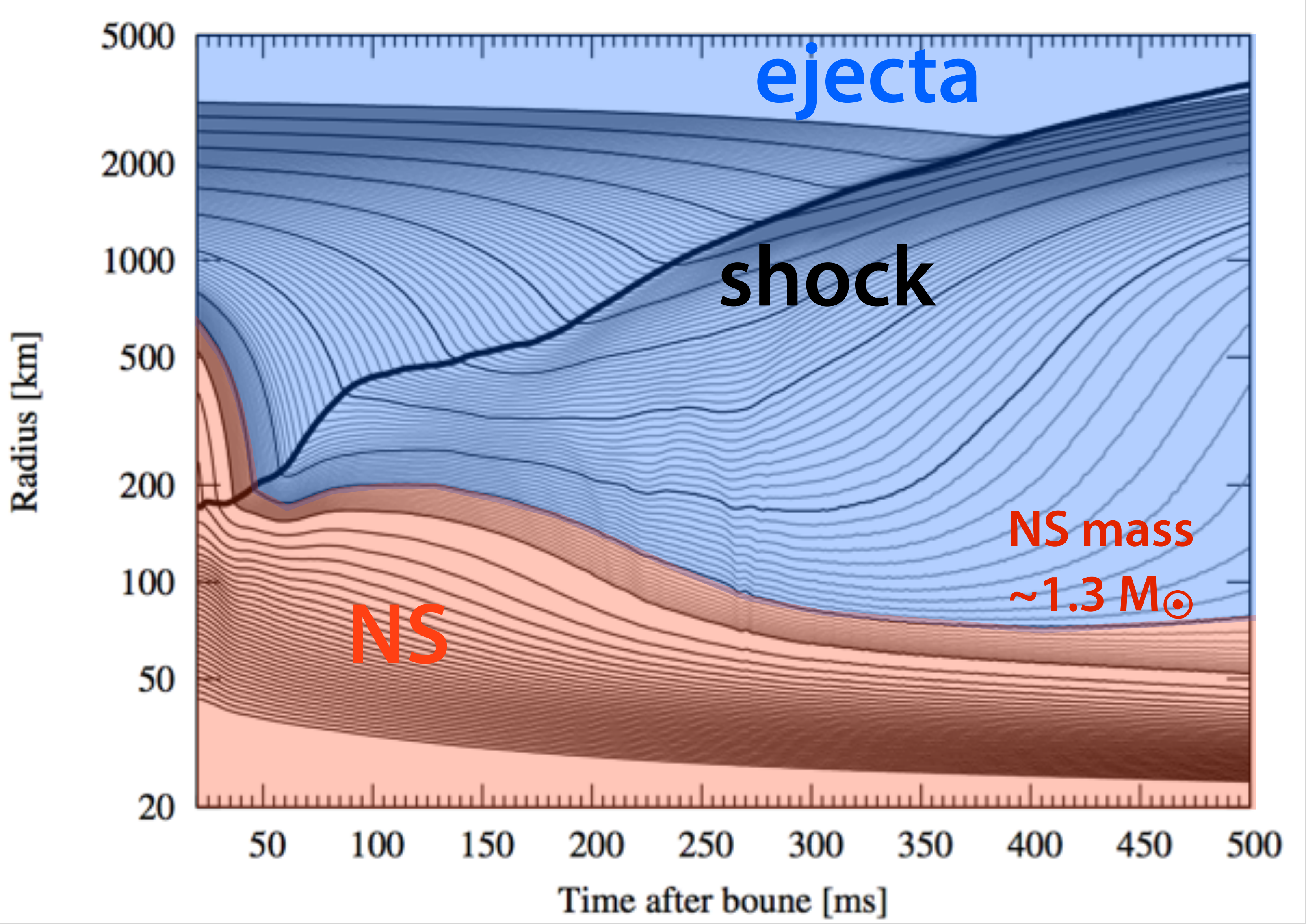
From SN to NS

[Suwa, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ, **764**, 99 (2013); Suwa, PASJ, **66**, L1 (2014)]

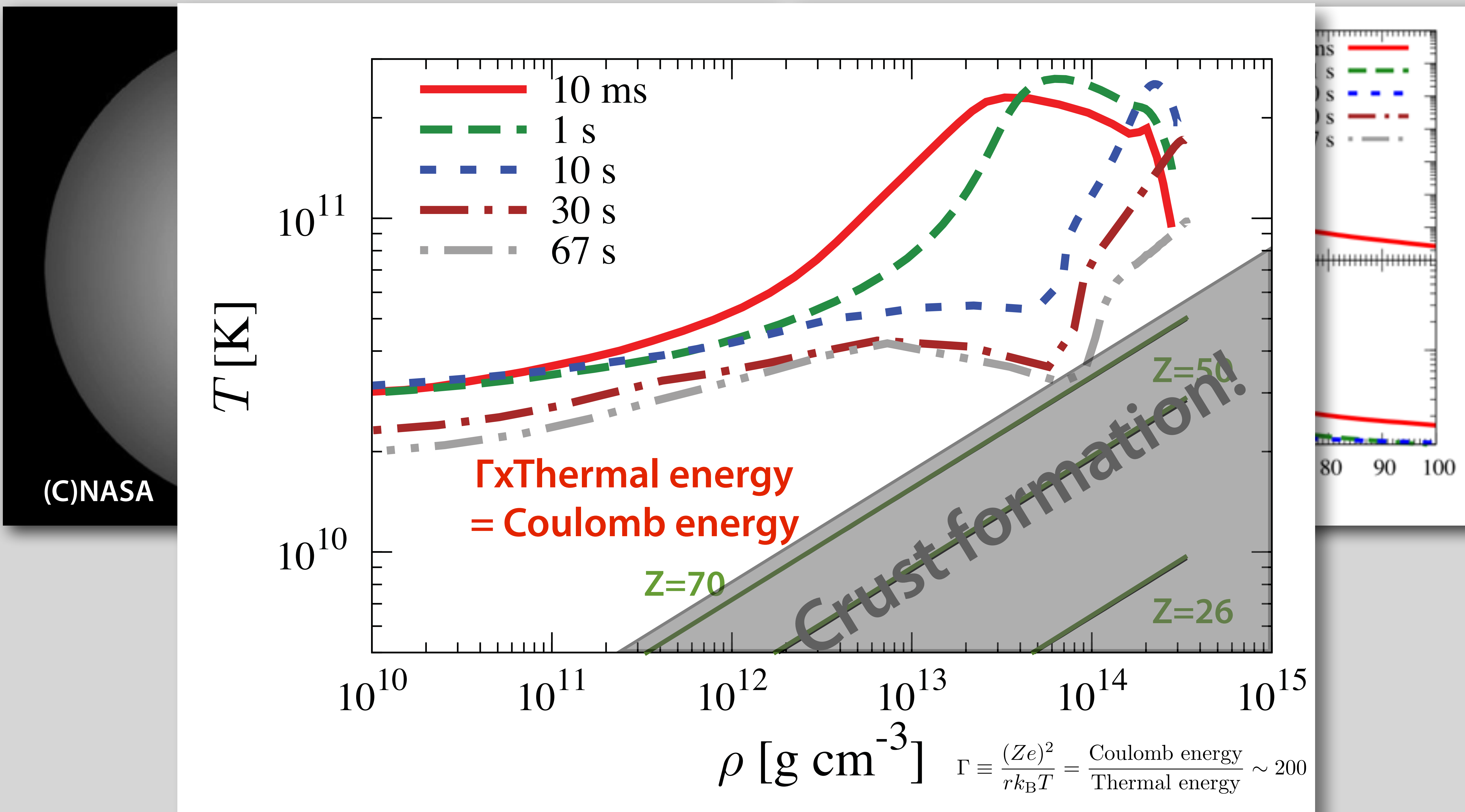




* **Progenitor:** $11.2\ M_\odot$ (Woosley+ 2002)
* **Successful explosion! (but still weak with E_{exp}~10^{50} erg)**
* **The mass of NS is ~$1.3\ M_\odot$**
* **The simulation was continued in 1D to follow the PNS cooling phase up to ~70 s p.b.**

From SN to NS

[Suwa, PASJ, **66**, L1 (2014)]

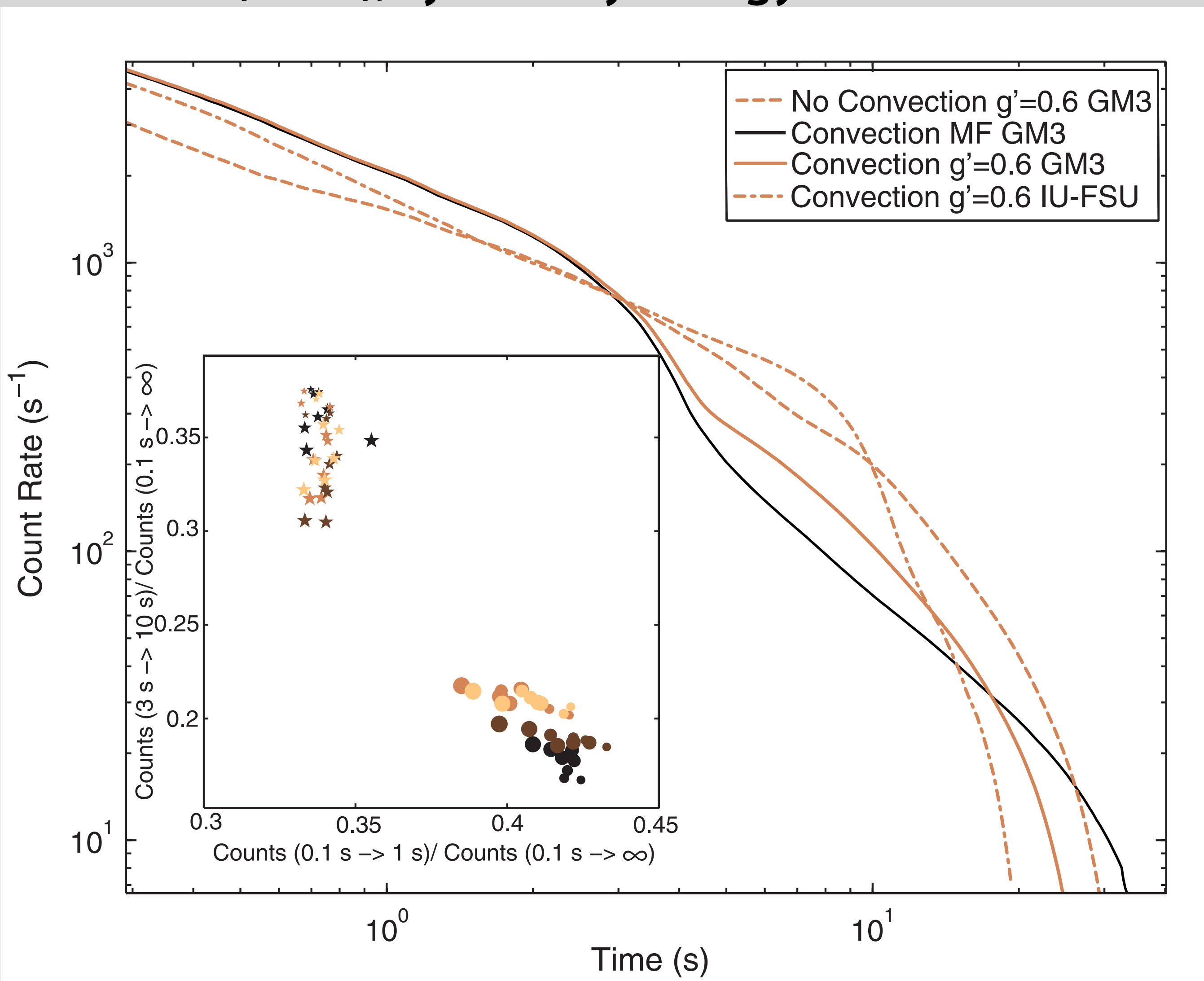


From SN to NS: Implications

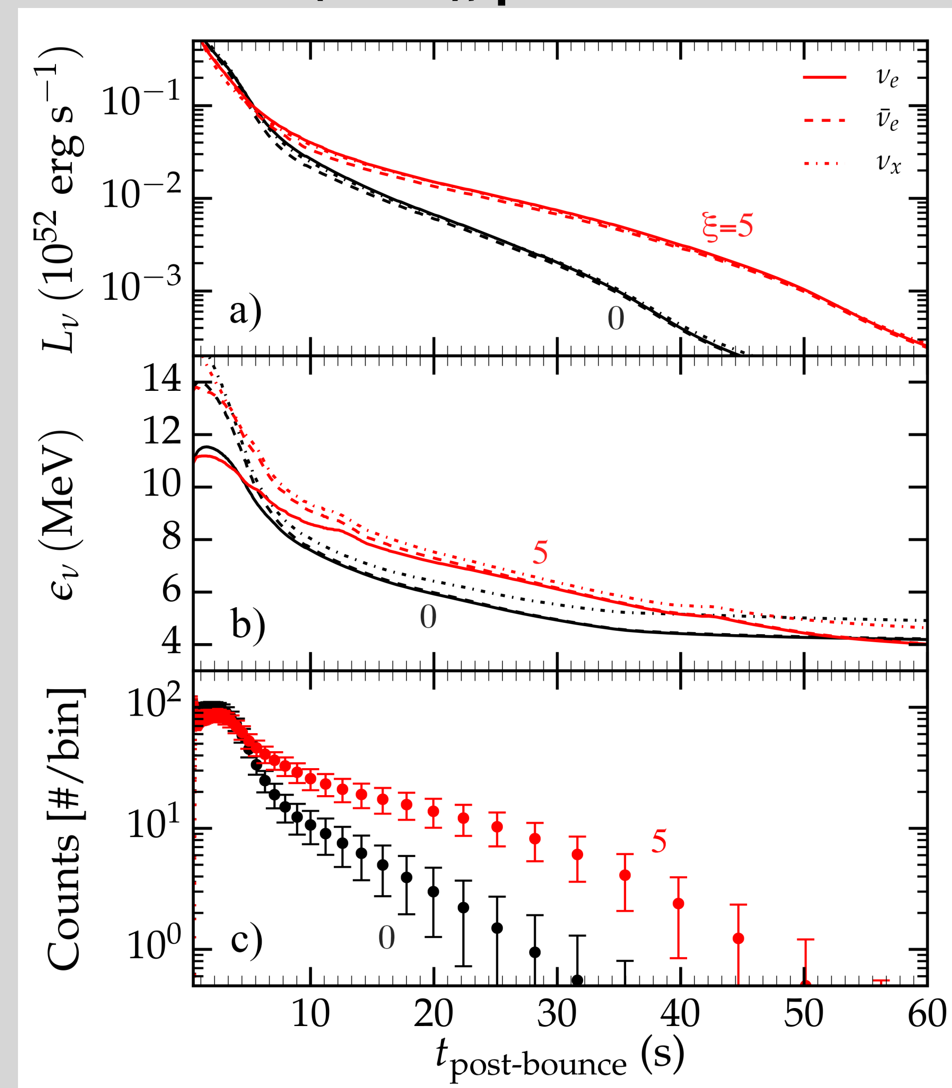
- **Crust formation time should depend on EOS** (especially symmetry energy?)
- **We may observe crust formation via neutrino luminosity evolution of a SN in our galaxy**
  - Cross section of neutrino scattering by heavier nuclei or *nuclear pasta* is much larger than that of neutrons and protons
  - Neutrino luminosity may be significantly changed when a NS has heavier nuclei!
- **Magnetar (large B-field NS) formation**
  - competitive process between crust formation and magnetic field escape from NS

Neutrino probe of nuclear physics

Robertz+ (2012); symmetry energy and convection



Horowitz+ (2016); pasta formation



Summary

Take away message

1. **Supernova simulations are exploding!**

2. **Nuclear equation of state is an important ingredient which can change explodability. Softer seems better.**

3. **Neutrino transfer is essential, but still needs lot of works to obtain solution. 7D solutions are reachable in the next decade.**

4. **Consistent modeling from iron cores to (cold) neutron stars is doable now. Neutrino observations by Super-K and Hyper-K will tell us nuclear physics aspects as well as astrophysics.**