超新星の爆発メカニズムとマルチメッセンジャー

Explosion Mechanisms of Core-Collapse Supernovae and the Multi-messenger Observables

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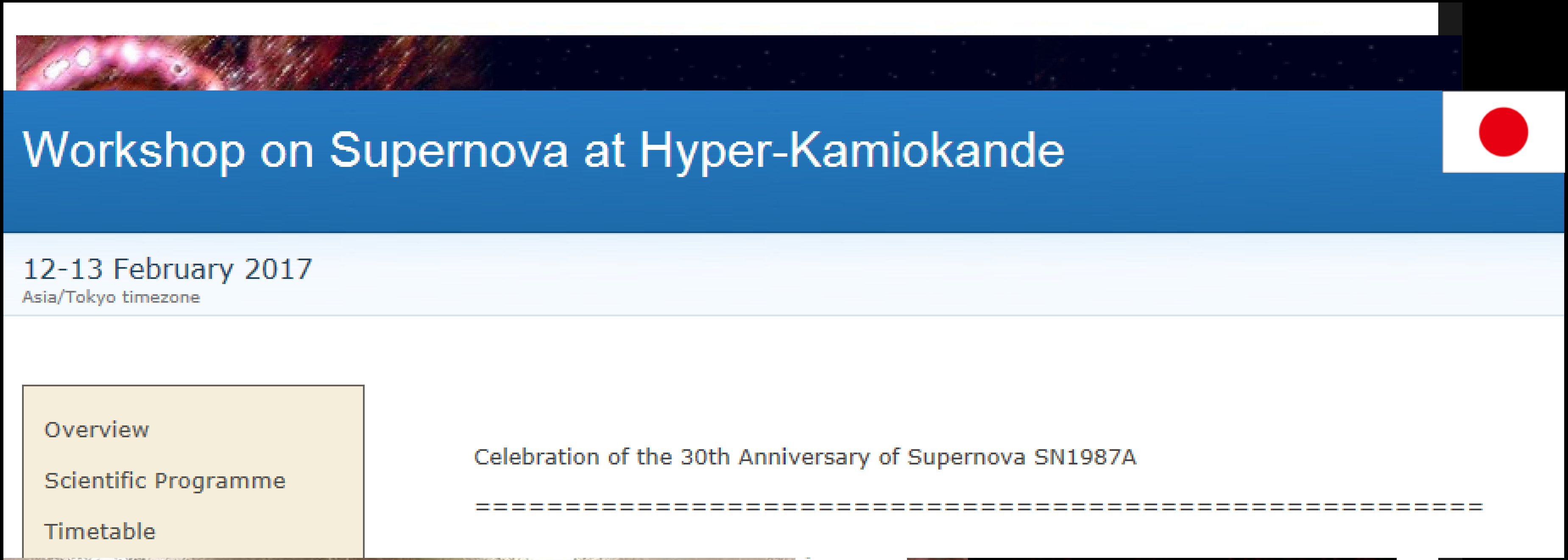
新学術「地下素核研究」
第４回超新星ニュートリノ研究会
2018年1/7, 箱根静雲荘

Many workshops to celebrate 30 years of SN1987A !



Workshop on Supernova at Hyper-Kamiokande

12-13 February 2017
Asia/Tokyo timezone

- Overview
- Scientific Programme
- Timetable

Celebration of the 30th Anniversary of Supernova SN1987A

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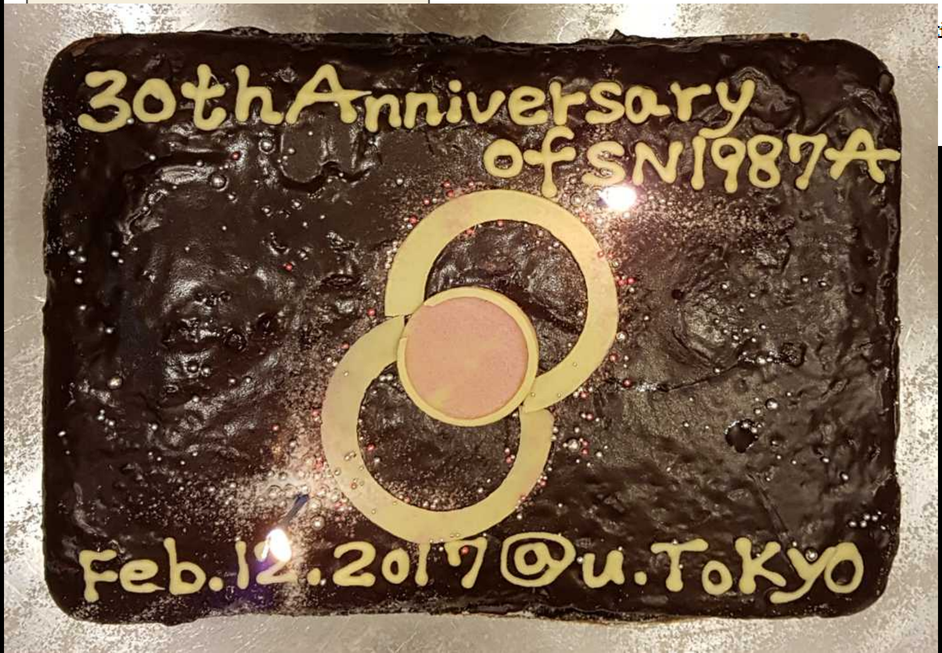
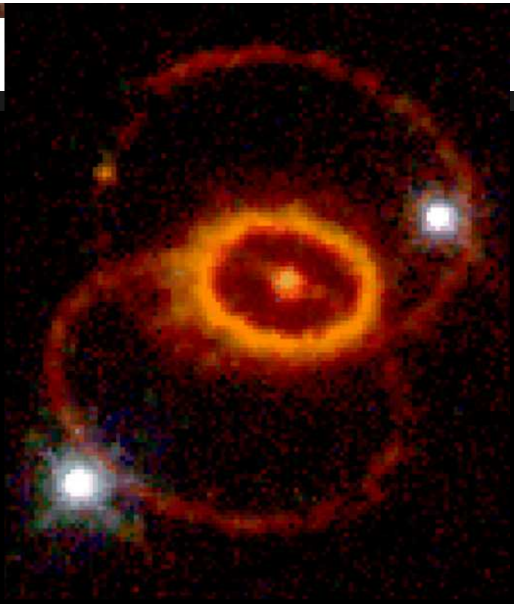
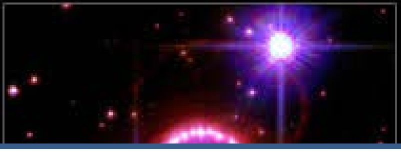
prospekt" - al





Looking back ~30 years, significant progress made in GW oservation !



10^{-18}

Typical thresholds of proto-types in 1989

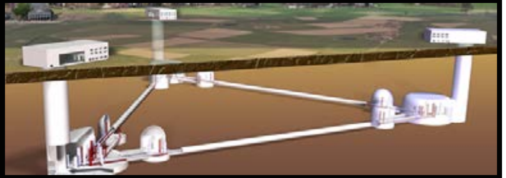
(MIT, Garching, Caltech, Glasgow and Tokyo)

Sensitivity curves of laser interferometers

10 km long:

Einstein Telescope (ET)

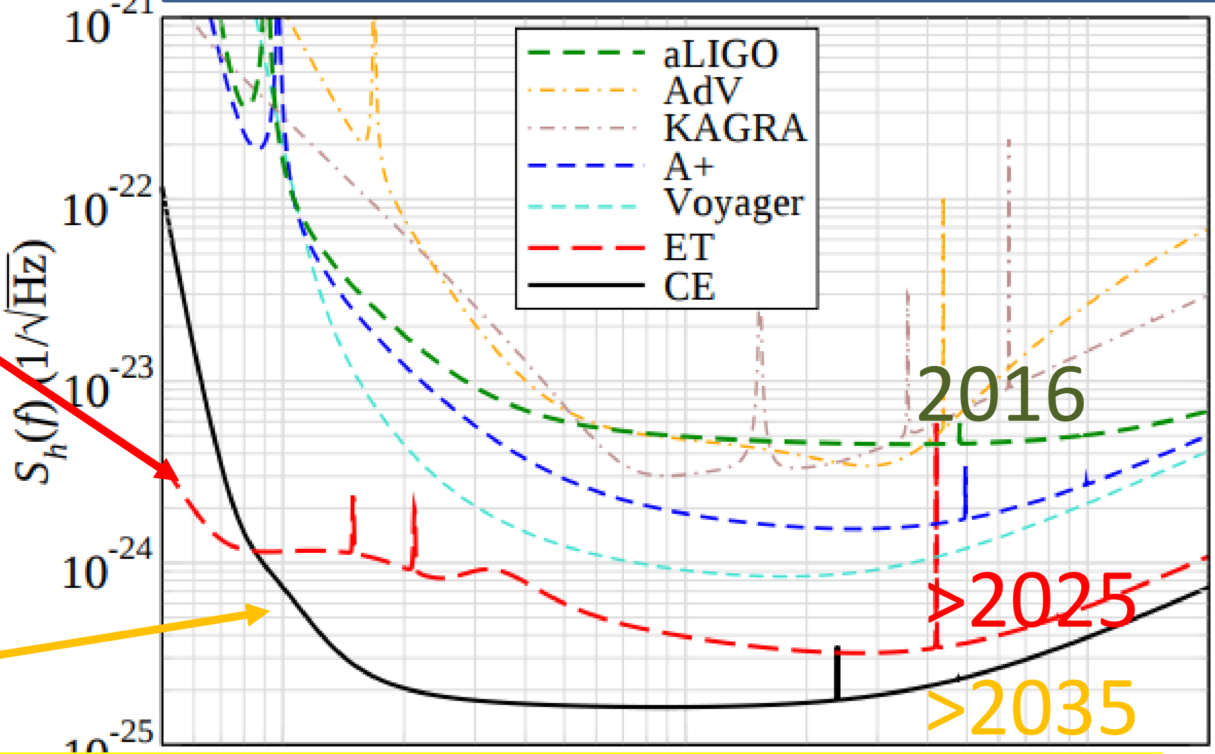
could start ~2025.



40 km long:

Cosmic Explore (CE)

could operate ~2035.



GW astronomy is no more a dream !

The base-line and final goal (s)

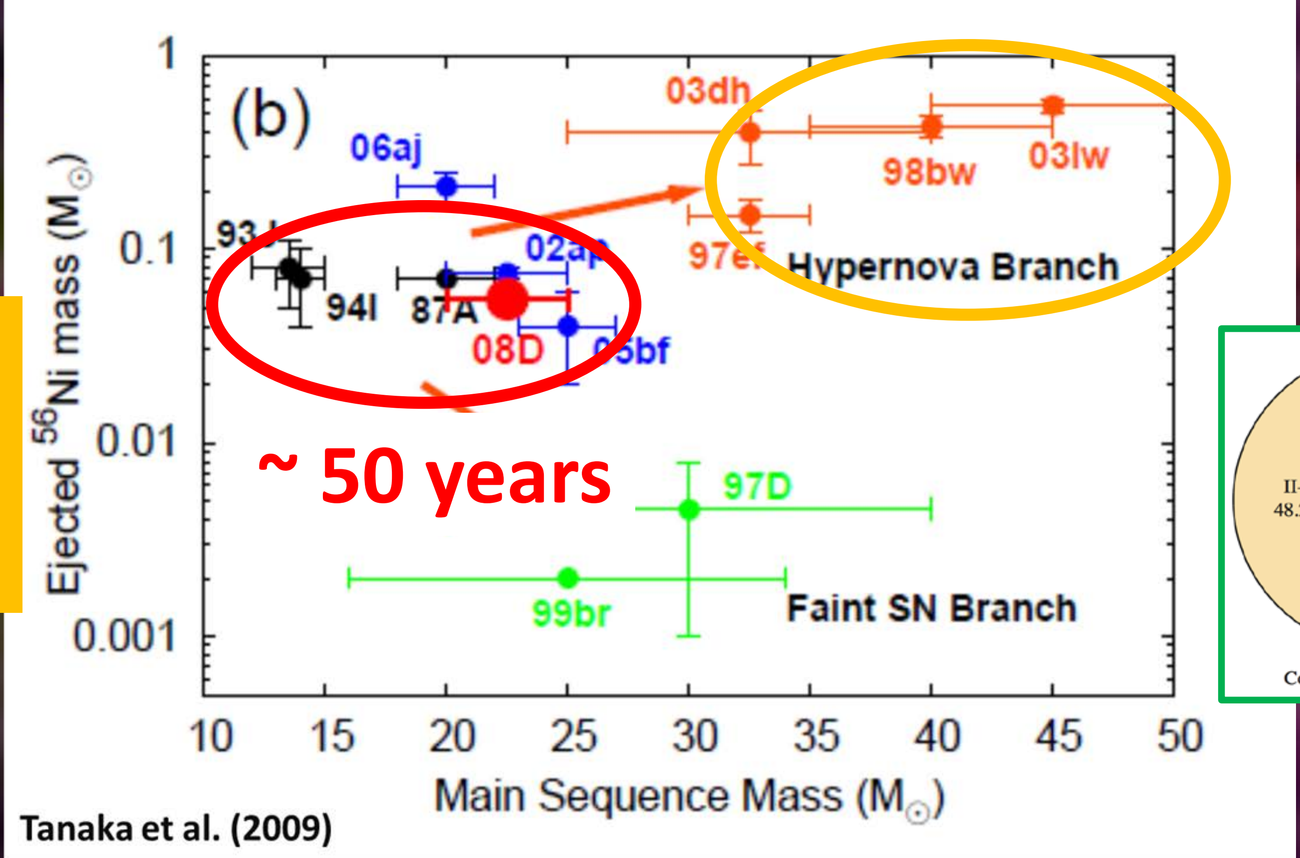
What is the physics for exploding massive stars?

~ 10FOE

~ 1 FOE

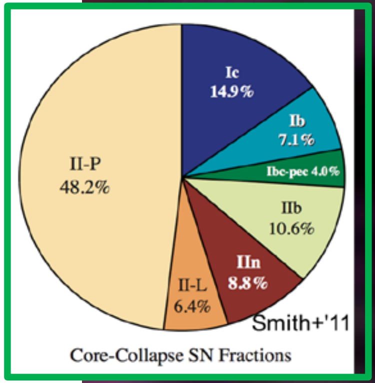
FOE: Fifty-one-erg
10^{51} erg
= 1 Bethe

Numerical study:
Colgate & White
(1966)



~ 50 years

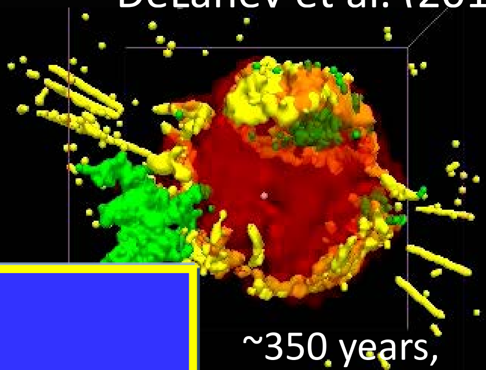
Tanaka et al. (2009)



Core-Collapse SN Fractions

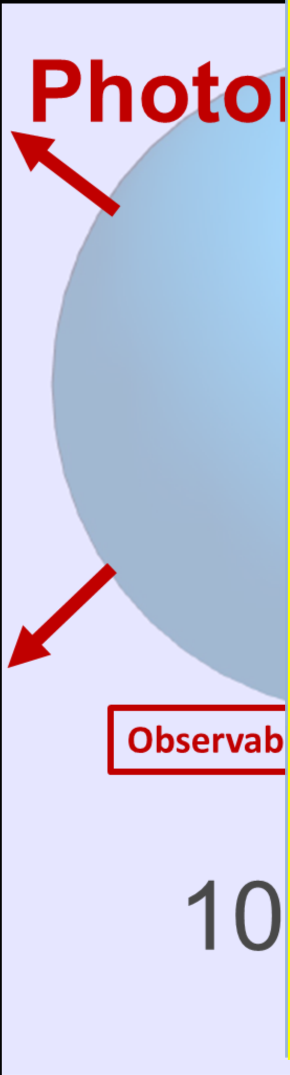
1). For which types of the progenitors (IIp, Ib/Ic, IIn) is rotation/B field most important ?
2). and 3). If important, why and how ?
4). Collapsar, Magnetar scenarios: Which one successful (or other) ? why ?
5). How long will it take before first-principles doable ? Strategies ?

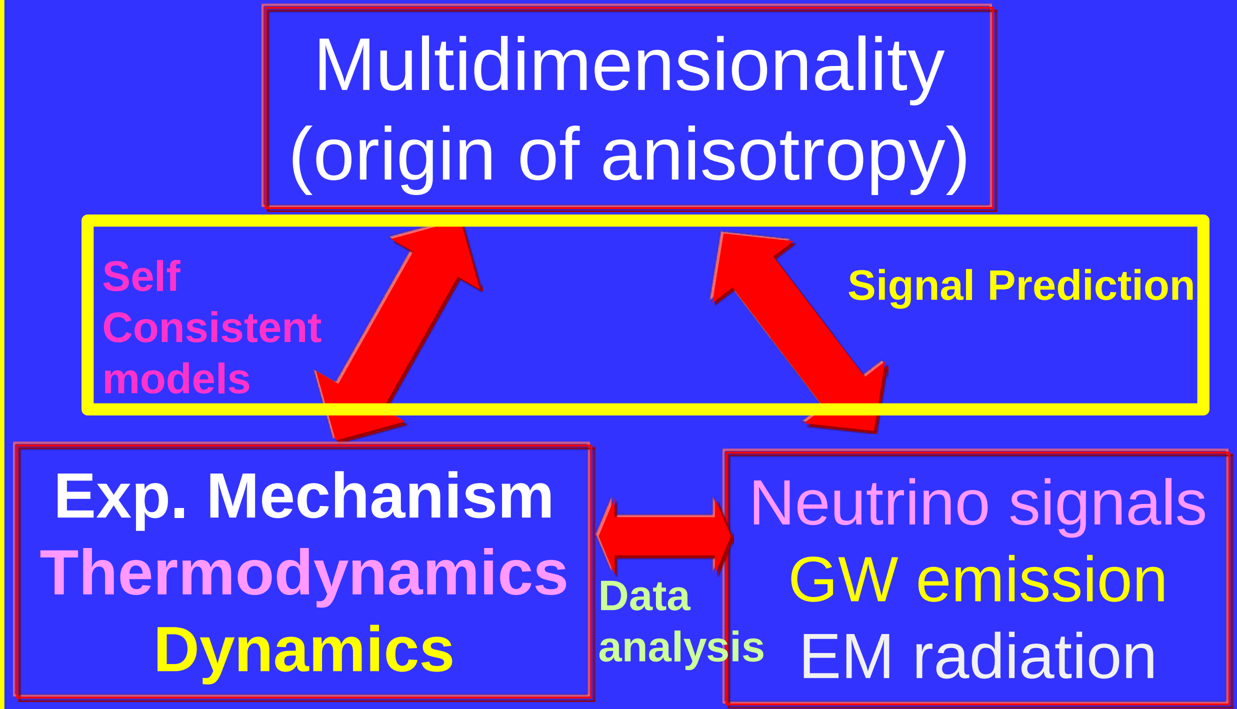
Typical Scales of CCSN multimessenger



DeLanev et al. (2010)

~350 years,
Type IIb





Multidimensionality
(origin of anisotropy)

Self Consistent models

Signal Prediction

Exp. Mechanism
Thermodynamics
Dynamics

Data analysis

Neutrino signals
GW emission
EM radiation

✓A **Final goal of SN modelers.**
:To decipher explosion dynamics via
Muti-messenger observables
(neutrinos, GW, electromagnetic waves)

Outline

✓ **Brief introduction** **(5 min)**

what we can learn from SN multi-messengers ?

✓ **Recent progresses in “Supernova Theory”** **(30 min)**

☆ **The Core-Collapse Supernova Theory**

:what is the essence to blow up massive stars?

☆ **Candidate mechanisms:** **based on first-principle multi-D radiation-hydrodynamic simulations**

✓ **Observational Signatures** **(30 min)**

☆ **Detectability of neutrino and gravitational-wave signals**

☆ **Perspectives toward “MM” astronomy**

(correlation analysis between GWs/neutrinos, electromagnetic messengers)

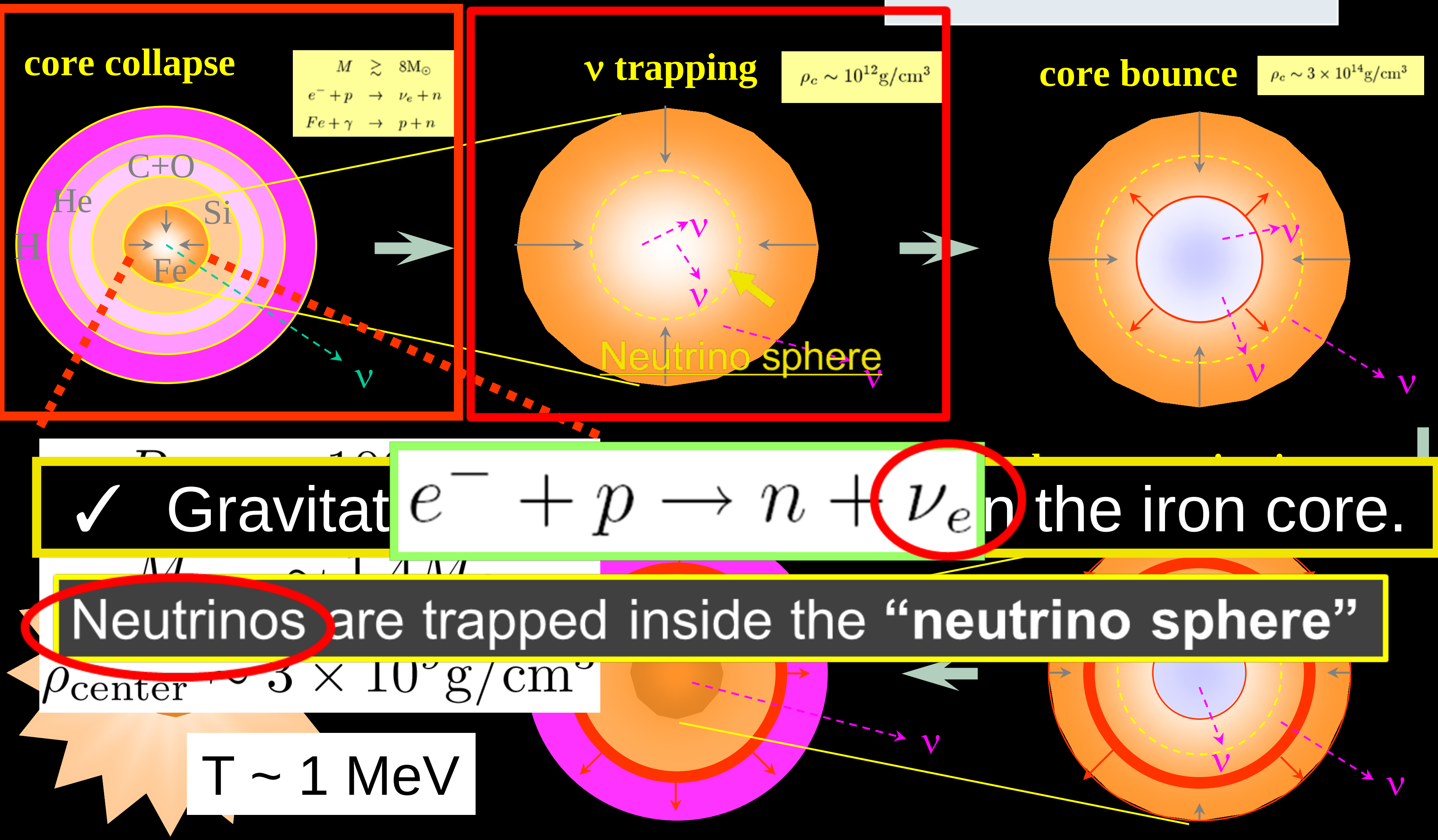
What can we learn from the central engine ?

K.Sato (1975)

Standard scenario of core

(e.g., Kotake+06, Foglizzo+14, M … view)

$$\rho_{\text{center}} \approx 10^{12}\,\mathrm{g/cm}^3$$
$$\rho_{\text{trap}} \approx 1.4 \times 10^{11}\,\mathrm{g/cm}^3$$



✓ Gravitat … n the iron core.

$$e^- + p \rightarrow n + \nu_e$$

Neutrinos are trapped inside the “**neutrino sphere**”

$\rho_{\text{center}} \ \ 3 \times 10\ \mathrm{g/cm}^3$

T ~ 1 MeV


(Weinberg)

Step 2 Neutrino Trapping


(Salam)

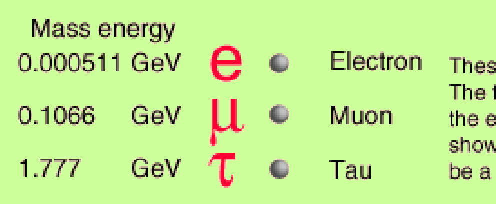
Neutrino → **Weak interacting particle**

（Neutral-rino: neutral-particle, light mass (<eV)）

$$\sigma \sim 10^{-38}\mathrm{cm}^2 \quad (\mathrm{at\ 1GeV}) \ll \sigma_{\mathrm{T}} \sim 10^{-25}\mathrm{cm}^2$$

Representative Neutrino reactions in the SN core

Neutrino emission/absorption	Scattering with（N：nucleon （A, Z）： Nuclei)	Pair reaction Bremsstrahlung
$p + e^- \rightleftarrows n + \nu_e$ $n + e^+ \rightleftarrows p + \bar{\nu}_e$	$\nu + N \rightleftarrows \nu + N$	$N + N \rightleftarrows N + N + \nu + \bar{\nu}$ $e^+ + e^- \rightleftarrows \nu + \bar{\nu}$
$(A, Z) + e^- \rightleftarrows (A, Z-1) + \nu_e$	$\boxed{\nu + (A, Z) \rightleftarrows \nu + (A, Z)}$ $\nu + e^{\pm} \rightleftarrows \nu + e^{\pm}$	

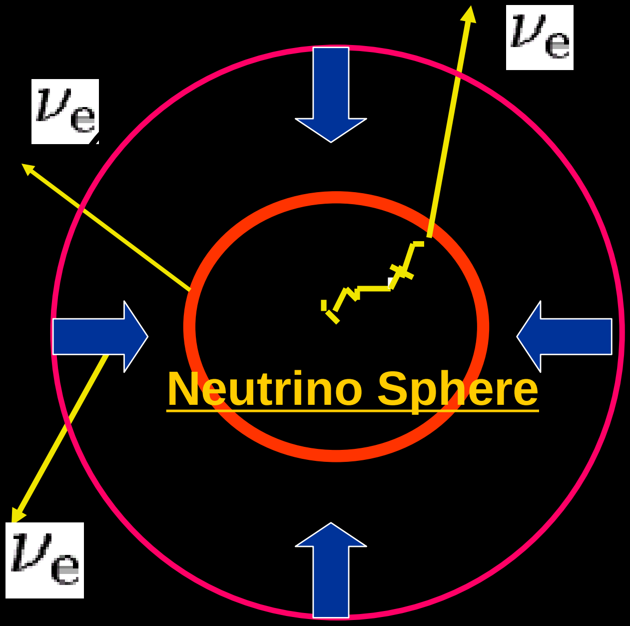


Mass energy				
0.000511 GeV	e	●	Electron	Thes The
0.1066 GeV	μ	●	Muon	the e show
1.777 GeV	τ	●	Tau	be a

(see, however, Bollig et al (2017))

The condition of “Neutrino trapping”

K. Sato (1975)
PTP



To judge whether neutrinos can be trapped or not in the iron core, Compare the two timescales !

Free-fall timescale $\tau_{\rm ff}$

Diffusion timescale due to coherent neutrino-A scattering $\tau_{\rm diff}$

$$\begin{cases} \rho \dfrac{\partial^2 r}{\partial t^2} = -\dfrac{GM_r \rho}{r^2} \\ \rho \sim \dfrac{M}{4\pi/3R^3} \end{cases}$$

$$N_{\rm R} = \left(\frac{R}{\lambda}\right)^2$$

Number of scattering (random walk)

$$N_{\rm R}\frac{\lambda}{c} = \frac{R^2}{c\lambda}$$

Diffusion timescale

$$t_{\rm diff} = \frac{3R^2}{c\lambda}$$

$$R_{\rm core} = \left(\frac{3M}{4\pi\rho}\right)^{1/3}$$

$$t_{\rm diff} \leq t_{\rm dyn}$$

Mean free-path by the coherent scattering

$$\lambda_\nu = \frac{1}{\sigma n_A} \approx 10^7 {\rm cm} \left(\frac{\rho}{3\times10^{10}{\rm gcm}^{-3}}\right)^{-1} \left(\frac{E_\nu}{12.6{\rm MeV}}\right)^{-2} \left(\frac{A}{56}\right)^{-1} \left(\frac{Y_e}{26/56}\right)^{-\frac{2}{3}}$$

Average neutrino energy

$$E_\nu \approx \frac{5}{6}\mu_e = \frac{5}{6}\left(3\pi^2\frac{\rho Y_e}{m_p}\right)^{\frac{1}{3}} \hbar c \approx 12.6{\rm MeV}\left(\frac{\rho}{3\times10^{10}{\rm g\ cm}^{-3}}\right)^{\frac{1}{3}} \left(\frac{Y_e}{26/56}\right)^{\frac{1}{3}}$$

$\tau_{\rm ff} \sim$

$^{-3}$)

✓ The position of the neutrino sphere is energy-dependent !

$$R_\nu \approx 1.0\times10^7\ {\rm cm}\left(\frac{E_\nu}{10{\rm MeV}}\right)$$

For lower-energy neutrinos,
the neutrino sphere forms deeper inside, because they need
a denser environment to be opaque!

s).

Muon creation in supernova matter facilitates neutrino-driven explosions

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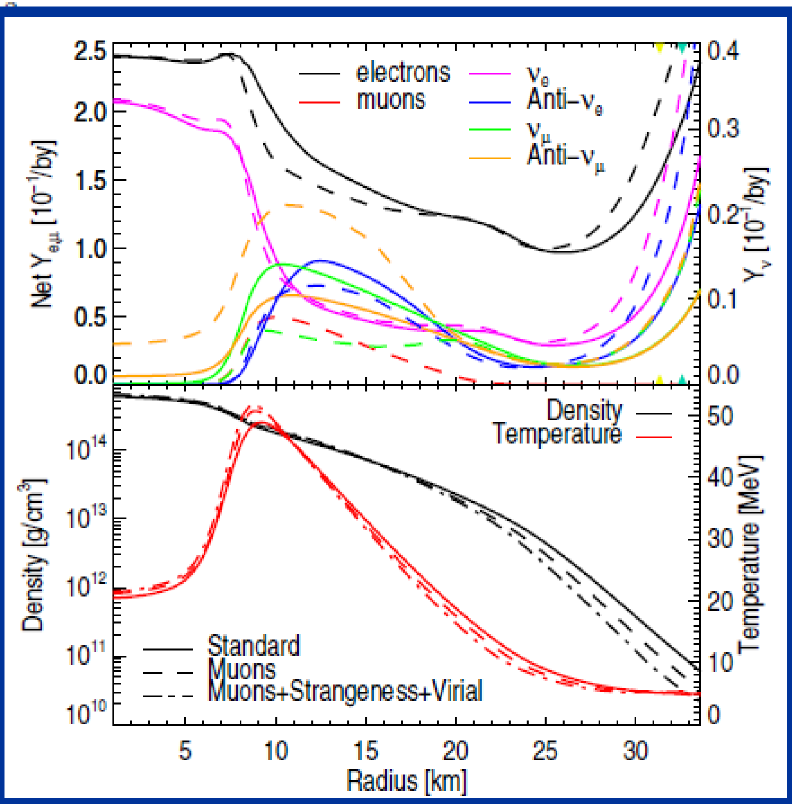
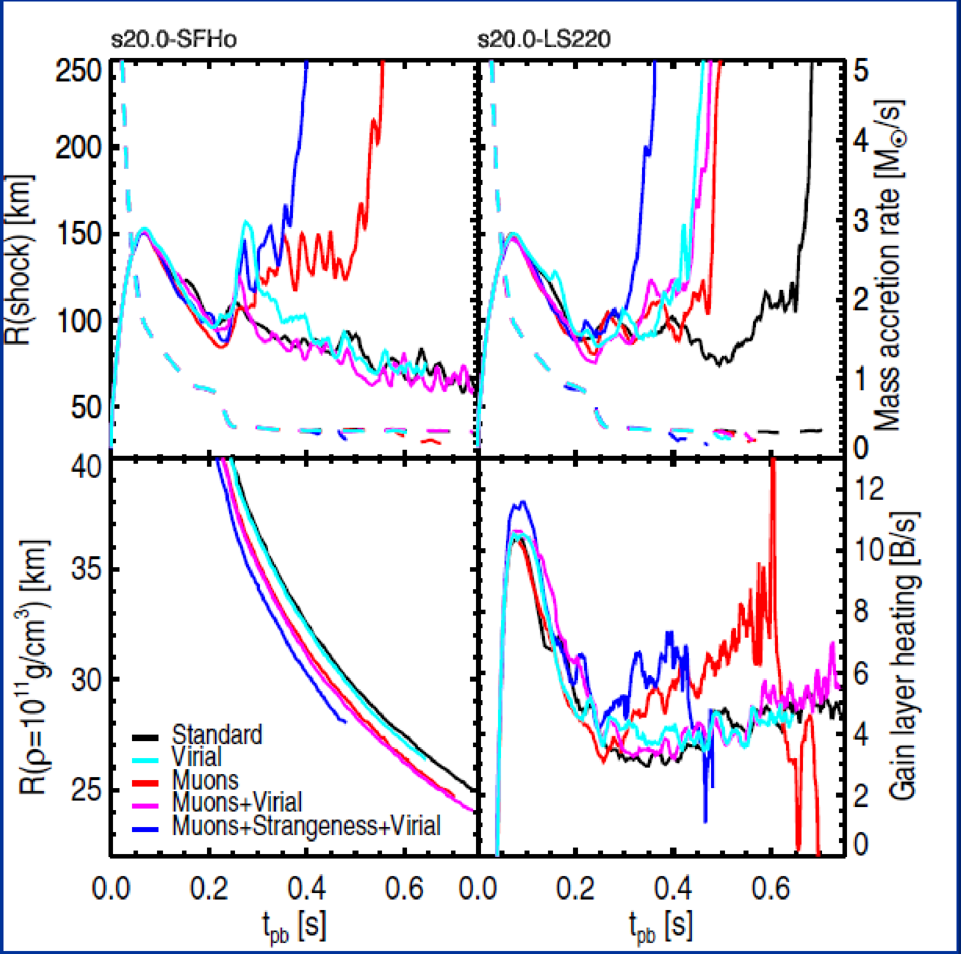
[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany*

2017, PRL

- ✓ 20 M_{sun} star (Woosley & Heger 2007)
- ✓ VERTEX-PROMETHIUS code





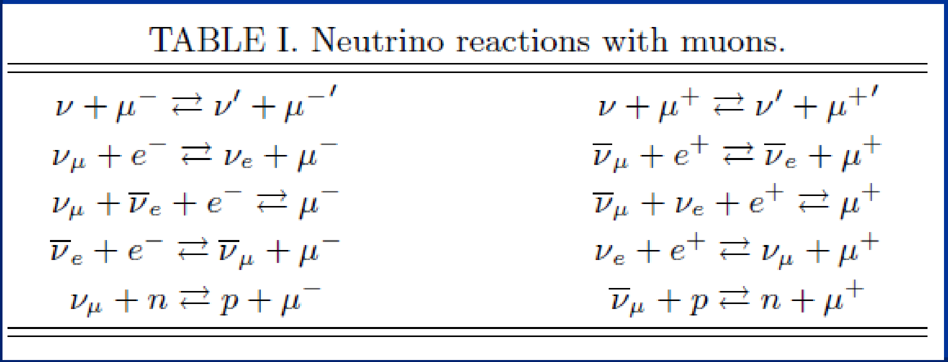


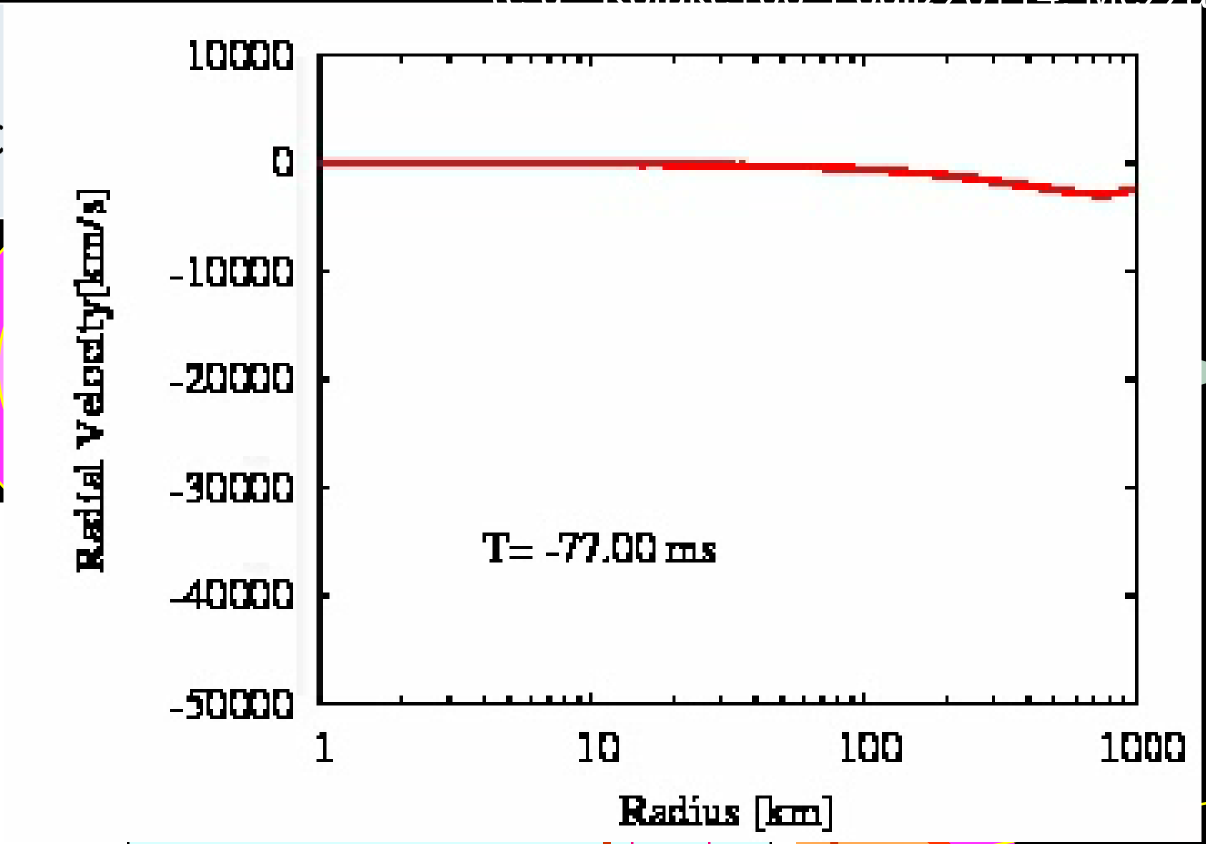
TABLE I. Neutrino reactions with muons.

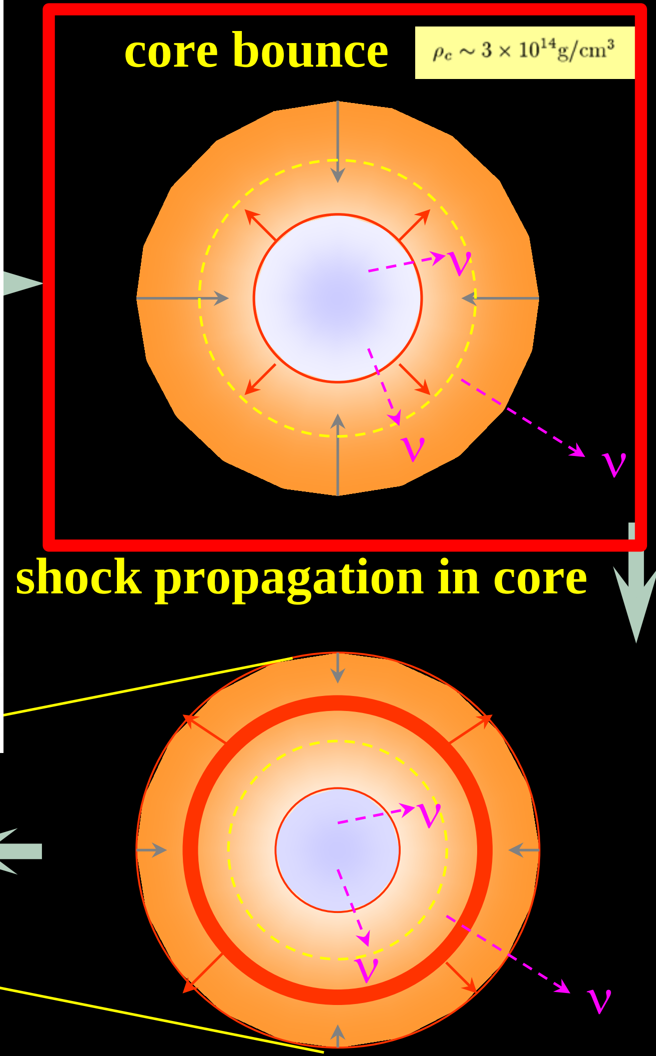
$\nu + \mu^- \rightleftarrows \nu' + \mu^{-\prime}$	$\nu + \mu^+ \rightleftarrows \nu' + \mu^{+\prime}$
$\nu_\mu + e^- \rightleftarrows \nu_e + \mu^-$	$\overline{\nu}_\mu + e^+ \rightleftarrows \overline{\nu}_e + \mu^+$
$\nu_\mu + \overline{\nu}_e + e^- \rightleftarrows \mu^-$	$\overline{\nu}_\mu + \nu_e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

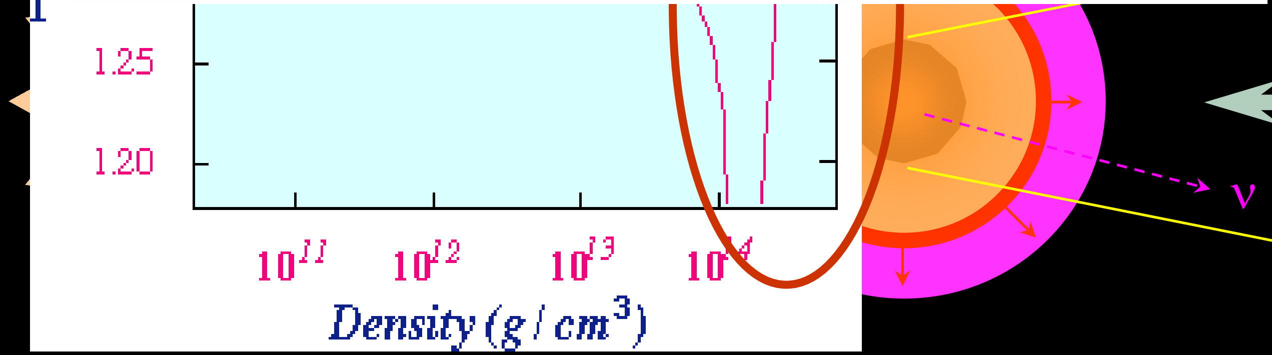
ore-collapse SNe

(e.g., Kotake+06, Foglizzo+14, Mezzacappa+15, Janka17 for a review)

Evolution of Radial velocity profiles
based on radiation-transport simulation (MGFLD) KK+06





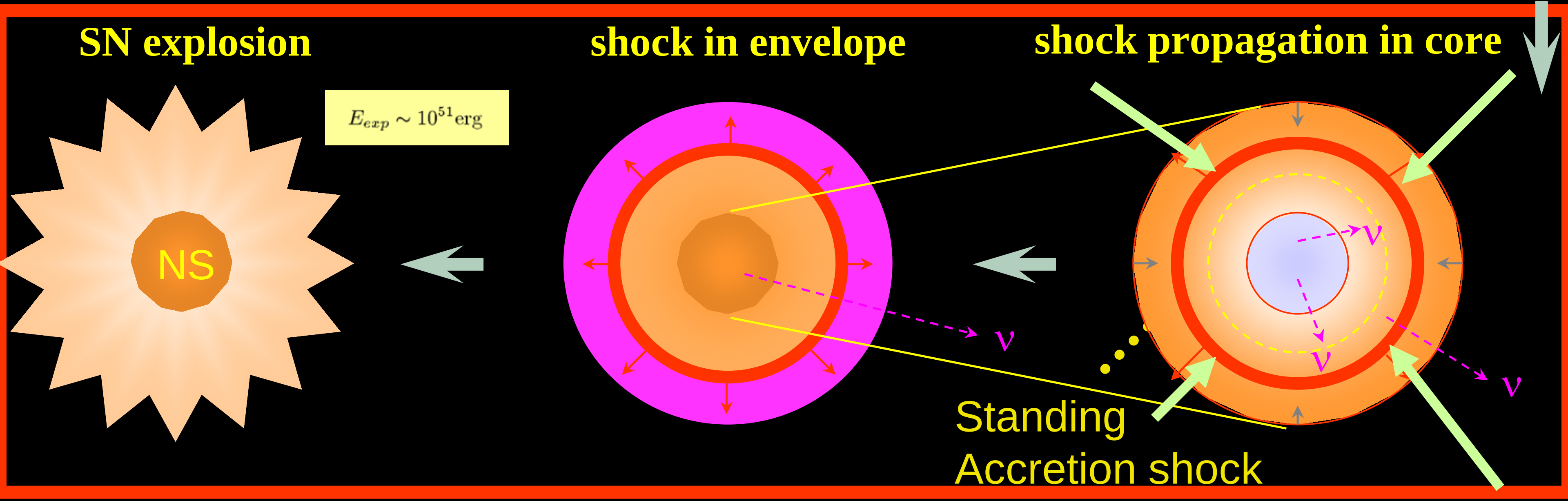


Short Summary (till shortly after bounce)

✓ SN simulations over these 20 years show that the bounce shock always stall because the kinetic energy of the shock is lost by the photo-dissociation of iron nuclefi.
→ Direct “prompt” hydrodynamic explosion fails.

✓The bounce shock turns into the standing accretion shock.

✓The supernova problem is how to revive the stalled shock into explosion!

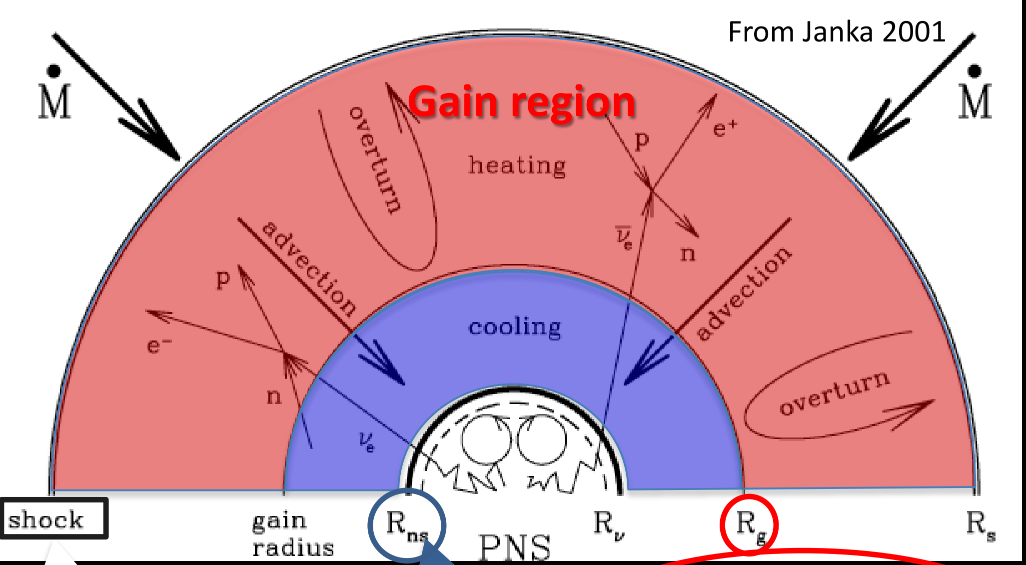


SN explosion **shock in envelope** **shock propagation in core**

$E_{exp} \sim 10^{51}\mathrm{erg}$

Standing
Accretion shock

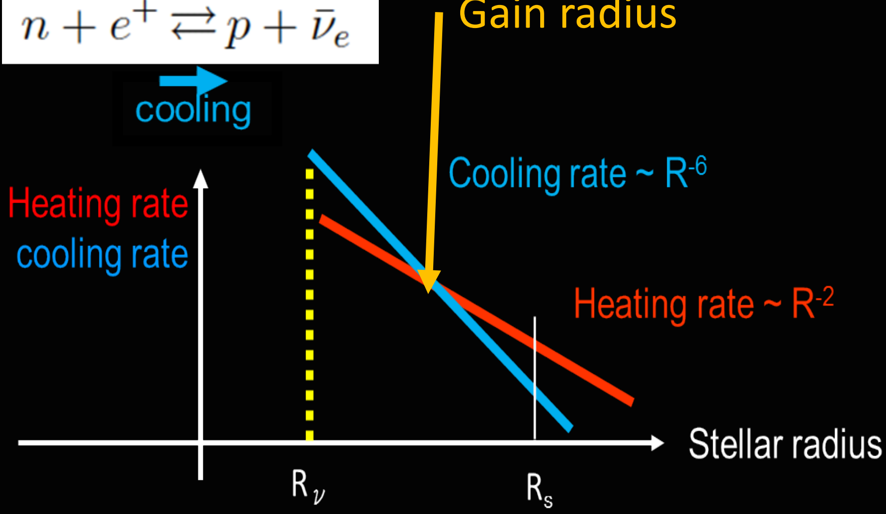
Typical scales after bounce and Density-Temperature relation



heating

$$p + e^- \rightleftarrows n + \nu_e$$
$$n + e^+ \rightleftarrows p + \bar{\nu}_e$$

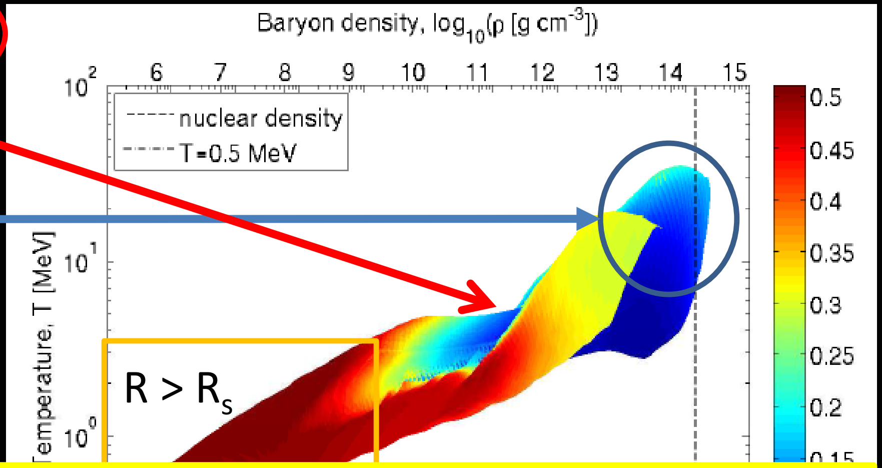
cooling



Gain Radius
R_g ~ 80km

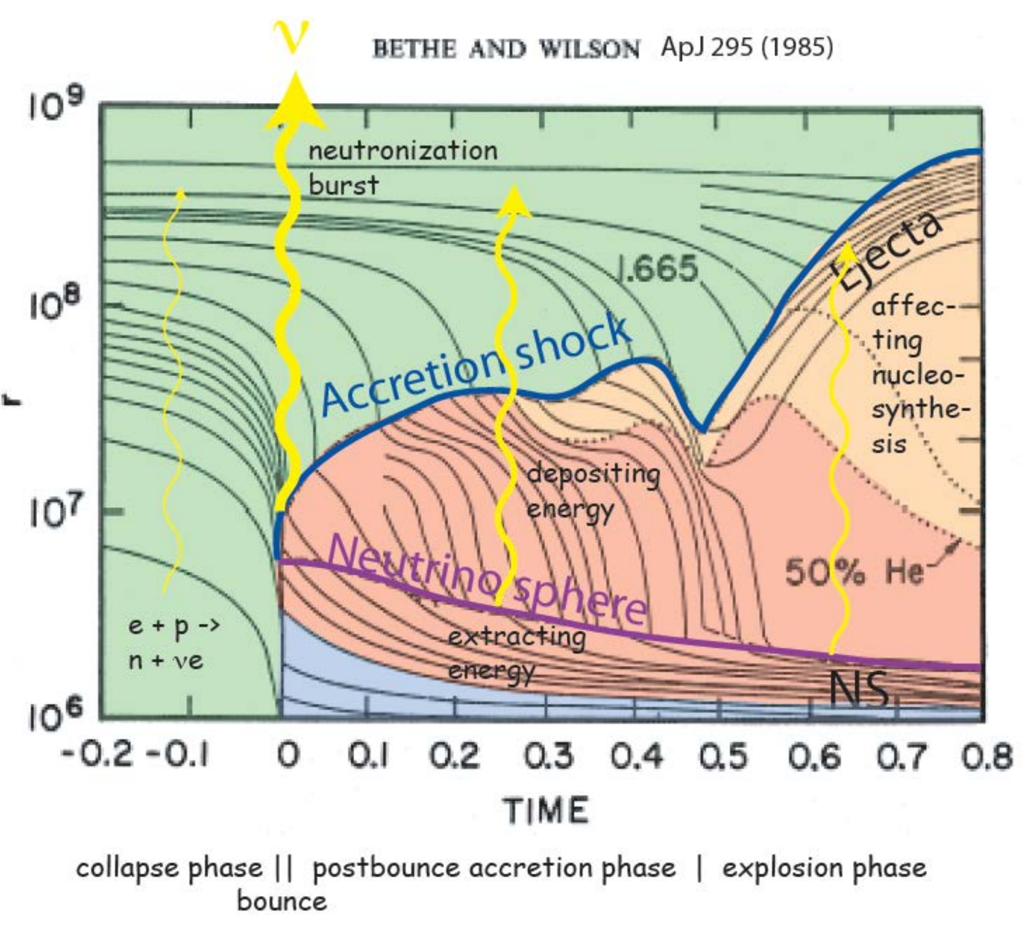
R_{PNS} , R_ν ~ 50km
ρ_c ~ 10^{14} g/cc, T_c ~ 10 MeV

$R_{stalled\_shock}$ ~ 200km
(R_{core} ~ 1500 km)
$\rho < 10^9$ g/cc, T ~ 1 MeV

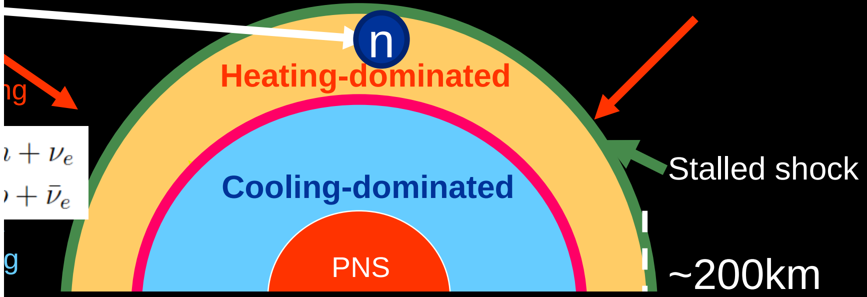


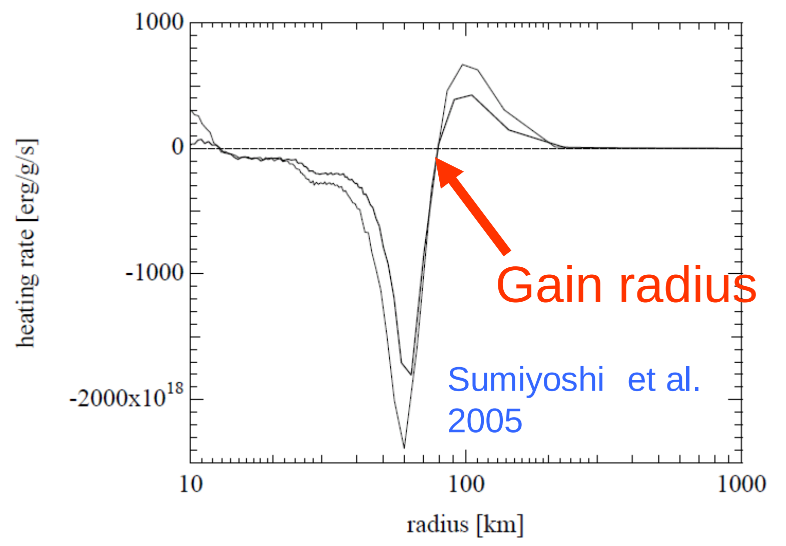
✓ Travel time (τ_{gain}) in the "gain region" ***longer***
Gain mass (M_{gain} :mass in the "gain region") ***bigger***,
more favorable for explosions !

How the neutrino mechanism works ?



BETHE AND WILSON ApJ 295 (1985)





Sumiyoshi et al. 2005

The gravitational binding energy of single neutron

$$-\frac{GM_{\mathrm{NS}}m_u}{R} = -13.0\left(\frac{M_{\mathrm{NS}}}{1.4M_\odot}\right)\left(\frac{R}{150\,\mathrm{km}}\right)^{-1}\quad[\mathrm{MeV/nucleon}].$$

- ✓ If the neutrino heating could last $> \sim 0.25$ sec, the absorbed energy exceeds the local grav. binding energy -> inflows turns into outflows !
- ✓ More correctly neutrino cooling occurs, which delays the onset of explosion.

After +50 years of CCSN modeling : "Multi-D" neutrino mechanism

(pioneered by Colgate & White (1966), review by Kotake & Kuroda (2016), Janka (2012), Burrrows (2013))

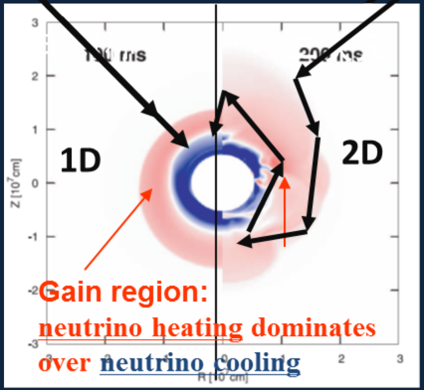
"Four steps" in neutrino-driven explosions

(see, e.g., Suwa et al. 2010,2011,2013, ApJ)

1st : After bounce, the bounce shock stalls.

2nd: Neutrino-driven convection and the SASI.
(Standing-Accretion-Shock-Instability)

3rd: In the heating region, dwell-time of material gets longer due to non-radial motions in multi-D environments.
(Turbulence helps explosion).



Gain region:
neutrino heating dominates over neutrino cooling

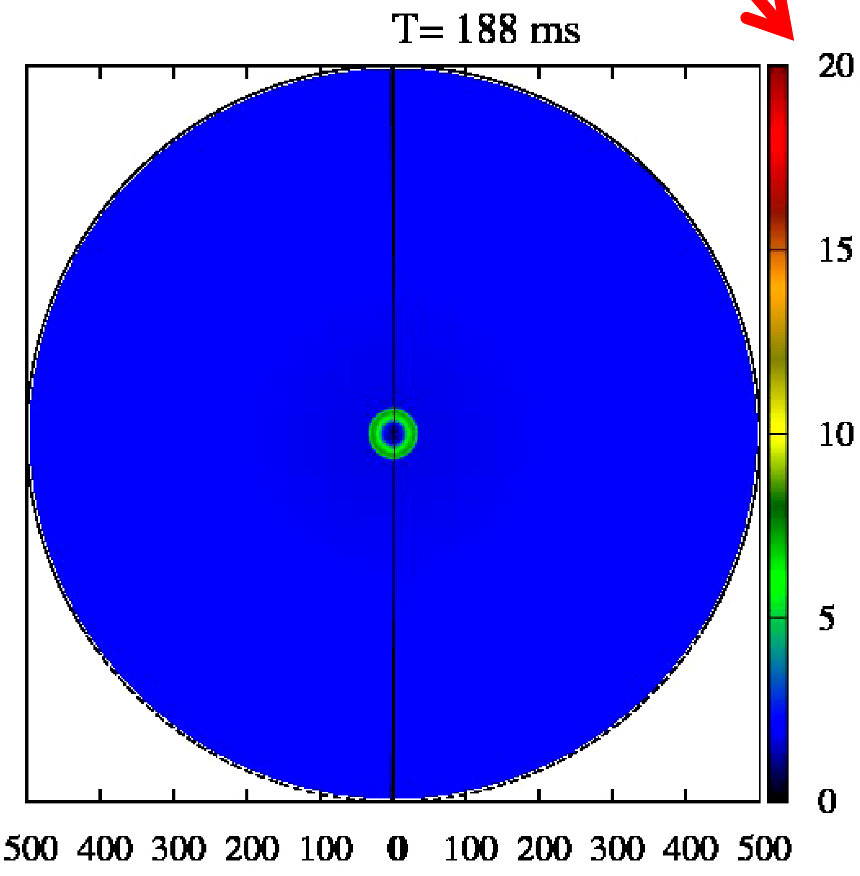
4th: At around O(100)s ms after bounce, neutrino-driven explosions set in.

2D radiation-hydro simulation of a 15 M_{sun} star

✓ IDSA scheme for spectral neutrino transport

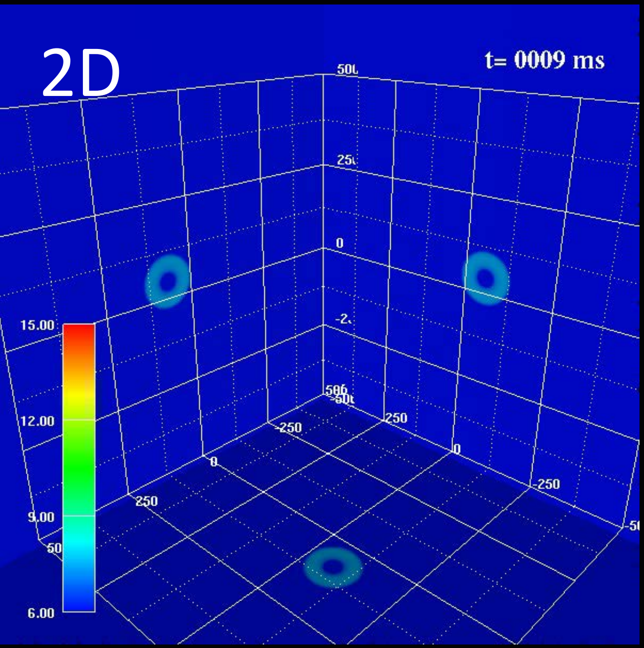
✓ Lattimer-Swesty EOS (K=220 MeV)
:compatible with 2 M_{sun} NS observation

Color scale: entropy

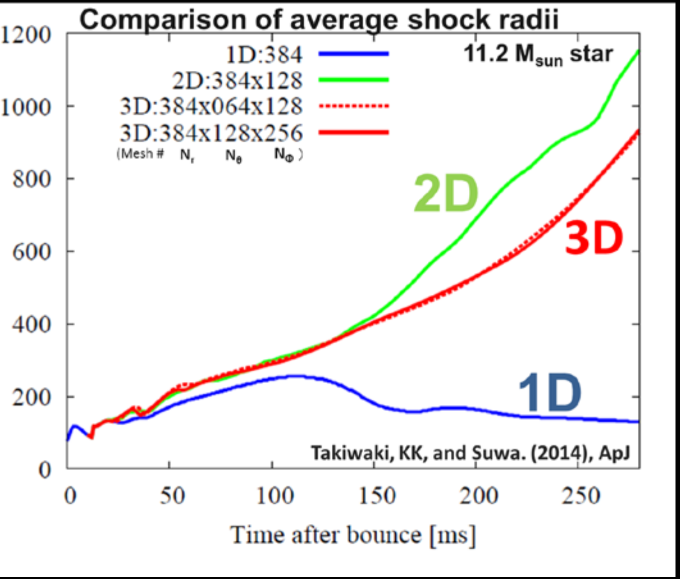


Suwa, KK et al. (2013

3D vs. 2D



(e.g., Takiwaki,KK, Suwa (2012,2014), ApJ)



Takiwaki, KK, and Suwa. (2014), ApJ

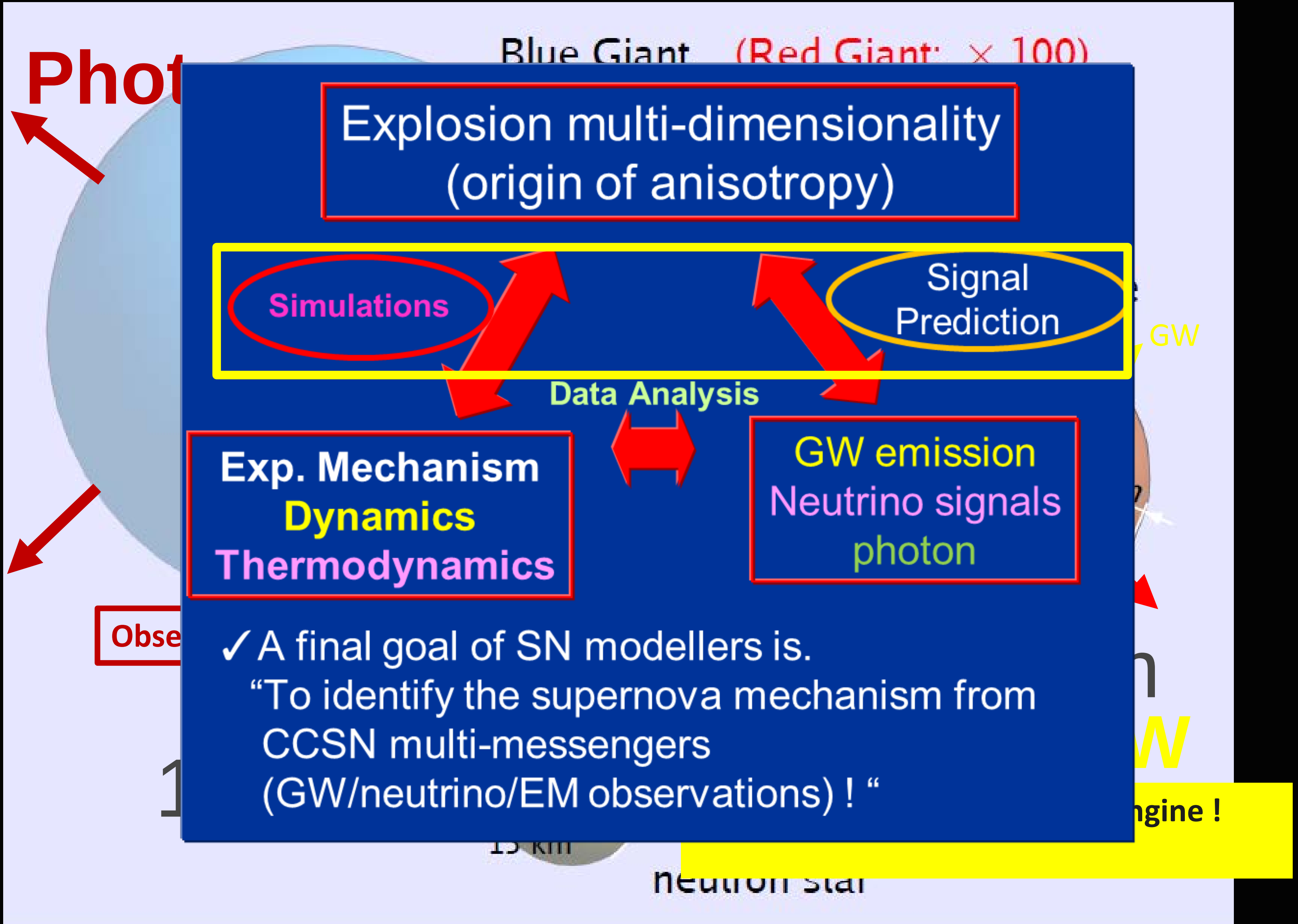
✓ **3D explosions are generally weaker than 2D.**
(11.2, 27 M_{sun} : Hanke et al. (2014), however, not for 9.6 M_{sun} Melson et al. (2015))
⇒ **The "3D vs. 2D problem" is progenitor dependent.**

✓ **No "Bethe" models obtained in 3D….**

⇒ **Need to find ingredients to foster 3D explosions !**

Candidates: Rotation (Takiwaki+16, Summa+17),
General Relativity (Kuroda+14, Ott+17),
Microphysics (Melson+16, KK+17)

Multi-messengers from CCSNe:



Explosion multi-dimensionality (origin of anisotropy)

Simulations

Signal Prediction

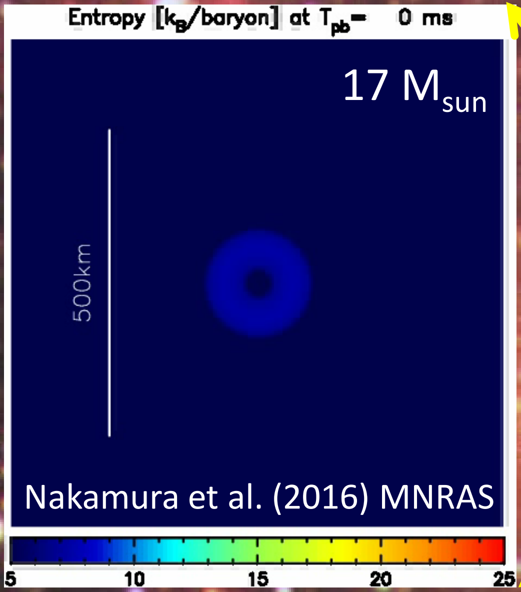
Data Analysis

Exp. Mechanism
Dynamics
Thermodynamics

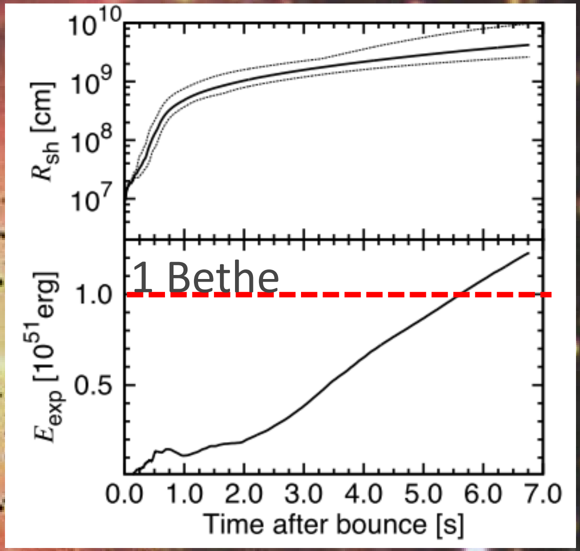
GW emission
Neutrino signals
photon

✓A final goal of SN modellers is.
"To identify the supernova mechanism from CCSN multi-messengers (GW/neutrino/EM observations) ! "

Drill for SN 2018xx !



Nakamura et al. (2016) MNRAS

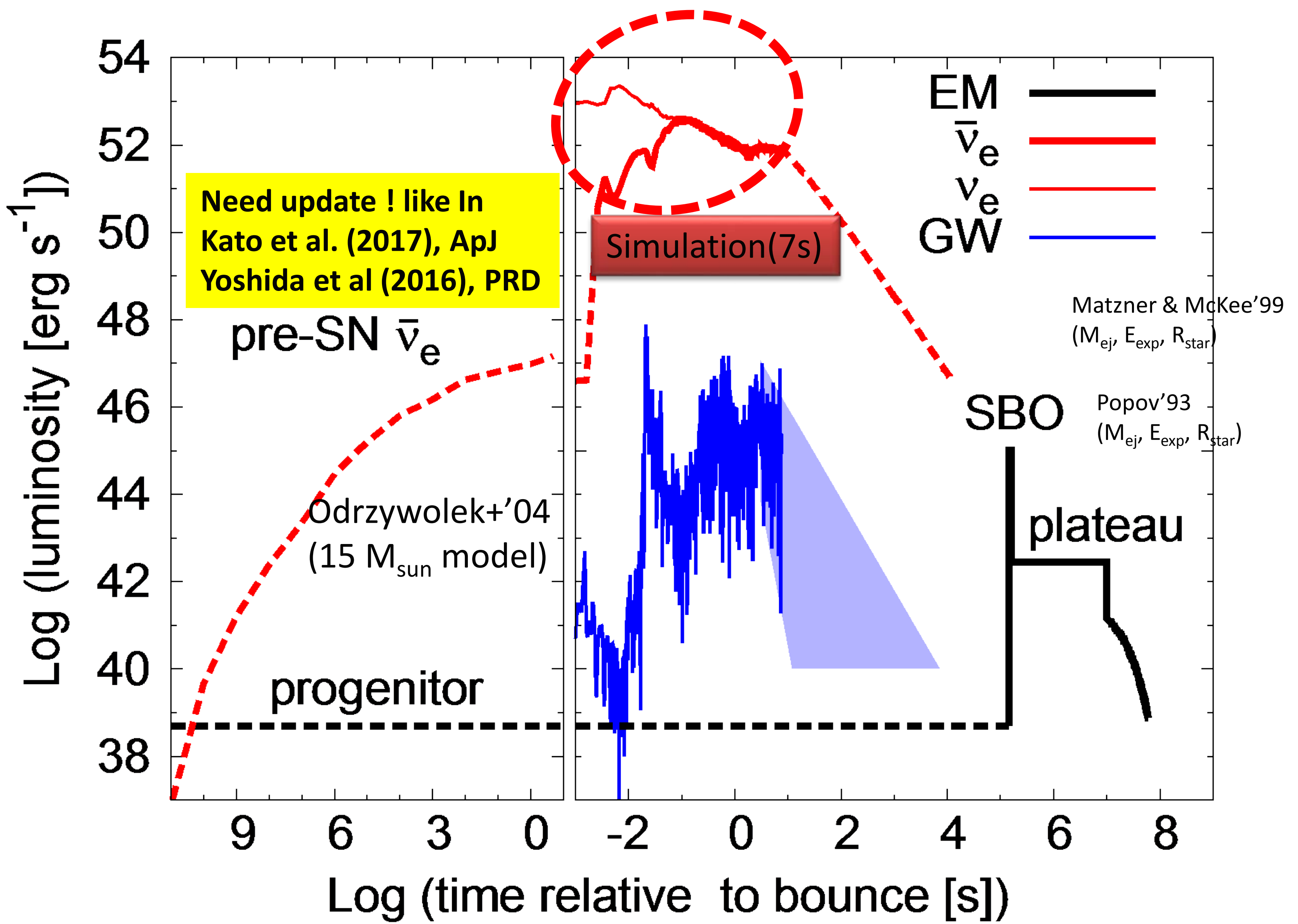


For the next Galactic event (several/century..),
how we observe multi-messengers and
what we can learn about the
supernova physics ?

Overview of "Multi-messenger signals" from exploding 17 M_{sun} star

Nakamura, Horiuchi, Tanaka, Hayama, Takiwaki, KK (MNRAS) 2016

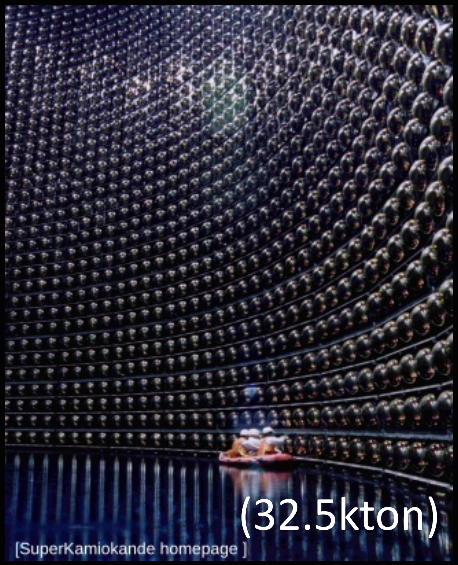
Energetics: $E_{neutrino}$ ~10^{53} erg, $E_{kinetic}$ ~10^{51}erg, E_{photon} ~ 10^{49} erg, E_{GW} ~ 10^{46} erg



Need update ! like In Kato et al. (2017), ApJ Yoshida et al (2016), PRD

First Alert: Neutrinos ! (here for a Galactic event @ 8.5 kpc)

Super Kamiokande (SK):



Inverse-β decay

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

~15000 events

Timing information

~**bounce** ±3 ms

(e.g., IceCube)

Electron scattering

$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$

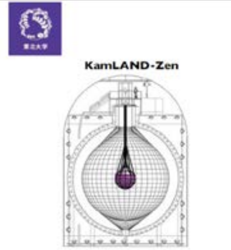
~514 events

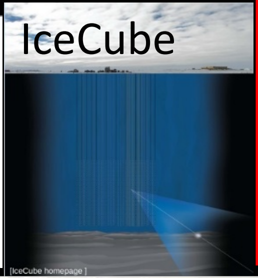
⇒ Position informat

~ 6° (SK),

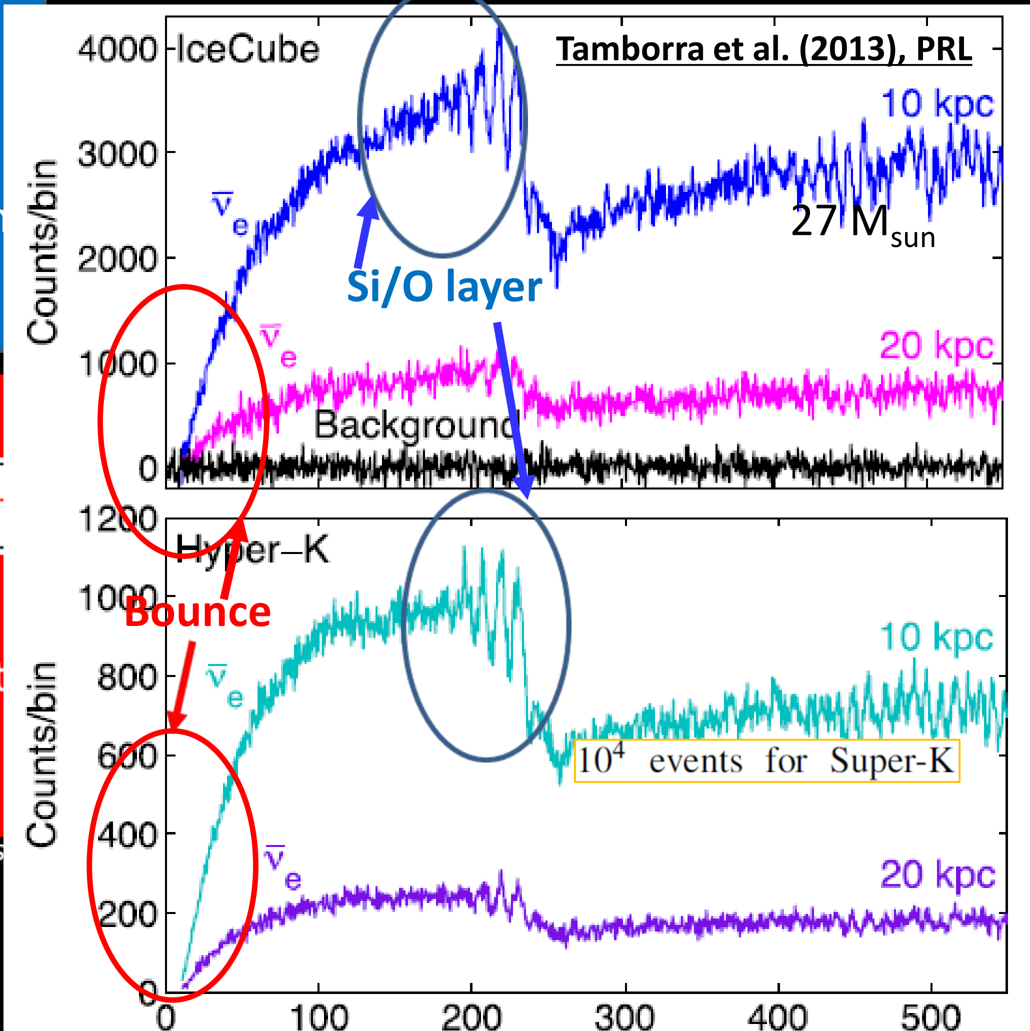
~ 3° (Gd-SK)

Beacom & Vagins



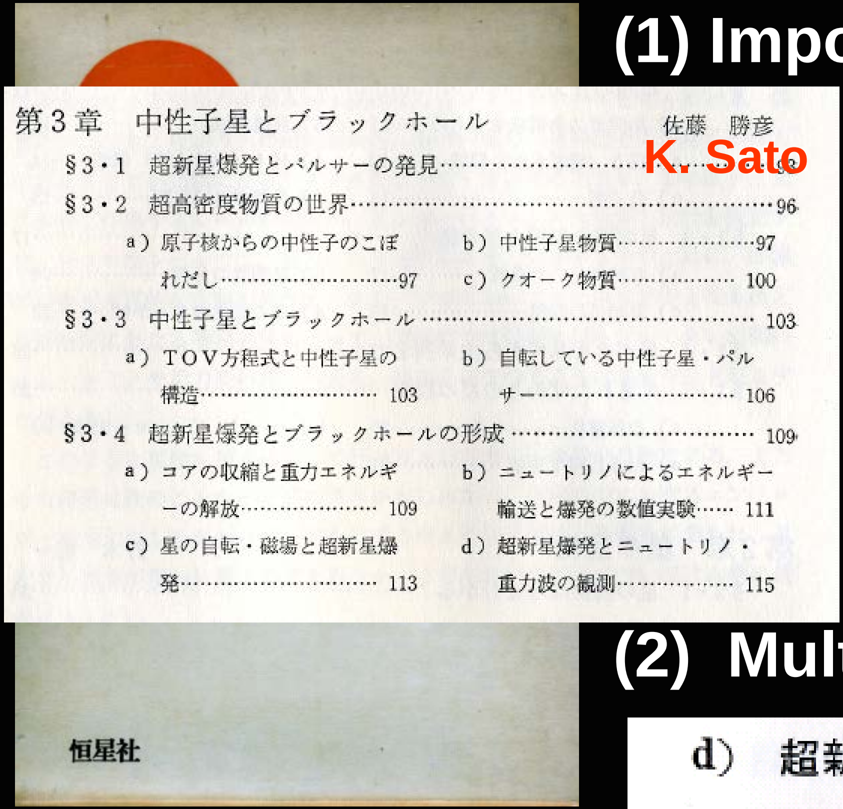


Nakamura, Horiuchi et al. (2016) MNRAS



✓For a galactic source, Can learn about SN physics.
(Bounce time, progenitor structure, compactness
(see Nakamura-san's talk !)
SASI modulation ⇒ Direct messenger of explosion.

From an old textbook….

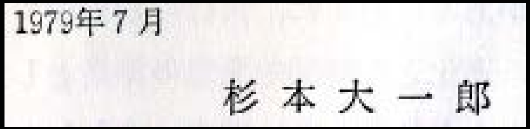


第３章　中性子星とブラックホール　佐藤　勝彦

K. Sato

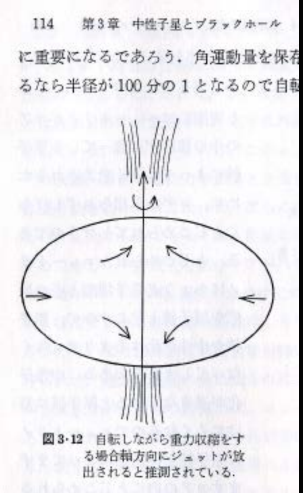
恒星社

Stellar evolutions and their fate: edited by D. Sugimoto published in 1979



1979年７月
杉本大一郎

(1) Importance of rotation, B-field



に重要になるであろう．角運動量を保
るなら半径が100分の１となるので自

図3·12　自転しながら重力収縮をする場合軸方向にジェットが放出されると推測されている．

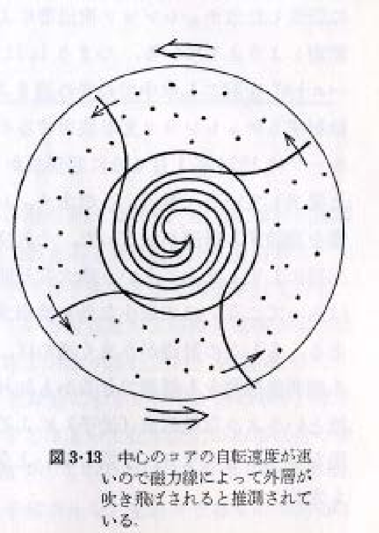
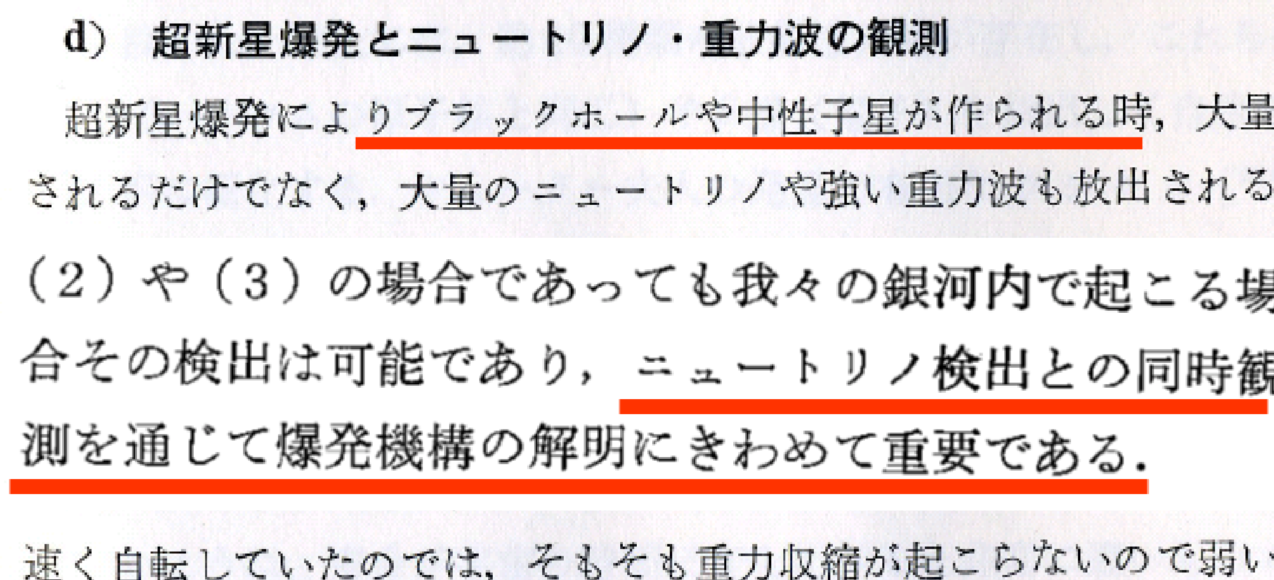


図3·13　中心のコアの自転速度が速いので磁力線によって外層が吹き飛ばされると推測されている．

(2) Multi-messenger astronomy



d）超新星爆発とニュートリノ・重力波の観測

超新星爆発によりブラックホールや中性子星が作られる時，大量
されるだけでなく，大量のニュートリノや強い重力波も放出される
（２）や（３）の場合であっても我々の銀河内で起こる場
合その検出は可能であり，ニュートリノ検出との同時観
測を通じて爆発機構の解明にきわめて重要である．

速く自転していたのでは，そもそも重力収縮が起こらないので弱い

Gravitational Waves (GWs) from Stellar Collapse

GW amplitude from the quadrupole formula

(see reviews in Ott (2009), Fryer & New (2011), Kotake (2013), Kotake and Kuroda (2016) in “Handbook of Supernovae”)

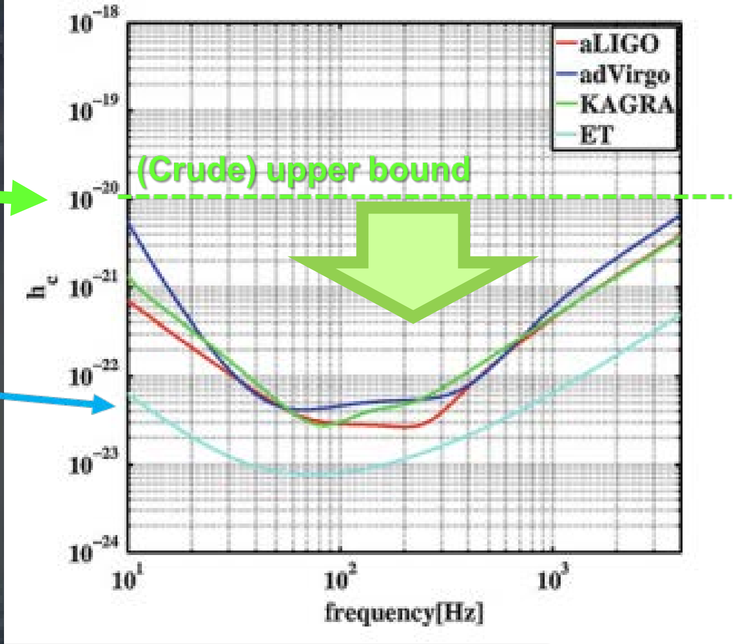
$$h_{ij} = \frac{2G}{c^4 R}\frac{\partial^2}{\partial t^2}Q_{ij} \sim \frac{R_s}{R}\left(\frac{v}{c}\right)^2$$

Quadrupole moment

Typical values at the formation of Neutron Star (NS)

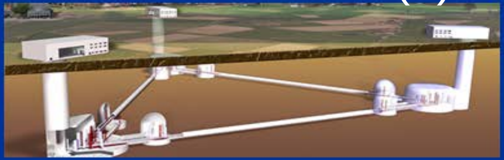
$$R_s = 3\ \mathrm{km}\left(\frac{M}{M_\odot}\right) \quad v/c = 0.1 \quad R = 10\ \mathrm{kpc}$$

$$h \sim 10^{-20}$$



Good news ! (Future)

10 km long:
Einstein Telescope (ET)
could start ~2025(?)



40 km long:
Cosmic Explore (CE)
could operate ~2035(?)

✓CCSN event in our galaxy (several/century) is primary target !

More correctly..

$$h_{ij} = \epsilon \frac{R_s}{R}\left(\frac{v}{c}\right)^2$$

ϵ : the degree of anisotropy.

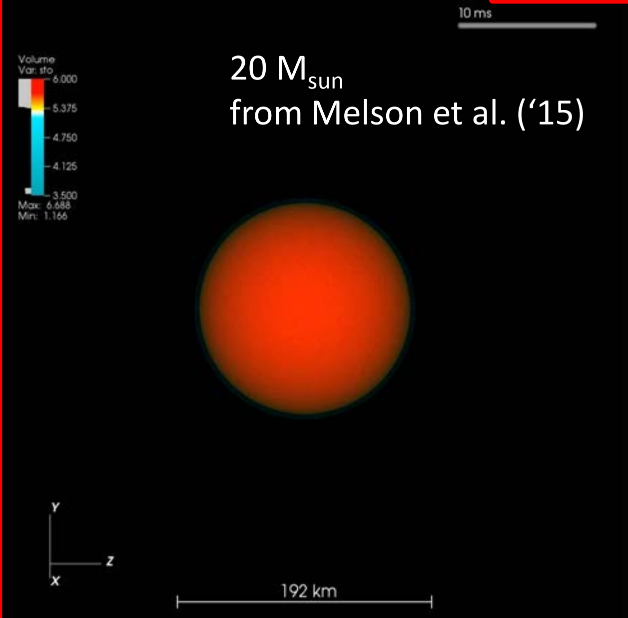
If collapse proceeds spherically, $\epsilon = 0$ no GWs !

What makes the SN-dynamics deviate from spherical symmetry is essential for the GW emission mechanism !

Two candidates : **The key** is "initial rotation rate" (Ω_0) of the iron core

(See reviews in Janka ('17), Mezzacappa et al. ('15), Foglizzo et al. ('15), Burrows ('13), Kotake et al. ('12))

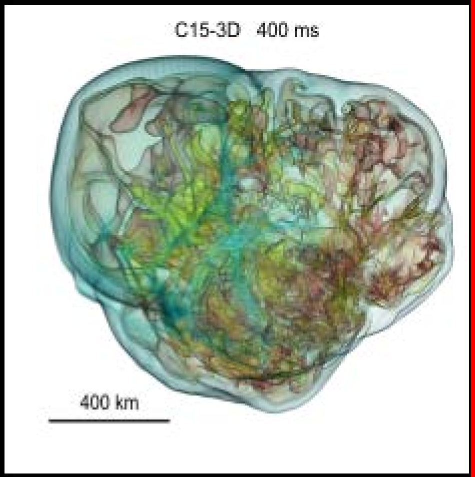
	Neutrino mechanism	**MHD mechanism**
Progenitor	Non- or slowing- rotating star $(\Omega_0 < \sim 0.1\ \mathrm{rad/s})$	Rapidly rotating star with strong B fields $(\Omega_0 > \sim\pi\ \mathrm{rad/s}, B_0 > \sim 10^{11}\ \mathrm{G})$
Main origin of GW emission	Turbulent Convection and SASI	Rotating bounce and Non-axisymmetric instabilities
Progenitor fraction	Main players	~1 (?) % (Woosley & Heger (07), ApJ): (hypothetical link to magnetar, collapsar)



20 M_{sun}
from Melson et al. ('15)

11.2 M_{sun} from
Nakamura et al. in prep

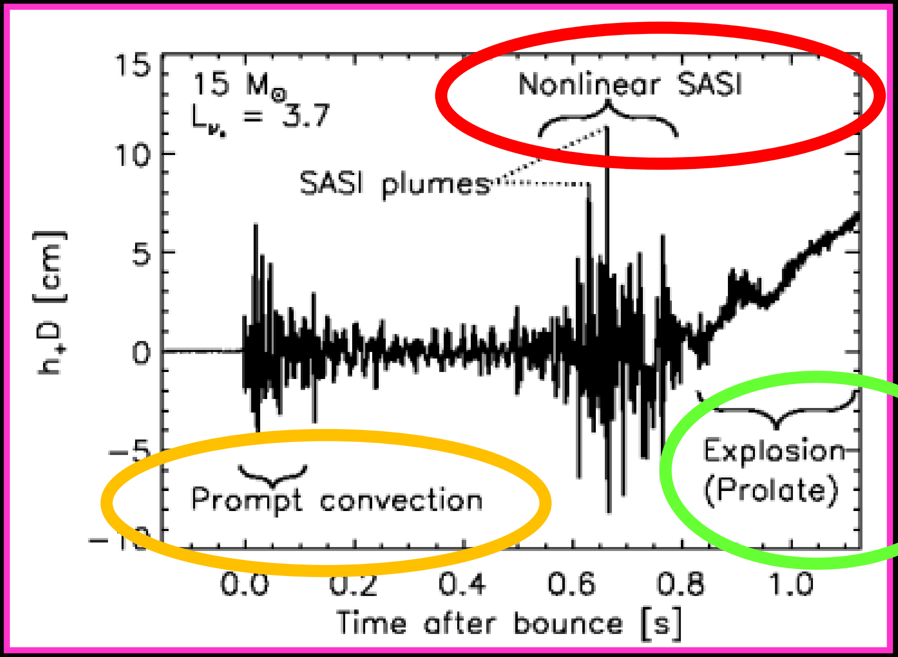
15 M_{sun} star
from Lentz et al. ('15)



(see also, Burrows et al. ('17), Melson et al. ('15), Lentz et al. ('15), Roberts et al. ('16), B. Mueller ('15), Takiwaki et al. ('16))

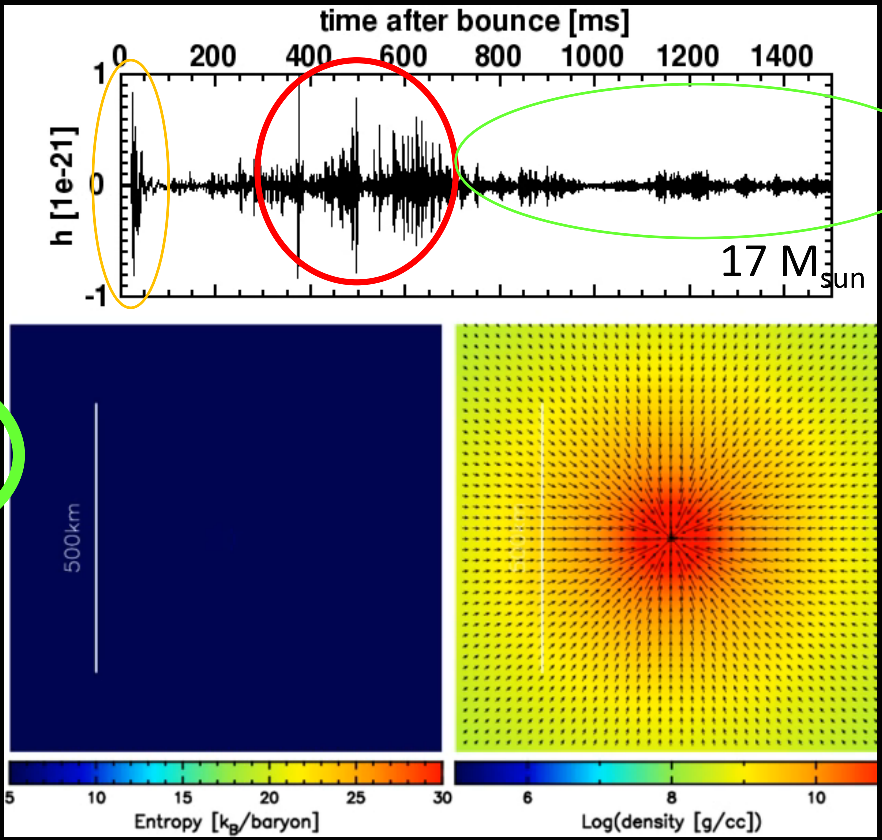
GW signatures from 2D neutrino-driven explosion

Waveform from Murphy et al. (2009) ApJ



(Later confirmed by B. Mueller et al. (‘13), ApJ, Yakunin et al. (2015), PRD)

Waveform from Nakamura et al. (‘16) MNRAS



✓**Three generic phases** in neutrino-driven models:

1. **Prompt-convection phase : within ~50 ms post-bounce**
2. **Non-linear phase (Convection/SASI) : Downflows hit the PNS surface**
3. **Explosion phase : Long-lasting signal but terminates if BH forms**

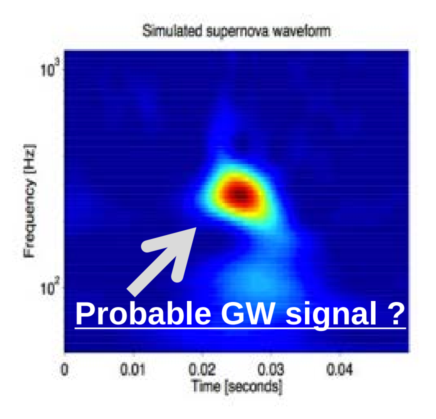
(Müller et al. (2004, ApJ), Cerda-Duran et al. (2013, ApJ))

✓ **Waveforms have no template character: stochastic explosion processes.**

How to detect GWs with no-template features…

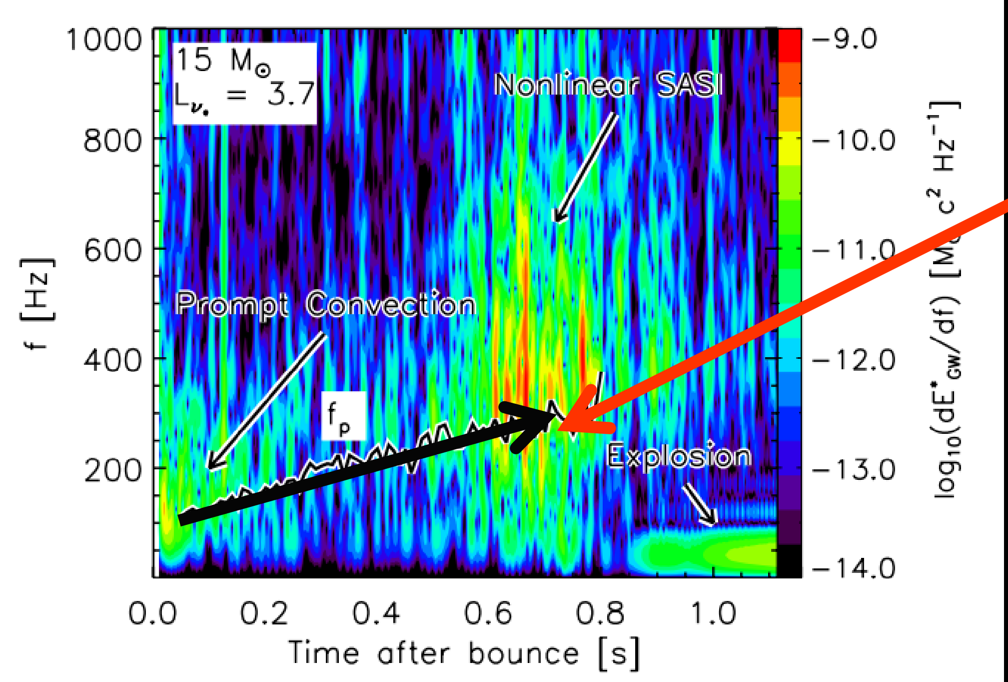
✓ **Excess power method**: Flanagan & Hugh (1998)

- ⇒ **Decompose data-stream into time-frequency domains**
- ⇒ **Search for "hot" regions with excess power in the spectrogram !**



Probable GW signal ?

✓ GW spectrogram from Murphy et al. ('09) ApJ.



☆ **Increase of typical frequency**
⇒ the g-mode frequency of PNS

$$f_p = \frac{N}{2\pi} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

M, R, T : mass, radius & temperature of PNS, Γ : stiffness of EOS

Due to mass accretion, M ↗, R ↘

⇒ f_p ↗

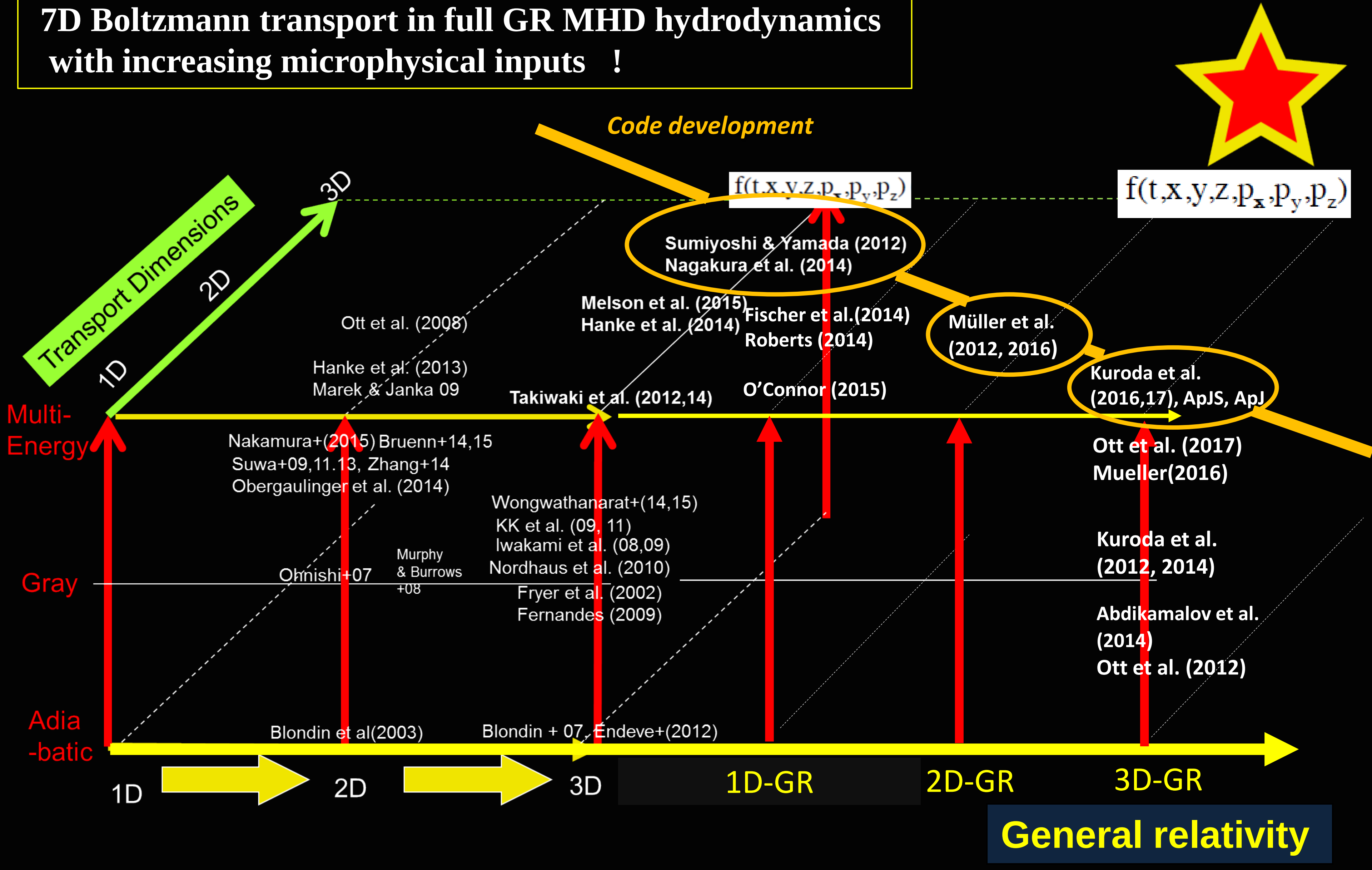
(see complete derivation in B. Mueller et al. ('13), ApJ)

- ✓ **(With no template character…) Three generic phases are in the spectrogram !**
- ✓ Secular increase of typical GW frequency (f_p) **reflects the PNS evolution**.
- ✓ On top of f_p, the high frequency component comes from strong downflows to PNS.
- ✓ **These qualitative features are common to more recent 2D and 3D models**.
- ✓ The GW amplitudes ~ 1/10 than in 2D (KK et al. 2009, Yakunin et al. (2017))

Recent Status of CCSN simulations

Disclaimer: only CCSNs

Ultimate goal:
7D Boltzmann transport in full GR MHD hydrodynamics
with increasing microphysical inputs !



Code development

Transport Dimensions

1D 2D 3D

$f(t,x,y,z,p_x,p_y,p_z)$

$f(t,x,y,z,p_x,p_y,p_z)$

Multi-Energy

Gray

Adia-batic

Sumiyoshi & Yamada (2012)
Nagakura et al. (2014)

Ott et al. (2008)

Melson et al. (2015)
Hanke et al. (2014)

Fischer et al.(2014)
Roberts (2014)

Müller et al. (2012, 2016)

Hanke et al. (2013)
Marek & Janka 09

Takiwaki et al. (2012,14)

O'Connor (2015)

Kuroda et al. (2016,17), ApJS, ApJ

Nakamura+(2015) Bruenn+14,15
Suwa+09,11.13, Zhang+14
Obergaulinger et al. (2014)

Ott et al. (2017)
Mueller(2016)

Wongwathanarat+(14,15)
KK et al. (09, 11)
Iwakami et al. (08,09)
Nordhaus et al. (2010)
Fryer et al. (2002)
Fernandes (2009)

Ohnishi+07

Murphy
& Burrows
+08

Kuroda et al. (2012, 2014)

Abdikamalov et al. (2014)
Ott et al. (2012)

Blondin et al(2003)

Blondin + 07, Endeve+(2012)

1D 2D 3D 1D-GR 2D-GR 3D-GR

General relativity

First full-3D-GR simulations with multi-energy neutrino transport (M1)

Kuroda, KK, Takiwaki, Thielemann submitted

(see also,GR models using the CoCoNuT code (CFC(+) by Cerda-Duran+2011, Obergaulinger and Aloy (2017): 2D by Dimmelmeier et al. (2007), B. Mueller (2015), B. Mueller et al. (2017):3D)

✓ "FUGRA" : FUlly General Relativistic code with multi-energy neutrino trAnsport

Kuroda, Takiwaki, and KK, ApJS. (2016)

The marriage of **BSSNOK formalism** (3D GR code, Kuroda & Umeda (2010, ApJS)) $G = \{\tilde{\gamma}_{ij}, \tilde{A}_{ij}, \phi, K, \tilde{\Gamma}^i, \alpha, \beta^i\}$

+ **M1 scheme**; Shibata+2011, Thorne 1981, (see also, Just et al. (2015), O'Connor (2015) for recent work)

✓ Evolution equation of neutrino radiation energy

$$\partial_t \sqrt{\gamma} E_{(\varepsilon)} + \partial_i \sqrt{\gamma} (\alpha F^i_{(\varepsilon)} - \beta^i E_{(\varepsilon)}) + \sqrt{\gamma} \alpha \partial_\varepsilon (\varepsilon \tilde{M}^\mu_{(\varepsilon)} n_\mu) = \sqrt{\gamma} (\alpha P^{ij}_{(\varepsilon)} K_{ij} - F^i_{(\varepsilon)} \partial_i \alpha - \alpha S^\mu_{(\varepsilon)} n_\mu),$$

✓ Evolution equation of radiation flux

$$\partial_t \sqrt{\gamma} F_{(\varepsilon)i} + \partial_j \sqrt{\gamma} (\alpha P_{(\varepsilon)i}{}^j - \beta^j F_{(\varepsilon)i}) - \sqrt{\gamma} \alpha \partial_\varepsilon (\varepsilon \tilde{M}^\mu_{(\varepsilon)} \gamma_{i\mu}) = \sqrt{\gamma} [-E_{(\varepsilon)} \partial_i \alpha + F_{(\varepsilon)j} \partial_i \beta^j + (\alpha/2) P^{jk}_{(\varepsilon)} \partial_i \gamma_{jk} + \alpha S^\mu_{(\varepsilon)} \gamma_{i\mu}]$$

✓ Analytic Closure with the use of Minerbo-type Eddington factor **(Murchikova, Abdikamalov + (2017))**

$$P^{ij}_{(\varepsilon)} = \frac{3\chi_{(\varepsilon)} - 1}{2} P^{ij}_{\mathrm{thin}(\varepsilon)} + \frac{3(1 - \chi_{(\varepsilon)})}{2} P^{ij}_{\mathrm{thick}(\varepsilon)}$$

$$\chi_{(\varepsilon)} = \frac{5 + 6\bar{F}^2_{(\varepsilon)} - 2\bar{F}^3_{(\varepsilon)} + 6\bar{F}^4_{(\varepsilon)}}{15}$$

Closed set of rad-hydro equations

$$\partial_t \rho_* + \partial_i (\rho_* v^i) = 0,$$

$$\partial_t \sqrt{\gamma} S_i + \partial_j \sqrt{\gamma} (S_i v^j + \alpha P \delta^j_i) = -\sqrt{\gamma} [S_0 \partial_i \alpha - S_k \partial_i \beta^k - 2\alpha S^k_k \partial_i \phi + \alpha e^{-4\phi} (S_{jk} - P\gamma_{jk}) \partial_i \tilde{\gamma}^{jk}/2 + \alpha \int d\varepsilon S^\mu_{(\varepsilon)} \gamma_{i\mu}],$$

$$\partial_t \sqrt{\gamma} \tau + \partial_i \sqrt{\gamma} (\tau v^i + P(v^i + \beta^i)) = \sqrt{\gamma} [\alpha K S^k_k/3 + \alpha e^{-4\phi} (S_{ij} - P\gamma_{ij}) \tilde{A}^{ij} - S_i D^i \alpha + \alpha \int d\varepsilon S^\mu_{(\varepsilon)} n_\mu],$$

$$\partial_t (\rho_* Y_e) + \partial_i (\rho_* Y_e v^i) = \sqrt{\gamma} \alpha m \int \frac{d\varepsilon}{\varepsilon} (S^\mu_{(\nu_e,\varepsilon)} - S^\mu_{(\bar{\nu}_e,\varepsilon)}) u_\mu$$

Table 1

The Opacity Set Included in this Study and their References

Process	Reference
$n\nu_e \leftrightarrow e^- p$	Bruenn (1985), Rampp & Janka (2002)
$p\bar{\nu}_e \leftrightarrow e^+ n$	Bruenn (1985), Rampp & Janka (2002)
$\nu_e A \leftrightarrow e^- A'$	Bruenn (1985), Rampp & Janka (2002)
$\nu p \leftrightarrow \nu p$	Bruenn (1985), Rampp & Janka (2002)
$\nu n \leftrightarrow \nu n$	Bruenn (1985), Rampp & Janka (2002)
$\nu A \leftrightarrow \nu A$	Bruenn (1985), Rampp & Janka (2002)
$\nu e^\pm \leftrightarrow \nu e^\pm$	Bruenn (1985)
$e^- e^+ \leftrightarrow \nu \bar{\nu}$	Bruenn (1985)
$NN \leftrightarrow \nu \bar{\nu} NN$	Hannestad & Raffelt (1998)

✓3 flavor neutrino transport

✓Base-line opacity

(t.b.updated)

GW signautures from 3D-GR models with strong SASI vs. weak SASI activity

(from **Kuroda, KK, & Takiwaki ApJL (2016), see also Andresen, B, E Müller and Janka (2017)**)

✓ Two EOSs → SFHx (Steiner et al. (2013), fits well with experiment/NS radius,Steiner+(2011)), HS(TM1) (Shen et al. (1998)).

✓ 15 M_{sun} s

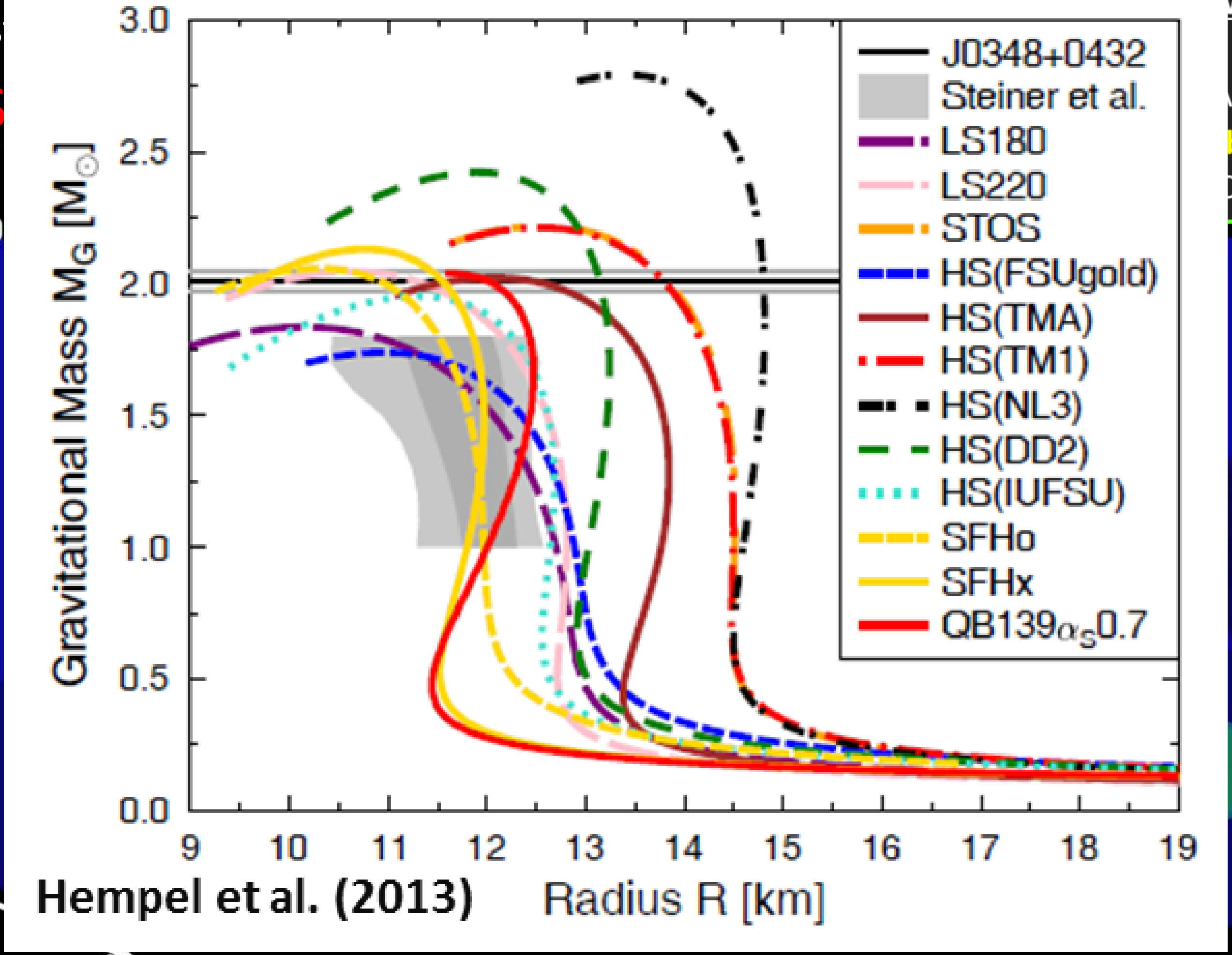
S

vith neutrino

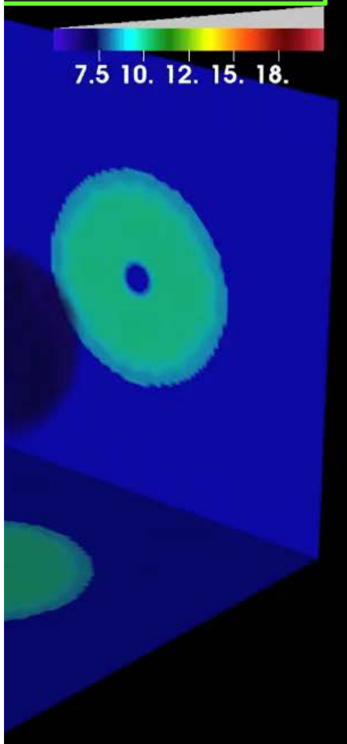
ApJ, 2014, PRD)

ble !

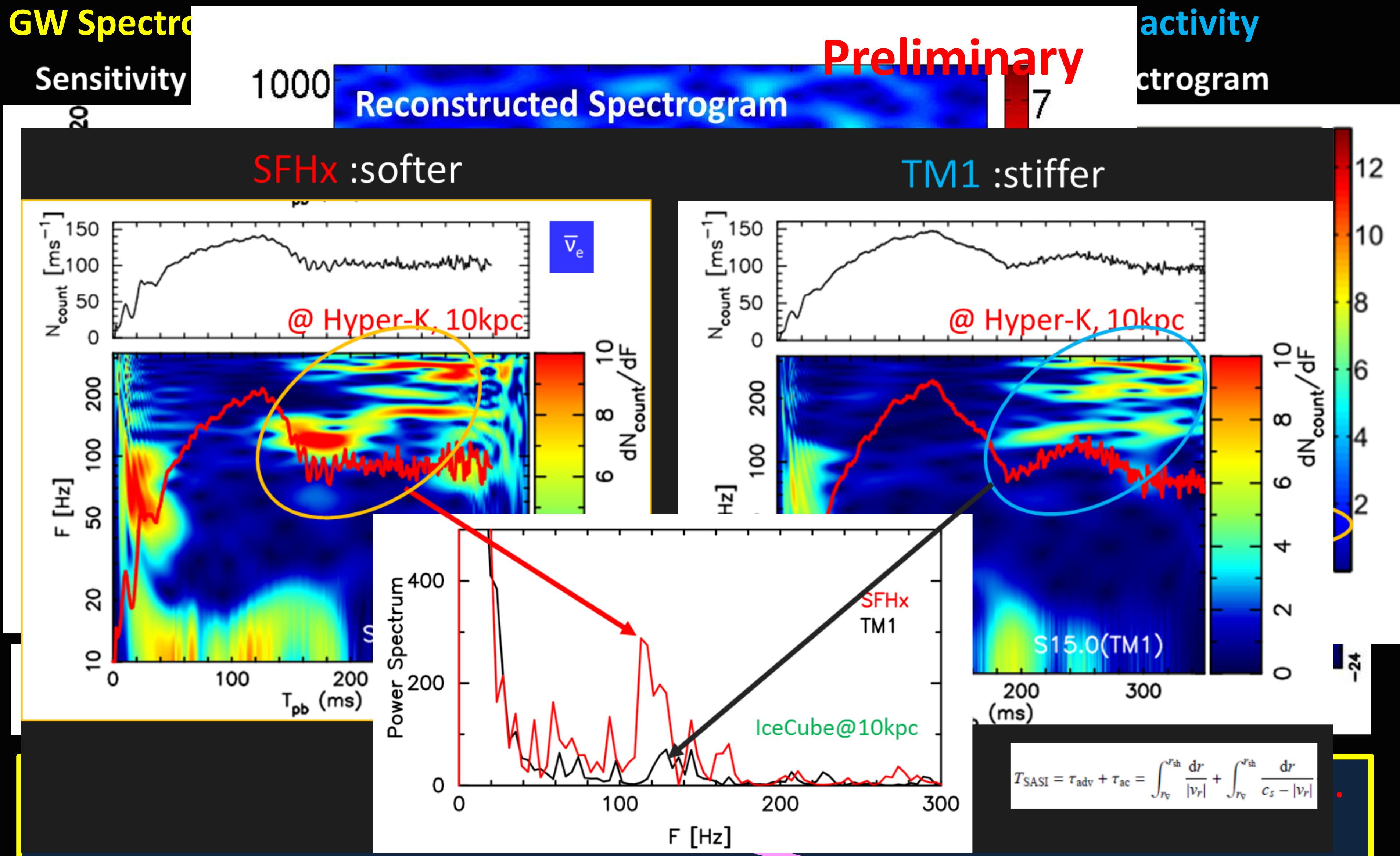
016))



Hempel et al. (2013)



✓ SASI activity higher for softer EOS (due to shorter growth rate, e.g., Foglizzo et al. ('06)).



$$T_{\rm SASI} = \tau_{\rm adv} + \tau_{\rm ac} = \int_{r_\nu}^{r_{\rm sh}} \frac{{\rm d}r}{|v_r|} + \int_{r_\nu}^{r_{\rm sh}} \frac{{\rm d}r}{c_s - |v_r|}$$

is only 2~3 kpc, but could extend out to 100 kpc when **ET and CE are on-line (>2035).**

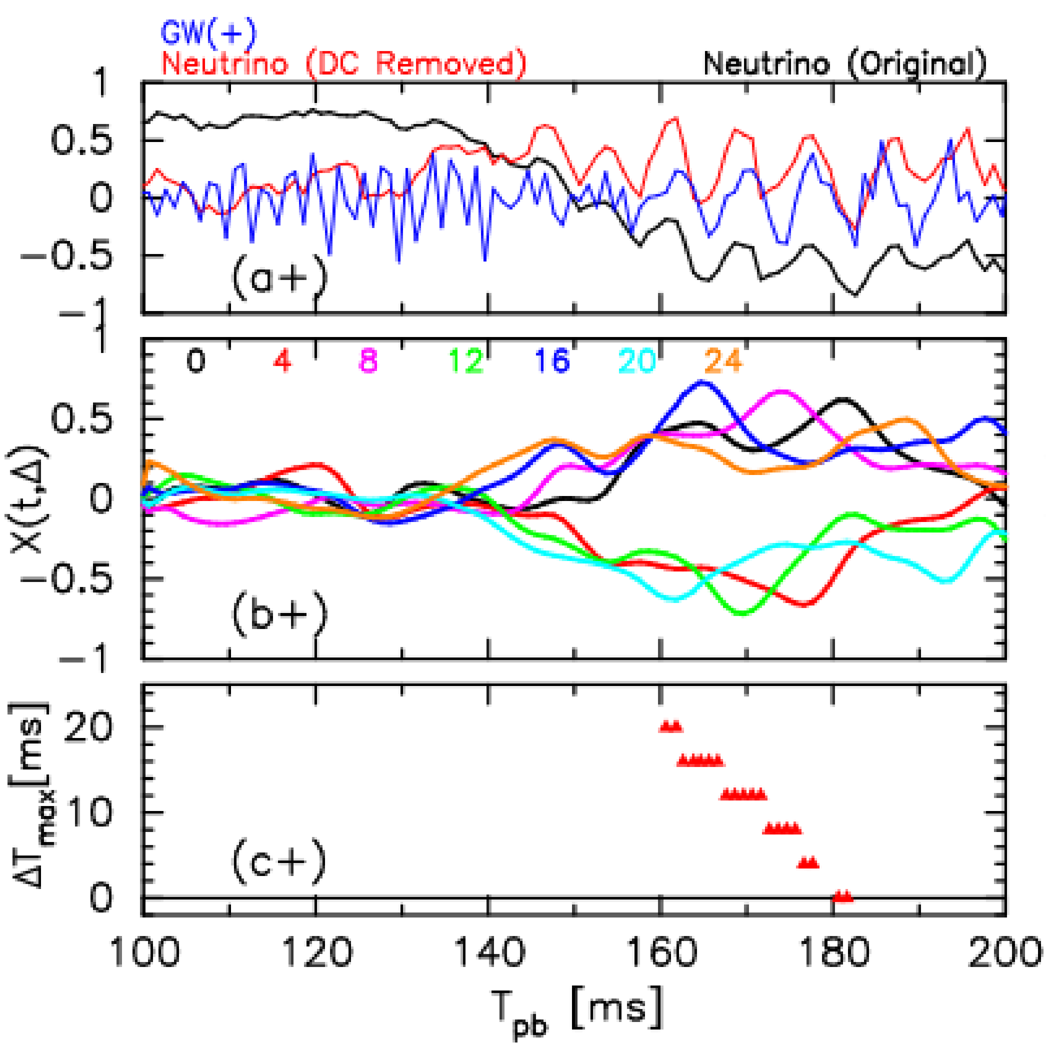
✓ **Detection of neutrinos (Super-K, IceCube) important to get timestamp of GW detection.**

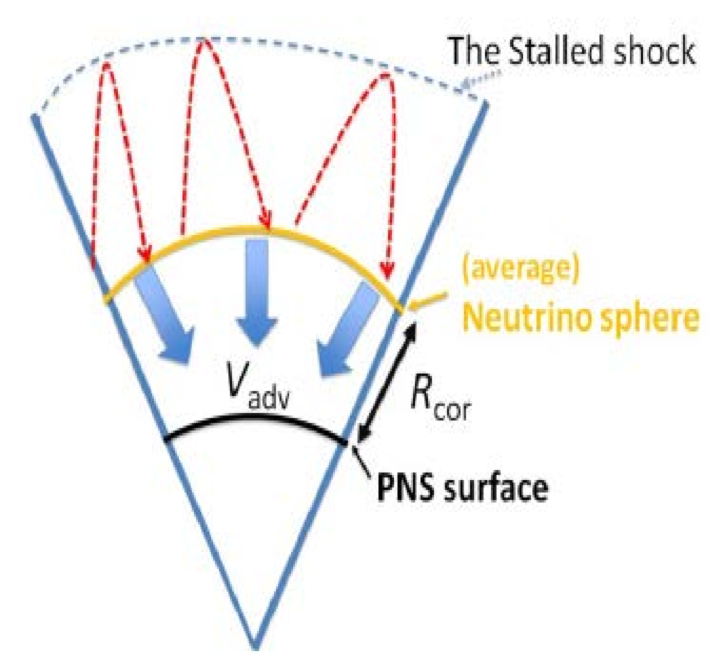
✓ **The SASI activity, if very high, results in characteristic signatures** in both **GWs and neutrino signals** (e.g., Tamborra et al. (2012) for SASI-induced neutrino signals).

Correlation between GWs and neutrinos with strong SASI activity (15 M_{sun} + SFHx)

$$X(t,\Delta T)=\frac{\int d\tau H(t-\tau)A_\nu(\tau+\Delta T)A_{\rm GW}(\tau)}{\sqrt{\int d\tau H(t-\tau)(A_\nu(\tau+\Delta T))^2}\sqrt{\int d\tau H(t-\tau)(A_{\rm GW}(\tau))^2}}$$

Kuroda, KK, Hayama, Takiwaki
(2017, ApJ)





$$\Delta T_{max} \sim R_{cor} / V_{adv}$$
$$\sim O(10)\ \mathrm{km}/(10^{7\sim8}\ \mathrm{cm/s})$$
$$\sim O(10)\ \mathrm{ms}$$

✓ The simultaneous detection potentially tells the distance between the neutrino sphere and PNS radius ! (Need to follow long-term 3D evolution how long this continues..)

The Origin of the Nobel-Prize-awarded BHs (7 ~40 M_{sun}) ?

The

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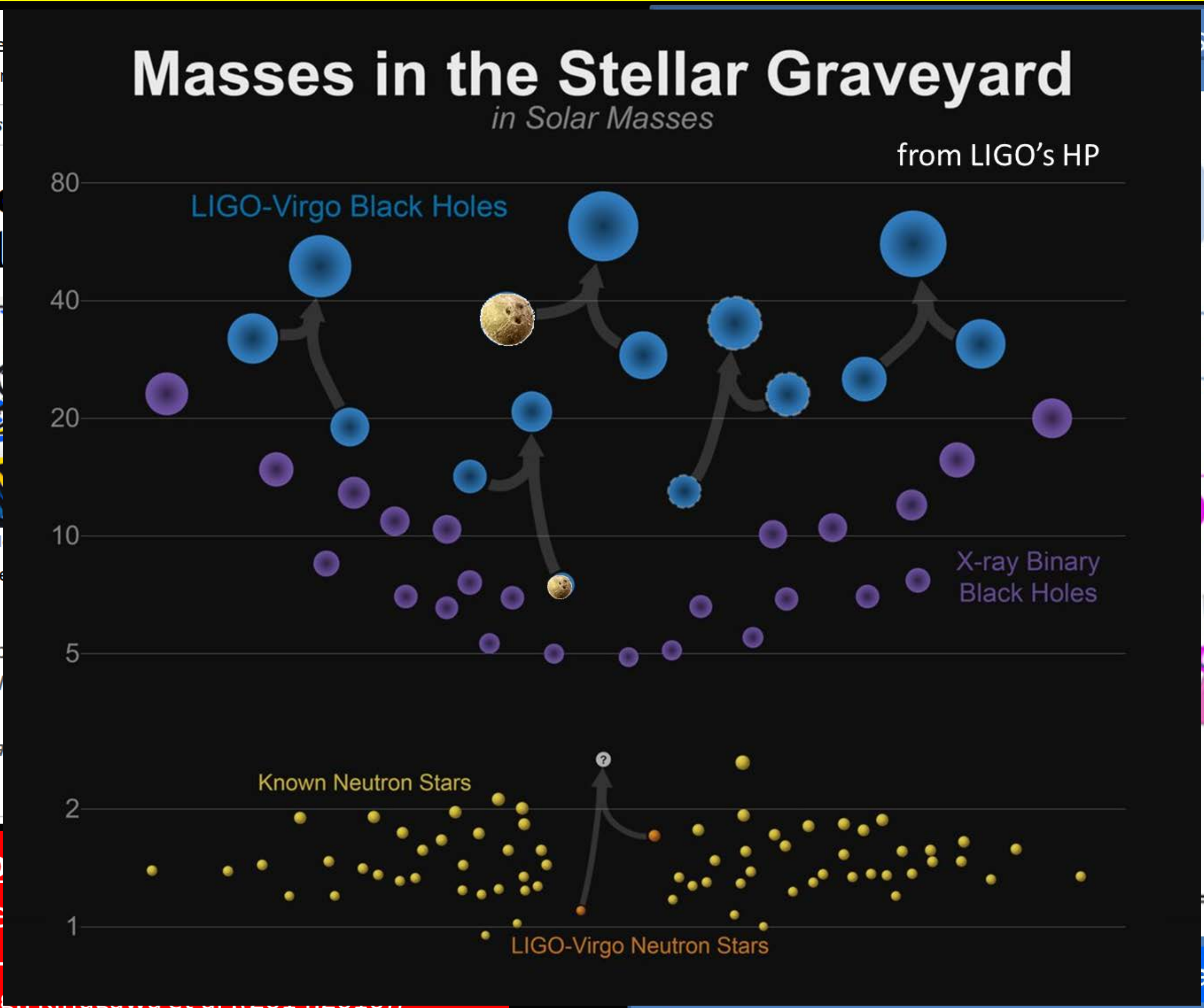
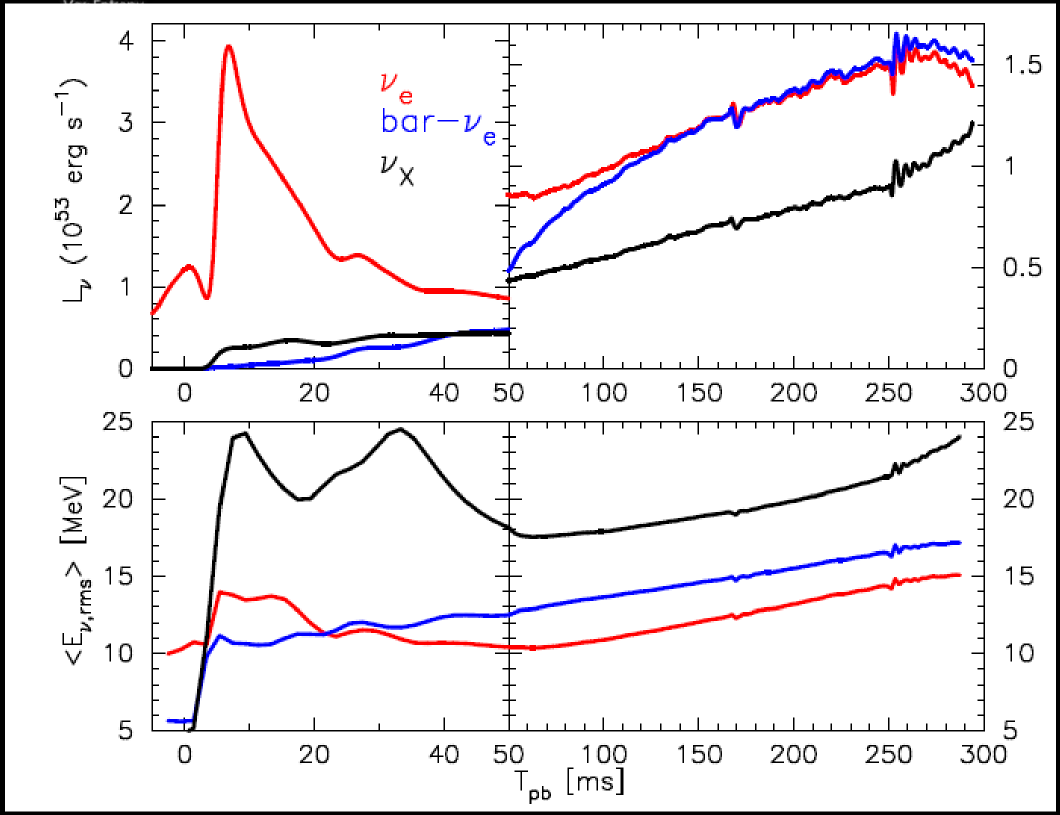
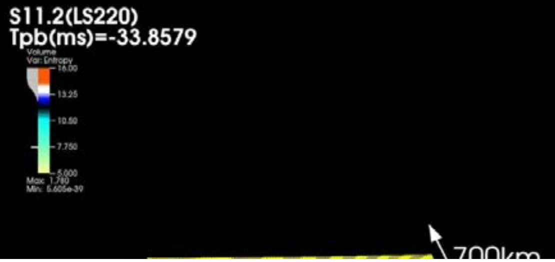


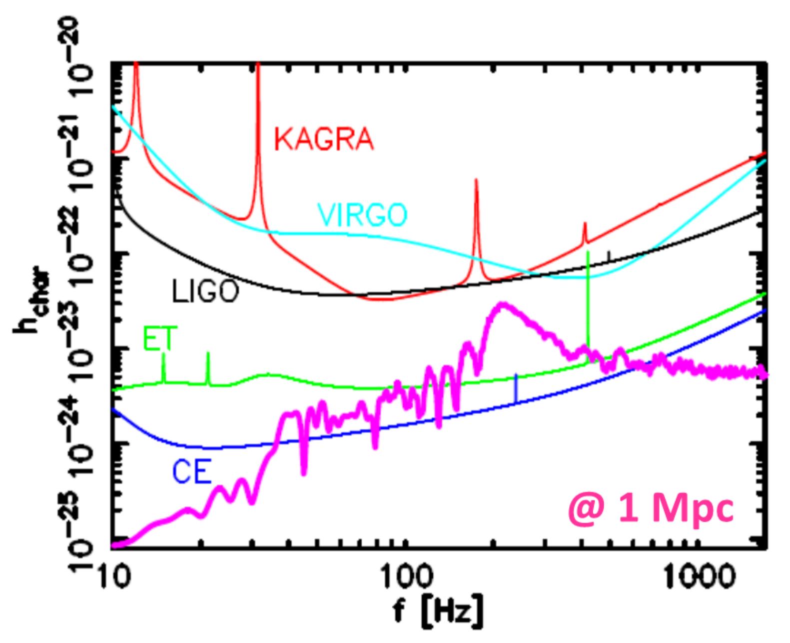
- ✓ **Lo**
  ne
  BH
  (e.g.) Kinugawa et al.(2014,2016))

✓ FUGRA results of 70 M_{sun} (M_{CO} ~ 28.5 M_{sun}) (progenitor from Takahashi et al. (2014))

Z70.0(LS220)
Tpb(ms)=-2.59983





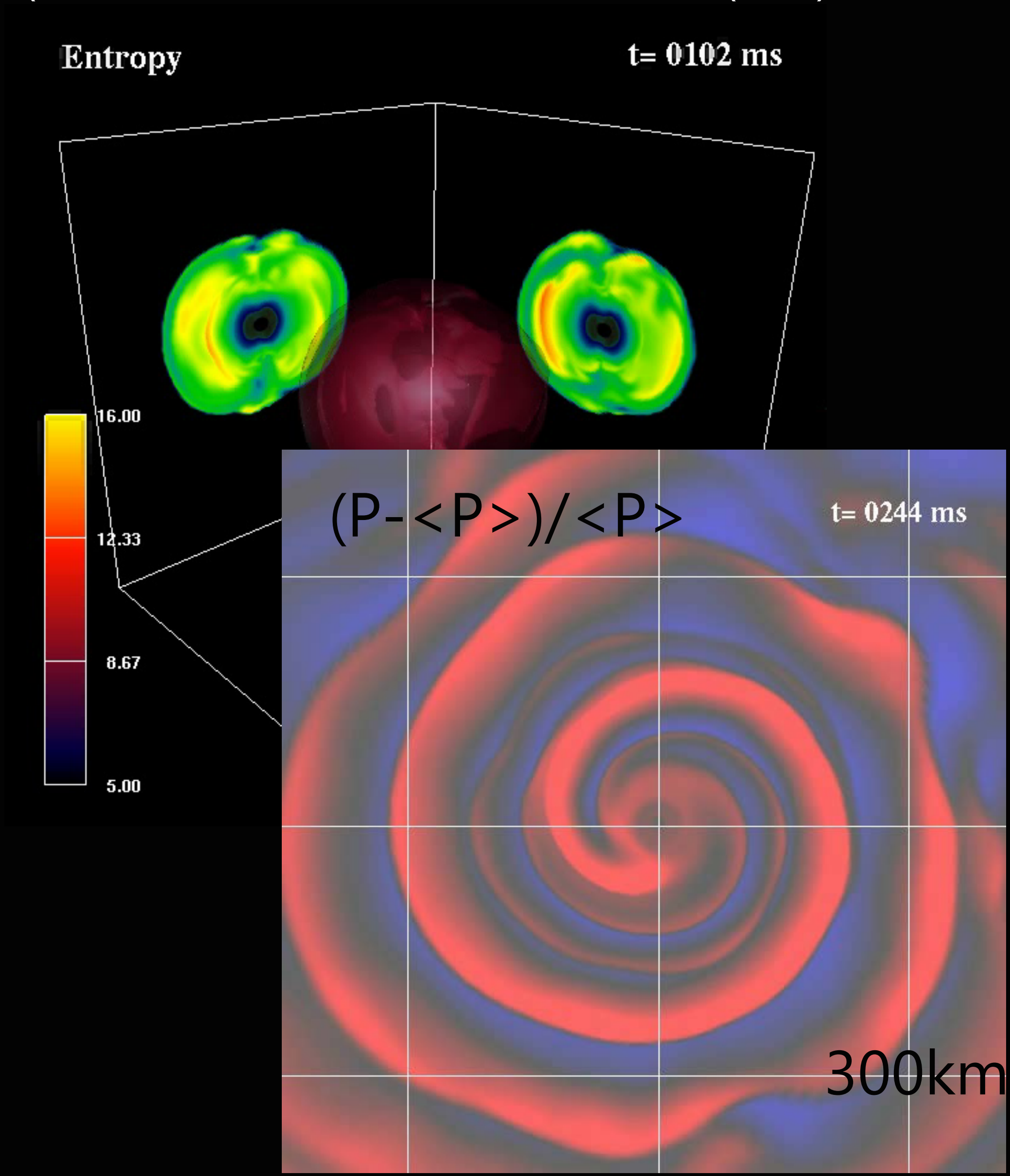


- ✓ **Earliest BH formation** after bounce (～300 ms postbouce) !
- ✓ Before the BH formation, **monotonic increase** of neutrino luminosity and rms energy.
  (**consistent with** 1D, e.g., Sumiyoshi+ (2006), Nakazato(+2008,2013), Fischer+ (2009), Huedepohl+(2016))
- ✓ Strong GW emission is visible to 1 Mpc, **but not** O(100) Mpc…
- ✓ Our code needs upgrade to follow long after BH formation…

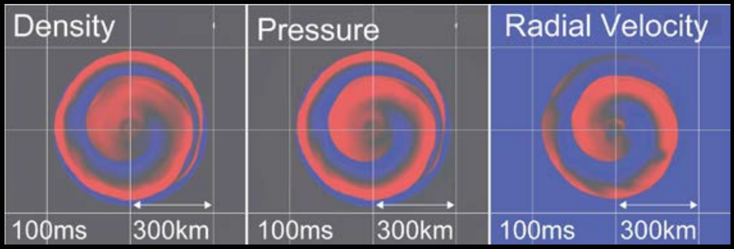
Switching gears to **MHD mechanism (rapid rotation required !!)**

3D rotating explosion simulation of a 27 M_{sun} star (Ω_0 = 2 rad/s) with IDSA.

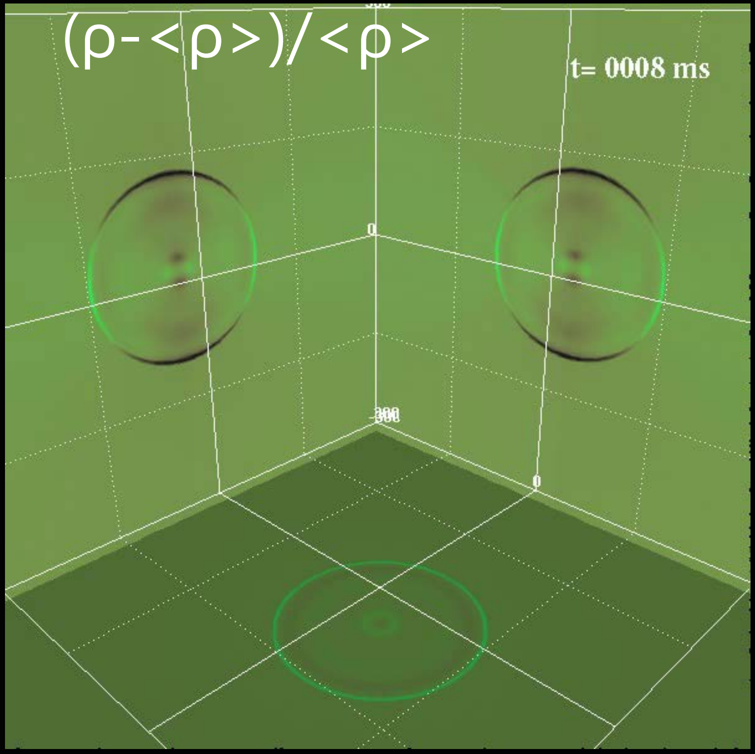
(Takiwaki, KK, and Suwa, MNRAS Letters, (2016), see also Summa et al. (2017)).



✓ One-armed (low T/|W|) instability



✓ Spiral waves enhance energy transport from PNS to gain region !

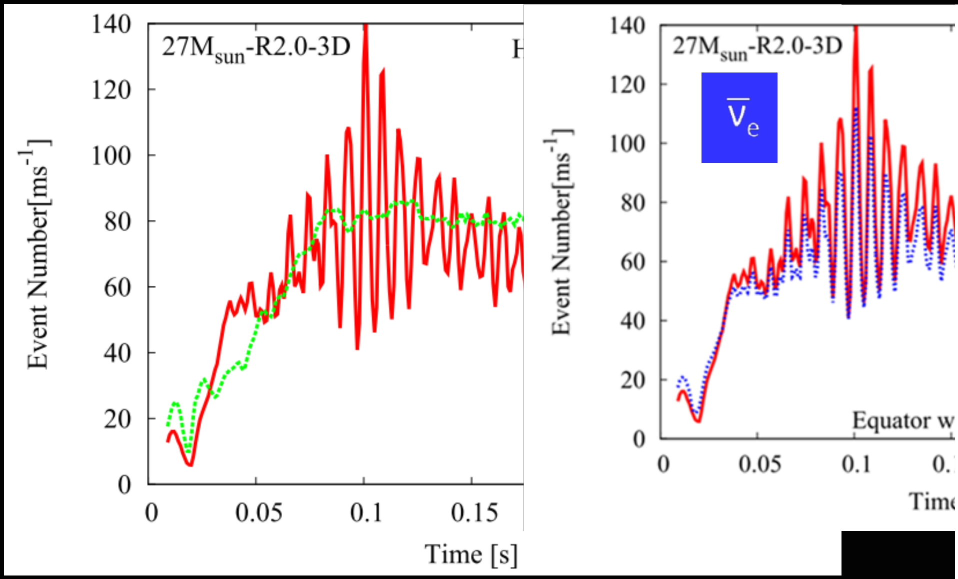


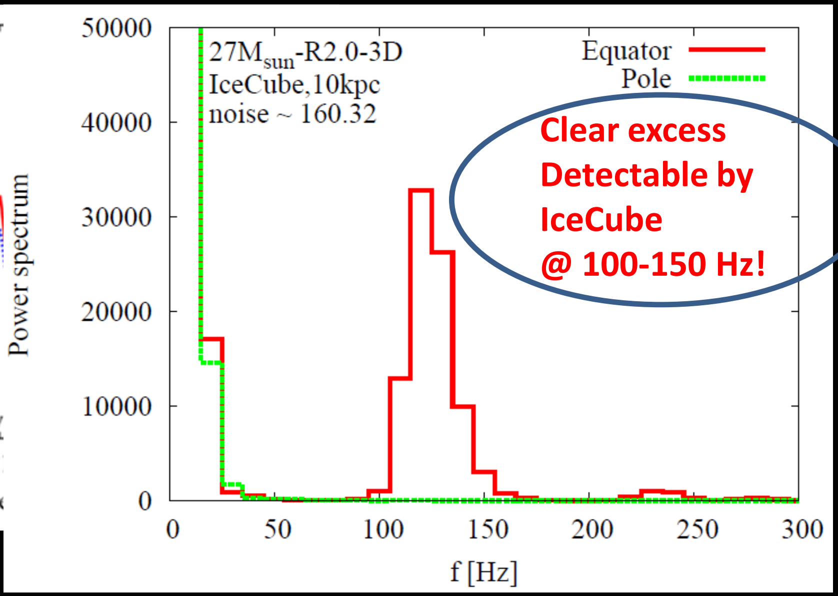
Neutrino signatures from rapidly rotating explosion of 27 M_{sun} star

Takiwaki and KK (2018), MNRAS Letters

Quasi-periodic variation !

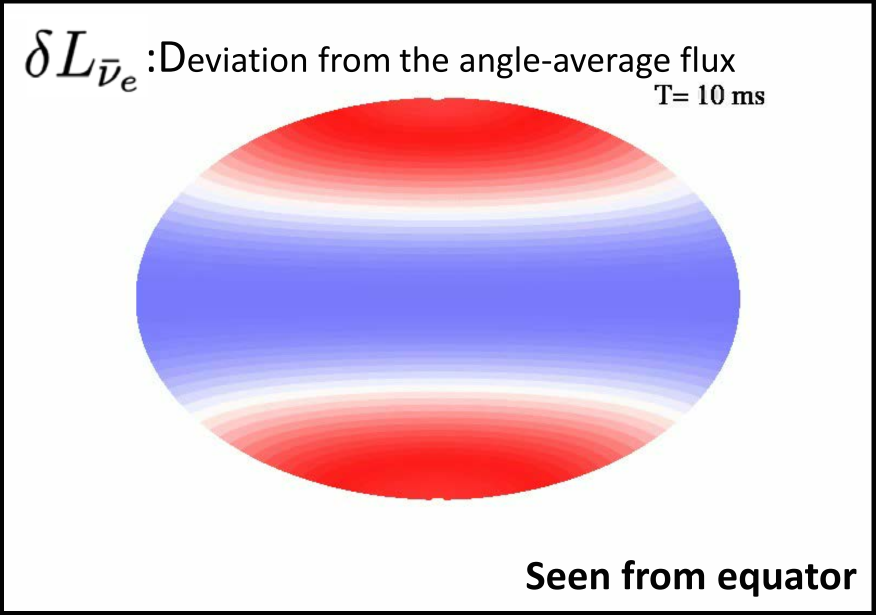
May survive with coll. oscillation





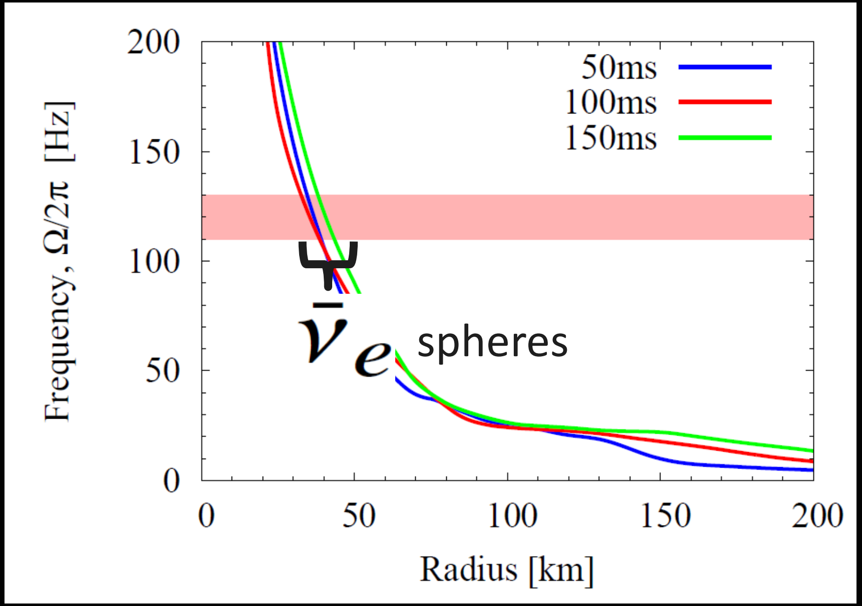
Clear excess
Detectable by
IceCube
@ 100-150 Hz!

$\delta L_{\bar{\nu}_e}$:Deviation from the angle-average flux



Seen from equator

“Lighthouse effect”

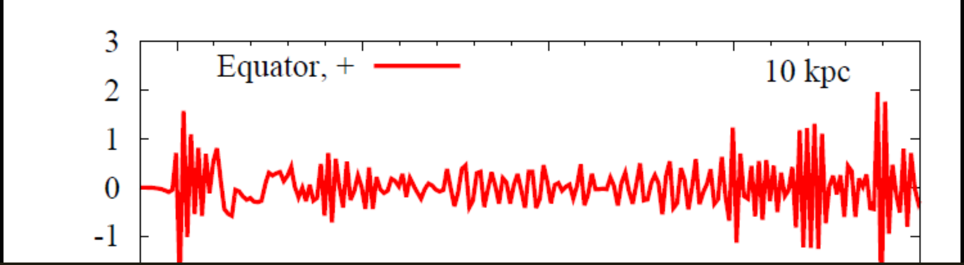


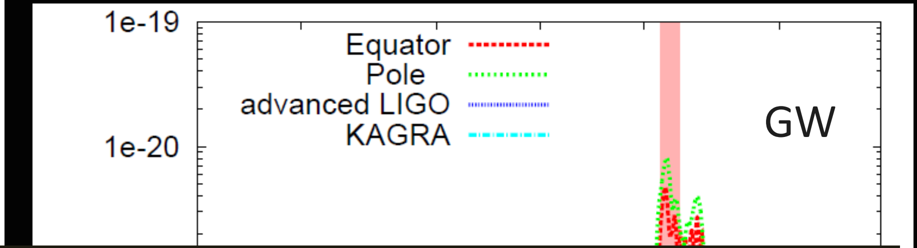
$\bar{\nu}_e$ spheres

Correlation of GW and neutrino signatures from the 3D rotating model,

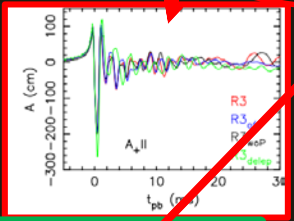
Gravitational waveform (27 M_{sun}, Ω_0 = 2rad/s)

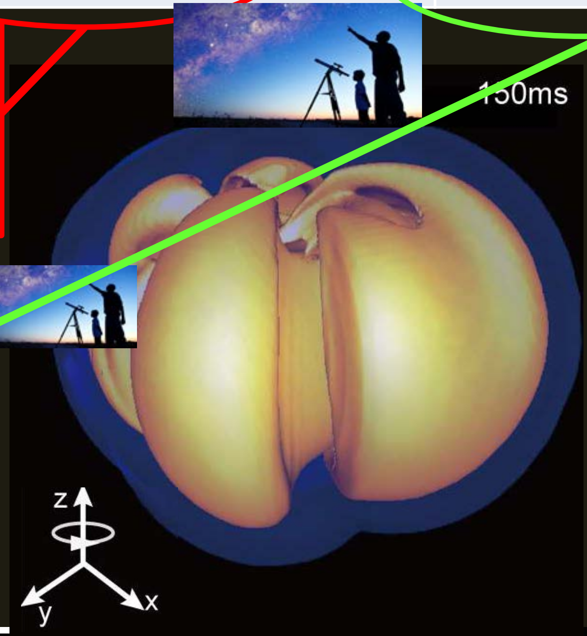
Takiwaki and KK (2018), MNRAS Letters

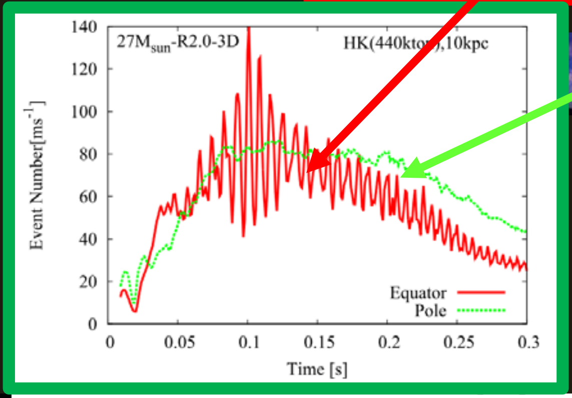


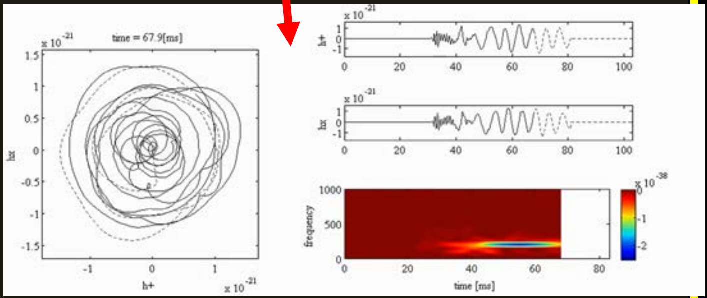


Directionality	Equator	Pole
Gravitational Wave	Type I signal	✓ Quasi-periodic signals from non-axis. instability ✓ Circular polarization
Neutrinos	Light-house effect	No surprise …









Need improvement in opacity of our 3D-GR code (with energy transport)!

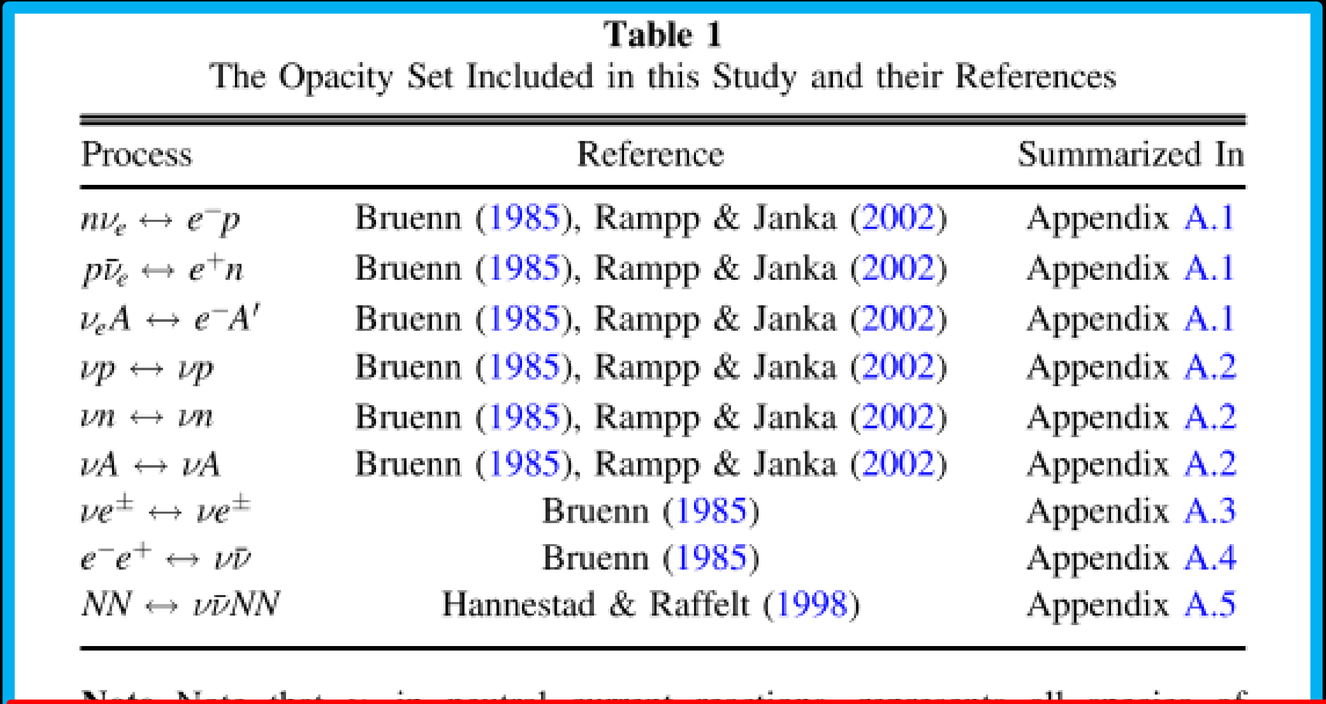


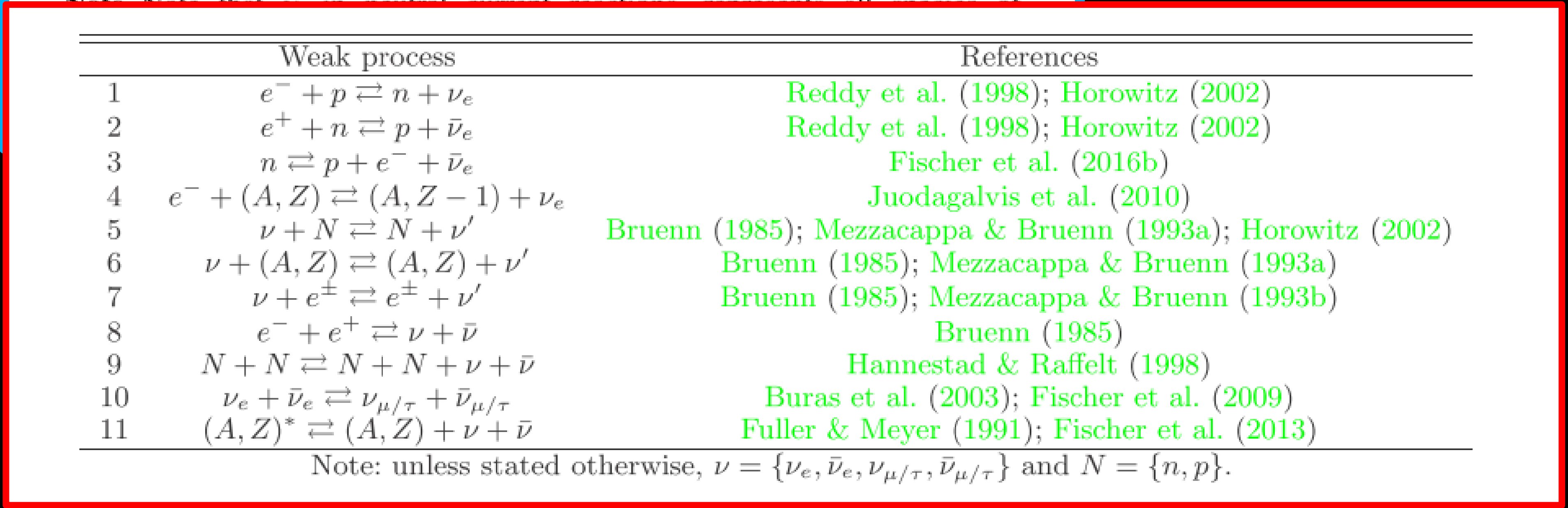
Table 1
The Opacity Set Included in this Study and their References

Process	Reference	Summarized In
$n\nu_e \leftrightarrow e^-p$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.1
$p\bar{\nu}_e \leftrightarrow e^+n$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.1
$\nu_e A \leftrightarrow e^-A'$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.1
$\nu p \leftrightarrow \nu p$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.2
$\nu n \leftrightarrow \nu n$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.2
$\nu A \leftrightarrow \nu A$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.2
$\nu e^\pm \leftrightarrow \nu e^\pm$	Bruenn (1985)	Appendix A.3
$e^-e^+ \leftrightarrow \nu\bar{\nu}$	Bruenn (1985)	Appendix A.4
$NN \leftrightarrow \nu\bar{\nu}NN$	Hannestad & Raffelt (1998)	Appendix A.5

Note. Note that ν in neutral-current reactions represents all species of

KTK (2016), ApJS
(essentially,
Bruenn rates +
Bremsstrahlung)

Most advanced set
(e.g., Fischer(2016),
Bollig et al. (2017))

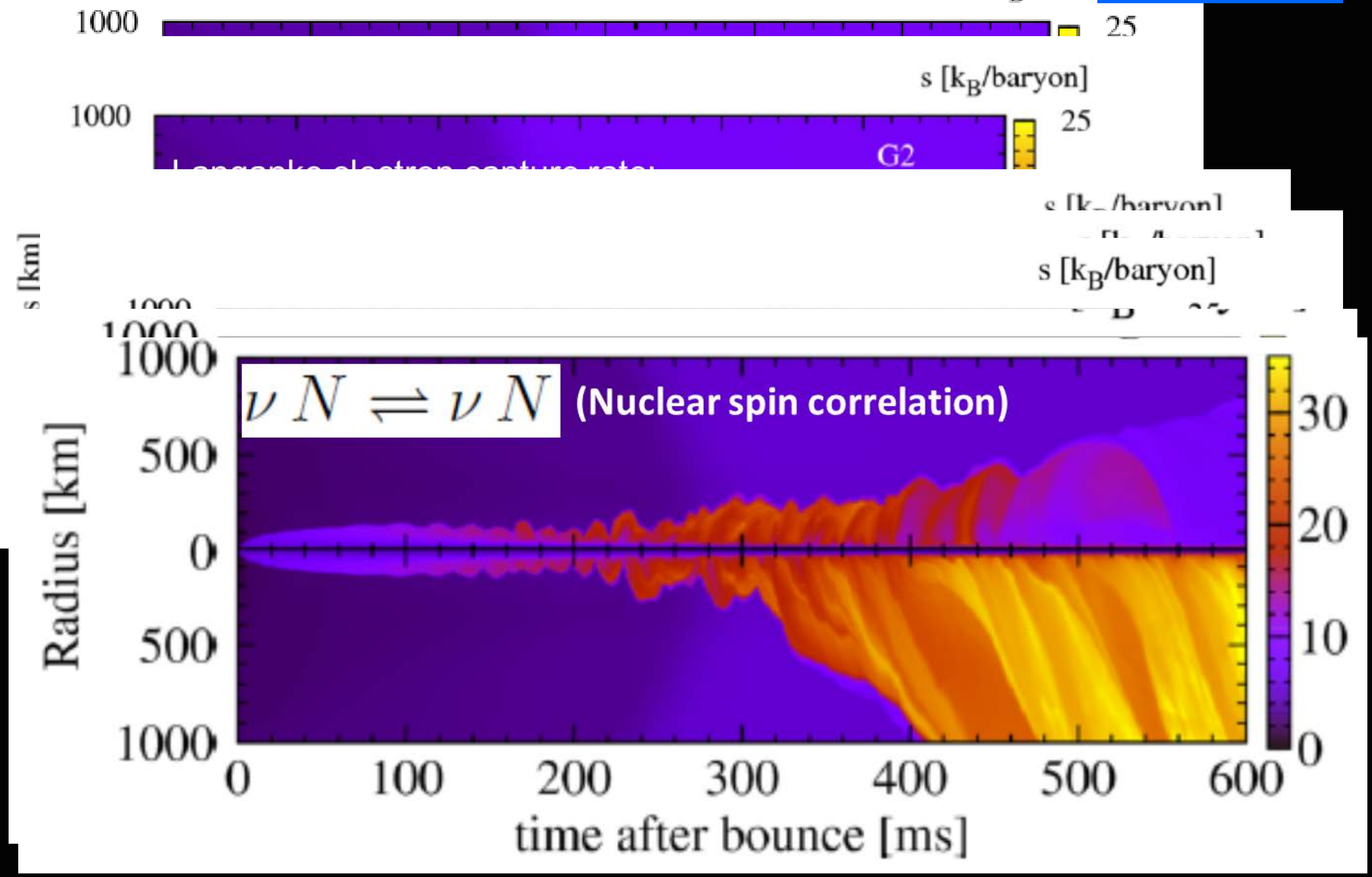


	Weak process	References
1	$e^- + p \rightleftarrows n + \nu_e$	Reddy et al. (1998); Horowitz (2002)
2	$e^+ + n \rightleftarrows p + \bar{\nu}_e$	Reddy et al. (1998); Horowitz (2002)
3	$n \rightleftarrows p + e^- + \bar{\nu}_e$	Fischer et al. (2016b)
4	$e^- + (A,Z) \rightleftarrows (A,Z-1) + \nu_e$	Juodagalvis et al. (2010)
5	$\nu + N \rightleftarrows N + \nu'$	Bruenn (1985); Mezzacappa & Bruenn (1993a); Horowitz (2002)
6	$\nu + (A,Z) \rightleftarrows (A,Z) + \nu'$	Bruenn (1985); Mezzacappa & Bruenn (1993a)
7	$\nu + e^\pm \rightleftarrows e^\pm + \nu'$	Bruenn (1985); Mezzacappa & Bruenn (1993b)
8	$e^- + e^+ \rightleftarrows \nu + \bar{\nu}$	Bruenn (1985)
9	$N + N \rightleftarrows N + N + \nu + \bar{\nu}$	Hannestad & Raffelt (1998)
10	$\nu_e + \bar{\nu}_e \rightleftarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$	Buras et al. (2003); Fischer et al. (2009)
11	$(A,Z)^* \rightleftarrows (A,Z) + \nu + \bar{\nu}$	Fuller & Meyer (1991); Fischer et al. (2013)

Note: unless stated otherwise, $\nu = \{\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau}\}$ and $N = \{n, p\}$.

2D IDSA simulation of 20 M_{sun} (Woosley and Heger (2007)

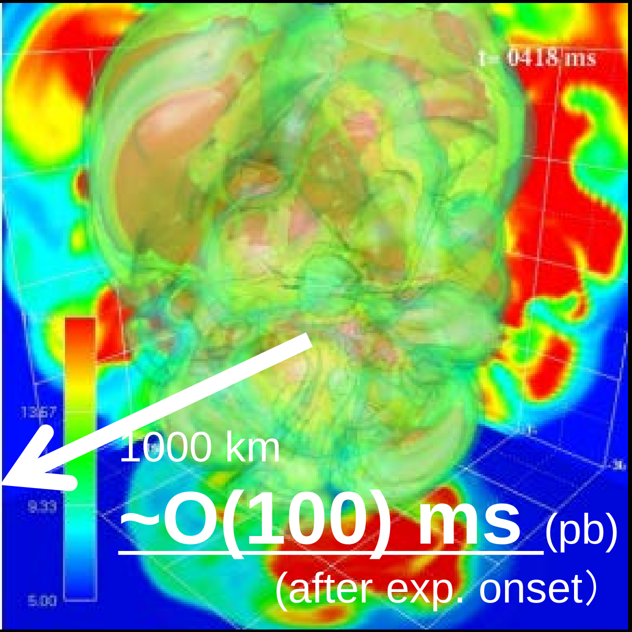
KK et al. (2017)



✓Quantitative GW･neutrino signal prediction, the updates in opacities mandatory!

Next 10 years: Where are we and are we going ?

“A” self-consistent 3D model



1000 km

~O(100) ms (pb)

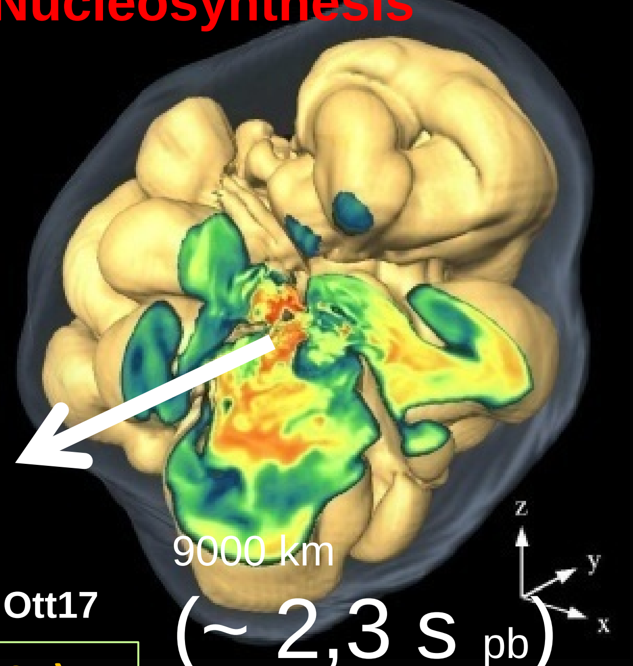
(after exp. onset)

Takiwaki, KK, Suwa (2016), Melson+15, Ott17

For some progenitors (11.2,15,20.27), the stalled shock revived !
(5D/4D with approximate transport)

Gray-transport simulation

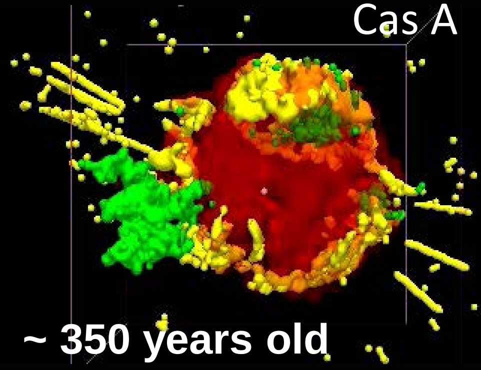
Nucleosynthesis



9000 km

(~ 2,3 s pb)

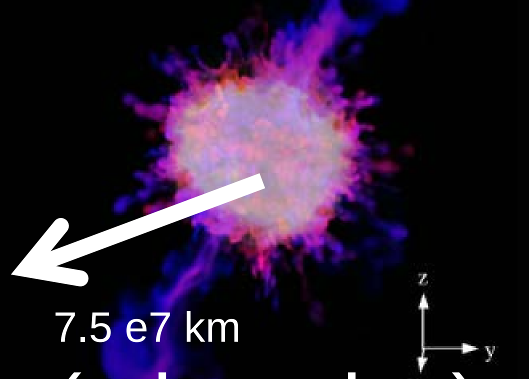
Wongwathanarat et al. (2015)



~ 350 years old

DeLaney et al. (2010)

Hydrodynamic model:
Mixing, RT, RM instabilities



7.5 e7 km

(min – day)

Wongwathanarat et al. (2016)

To-do-1: Long-term evolution in self-consistent 3D (GR) models
⇒ confront CCSN theory with observation ⇒ Pragmatism

To-do-2 : Full GR and Boltzmann project :
⇒ ultimately test whether the stalled shock would revive. ⇒ Perfectionism

SN 20xx ! in the Galactic center: End-to-End Bridging Simulations

sec	min		hours		day		years
- 4	- 3	- 2		- 1	0	2	>3

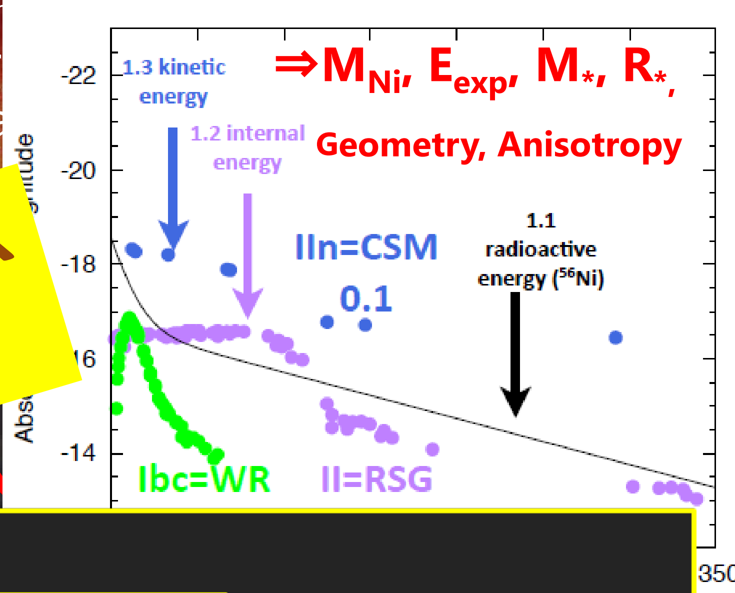
Log (day)

SK detects ~ 10,000 neutrinos

< 15min SURGE meeting (Supernova Urgen

< 1 hour SK provide alert: Astronomer

(onset of neutri st, dura



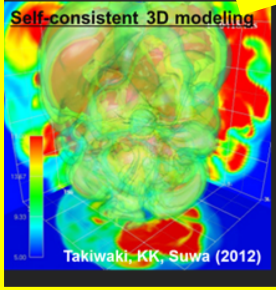
K, SK, KamLAND, LIGO, Virgo

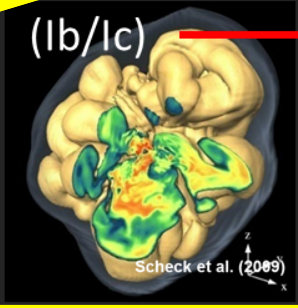
KAGRA, Hyper-K, and Post-K

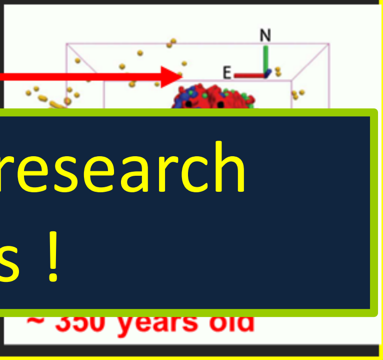
ET, CE, DUNE…..

Self-Cons

Self-consist ock-breakout







Multi-messenger research
in steady progress !

Summary

1. In 2D, a number of explosion models (> 400) obtained by independent groups.
   Some are enough energetic to account for observations (E_{exp}, Ni).

2. 3D explosions generally under-energetic than 2D.
   - progenitor dependence yet unclear.

   ✓ Need to find some ingredients to foster 3D explosions.
   - Need neutrino physics update ? (e.g., Melson et al. (2015), KK+(2017))
   - Impact of rotation/magnetic fields needs to be clarified in 3D self-consistent models.

     (e.g., Takiwaki and Kotake (2018), Obergaulinger et al. (2016))

3. 3D GR modelling has just started with increasing microphysical inputs.
   (e.g., It takes time … next generation machines needed !)

4. Multi-messenger analysis of neutrino and GWs are in steady progress.
   : provide information to measure “SASI” activity.
   and to break the degeneracy (M_{PNS}, R_{PNS}, T_{PNS}, R_{shock}, EOS etc.)
   ⇒ important probe to the explosion physics for the SN20xx !

Many thanks!