文部科学省科学研究費補助金「新学術領域研究」 科研費 KAKENHI
重力波天体の多様な観測による宇宙物理学の新展開
New development in astrophysics through multimessenger observations of gravitational wave sources

HPCI戦略プログラム分野5
「物質と宇宙の起源と構造」

超新星爆発による
ニュートリノ信号と重力波信号

諏訪 雄大

(京都大学 基礎物理学研究所 & Max-Planck-Institut für Astrophysik)

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Max Planck Institute for Astrophysics

YIPQS YITP Kyoto

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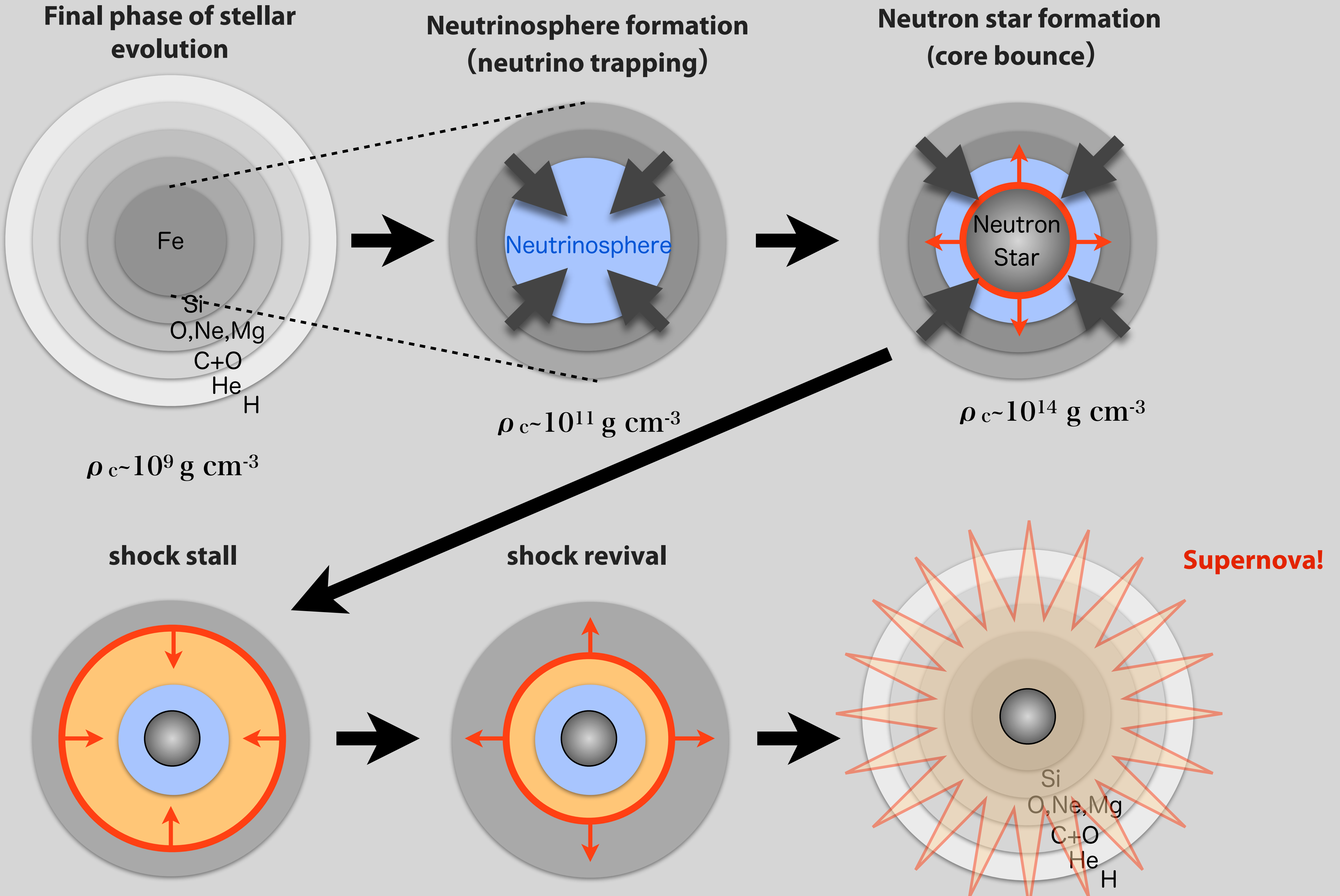
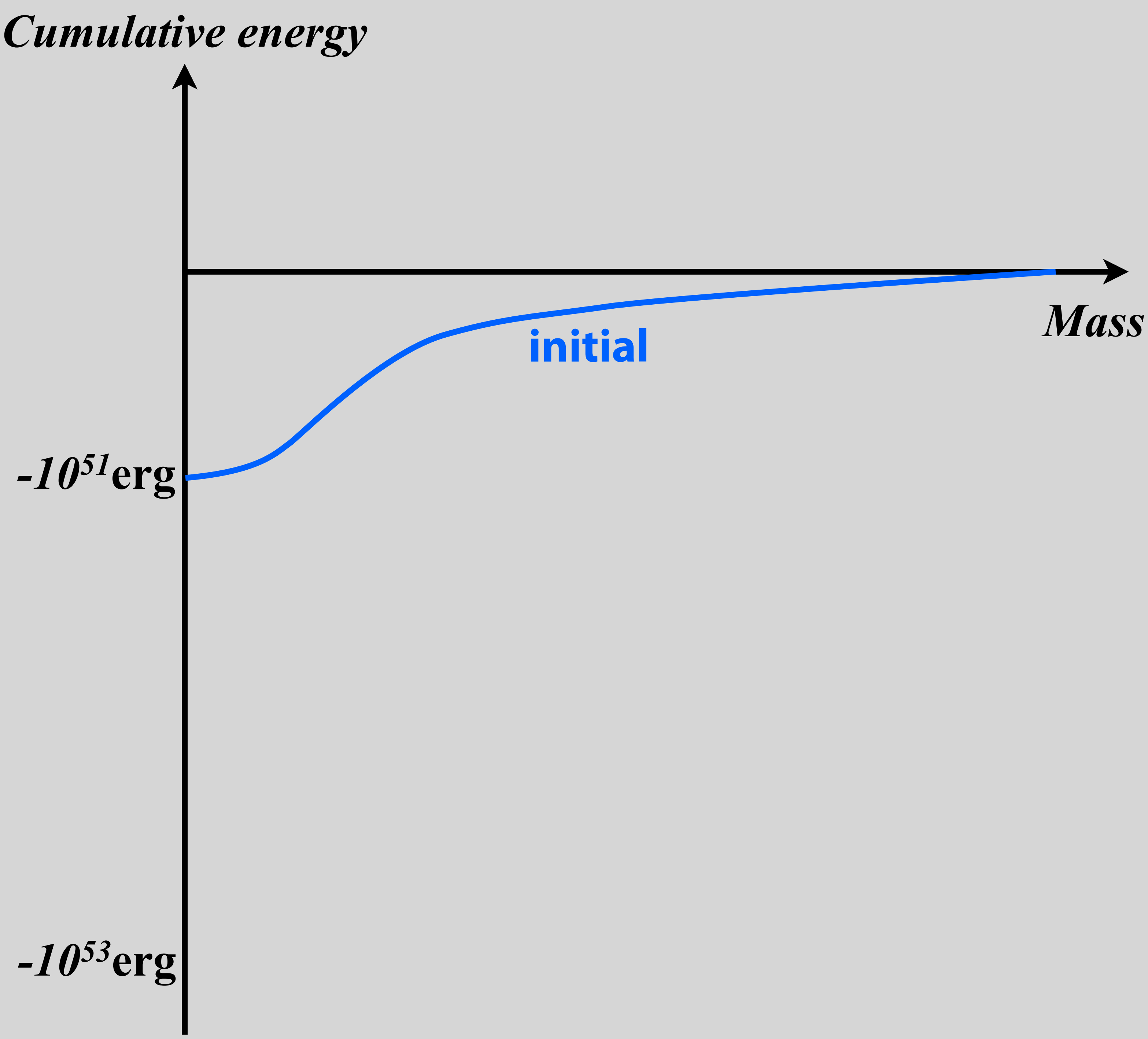
Standard scenario of core-collapse supernovae



Energetics



- Energy release by gravitational collapse
- most of energy is escaping as neutrinos
- part of energy is transferred from inside to outside
- **How?**

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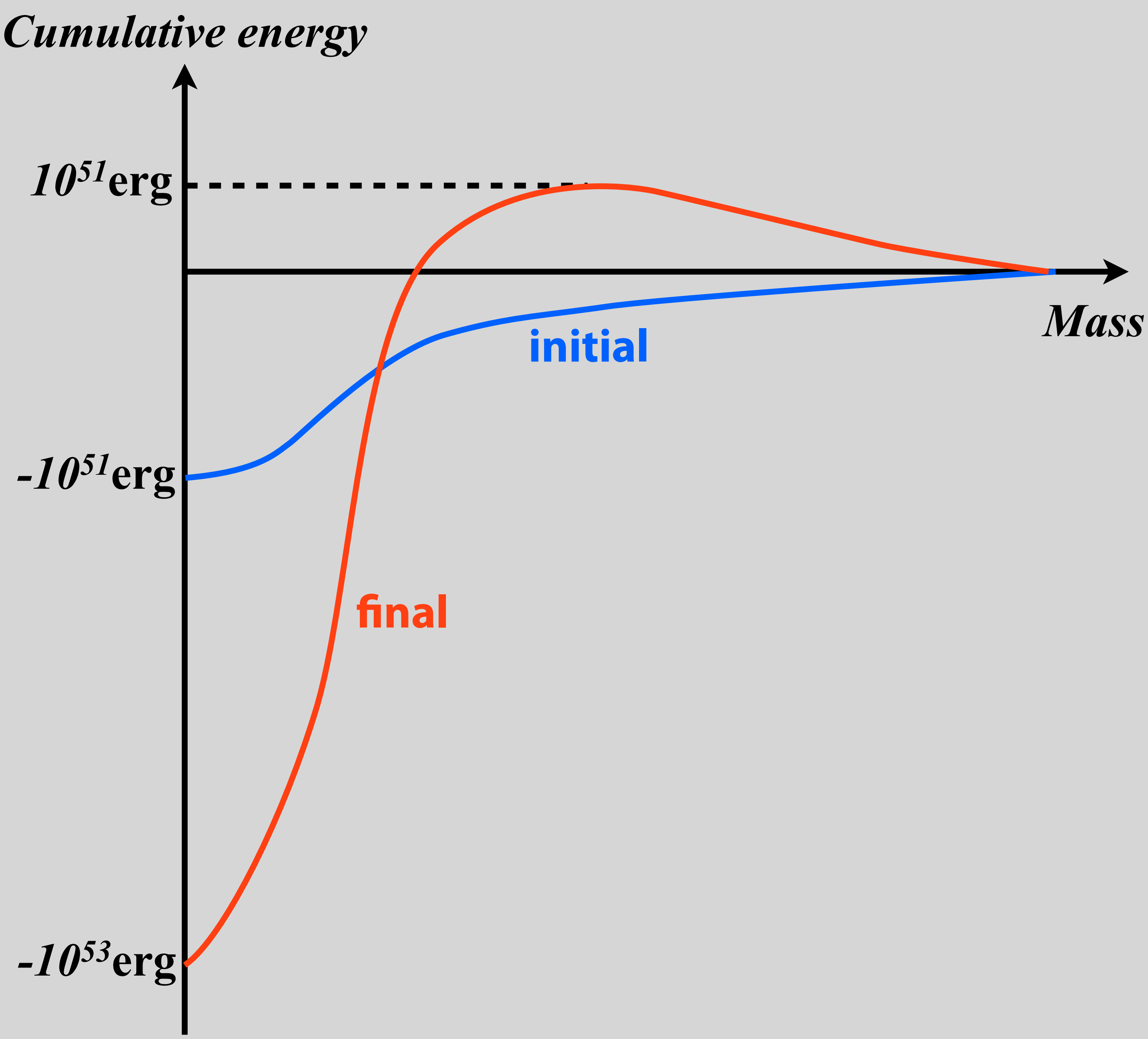

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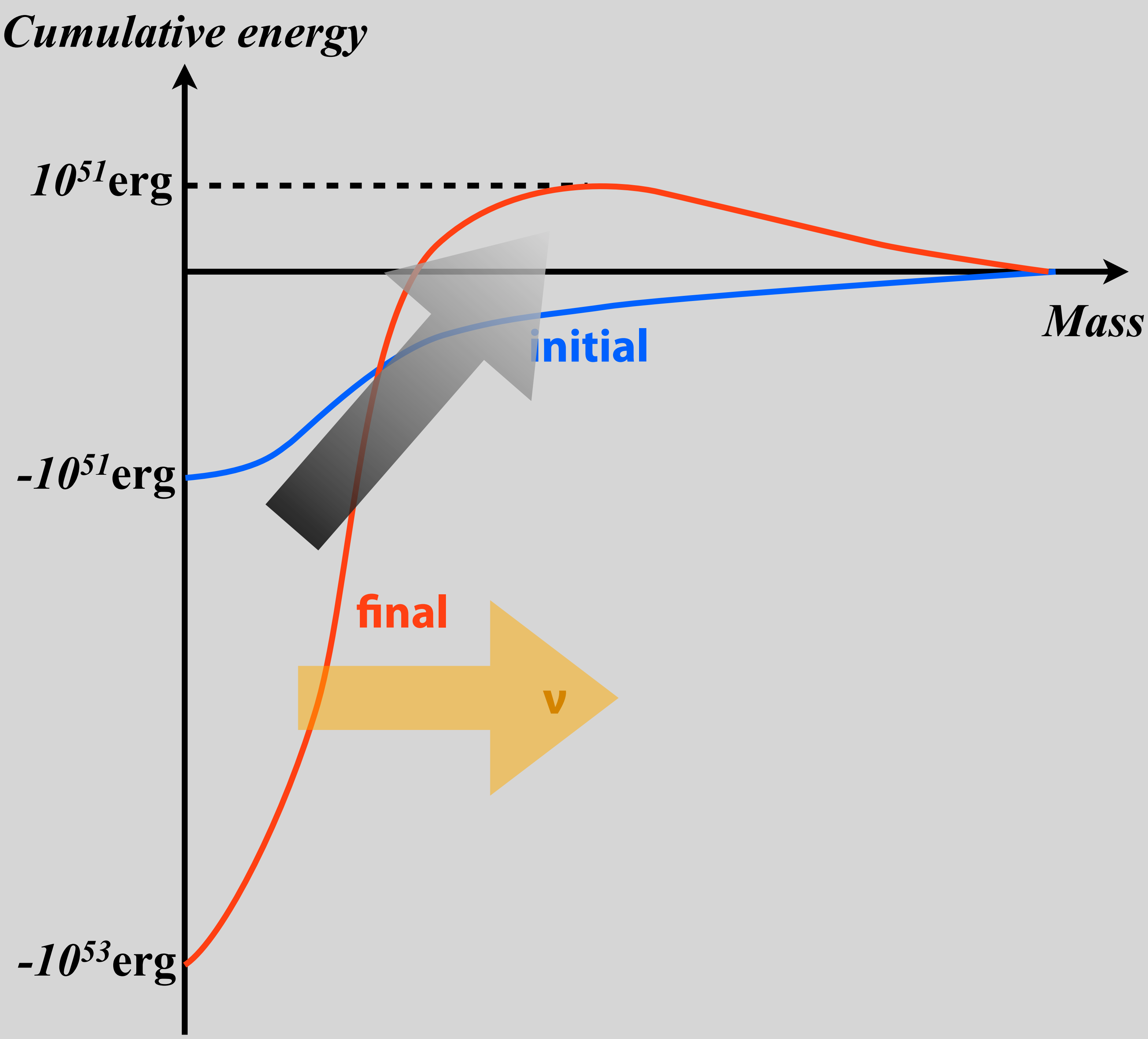

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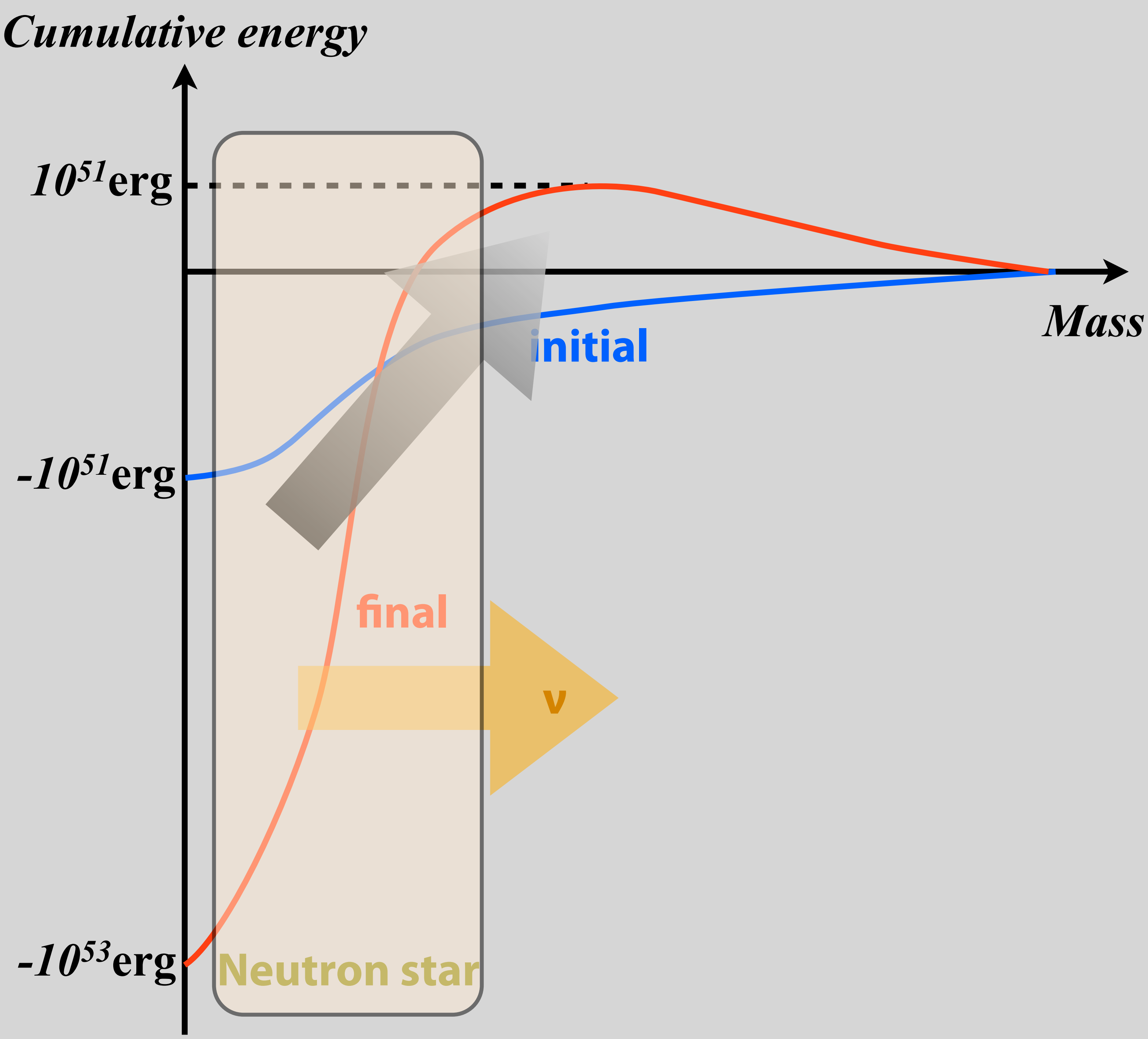

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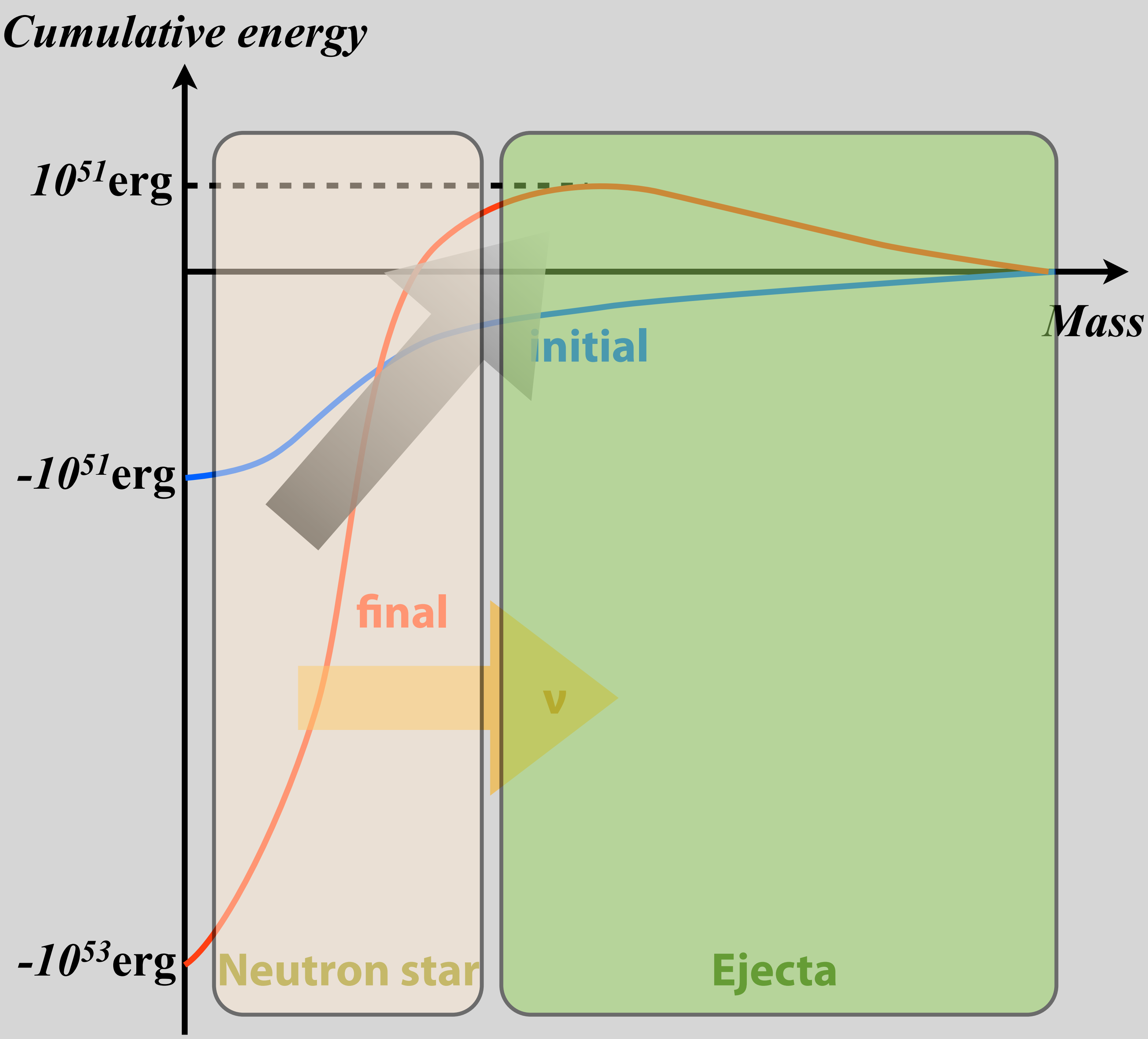

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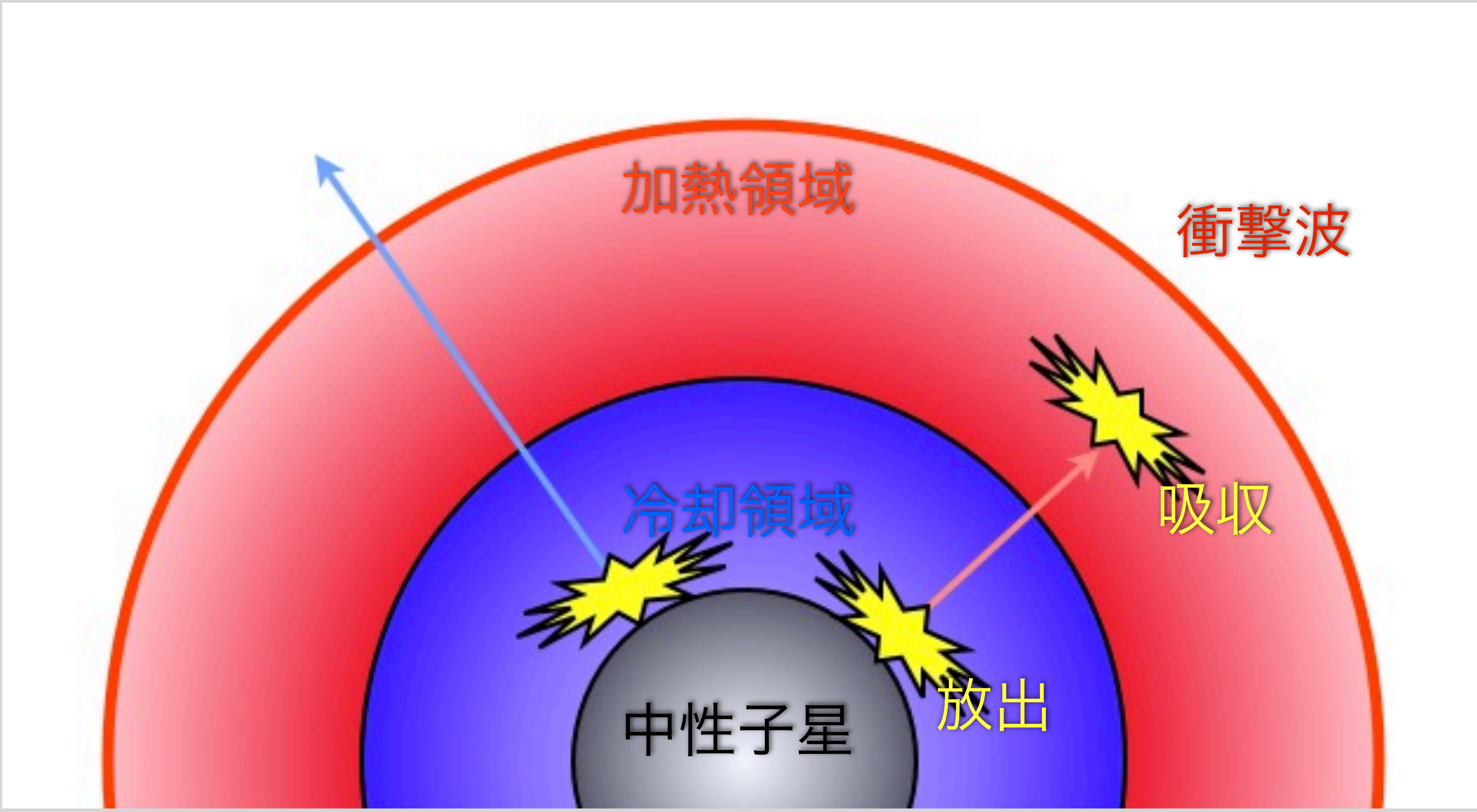
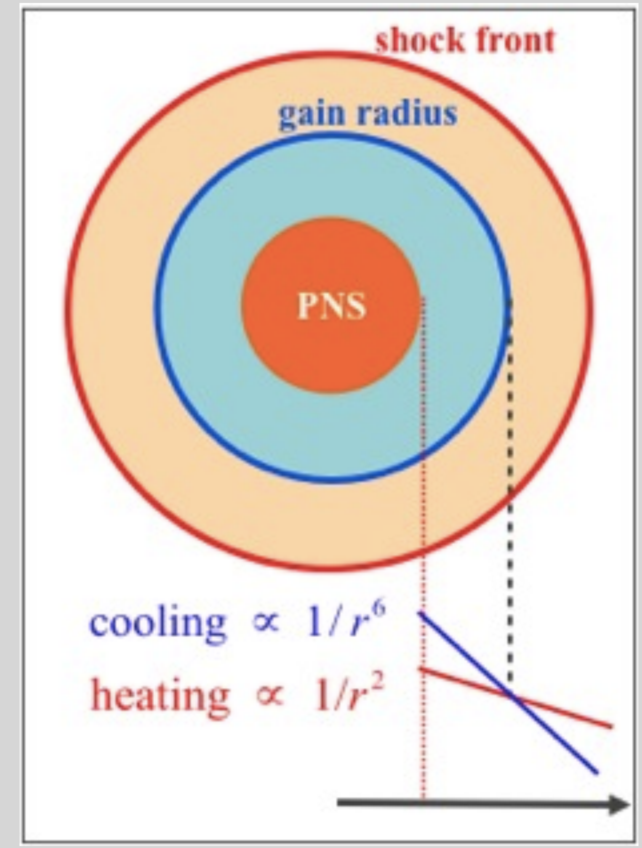
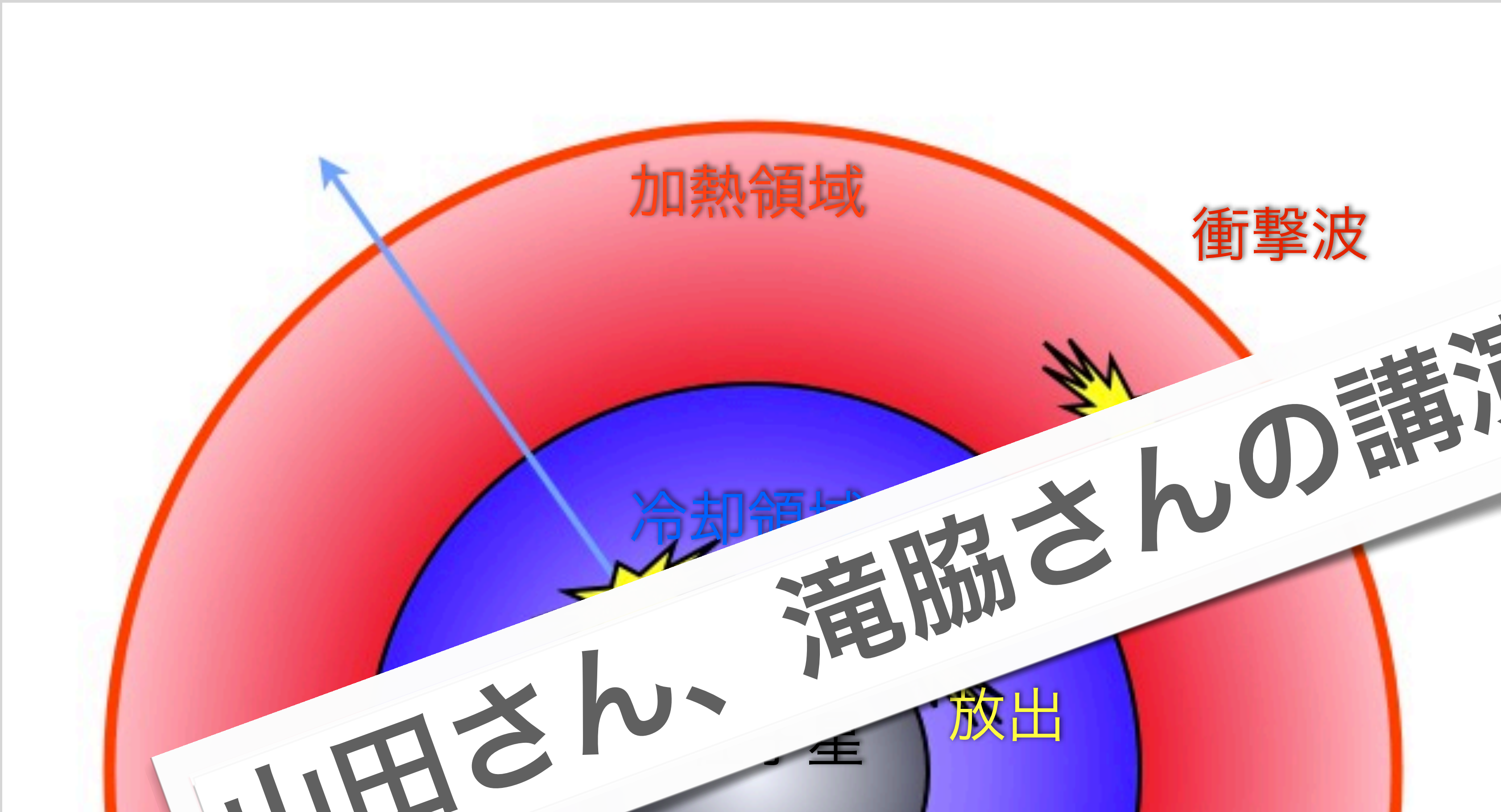
Standard model: neutrino-driven explosion

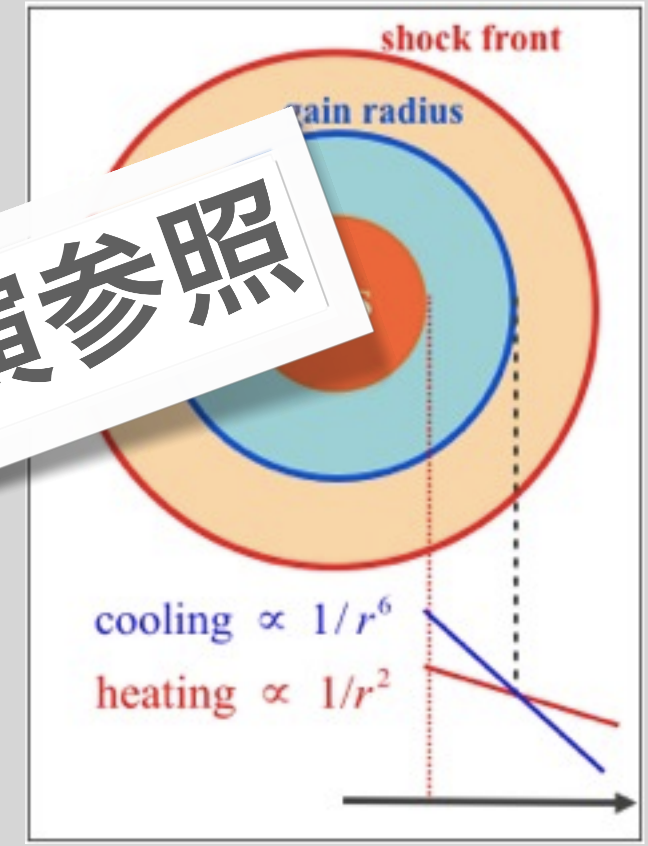




- Energy is transferred by neutrinos
- Most of them are just escaping from the system, but are partially absorbed
- In gain region, neutrino heating overwhelms neutrino cooling

Standard model: neutrino-driven explosion





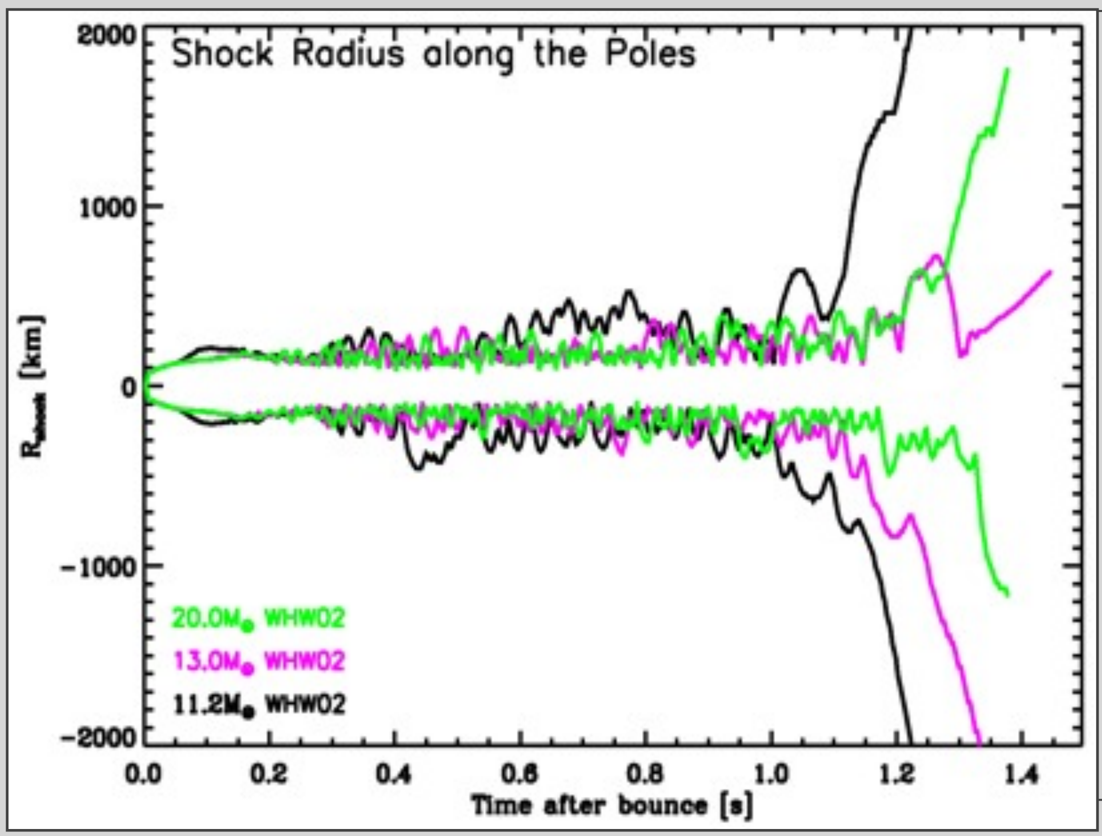
山田さん、滝脇さんの講演参照

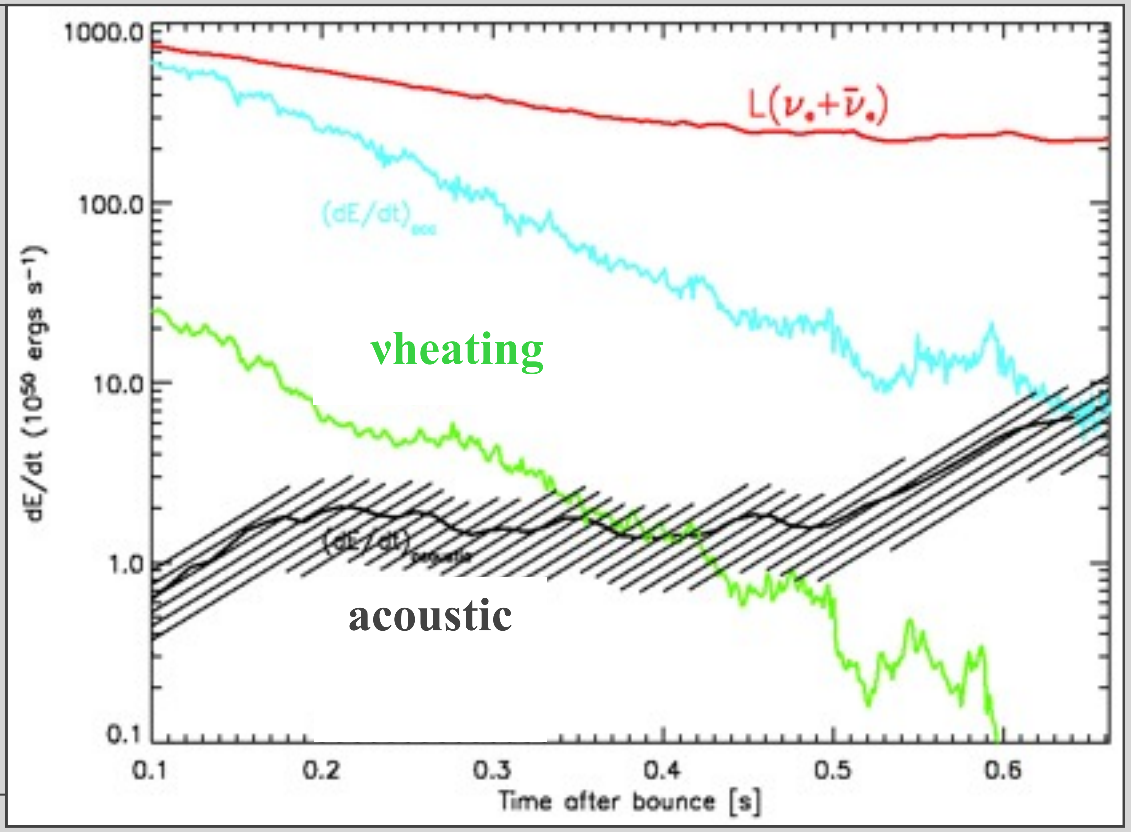
- Energy is transferred by neutrinos
- Most of them are just escaping from the system, but are partially absorbed
- In gain region, neutrino heating overwhelms neutrino cooling

Alternatives: acoustic explosion

(Burrows+ 06,07)

- SASI がPNSを叩く=> PNSを揺らす
- PNSの振動が音波を生み、衝撃波を叩く
- 音波によるエネルギー供給がニュートリノを凌駕(?)
- Shock revival by acoustic power

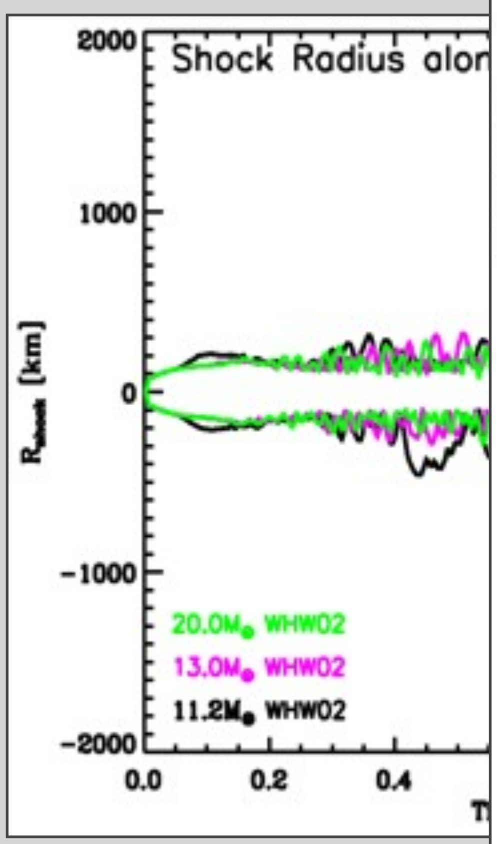


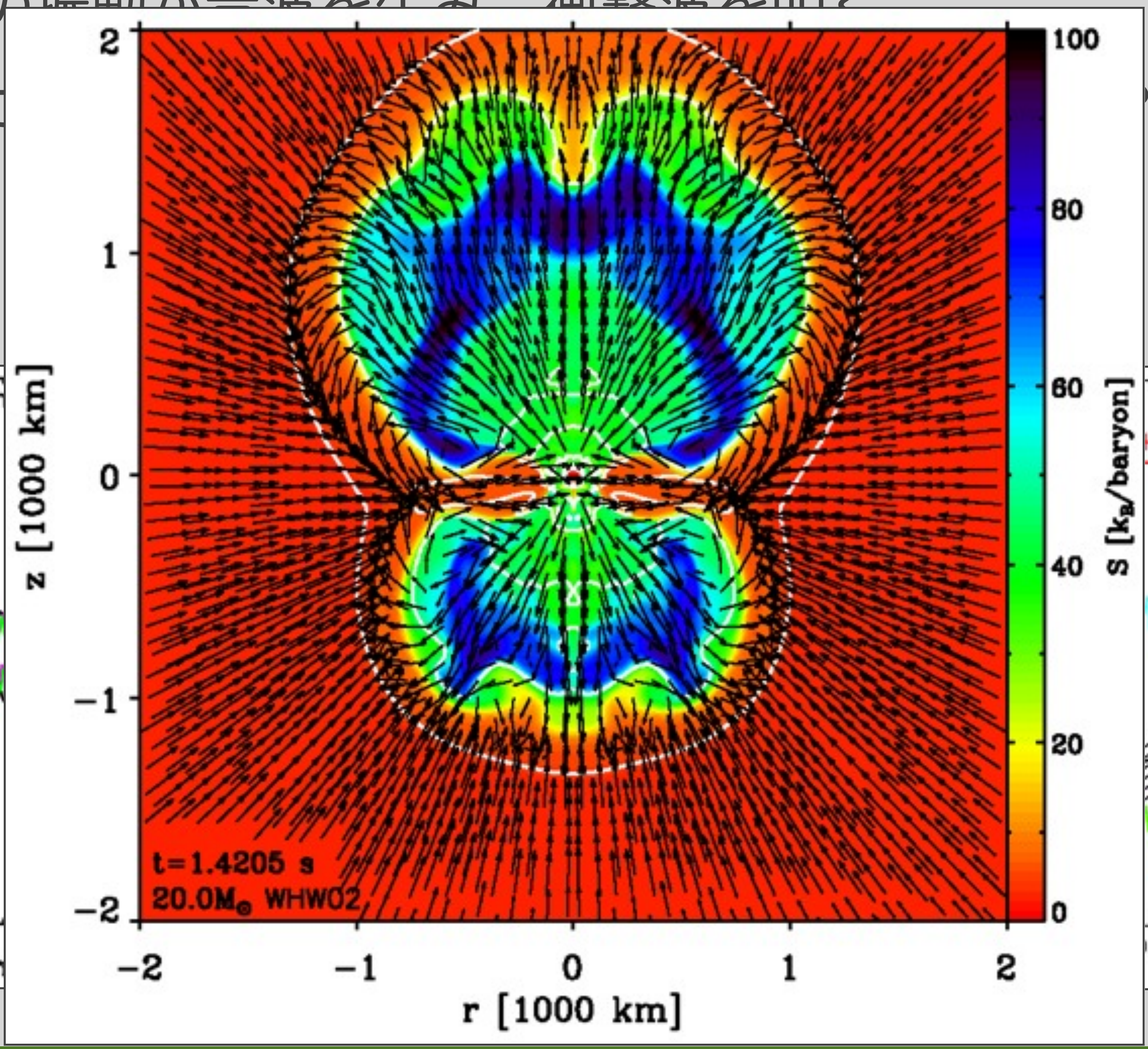


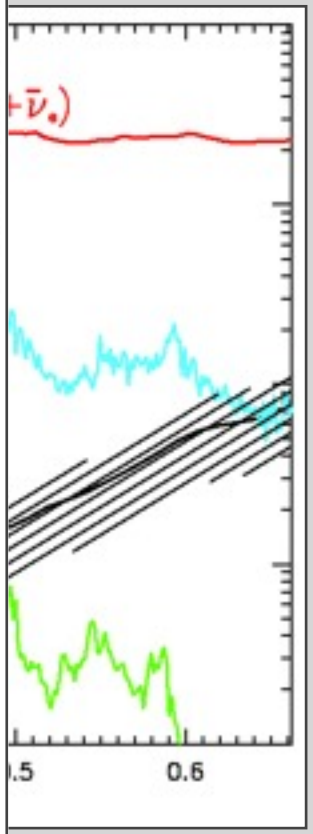
Alternatives: acoustic explosion

(Burrows+ 06,07)

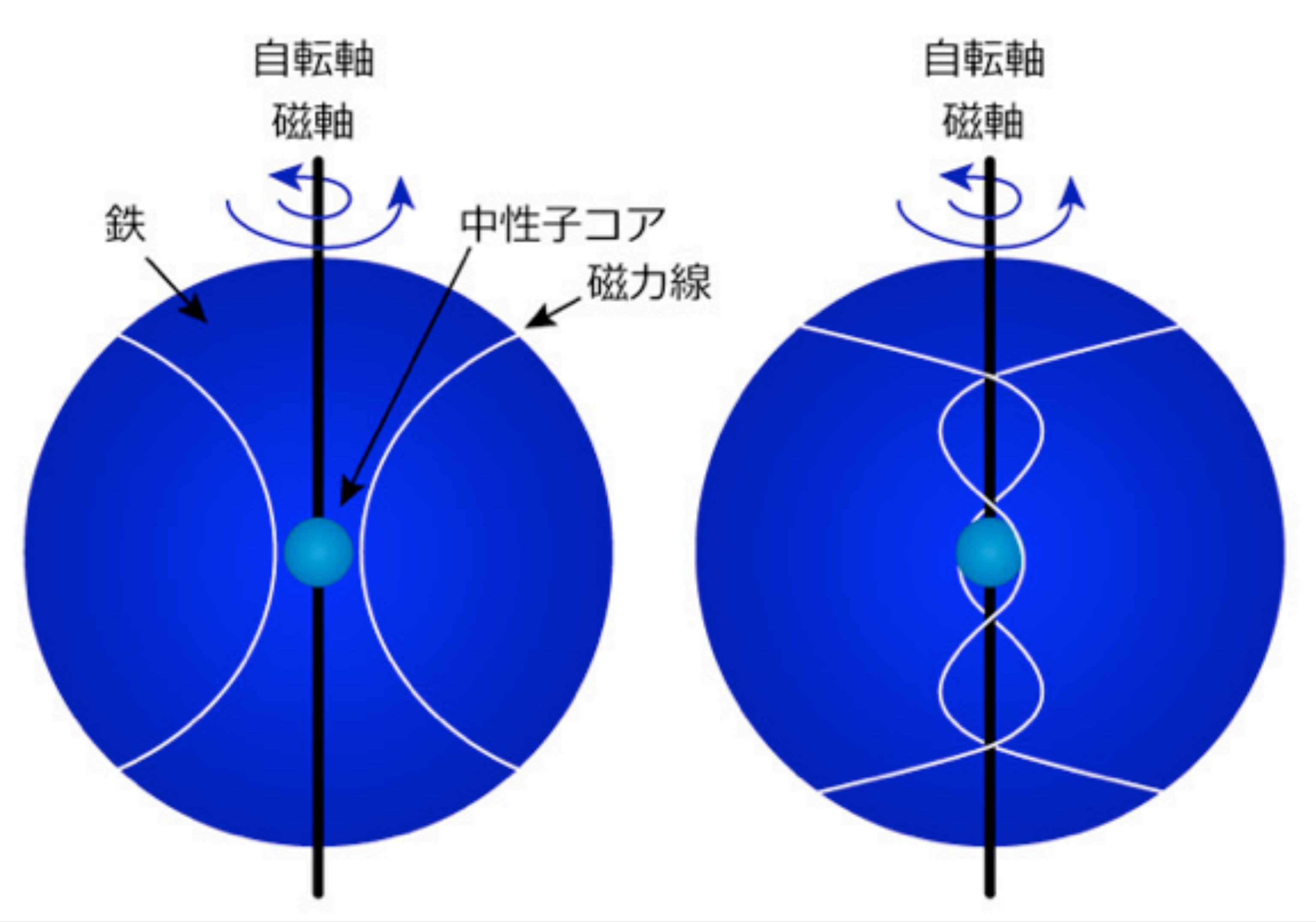
- SASI がPNSを叩く=> PNSを揺らす
- PNSの
- 音波に
- Shock







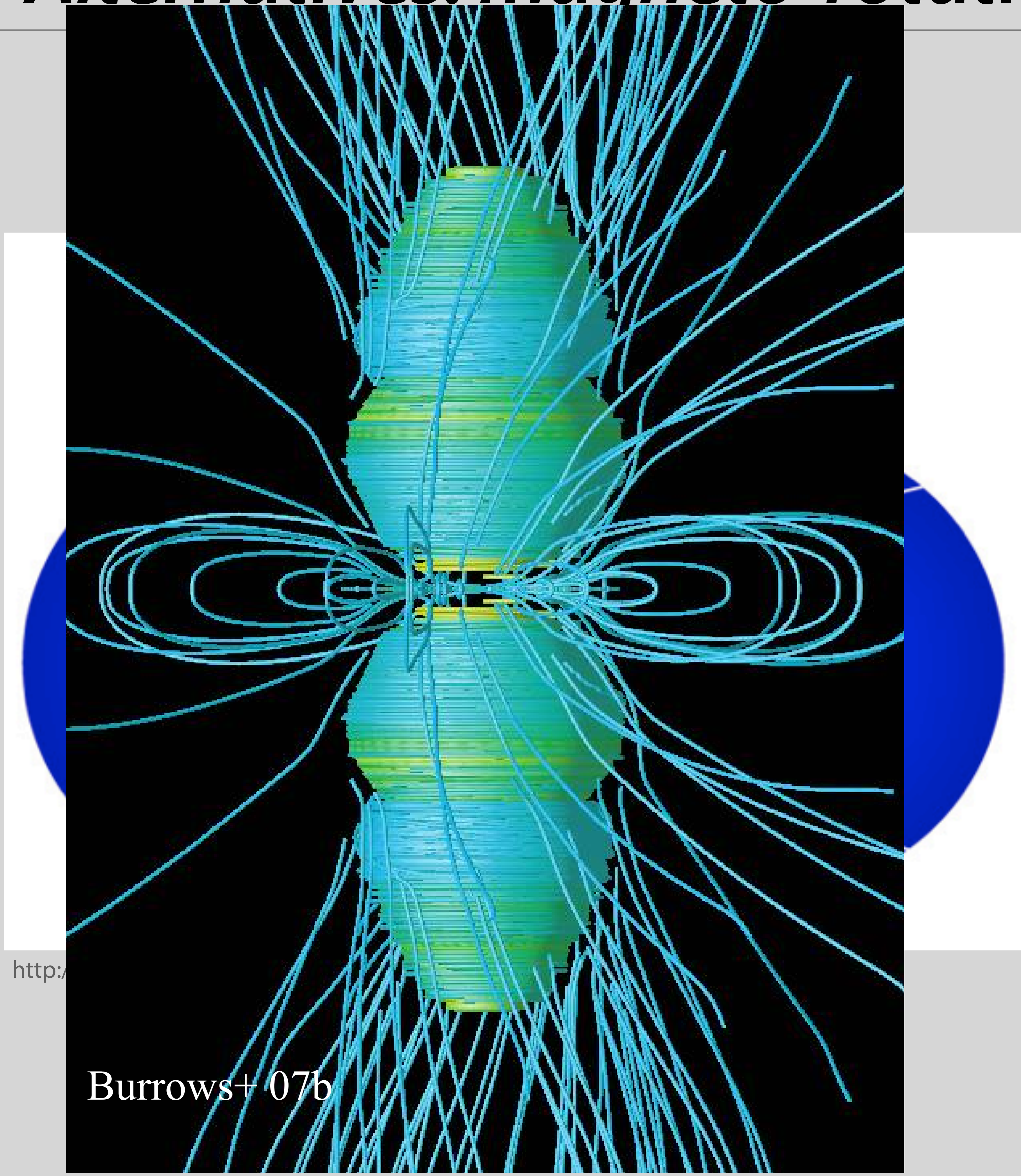
Alternatives: magneto-rotational explosion



http://www.jicfus.jp/jp/promotion/pr/mj/2011-2/

* 星が微分回転していると、それに伴って磁場を巻く
* 巻かれた磁場は極方向に圧力を及ぼす
* 初期条件として、強い回転と強い磁場を持っている場合、回転軸に沿ってアウトフローが形成される

Alternatives: magneto-rotational explosion



http:/

* 星が微分回転していると、それに伴って磁場を巻く
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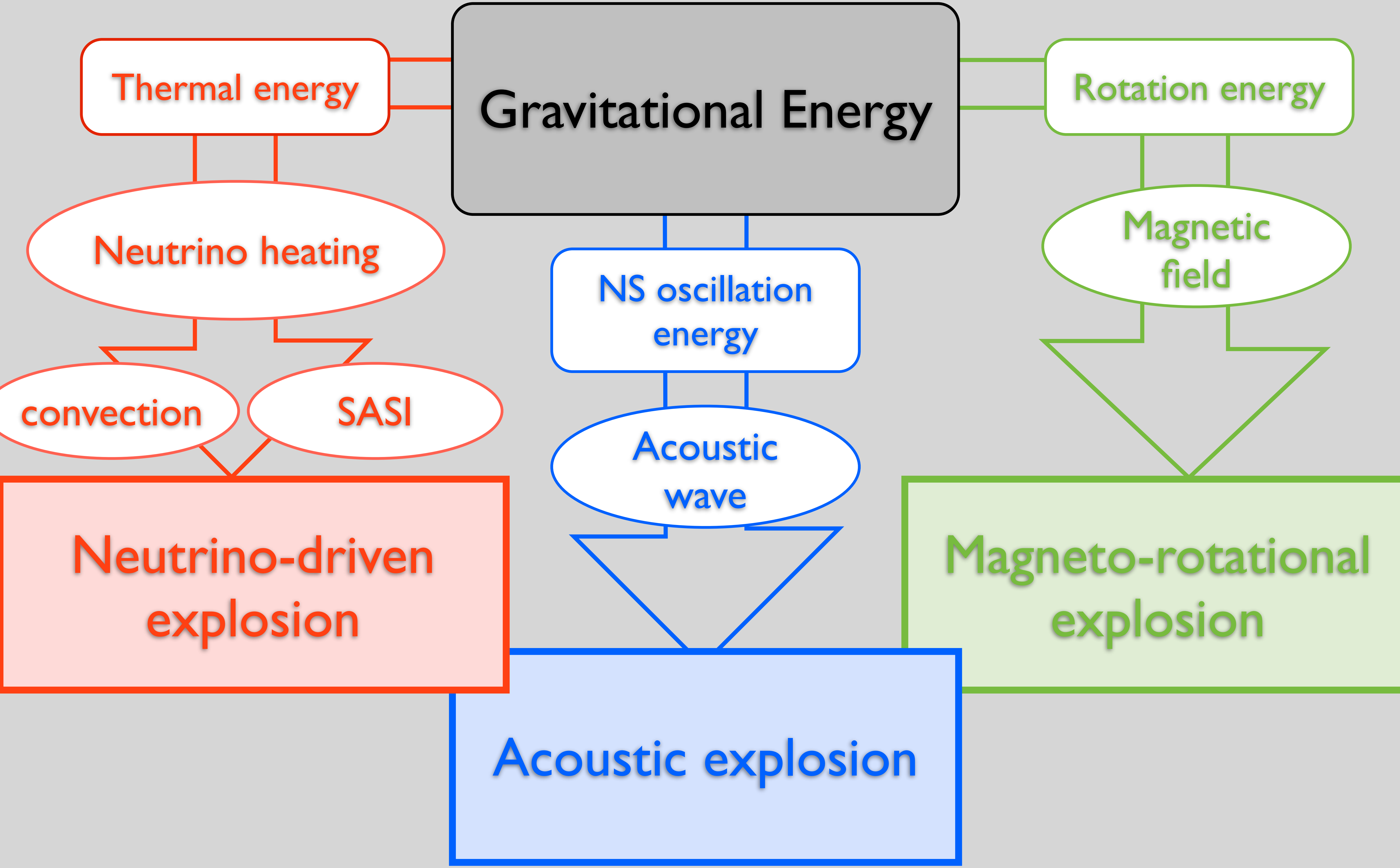
Summary of explosion mechanism



Summary of explosion mechanism

* **Neutrino-driven explosion**
  - Standard scenario
  - Community is trying to produce explosion on this line for >~ 50 years
  - In 2D and 3D, we obtained weak explosions (Germany, Japan, US)

* **Acoustic explosion**
  - Impedance mismatch is problem?
  - Long timescale to work (>~1s)
  - Only one group (in US) obtained explosion

* **Magneto-rotational explosion**
  - Both strong magnetic field are necessary
  - Inconsistent with standard stellar evolution calculation?

Other exotic scenarios
- QCD phase transition
- axion heating
- ...

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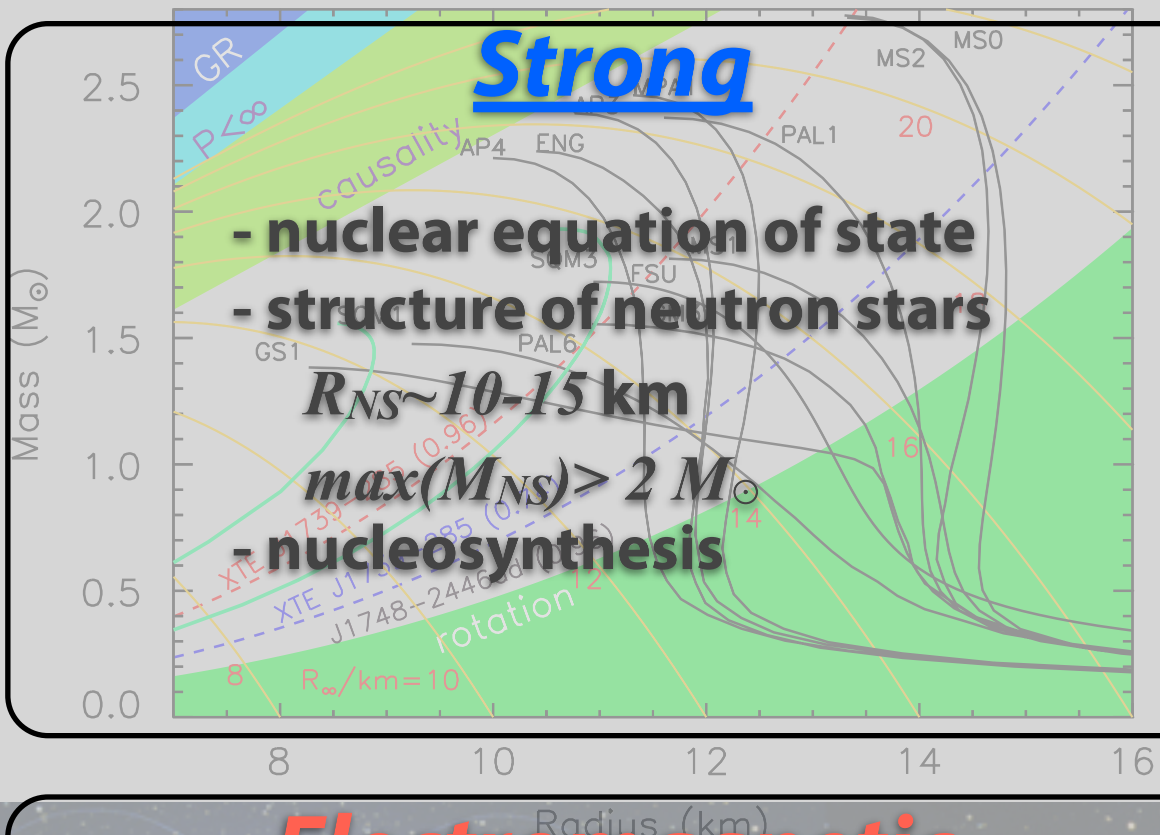
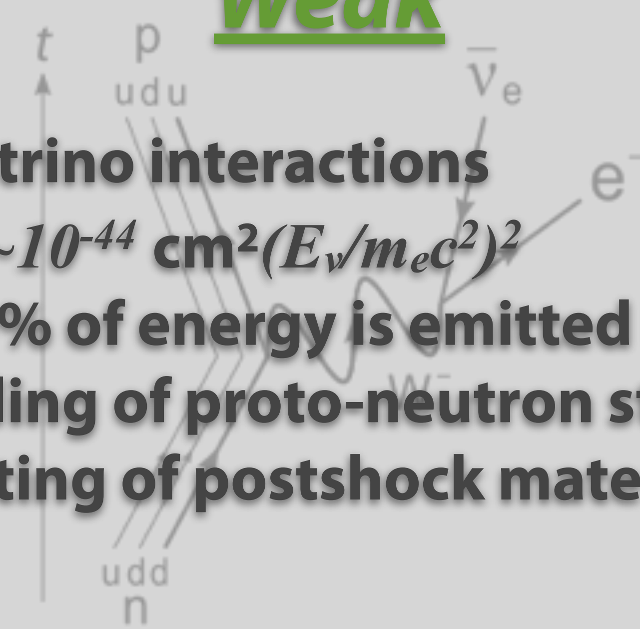
Core-collapse supernovae

In these violent explosions, all known <u>interactions</u> are involving and playing important roles;



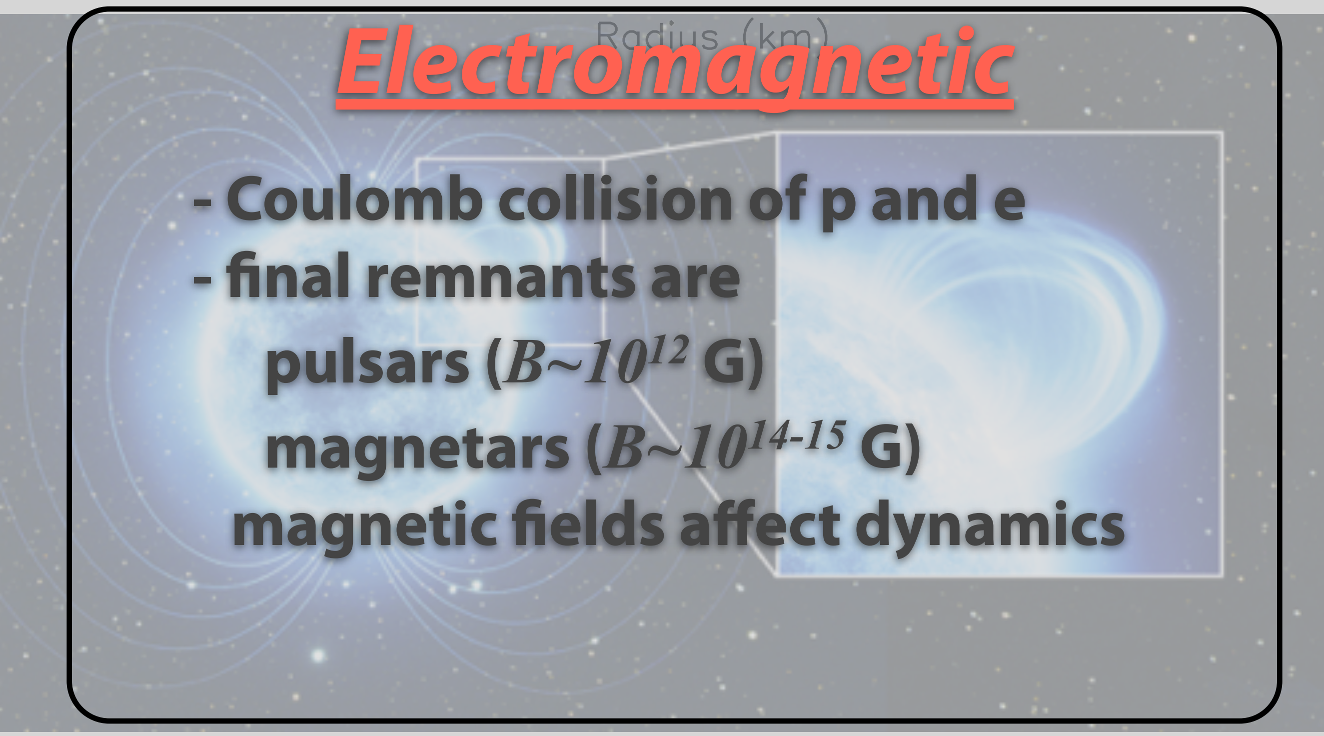
Strong

- nuclear equation of state
- structure of neutron stars
  - R_{NS}~10-15 km
  - $max(M_{NS}) > 2\,M_\odot$
- nucleosynthesis



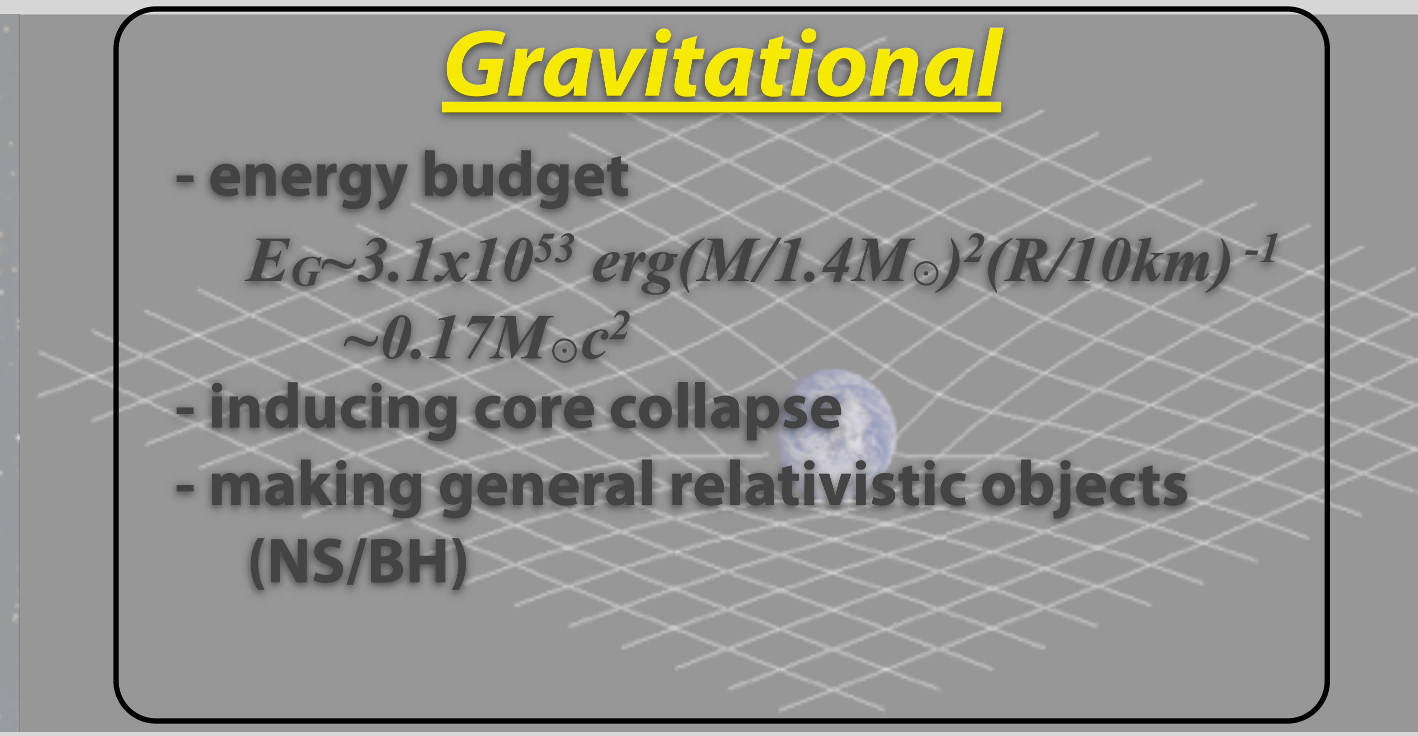
Weak

- neutrino interactions
  - $\sigma_\nu \sim 10^{-44}$ cm$^2 (E_\nu/m_e c^2)^2$
- ~99% of energy is emitted by ν's
- cooling of proto-neutron star
- heating of postshock material



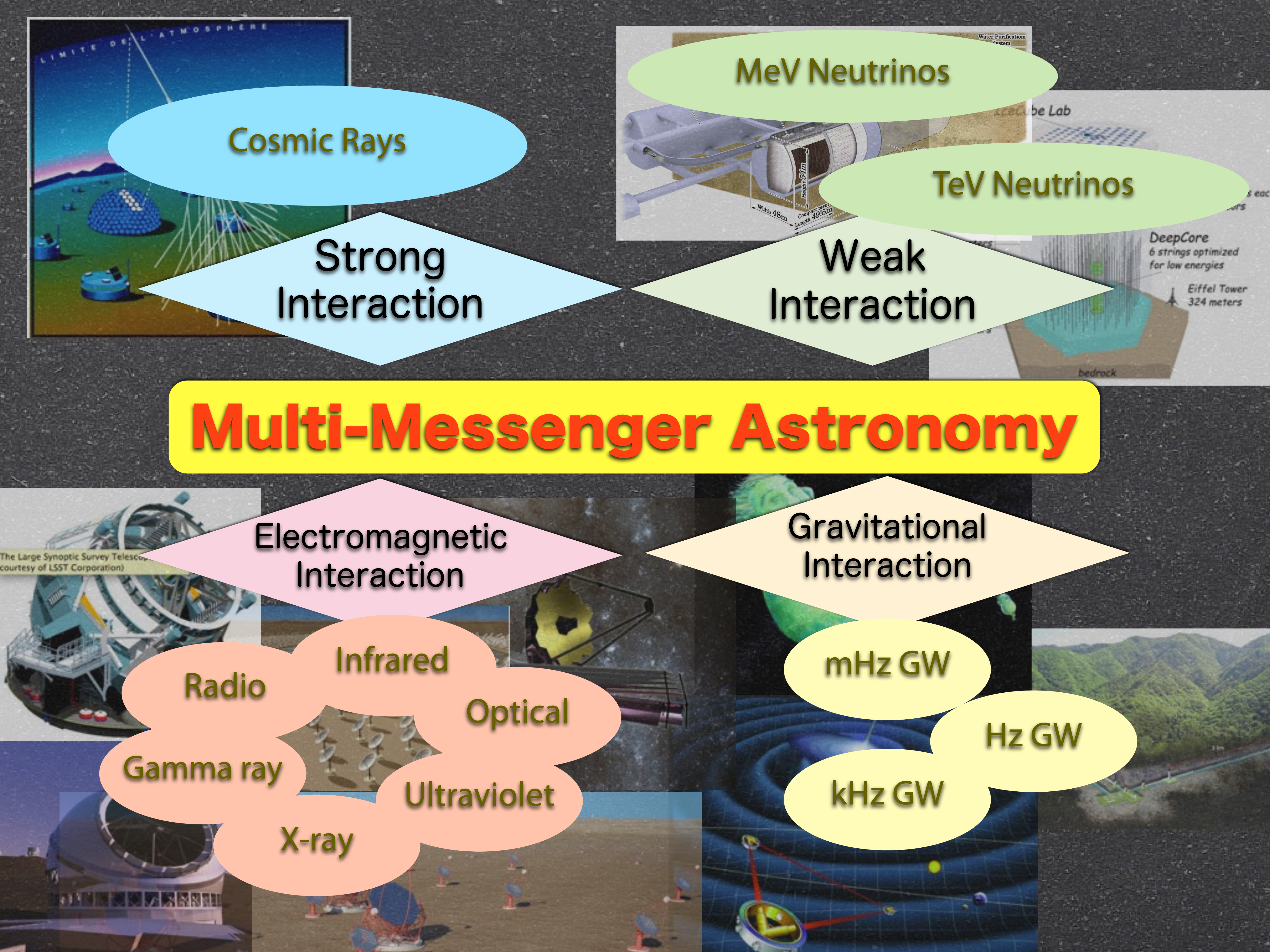
Electromagnetic

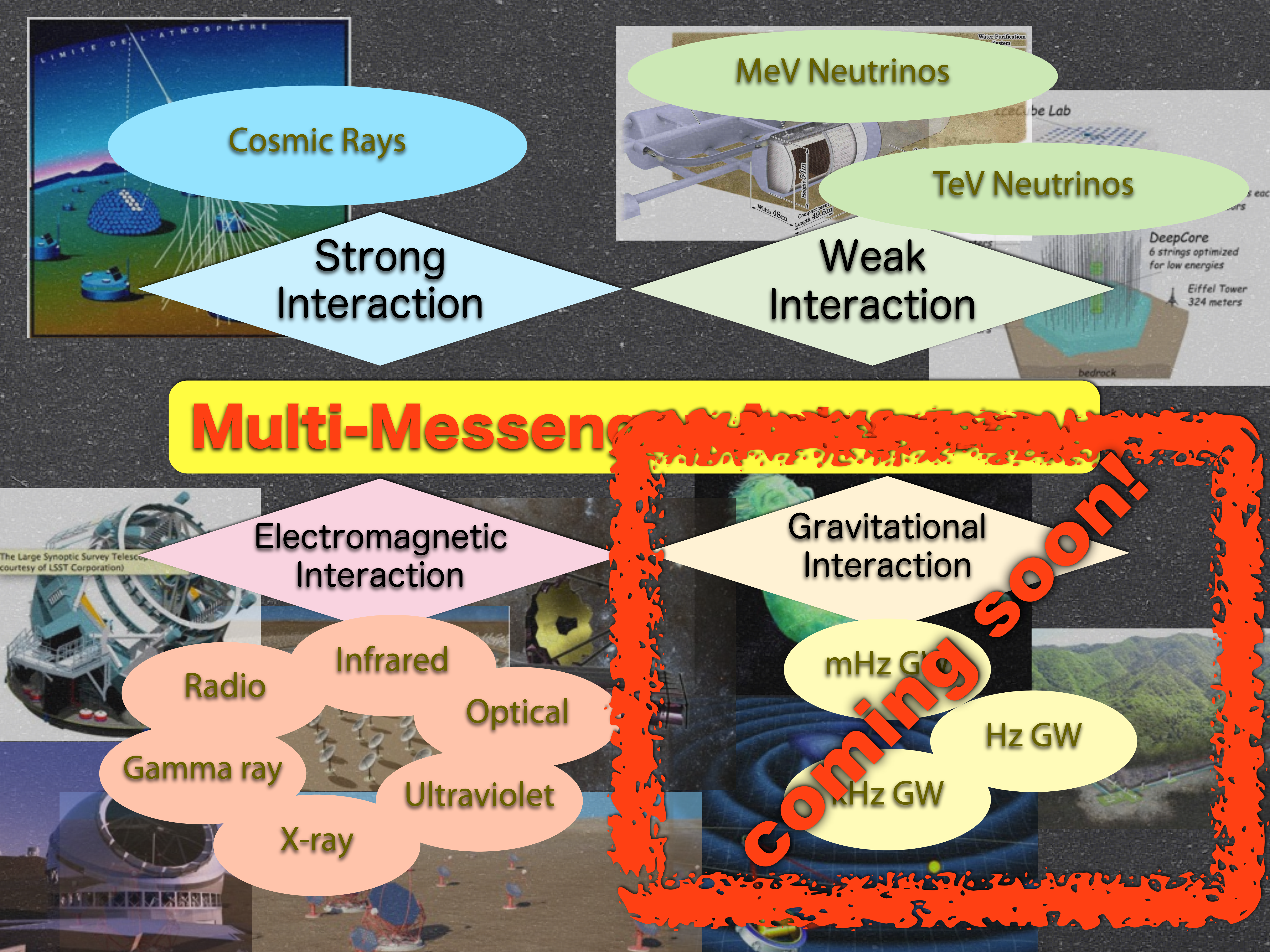
- Coulomb collision of p and e
- final remnants are
  - pulsars (B~10^{12} G)
  - magnetars (B~$10^{14\text{-}15}$ G)
  - magnetic fields affect dynamics



Gravitational

- energy budget
  - $E_G \sim 3.1\times10^{53}\,erg(M/1.4M_\odot)^2(R/10km)^{-1}$
  - $\sim 0.17 M_\odot c^2$
- inducing core collapse
- making general relativistic objects (NS/BH)


Multi-Messenger Astronomy
Strong Interaction
Cosmic Rays
Weak Interaction
MeV Neutrinos
TeV Neutrinos
Electromagnetic Interaction
Radio
Infrared
Optical
Gamma ray
Ultraviolet
X-ray
Gravitational Interaction
mHz GW
Hz GW
kHz GW
DeepCore
6 strings optimized for low energies
Eiffel Tower
324 meters
bedrock



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Radio
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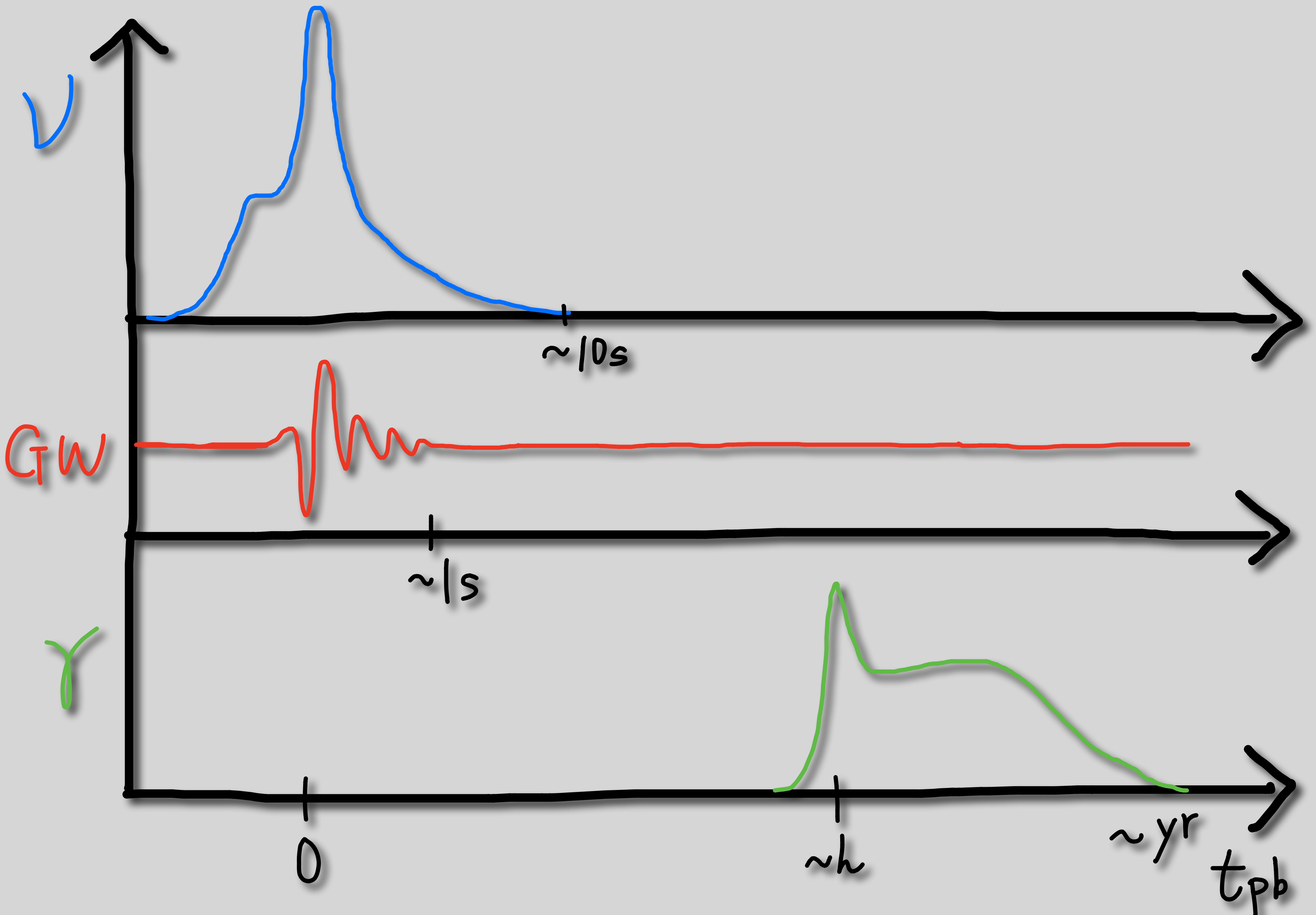
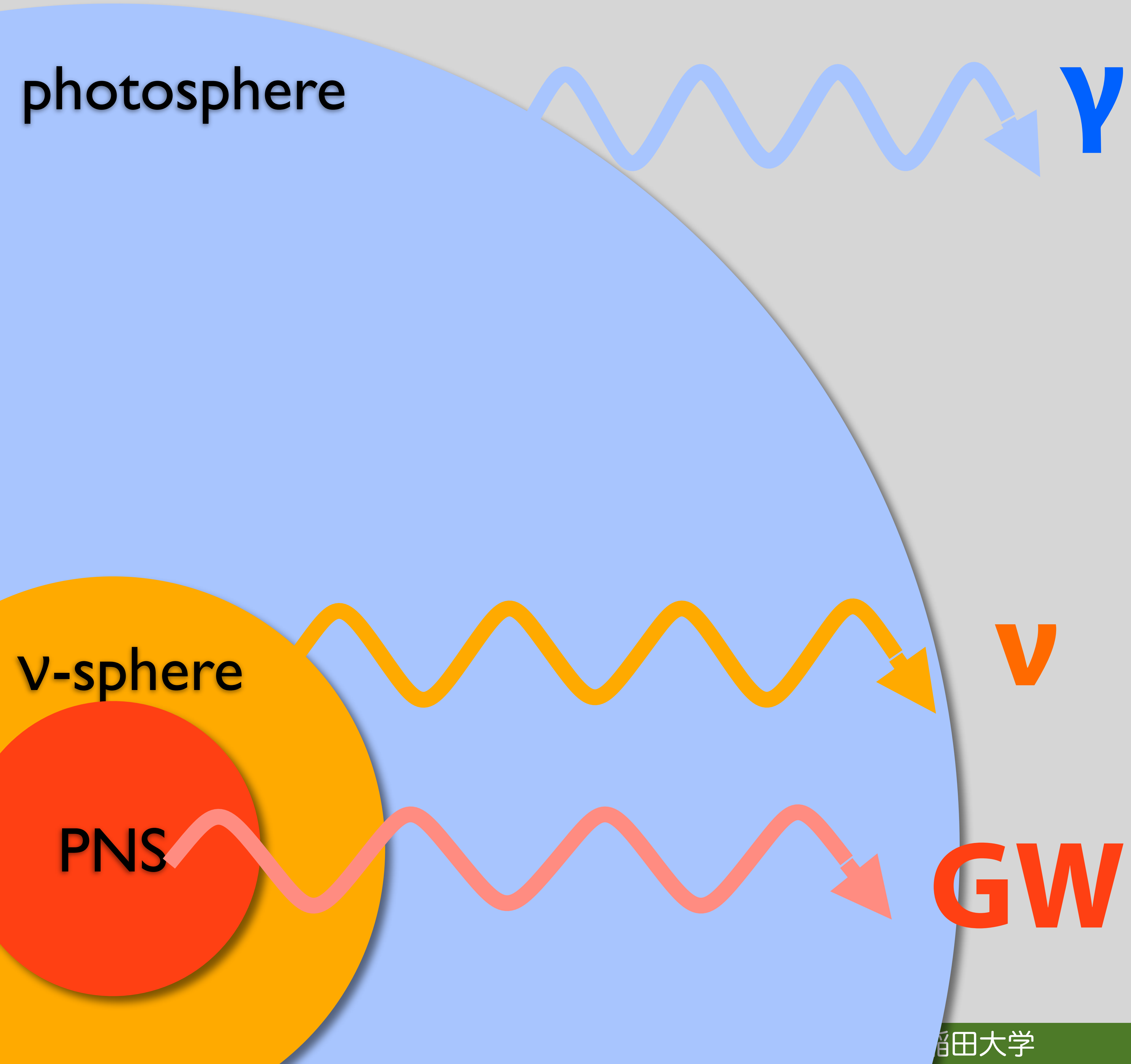
Optical
Gamma ray
Ultraviolet
X-ray
Gravitational Interaction
mHz GW
Hz GW
kHz GW
coming soon!

SN and various emissions



“Optical depth”



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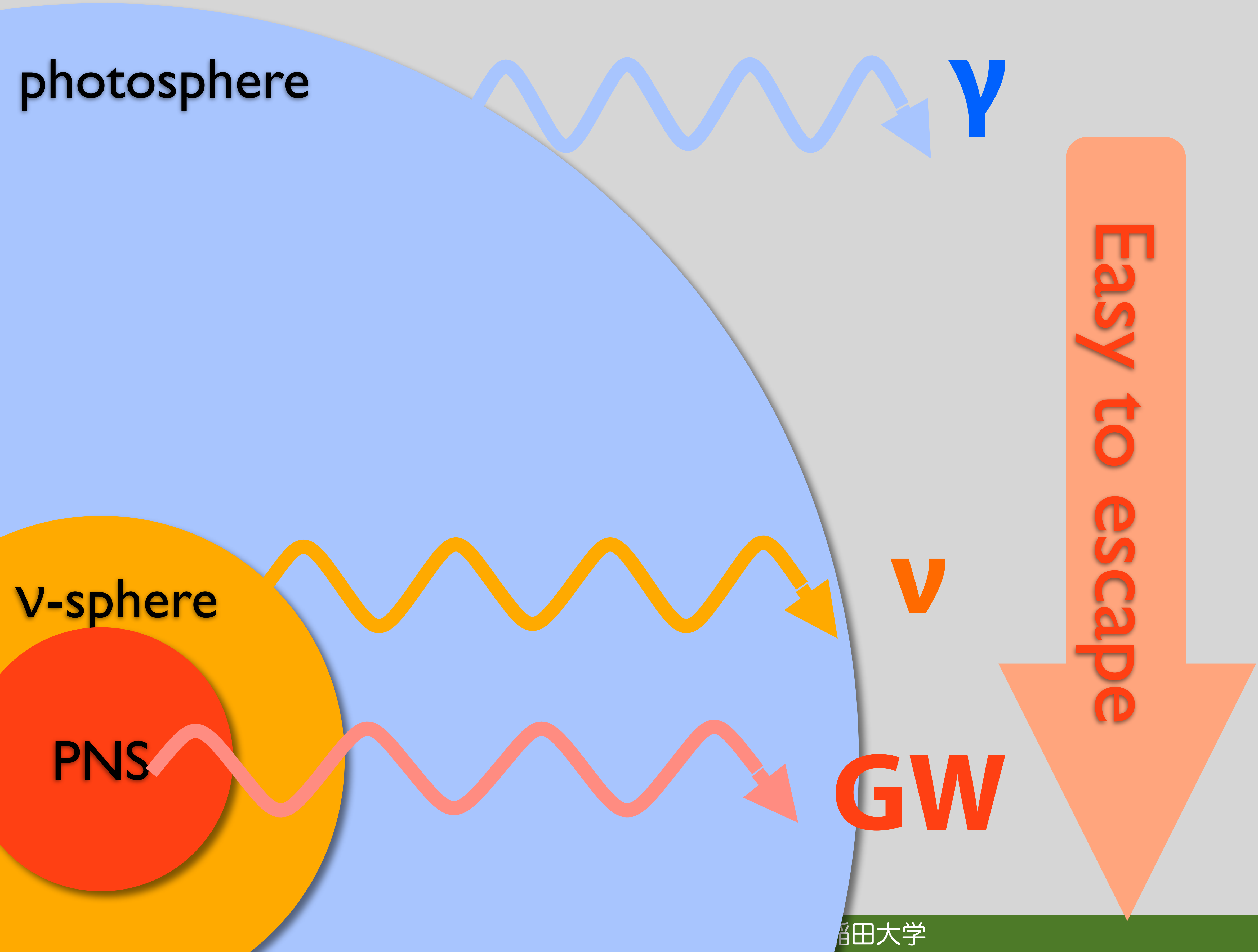

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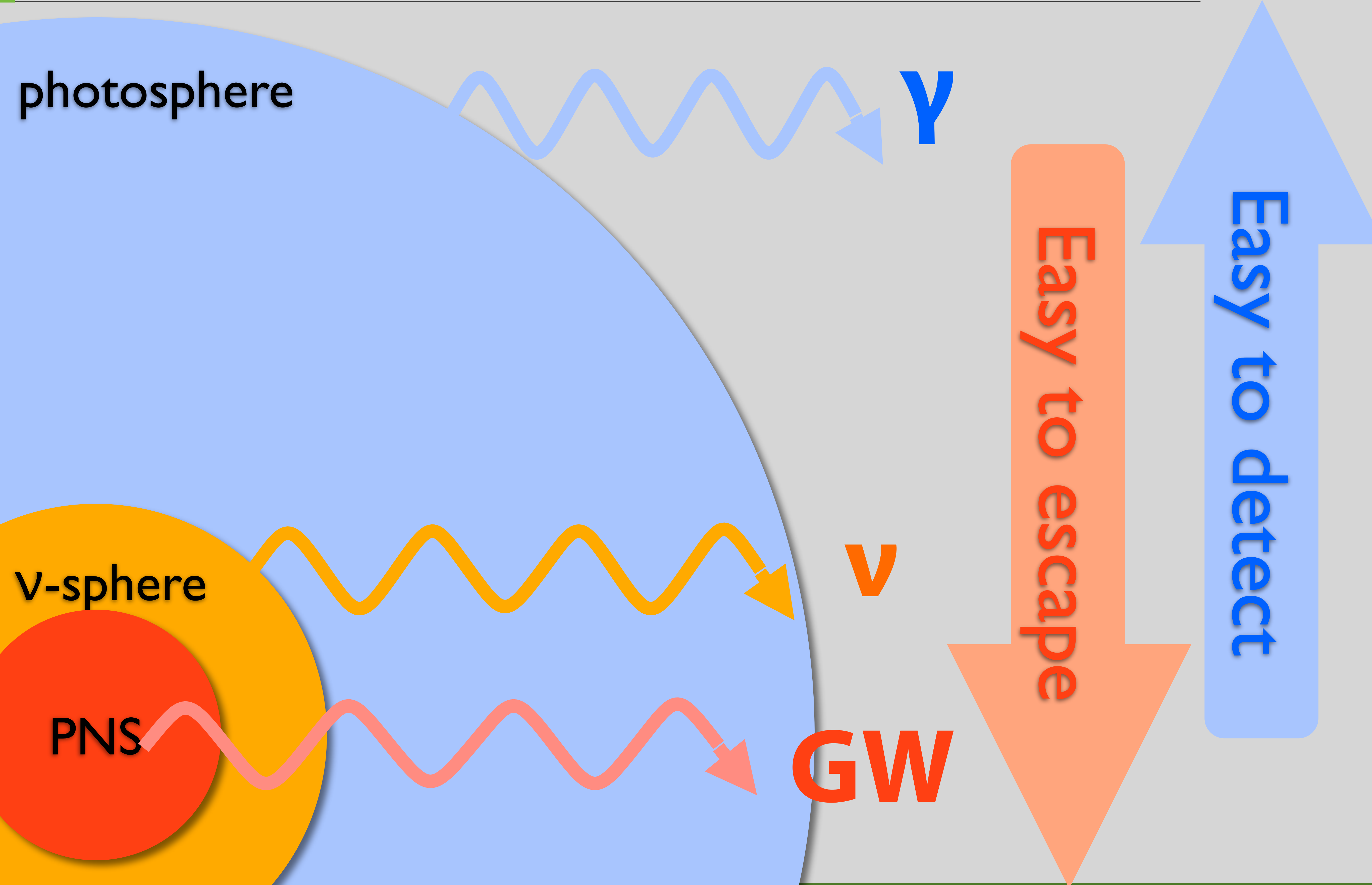

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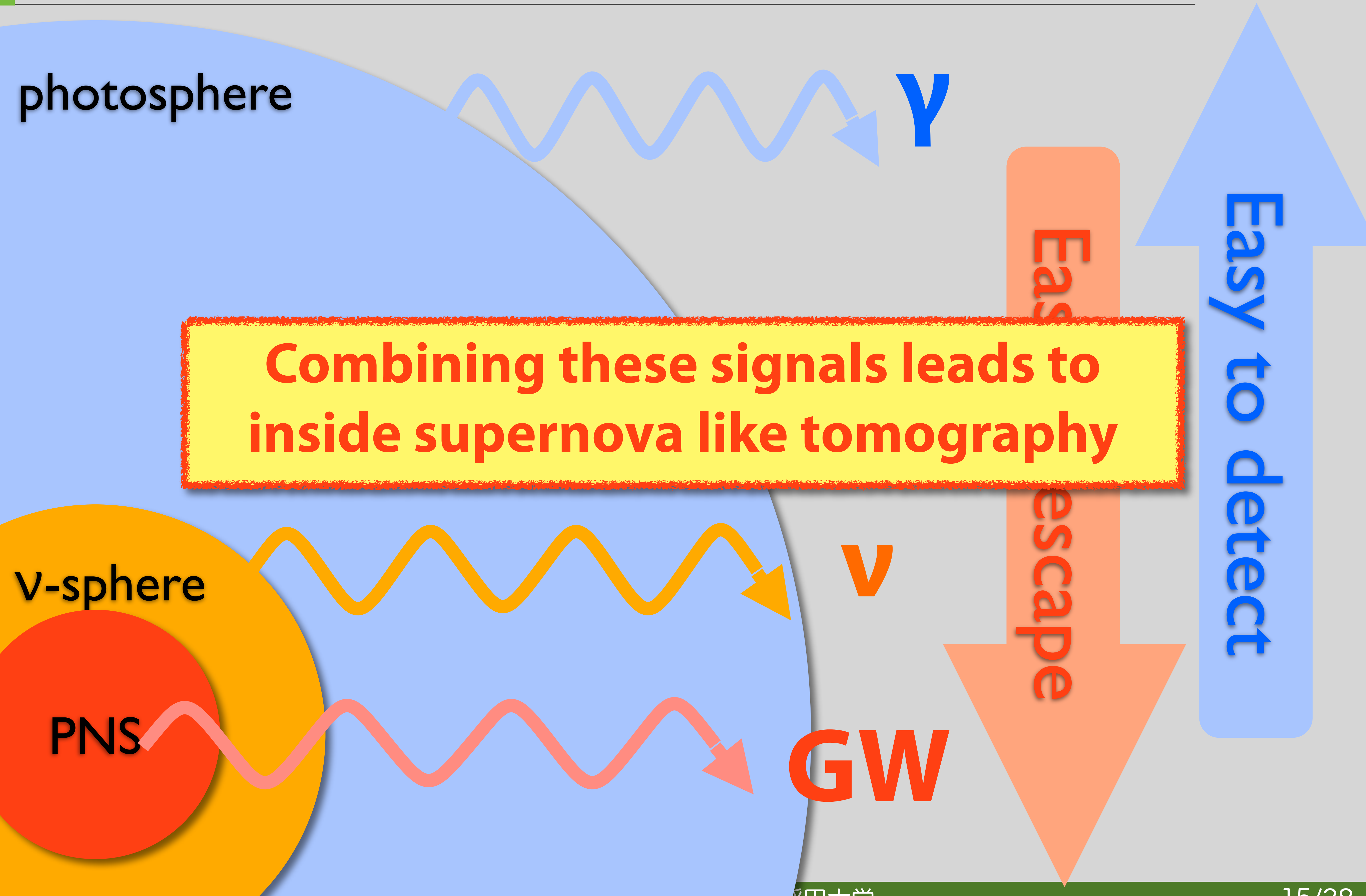
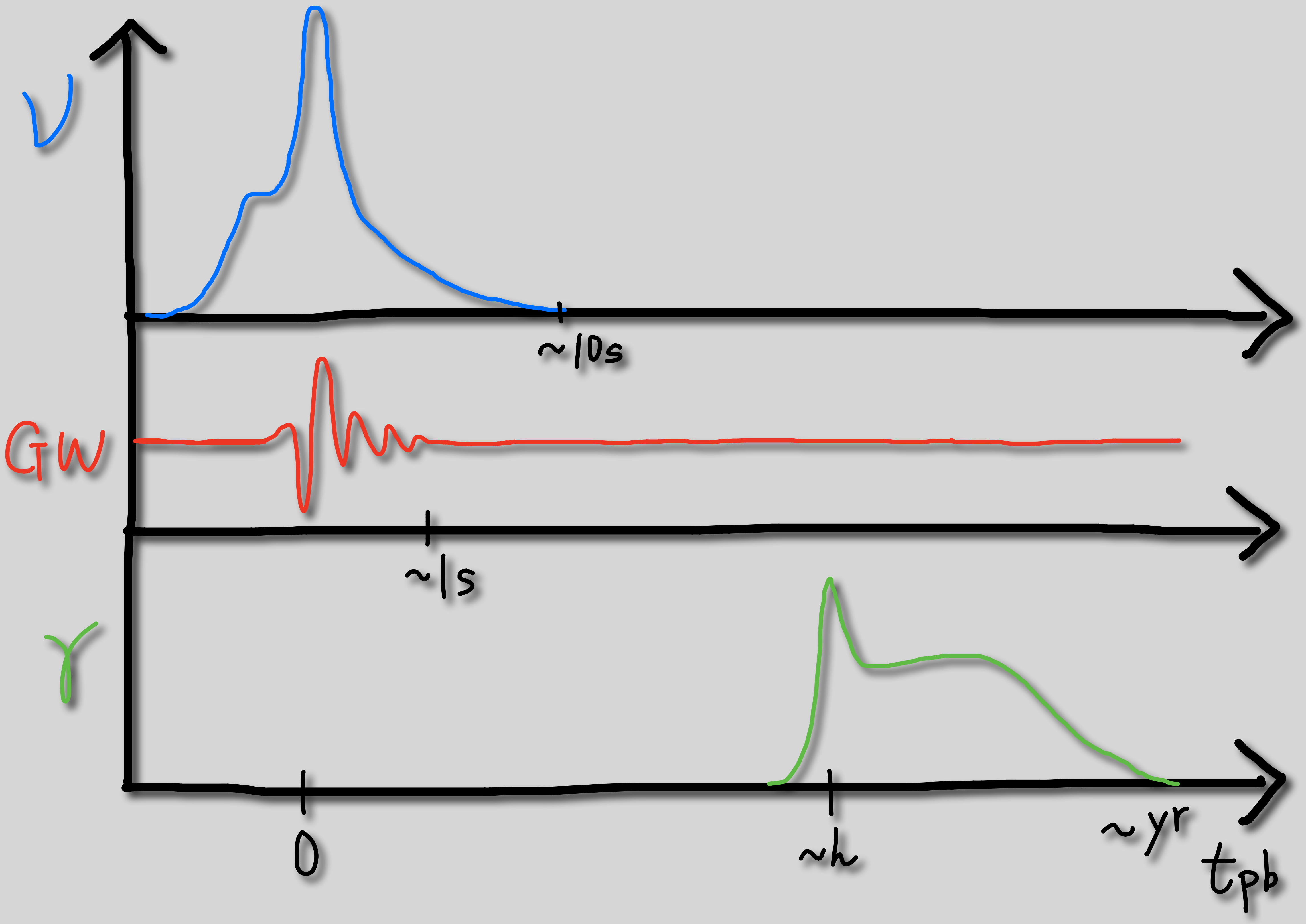


Combining these signals leads to inside supernova like tomography

Multi-messenger time domain astronomy of CCSN



Ideal scenario

1. **ν discovery** (Si burning phase? neutronization burst?)
    - angular resolution ~ degree
    - circulate detection worldwide
2. **γ confirm** (shock breakout, diffusion cooling, Co decay)
    - delay for ~ hours to days, depending on progenitor radius
    - follow up from radio to gamma-ray
3. **GW analysis** (burst, BH formation?)
    - time coincidence with ν (and spacial coincidence?)
    - even non-detection can put constraint on explosion mechanism

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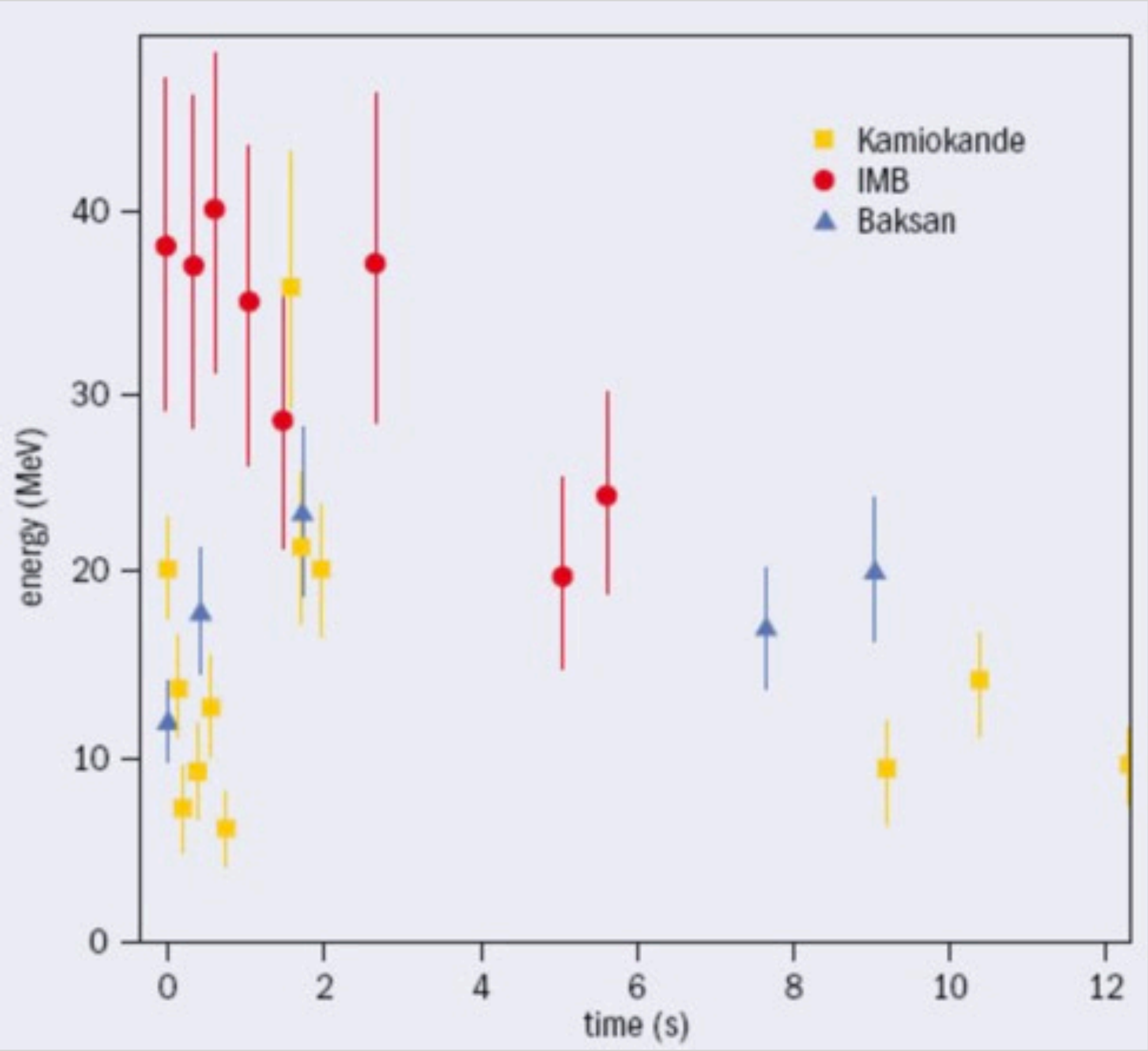
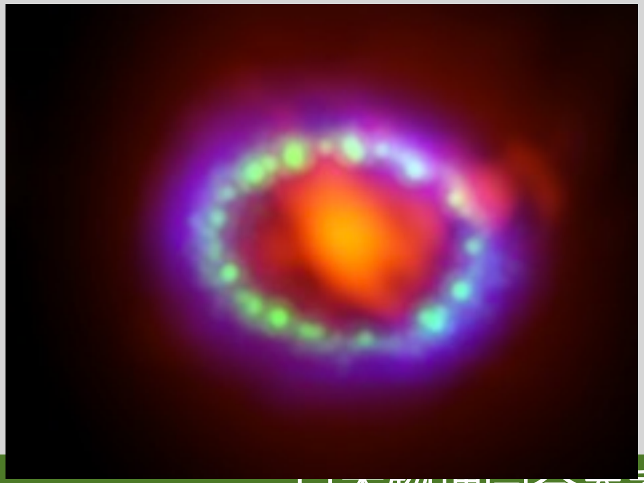
Remember SN 1987A



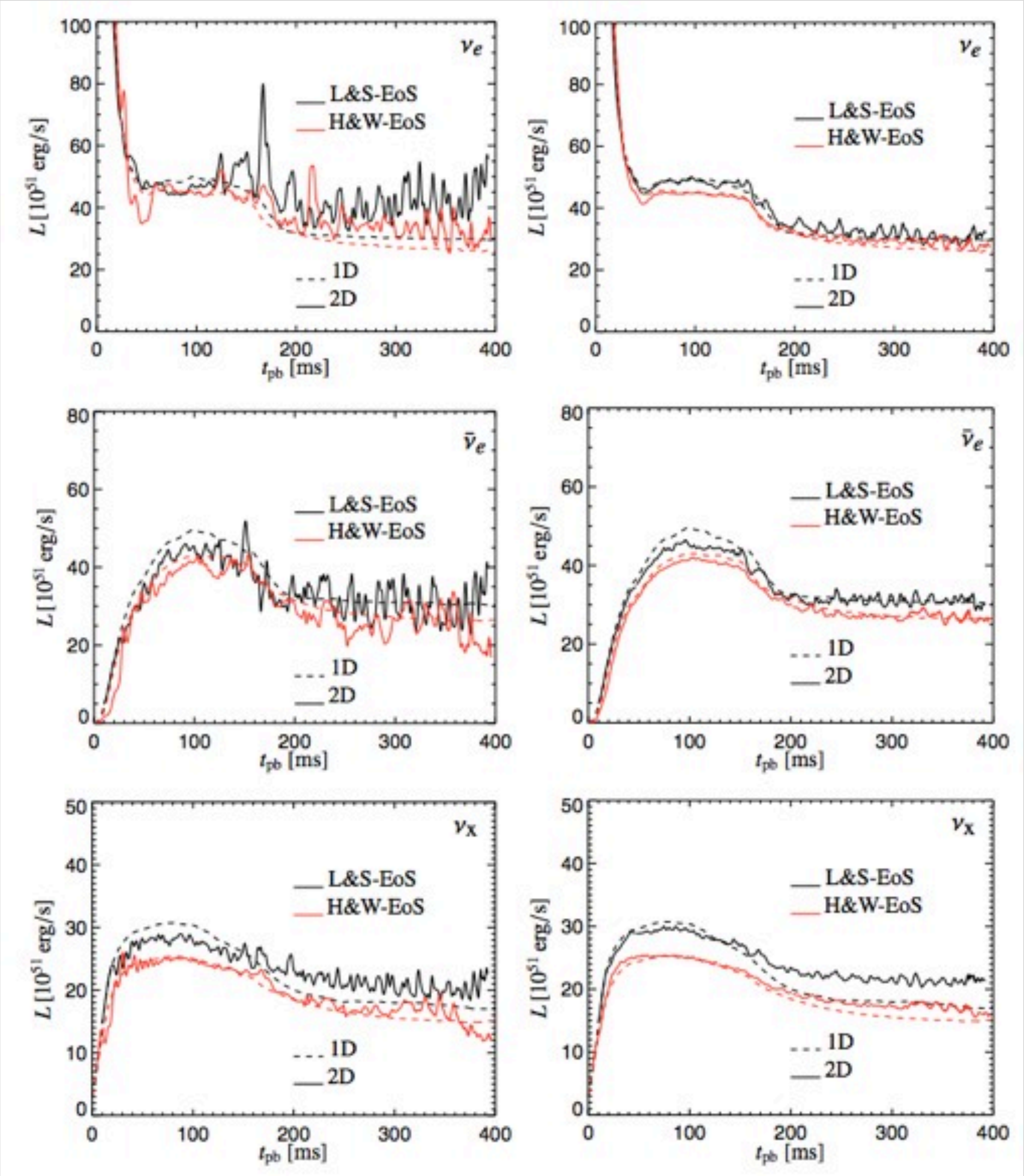
Hirata+ 87, Bionta+ 87, Alekseev+87



- From SN 1987A, ~20 neutrinos were detected within ~10 s
- Dawn of "neutrino astronomy"
- It was confirmed by optical obs.
- They were the justifications of
  - neutrino trapping scenario, which predicts that the neutrino emission lasts for the diffusion timescale (~ 10s)
  - the total energy of neutrinos being exactly the amount of theoretical prediction (~10^{53} erg)
- **Neutrino must be detected irrelevant to the detail of central core for the nearby event**

Neutrino emission: neutrino-driven explosion

Marek & Janka 2009



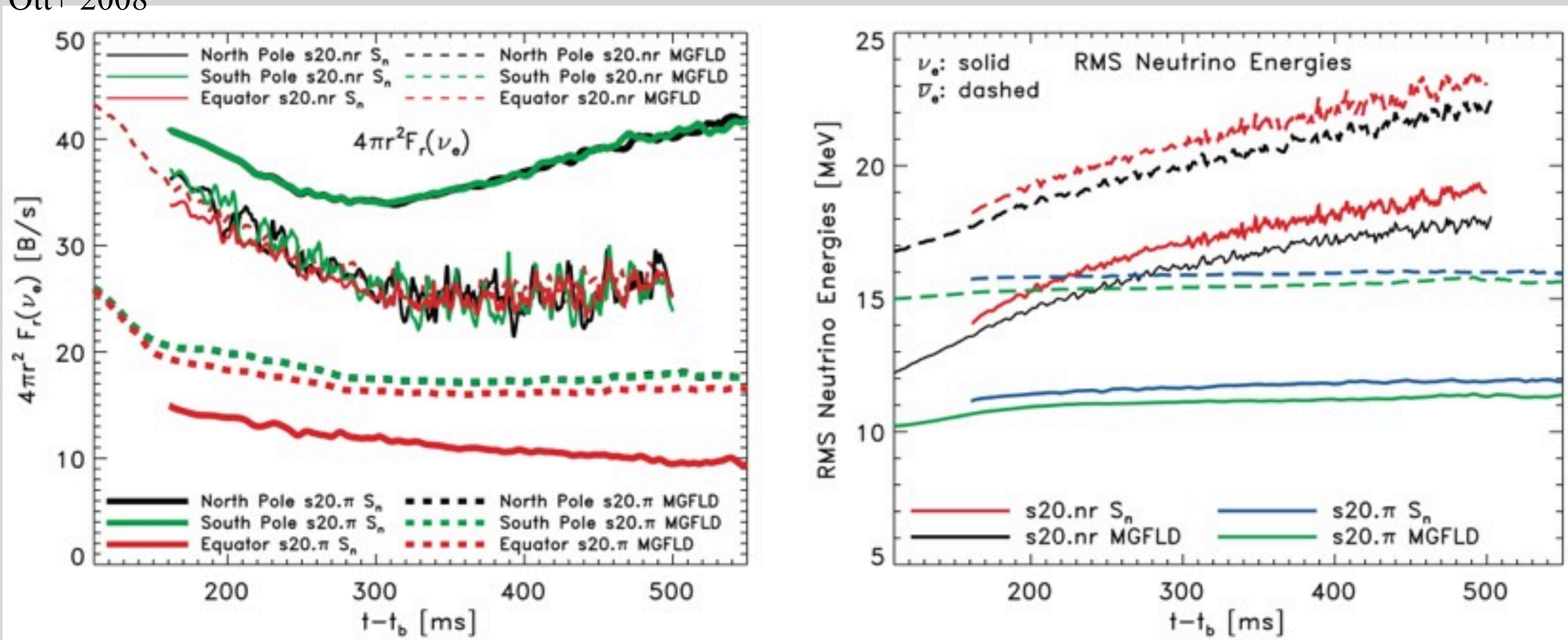
* Basic features (average energy, luminosity, etc.) are similar between 1D and 2D simulations
* Turbulent motion around neutrinosphere is imprinted in the luminosity and spectral evolution for 2D simulation

Neutrino emission: acoustic explosion

* N/A
* similar to neutrino-driven explosion?

Neutrino emission: magneto-rotational explosion

Ott+ 2008



- Rotation strongly deforms the neutrinosphere's shape
- The direction dependence of neutrino emission is generated
- Neutrinos favors the pole due to small optical depth

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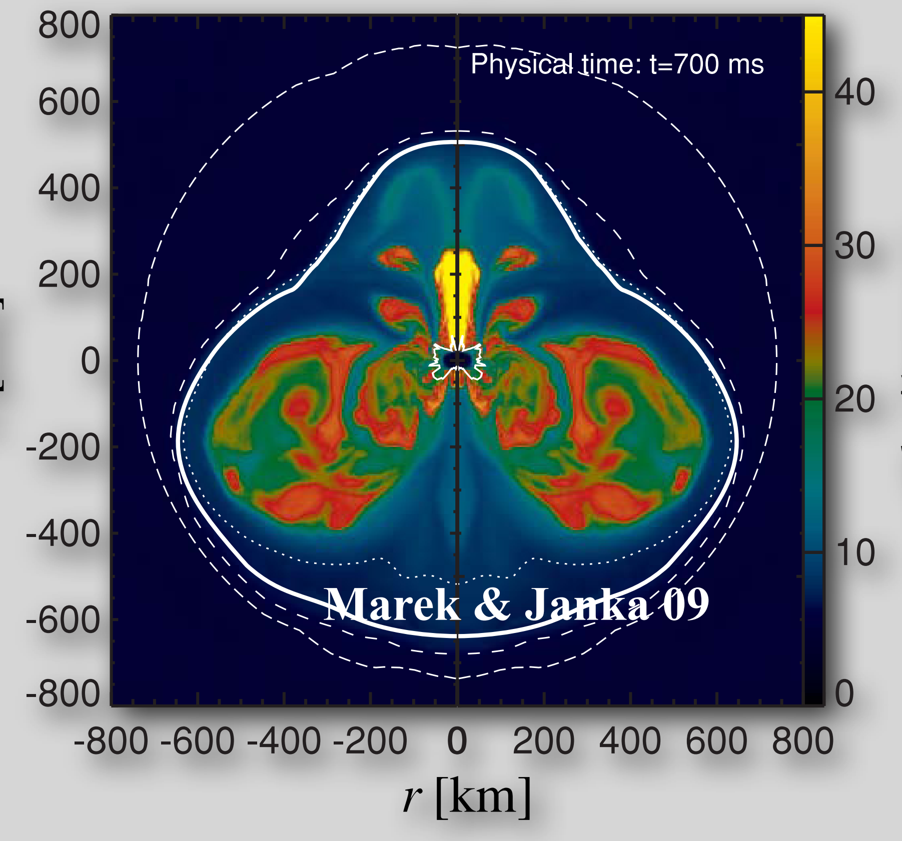
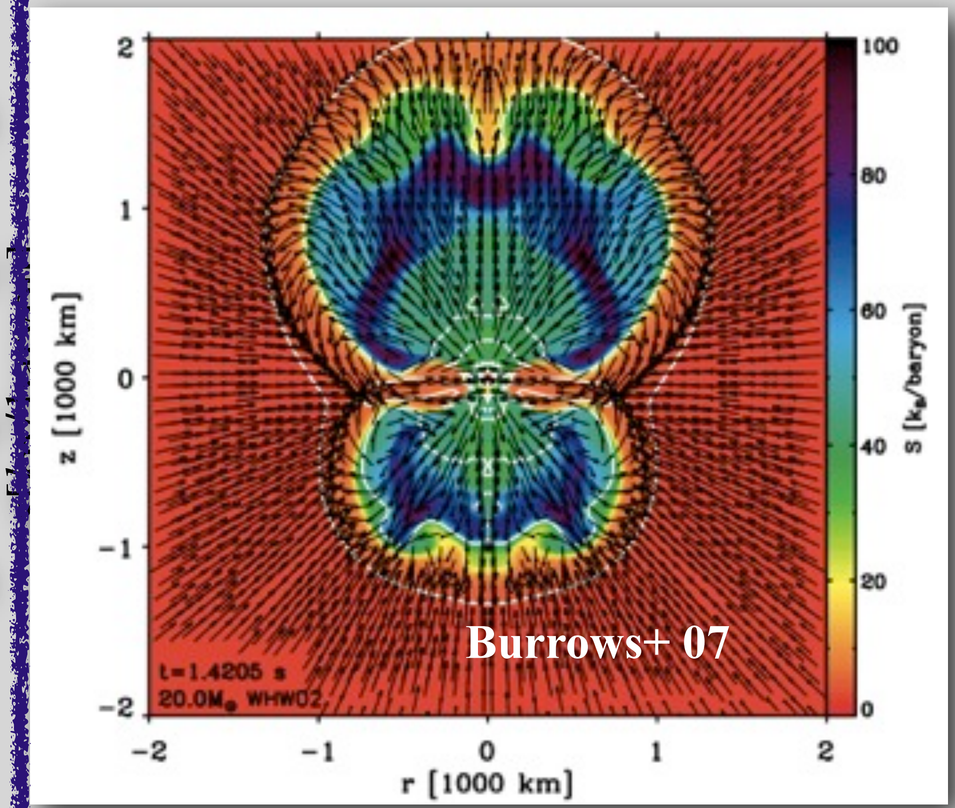
SN and GW

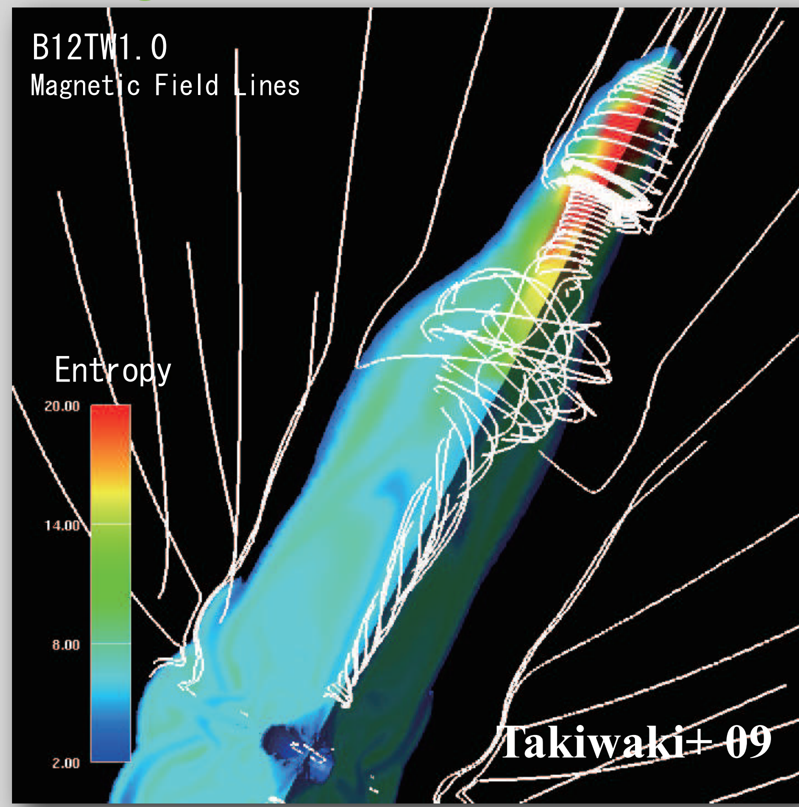
Neutrino-driven

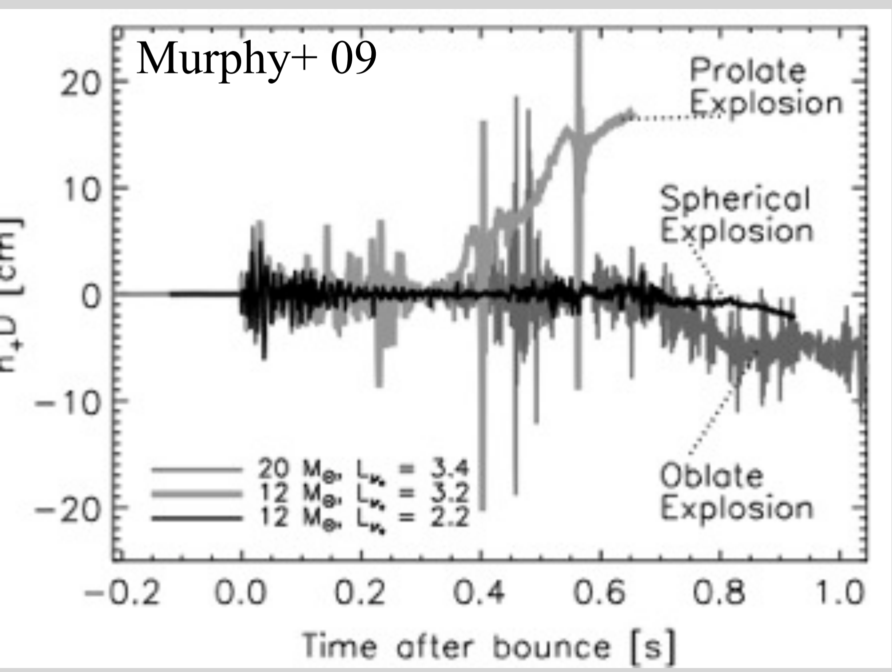


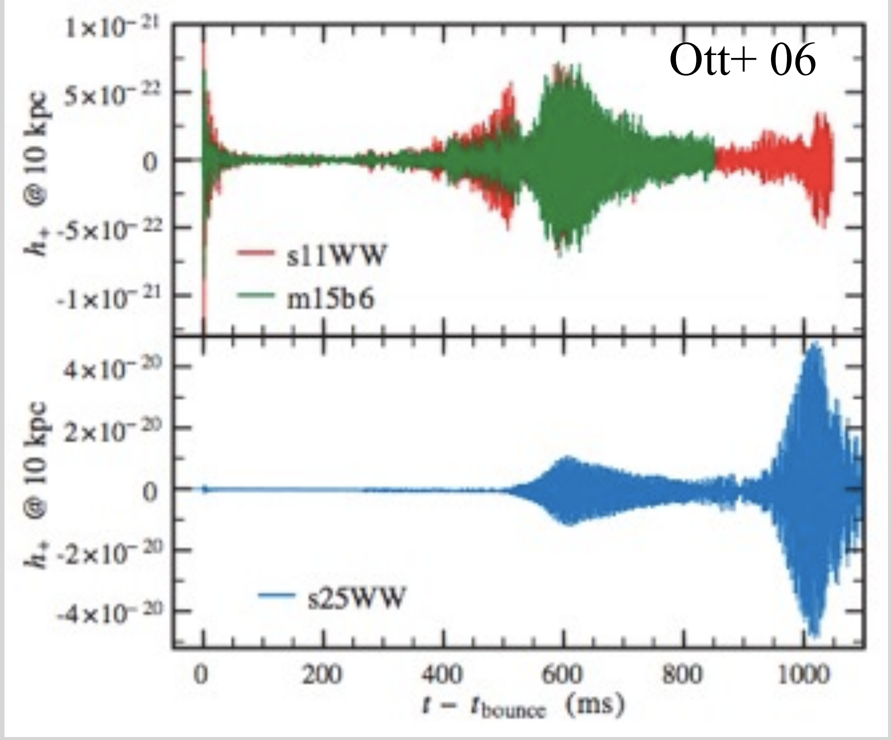
Acoustic

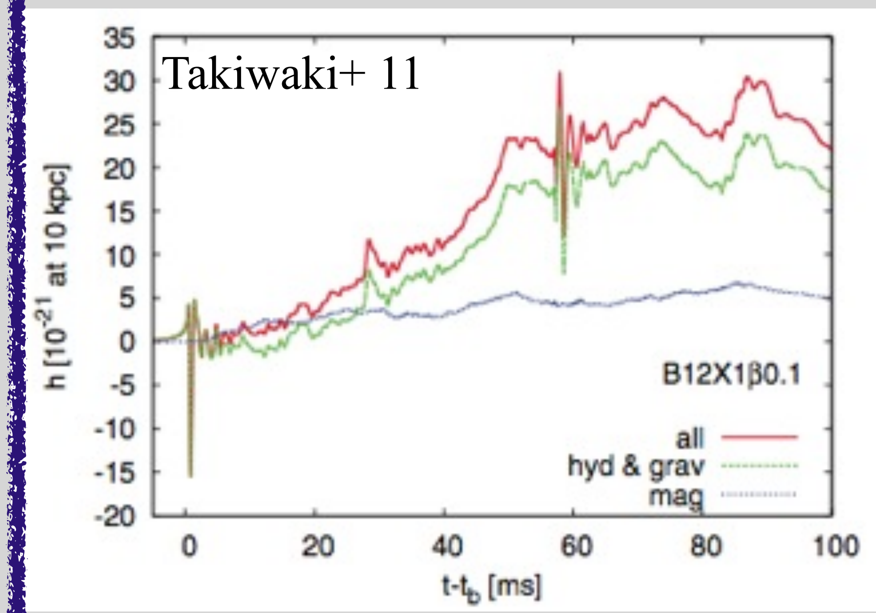


Magneto-rotational



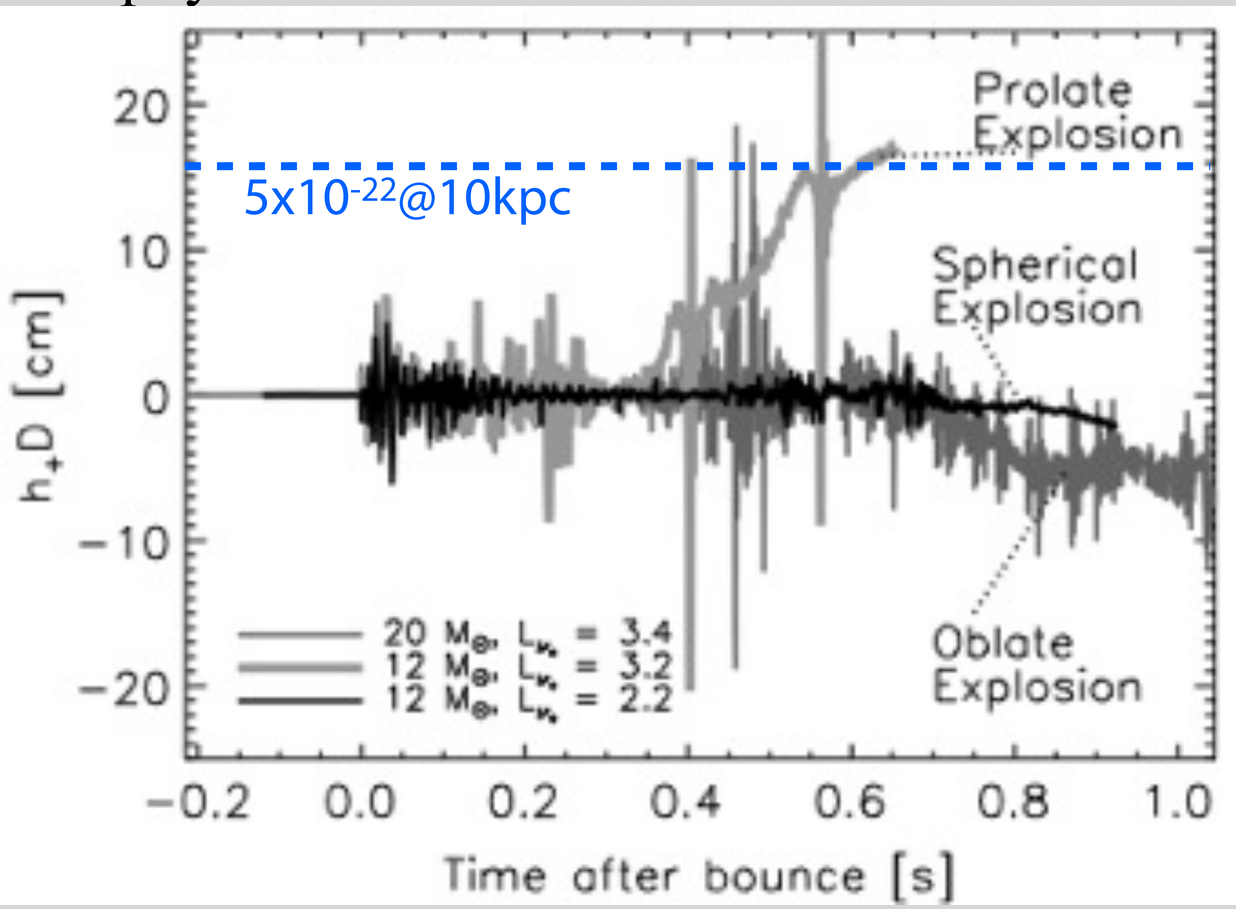


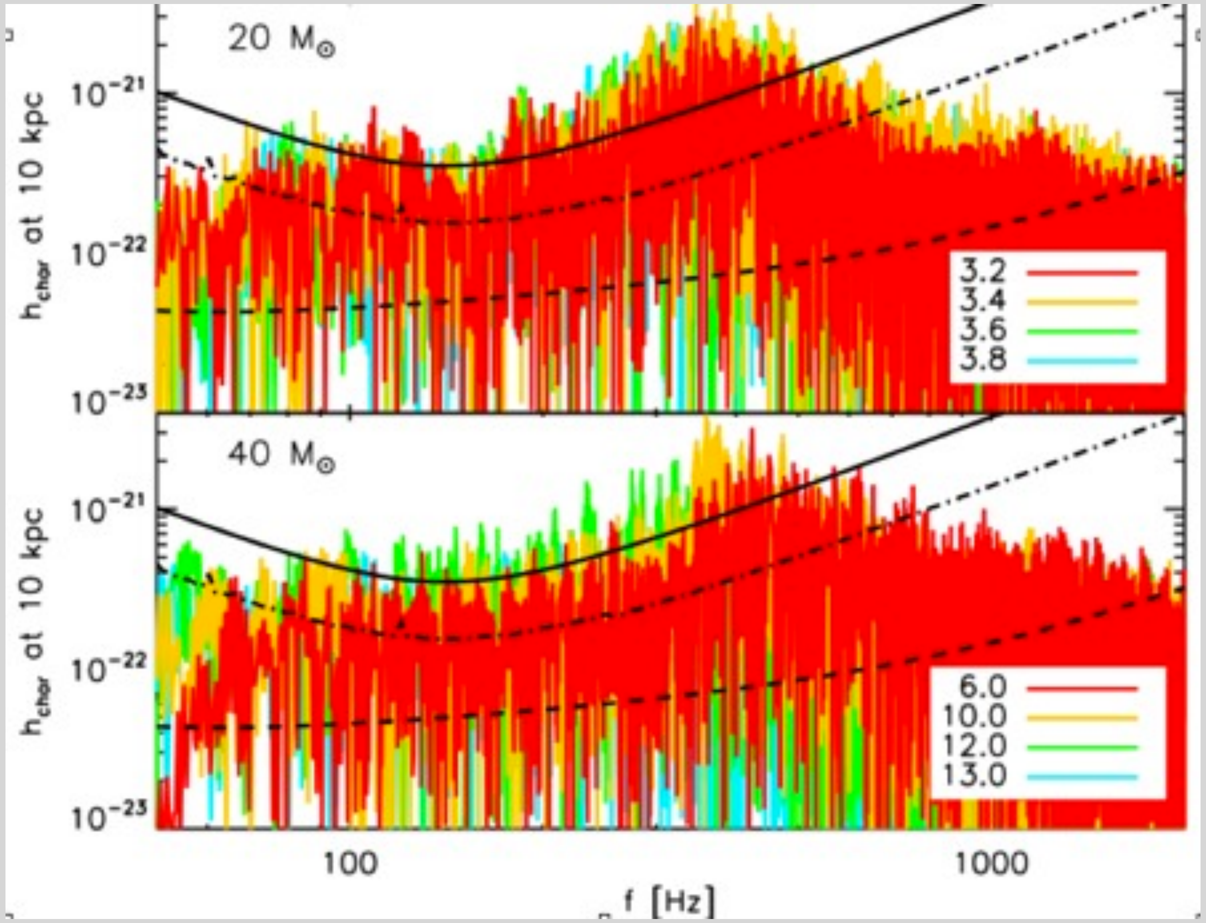




GW emission: neutrino-driven explosion

Murphy+ 09

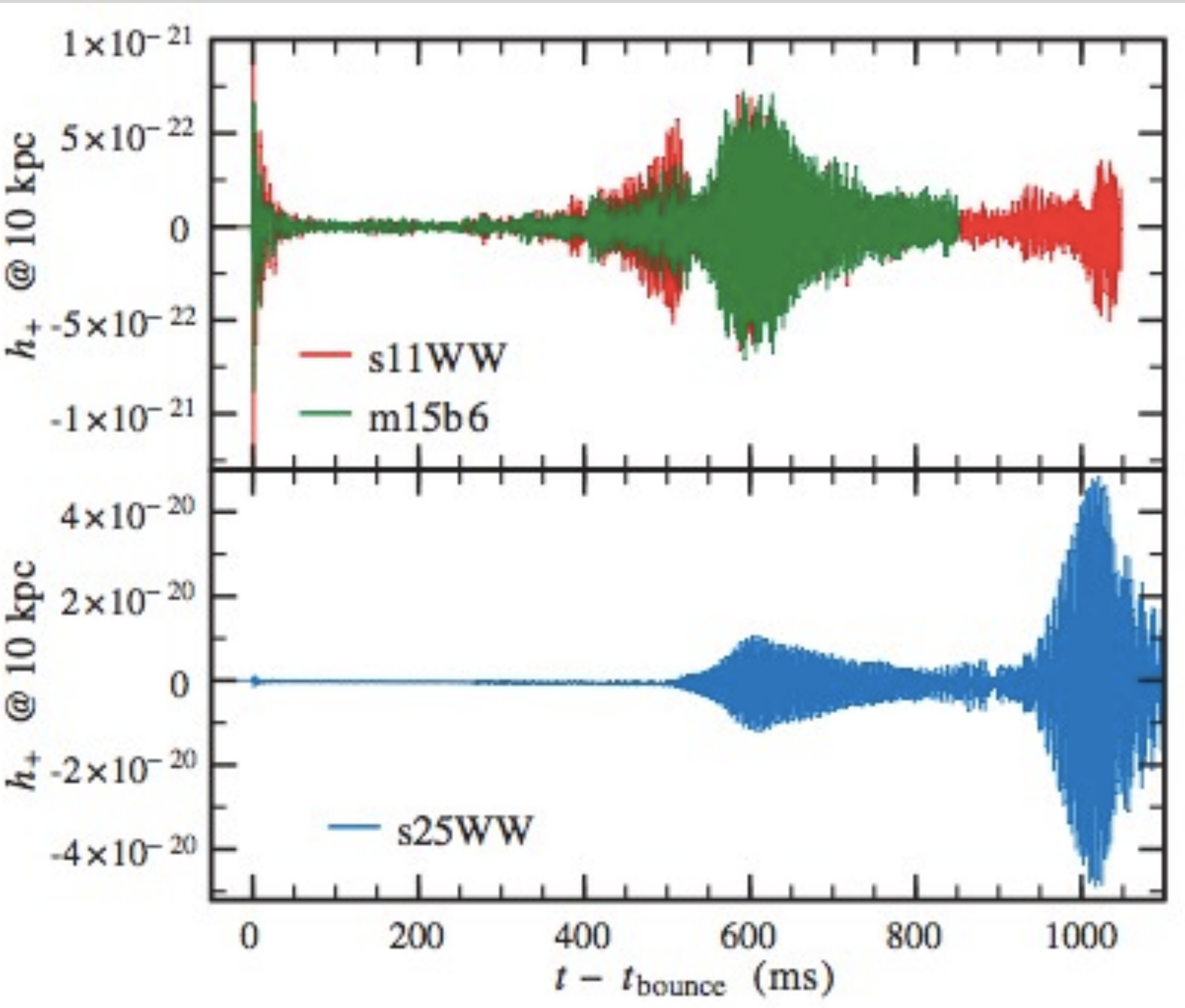


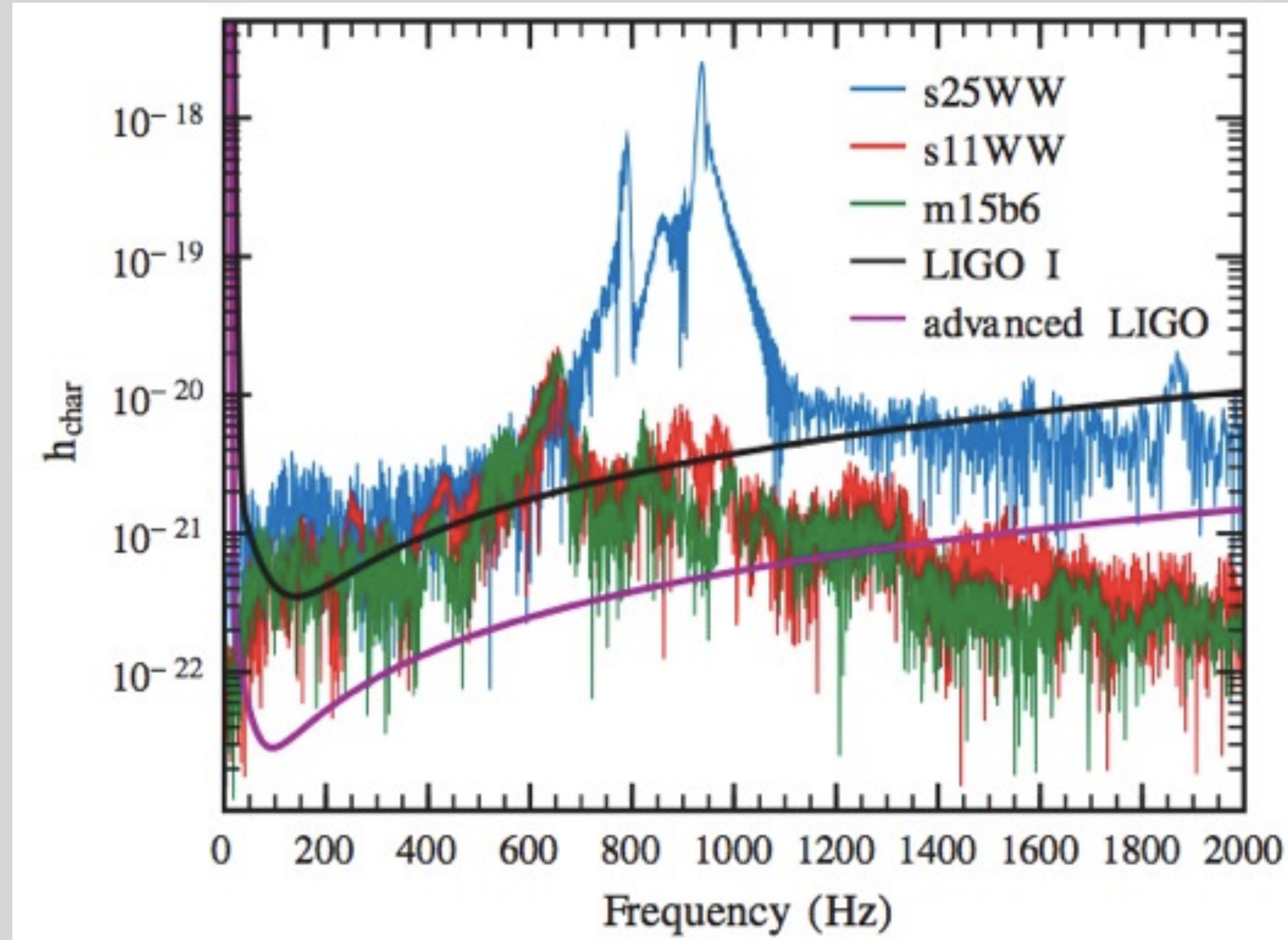


- GW from convective motion and ejecta
  - high frequency (~(100) Hz): convective motion
  - low frequency (~O(10) Hz): anisotropic ejecta
- In addition, anisotropic neutrinos generate GW (e.g., Burrows & Hayes 96)

GW emission: acoustic explosion

Ott+ 06

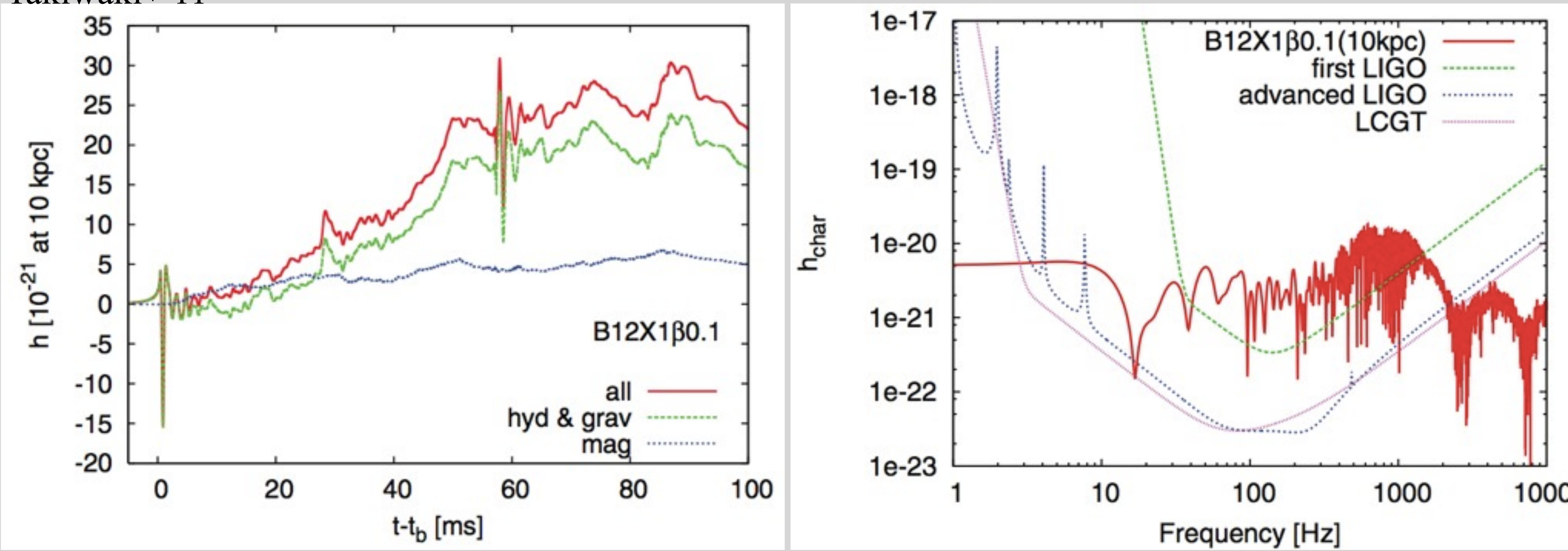




- Strong GW emission from PNS oscillation (E_{GW}~10^{50} erg!)
- Late onset of GW emission
- Typical frequency of GW corresponds to characteristic frequency of PNS, i.e. sharp peak

GW emission: magneto-rotational explosion

Takiwaki+ 11



- Due to strong rotation, the prompt GW (<10 ms) signal is the largest
- The amplitude strongly depends on the initial condition
- Outflow would make offset of h, which corresponds to low frequency component

Summary of GW emission

* **Neutrino-driven explosion**
  * GW emission from convective motion and anisotropic ejecta
  * The weakest among explosion models
* **Acoustic explosion**
  * characteristic frequency of NS oscillation
  * possibly very strong
* **Magneto-rotational explosion**
  * GW emission at the bounce due to strong rotation
  * Strongest in general

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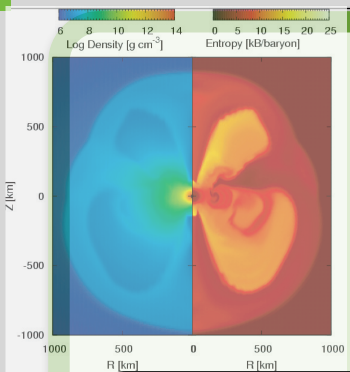
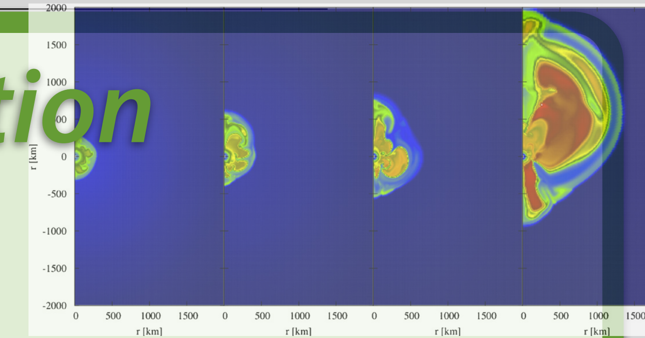
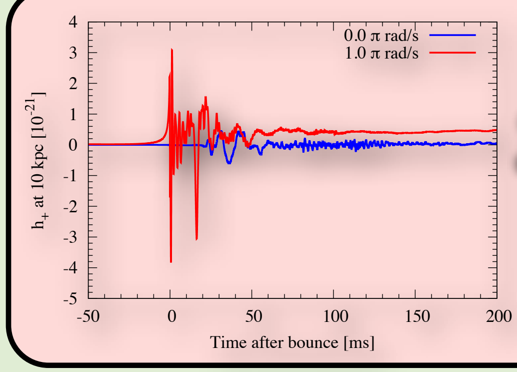
Workflow



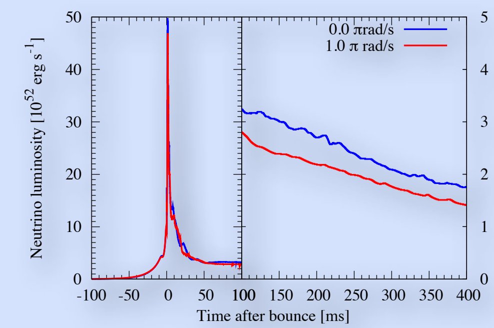
multi-dimensional neutrino-radiation hydrodynamic simulations



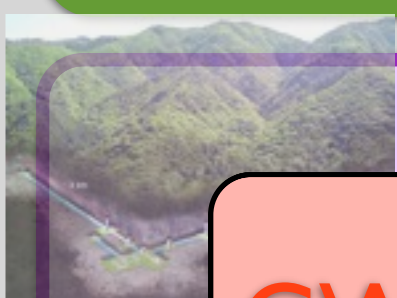


gravitational waves

neutrinos

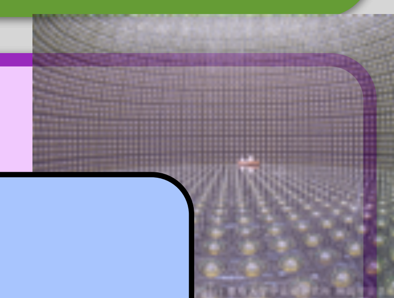


mock data generation



GW detector simulation

ν detector simulation



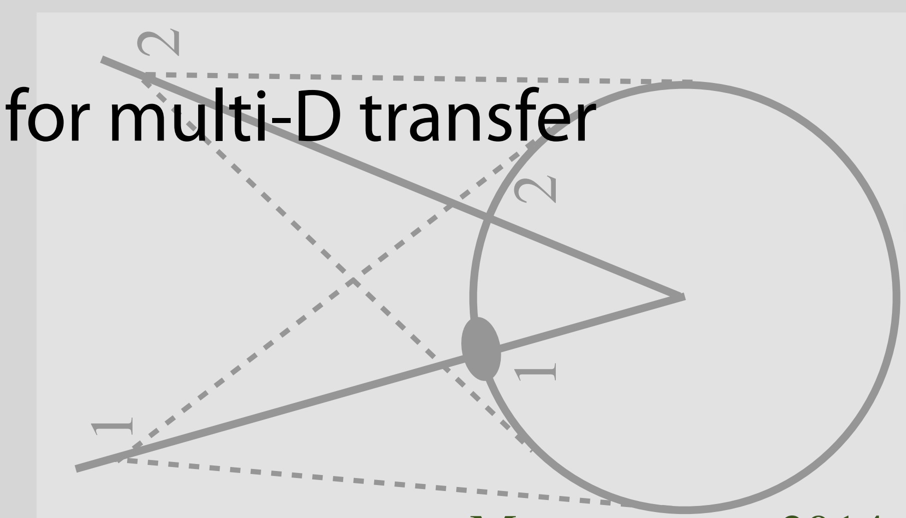
Concurrent data analysis of GW and ν to probe the innermost profile of core-collapse supernovae

Numerical simulation

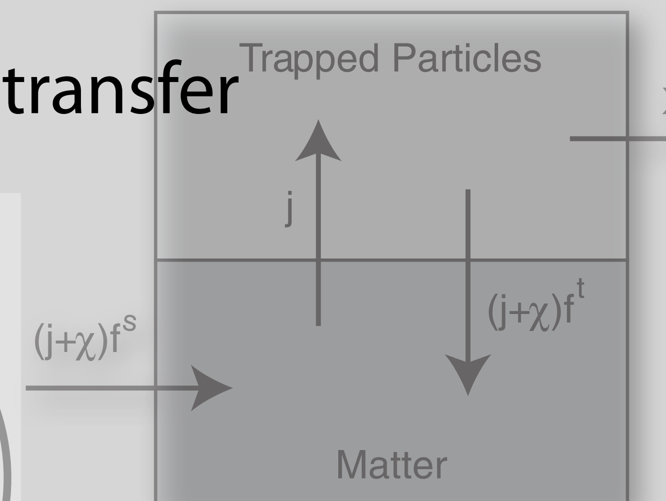
See
Suwa et al., PASJ, 62, L49 (2010)
Suwa et al., ApJ, 738, 165 (2011)
Suwa et al., ApJ, 764, 99 (2013)
Suwa, PASJ, 66, L1 (2014)
Suwa et al., arXiv:1406:6414
for more details

- Progenitor: 11.2 $M_\odot$ (Woosley, Heger, & Weaver 02)
- 2D (axial symmetry) (ZEUS-2D; Stone & Norman 92)
- MPI+OpenMP hybrid parallelized
- Hydrodynamics+Neutrino transfer (***neutrino-radiation hydrodynamics***)
  - Isotropic diffusion source approximation (***IDSA***) for neutrino transfer (Liebendörfer+ 09)
  - Ray-by-Ray plus approximation for multi-D transfer
- Shellular rotation is imposed

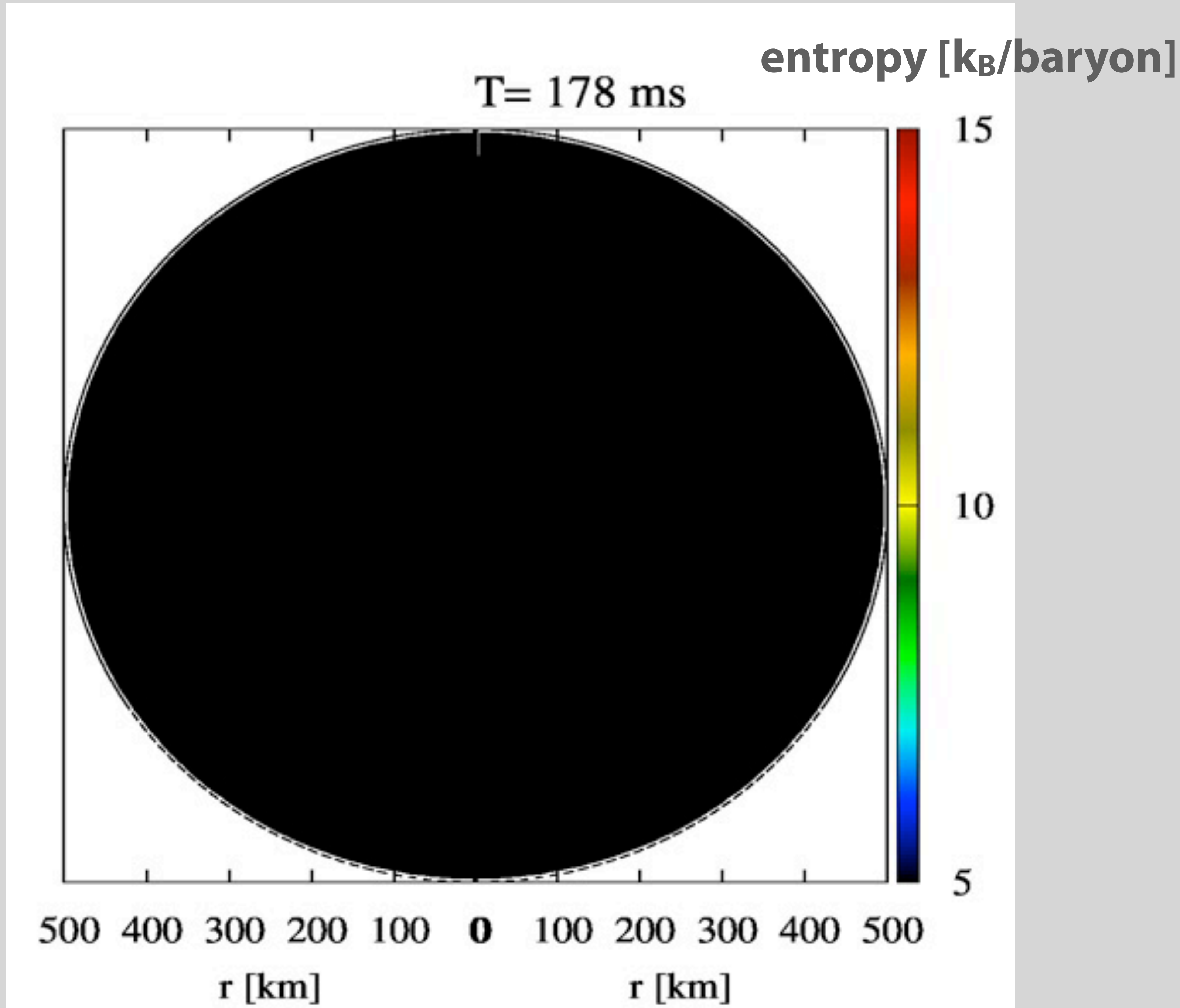
$$\Omega(r) = \Omega_0 \frac{r_0^2}{r^2 + r_0^2}$$



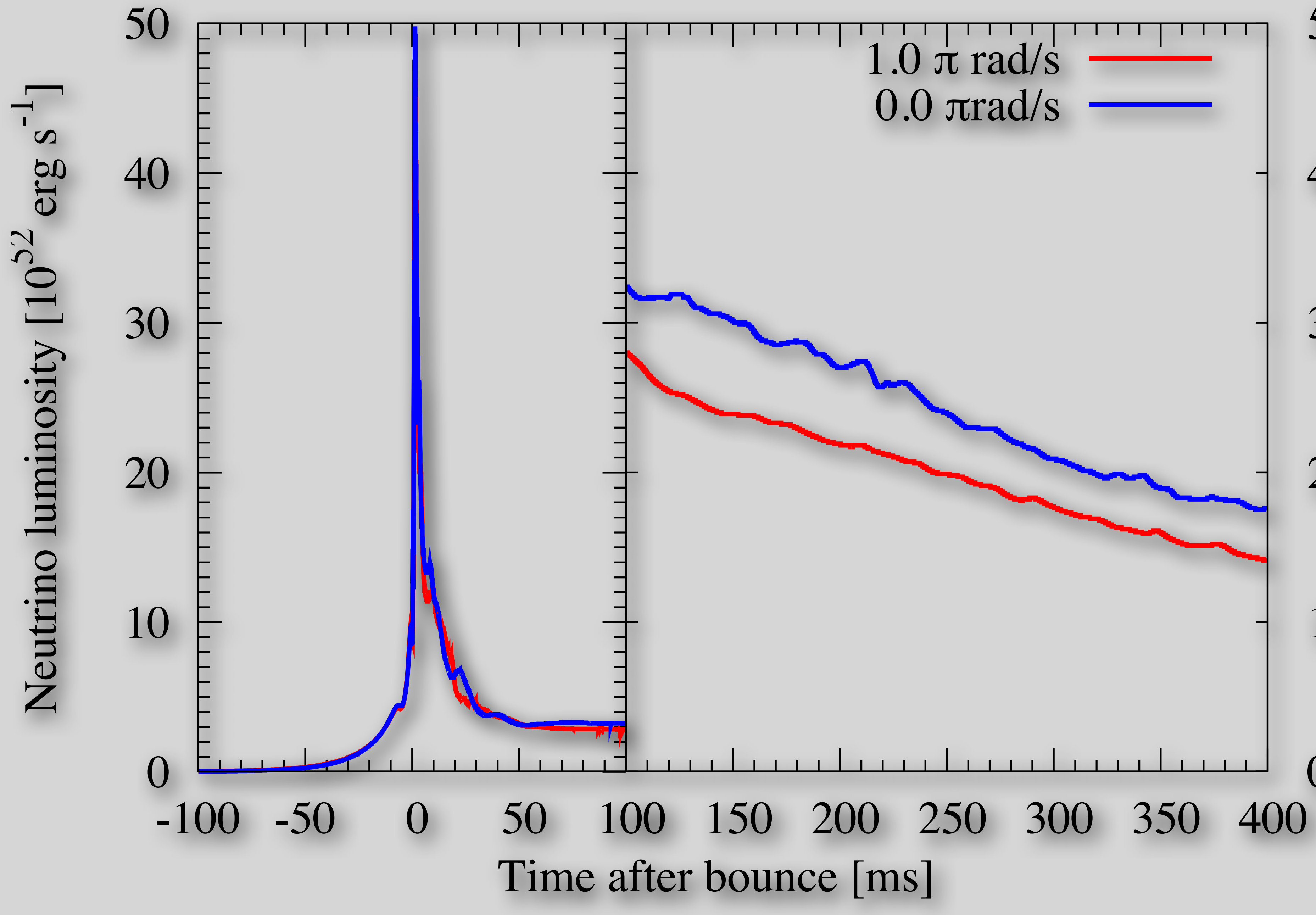
Mezzacappa+ 2014



Supernova explosion simulation

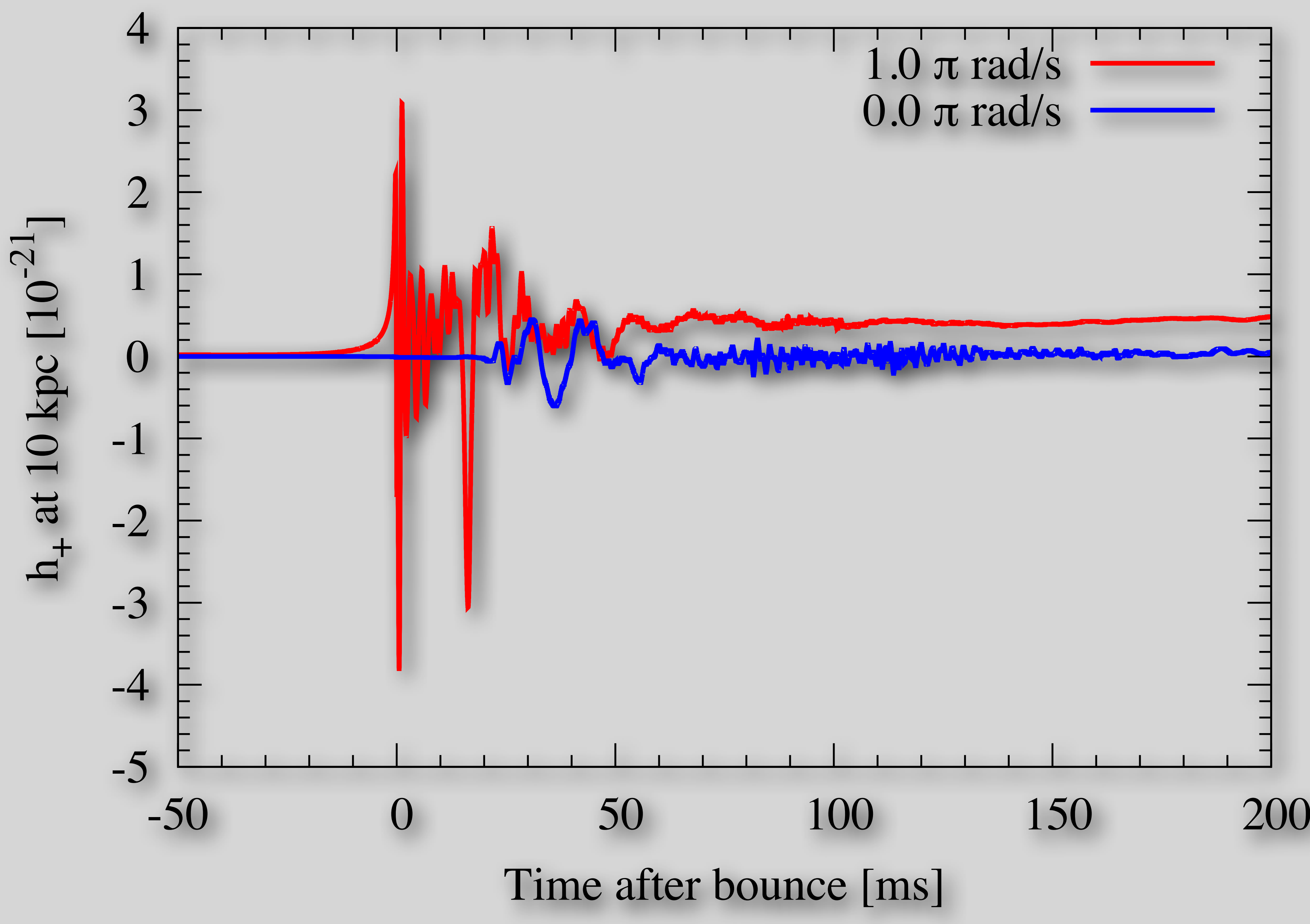


Neutrino signal



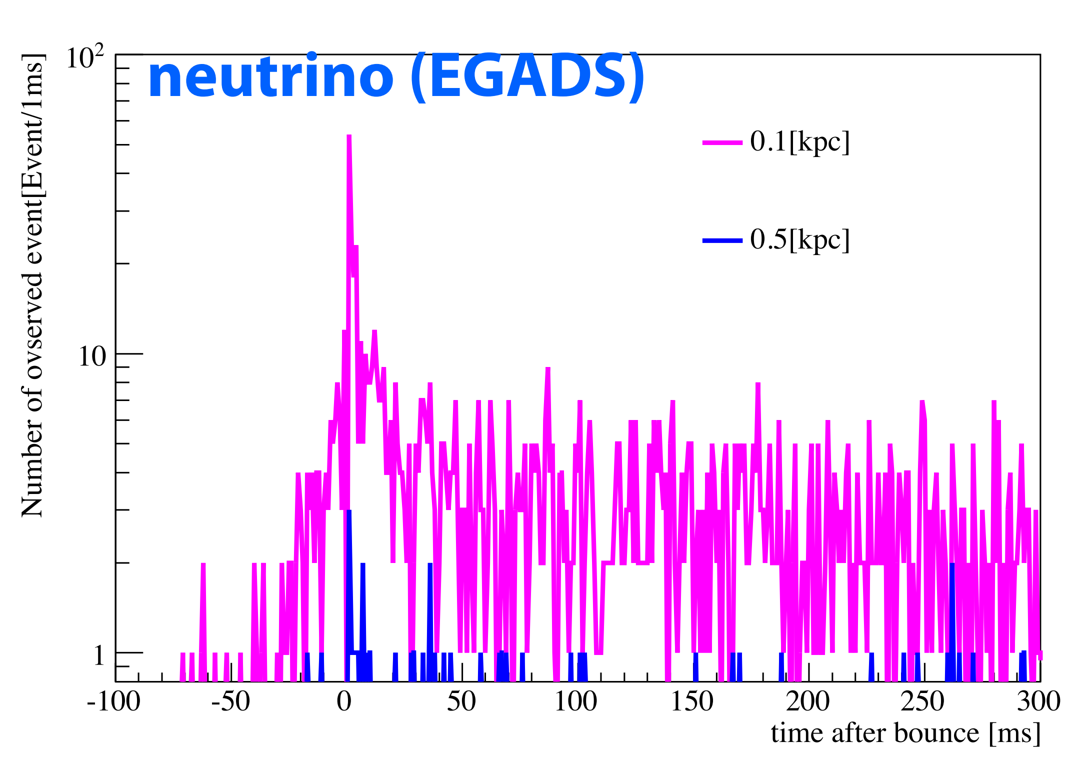
Although neutrino signals are slightly changed by the rotation, the main features (amplitude, time scale, etc.) are independent on rotation.

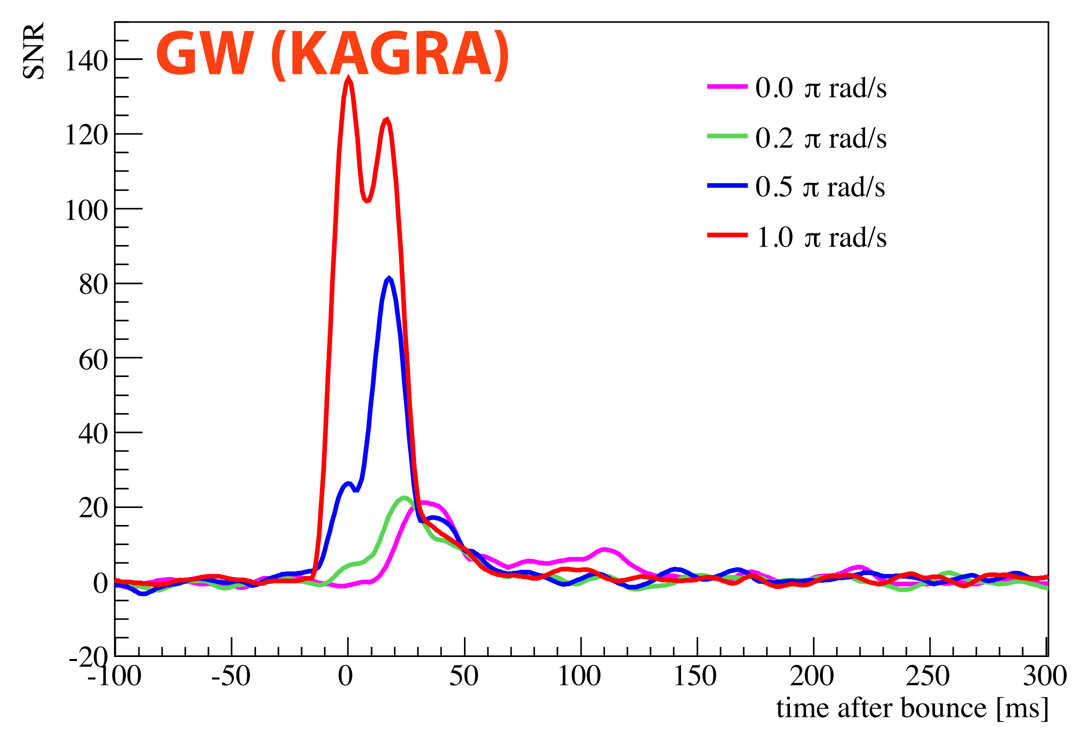
GW signal



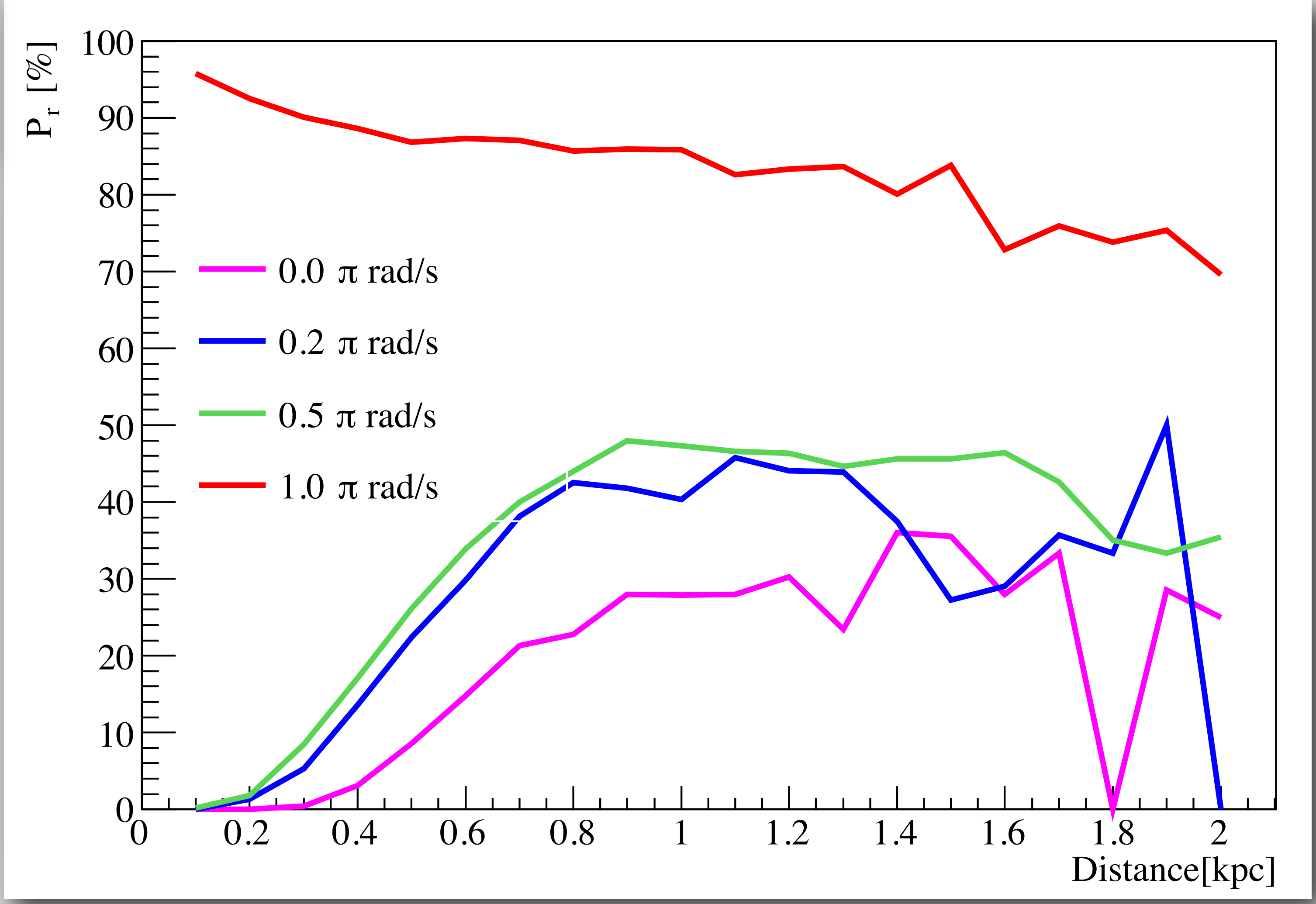
GW signals strongly depend on the rotation. Faster rotation leads to earlier GW emission due to asymmetric core bounce induced by the rotation. This time difference can be used as probe of the rotation.

Probing the central rotation by ν and GW



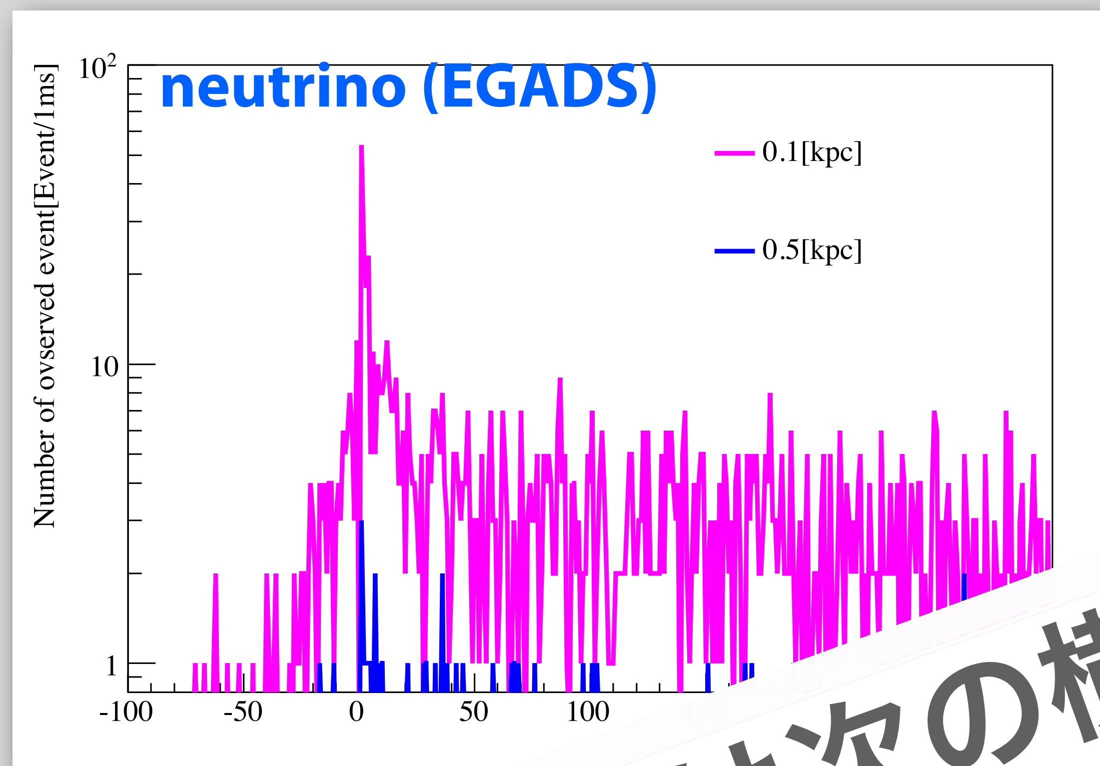


1. Assuming ***EGADS*** **(ν)** **and** ***KAGRA*** **(GW), we generate mock data of neutrinos and GWs taking into account the realistic noise level.** These detectors are located in Kamioka mine (the same place!). EGADS (~100t) is the prototype of Super-Kamiokande (~22.5kt) loading Gd.
2. **We perform data analysis for investigating whether we can probe the central rotation using the onset time difference of neutrinos and GWs.**



Yokozawa+, YS+ , arXiv:1410.2050

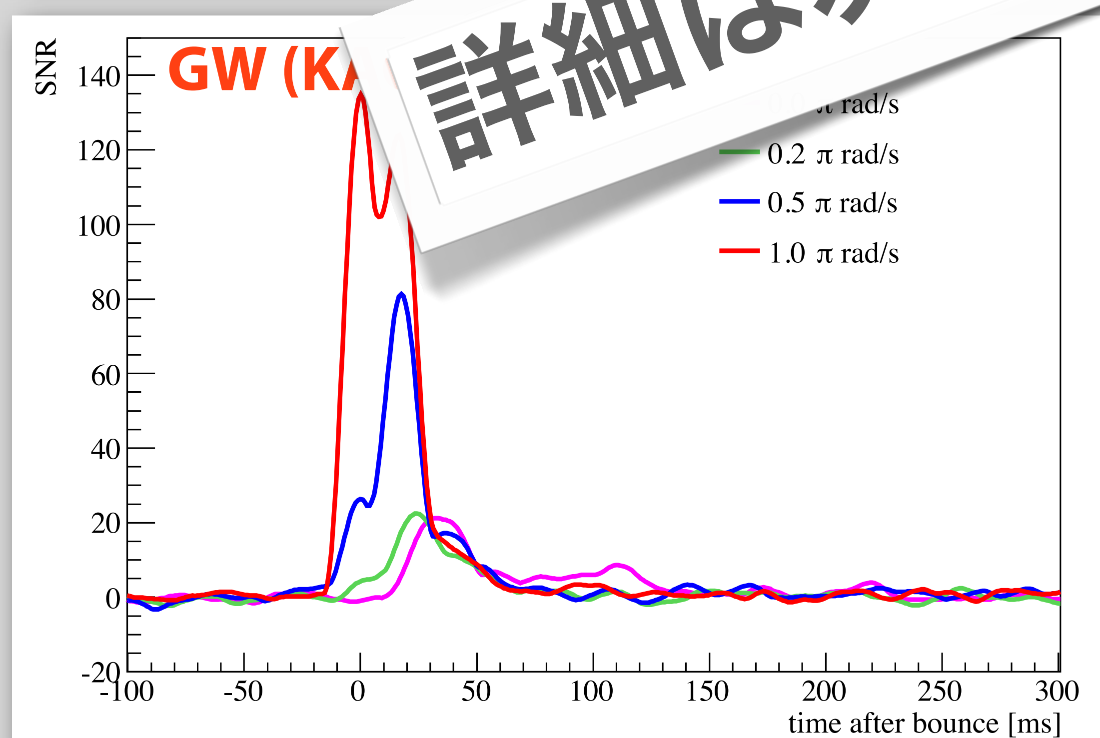
Probing the central rotation by ν and GW

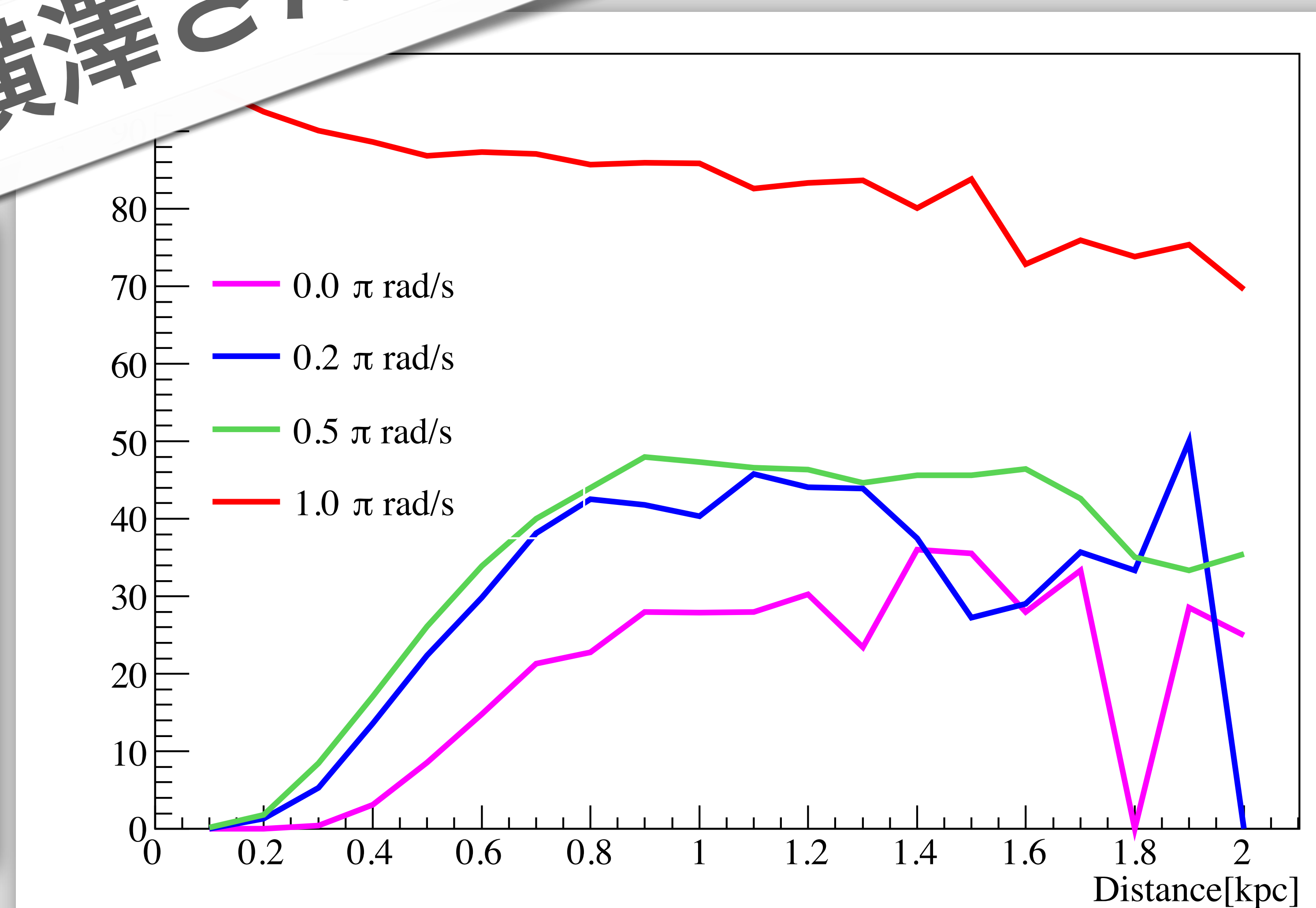


1. Assuming *EGADS* (ν) and *KAGRA* (GW), we generate mock data of neutrinos and GWs taking into account the realistic noise level. These detectors are located in Kamioka mine (the same place!). E... S (~100t) is the prototype of Super-Kamiokande (~2... Gd.

2. We perform ... vestigating whether we can ... ion using the onset ... trinos and GWs.

詳細は次の横澤さんの講演で





Yokozawa+, YS+ , arXiv:1410.2050

Is it robust?

- **Ambiguities**
  - **When prompt convection sets in?**
    depending on
    - **progenitor density structure (mass accretion rate history)**
    - **strength of convection *before* core collapse**
  - **GR**
    - **might change the typical frequency**
  - **magnetic fields**
    - **maybe minor**
  - **dimensionality (2D/3D)**
    - **maybe minor**

Contents

1. Candidates of explosion mechanisms
2. Multi-messenger time domain observations
3. Neutrino signals
4. Gravitational waves
5. Concurrent analysis
6. **Summary**

Summary

- **Multi-messenger time domain astronomy era is coming!**
- **As for CCSNe,**
  - **Neutrinos are promising**
    - high duty cycle is demanding
  - **Photons are necessary to confirm as astronomical source**
    - blind search in error circle of neutrinos / large FOV facilities
  - **Gravitational wave is smoking gun for explosion mechanism**
    - burst search analysis technic should be improved