

第12回超新星ニュートリノ研究会
より現実的な超新星ニュートリノデータを用いた
原始中性子星のパラメータ推定手法の検証

発表者

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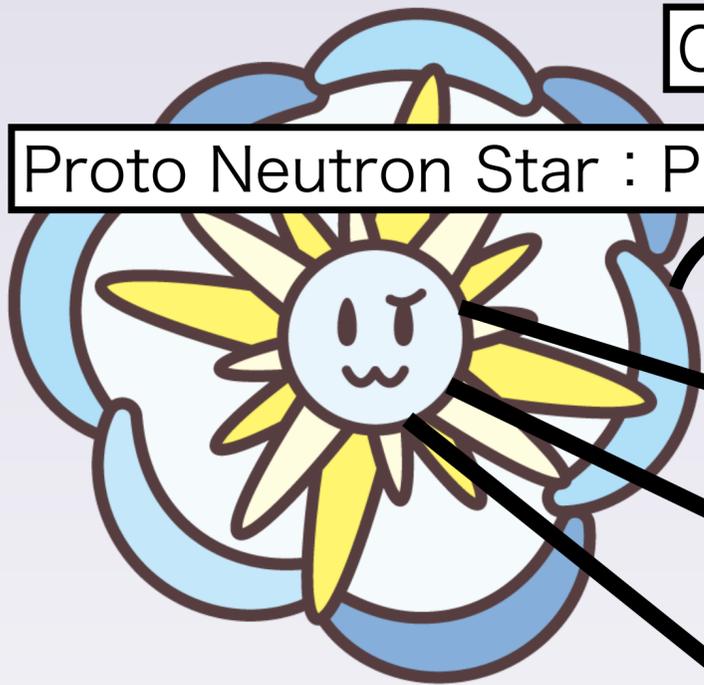
中里健一郎(九州大学), 芦田洋輔(東北大学), 小汐由介, 中西史美(岡山大学)

赤穂龍一郎(早稲田大学), Roger Wendell(京都大学),

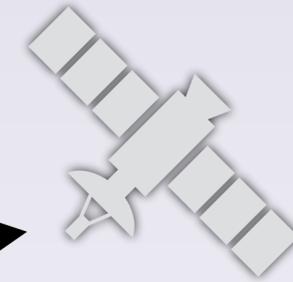
Supernova Neutrinos

Core-Collapse Supernova

Proto Neutron Star : PNS



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電磁波

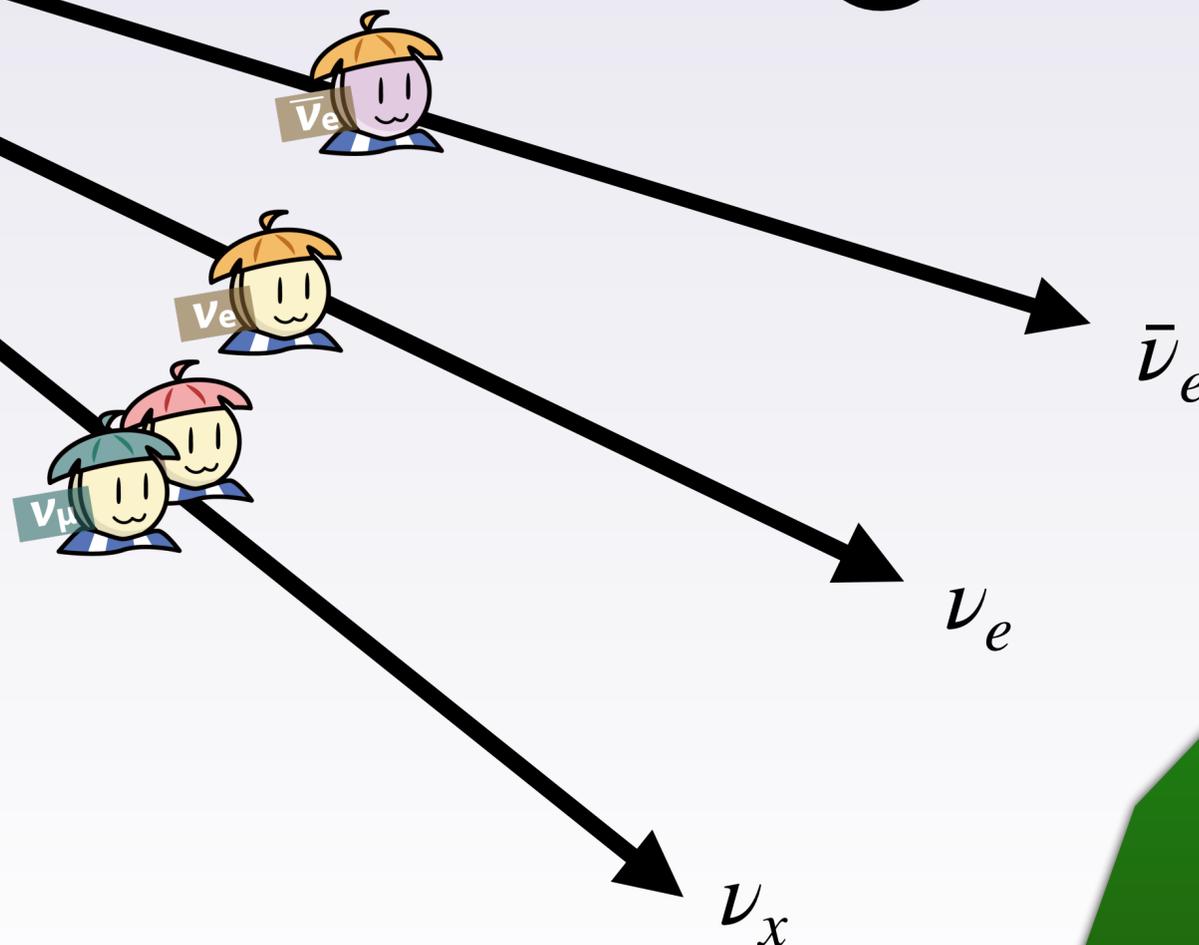
Cannot escape from the optical thick region

Neutrino

Escape from the high density region due to the weak interactions

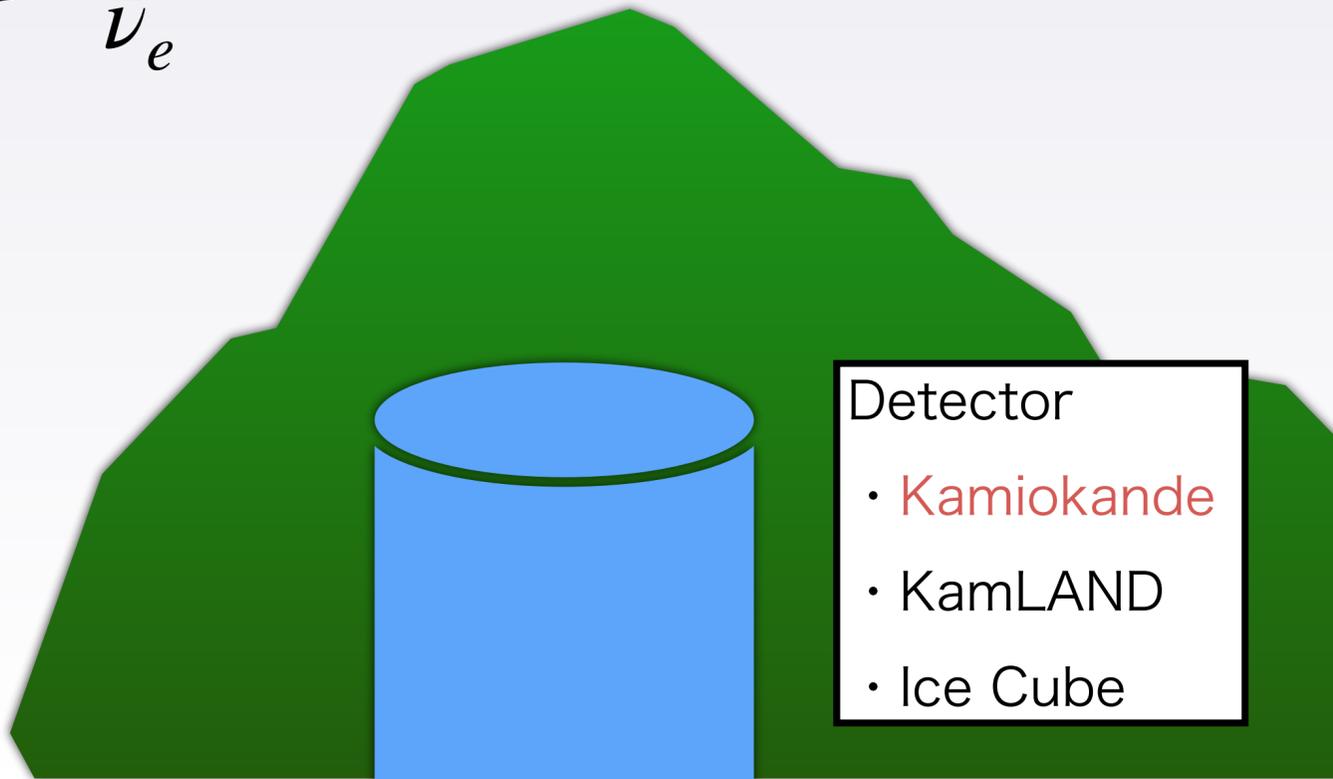


Bring information from the core to the outside



Detector

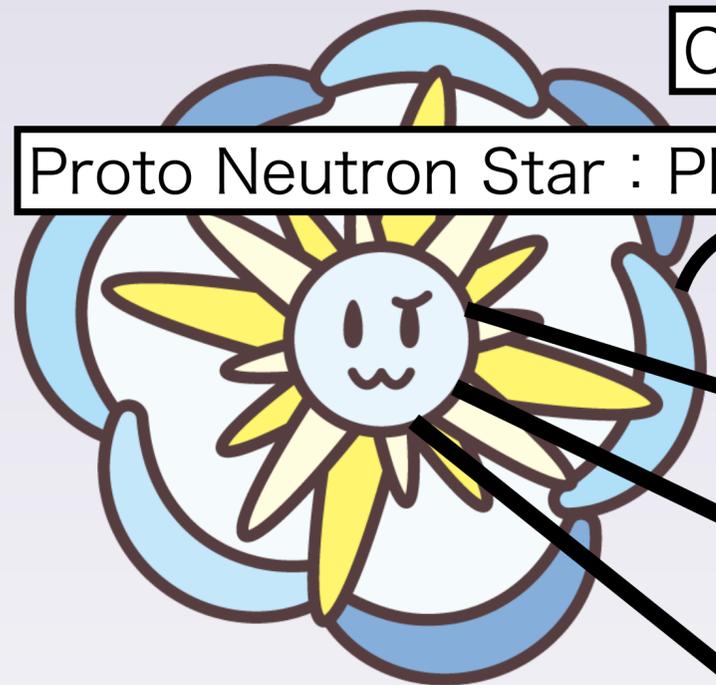
- Kamiokande
- KamLAND
- Ice Cube



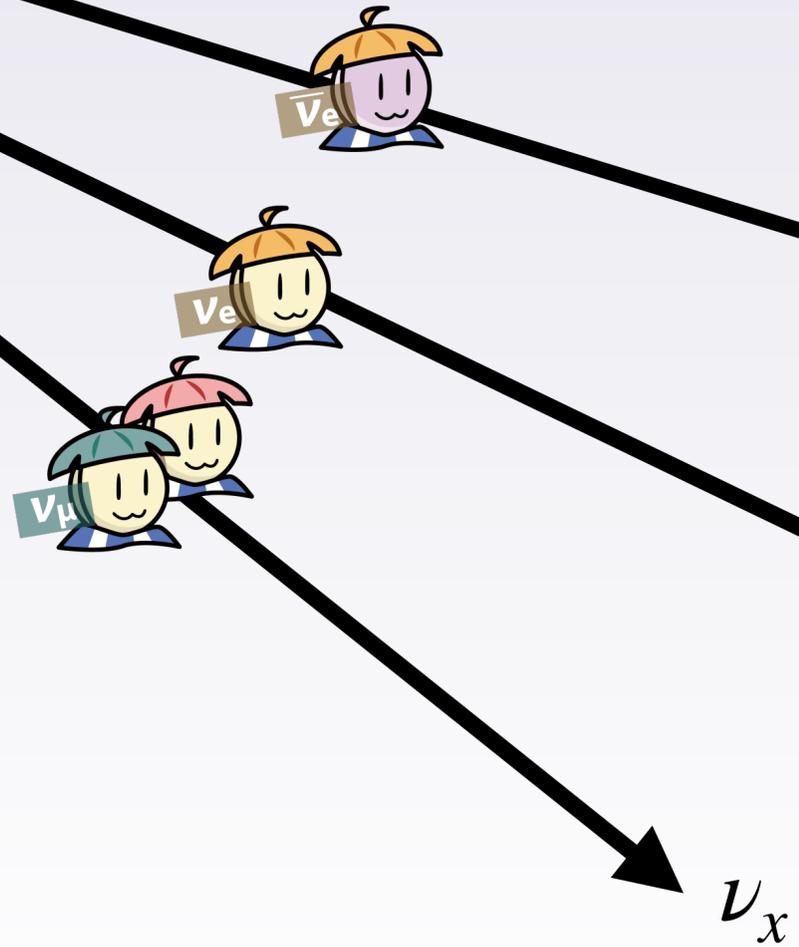
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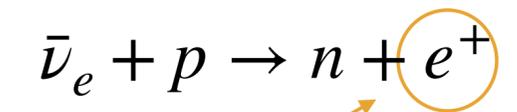
Escape from the high density region due to the weak interactions



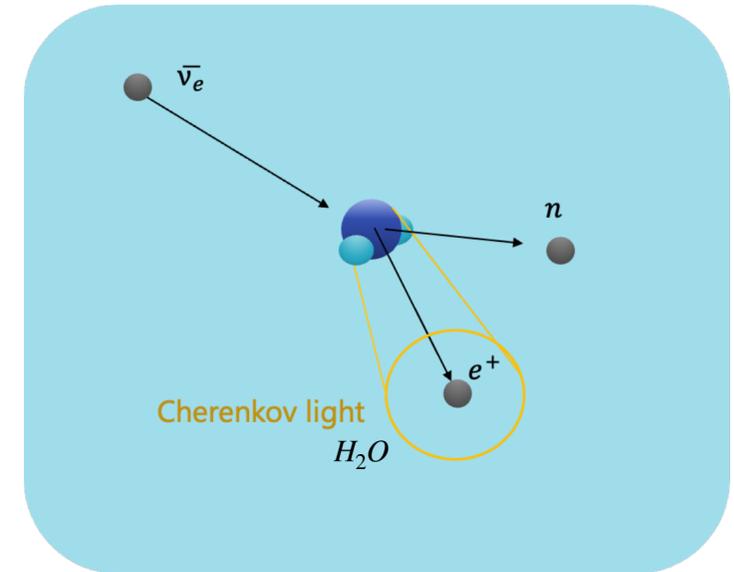
Bring information from the core to the outside

• Kamiokande

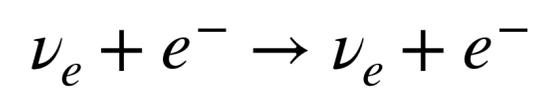
-Inverse beta decay



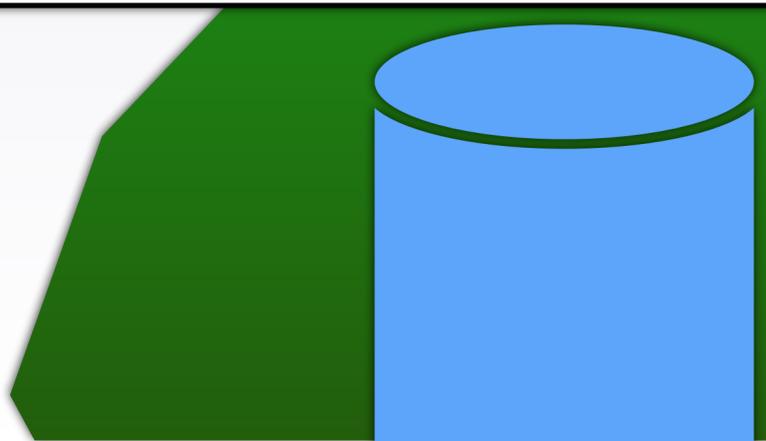
Observed



-Electron scattering



Directional sensitivity



- Detector
- Kamiokande
 - KamLAND
 - Ice Cube

Detecting Supernova neutrinos

We have observed only one event

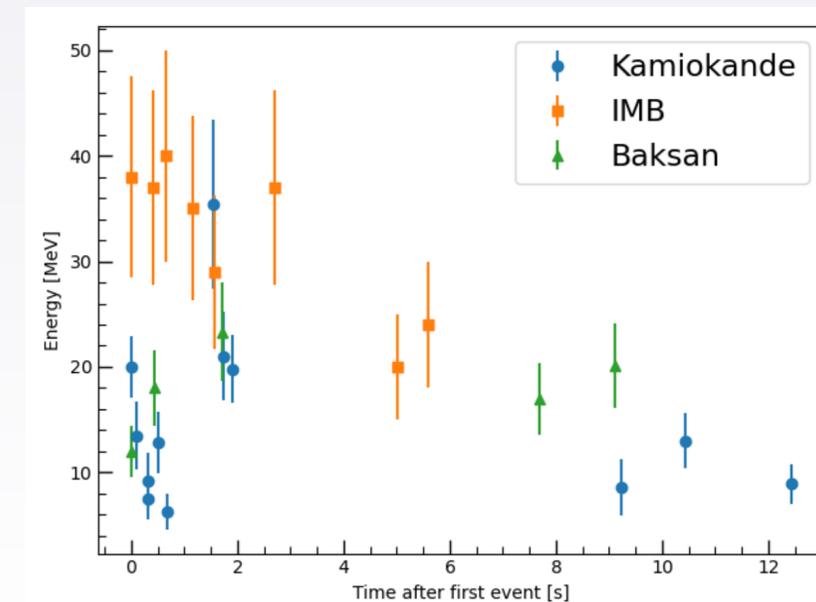
→ SN1987A (Located at Large Magellanic Cloud)

We are preparing the next events

- Capture the galactic event surely
- Separate Supernova neutrinos from backgrounds
- Early time observation of SN neutrino signals
- Methods for analyzing neutrino data



©Australian Astronomical Observatory



Total : 24 events

Kamiokande : Hirata et al. 1987

IMB : Bionta et al. 1987

Baksan : Alekseev et al. 1987

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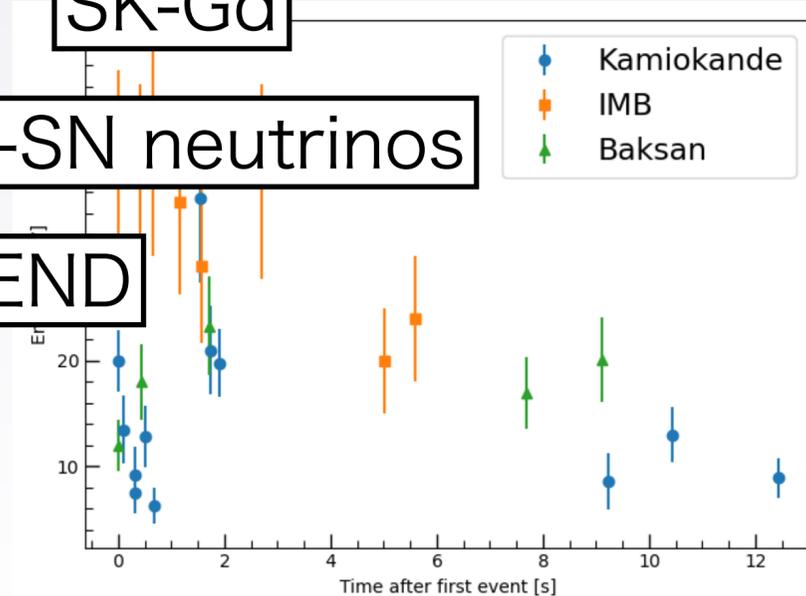
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Hyper-Kamiokande

SK-Gd

Pre-SN neutrinos

SPECIAL BLEND



Total : 24 events

Kamiokande : Hirata et al. 1987

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Detecting Supernova neutrinos

We have observed only one event

→ SN1987A (Located at Large Magellanic Cloud)

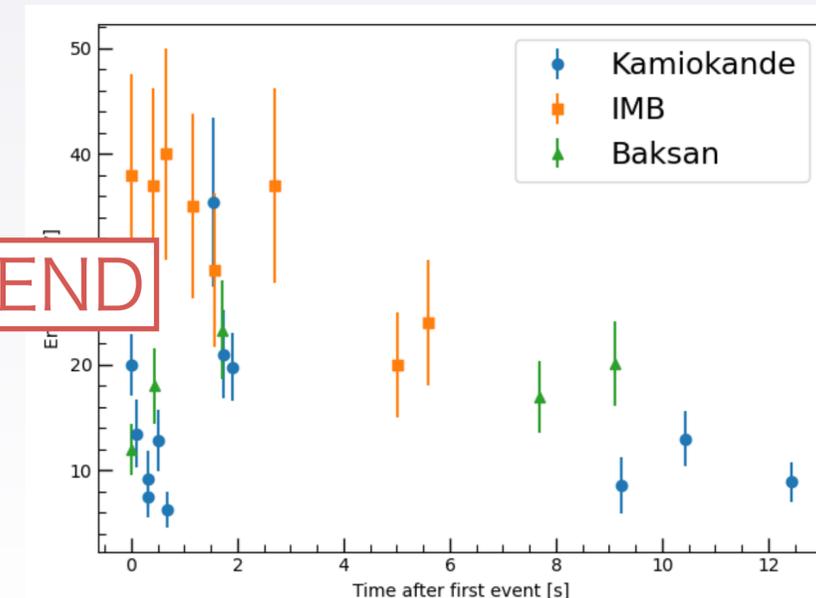
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SPECIAL BLEND



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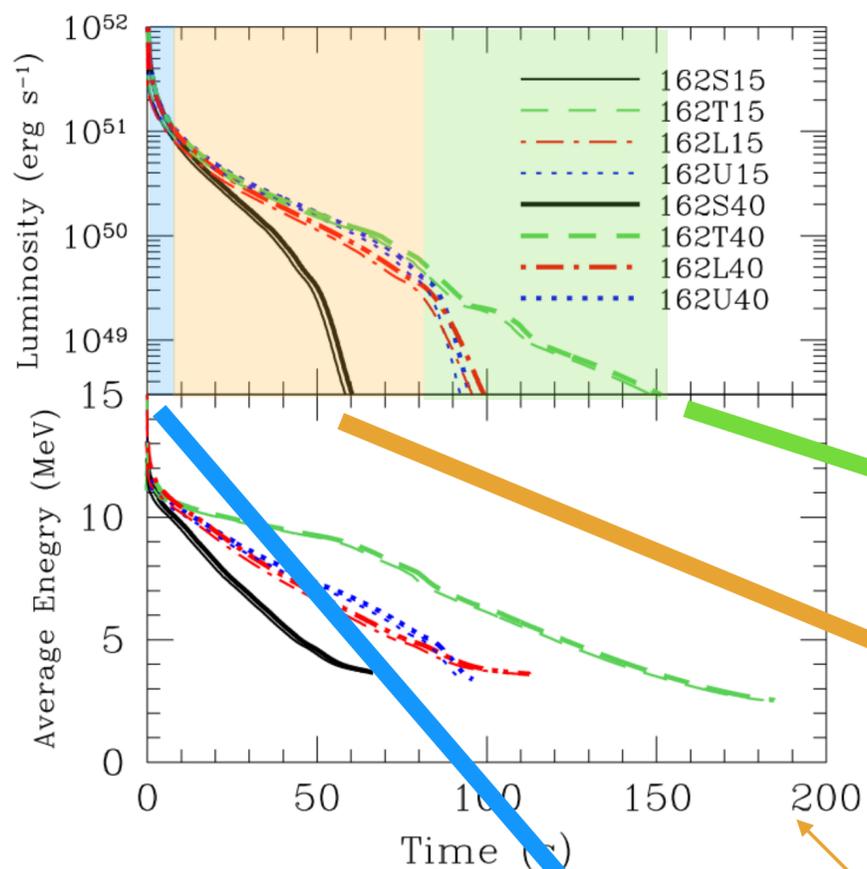
Total : 24 events

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PNS cooling phase



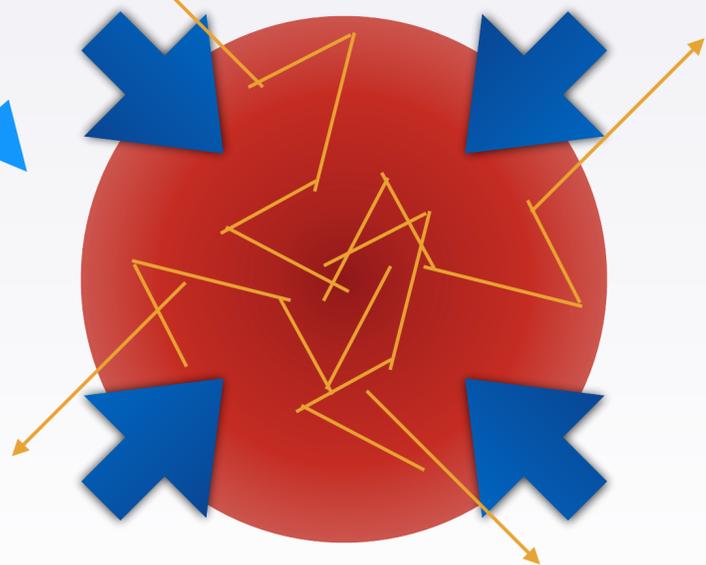
Early phase : Large uncertainties due to complicated physical situations

✓ Late phase : This can be expressed with simple physics

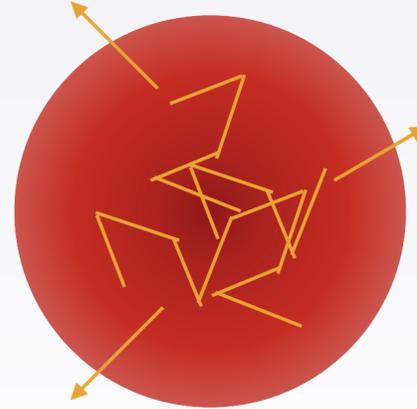


Valid for analytical solutions and estimation

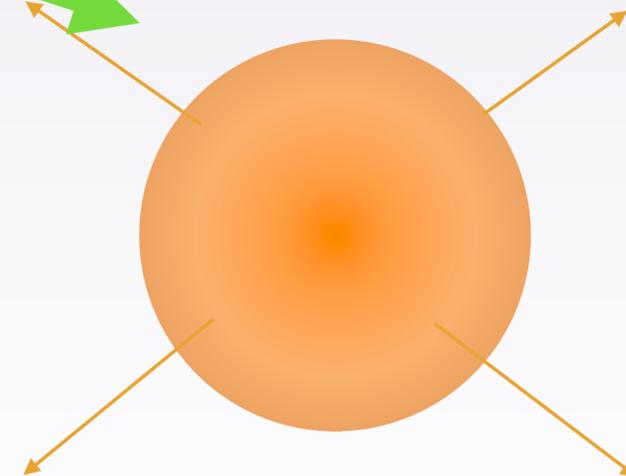
Nakazato +21



Mantle contraction

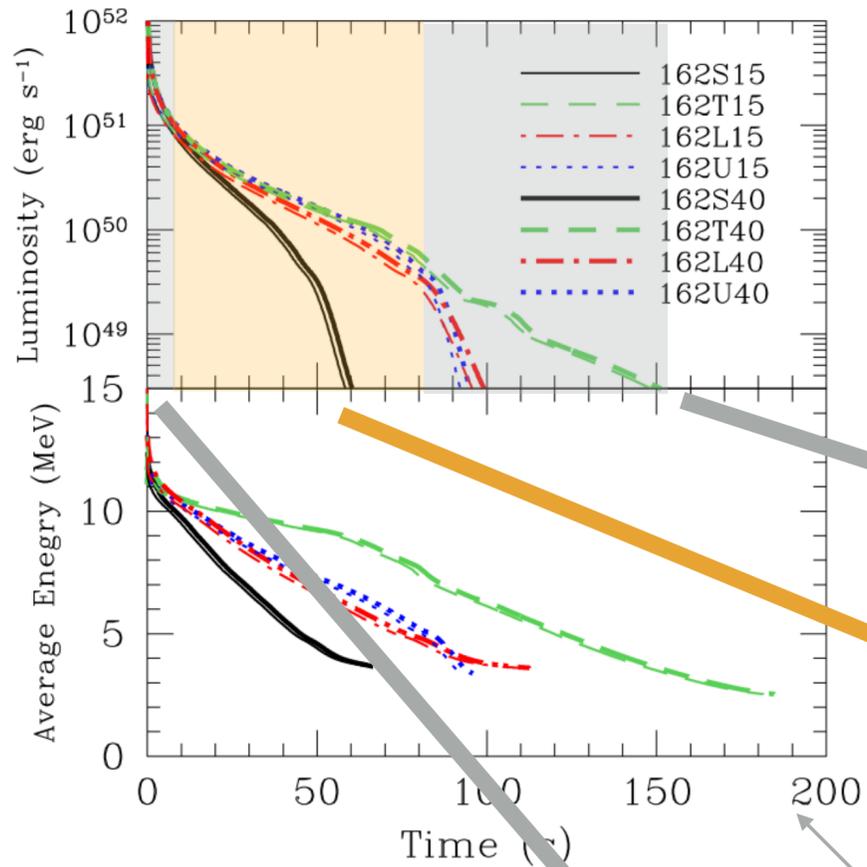


Shallow decay



Volume cooling

PNS cooling phase



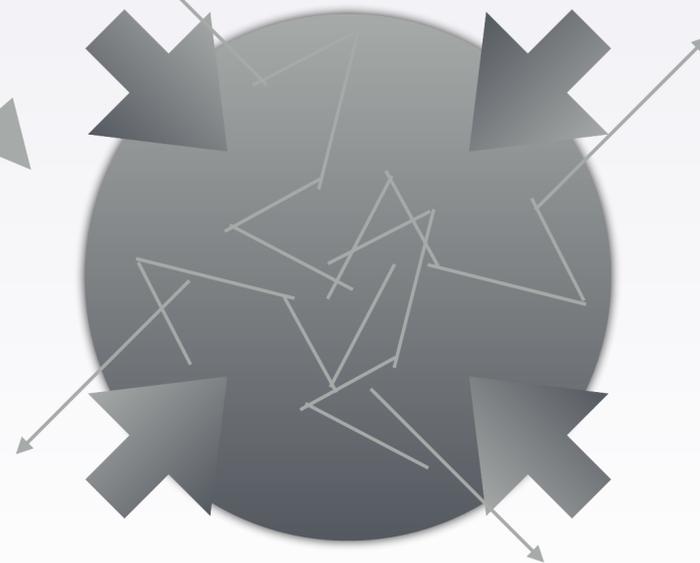
Nakazato +21

Analytic solution for neutrino observation (Suwa +21)

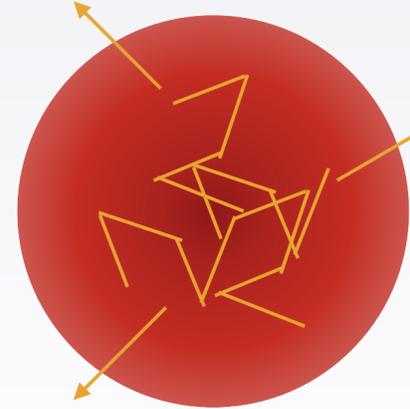
- $\gamma = 2$ Polytropic sphere
- Diffusion approximation
- Radius, Mass are constant etc.

Positron mean energy : $E_{e^+} \approx 25 \text{ MeV} \left(\frac{M_{\text{PNS}}}{1.4M_{\odot}} \right)^{3/2} \left(\frac{R_{\text{PNS}}}{10\text{km}} \right)^{-2} \left(\frac{g\beta}{3} \right) \left(\frac{t+t_0}{100 \text{ s}} \right)^{-3/2}$

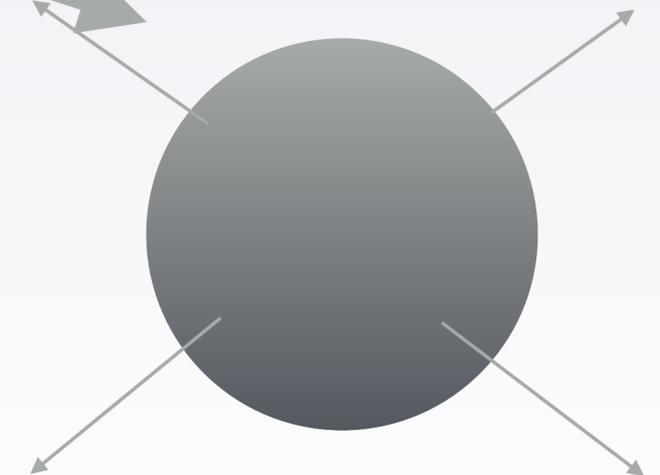
Event rate : $\mathcal{R} \approx 720 \text{ s}^{-1} \left(\frac{M_{\text{det}}}{32.5 \text{ kton}} \right) \left(\frac{D}{10 \text{ kpc}} \right)^{-2} \left(\frac{M_{\text{PNS}}}{1.4M_{\odot}} \right)^{15/2} \left(\frac{R_{\text{PNS}}}{10 \text{ km}} \right)^{-8} \left(\frac{g\beta}{3} \right)^5 \left(\frac{t+t_0}{100 \text{ s}} \right)^{-15/2}$



Mantle contraction



Shallow decay



Volume cooling

SPECIAL BLEND

Parameter estimation of PNS using SN neutrinos observational data

解析コード : SPECIAL BLEND (Harada +23)

Analytic solution(Suwa +21) × Bayesian estimation → PNS's mass, radius,
total emitted neutrino energy

Neutrino observation

Positron mean energy : $\langle \epsilon \rangle_i$

Time : t_i

SPECIAL BLEND

Output

PNS mass : M_{PNS}

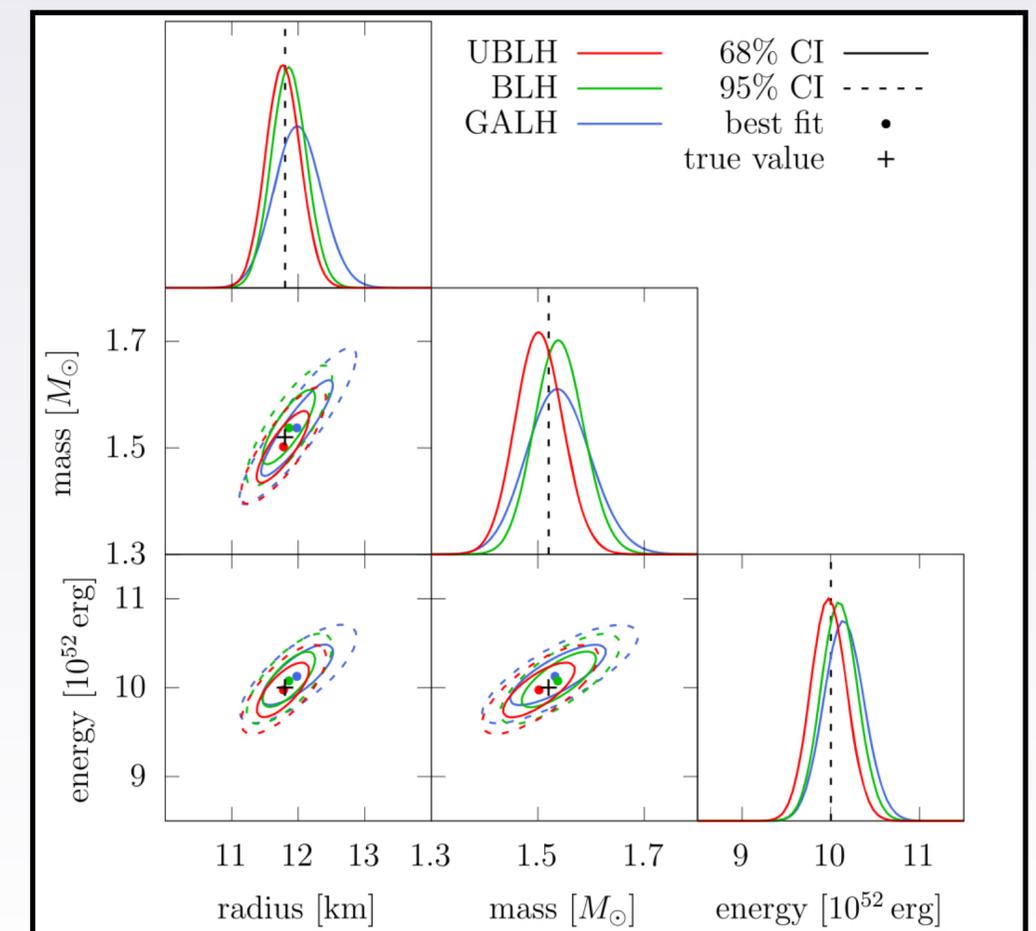
PNS radius : R_{PNS}

Total emitted neutrino energy : E_{tot}

From other observations

Distance : D Detector mass : M_{det}

Phenomenological parameters : $g\beta$



Application to realistic data

Problem : Is this estimation reliable for more realistic data ?

Backgrounds, approximations applied to analytic solutions may affect the accuracy

後の森正光さんの公演

Purpose : Confirm the accuracy using more realistic data

Generate mock data from numerical simulations for several EoS models

(FOREST : Mori in prep.)

- Used models (Nakazato +22)

EoS : Shen, LS220, Togashi, Togashi+Shen, Furusawa+Togashi

- Mock data conditions

$d = 10$ kpc, $M_{det} = 32.5$ kton (Super-Kamiokande Full volume)

How to estimate

- ① Full-time analysis for each EoS models

Mass and $g\beta$ are degenerate, so they cannot be determined independently



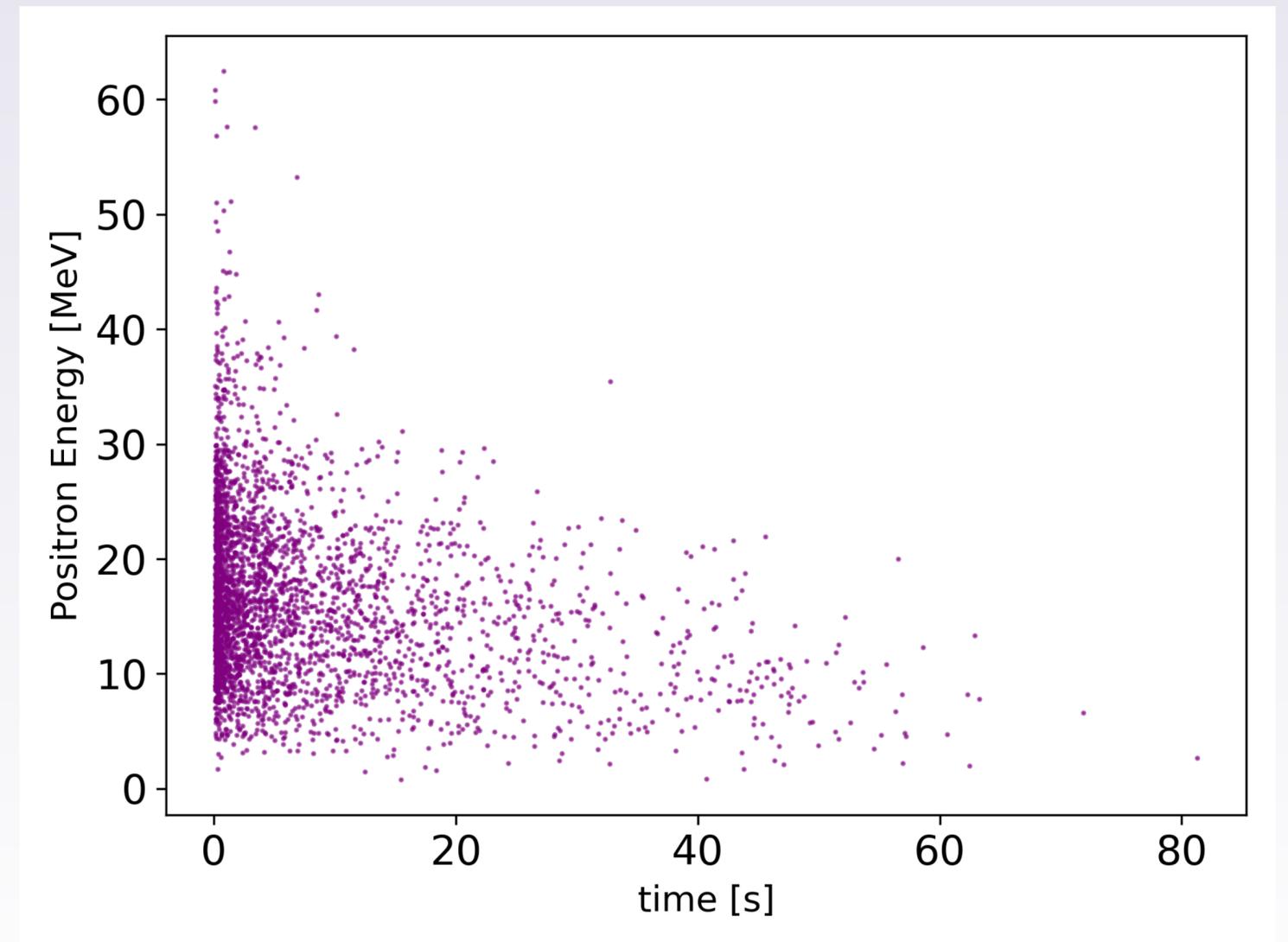
Check the accuracy using radius

$$R_{PNS} = 10 \text{ km} \left(\frac{\mathcal{R}}{720\text{s}^{-1}} \right)^{1/2} \left(\frac{E_{e^+}}{25\text{MeV}} \right)^{-5/2} \left(\frac{M_{det}}{32.5\text{kton}} \right)^{-1/2} \left(\frac{D}{10 \text{ kpc}} \right)$$

- ② Time evolution analysis

Every 100 events from the first time event

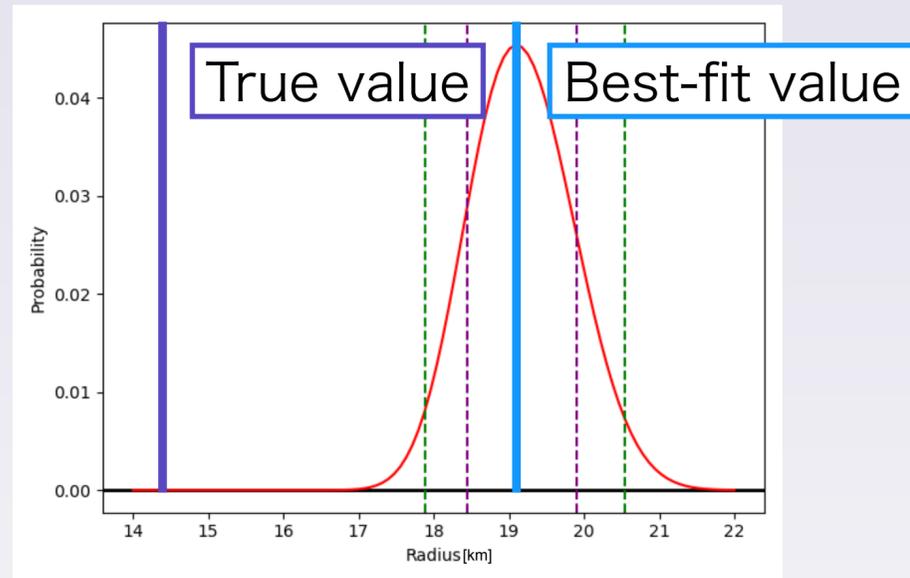
This method highlights the time evolution for the selected events



Result : All events

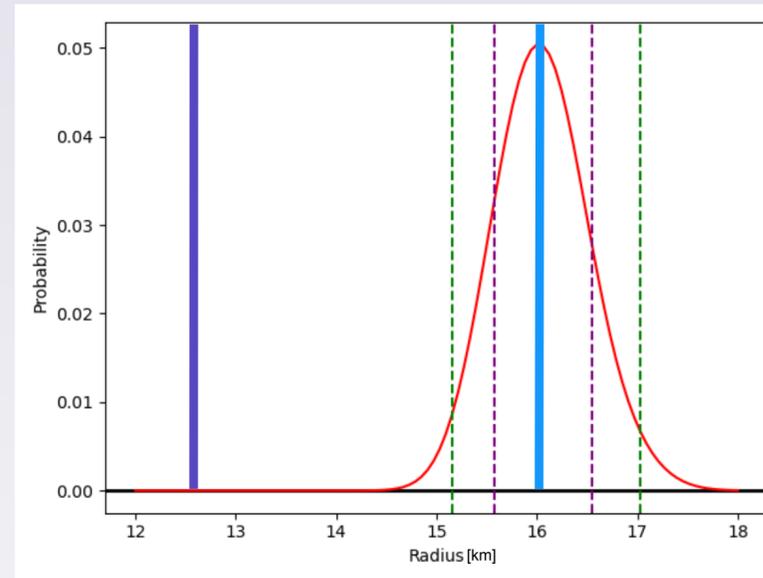
✓ Shen

14.33km 19.09km



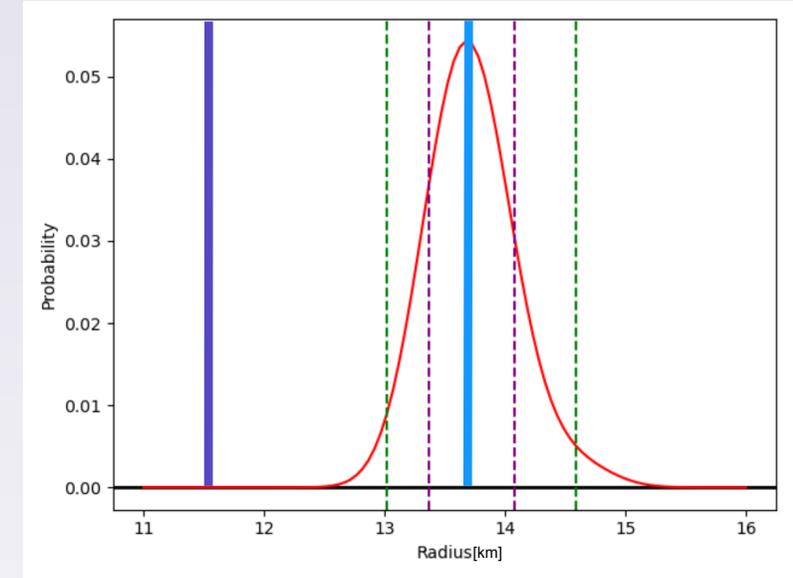
✓ LS220

12.73km 16.00km



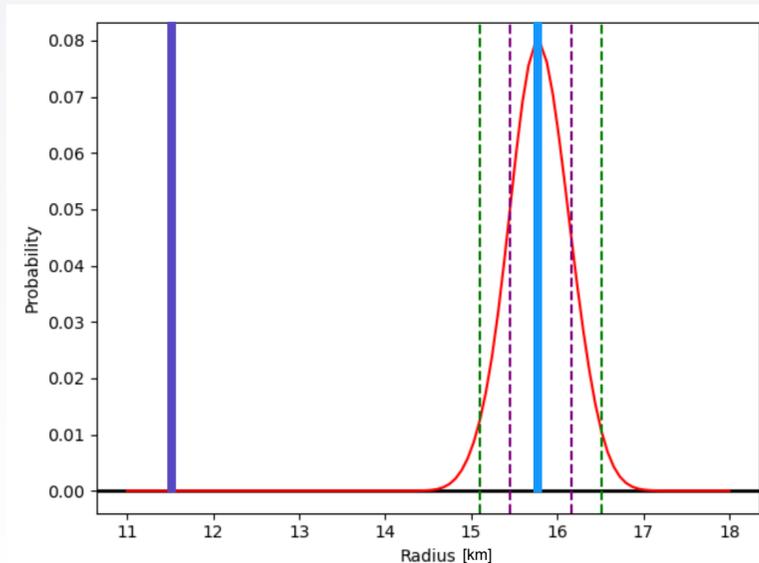
✓ Togashi

11.54km 13.68km



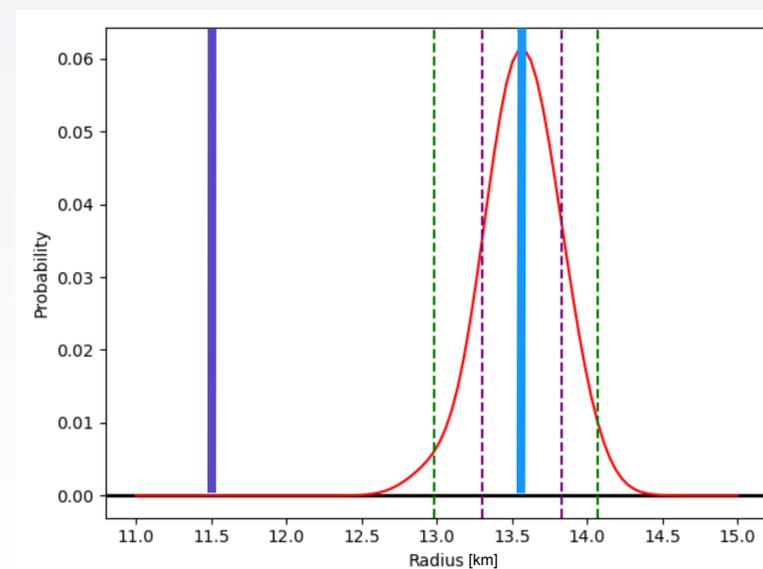
✓ Togashi+Shen

11.45km 15.81km



✓ Furusawa+Togashi

11.5km 13.59km

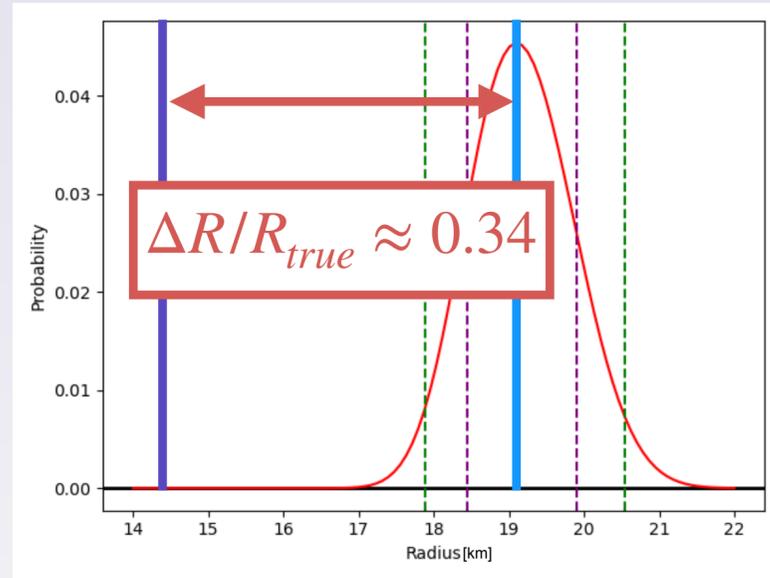


The estimated radius is larger than results of numerical simulation

Result : All events

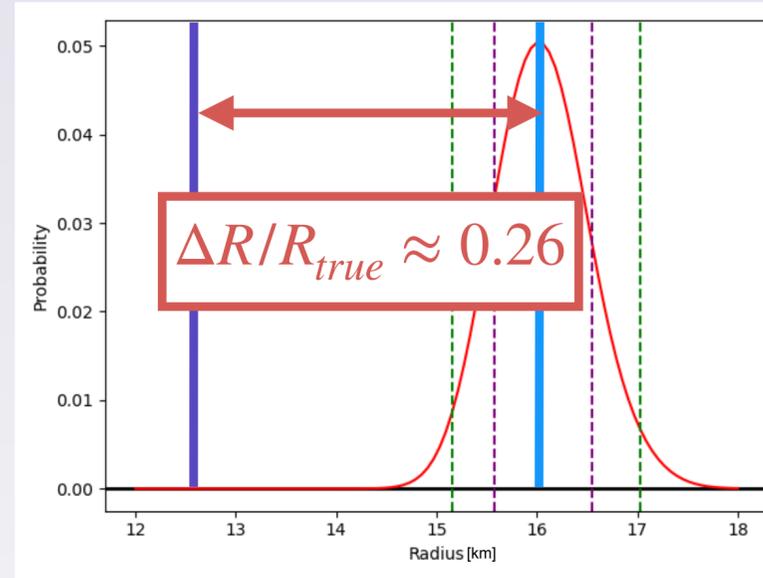
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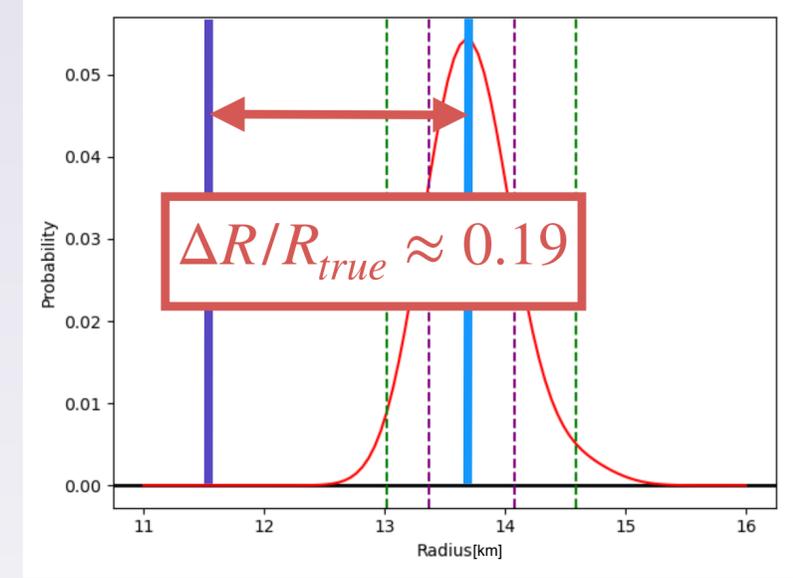
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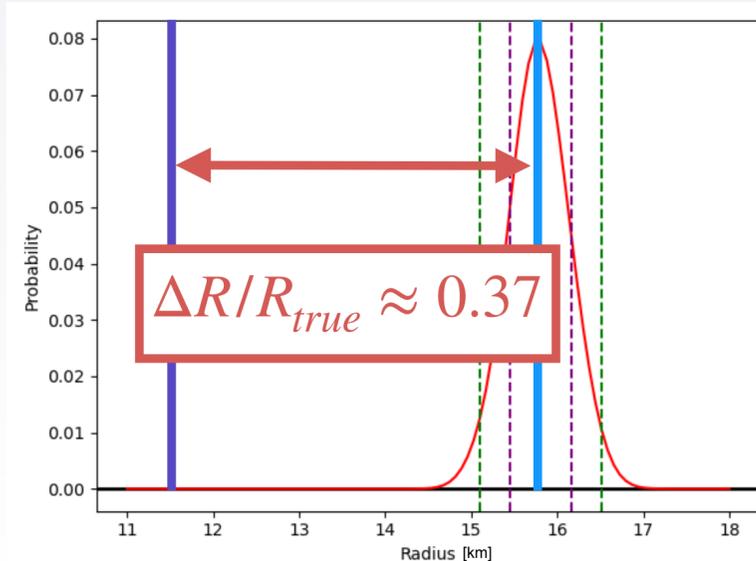
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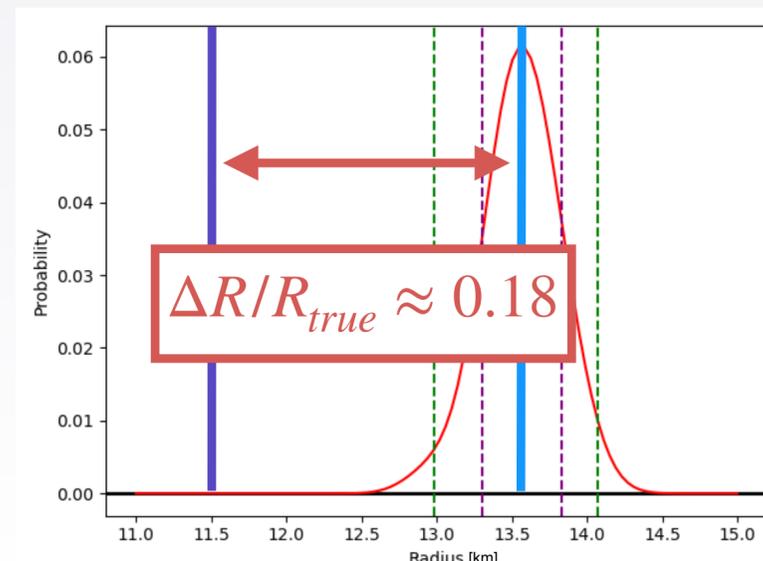
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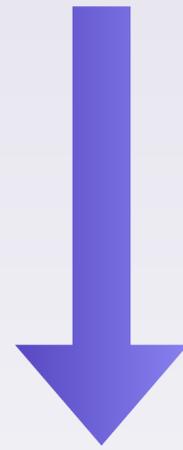
The estimated radius is larger than that obtained from numerical simulations

$$\Delta R/R_{true} \approx 20 - 40 \%$$

Time evolutions of the radius

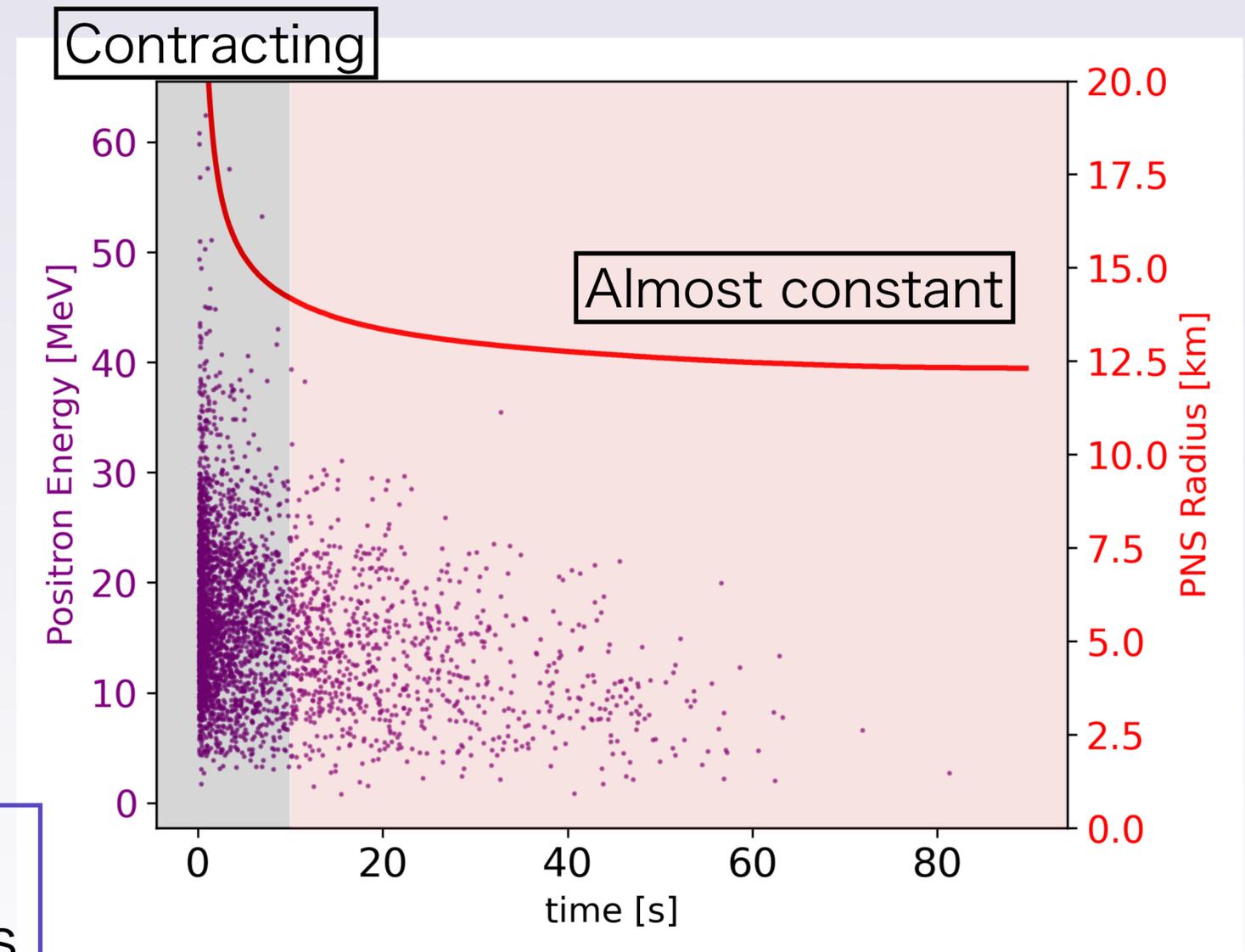
The analytic solution assumes that the radius is constant

→ Early phase events are not suitable



Use only the late-time events
when the radius is almost constant

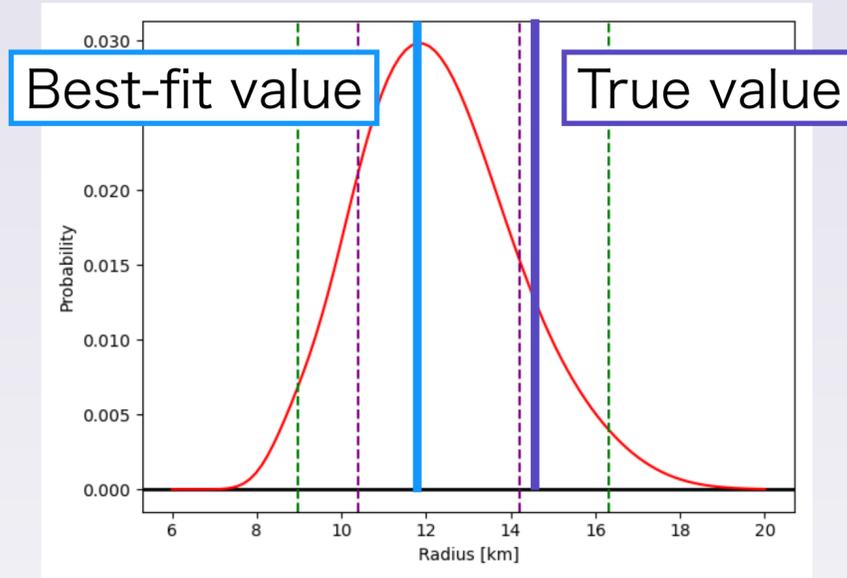
Different settings for each EoSs are required,
but events before 10s are excluded in this analysis



Result : removing events before 10s

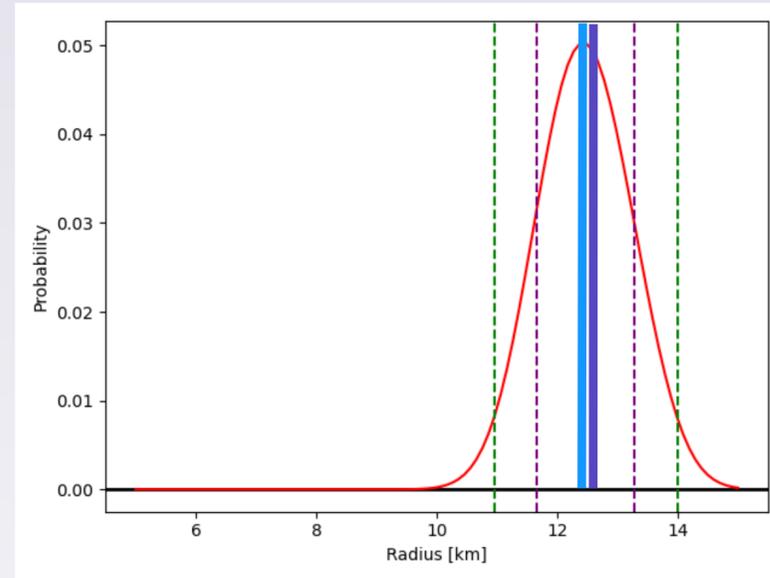
✓ Shen

11.80km 14.33km



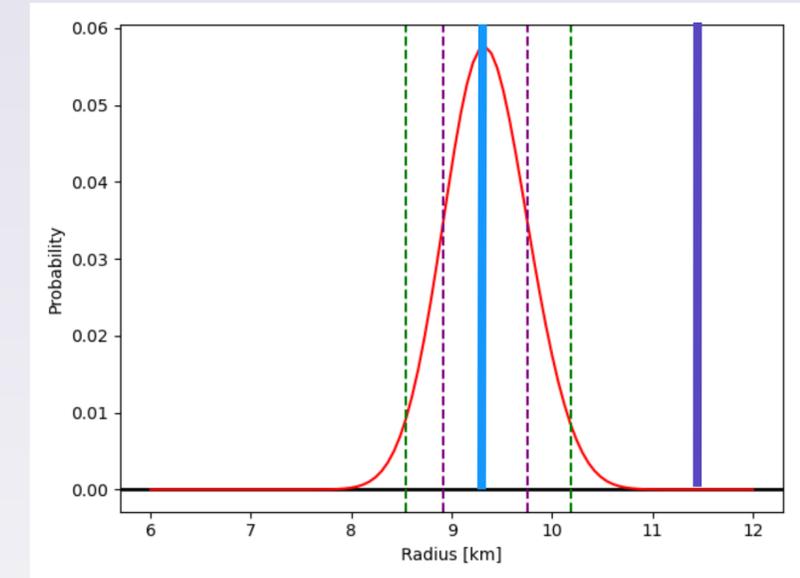
✓ LS220

12.47km 12.73km



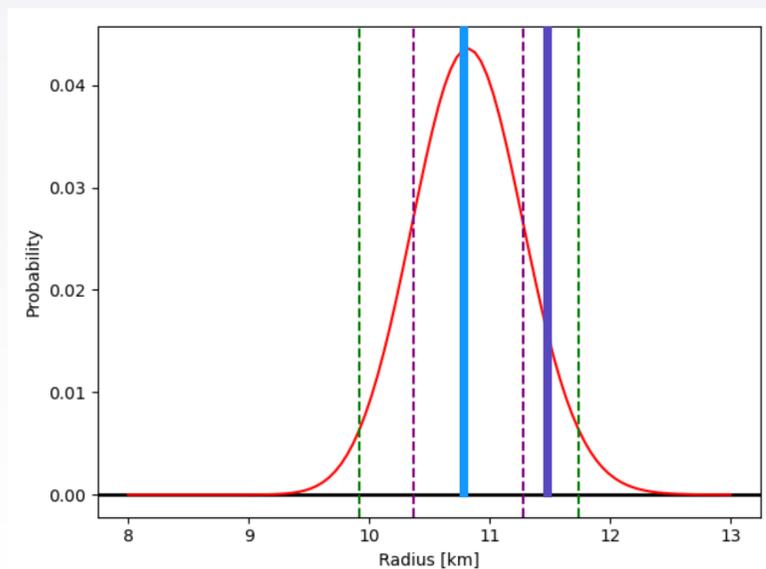
✓ Togashi

9.33km 11.54km



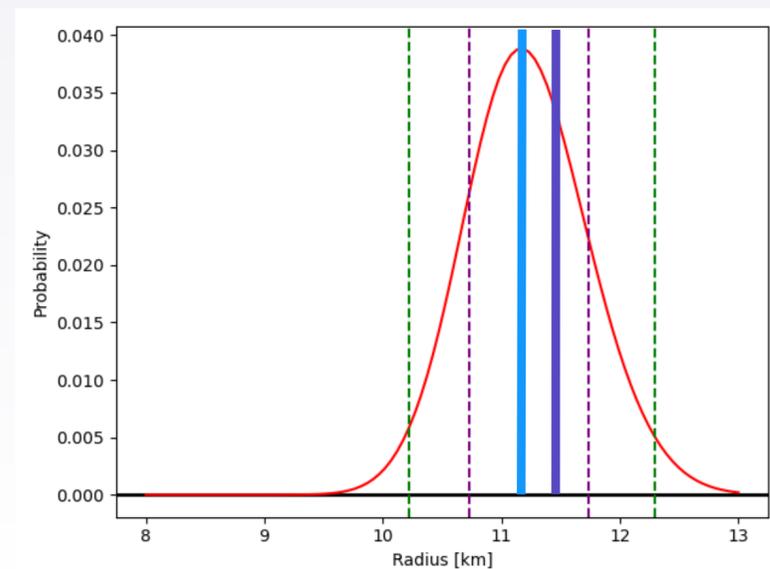
✓ Togashi+Shen

10.82km 11.45km



✓ Furusawa+Togashi

11.18km 11.5km

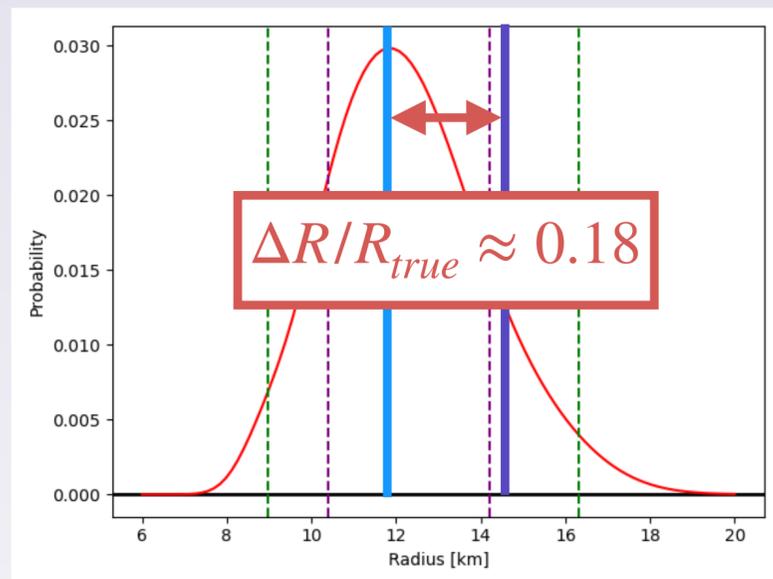


Better than full time estimation

Result : removing events before 10s

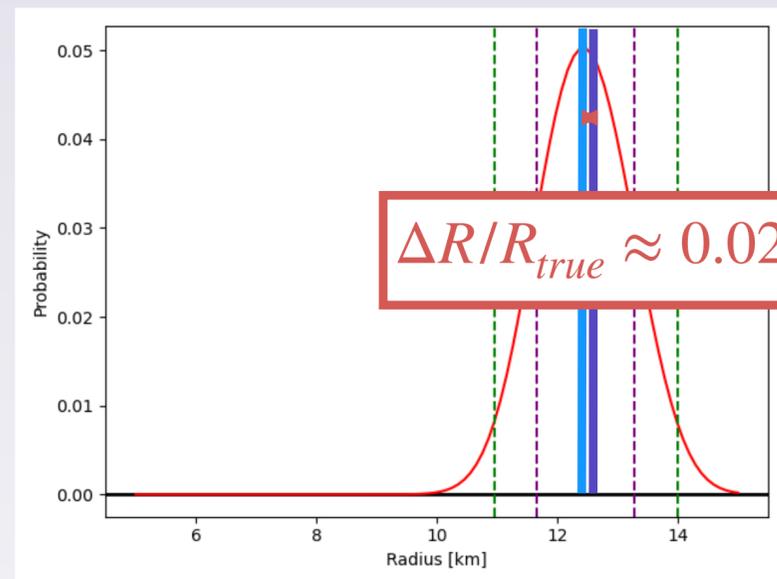
✓ Shen

11.80km 14.33km



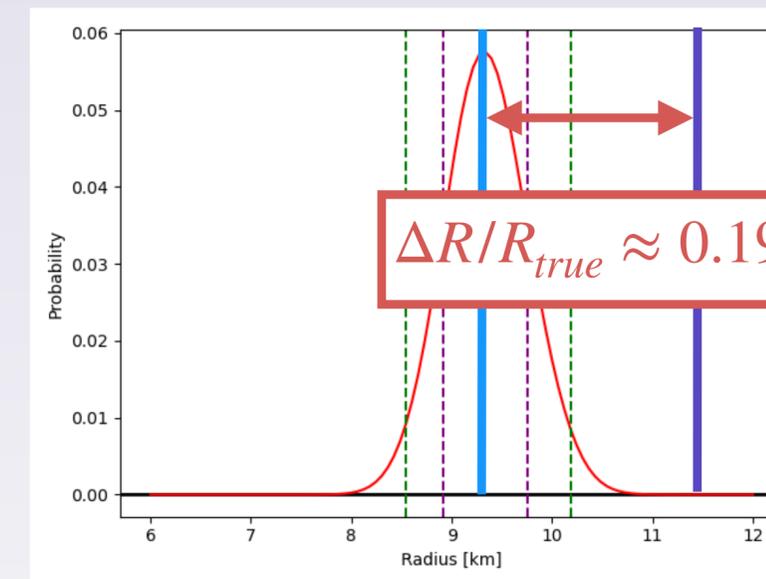
✓ LS220

12.47km 12.73km



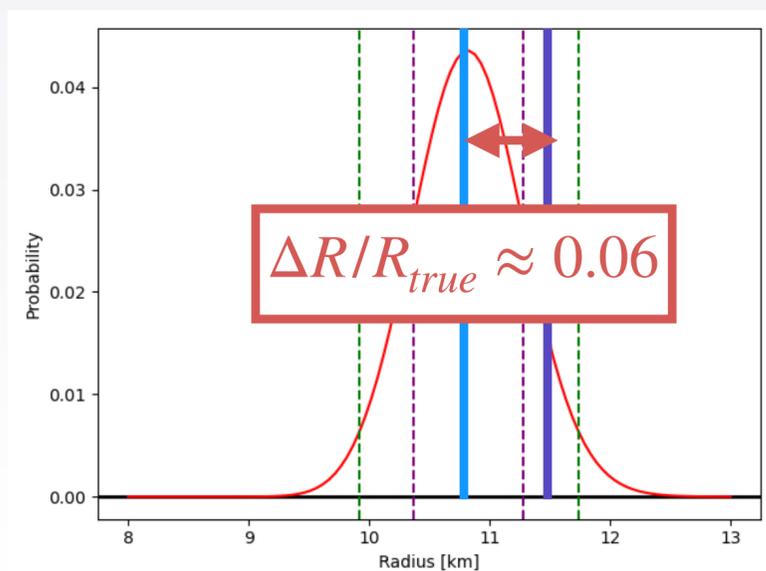
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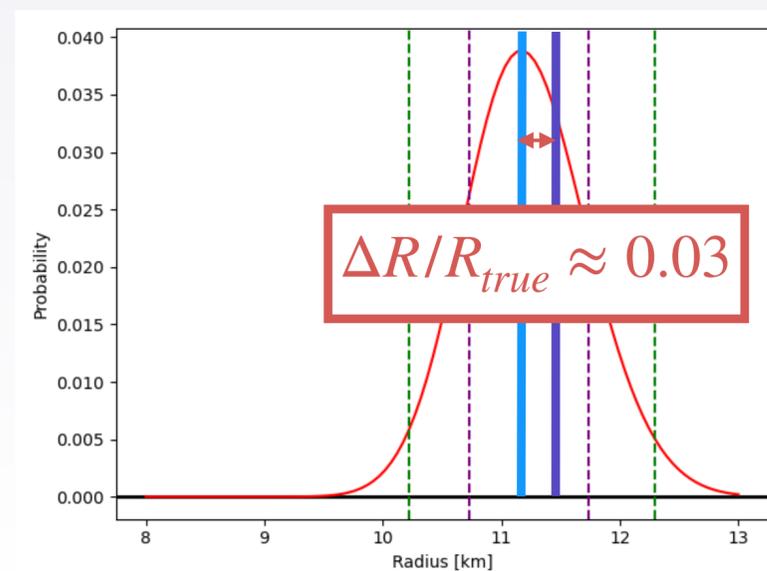
✓ Togashi+Shen

10.82km 11.45km



✓ Furusawa+Togashi

11.18km 11.5km



Better than full time estimation

$$\Delta R/R_{true} \approx 2 - 20 \%$$

Removal time needs to be adjusted
for each EoSs

How to estimate

① With each EoSs, Full time analysis

Mass and $g\beta$ are degenerated, cannot determine independently



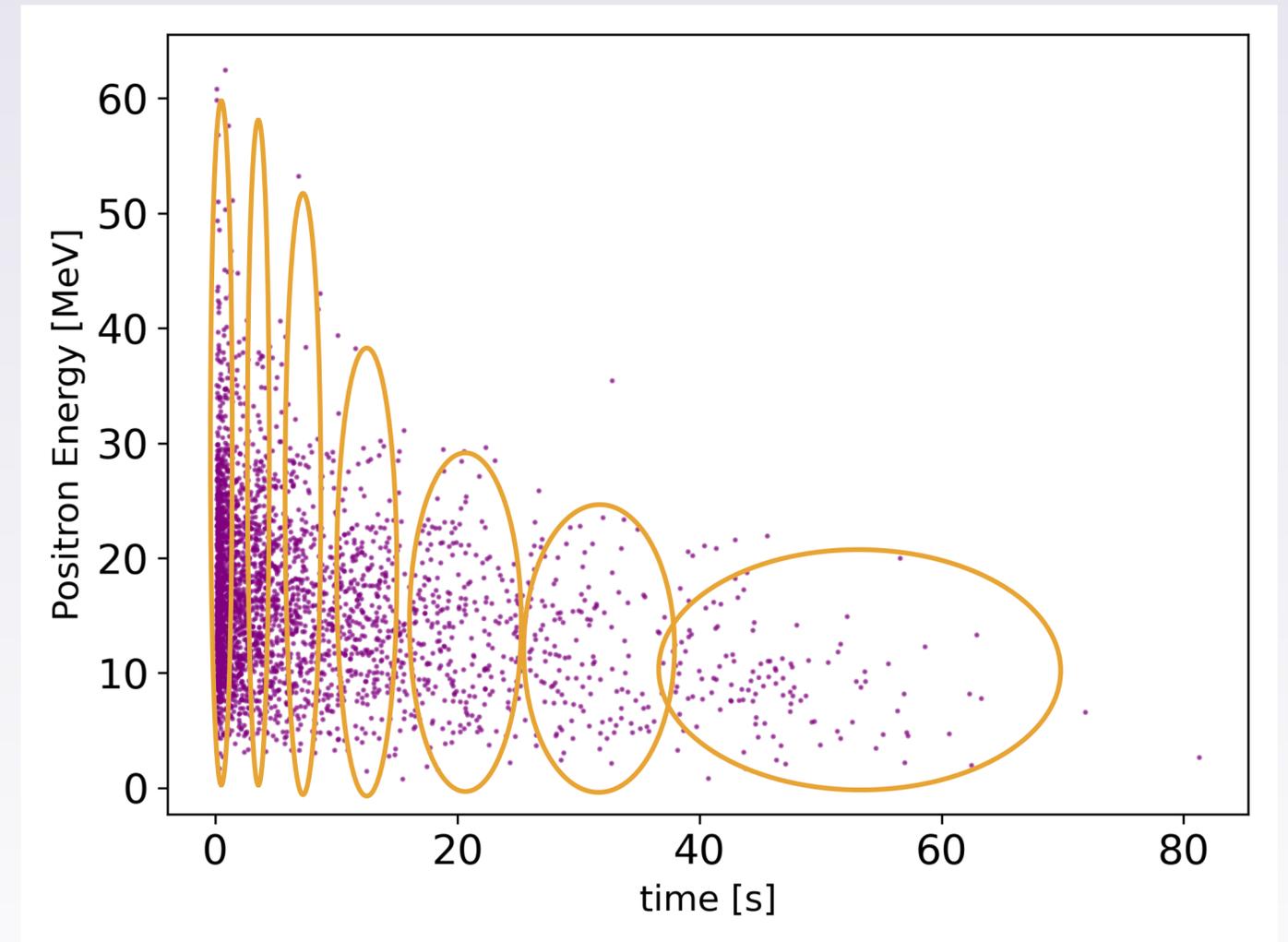
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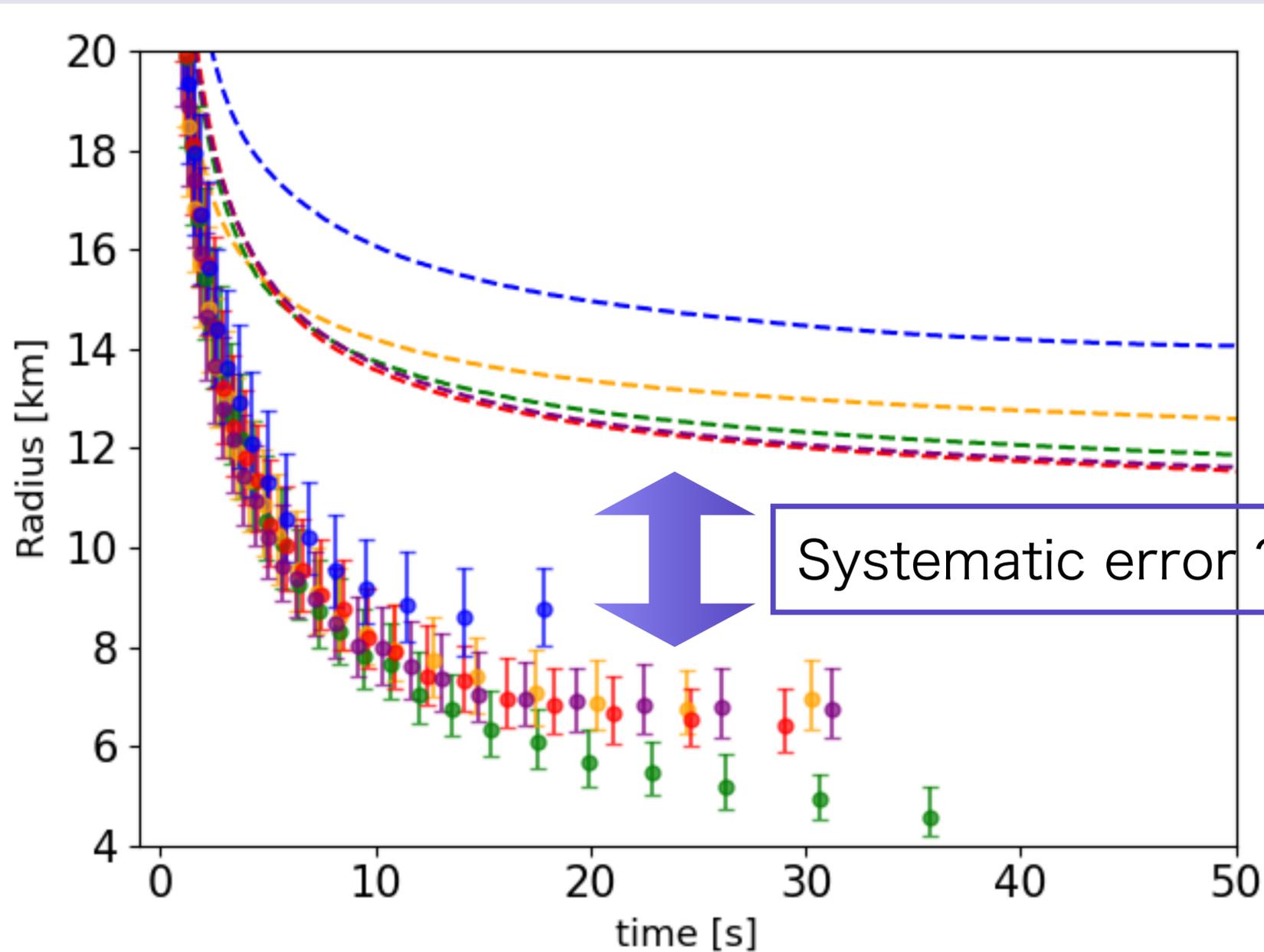
② Time evolution analysis

Every 100 events starting from the first time event

This method highlights the time evolution for the selected events



Estimate the time evolution



- Estimate the contraction of the radius
- The EoS affects strength of the contraction
- The difference between numerical results may be due to some systematic errors
 - ✓ Analytic vs Numerical
 - some approximations
 - correction factor
 - EoS
 - ✓ Estimation system
 - SPECIAL BLEND or FOREST

Conclusion and Future works

Conclusion

- ✓ The difference between numerical and analytical solution arise some systematic errors
- ✓ For the numerical solution data, the time-cut is important due to the PNS's contraction
- ✓ By selecting events appropriate, the time evolution of radius can be estimated

Future works

- ✓ Further verification on the other conditions and update analytic solution
 - Independent of the factor $g\beta$
 - Fermi energy integration considering the energy threshold E_{th}
- ✓ Systematic determination of time-cut
- ✓ Devising the time evolution estimation
- ✓ Estimate SN1987A considering systematic and Poisson errors