Low-energy neutrino astrophysics in KamLAND

Koji Ishidoshiro (Tohoku Univ.)

Ref:

Asakura et al., arXiv:1506.01775

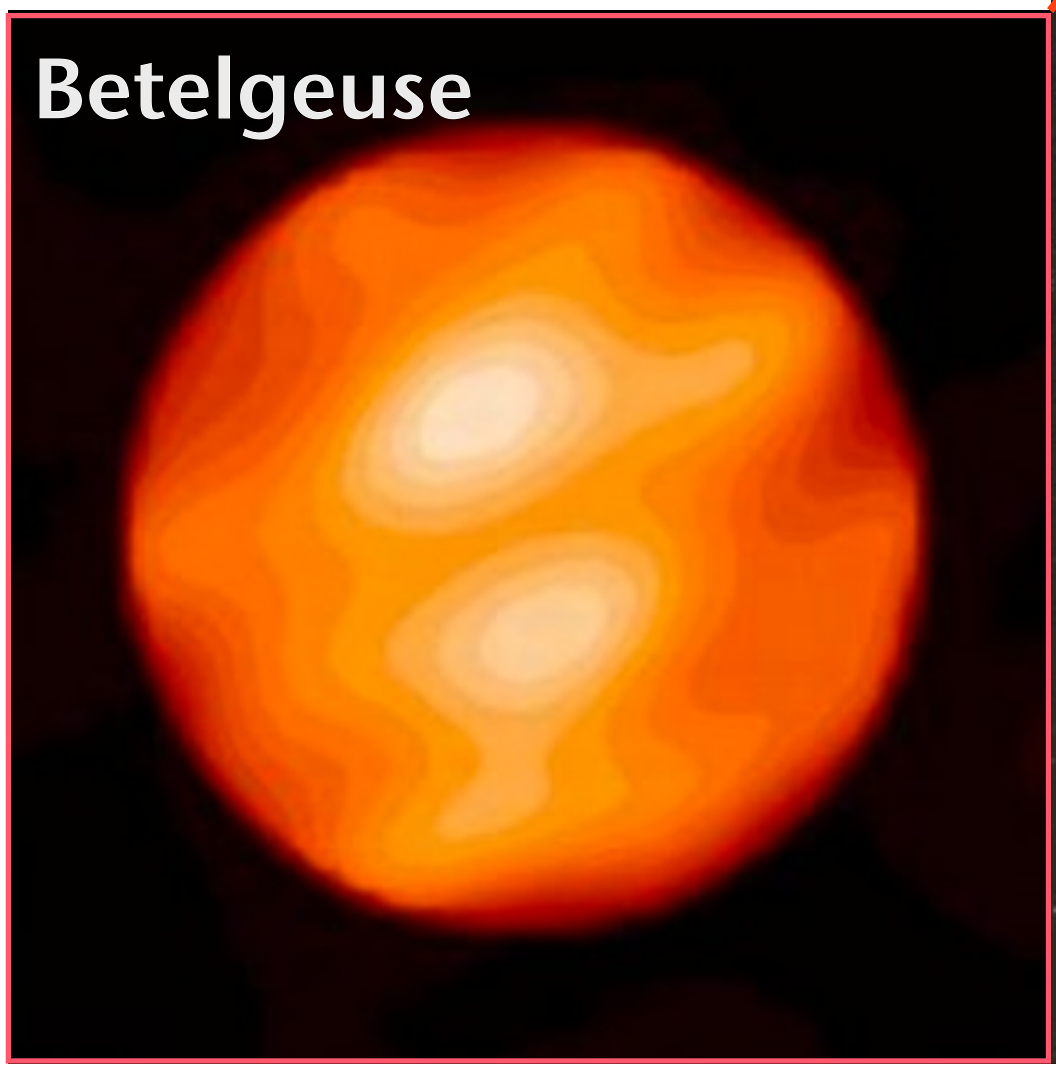
Kato et al., arXiv:1506.02358

Asakura et al., ApJ, 806, 87 (2015)

KEK physics seminar, June 30 (2015)

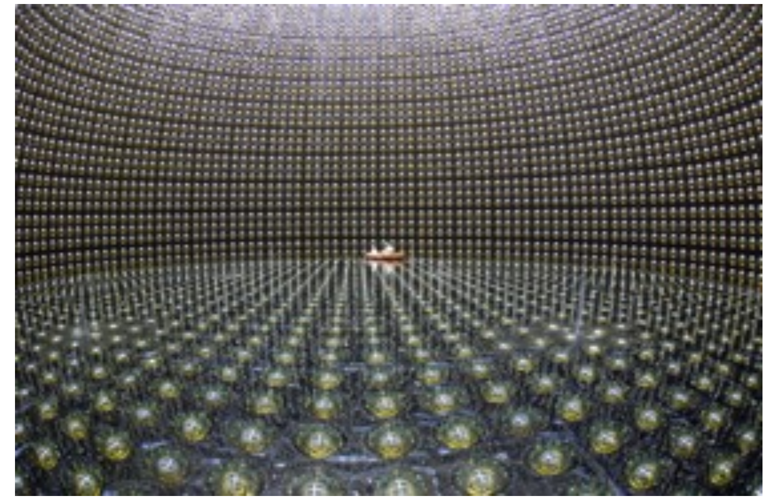
Betelgeuse

- Red-super giant
- Next SN candidate
- ~200pc



First detection

Subaru (optical)



Super-Kamiokande

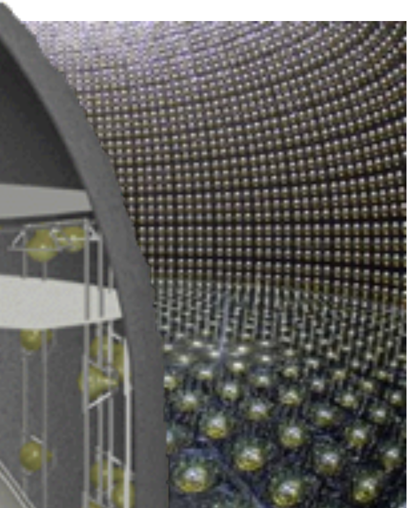
Fermi (gamma-ray)

LIGO (GW)

ALMA (Radio waves)

First detection

Subaru (o



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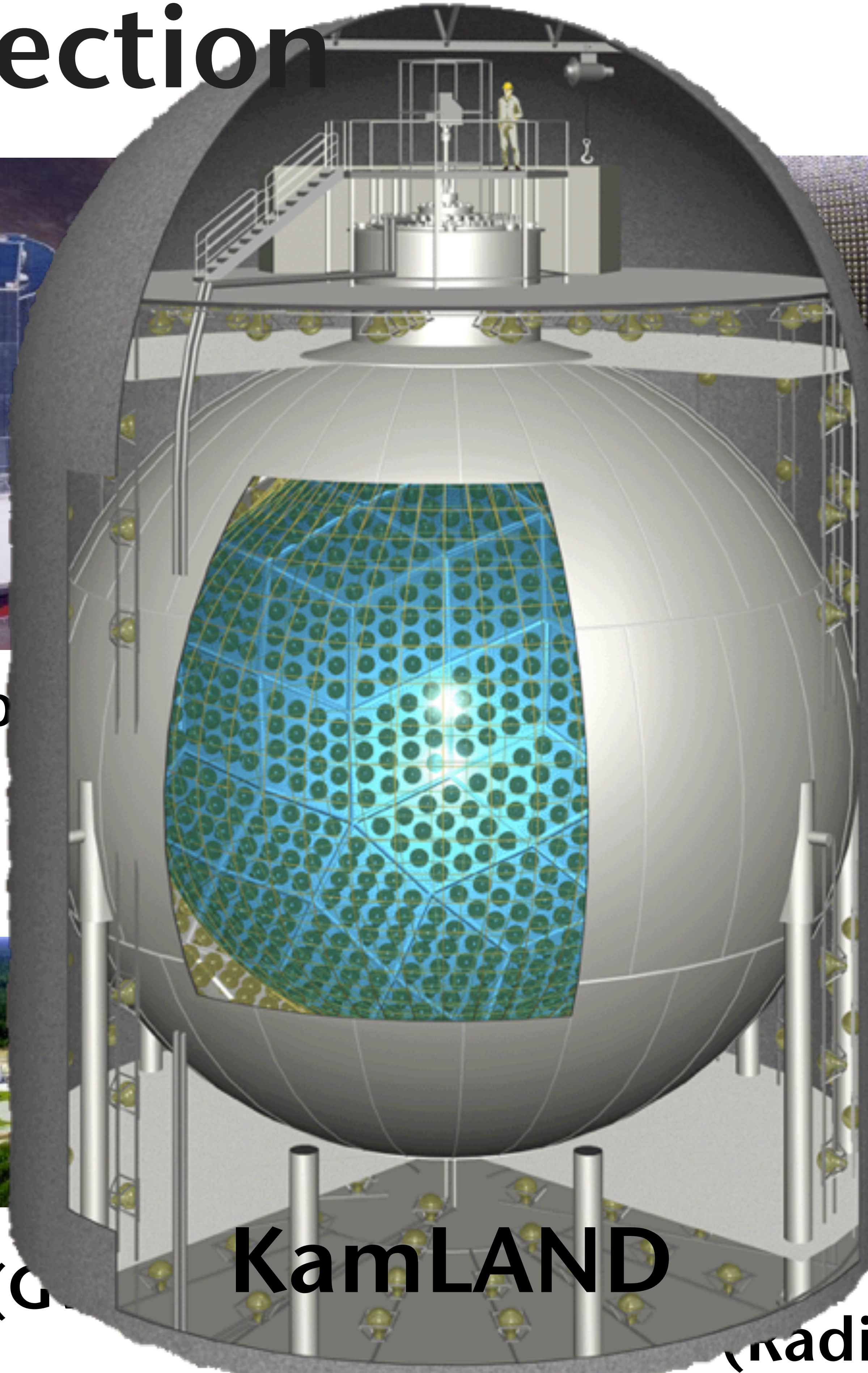
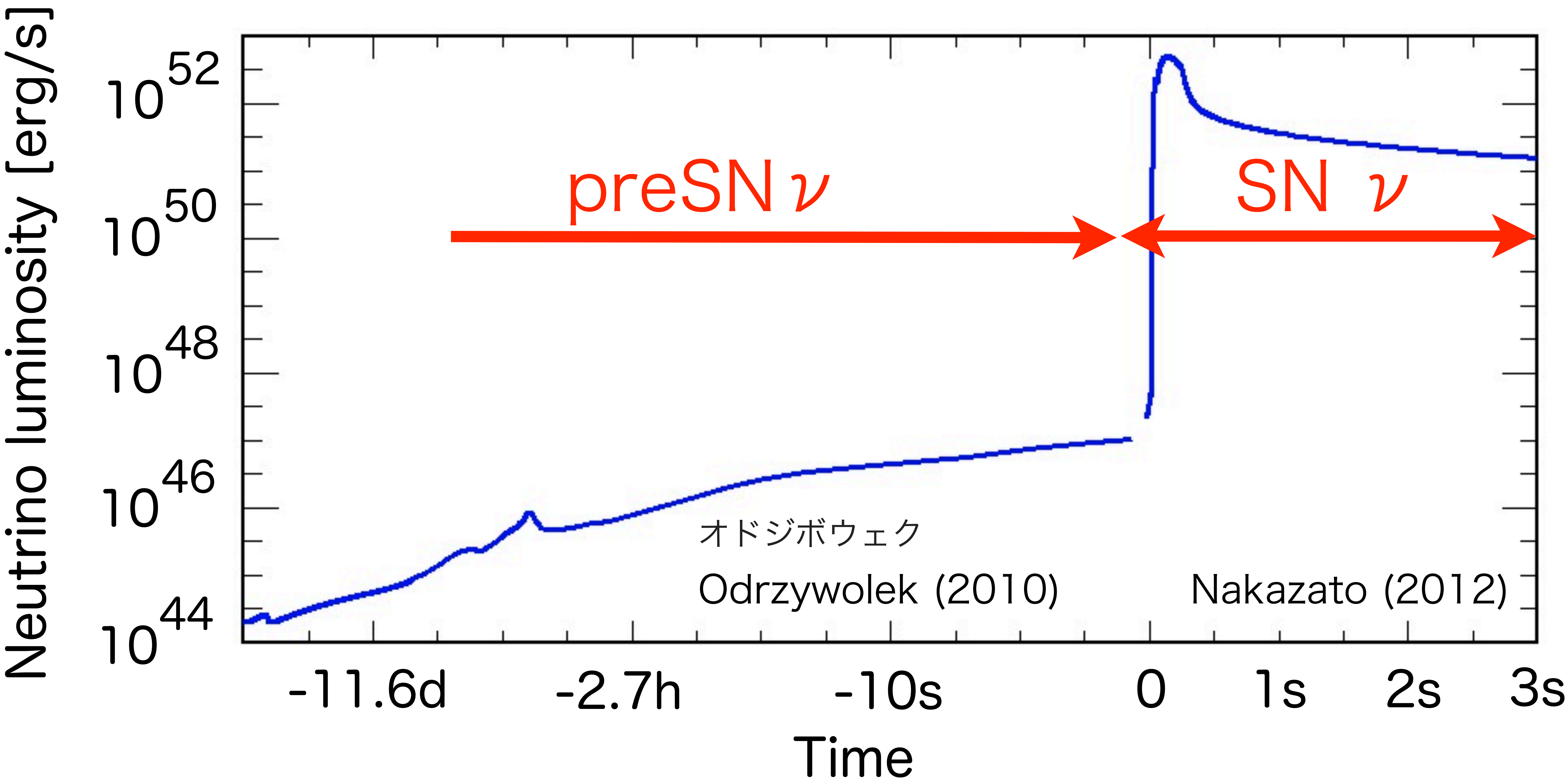
ma-ray)

LIGO (G

(Radio waves)



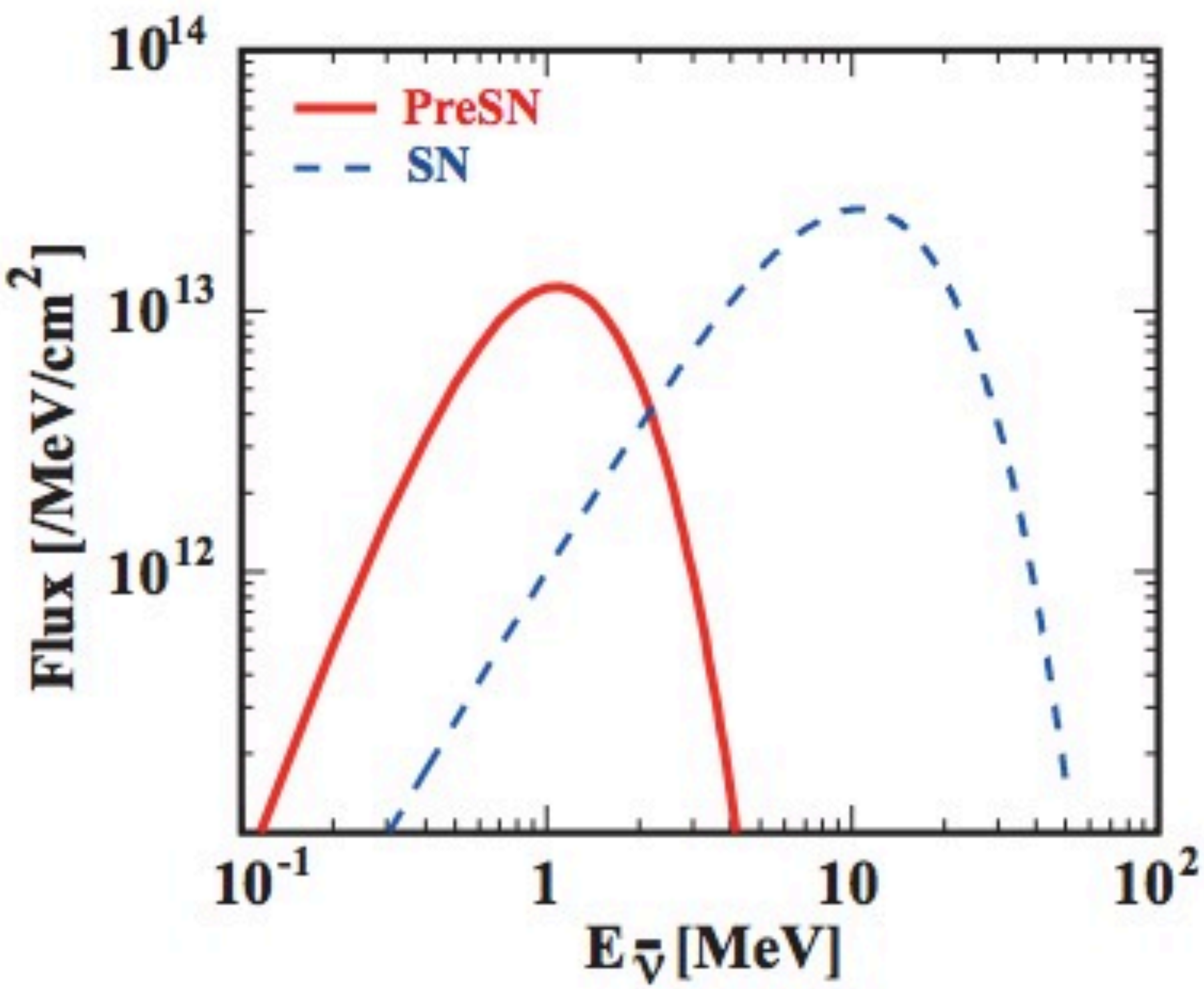
Neutrinos Luminosity



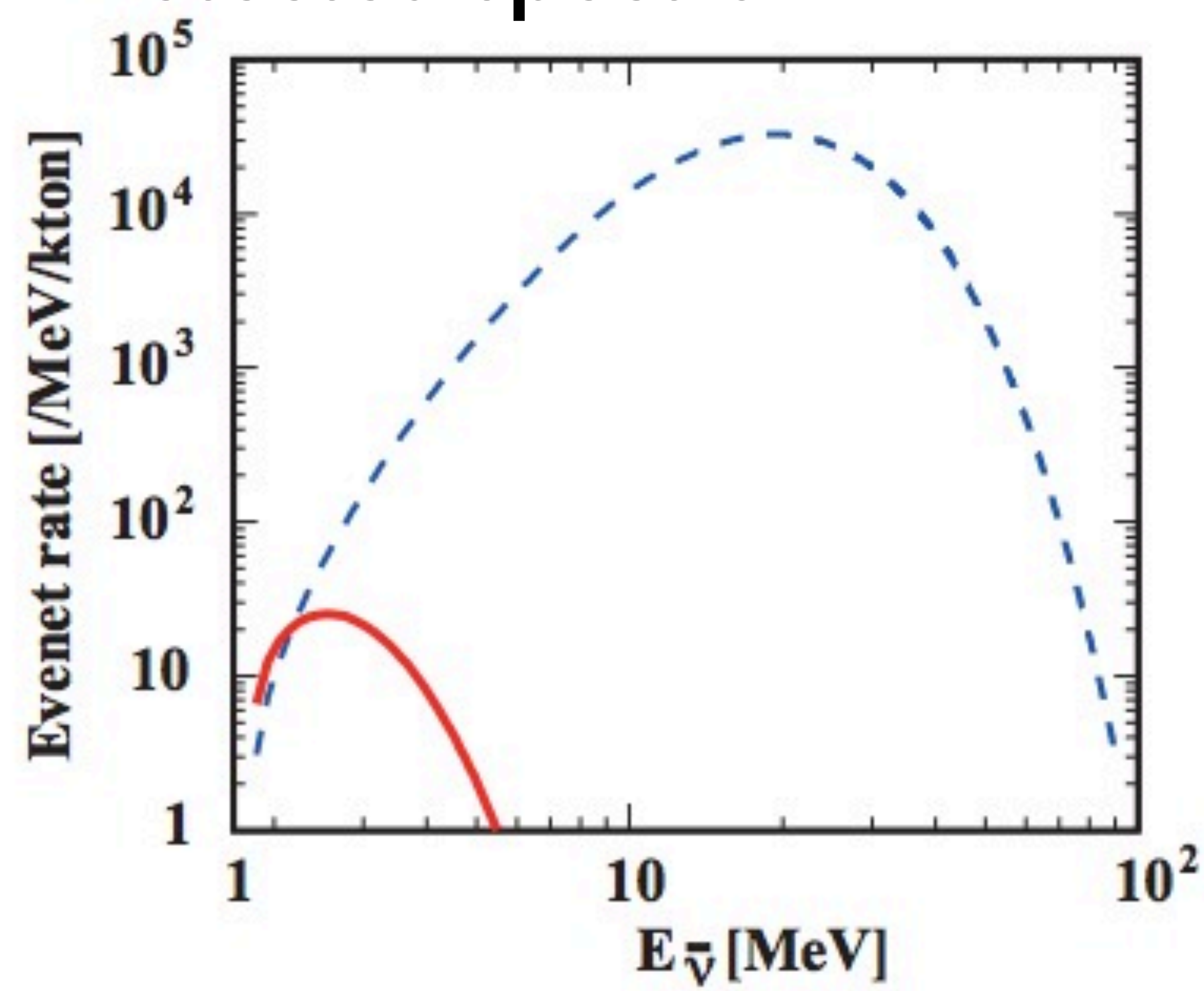
Integrated spectrum on Earth

Assumption: d=200 pc
Integration in the last 48 hours before collapse

Flux



Detected spectrum



New possibility in neutrino astrophysics

Topics

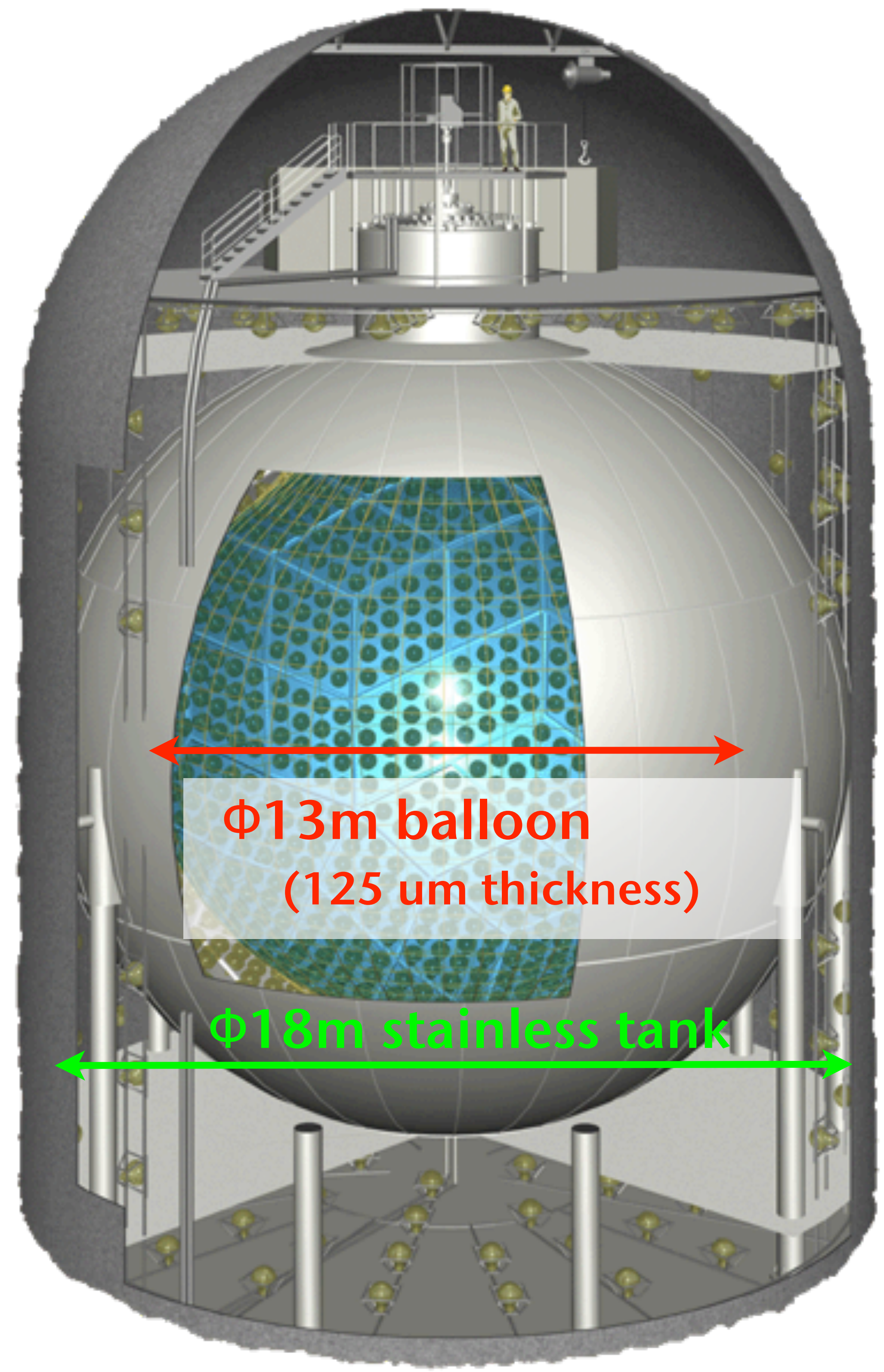
- PreSN neutrinos
- Neutrinos from GRBs

KamLAND

KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector (since 2002)

- 1,000 m depth (Kamioka mine)
- 1,000 t liquid scintillator
  Dodecan (80%), Psedocumene (20%), PPO (1.36g/l)
- 1,325 17inch + 554 20inch PMTs

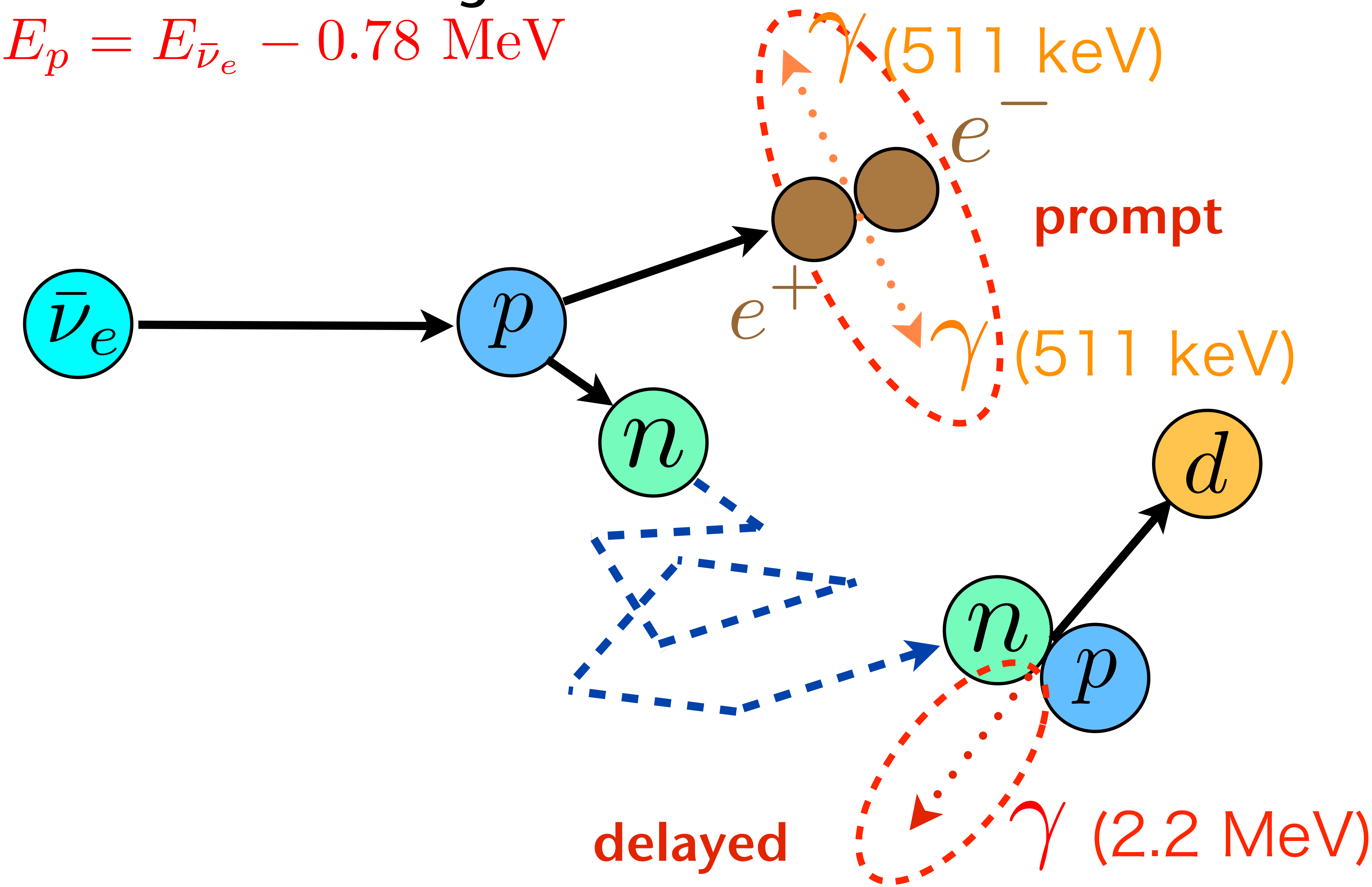


Outer detector (for muon veto)
- 3.2kton water cherenkov detector
- ~100 20inch PMTs

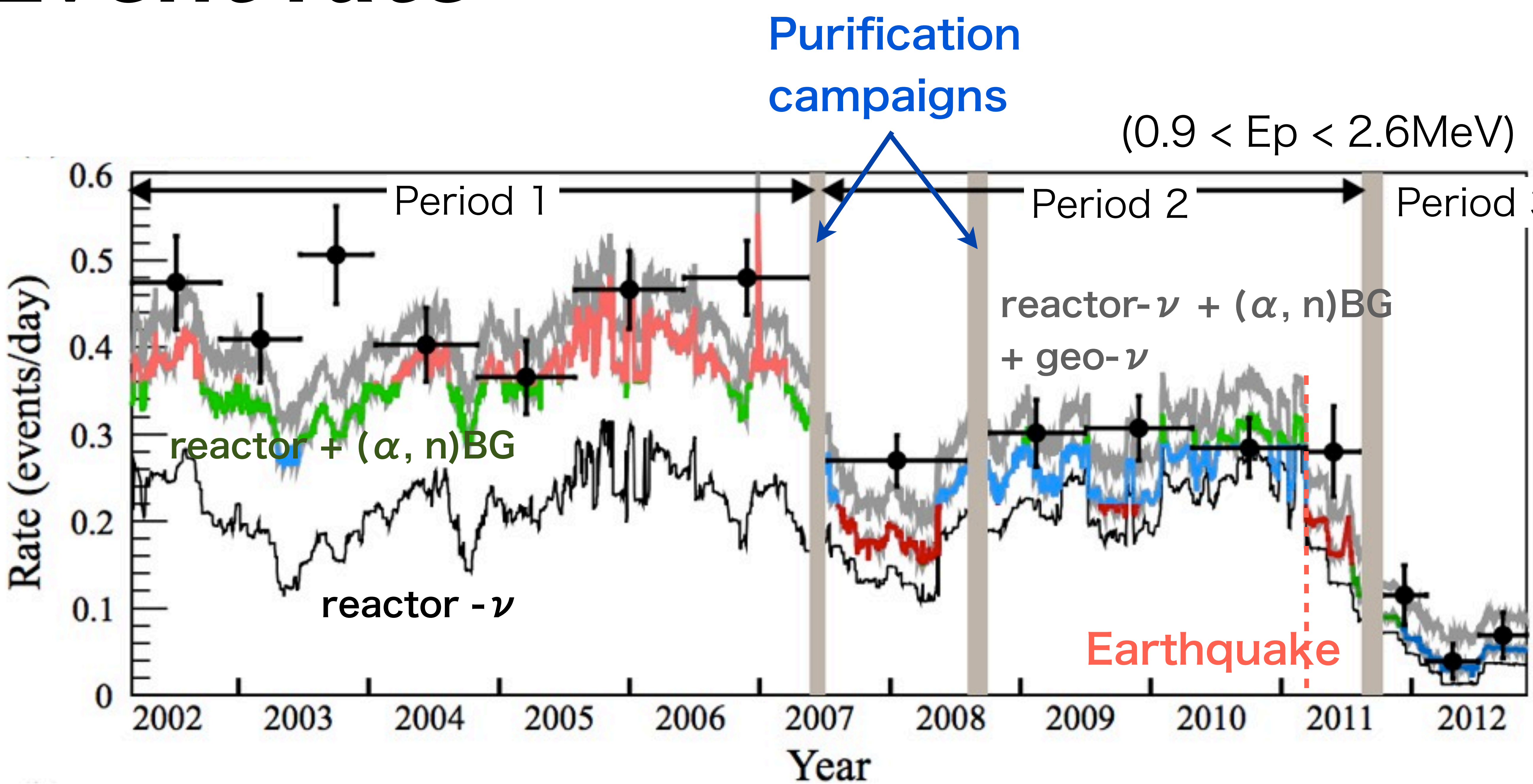
Anti-neutrino detection

Inverse-beta decay: delayed coincidence measurement

- **time-spatial correlated events**
- **Reduction of background events**
- $E_p = E_{\bar{\nu}_e} - 0.78\ \mathrm{MeV}$



Event rate



History of background

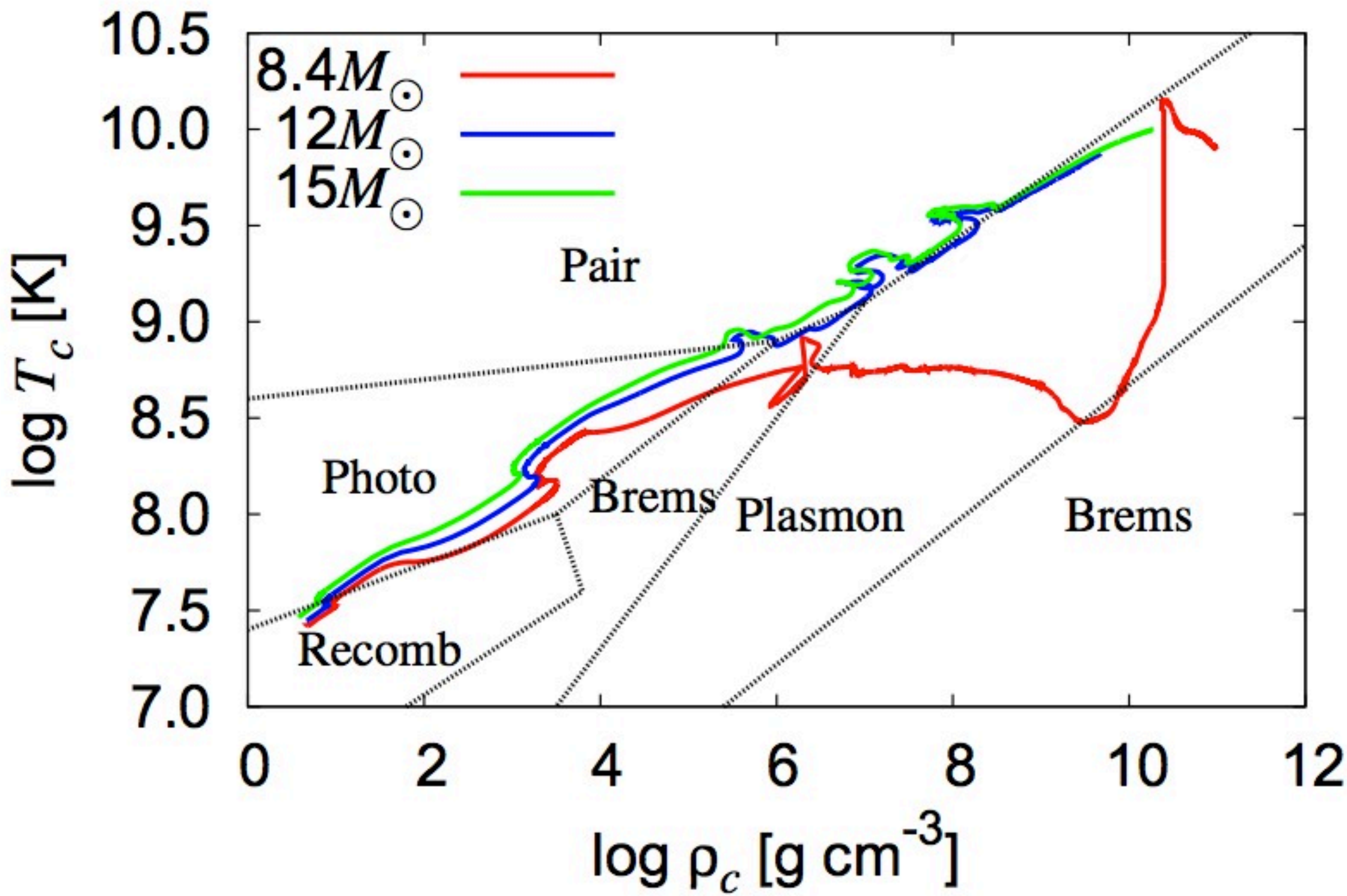
- Non-neutrino backgrounds were decreased after purification campaigns.
- Reactor neutrinos were significantly decreased after the earthquake.

Pre-supernova neutrinos

Pre-supernova stars

Neutrino cooling in the stellar evolution

C. Kato et al., arXiv:1506.02358



Pre-supernova stars

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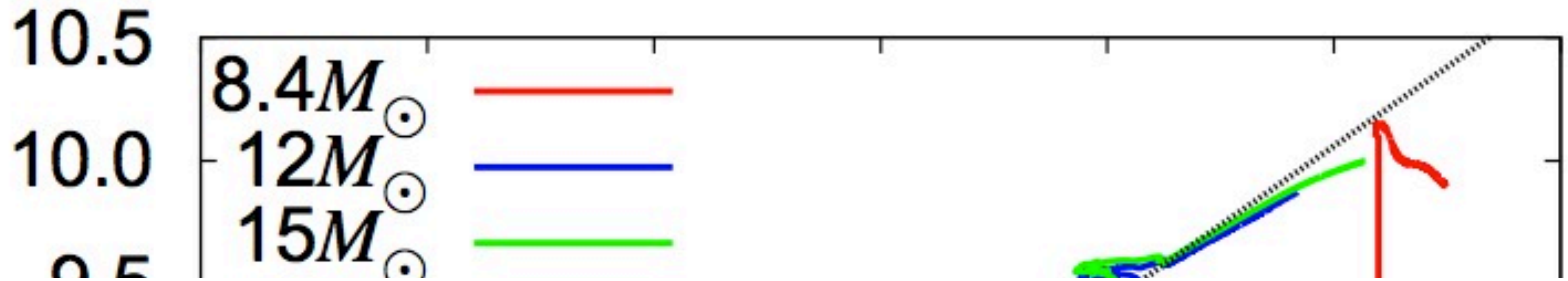
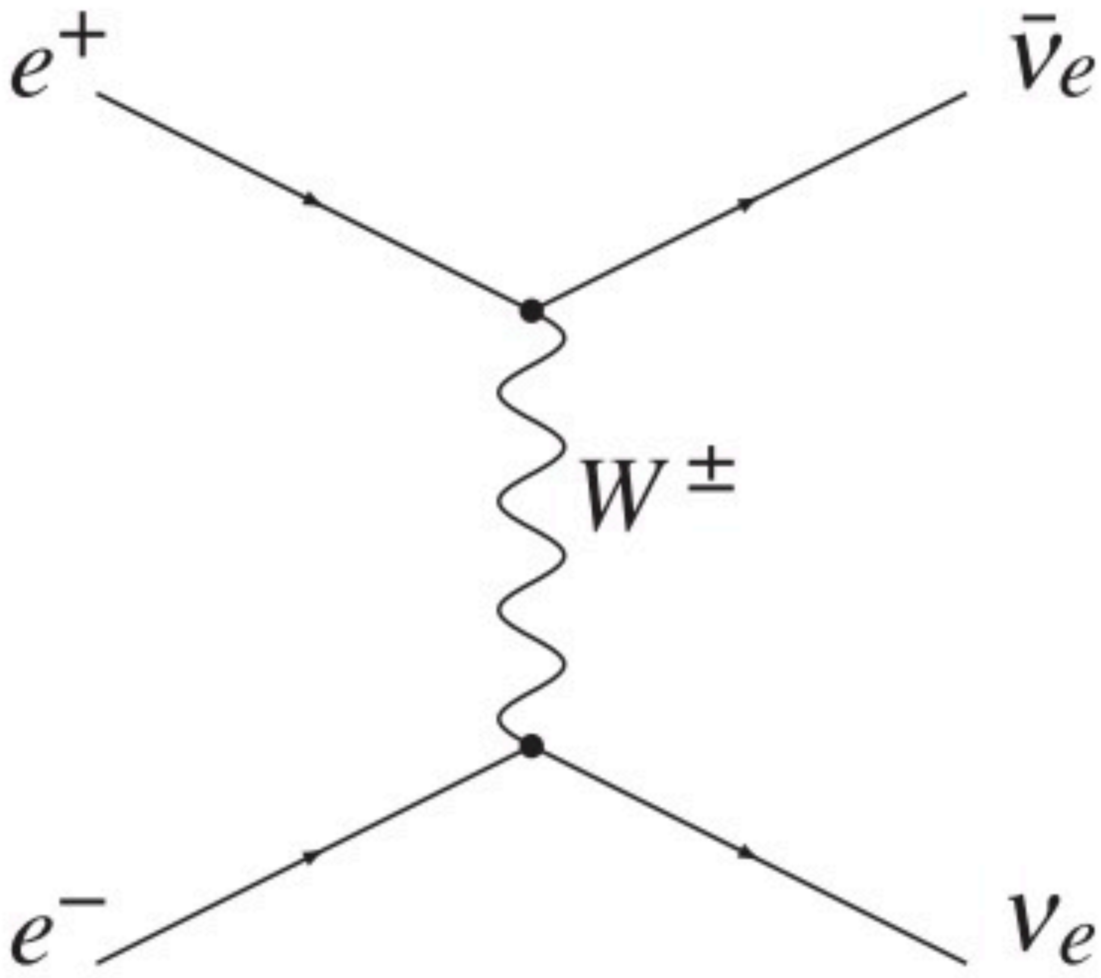
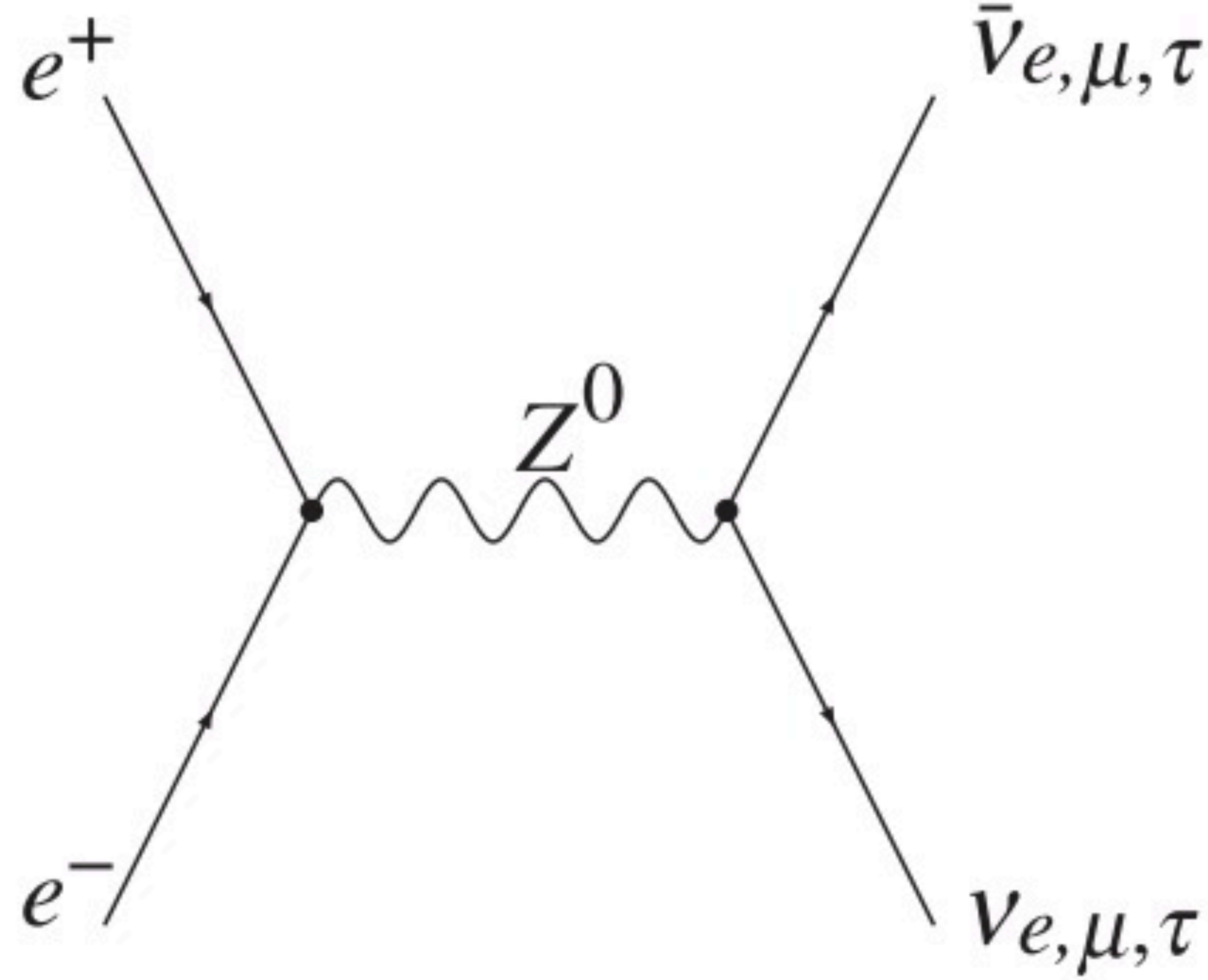
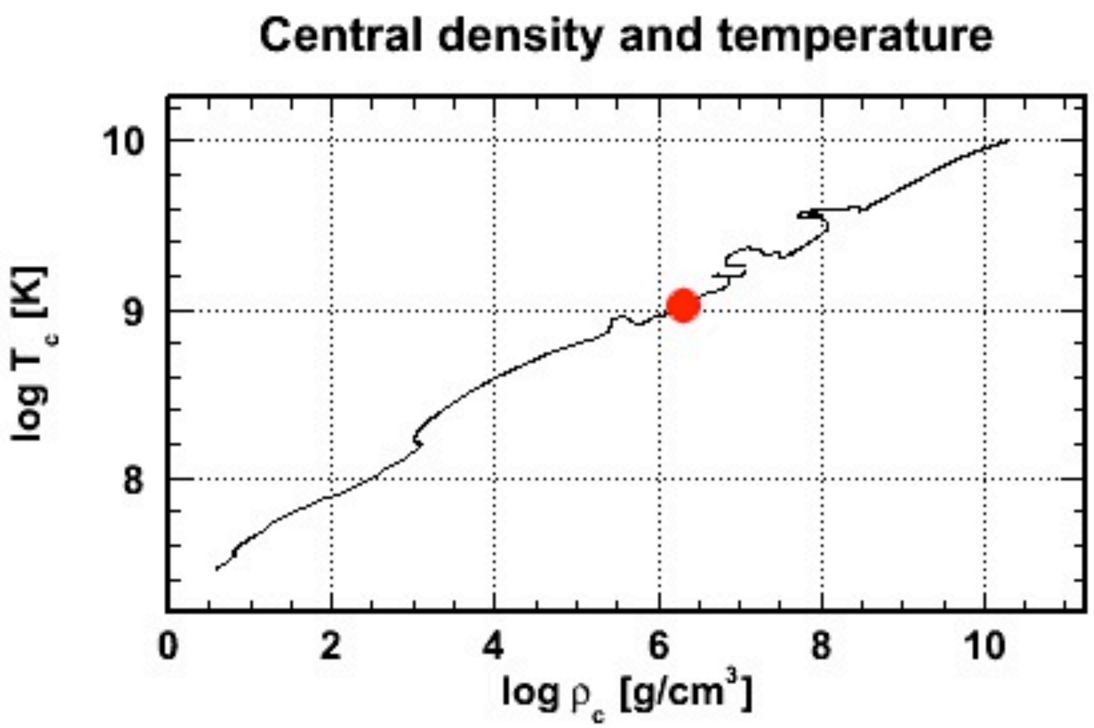


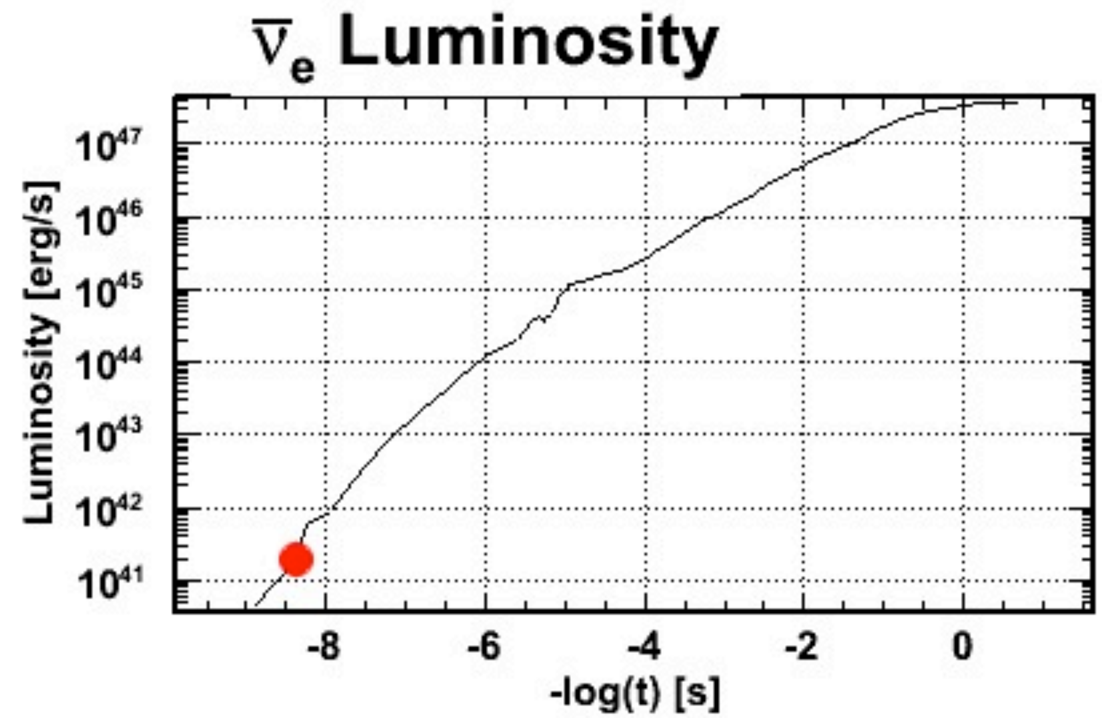


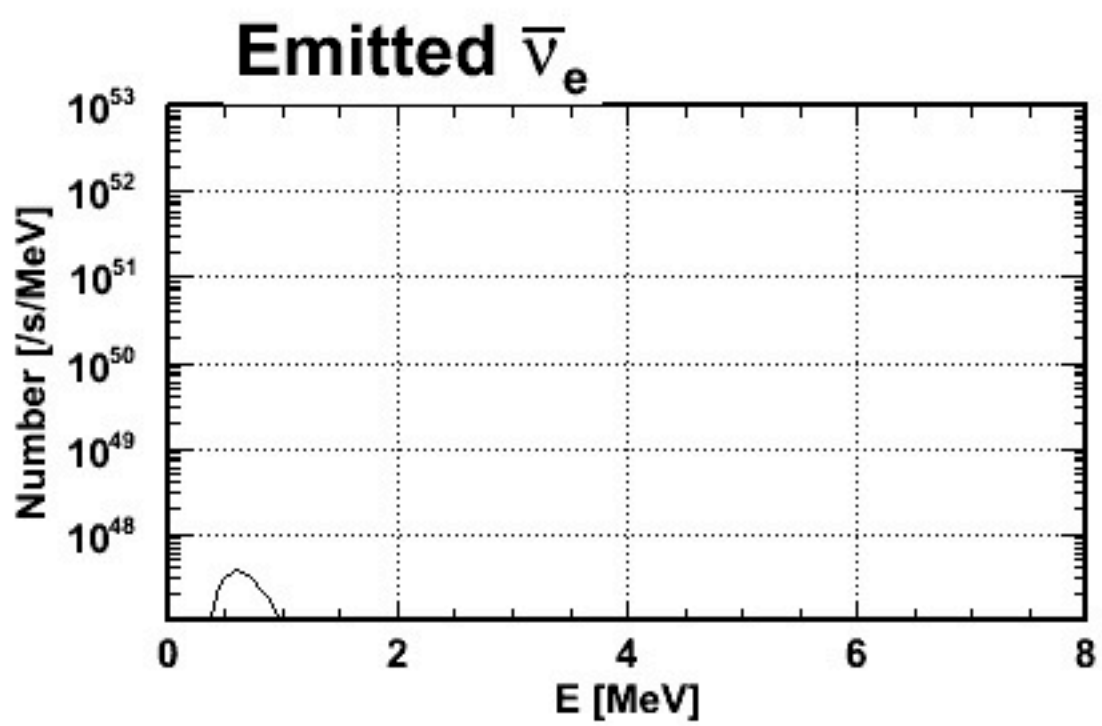


Several snapshots (15Msun)

C. Kato et al., arXiv:1506.02358



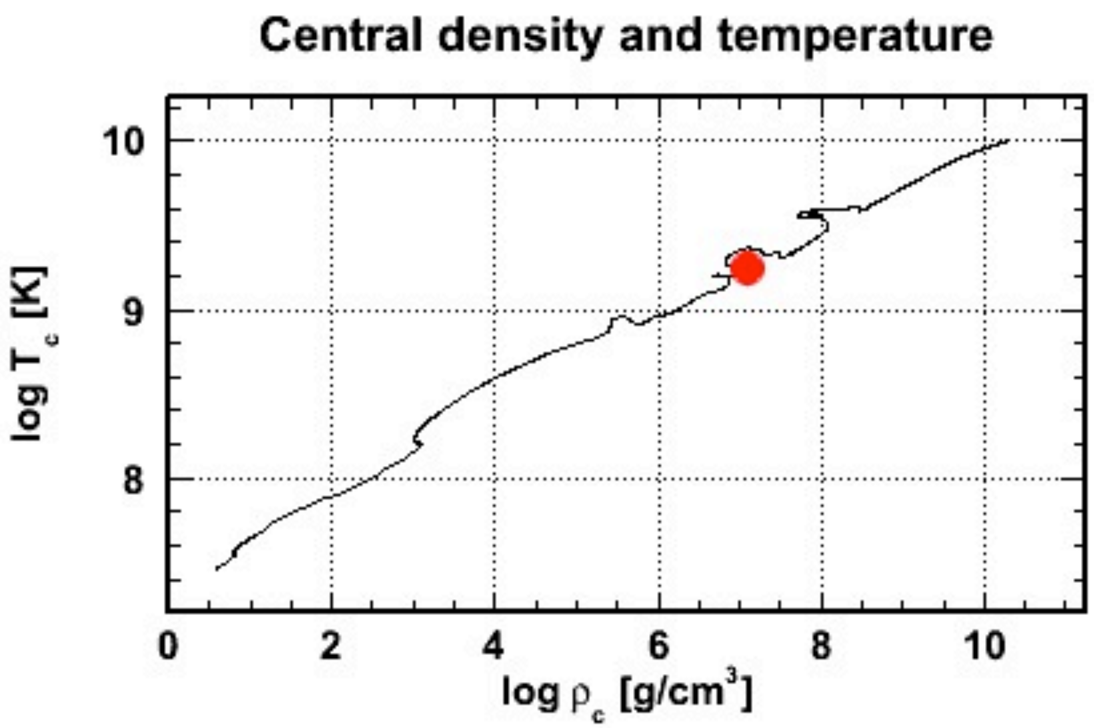


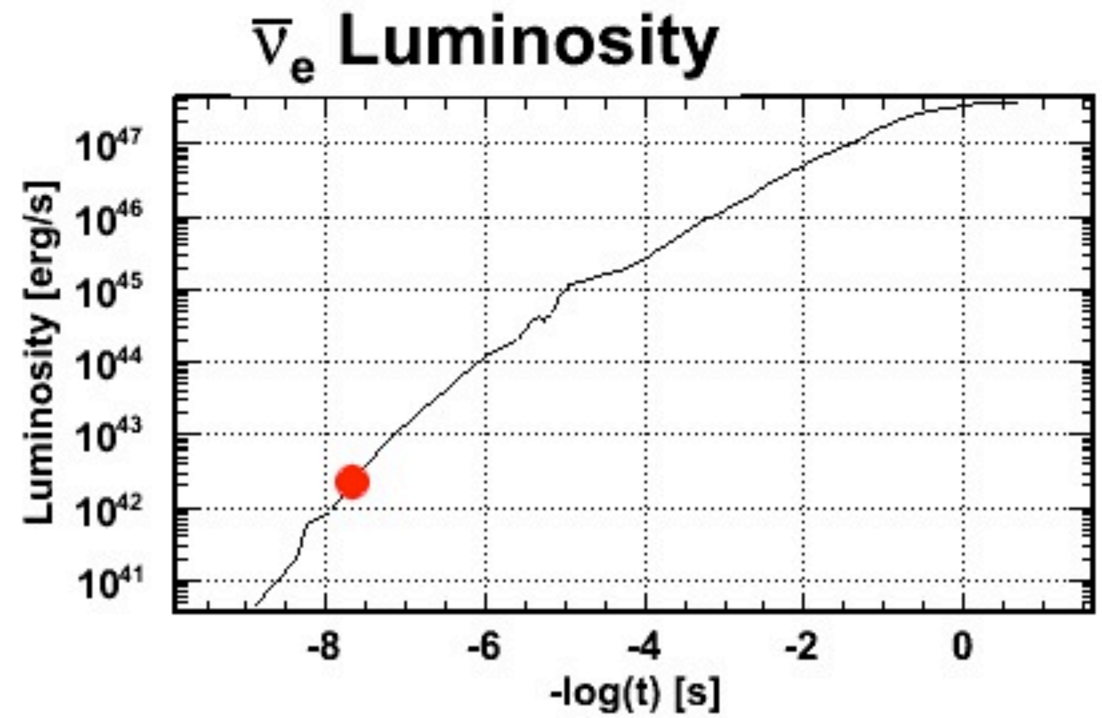


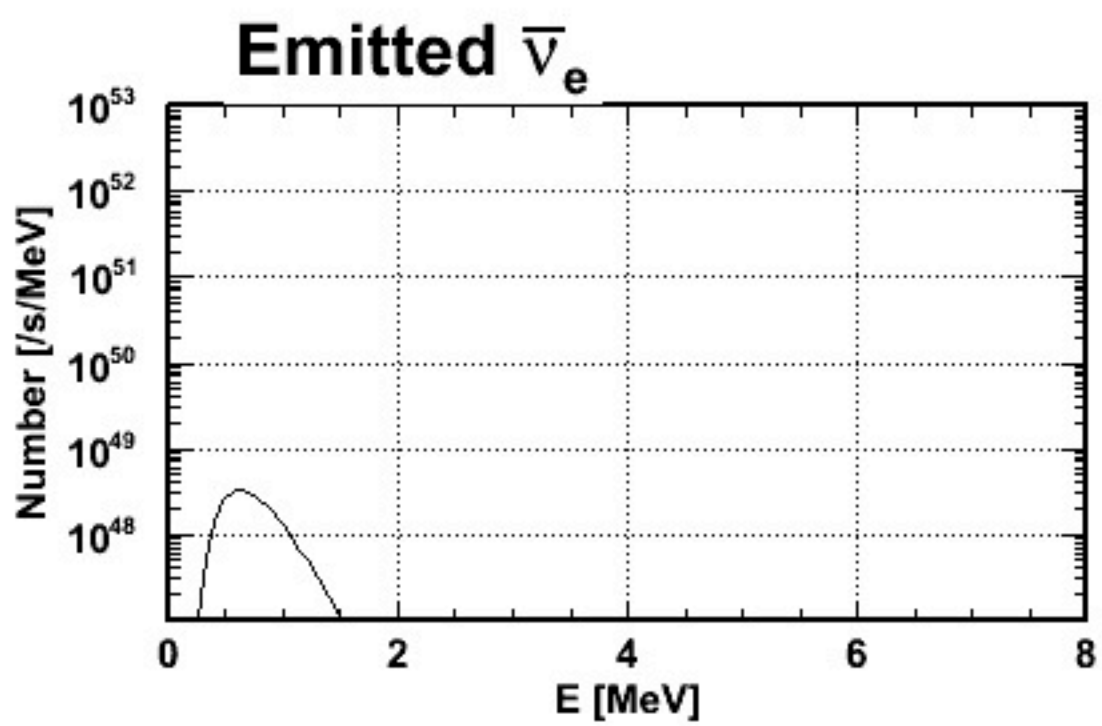
Time to collapse: 7.68 yr

Several snapshots (15Msun)

C. Kato et al., arXiv:1506.02358



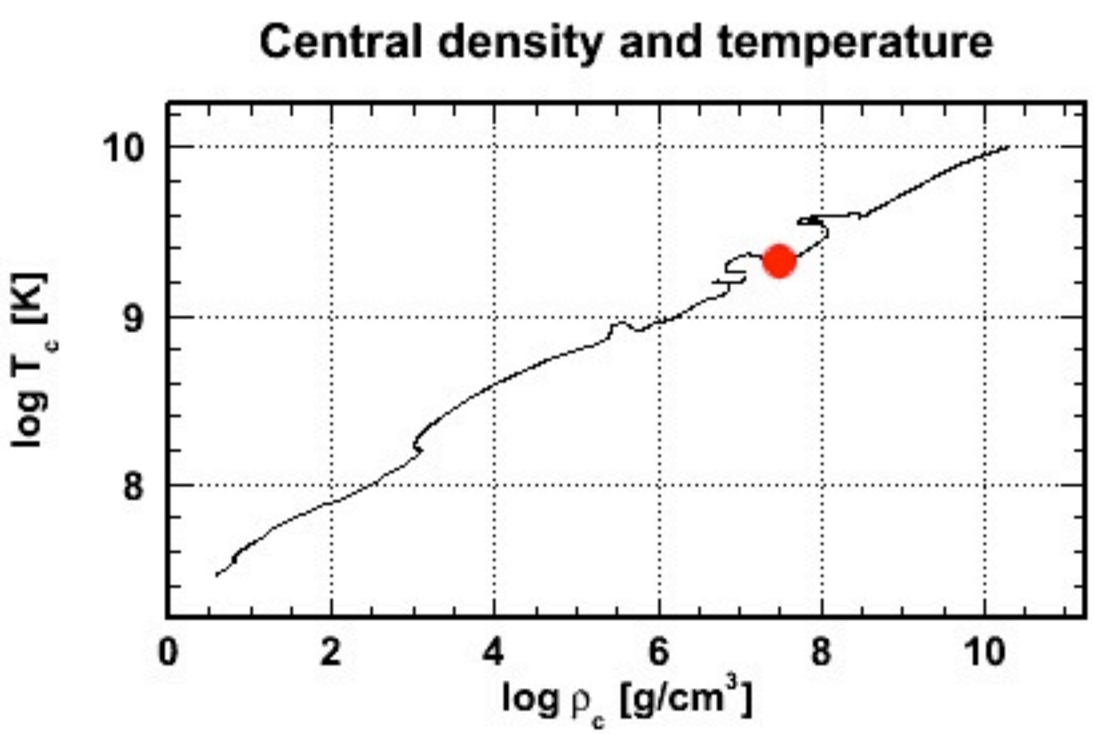


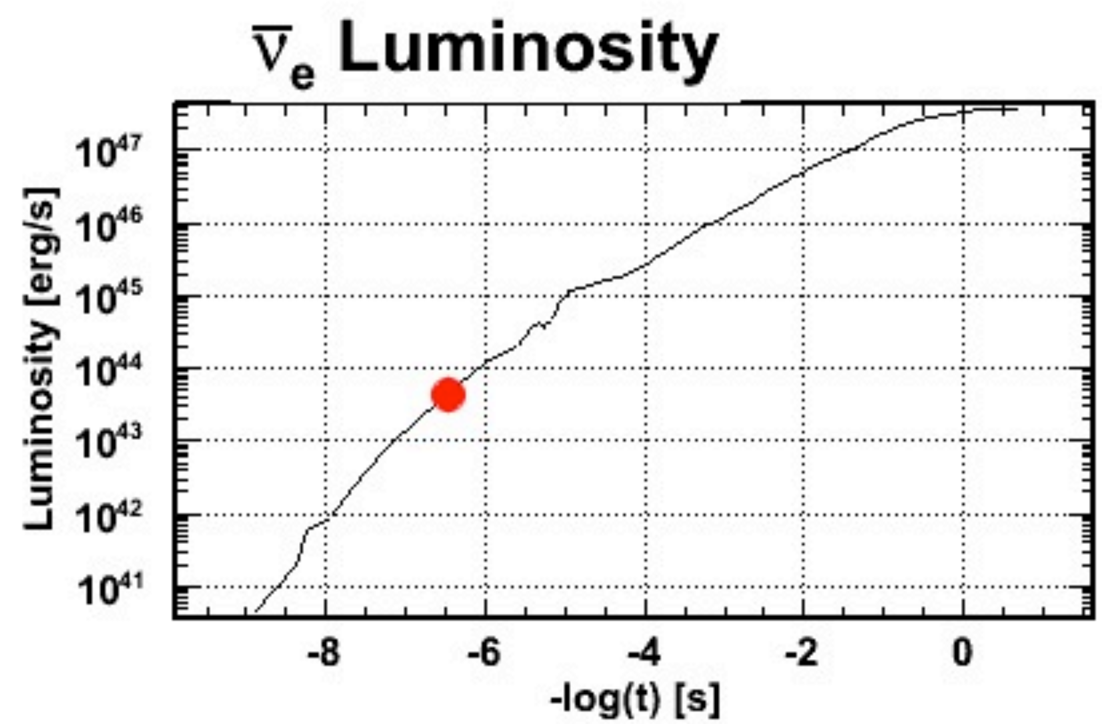


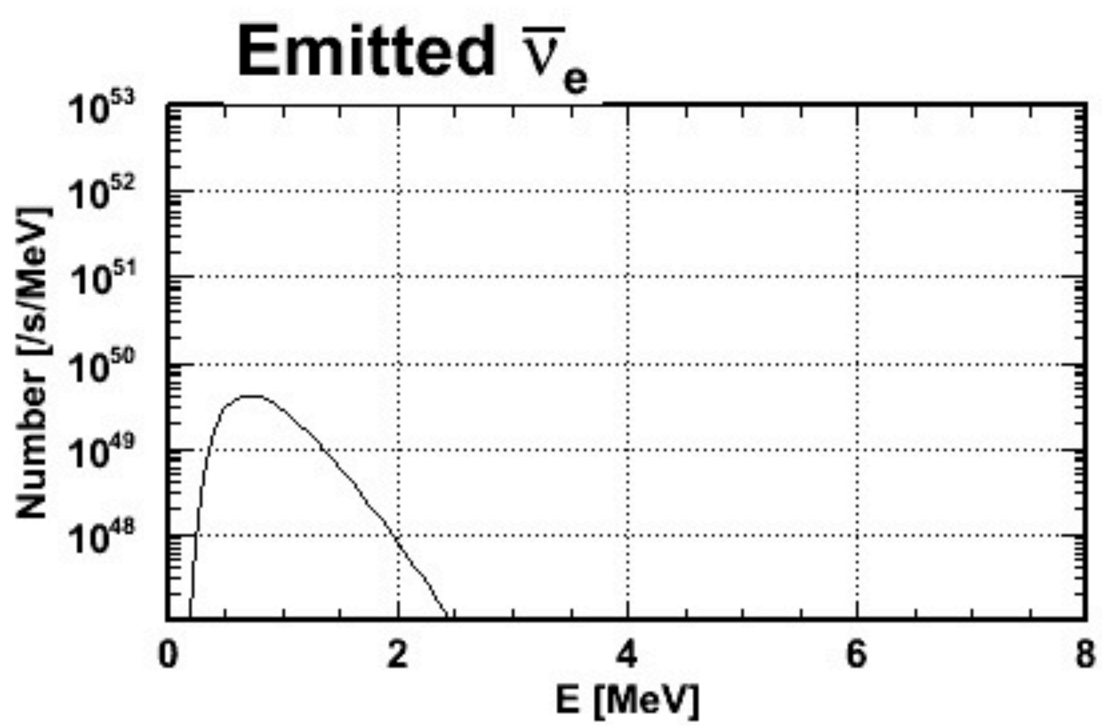
Time to collapse: 1.45 yr

Several snapshots (15Msun)

C. Kato et al., arXiv:1506.02358



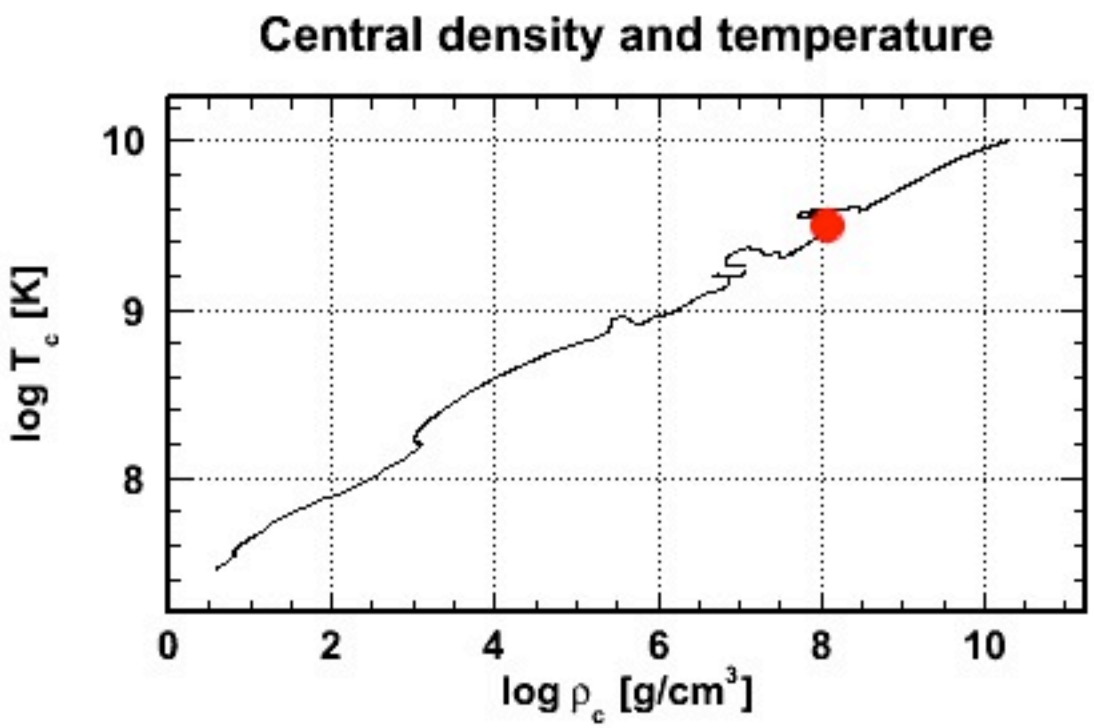


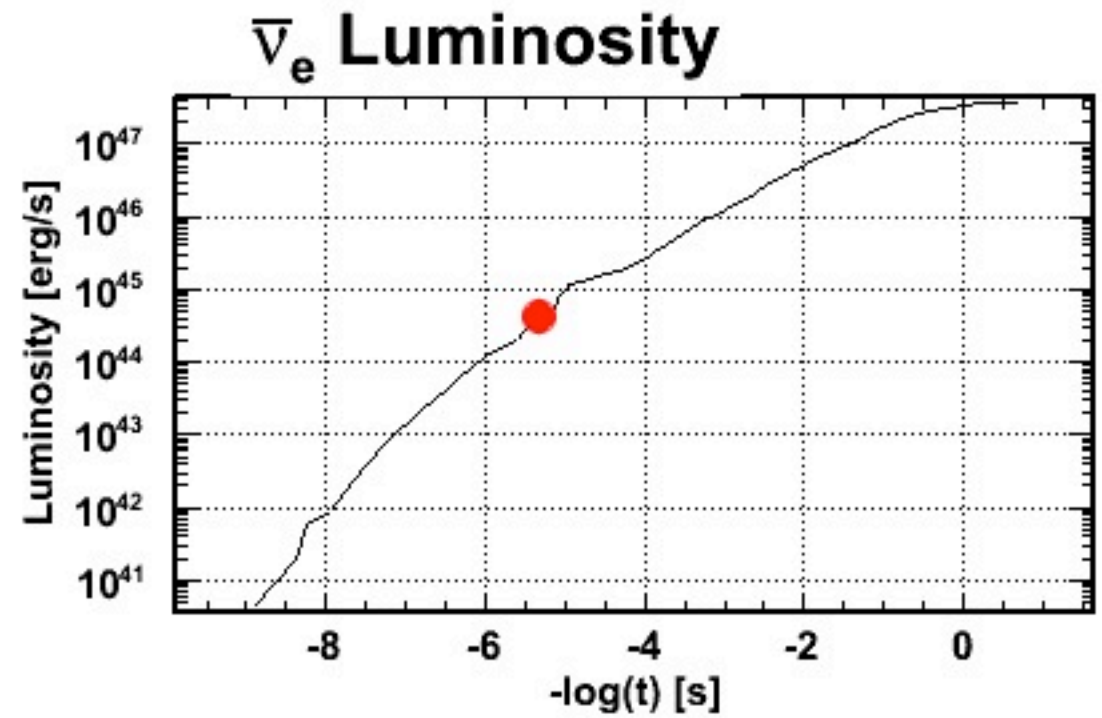


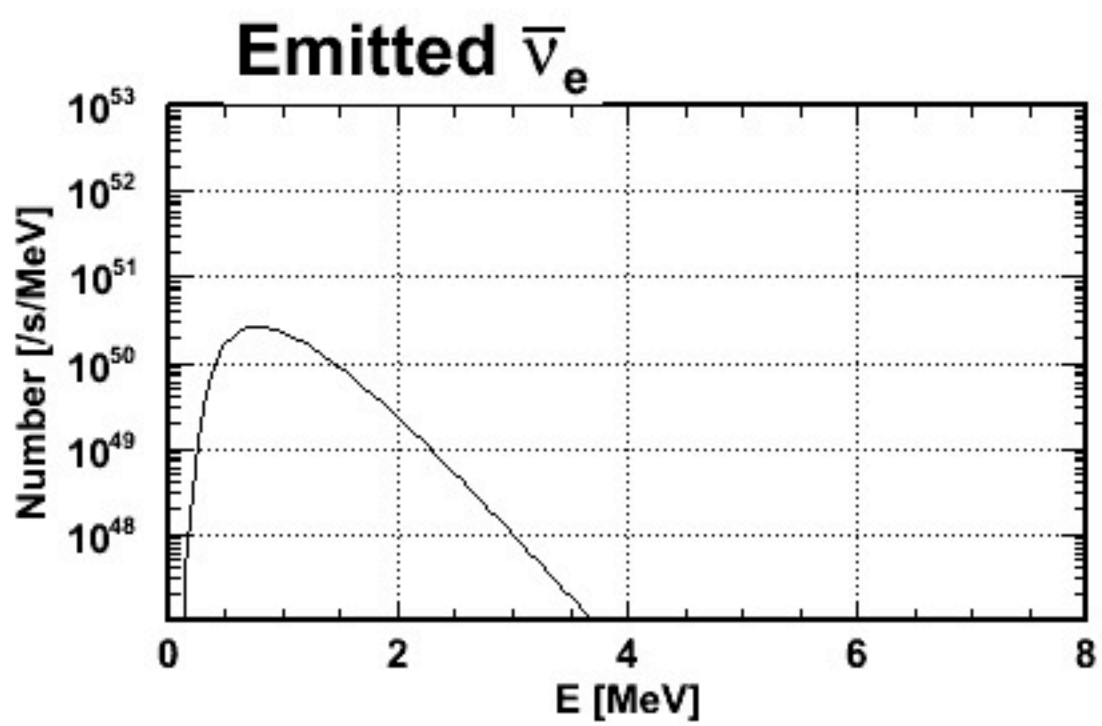
Time to collapse: 35.12 day

Several snapshots (15Msun)

C. Kato et al., arXiv:1506.02358



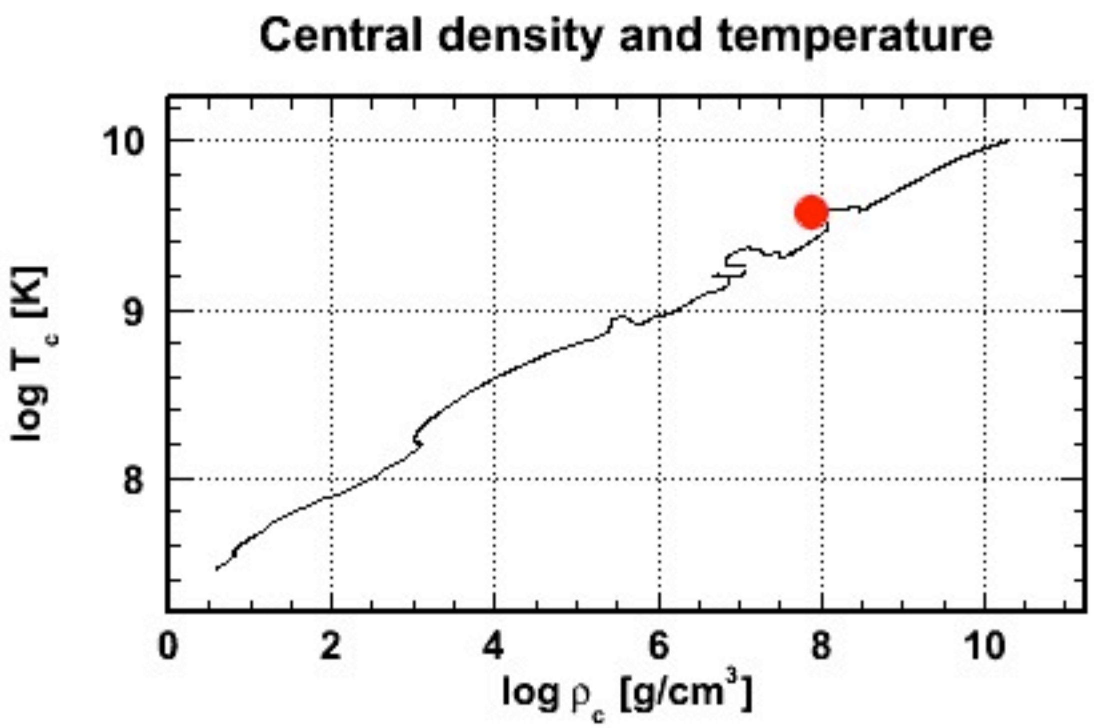


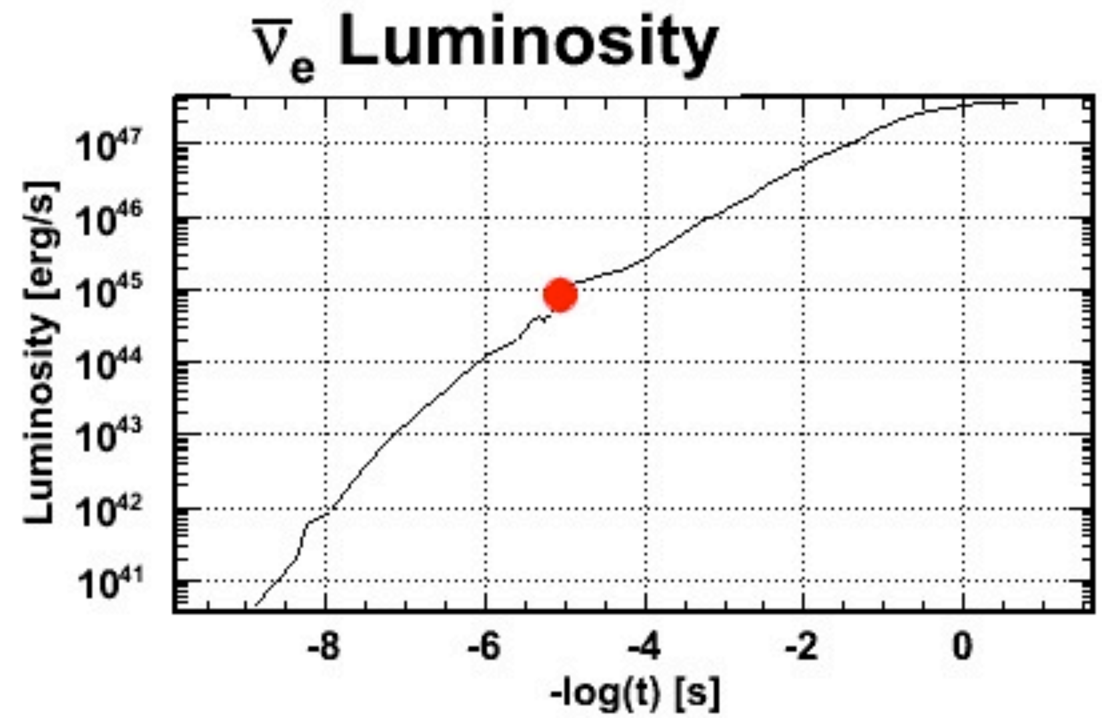


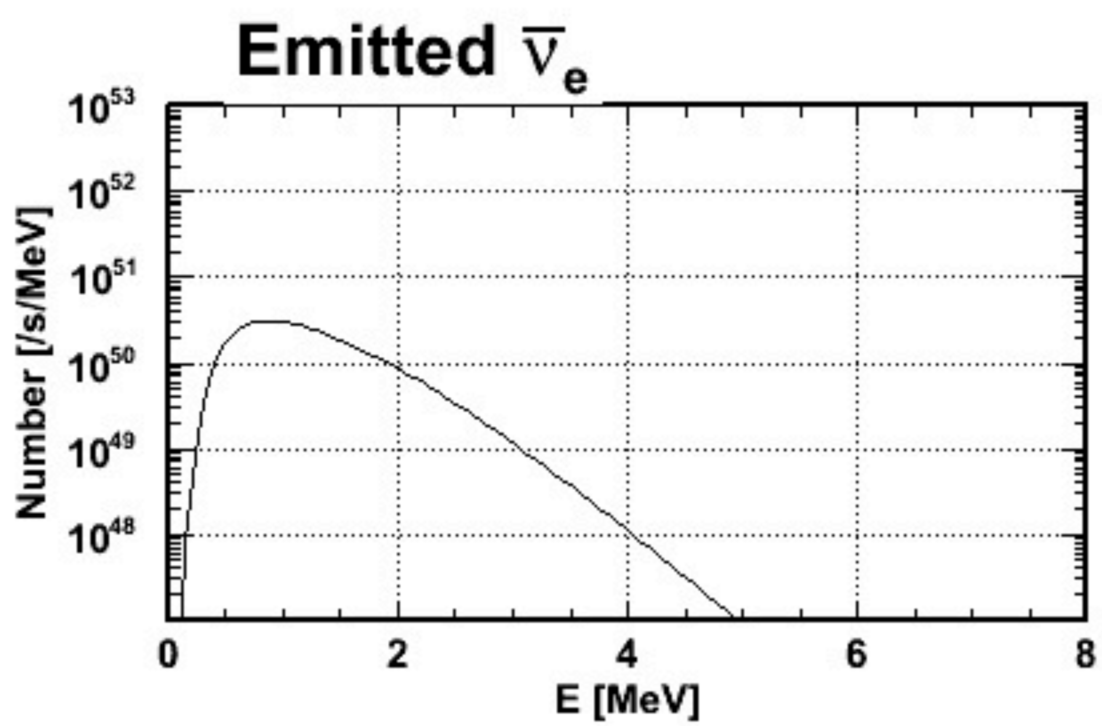
Time to collapse: 2.43 day

Several snapshots (15Msun)

C. Kato et al., arXiv:1506.02358



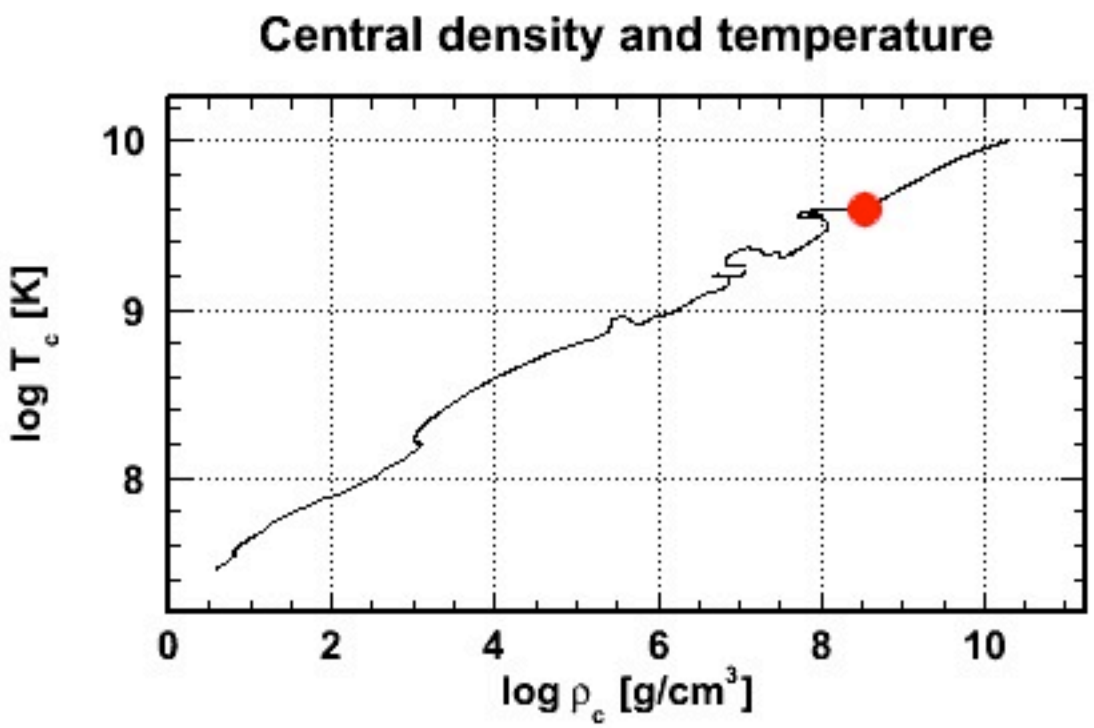


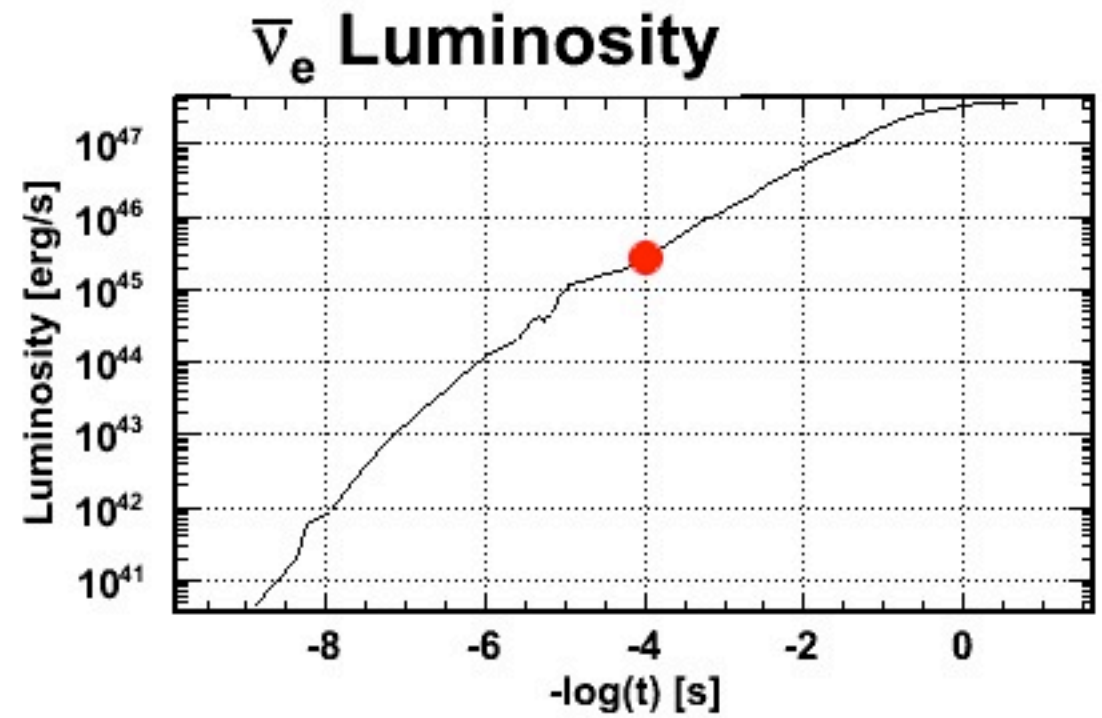


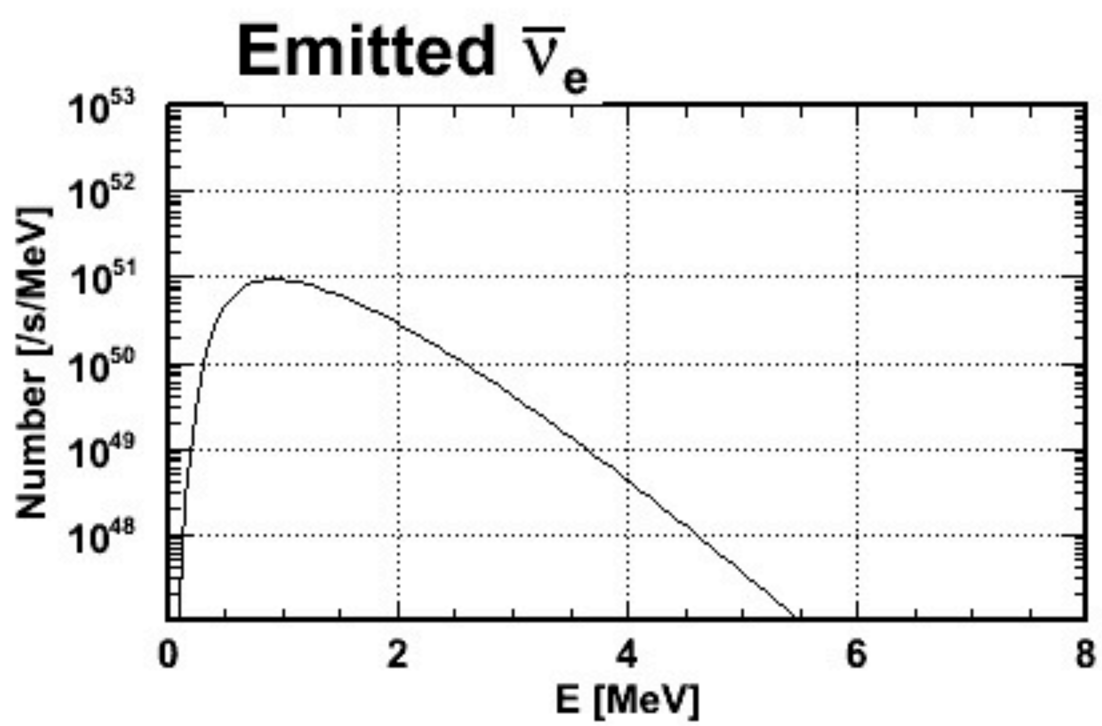
Time to collapse: 1.29 day

Several snapshots (15Msun)

C. Kato et al., arXiv:1506.02358



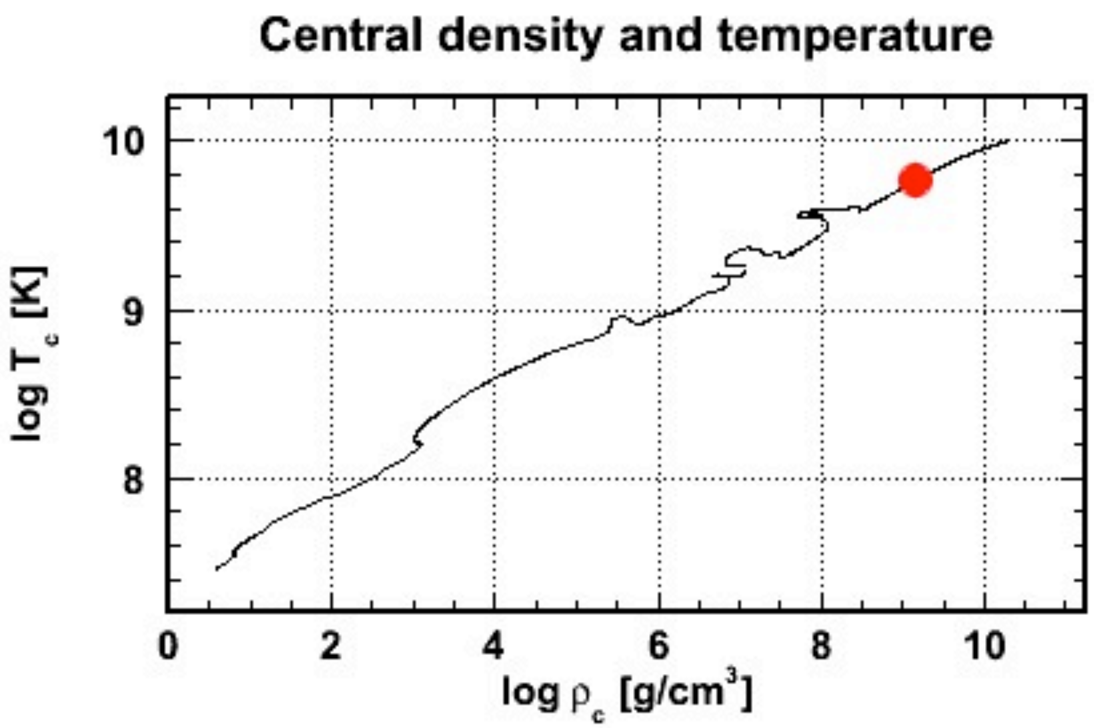


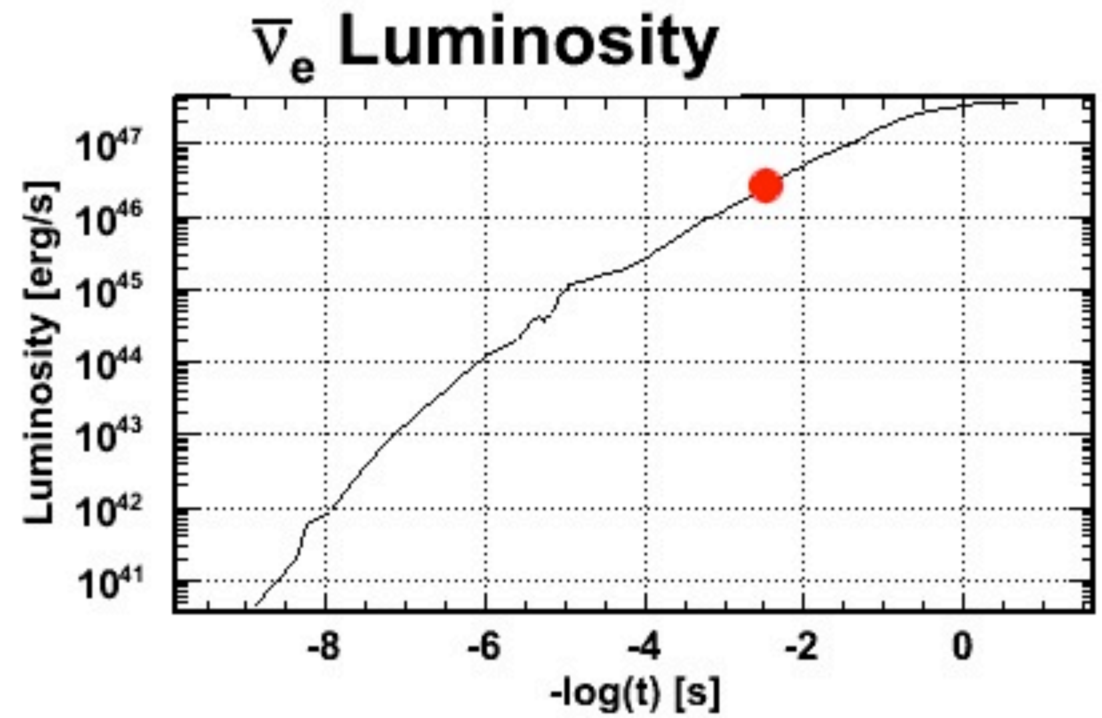


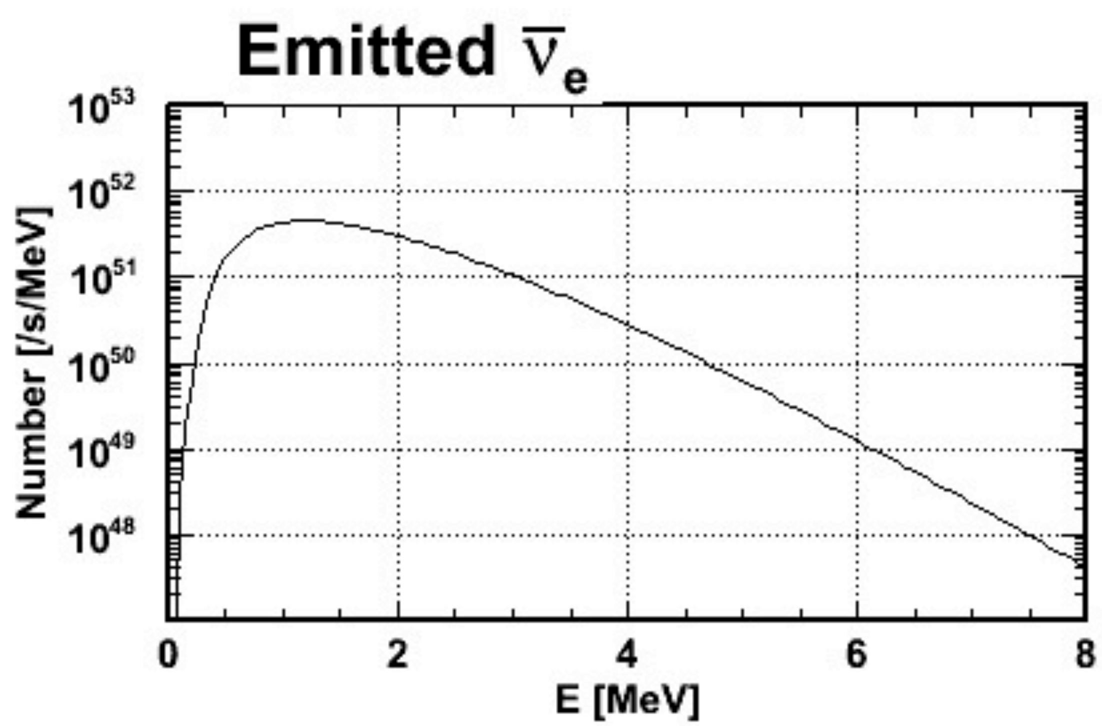
Time to collapse: 2.74 hr

Several snapshots (15Msun)

C. Kato et al., arXiv:1506.02358



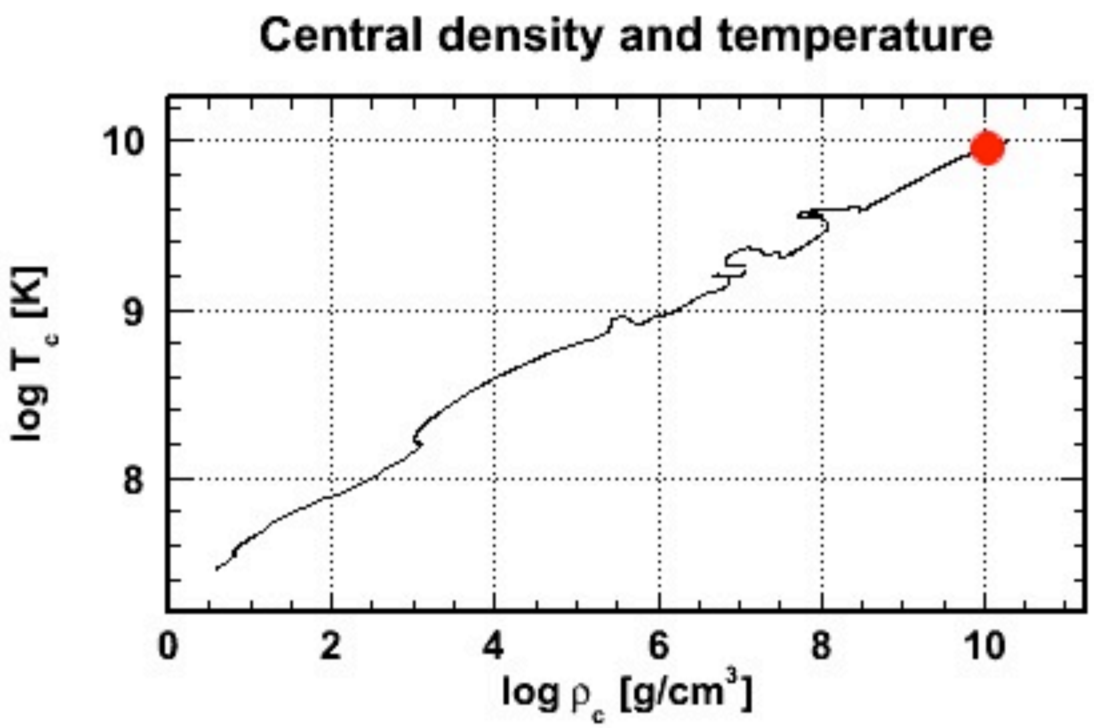


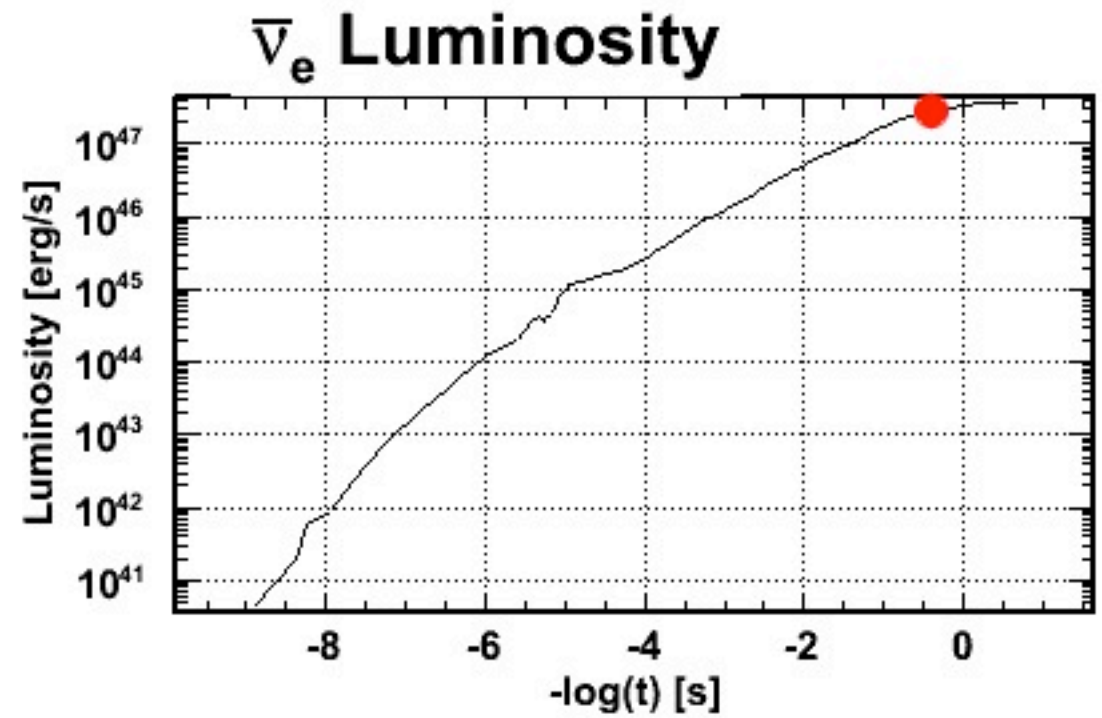


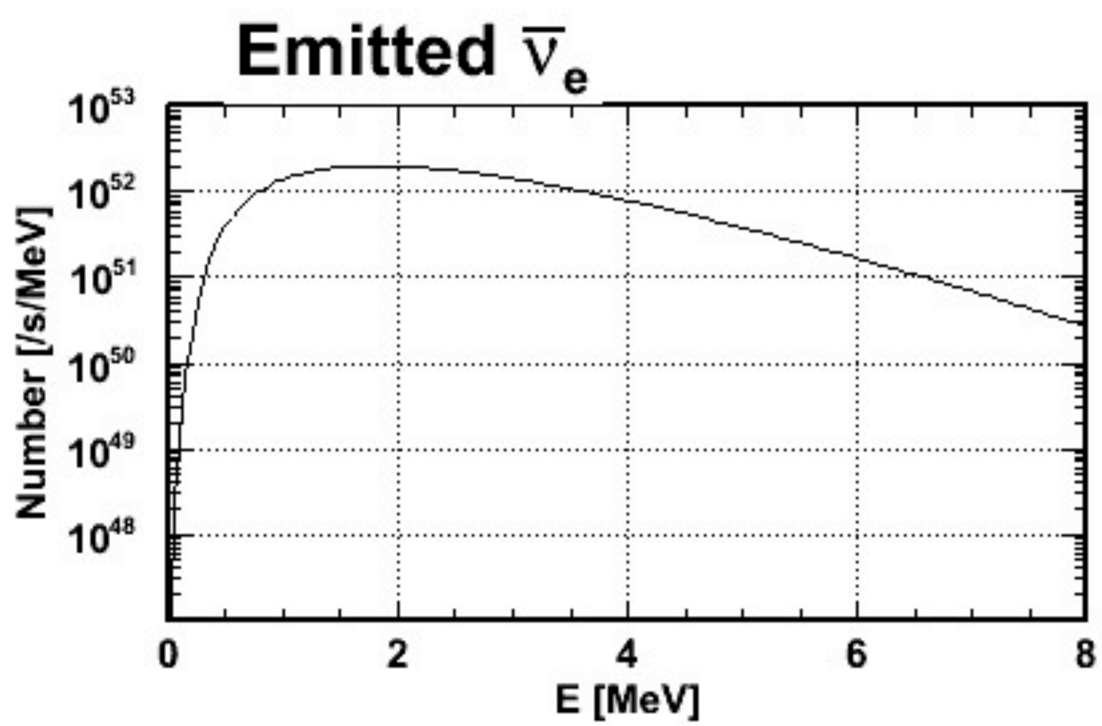
Time to collapse: 4.94 min

Several snapshots (15Msun)

C. Kato et al., arXiv:1506.02358



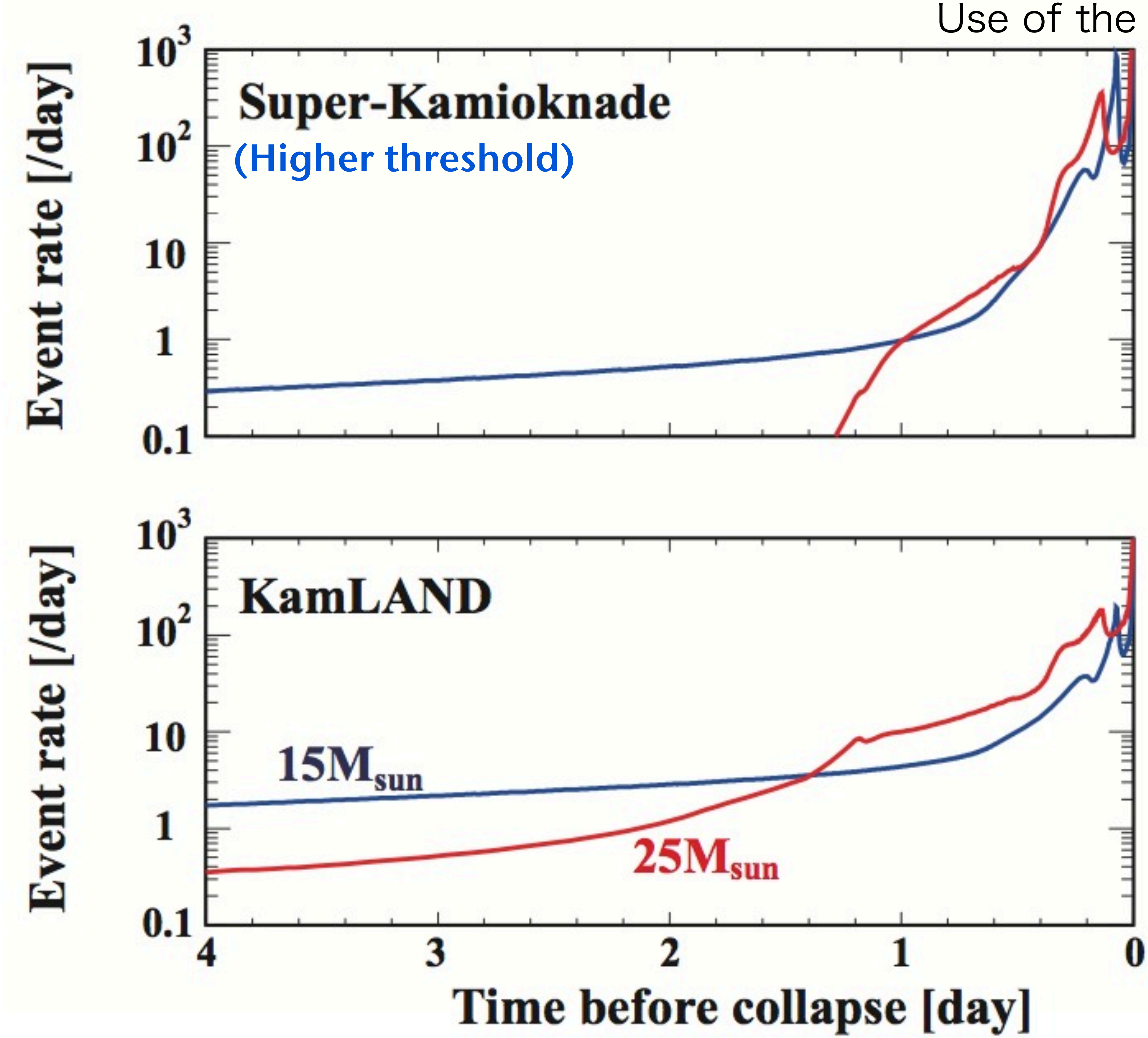




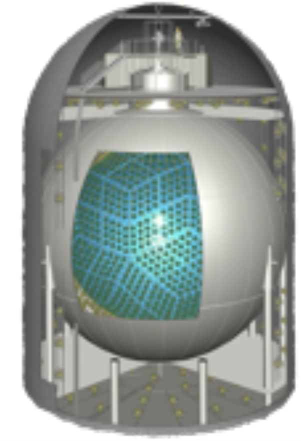
Time to collapse: 2.45 sec

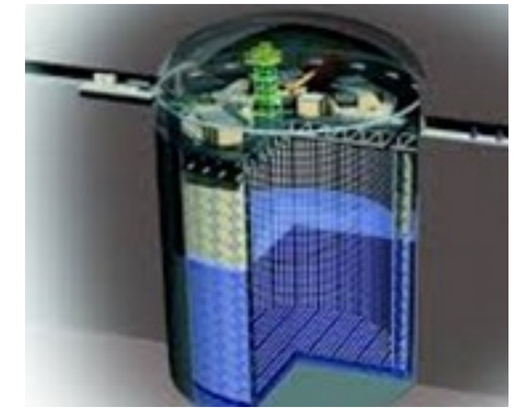
Event rate (d=200pc)

Use of the Odrzywolek model



KamLAND vs SK





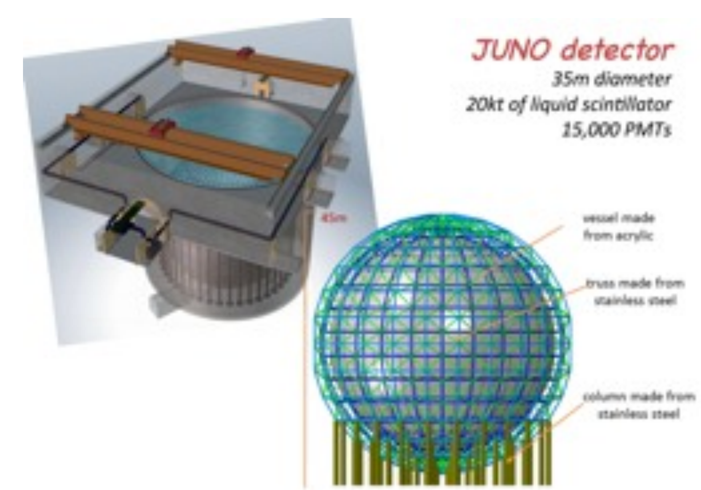
Expected number of events

detector	8.4 $M_\odot$		12 $M_\odot$		15 $M_\odot$	
	normal	inverted	normal	inverted	normal	inverted
Super-K	2.47×10^{-2}	9.68×10^{-3}	21	7	61	21
KamLAND	1.06×10^{-3}	1.50×10^{-3}	31	9	43	13
Hyper-K	0.30	0.13	9	3	77	28
JUNO	2.12×10^{-2}	8.03×10^{-3}	618	189	864	266

C. Kato et al., arXiv:1506.02358

Background rate

- SK background:
  ~200 event/day
- KamLAND background:
  < 1 event/day



Low threshold measurements
Delayed coincidence method

KamLAND is suitable for preSN neutrinos.

Physics from preSN neutrinos

Expected number of events

detector	8.4 $M_\odot$ normal	8.4 $M_\odot$ inverted	12 $M_\odot$ normal	12 $M_\odot$ inverted	15 $M_\odot$ normal	15 $M_\odot$ inverted
Super-K	2.47×10^{-2}	9.68×10^{-3}	21	7	61	21
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C. Kato et al., arXiv:1506.02358

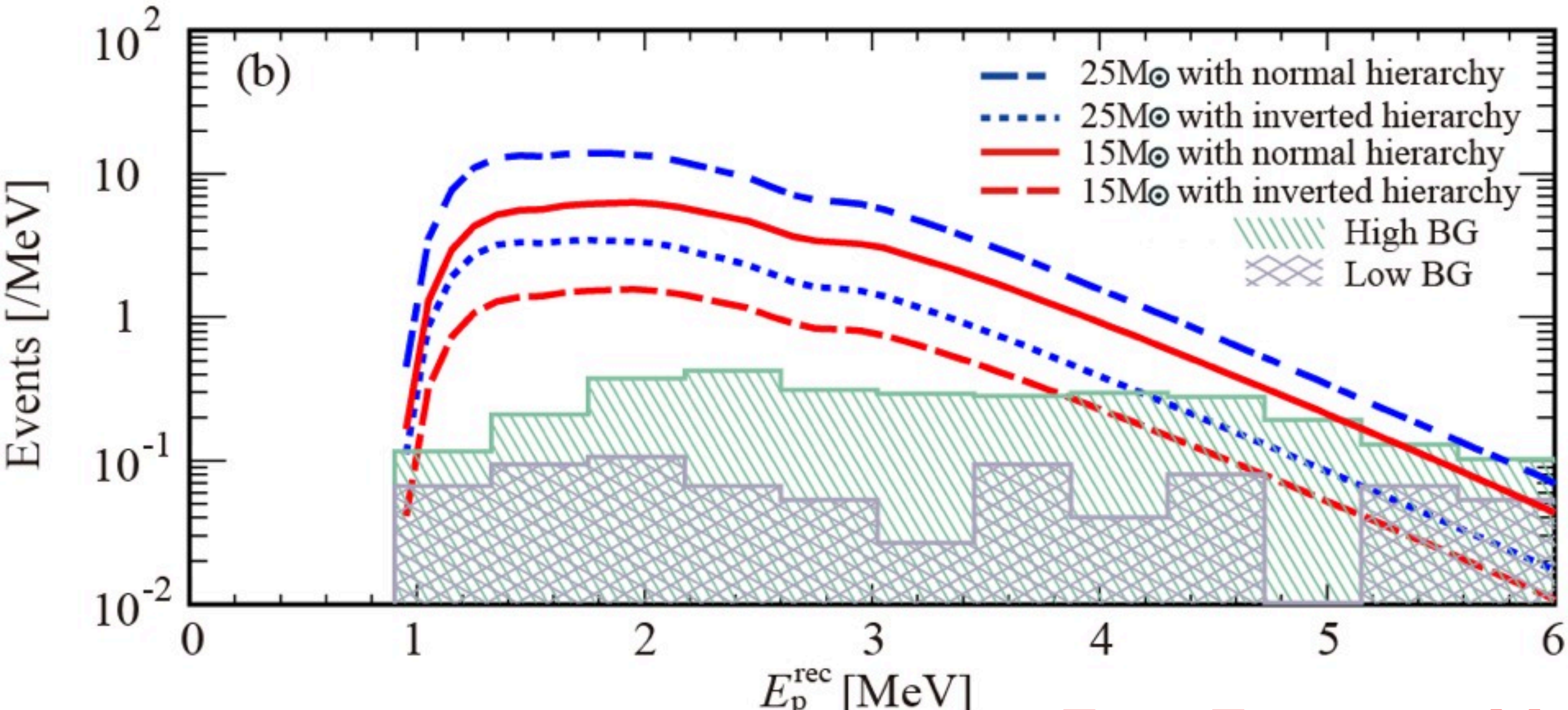
New possibility:

- Reconstruction of the mass and neutrino mass hierarchy (ONe core or Fe core ?)
- Very early alarm before collapse

KamLAND sensitivity and alarm before collapse

Signal vs Backgrounds

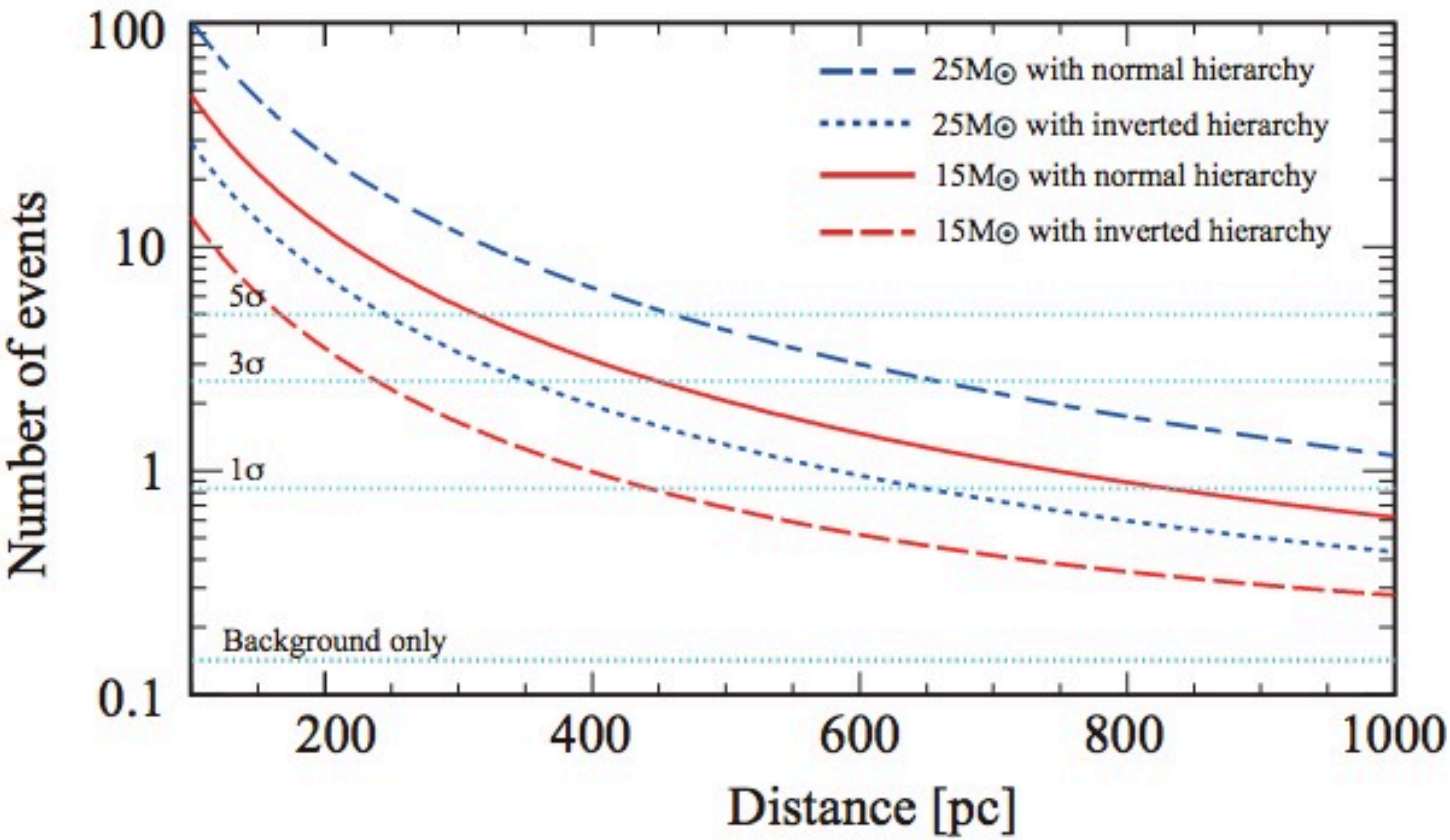
PreSN data from Odrzywolek (M = 15 M_{sun} and 25 M_{sun})
Integrated number of events in the last 48 hr.
Energy depend likelihood selection (KamLAND standard)



$$E_p = E_{\bar{\nu}_e} - 0.78\ \mathrm{MeV}$$

Number of events vs distance

Assumption of low-reactor backgrounds
Energy range: 0.9 < Ep < 3.5 MeV
3σ detection range: 220 - 660 pc



Alarm before collapse

PreSN neutrinos: very early alarm to supernovae
Evaluation sensitivity using Betelgeuse.

Betelgeuse

- Red-super giant
- Very close SN candidate
- Large errors for mass and distance

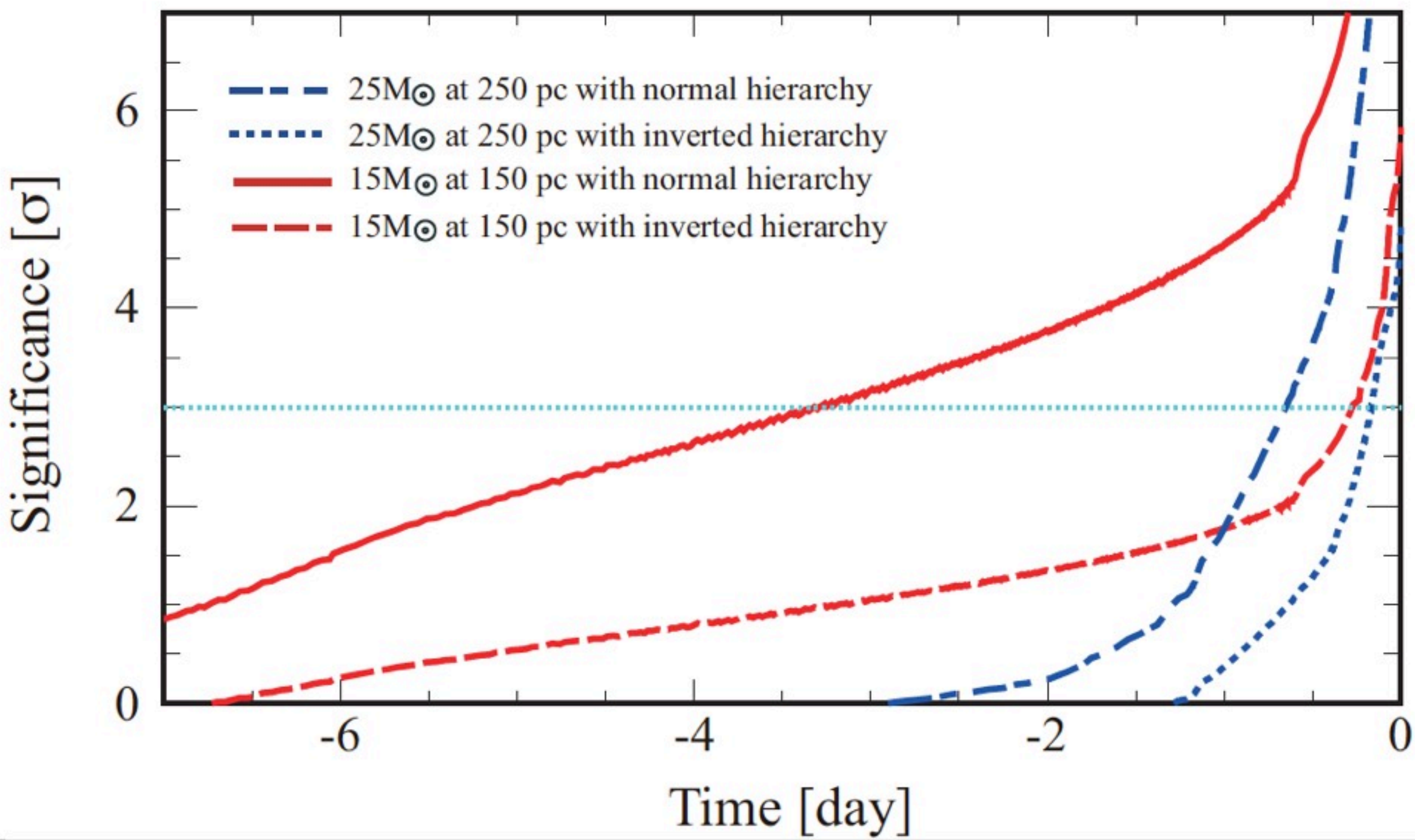
Table 8
Stellar Properties Inferred as a Function of Distance

Property	Distance		
	150 pc	200 pc	250 pc
Bolometric luminosity (ergs s^{-1})	4.87	5.12	5.31
Initial mass ($M_\odot$)	~17	~20	~24
Age (10^6 Yr)	~13	~10	~8
Space velocity (LSR)[U', V', W'] (km s^{-1})	[−12, 2, 22]	[−13, 0, 29]	[−13, −1, 35]

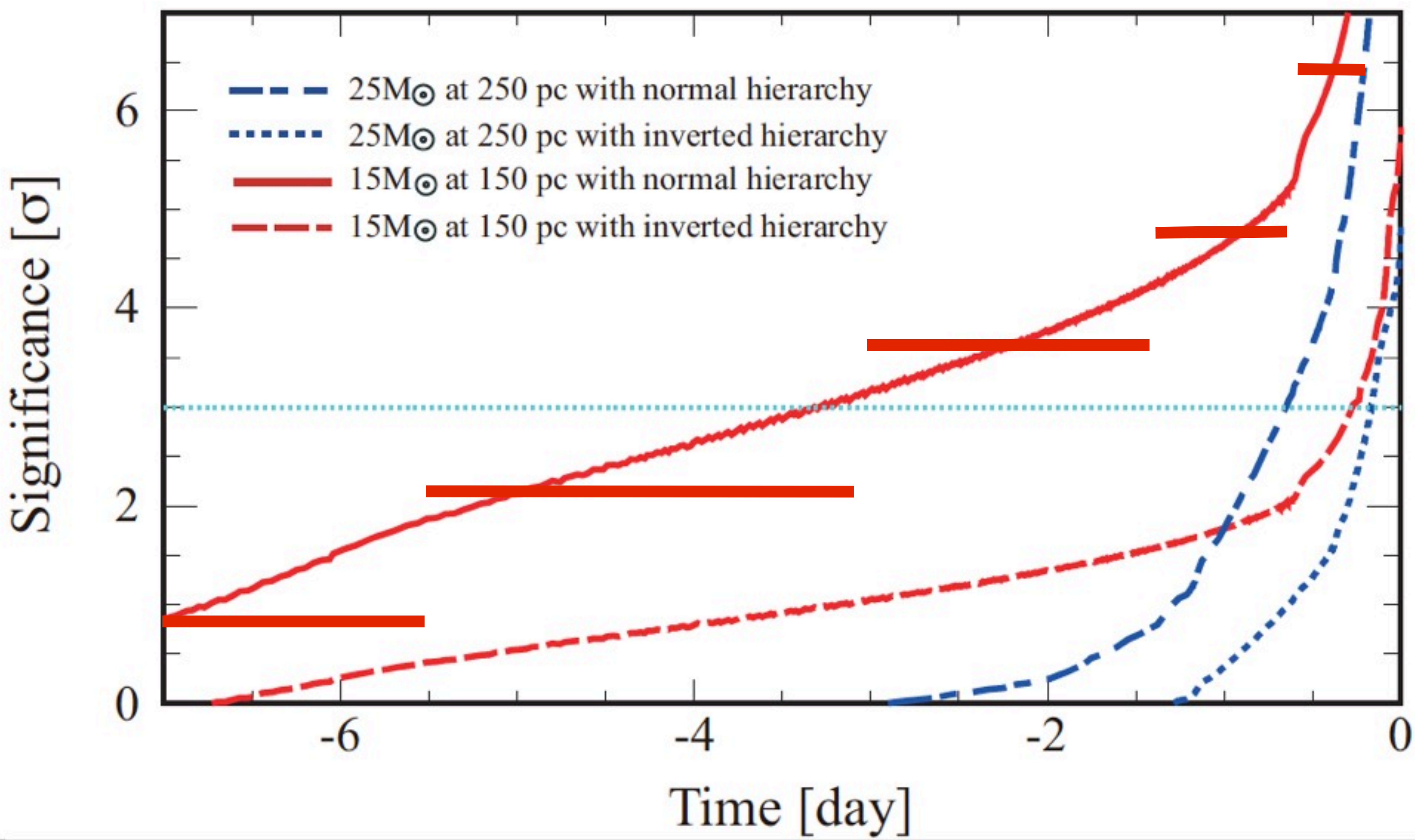
THE ASTRONOMICAL JOURNAL, 135:1430–1440, 2008 April

- Two extreme models
  + $M = 15M_{sun}$, $d = 150$ pc
  + $M = 25M_{sun}$, $d = 250$ pc

Evolution of significance

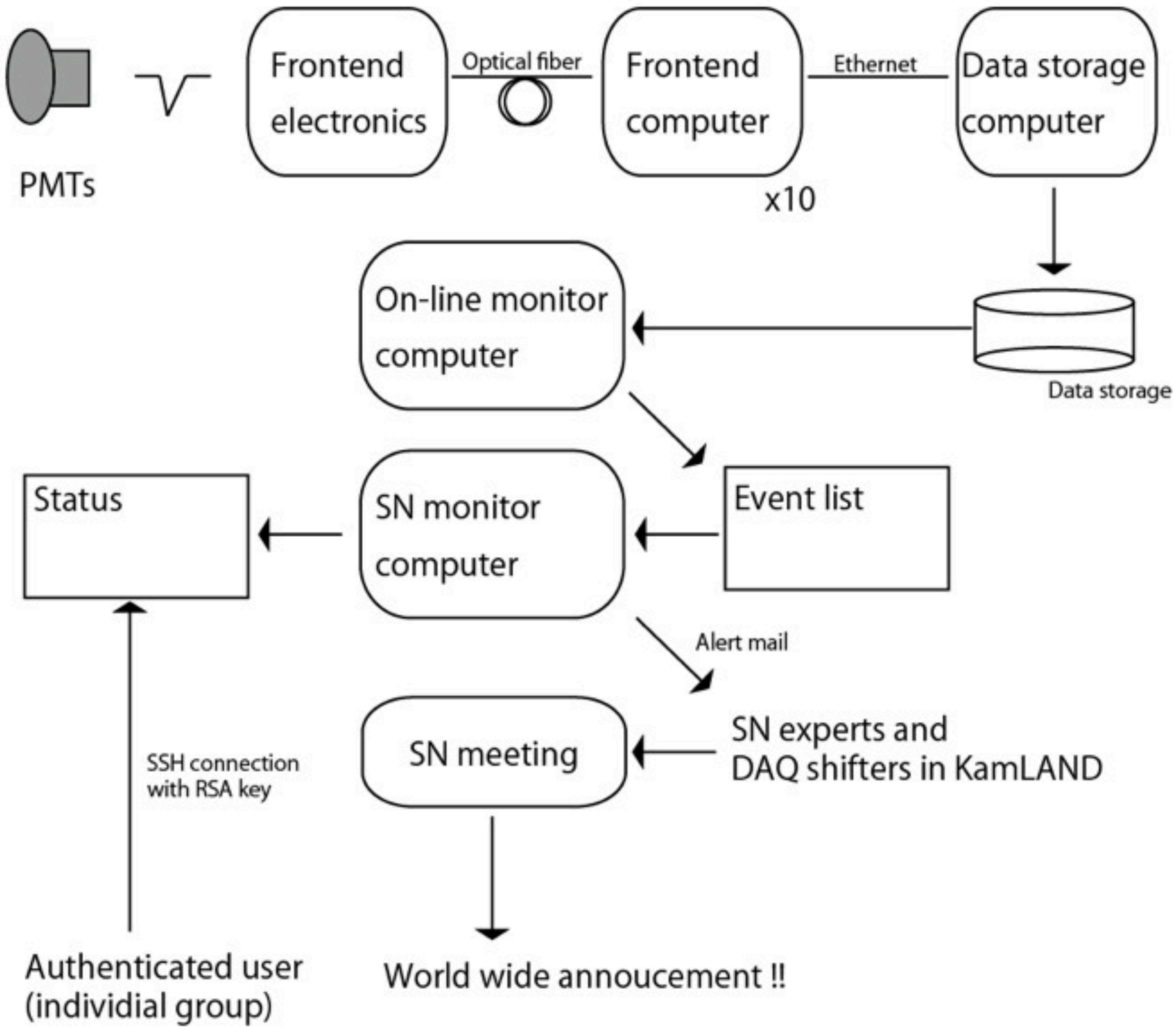


Evolution of significance



Early alarm system

Semi-realtime significance (t_{delay} ~ 20-30 min.)
Open for other groups.



Summary of PreSN

Detection of preSN signal is possible.

3σ detection range: 220 - 660 pc

Betelgeuse SN

- 3σ detection is possible before collapse.
- we open detection significance as alarm.

Current users:

Super-K, XMASS, SNO+ (neutrino detectors)

LIGO, GEO600 (gw detectors)

Future improvements

- Combined alarm system with other detectors

Detection range: a few kpc

Study
- thermal neutrinos from GRBs

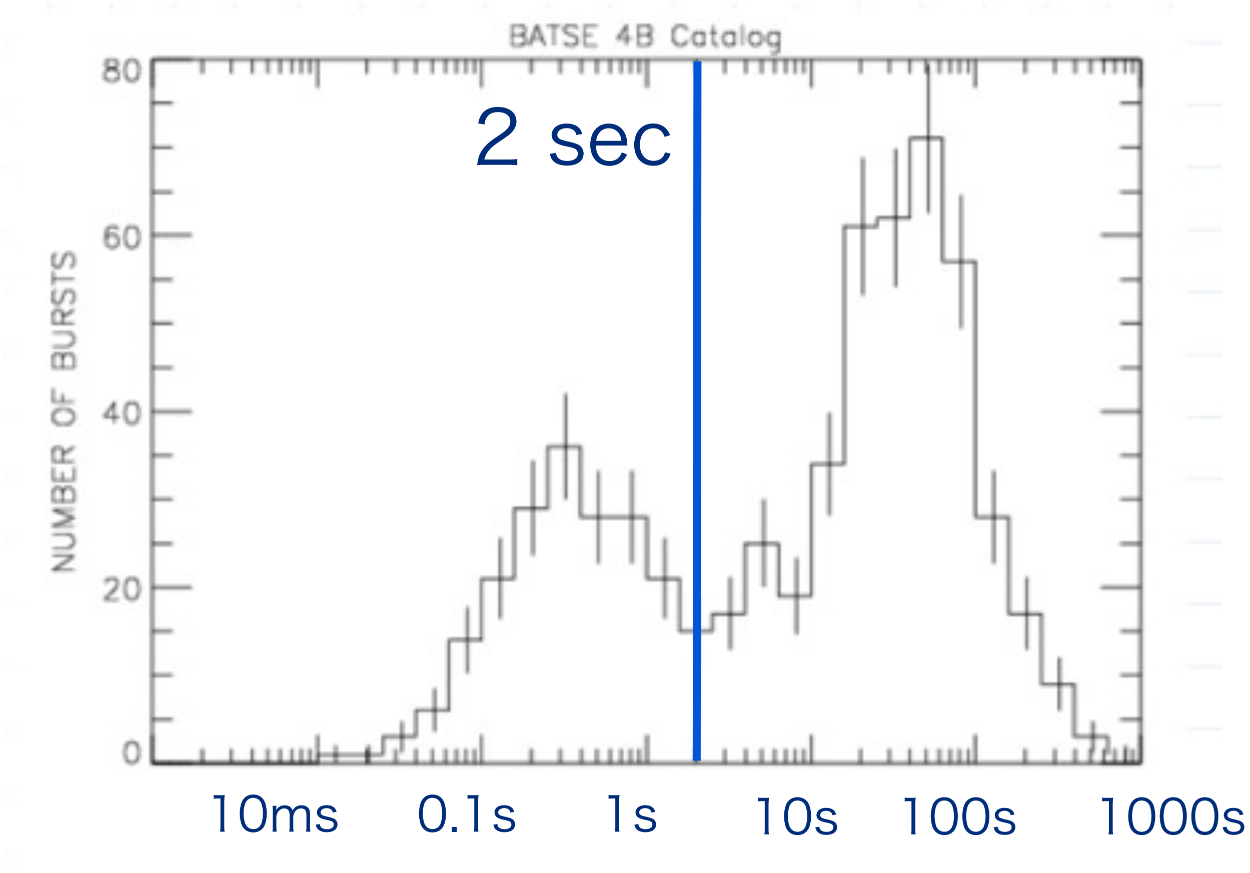
What are Gamma Ray Bursts (GRBs)?

The brightest evens in the universe.

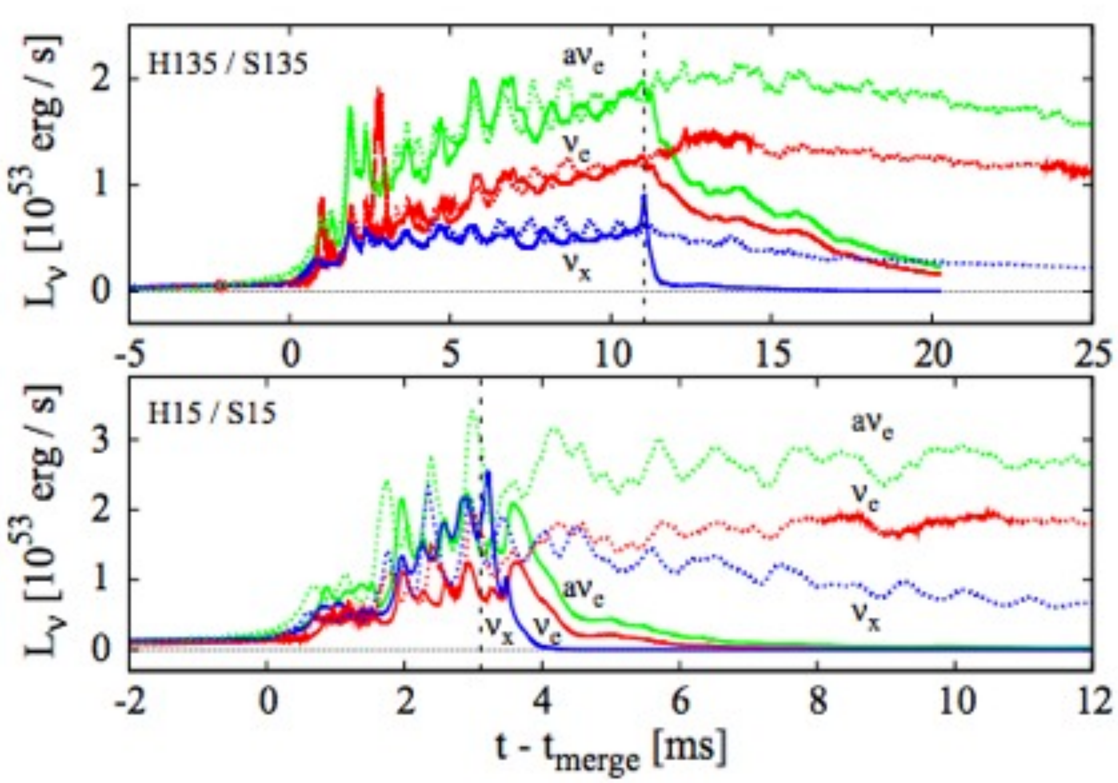
- Flashes of gamma-rays
- T = 10ms - 1000s (long GRB and short GRB)
- Huge energy (10^{53} erg) release

ref: 1 erg ~ 624 GeV

Duration time



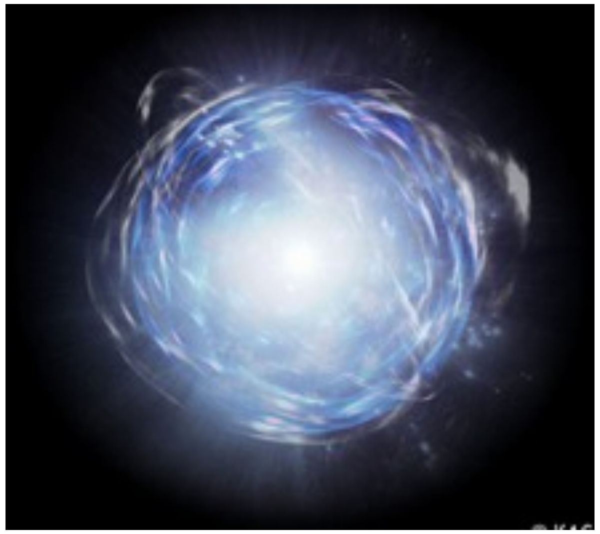
Neutrino emission

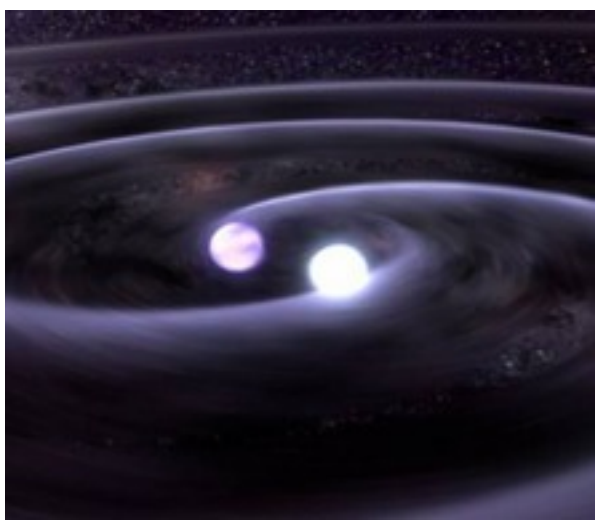


PRL, 107,051102 (2011)

Basic scenario of GRB

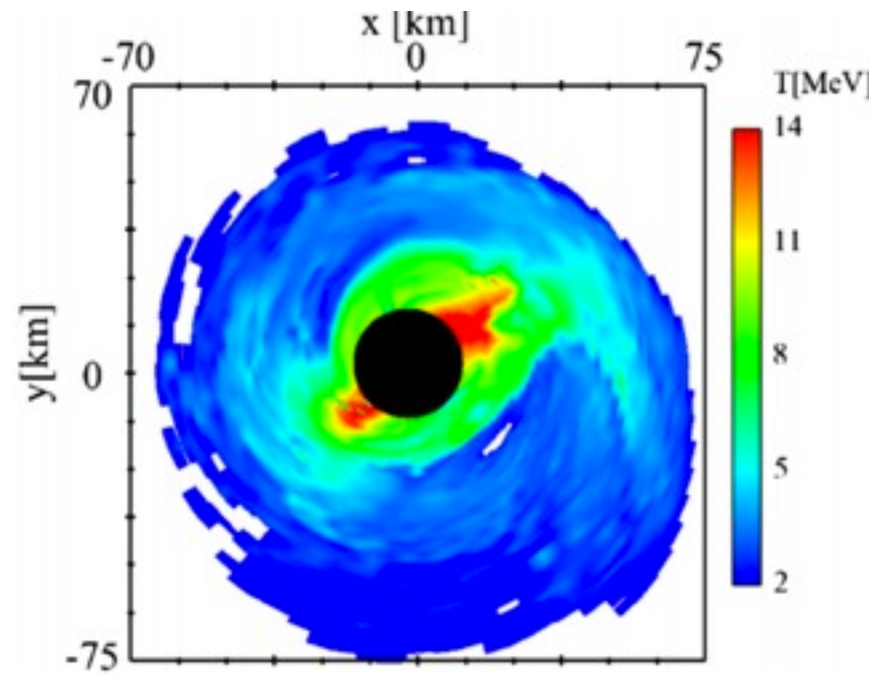
Hypernovae for long GRBs

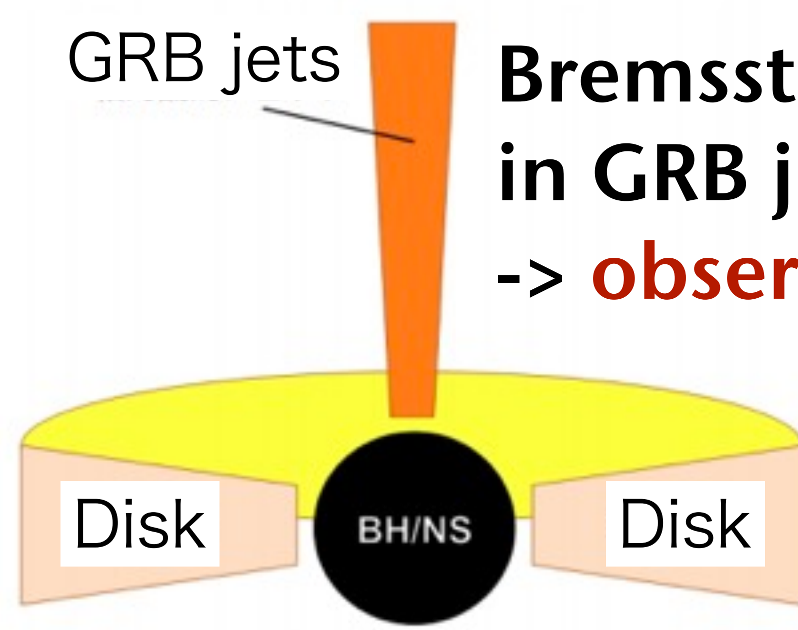




Merger of binary neutron stars for short GRBs

BH + accretion disk

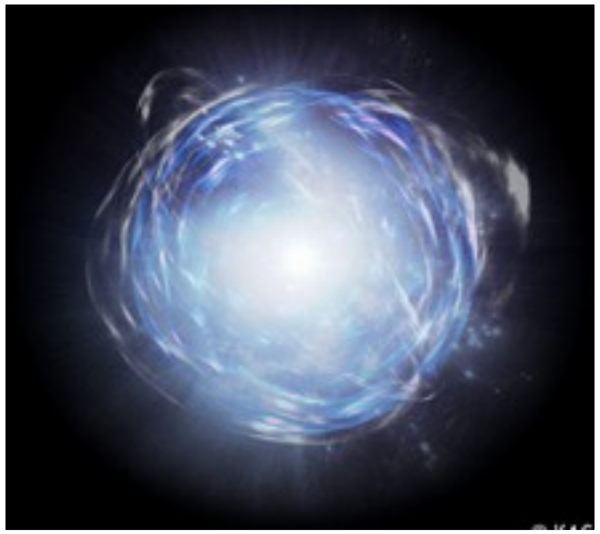


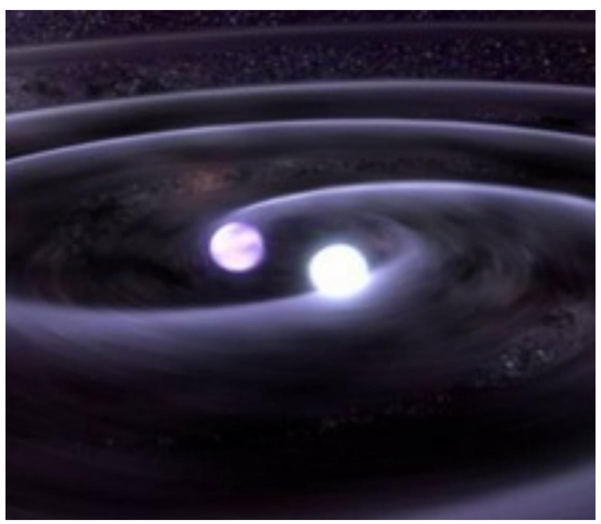


Bremsstrahlung X-ray flash in GRB jets
-> observed as GRB.

Basic scenario of GRB

Hypernovae for long GRBs





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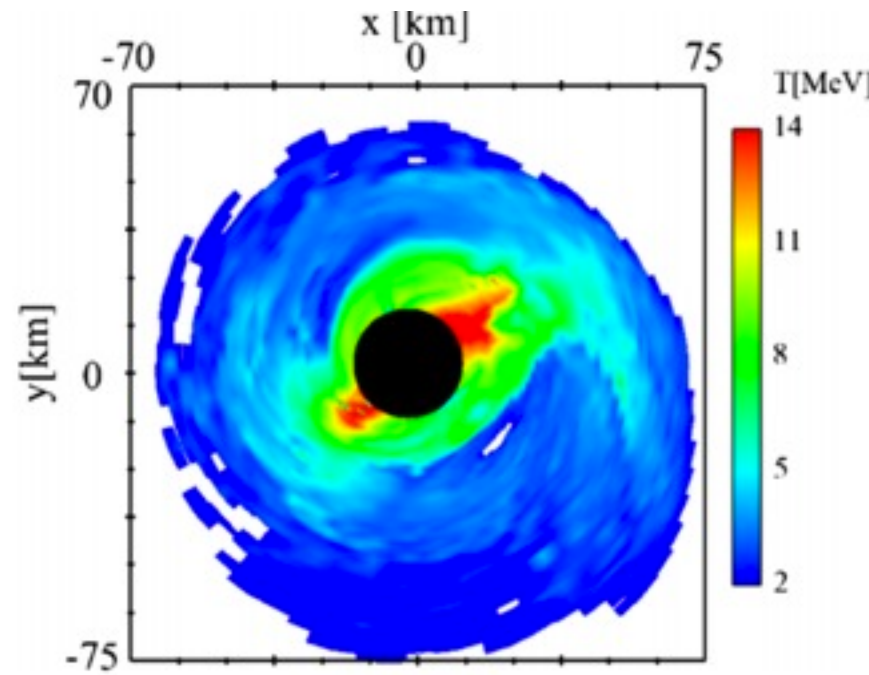
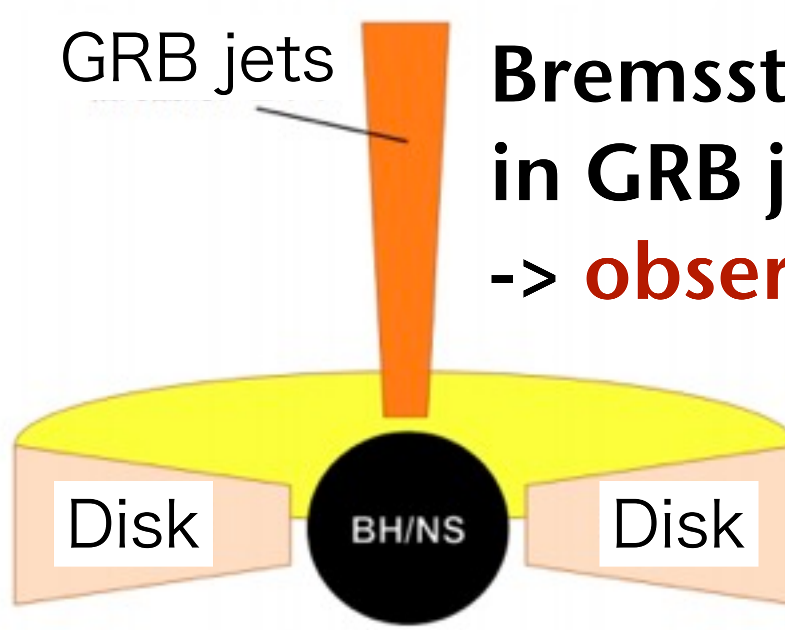


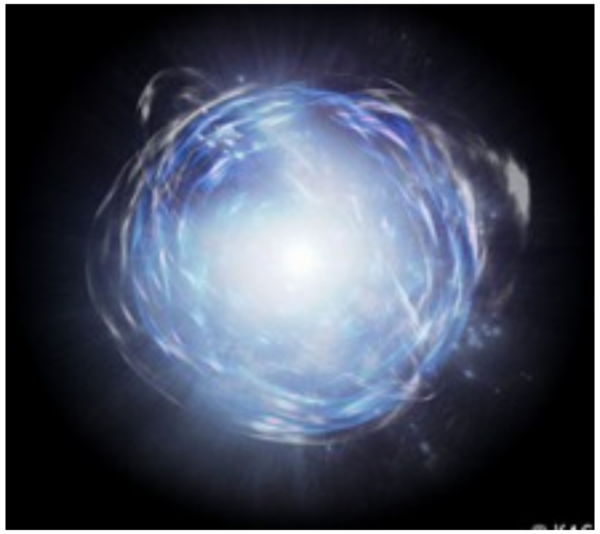
Not well establishment !!

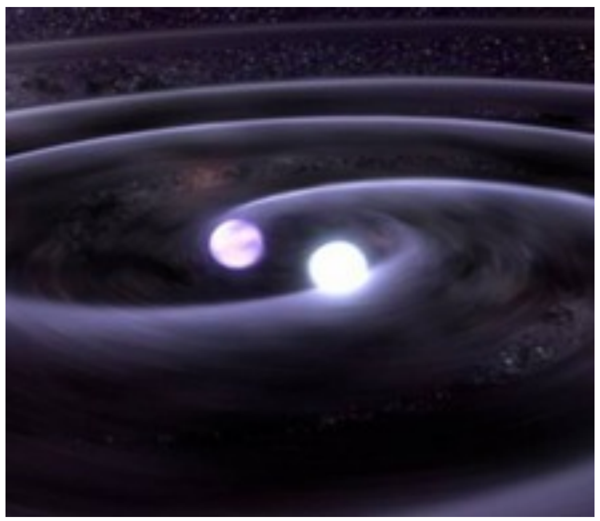


Bremsstrahlung X-ray flash in GRB jets
-> observed as GRB.

Basic scenario of GRB

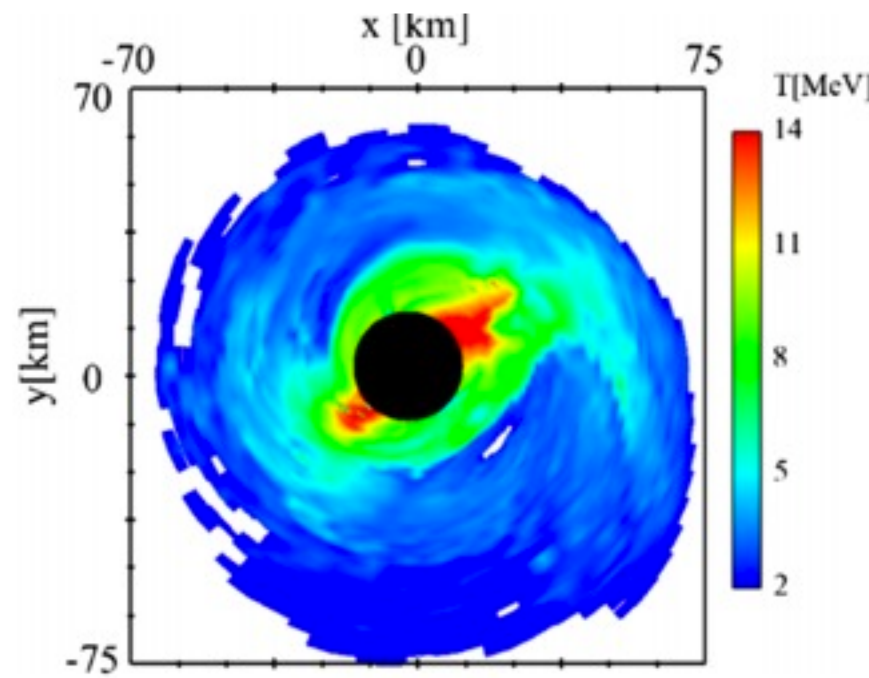
Supernovae for long GRBs





Merger of binary neutron stars for short GRBs

BH + accretion disk



Neutron production on the disk

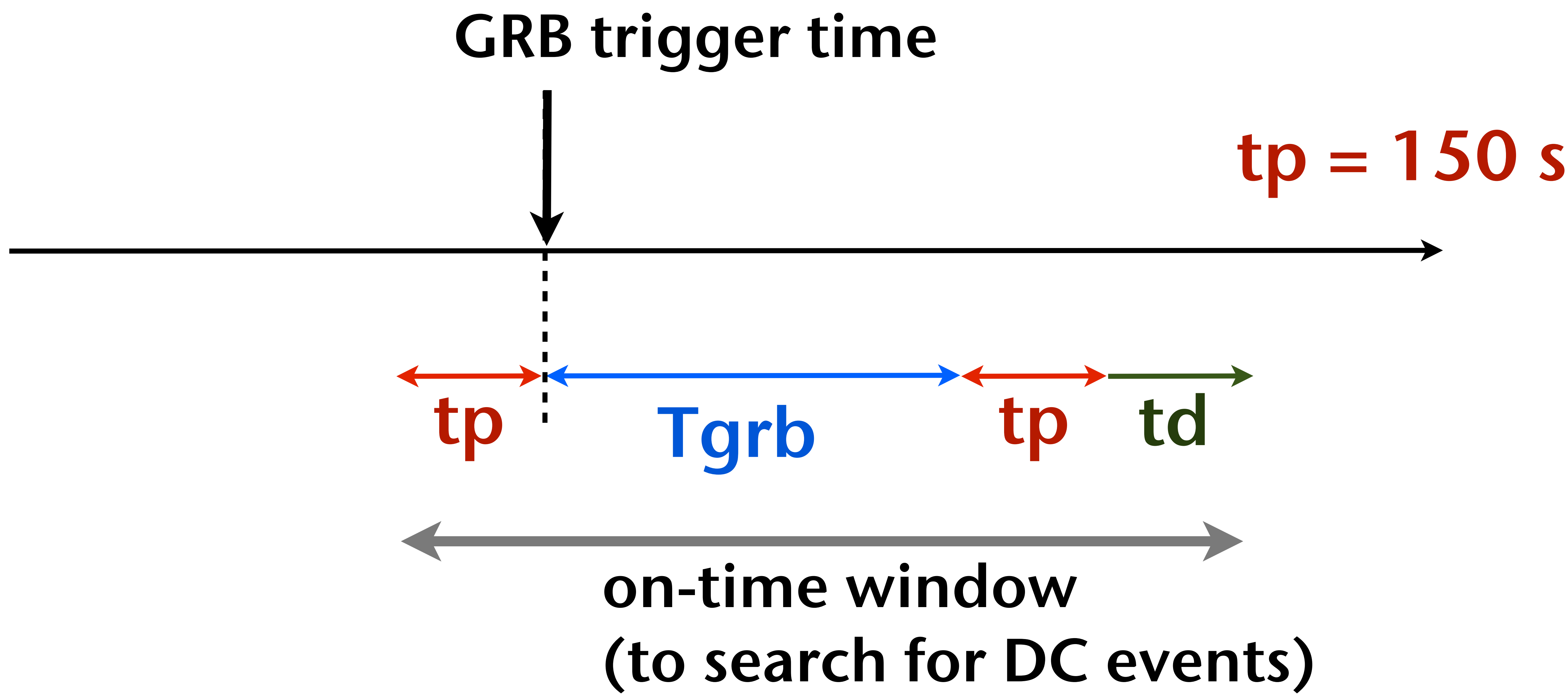
$$n + e^+ \rightarrow p + \bar{\nu_e}$$

$$(e^+ + e^- \rightarrow \nu_e + \bar{\nu_e})$$

(Thermal) neutrino:
unique tool to study GRB central region

Coincidence analysis

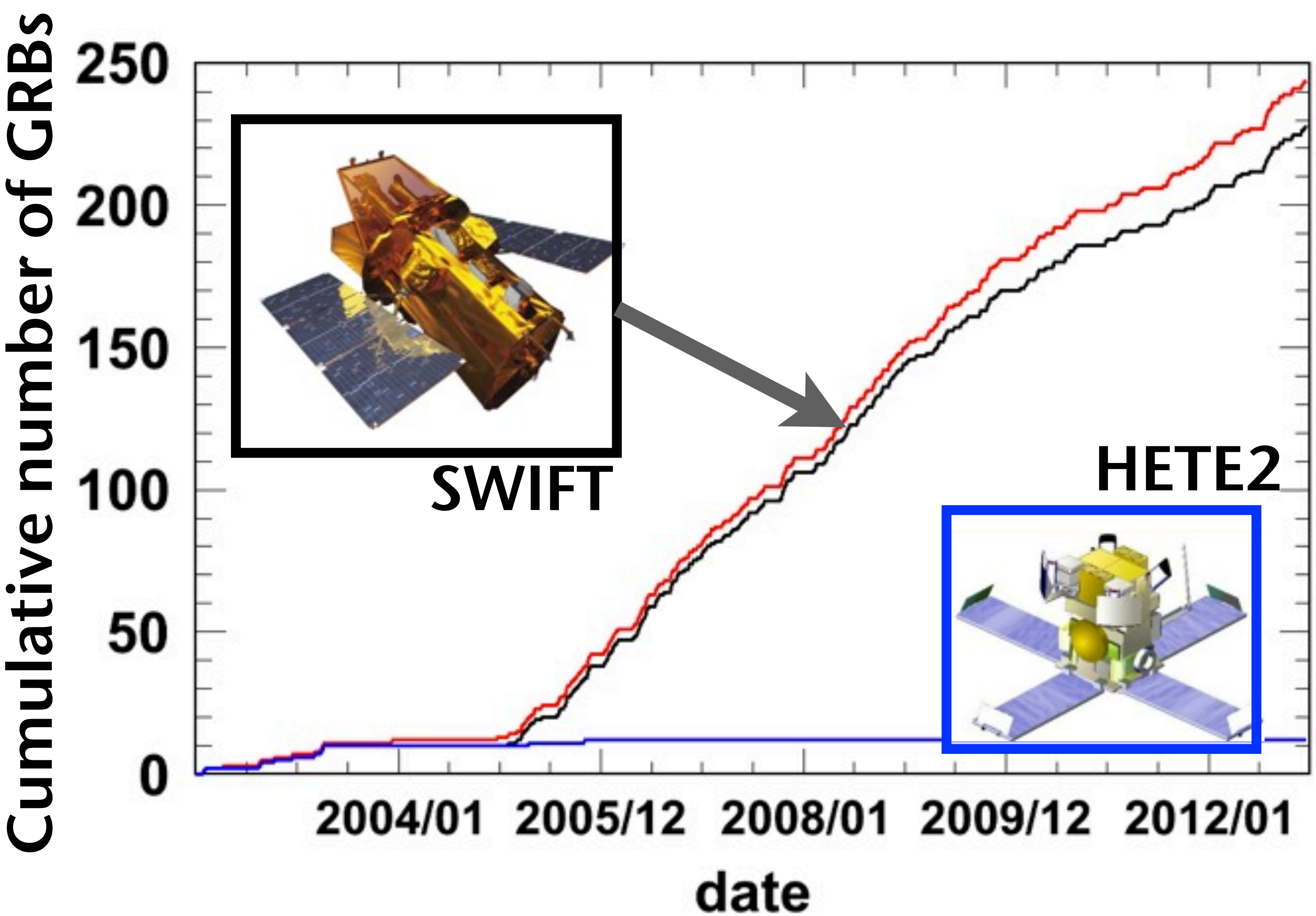
- Use of redshift-known GRBs
- GRB population analysis (long and short GRBs)
- Coincidence analysis between KamLAND DC events and GRBs



Used GRB List

SWIFT era

- many redshift-known GRBs (>300)
- 213 long GRBs, 18 short GRBs.



FERMI

KamLAND data

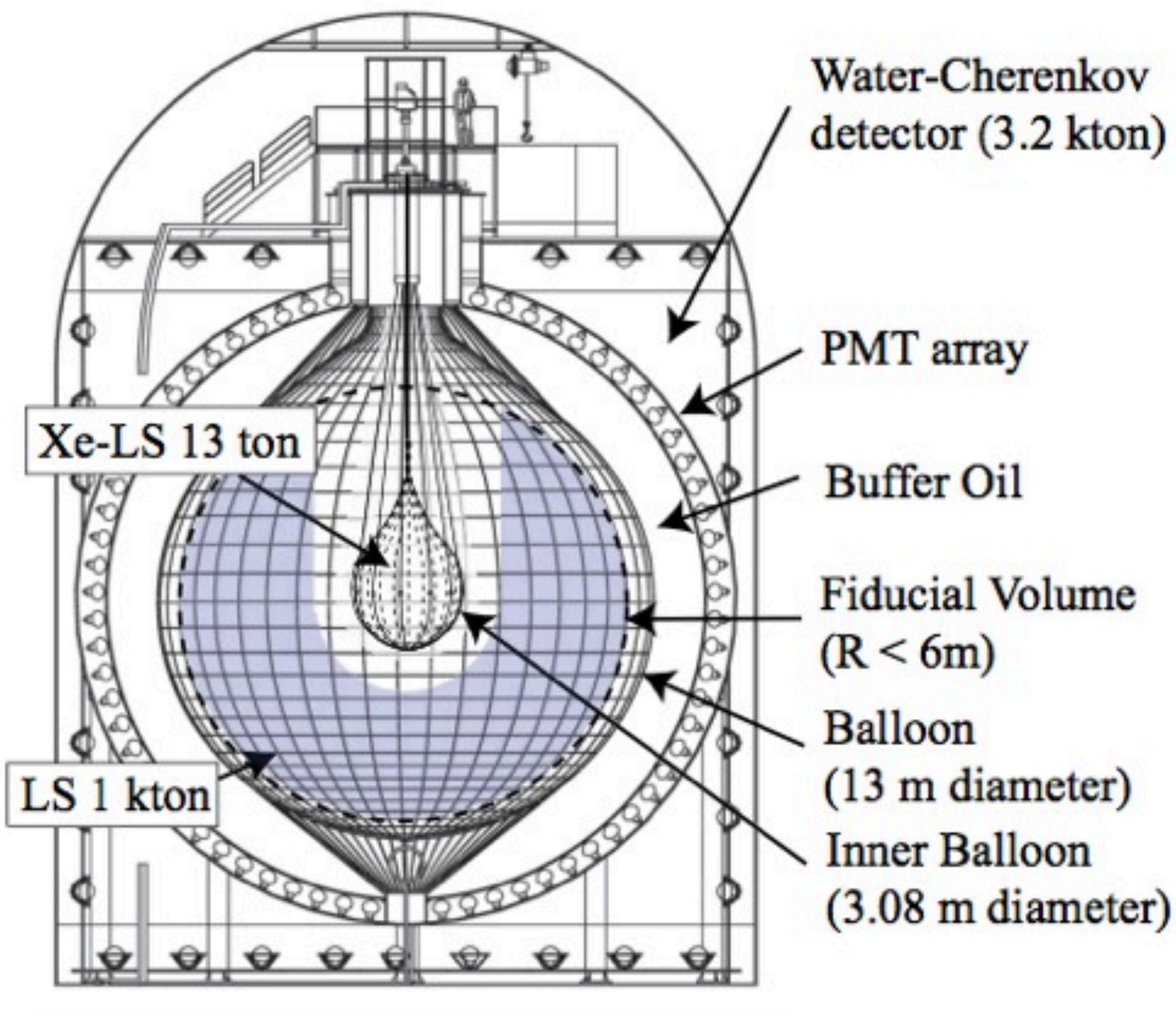
Selection criteria

KamLAND phase (normal-reactor phase)

- 7.5 < Ep < 100 MeV

KamLAND-Zen phase (low-reactor phase)

- 0.9 < Ep < 100 MeV, inner balloon cut



KamLAND data

Selection criteria

KamLAND phase (normal-reactor phase)

- 7.5 < Ep < 100 MeV

KamLAND-Zen phase (low-reactor phase)

- 0.9 < Ep < 100 MeV, inner balloon cut

Background estimation

KamLAND phase (normal-reactor phase)

- # of DC events: 56 => 9.3×10^{-4} event/h

KamLAND-Zen phase (low-reactor phase)

- # of DC events: 83 => 7.9×10^{-3} event/h

Coincidence events

Results for long GBRs:

- No coincidence DC event
- Total window length: 25.2h (18.3 + 6.8 h)
- Expected number: 0.074

⇒ FC upper limits: $N_{90}=2.365$

Results for short GBRs:

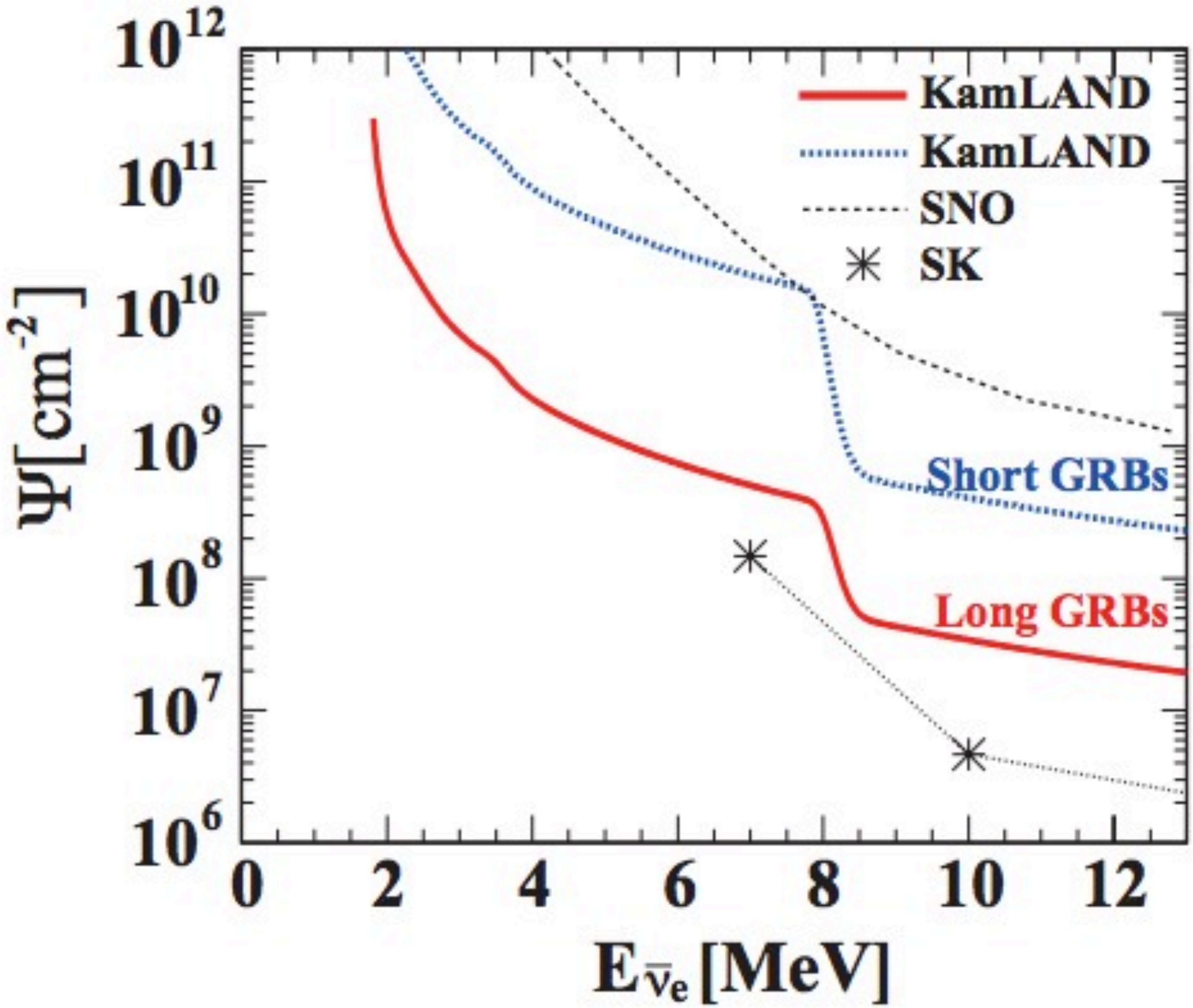
- No coincidence DC event
- Total window length: 14.5h (1.33 + 0.1 h)
- Expected number: 2.2×10^{-3}

⇒ FC upper limits: $N_{90}=2.435$

Astrophysical interpretation

Fluence limit

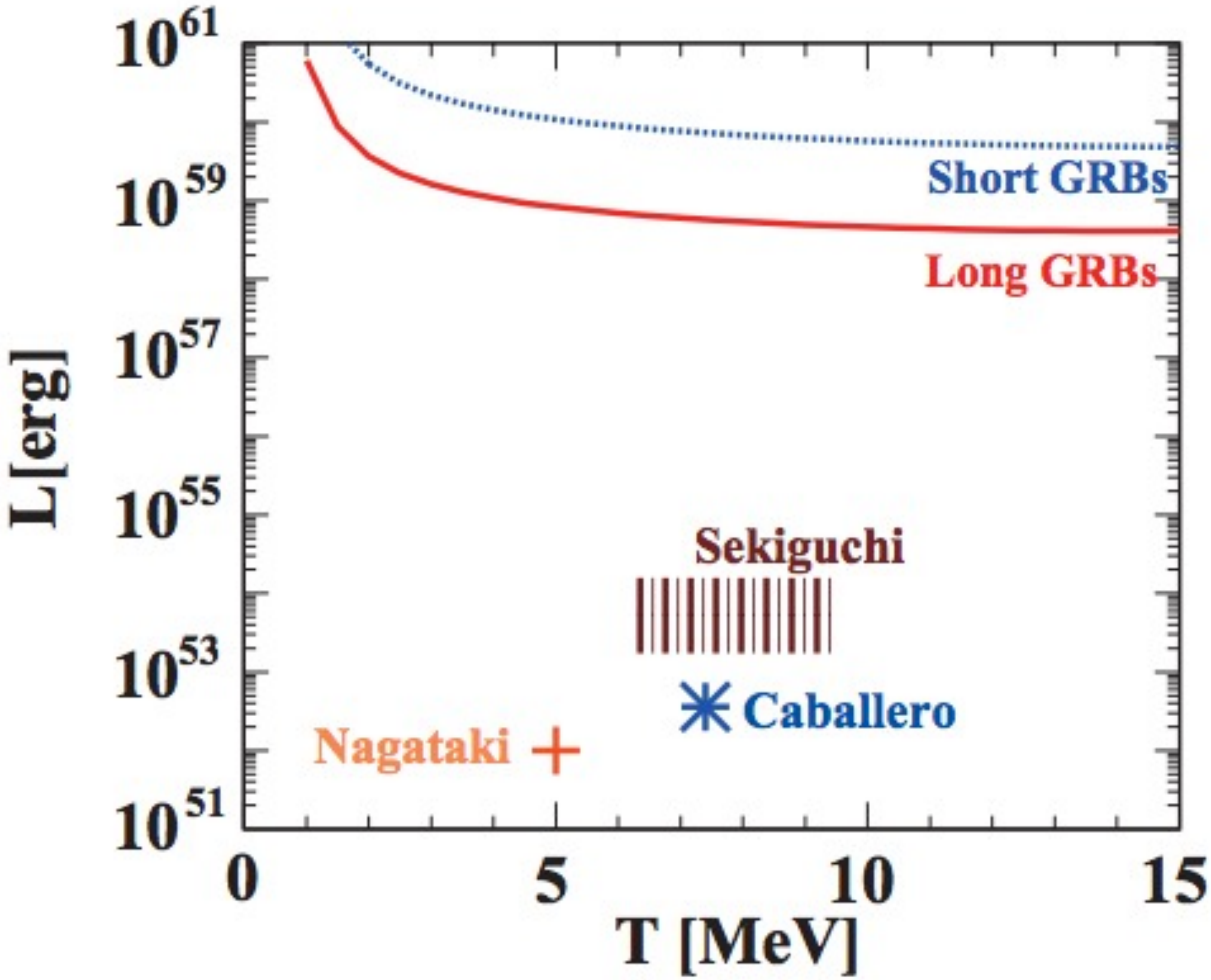
(assuming monochromatic neutrinos at specific energy)



Astrophysical interpretation

L-T constraint

Fermi-Dirac: $\psi(E_{\overline{\nu}_e}, T, L) = \frac{120}{7\pi^4}\frac{L}{T^4}\frac{E_{\overline{\nu}_e}^2}{\exp(E_{\overline{\nu}_e}/T)+1}$



Summary of GRB analysis

Coincidence search used

- 213 long GRBs
- 18 short GRBs

No coincidence DC event

Astrophysical interpretation

- Tightest fluence limits below 7 MeV
- First L-T constraint

This constraint is used to compare theoretical studies.

Summary

Summary

KamLAND: the largest LS detector

Initial motivation:

neutrino oscillation and geo-neutrino

Current highest priority:

neutrino-less double-beta decay (KamLAND-Zen)

KamLAND:

- designed to muti-purpose detector
- strong advantages in low-energy neutrino astrophysics

Unique possibility to study preSN neutrino

Thermal neutrinos from GRBs

(7Be and 8B solar neutrino)

(Supernova relic neutrino)

End