progress report of
subscription research (公募研究)

Supernova Neutrino Light Curves beyond 10 s

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collaboration with;

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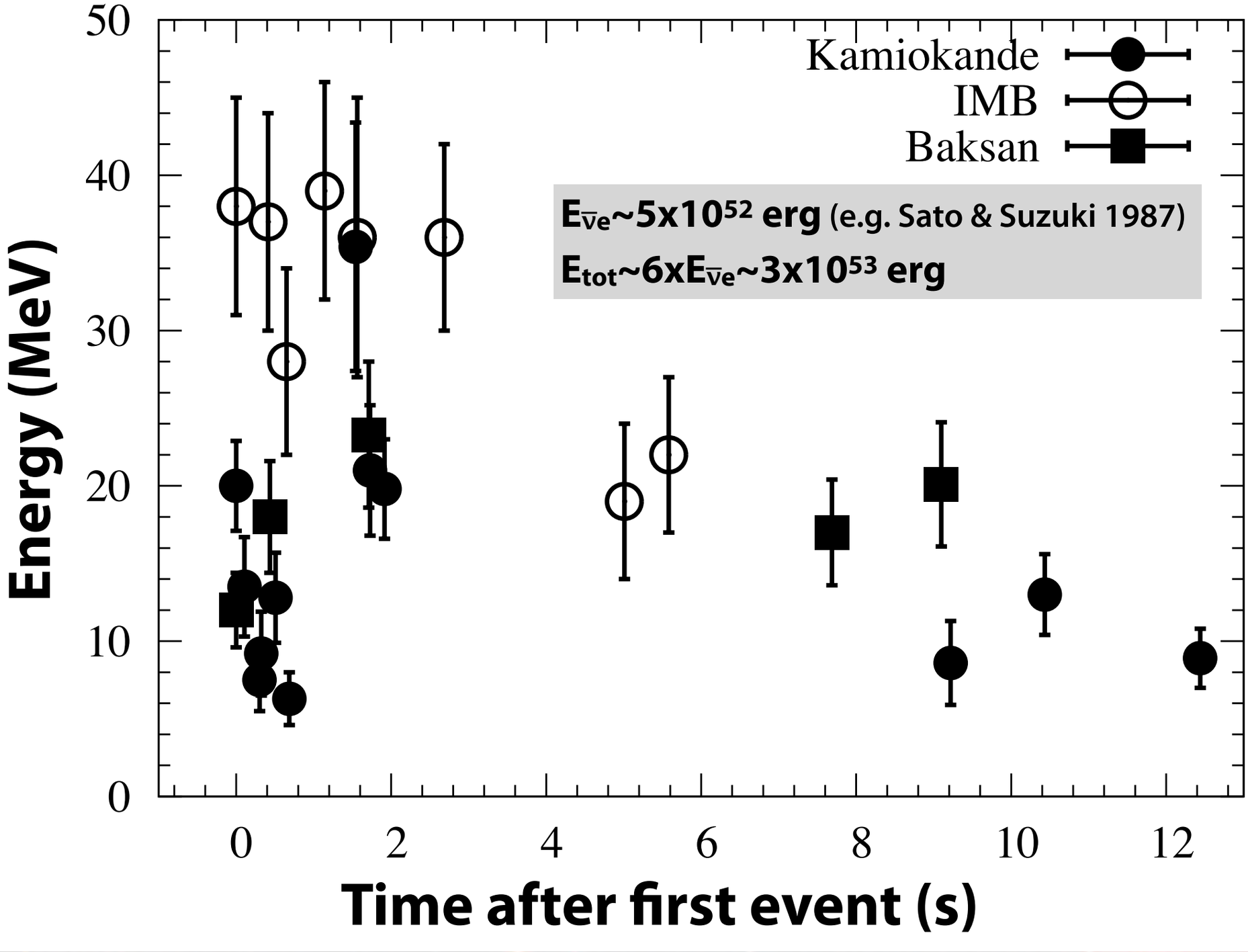
SN1987A

Neutrinos from SN 1987A (Feb. 23 1987)



NASA/ESA

How many and long can we observe ν now?

* **How many?**
  - **11 events from SN1987A with Kamiokande**
    - **M=2.14 kton (full volume of inner tank)**
    - **D=51.2 kpc (LMC)**
  - **SK (M=32.5 kton), D=10 kpc => 4400 events (with *O*(10)% of statistical error)**

* **How long?**
  - **12.4 s for SN1987A**
  - **How long can we observe neutrinos from a Galactic SN? It's highly uncertain.**

The latest SN found in our Galaxy, G1.9+0.3 (<150 years old) © NASA

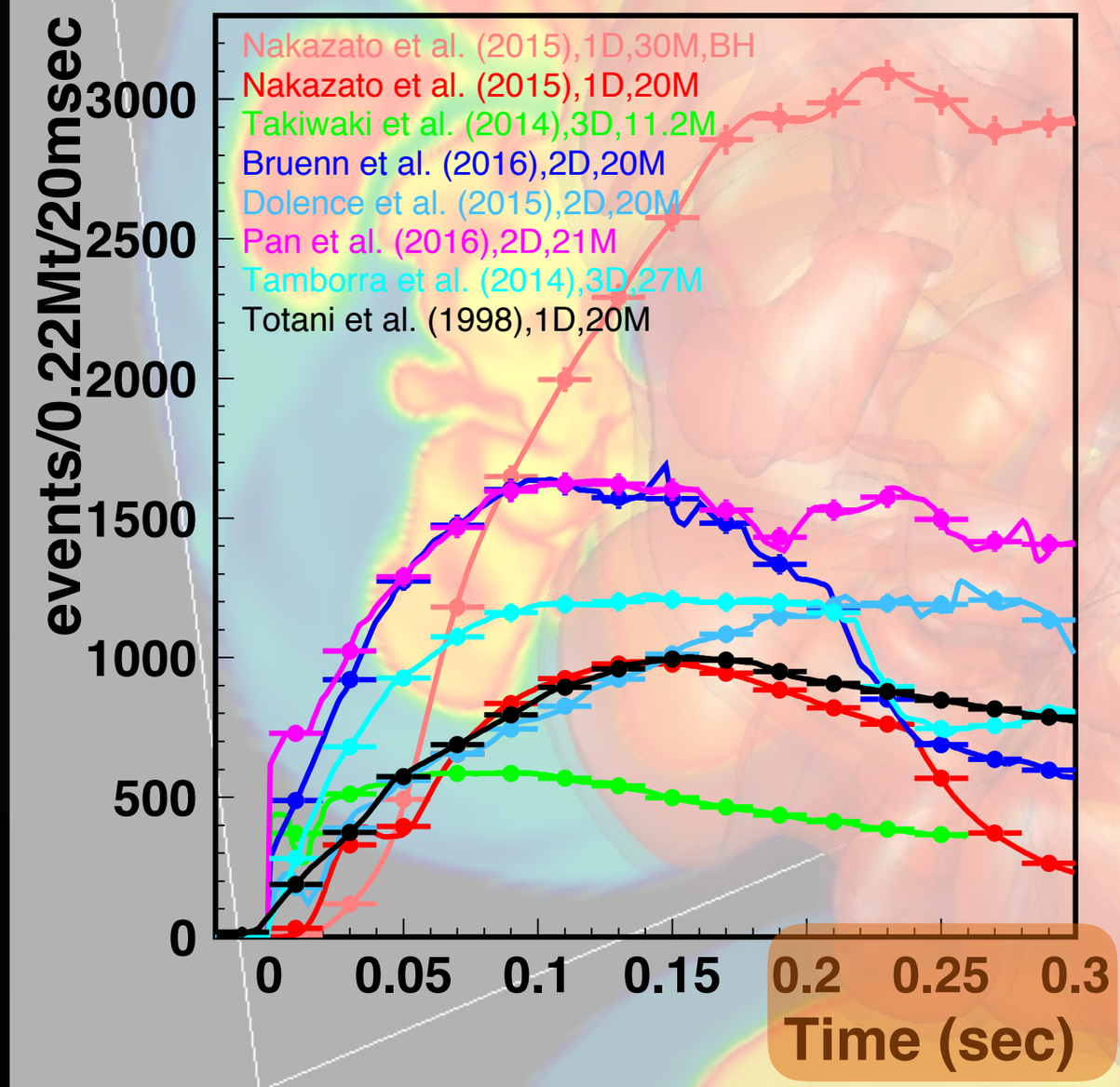
Many neutrinos from next Galactic SN

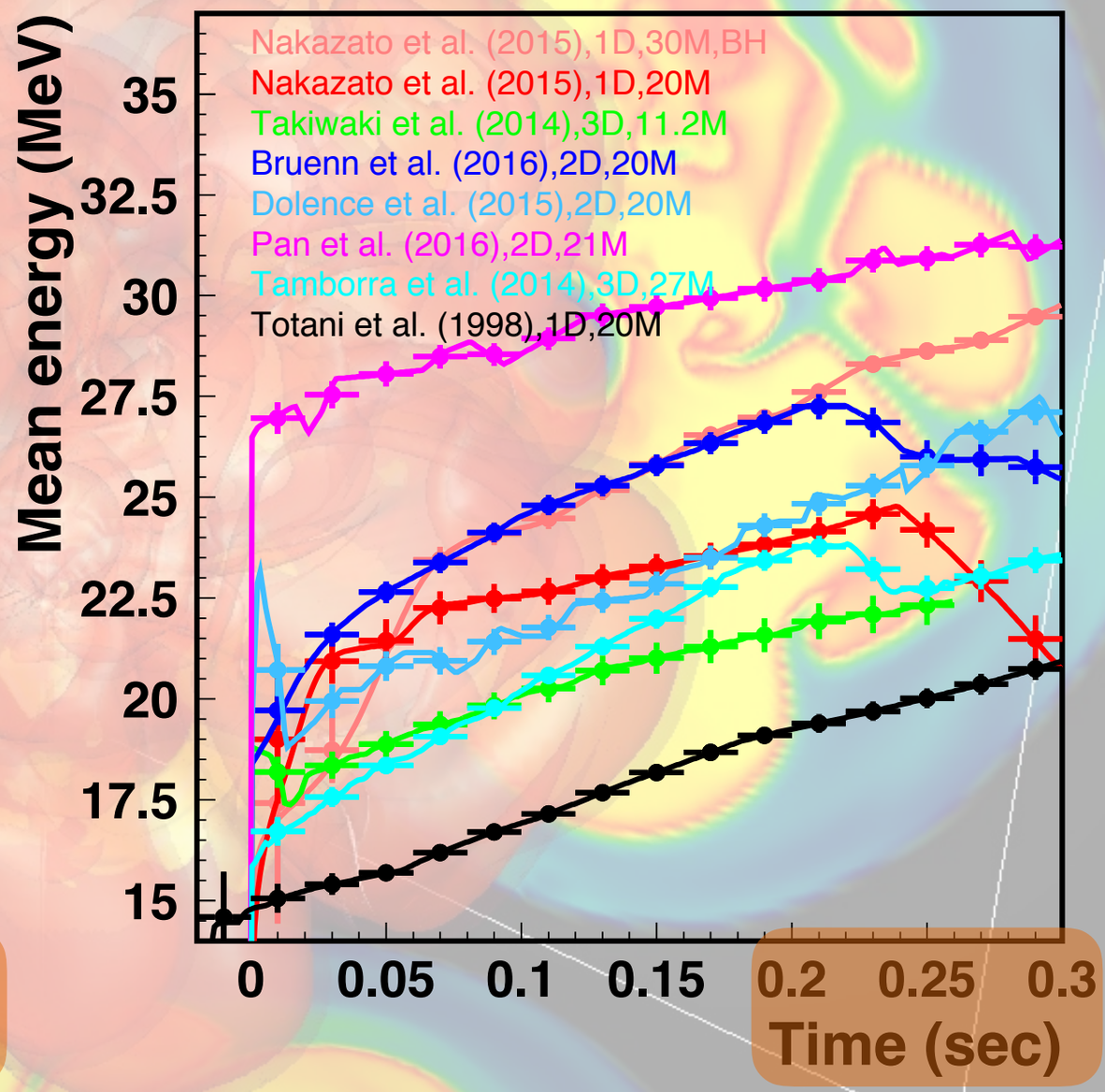
10kpc

Detector	Type	Mass (kt)	Location	Events	Status
Super-Kamiokande	H_2O	32	Japan	7000	Running
LVD	C_nH_{2n}	1	Italy	300	Running
KamLAND	C_nH_{2n}	1	Japan	300	Running
Borexino	C_nH_{2n}	0.3	Italy	100	Running
IceCube	Long string	(600)	South pole	(10^6)	Running
Baksan	C_nH_{2n}	0.33	Russia	50	Running
HALO	Pb	0.08	Canada	30	Running
Daya Bay	C_nH_{2n}	0.33	China	100	Running
NOνA*	C_nH_{2n}	15	USA	4000	Running
MicroBooNE*	Ar	0.17	USA	17	Running
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
DUNE	Ar	40	USA	3000	Future
Hyper-Kamiokande	H_2O	374	Japan	75 000	Future
JUNO	C_nH_{2n}	20	China	6000	Future
RENO-50	C_nH_{2n}	18	Korea	5400	Future
PINGU	Long string	(600)	South pole	(10^6)	Future

Scholberg 2018

Current simulation data is not long enough

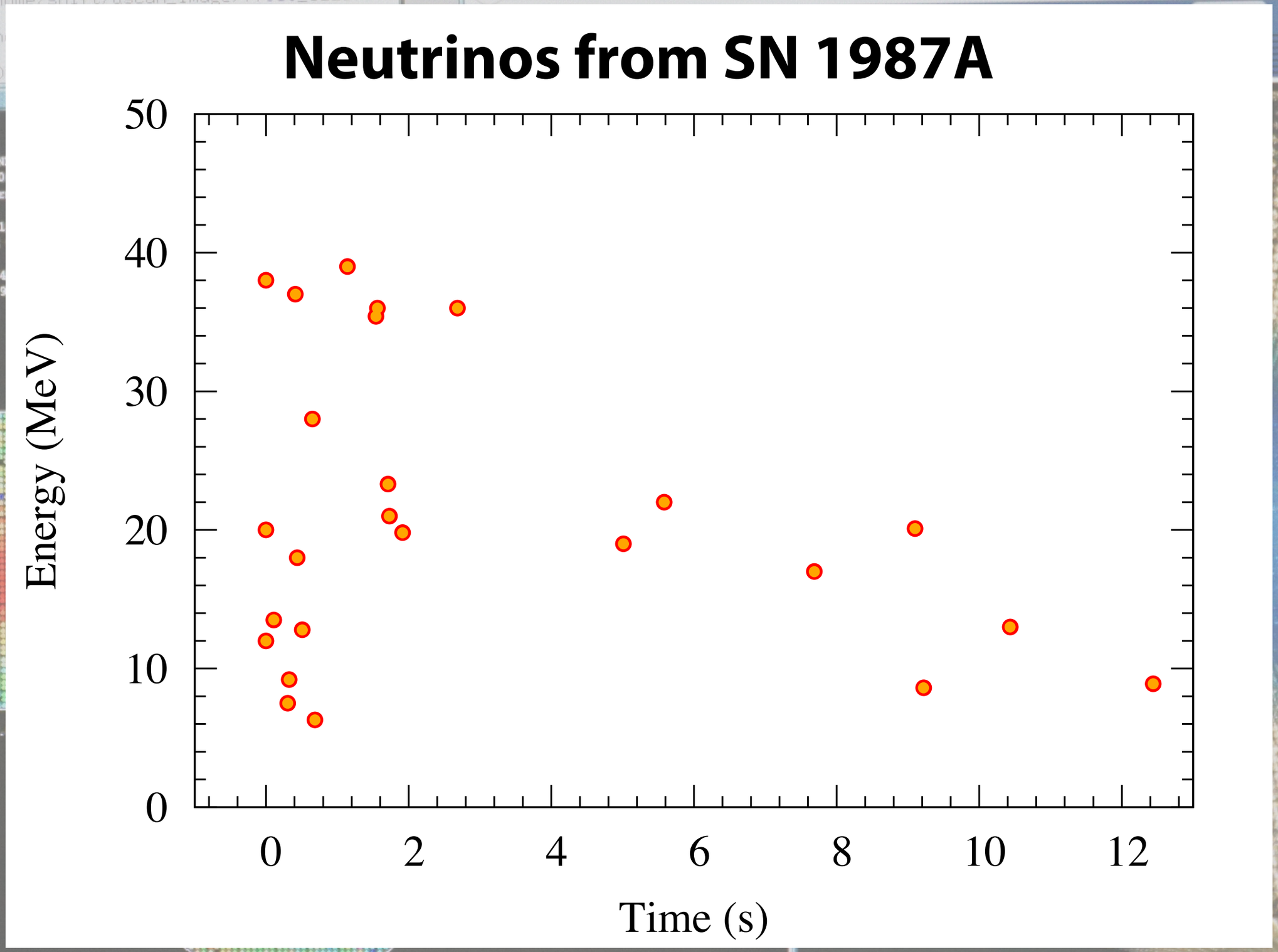




Hyper-Kamiokande Design Report, arXiv:1805.04163

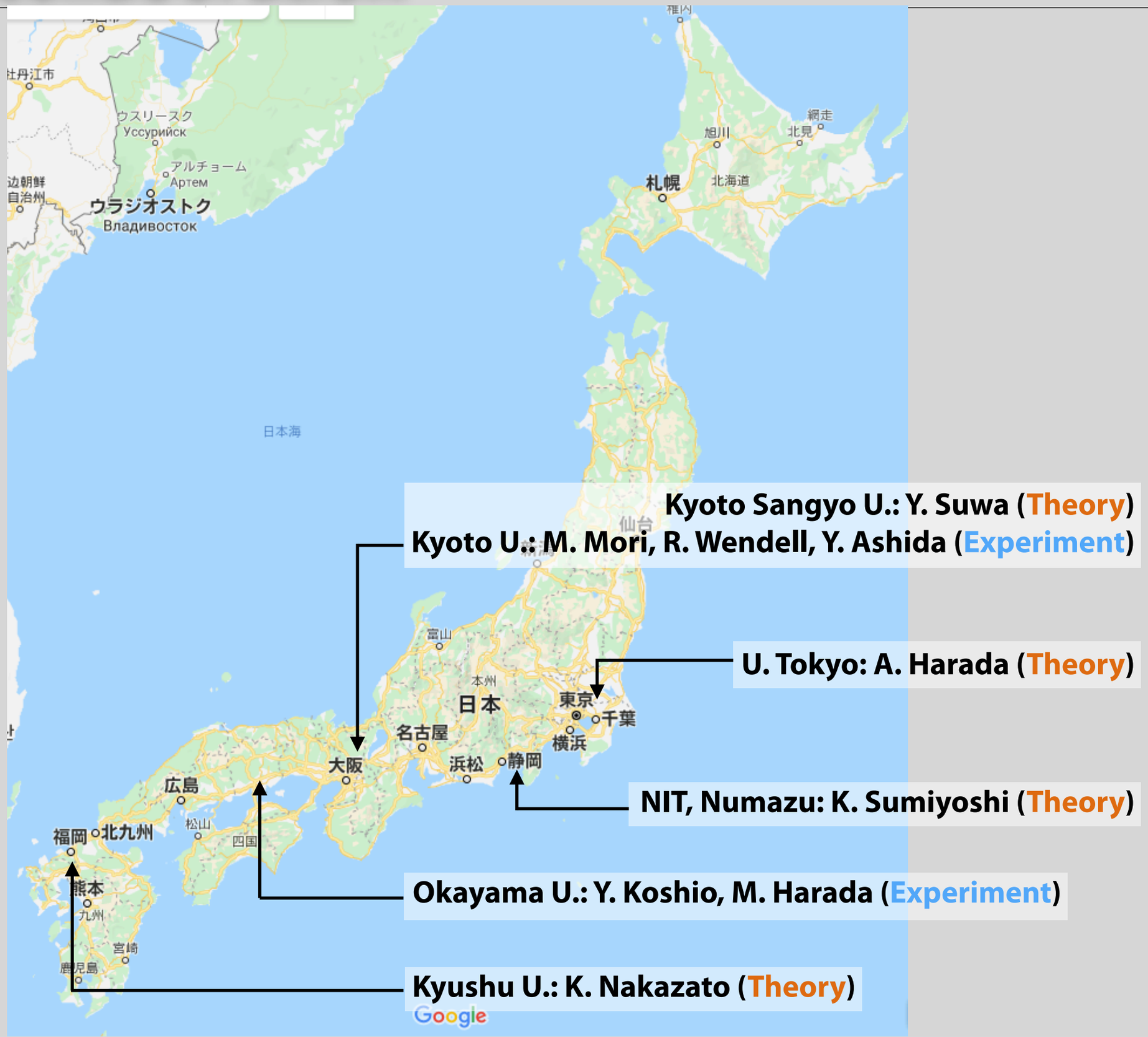
Takiwaki, Kotake, Suwa (2014)

Long-term evolution is essential

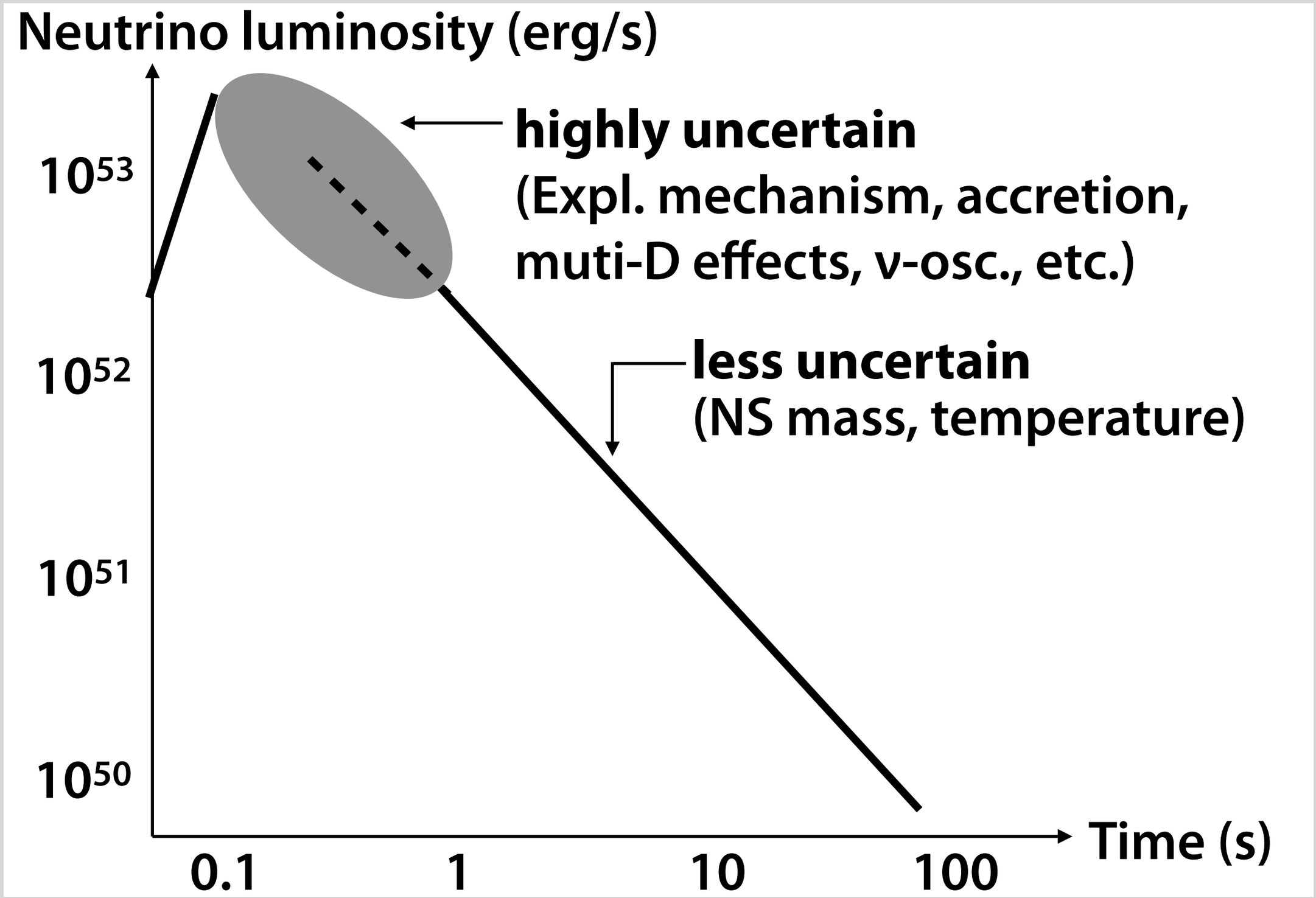


nuLC collaboration

“nuLC”
=neutrino Light Curve



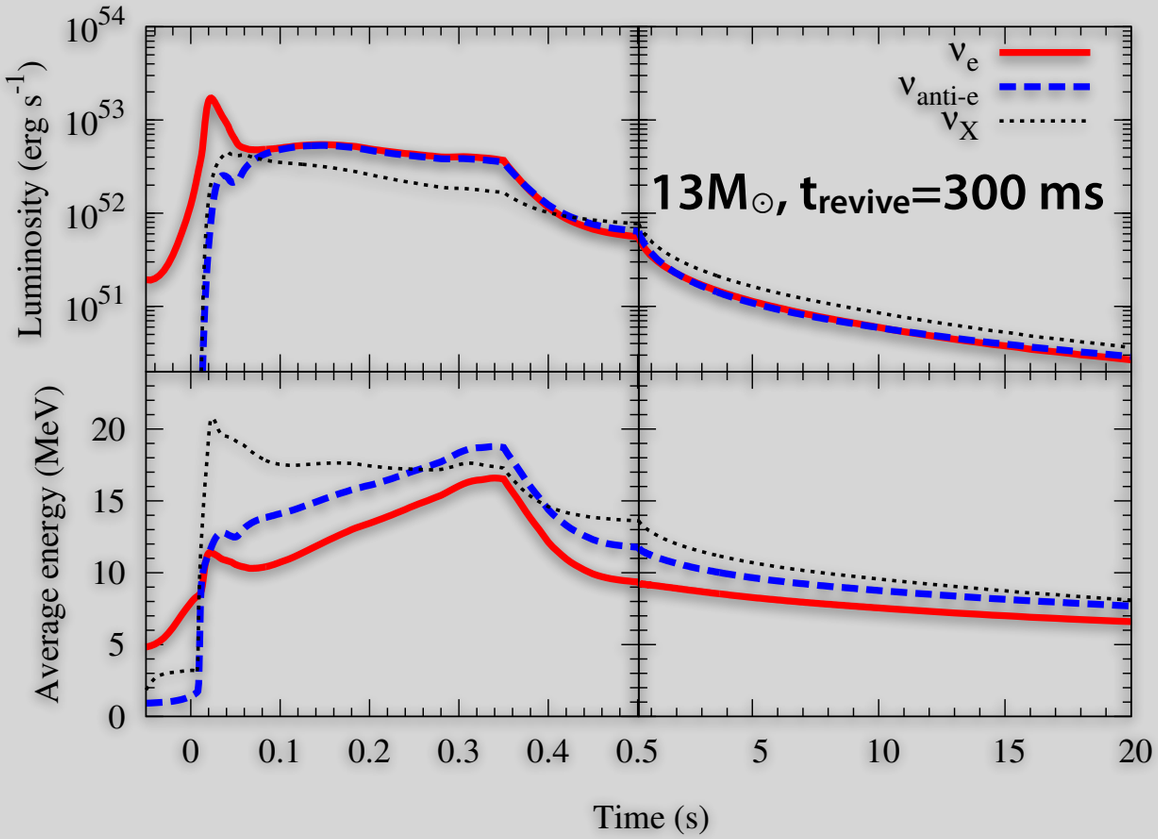
Late time ν-LC is simpler



Numerical simulations

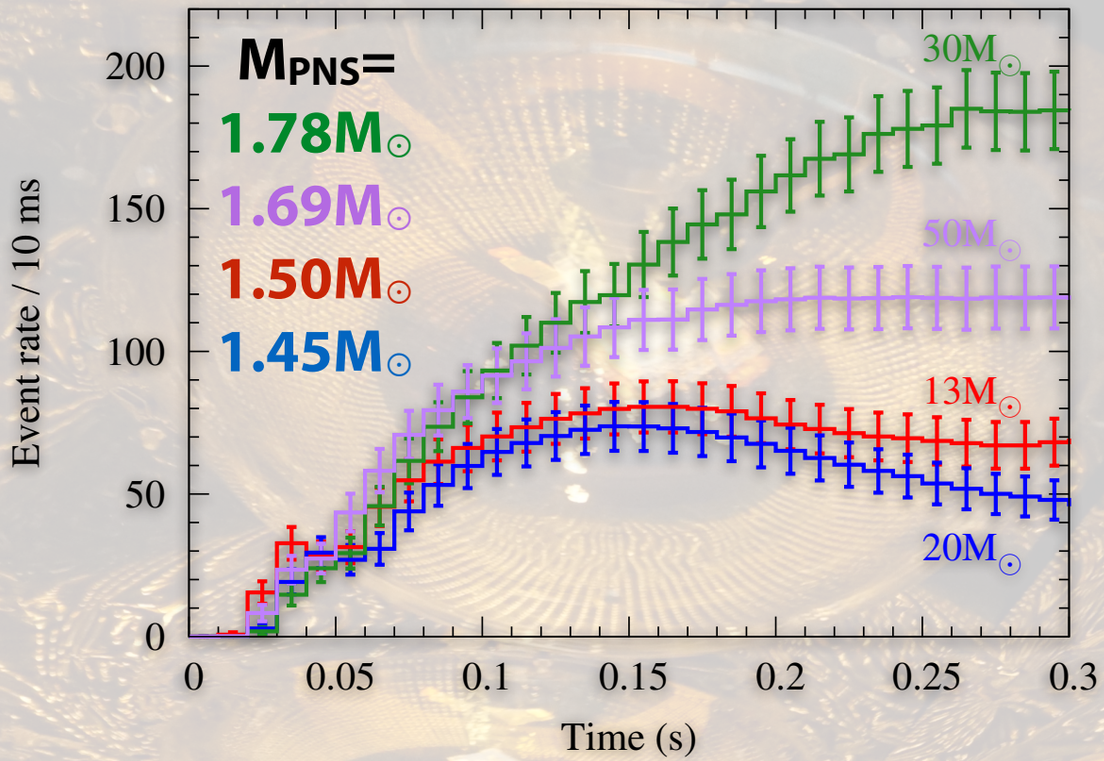
Supernova Neutrino Database
http://asphwww.ph.noda.tus.ac.jp/snn/

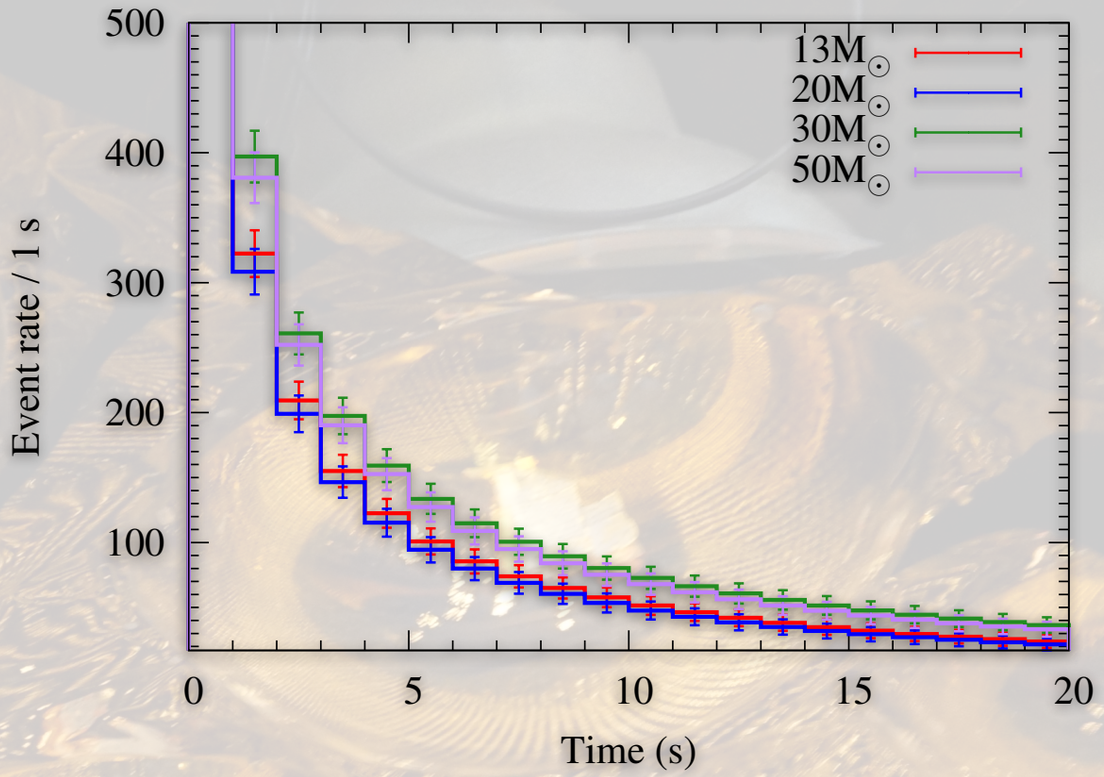
* **Hydro. simulation** (t<0.3s)
  - dynamical, GR, Boltzmann neutrino transport, nuclear EOS, 1D
    Yamada 1997, Sumiyoshi+ 2005
* **PNS cooling simulation** (t>0.3s)
  - static (TOV), FLD neutrino transport, nuclear EOS, 1D
    Suzuki 1993
* **Connection**
  - Interpolate two results with t_{revive}=100, 200, 300 ms (appox. explosion time)
    Nakazato+ 2013
* **Progenitor**
  - **13, 20, 30, 50 $M_\odot$**
    Umeda+ 2012



Event rate evolution

[Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, **881**, 139 (2019)]





- **Event rate evolution is calculated up to 20 s**
  - **with neutrino luminosity and spectrum**
  - **with full volume of SK's inner tank (32.5 kton)**
  - **from an SN at 10 kpc**
  - **only with inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)**
- **Event rate is not related to progenitor mass, but PNS mass**

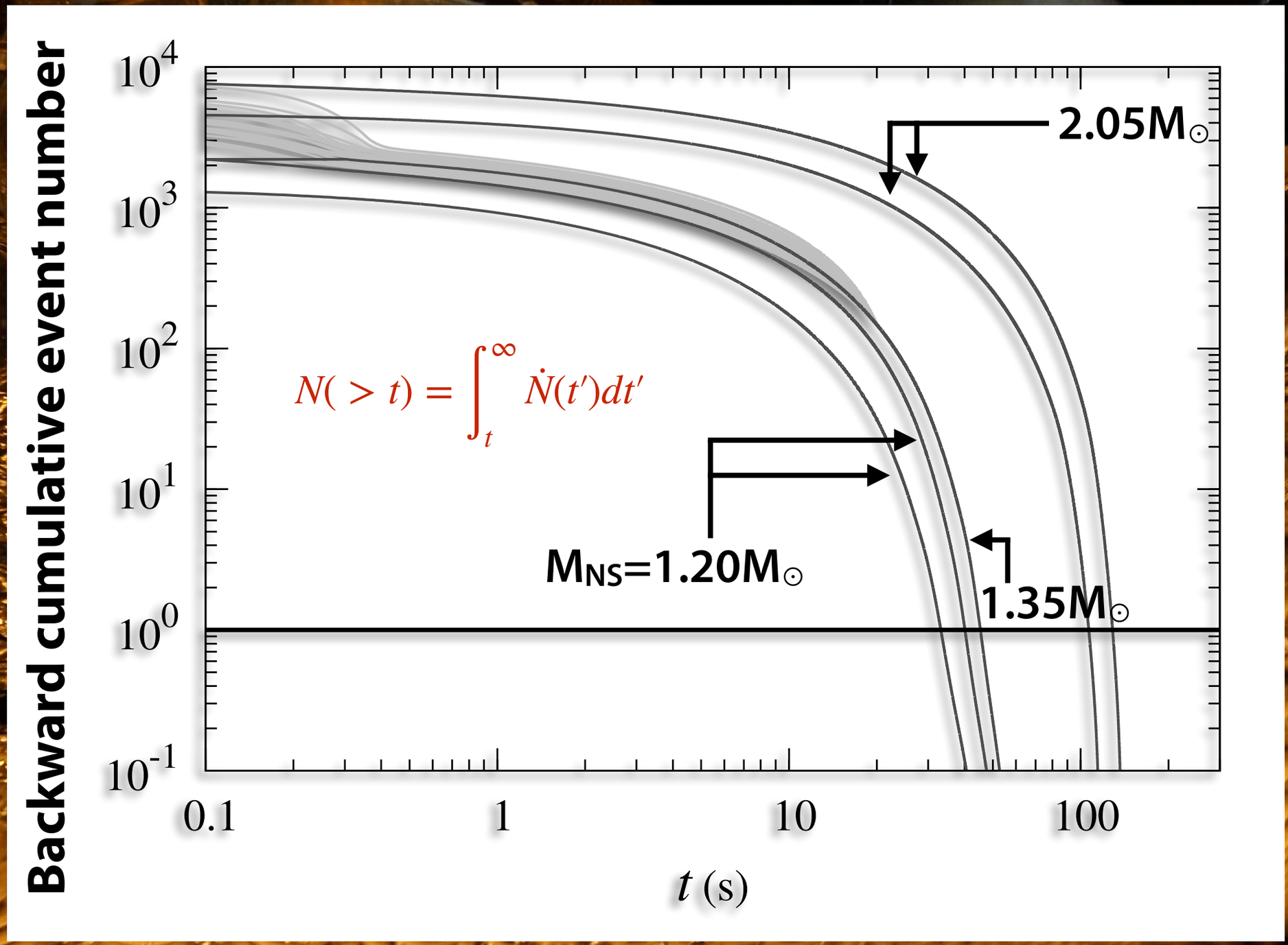
Longer simulations with broader NS mass range

- **Even 20 s after the explosion, the event rate is still high**
- **known mass range of NS is large: [1.17, 2.01]$M_\odot$**
  Demorest+ 2010, Antoniadis+ 2013, Martinez+ 2015
  (see also Cromartie+ 2019 for a recent update)

- **Additional long-term simulations for PNS cooling**
  - **canonical model has M_{NS}=1.35$M_\odot$**
  - **parametric models**
    - **with M_{NS}=1.20$M_\odot$ and 2.05$M_\odot$**
    - **with two extreme entropy profiles (low and high)**
  - **up to the *last* detectable event**

How long can we see SN with neutrinos?

[Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, **881**, 139 (2019)]



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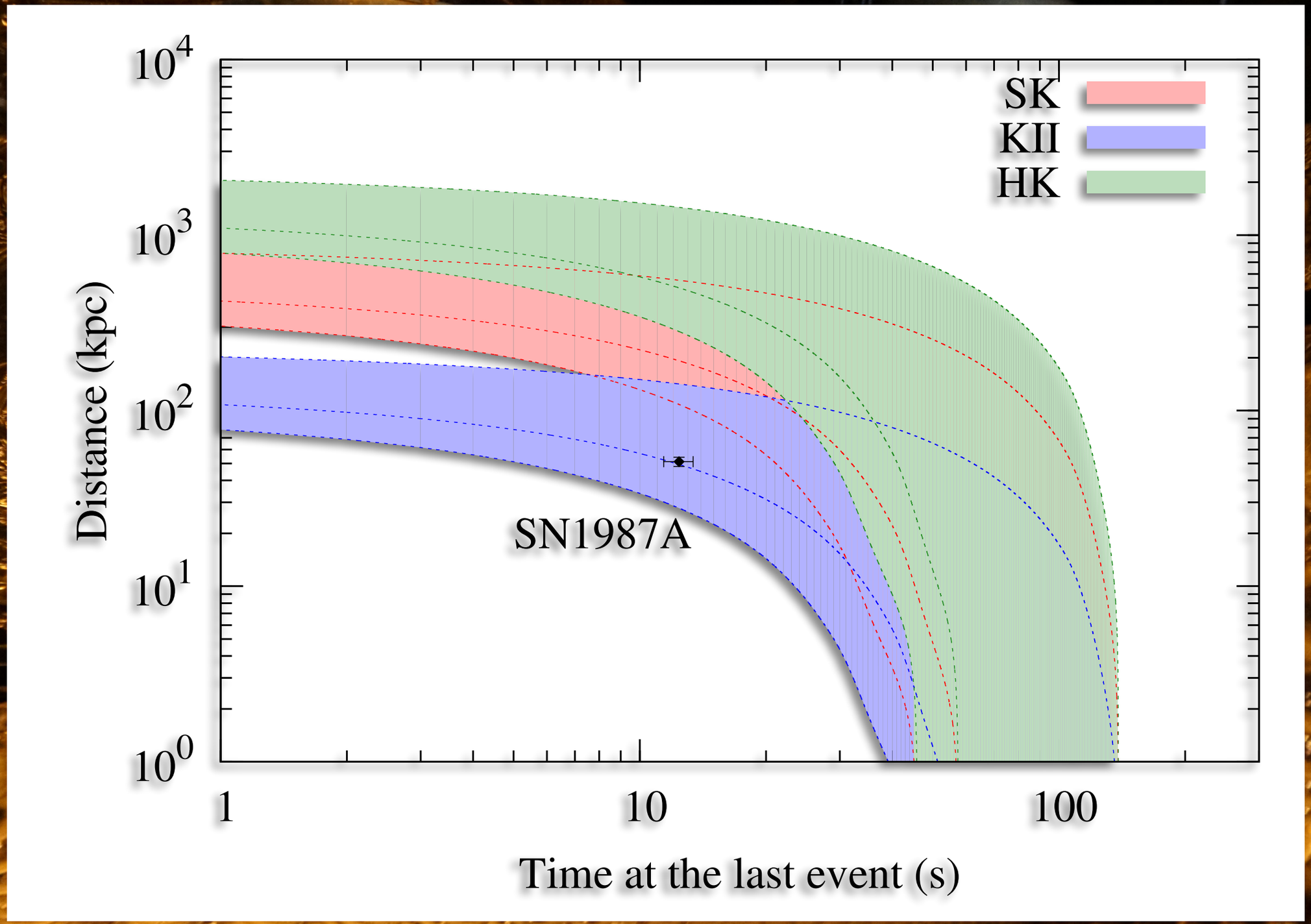
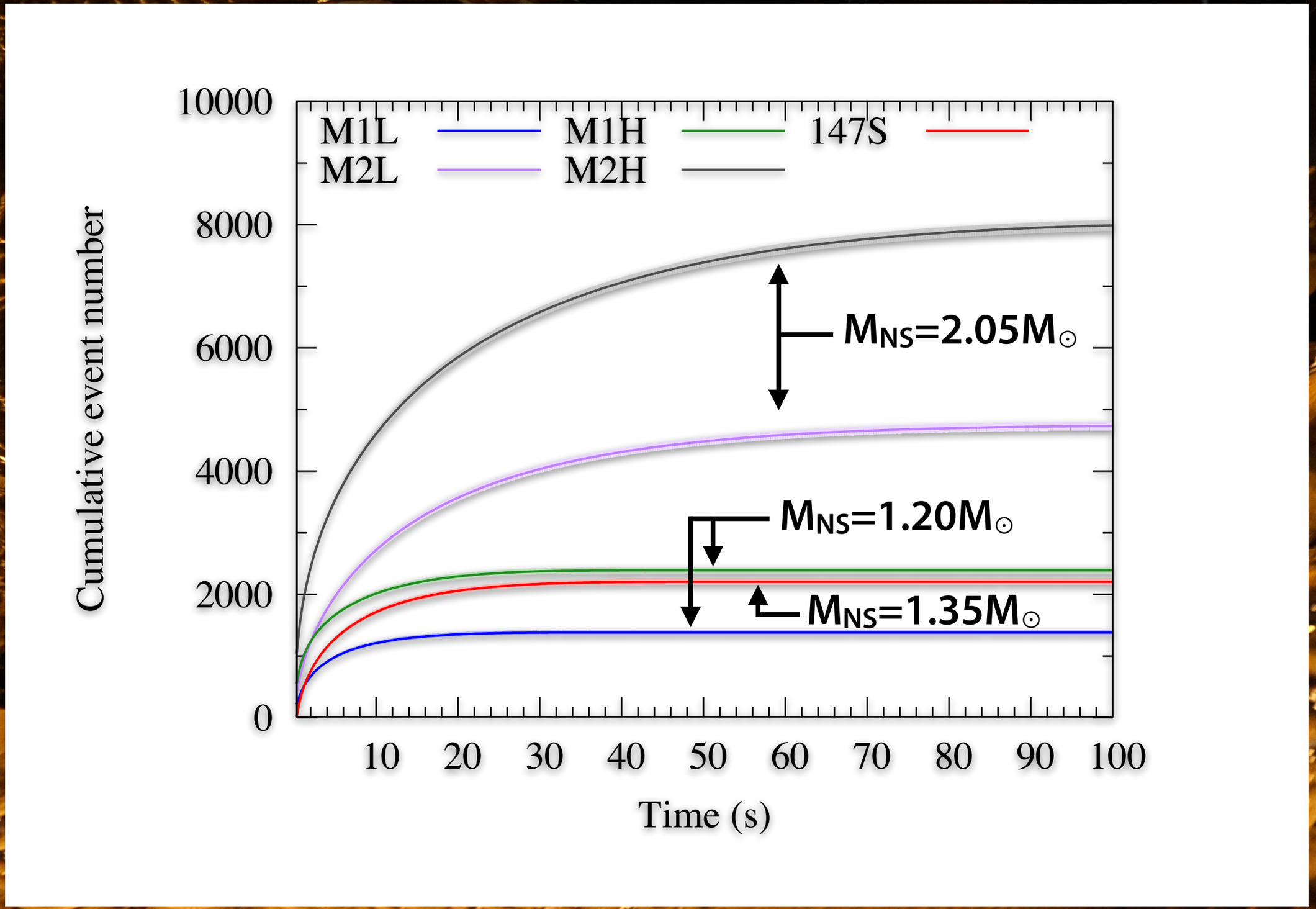
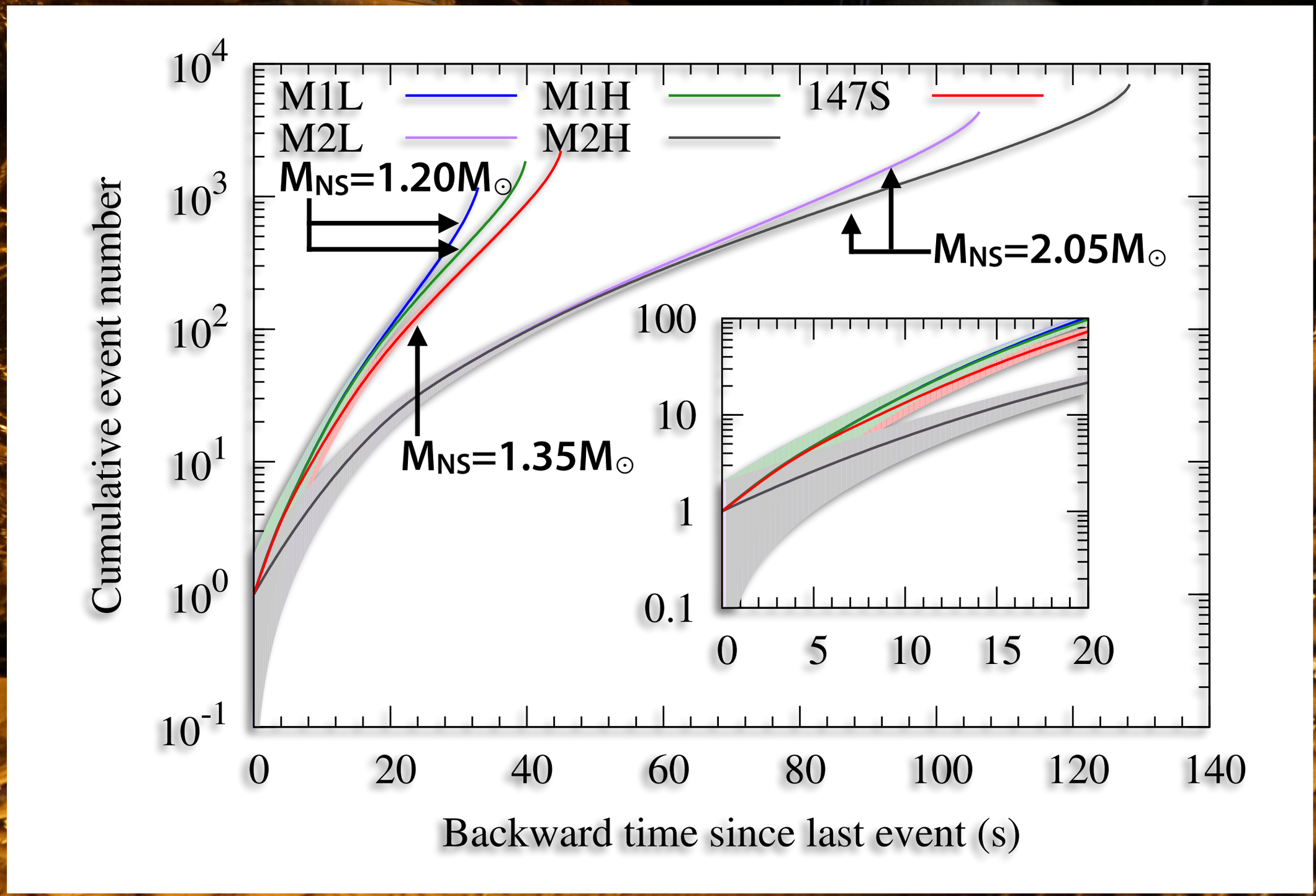


How to analyze neutrinos?



Backward cumulative plot

[Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, **881**, 139 (2019)]



Summary

* **Neutrinos from the next Galactic SN are studied**

* **Take home message**
  - **O(10^3) ν will be detected, correlated to M_{NS}**
  - **Observable time scale is O(10)s, even > 100s**
  - **Backward cumulative event number is useful**

* **Next step**
  - **spectral analysis**
  - **EOS dependence**
  - **other processes (νe, ν^{16}O)**