progress report of
subscription research (公募研究)

Analytic solutions for neutrino-light curves of supernovae

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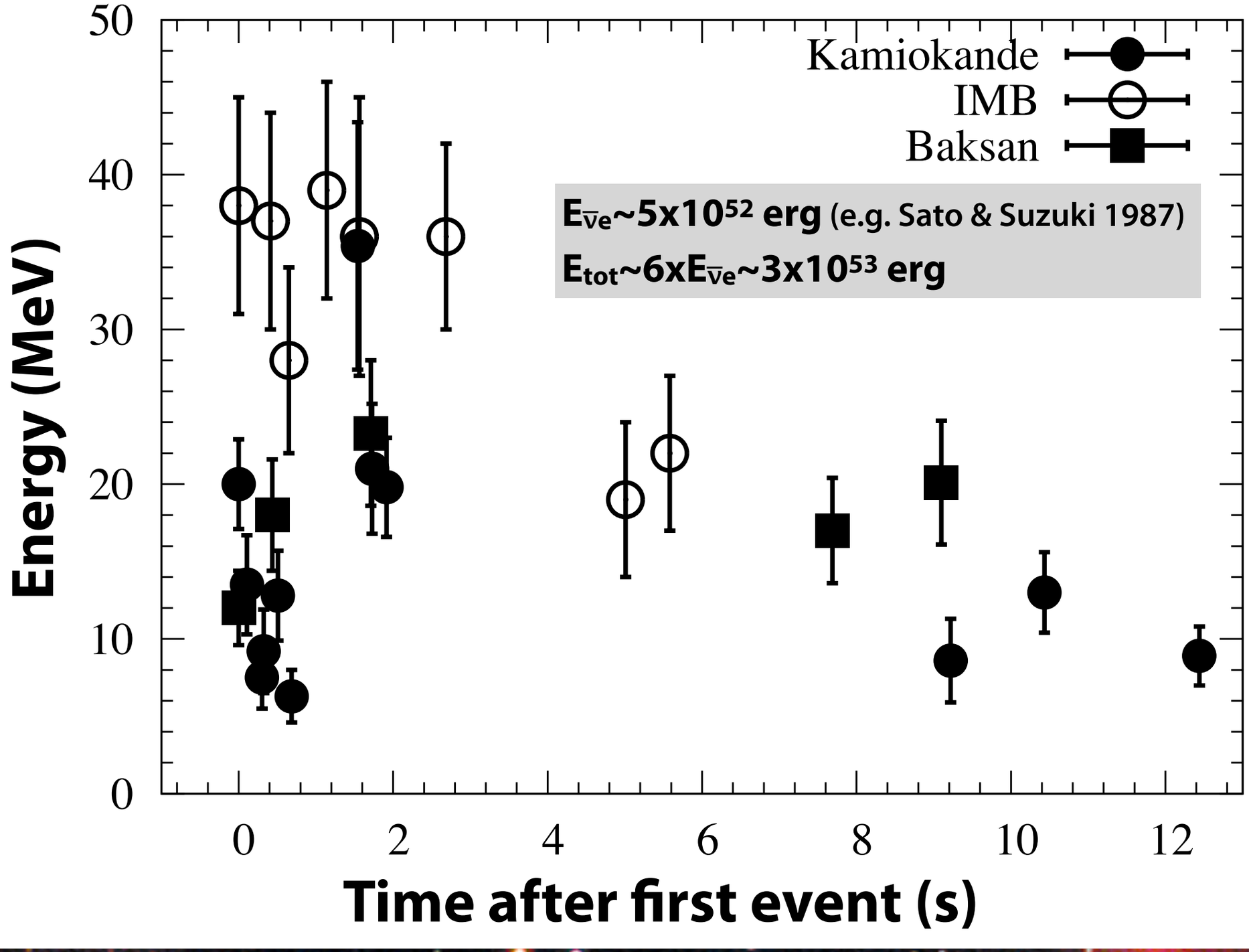
with nuLC collaboration

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? No conclusive estimation so far!**

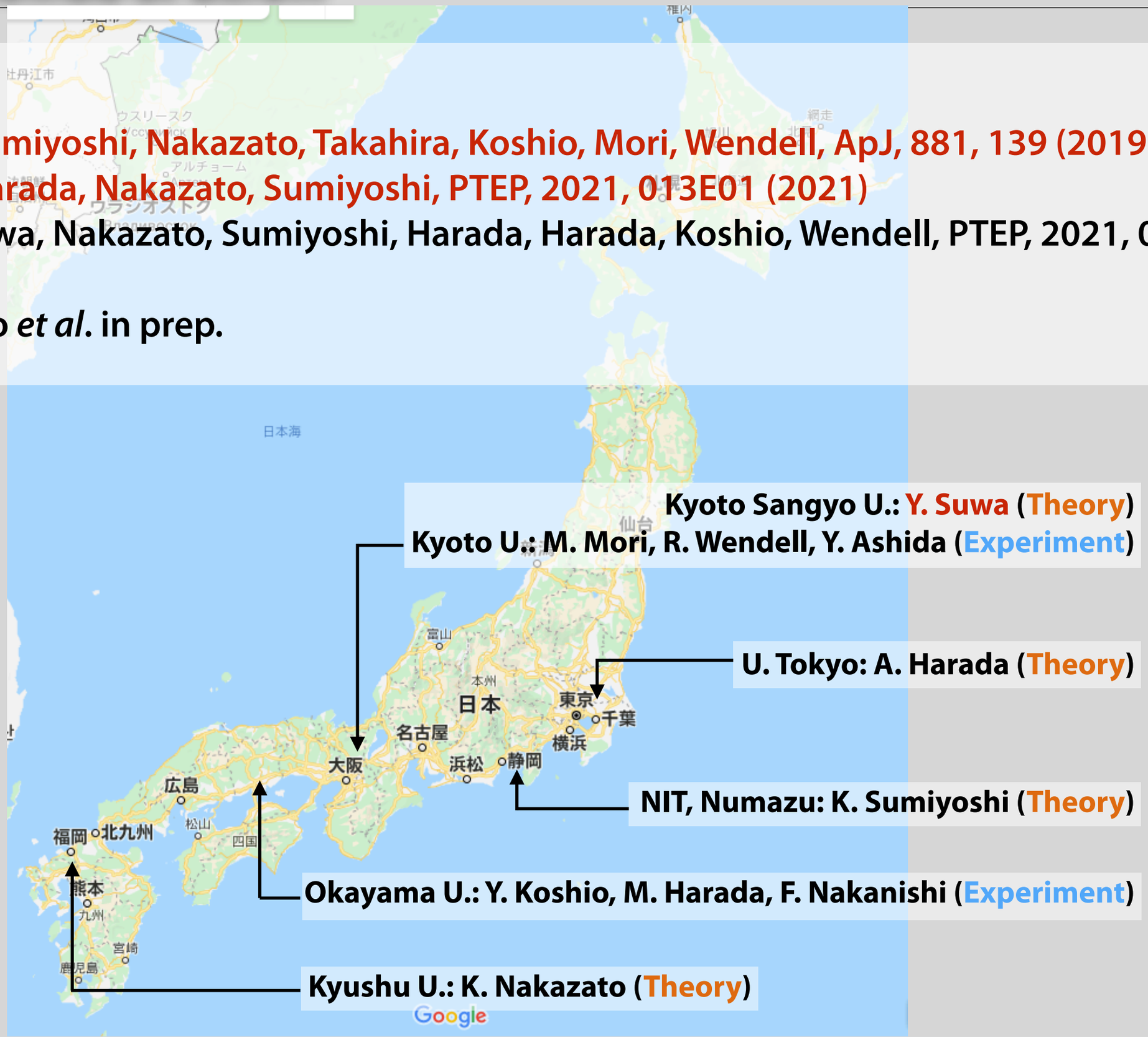
The latest SN found in our Galaxy, G1.9+0.3 (<150 years old) © NASA

nuLC collaboration

“nuLC”
=neutrino Light Curve

Papers:

1. **Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019)**
2. **Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 013E01 (2021)**
3. **Mori, Suwa, Nakazato, Sumiyoshi, Harada, Harada, Koshio, Wendell, PTEP, 2021, 023E01 (2021)**
4. **Nakazato *et al*. in prep.**



Kyoto Sangyo U.: Y. Suwa (Theory)
Kyoto U.: M. Mori, R. Wendell, Y. Ashida (Experiment)

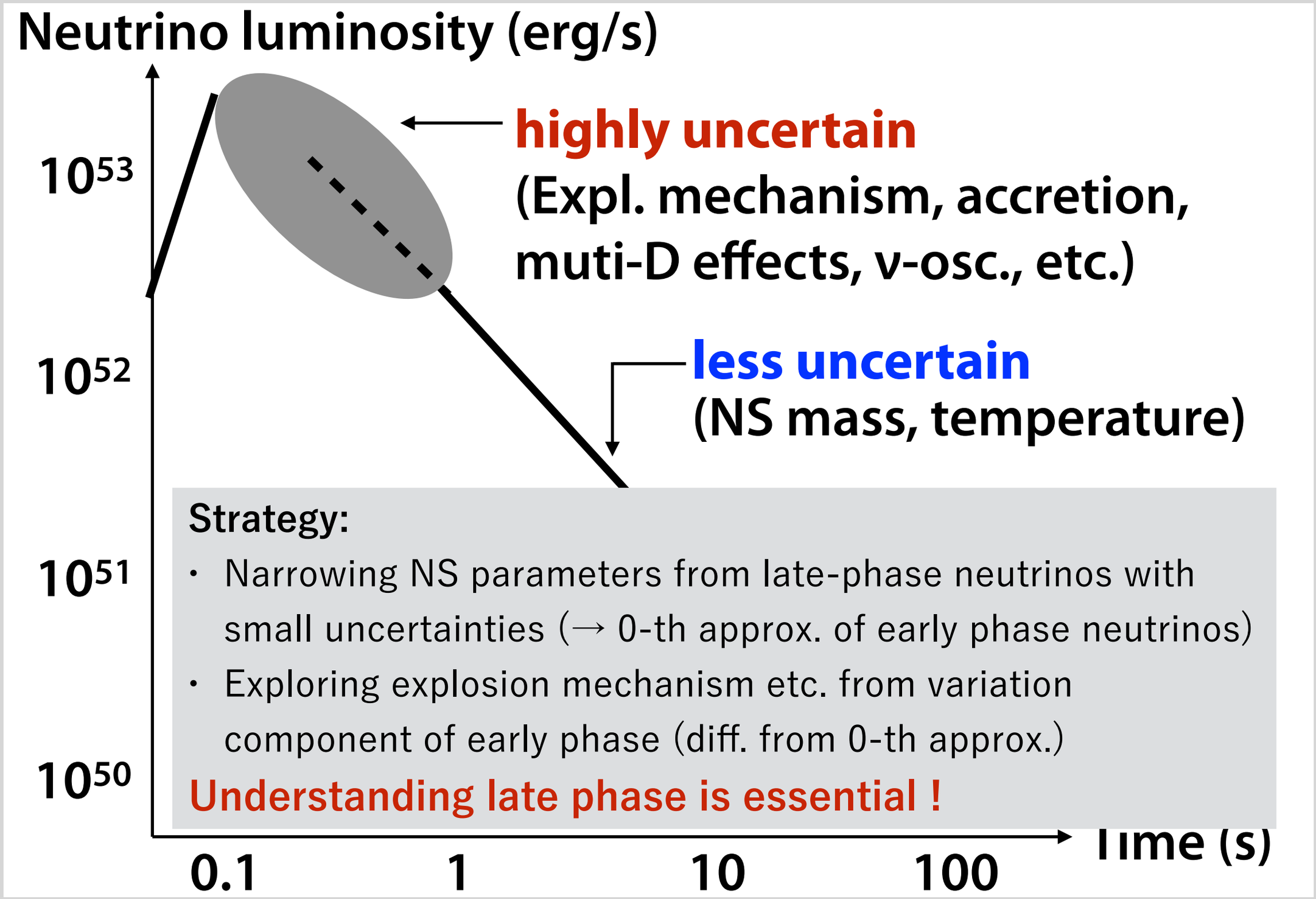
U. Tokyo: A. Harada (Theory)

NIT, Numazu: K. Sumiyoshi (Theory)

Okayama U.: Y. Koshio, M. Harada, F. Nakanishi (Experiment)

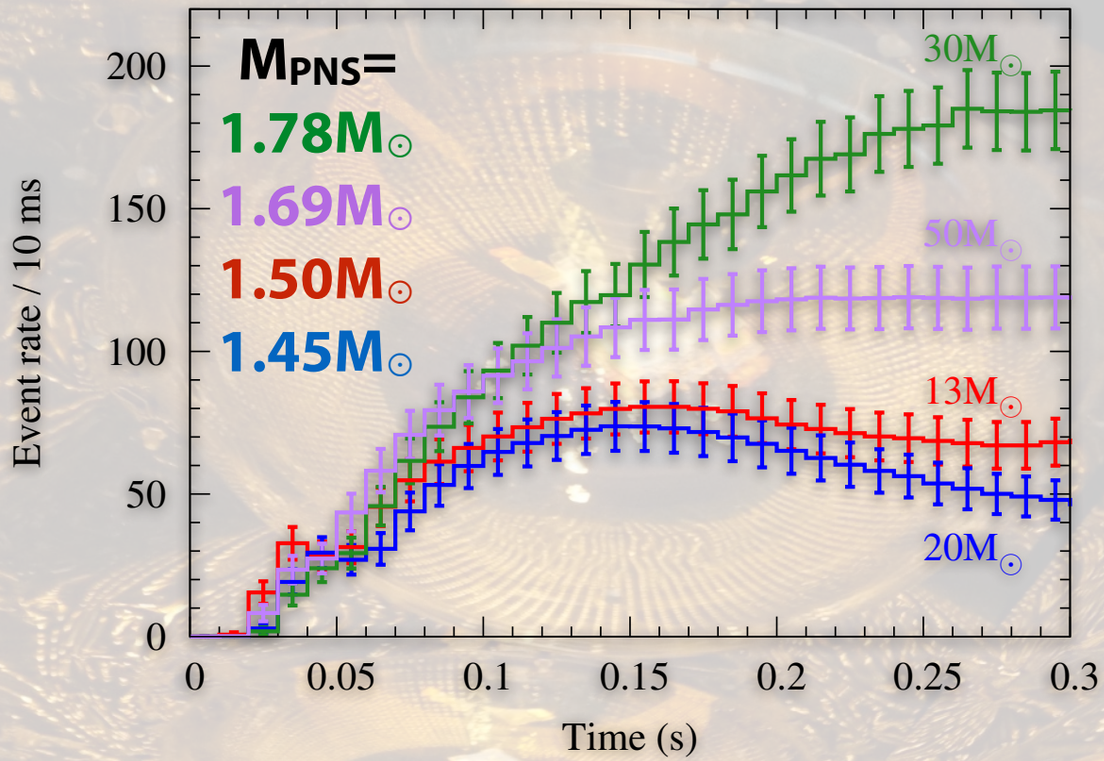
Kyushu U.: K. Nakazato (Theory)

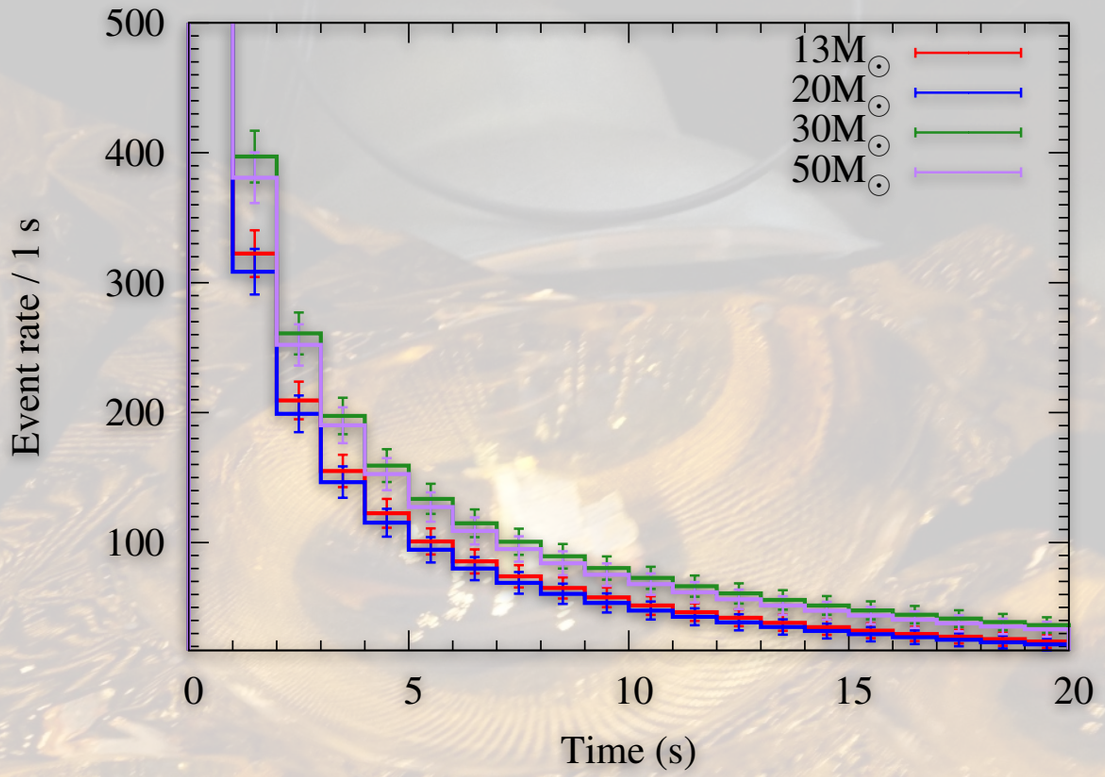
Late time ν-LC is simpler



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**

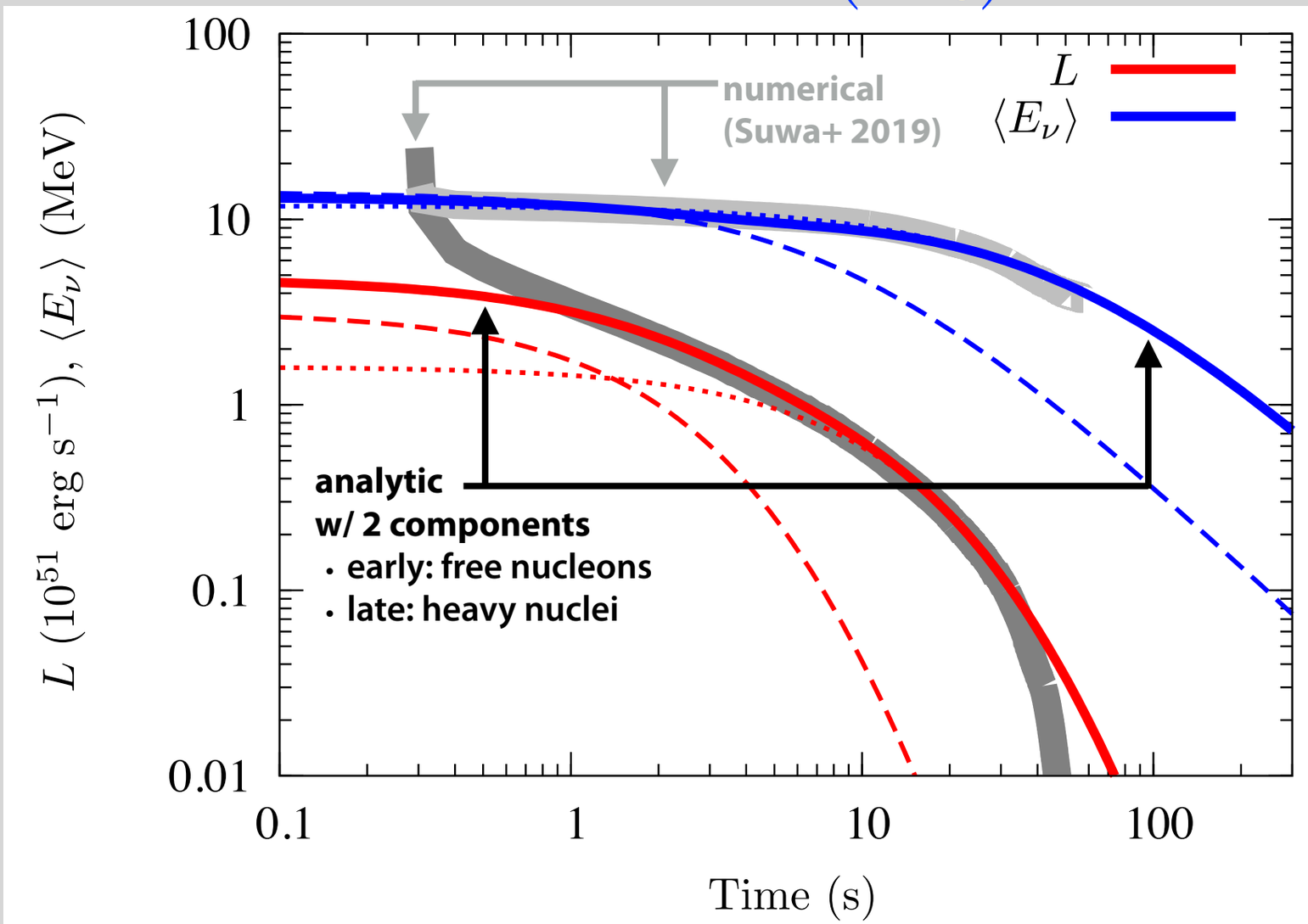
Analytic solutions

[Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 0130E01 (2021)]

* **Solve neutrino Boltzmann eq. analytically**

  - **Neutrino luminosity:** $L = 3.3 \times 10^{51}\,\mathrm{erg\,s^{-1}} \left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{6} \left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-6} \left(\frac{g\beta}{3}\right)^{4} \left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-6}$

  - **Neutrino average energy:** $\langle E_\nu \rangle = 16\,\mathrm{MeV} \left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{3/2} \left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-2} \left(\frac{g\beta}{3}\right) \left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-3/2}$



Observables with analytic solutions

[Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 0130E01 (2021)]

* **Event rate w/ SK from SN @10kpc**

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

* **Positron average energy**

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

* **PNS radius**

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

* **Consistency relation of analytic model**

$$\frac{\mathscr{R}\dddot{\mathscr{R}}}{\dot{\mathscr{R}}^2} = \frac{17}{15}$$

Summary

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

* **Take home messages**
  - **O(10³) ν will be detected, correlated to M_{NS}**
  - **Observable time scale is O(10)s, even > 100s**
  - **Simple analytic expressions are available**

* **Next step**
  - **spectral analysis**
  - **EOS dependence**