12th SNν Workshop
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九州大学
基幹教育院
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鉱物飛跡検出器で探る近傍超新星の履歴

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Paleodetectors

- Damage track detection in mineral
- Geologic time scale; >O(100) Myr

damage track

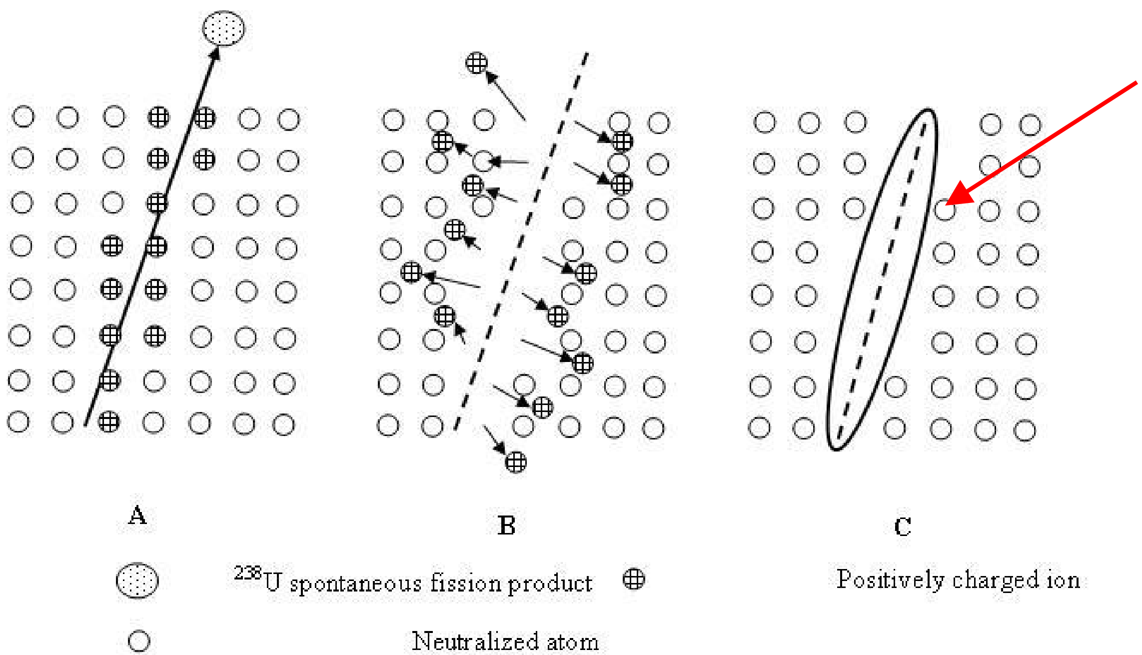

Figure 1. Track formation in a simple crystalline solid: **A** the atoms have been ionize by the massive charged particle which has just passed; **B** the mutual repulsion of the ion has separated them and forced them into the lattice; C observable track after etching (Modified after Fleischer et al., 1965a)

Epsomite
$Mg(SO_4)\cdot 7(H_2O)$

c.f. Naka-san's talk
@ 10th SN ν Workshop

Science with paleodetectors

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- Search for rare events
  - ✓ Dark matter (WIMP, Q-ball, monopole)
  - ✓ Cosmic-ray of ultra heavy nuclei
  - ✓ Neutrinos
- Small size but long exposure
- Backgrounds from ^{238}U etc.
  - ✓ ^{234}Th from α decays ($^{238}\mathrm{U} \rightarrow {}^{234}\mathrm{Th} + \alpha$)
  - ✓ Fast neutrons from (α, n) reactions
  - ✓ Neutrons from spontaneous fissions

ν coherent scattering

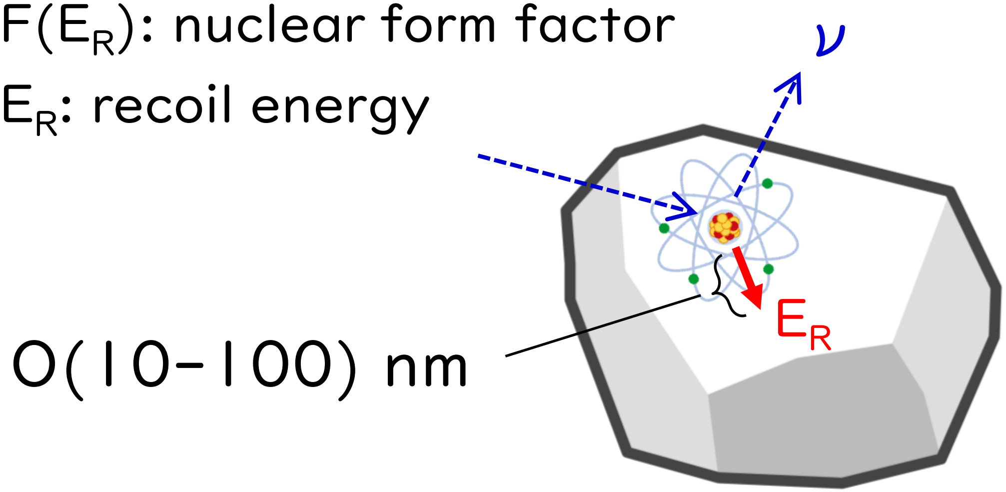
- Neutral current interaction with neutrinos of <O(100) MeV
  - ✓ Flavor independent

$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{4\pi} Q_W^2 m_T \left(1 - \frac{m_T E_R}{2E_\nu^2}\right) F^2(E_R)$$

$$Q_W = (A_T - Z_T) - (1 - 4\sin^2\theta_W) Z_T$$

$F(E_R)$: nuclear form factor

E_R: recoil energy



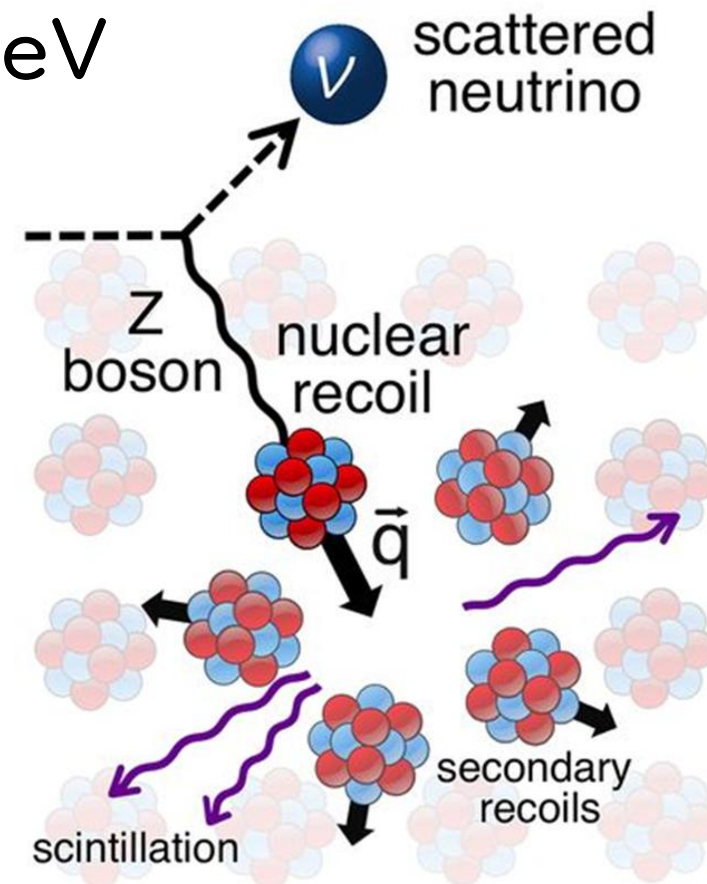


Image credit: COHERENT Collaboration

Galactic supernovae

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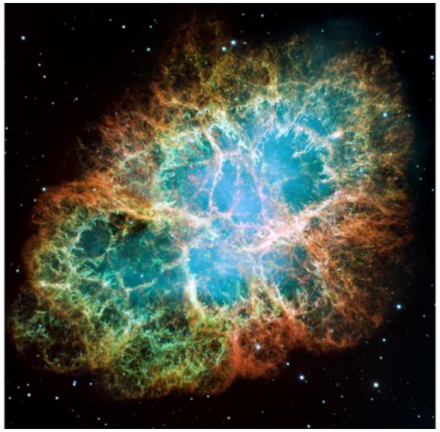
- Event rate: a few per century
- Age of the solar system is 4.6 Gyr
- The Earth has experienced $O(10^8)$ times of Galactic supernova neutrino burst

http://umdb.um.u-tokyo.ac.jp/DPastExh/Publish_db/1997DM/DM_CD/DM_CONT/INSEKI/HOME.HTM



https://hubblesite.org/contents/media/images/2005/37/1823-Image.html

Baum et al. (2020)

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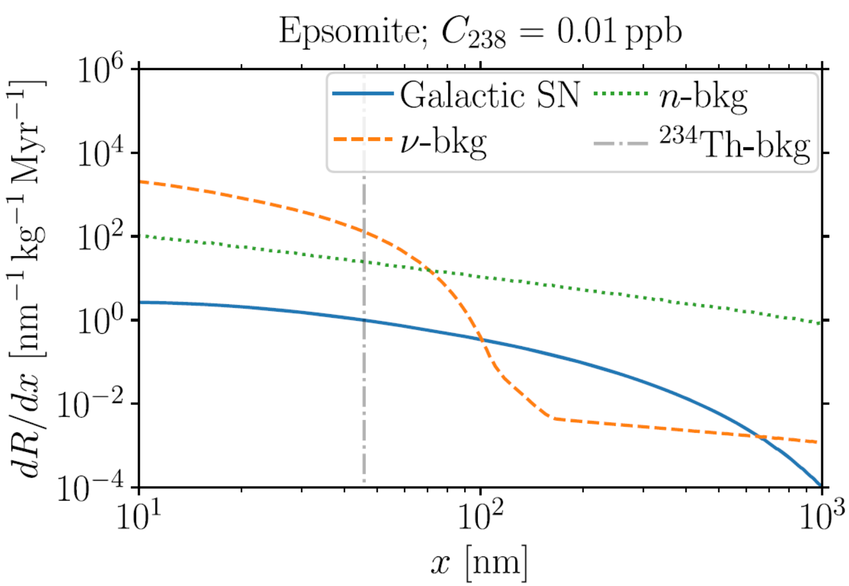
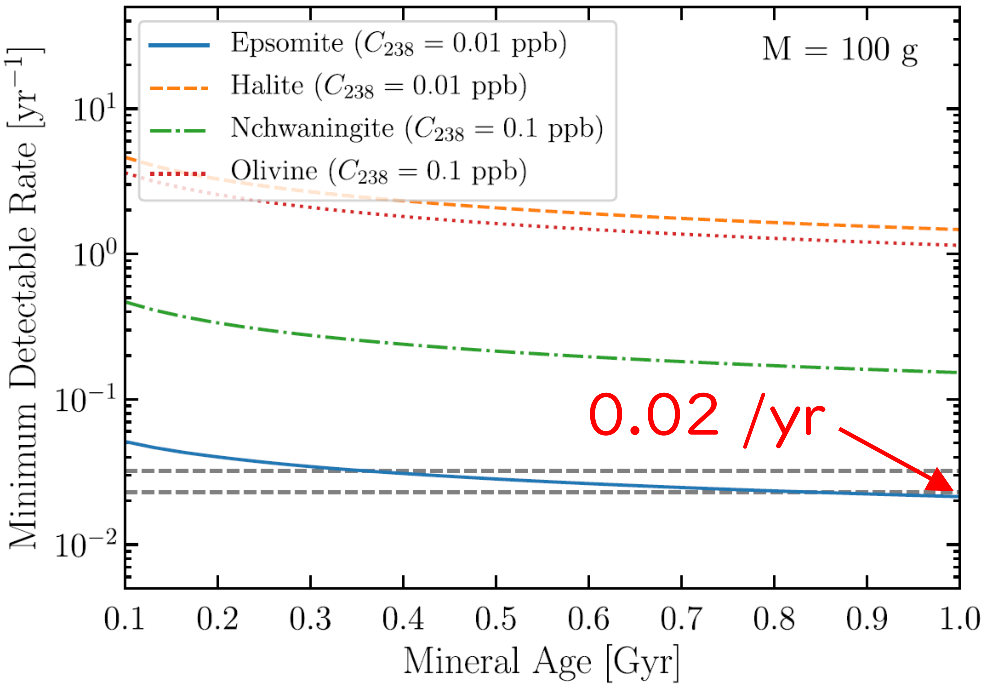
- Neutrinos from past Galactic supernovae are recorded in paleodetectors
  - ✓ If SN rate >0.02 /yr, signal is detectable using epsomite with 100 g & age of 1 Gyr

Length spectrum of damage track





Present study

1. Spectrum of supernova neutrinos depends on nuclear equation of state
2. Stellar collapse exhibits diversity (the remnants may be high-mass neutron stars or black holes)

   ✓ In the previous study (Baum et al., 2020), a single spectrum with simple form was assumed for the supernova neutrinos

- We adopt numerical models of neutrino spectra from Ashida & Nakazato (2022)

Minimum detectable rate

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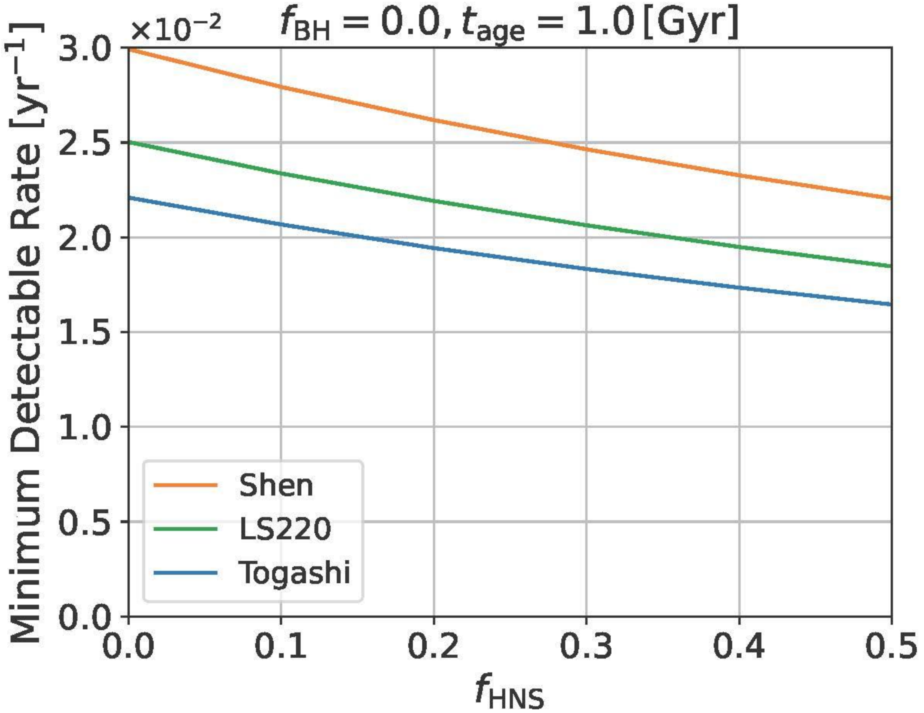
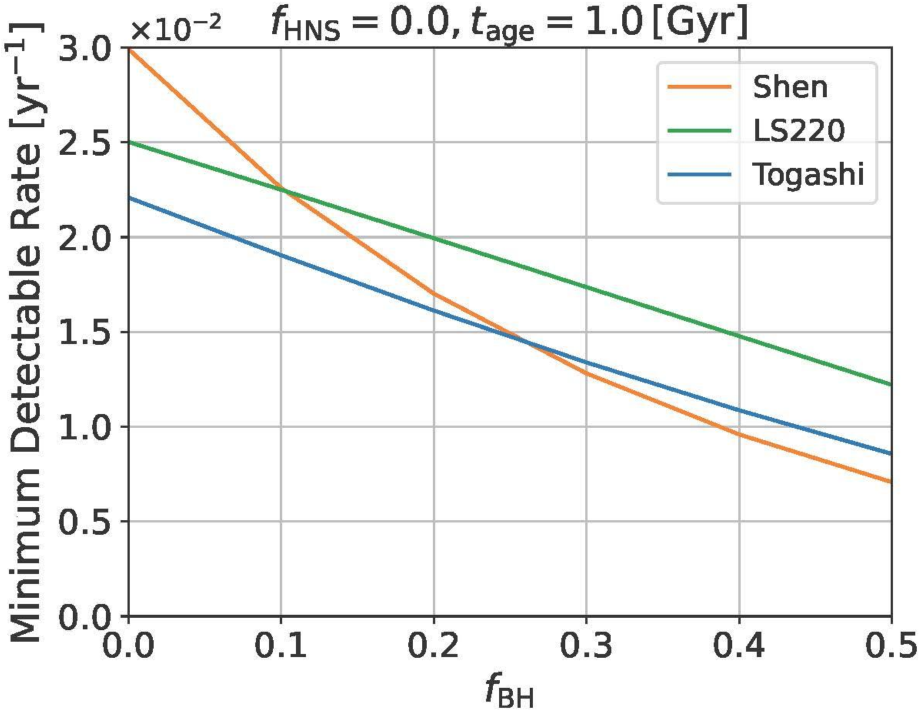
- Previous (Baum et al. 2020): 0.02 /yr





f_{HNS}: fraction of SNe with high-mass NSs

f_{BH}: fraction of BH-forming collapses

Diversity & uncertainty (I)

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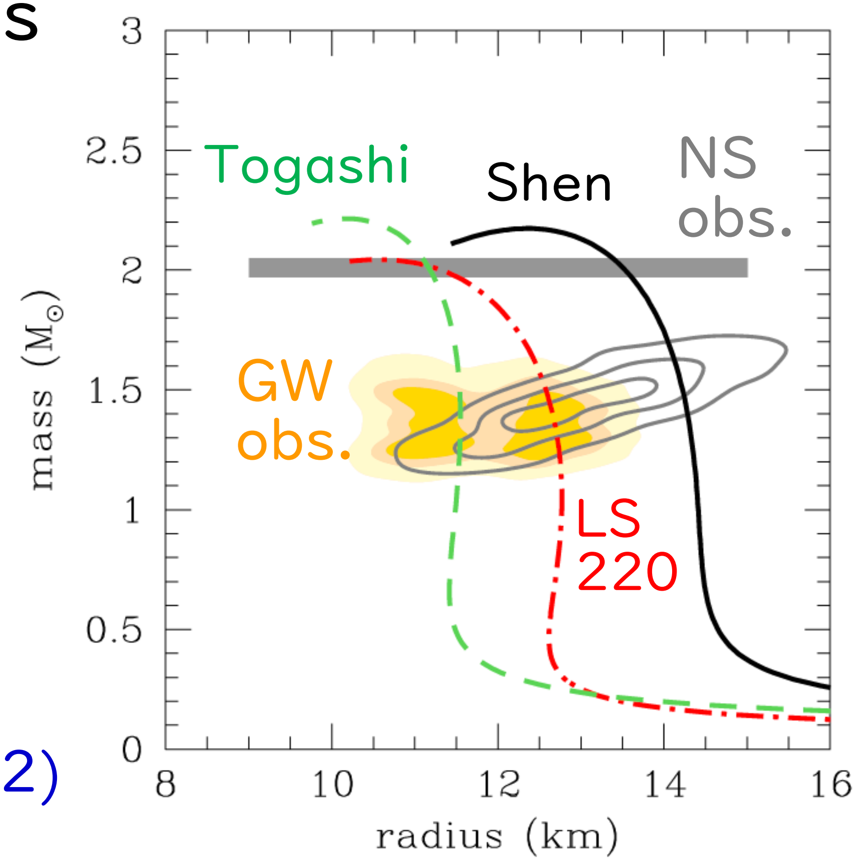
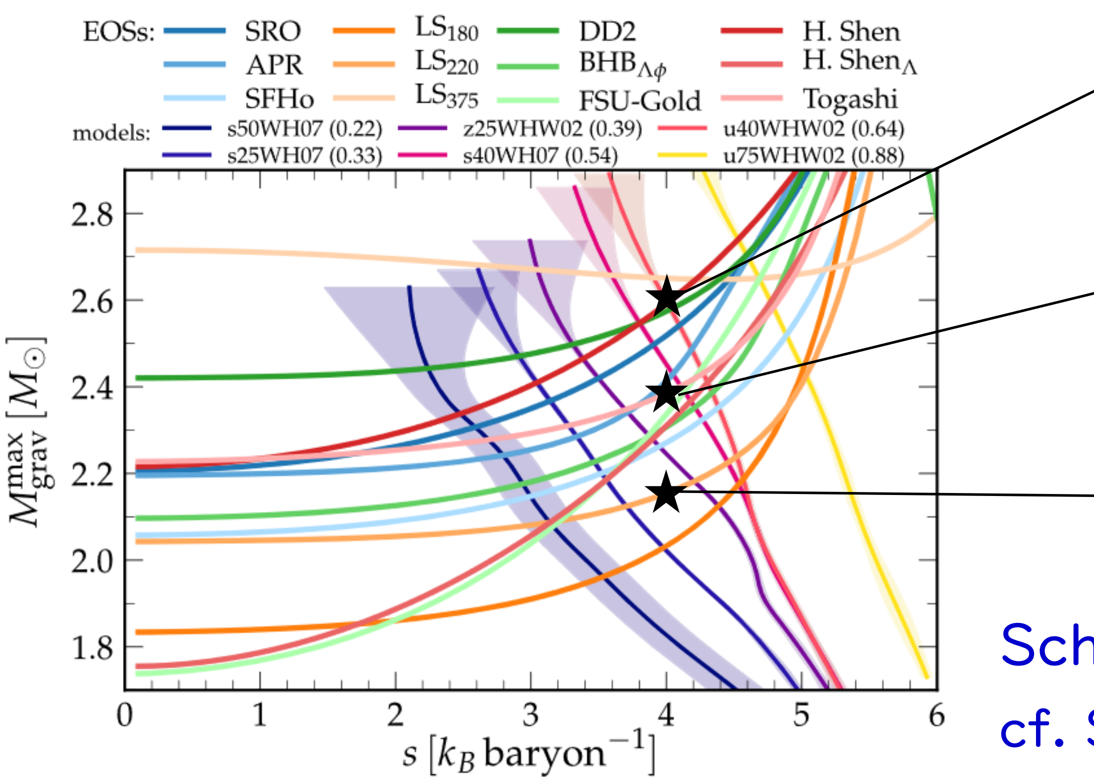
- For NS formation, the neutrino emission reflects the gravitational binding energy
  - ✓ Larger for larger mass and smaller radius
  - ✓ Togashi > LS > Shen



Adapted from Nakazato et al. (2022)

Diversity & uncertainty (2)

- For BH formation, the maximum mass of NSs determines the neutrino emission
  - ✓ Finite temperature should be considered



Shen

>

Togashi

>

LS220

Schneider et al. (2020)

cf. Suwa et al. (2025)

Radial migration of the Sun

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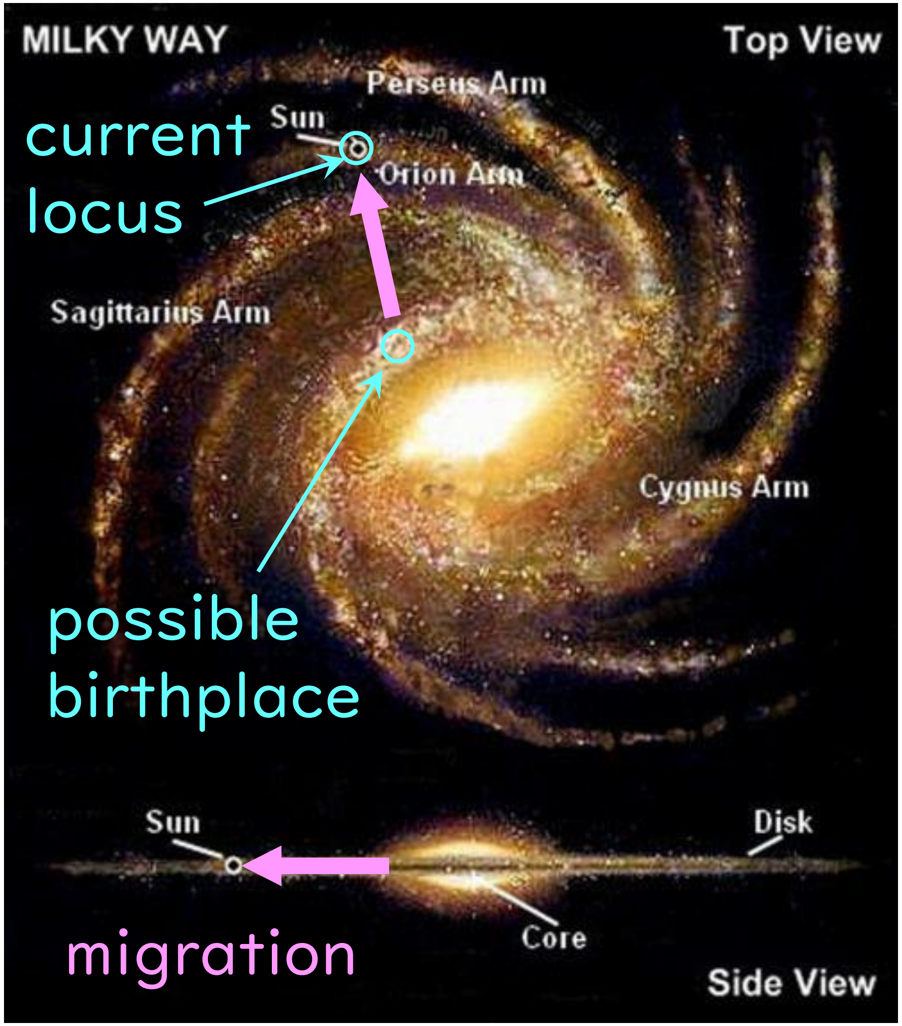
- Solar system has radially migrated
- Encounters with spiral arms
  - ✓ Star forming region
  - ✓ Strong irradiation including cosmic rays from SNe



Impact on the Earth

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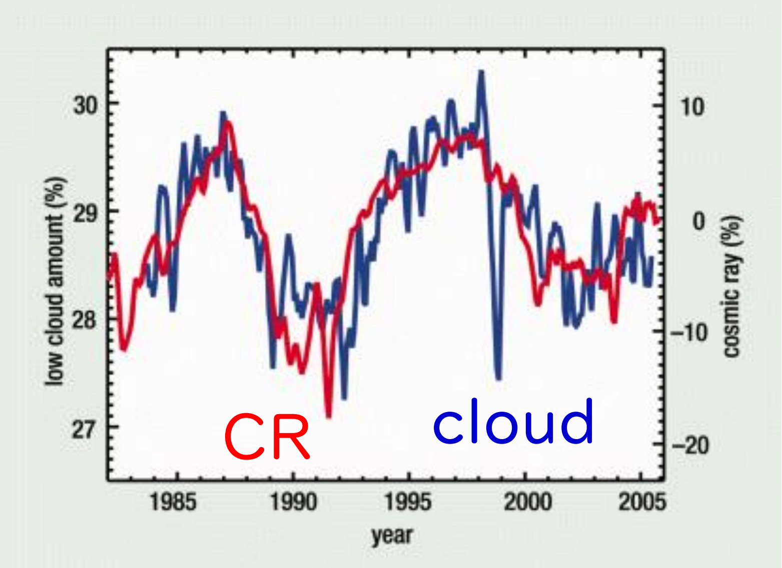
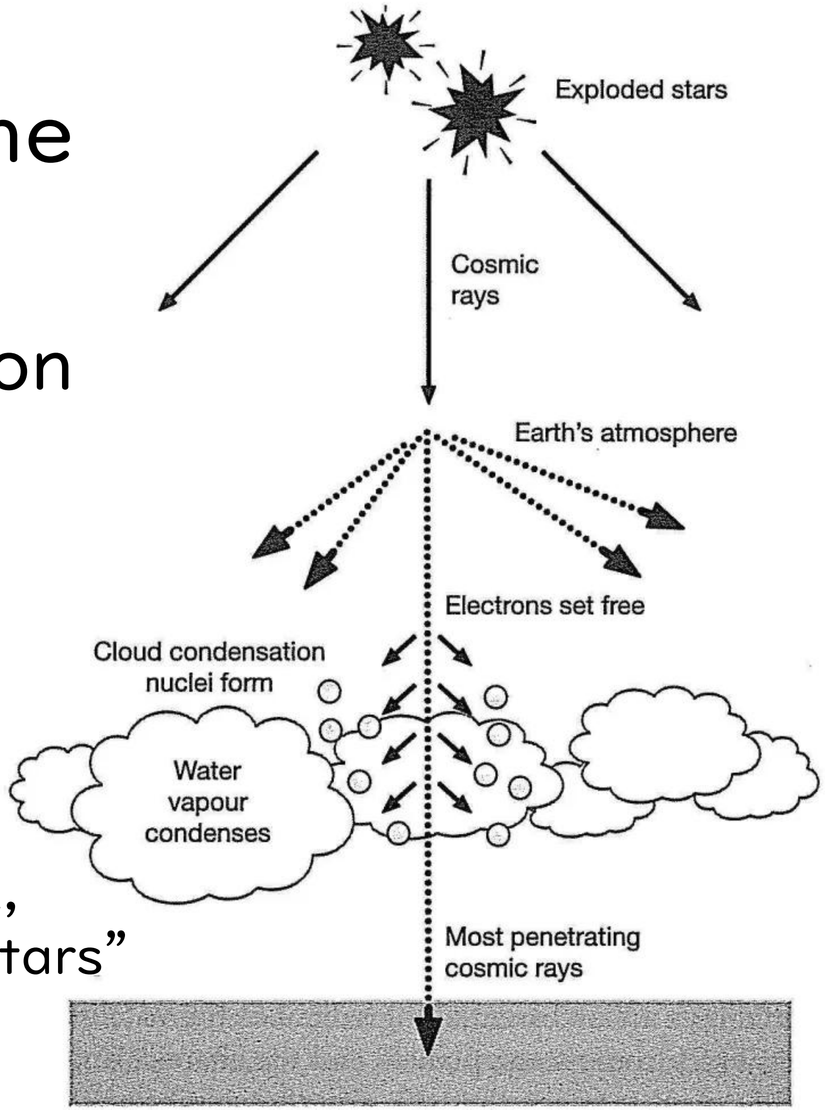
- An enormous influx of cosmic rays increase the seed of cloud
  - ✓ Ionization and nucleation
- Strong cooling effect



Svensmark, "Chilling stars" (2007)



Snowball Earth (全球凍結)

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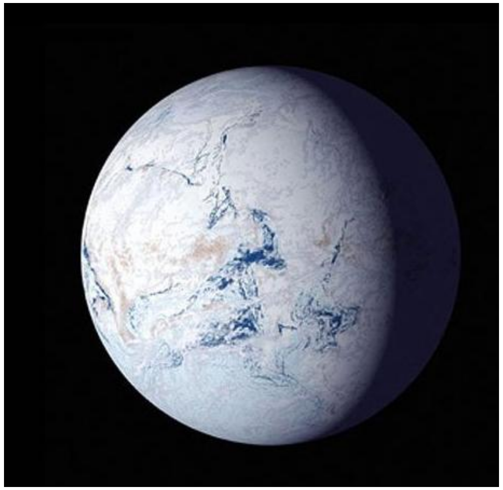
- Earth's surface was entirely ice-covered
  - ✓ Once snow and ice begin to spread, Earth reflects more sunlight, receives less heat, and accelerates the cooling
- Thought to have occurred three times: about 2.2 Gyr, 0.75 Gyr, and 0.65 Gyr ago
- Caused by burstlike SNe?
  - ✓ Tsujimoto & Baba (2020)



https://astrobiology.nasa.gov/news/sustaining-aerobic-eukaryotes-on-snowball-earth/

Detection of burstlike SNe

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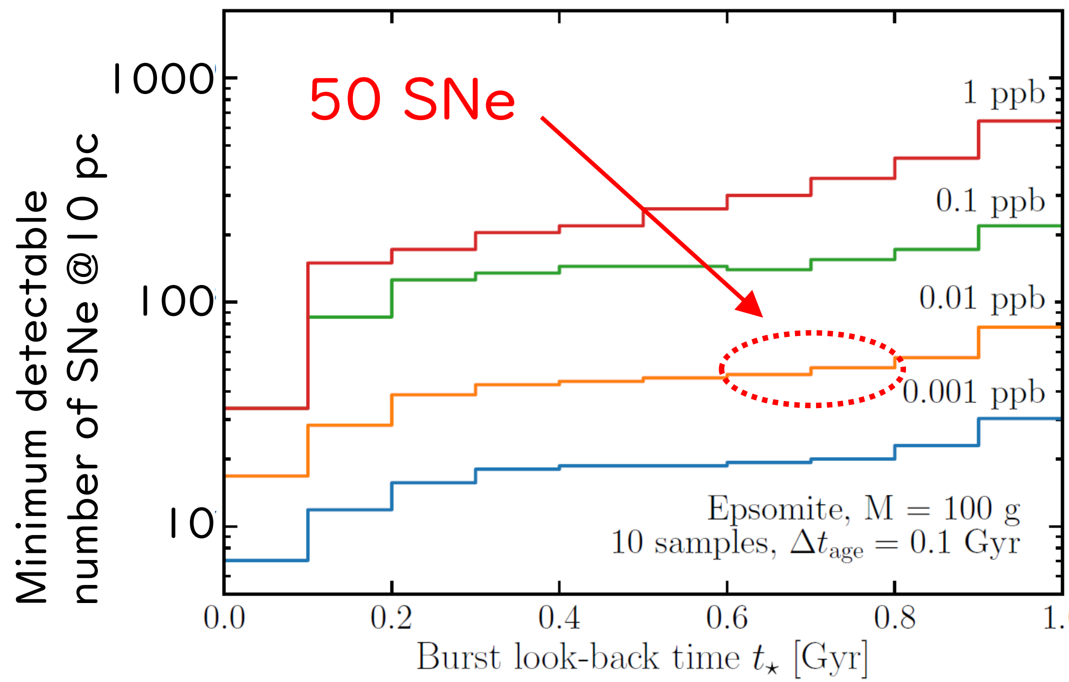
- Paleodetectors have sensitivity to time- and space-localized SN events
  - ✓ 10 samples with ages of 0.1, 0.2, ⋯ 1 Gyr
  - ✓ Burst of >50 SNe @10 pc, 0.6-0.8 Gyr ago is detectable

Adapted from Baum et al. (2020)



Minimum detectable SN

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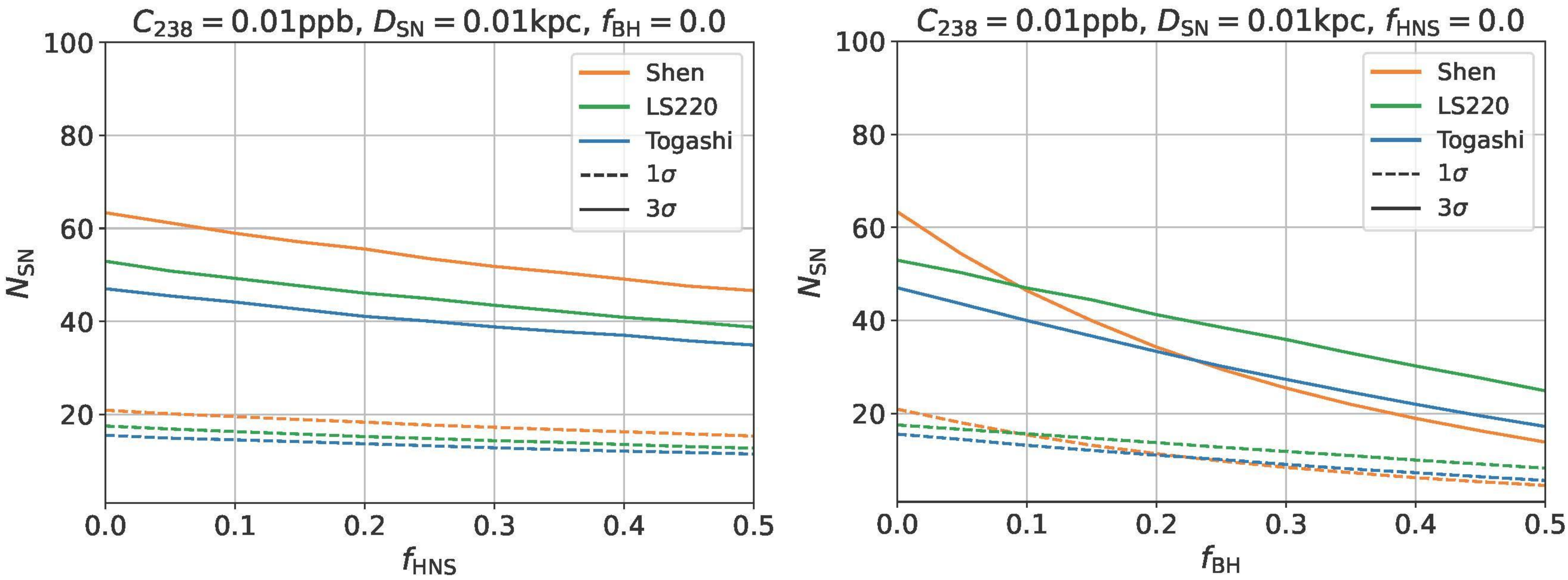
- Previous (Baum et al. 2020): 50 SNe



f_{HNS}: fraction of SNe with high-mass NSs

f_{BH}: fraction of BH-forming collapses

Young massive cluster

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- Young stars are packed into a very small volume containing >10000M⊙
  - ✓ e.g., Westerlund 1 (most massive): 63000M⊙, 1 pc radius, 3.5 Myr old
- O(100) SN events are expected

$$N_{\rm SN} = M_\star \frac{\int_{8M_\odot}^{100M_\odot} \psi_{\rm IMF}(M)\, dM}{\int_{0.1M_\odot}^{100M_\odot} M\psi_{\rm IMF}(M)\, dM}$$

O(10000) M⊙

O(0.01) /M⊙

Westerlund 1 (JWST)

Summary

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- Paleodetectors are expected to probe past supernova activities in Galaxy
- Burstlike supernova events nearby the Earth, which might cause snowball Earth, are also the target of paleodetectors
- The detectability depends on the nuclear equation of state and fate of stellar collapses