Galactic Cosmic Rays and Diffuse Gamma-rays in Baryon Cycle of Milky Way

We consider the Milky Way Evolution based on the ISM physics

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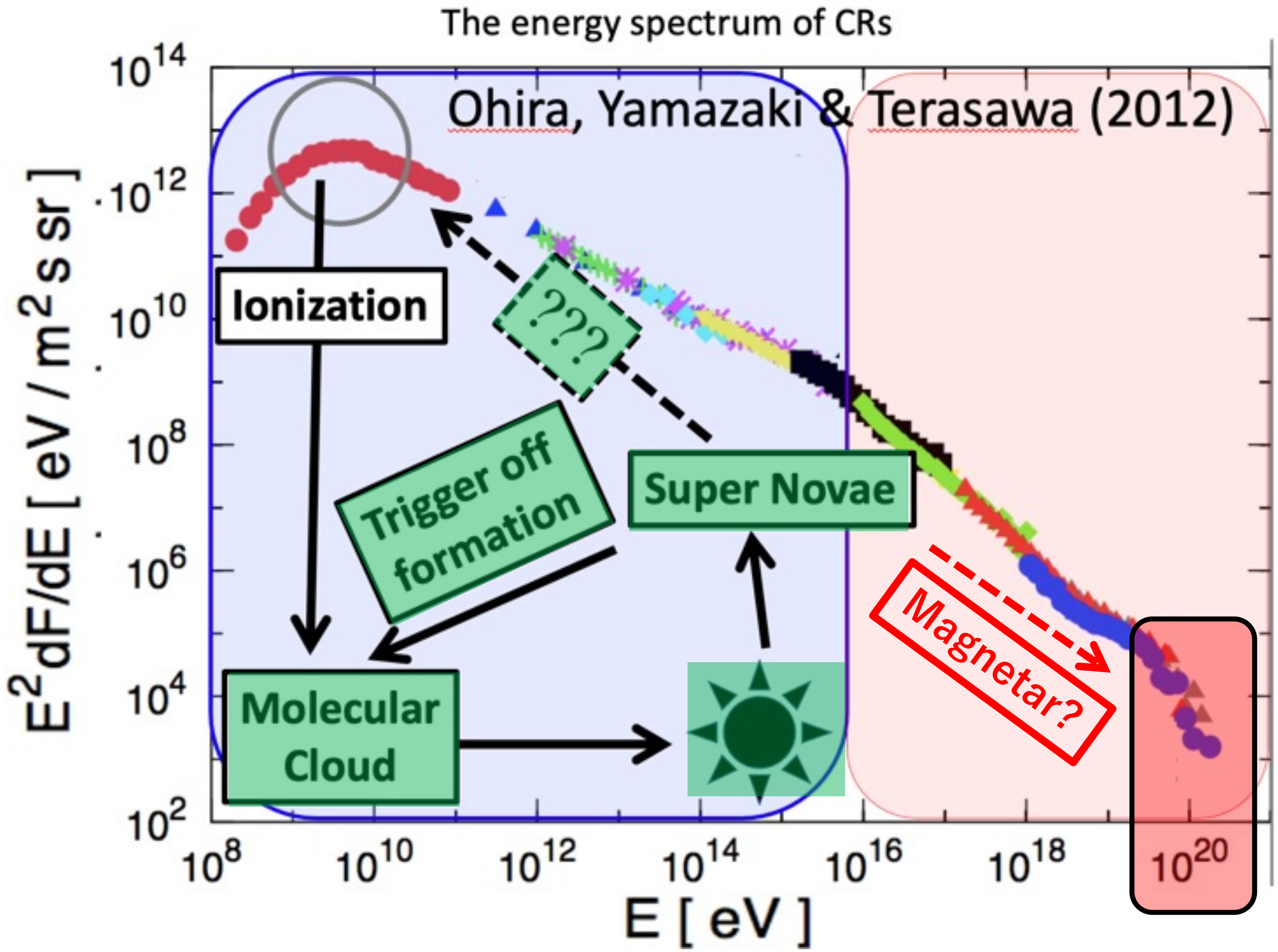
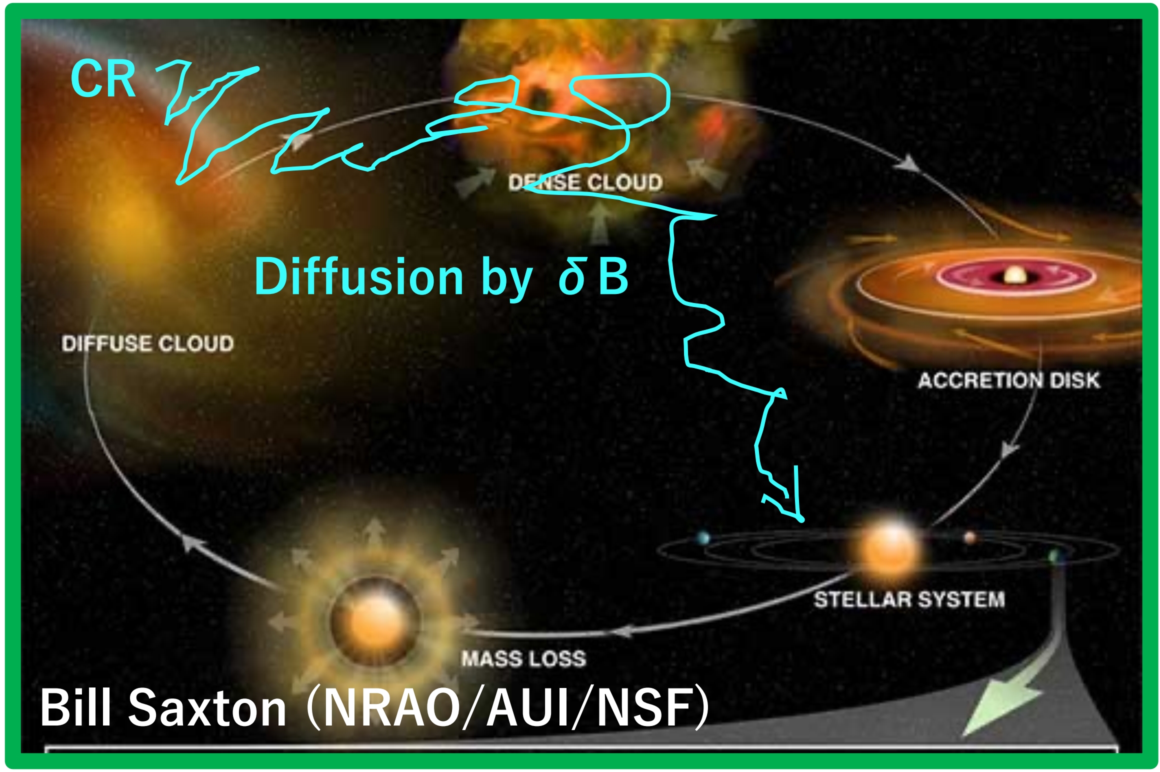
MeV-PeV Frontieres: New Perspectives in Gamma-Ray Astronomy and Particle Acceleration
(2025/12/16, ICRR)

(Galactic) Cosmic Rays & Galaxy Evolution (=baryon cycle)





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- Supernova shocks are important drivers of the Galactic matter cycle.

→ *Continuity* of the Star Formation will be a novel concept.

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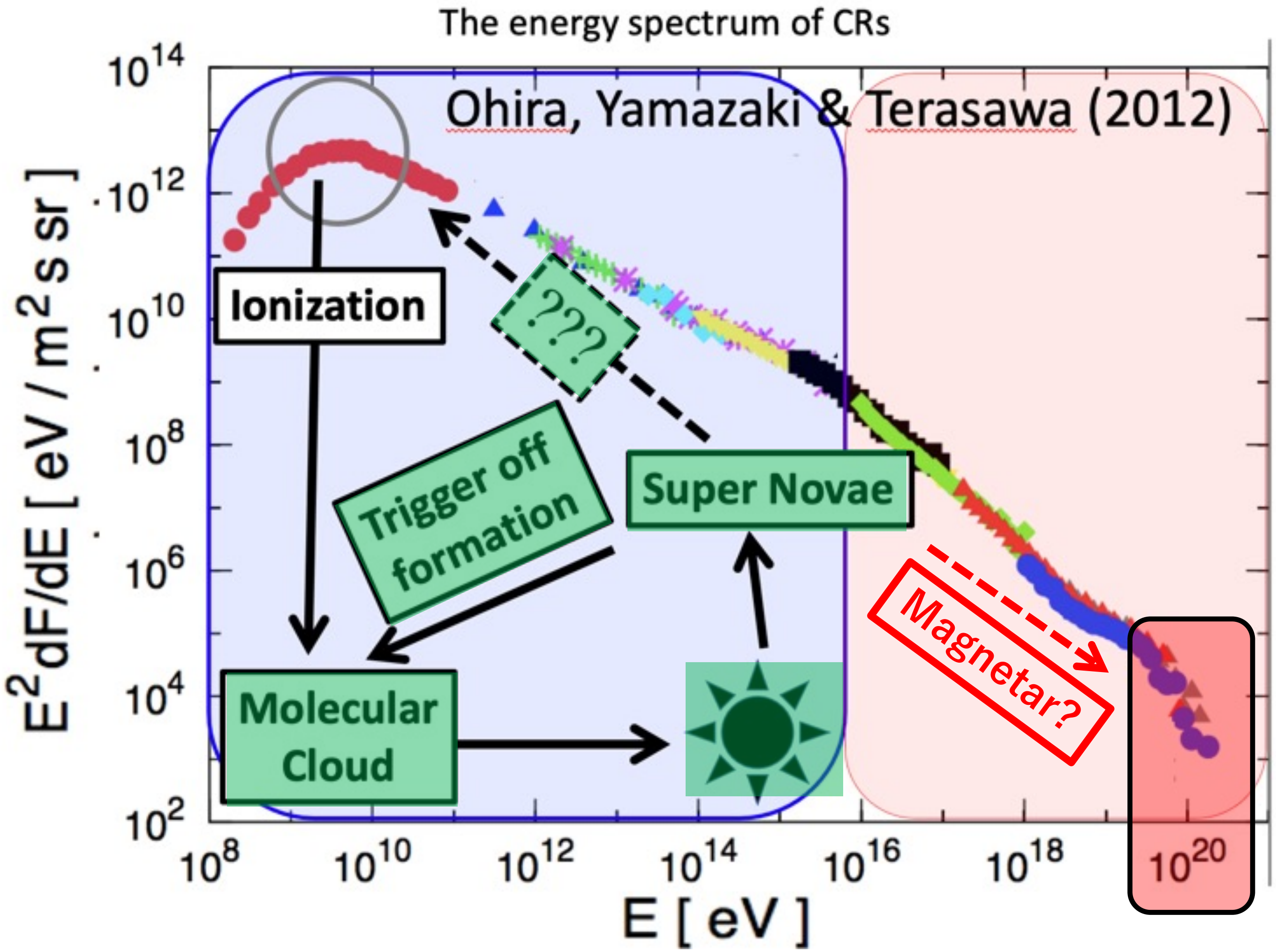
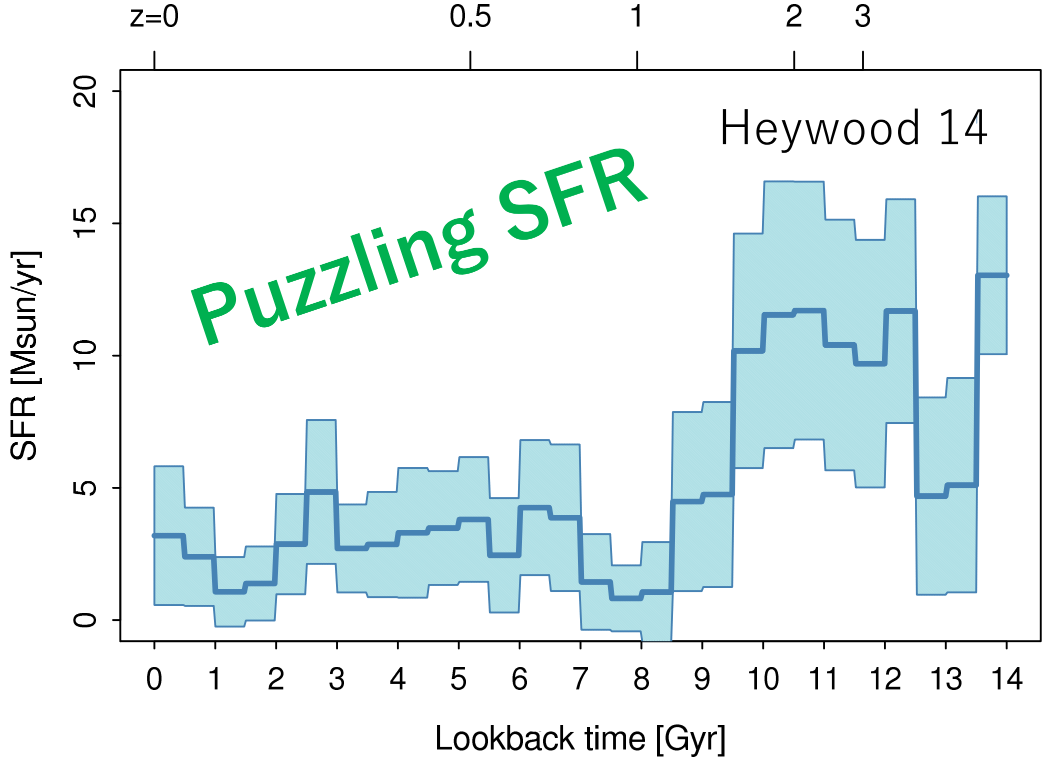


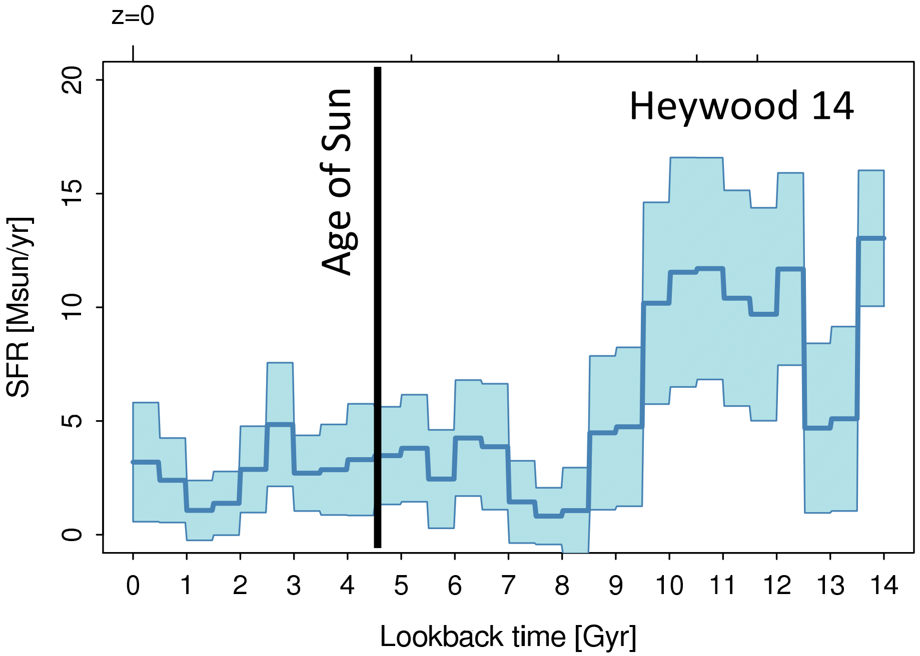


***Continuity* of the Star Formation**

To explain the star formation history of MW, the effects of CRs can be important.

(JS & Inutsuka 2022; JS et al. 2024, JS & Asano 2024)

"Puzzling" Star Formation History
(in the context of the standard Cosmology)



Total mass of DM: ~ 10^{12} M_{sun}

Total mass of stars: ~ 4-6 x 10^{10} M_{sun}

Current SFR: ~ 1 M_{sun}/yr

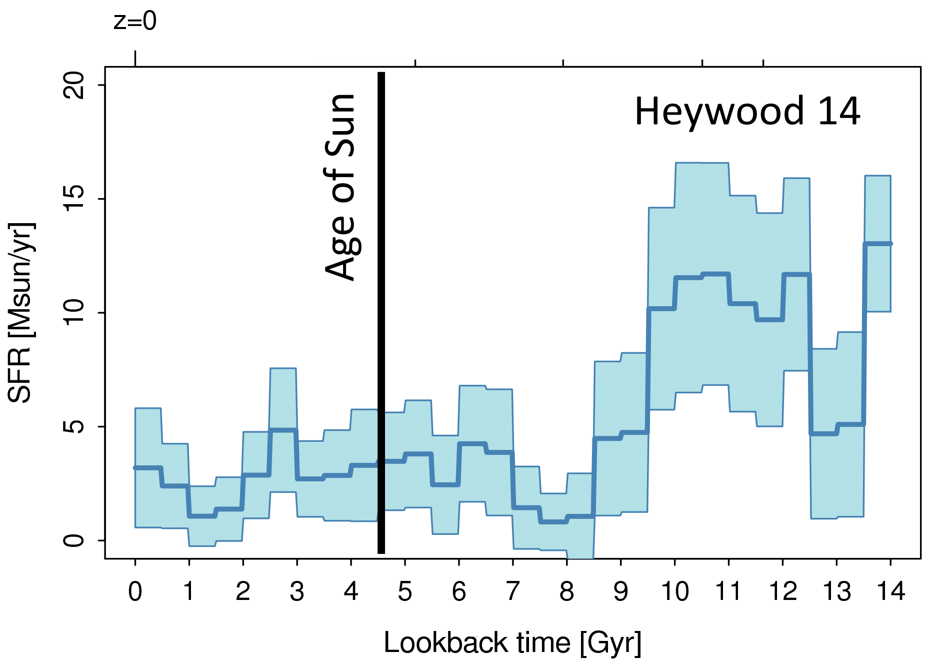
Total gas mass: ~ 10^{9} M_{sun}

Cf. Bland-Hawthorn & Gerhard 16, the Planck Collaboration 18

➢ **From the context of Cosmology …**

1. The total mass of baryon may be ~ 10^{11} M_{sun}.
2. Why is a half of baryons converted to the stars?
3. Why dose the only ~1 % of baryon remain in the disk?

"Puzzling" Star Formation History
(in the context of the current Galactic disk condition)



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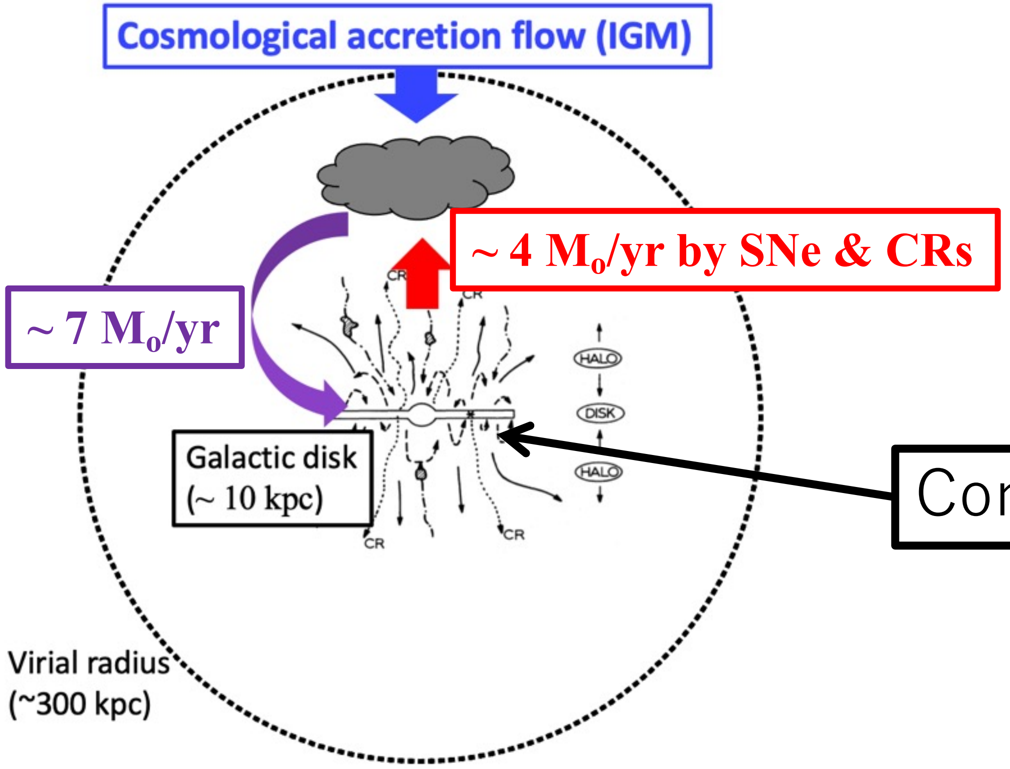
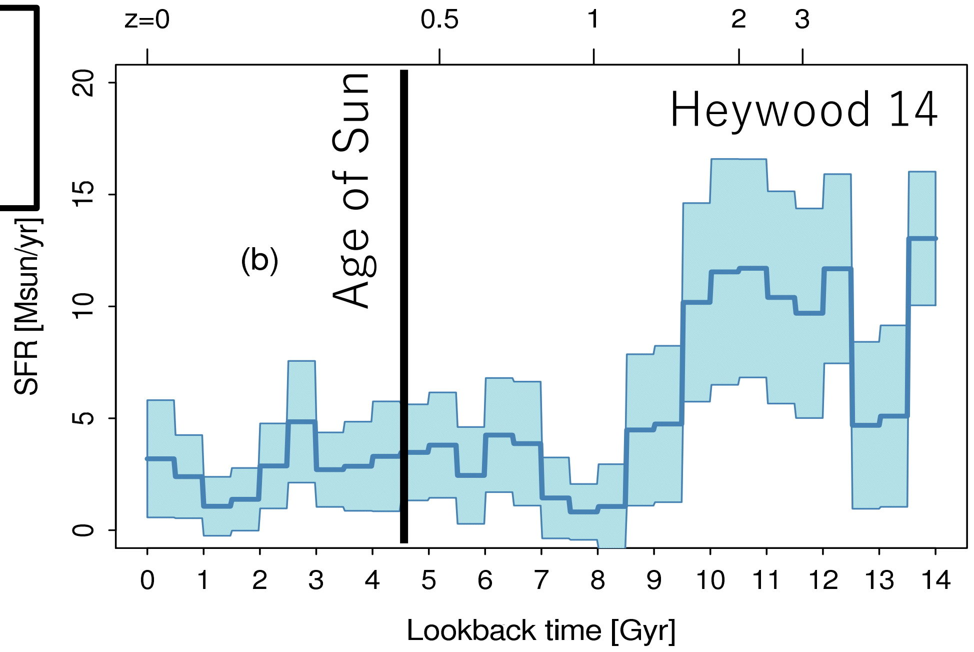
- **From the current MW …**

1. The gas should be depleted within ~ 1 Gyr !
2. Replenishment of gas is required.
3. Galactic halo (CGM) may be a dominant gas reservoir.

Simplest Answer for the Star Formation History





Consequent star formation at the disk

✓ Almost constant SFR

→ quasi steady-state

→ **SFR ~ 7 M$_\odot$/yr – 4 M$_\odot$/yr ~ 3 M$_\odot$/yr**

JS, Inutsuka & Nagashima (2024):

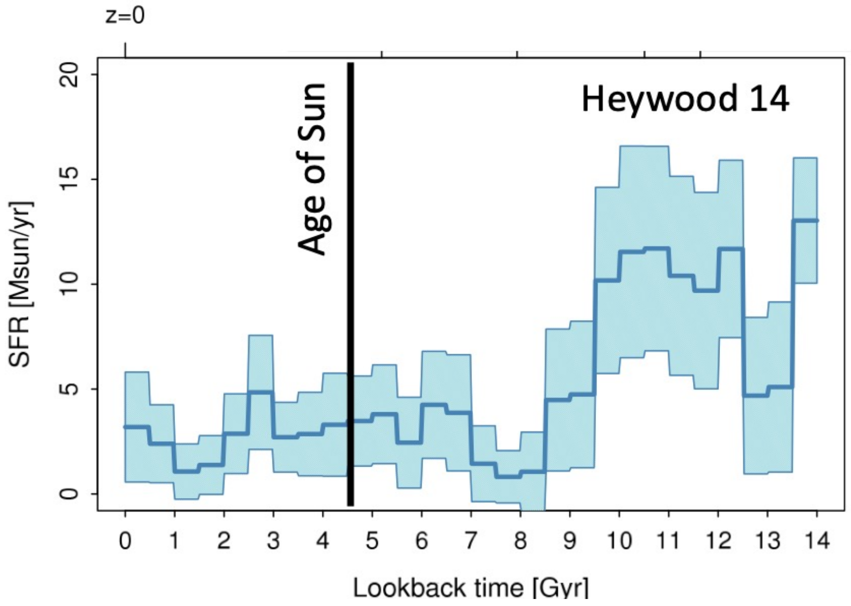
The constant SFR is explained by the balance between…

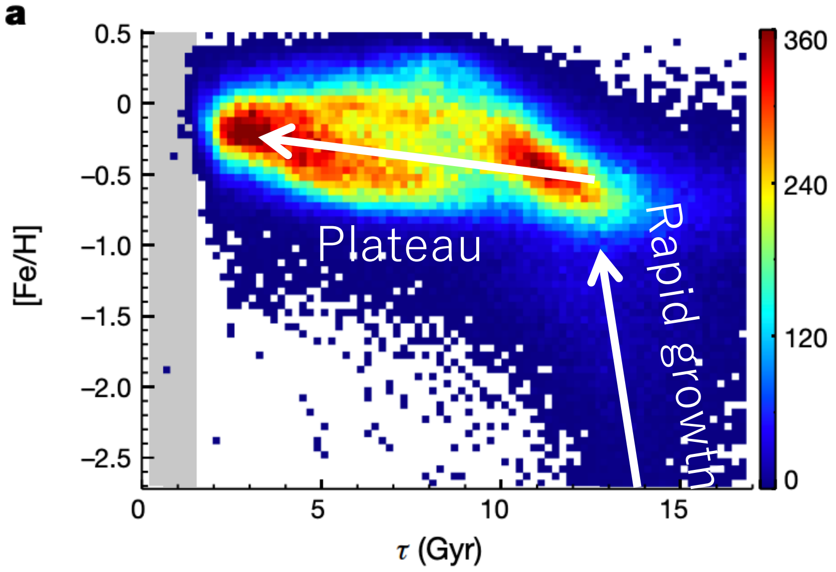
Mass accretion from halo and

Galactic wind from the disk (this talk).

See also, Hopkins+2018, Armillotta+2024, Habegger & Zweibel 25, and so on (too many papers!)

Metal Mass Inferred by the Star Formation History





Xing & Rix (2022, by Gaia)

- ***Total Metal Mass* ejected by Supernovae**

SFR ~ 3 Mo/yr

Salpeter IMF → Massive Star Formation Rate ~ 0.1 Mo/yr

→ ~ (SFR) x (Massive Star fraction) x (CO core mass fraction) x (14 Gyr)

~ (3 Mo/yr) x (0.1) x (3 Mo/8 Mo) x (14 Gyr)

~ 1.6 x 10^9 Mo

- **Galactic Disk**

Total Gas mass ~ 10^9 Mo

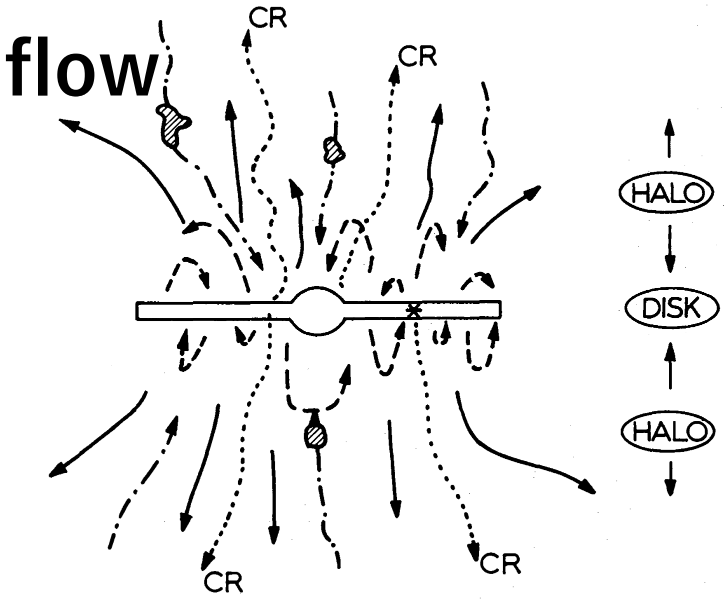
Metallicity Zo ~ 0.01 → Metal mass ~ 10^7 Mo

Significant fraction of the metals must be removed from the disk continuously.

→ Galactic Wind driven by CRs can achieve this!

→ CRs regulate the metal mass (=building blocks of the planets & life) in the disk.

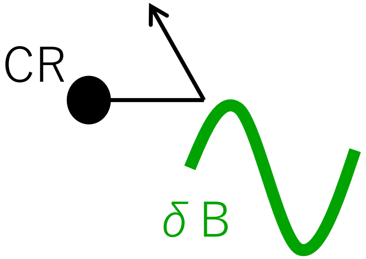
Essence for the Galactic Wind (SJ & Inutsuka 2022)
Radiative cooling & CR heating



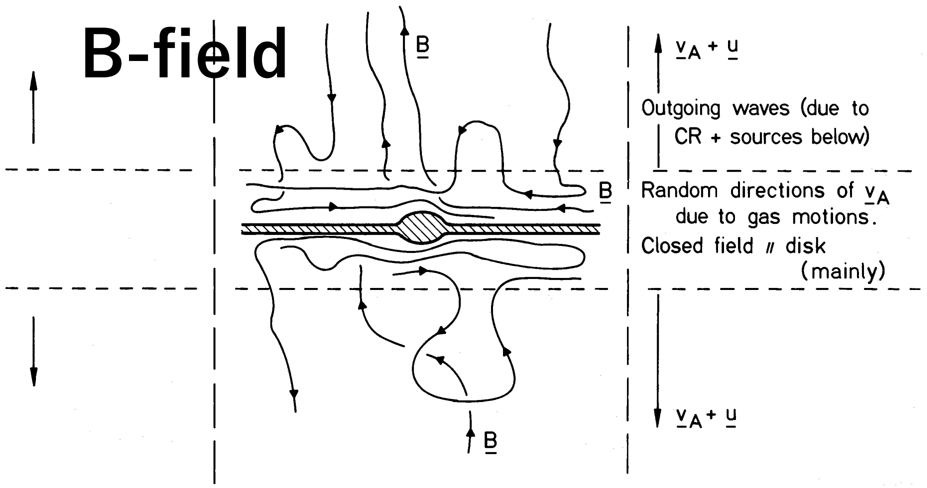
(Shapiro & Field 76)

Radiative cooling → $T < T\_vir$ → wind never launching

Heating by CRs→ Comparable with Radiative cooling!



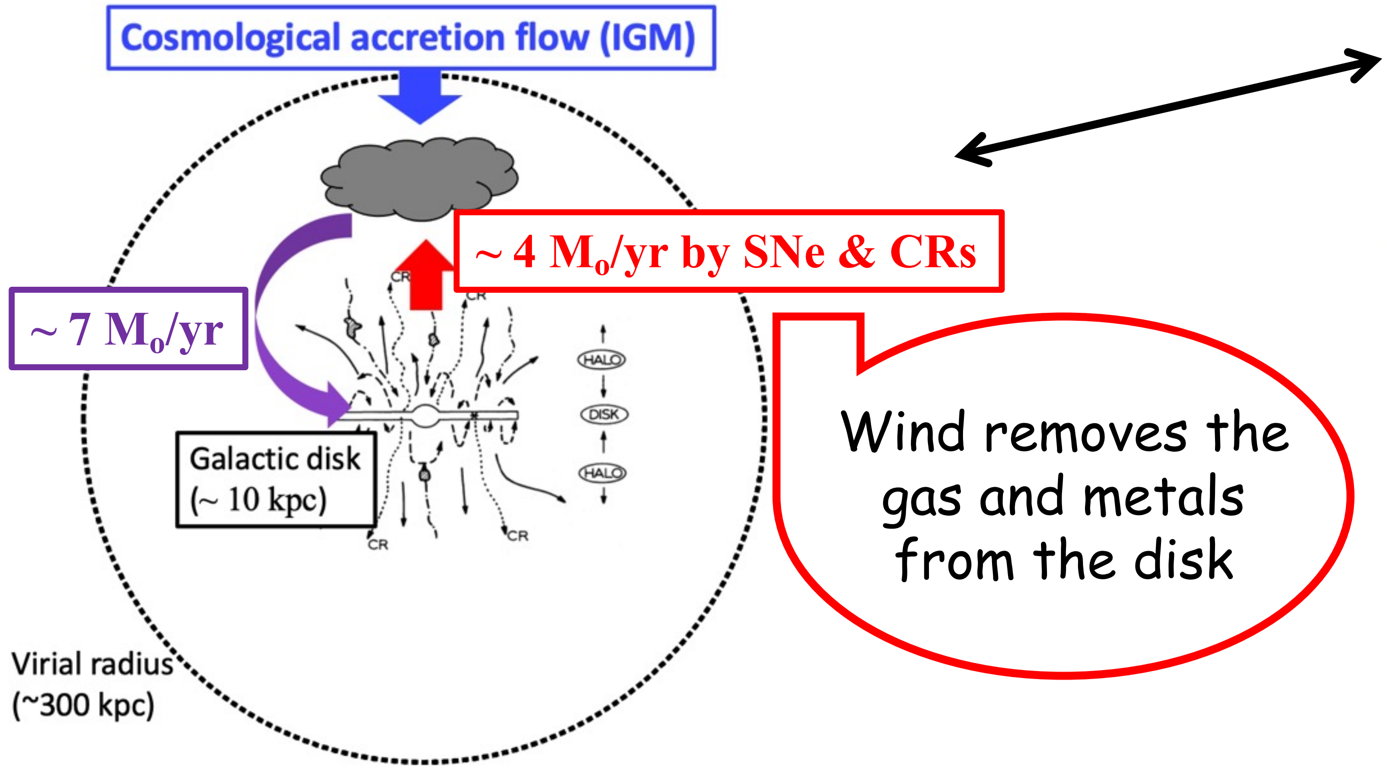
CRs scattered by δB
→Momentum transferred to δB
→ δB grows
→dissipation of δB
→**Thermal gas heated**

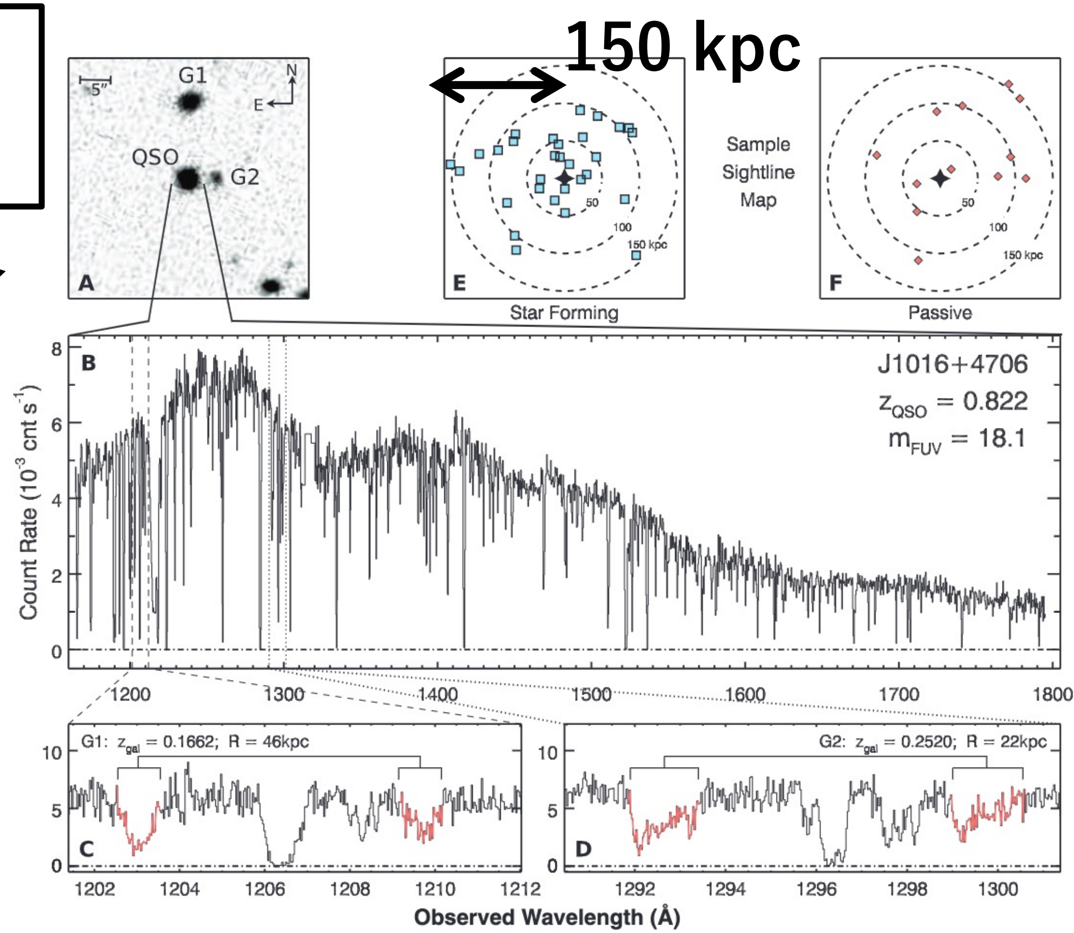


$$\Gamma = |V_A \nabla P_{cr}| \ (\mathrm{erg/cc/s})$$ (e.g., Kulsrud 2005)

$$\frac{n^2\Lambda}{Q_w} \simeq 0.91 \left(\frac{n}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{5/2} \left(\frac{B}{1\ \mu\mathrm{G}}\right)^{-1} \left(\frac{P_{cr}}{0.3\ \mathrm{eV\ cm}^{-3}}\right)^{-1} \times \left(\frac{H_{cr}}{10\ \mathrm{kpc}}\right) \left(\frac{\Lambda}{10^{-22}\ \mathrm{erg\ cm}^3\ \mathrm{s}^{-1}}\right). \quad (20)$$

Evidence of Galactic Wind: Metal polluted halo of external galaxies



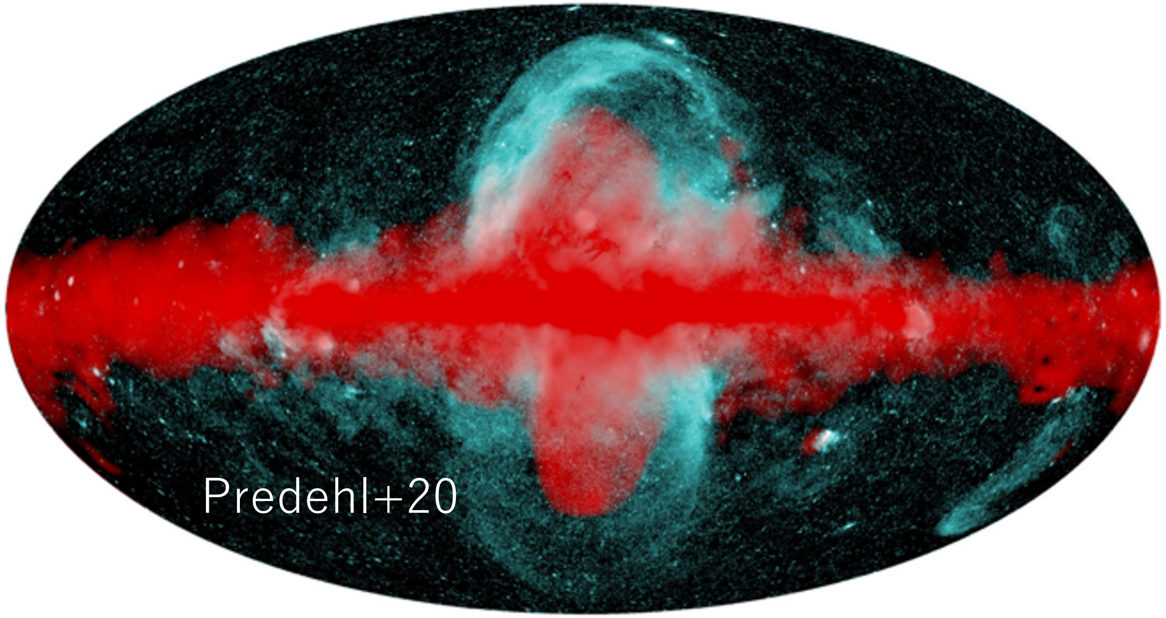


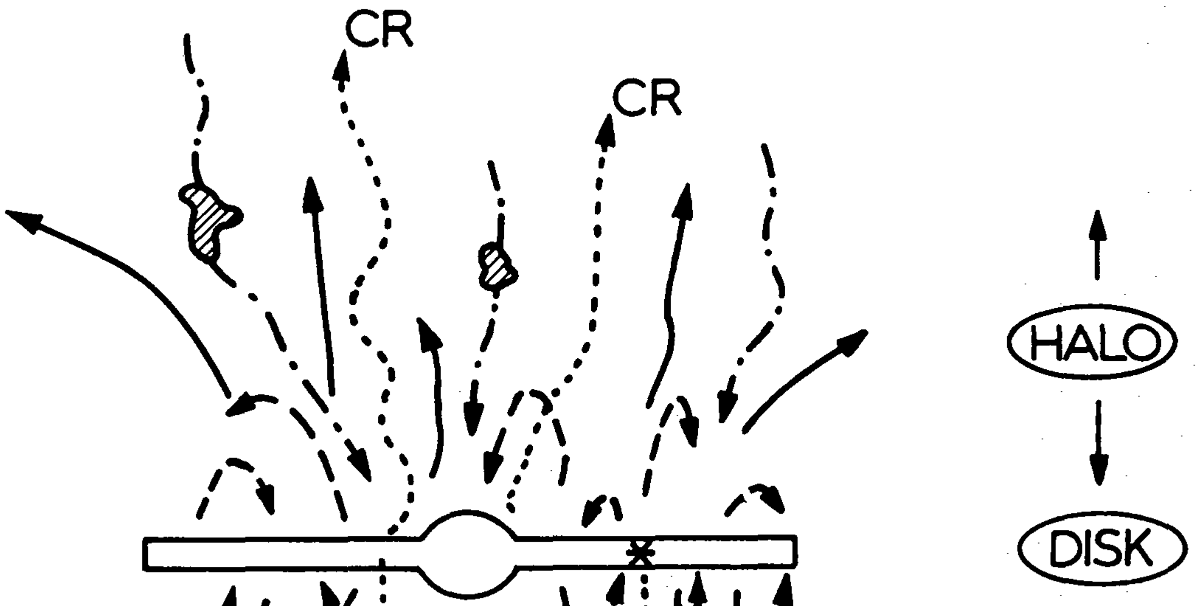
JS & Inutsuka (2022):

The CRs can drive the wind from the *bottom of Milky Way halo*.

We must understand the wind from the *disk* (to remove the metals).

Fermi & eROSITA Bubbles: Byproducts of Galactic Wind





Breitschwerdt+91

Usefull Hints of the disk-halo interaction:

T ~ 0.1 keV (~virial temp. of the MW)

→eROSITA bubble (X-ray) is consistent with the wind scenario.

→Fermi bubble (gamma-ray) is not clear.

If we apply the wind scenario for the MW evolution…

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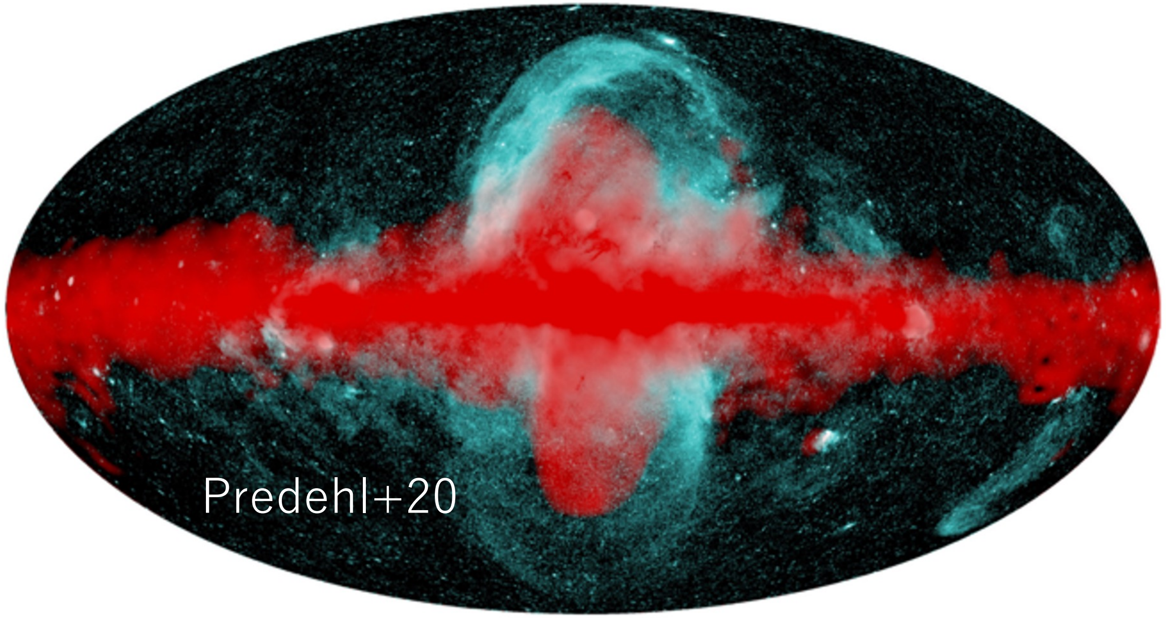
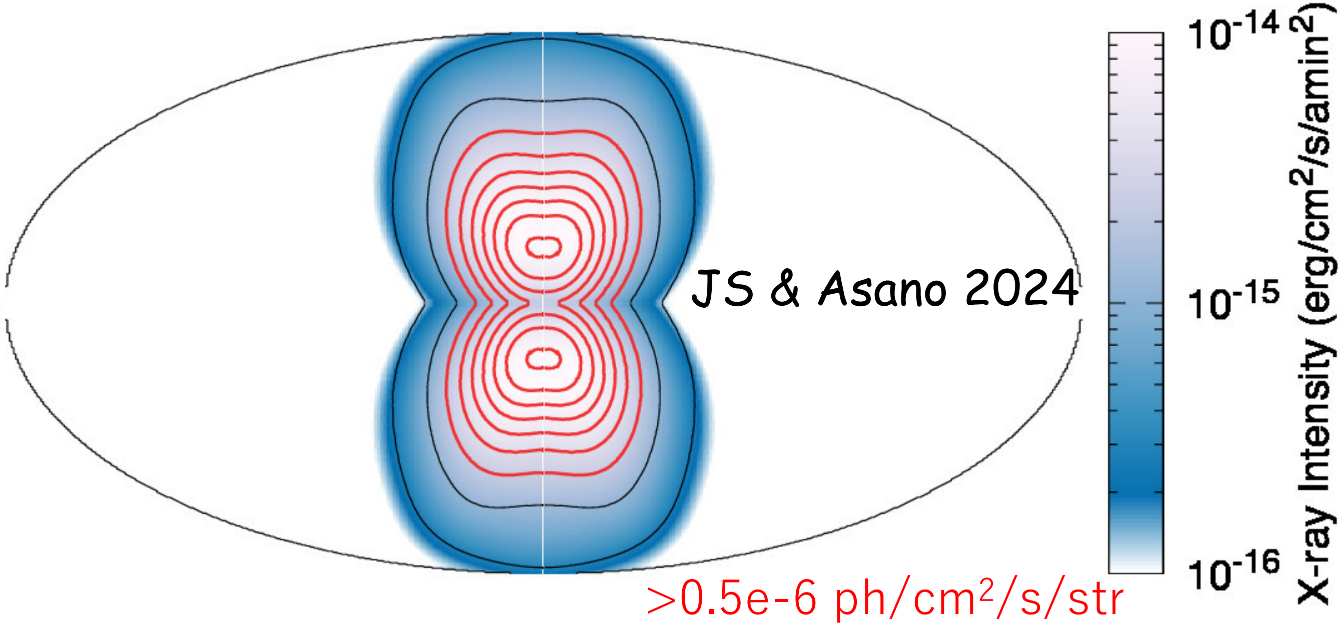




Assumption:

~5-10 % of SNe energy is consumed for launching the wind.
→The bubbles & MW evolution can be explained simultaneously.

*Further investigations of the bubbles are going on w/ Takeishi-san, S. Abe-kun, Mizuno-san for gamma-ray observations & w/ Inamoto-kun for theoretical study.

*Hadronic γ-ray scenario $p_{cr} + p_{gas} \rightarrow 2\gamma, \nu$

Problem: ~5-10 % of SNe energy

w/o CRs (Oku+22)

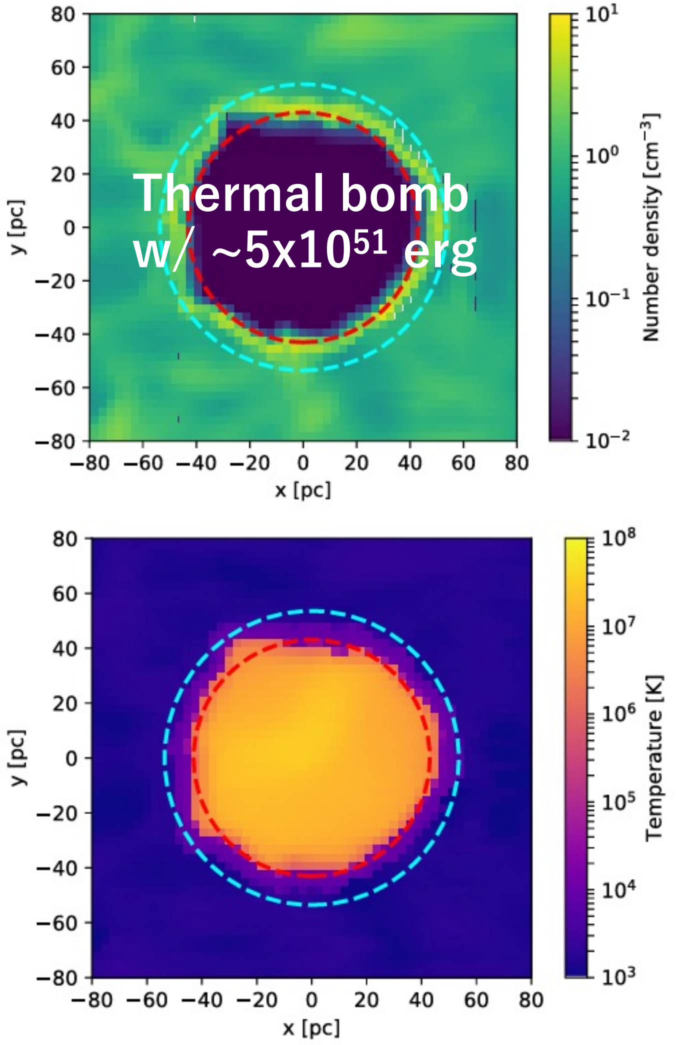


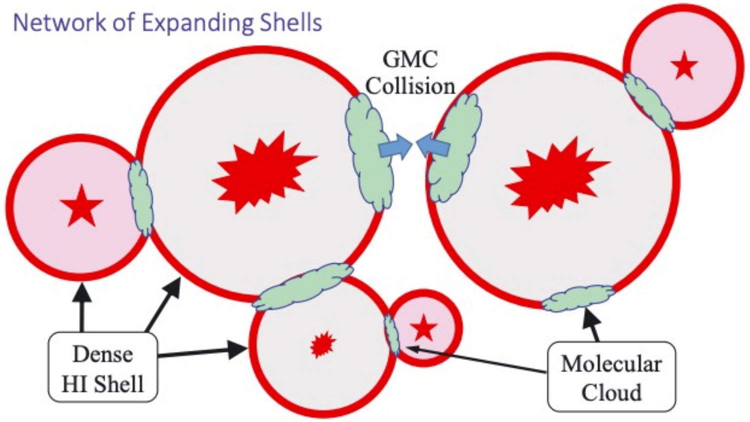
Figure 2. Slice plot of gas number density and temperature distribution at $t = 0.53$ Myr for the case of $n_{\rm H} = 1$ cm^{-3}, $Z = Z_\odot$, $\Delta t_{\rm SN} = 0.1$ Myr. The inner red circle shows $R_{\rm hot}$, while the outer cyan circle shows $R_{\rm bub}$.

←So-called *feedback* study for Galaxy formation/evolution

Supernovae: One of The Most Energetic Events
Limited at ~50 pc << disk thickness
→ Too weak feedback (for wind)

Opposite Sence?

Inutsuka+15



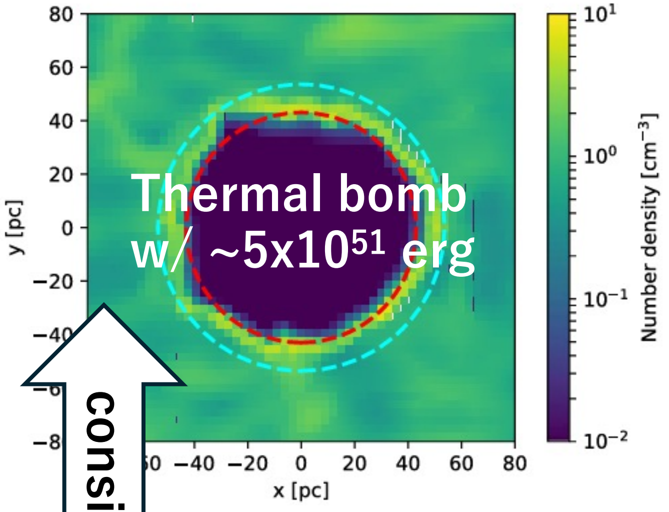
Modern Theory of Star Formation:
SNe *promote* the star formation

Diffuse gas → Molecular gas → Star Formation

SN shocks, Expansion of Ionization Sphere, etc.

Problem: ~5-10 % of SNe energy

w/o CRs (Oku+22)



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Limited at ~50 pc << disk thickness
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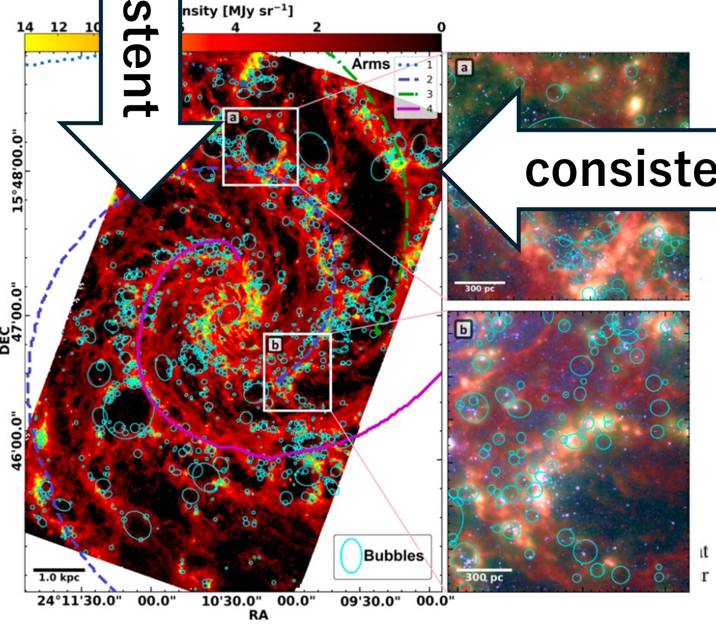
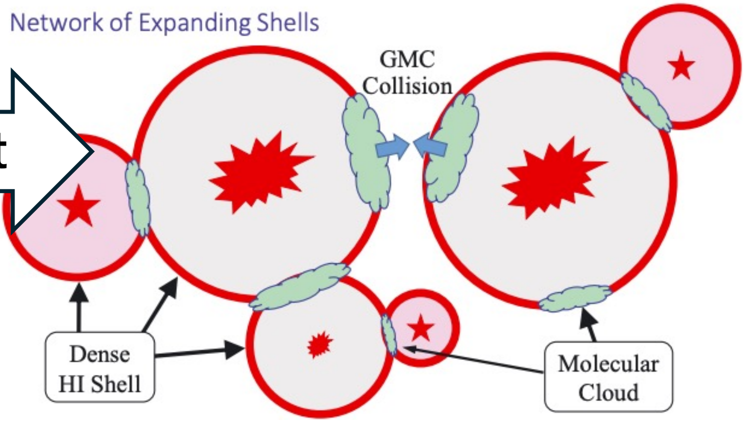
Opposite Sence?
→ We consider CRs

consistent



consistent

Inutsuka+15



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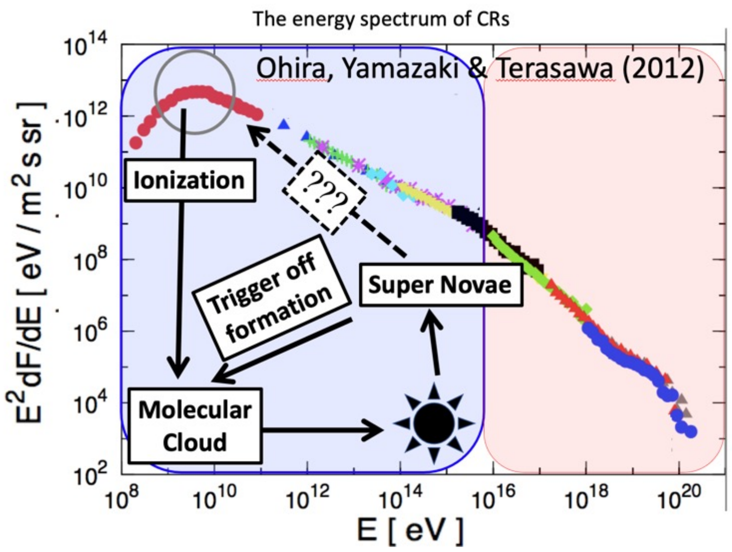
Expectations for CRs: ~5-10 % of SNe energy



e.g., Ferrier+01

Strongness: Diffusion→ Go to the halo (cf. Fermi bubble)

Weakness: Energetics→ ~10^{50} erg (per one SN)

The CRs are *additional* energies for the hydrostatic ISM.

If CRs can transfer their energy to the ISM, the energetic outflow can be launched from the disk.

Typical ISM (volume average):
Density ~ 0.1 /cc,
Temperature ~ 10^4 K,
disk thickness ~ 300 pc
→ Internal Energy ~ 10^{51} erg (n/0.1 cm^{-3})(T/10^4 K)(r/300 pc)^3

Cosmic Ray Hydrodynamics

Hydrodynamics (thermal plasma)

$$\frac{\partial \rho_{\rm g}}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r^2}\left(r^2 \rho_{\rm g} v_{\rm g}\right) = 0, \quad (1)$$

$$\rho_{\rm g}\left[\frac{\partial v_{\rm g}}{\partial t} + v_{\rm g}\frac{\partial v_{\rm g}}{\partial r}\right] = -\frac{\partial}{\partial r}\left(P_{\rm g} + P_{\rm cr}\right), \quad (2)$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho_{\rm g}{v_{\rm g}}^2 + \varepsilon_{\rm g}\right) + \frac{1}{r^2}\frac{\partial}{\partial r^2}\left[\left(\frac{1}{2}\rho_{\rm g}{v_{\rm g}}^2 + P_{\rm g} + \varepsilon_{\rm g}\right) v_{\rm g}\right]$$
$$= n_{\rm g}\left(\Gamma_{\rm g} - n_{\rm g}\Lambda\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \mathcal{K}\frac{\partial T_{\rm g}}{\partial r}\right)$$
$$-v_{\rm g}\frac{\partial P_{\rm cr}}{\partial r} + \int p v f \left(\frac{dp}{dt}\right)_{\rm C} dp + \left|\mathcal{V}_{\rm A}\frac{\partial \varepsilon_{\rm cr}}{\partial r}\right|, \quad (3)$$

$$P_{\rm g} = (\gamma_{\rm g} - 1)\varepsilon_{\rm g} = n_{\rm g} k T_{\rm g} = \frac{\rho_g}{\bar{m}} k T_{\rm g}, \quad \gamma_{\rm g} = \frac{5}{3}, \quad (4)$$

Cosmic Ray Transport

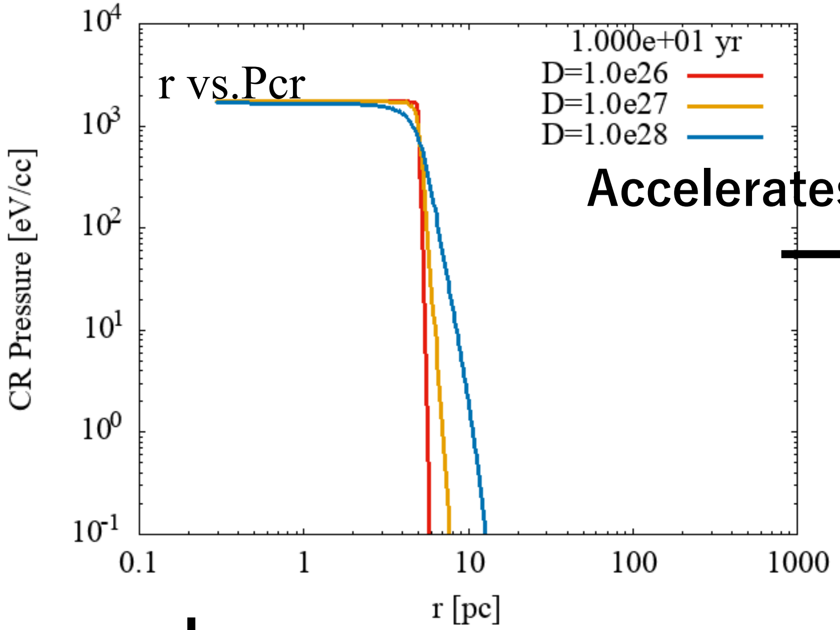
$$\frac{\partial f}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(v_{\rm g} f - \mathcal{D}\frac{\partial f}{\partial r}\right)$$
$$= \frac{1}{r^2}\frac{\partial}{\partial r}\left(\frac{r^2 v_{\rm g}}{3}\right)\frac{\partial f}{\partial p} - \frac{\partial}{\partial p}\left[f\left(\frac{dp}{dt}\right)_{\rm C}\right] - \left|\mathcal{V}_{\rm A}\frac{\partial f}{\partial r}\right|, \quad (5)$$

$$\varepsilon_{\rm cr} = \int \epsilon f dp, \quad \epsilon(p) = \sqrt{(m_{\rm p}c^2)^2 + (pc)^2} - m_{\rm p}c^2, \quad (6)$$

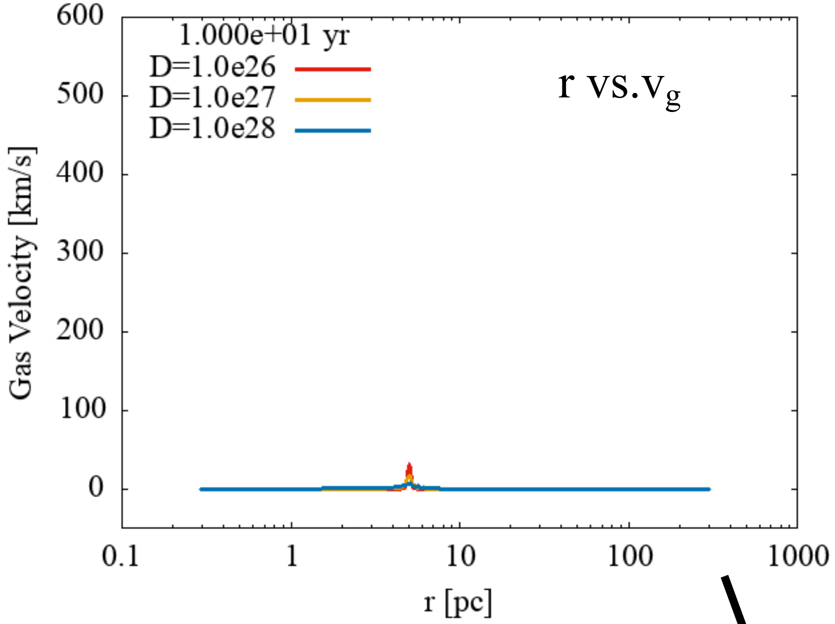
$$P_{\rm cr} = \int \frac{pv}{3} f dp, \quad v(p) = \frac{pc^2}{\epsilon(p) + m_{\rm p}c^2}. \quad (7)$$

Follow ~10 Myr evolution of fluid & CRs

- ~10 Myr is average residence time of CR at the disk.
- The CR momentum distribution is considered (new).



Accelerates the gas

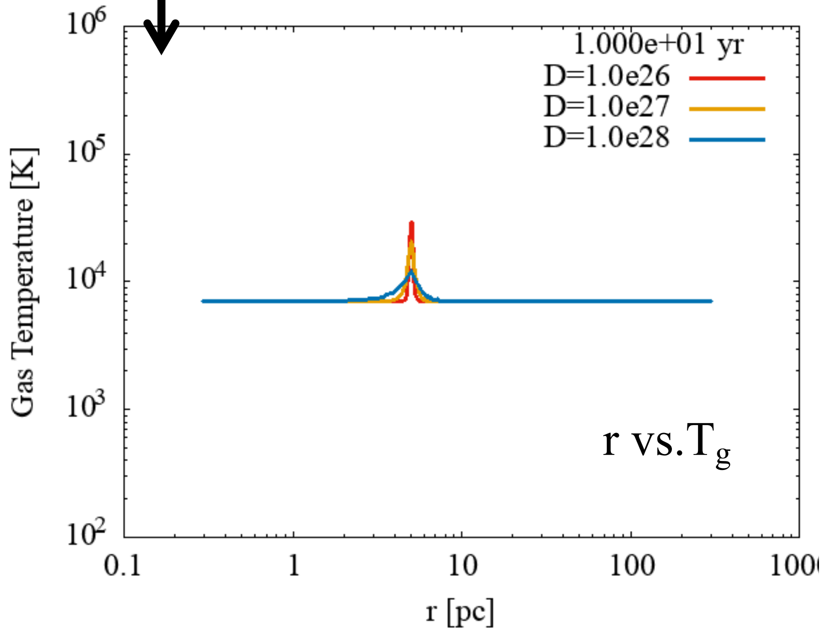


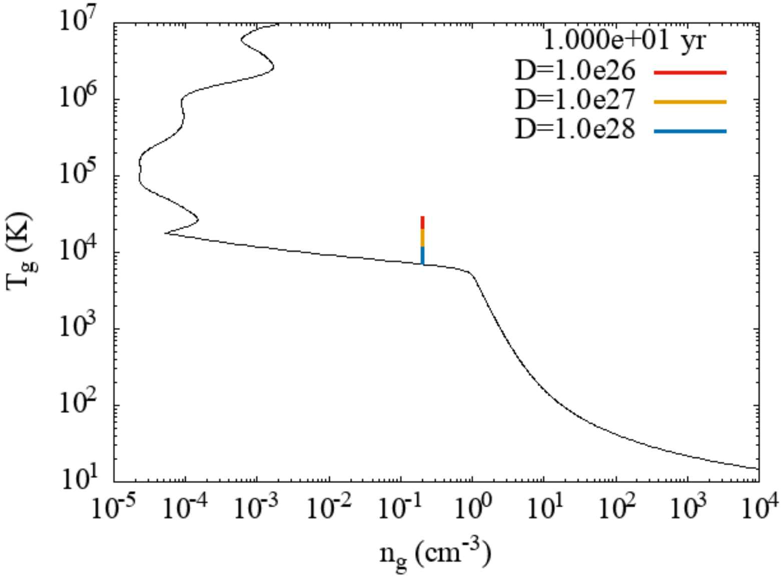
***Initial conditions of gas**
v_g = 0 km/s
T_g = 7000 K
n_g = 0.2 /cc
(equilibrium density)
B_{ism} = 1 μG
(fixed, for CR heating)

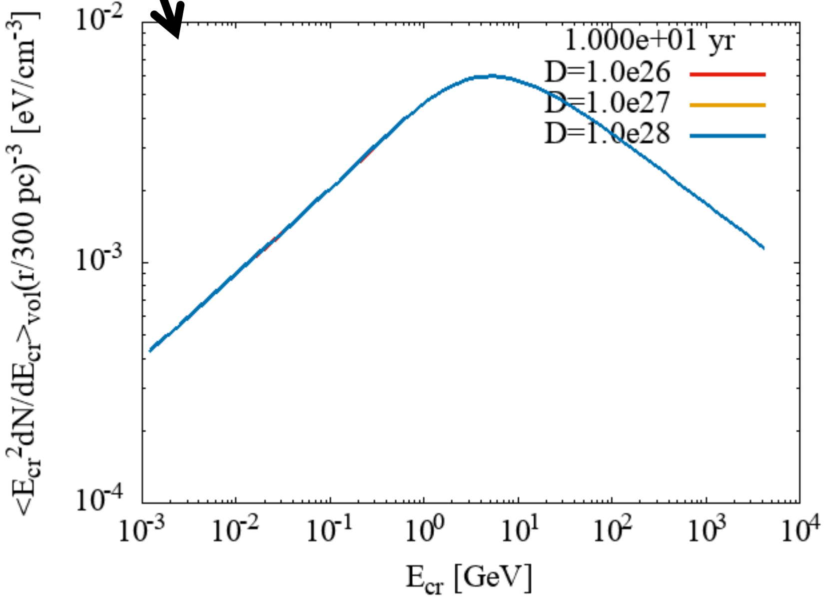
Shimoda, Asano & Inutsuka (2025)

Heats the gas

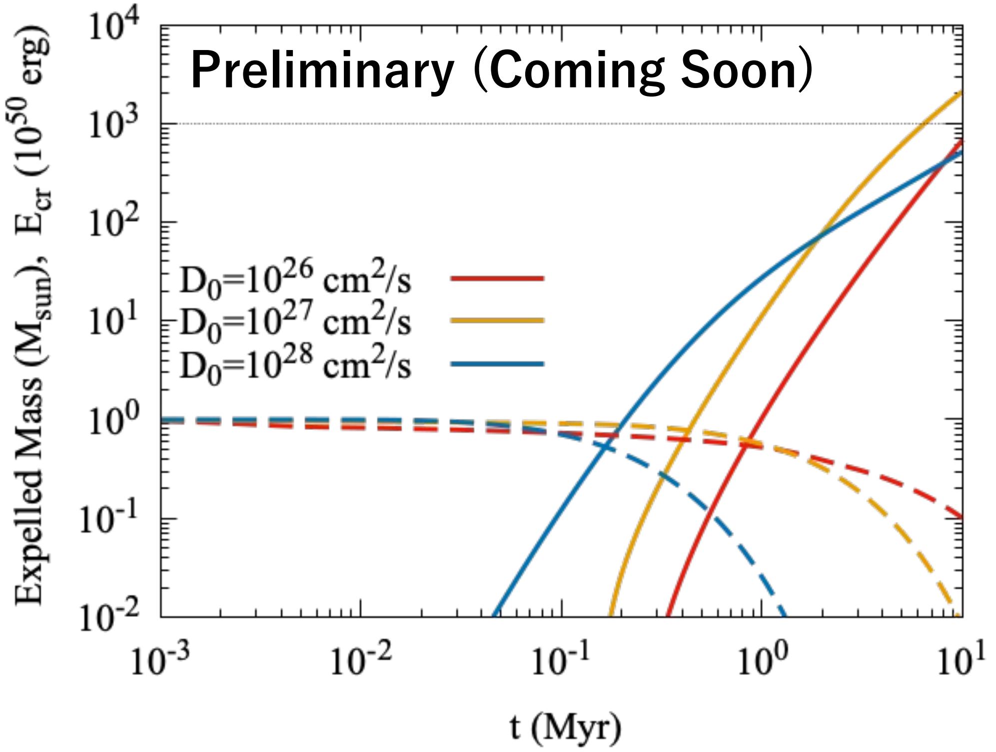
Affects the CR spectra

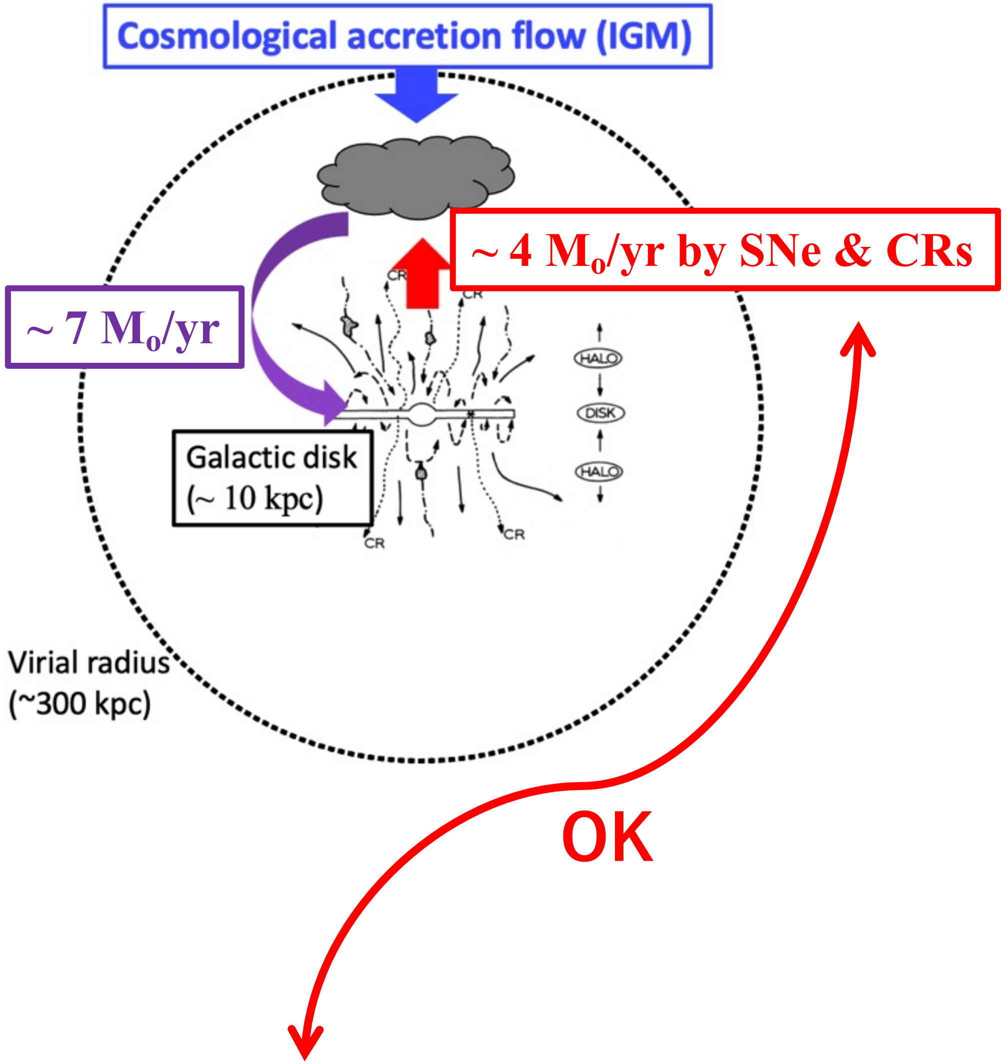






How much work do CRs have?





~1000 Mo is removed from the disk by CRs

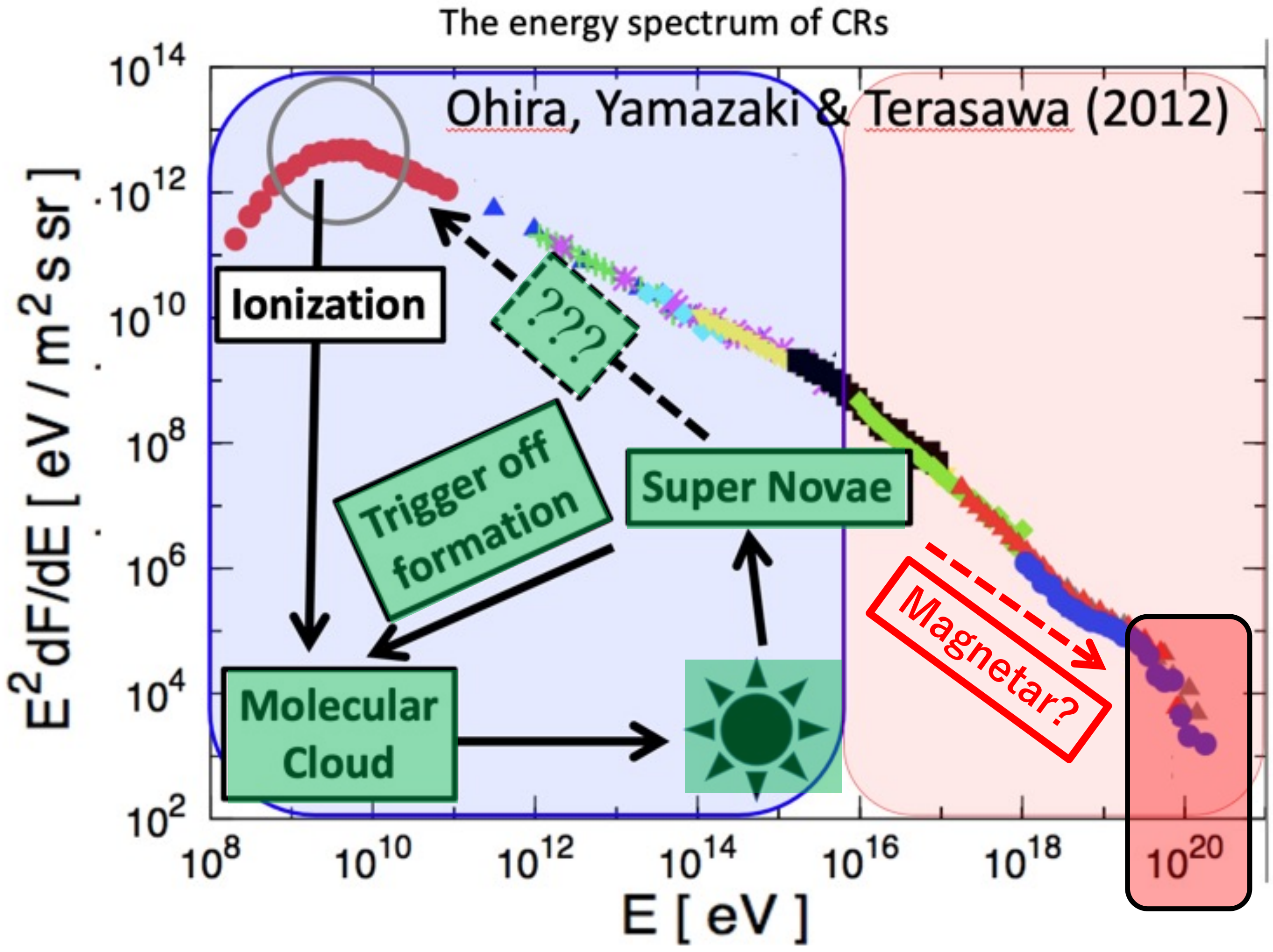
→Mass loss rate of the disk ~ (1000 Mo)*(SN rate) ~ 10 Mo/yr (SN rate/0.03 yr^{-1})

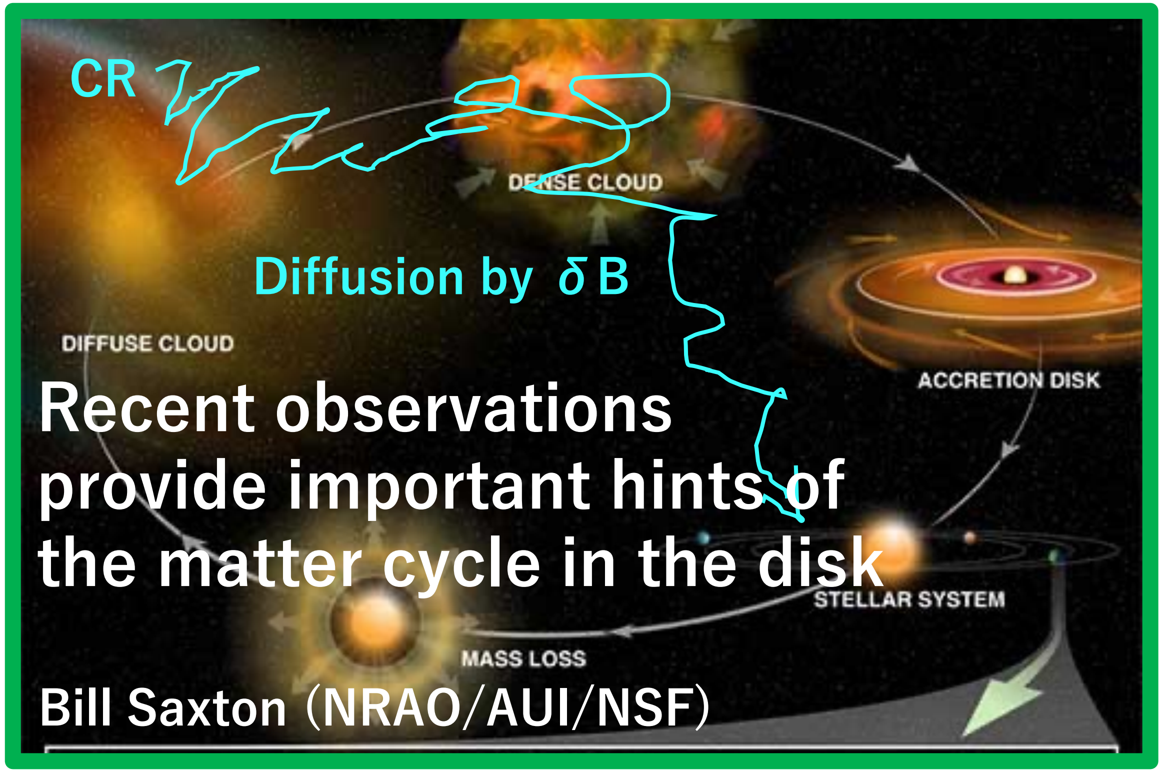
We should examine as next steps:

1) Observational Counterparts

2) Acceleration of the removed gas at the disk-halo interface

(Galactic) Cosmic Rays & Galaxy Evolution (=baryon cycle)



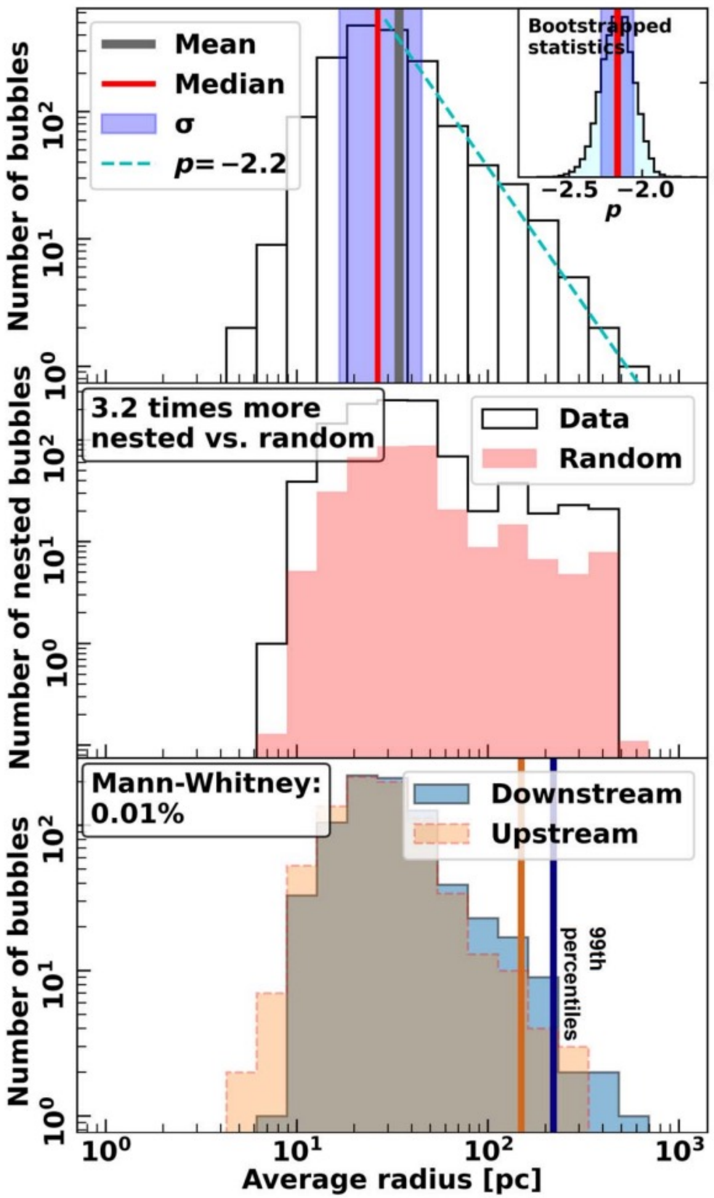


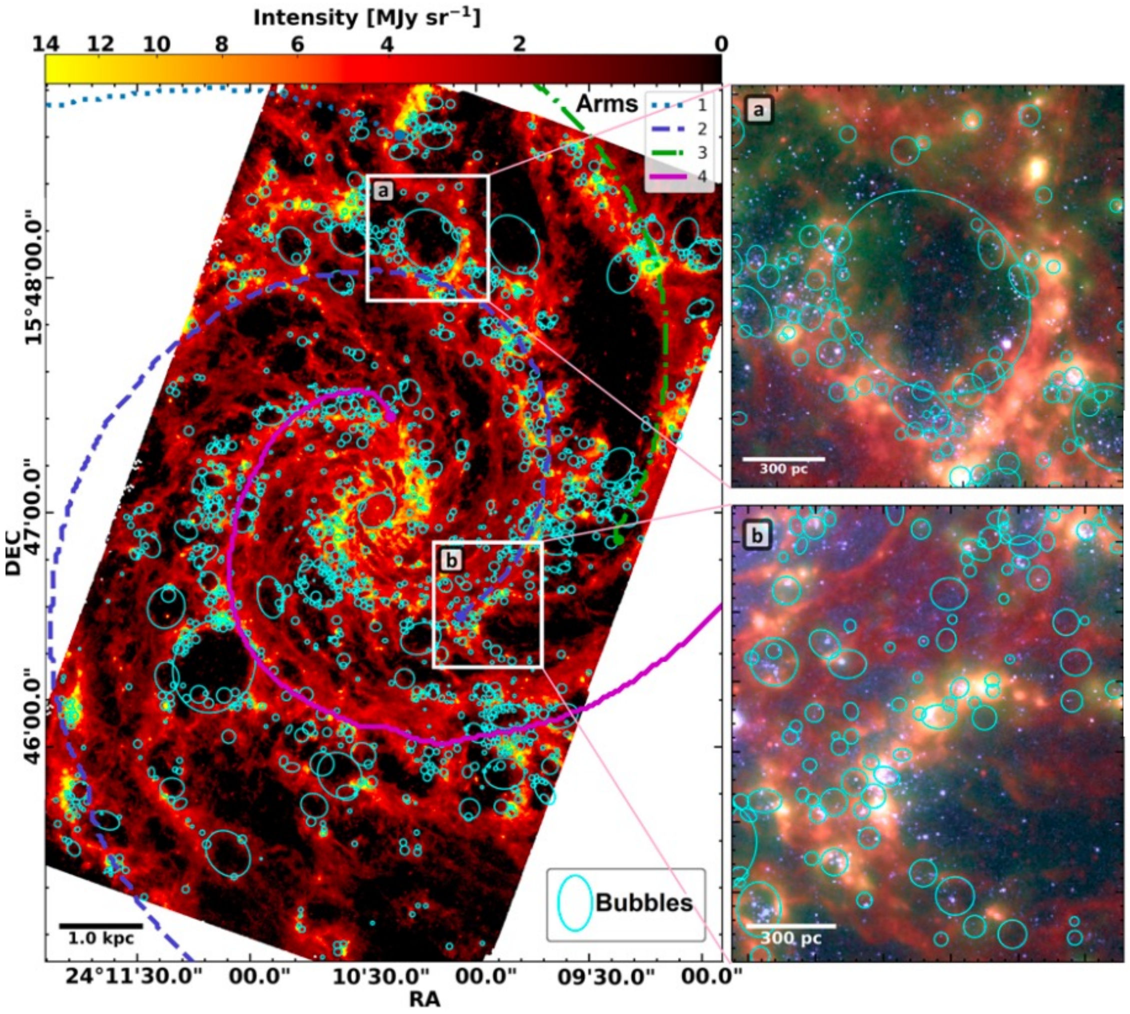
- Galactic CRs are accelerated at supernova shocks.
- Supernova shocks are important drivers of the Galactic matter cycle.

→ *Continuity* of the Star Formation will be a novel concept.

JWST bubbles: Evidence of the Matter Cycle

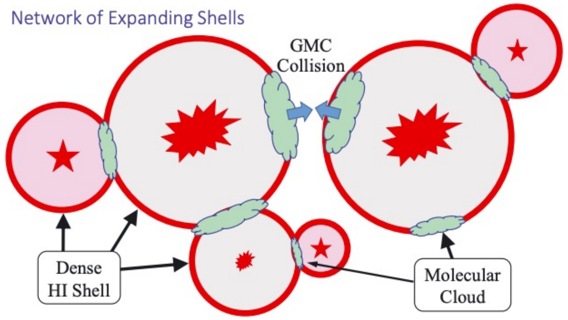
~30 pc





NGC 628: SFR~1.7 Mo/yr
Watkins+23

Consistent with the modern star formation scenario by Inutuska+15



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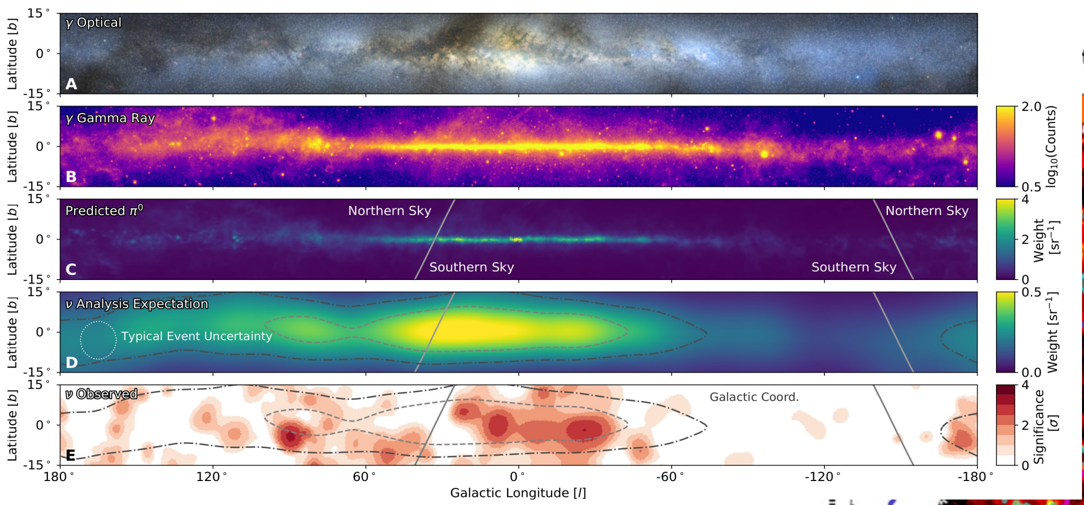

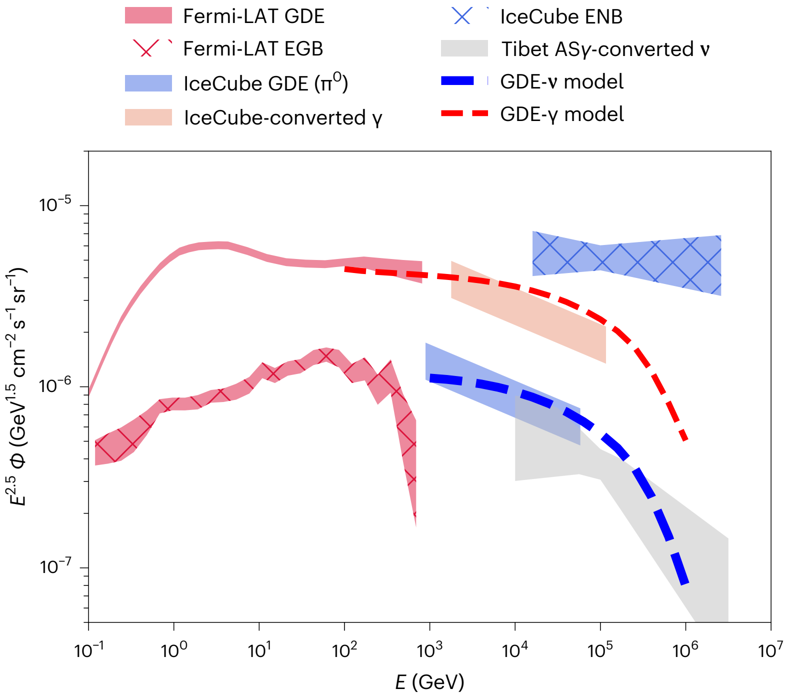

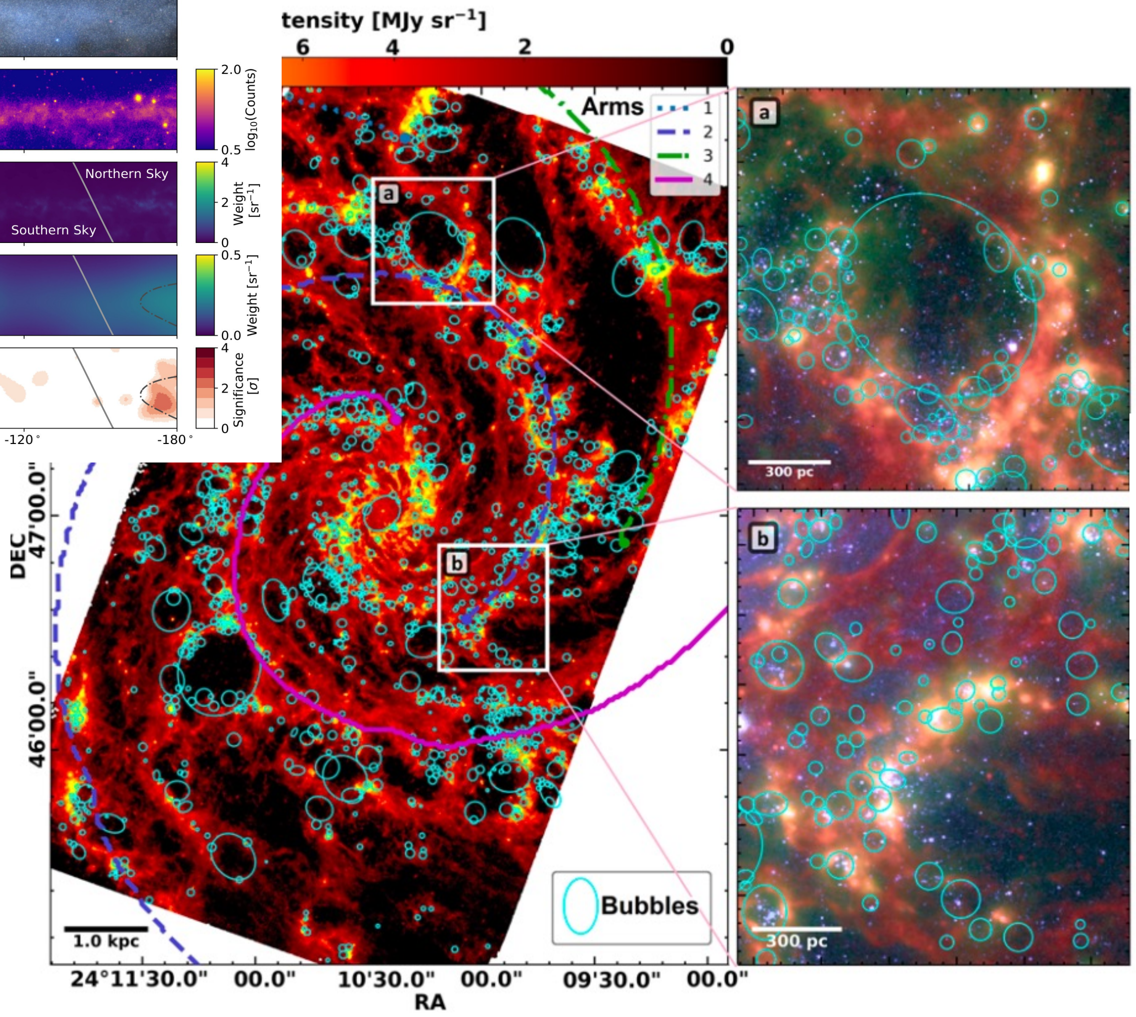

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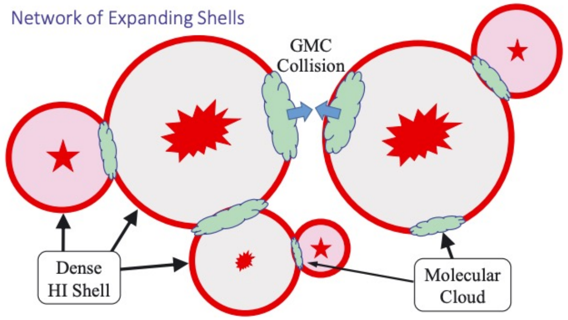
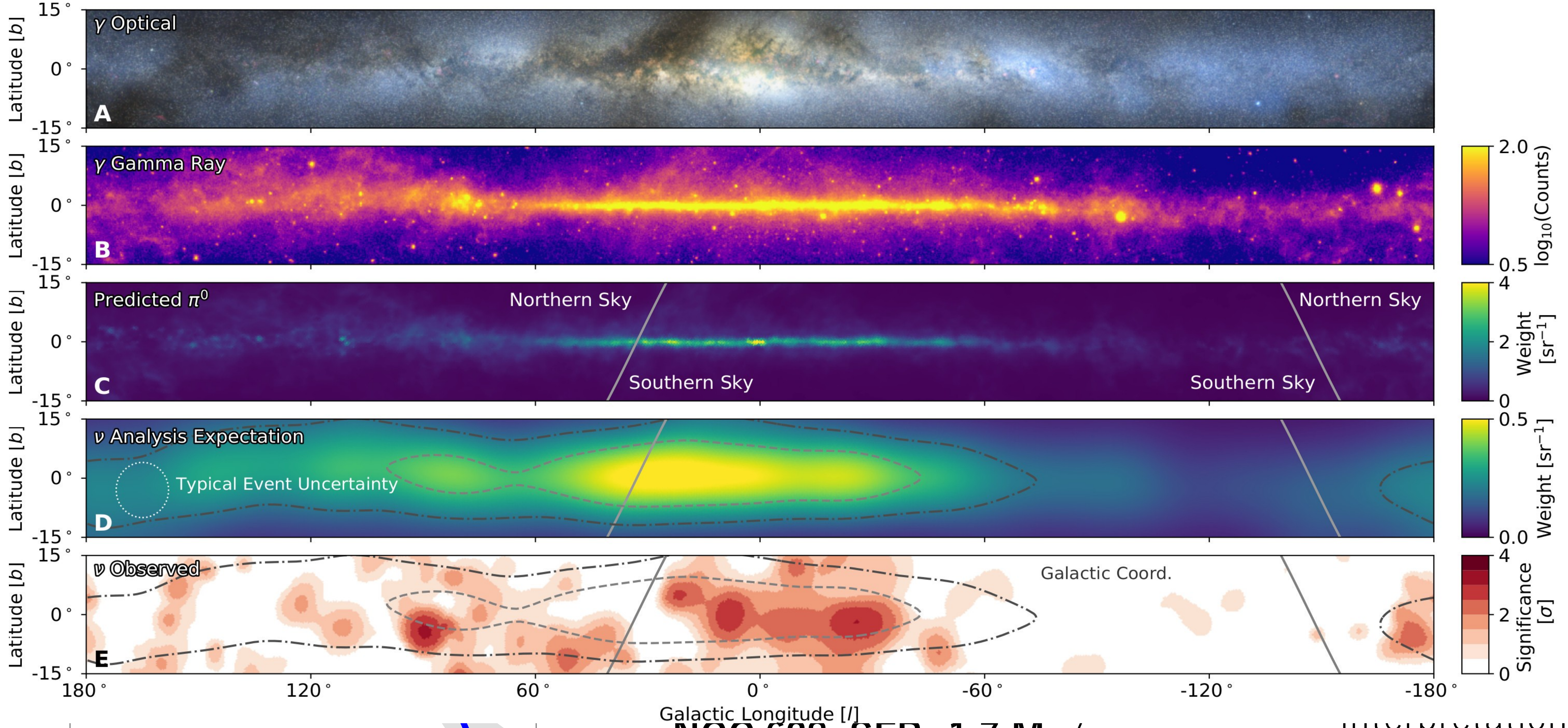


Important for the interpretations of the Galactic diffuse emissions

JWST bubbles: Evidence of the Matter Cycle



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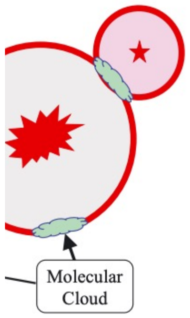

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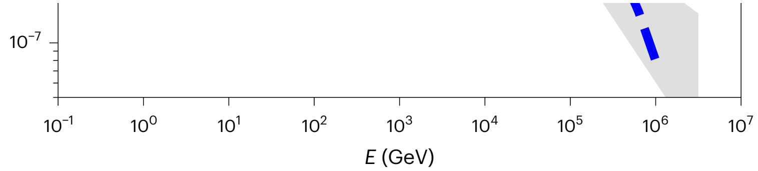

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of the Galactic diffuse emissions

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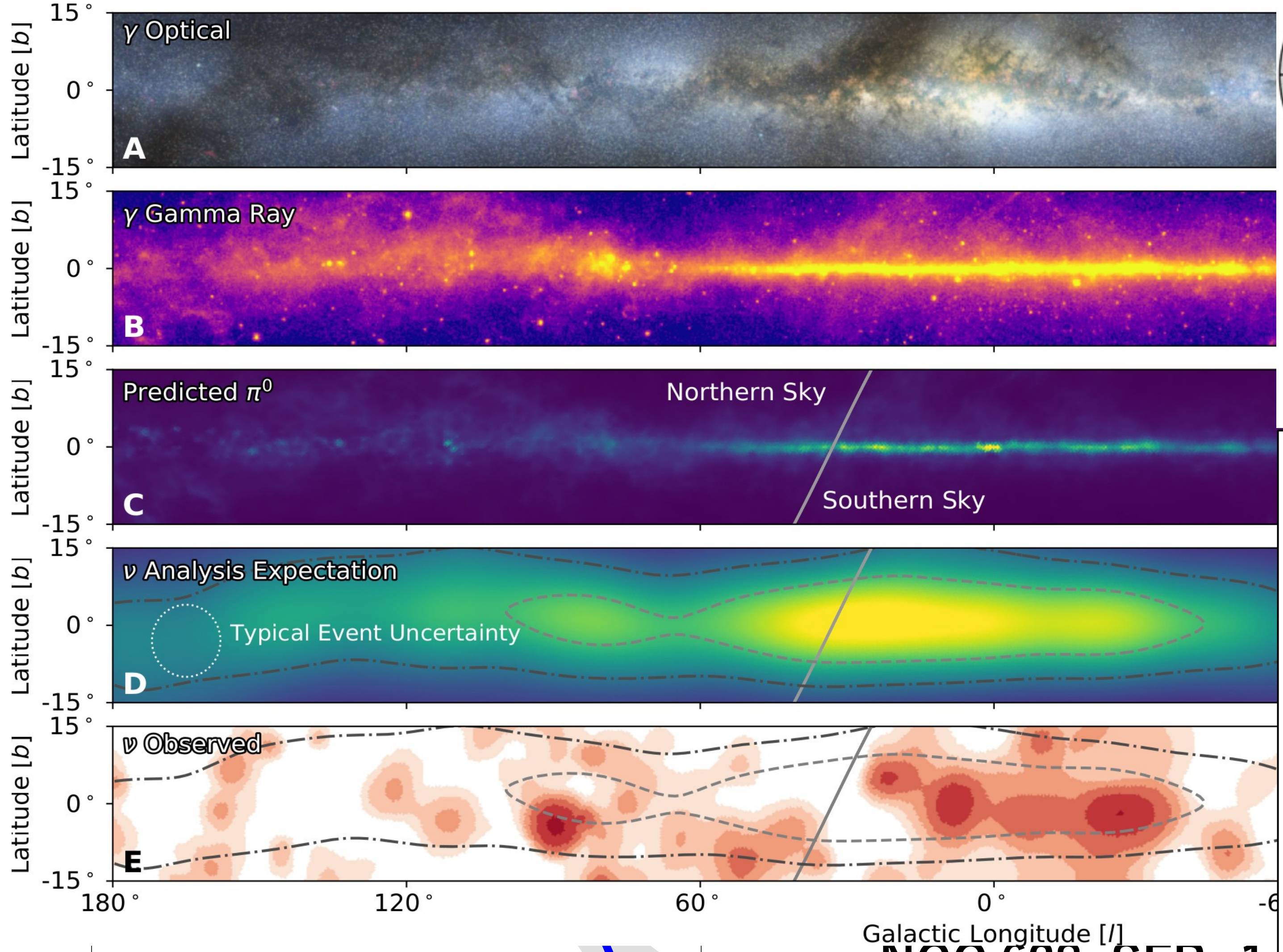
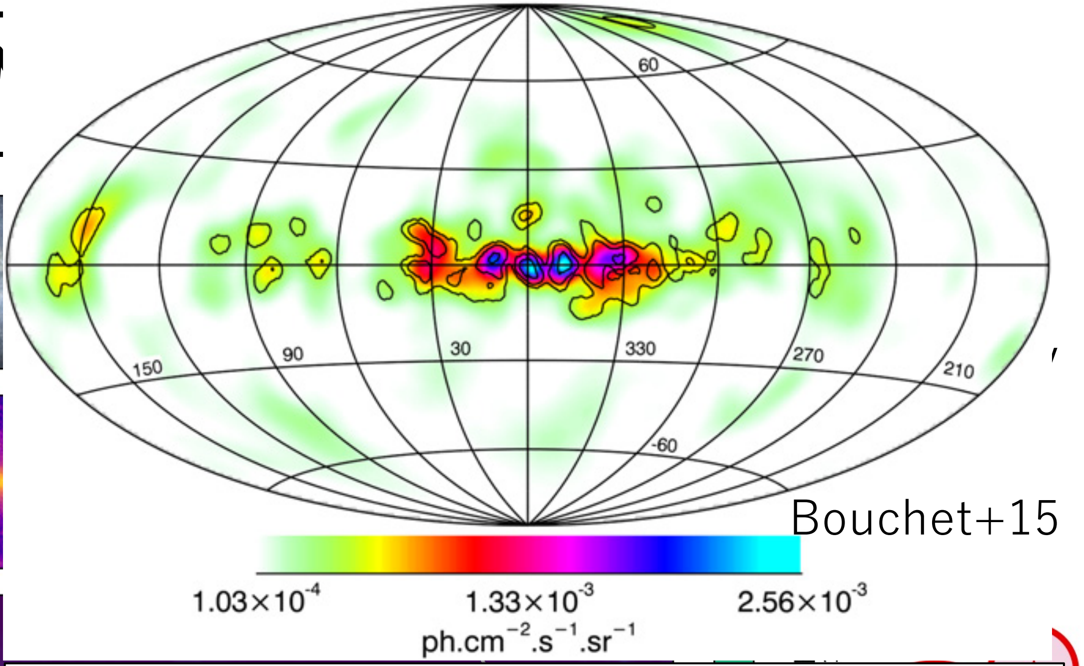
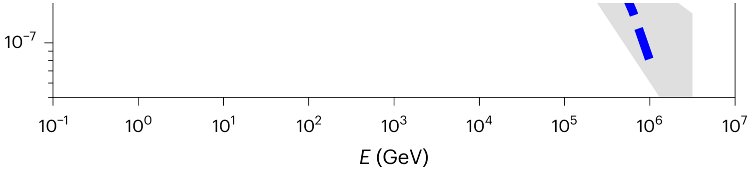




Bouchet+15

^{26}Al line @1 MeV
→Important hints of SNe & Subsequent Galactic Evolution.

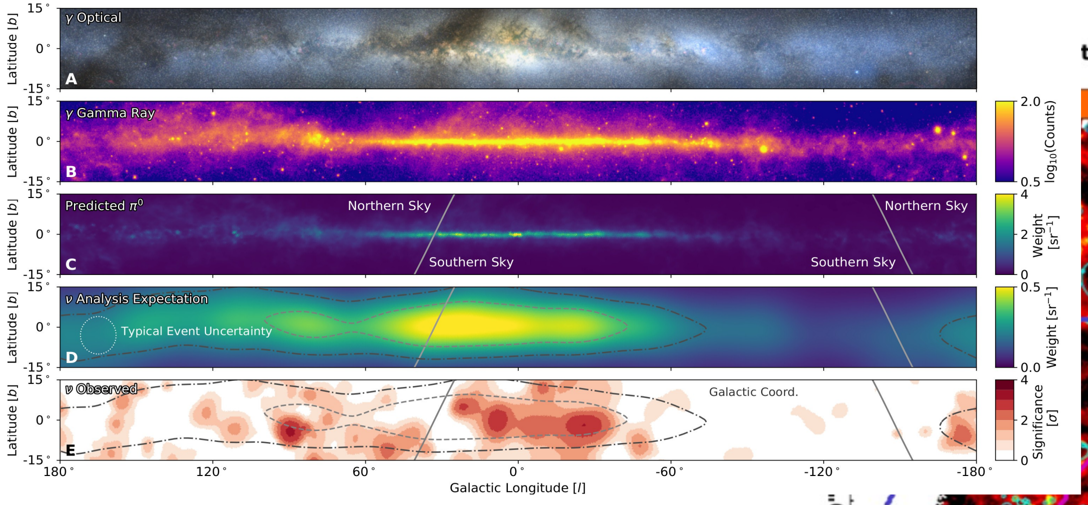
*the solar system shows an enrichment of ^{26}Al→hints of the birthplace of the solar system? (e.g., Fujimoto et al. 2018)
*^{26}Al is main heating source of planetary nebula→important for the planet formation

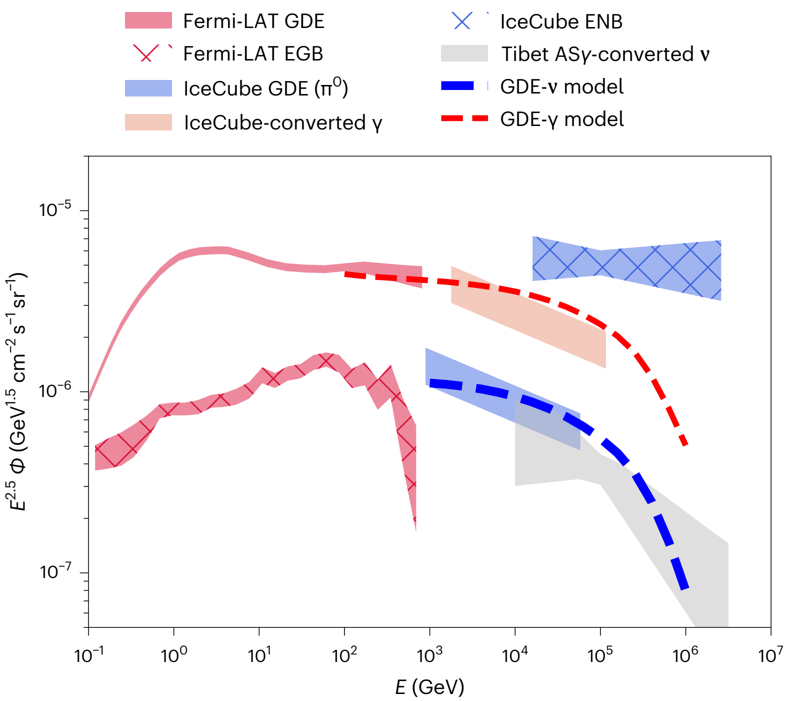


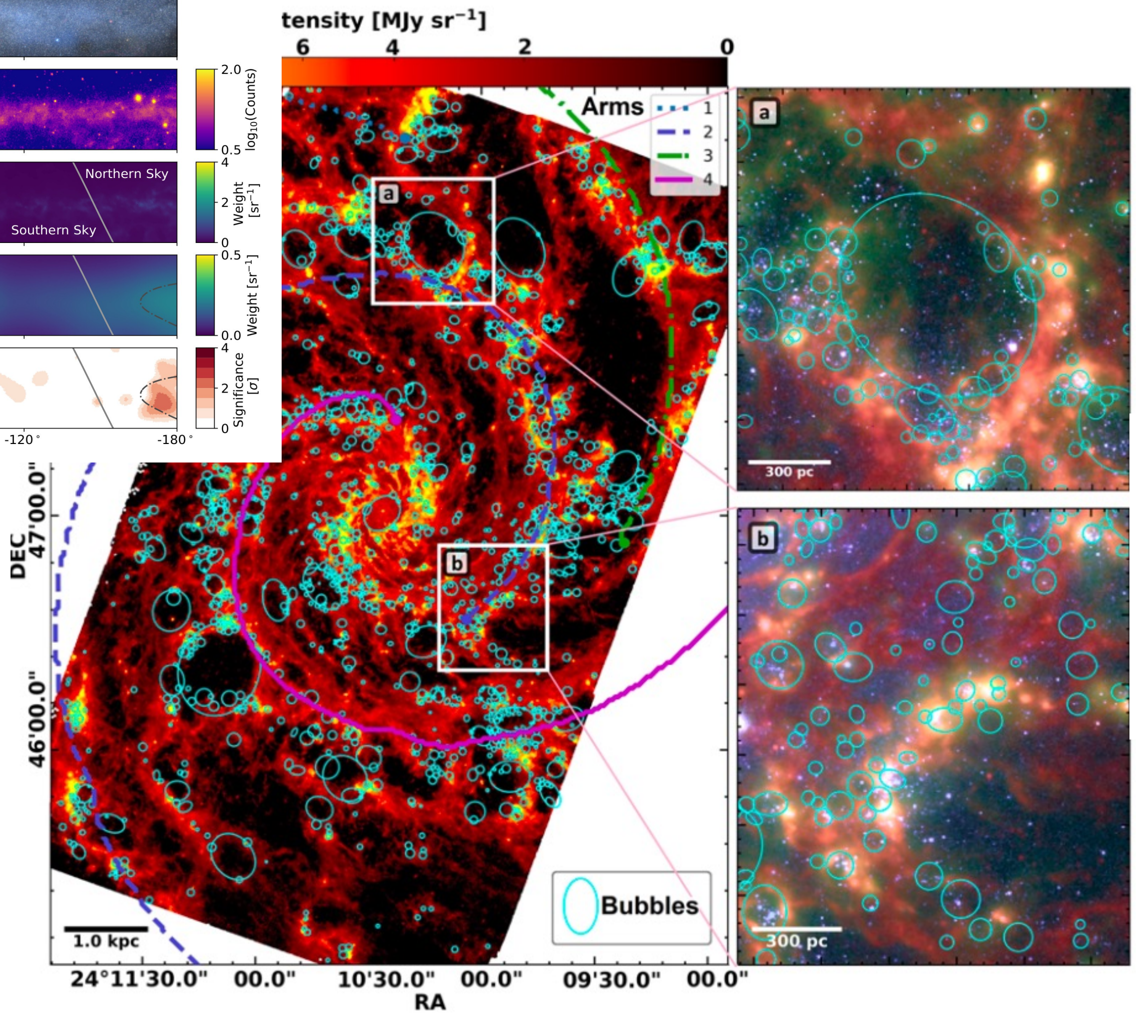
NGC 628: SFR~1.7 M☉/yr
Watkins+23

Galactic diffuse emissions

JWST bubbles: Evidence of the Matter Cycle

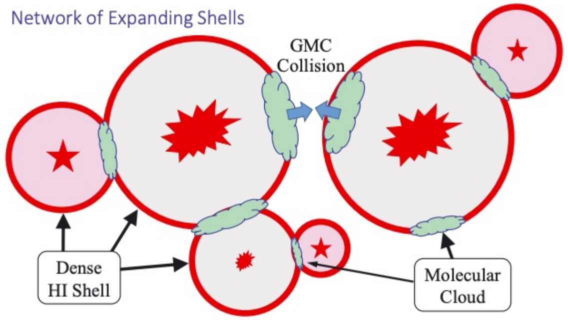






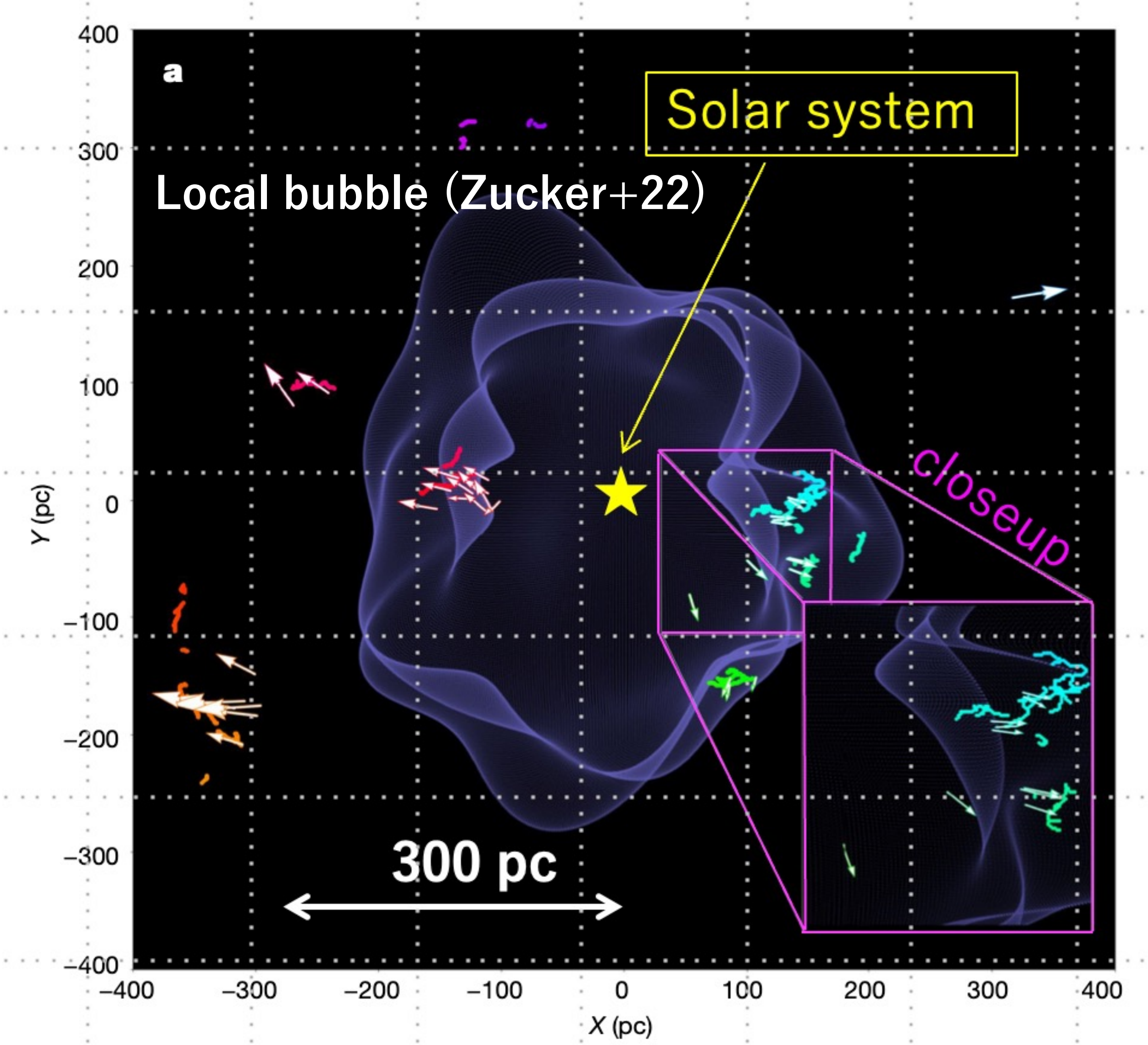
NGC 628: SFR~1.7 Mo/yr
Watkins+23

Consistent with the modern star formation scenario by Inutuska+15



Important for the interpretations of the Galactic diffuse emissions

Local Bubble : *Local* Evidence of the Matter Cycle



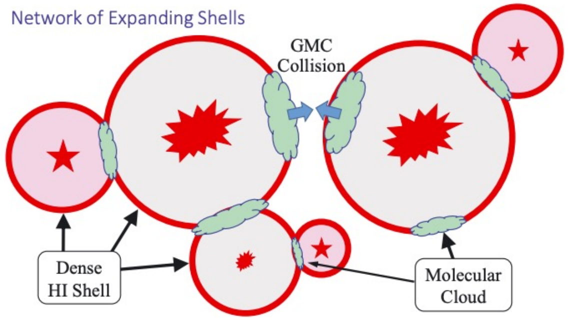
The star forming regions are located at the Local Bubble shell (Zucker+22). The solar system is centered on the bubble.

- **How about CRs & Gamma-rays？**

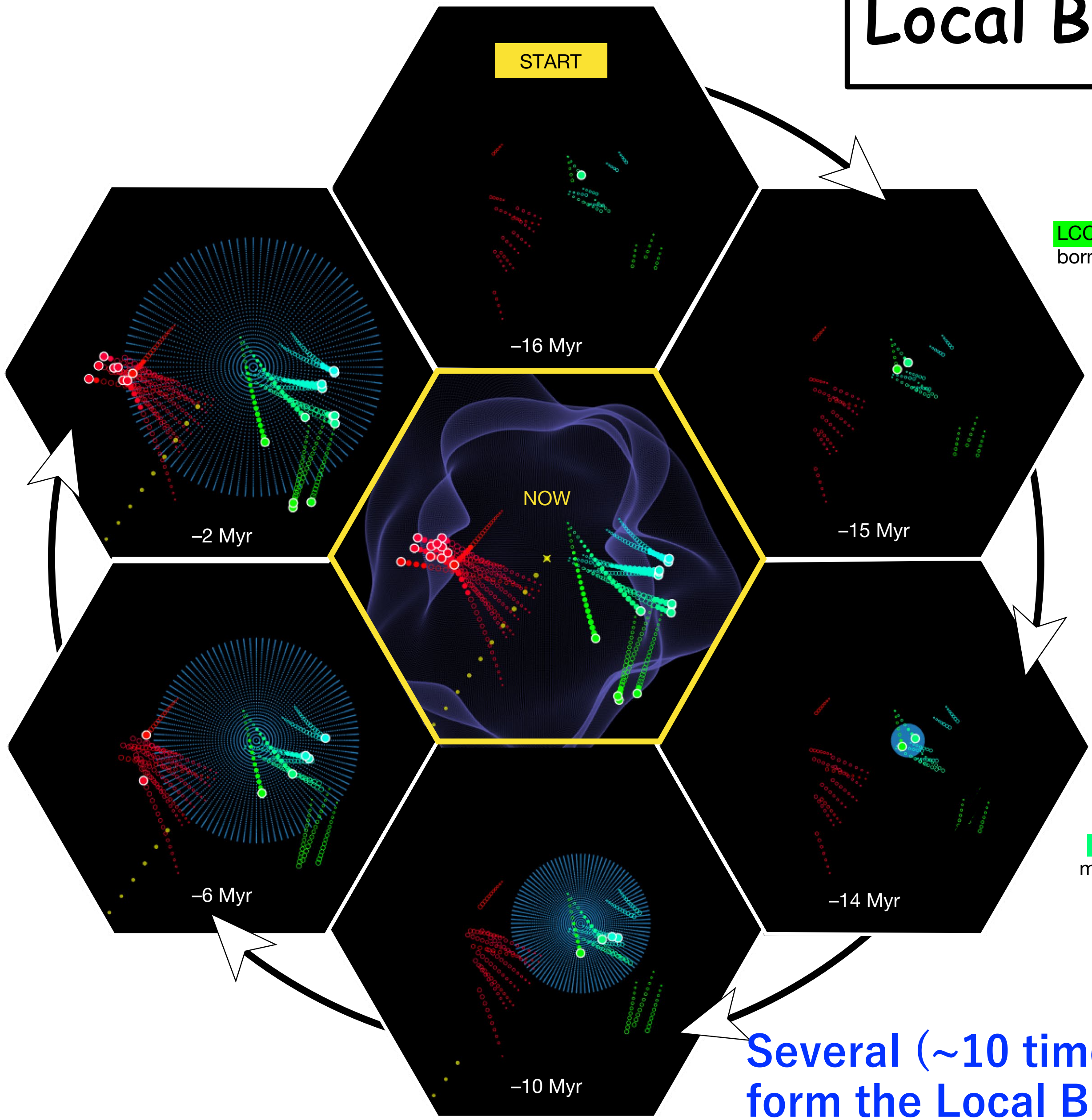
Local Star Formation Time ~ 1-10 Myr

Residence Time of CRs ~ 1-10 Myr.

Local SNe History is also useful info.

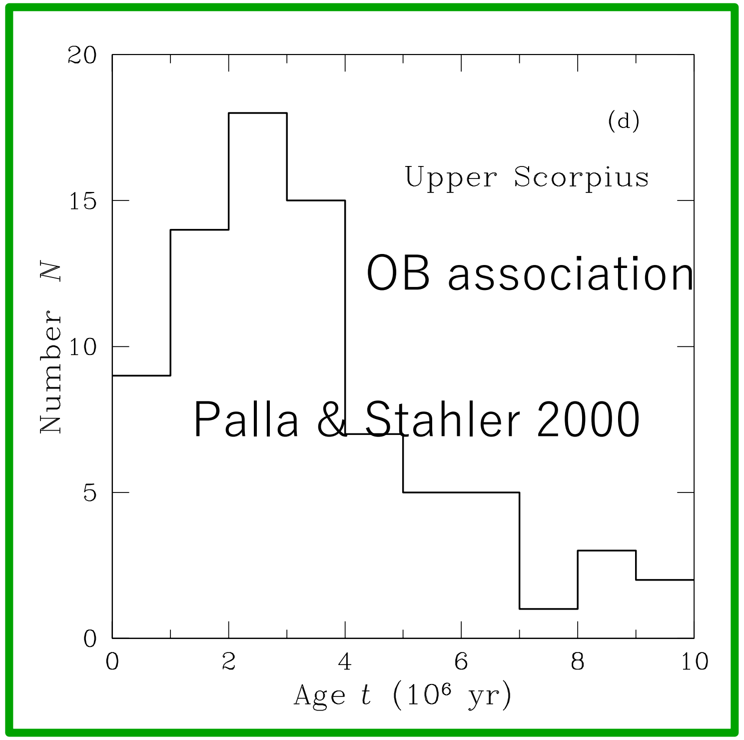


Local Bubble: Star forming Regions



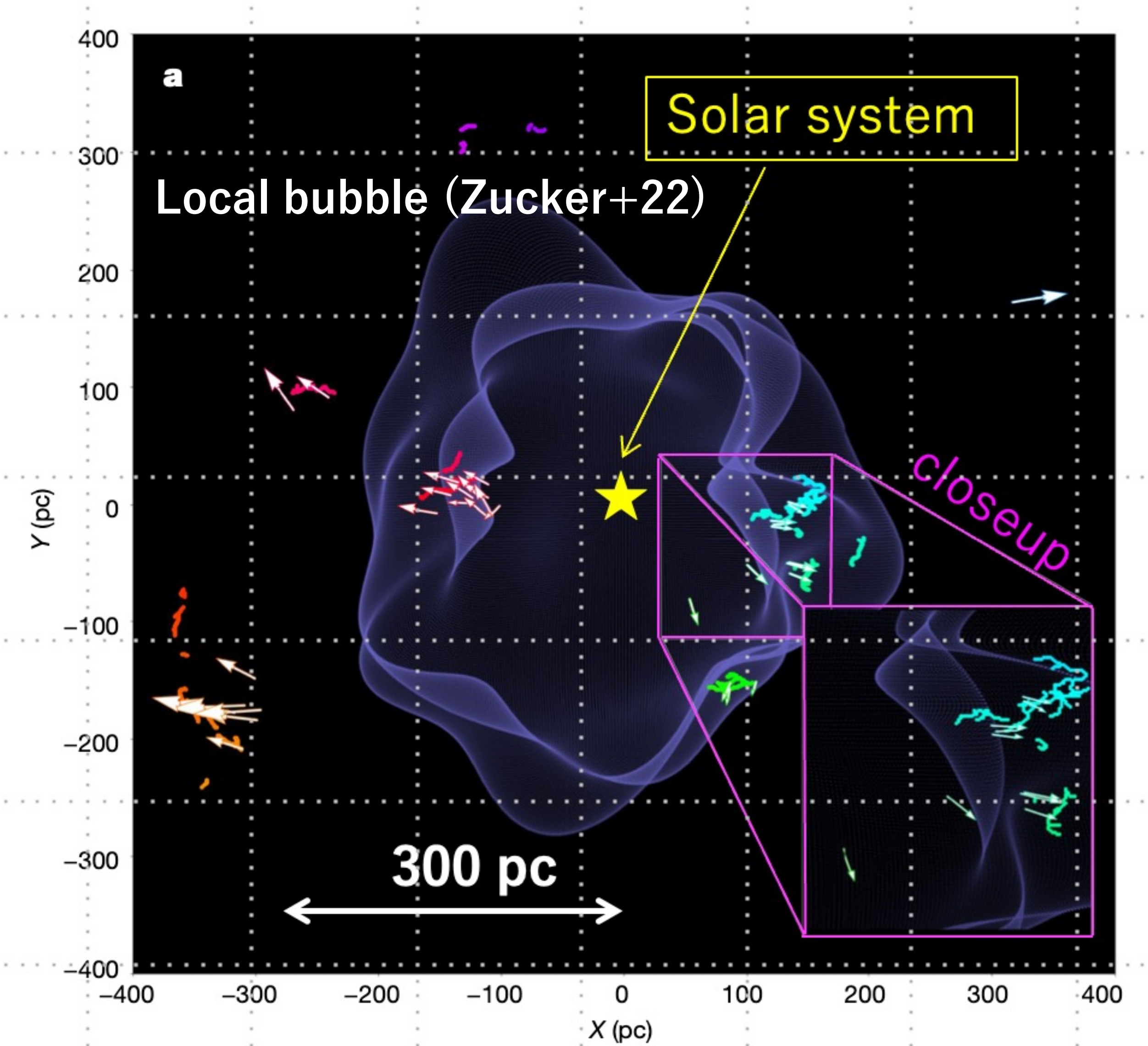
UCL = Upper Centaurus Lupus
LCC = Lower Centaurus Crux

example

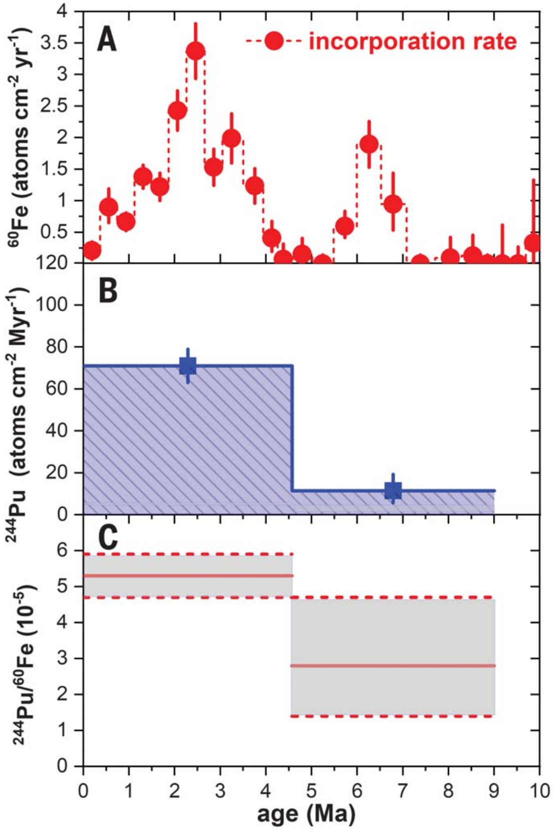


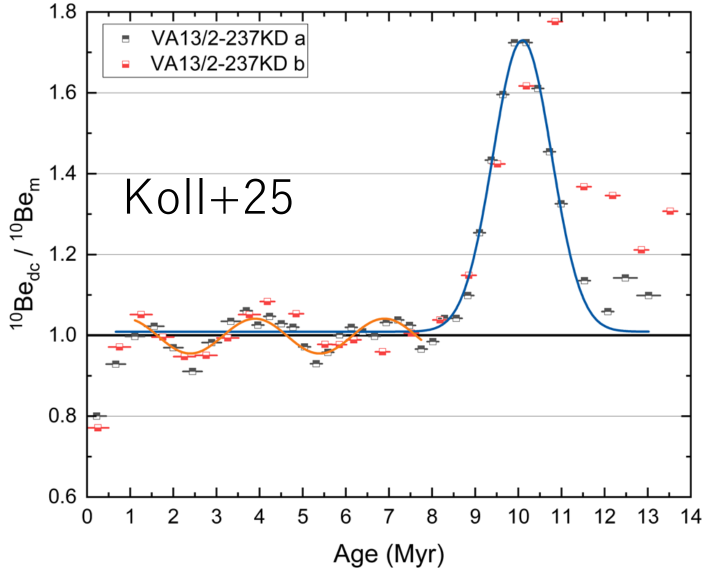
Several (~10 times) SN events occurred around there and form the Local Bubble (Zucker et al. 2022)

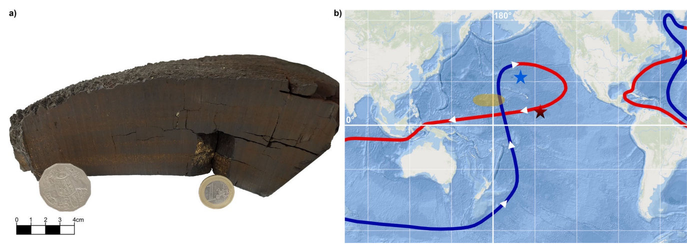
Pacific Ocean Crust：Nearby SNe History



^{60}Fe (half-life, 2.6 Myr) & ^{10}Be (1.4 Myr) in Pacific Ocean Crust







Nearby SNe Activities at ~1-3 Myr ago & ~6 Myr ago

Cosmic Ray Hydrodynamics (the same as the previous one)

Hydrodynamics (thermal plasma)

$$\frac{\partial \rho_{\rm g}}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r^2}\left(r^2 \rho_{\rm g} v_{\rm g}\right) = 0, \qquad (1)$$

$$\rho_{\rm g}\left[\frac{\partial v_{\rm g}}{\partial t} + v_{\rm g}\frac{\partial v_{\rm g}}{\partial r}\right] = -\frac{\partial}{\partial r}\left(P_{\rm g} + P_{\rm cr}\right), \qquad (2)$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho_{\rm g} {v_{\rm g}}^2 + \varepsilon_{\rm g}\right) + \frac{1}{r^2}\frac{\partial}{\partial r^2}\left[\left(\frac{1}{2}\rho_{\rm g} {v_{\rm g}}^2 + P_{\rm g} + \varepsilon_{\rm g}\right) v_{\rm g}\right]$$
$$= n_{\rm g}\left(\Gamma_{\rm g} - n_{\rm g}\Lambda\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \mathcal{K}\frac{\partial T_{\rm g}}{\partial r}\right)$$
$$-v_{\rm g}\frac{\partial P_{\rm cr}}{\partial r} + \int p v f \left(\frac{dp}{dt}\right)_{\rm C} dp + \left|\mathcal{V}_{\rm A}\frac{\partial \varepsilon_{\rm cr}}{\partial r}\right|, \qquad (3)$$

$$P_{\rm g} = (\gamma_{\rm g} - 1)\varepsilon_{\rm g} = n_{\rm g} k T_{\rm g} = \frac{\rho_g}{\bar{m}} k T_{\rm g}, \quad \gamma_{\rm g} = \frac{5}{3}, \qquad (4)$$

Cosmic Ray Transport

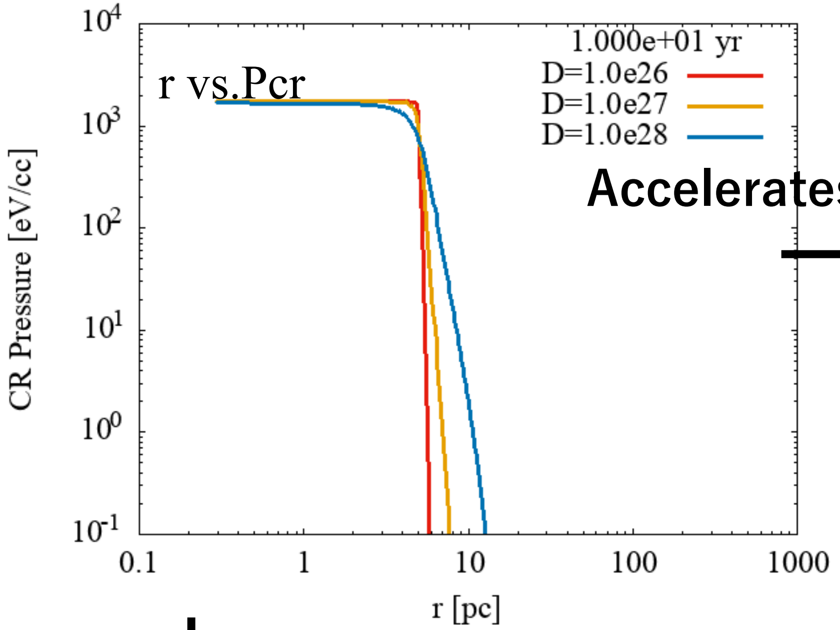
$$\frac{\partial f}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(v_{\rm g} f - \mathcal{D}\frac{\partial f}{\partial r}\right)$$
$$= \frac{1}{r^2}\frac{\partial}{\partial r}\left(\frac{r^2 v_{\rm g}}{3}\right)\frac{\partial f}{\partial p} - \frac{\partial}{\partial p}\left[f\left(\frac{dp}{dt}\right)_{\rm C}\right] - \left|\mathcal{V}_{\rm A}\frac{\partial f}{\partial r}\right|, \qquad (5)$$

$$\varepsilon_{\rm cr} = \int \epsilon f \, dp, \quad \epsilon(p) = \sqrt{(m_{\rm p}c^2)^2 + (pc)^2} - m_{\rm p}c^2, \qquad (6)$$

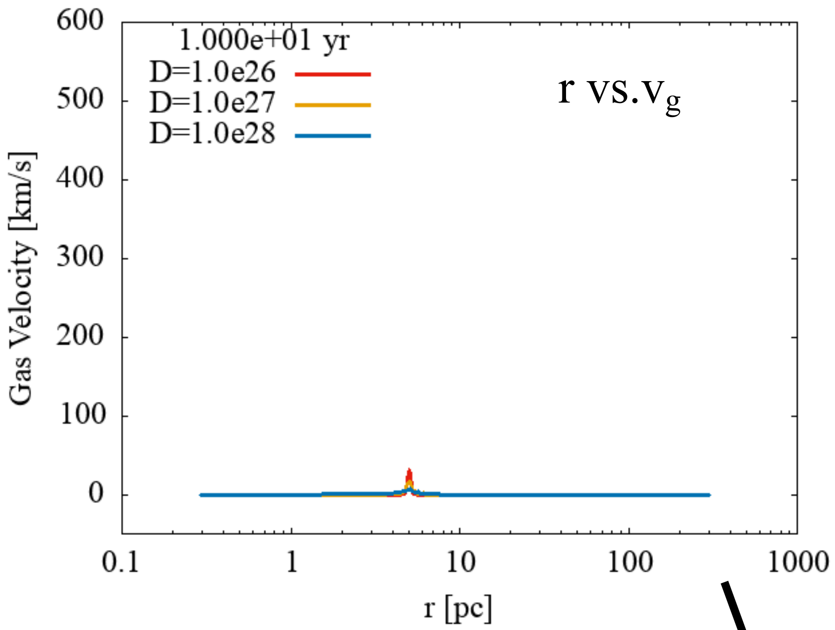
$$P_{\rm cr} = \int \frac{pv}{3} f \, dp, \quad v(p) = \frac{pc^2}{\epsilon(p) + m_{\rm p}c^2}. \qquad (7)$$

Follow ~10 Myr evolution of fluid & CRs

- ~10 Myr is average residence time of CR at the disk.
- The CR momentum distribution is considered (new).



Accelerates the gas

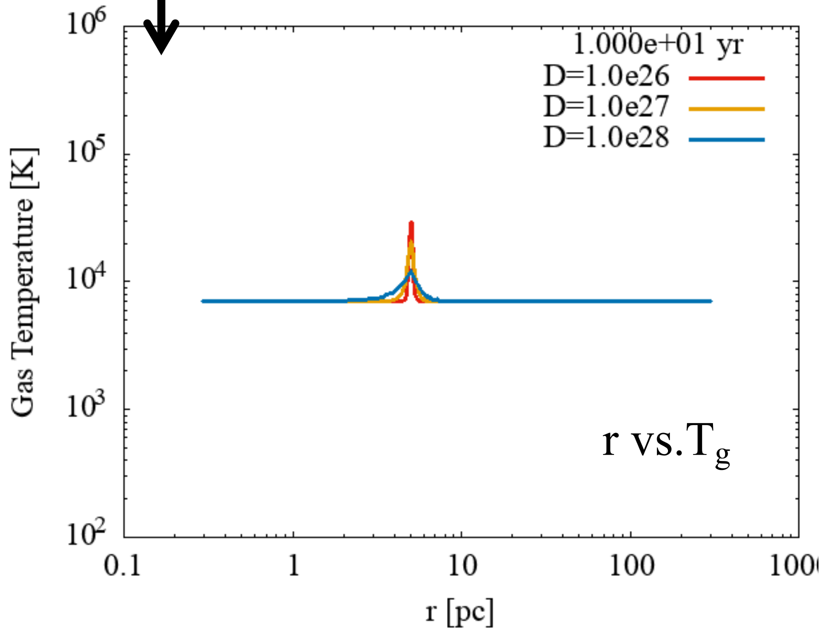


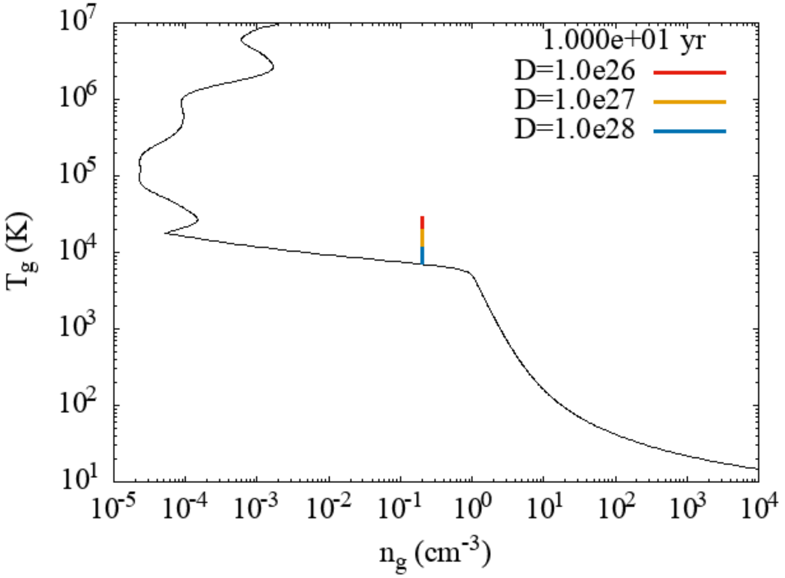
***Initial conditions of gas**
v_g = 0 km/s
T_g = 7000 K
n_g = 0.2 /cc
(equilibrium density)
B_{ism} = 1 μG
(fixed, for CR heating)

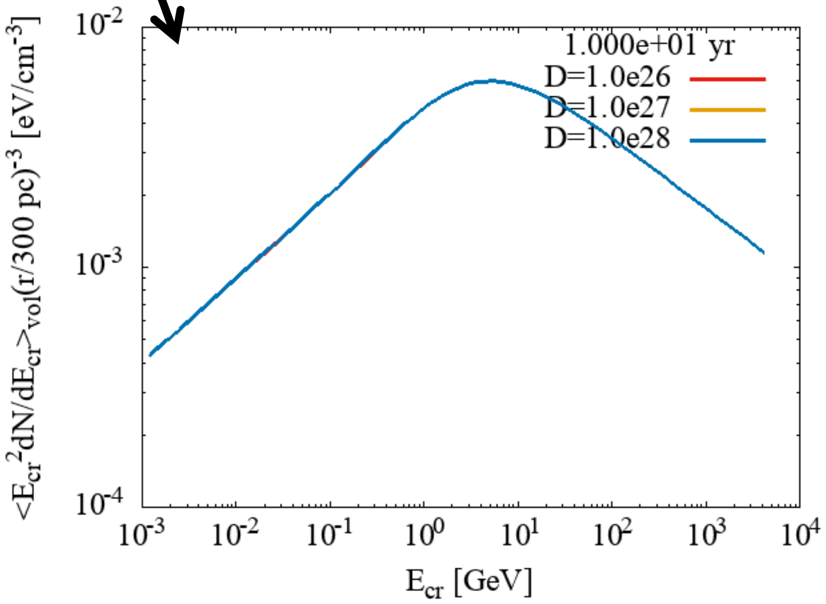
Shimoda, Asano & Inutsuka (2025)

Heats the gas

Affects the CR spectra

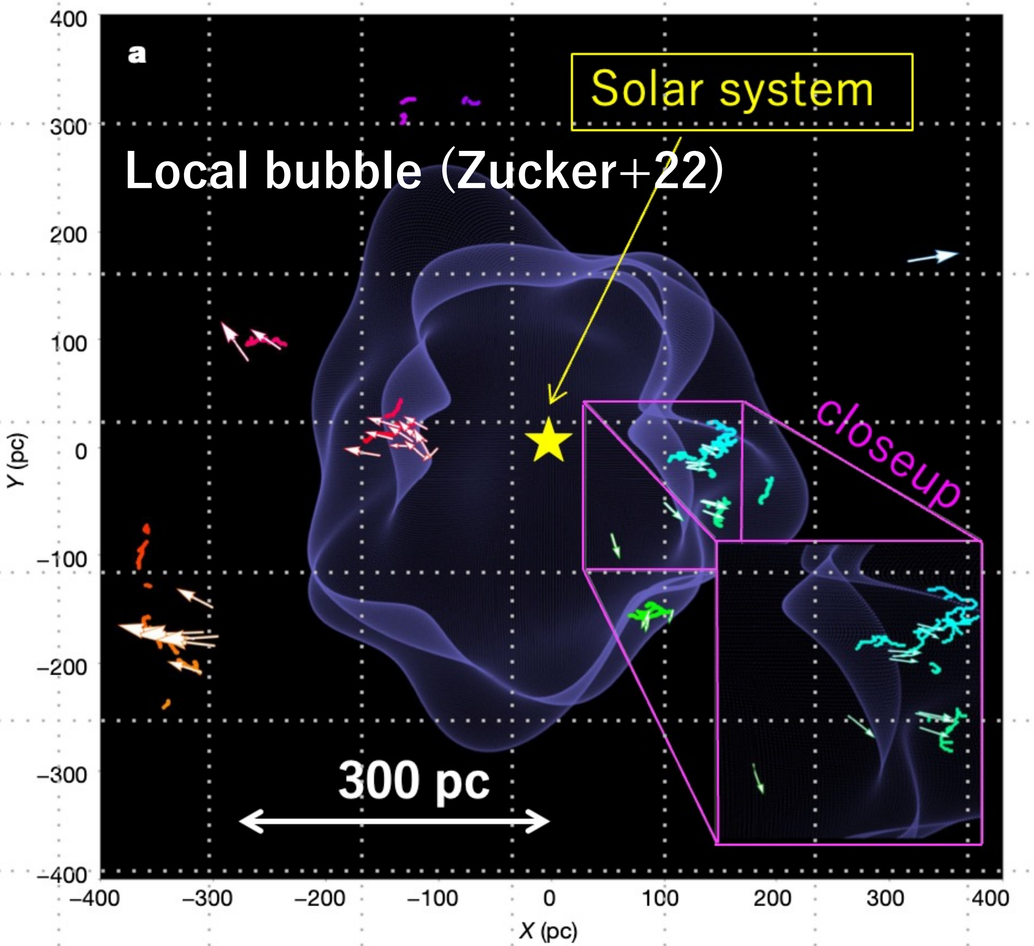


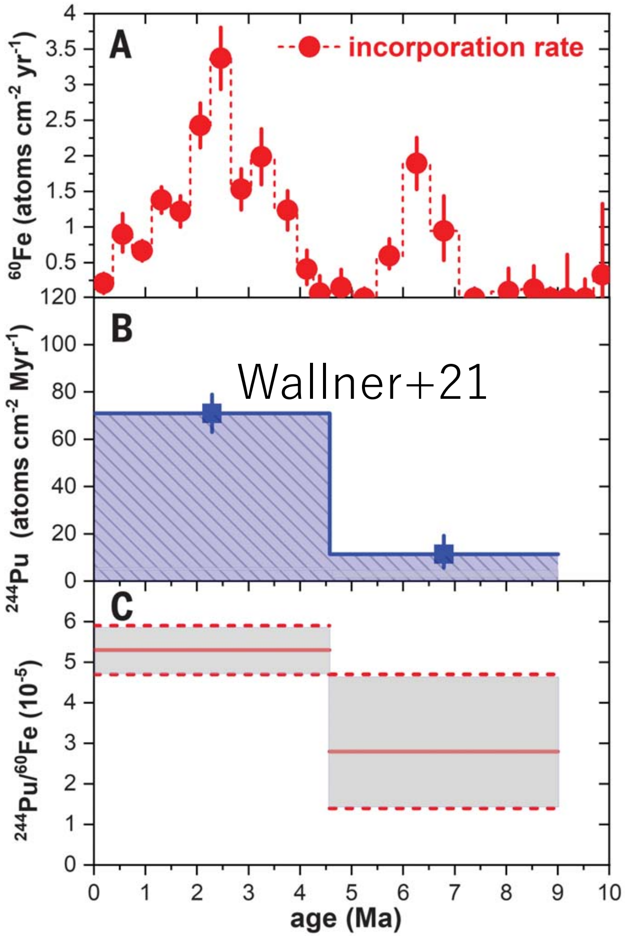


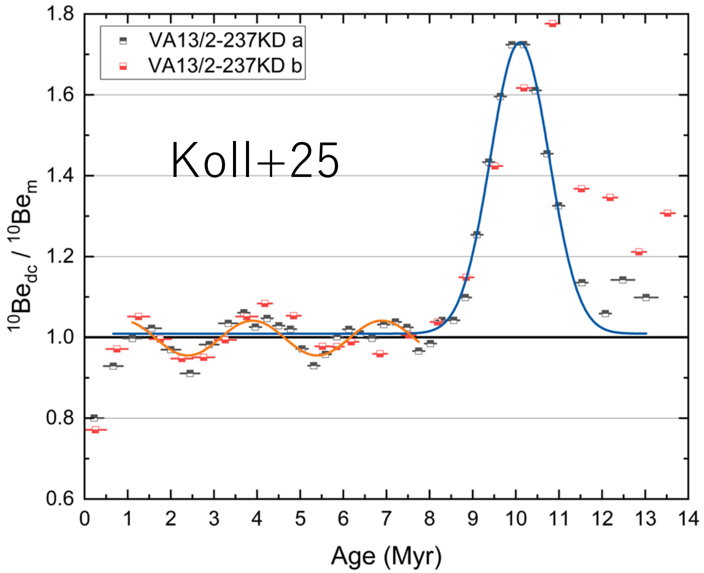


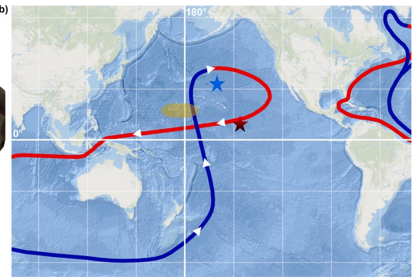
Observational Counterparts

^{60}Fe (half-life, 2.6 Myr) & ^{10}Be (1.4 Myr)
@Pacific Ocean crust







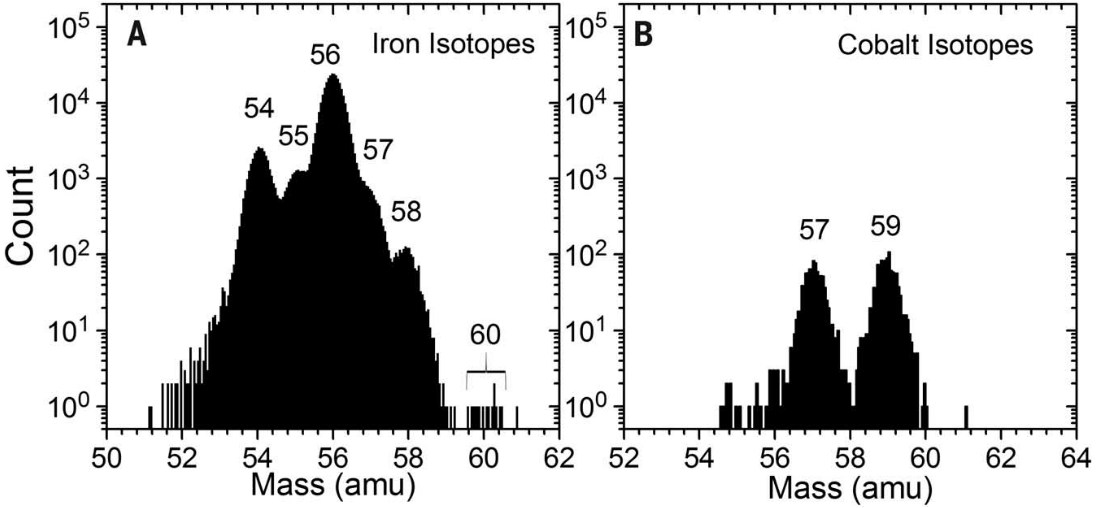


Astronomy (Zucker+22):
Solar system experienced several times SNe within ~10 Myr

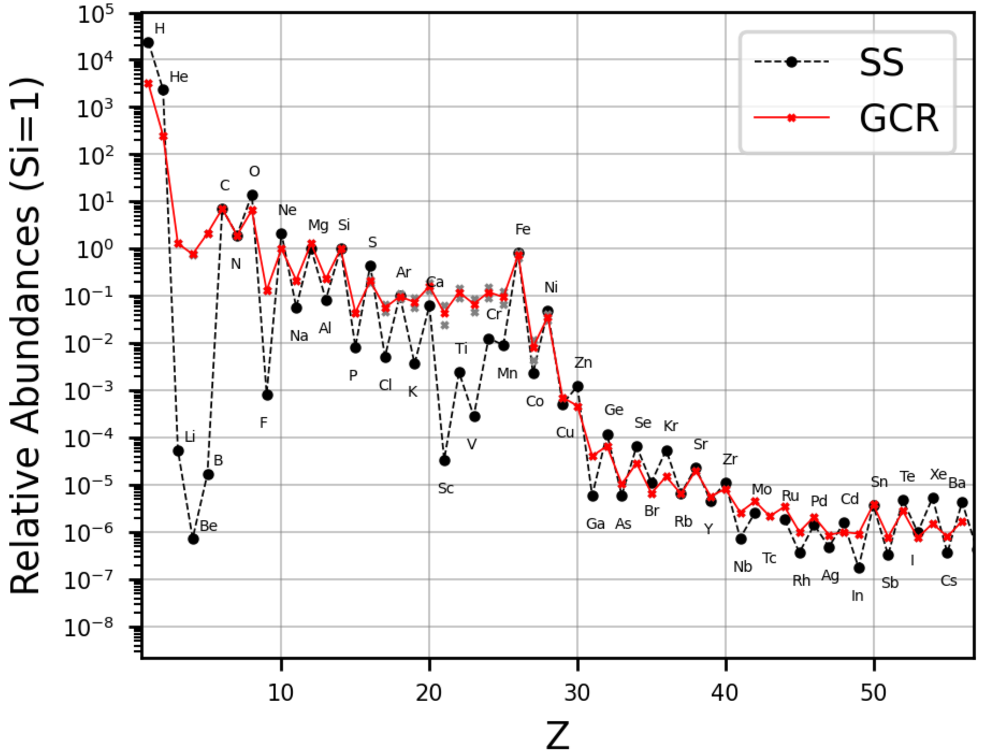
Geology (Wallner+21, Koll+25):
Pacific Ocean crust shows enhancements of ^{60}Fe (~3 & 6 Myr ago) and ^{10}Be (~10 Myr ago).

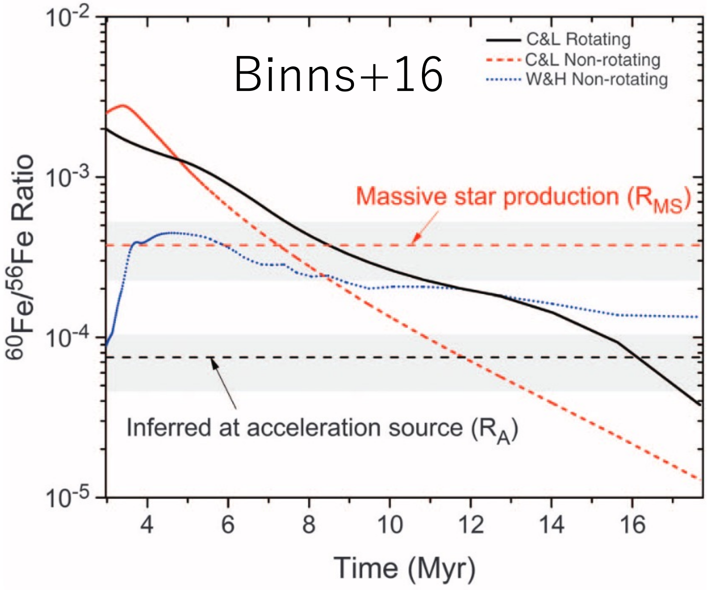
SNe History is also consistent with Cosmic Ray observation

Hint 2: Cosmic Ray ^{60}Fe (half-life, 2.6 Myr)



CALET collabo.





CR ^{60}Fe are observed at the *present*.
In comparison of ^{59}Ni observations & Modeling of OB association, a mean time between the nuclear synthesis and acceleration is:

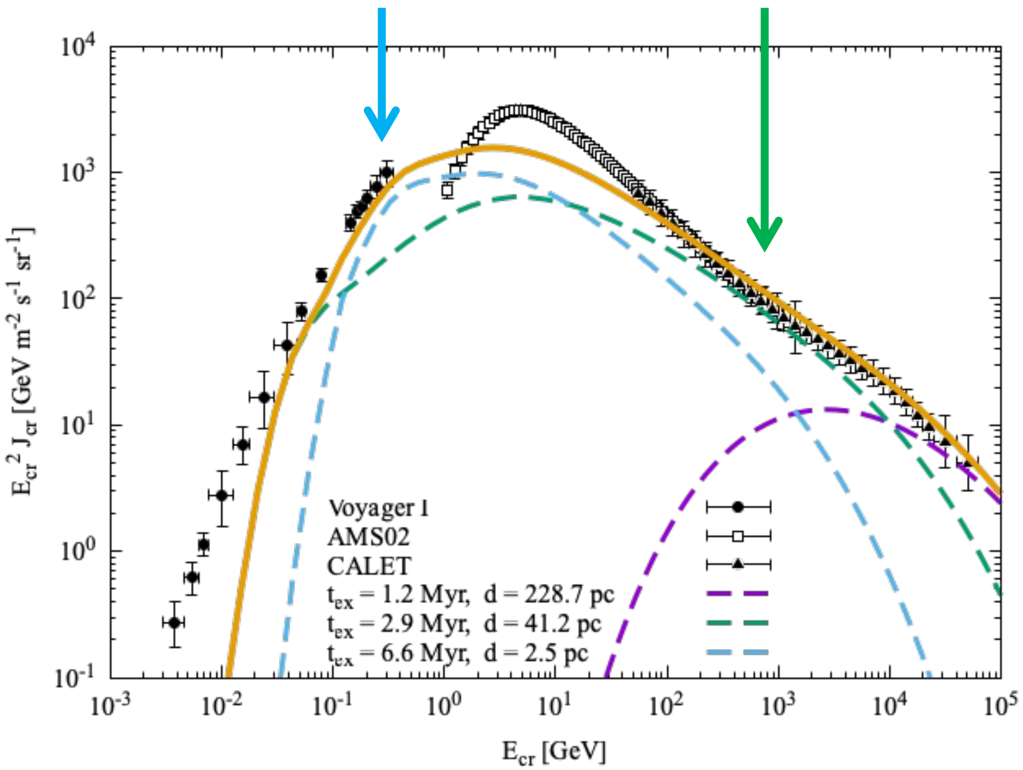
100 kyr < T < several Myr

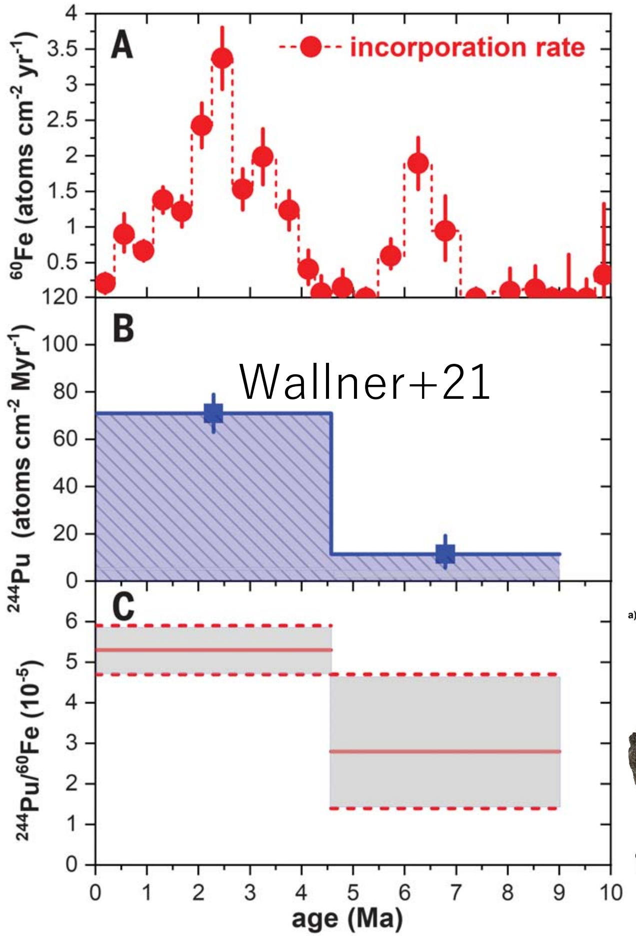
(^{59}Ni half-life, 76 kyr)

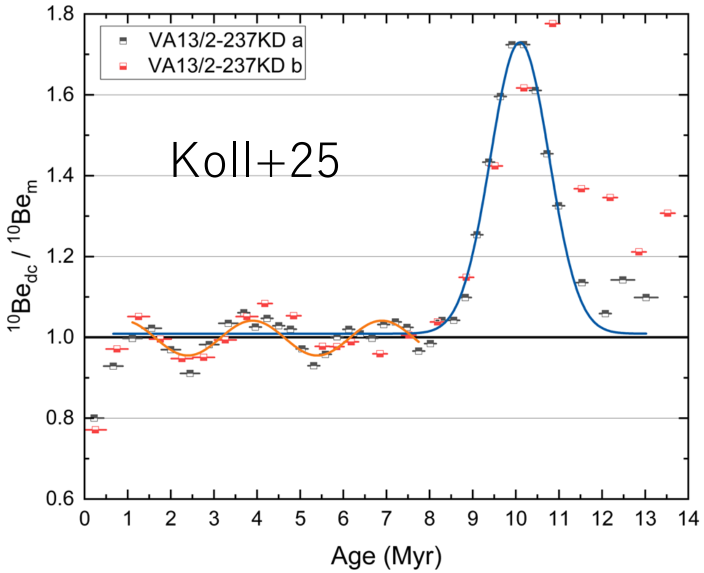
Observational Counterparts

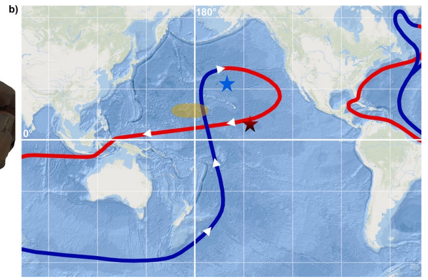
^{60}Fe (half-life, 2.6 Myr) & ^{10}Be (1.4 Myr) @Pacific Ocean crust

CR *age*: ~6 Myr ~3 Myr









Galactic CR spectrum can be consistent with them.

→ We can start *CR Archaeology* by the radio isotope analysis.

(e.g., ^{10}Be/^{9}Be is a traditional example)

Summary

SFR ~ 7 Mo/yr - 4 Mo/yr ~ 3 Mo/yr
4 Mo/yr can be determined by the CRs

We should examine as next steps:

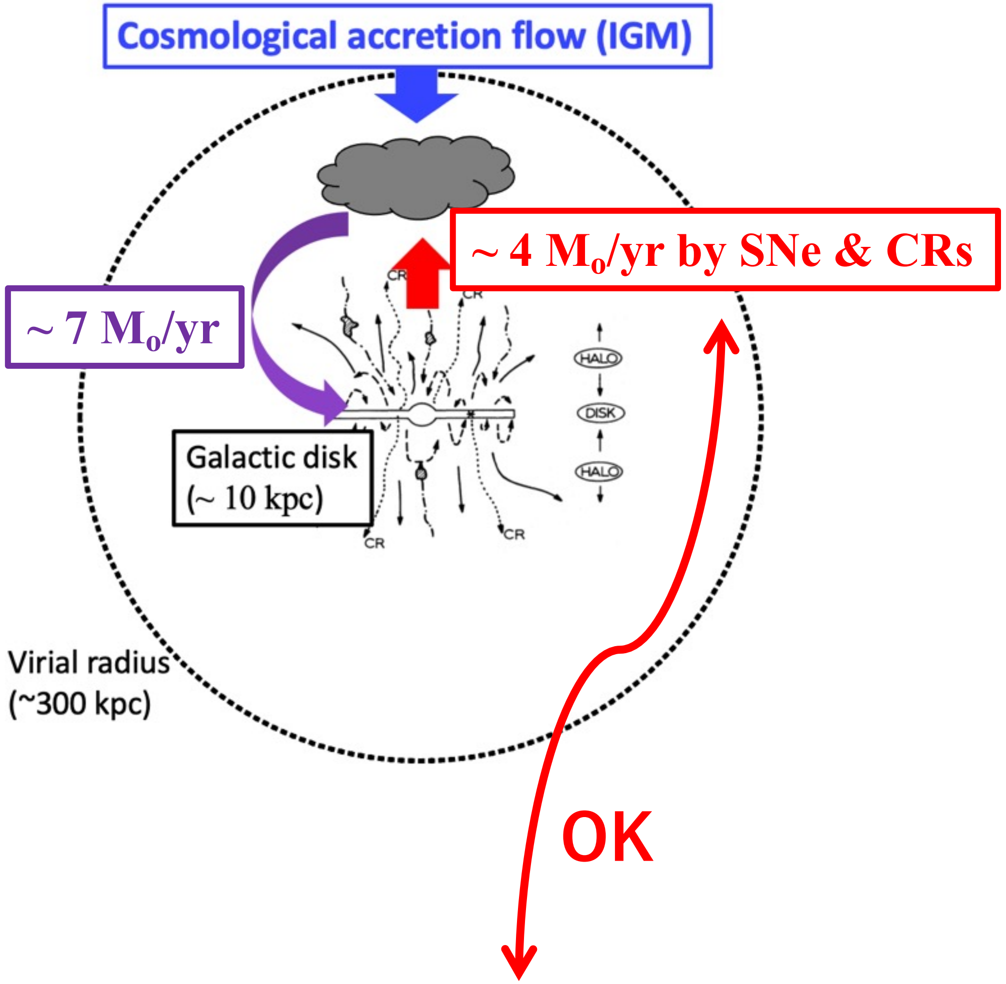
1) Observational Counterparts

CR Archaeology,
WANTED ^{9}Be (beryllium 9) in stars, spectroscopy of external galaxies, and so on.

*Big Bang→^{7}Be (half-time 53 days)→^{7}Li
*Triple alpha→^{8}Be (half-time 6.7e-17 s)+^{4}He→^{12}C
*Cosmic Ray Nuclear Spallation→^{9}Be (stable)

2) Acceleration of the removed gas at the disk-halo interface

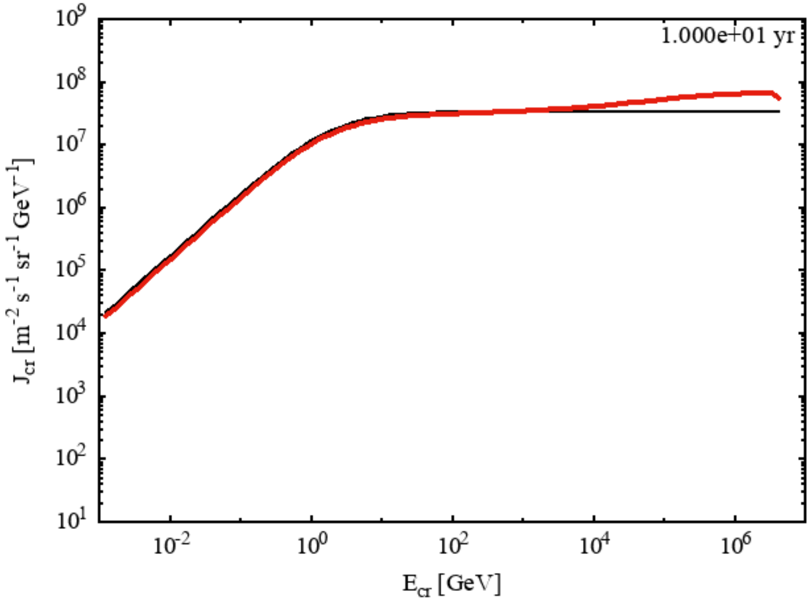
We will investigate

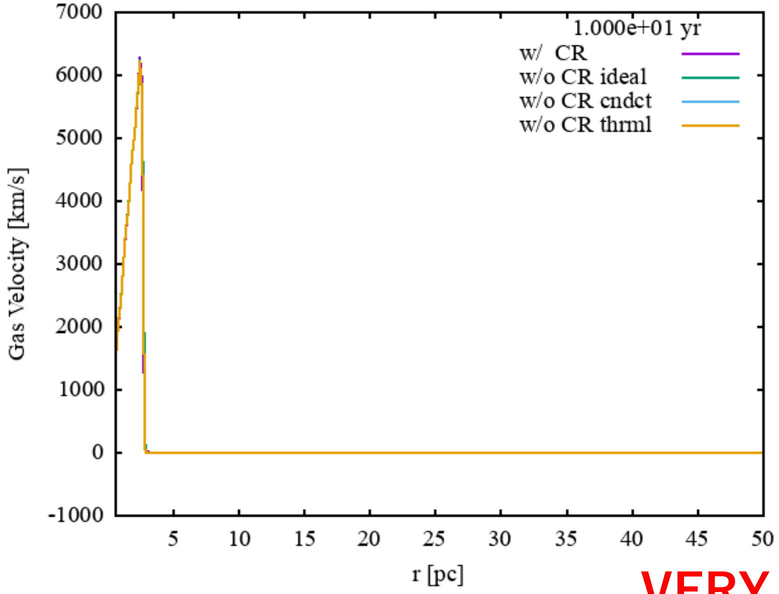


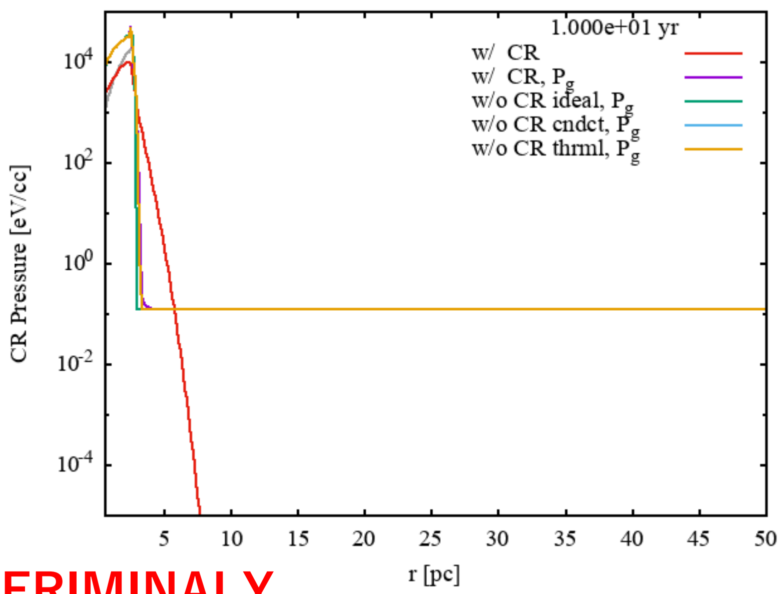
~1000 Mo is removed from the disk by CRs
→Mass loss rate of the disk
~ (1000 Mo) x (SN rate)
~ 10 Mo/yr (SN rate/0.03 yr^{-1})

Supernova remnants w/ prompt injection (injection only at very early stage)

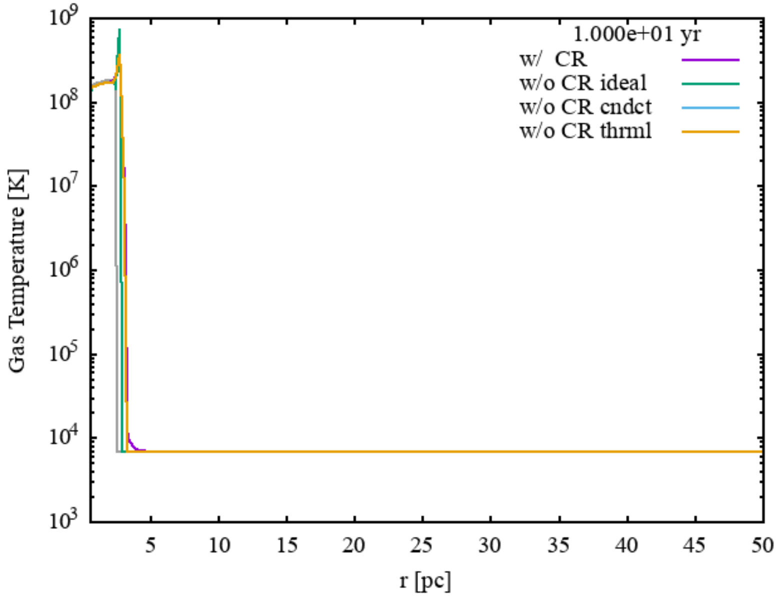
CR spectrum @ r = 1 pc

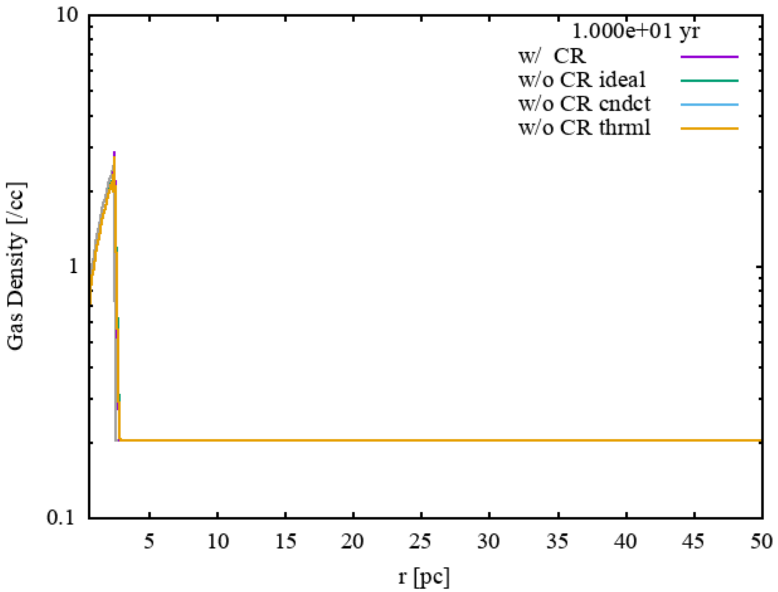






VERY PRERIMINALY





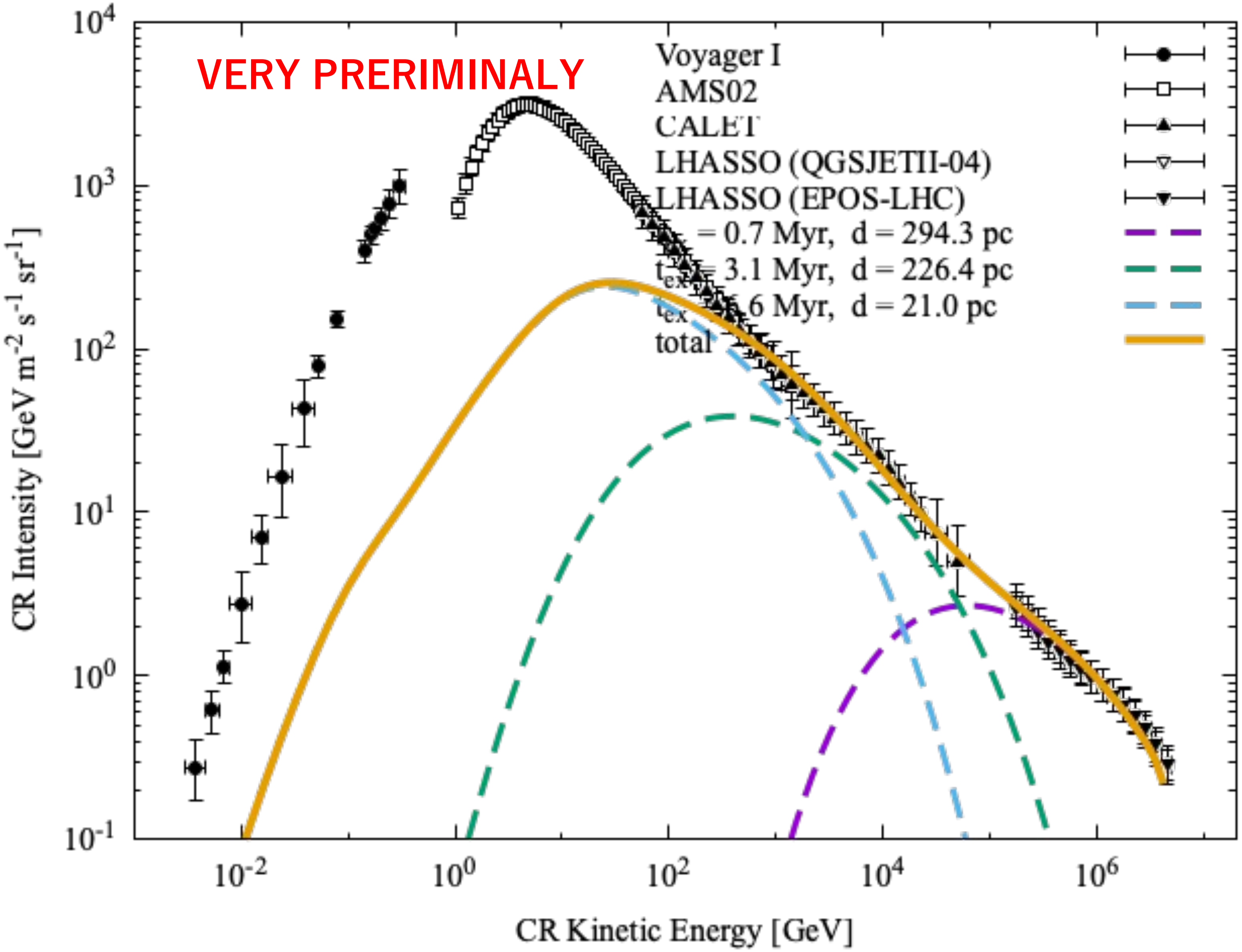
The Ejecta are heated/disturbed at ~ several kyr.

Some CRs remain inside the remnant.
Hadronic gamma-rays are not so bright due to the small density of ejecta.

Detailed theoretical models & calculations may be required.

Supernova remnants w/ prompt injection (injection only at very early stage)

CR spectrum @ r = 1 pc



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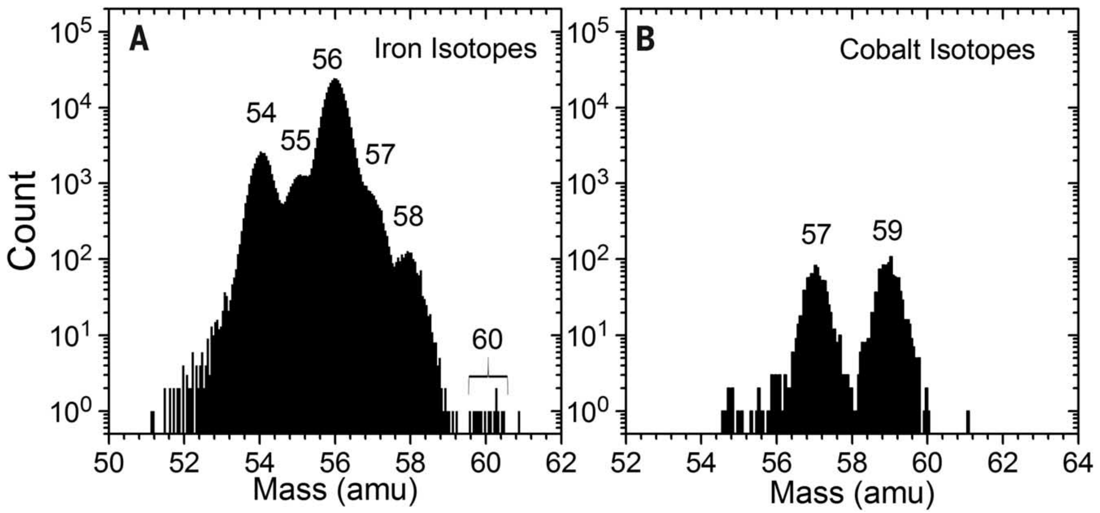
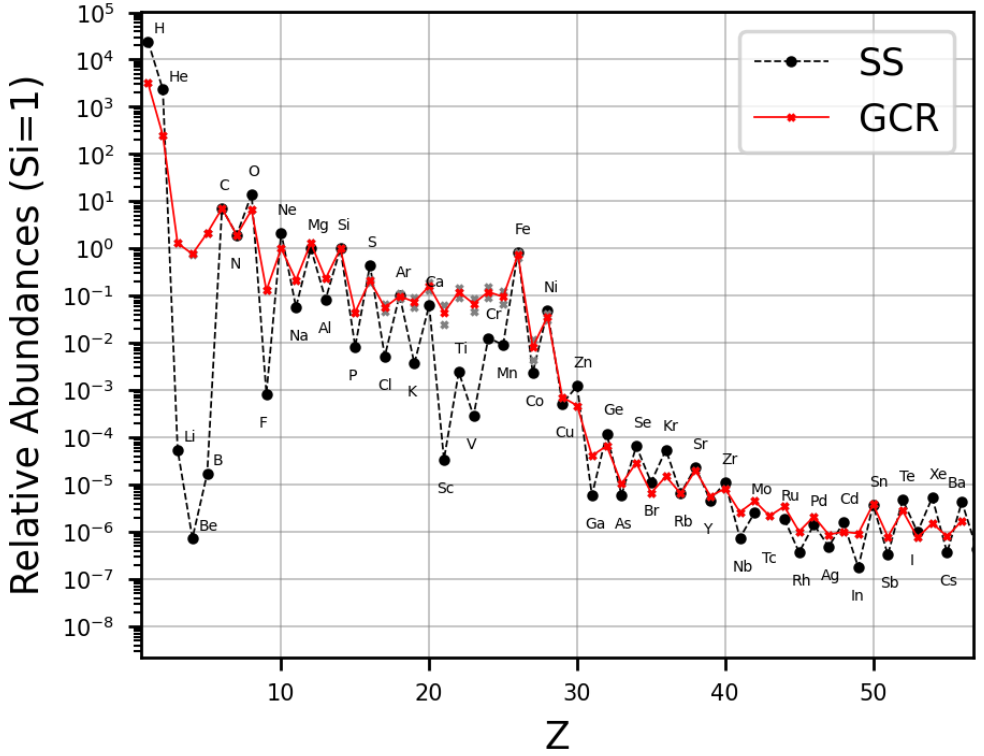
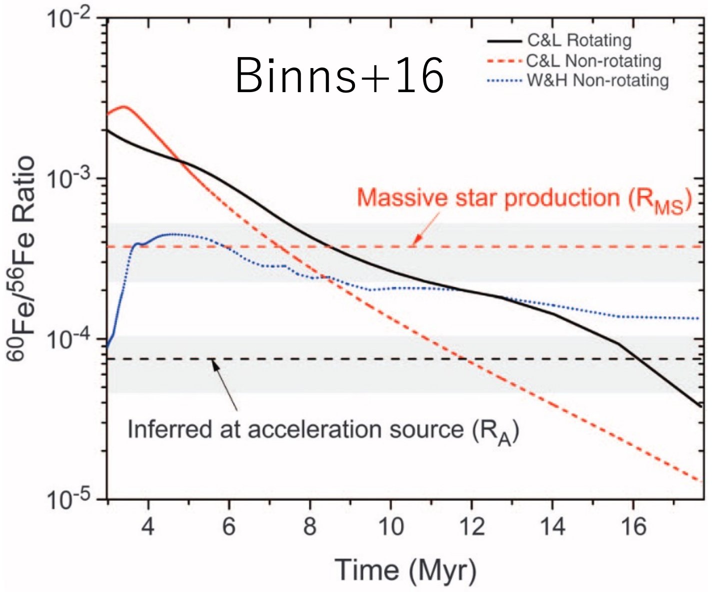
Cosmic Rays

Hint 2: Cosmic Ray ^{60}Fe (half-life, 2.6 Myr)



CALET collabo.





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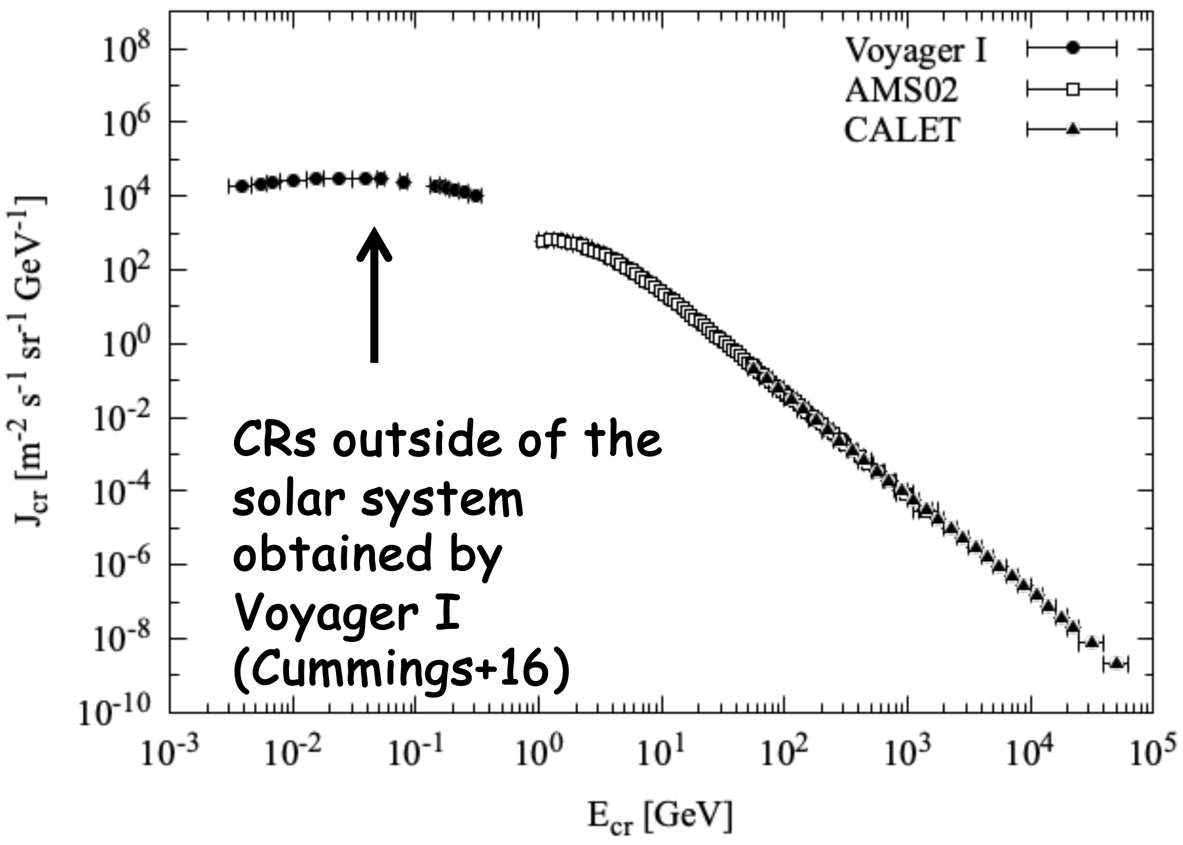
Cosmic Rays

https://matisse.web.cern.ch/science.html

Hint 3: Low-Energy CR (↓ protons)



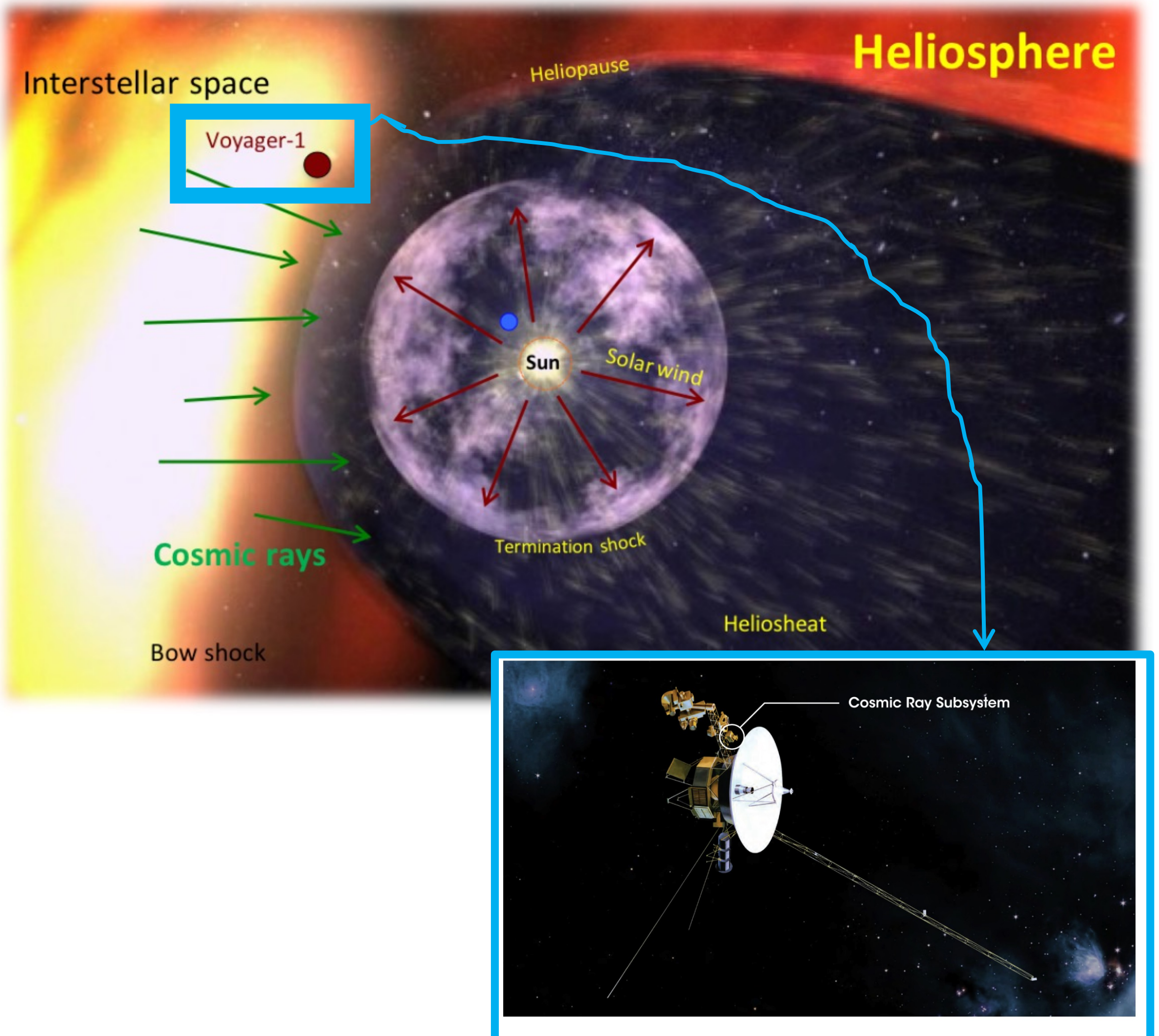


Illustration of NASA's Voyager spacecraft, with the Cosmic Ray Subsystem (CRS) highlighted.
Credits: NASA's Goddard Space Flight Center/Jet Propulsion Laboratory/Mary Pat Hrybyk-Keith