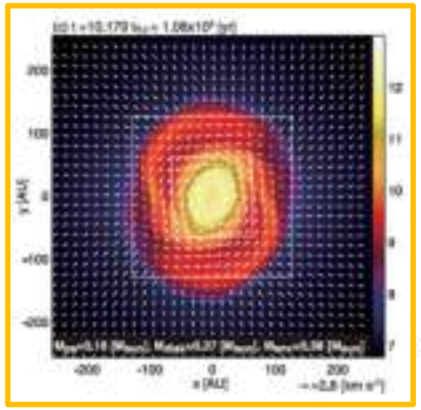
Roles of Cosmic-Rays in Astrophysics: The History of Our Galaxy (arXiv:2306.16887)

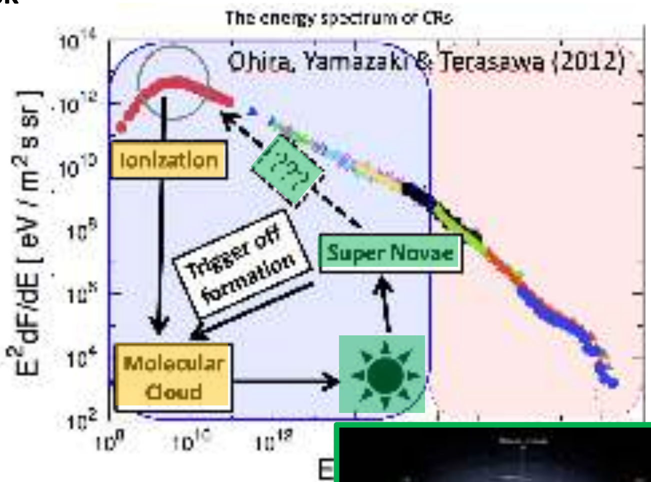
Jiro Shimoda

マルチメッセンジャー天文学の展開, 2023, November, 2

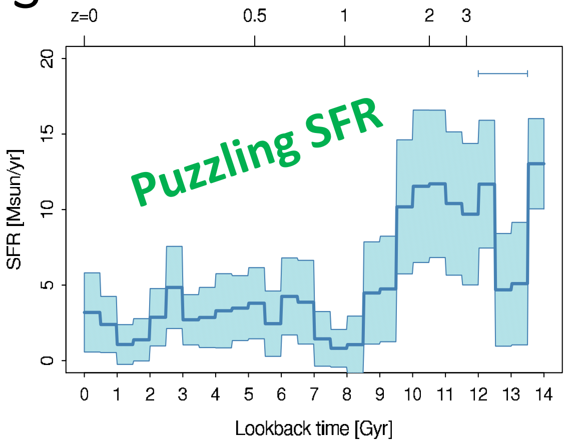
Roles of Galactic Cosmic Rays

Evolution of the Protoplanetary disk

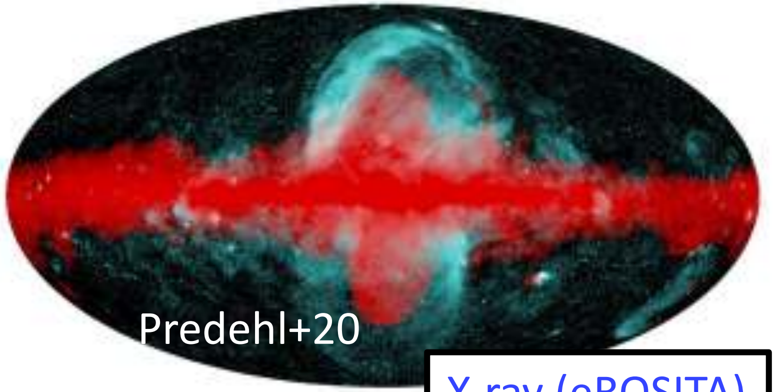




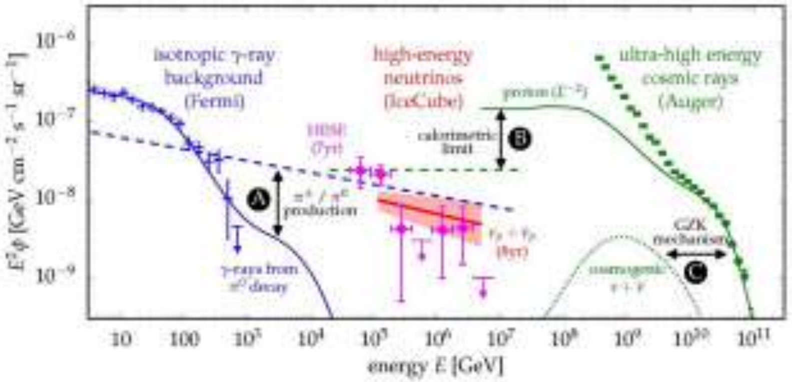
CR ionization rate controls the size/life-time of protoplanetary disk via the angular momentum transportation by B-field.
→ *Planet formation*



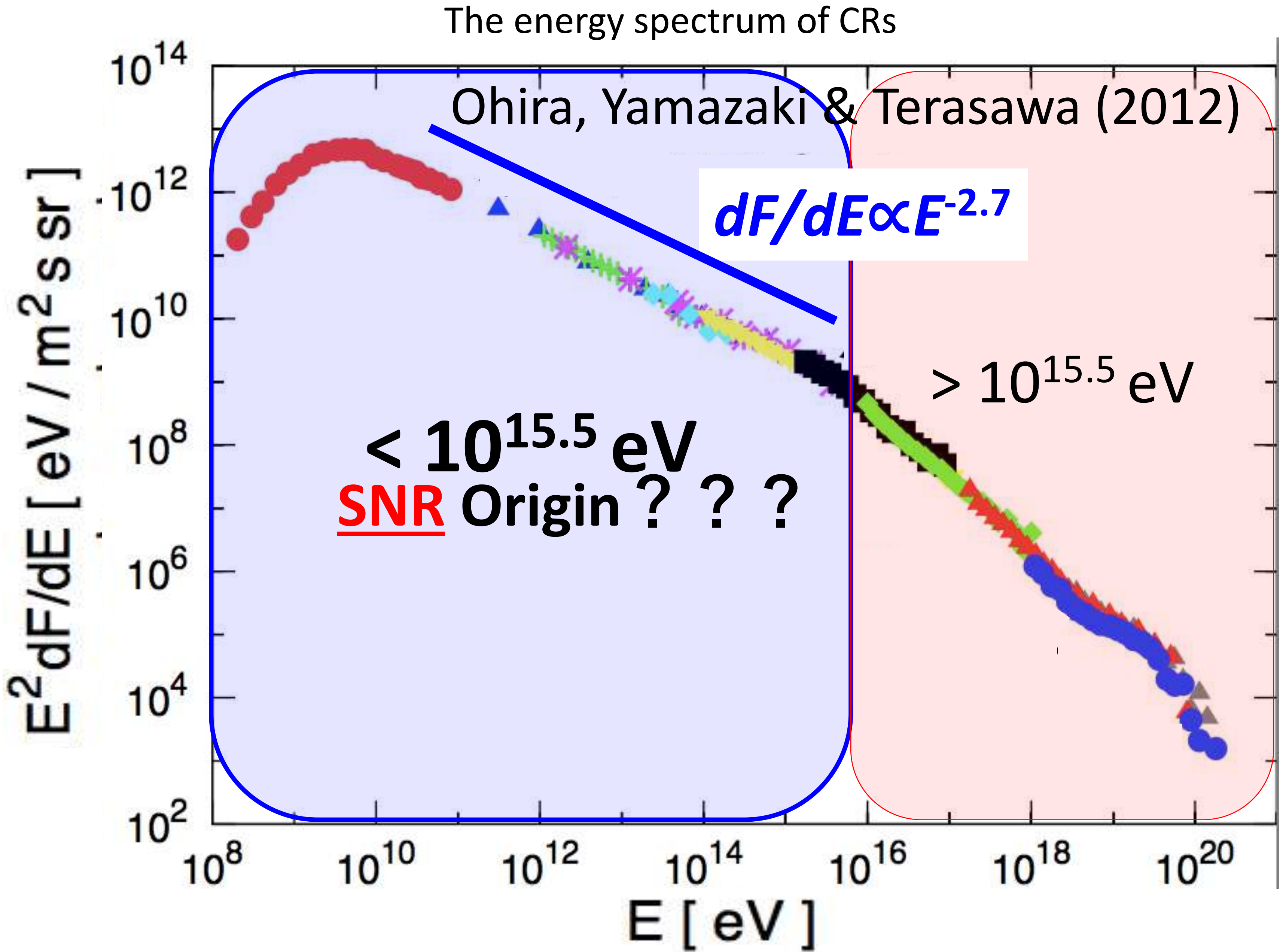
The long-term SFR is regulated by the galactic wind driven by CRs.
→ *Galaxy formation*



X-ray (eROSITA)
γ-ray (Fermi)



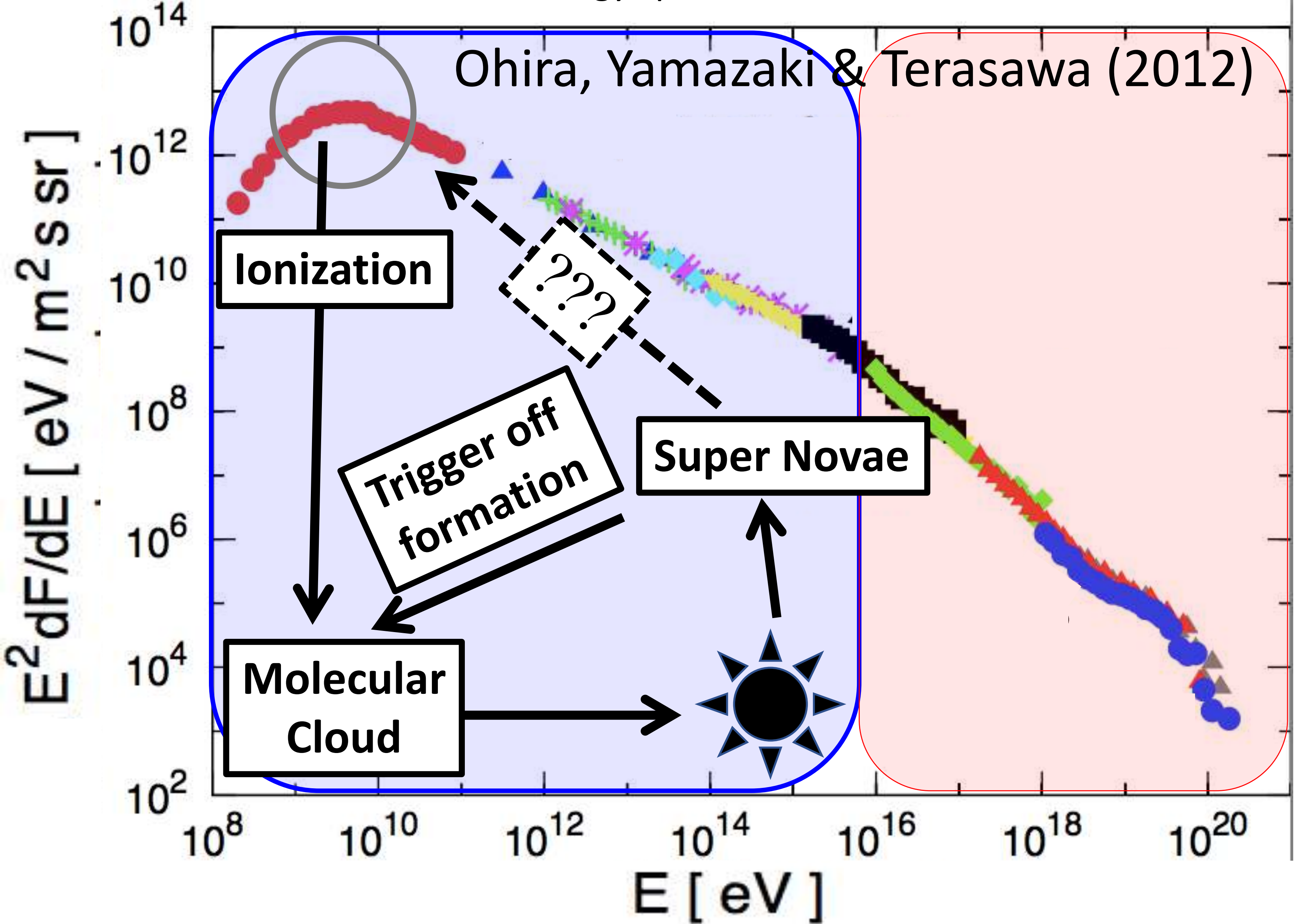
Cosmic Rays



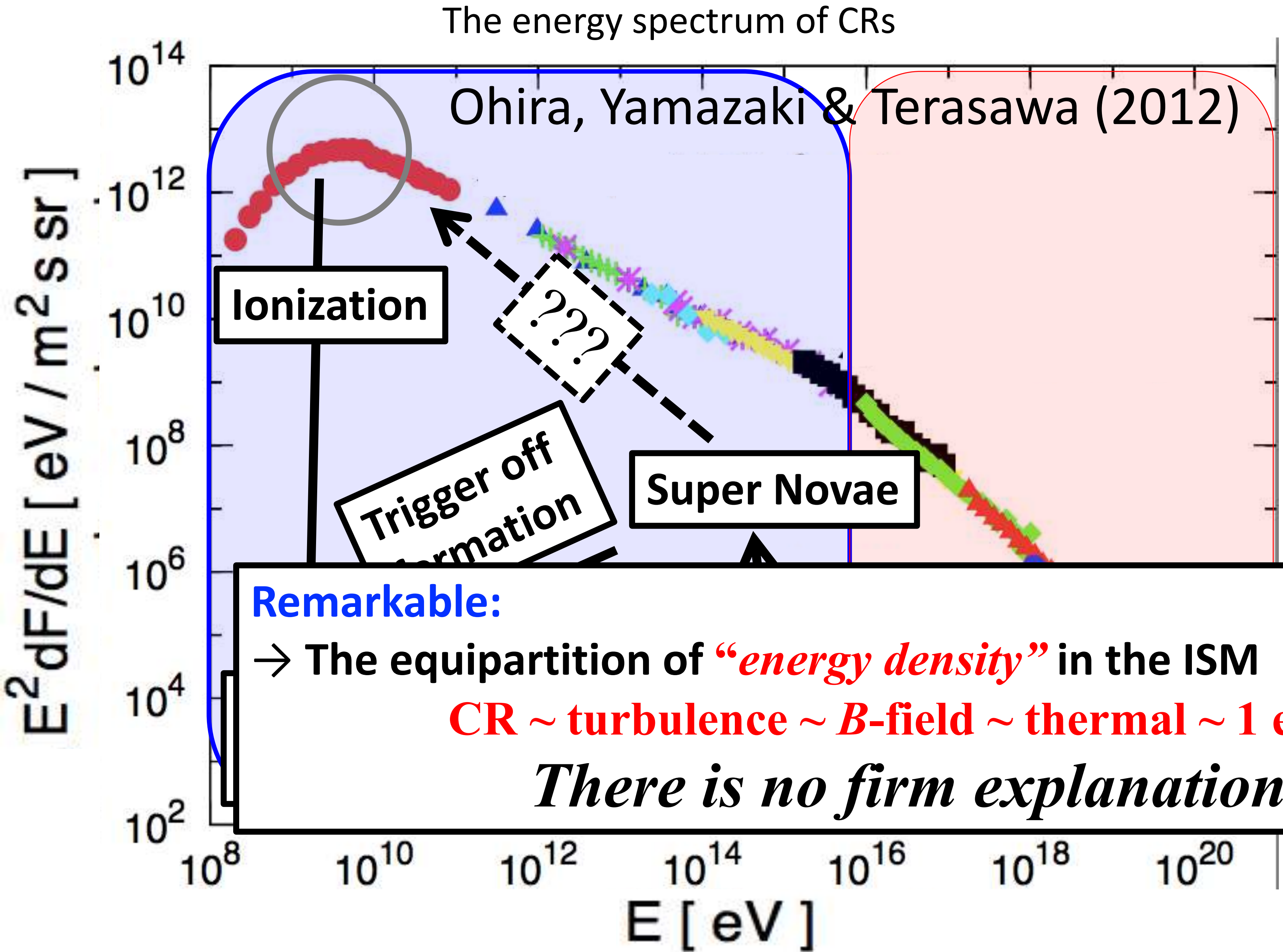
The energy spectrum of CRs
Ohira, Yamazaki & Terasawa (2012)
dF/dE∝E^-2.7
> 10^15.5 eV
< 10^15.5 eV
SNR Origin？？？
E^2 dF/dE [eV / m^2 s sr]
E [eV]
10^14
10^12
10^10
10^8
10^6
10^4
10^2
10^8
10^10
10^12
10^14
10^16
10^18
10^20

Roles of Galactic Cosmic Rays

The energy spectrum of CRs



Roles of Galactic Cosmic Rays



Remarkable:

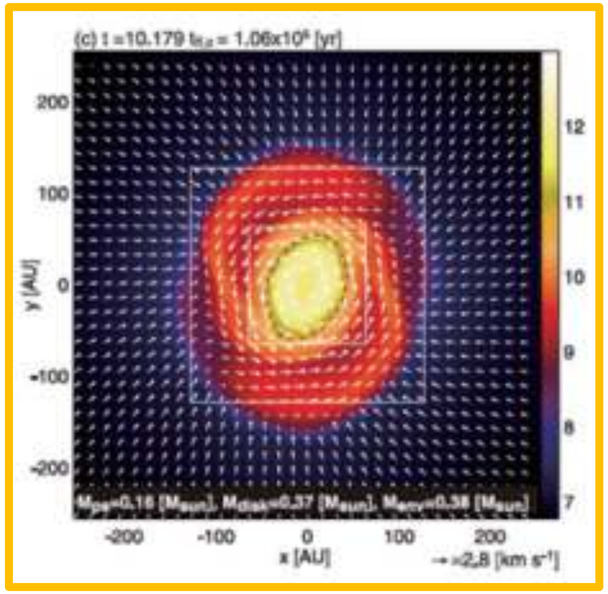
→ **The equipartition of *"energy density"* in the ISM**

CR ~ turbulence ~ *B*-field ~ thermal ~ 1 eV/cc

There is no firm explanation.

Roles of Galactic Cosmic Rays

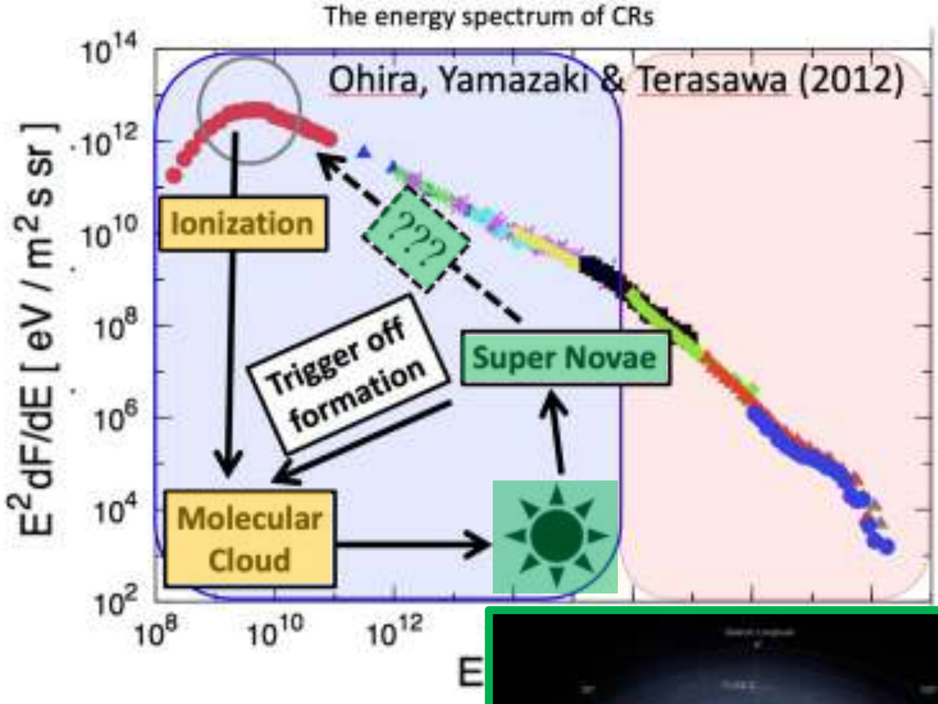
Evolution of the Protoplanetary disk

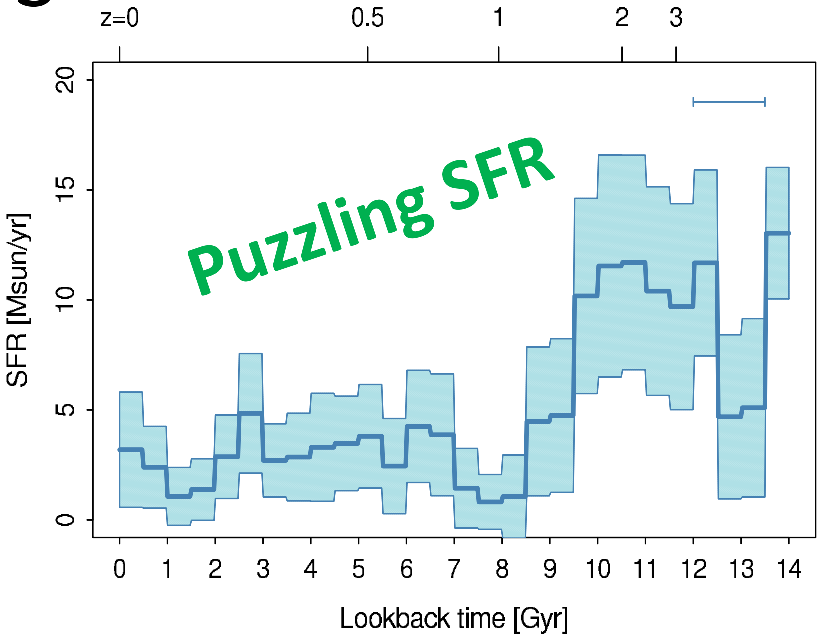


CR ionization rate

controls the size/life-time of protoplanetary disk via the angular momentum transportation by B-field.

→ ***Planet formation***

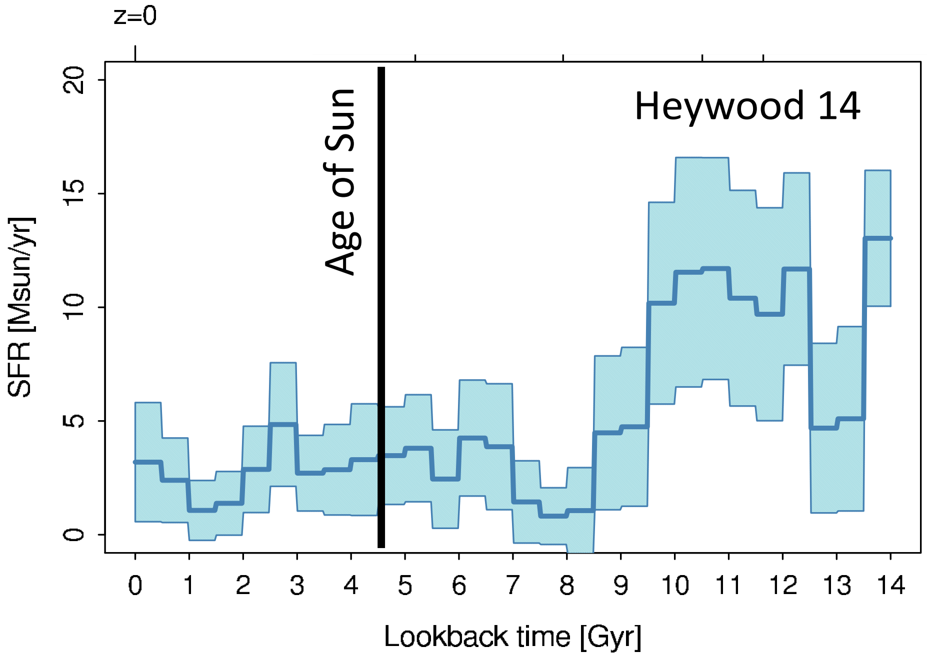




The long-term SFR is regulated by the galactic wind driven by CRs.

→ ***Galaxy formation***

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



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

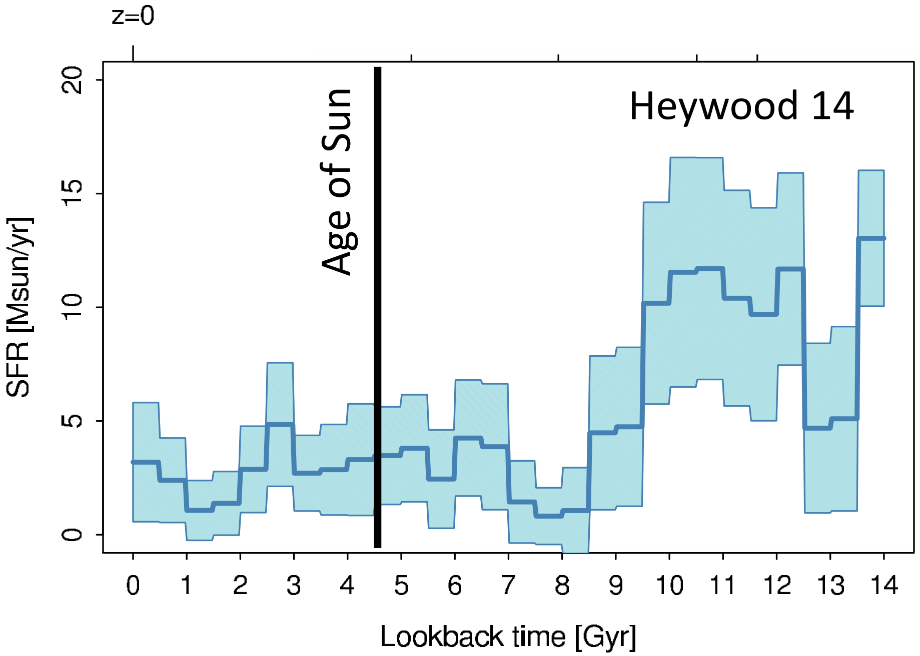
Total gas mass: ~ 10^{9} M_{sun}

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

- **From the 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.

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



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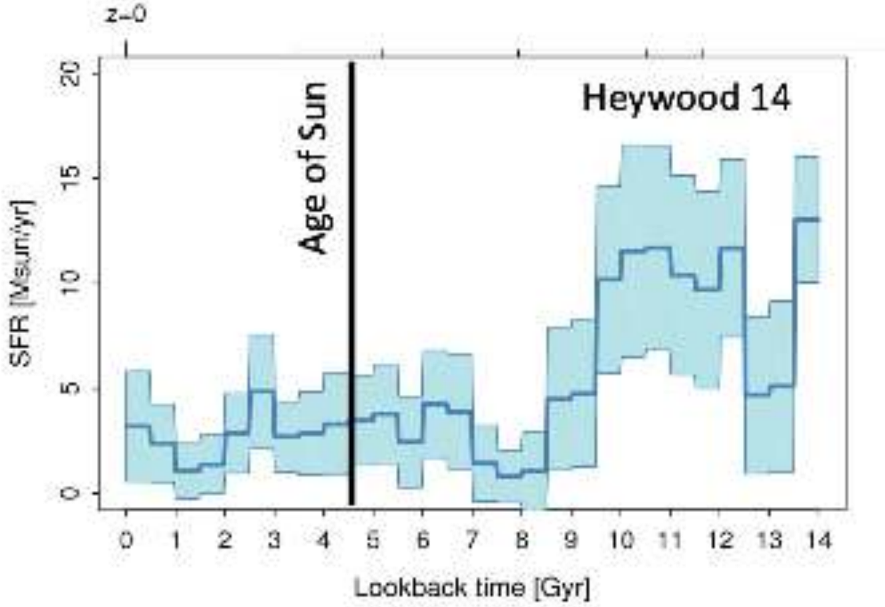
- **From the context of Cosmology …**

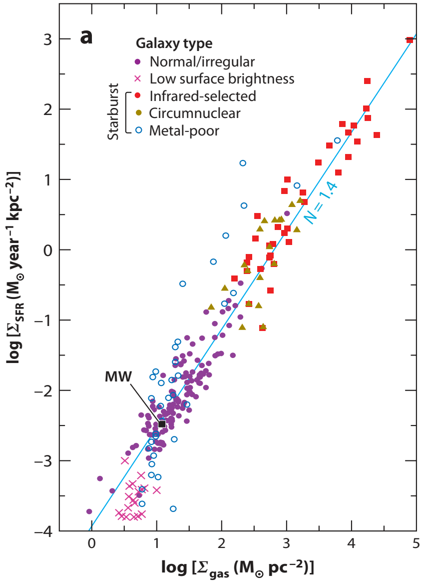
1. The total mass of baryon may be $\sim 10^{11}$ M_{sun}.
2. Why is a half of baryons converted to the stars?
3. Why dose the only $\sim$1 % of baryon remain in the disk?

"Puzzling" Star Formation History
(the metal amount)



@ disk
SFR ~ 3 Mo/yr
Gas mass ~ 10^9 Mo (Metallicity Zo ~ 0.01 → Metal mass ~ 10^7 Mo)
Salpeter IMF → Massive Star FR ~ 0.1 Mo/yr

Total Metal Mass Ejected by SNe
→ ~ (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



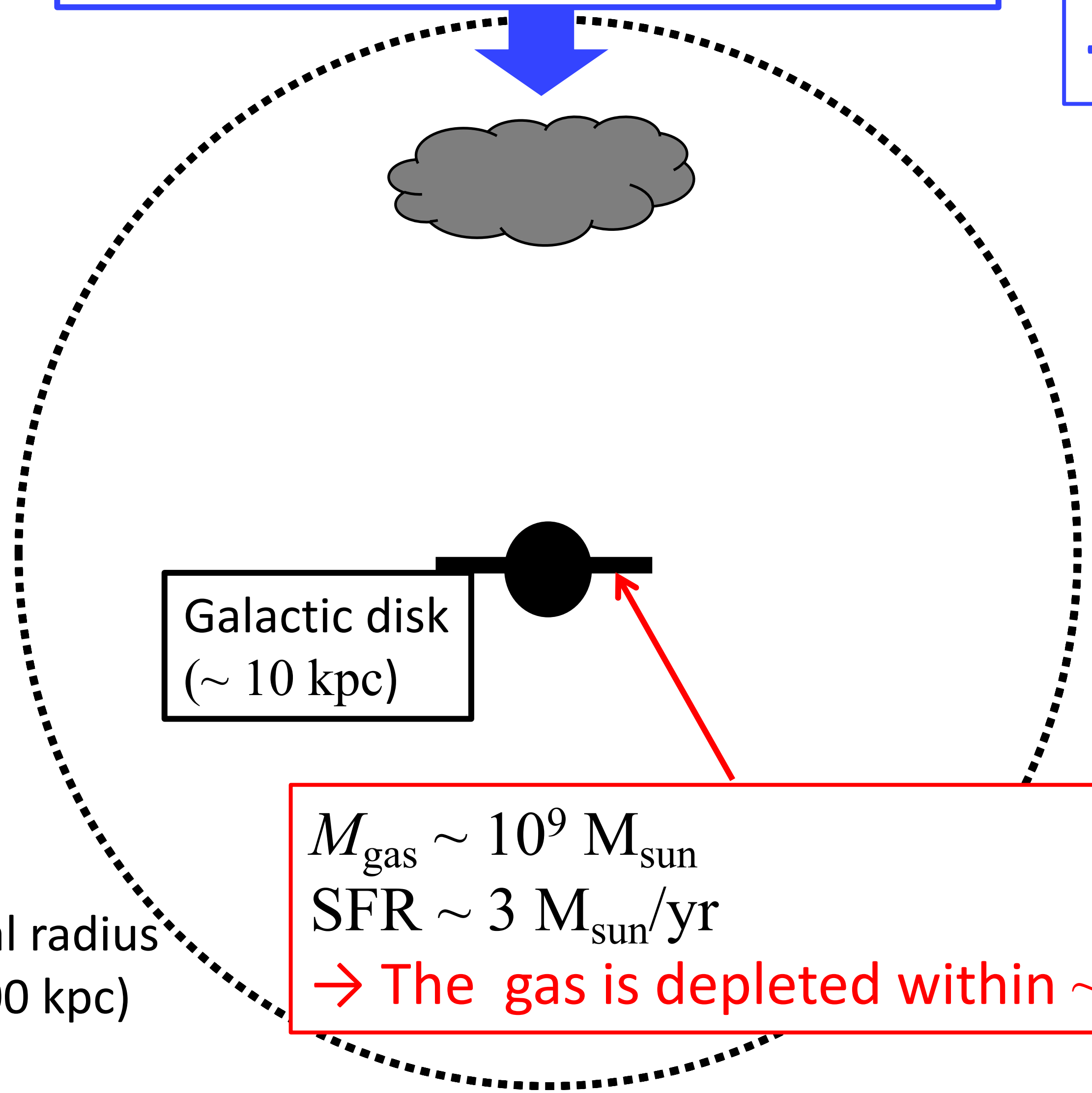
Most of the metals should be removed from the disk!
Only the *dilution* by the primordial gas accretion is not enough.

Kennicutt & Evans 12

Mass Budget of MW

DM: $\sim 10^{12}$ M_{sun}
Available gas: $\sim 10^{11}$ M_{sun}
Stars: $\sim$ 4-6 x 10^{10} M_{sun}
→ Why half?

Cosmological accretion flow (IGM)



$M_{gas} \sim 10^9$ M_{sun}
SFR $\sim$ 3 M_{sun}/yr
→ The gas is depleted within ~ 1 Gyr < t_{univ}=13.8Gyr!

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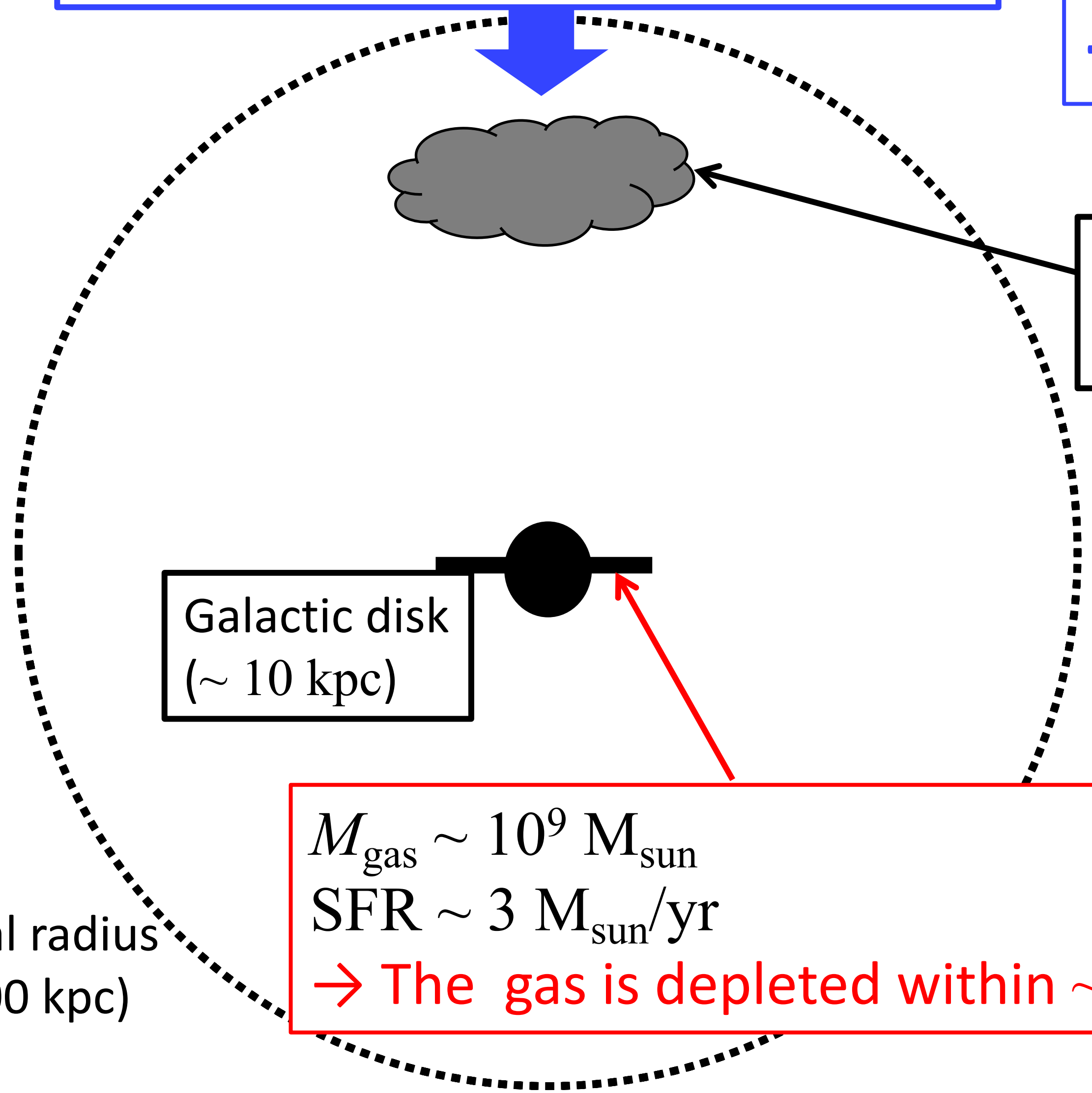

M_{gas} ~ 10^9 M_{sun}
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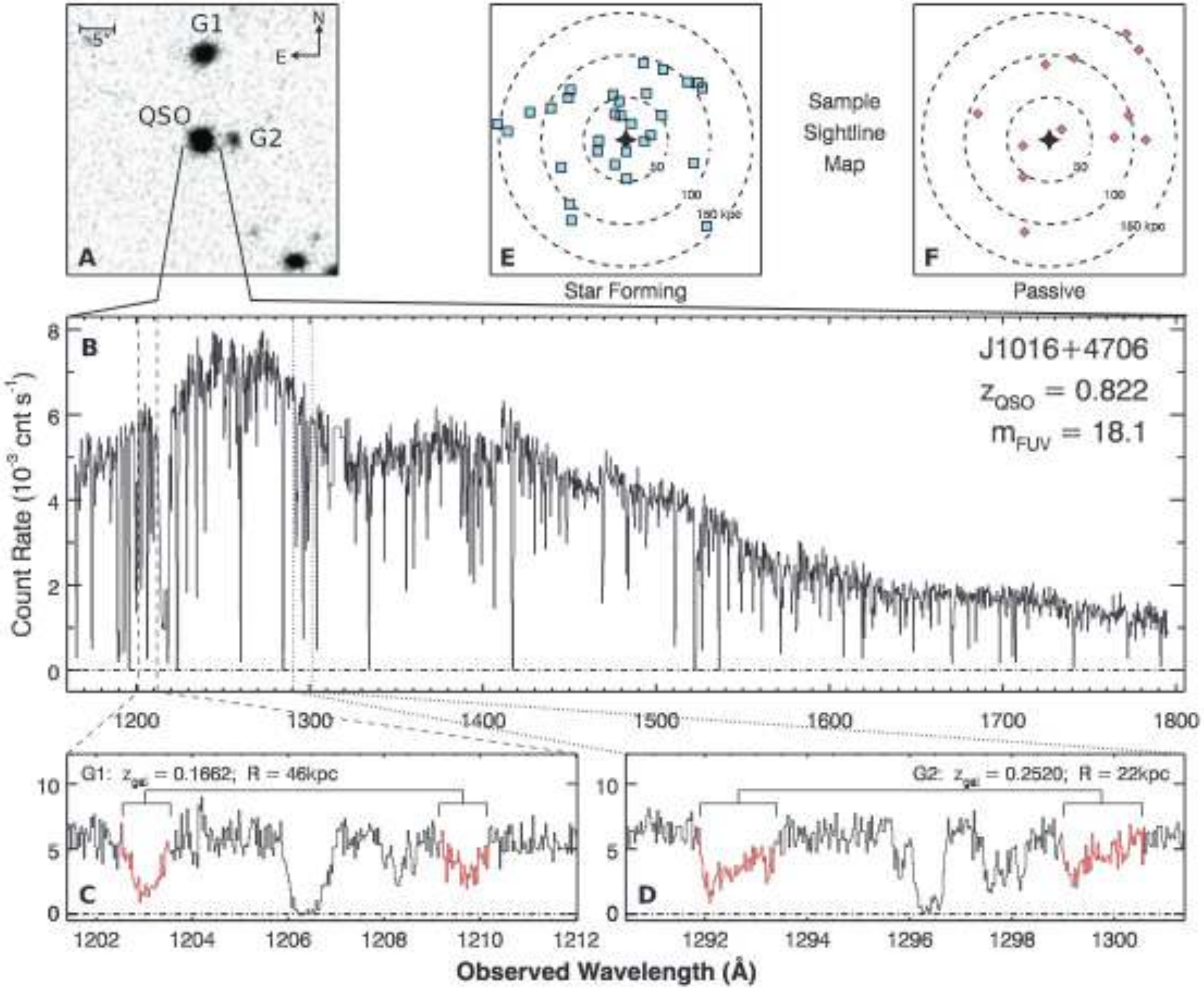
→ The gas is depleted within ~ 1 Gyr < t_{univ}=13.8Gyr!

Circum-Galactic Medium (CGM)



"Discovery" of hot, highly ionized medium around galaxies (Tumlinson+11, 17).

- O_{VI} absorption line
  - → T_{ionized} ~ 3 x 10^5 K, N_{OVI} ~ 10^{14} cm^{-2}
  - → Estimated total gas mass

~ 10^{10}–10^{12} M_{sun}

Mass Budget of MW

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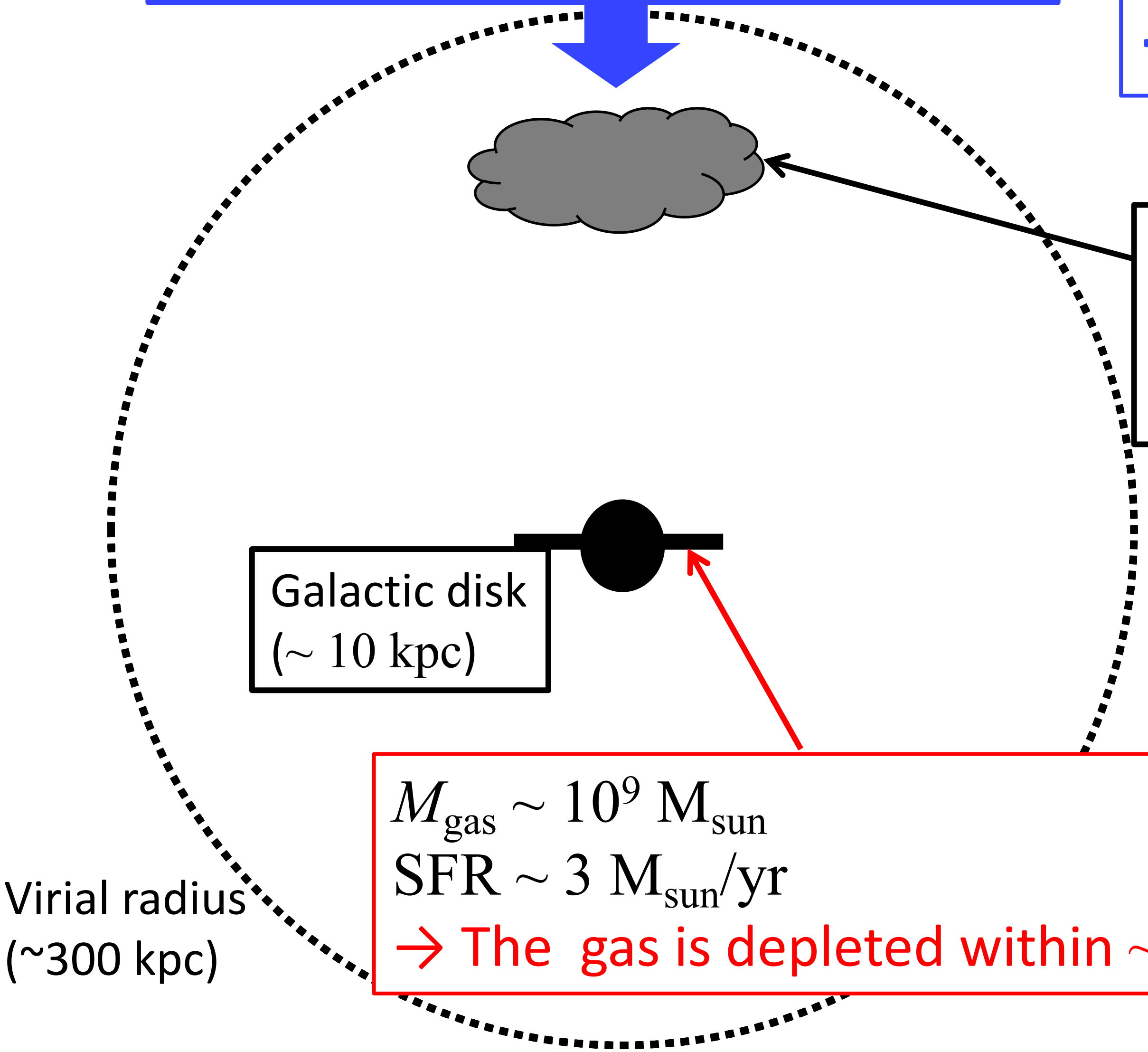
CGM contains ~10^{10}–10^{12} M_{sun} gas!
From obs. of external galaxies.
→ **metal polluted**



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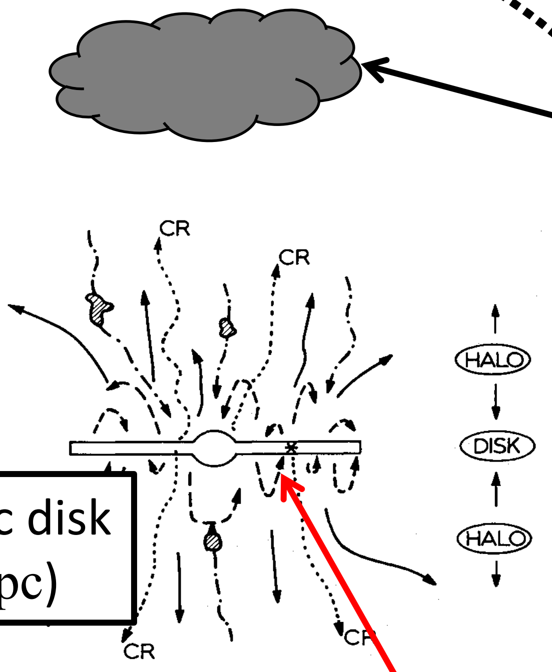

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→ **Wind is invoked (SJ & Inutsuka22)**

Galactic disk
(~ 10 kpc)

Virial radius
(~300 kpc)

M_{gas} ~ 10^9 M_{sun}
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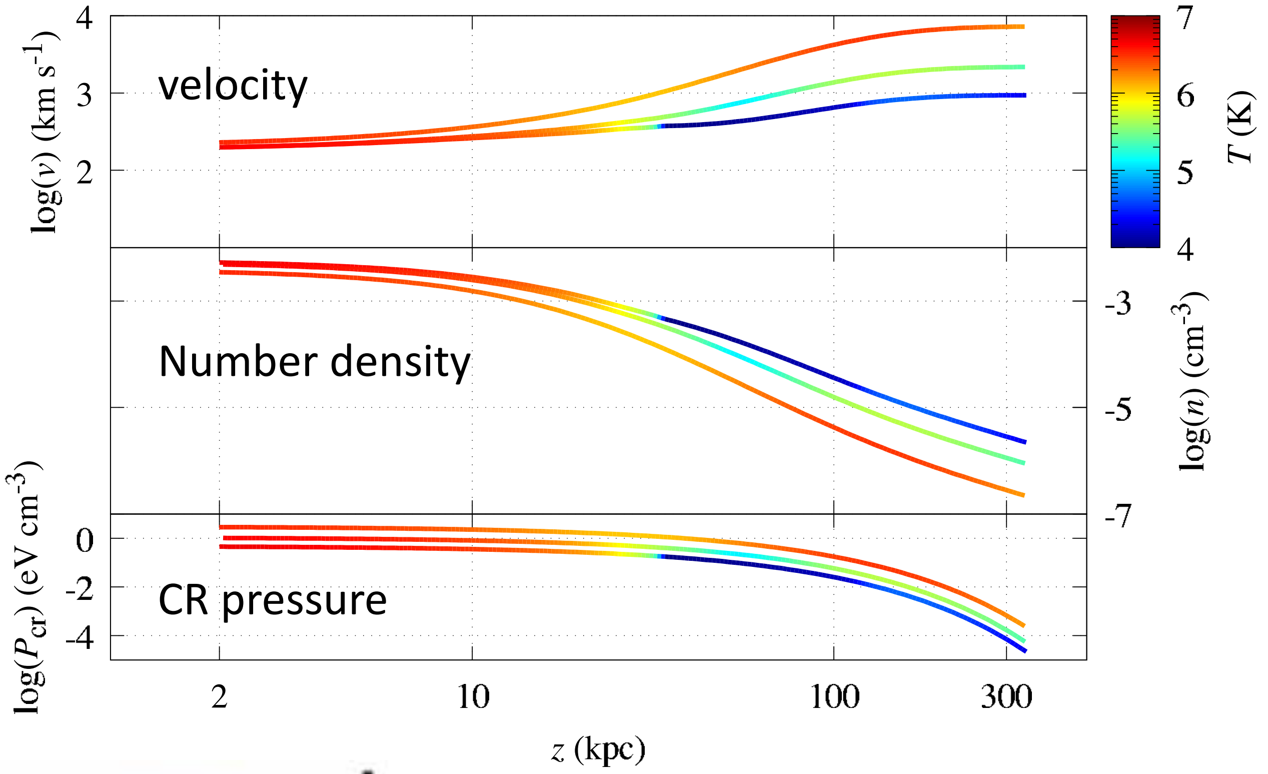
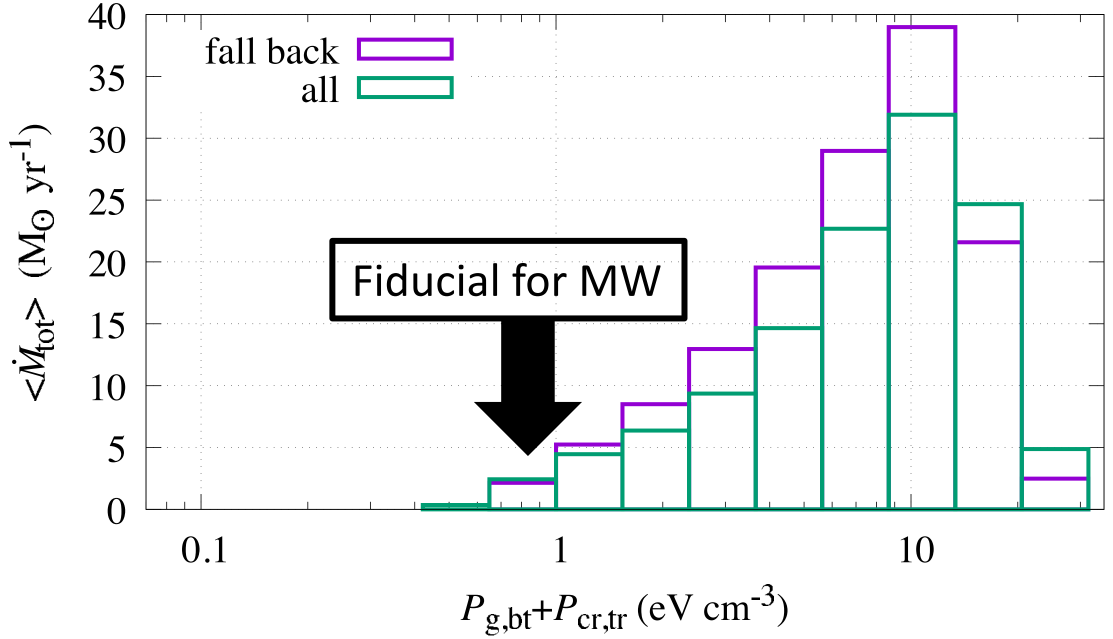
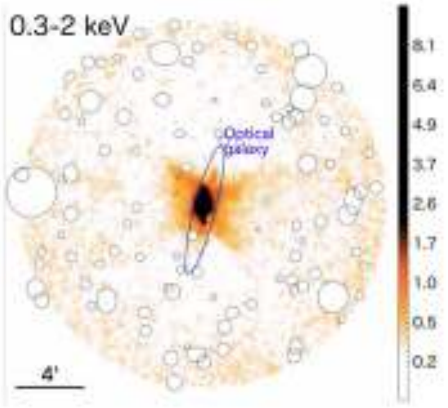
Galactic Wind Model (SJ & Inutsuka 22)



Mass loss rate of the disk by wind





NGC 3079
Hodges-Kluck+20

Temperature (<10 kpc): ~sub keV

Number density : ~10^{-3} cm^{-3}

Mass loss rate : ~ several M_{sun}/yr

Mass Budget of MW

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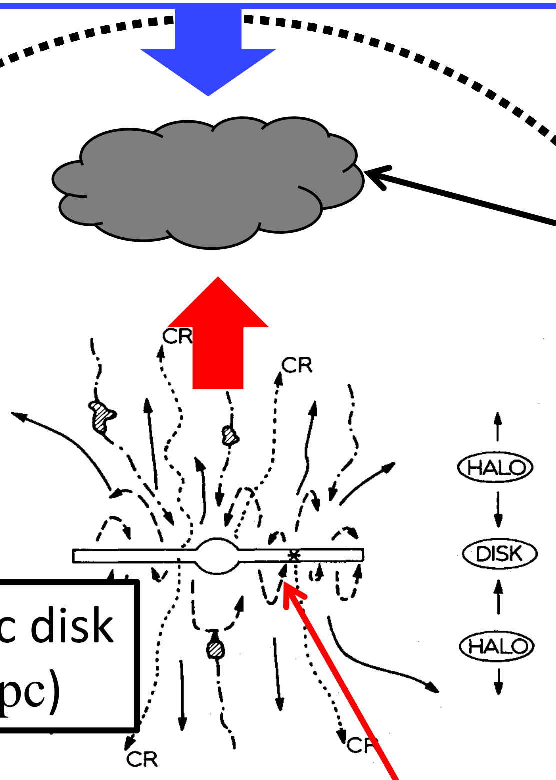

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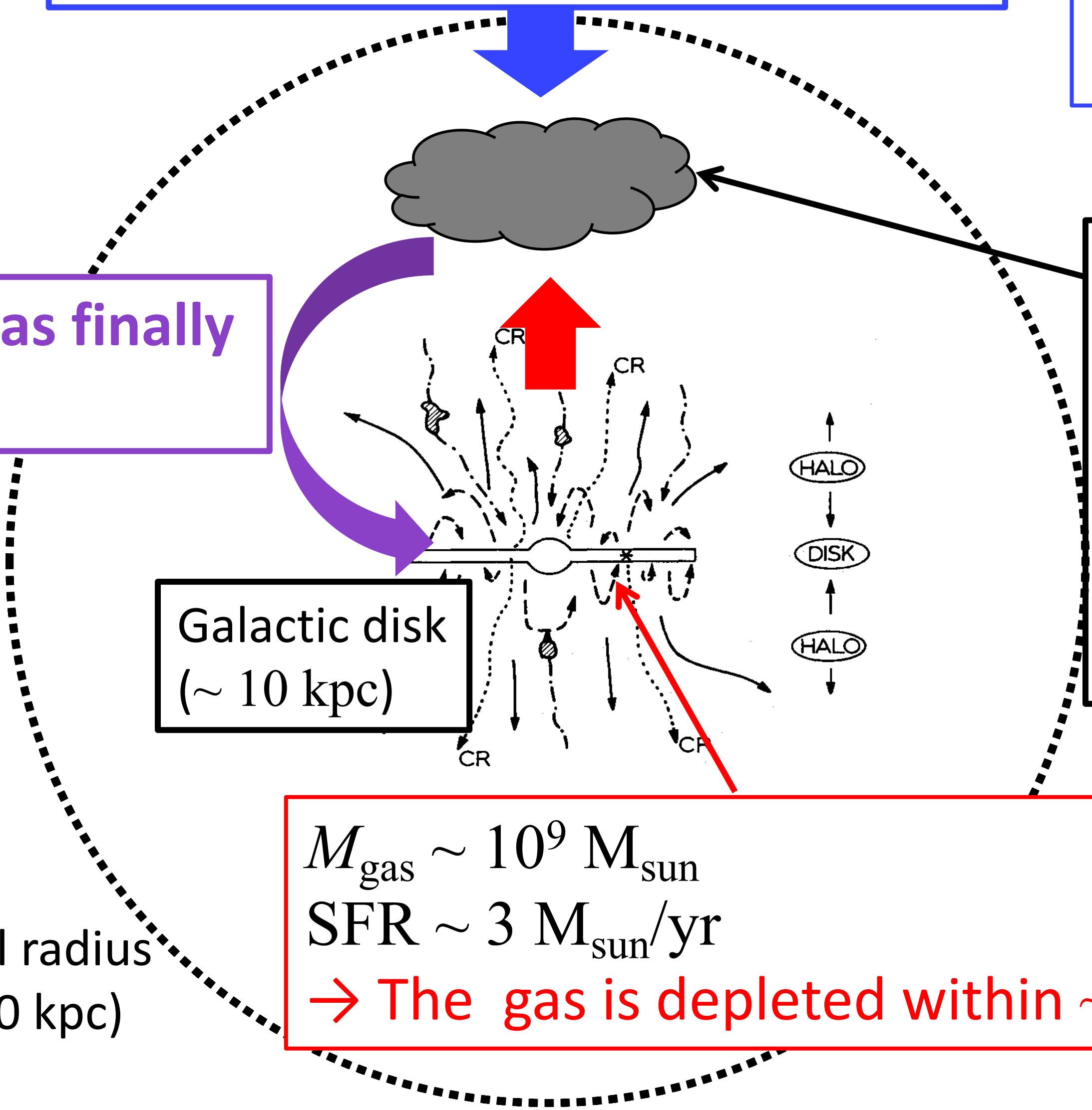
Cosmological accretion flow (IGM)

How much gas finally accretes???



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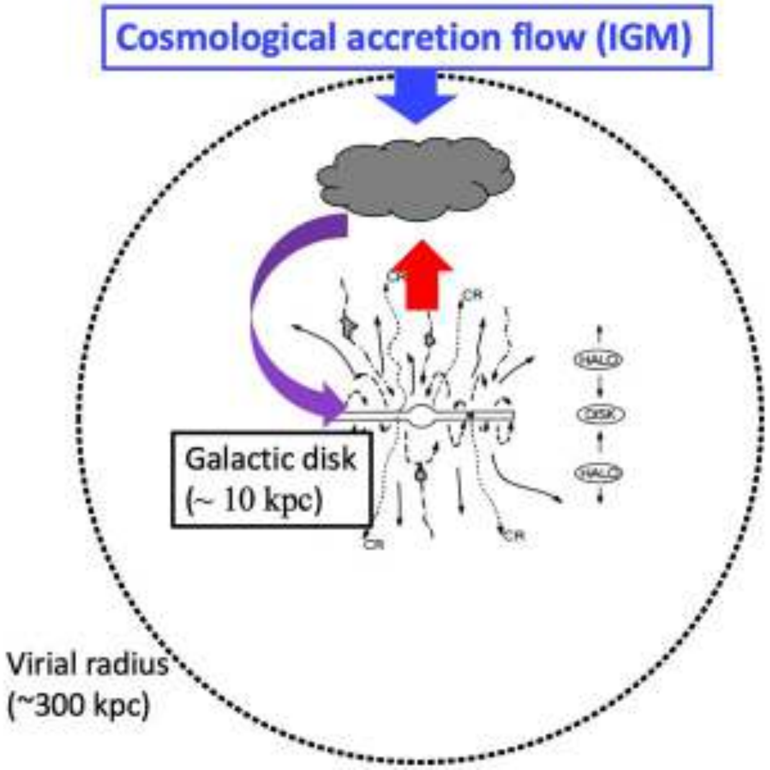
What is essence?



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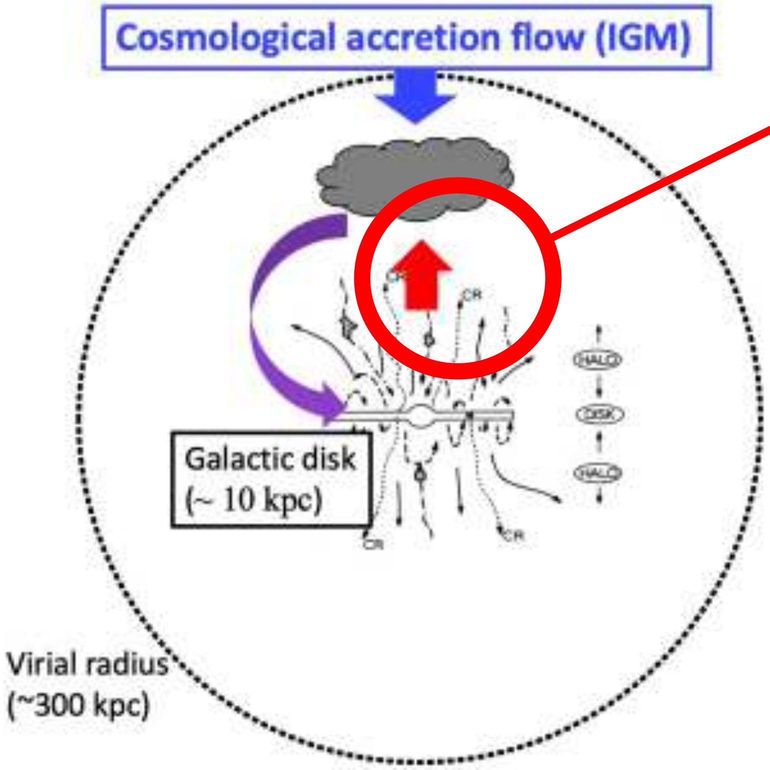
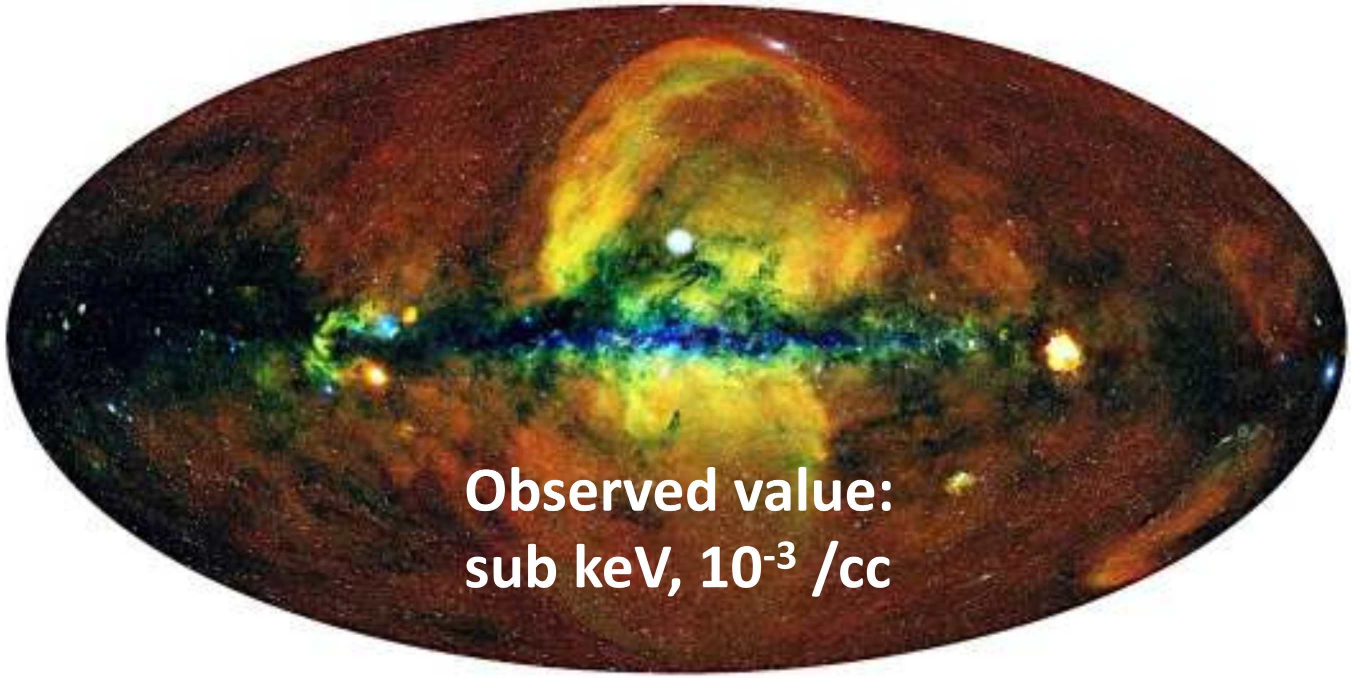


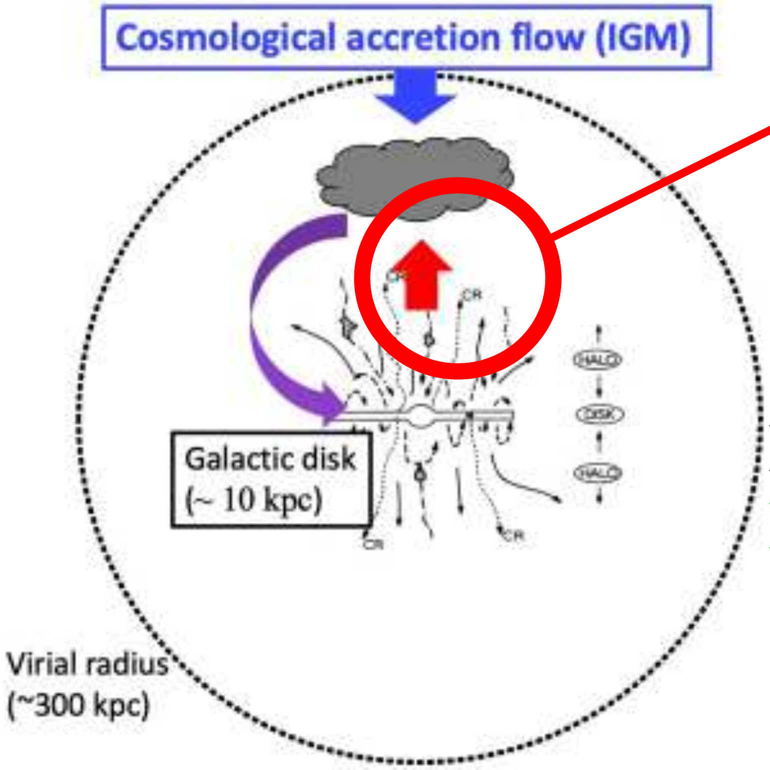
Galactic wind

Temperature (<10 kpc): ~sub keV
Number density : $\sim 10^{-3}$ /cc
Mass loss rate : ~ several M_{sun}/yr



eROSITAによる全天画像。0.3〜0.6keVのエネルギーのX線を赤、0.6〜1keVを緑、1〜2.3keVを青に色付けして合成されています。
Credit: MPE/IKI

What is essence?



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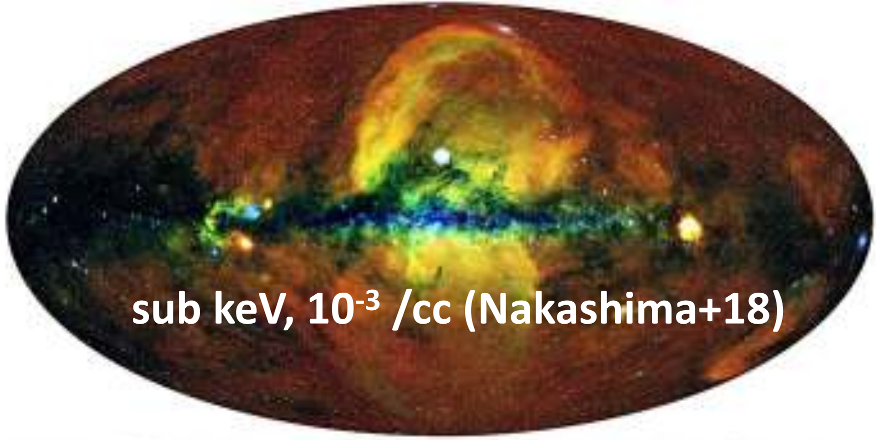

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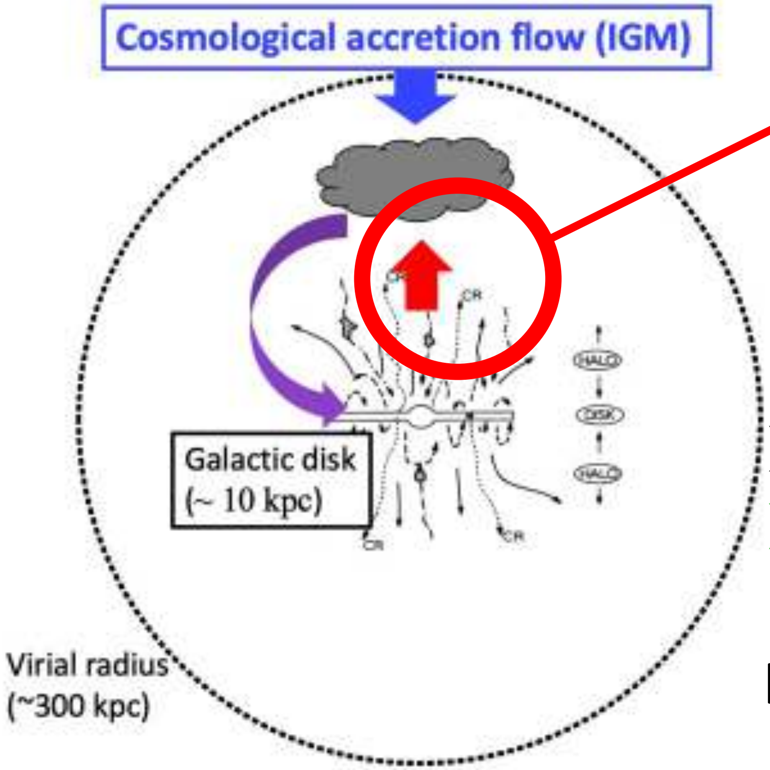
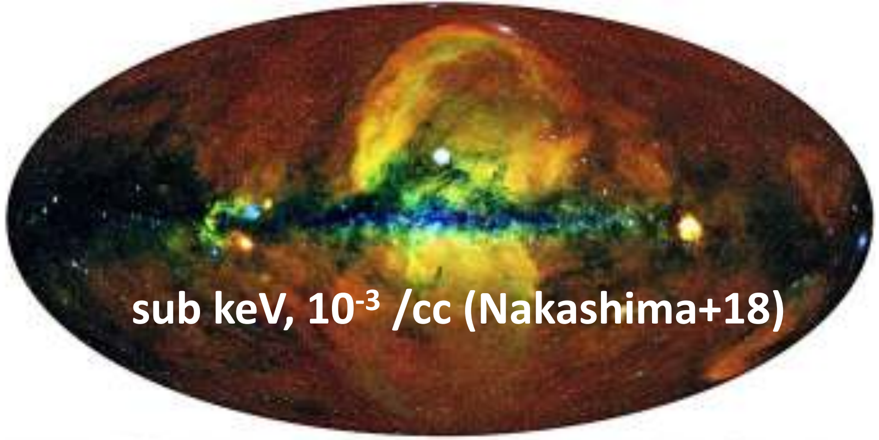
- **The X-ray emitting gas at the disk becomes the wind.**
- **The origin of the Galactic Diffuse X-ray Emission is an *open question*.**

What is essence?





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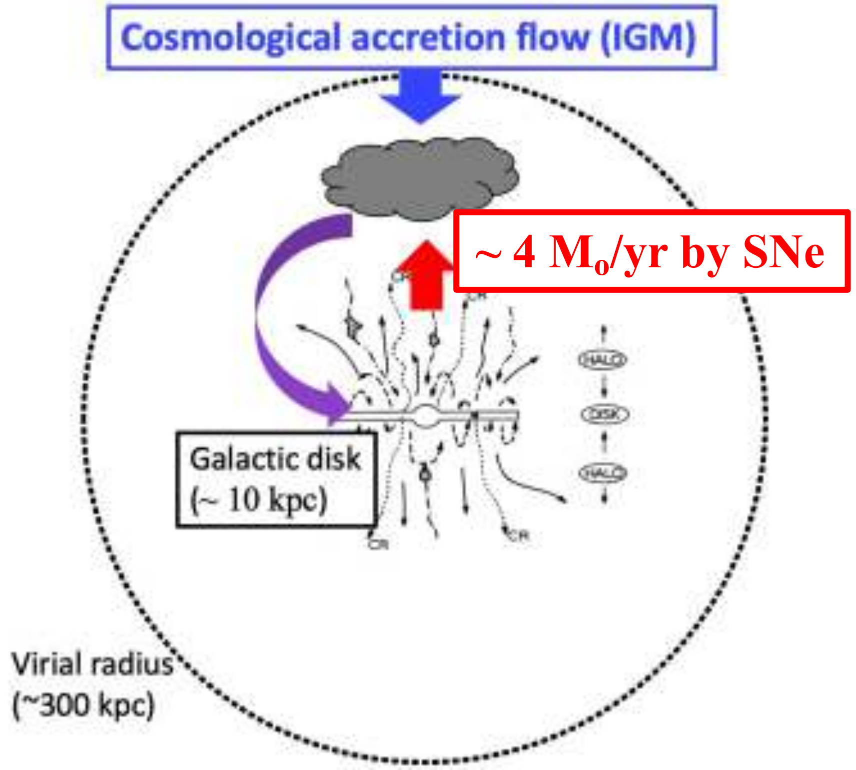
If ~10% of SNe energy is consumed for the X-ray gas…

$$\frac{3}{2}\frac{kT_{\rm w}}{m_{\rm p}}\dot{M}_{\rm w} = \eta L_{\rm SN} \;\Rightarrow\; \dot{M}_{\rm w} \sim 4\ M_{\odot}/{\rm yr}\left(\frac{\eta}{0.1}\right)\left(\frac{L_{\rm SN}}{10^{42}\ {\rm erg/s}}\right)\left(\frac{kT_{\rm w}}{0.3\ {\rm keV}}\right)^{-1}$$

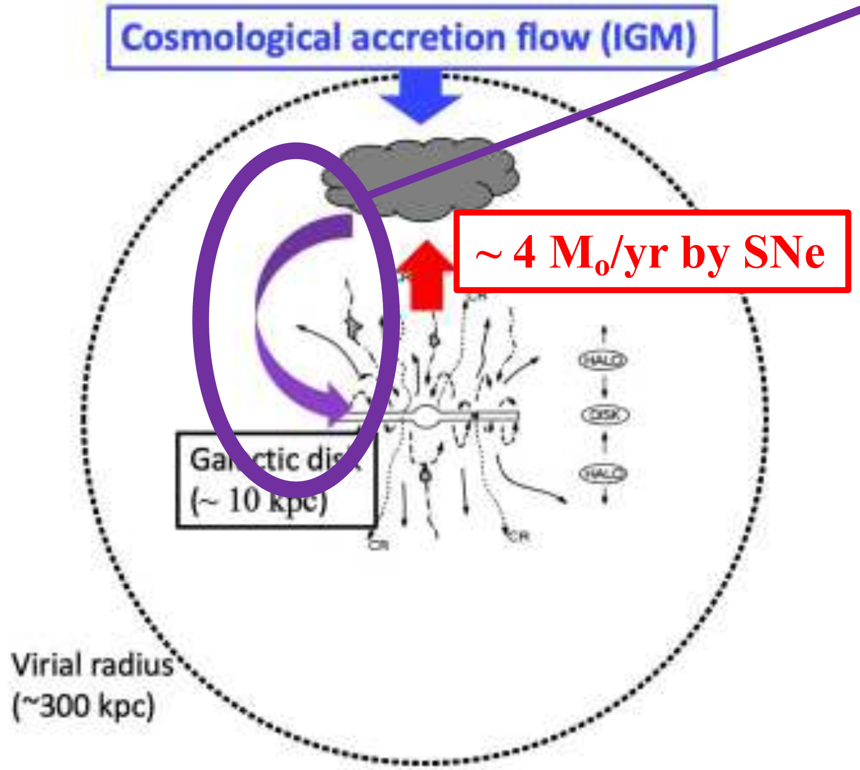
Consistent with both X-ray observations and theoretical model of wind

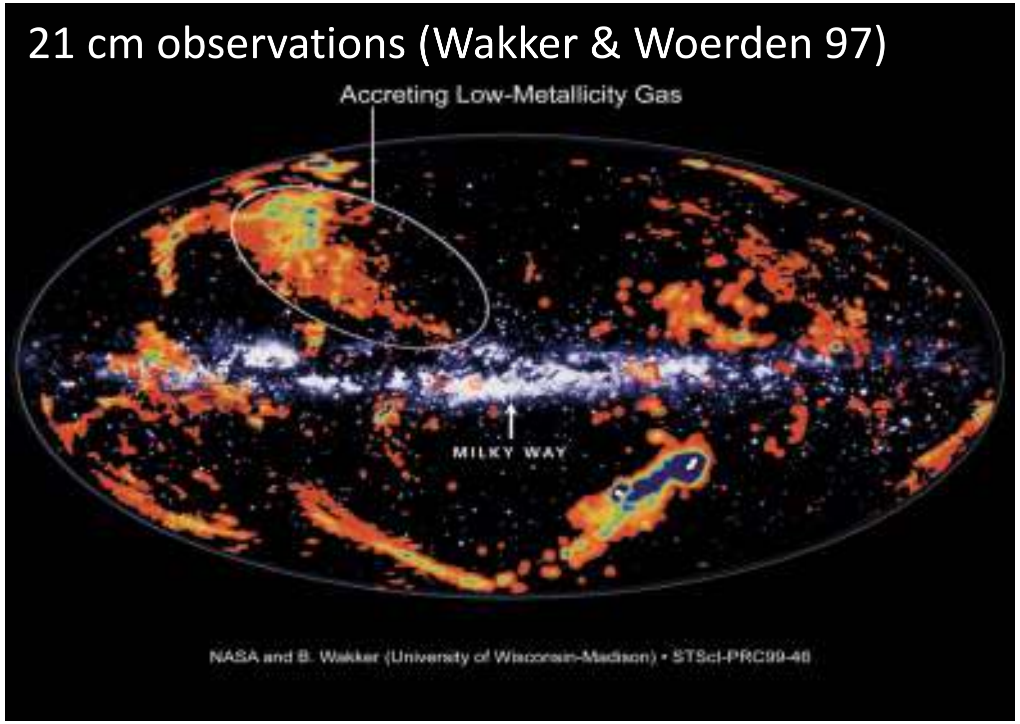
What is essence?



What is essence?

Accretion flow





Accretion gas is observed by 21 cm emission as known as ***High Velocity Cloud***.

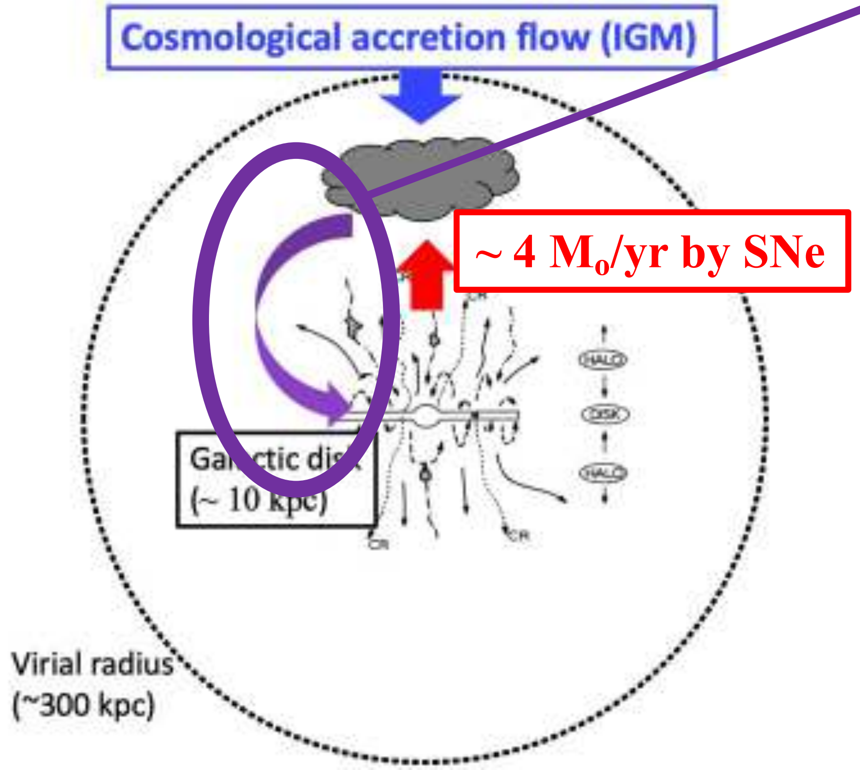
→ Is it responsible for the *inflow*?

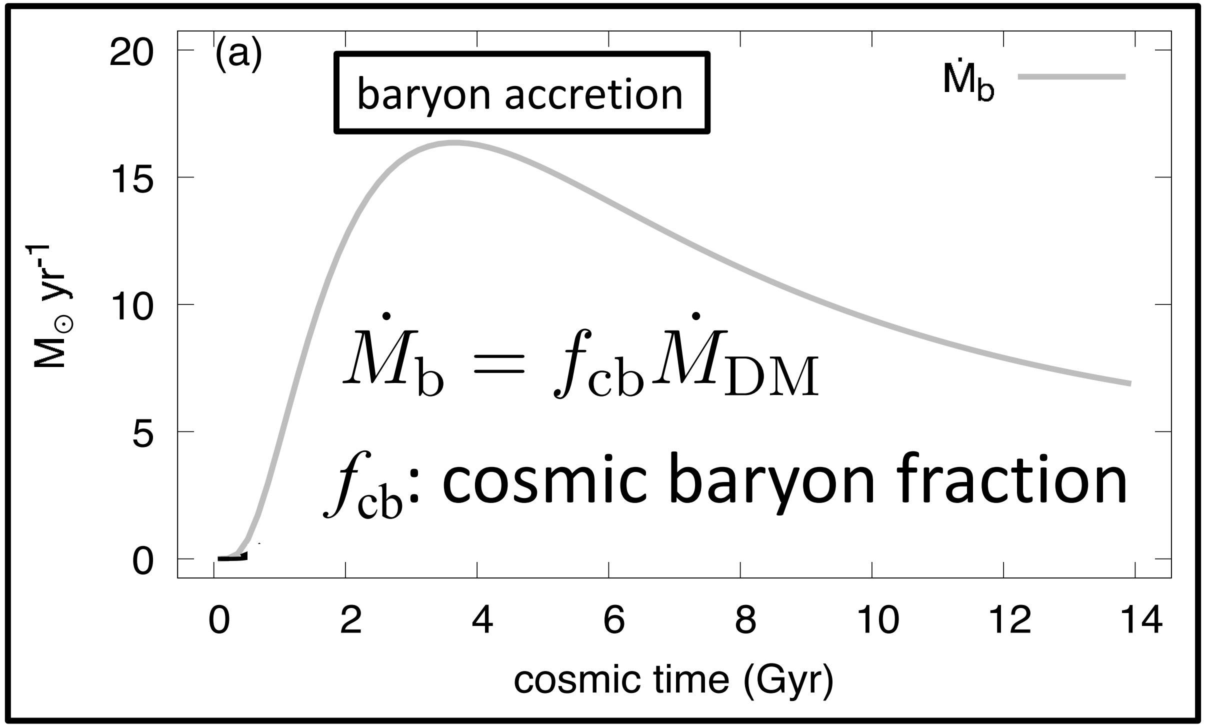
The origin & mass of HVCs is still an open question.

Accretion rate is not constrained by observations… → Theoretical estimates

What is essence?

Accretion flow

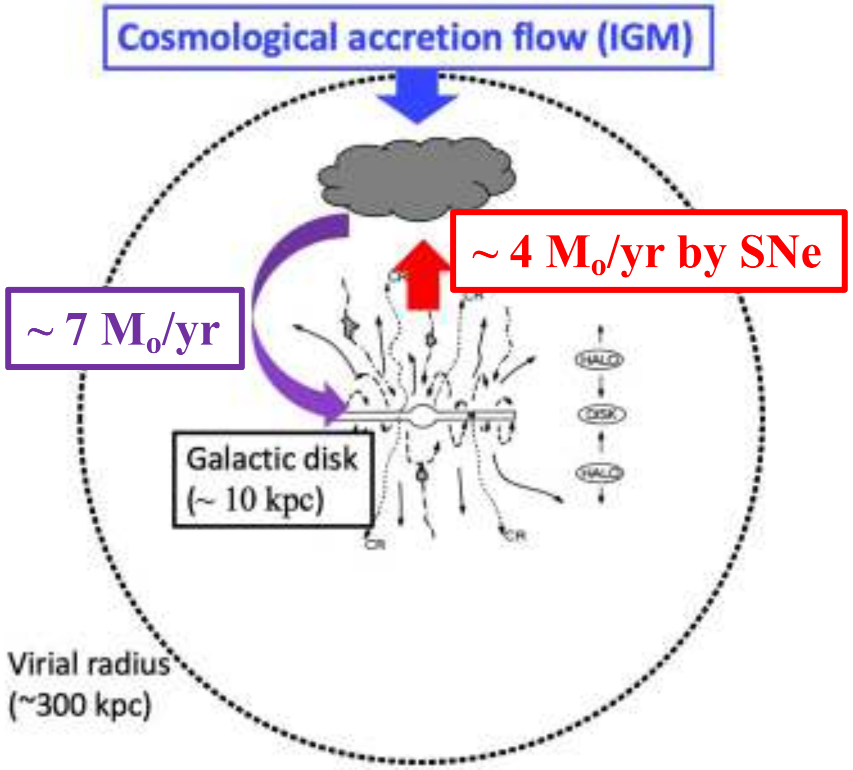




~ 7 M$_o$/yr

The baryon accretion rate
→ Use the results of the DM N-body simulation (Rodriguez-Puebla+16)

What is essence?



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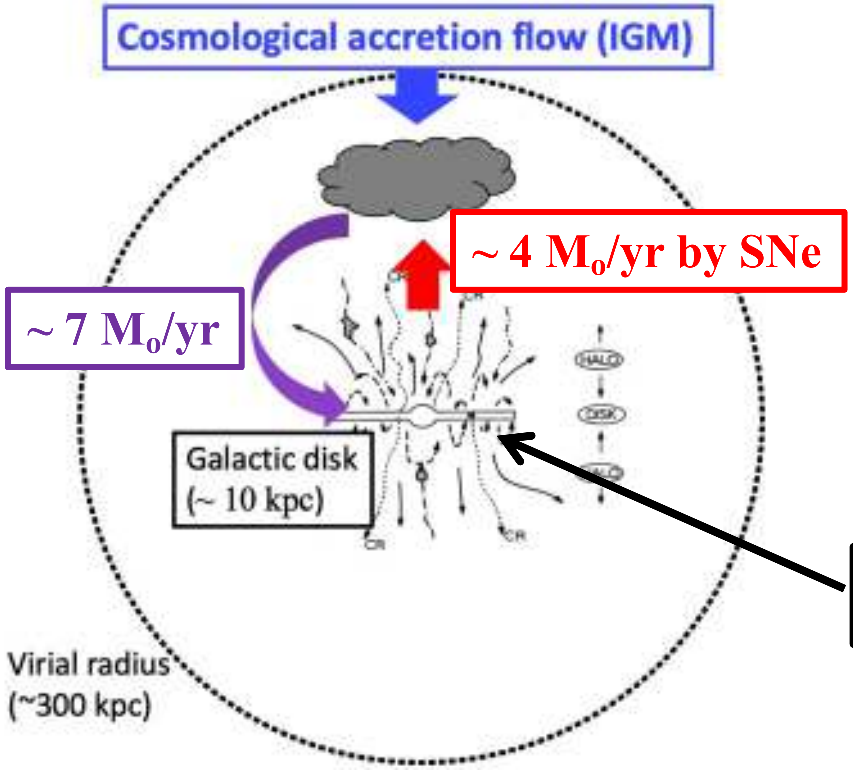
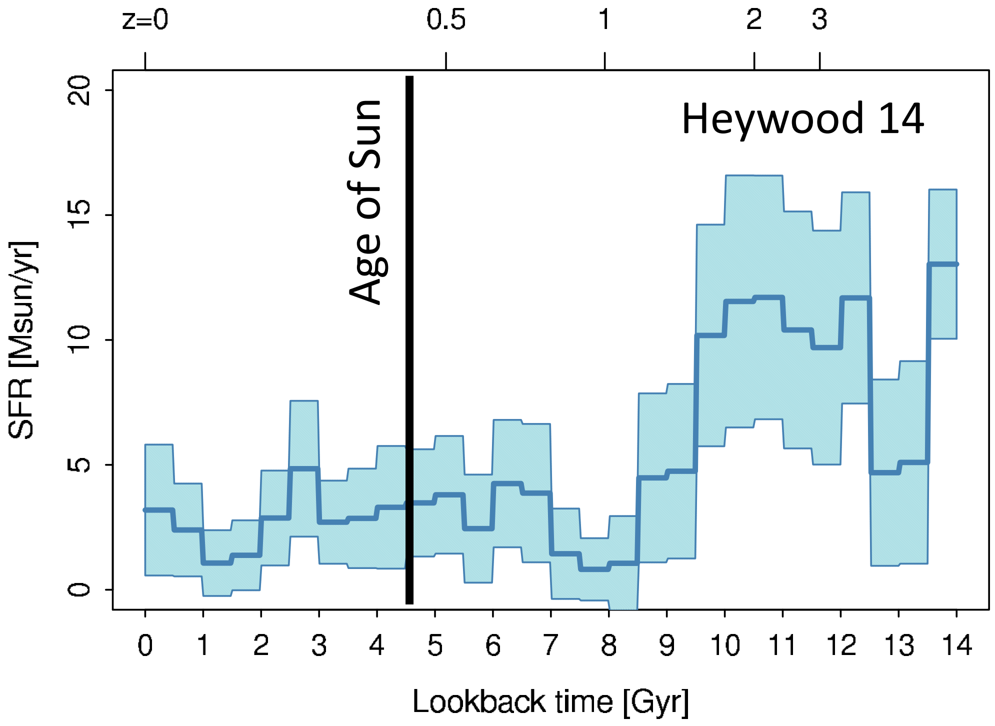




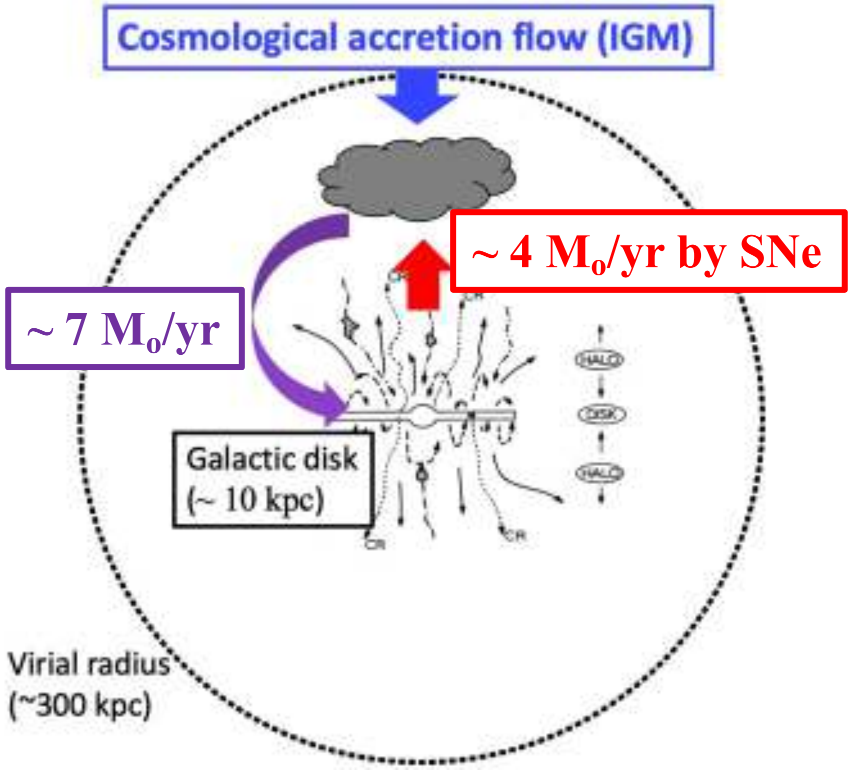
Consequent star formation at the disk

✓ Almost constant SFR

→ quasi steady-state

→ **SFR ~ 7 M_o/yr – 4 M_o/yr ~ 3 M_o/yr**

What is essence?



Problems

1. The origin of the X-ray emissions at/around the Galactic disk.
→Numerical simulations imply its existence, but actual physical processes are still under debate.

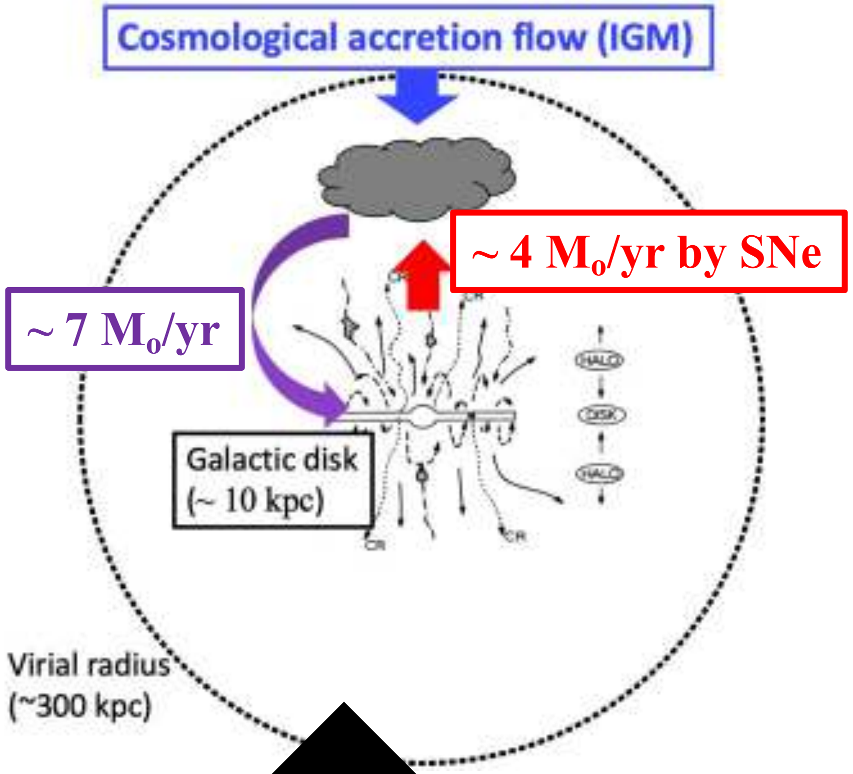
2. The existence of the Cosmological accretion gas onto the disk.
→If it has a virial temperature of ~ 10^6 K, the observations are difficult (FUV ~ soft X-rays are obscured).

3. The resultant disk & CGM conditions (including CRs, metal, etc.) are still unclear.

Done (arXiv:2306.16887)

We study the 3rd issue in this talk.

Toward the Next-generation Multi-messenger Astronomy



Key Concept

1. Cosmic-rays

$$p_{cr} + p_{gas} \rightarrow 2\gamma, \nu$$

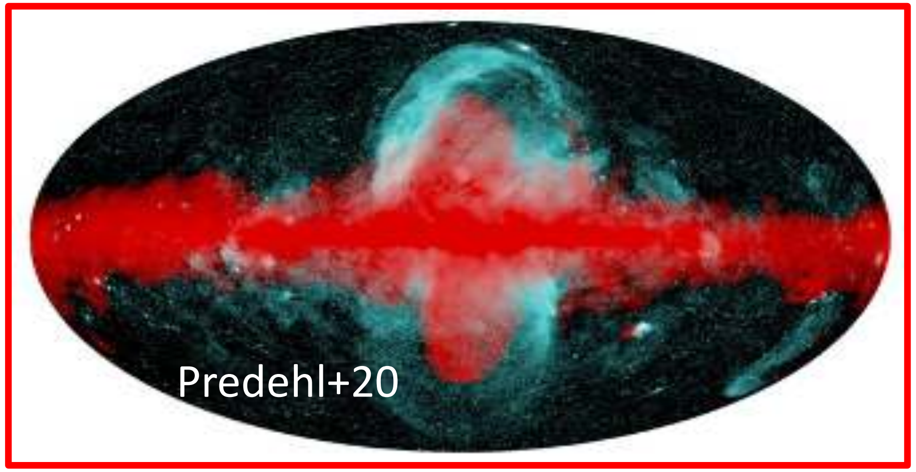
2. Gas dynamics around the Galaxy

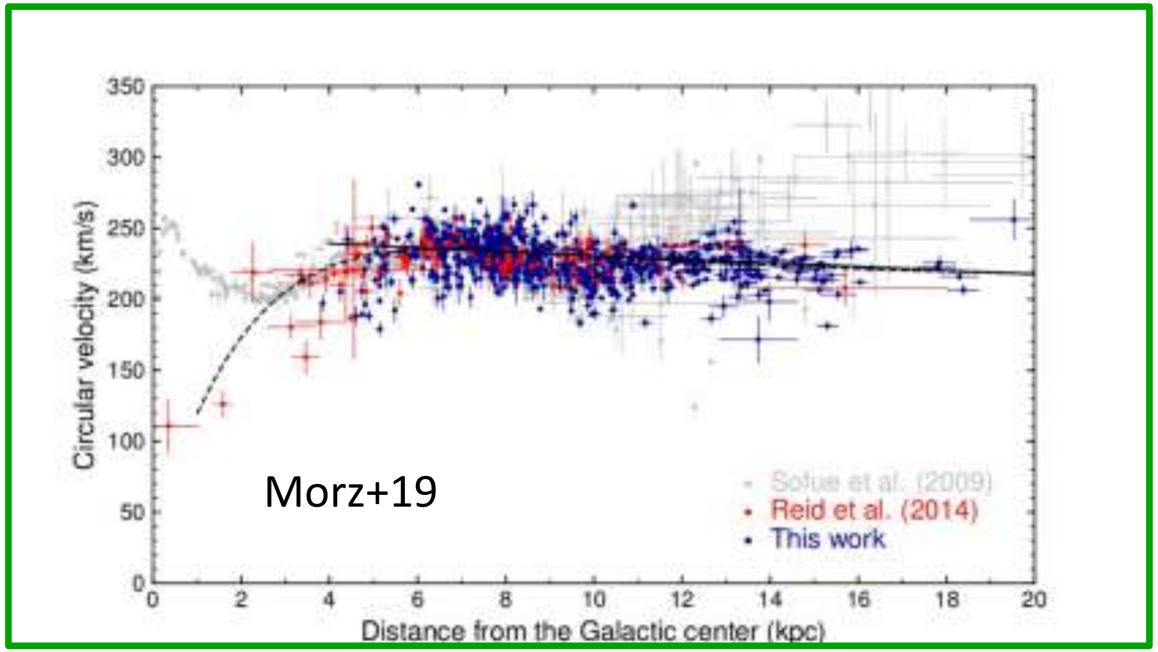
Provide the Initial Conditions of the stellar dynamics.
→ ***the Galactic Archaeology***

3. Star Formation at the disk.

Consider the gas & CR distributions around the Galaxy.

Toward the Next-generation Multi-messenger Astronomy





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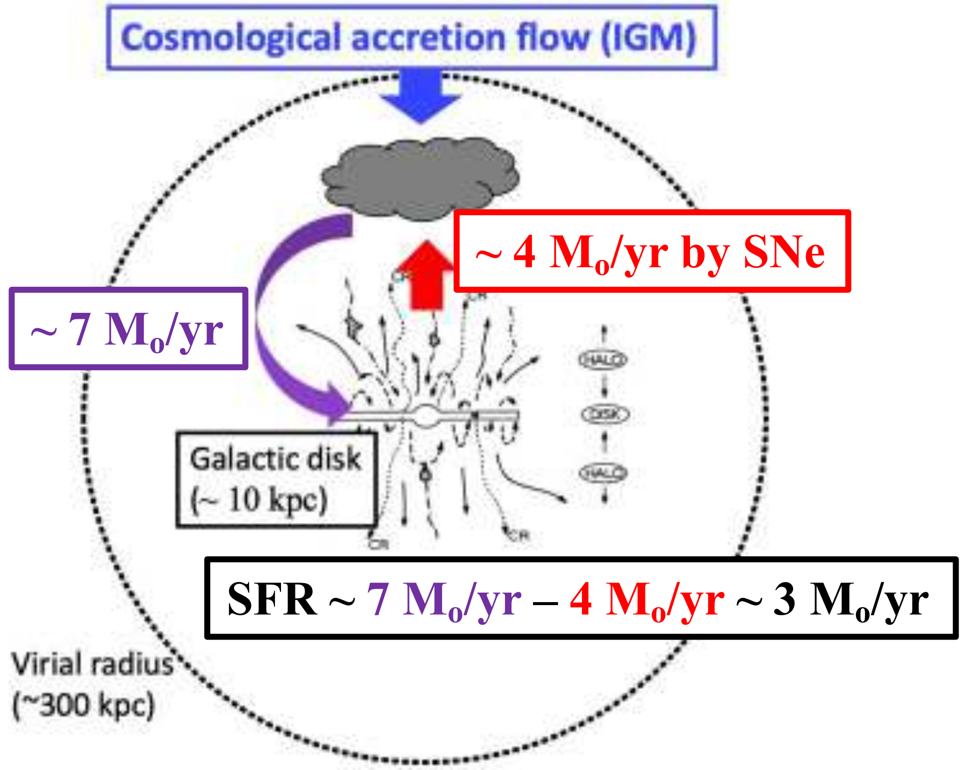
Test by Model



We have no time to introduce this model…
The details are shown in arXiv:2306.16887.

We construct a ***time-dependent* semi-analytic model** of the galactic system

Disk: 1D, α-disk model including

Low-mass stars

Massive stars

Neutron stars

Cosmic-rays — GW, ν emissions

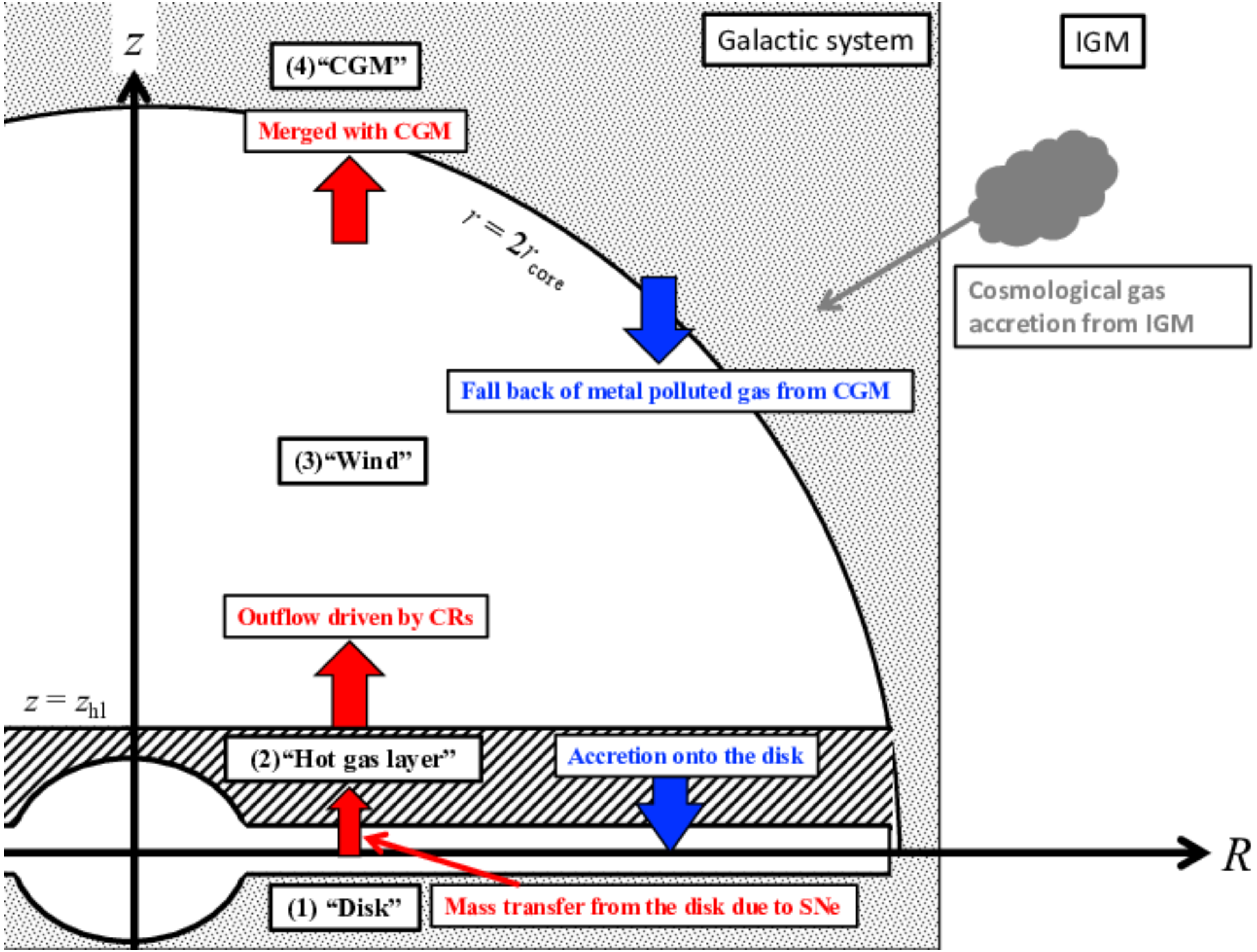
Metals — Planet formation, Cosmic life

Wind: test particle approximation

CGM: one-zone model

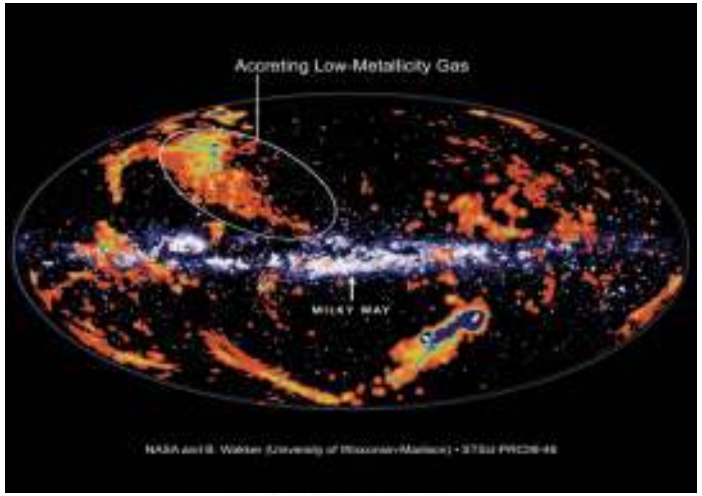
IGM: DM N-body simulation

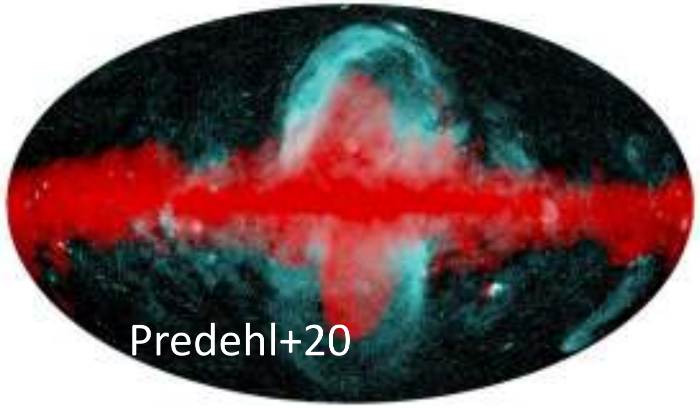
Model description



The model consists of 4 parts:

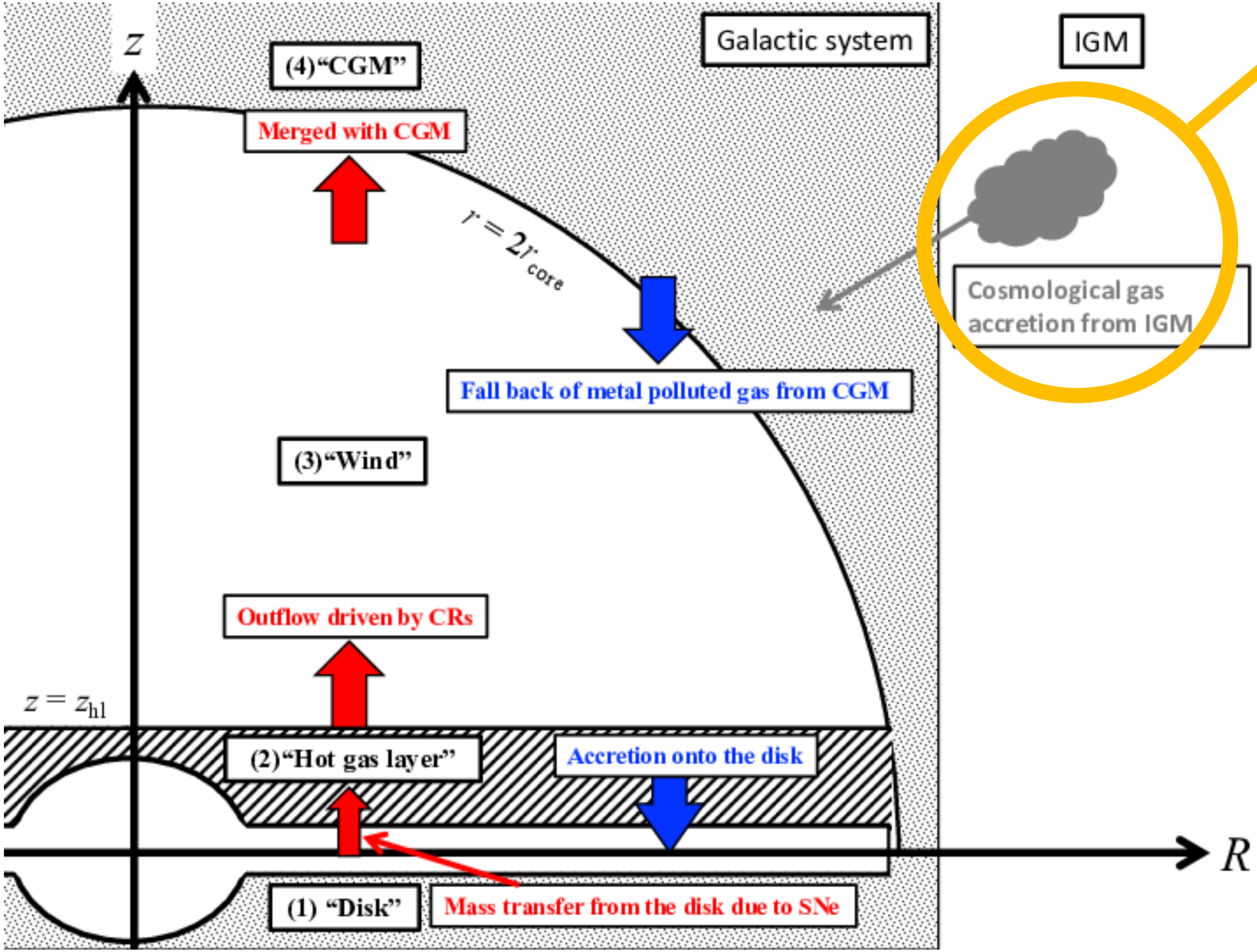
1) Galactic disk
2) Hot gas Layer
3) Wind region
4) CGM





Predehl+20

Model description



IGM acc. Rate
→ Use the results of the DM N-body simulation (Rodriguez-Puebla+16)

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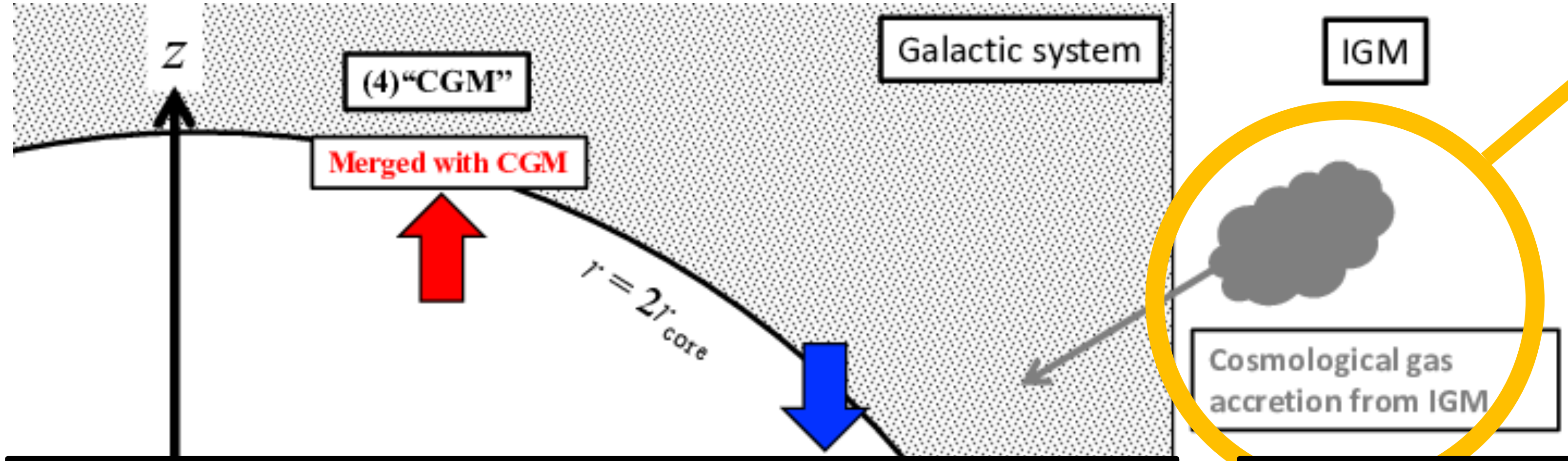

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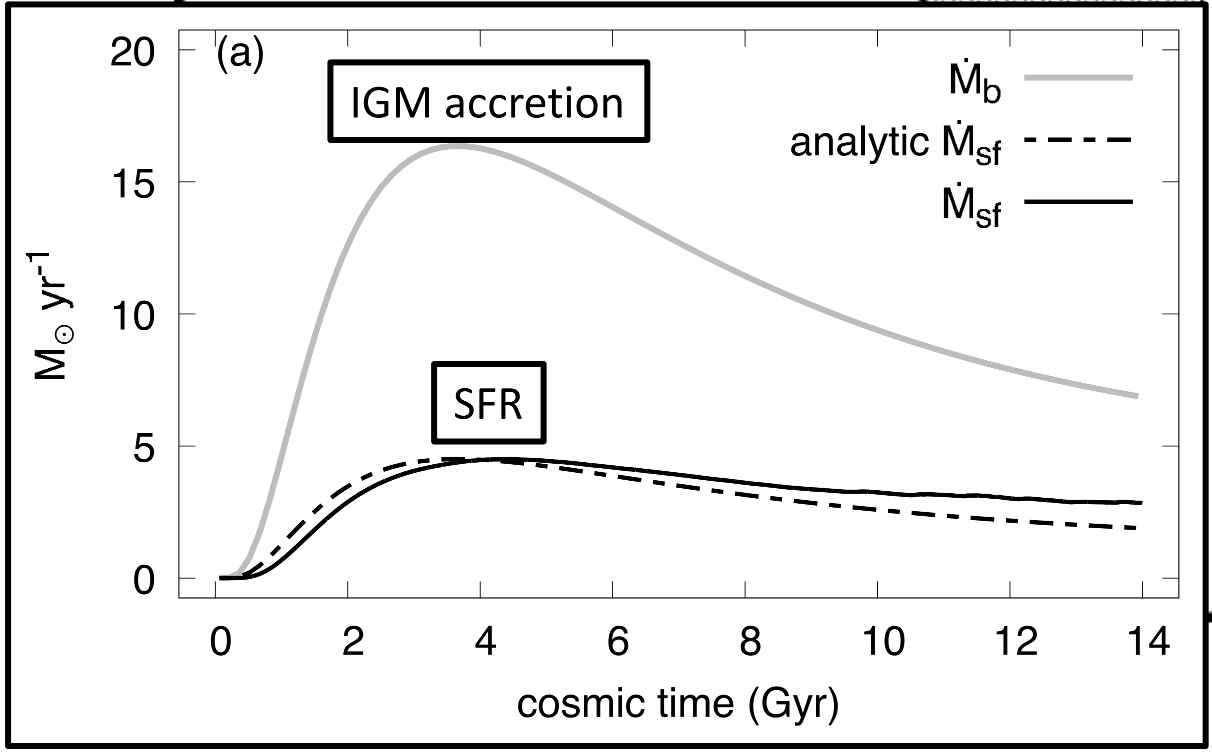

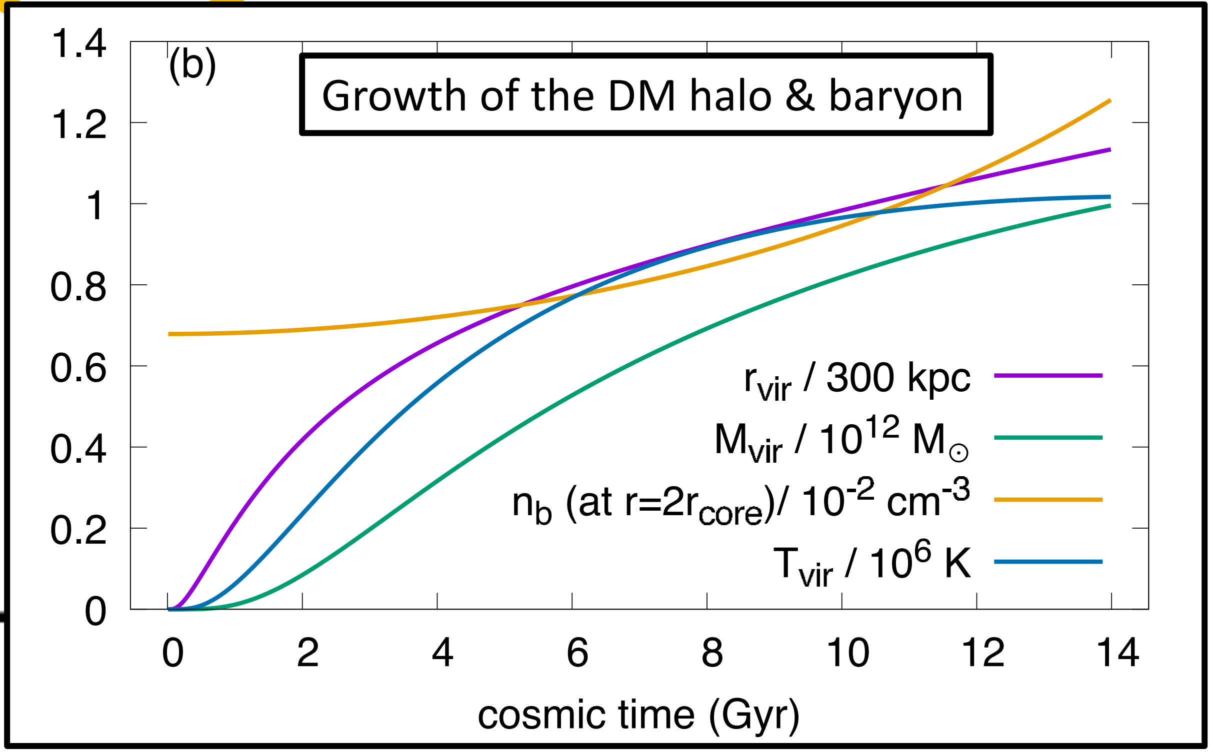

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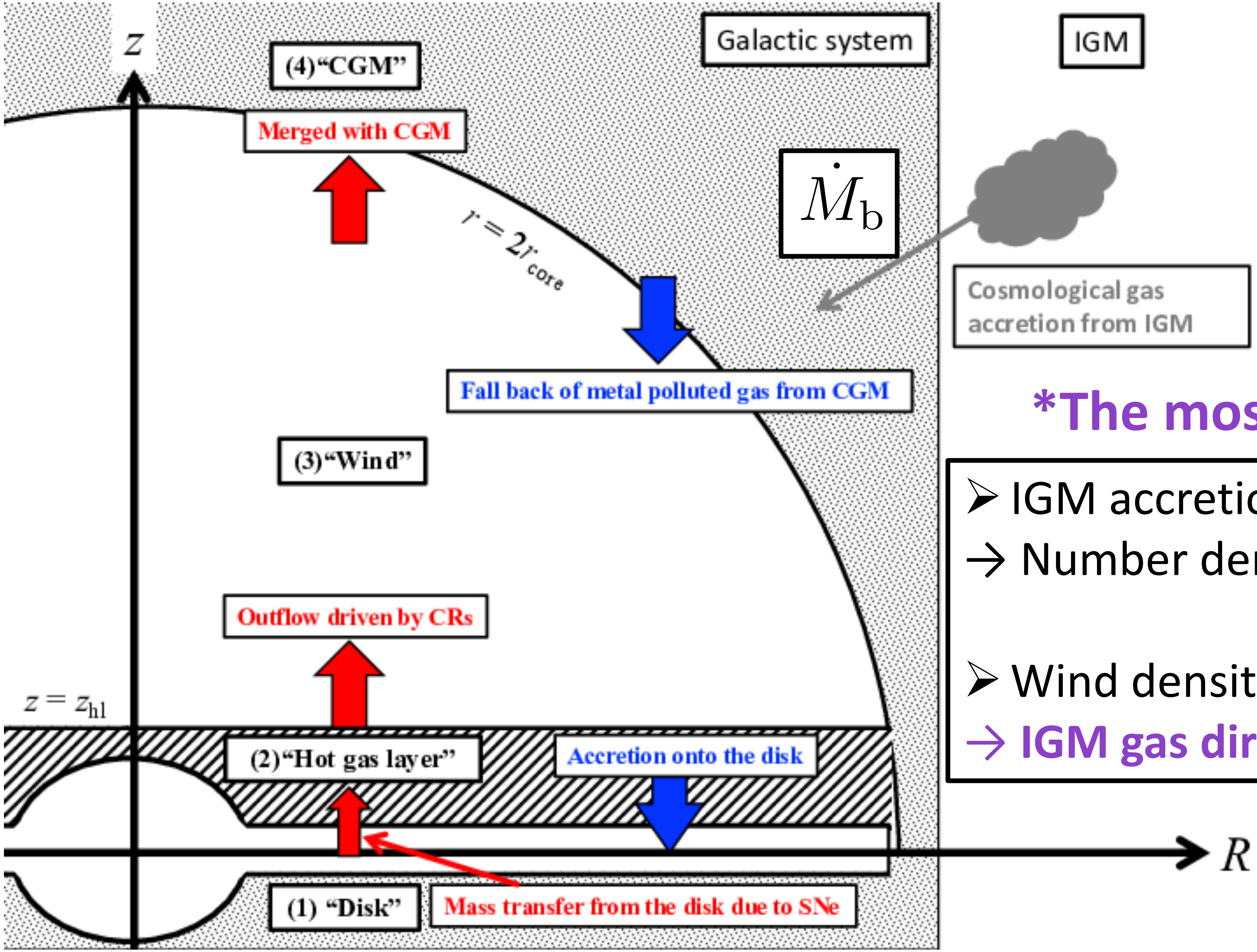
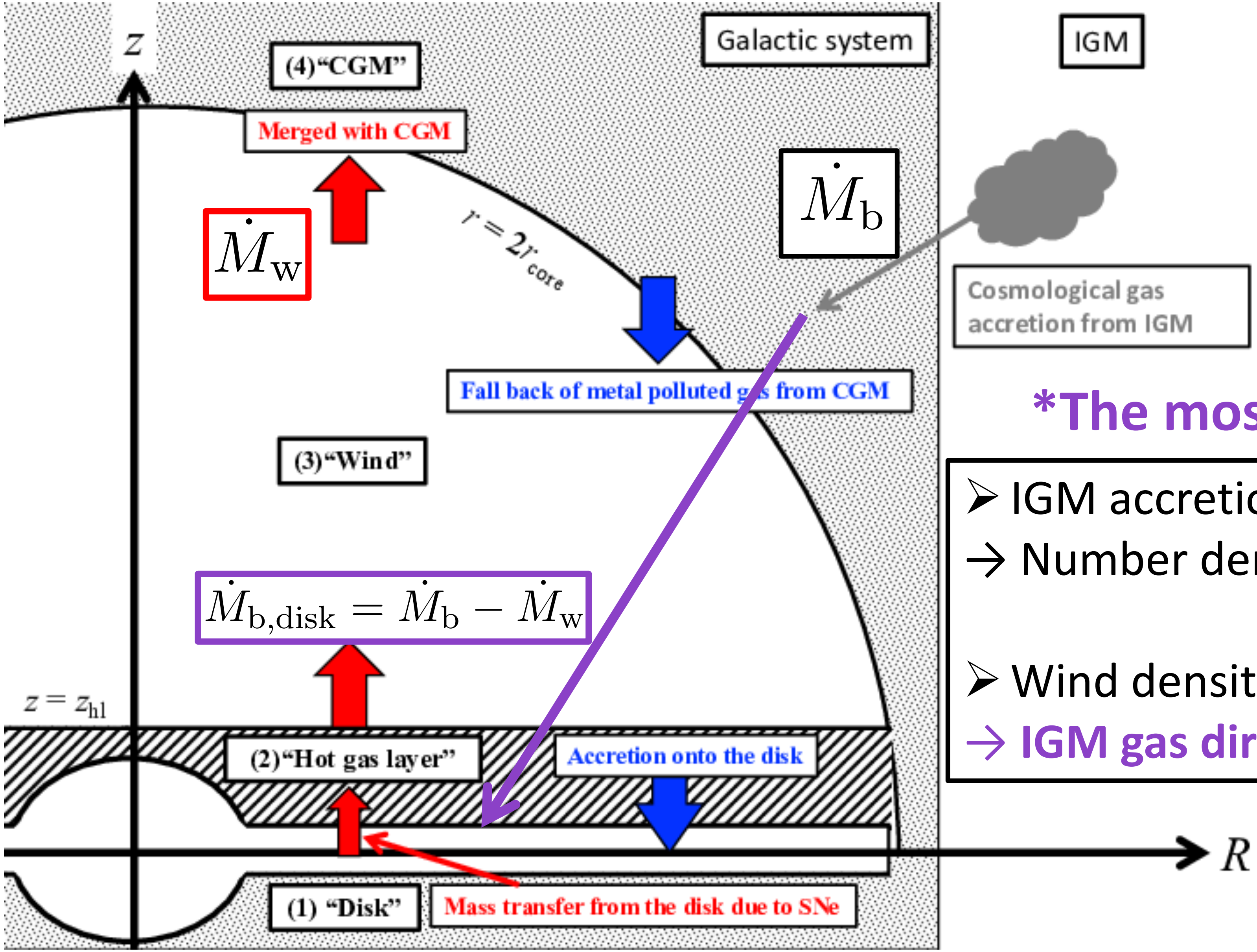


The most significant assumption

- IGM accretion gas
→ Number density: 10^{-2} cm^{-3} (on average)

- Wind density: 10^{-3} cm^{-3}
→ **IGM gas directly accretes onto the disk**

Model description



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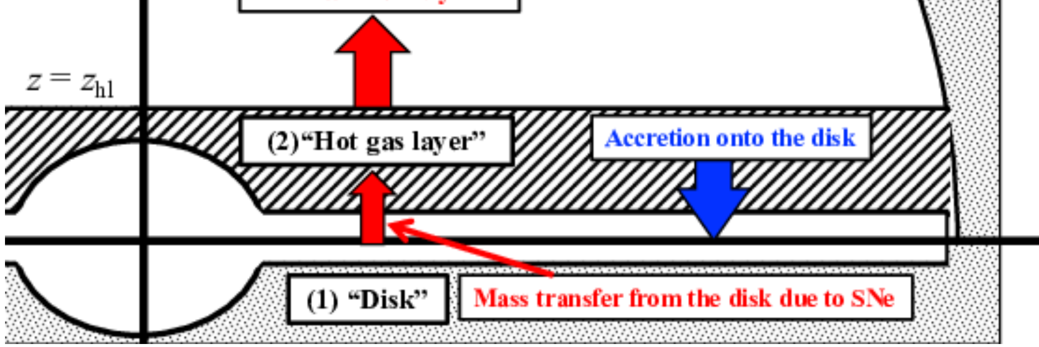
(1) Galactic disk



✓ **Simplest Accretion Disk Model (α-disk, Suzuki+16)**

$$\frac{\partial}{\partial t}(R\Sigma) - \mathcal{D}_\Sigma \frac{\partial^2}{\partial R^2}(R\Sigma) - \mathcal{V}_\Sigma \frac{\partial}{\partial R}(R\Sigma) = -R\dot{\Sigma}_{\rm blown} + R\dot{\Sigma}_{\rm acc} - R\dot{\Sigma}_{\rm sf} + R\dot{\Sigma}_{\rm ej},$$

$$\frac{d\Sigma_*}{dt} = (1 - f_{\rm ms})\dot{\Sigma}_{\rm sf},$$

$$\frac{d\Sigma_{\rm ms}}{dt} = f_{\rm ms}\dot{\Sigma}_{\rm sf} - \dot{\Sigma}_{\rm sn},$$

$$\frac{d\Sigma_{\rm ns}}{dt} = \frac{m_{*,\rm ns}}{\bar{m}_{*,\rm ms}}\dot{\Sigma}_{\rm sn},$$

$$\frac{d\Sigma_{\rm hl}}{dt} = \frac{\dot{\Sigma}_{\rm blown}}{2} - \frac{\Sigma_{\rm hl}}{z_{\rm hl}}C_{s,\rm hl},$$

$$\dot{\Sigma}_{\rm sf} = \frac{\epsilon_{\rm sf}}{\tau_{\rm sf}}\Sigma,$$

$$\dot{\Sigma}_{\rm ej} = \frac{m_{\rm ej}}{m_{*,\rm ms}}\dot{\Sigma}_{\rm sn} \quad \left[\dot{\Sigma}_{Z,\rm ej} = \left(\frac{m_{\rm ej}}{\bar{m}_{*,\rm ms}} + \frac{m_{\rm co}}{\bar{m}_{*,\rm ms}}\right)\dot{\Sigma}_{Z,\rm sn} \text{ (for metals)}\right],$$

$$\dot{\Sigma}_{\rm sn} = \frac{\Sigma_{\rm ms}}{\tau_{*,\rm ms}},$$

$$\dot{\Sigma}_{\rm blown} = \eta_{\rm w}\dot{\Sigma}_{\rm sn} \quad \left[\dot{\Sigma}_{Z,\rm blown} = \frac{\Sigma_Z}{\Sigma}\dot{\Sigma}_{\rm blown} \text{ (for metals)}\right].$$

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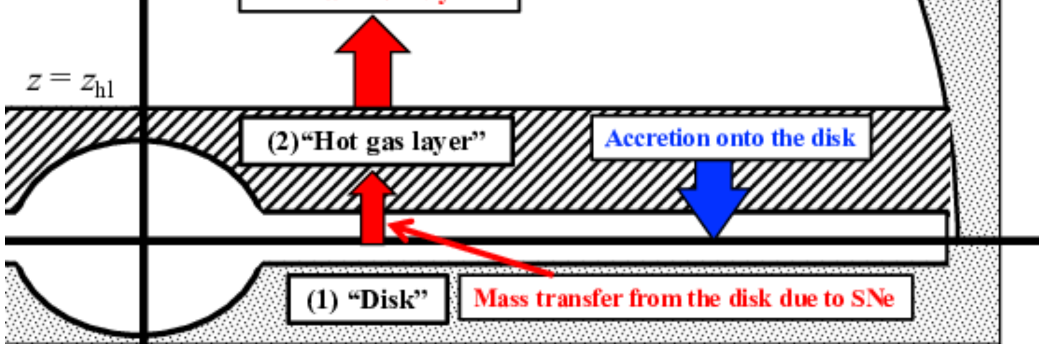

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(Stellar objects)

$$\frac{d\Sigma_{\rm hl}}{dt} = \frac{\dot{\Sigma}_{\rm blown}}{2} - \frac{\Sigma_{\rm hl}}{z_{\rm hl}}C_{s,\rm hl},$$

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$$\frac{kT_{\rm hl}}{m_{\rm p}}\dot{\Sigma}_{\rm blown} = \eta_{\rm blown}\frac{E_{\rm sn}}{\bar{m}_{*,\rm ms}}\dot{\Sigma}_{\rm sn}$$

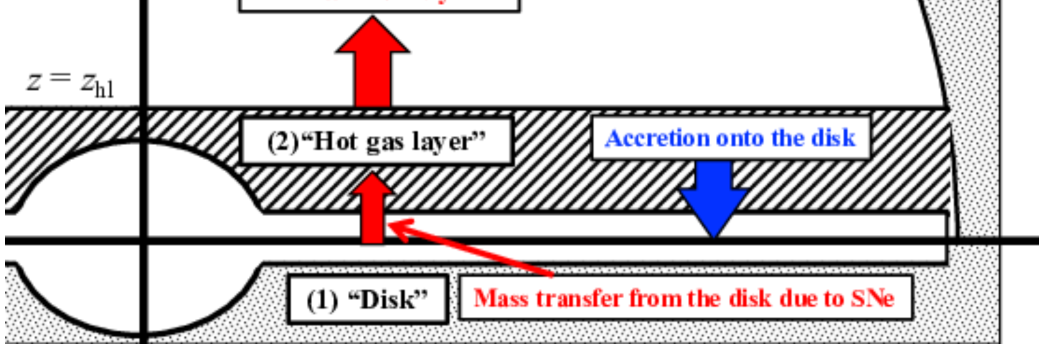
$$\dot{\Sigma}_{\rm blown} = \eta_{\rm blown}\frac{m_{\rm p}}{\bar{m}_{*,\rm ms}}\frac{E_{\rm sn}}{kT_{\rm hl}}\dot{\Sigma}_{\rm sn} \equiv \eta_{\rm w}\dot{\Sigma}_{\rm sn}$$

$$\eta_{\rm w} \simeq 6.58\left(\frac{\eta_{\rm blwon}}{0.1}\right)\left(\frac{E_{\rm sn}}{10^{51}\ \rm erg}\right)\left(\frac{T_{\rm hl}}{3\times10^6\ \rm K}\right)^{-1}\left(\frac{\bar{m}_{*,\rm ms}}{30.9\ M_\odot}\right)^{-1}$$

SNe expel the disk gas to the hot gas layer

→ results in the observed soft X-ray emission

(1) Galactic disk



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$$\frac{d\Sigma_{\rm ns}}{dt} = \frac{m_{*,\rm ns}}{\bar{m}_{*,\rm ms}}\dot{\Sigma}_{\rm sn},$$

(Stellar objects) ←

We solve the motion equations of **the low-mass stars & neutron stars.**

$$\frac{d\Sigma_{\rm hl}}{dt} = \frac{\dot{\Sigma}_{\rm blown}}{2} - \frac{\Sigma_{\rm hl}}{z_{\rm hl}} C_{s,\rm hl},$$

$$\dot{\Sigma}_{\rm sf} = \frac{\epsilon_{\rm sf}}{\tau_{\rm sf}}\Sigma,$$

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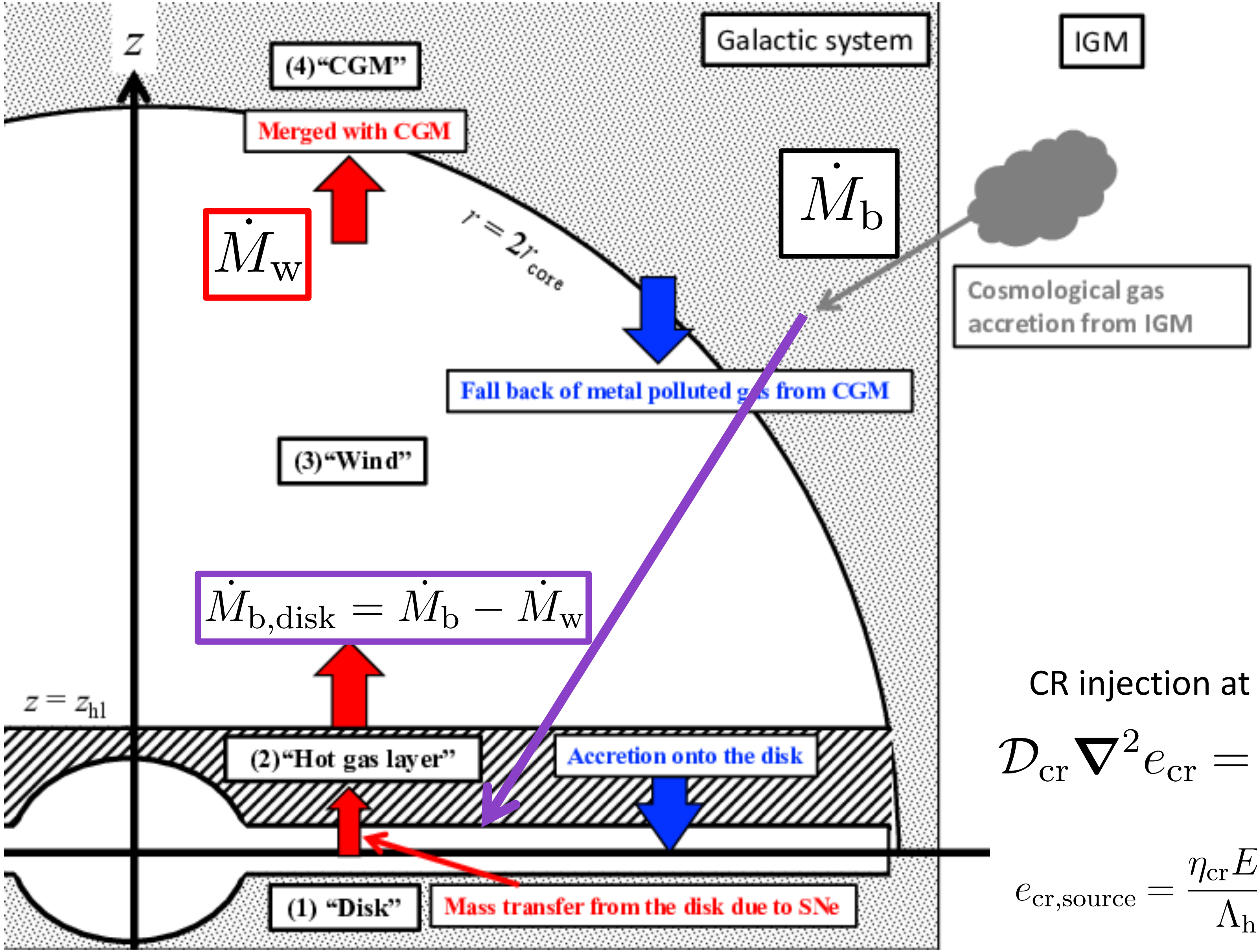
Model description



The model consists of 4 parts:

1) Galactic disk
2) Hot gas Layer
3) Wind region → test particle
4) CGM

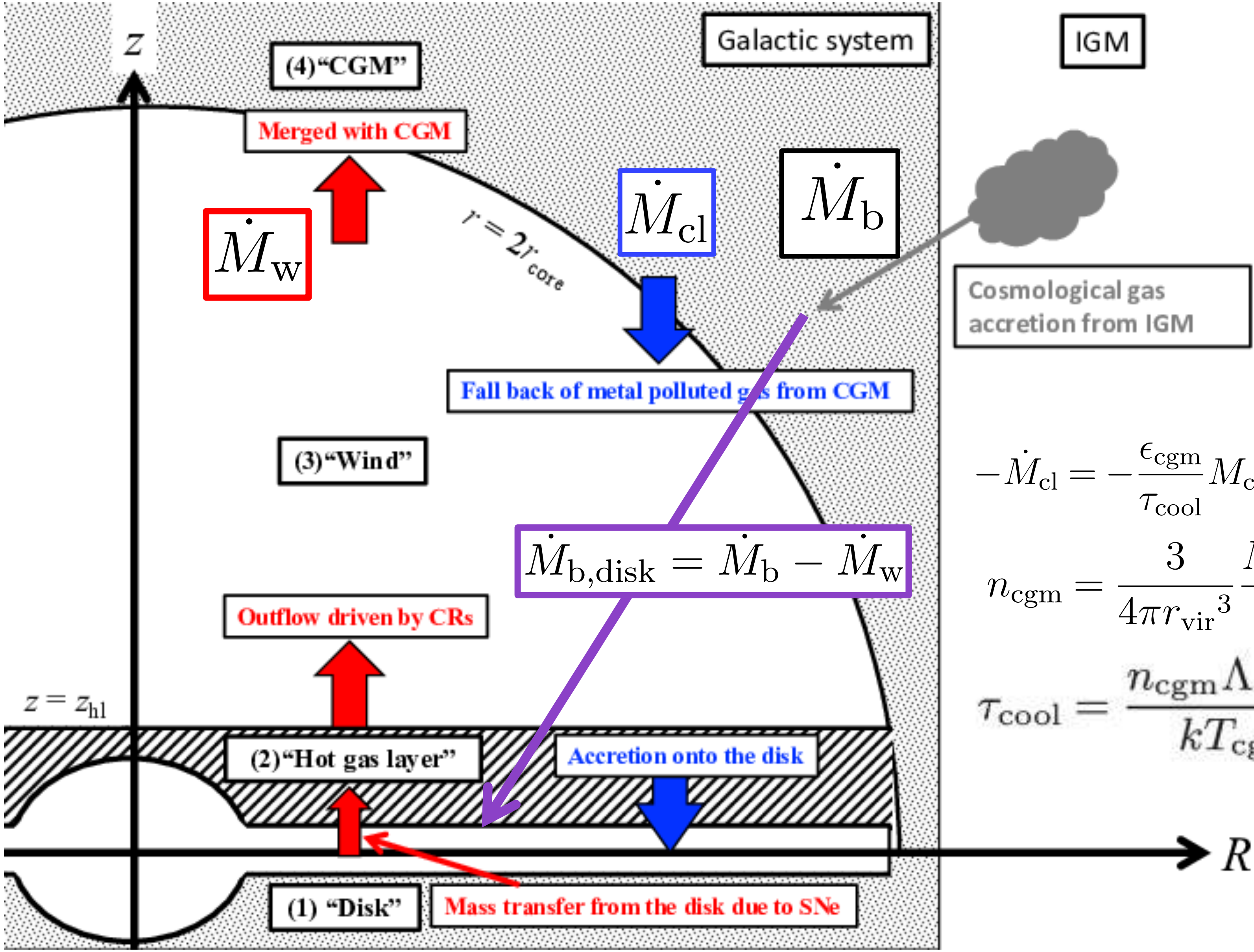
$$\frac{d\boldsymbol{v}_\mathrm{w}}{dt} = -\frac{\boldsymbol{\nabla} P_\mathrm{cr}}{\rho_\mathrm{w}} - \boldsymbol{g}$$

CR injection at the disk

$$\mathcal{D}_\mathrm{cr}\boldsymbol{\nabla}^2 e_\mathrm{cr} = \frac{e_\mathrm{cr,source}}{\tau_\mathrm{cr,esc}} \qquad H_\mathrm{cr} = \sqrt{\mathcal{D}_\mathrm{cr}\tau_\mathrm{cr,esc}}$$

$$e_\mathrm{cr,source} = \frac{\eta_\mathrm{cr} E_\mathrm{sn}}{\Lambda_\mathrm{h}} \frac{m_\mathrm{p}}{\bar{m}_{*,\mathrm{ms}}} \frac{\dot{\Sigma}_\mathrm{sn}}{\Sigma} \qquad P_\mathrm{cr} = (\gamma_c - 1) e_\mathrm{cr}$$

Model description



The model consists of 4 parts:
1) Galactic disk
2) Hot gas Layer
3) Wind region → test particle
4) CGM → one-zone

$$\frac{dM_{\rm cgm}}{dt} = \dot{M}_{\rm w} - \dot{M}_{\rm cl}$$

$$-\dot{M}_{\rm cl} = -\frac{\epsilon_{\rm cgm}}{\tau_{\rm cool}} M_{\rm cgm} = -\frac{\epsilon_{\rm cgm} k T_{\rm cgm}}{n_{\rm cgm}\Lambda_{\rm rad,\odot}} \left(1 - e^{-Z_{\rm cgm}/Z_\odot}\right) M_{\rm cgm}$$

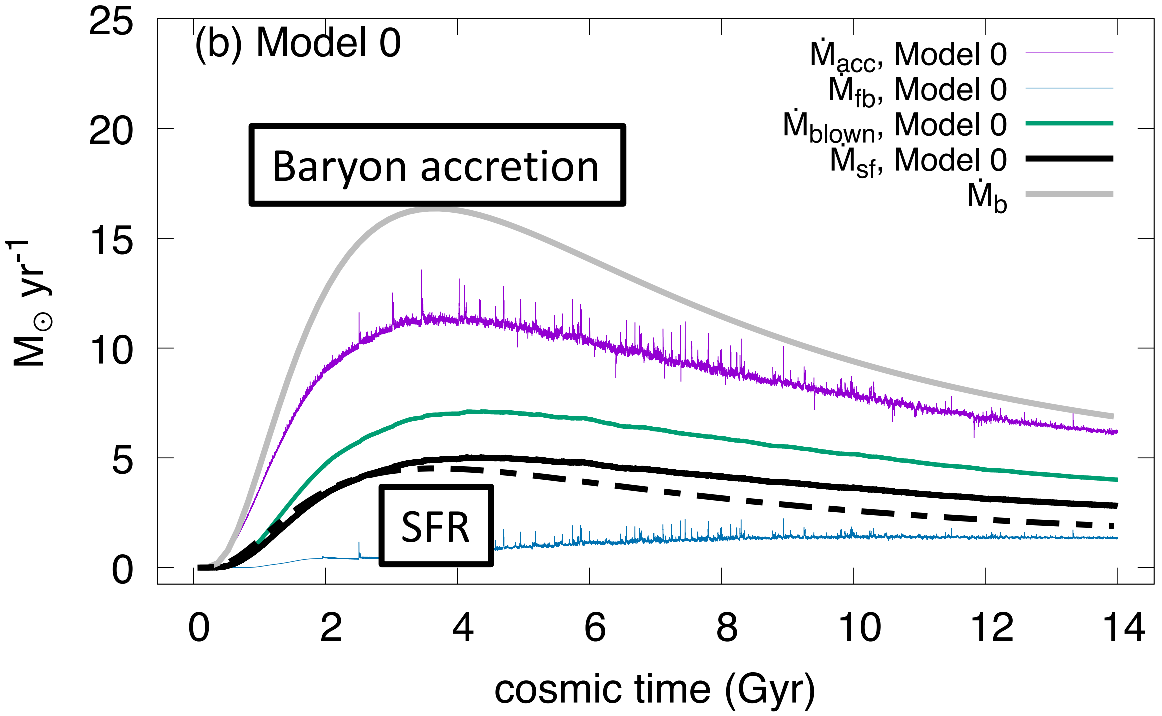
$$n_{\rm cgm} = \frac{3}{4\pi {r_{\rm vir}}^3} \frac{M_{\rm cgm}}{m_{\rm p}}$$

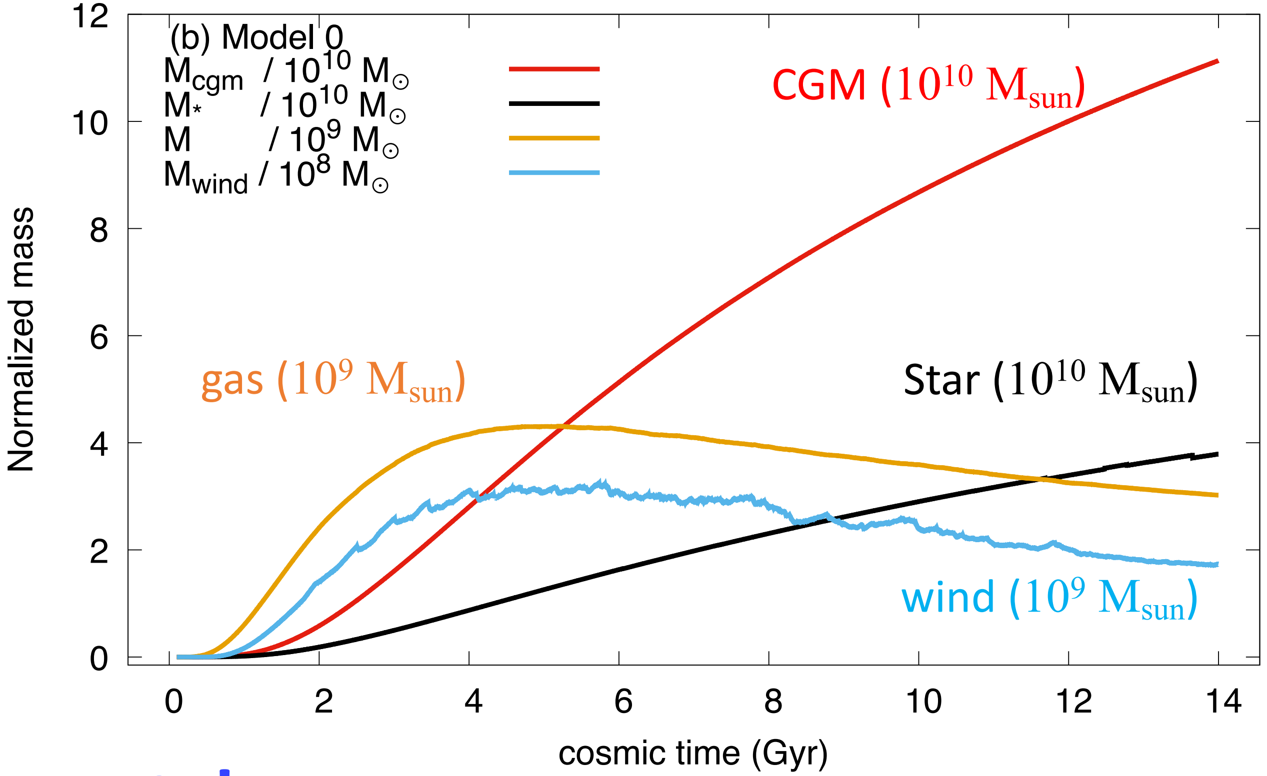
$$\tau_{\rm cool} = \frac{n_{\rm cgm}\Lambda_{\rm rad,\odot}}{kT_{\rm cgm}} \frac{Z_\odot}{Z_{\rm cgm}}$$

$$\epsilon_{\rm cgm} = 0.01$$

Efficiency of A. momentum transfer

Results



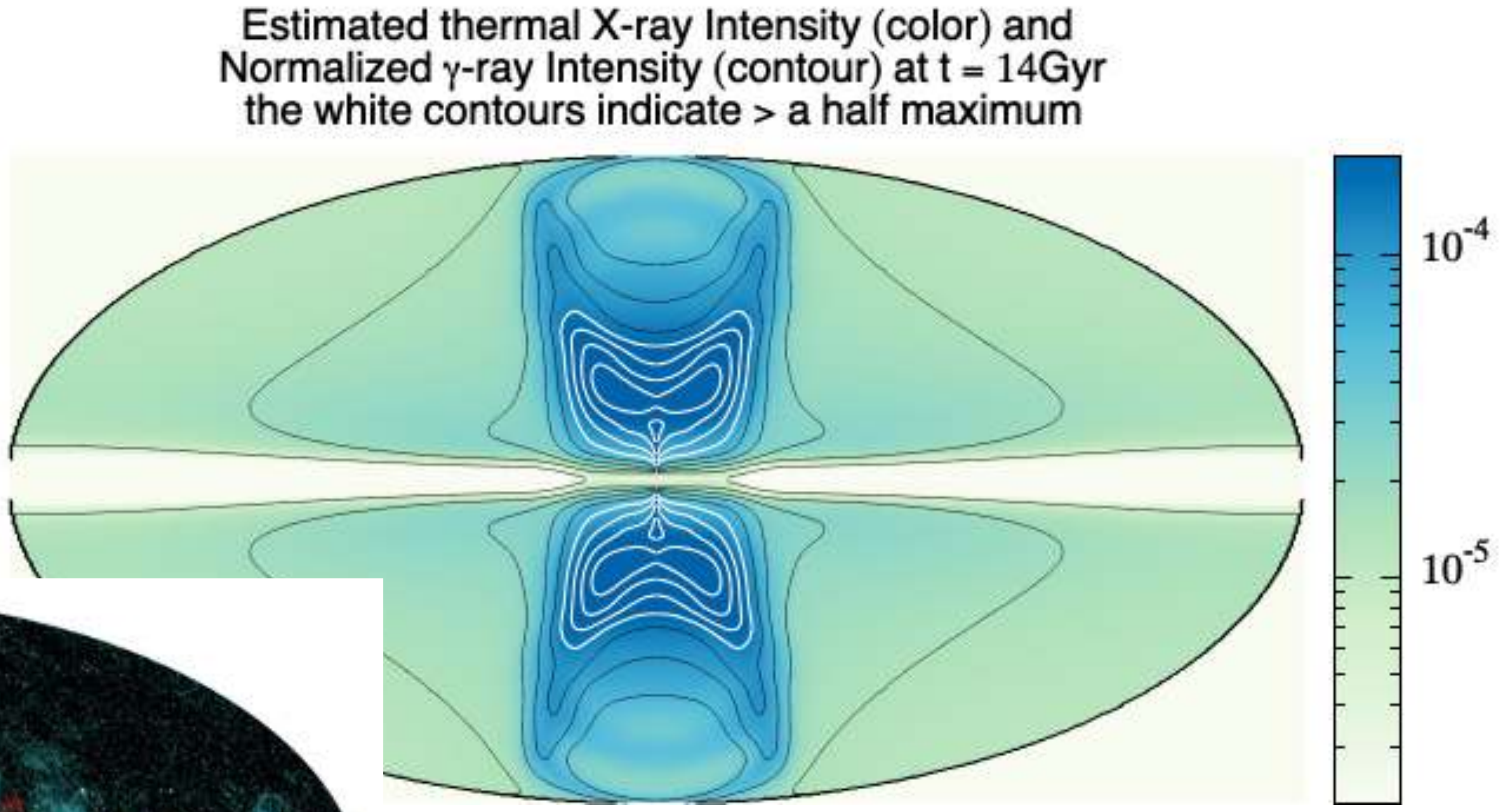


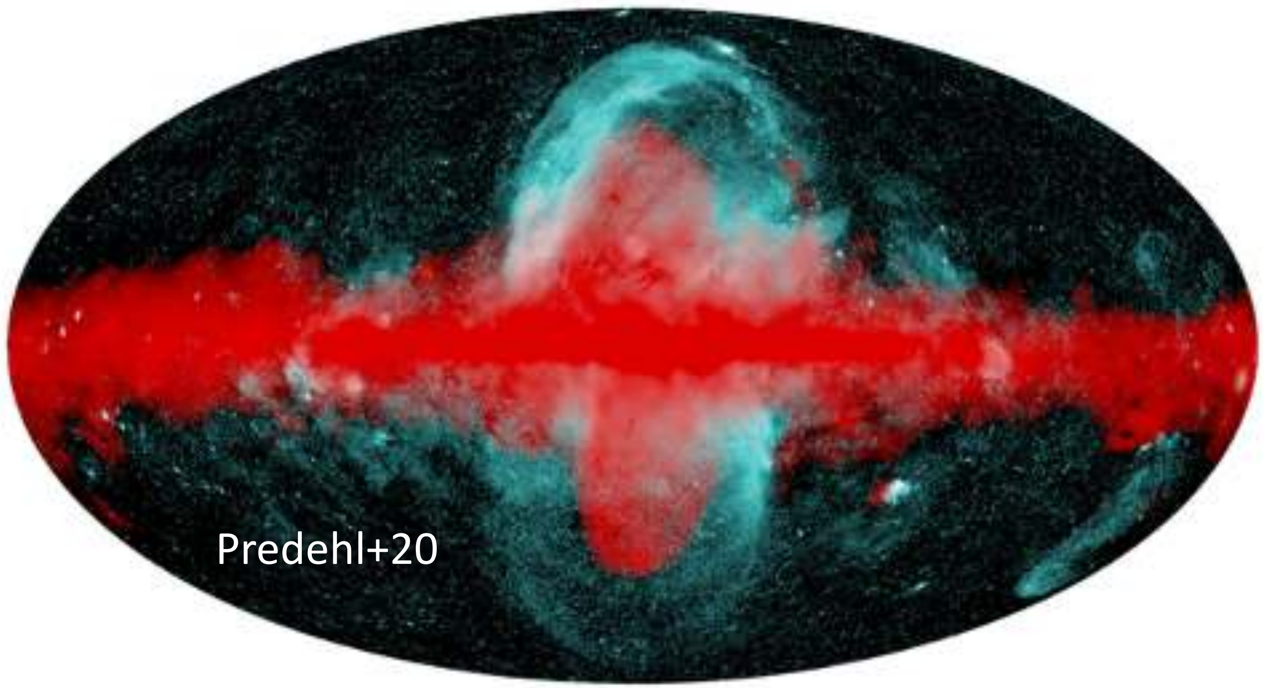
SFR becomes half of the IGM accretion rate!

Total mass of stars: $\sim 4 \times 10^{10}$ M_{sun} consistent with 4-6 $\times 10^{10}$ M_{sun}

Results

***Hadronic γ-ray**

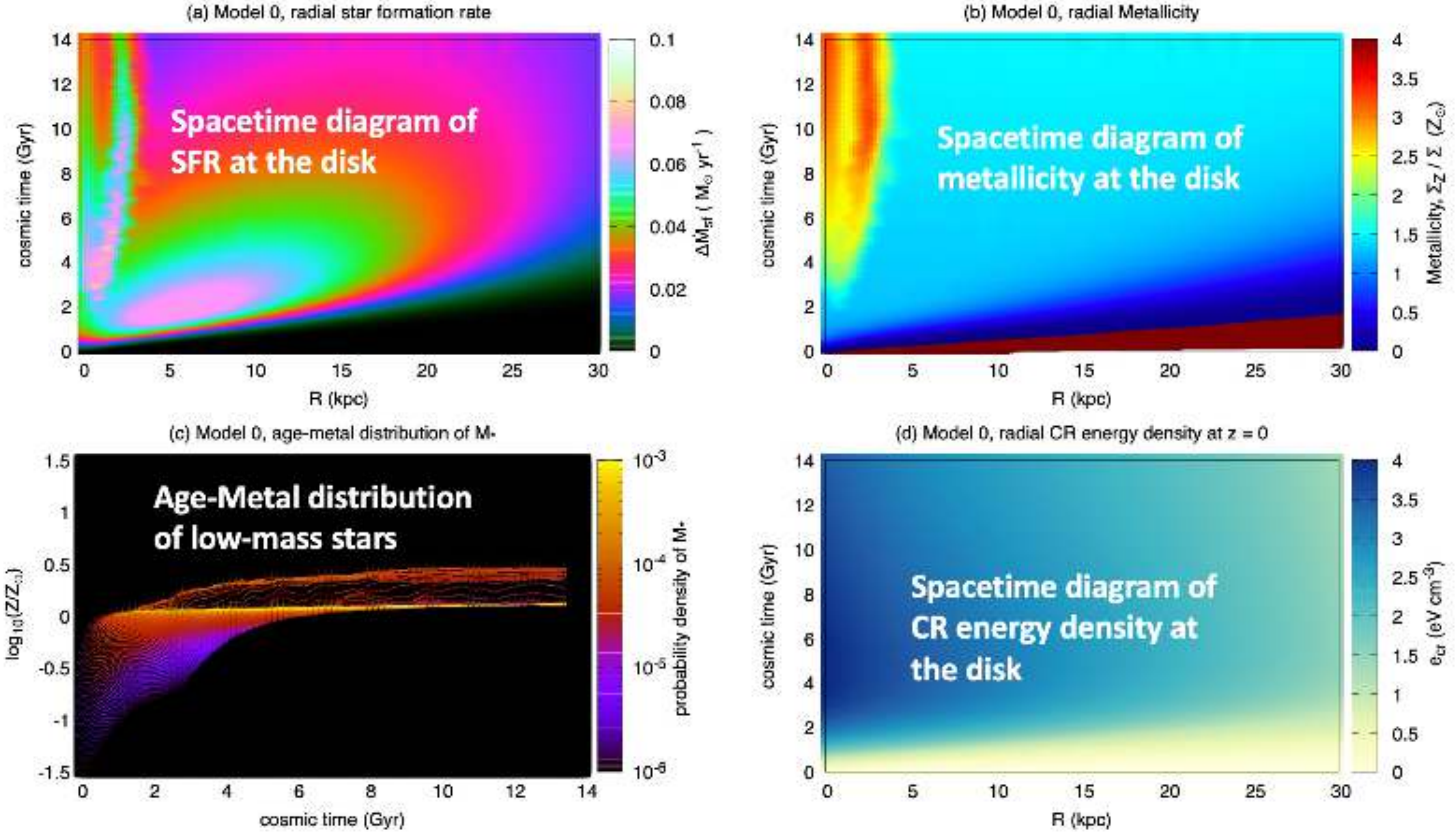




Our model reproduces the Fermi & eROSITA bubbles?
We are preparing quantitative comparison (coming soon)...

Other Results

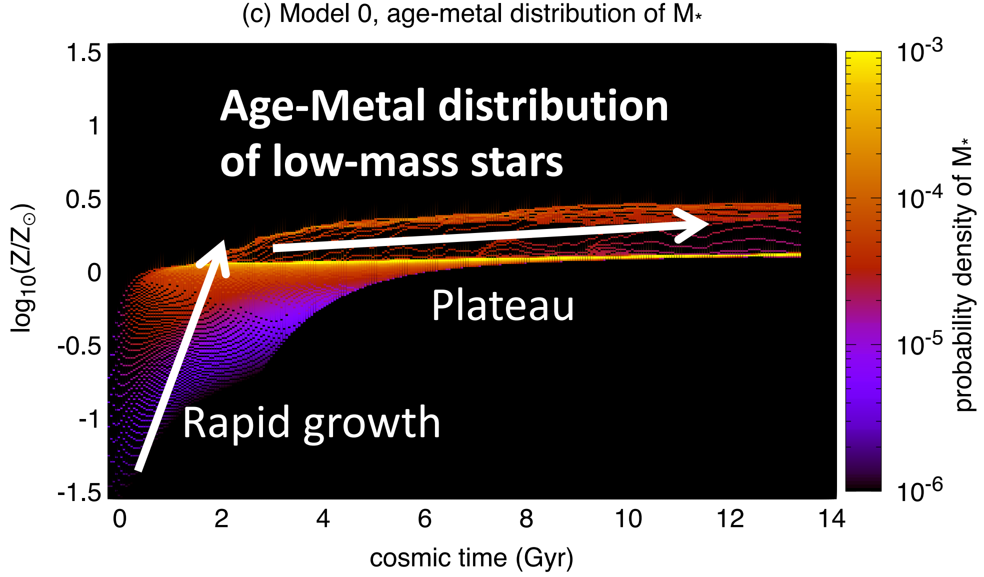
Star formation, Cosmic-rays, Metallicity are in good agreements!

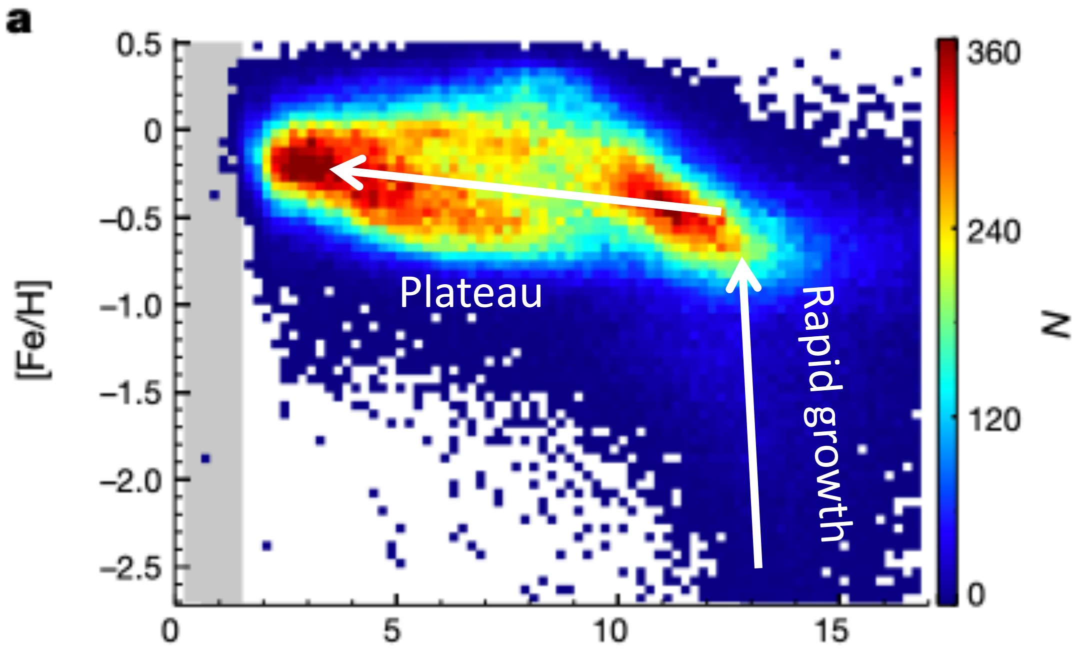


Other Results

Star formation, Cosmic-rays, Metallicity are in good agreements!

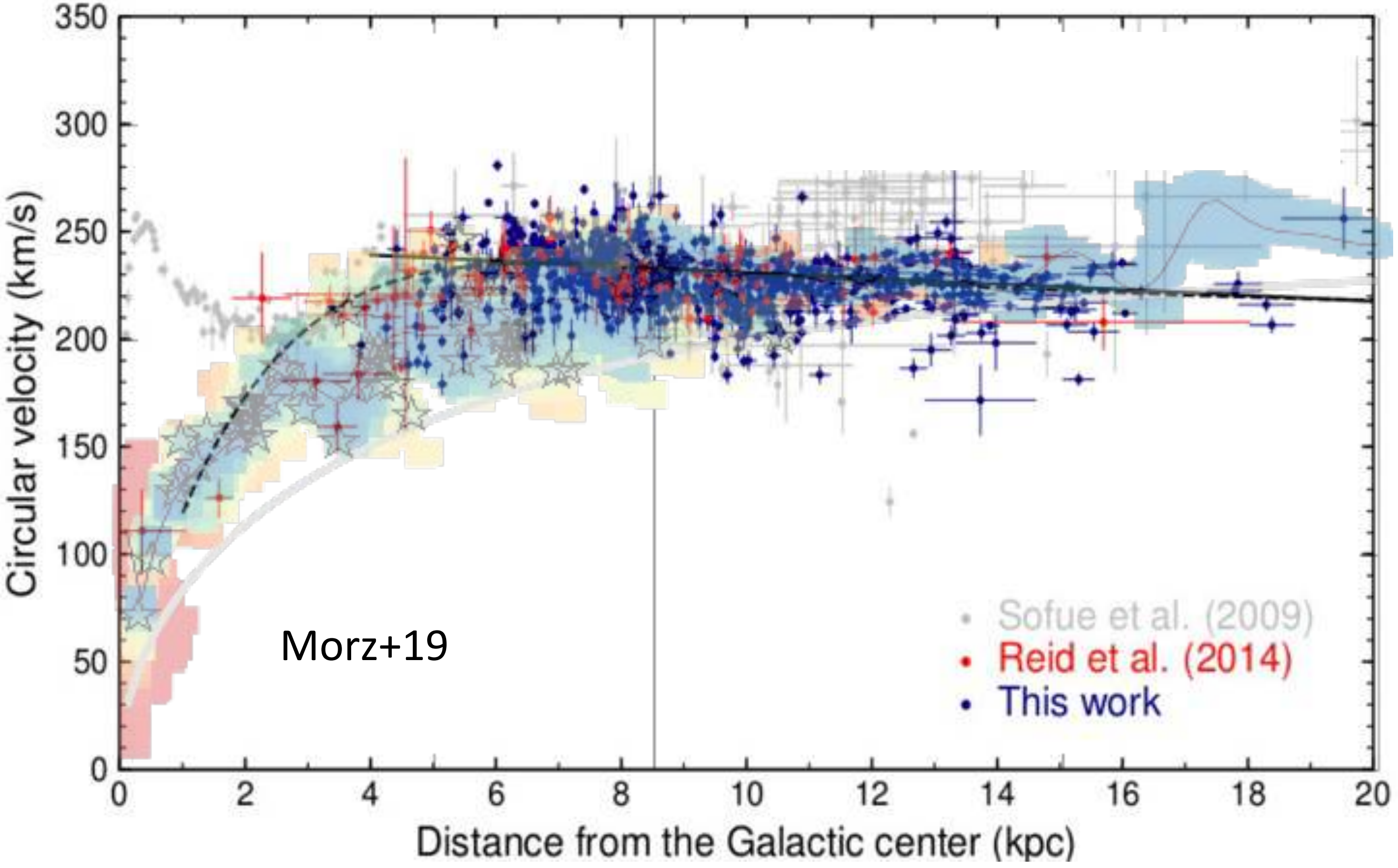
The age-metal distribution is almost consistent with the Gaia obs.





Xing & Rix (2022, by Gaia)

Other Results: Stellar Objects



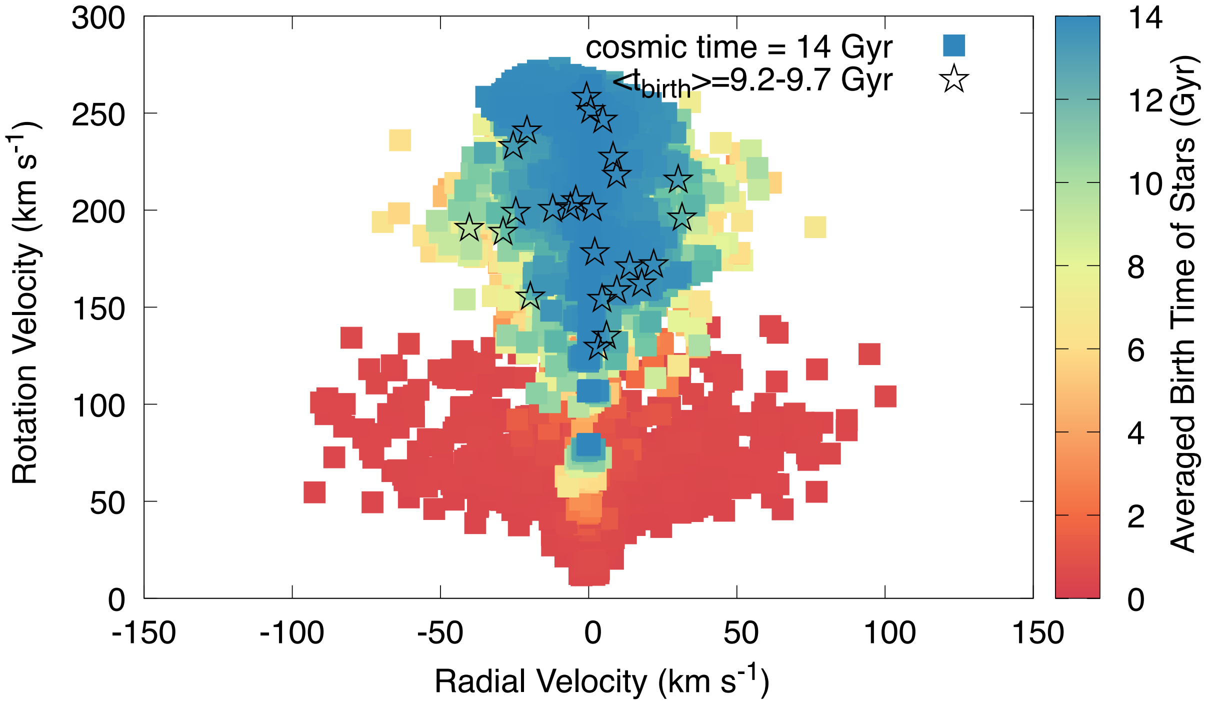
The rotation curve of stars can be consistent with the observations.

→ Assumed mass accretion is not so bad.

$$R\dot{\Sigma}_{\rm b,disk}(t,R) = \frac{\dot{M}_{\rm b} - \dot{M}_{\rm w} + \dot{M}_{\rm cl}}{4\pi} N_{\rm b,disk} \exp\left[-\frac{(R-r_{\rm core})^2}{2{r_{\rm core}}^2}\right]$$

Other Results: Stellar Objects

https://www.eurekalert.org/news-releases/620322



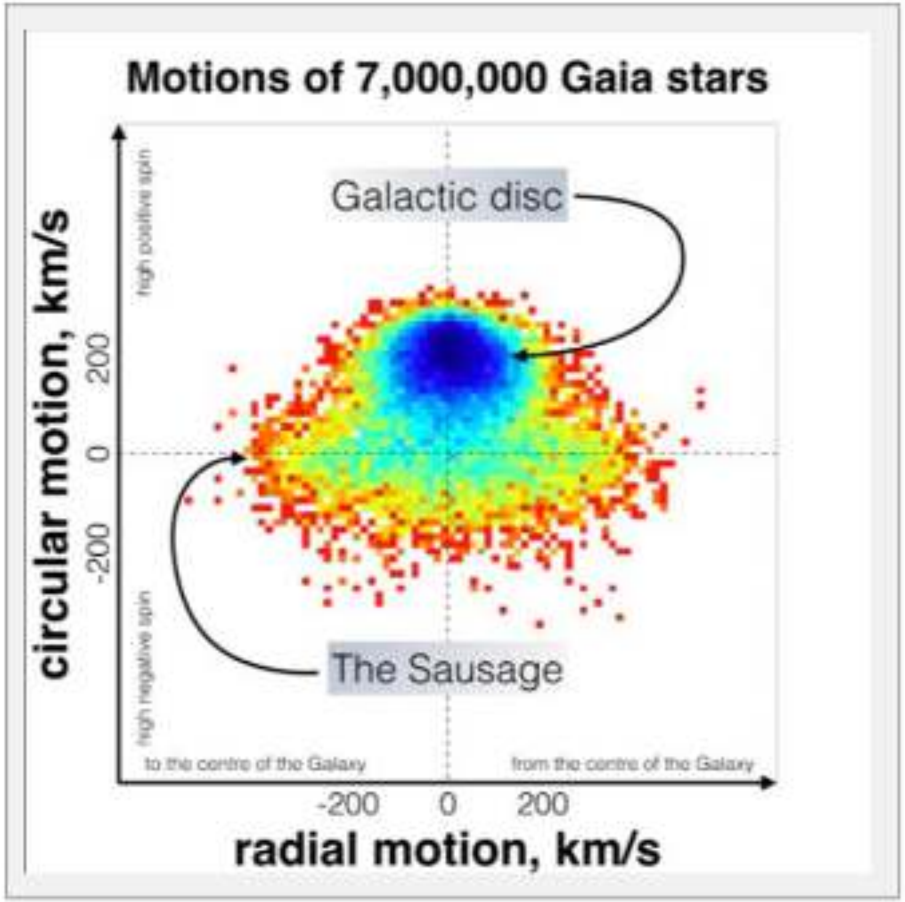
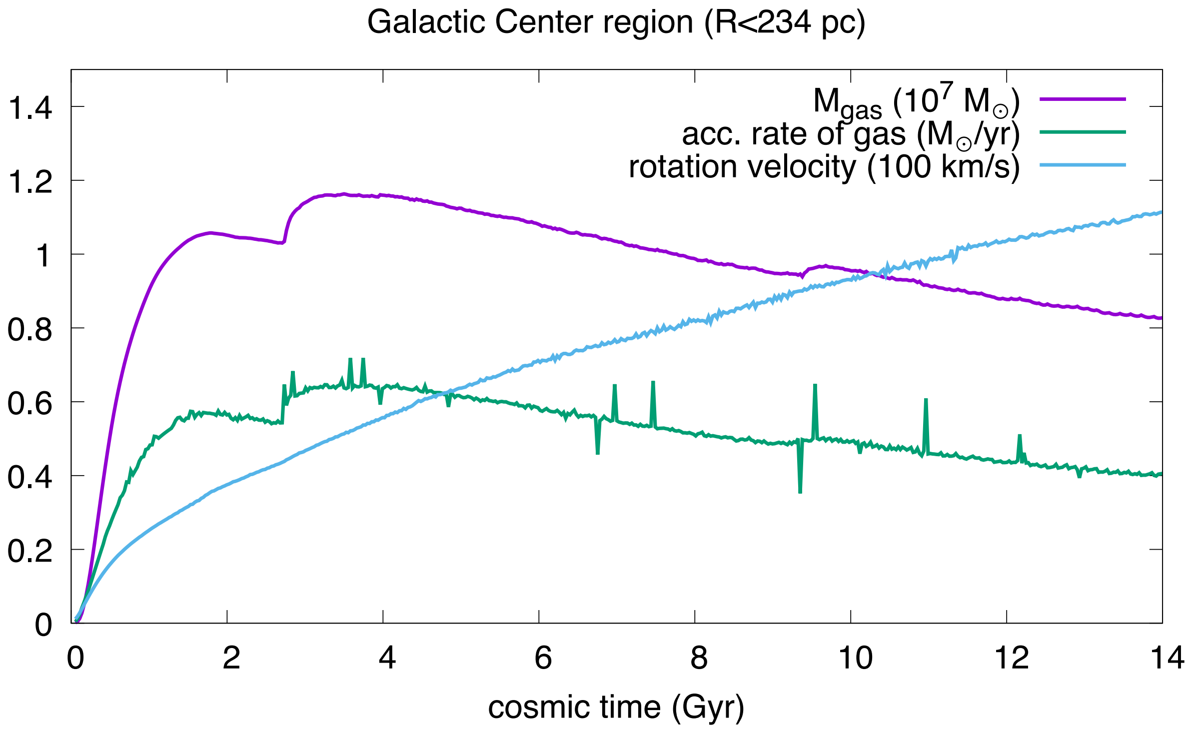
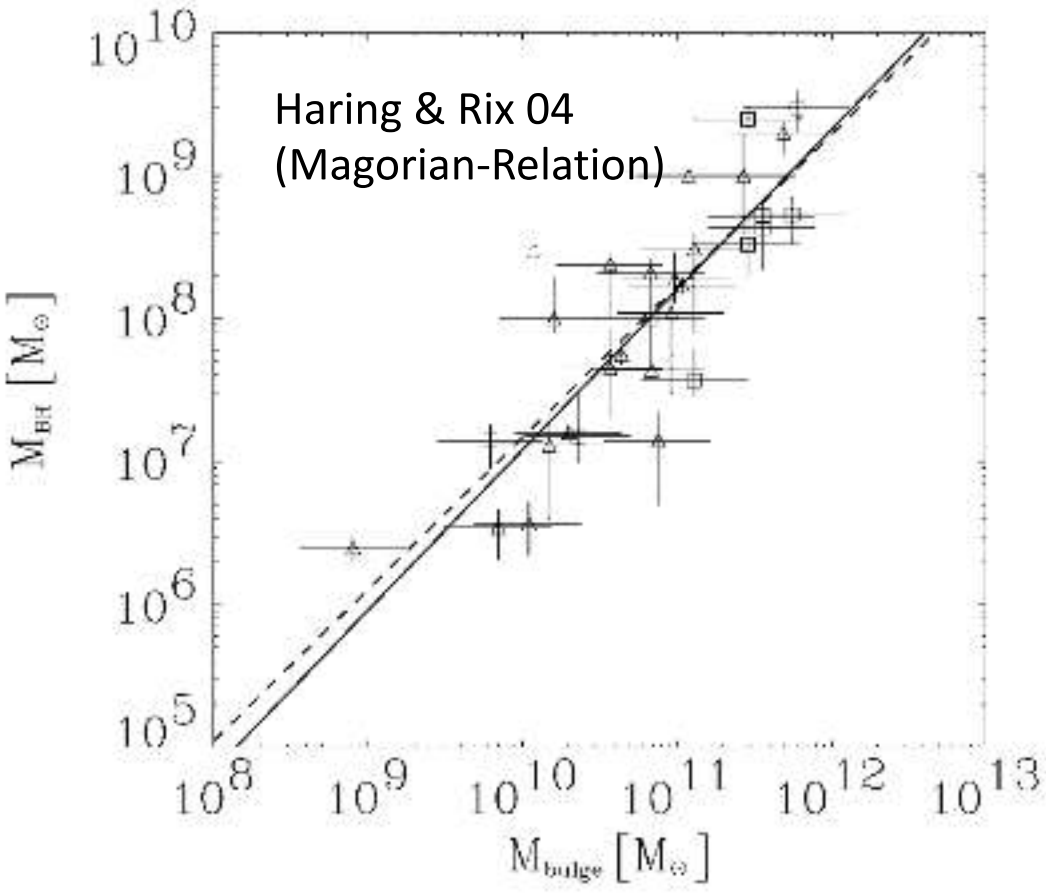


IMAGE: GAIA-SAUSAGE STRUCTURE DETECTED BY THE GAIA SATELLITE IN VELOCITY SPACE. (CREDIT: V. BELOKUROV ET AL. 2018, MNRAS, 478, 611).

"Flower" in the velocity space appears.
The similar structure is observed by Gaia?

Other Results: Galactic Center



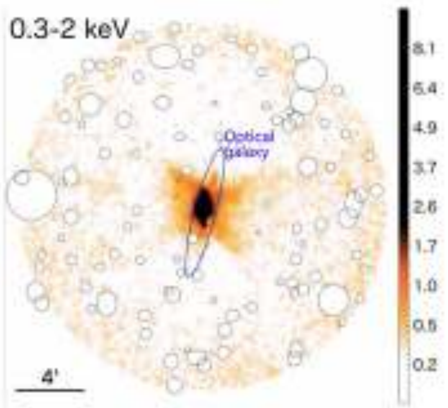


We can predict the mass evolution of around the Galactic center.

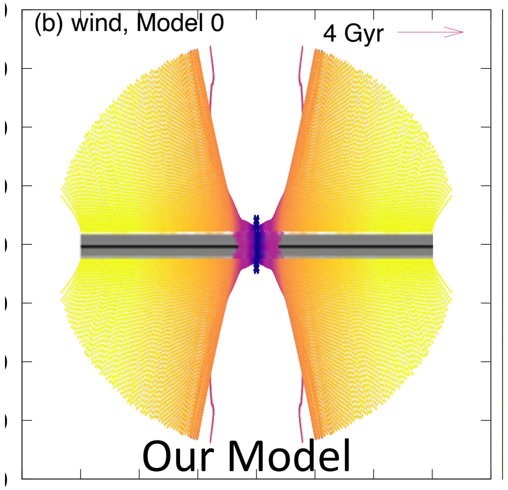
→ **Sgr A* formation & activity can be studied in future work.**

Future X-ray Observations

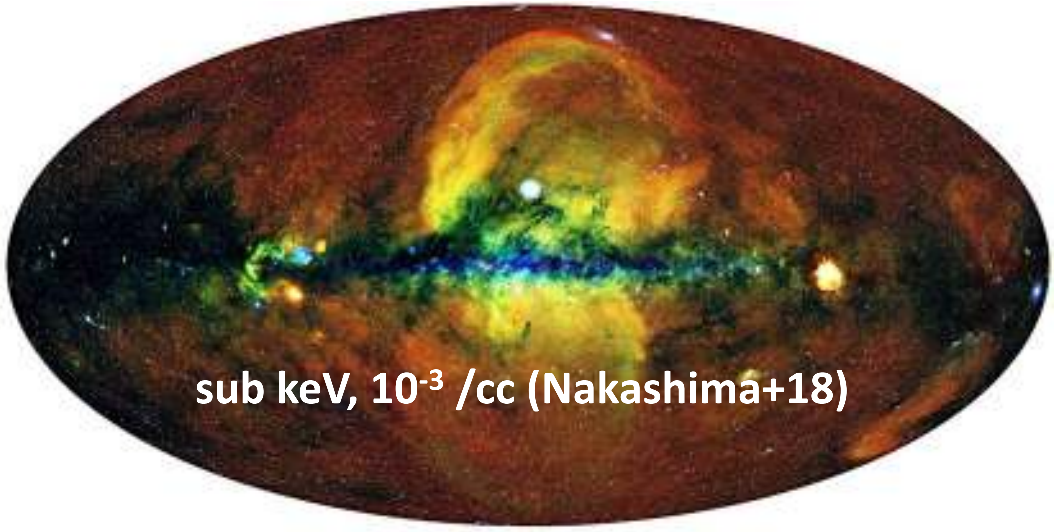
Is the wind scenario universal?



NGC 3079
Hodges-Kluck+20



Our Model



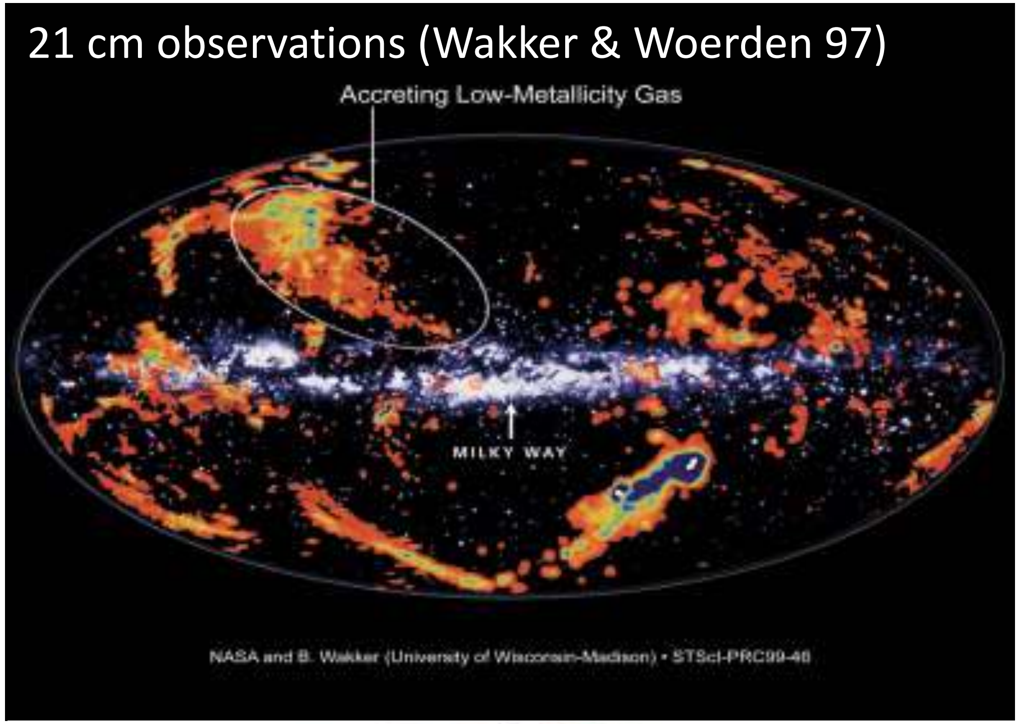
eROSITAによる全天画像。0.3~0.6keVのエネルギーのX線を赤、0.6~1keVを緑、1~2.3keVを青に色付けして合成されています。
Credit: MPE/IKI

$$\frac{kT_{\rm w}}{m_{\rm p}}\dot{M}_{\rm w} = \eta L_{\rm SN}$$

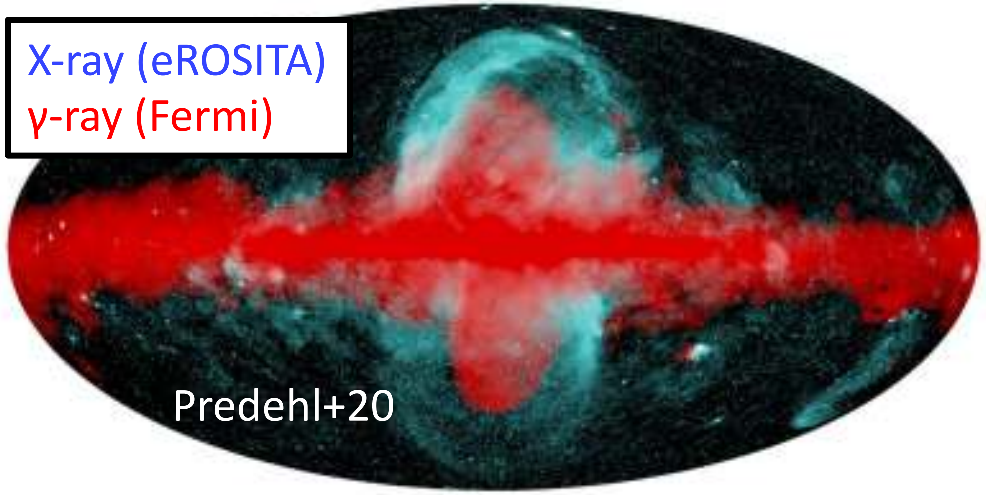
$$\dot{M}_{\rm w} \sim 4\ M_{\odot}/{\rm yr}\left(\frac{\eta}{0.1}\right)\left(\frac{L_{\rm SN}}{10^{42}\ {\rm erg/s}}\right)\left(\frac{kT_{\rm w}}{0.3\ {\rm keV}}\right)^{-1}$$

Observational tests by the X-ray emissions in external galaxies are required.
→ The next plan of X-ray space telescope, *JEDI*.

Remaining Theoretical Subjects



Accreting gas is observed by 21 cm emission as known as *High Velocity Cloud*.
→ Is it responsible for the *inflow*?
The origin & mass of HVCs is still an open question.



Recent X-ray and γ-ray surveys suggest a drastic activity of the galactic center.
→ Such bubble-like structures are also an open question.

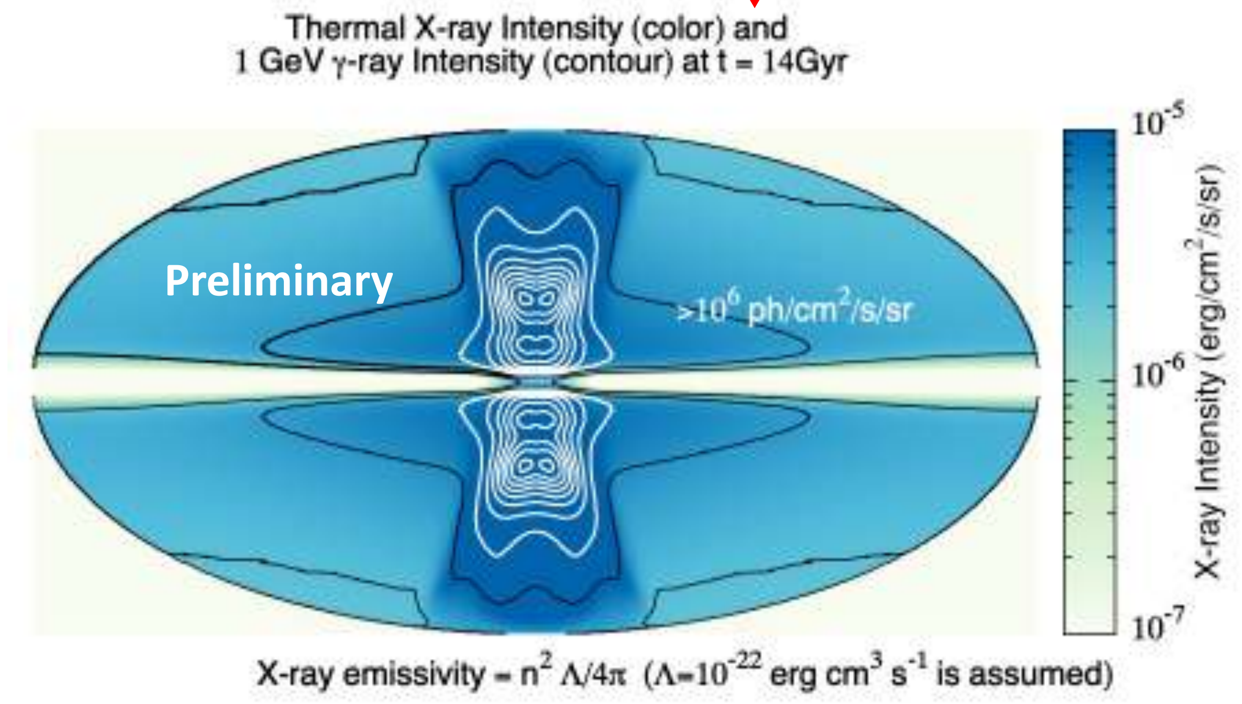
Toward the Next-generation Multi-messenger Astronomy

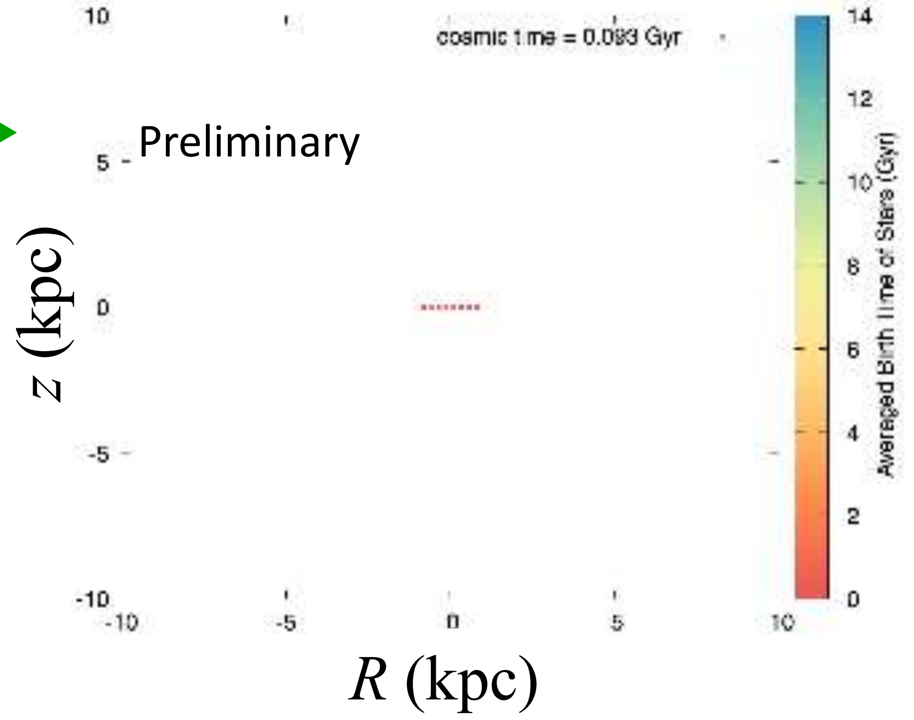
Current Simplifications

- The stars move ***only* in the radial direction.**
- The CRs are treated as ***fluid*.**

Vertical motion
→ Galactic Archeology

CR energy spectra
→ γ-ray & ν spectra





We suggest "γ-ray & Neutrino Astronomy" vs. "The Galactic Archaeology" as the Next-generation Multi-messenger Astronomy for studying Galactic Evolution!