

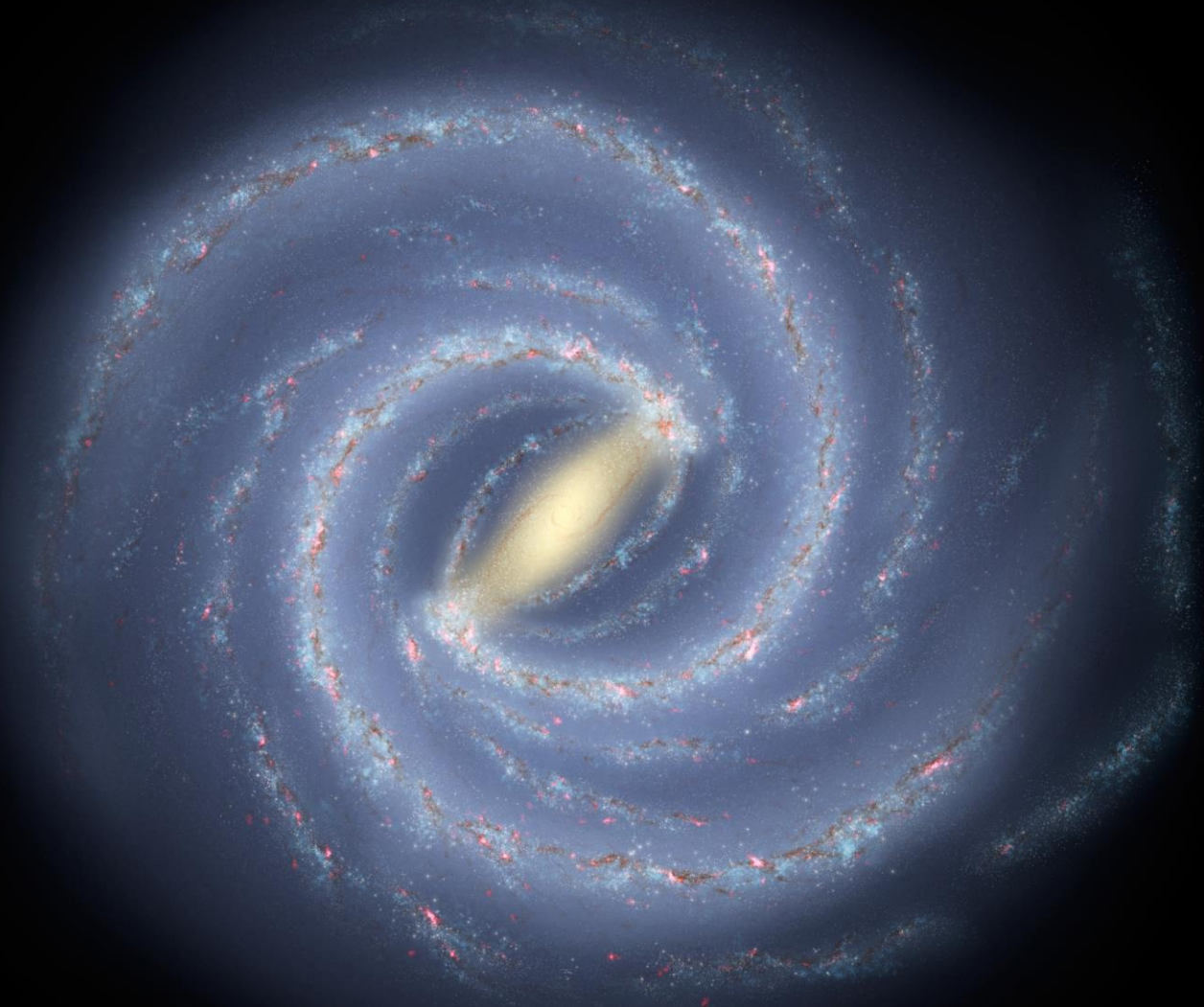
# Living in the Bubble

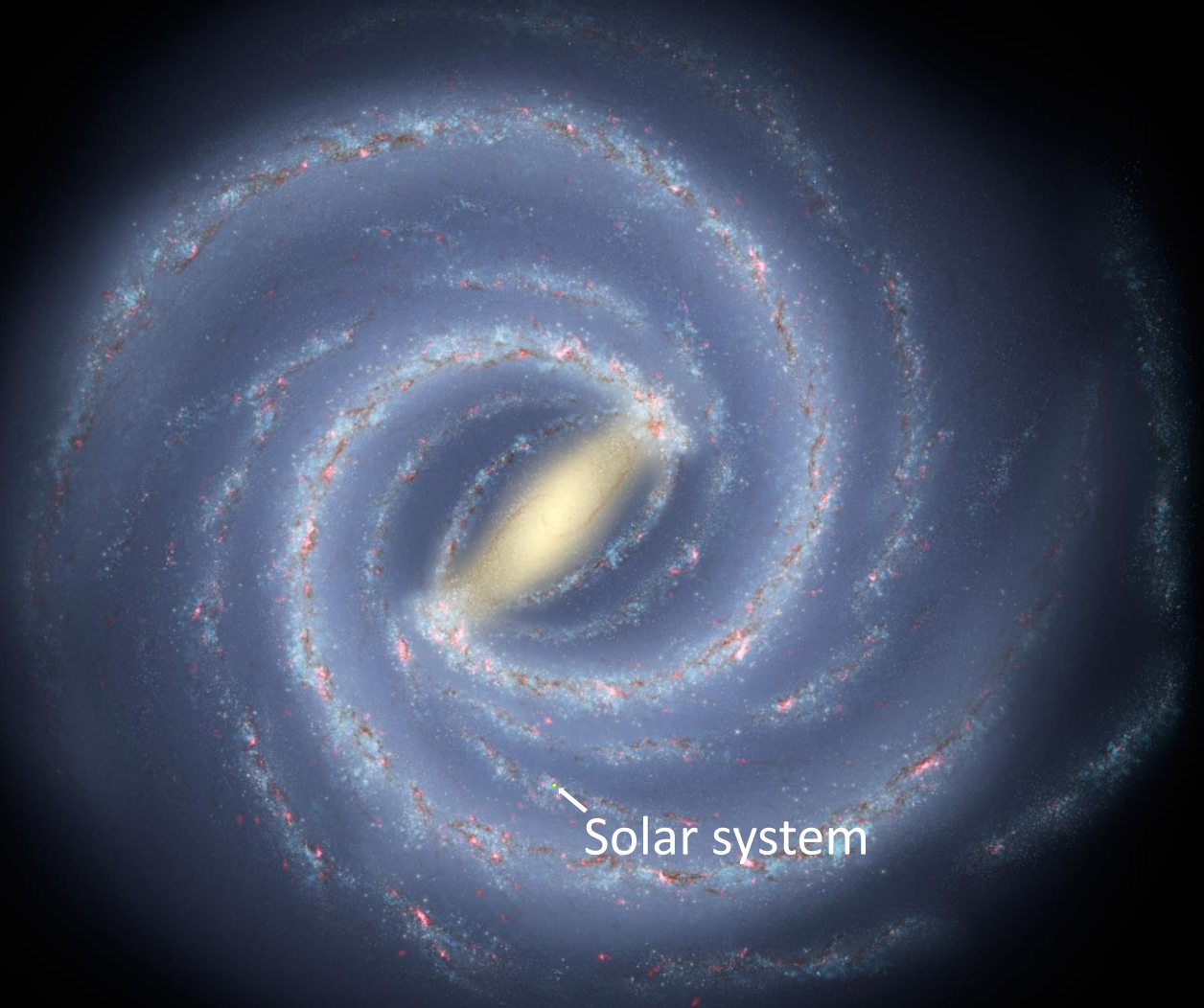
Structure, formation, and how it affects us

Efrem Maconi - Universität Wien

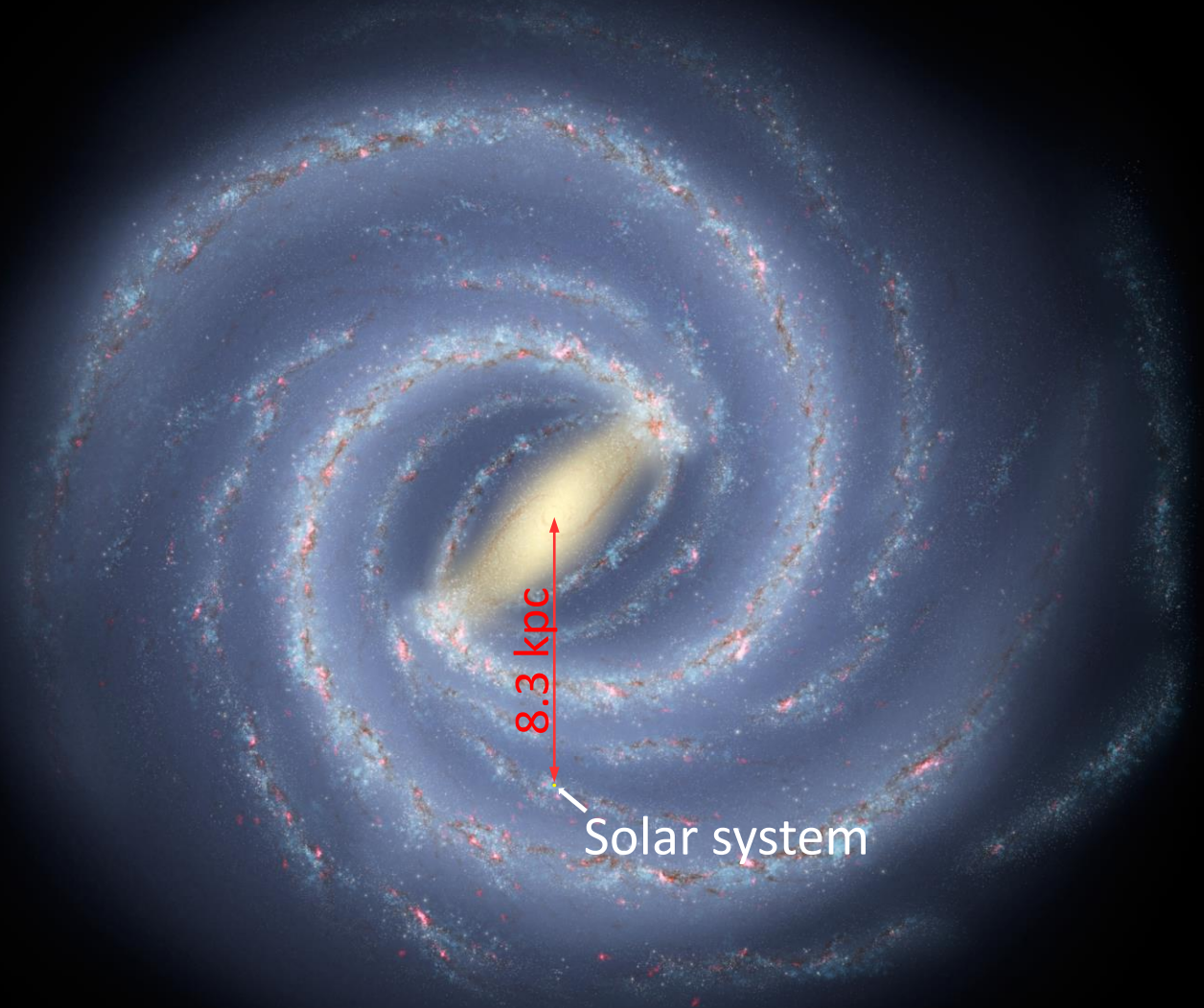
*In collaboration with:*

João Alves, Philipp Girichidis, Alyssa Goodman, Ralf Klessen, Federico Nati, Theo O'Neill, Stefan Reissl, Juan D. Soler, Catherine Zucker



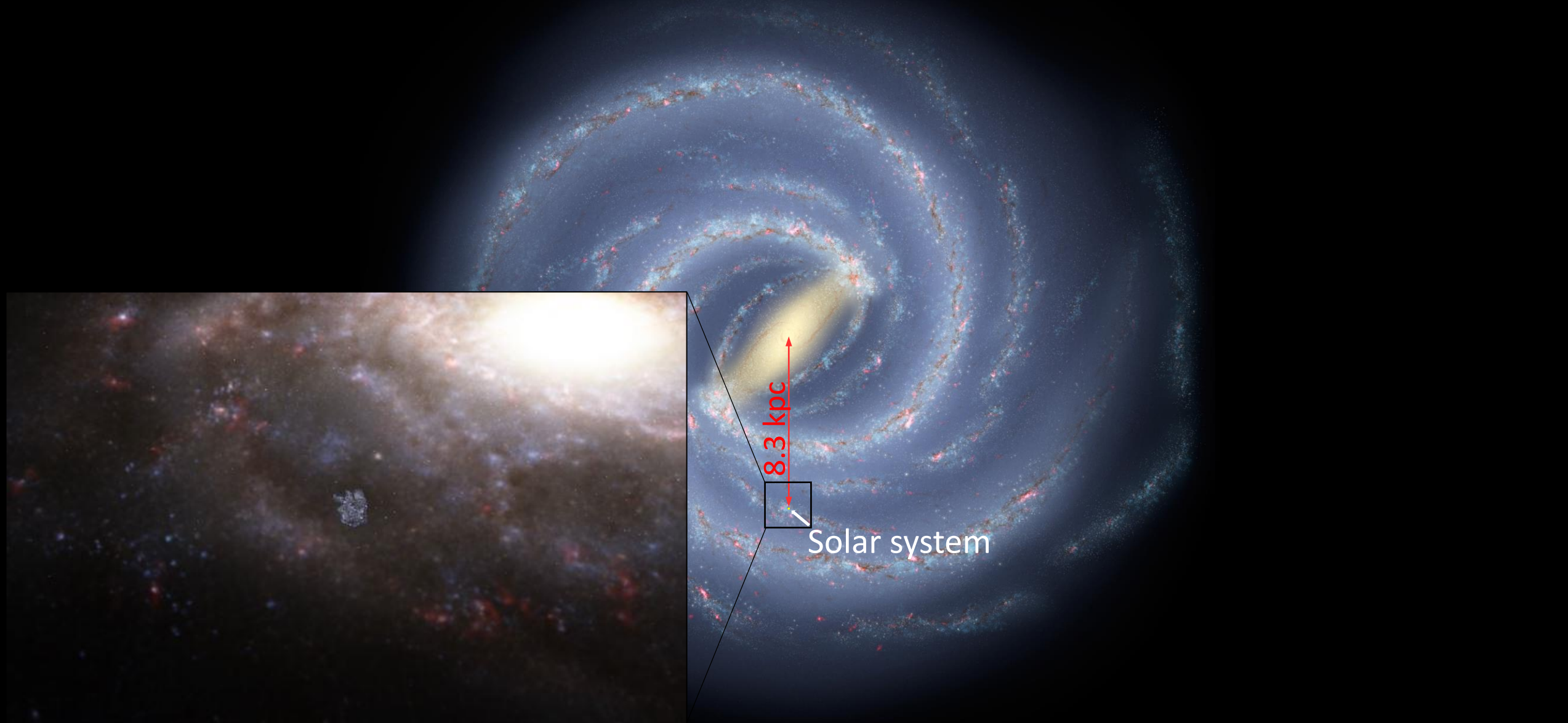


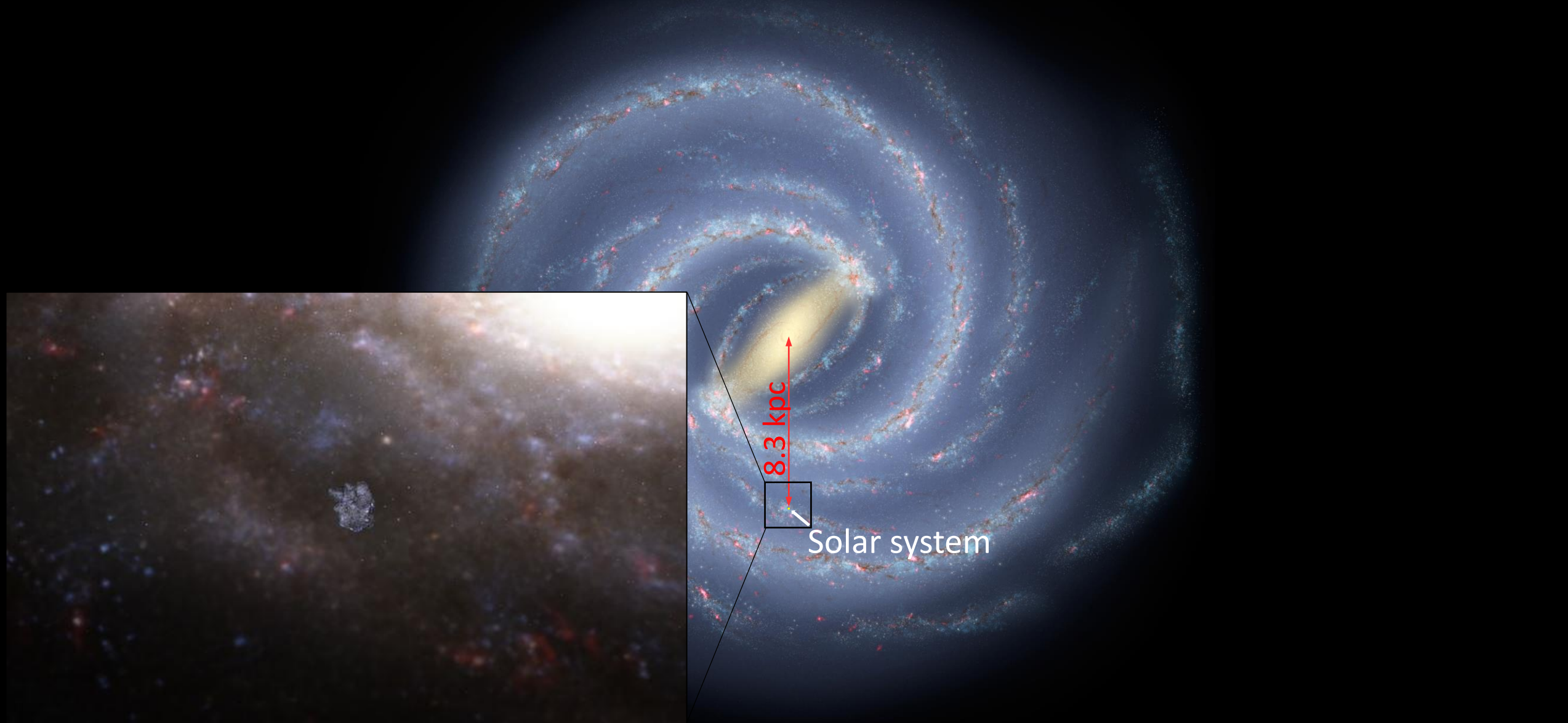
Solar system

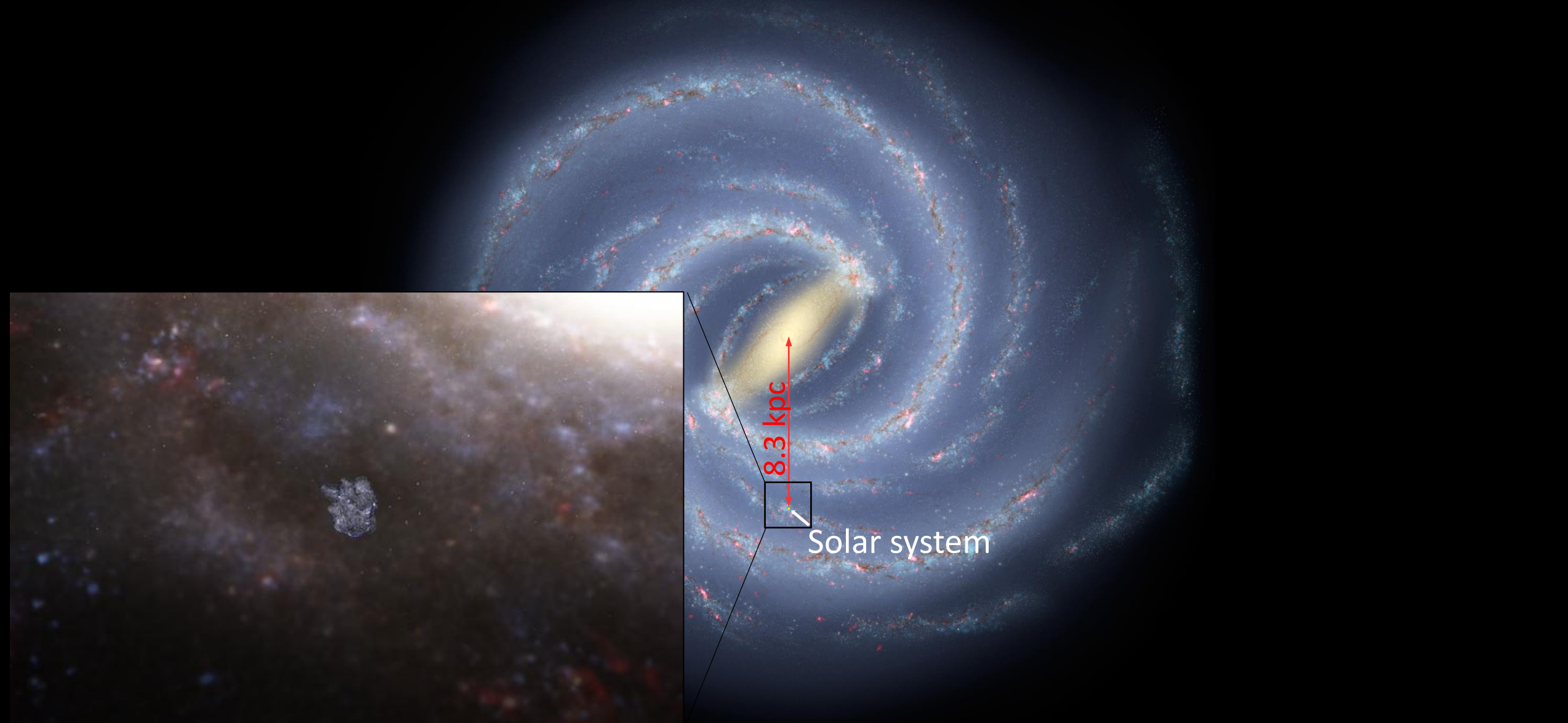


8.3 kpc

Solar system

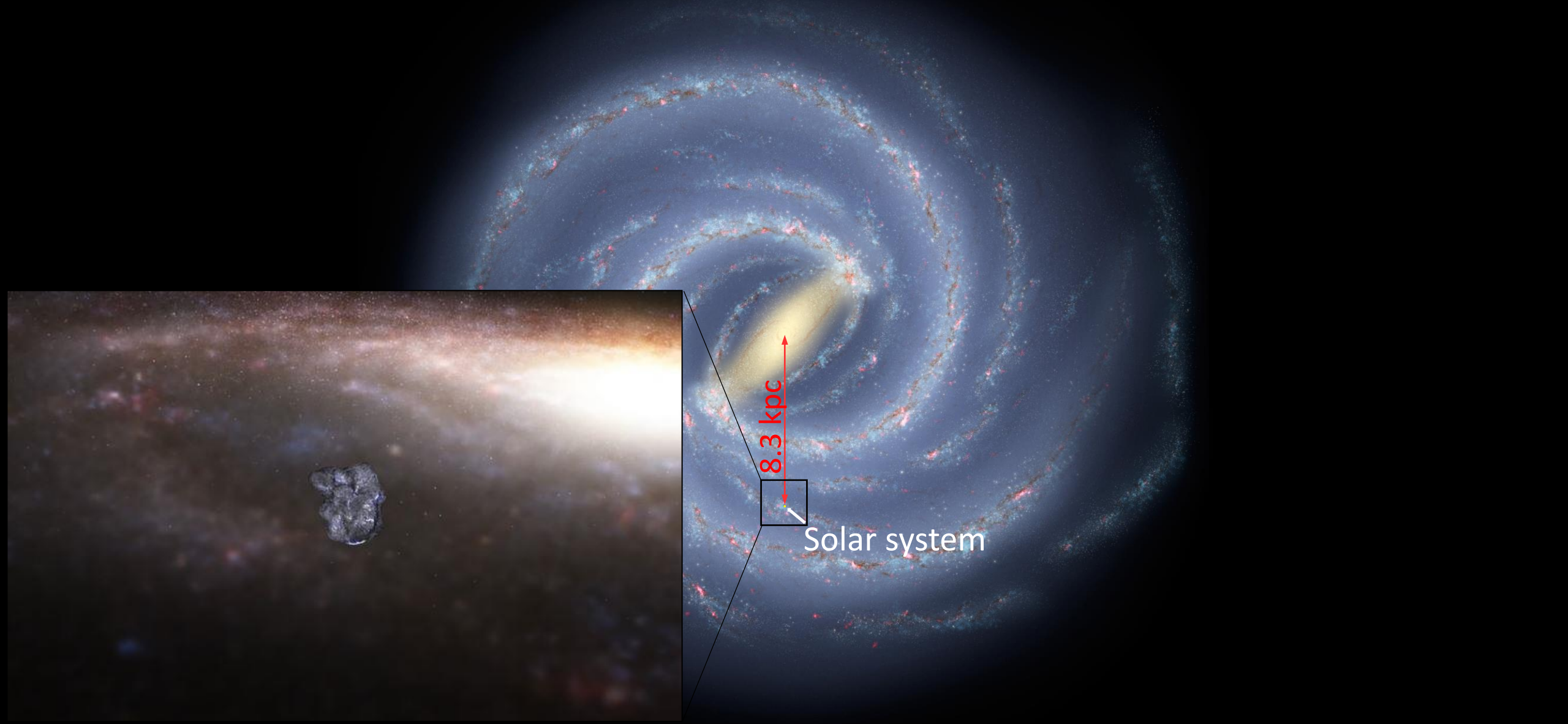


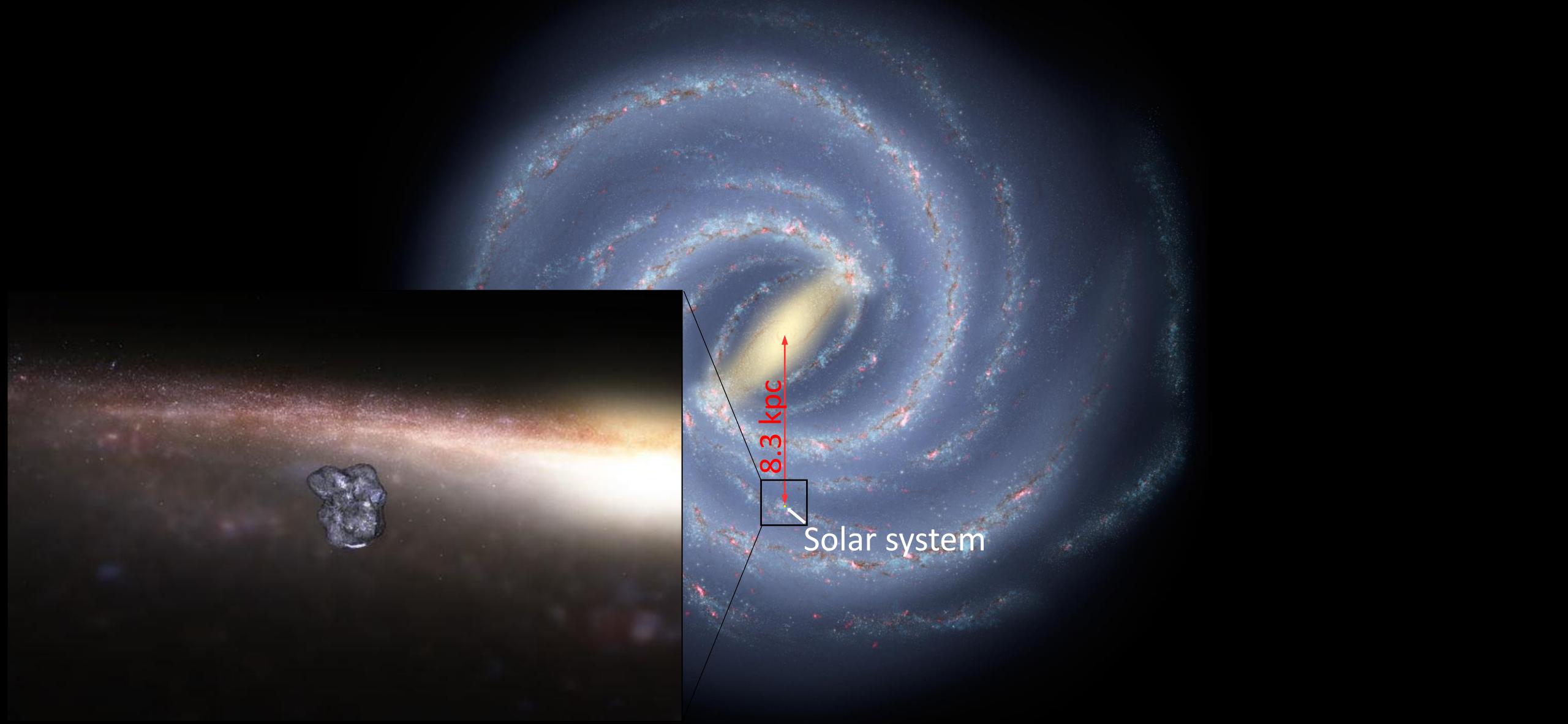






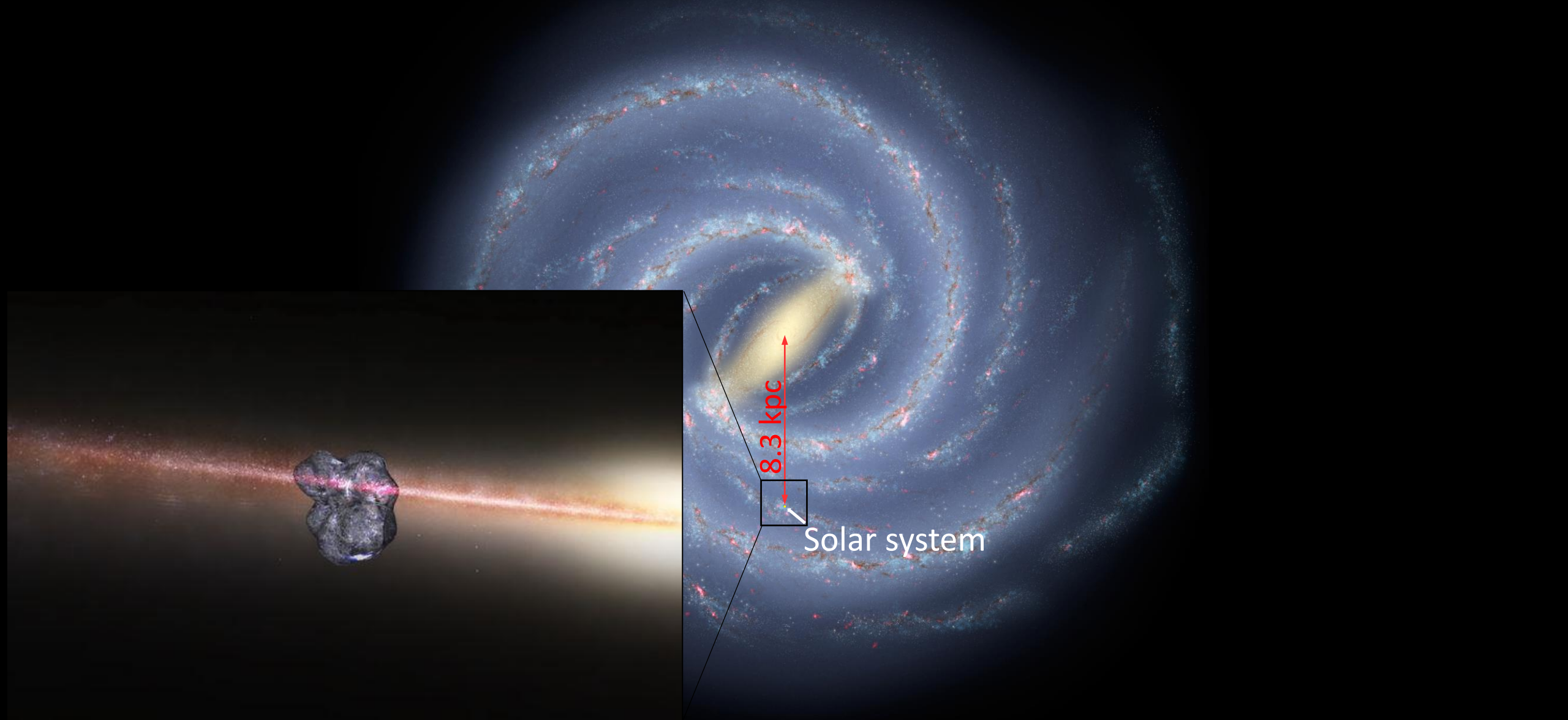


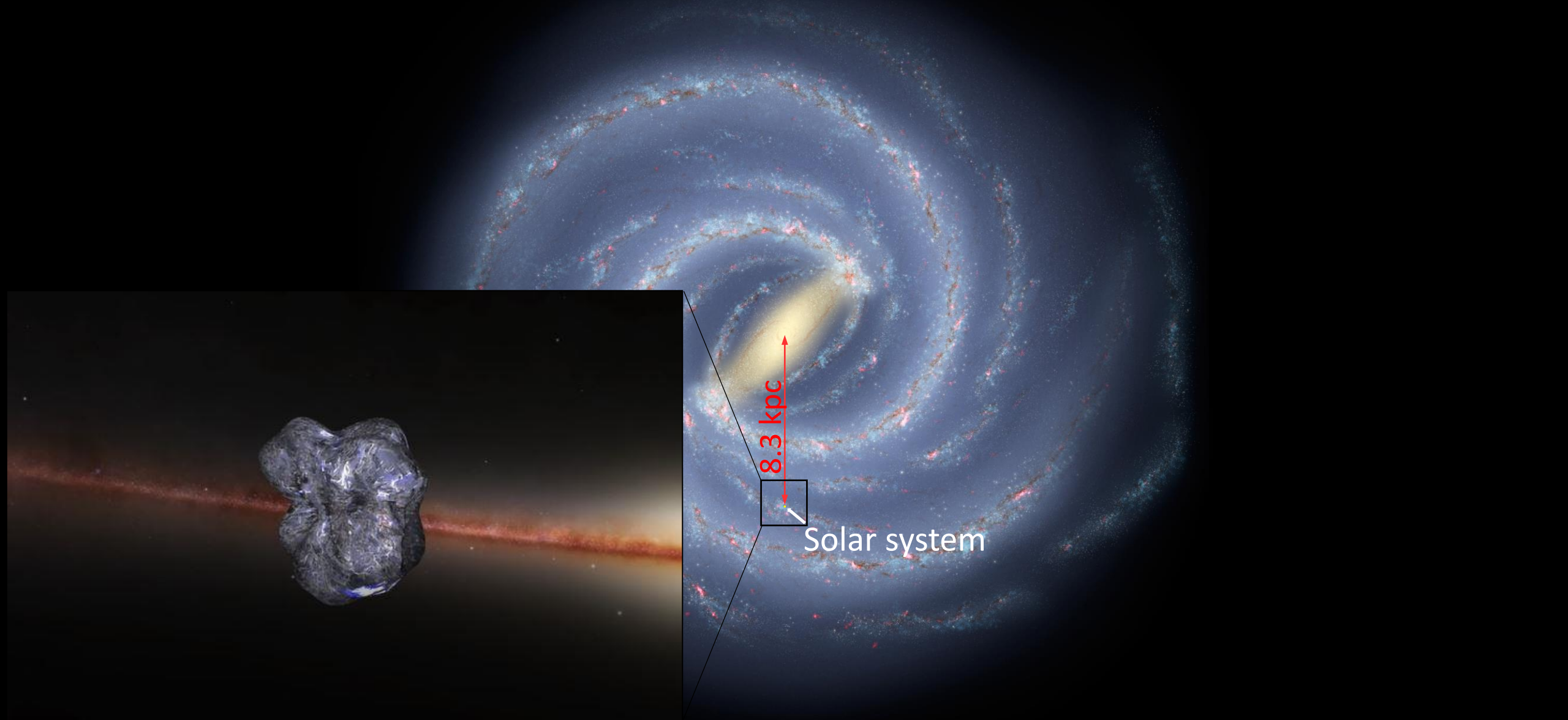


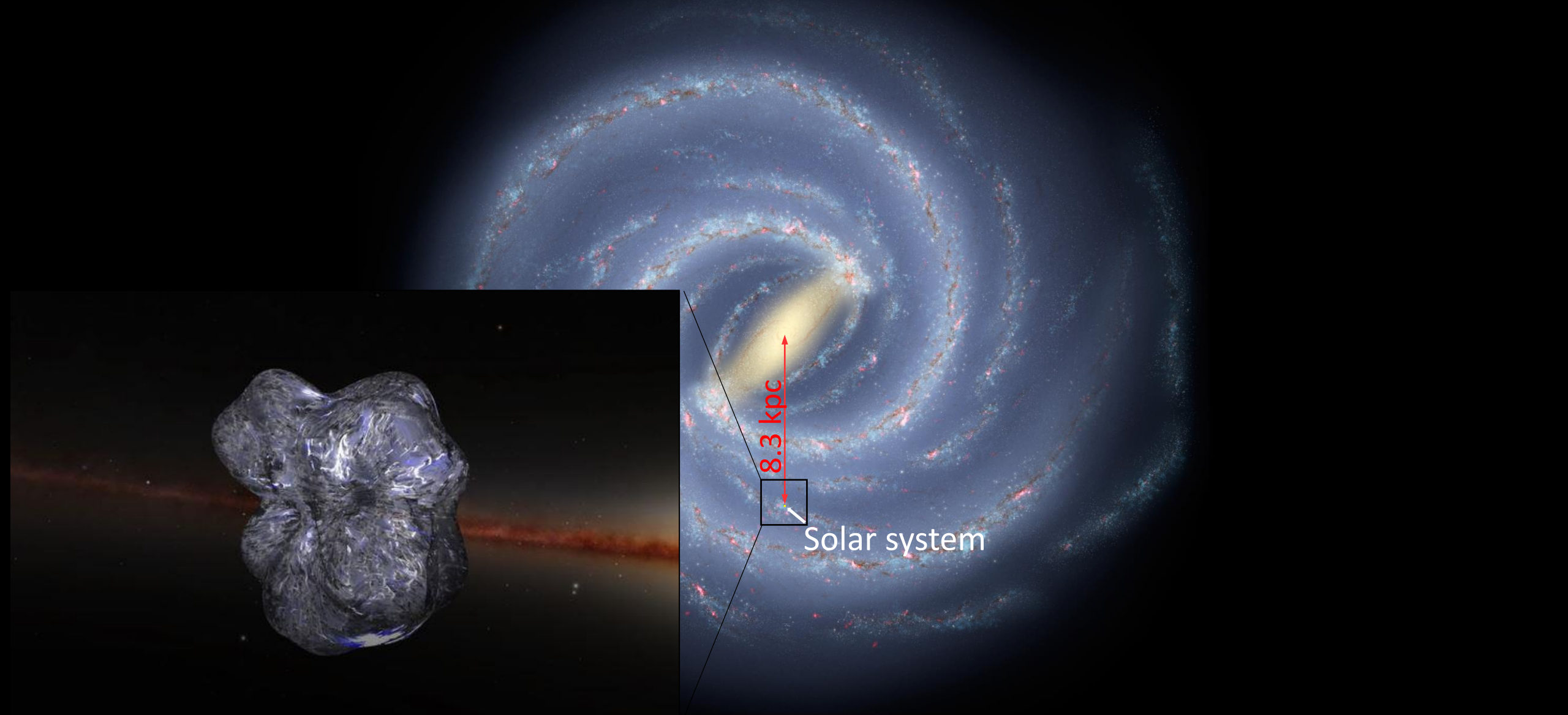


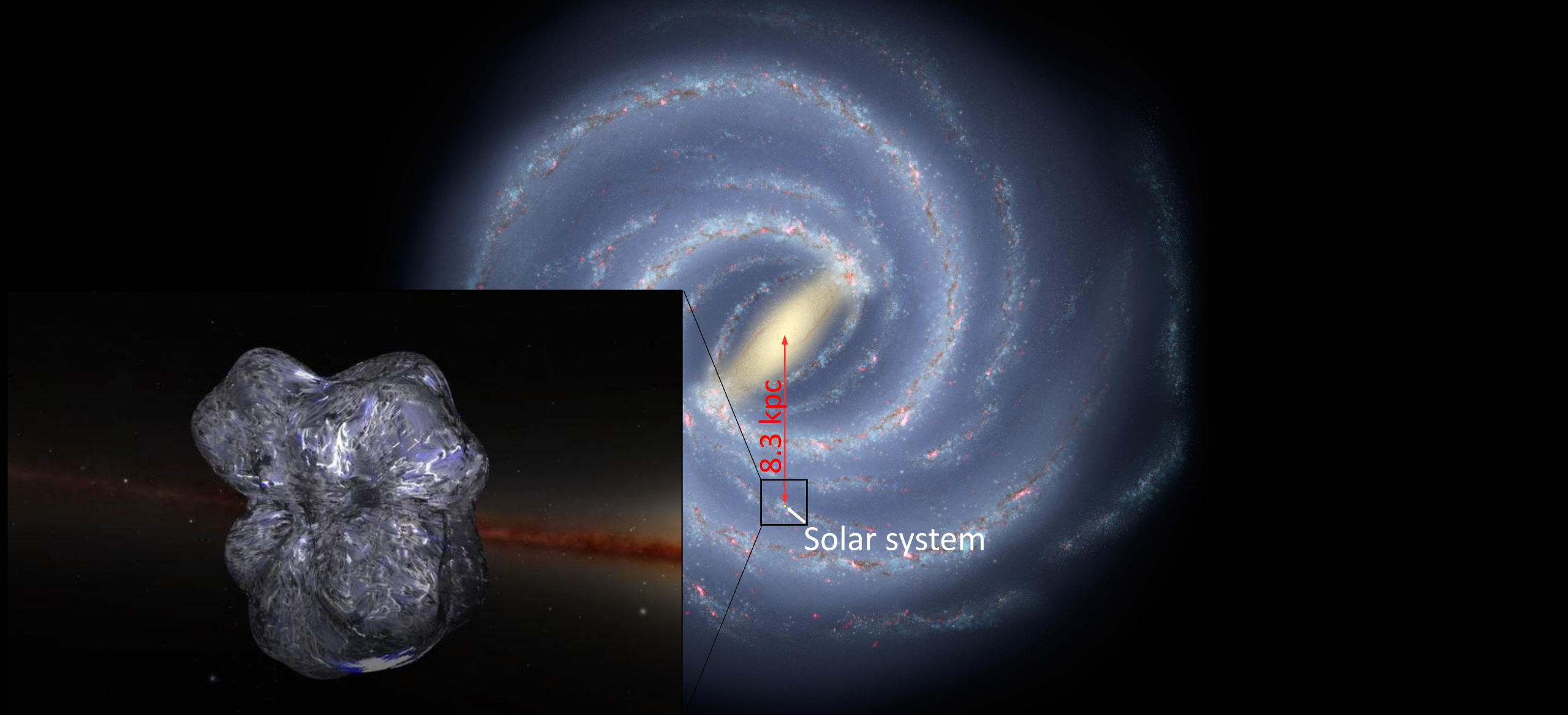
8.3 kpc

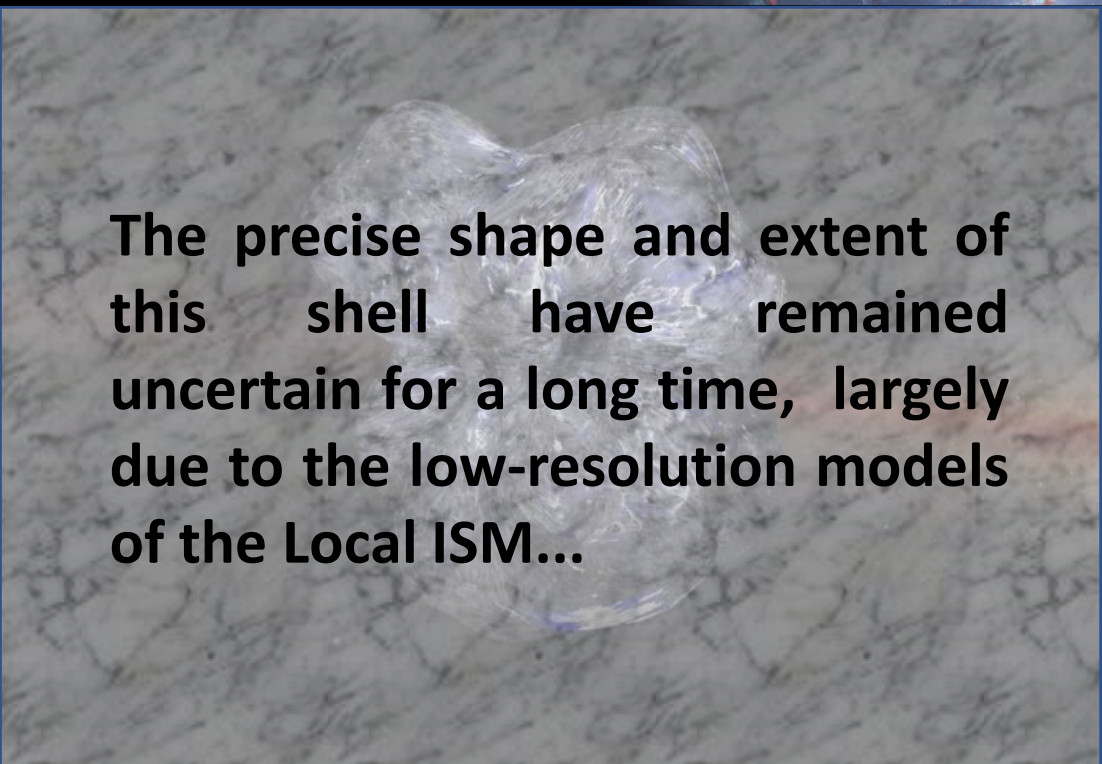
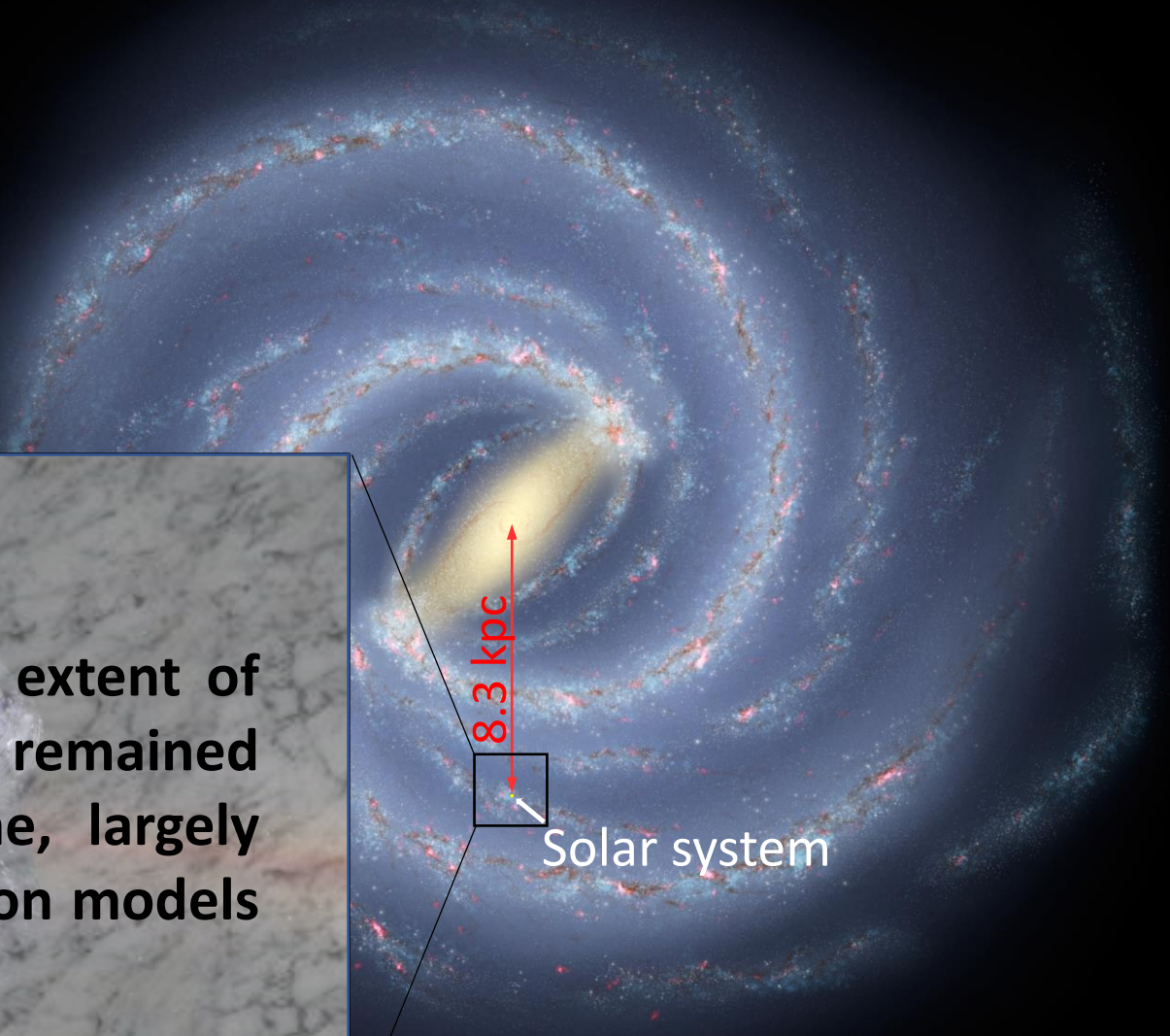
Solar system







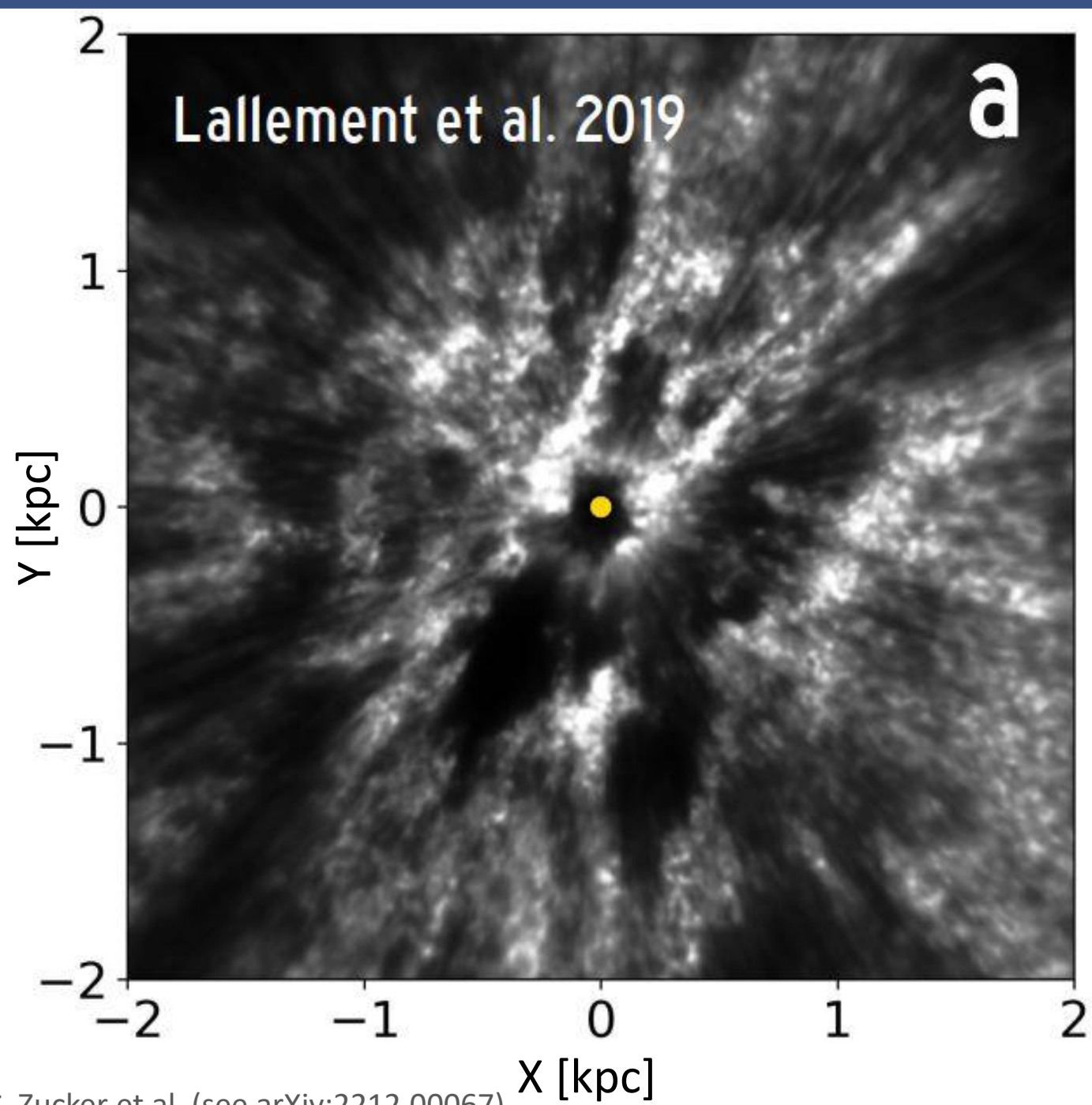


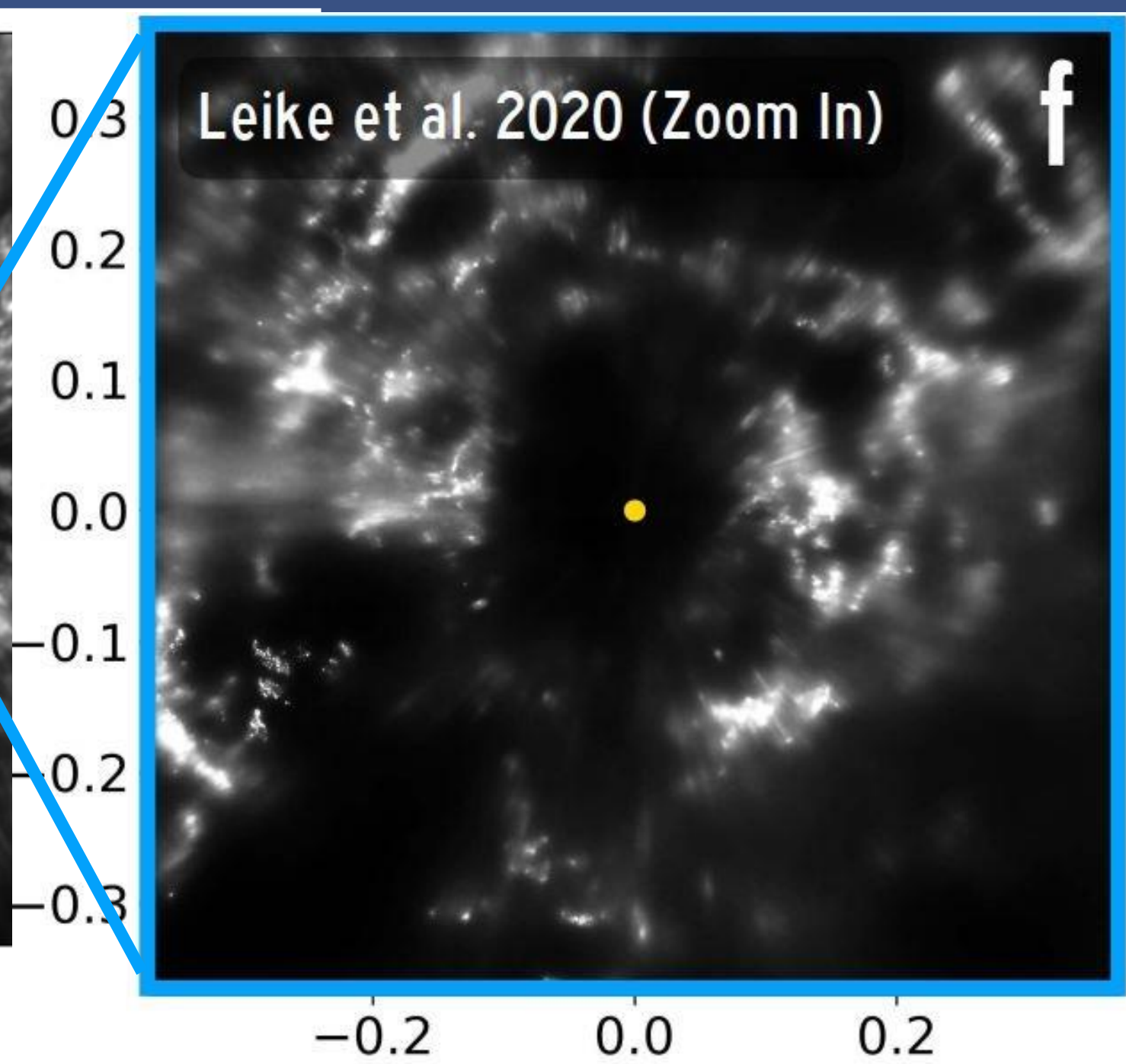
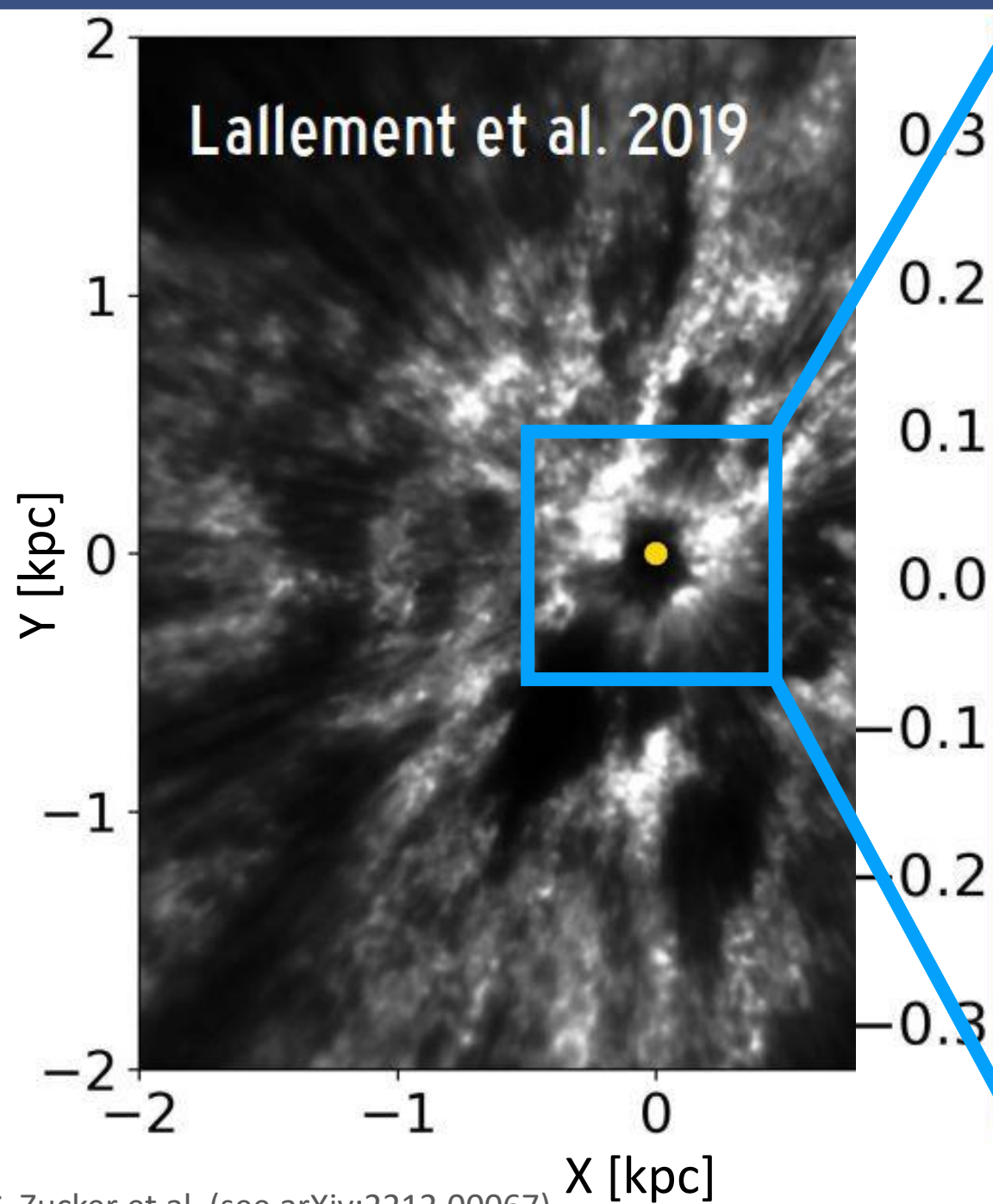


The precise shape and extent of this shell have remained uncertain for a long time, largely due to the low-resolution models of the Local ISM...

# The Solar Neighborhood in the Age of Gaia



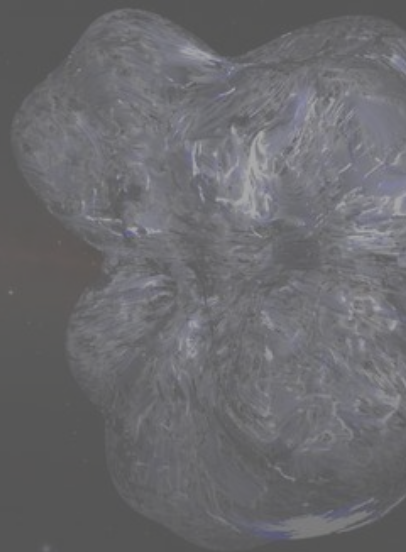




When did this story begin?

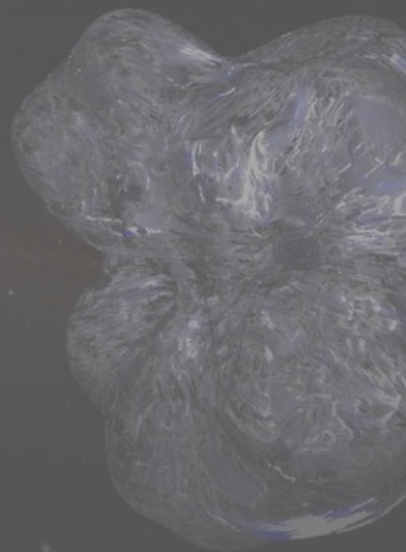
## Papers about the Local Bubble

- W. T. Sanders, et al. (1977)
- P. B. Lucke (1978)
- D.P. Cox. & R. J. Reynolds (1987)
- ...
- C. Zucker, et al. (2022)
- E. Maconi, et al. (Submitted)
- T. O'Neill et al. (2023; in preparation)



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# The birth of the Local Bubble

16

MILLION YEARS AGO

The **UCL** and **LCC** clusters in the  
**Sco-Cen OB Association**  
start to shine

16

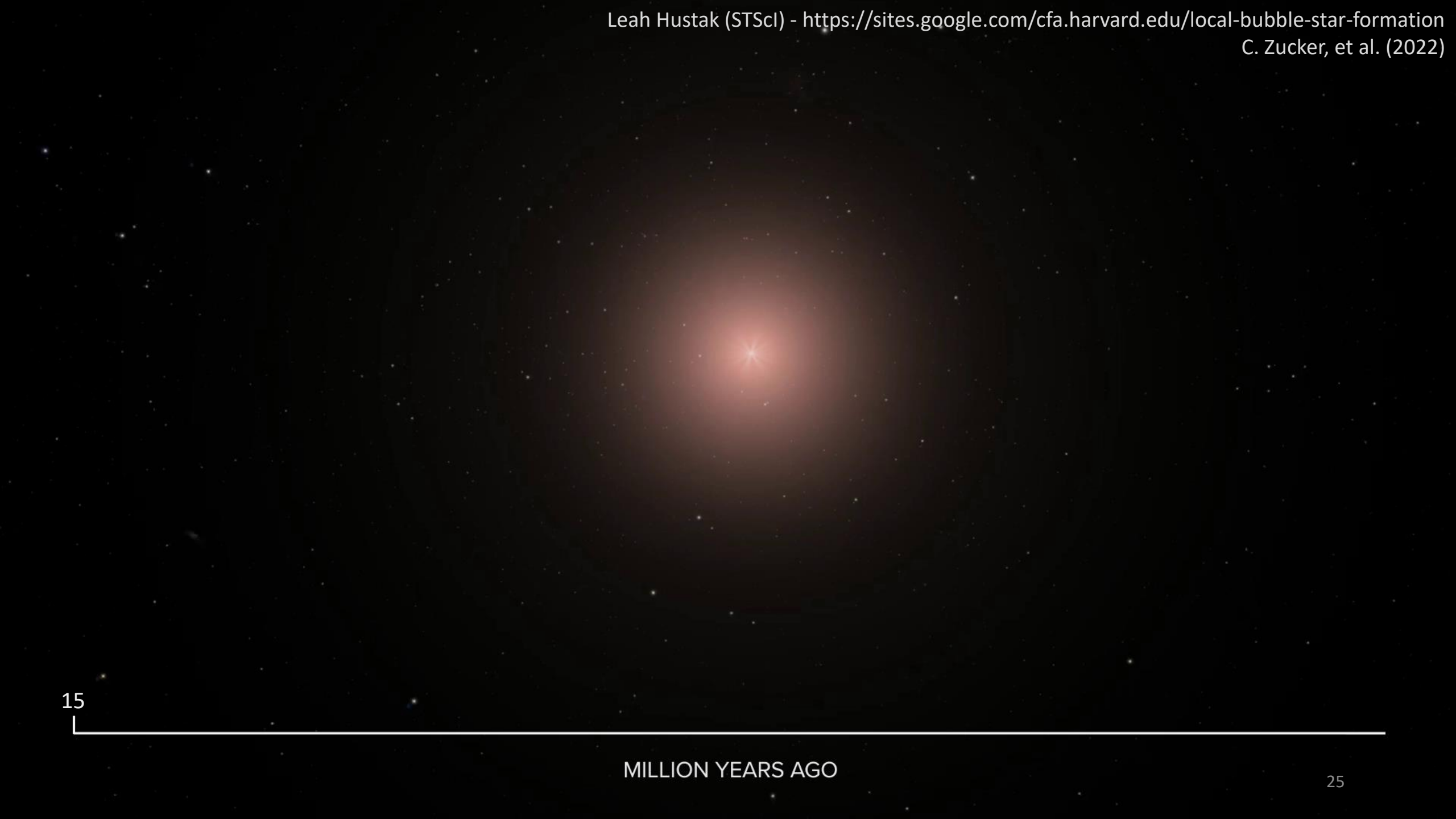
MILLION YEARS AGO



15

MILLION YEARS AGO

25



14

MILLION YEARS AGO



14

MILLION YEARS AGO





14

MILLION YEARS AGO

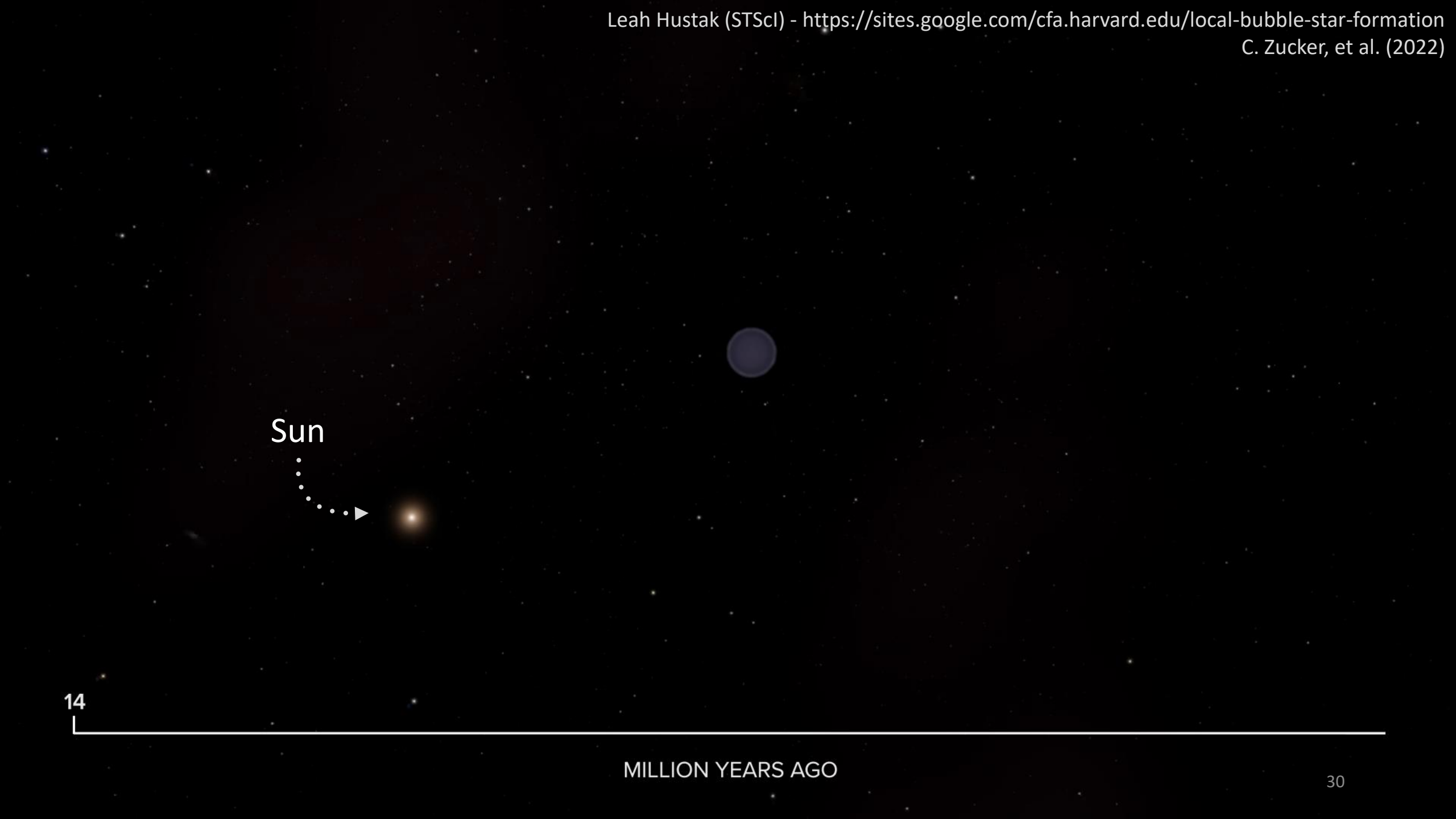
Sun



14

MILLION YEARS AGO

30







14

13

12

MILLION YEARS AGO





14 13 12 11

MILLION YEARS AGO



MILLION YEARS AGO



MILLION YEARS AGO



MILLION YEARS AGO





MILLION YEARS AGO



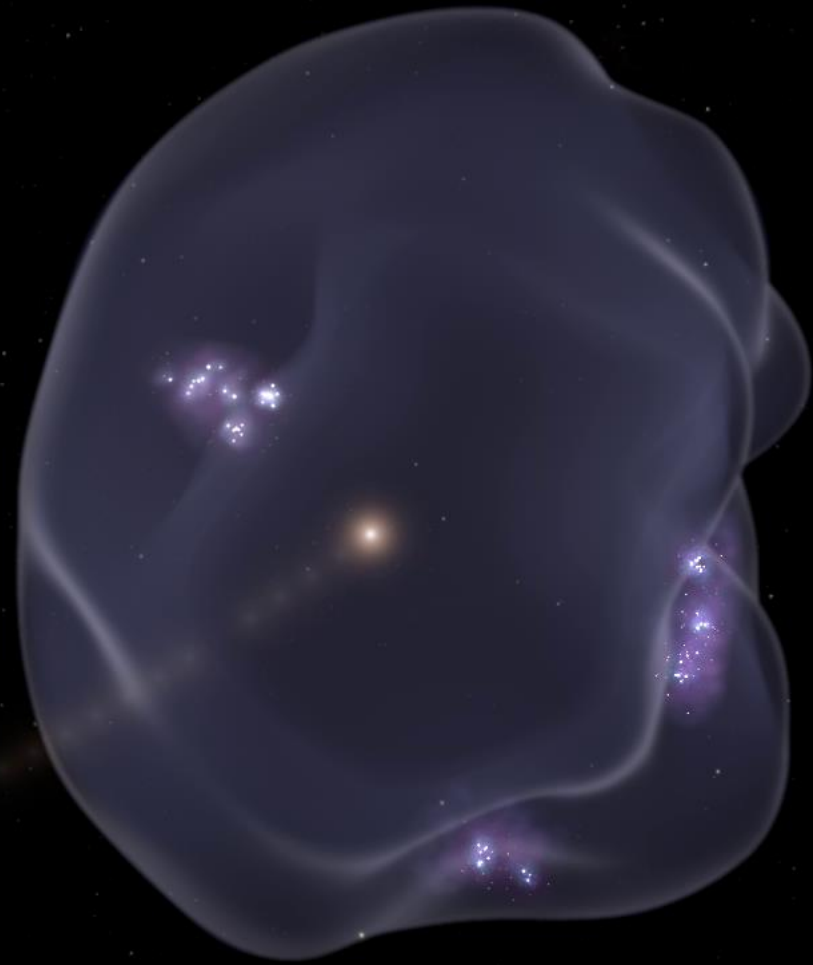
MILLION YEARS AGO



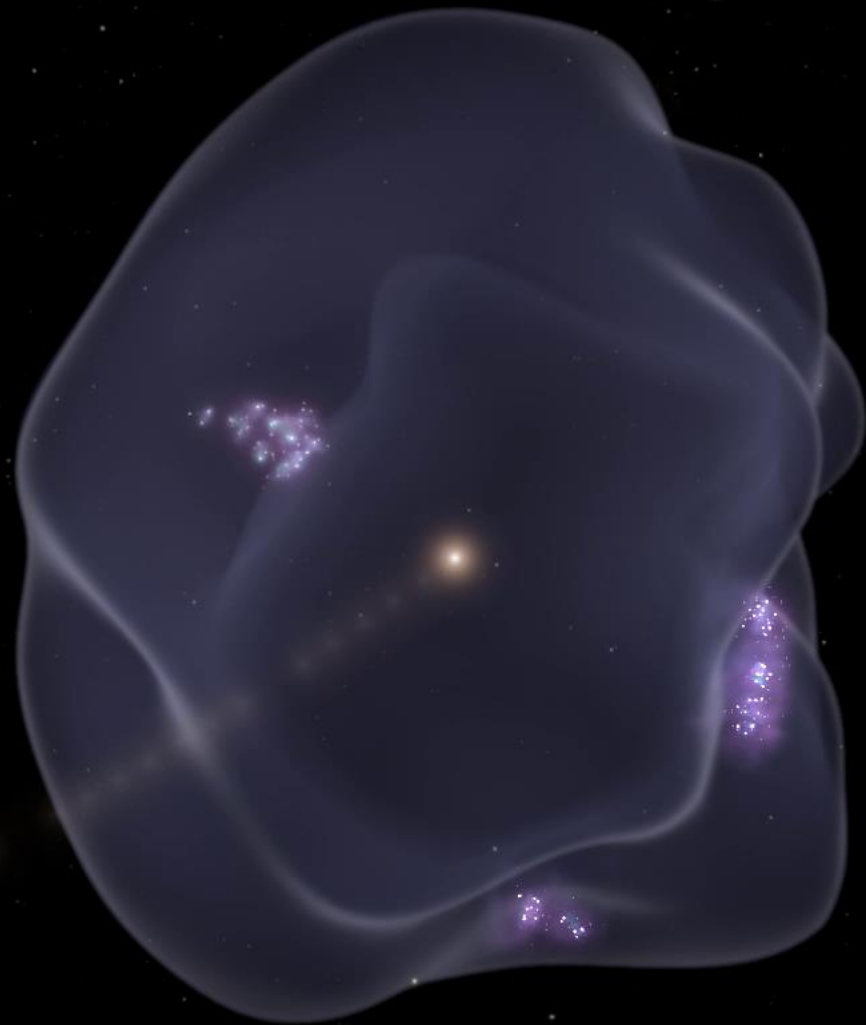
MILLION YEARS AGO







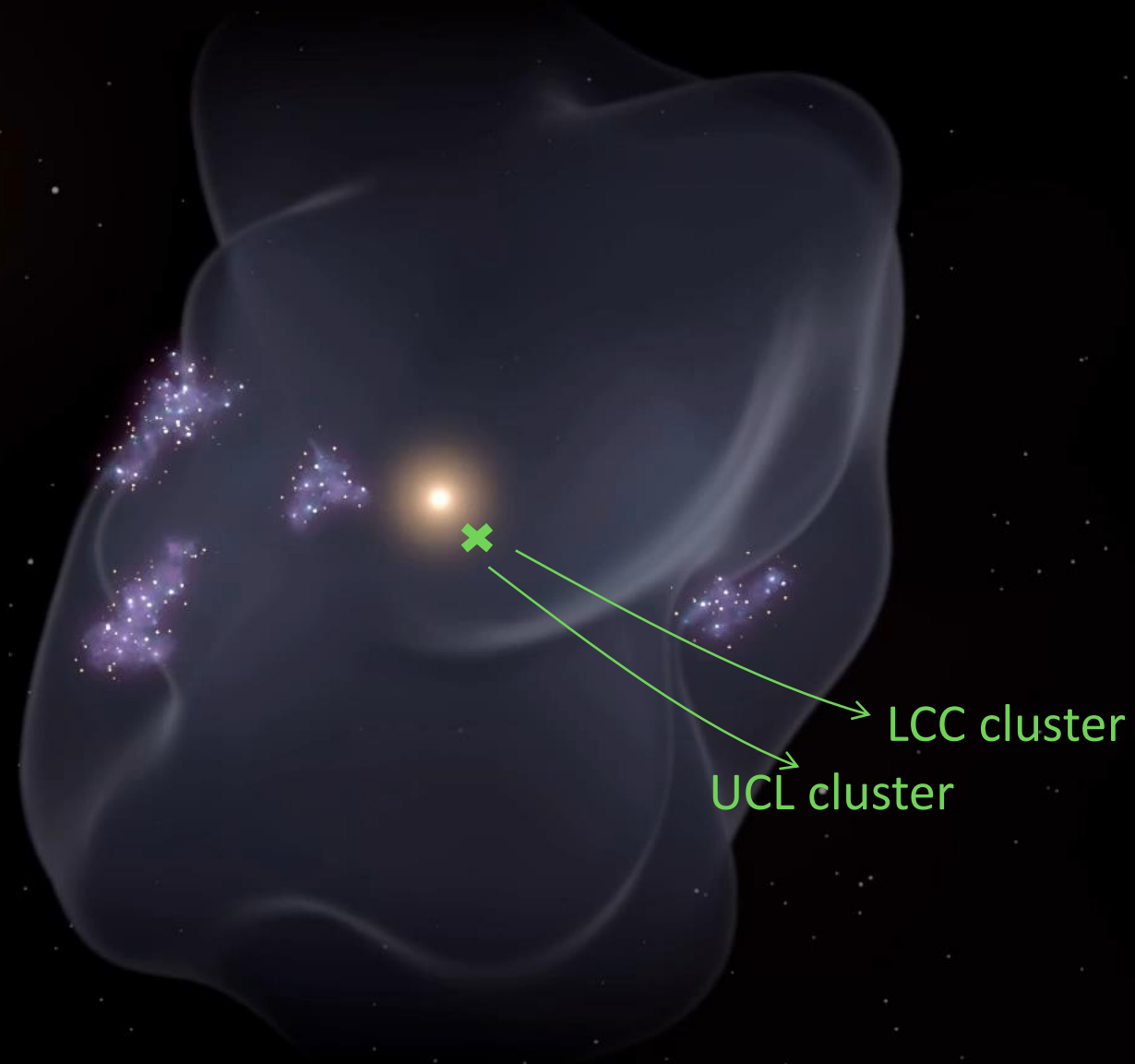
MILLION YEARS AGO



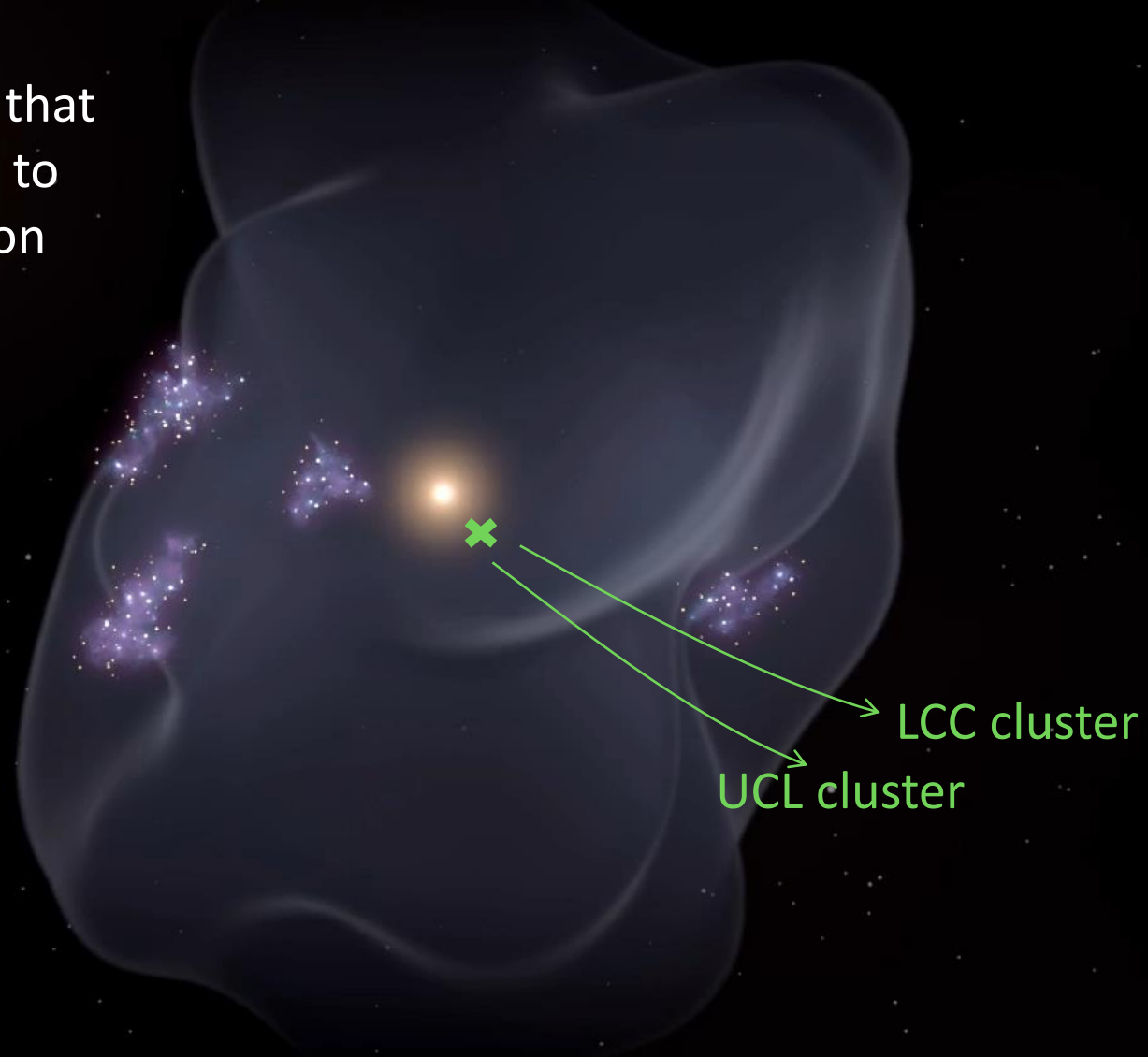
MILLION YEARS AGO



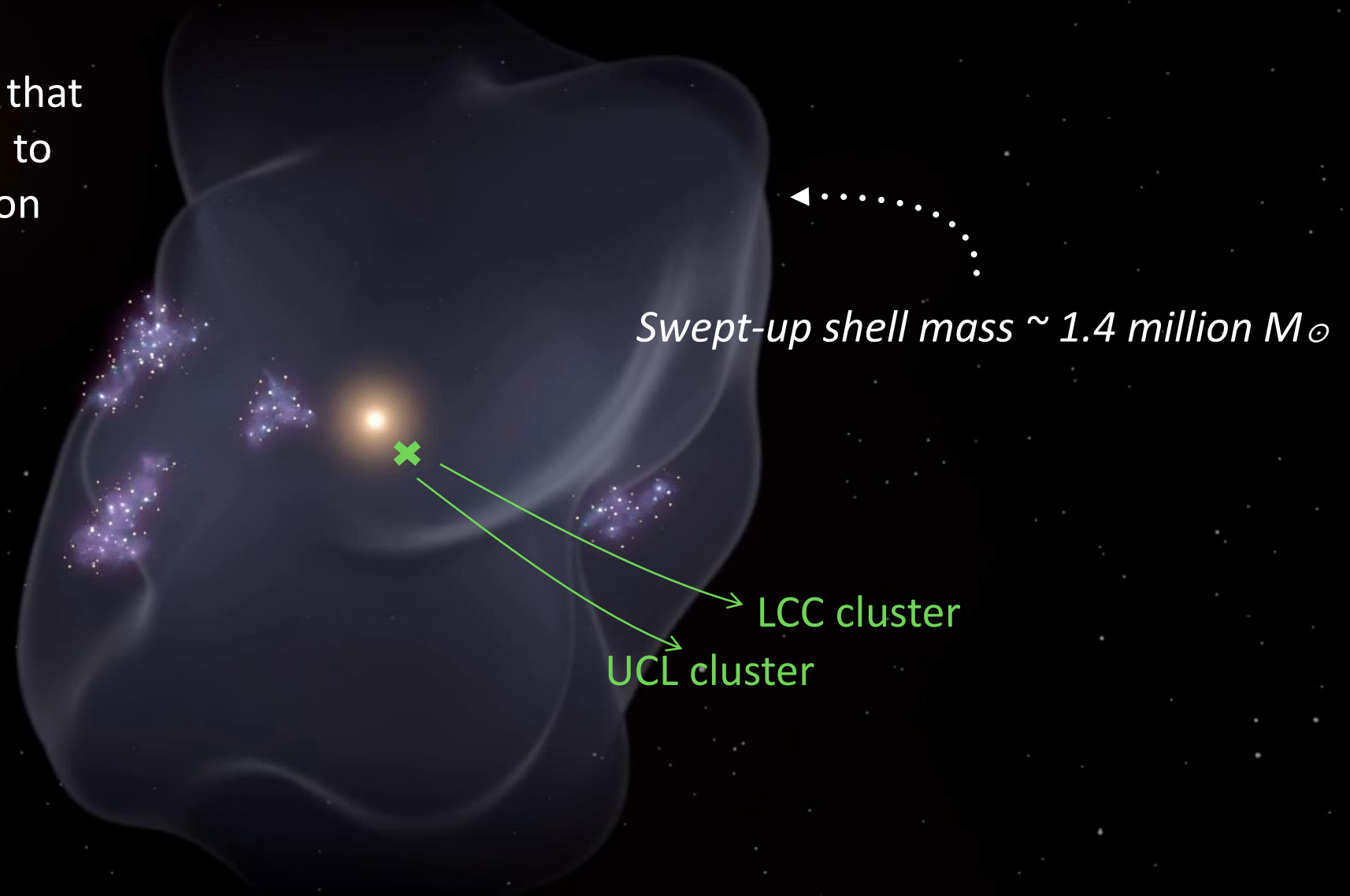




**Momentum** analysis indicates that  
15 supernovae were needed to  
power the bubble's expansion

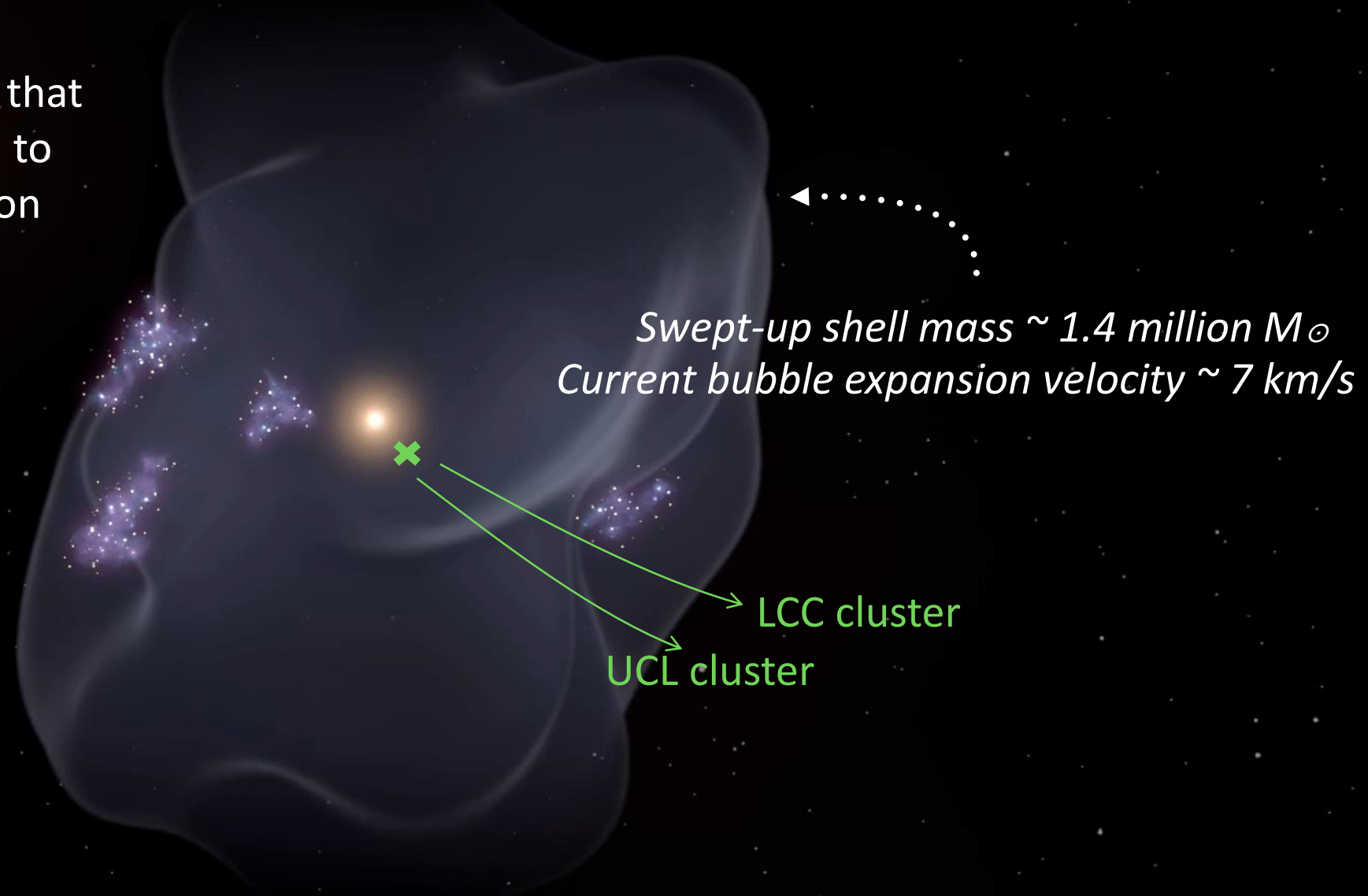


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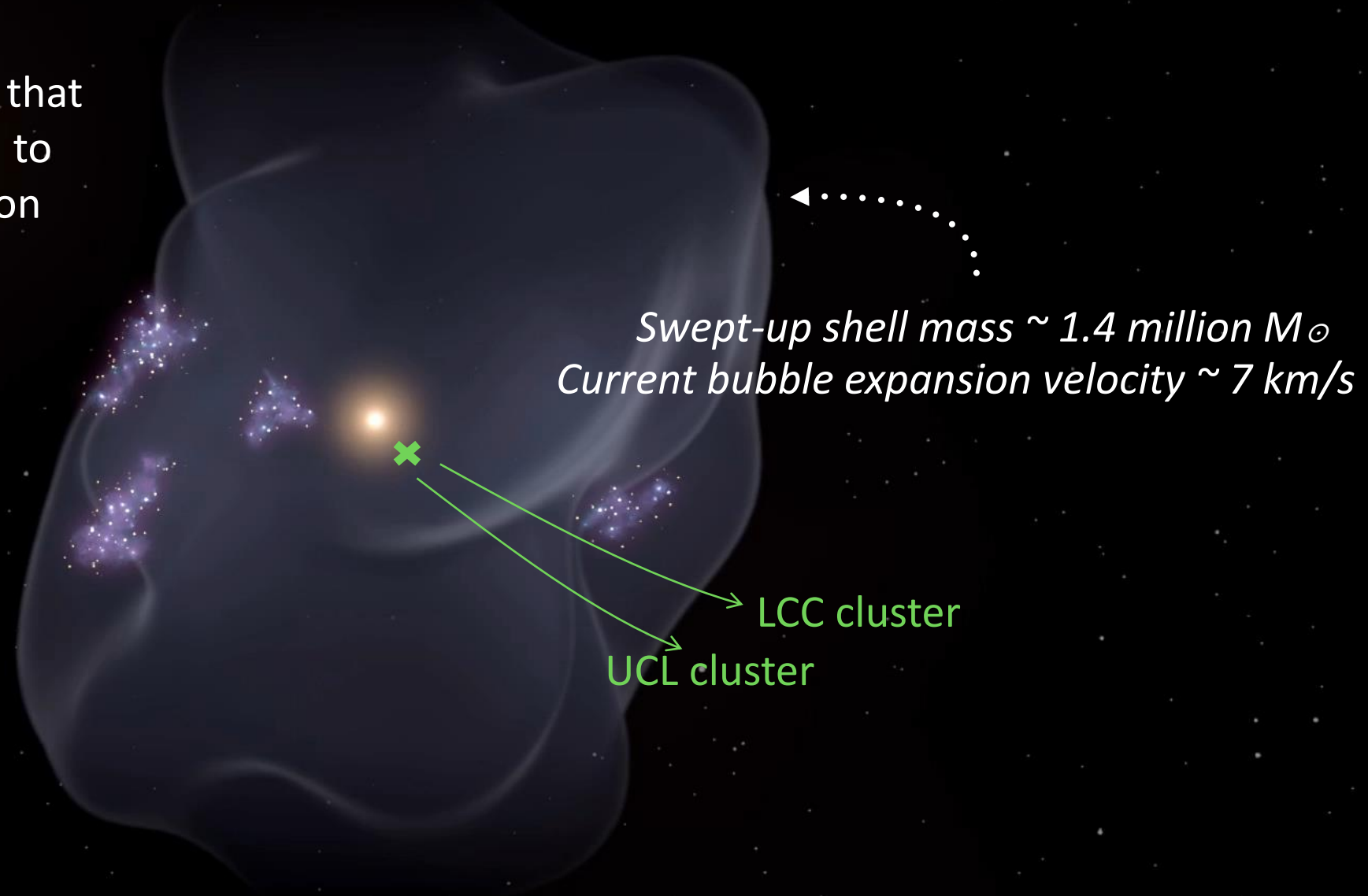




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15 supernovae were needed to  
power the bubble's expansion



*Swept-up shell mass  $\sim 1.4$  million  $M_{\odot}$   
Current bubble expansion velocity  $\sim 7$  km/s*

LCC cluster  
UCL cluster

Open or close bubble?

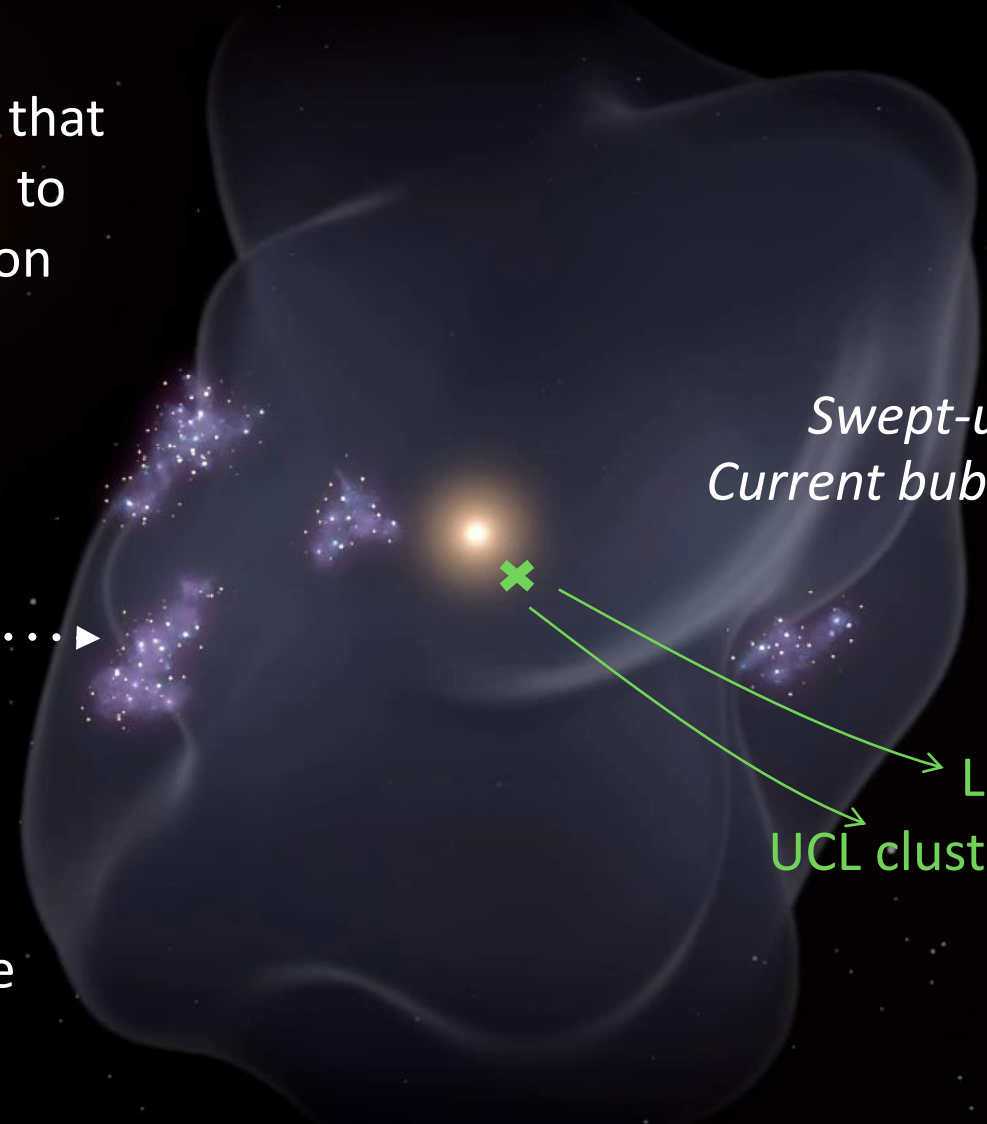
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*Swept-up shell mass  $\sim 1.4$  million  $M_{\odot}$   
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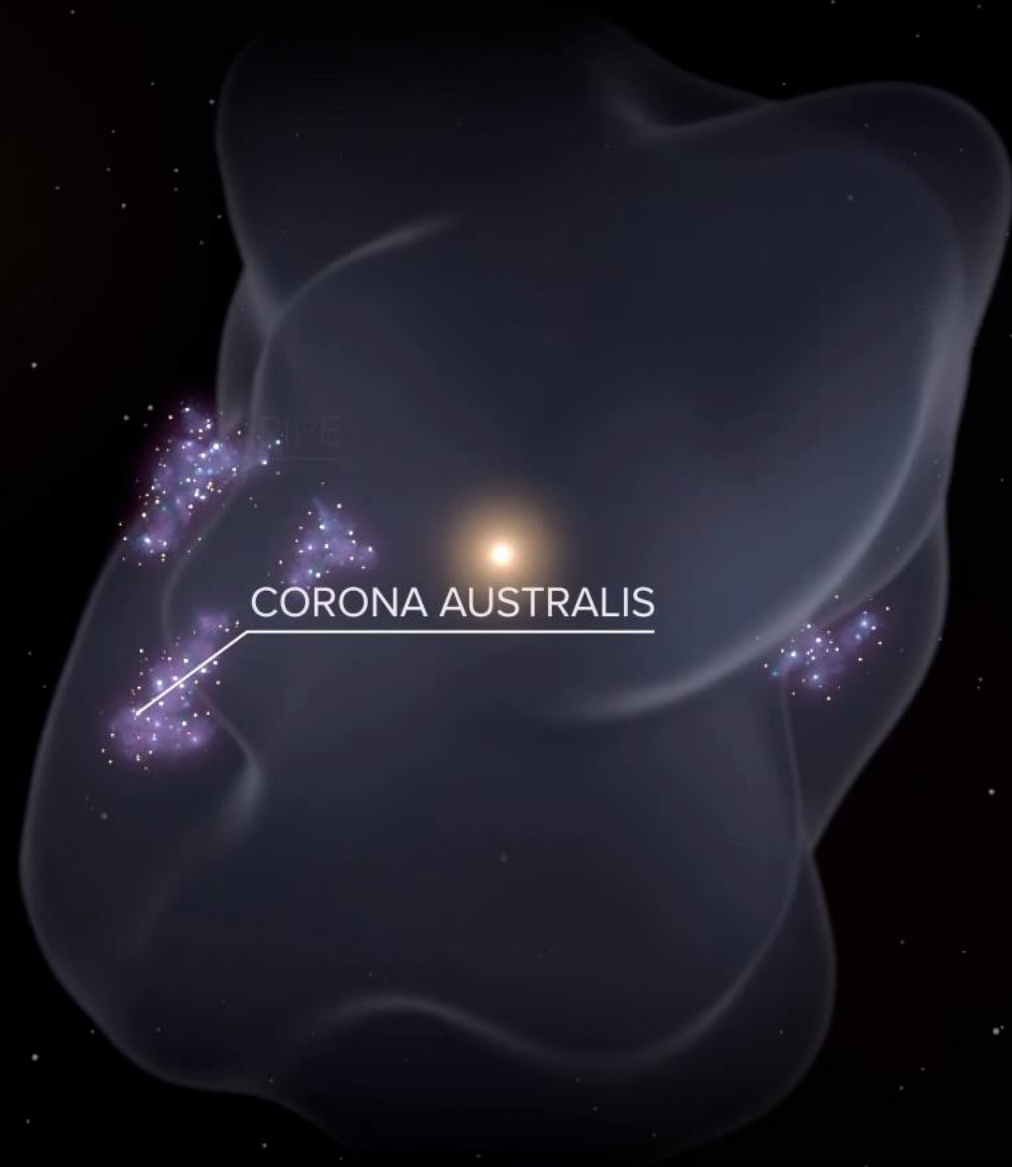
Star forming complexes in the  
solar vicinity lie on the LB surface

LCC cluster  
UCL cluster

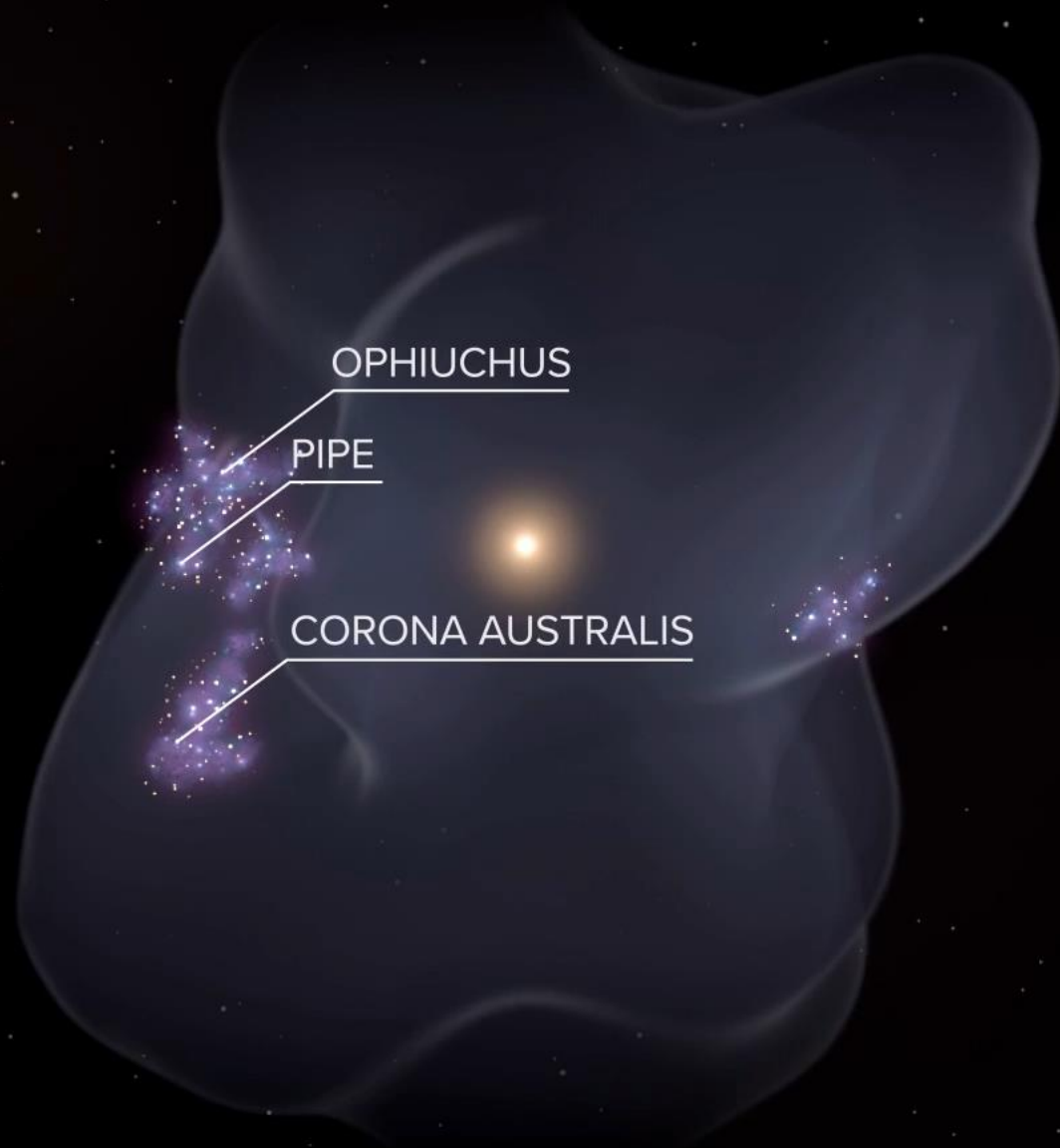
Open or close bubble?

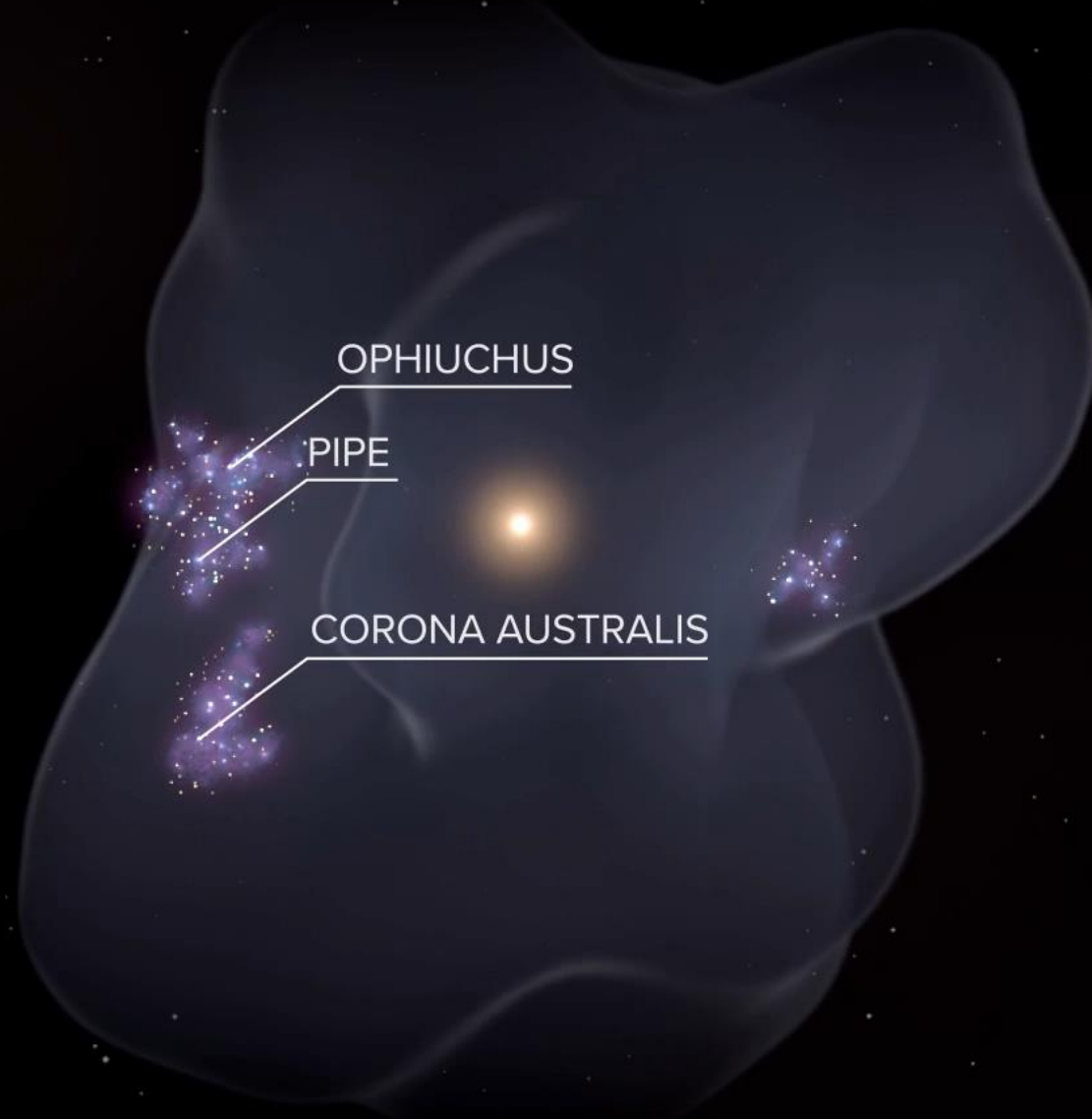


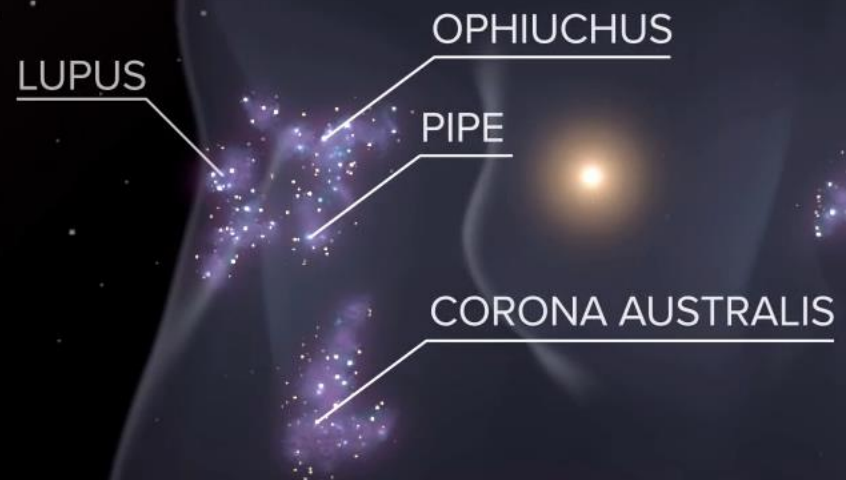




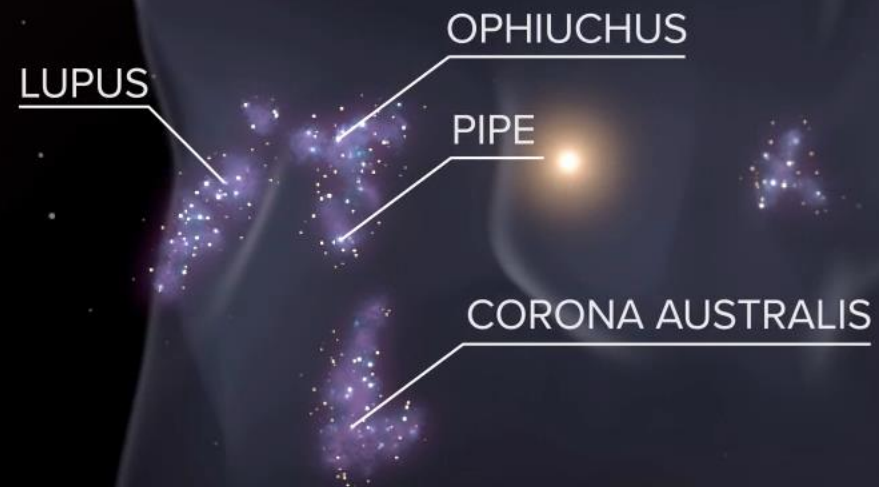
CORONA AUSTRALIS

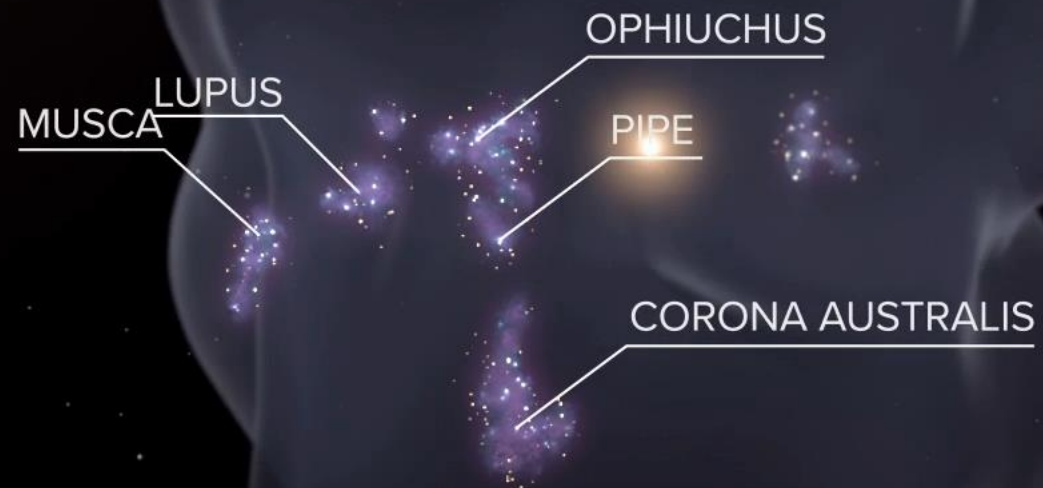


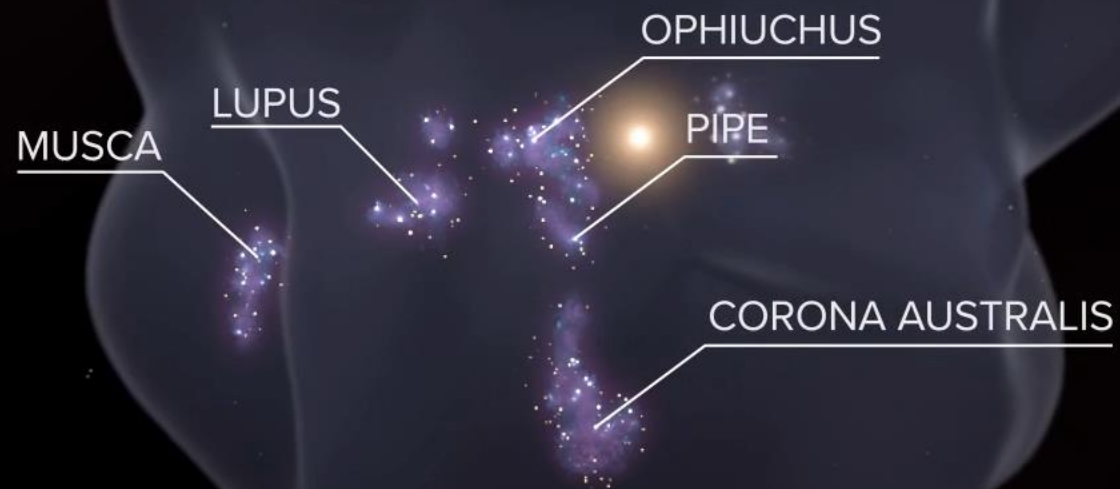


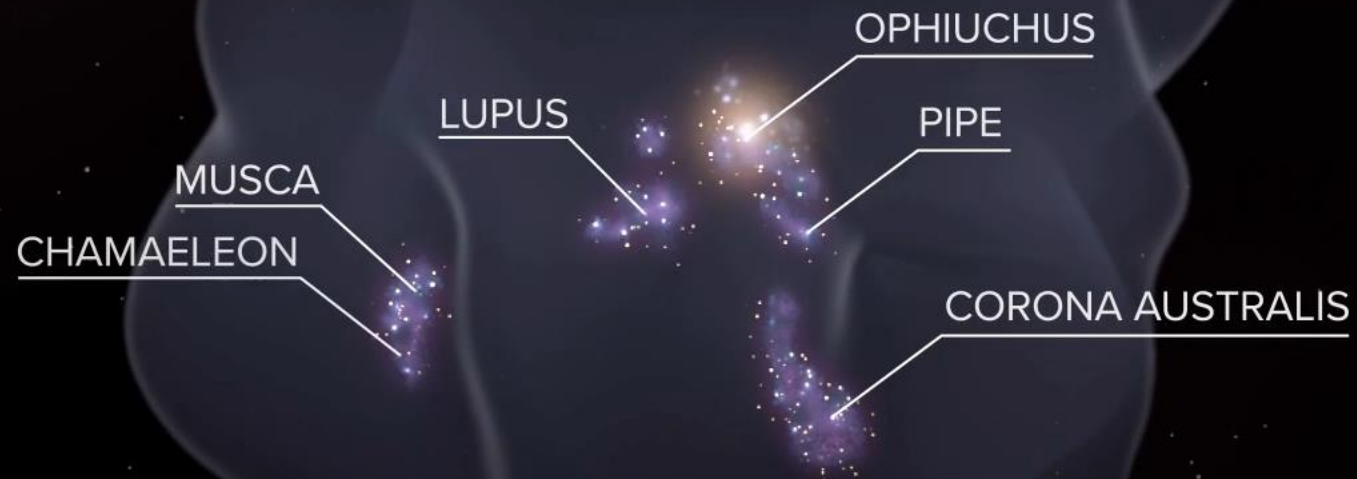








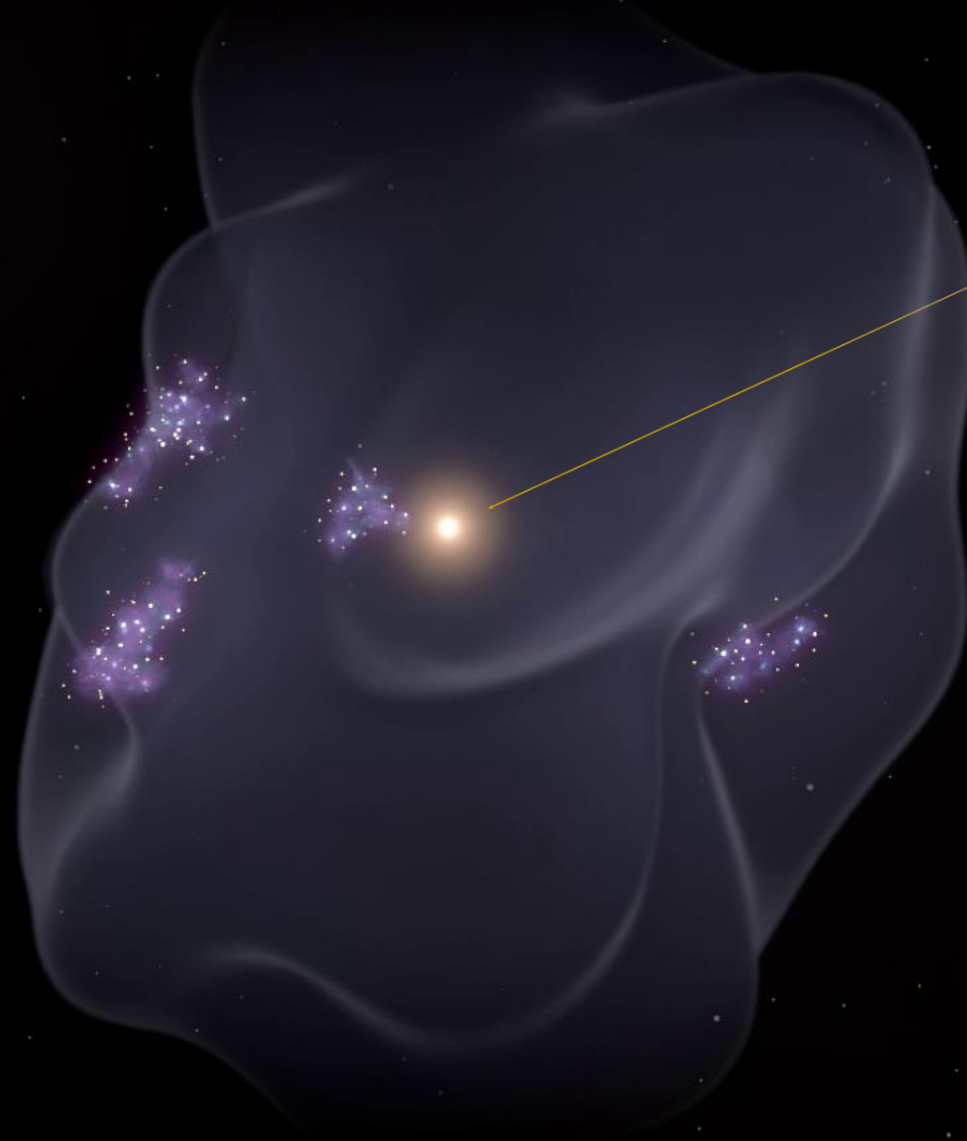




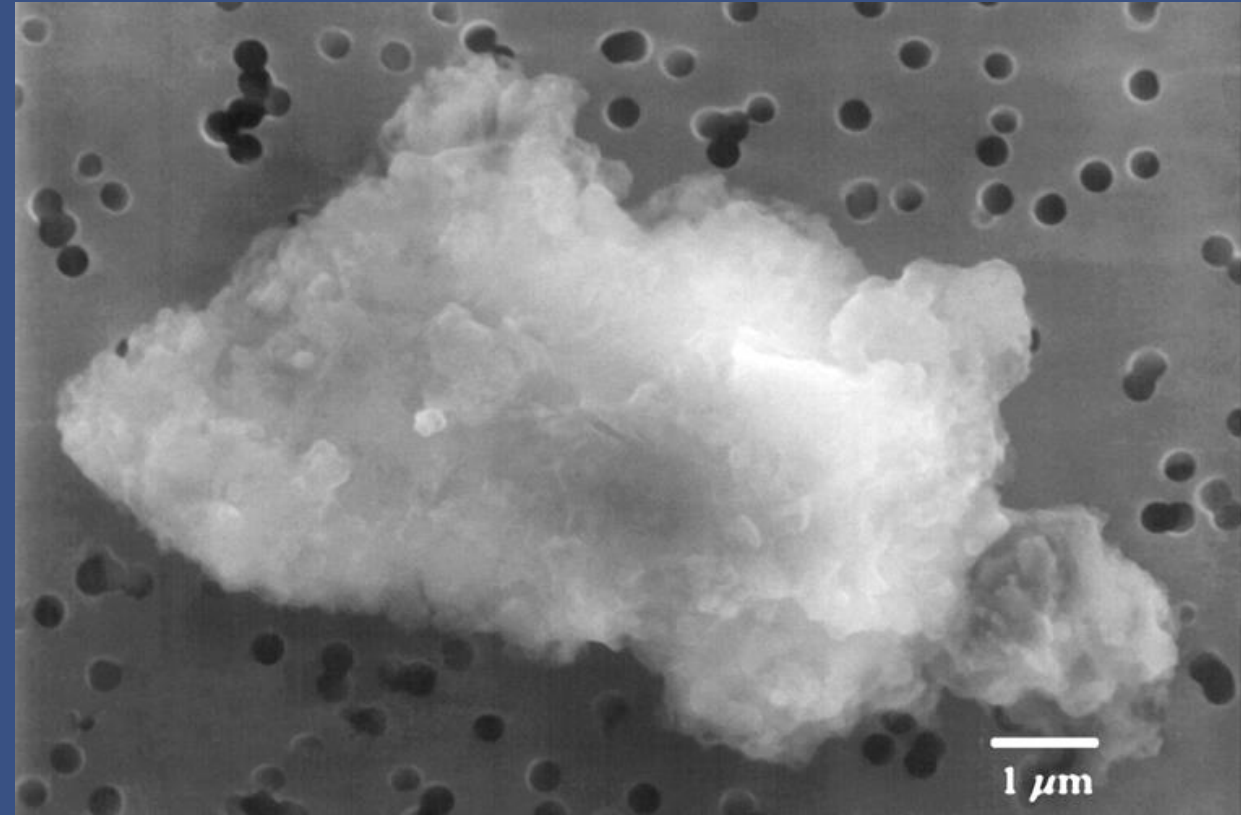
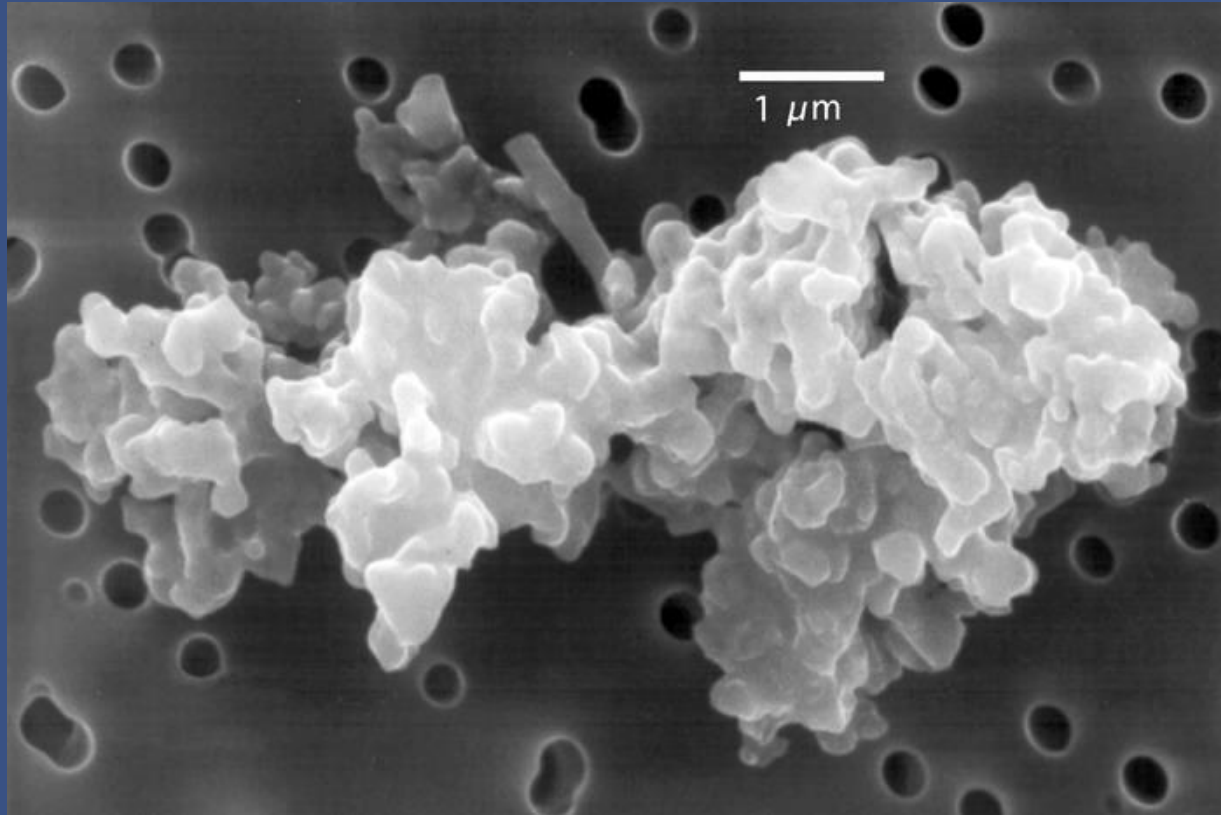
# The Local Bubble and the polarization of radiation

Mapping the Local Bubble's Magnetic Field in 3D

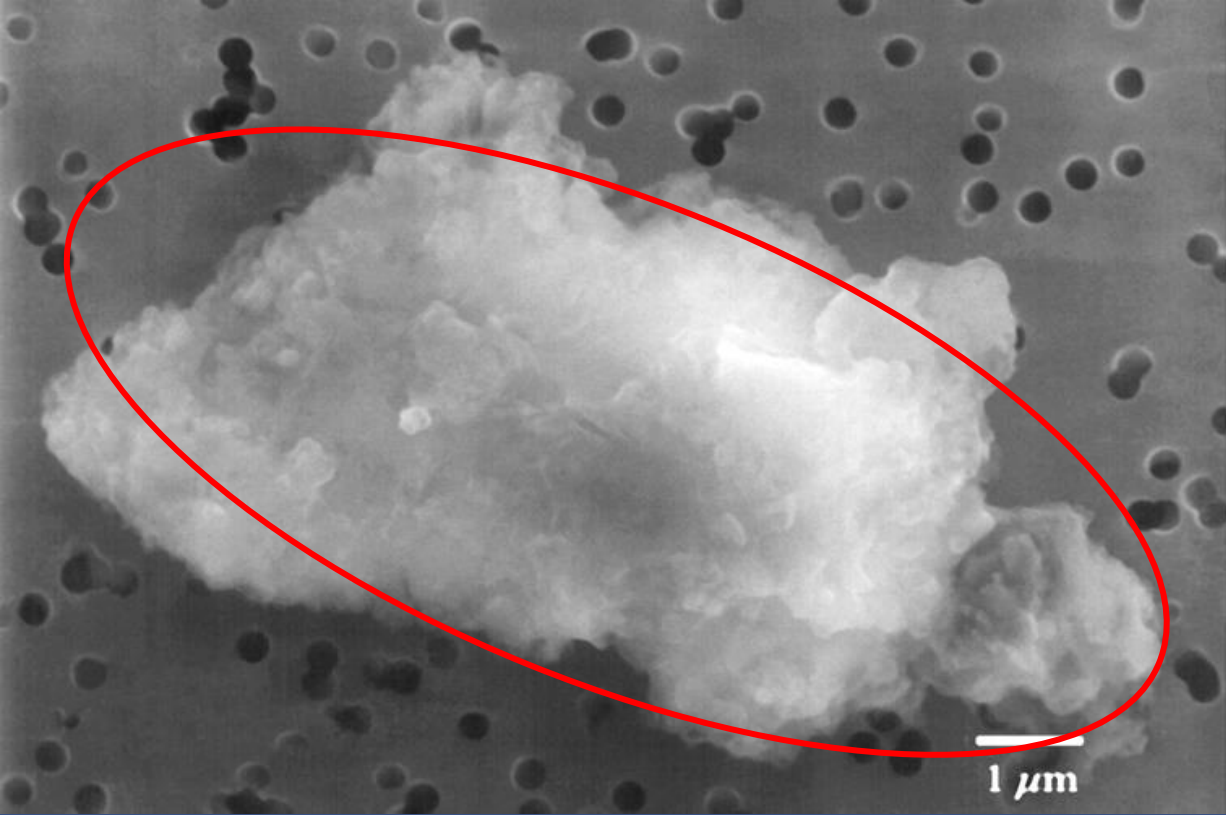
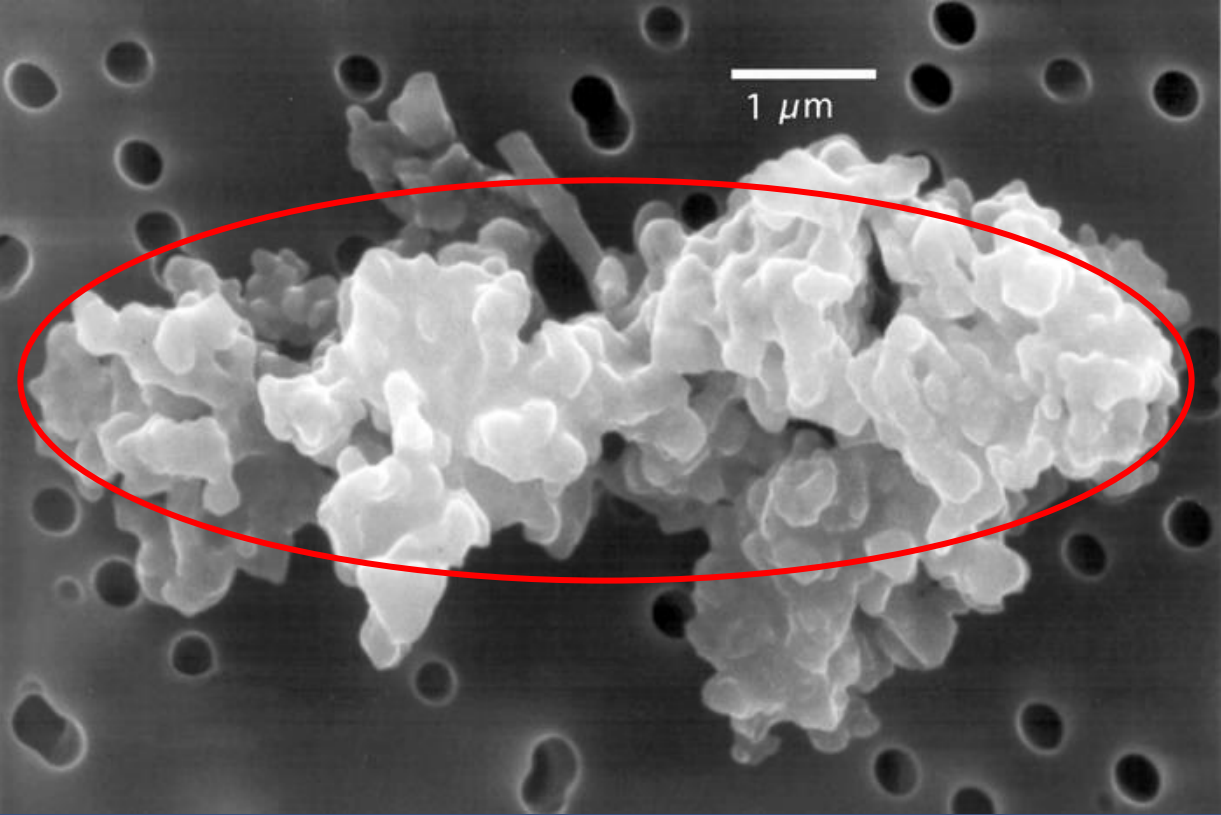
Synthetic polarization observations for a Local Bubble-like cavity



## Samples of interplanetary dust



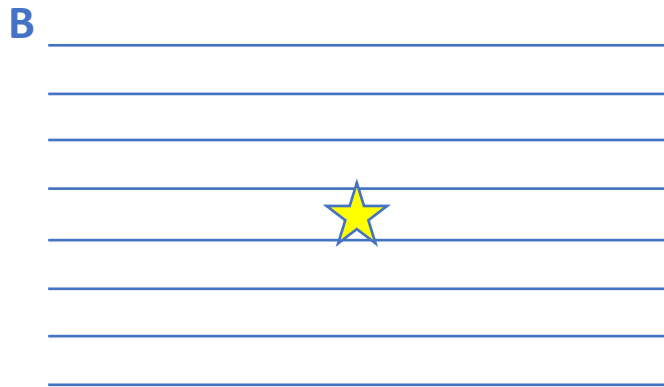
# Samples of interplanetary dust





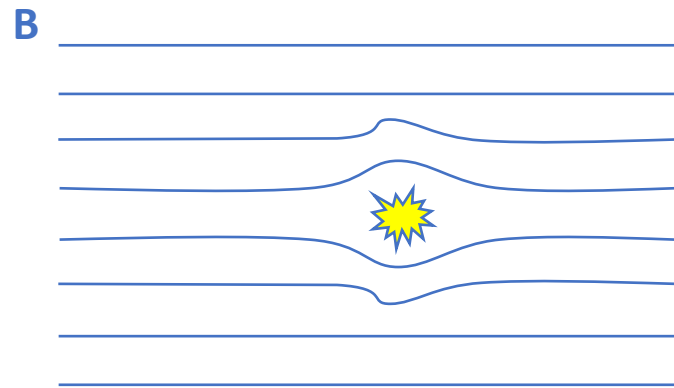
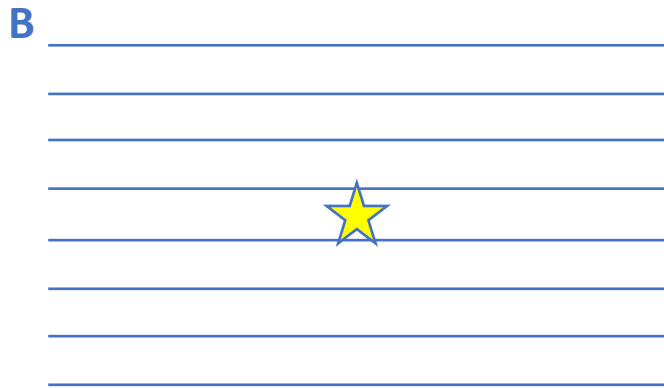
# Magnetic field morphology produced by the expansion of a super-bubble

[Ferriere et al. 1991]



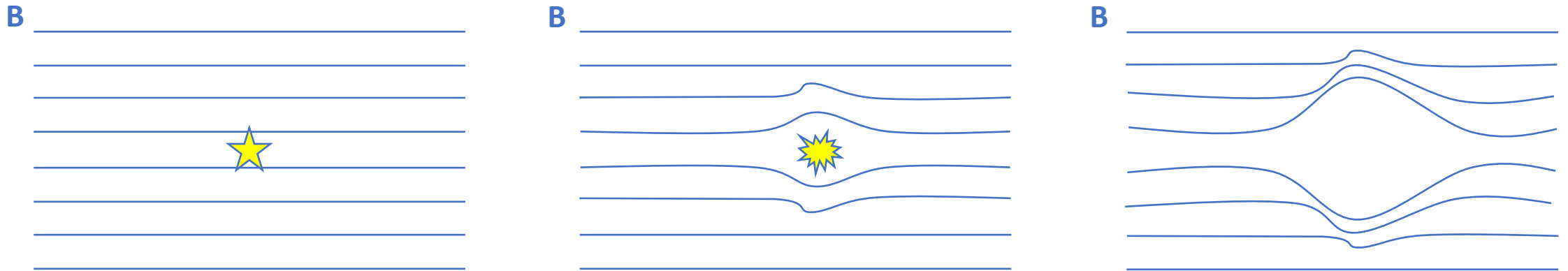
# Magnetic field morphology produced by the expansion of a super-bubble

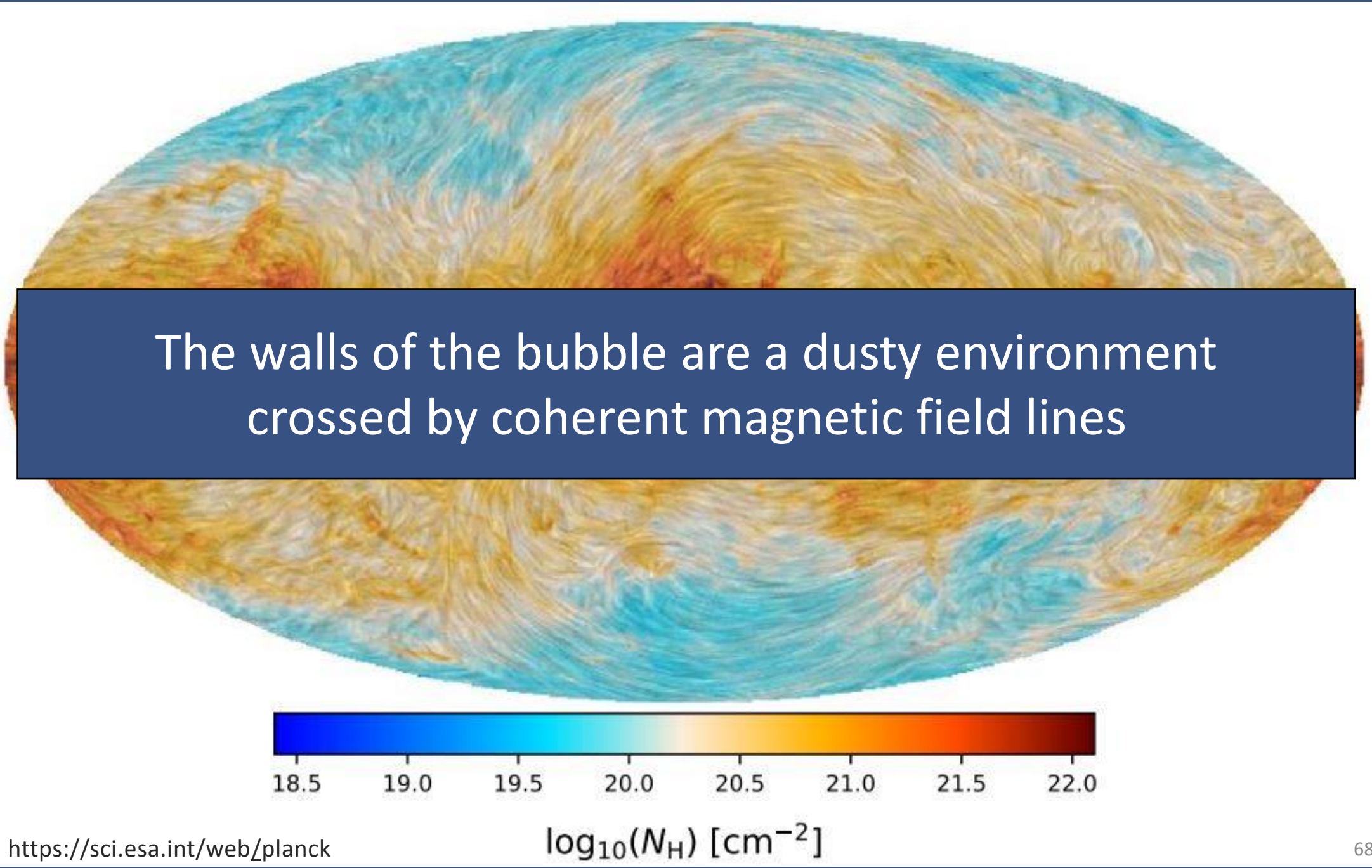
[Ferriere et al. 1991]



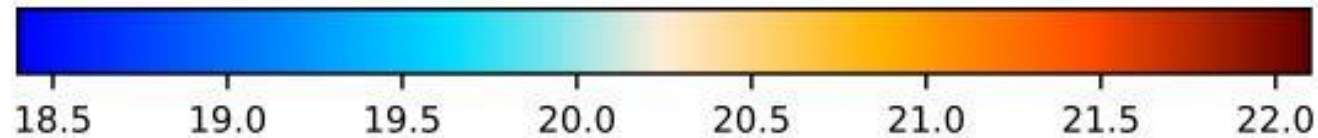
# Magnetic field morphology produced by the expansion of a super-bubble

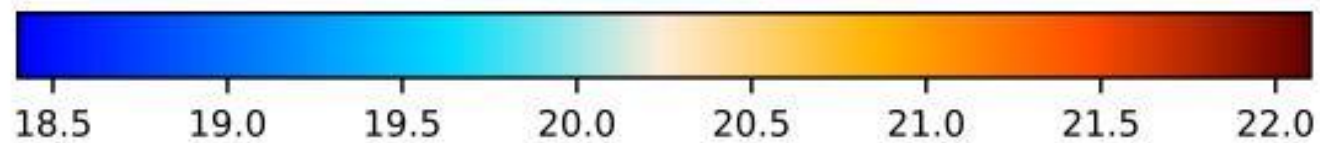
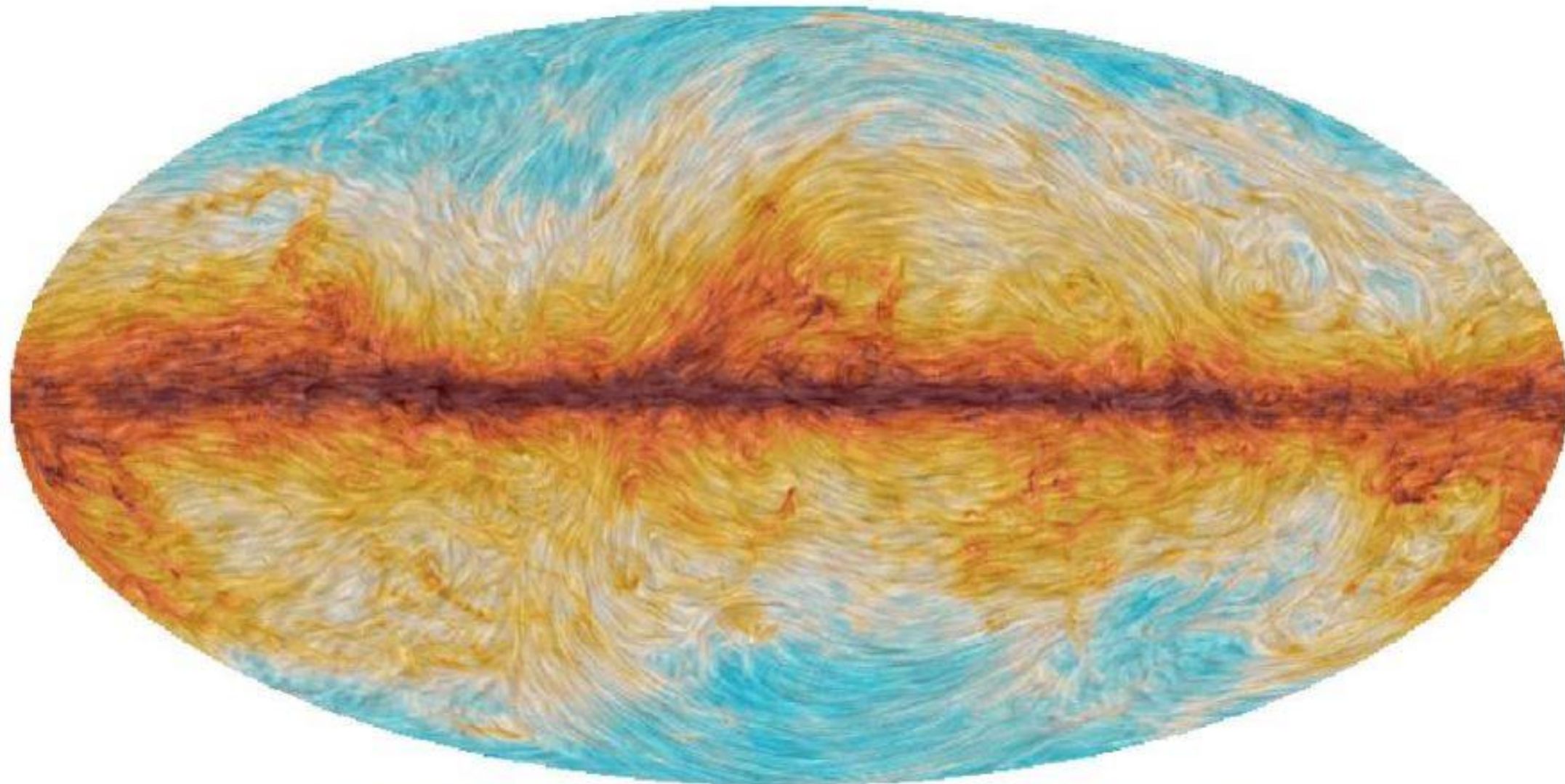
[Ferriere et al. 1991]





The walls of the bubble are a dusty environment  
crossed by coherent magnetic field lines



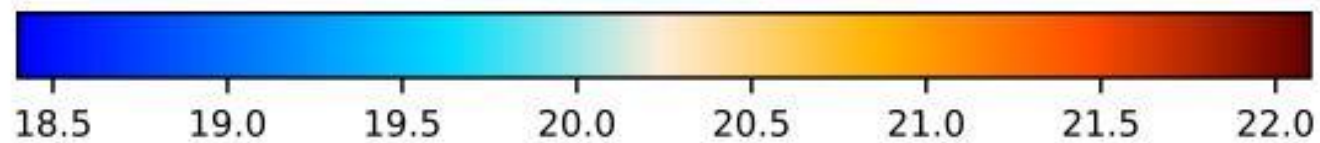
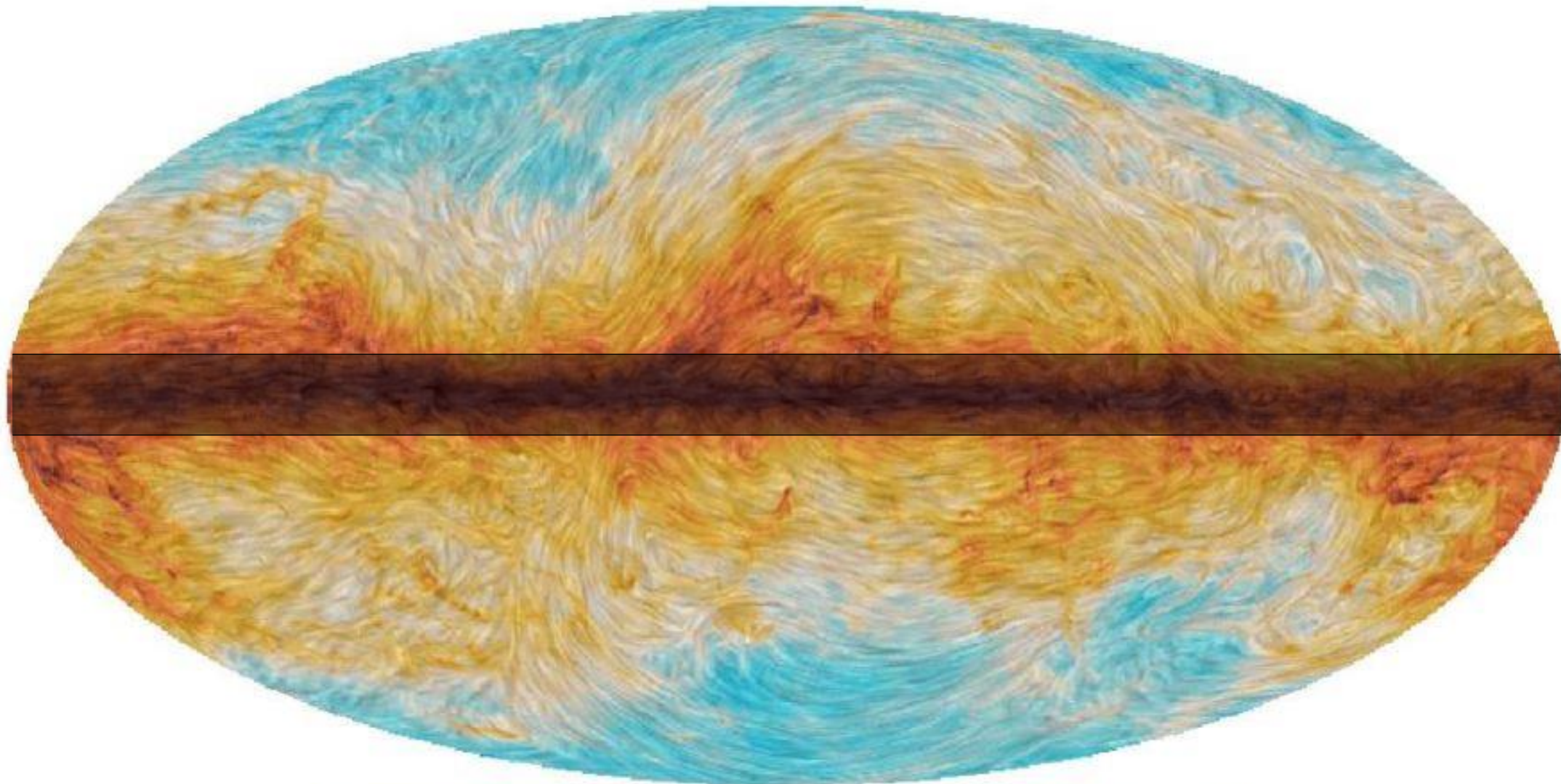


$\log_{10}(N_H) [\text{cm}^{-2}]$

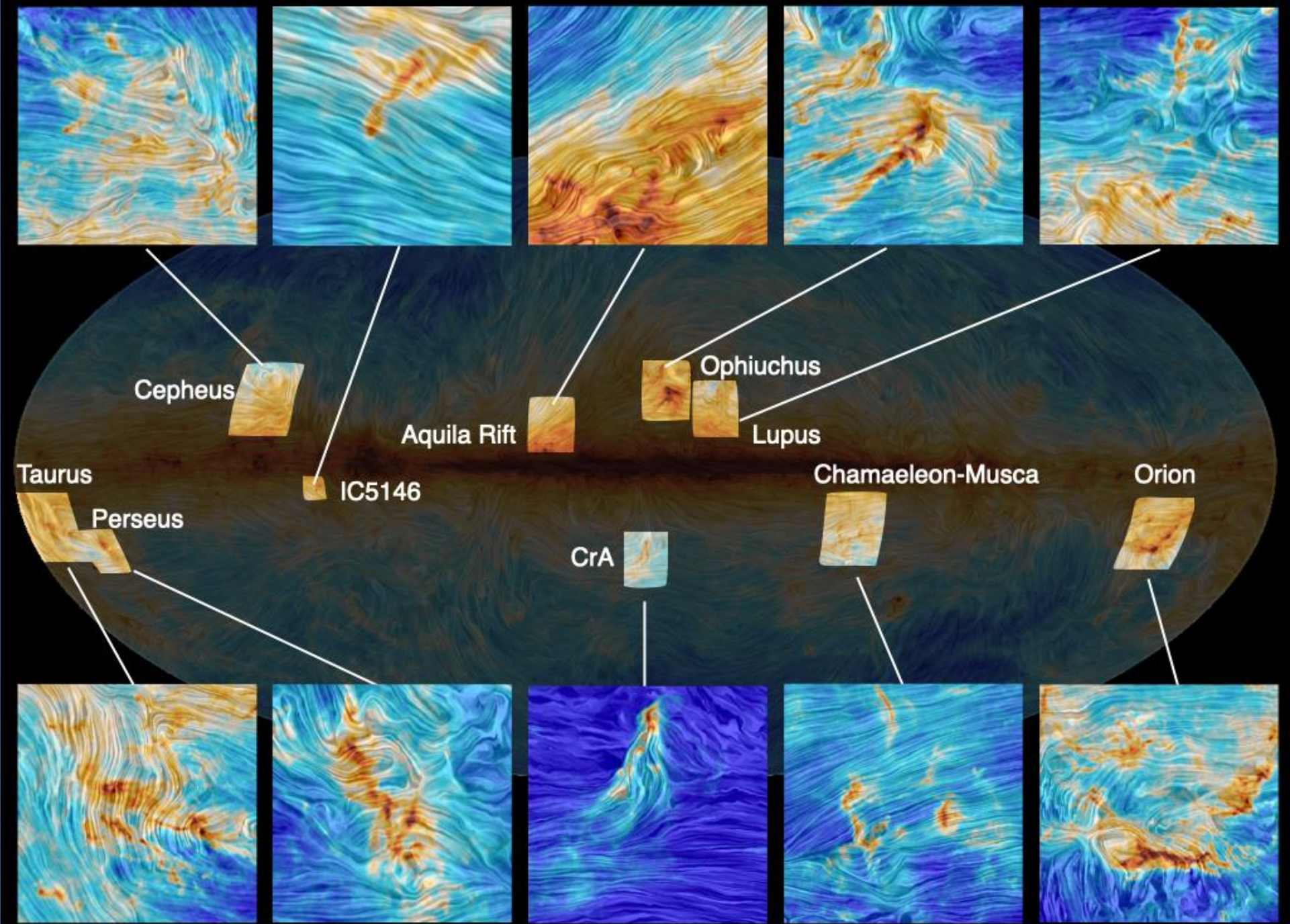
# The Local Bubble and the polarization of radiation

## Mapping the Local Bubble's Magnetic Field in 3D

Synthetic polarization observations for a Local Bubble-like cavity

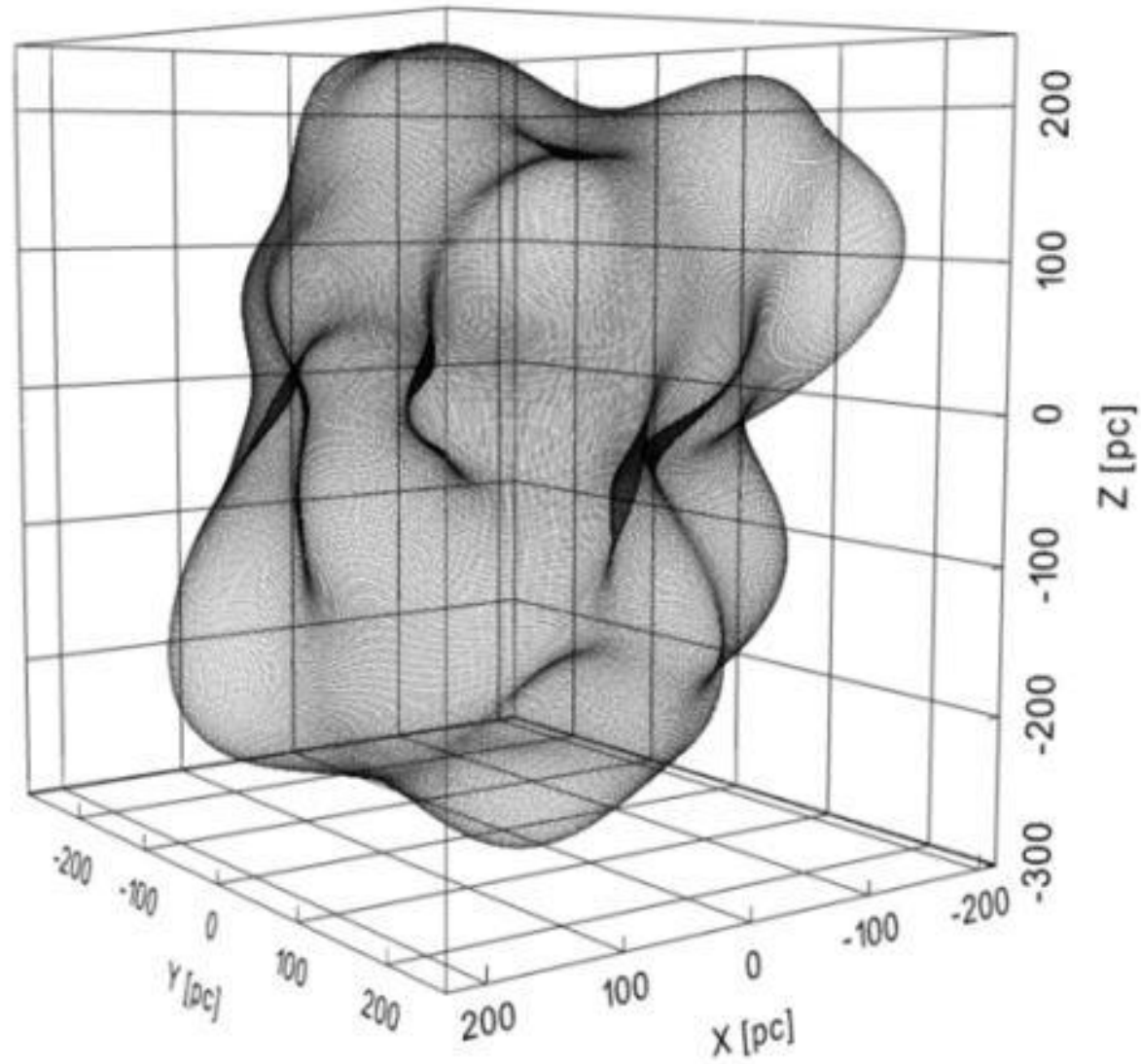


$\log_{10}(N_H) [\text{cm}^{-2}]$

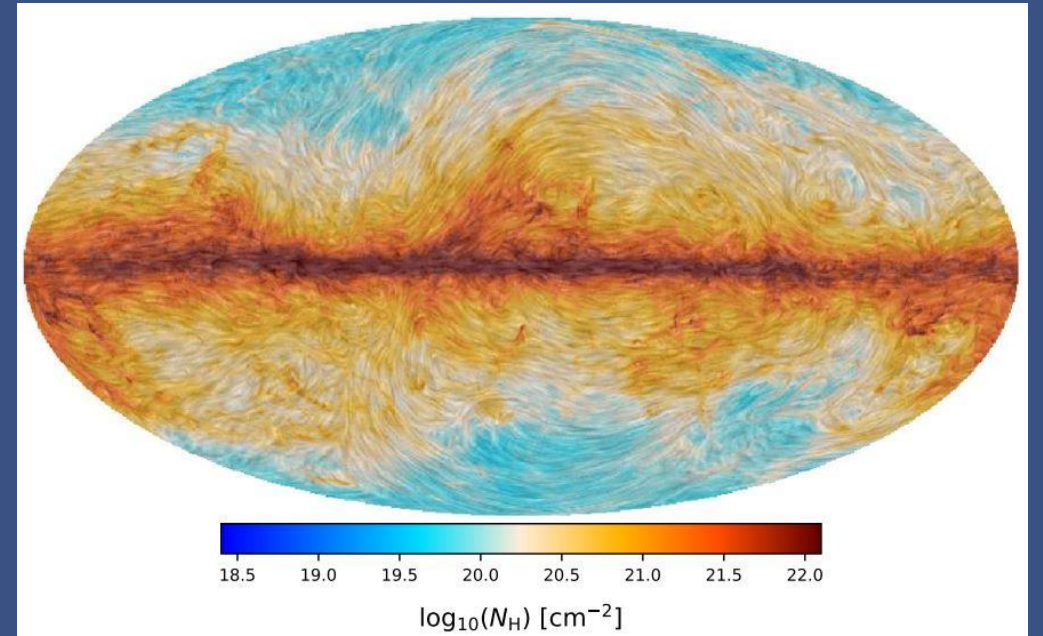
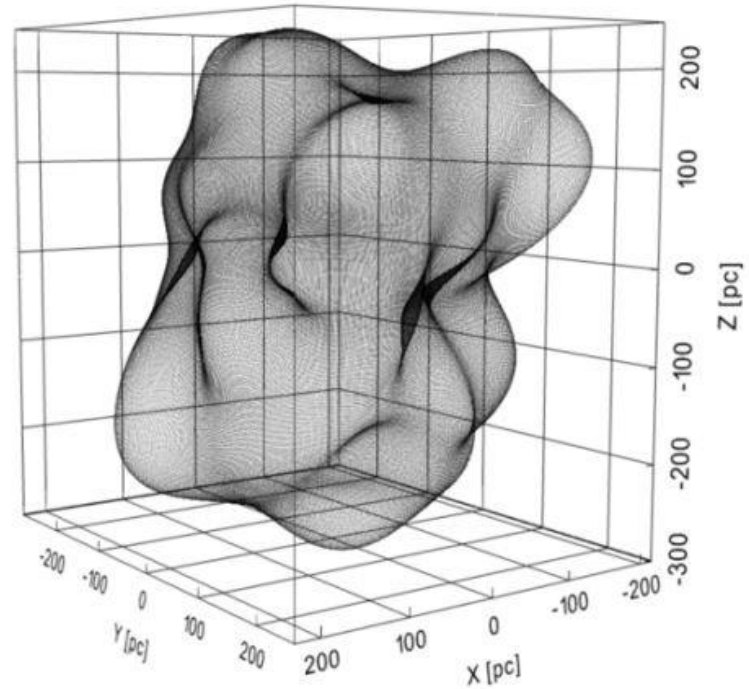




# Pelgrims+20 Model

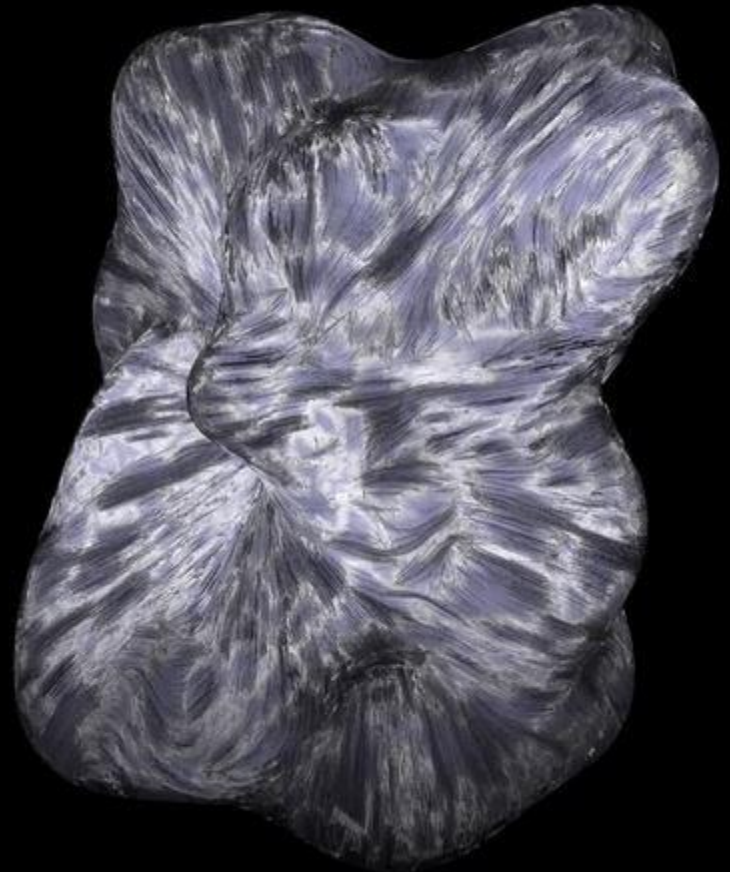
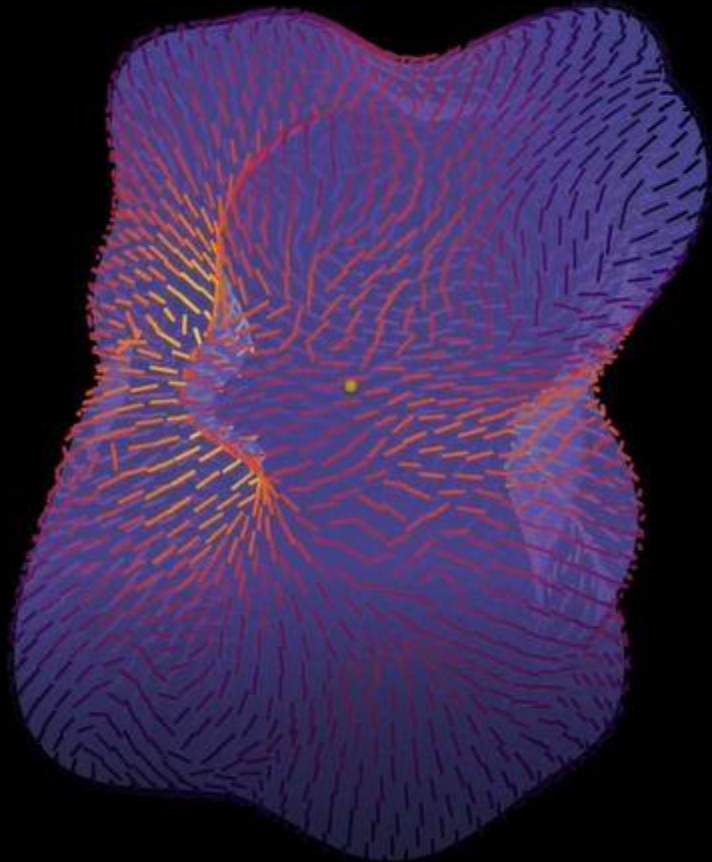


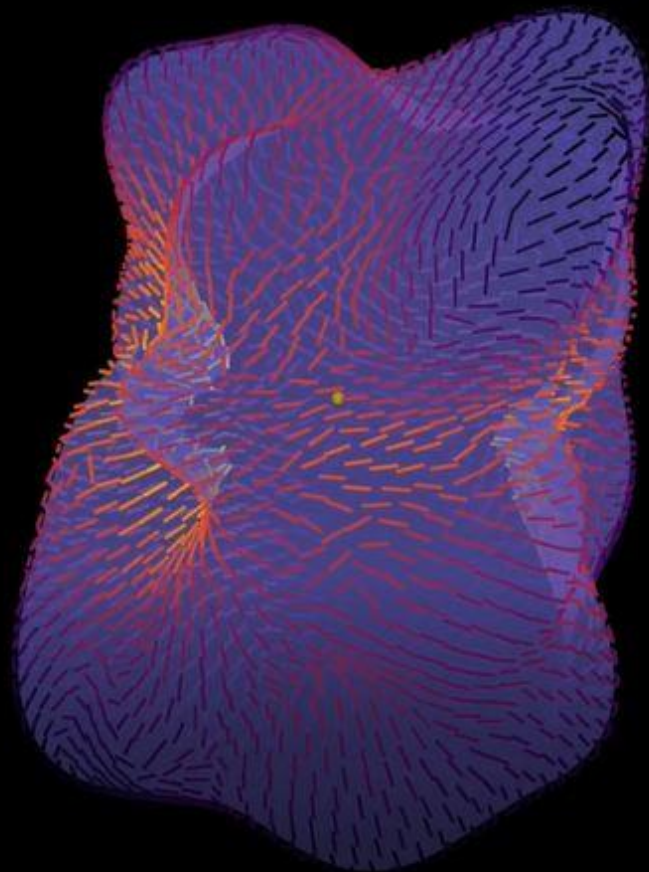
Pelgrims+20 Model

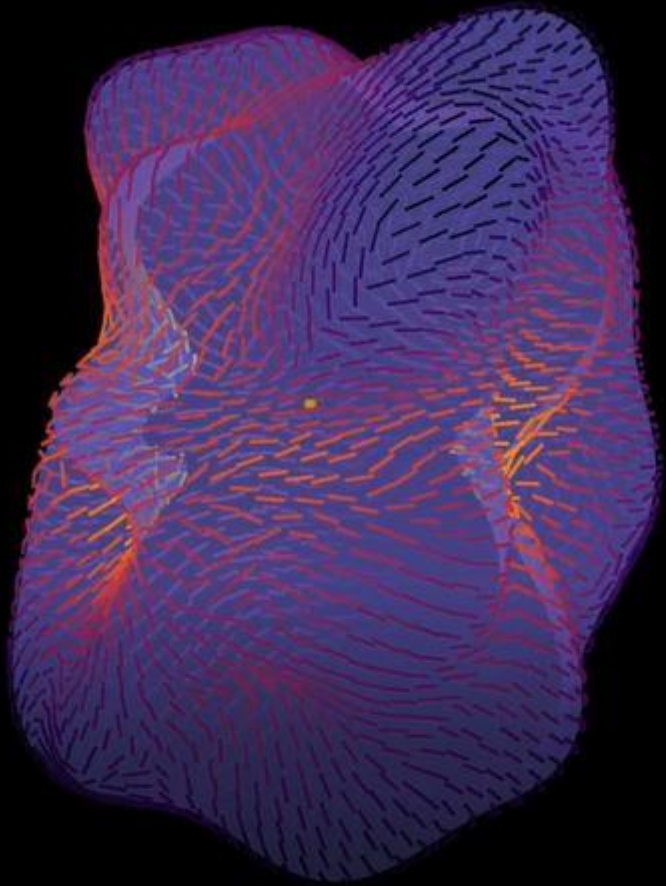


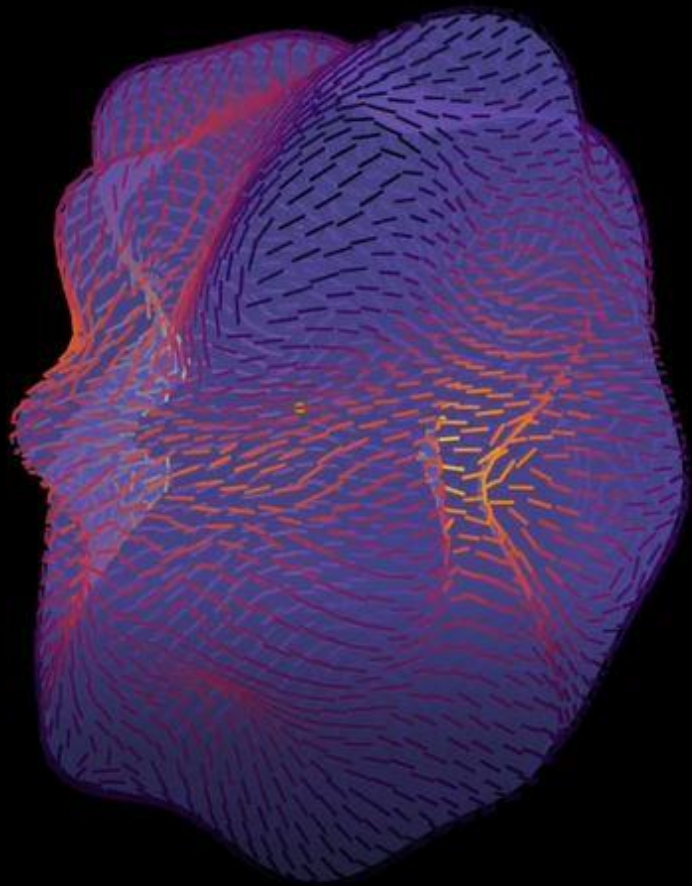


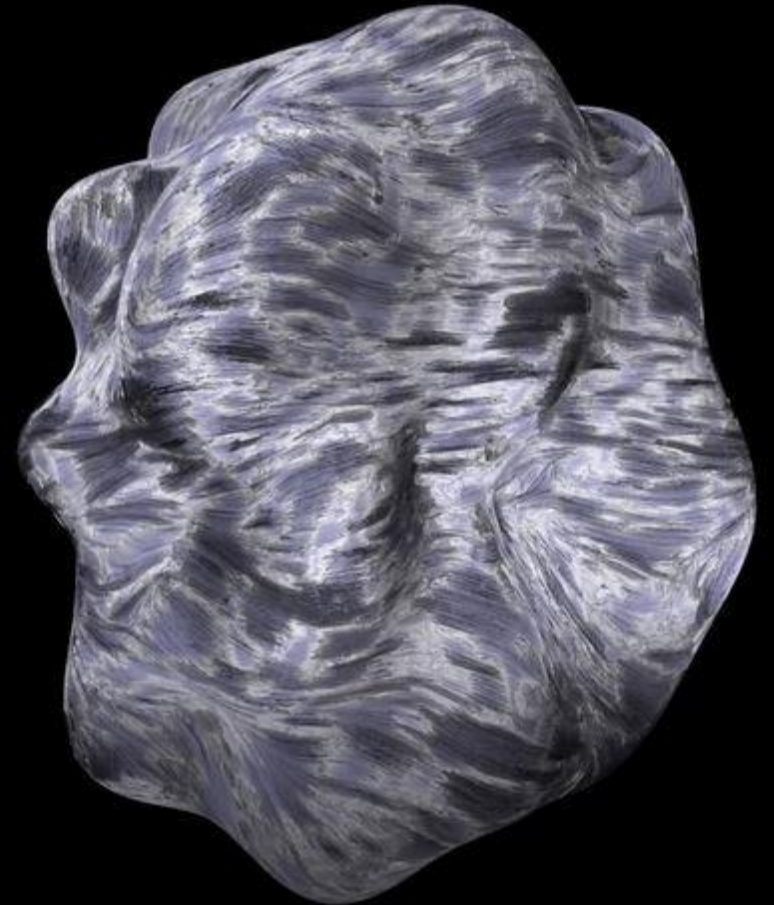
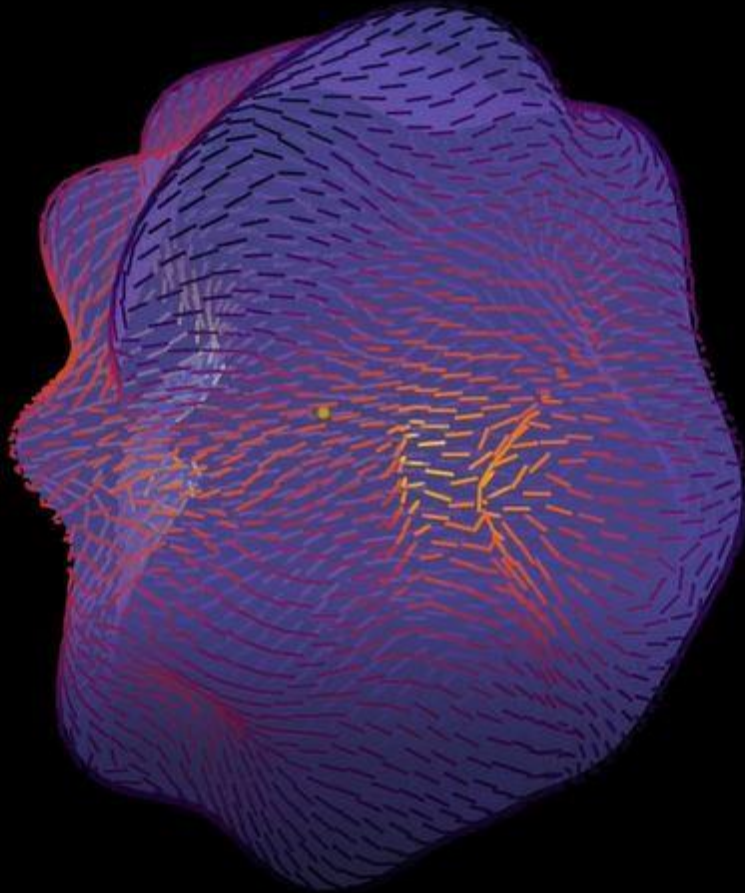
First 3D map of magnetic field morphology on the surface of the Local Bubble



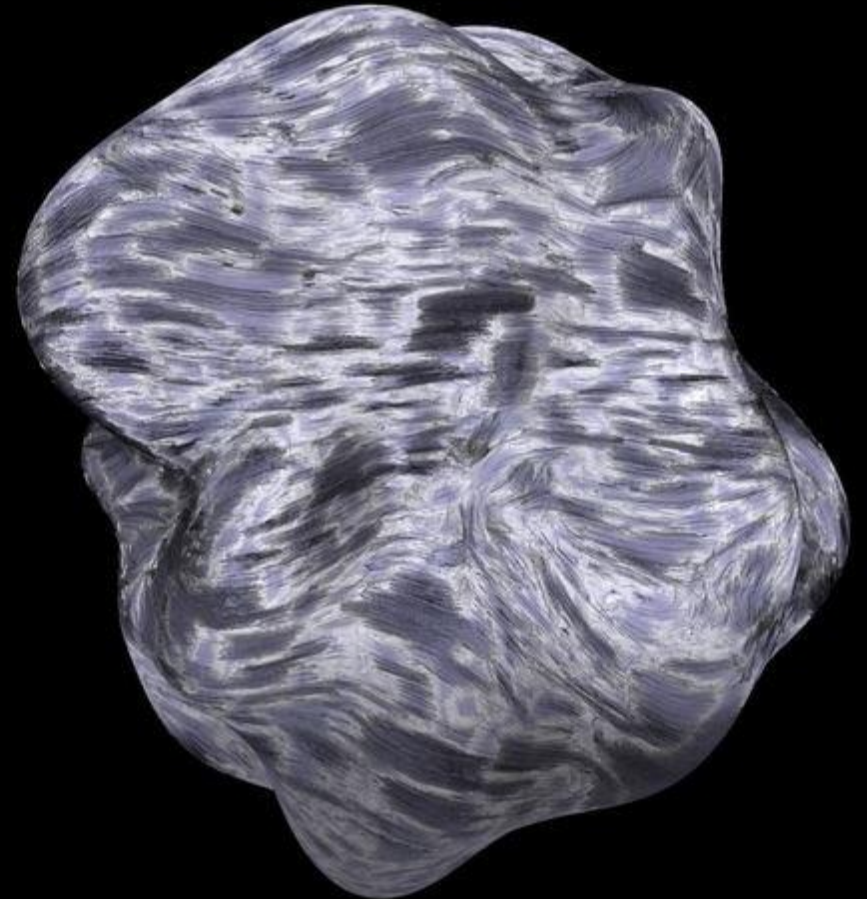
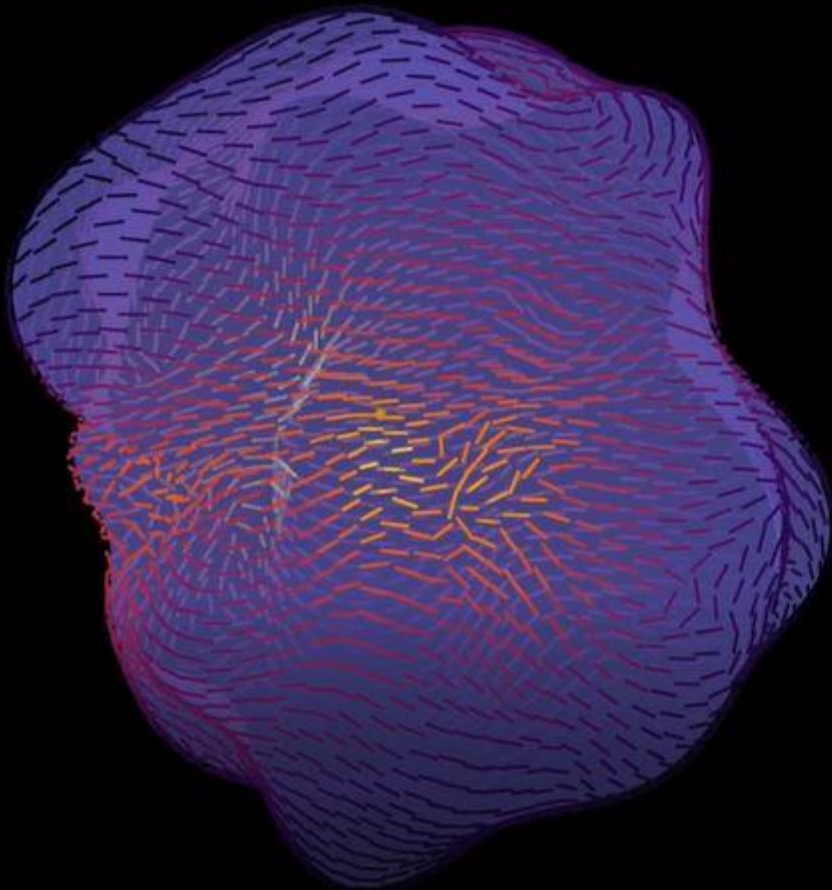


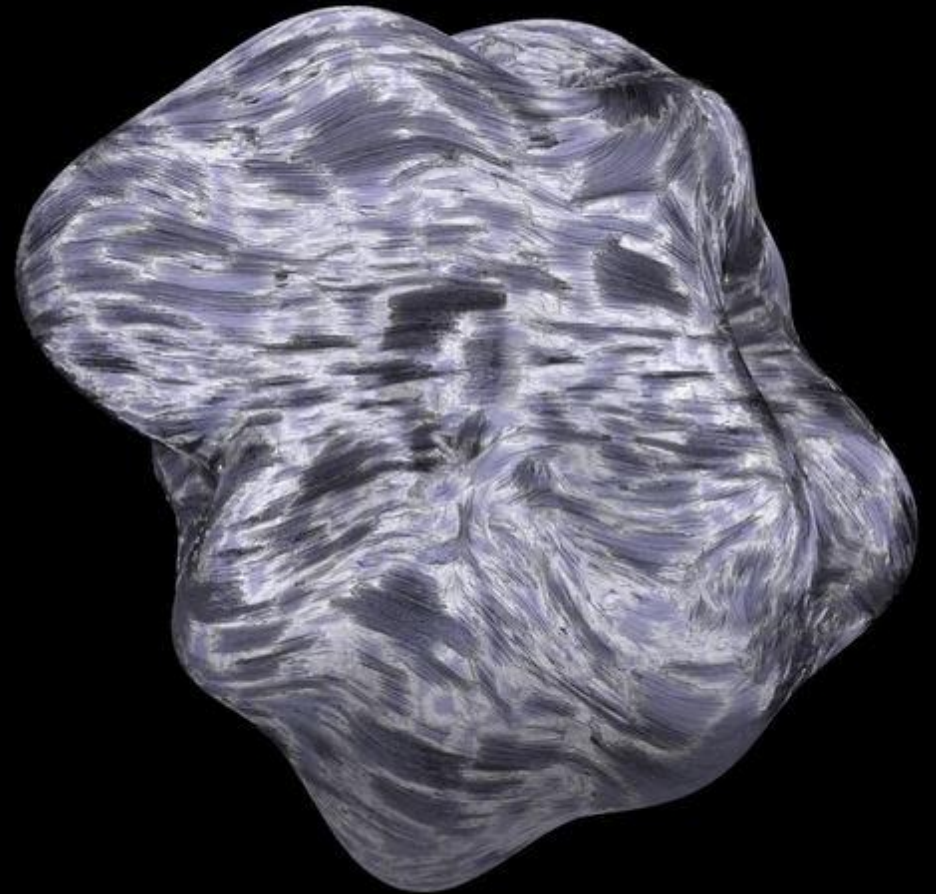
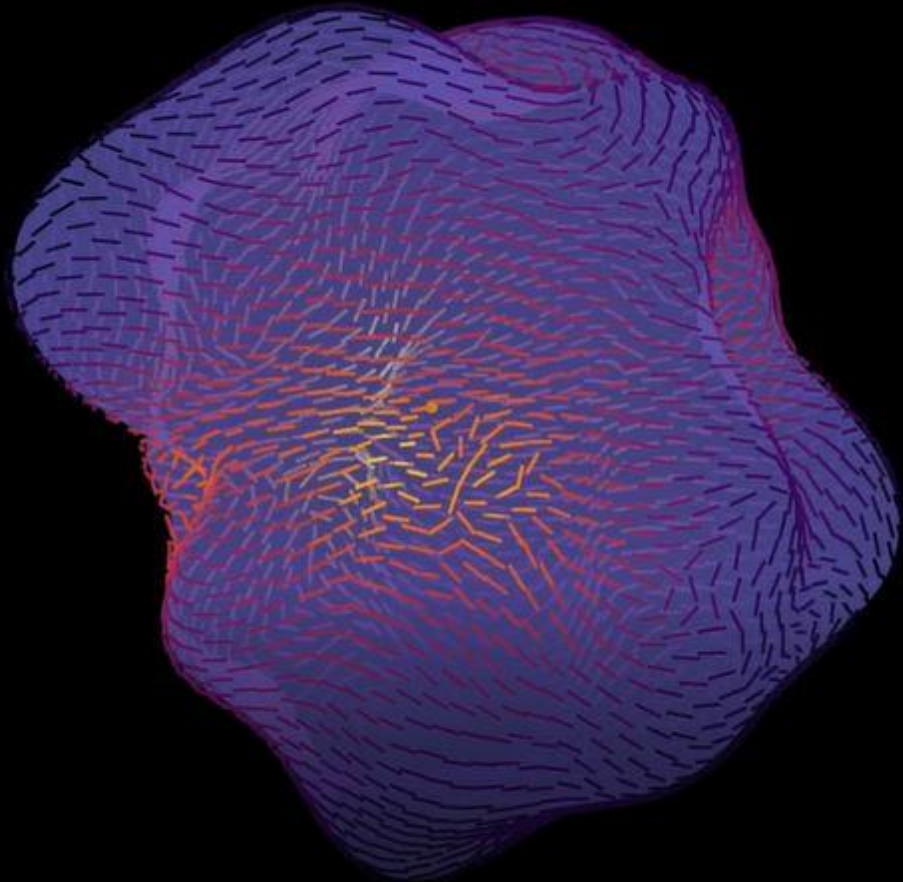


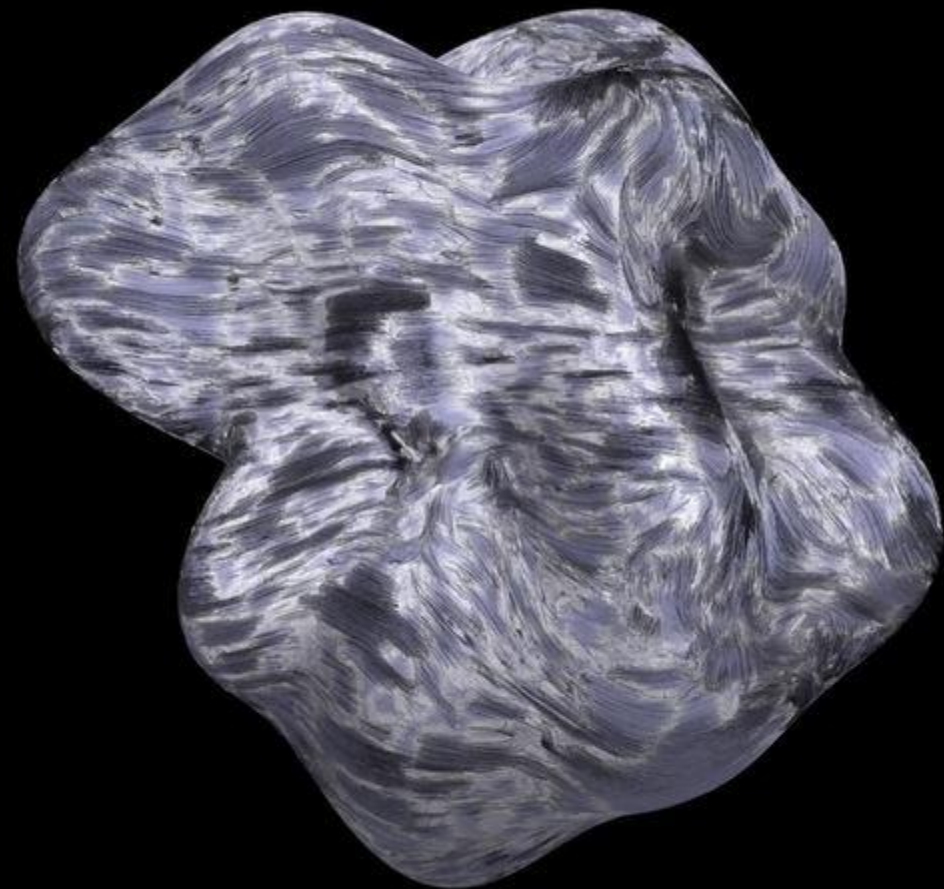
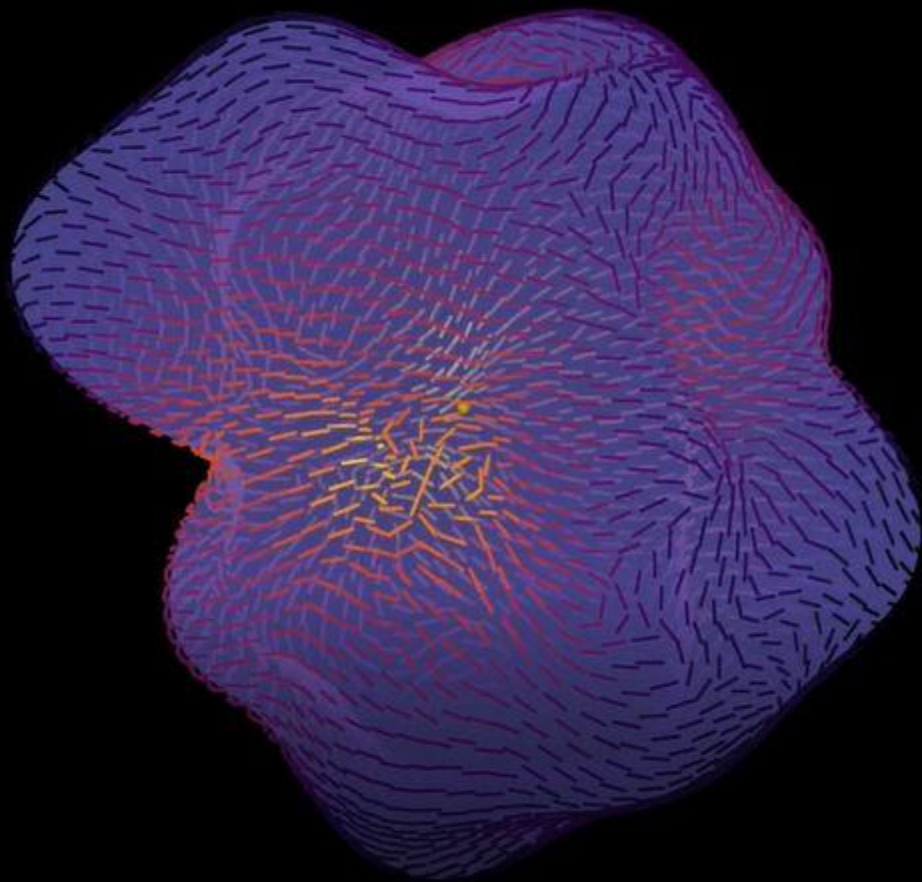












# The Local Bubble and the polarization of radiation

Mapping the Local Bubble's Magnetic Field in 3D

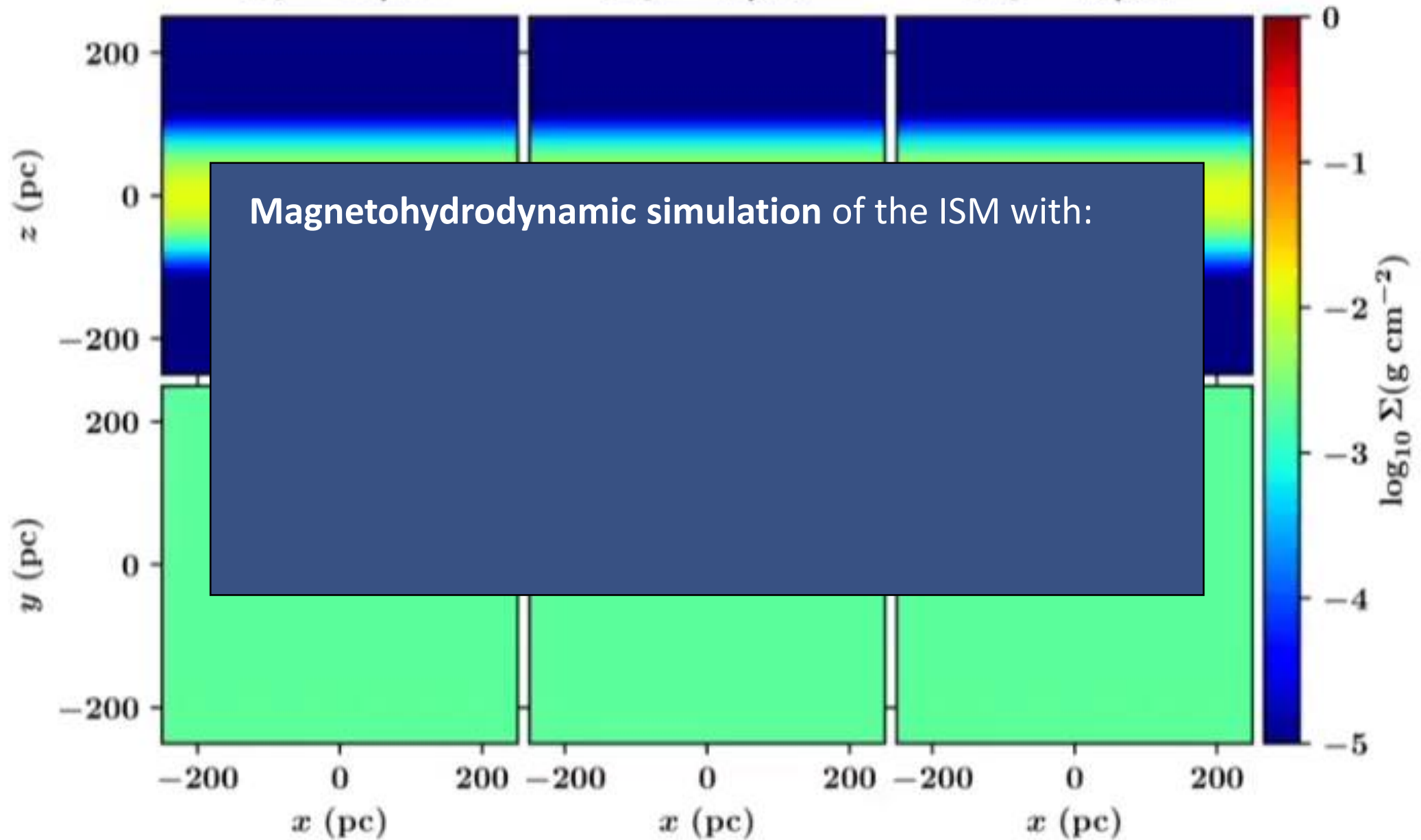
Synthetic polarization observations for a Local Bubble-like cavity

$t = 0$  Myr

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$



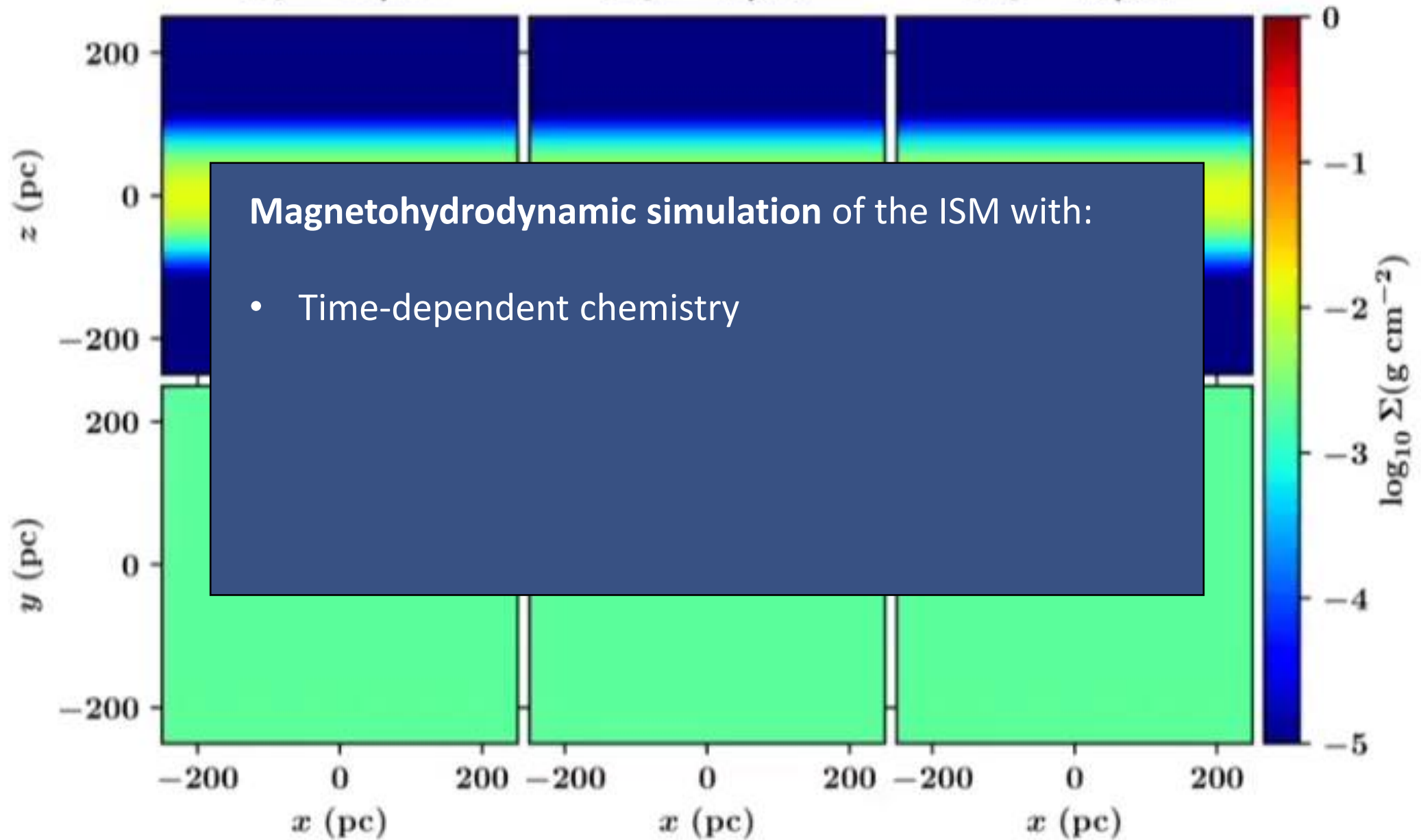
Magnetohydrodynamic simulation of the ISM with:

$t = 0$  Myr

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

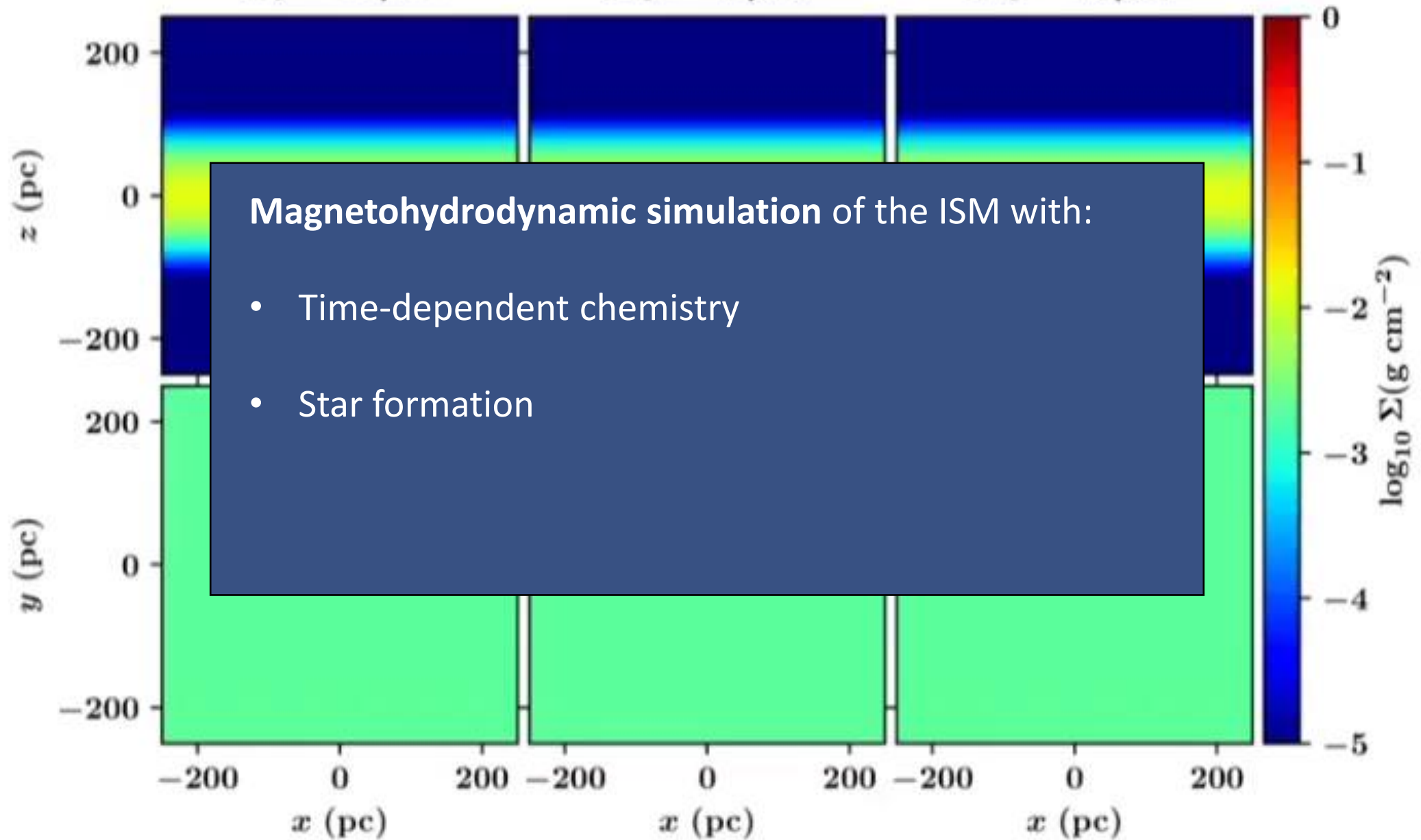


$t = 0$  Myr

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

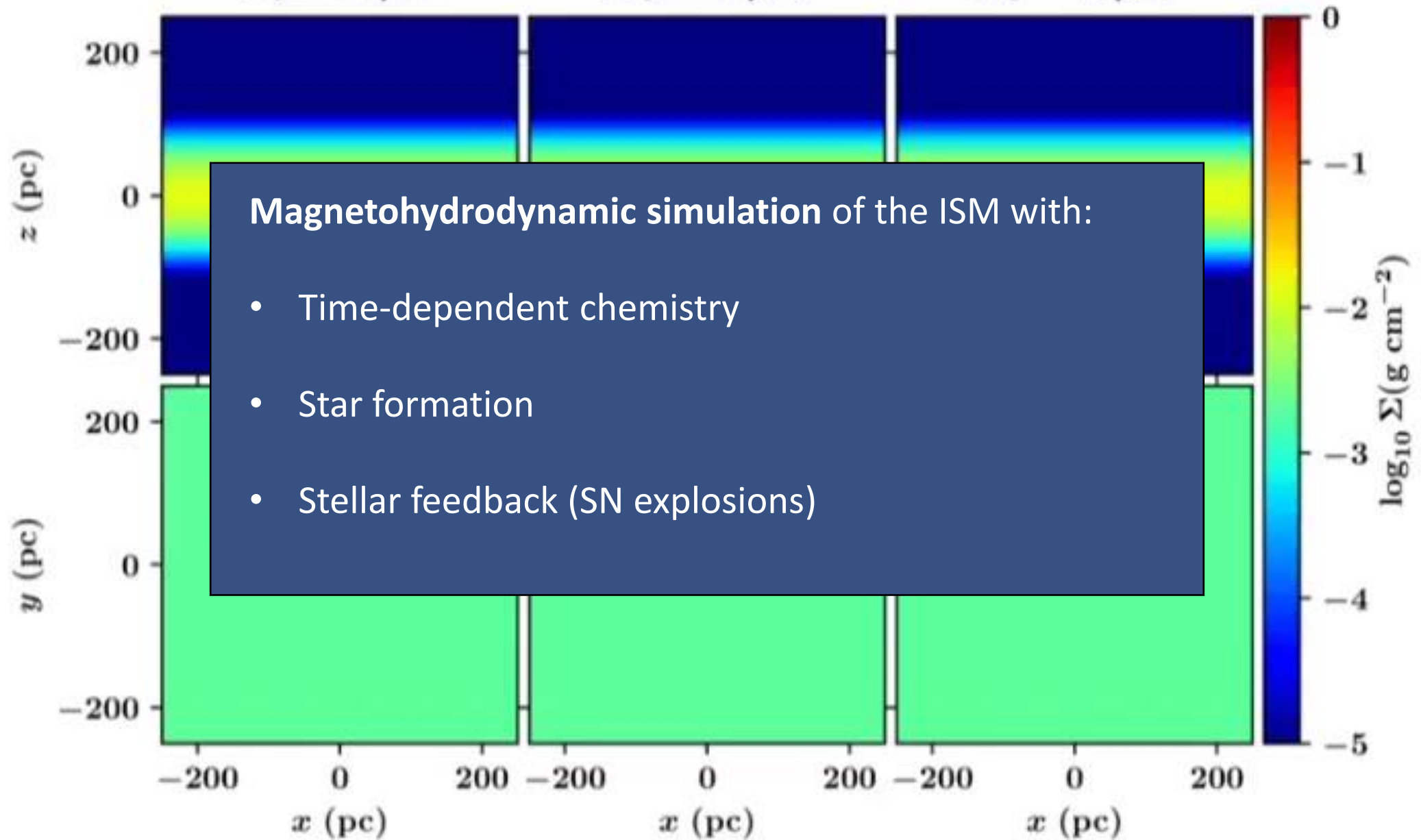


$t = 0$  Myr

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$



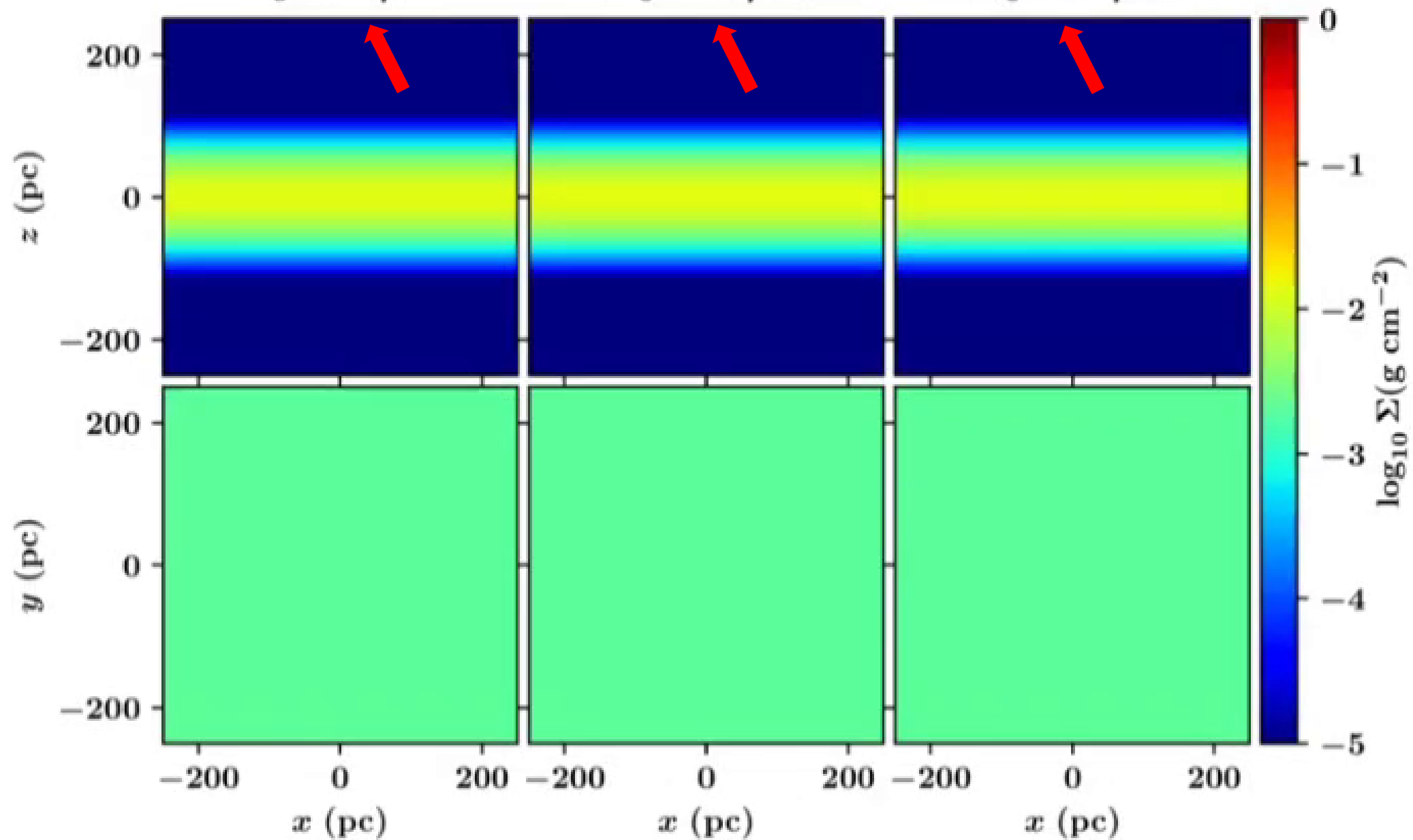


$t = 0$  Myr

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

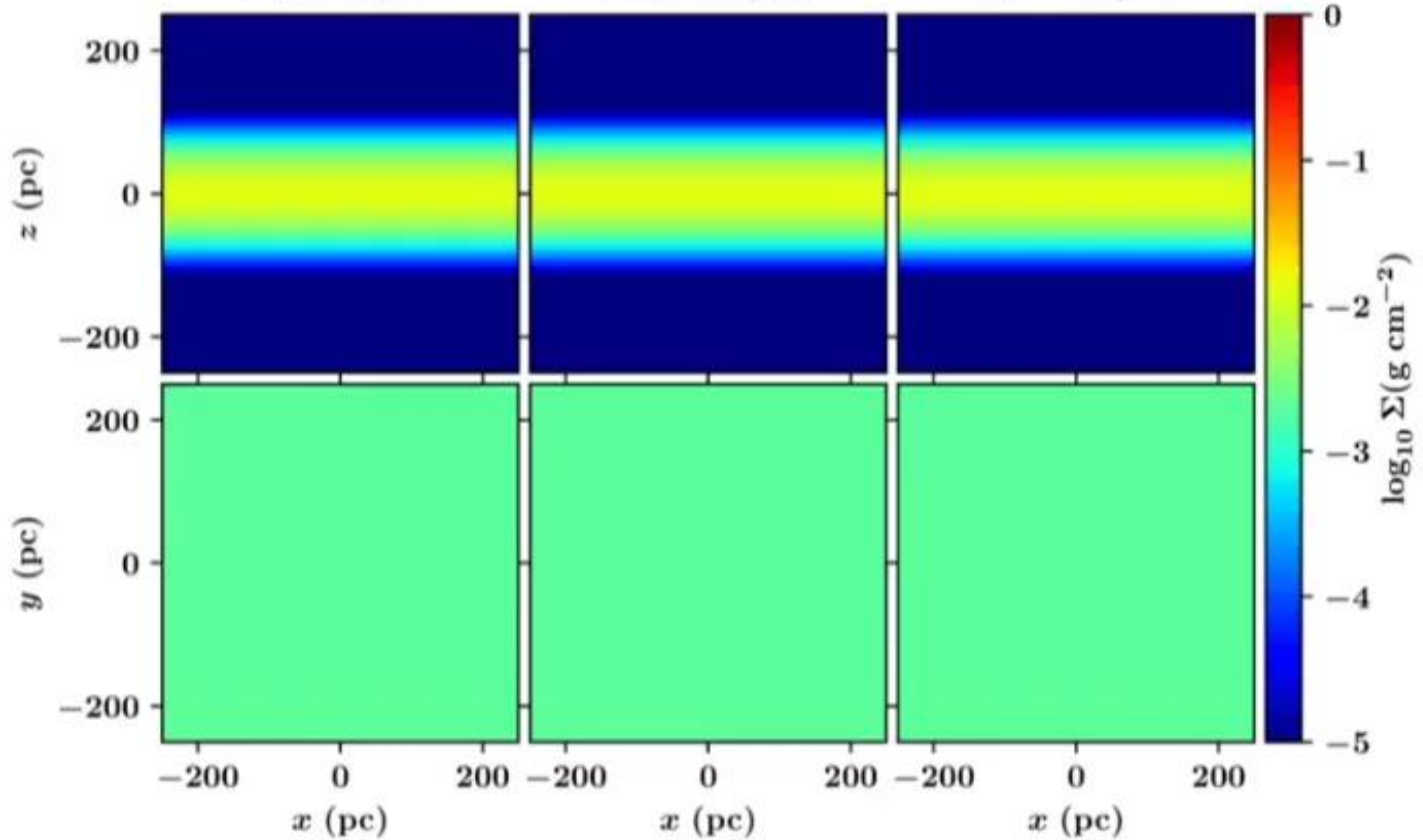


$t = 0$  Myr

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

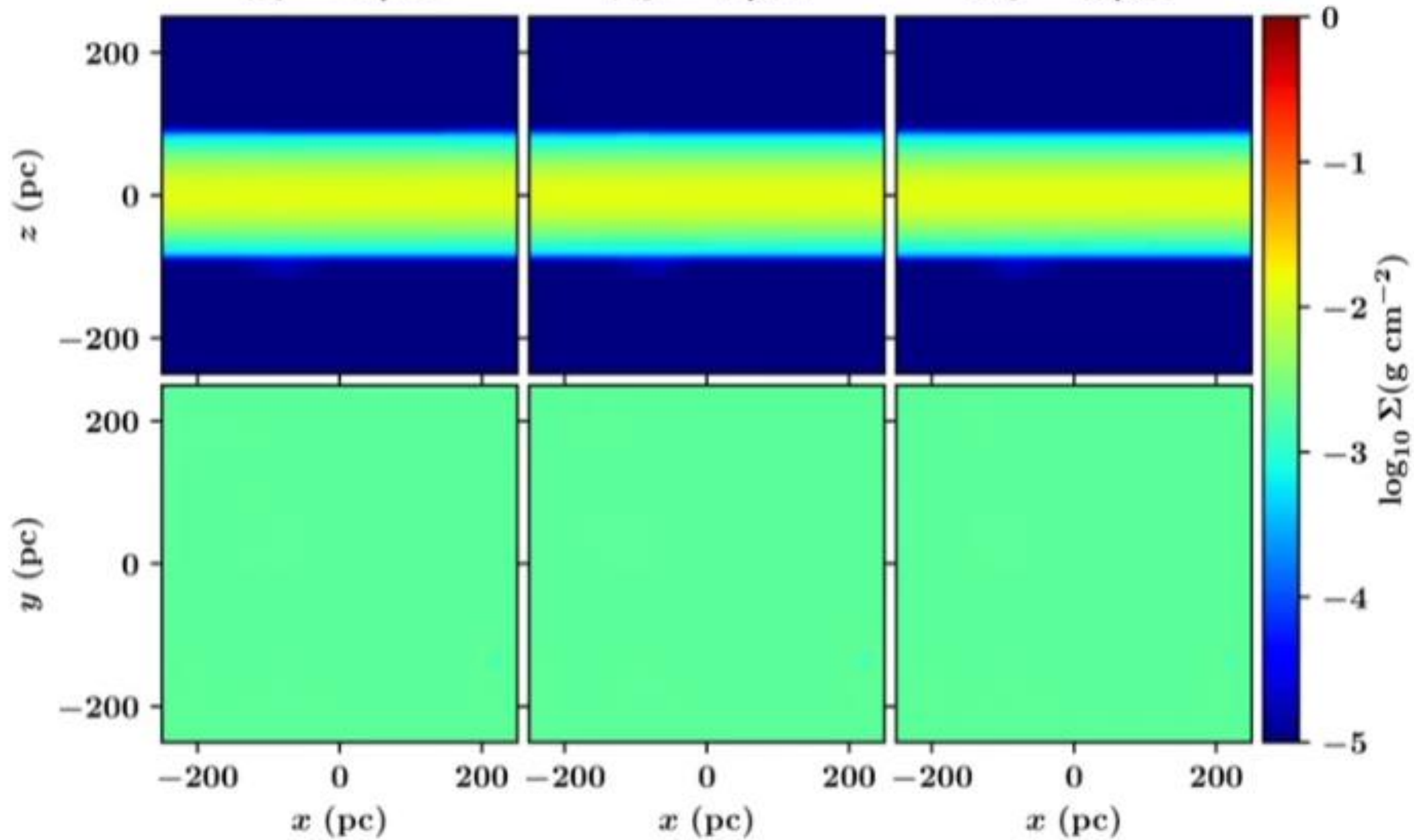


$t = 1 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

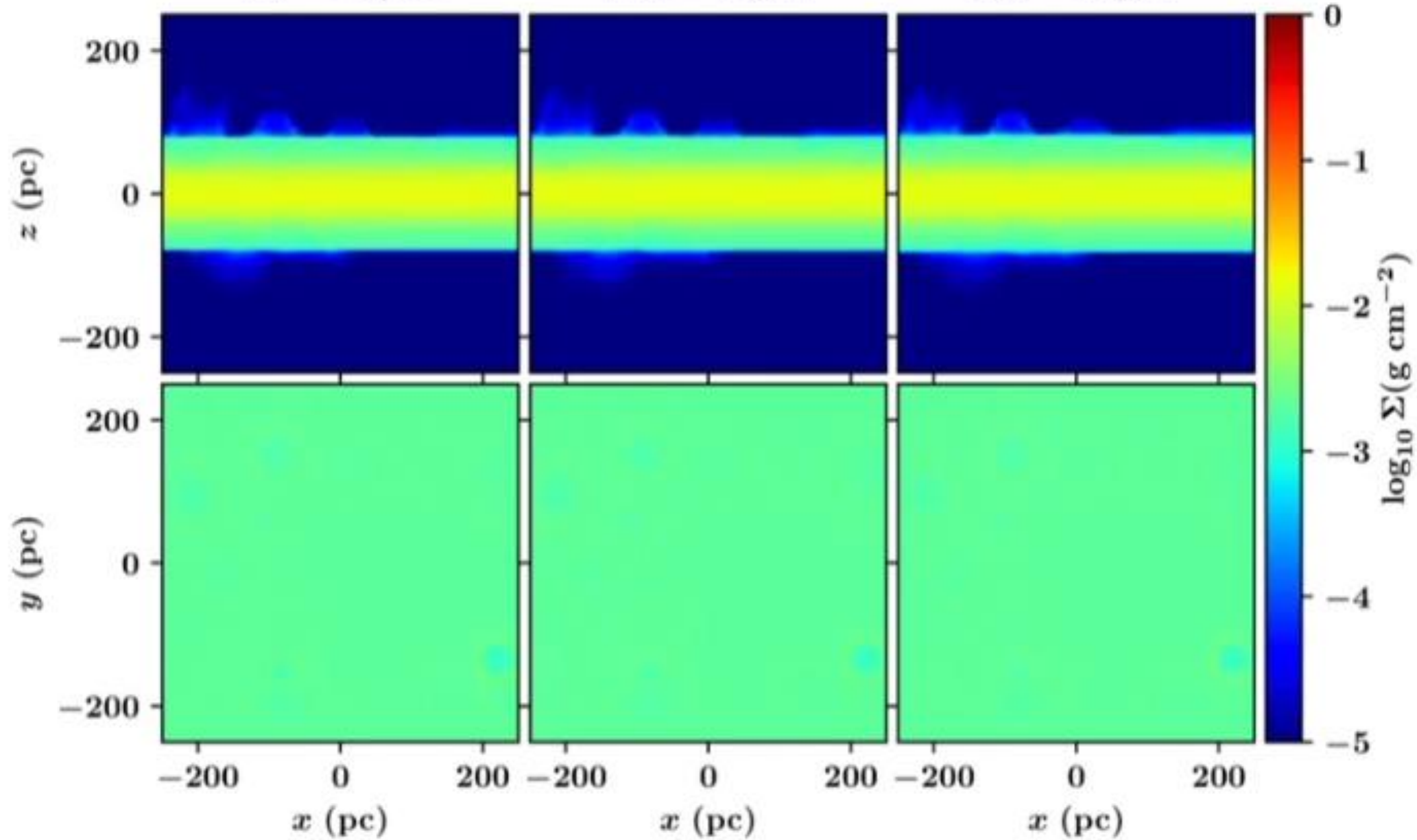


$t = 2 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

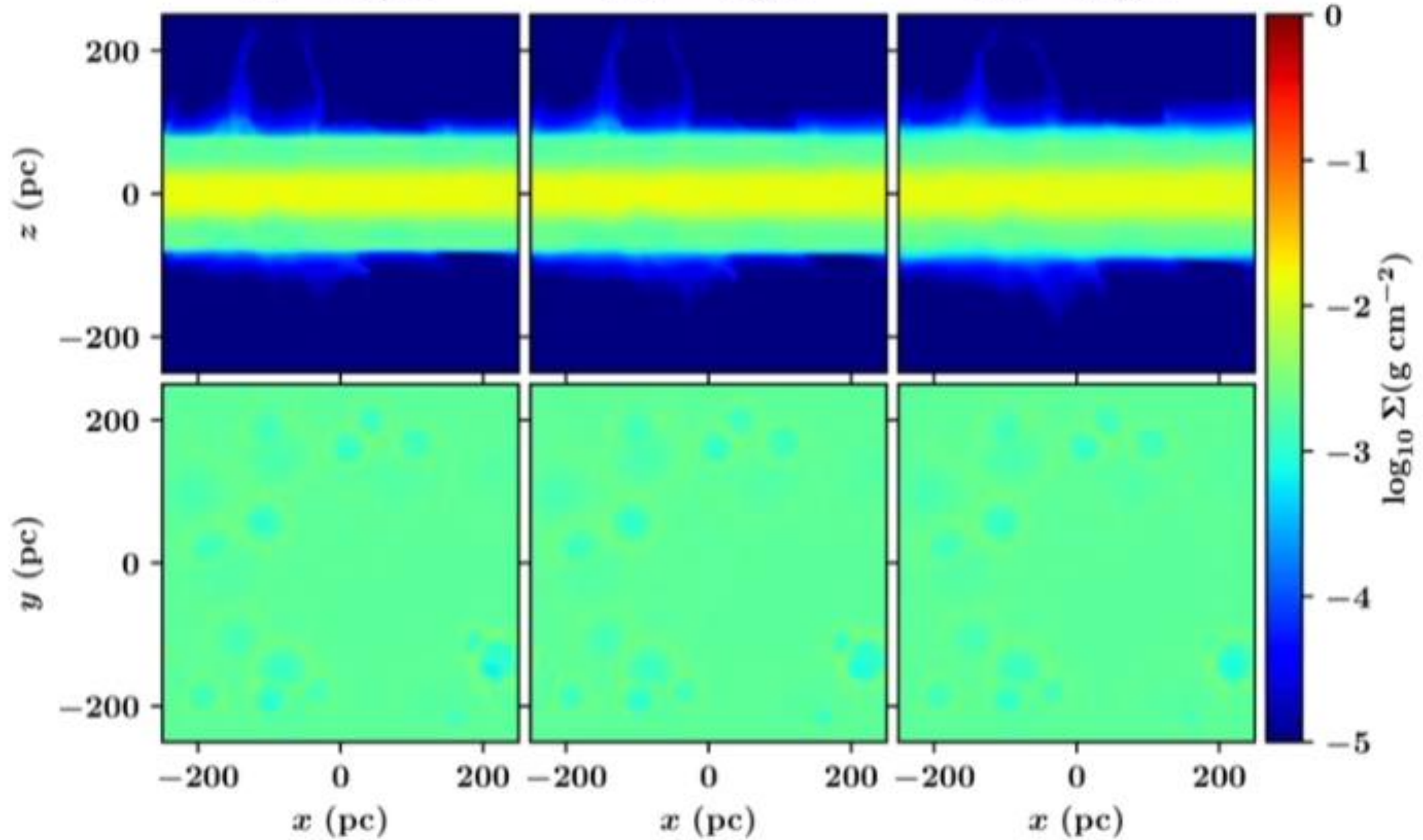


$t = 3 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

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$B_0 = 6 \mu\text{G}$

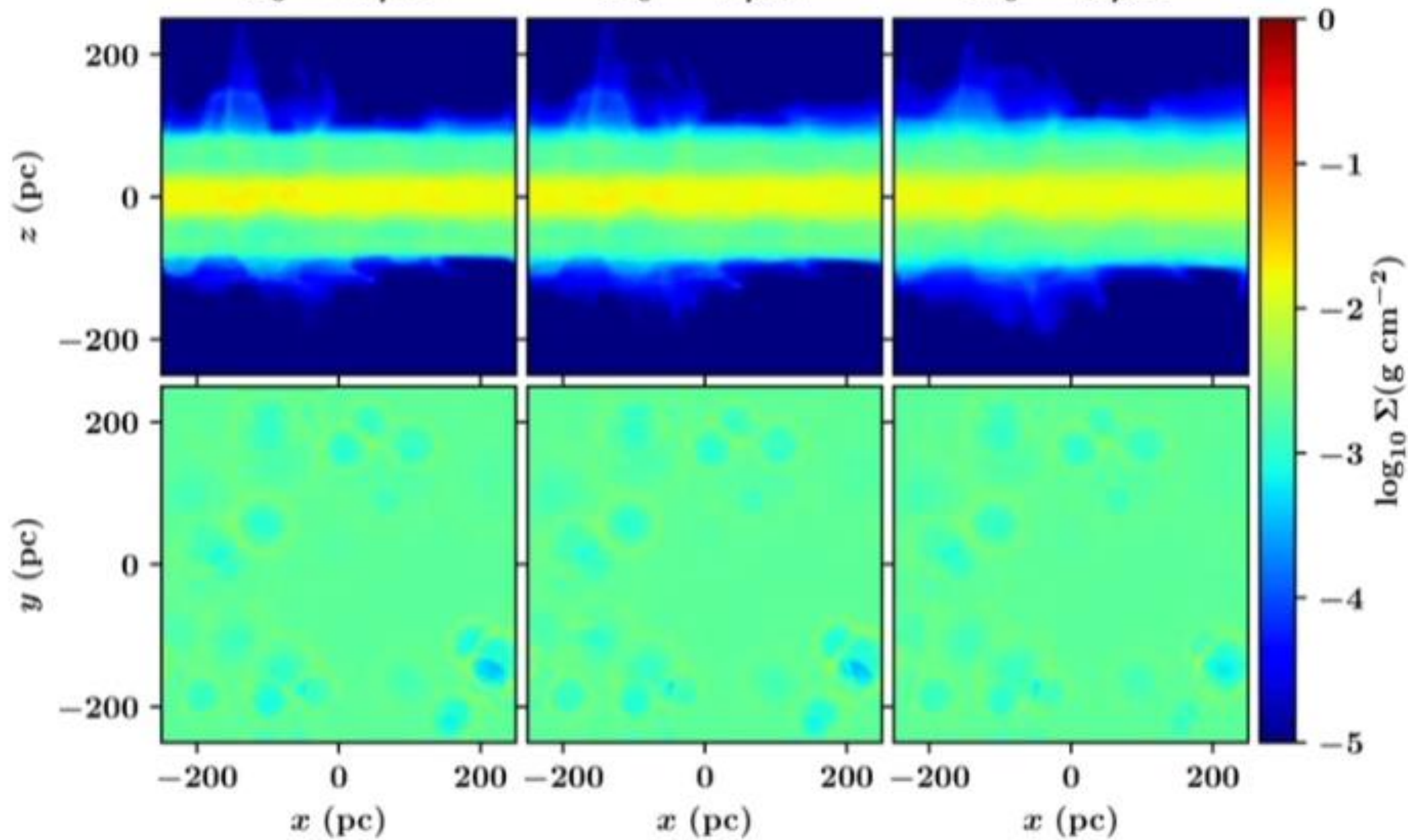


$t = 4 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

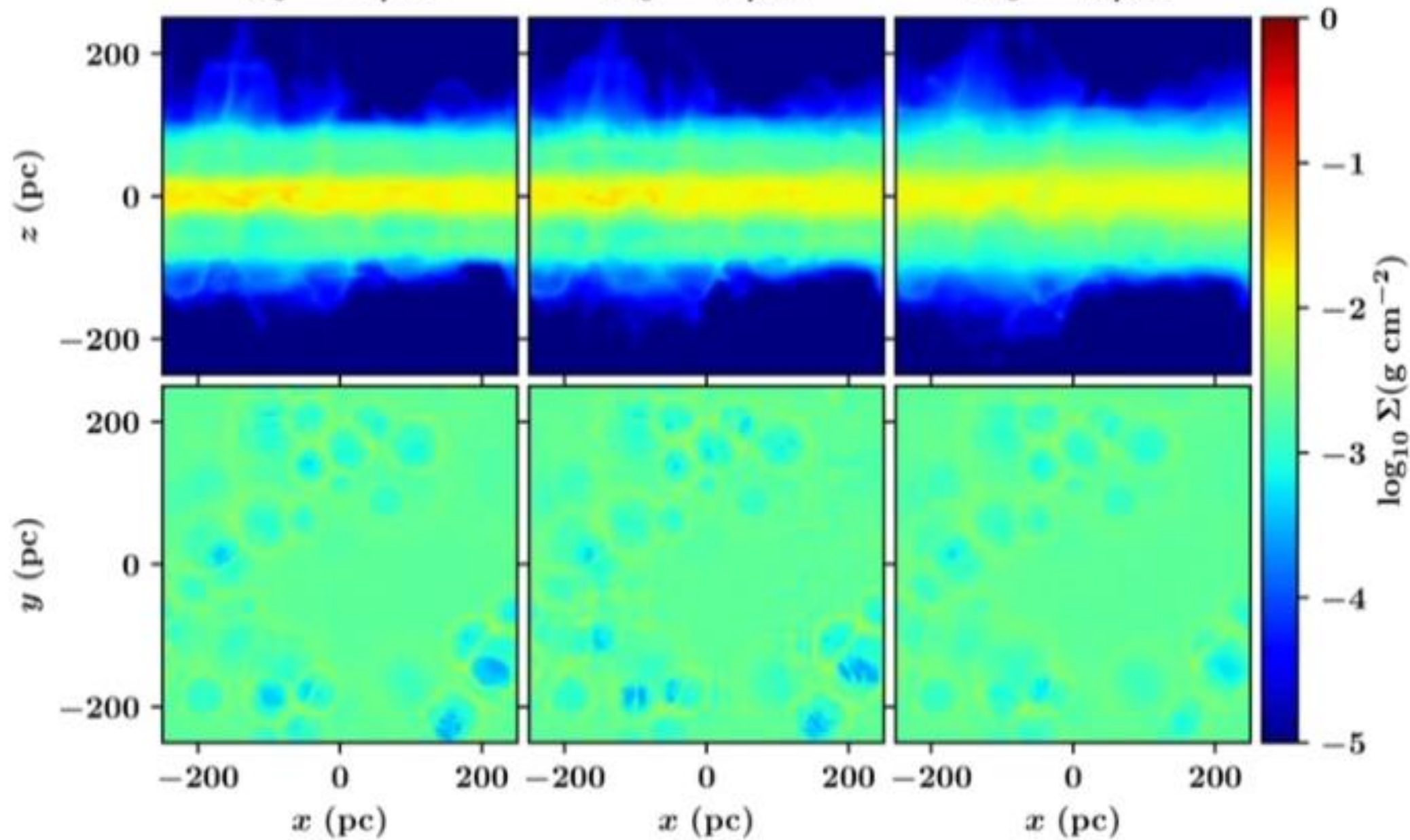


$t = 5 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

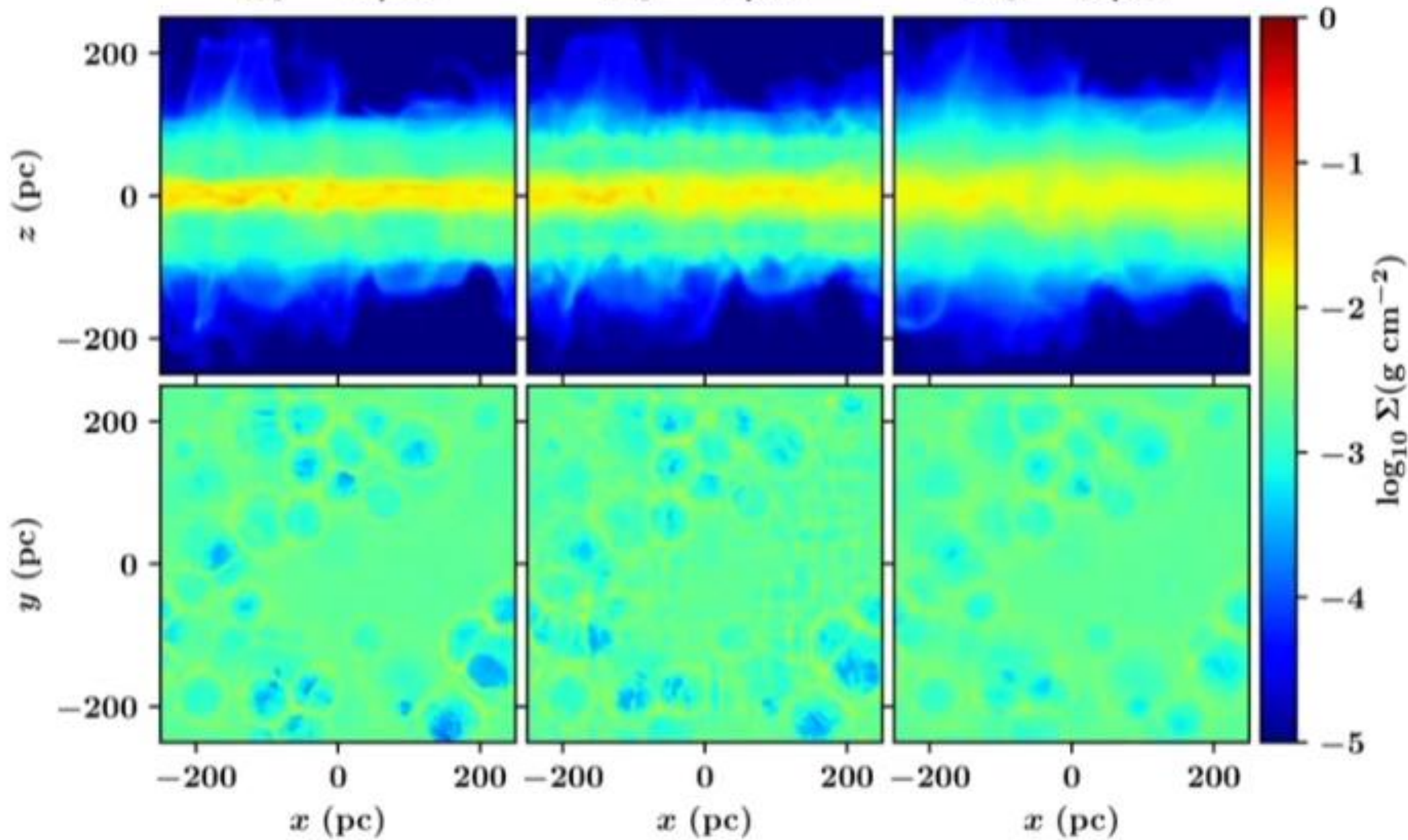


$t = 6 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$



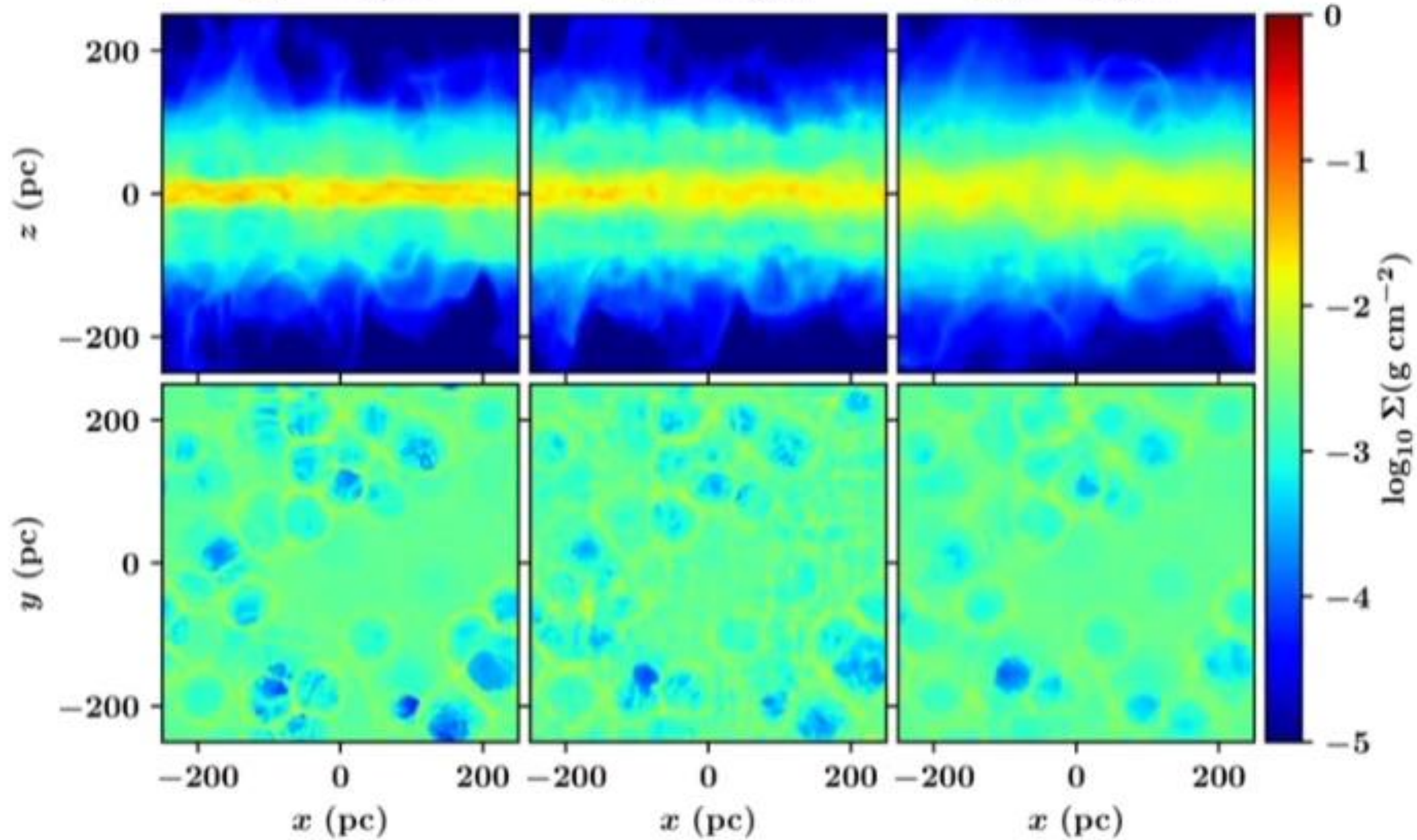


$t = 7 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

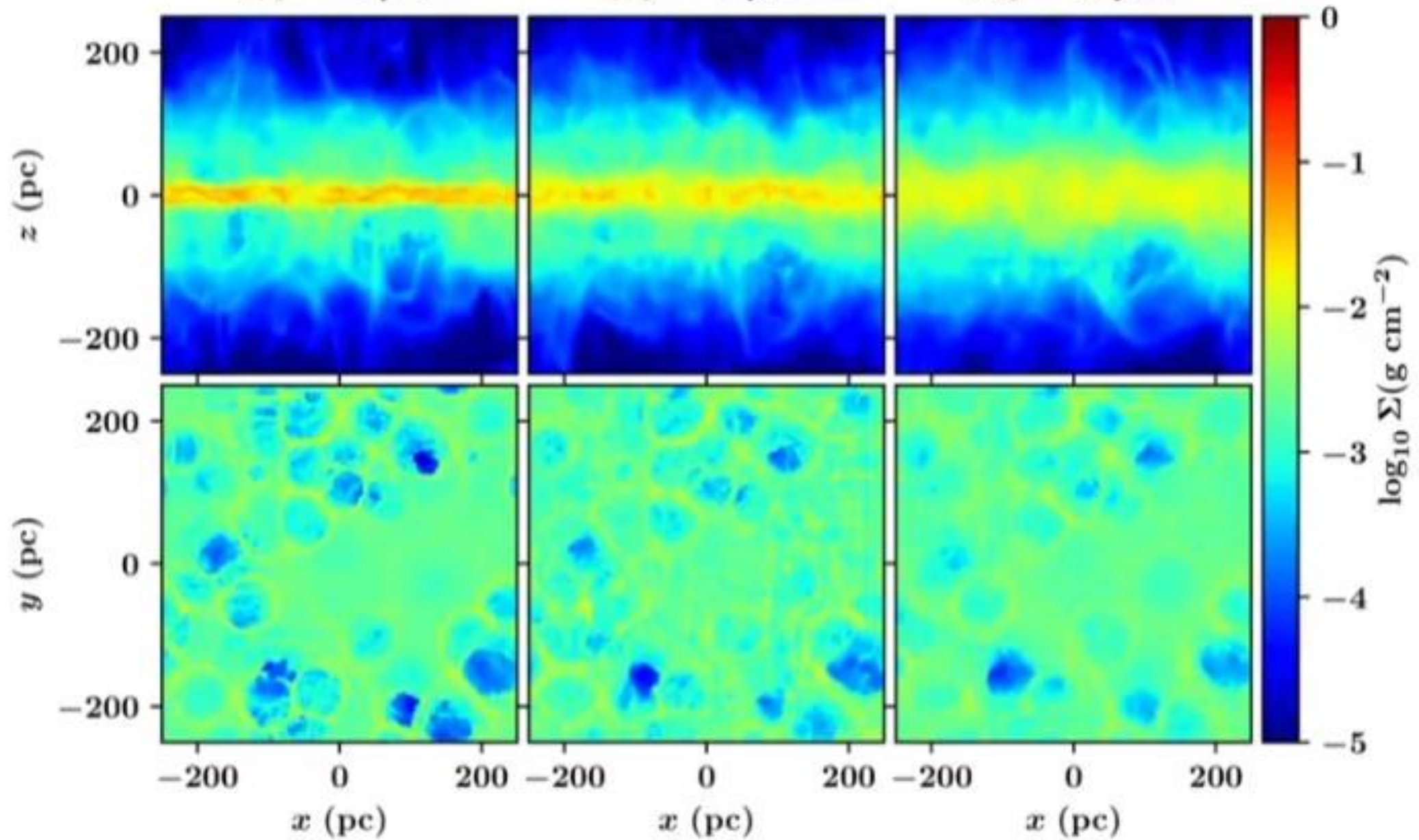


$t = 8 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

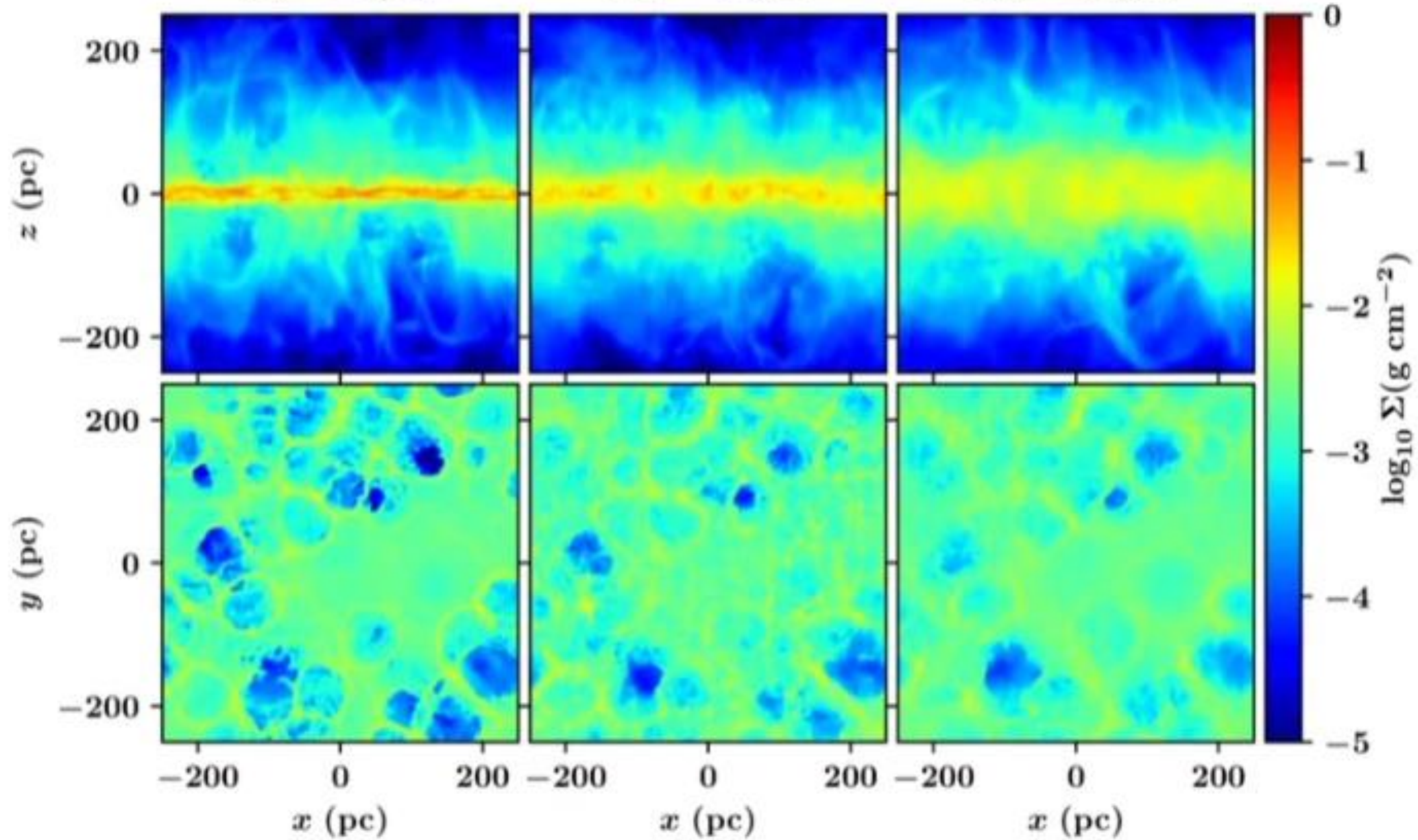


$t = 9 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

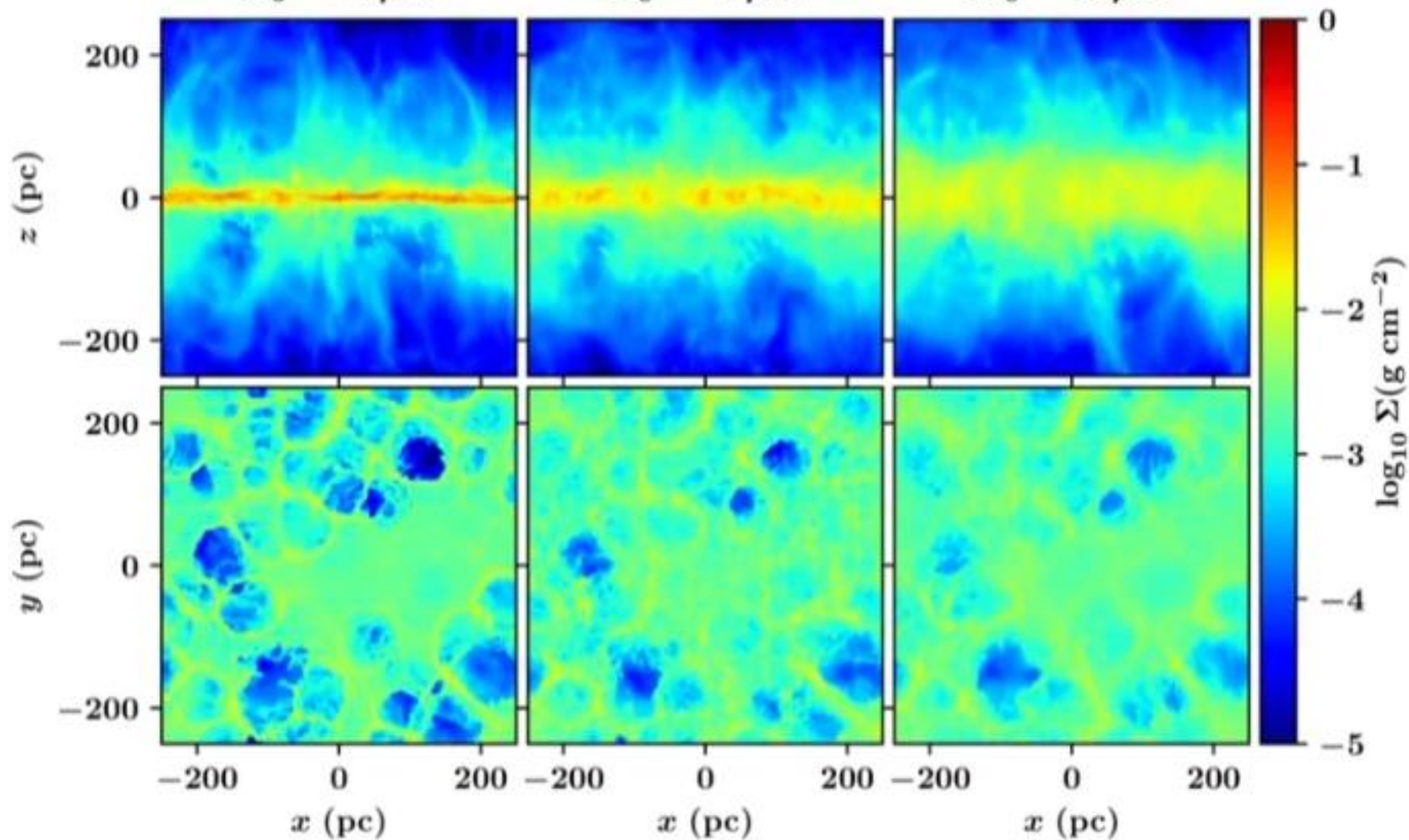


$t = 10 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

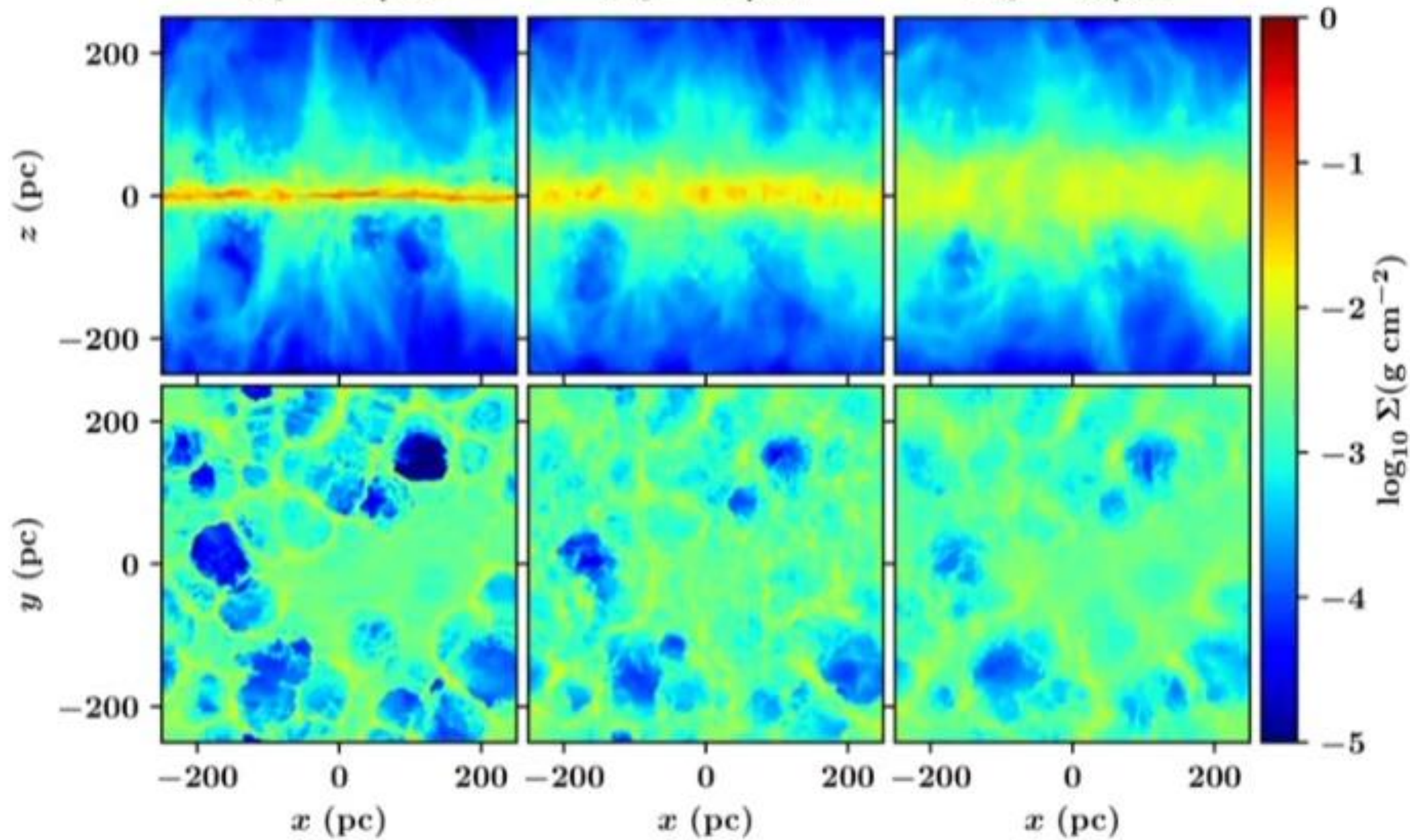


$t = 11 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

$B_0 = 6 \mu\text{G}$

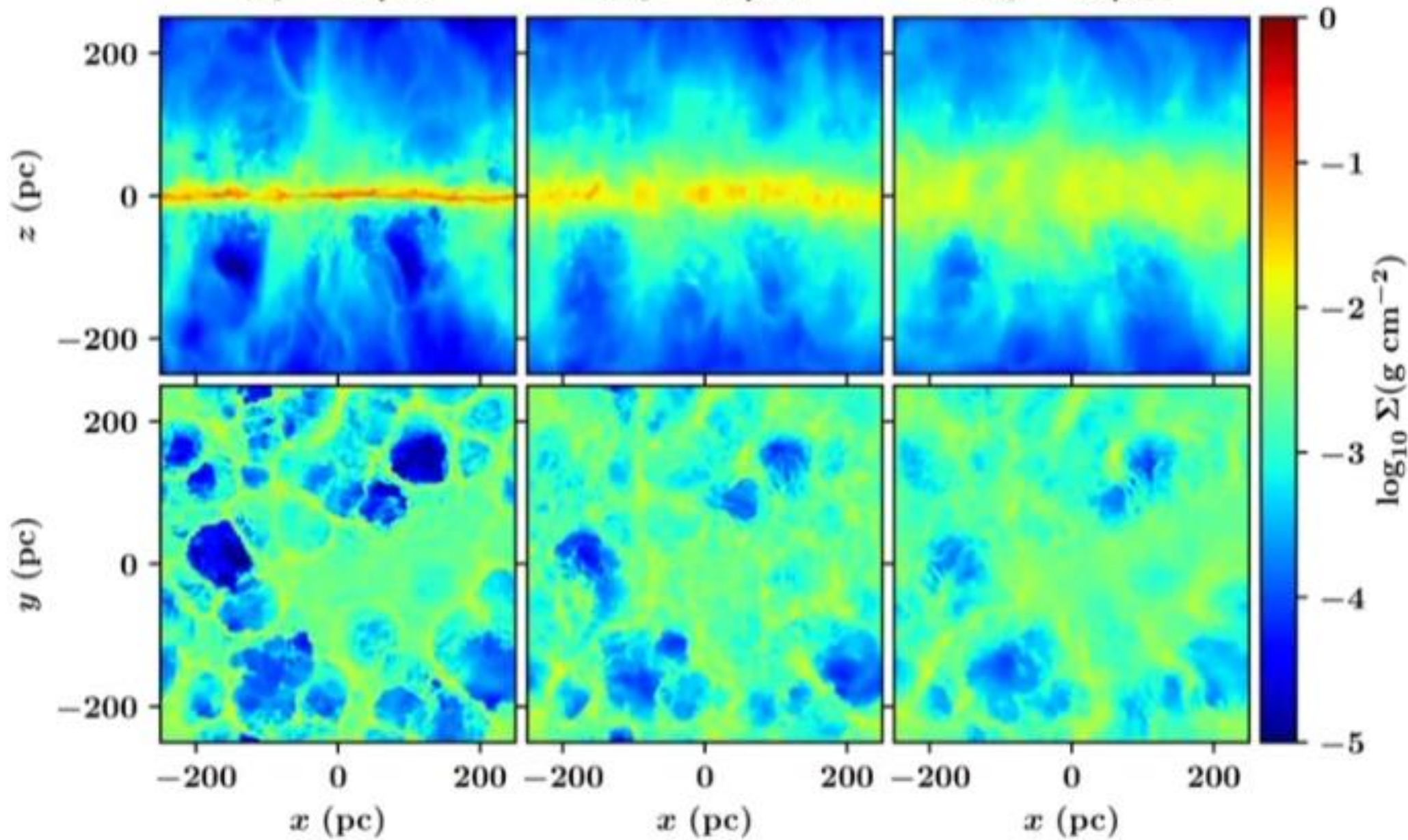


$t = 12 \text{ Myr}$

$B_0 = 0 \mu\text{G}$

$B_0 = 3 \mu\text{G}$

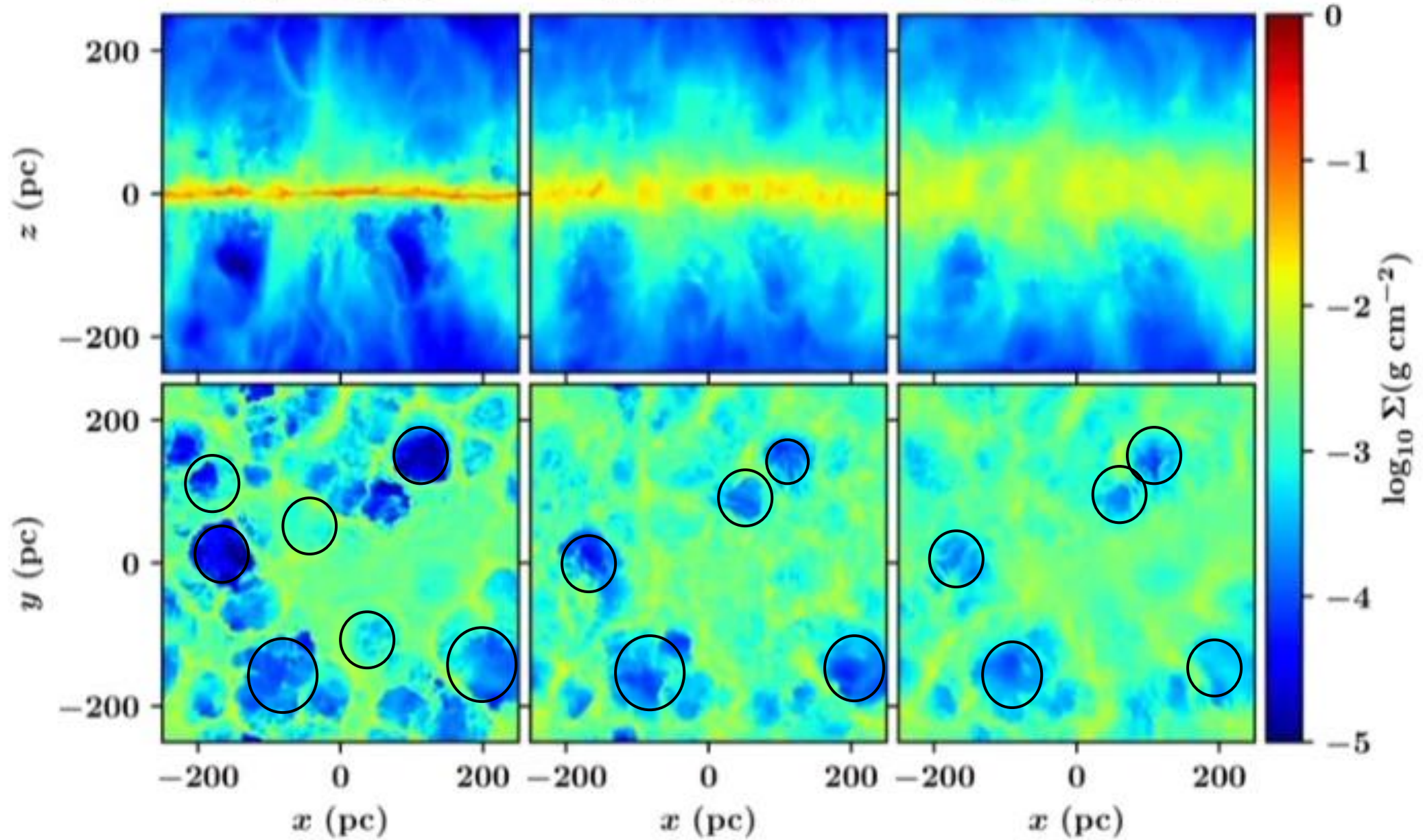
$B_0 = 6 \mu\text{G}$

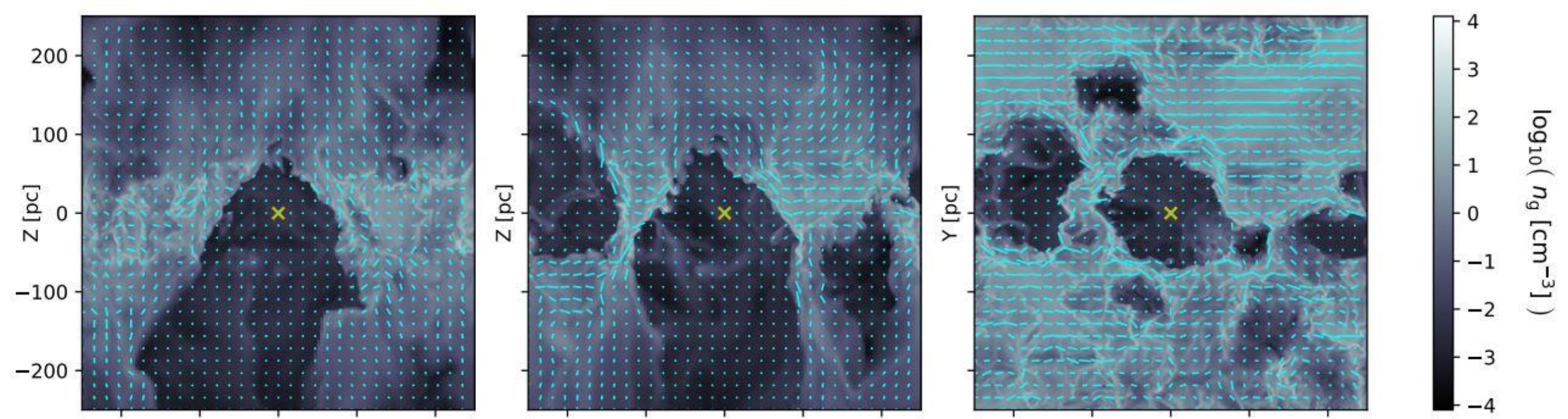


$t = 12 \text{ Myr}$   $B_0 = 0 \mu\text{G}$

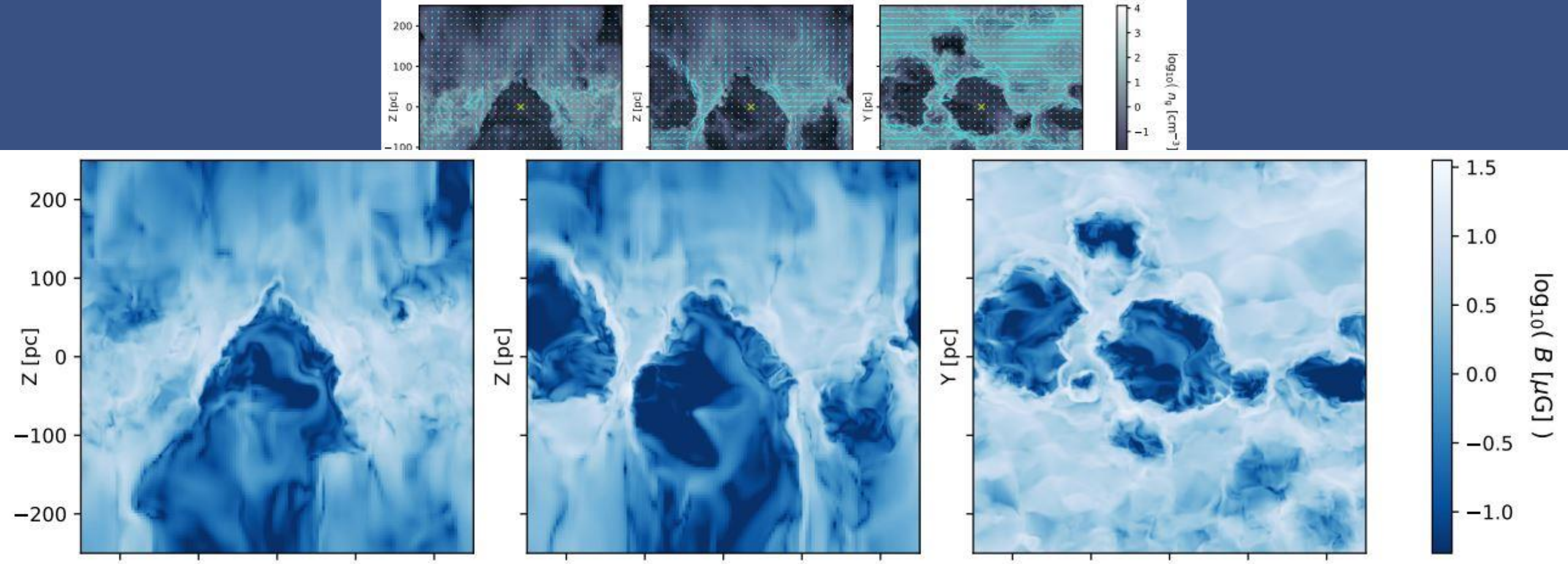
$B_0 = 3 \mu\text{G}$

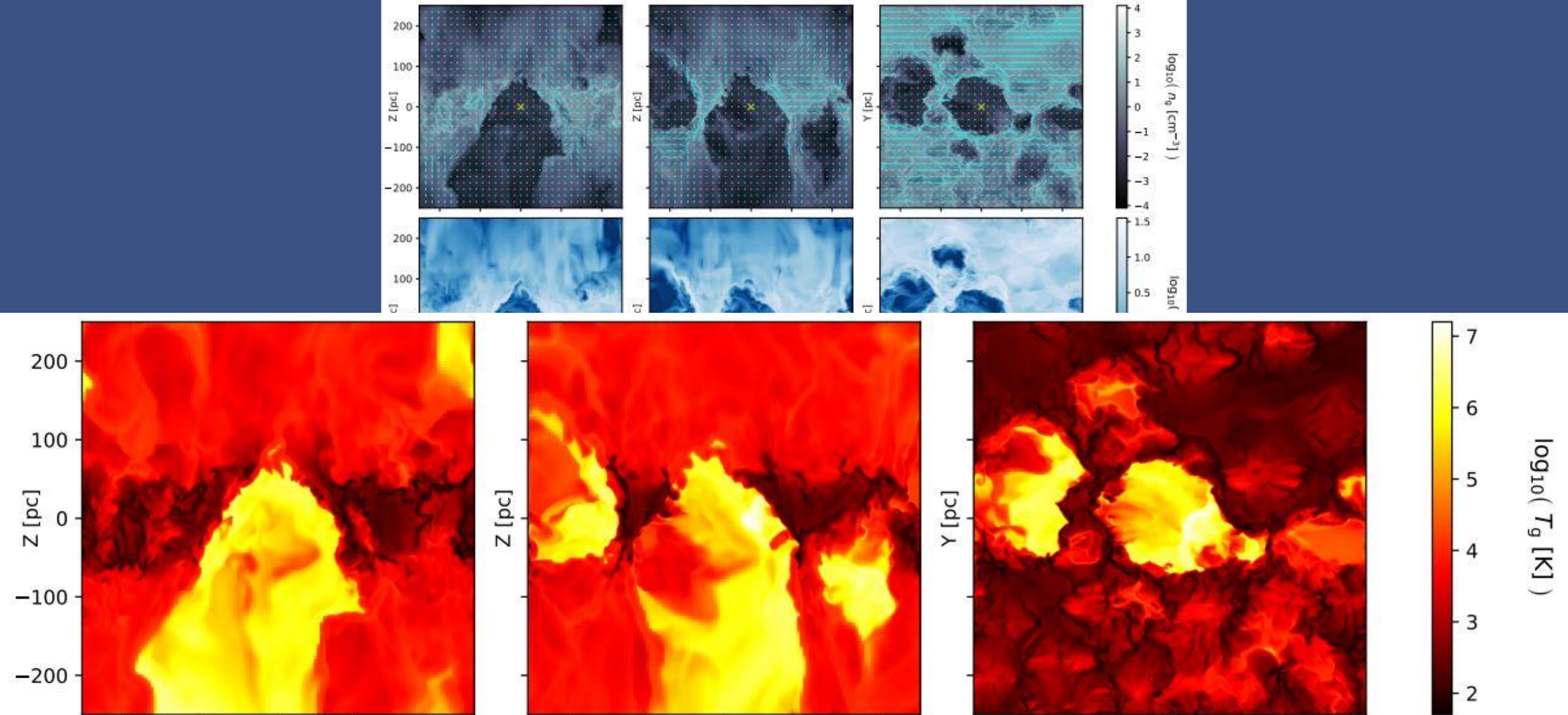
$B_0 = 6 \mu\text{G}$

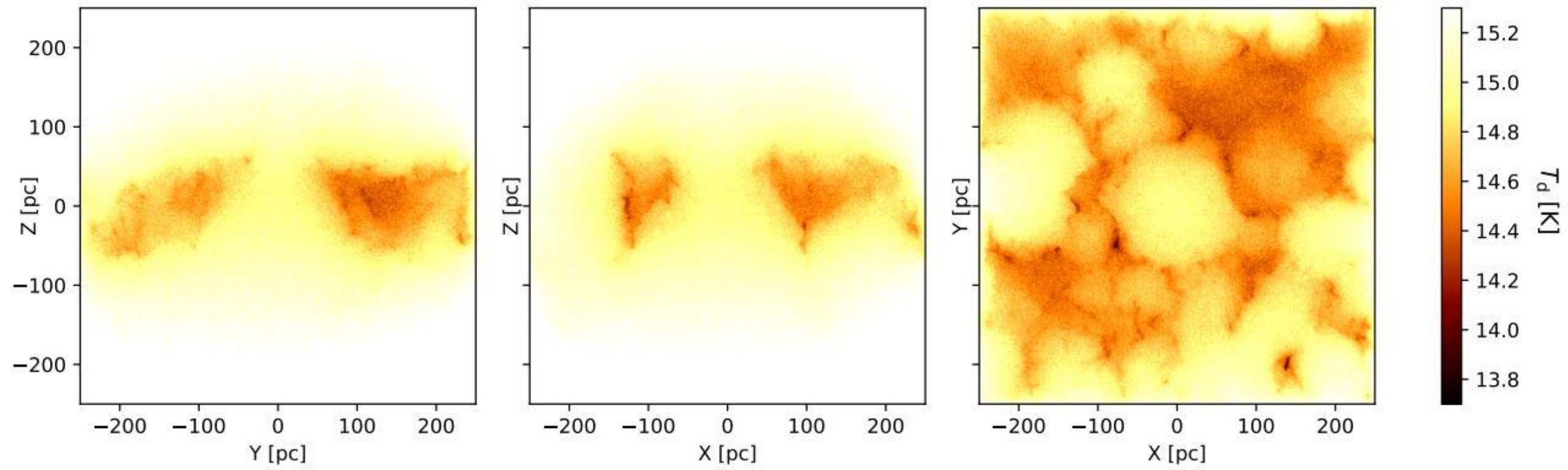
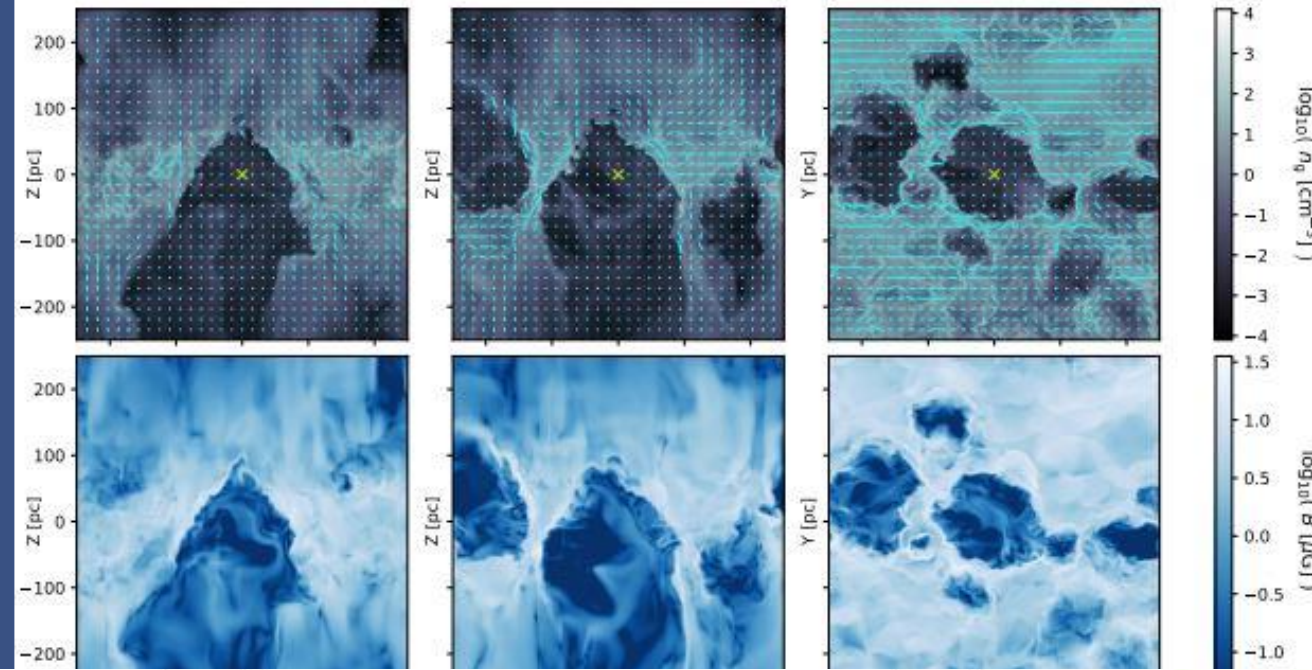


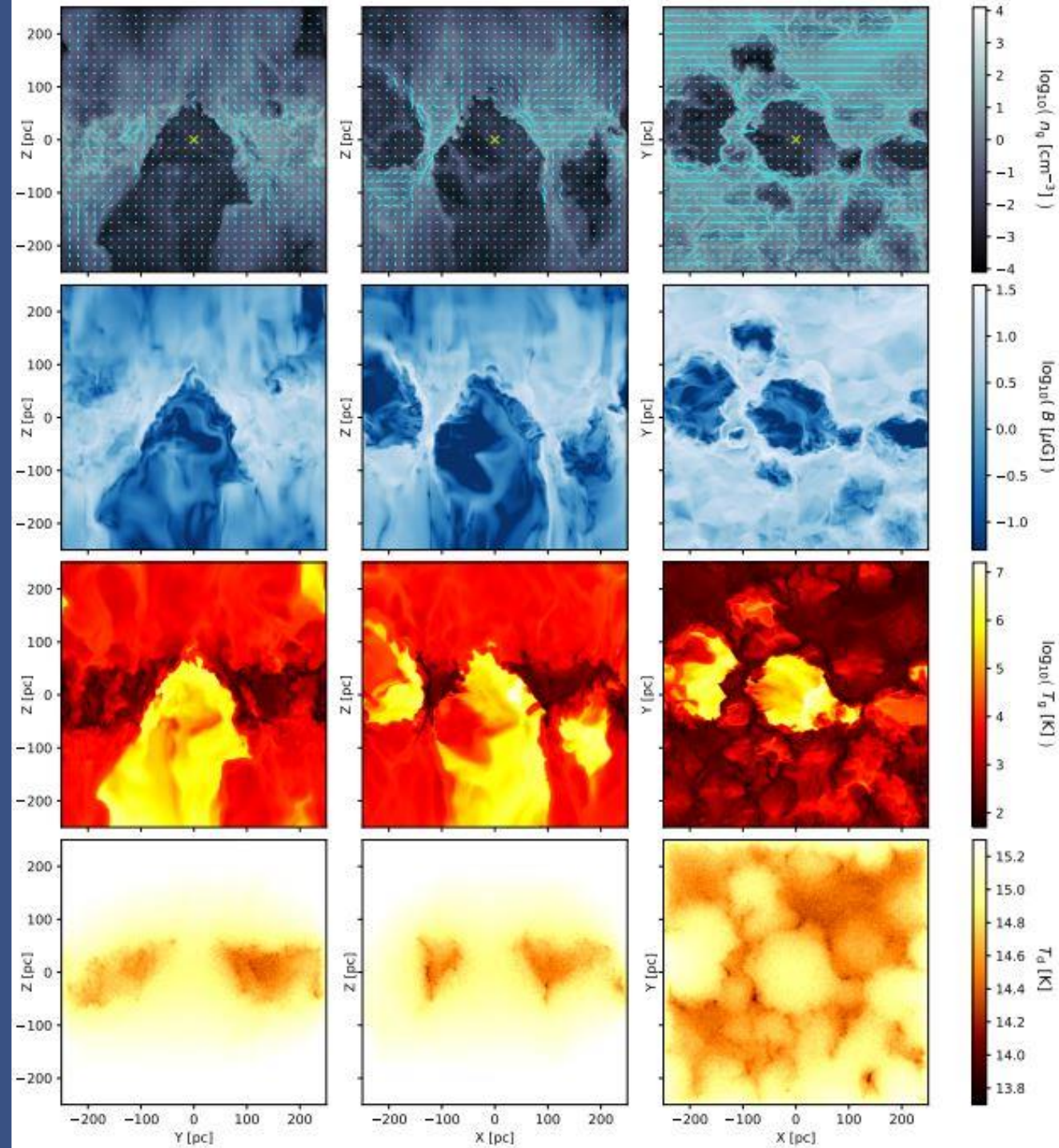


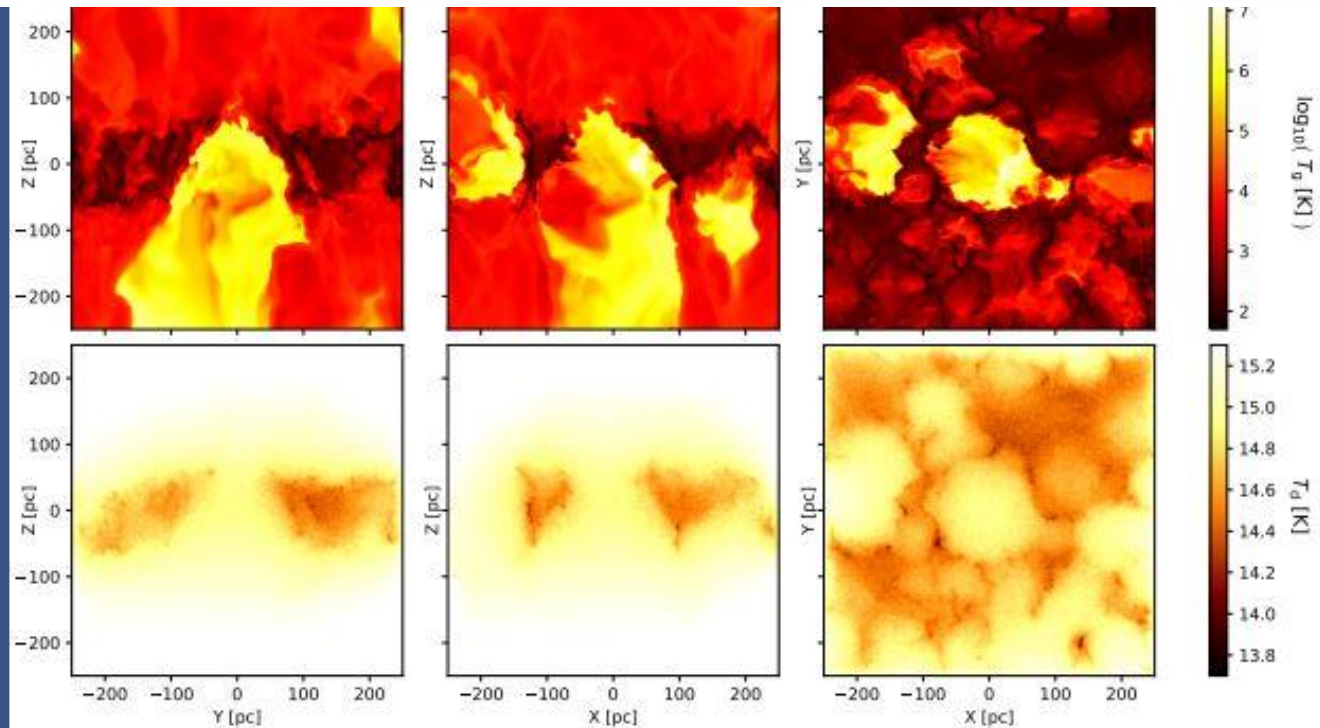
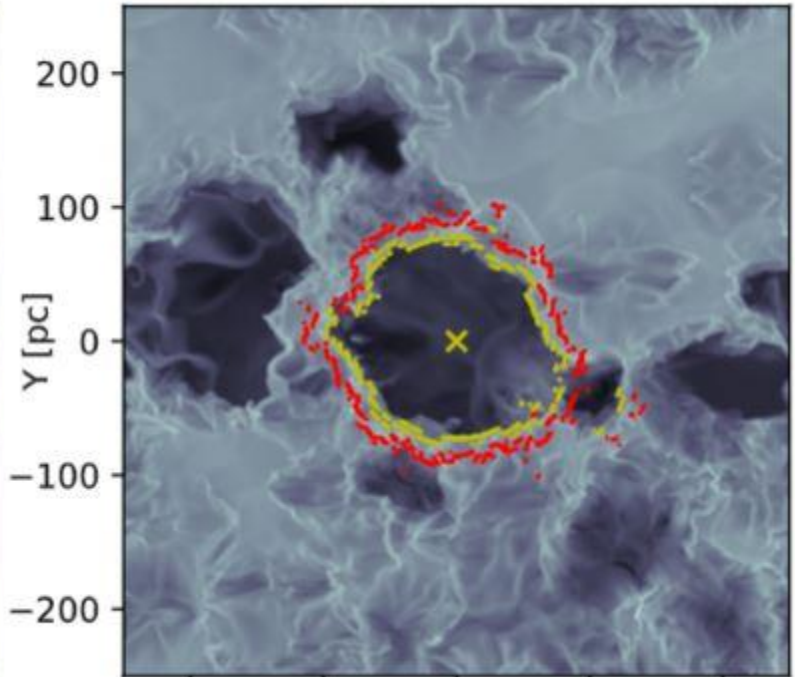
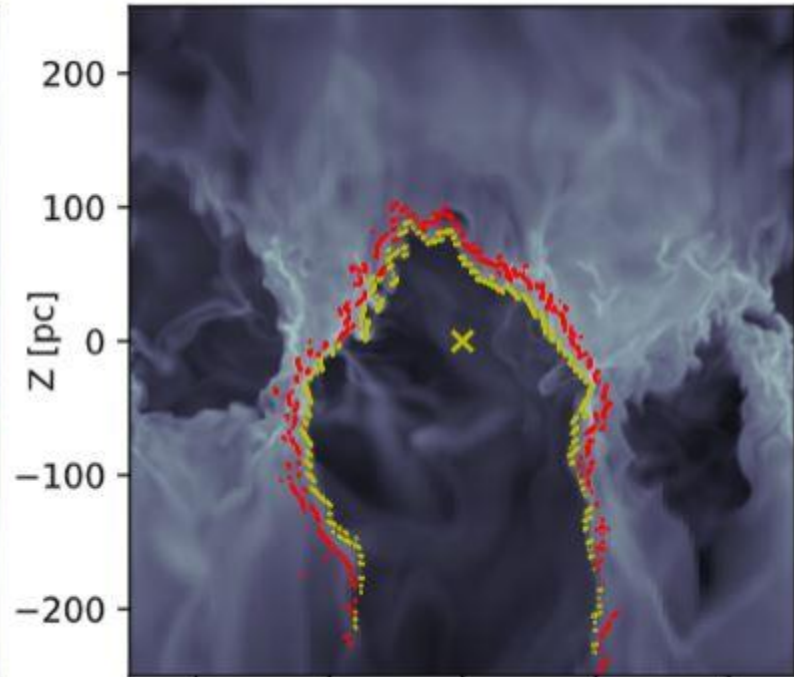
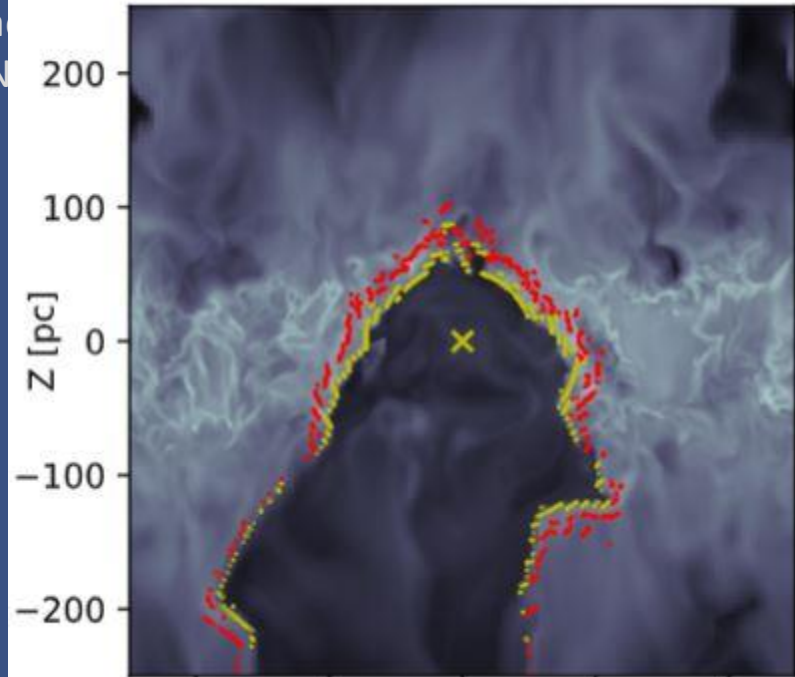


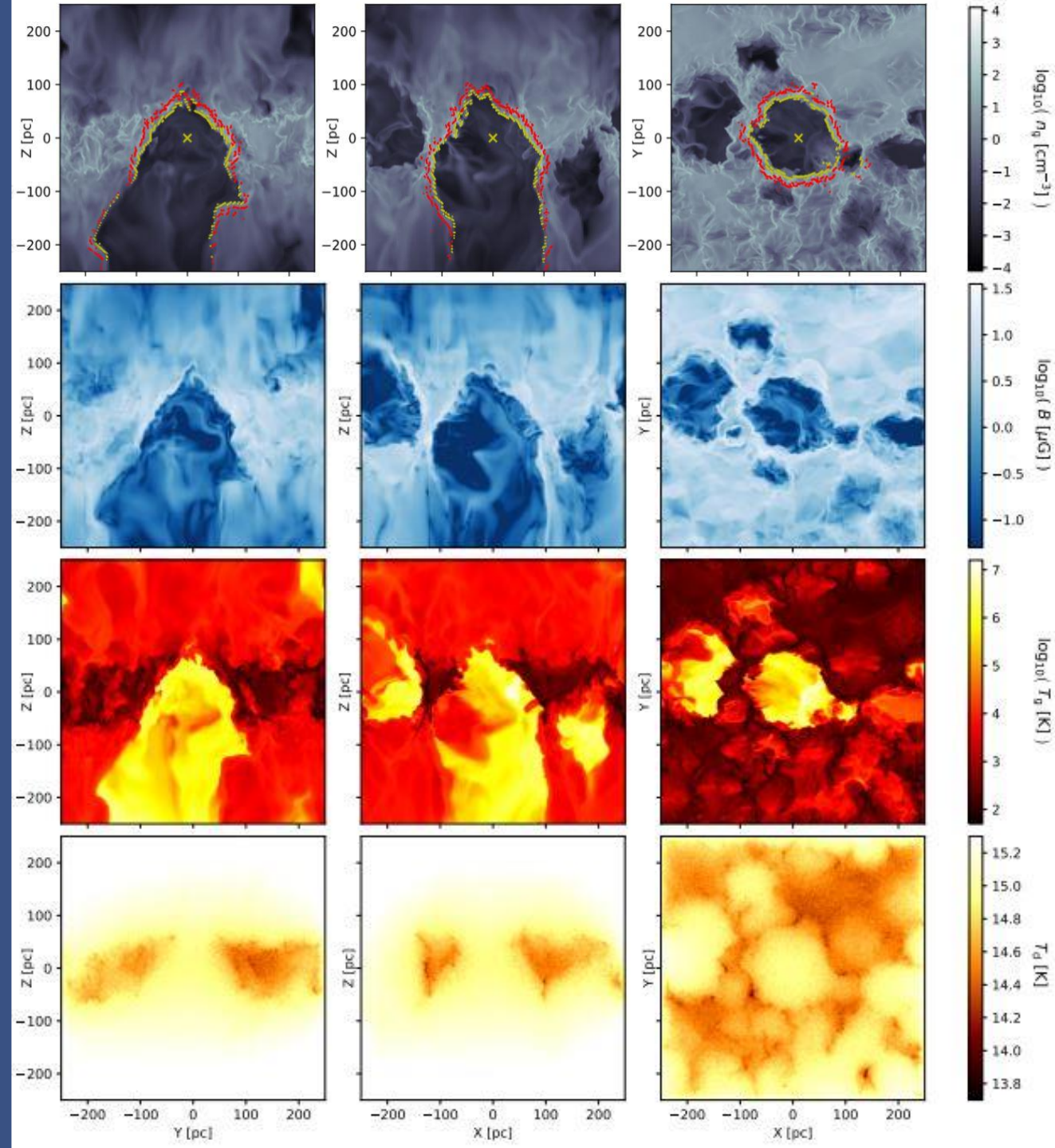












# Synthetic observations at 353 GHz

Radiative transfer code: POLARIS

## Input

- Gas density
- Gas temperature
- Magnetic fields
- Dust model
- Radiation sources



## Output

- Dust grain alignment
- Dust temperature
- polarization
- Column density
- ...

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Radiative transfer code: POLARIS

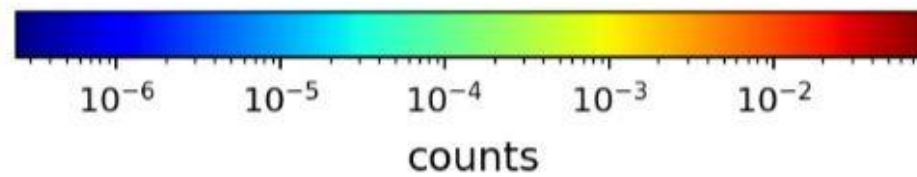
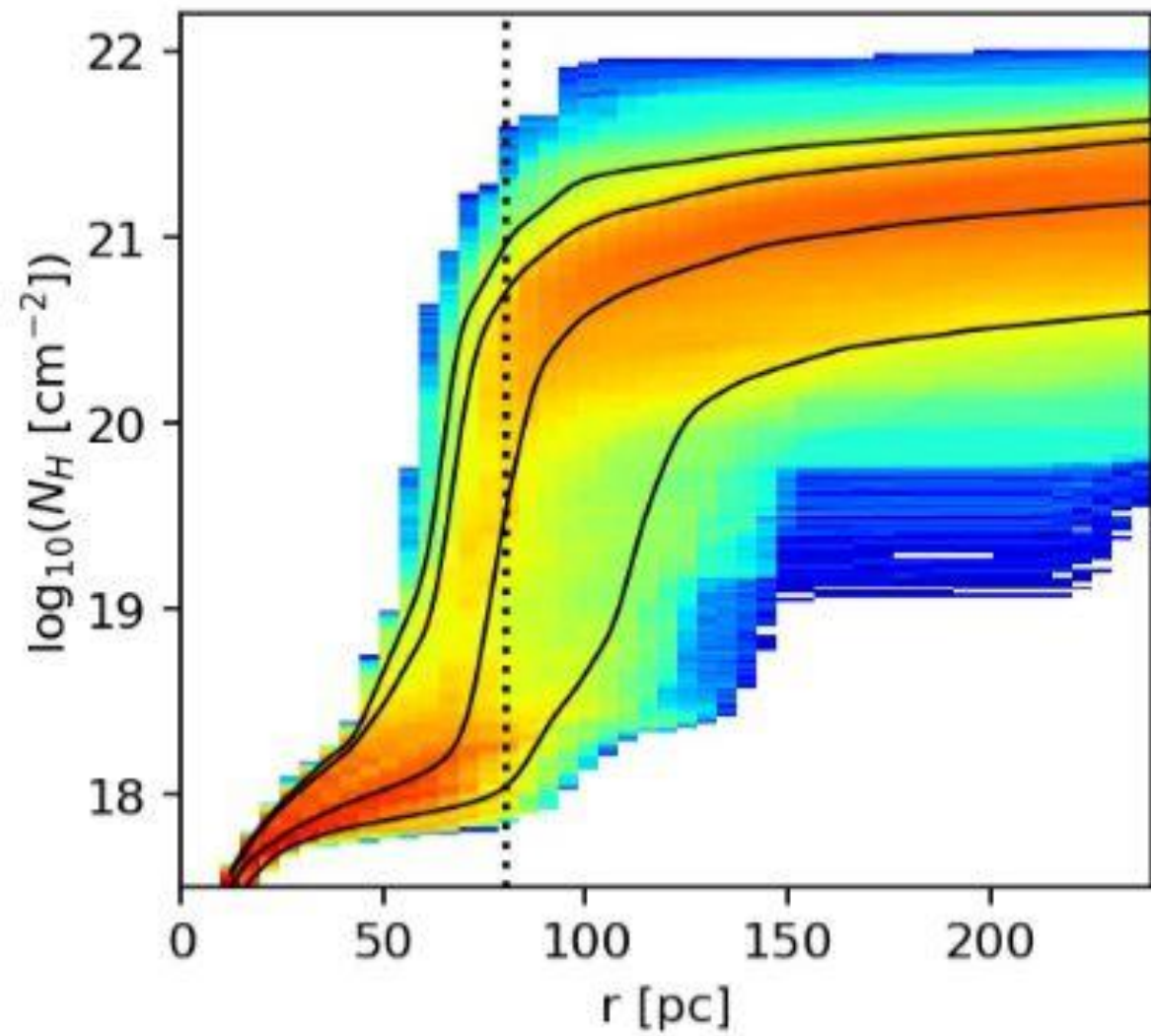
## Input

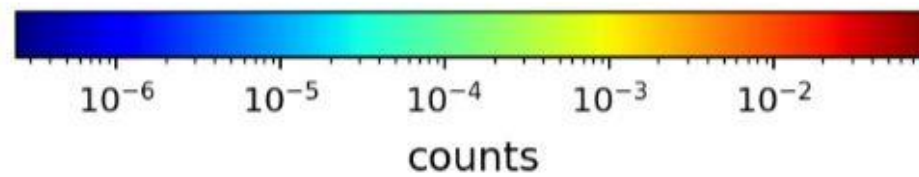
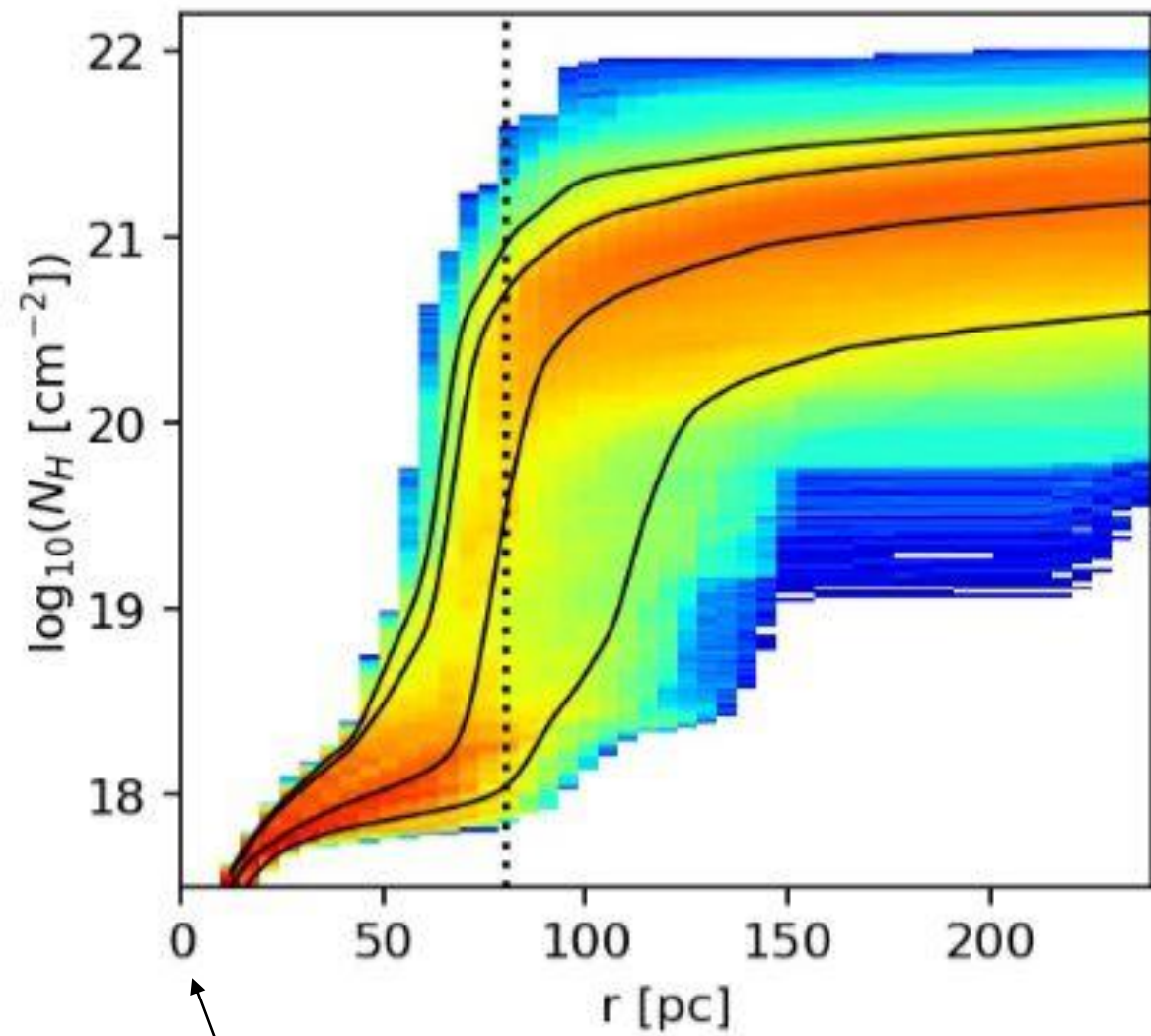
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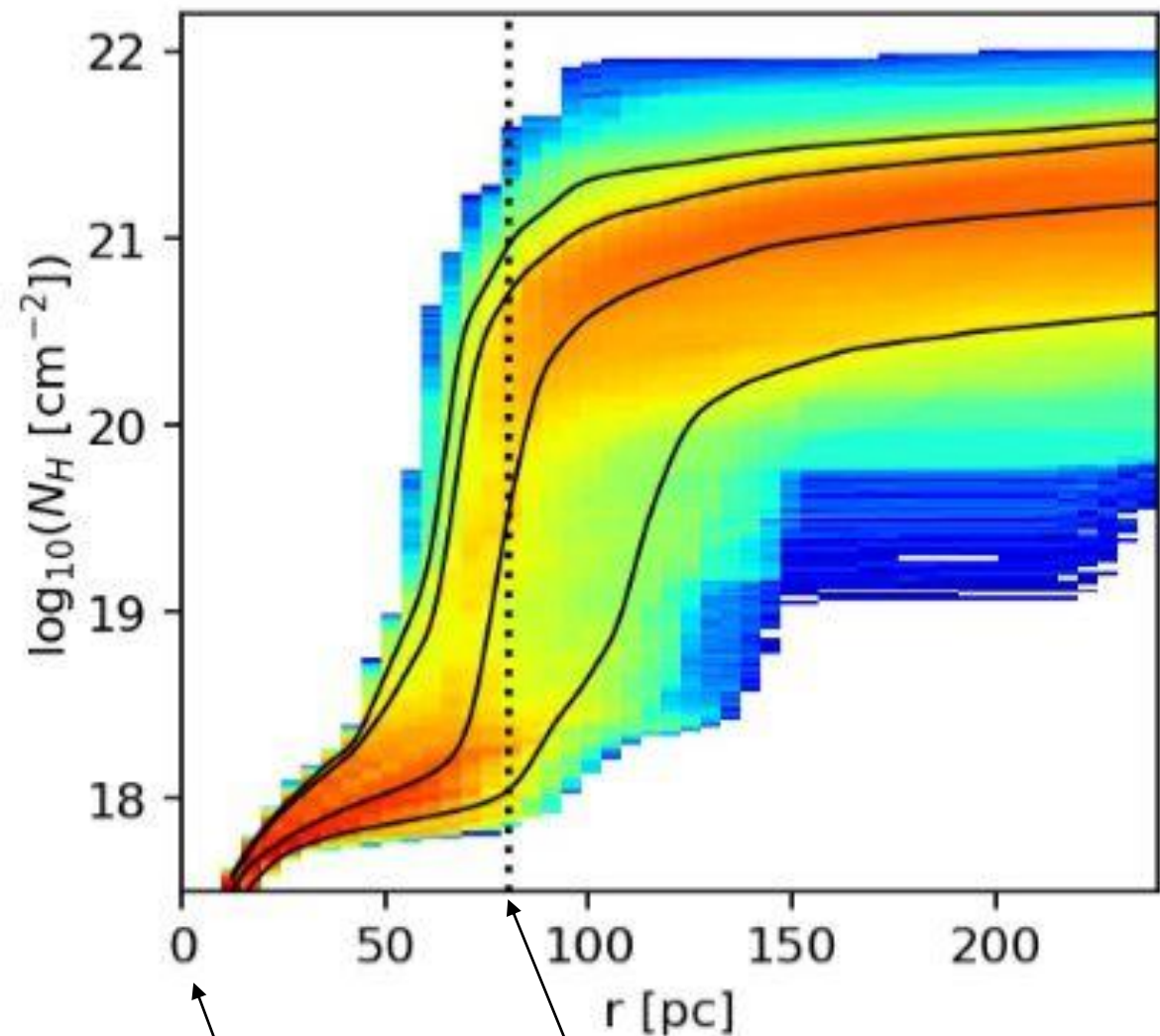


## Output

- Dust grain alignment
- Dust temperature
- Polarization
- Column density
- ...

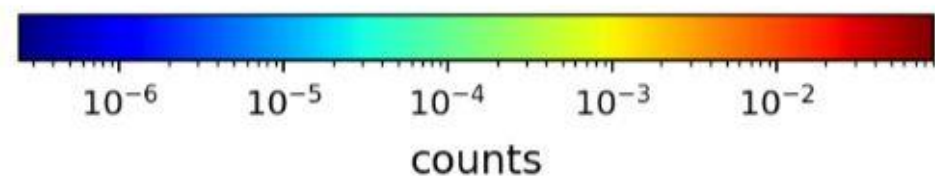


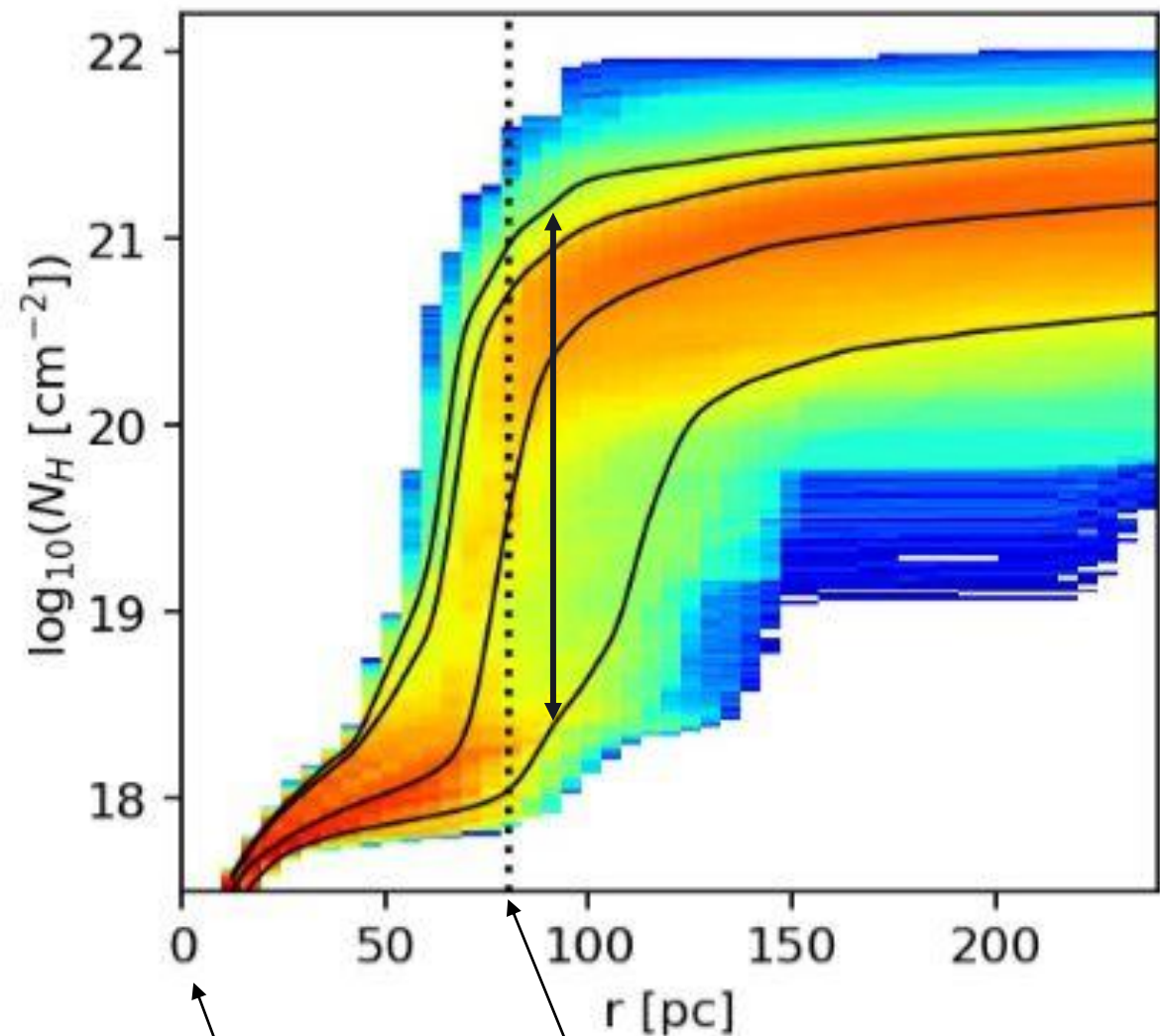




Observer

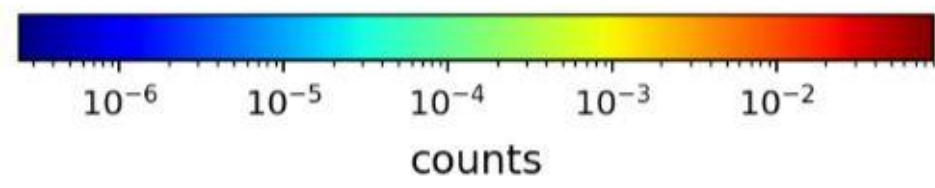
Distance to the bubble walls

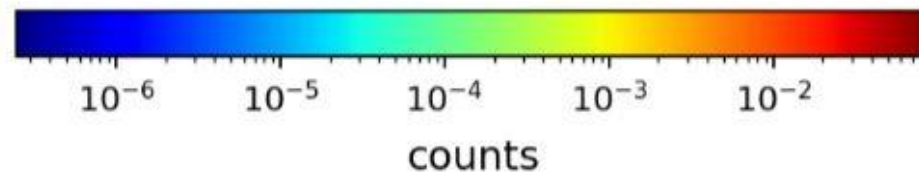
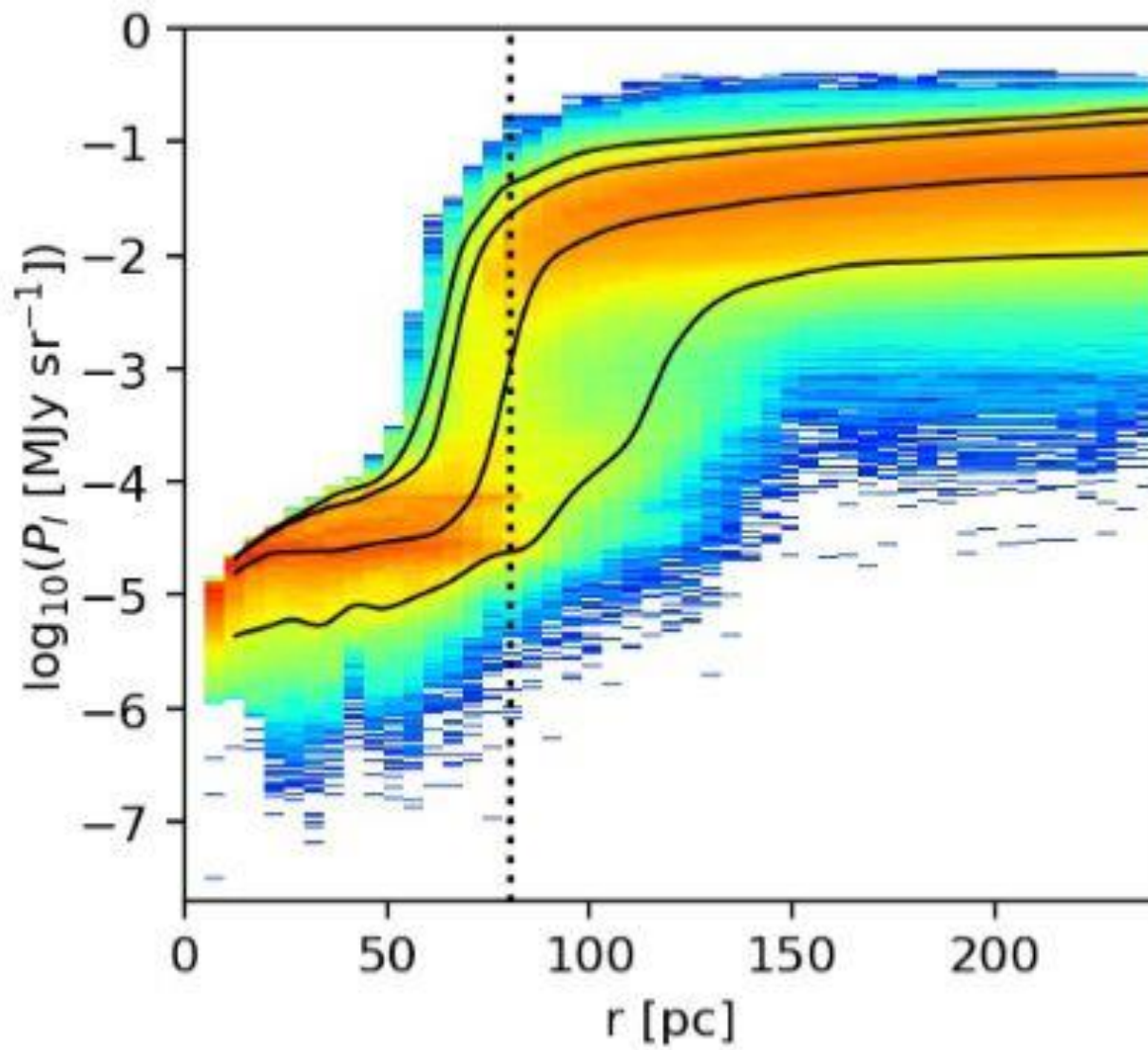
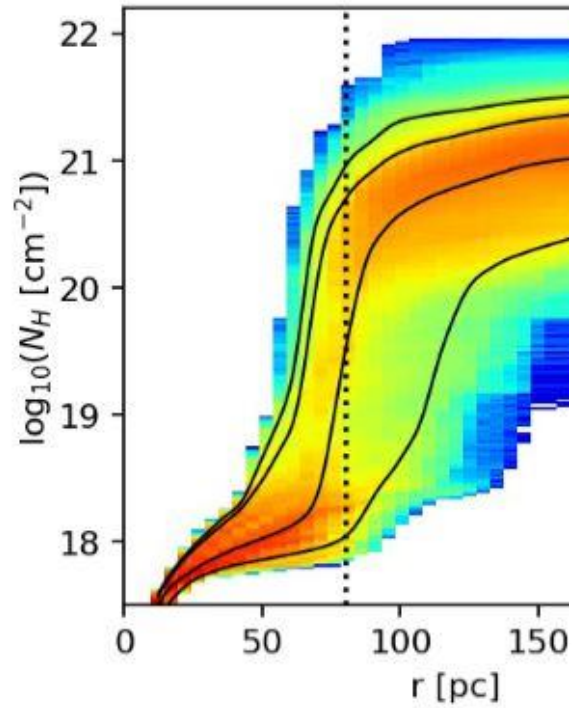


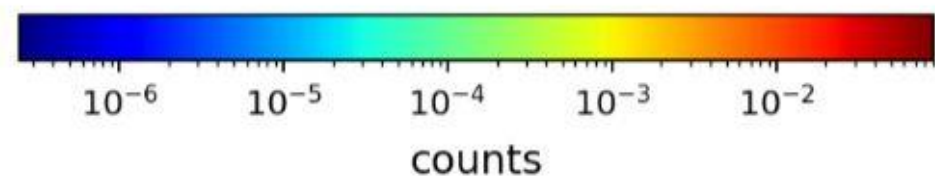
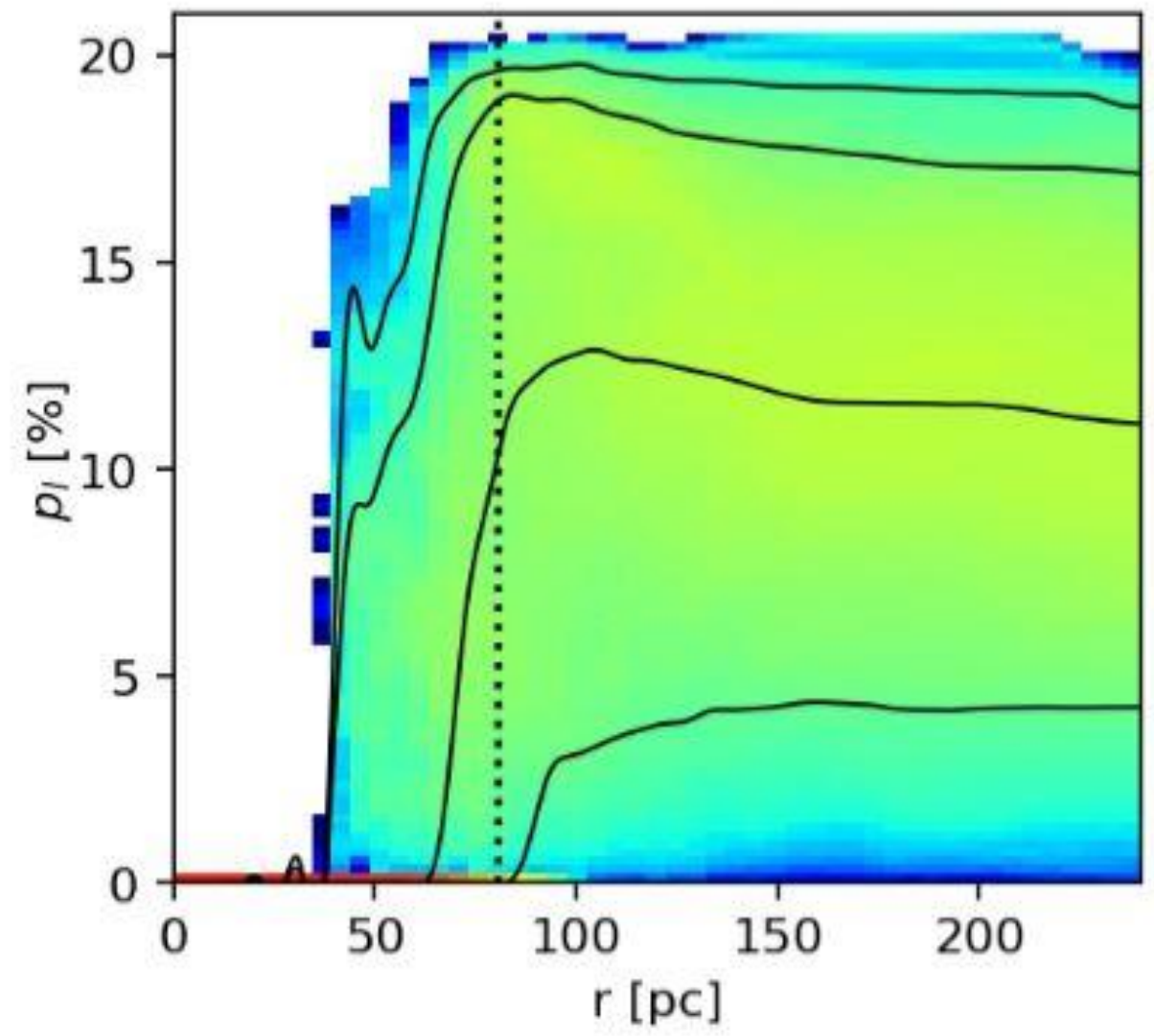
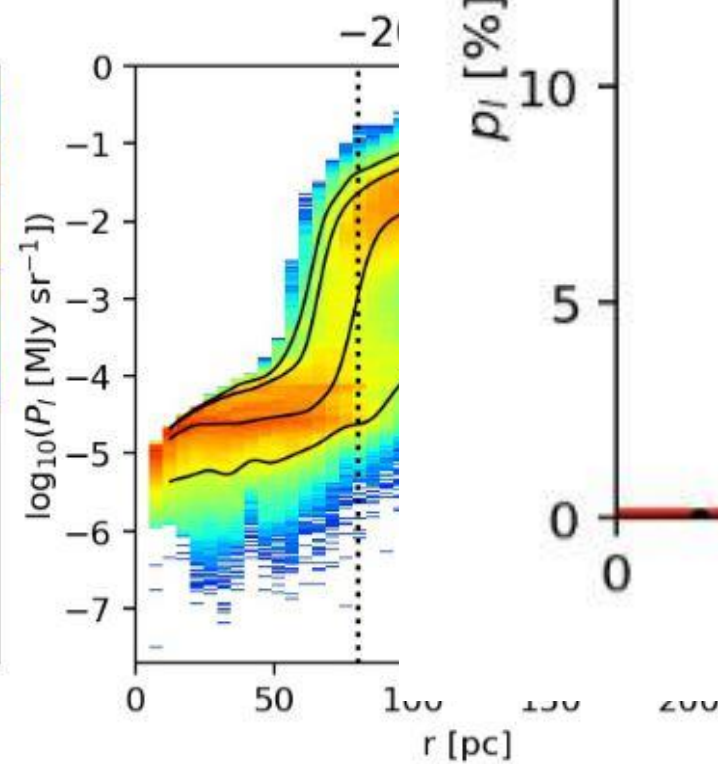
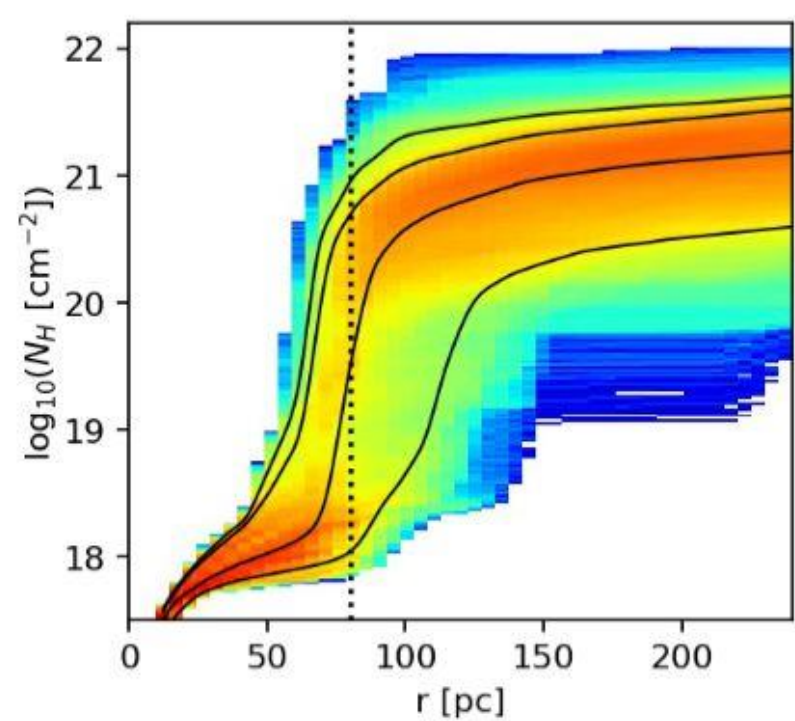


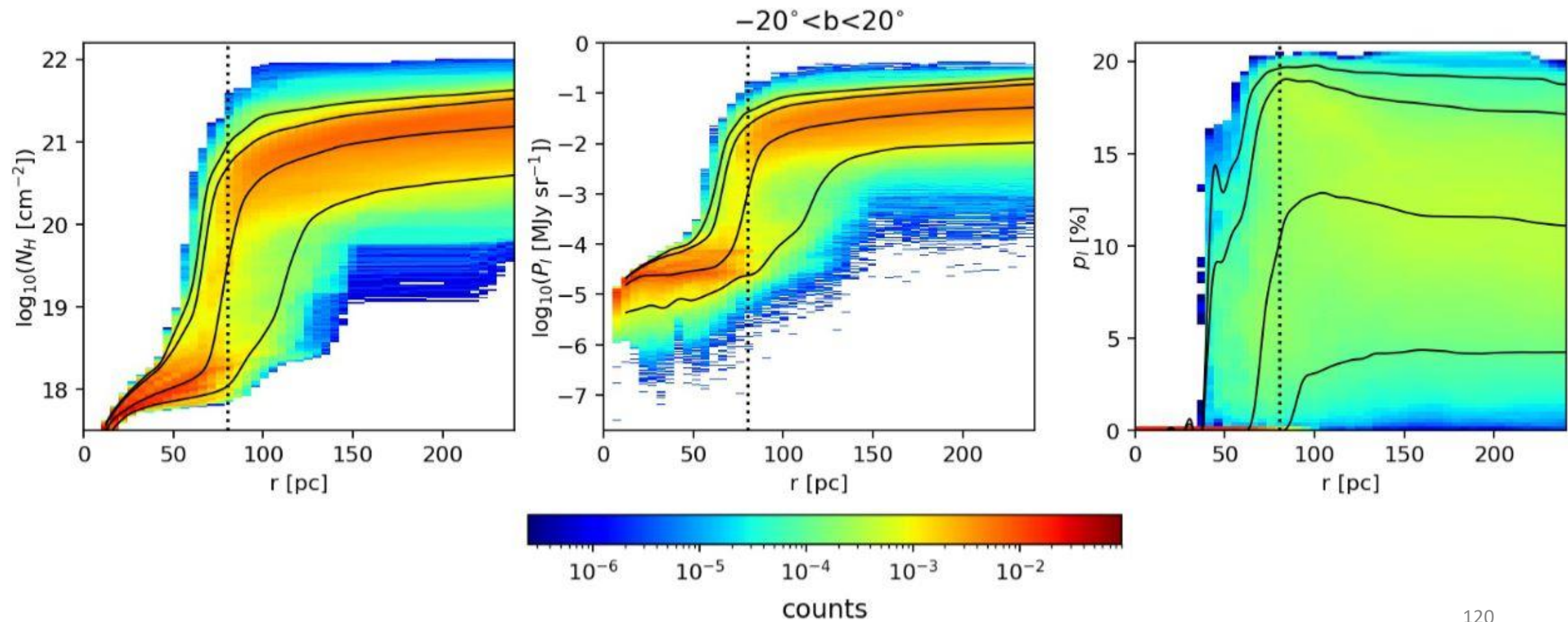
Observer

Distance to the bubble walls



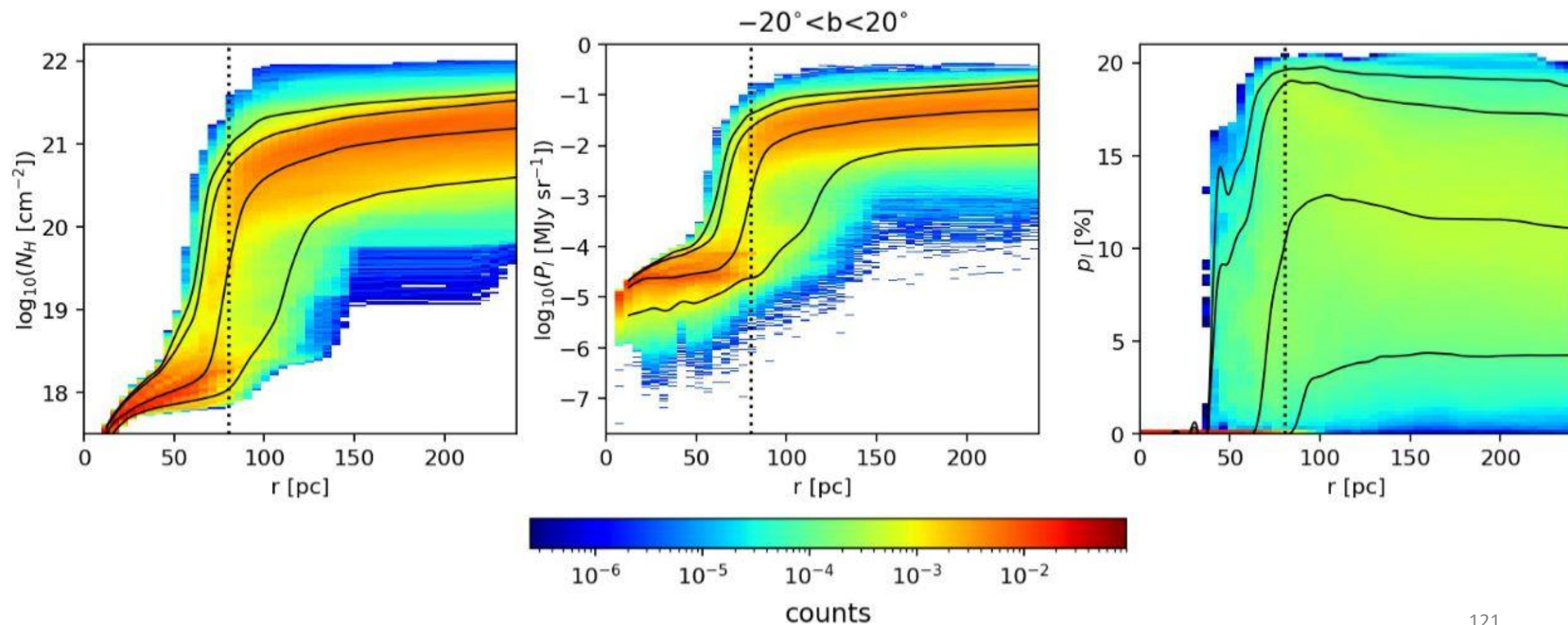


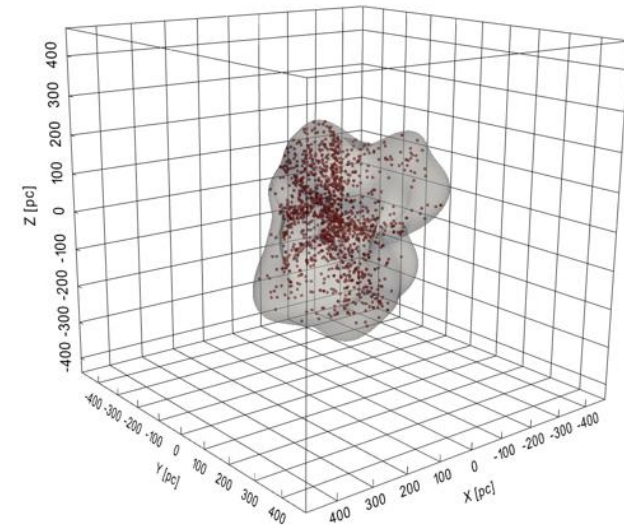
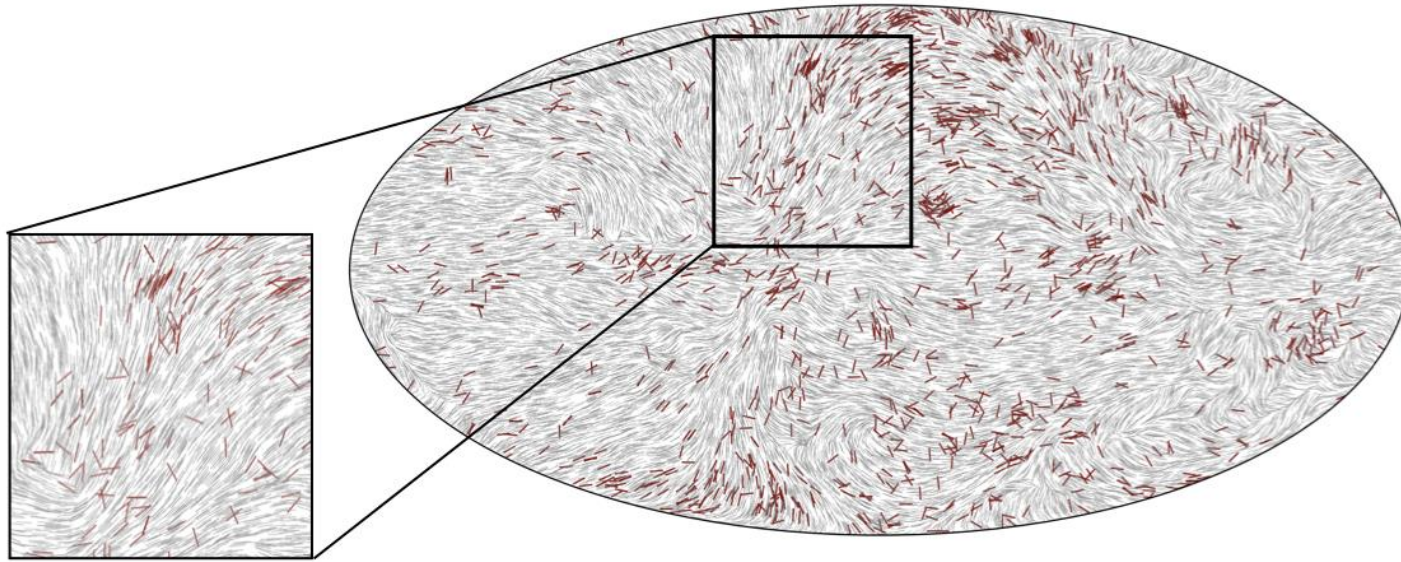


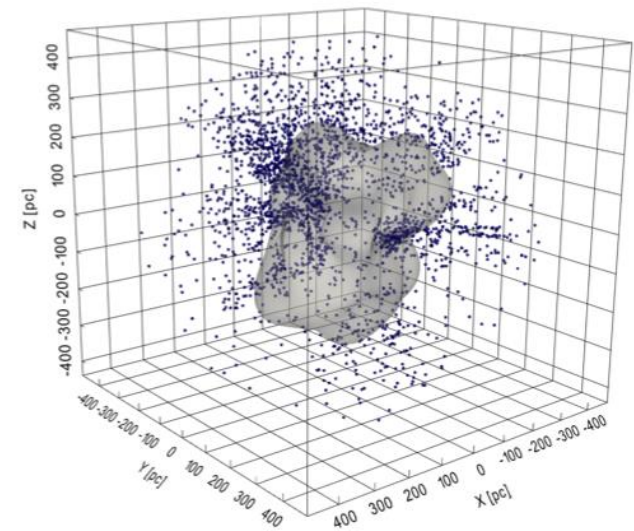
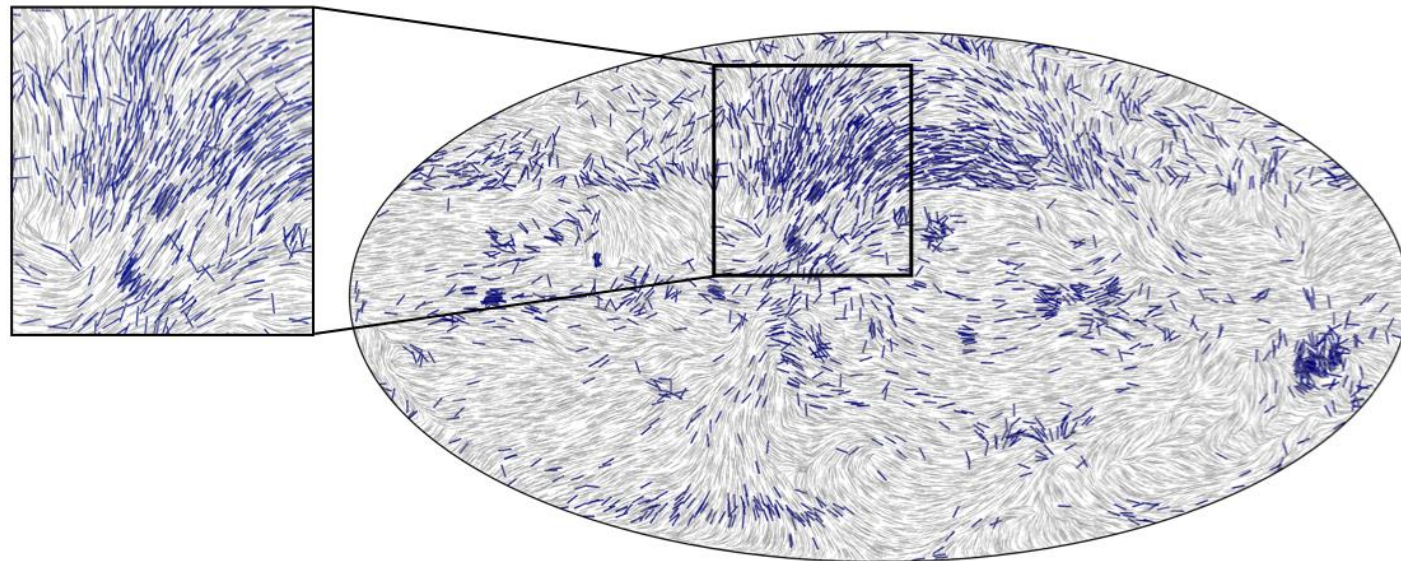
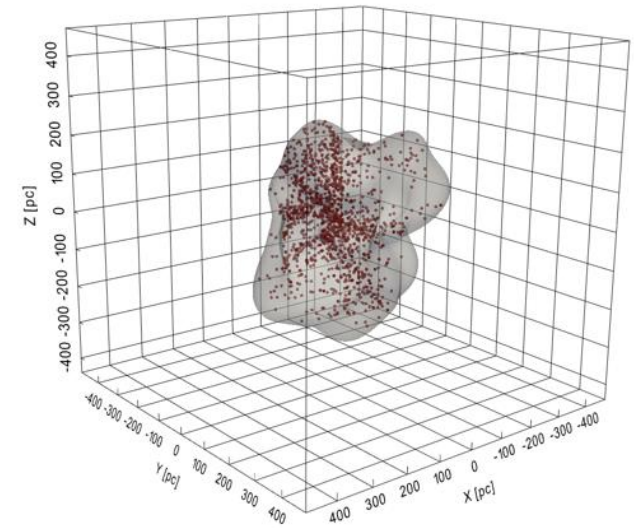
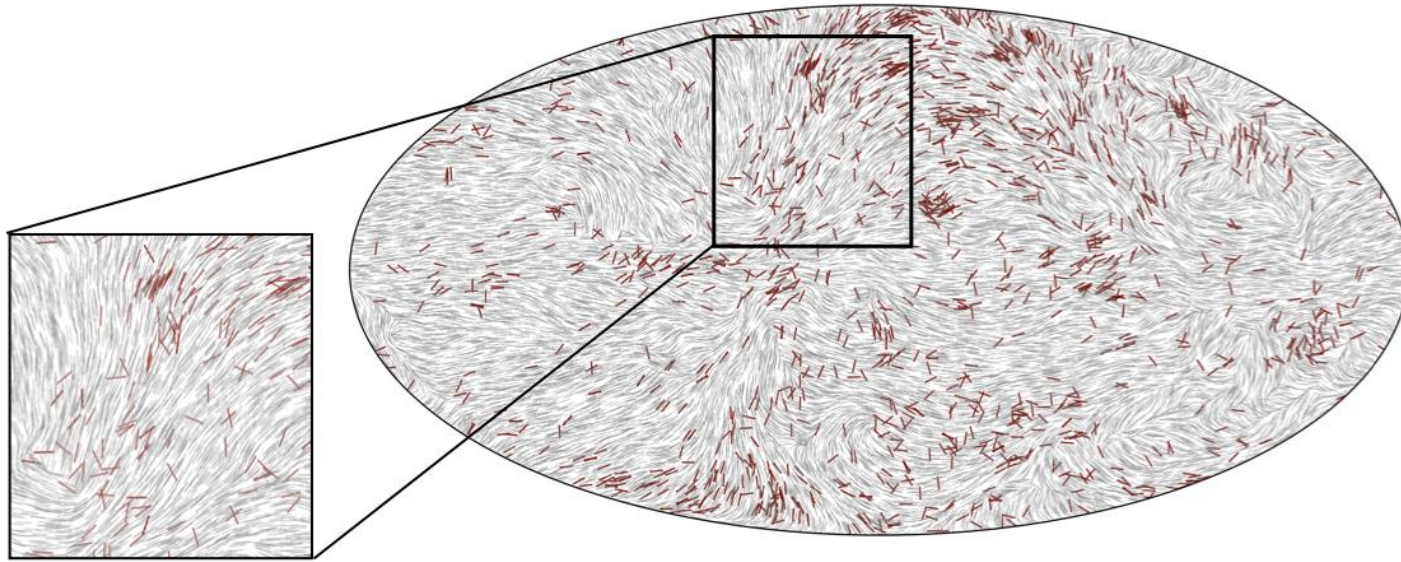


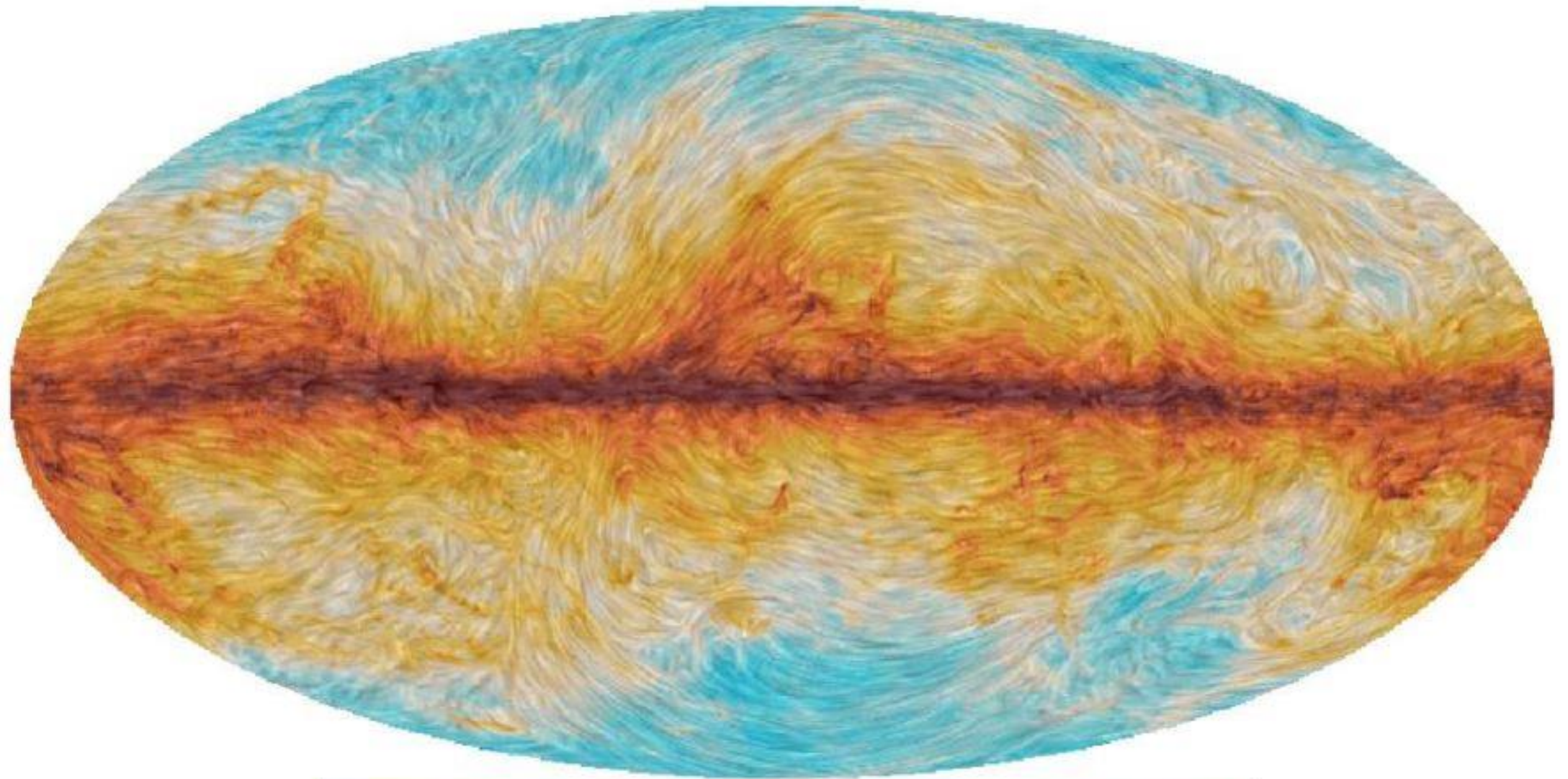


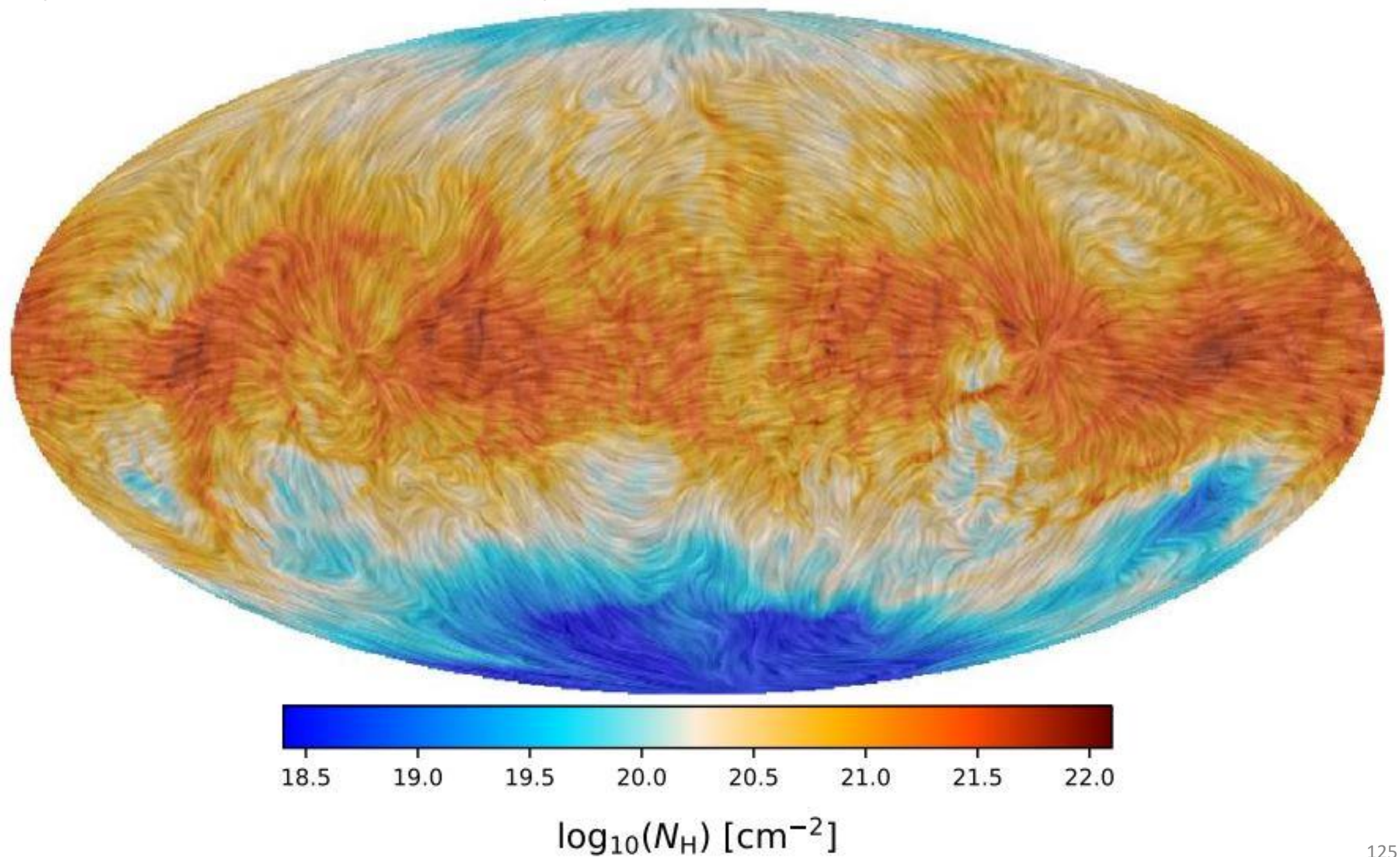
# The Local Bubble acts as a translucent polarization filter

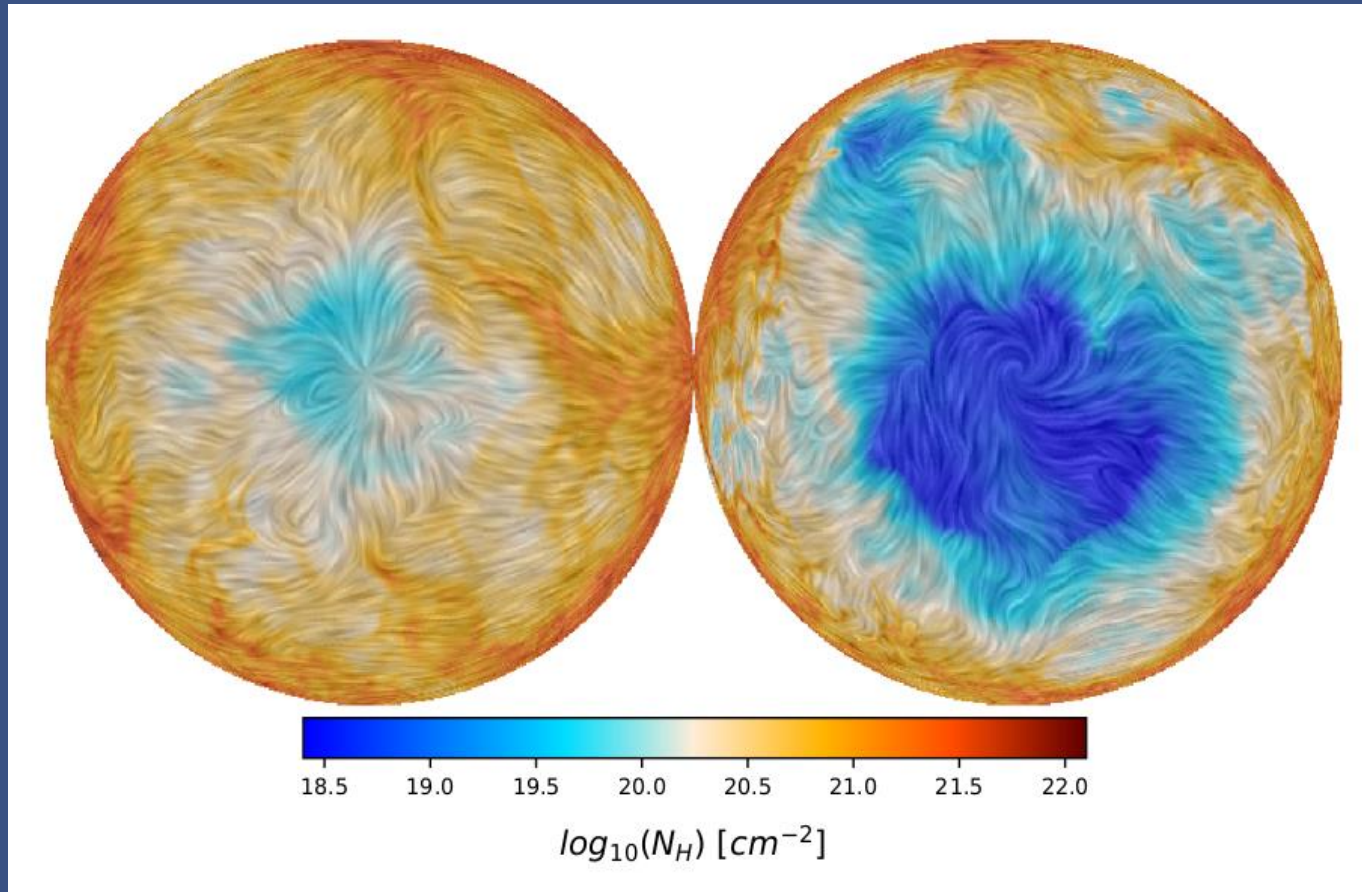




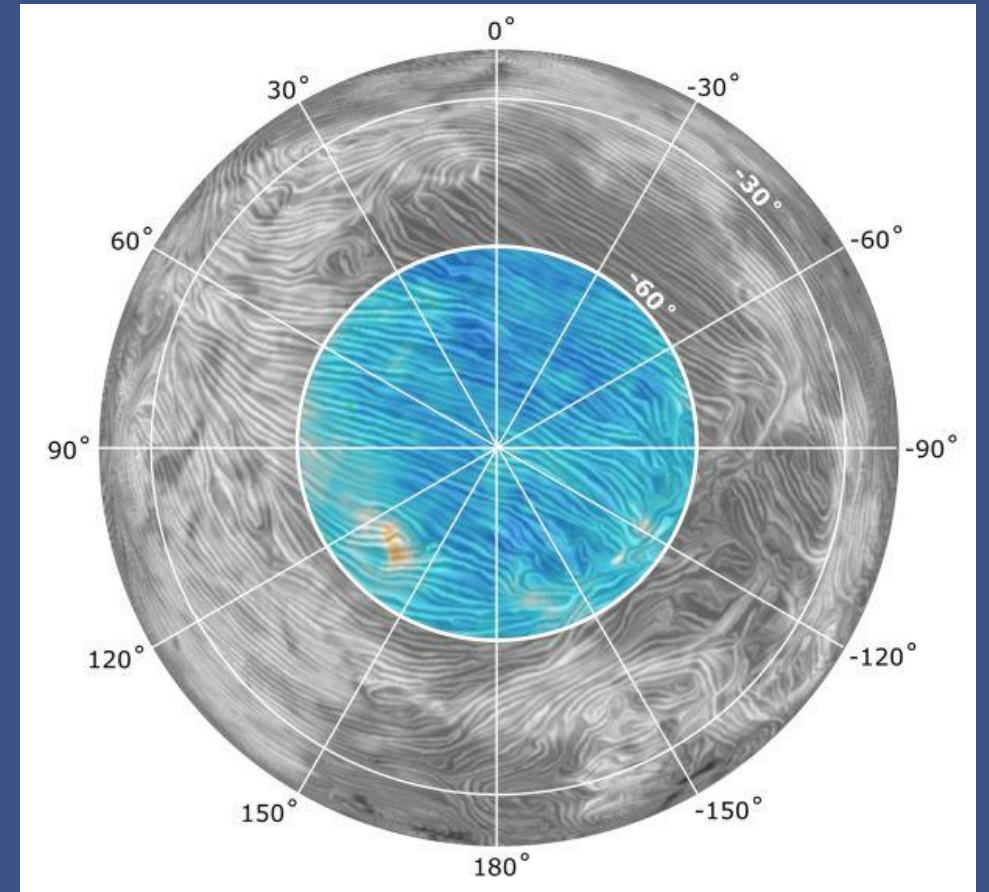








This project



Planck

The Solar System entering the Local Bubble

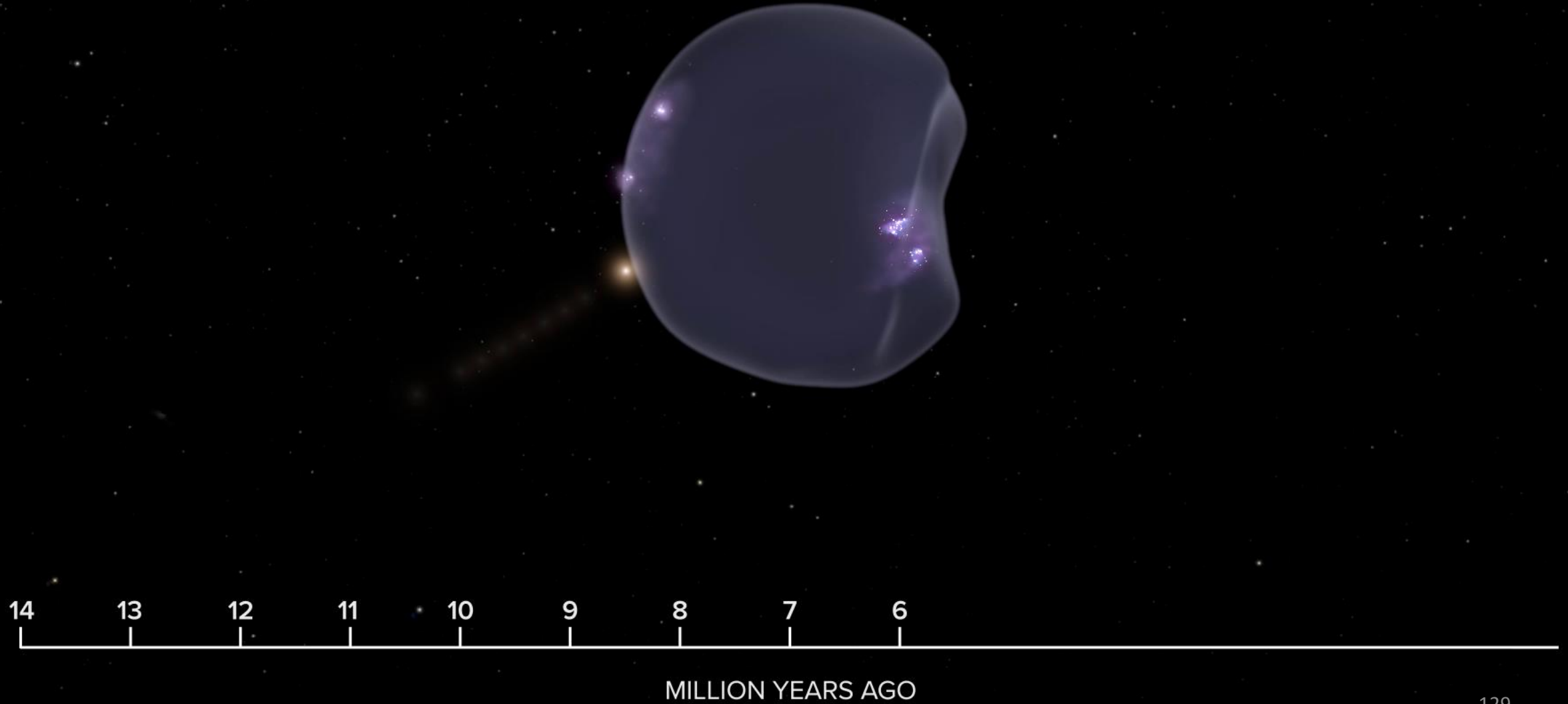
The Sun was over 300 pc away  
when the bubble first started  
forming...



14

MILLION YEARS AGO



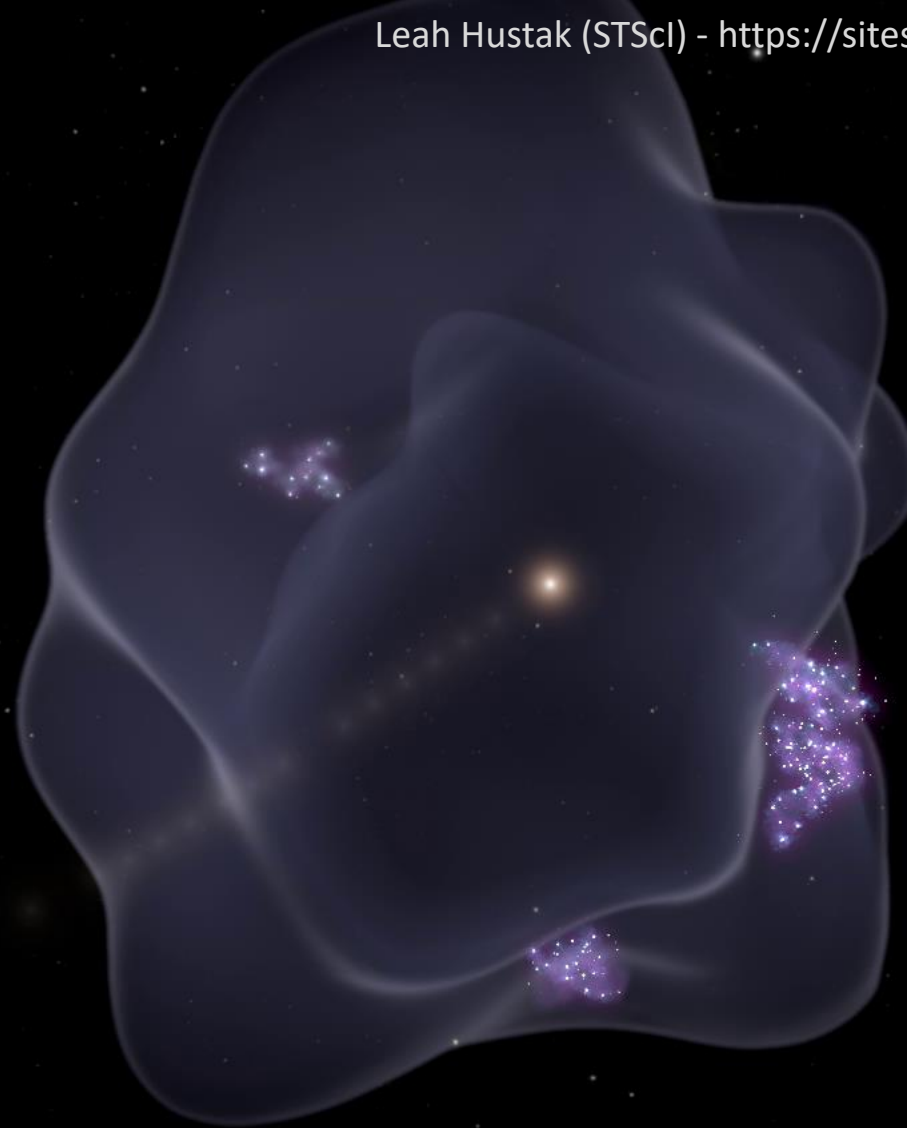




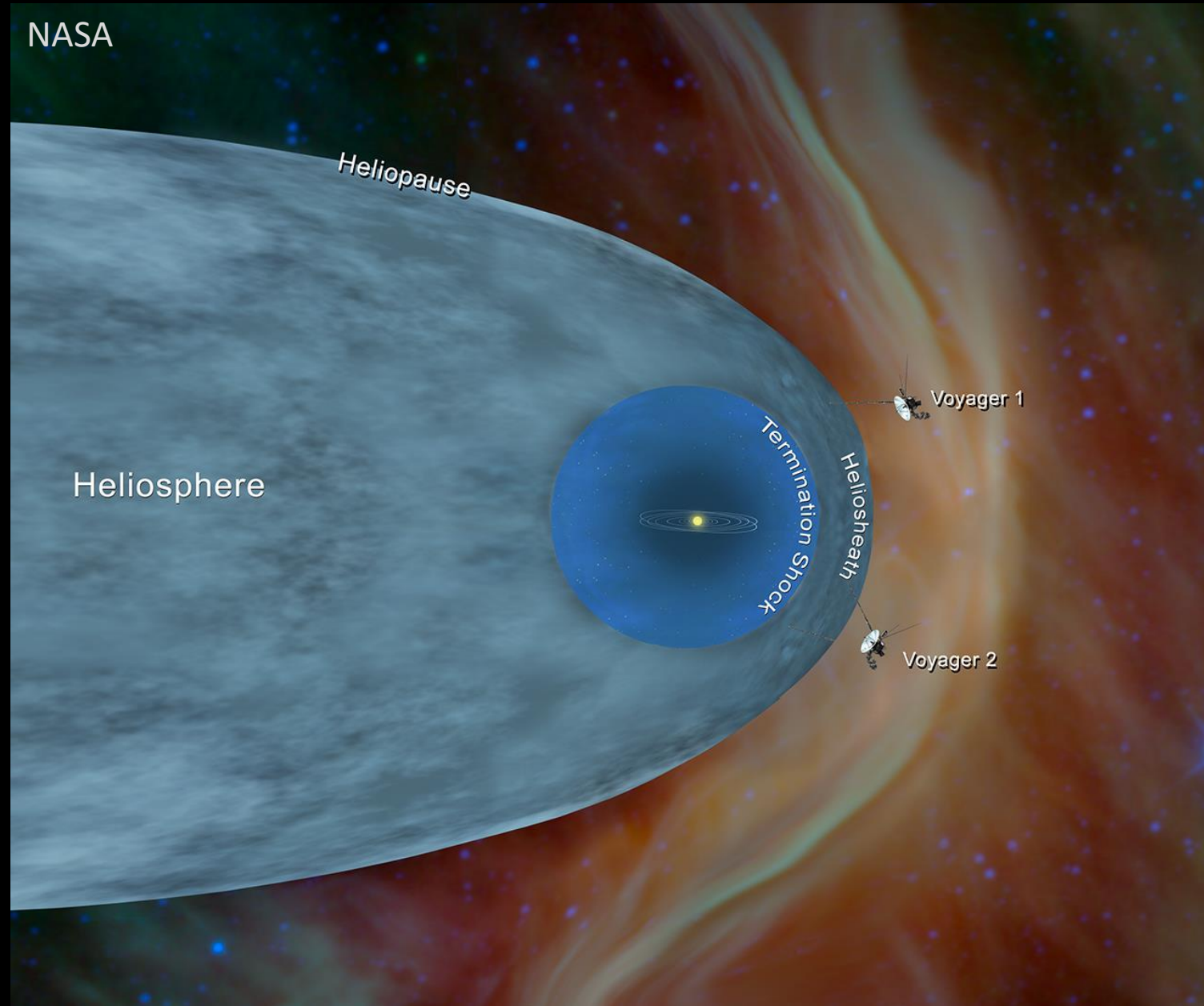
MILLION YEARS AGO



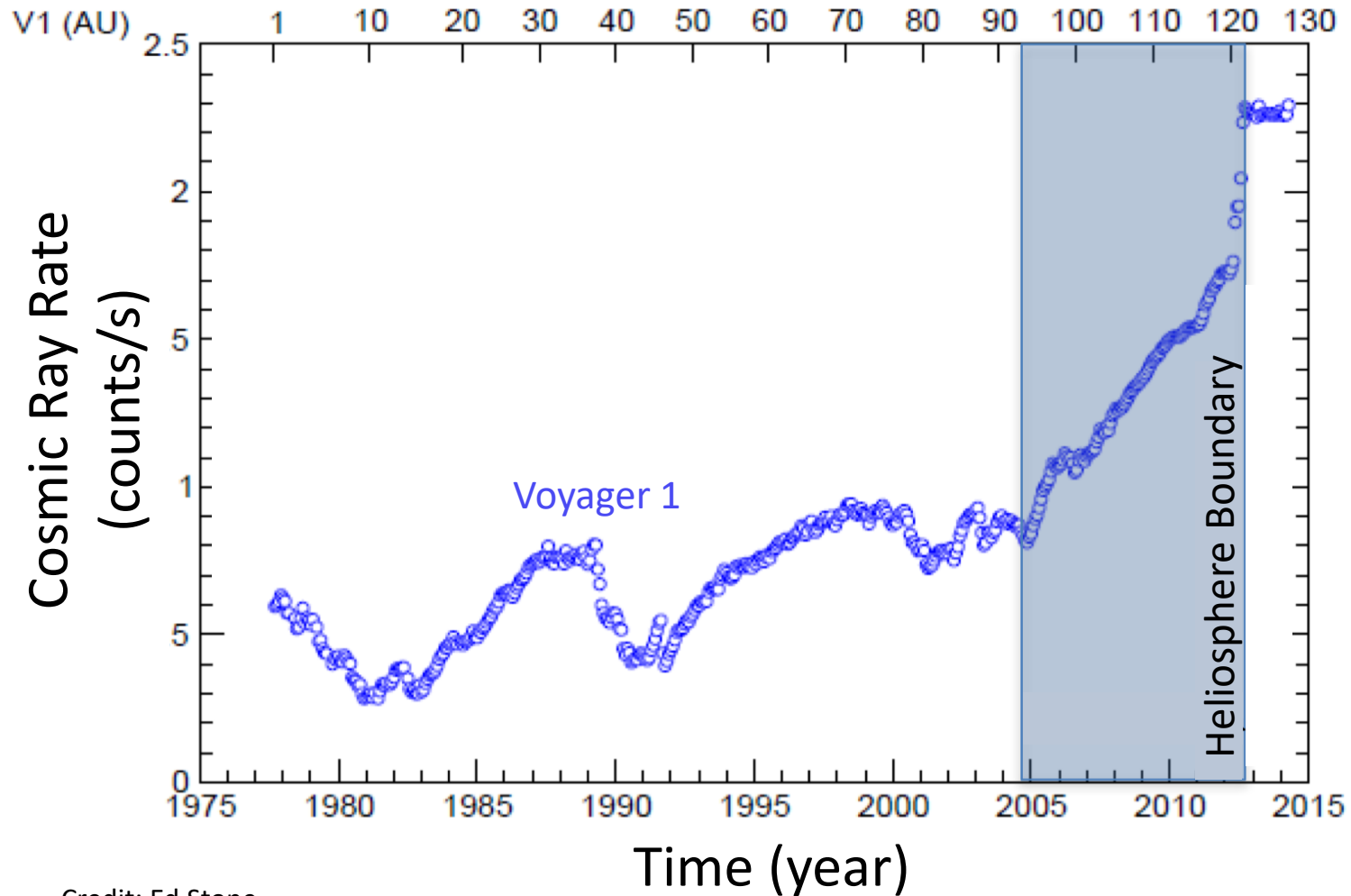
MILLION YEARS AGO



# The Heliosphere

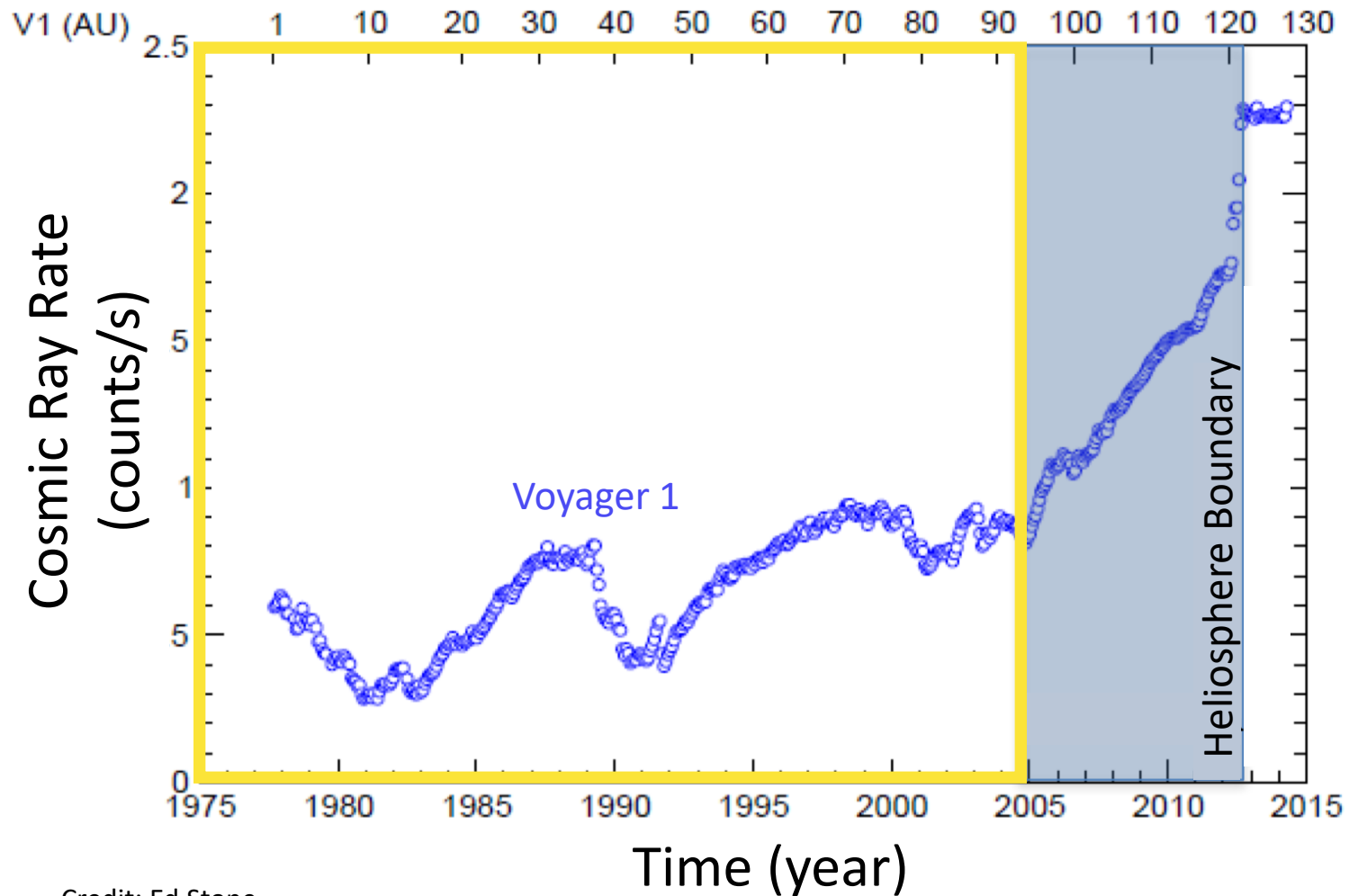


# Cosmic Ray measurement at Voyager 1



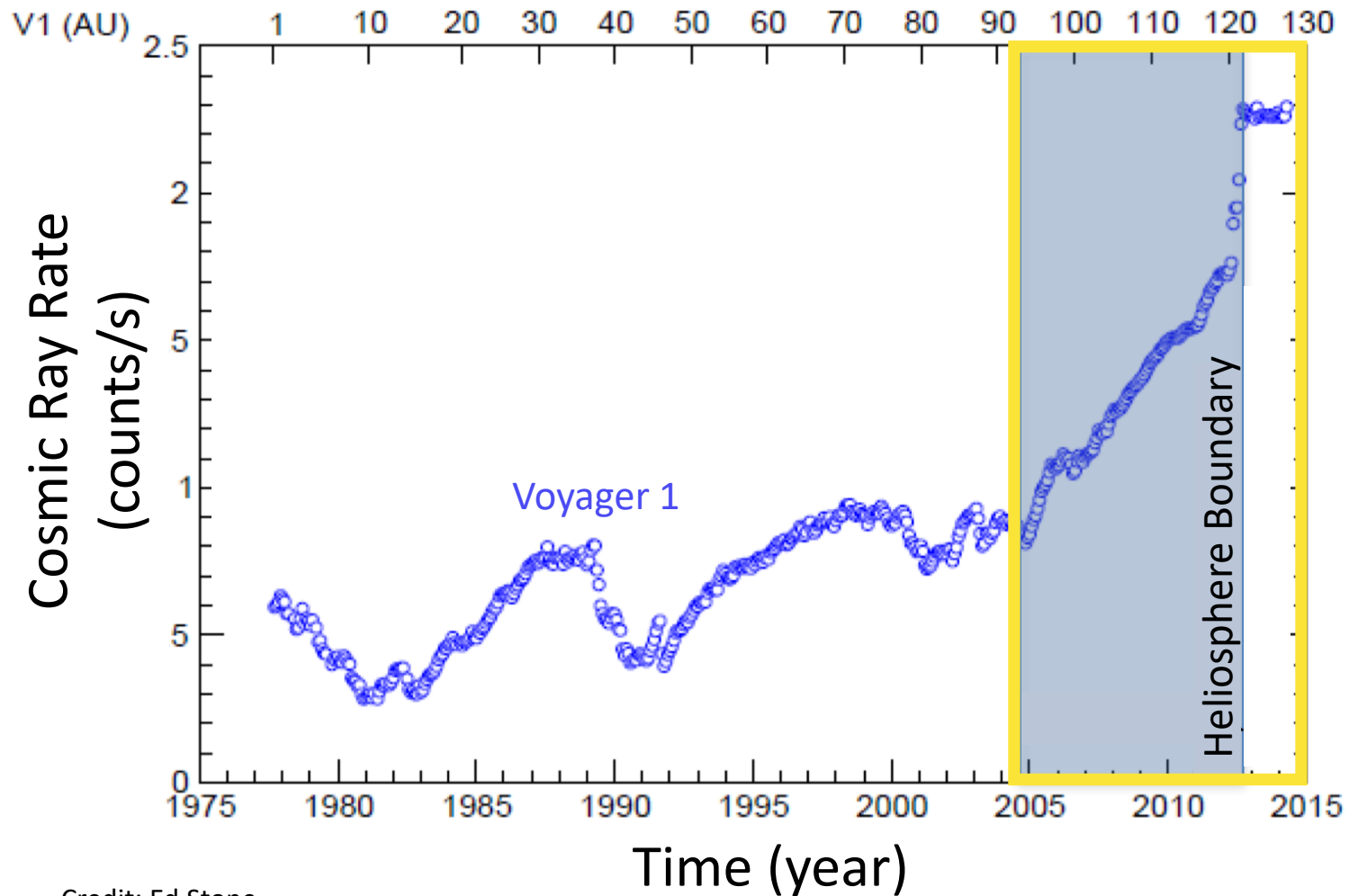
Credit: Ed Stone

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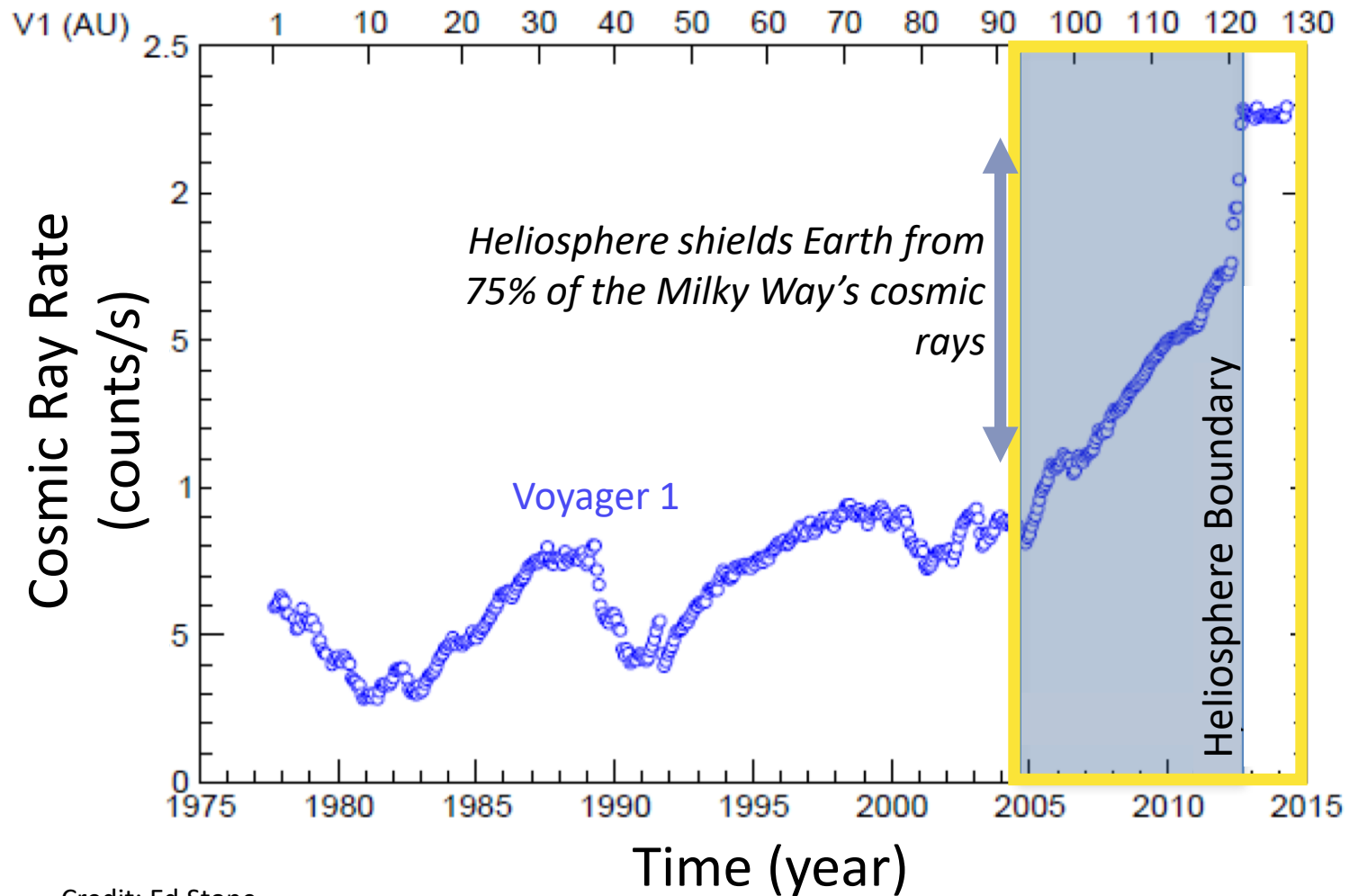
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Credit: Ed Stone



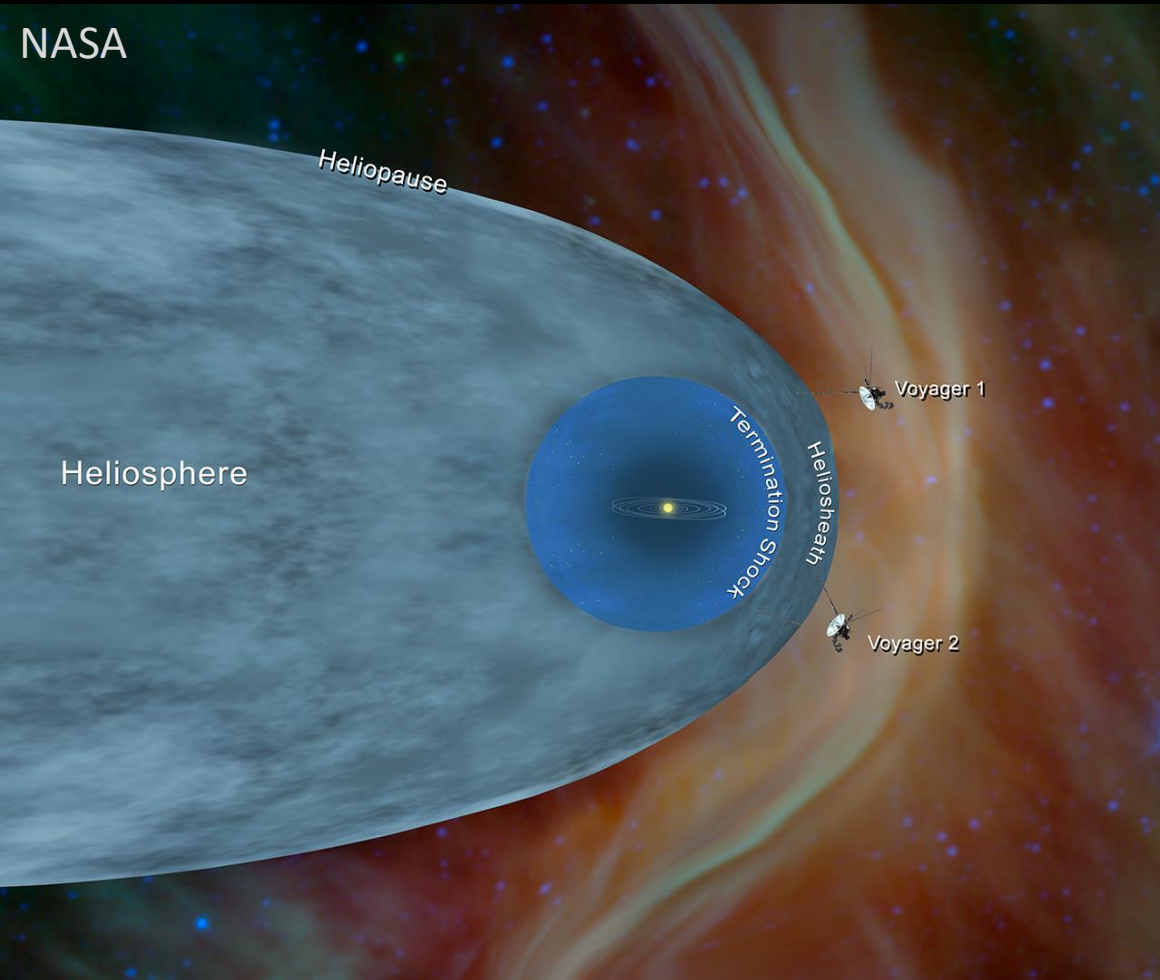
# Cosmic Ray measurement at Voyager 1



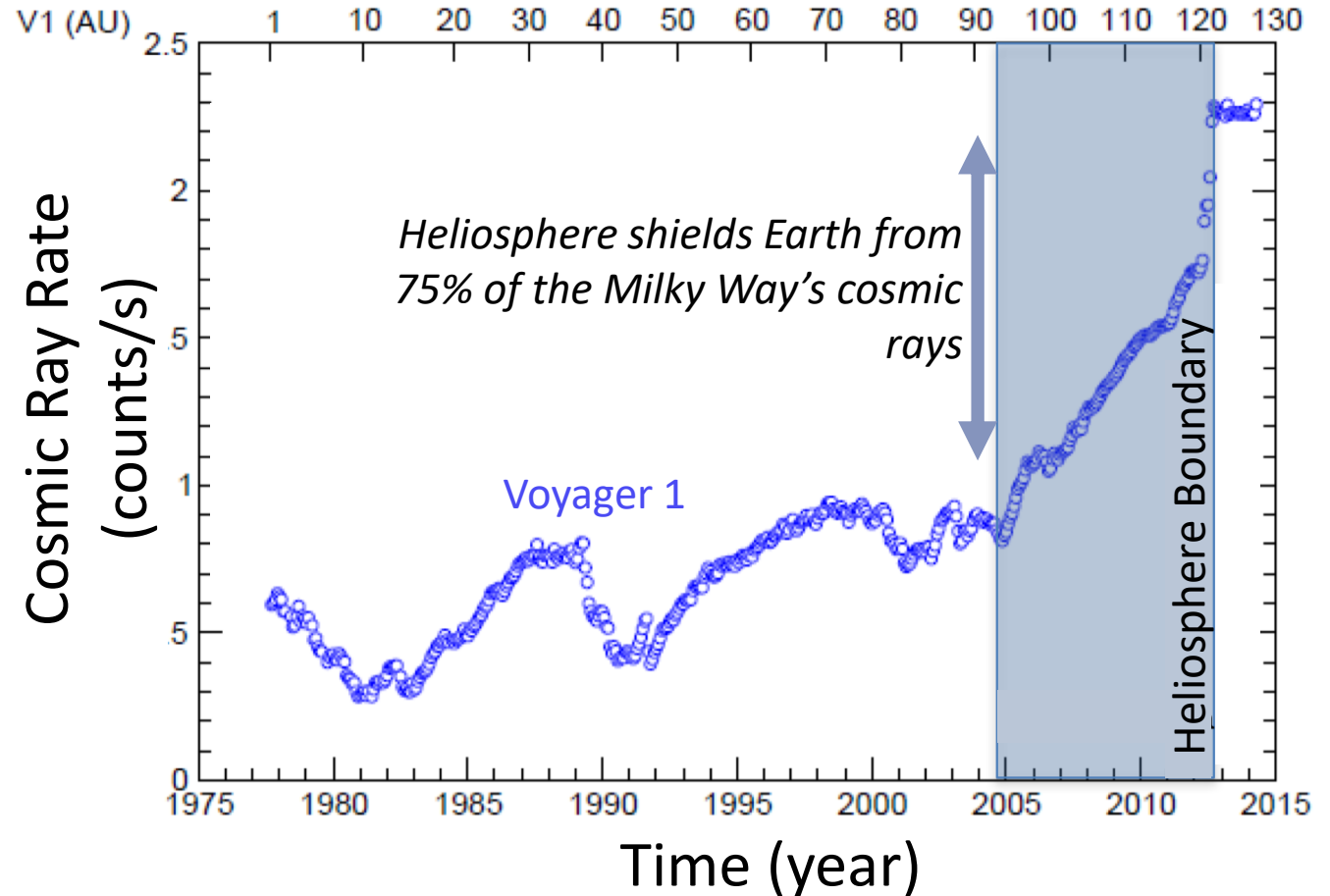
Credit: Ed Stone

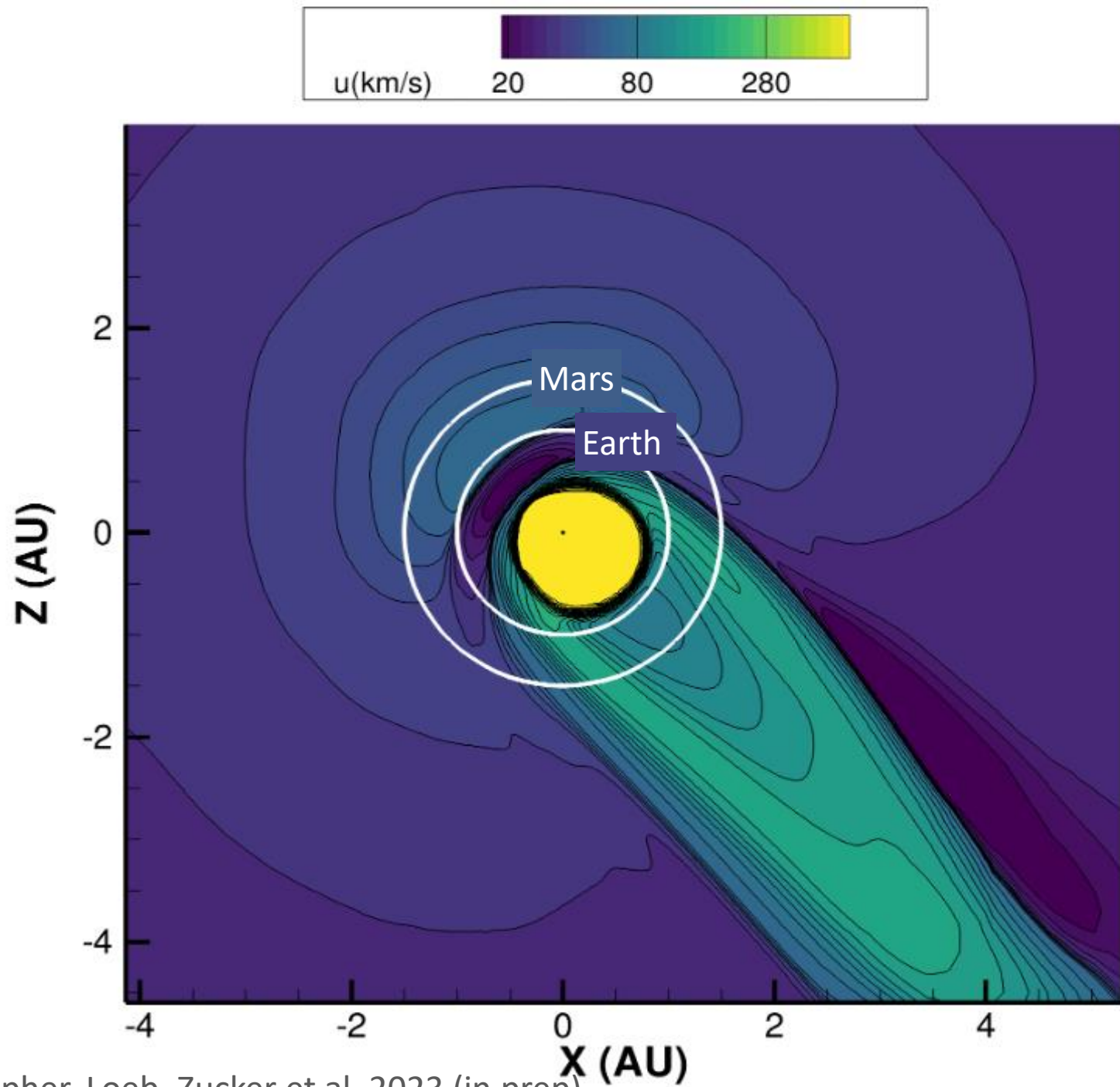
# The Heliosphere:

# Earth's Protective Cocoon

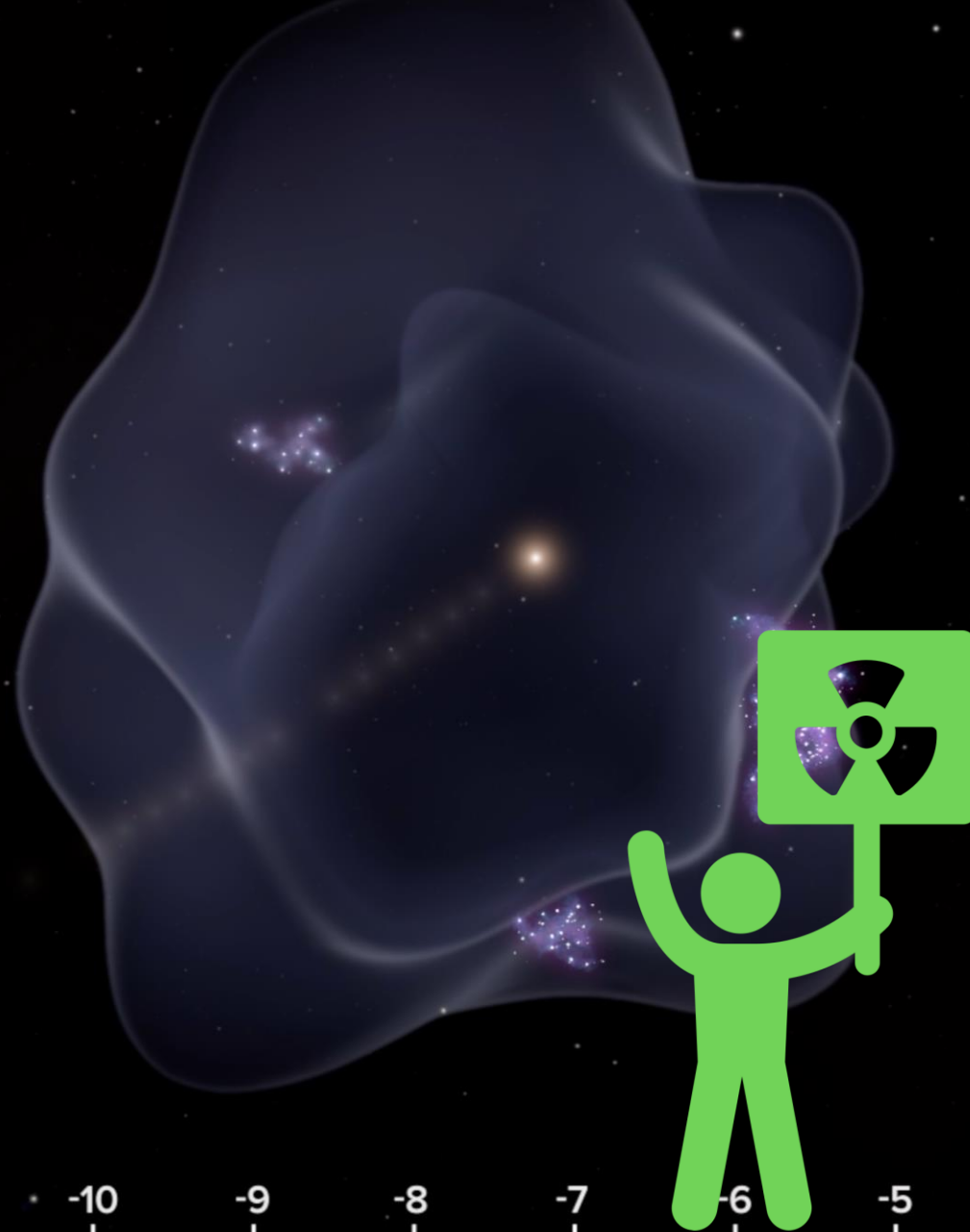


### Cosmic Ray measurements at Voyager 1





Opher, Loeb, Zucker et al. 2023 (in prep)

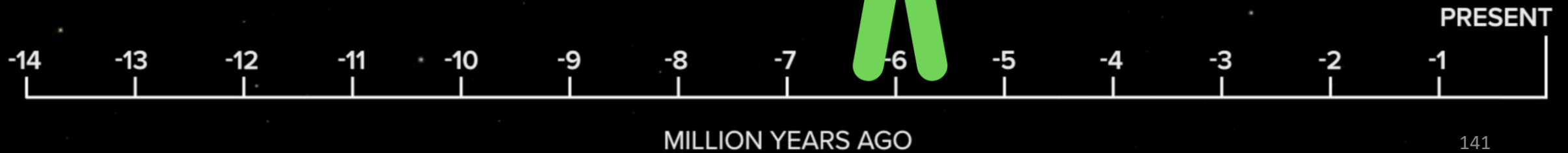
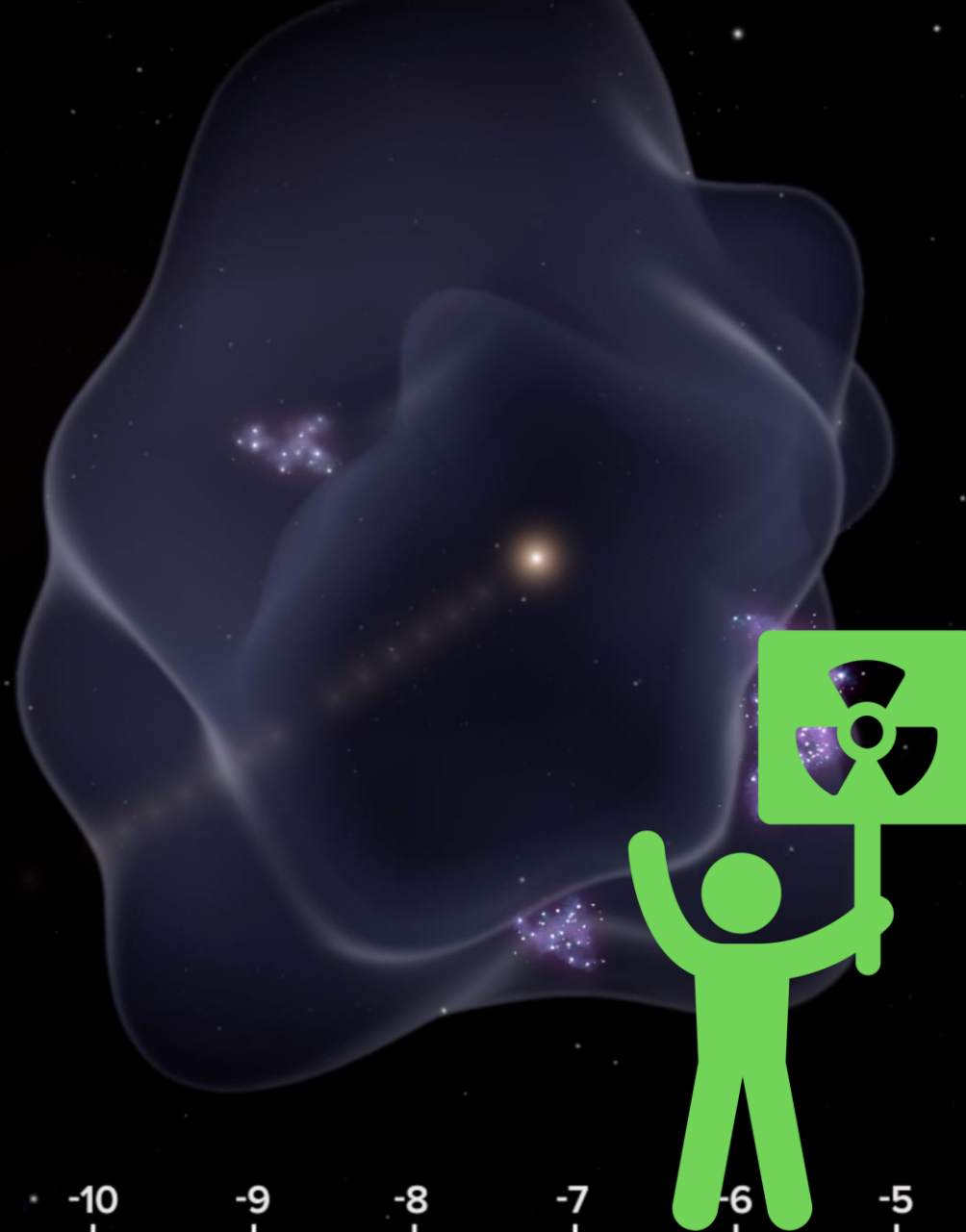


MILLION YEARS AGO

The timeline is consistent with  
supernova iron deposits in the  
Earth's crust!

[1] Wallner et al. 2016

[2] Breitschwerdt et al. 2016



# $^{60}\text{Fe}$ tracer



Credit to C. Zucker for this slide

# $^{60}\text{Fe}$ tracer

Created in supernova explosions



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Half-life of 2.6 Myr





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Half-life of 2.6 Myr

Overabundances found in:  
deep ocean, antarctic, lunar samples,  
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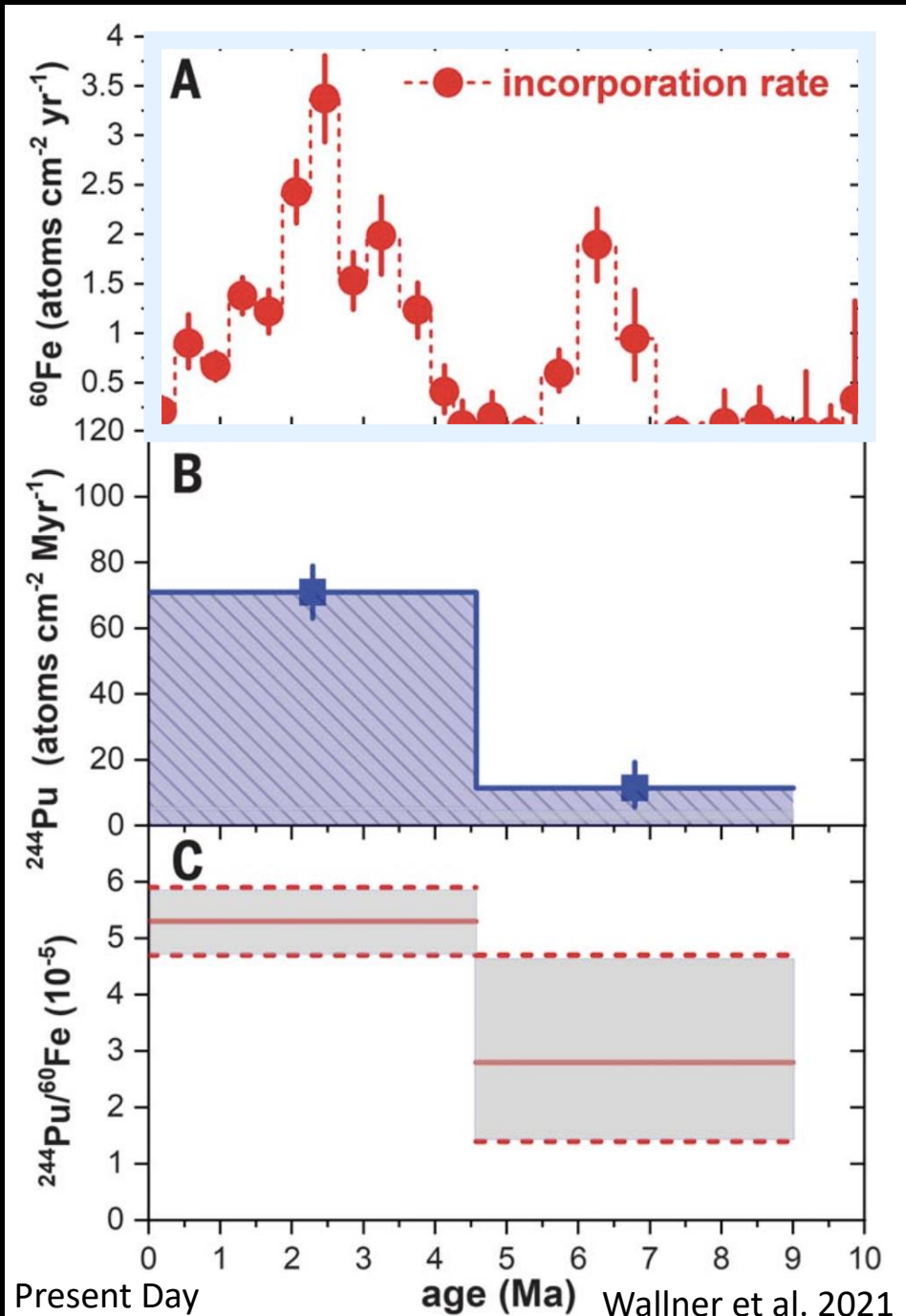


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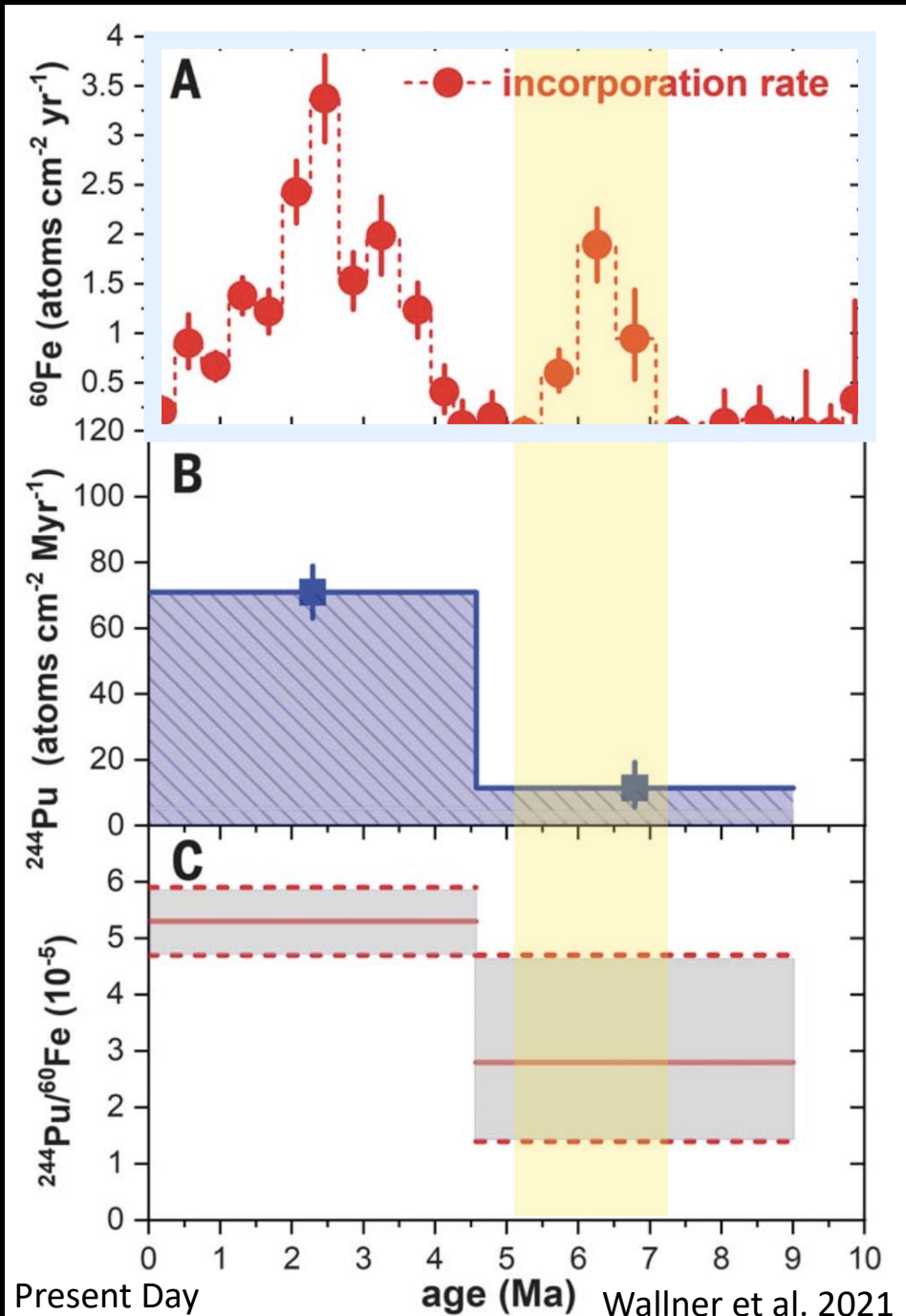


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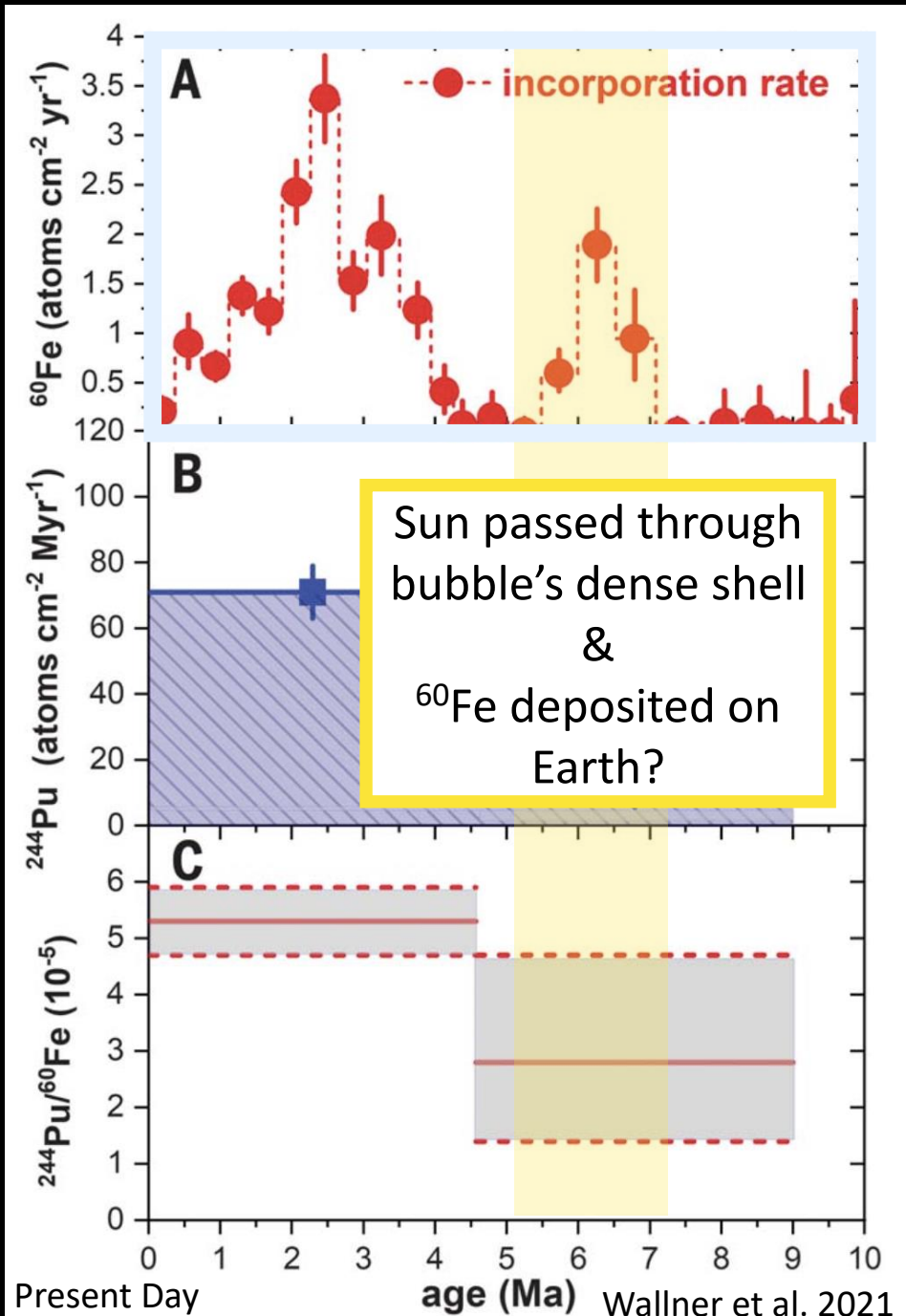


# $^{60}\text{Fe}$ tracer

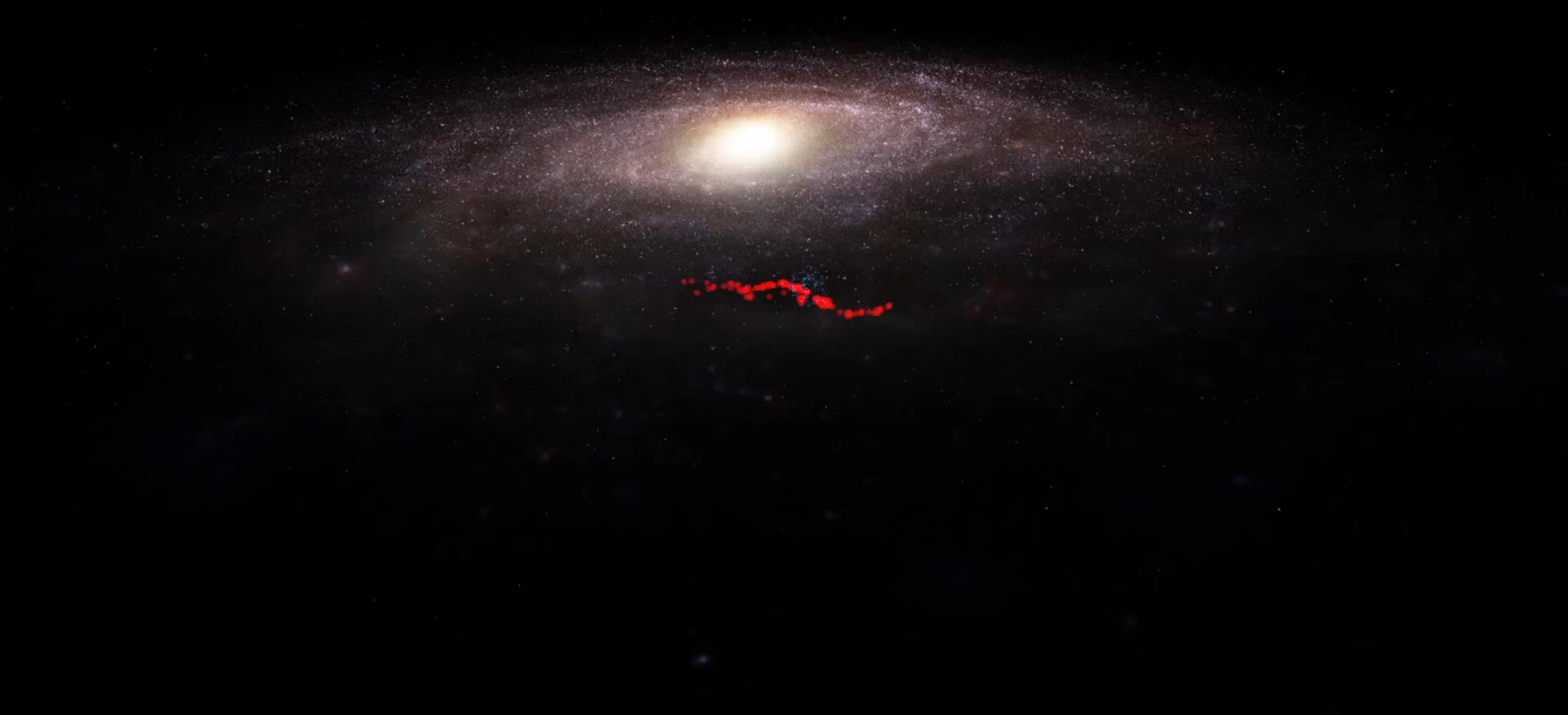
Created in supernova explosions

Half-life of 2.6 Myr

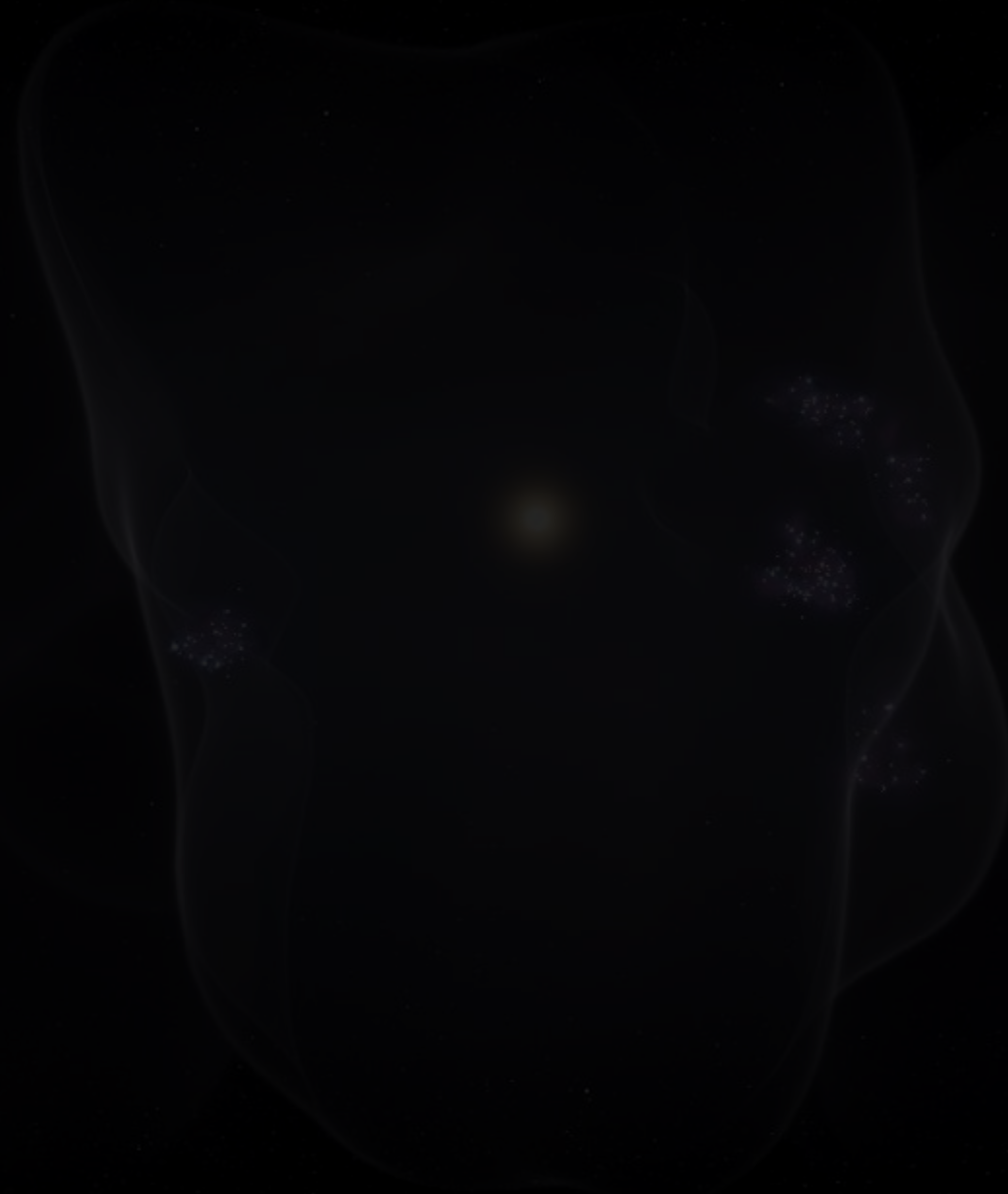
Overabundances found in:  
deep ocean, antarctic, lunar samples,  
cosmic rays



Video created by Micah Acinapura & Catherine Zucker using the OpenSpace software  
High resolution: [tinyurl.com/sf-across-scales](https://tinyurl.com/sf-across-scales)



# Conclusions



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We can reconstruct the **evolution** of the **Local Bubble** over the past 15 Myr

*The Local Bubble is originated by the explosions of 15-20 SN. It is currently expanding. Most of the nearby star-forming regions are located on its surface.*

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*Part of the Planck dust polarization map can be explained by the Local Bubble.  
A coherent large-scale field component may be necessary for explaining the observed polarization pattern at high Galactic latitudes.  
First 3D map of the magnetic field morphology on the surface of the Local Bubble.*



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The **Sun's trajectory** through the ISM over the past 10 Myr shaped the **properties** of the **heliosphere**

*Sun crossed the Local Bubble's shell 6 Myr ago, shrinking the heliosphere, exposing Earth to ISM and triggering influx of  $^{60}\text{Fe}$  isotopes on Earth.*