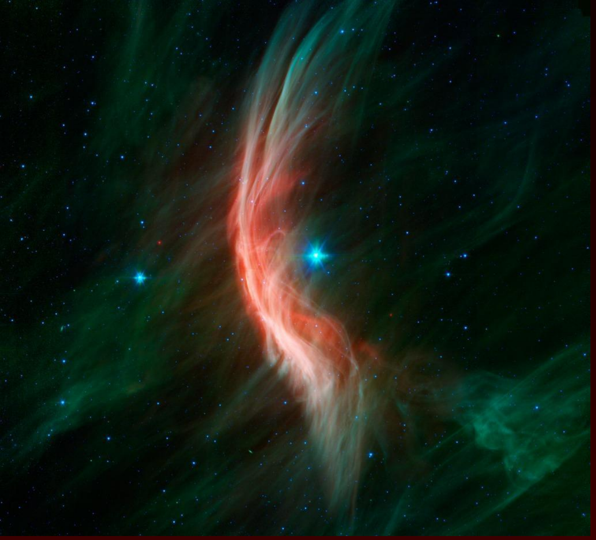
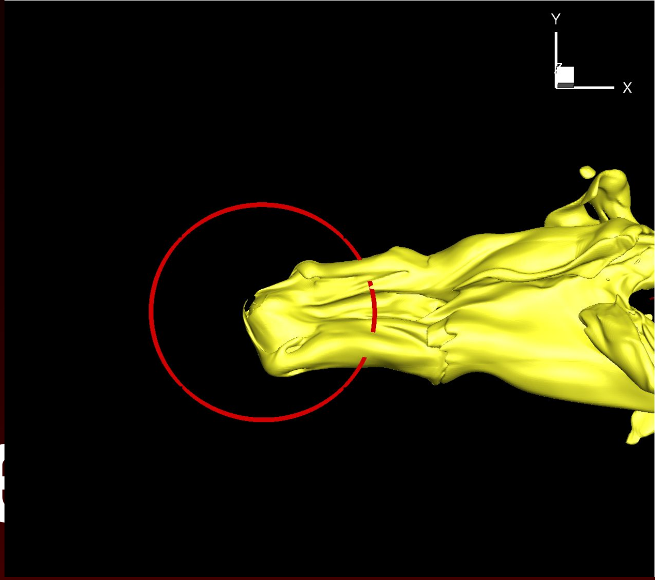
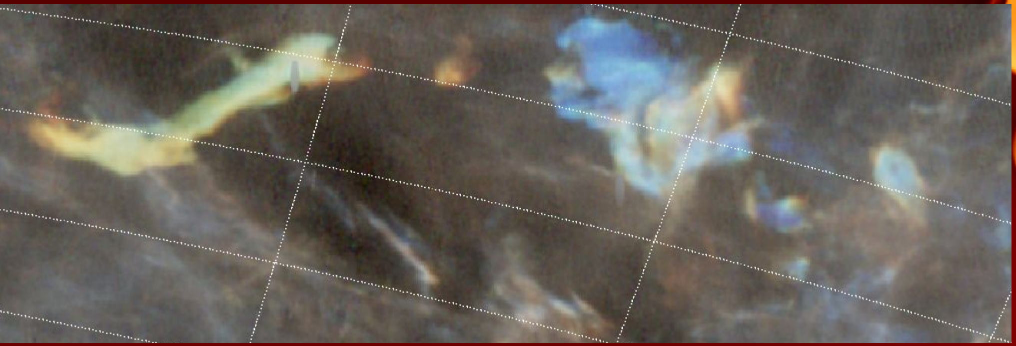




Paleo-heliosphere
Part I



Jesse Miller

Boston University

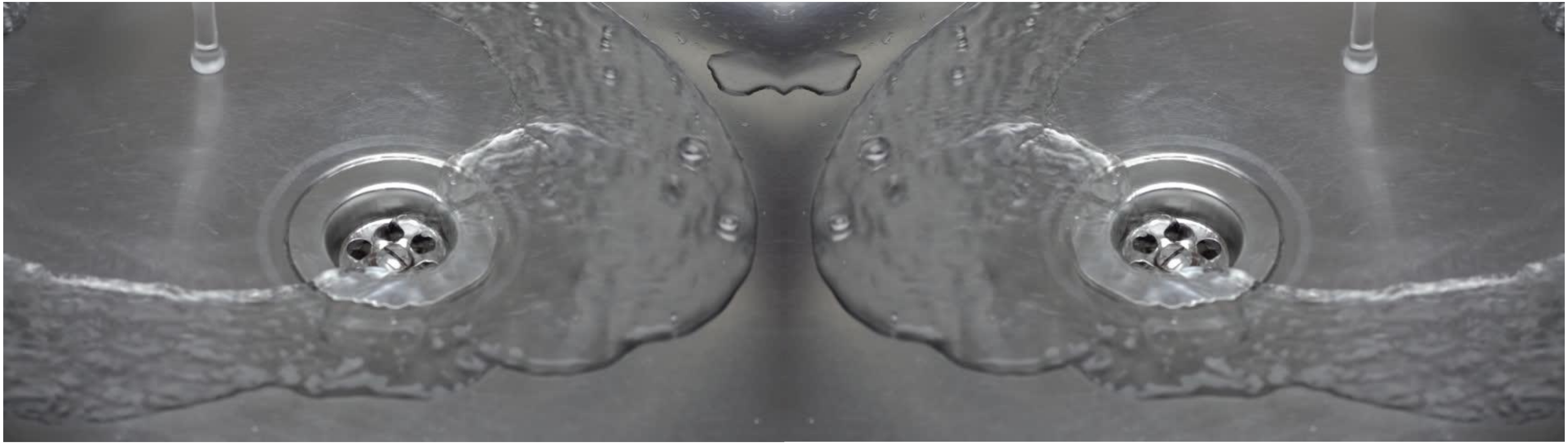
SHIELD summer school 2025

solar wind

Shutterstock

solar wind

interstellar medium



Shutterstock

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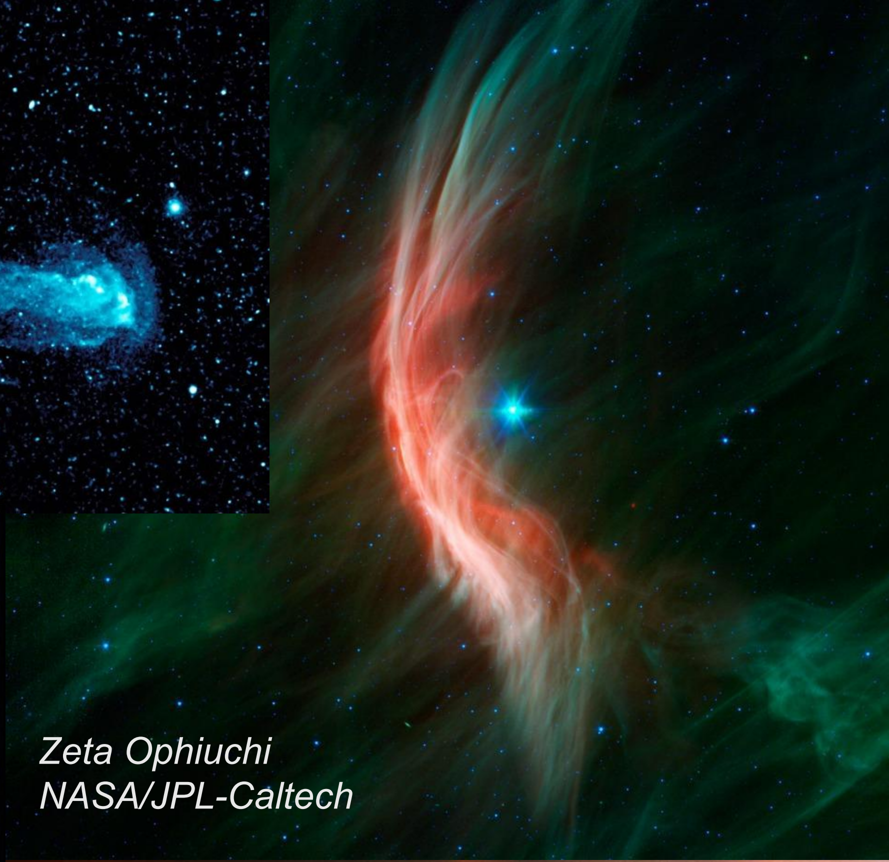
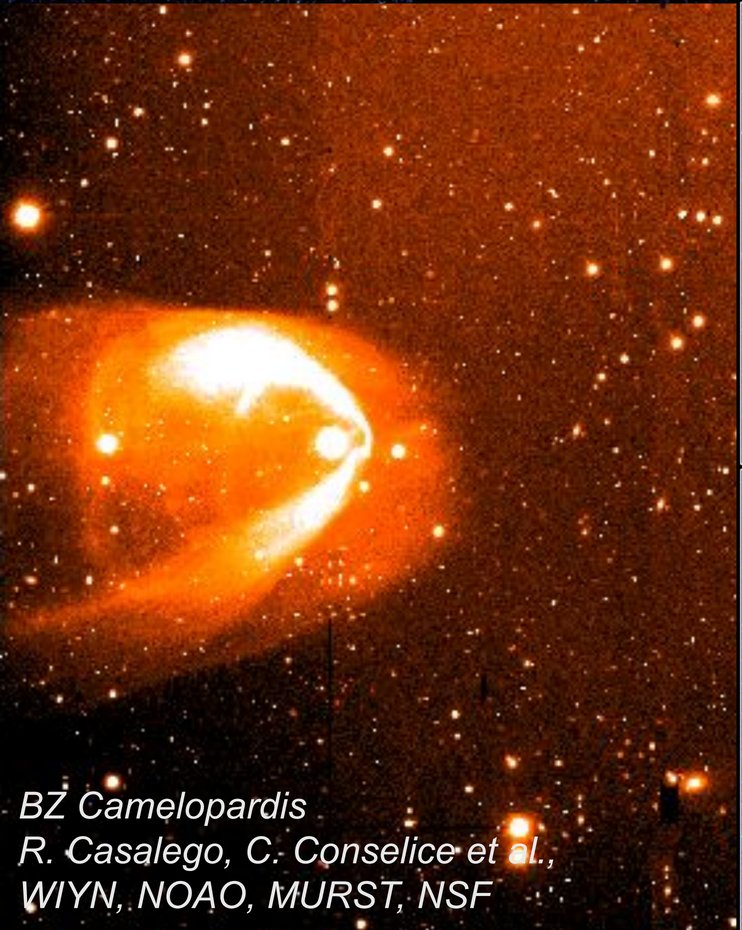
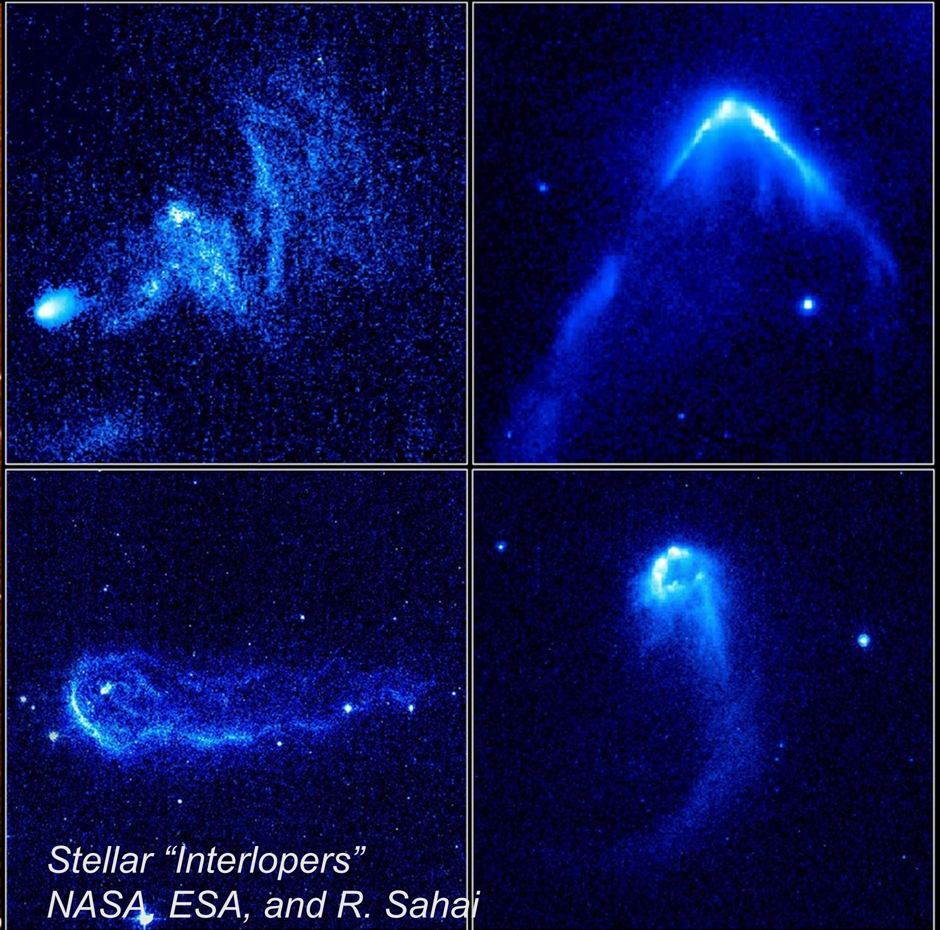
Mira
NASA GALEX



Zeta Ophiuchi
NASA/JPL-Caltech



BZ Camelopardis
R. Casalego, C. Conselice et al.,
WIYN, NOAO, MURST, NSF

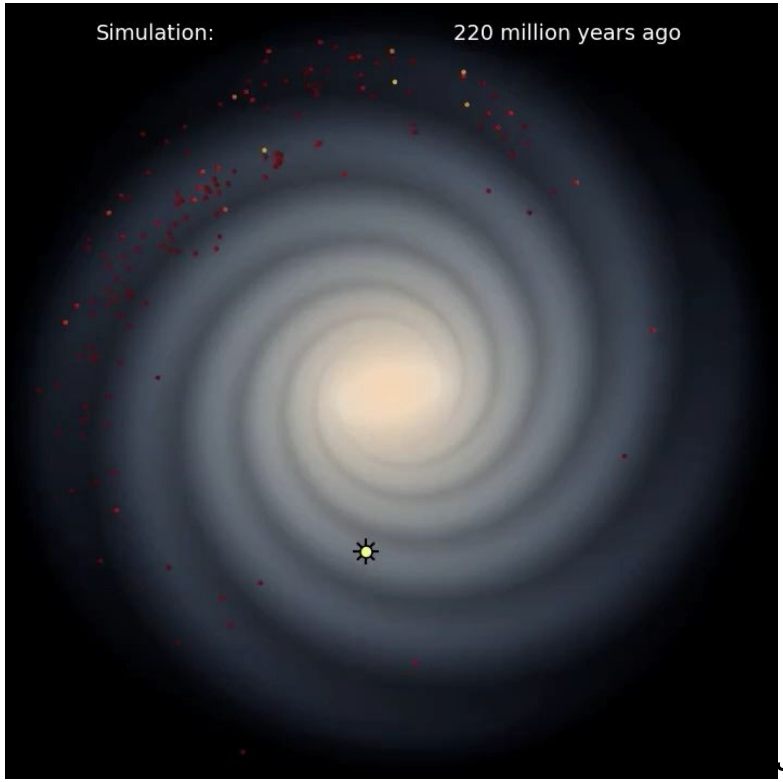


Stellar “Interlopers”
NASA, ESA, and R. Sahai

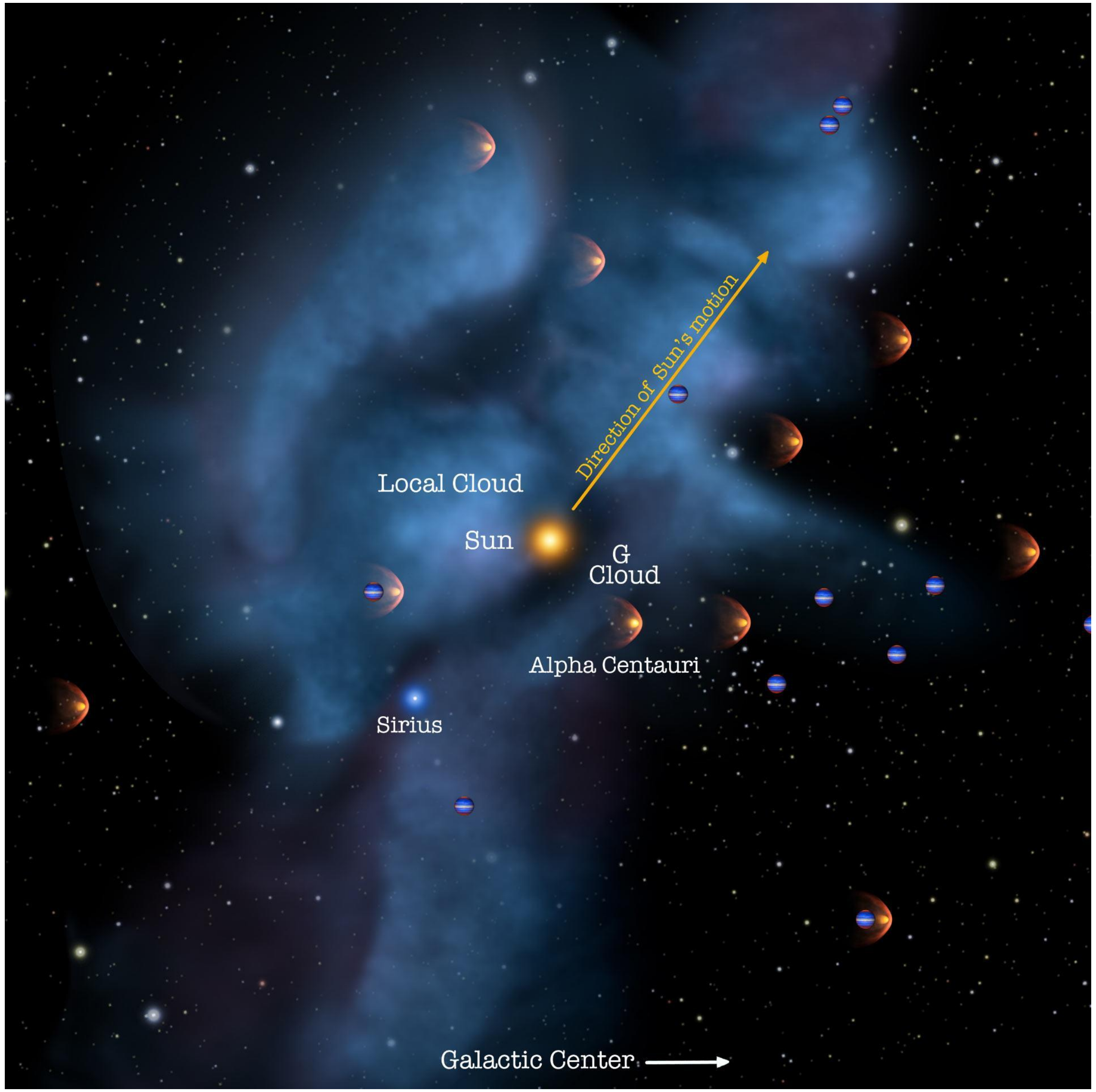
LL Orionis
NASA, ESA, Hubble Heritage team

Galactic environment

- Not constant over millions of years
  - Supernova explosions
  - Dense interstellar clouds



Jan Skowron / OGLE



NASA / Adler / University of Chicago / Wesleyan

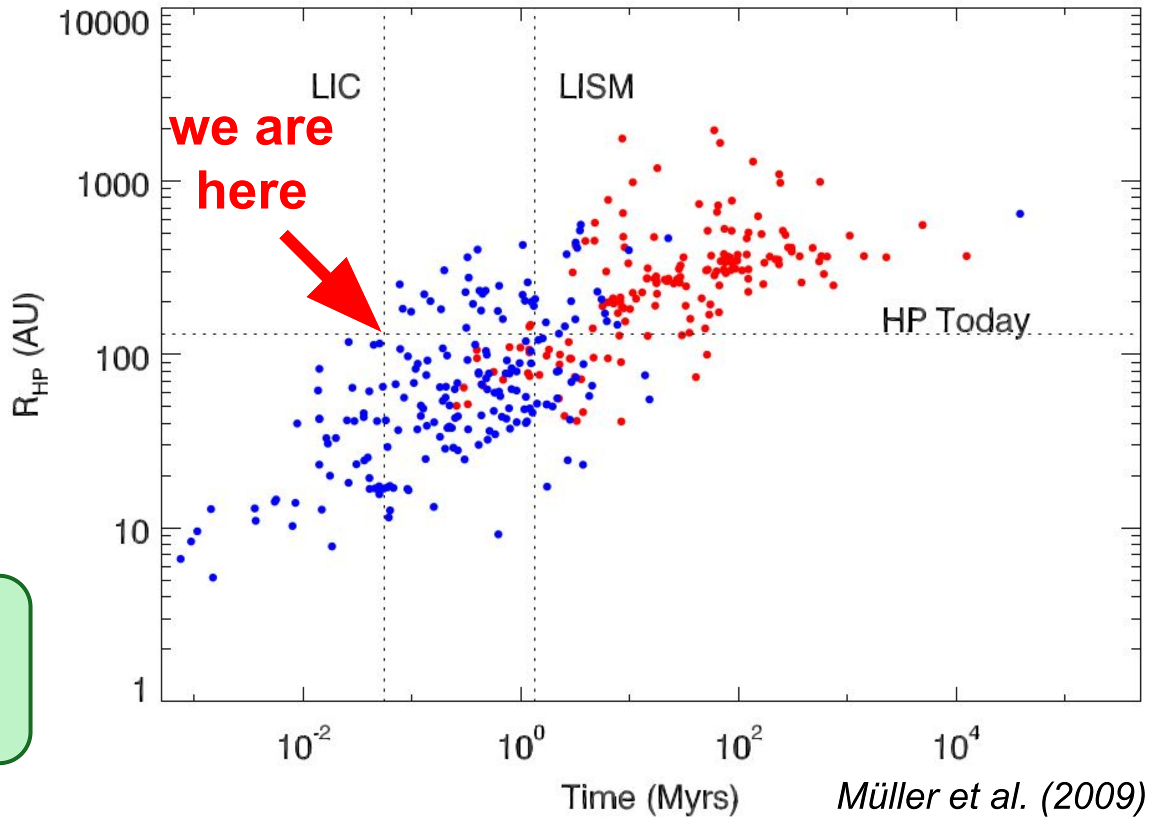
Size of the heliosphere (stagnation distance)

- For today, assume ram pressure balance, $P_{ram} = \rho v^2$
- Let's ignore:
  - Magnetic fields
  - Thermal pressure
  - Neutrals
  - Pickup ions
  - Cosmic rays
  - ....

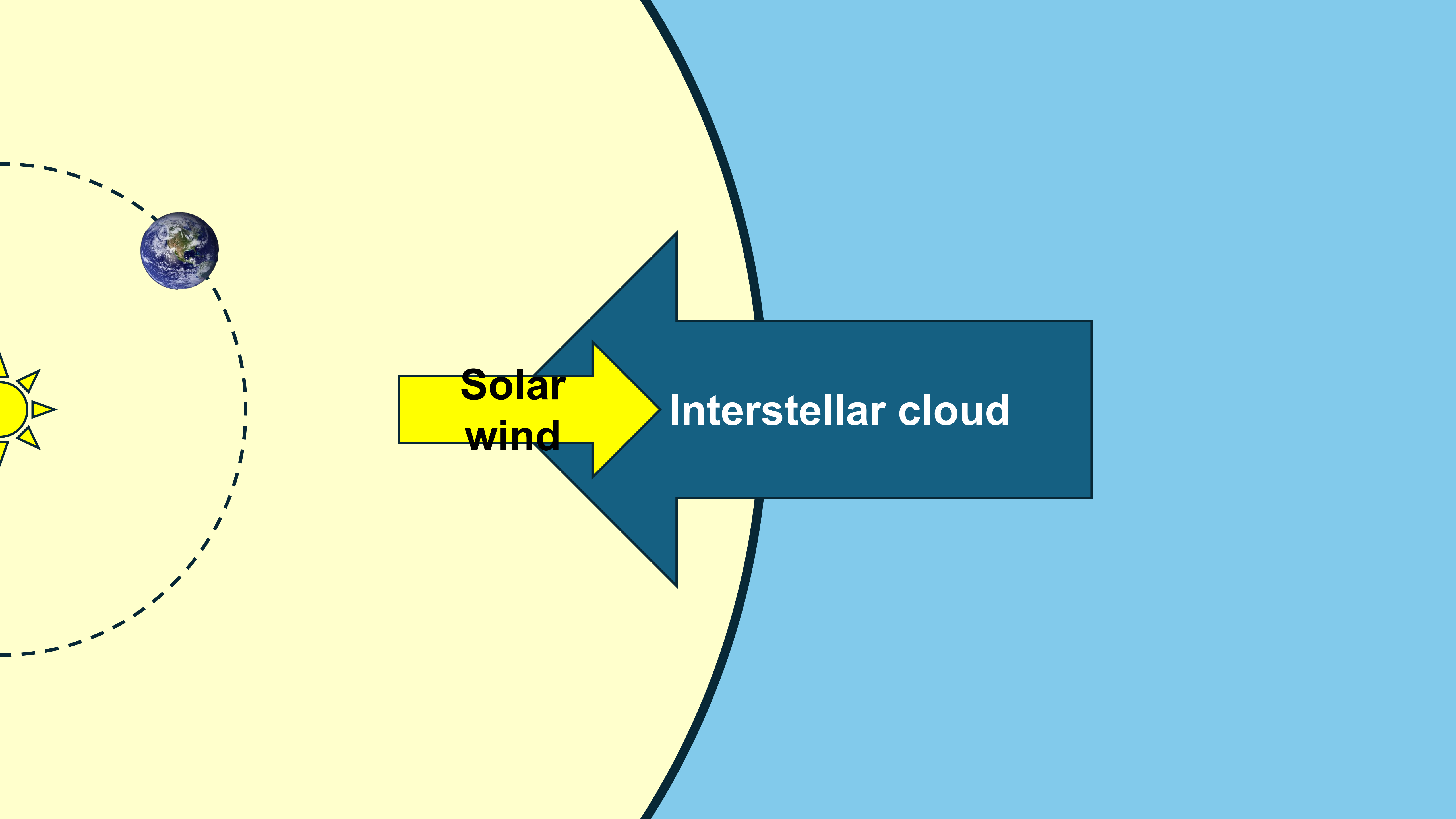
$$r_{stag} = \left(\frac{n_{sw} v_{sw}^2}{n_{ISM} v_{ISM}^2}\right)^{1/2} \text{ au}$$

$$r_{stag} = \left(\frac{\dot{M} v_{sw}}{4\pi \rho_{ISM} v_{ISM}^2}\right)^{1/2}$$

*assuming solar wind parameters at 1 au



Müller et al. (2009)


Solar wind
Interstellar cloud

How can we investigate extreme events in the paleo-helios

- Need a tracer – the smoking gun
- Spoiling the surprise, let's look for ^{60}Fe
  - Radioactive with half-life of 2.6 Myr
  - Not made on Earth
  - Not left over from solar system formation
  - Barely made in the solar system
  - Must come from extra-solar sources

(not this 60FE)

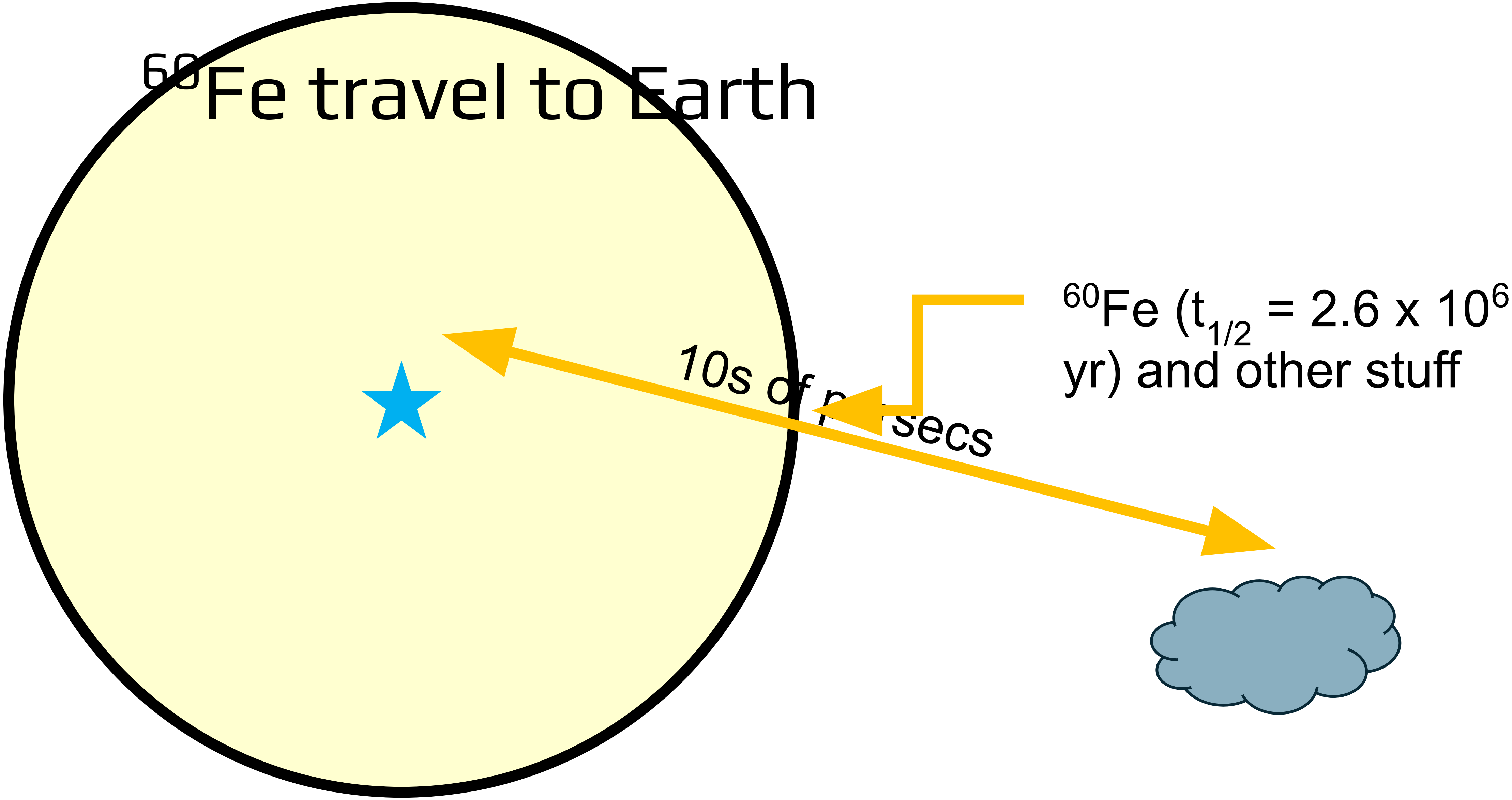
Like green bananas in Massachusetts:

- They didn't grow here, so…
- …they must have been brought here quickly

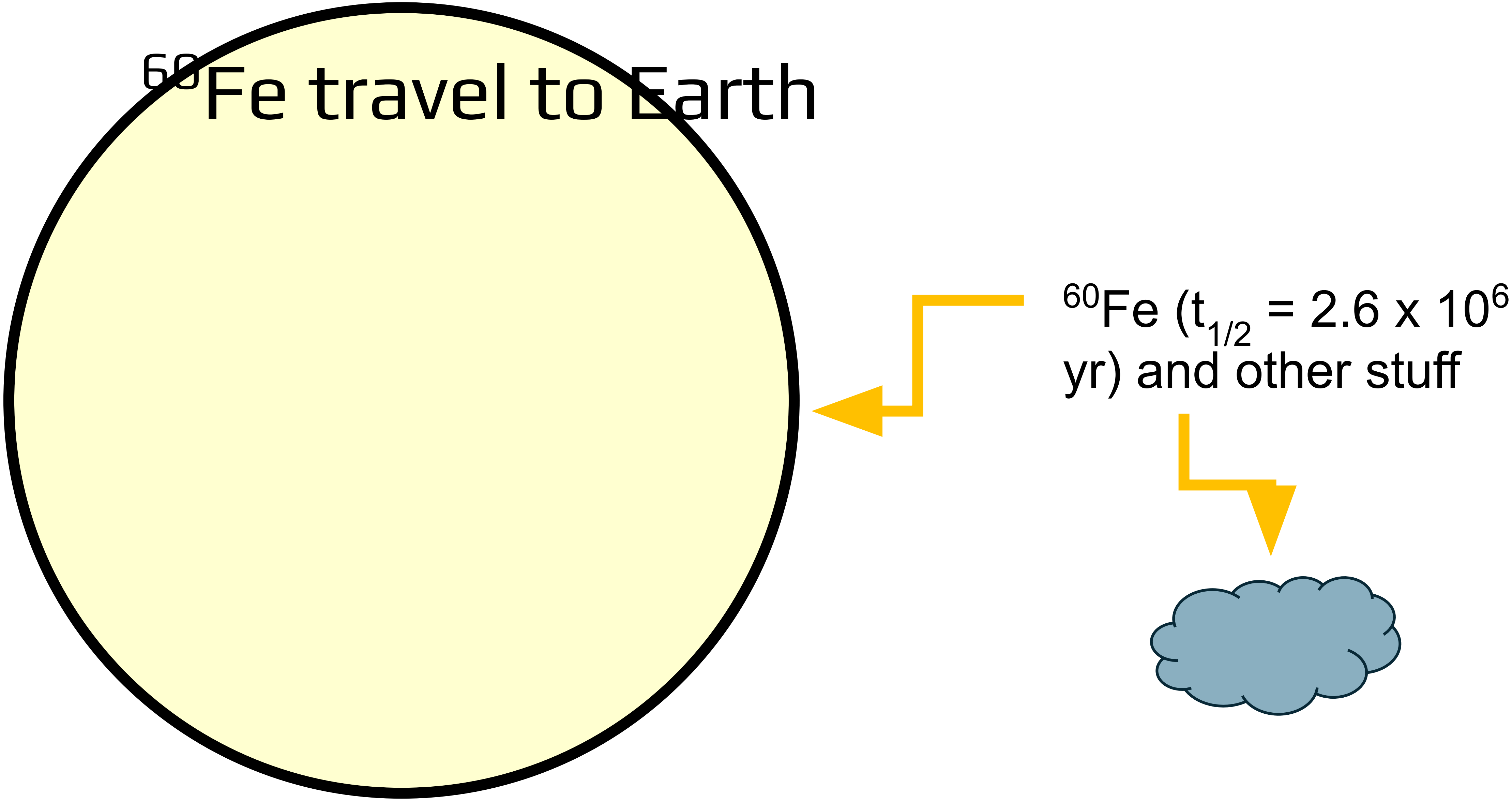
What makes ^{60}Fe?

- ~~Impactors/meteorites?~~
- ~~Passing super-AGB star?~~
- “Novae”
  - ~~Nova?~~
  - ~~Thermonuclear supernova?~~
  - Core-collapse supernova?
  - ~~Kilonova?~~
  - ~~Hypernova?~~
  - ~~Casanova?~~
  - ~~Bossa nova?~~
- Cold dense cloud?

^{60}Fe travel to Earth

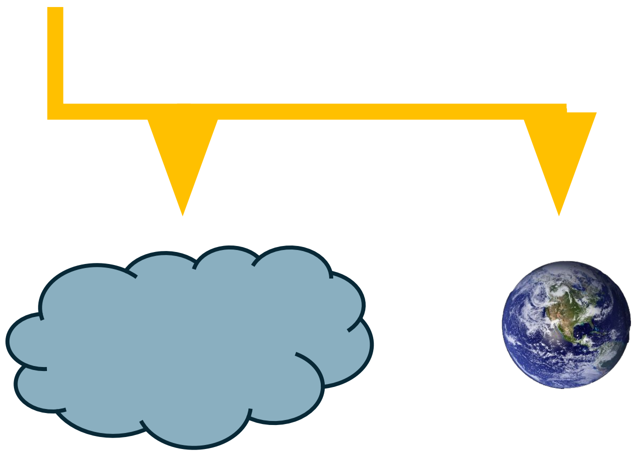


^{60}Fe travel to Earth



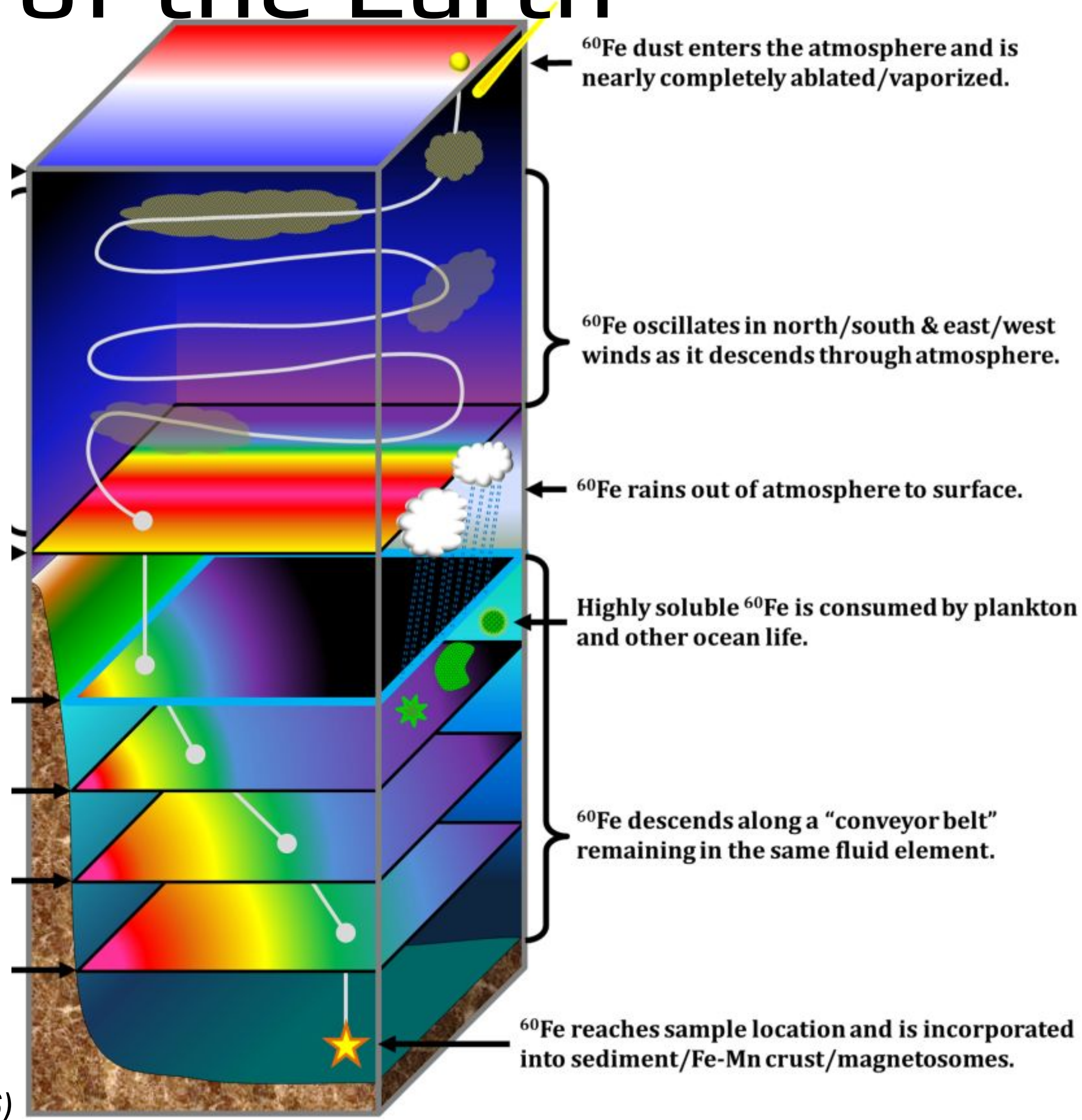
^{60}Fe travel to Earth

^{60}Fe ($t_{1/2}$ = 2.6 x 10^6 yr) and other stuff

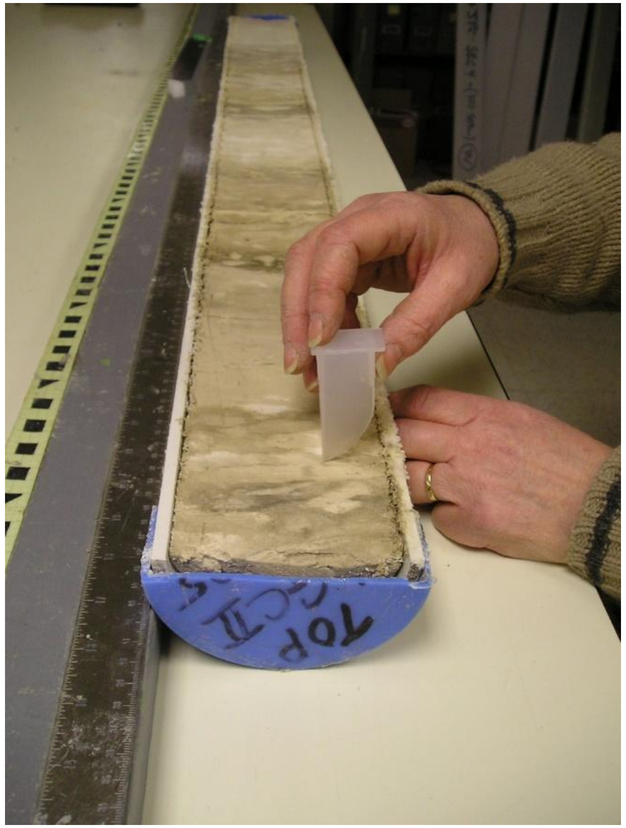


Journey to the surface of the Earth

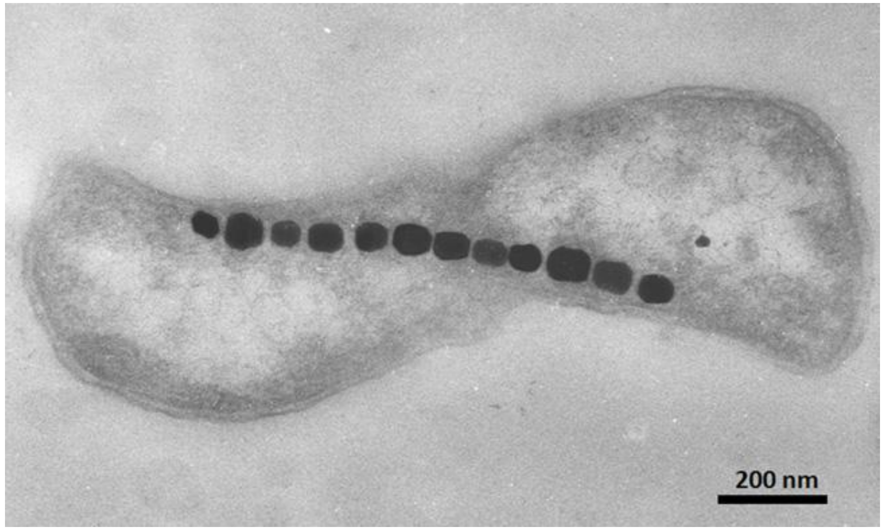
- Dust is vaporized in atmosphere
- Winds scramble location
- Rains onto surface
- Descends to sea floor
- Incorporated into geological samples



Fry et al. (2016)



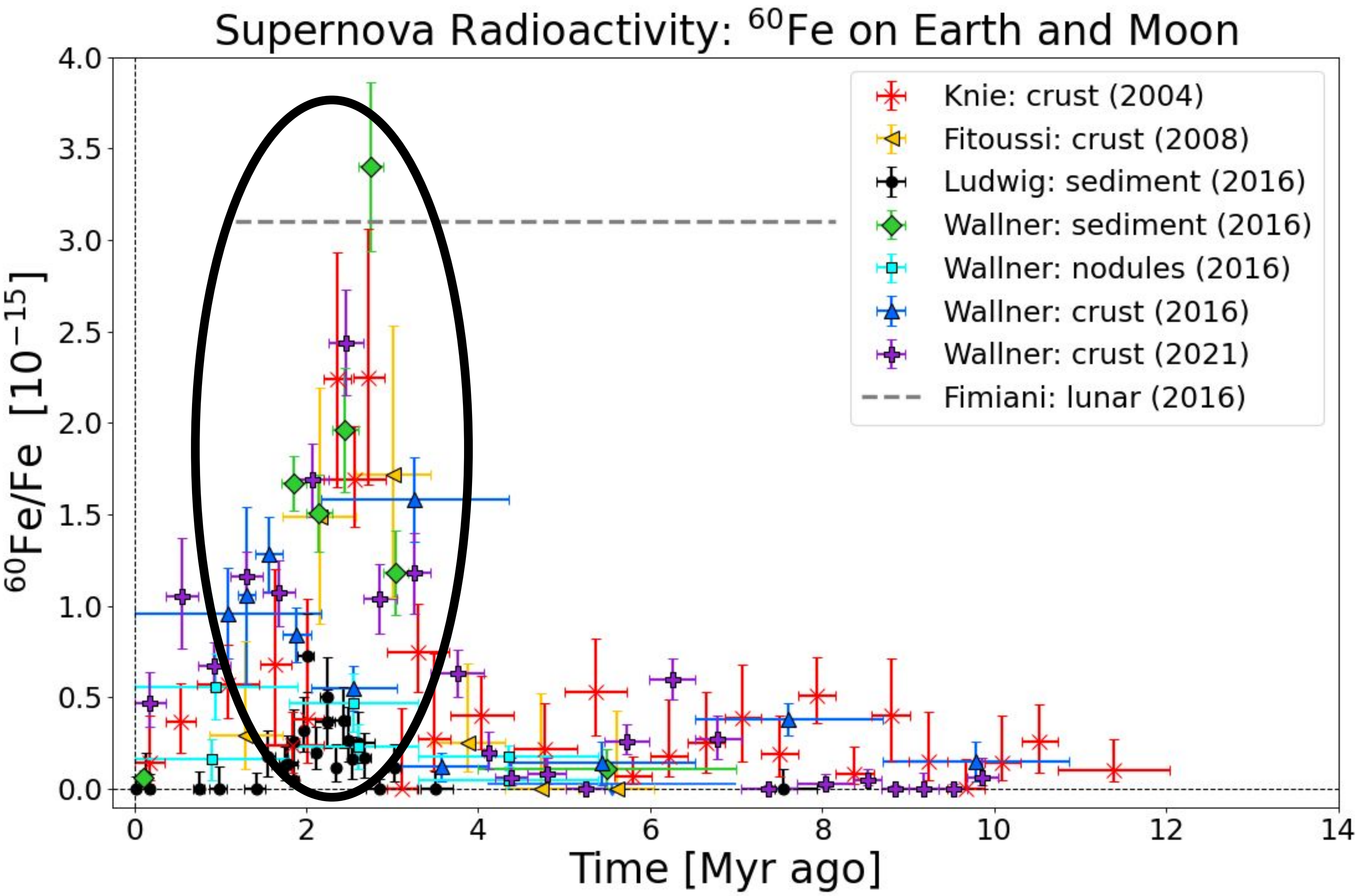
Oceanic sediment
Alan Mix, Oregon State University



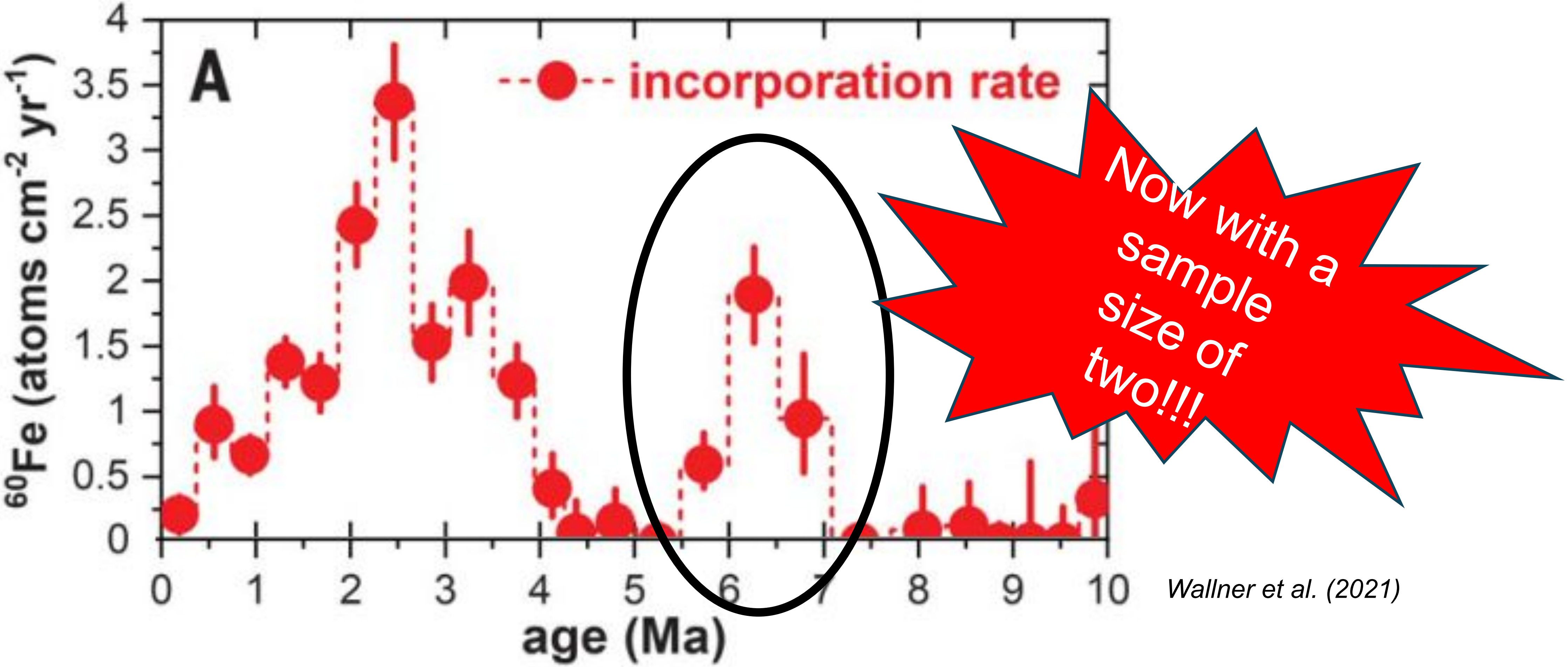
Magnetotactic bacterium
Nature Education

FeMn crust
Klaus Knie, Technical University of Munich

Astronaut Alan Bean taking a core sample
NASA Apollo photo AS12-49-7286



Ertel et al. (2023)



Wallner et al. (2021)

The end result is….

2-3 million years ago, the heliosphere encountered *drastic* compression

And 7-8 million years ago!

Now it´s your turn!

Calculate the size of the helio/astrosphere!

Interpret your answer – what are the implications of your result?

$$r_{stag} = \left(\frac{n_{sw} v_{sw}^2}{n_{ISM} v_{ISM}^2}\right)^{1/2} \text{ au}$$

$$r_{stag} = \left(\frac{\dot{M} v_{sw}}{4\pi \rho_{ISM} v_{ISM}^2}\right)^{1/2}$$

Group A

Heliosphere

~ vs ~

today's ISM

n_{sw} = 5 cm^{-3}
v_{sw} = 400 km/s

n_{ISM} = 0.1 cm^{-3}
v_{ISM} = 26 km/s

Group B

Heliosphere

~ vs ~

50 pc supernova

n_{sw} = 5 cm^{-3}
v_{sw} = 400 km/s

n_{ISM} = 0.02 cm^{-3}
v_{ISM} = 700 km/s

Group C

Heliosphere

~ vs ~

dense interstellar cloud

n_{sw} = 5 cm^{-3}
v_{sw} = 400 km/s

n_{ISM} = 3000 cm^{-3}
v_{ISM} = 20 km/s

Group D

Betelgeuse

~ vs ~

its environment

$\dot{M}$ = 10^{-6} M_{sun}/yr
v_{sw} = 21 km/s

ρ_{ISM} = 3.3 amu cm^{-3}
v_{ISM} = 50 km/s

Group E

Zeta Ophiuchi

~ vs ~

its environment

$\dot{M}$ = 2 * 10^{-8} M_{sun}/yr
v_{sw} = 1500 km/s

ρ_{ISM} = 4 amu cm^{-3}
v_{ISM} = 40 km/s

Group A
Heliosphere
~ vs ~
today's ISM

n_{sw} = 5 cm^{-3}
v_{sw} = 400 km/s

n_{ISM} = 0.1 cm^{-3}
v_{ISM} = 26 km/s

110 au

Group B
Heliosphere
~ vs ~
50 pc supernova

n_{sw} = 5 cm^{-3}
v_{sw} = 400 km/s

n_{ISM} = 0.02 cm^{-3}
v_{ISM} = 700 km/s

9.0 au

Group C
Heliosphere
~ vs ~
dense interstellar cloud

n_{sw} = 5 cm^{-3}
v_{sw} = 400 km/s

n_{ISM} = 3000 cm^{-3}
v_{ISM} = 20 km/s

0.82 au

Group D
Betelgeuse
~ vs ~
its environment

$\dot{M}$ = 10^{-6} M_{sun}/yr
v_{sw} = 21 km/s

ρ_{ISM} = 3.3 amu cm^{-3}
v_{ISM} = 50 km/s

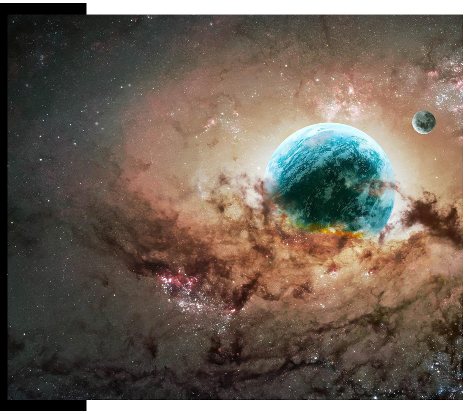
18,000 au
0.090 pc

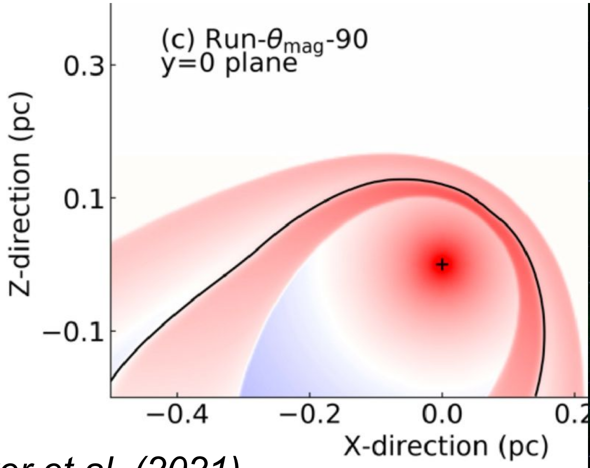
Group E
Zeta Ophiuchi
~ vs ~
its environment

$\dot{M}$ = 2 * 10^{-8} M_{sun}/yr
v_{sw} = 1500 km/s

ρ_{ISM} = 4 amu cm^{-3}
v_{ISM} = 40 km/s

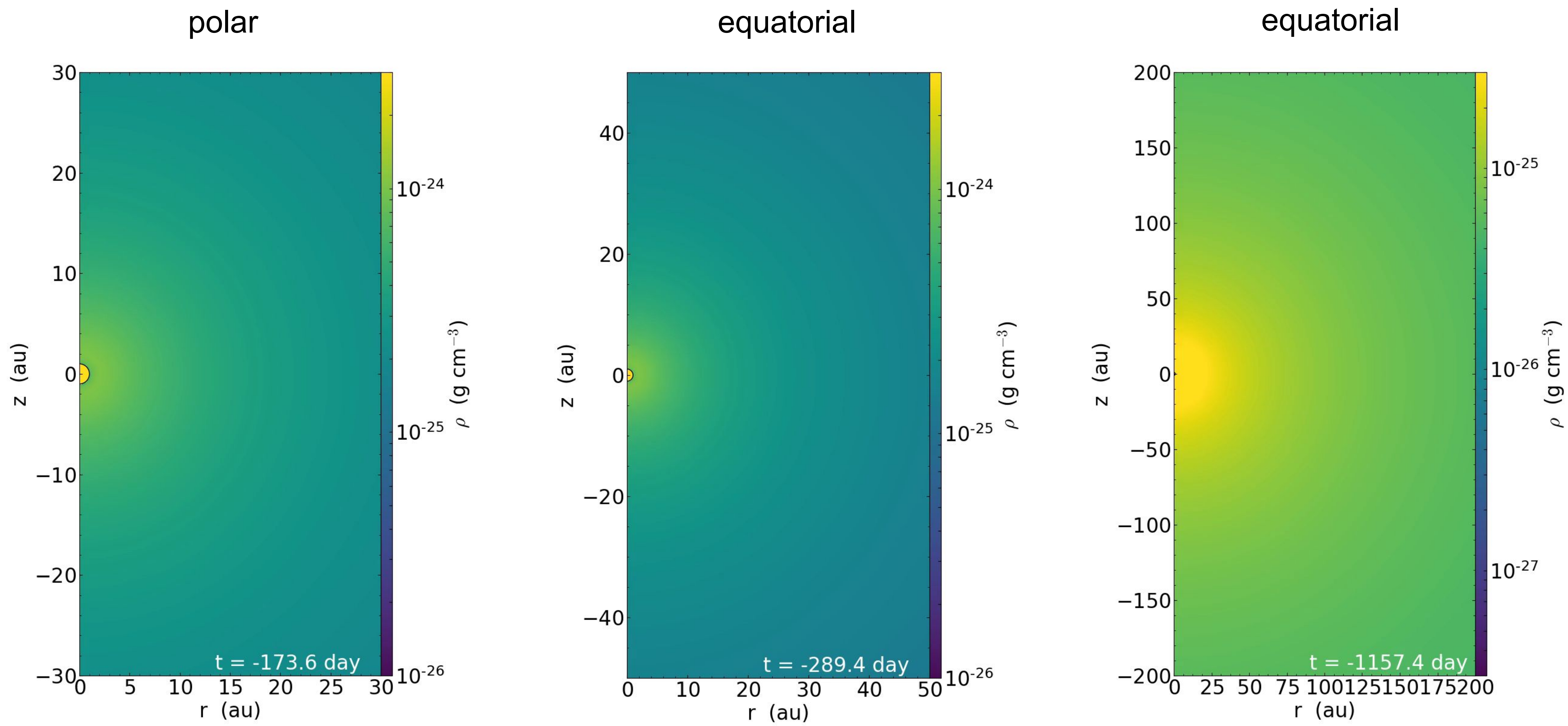
25,000 au
0.12 pc





Meyer et al. (2021)

Zeta Ophiuchi
NASA/JPL-Caltech



25 pc

50 pc

126 pc

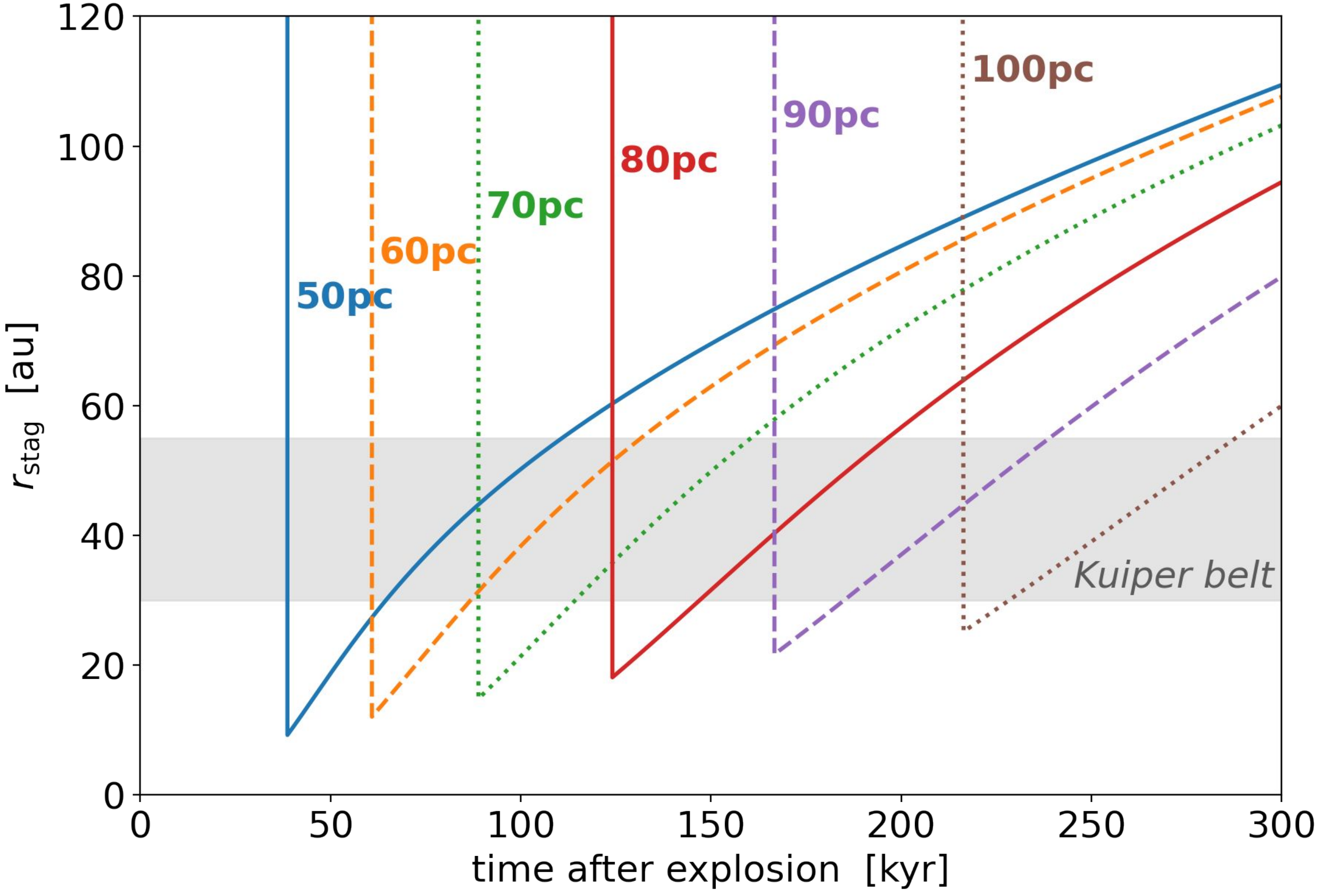
Supernova distance

Miller & Fields (2022)

Fading supernova remnant

- Still Sedov-Taylor remnant
    - Local Bubble medium
- Solve at constant location
- Find pressure balance with solar wind

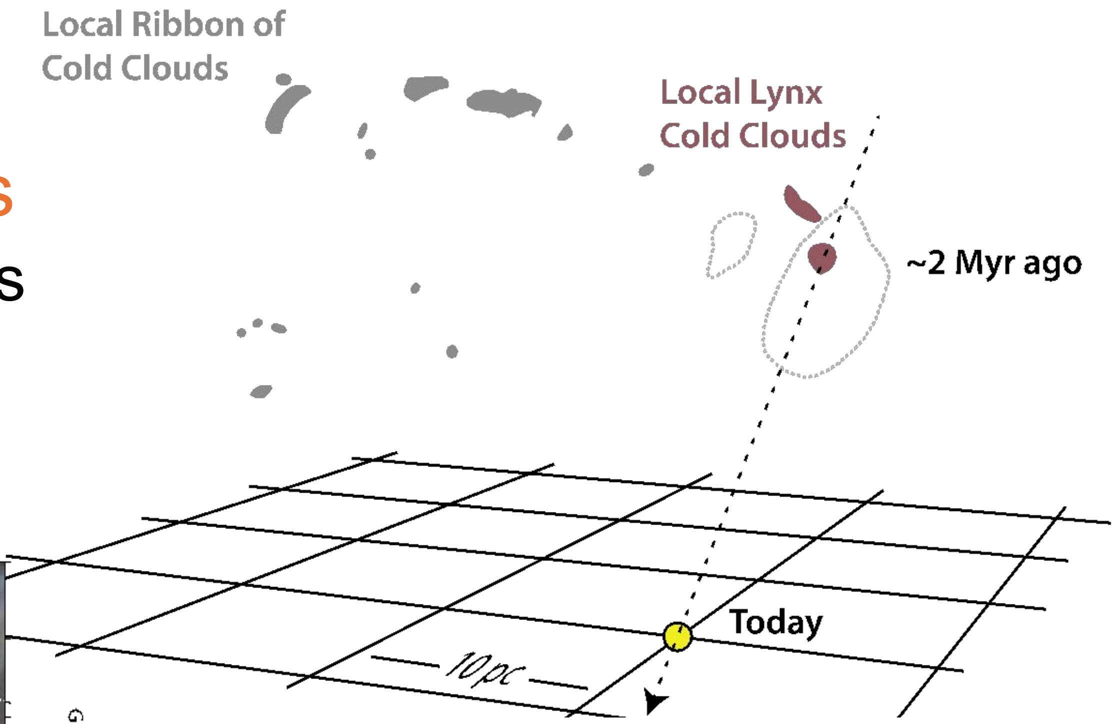
How much of the solar system (and for how long) is directly exposed to the supernova blast?

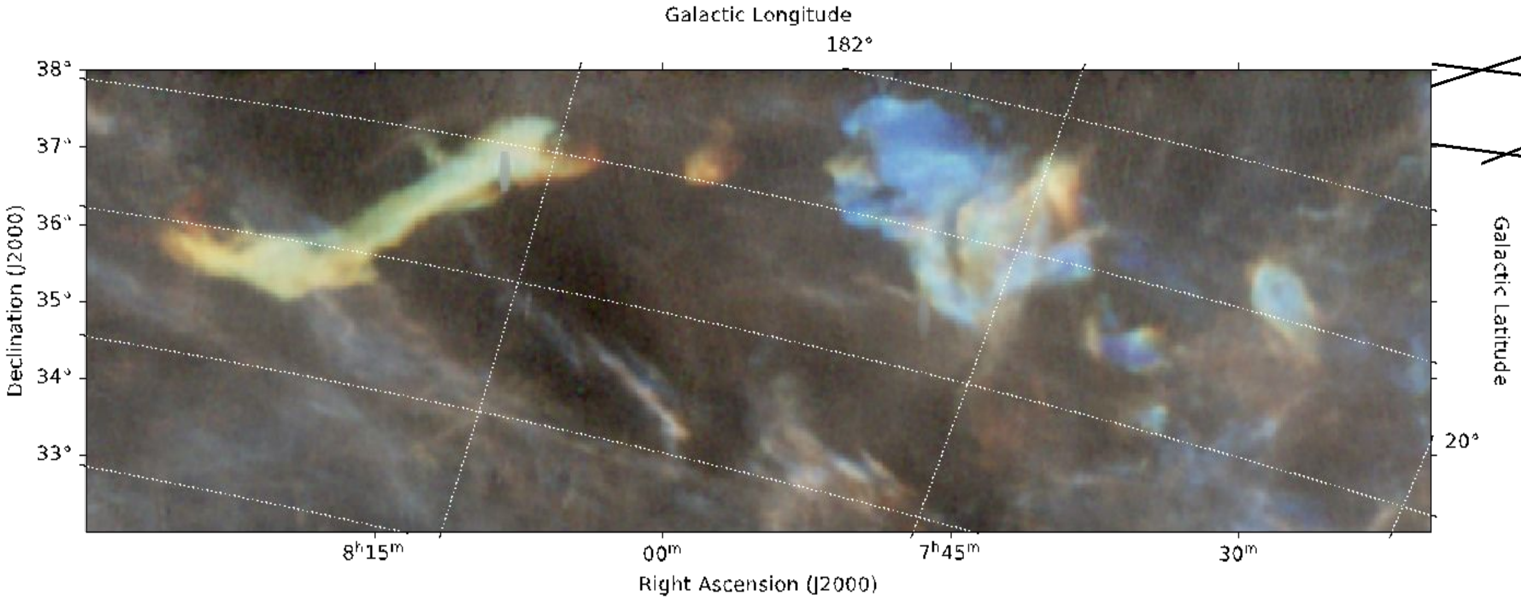


Miller & Fields (2022)

Now what about a cold cloud?

- Trace the Sun's path back in time
- Intersects Local Lynx of Cold Clouds
    - Part of the Local Ribbon of Cold Clouds

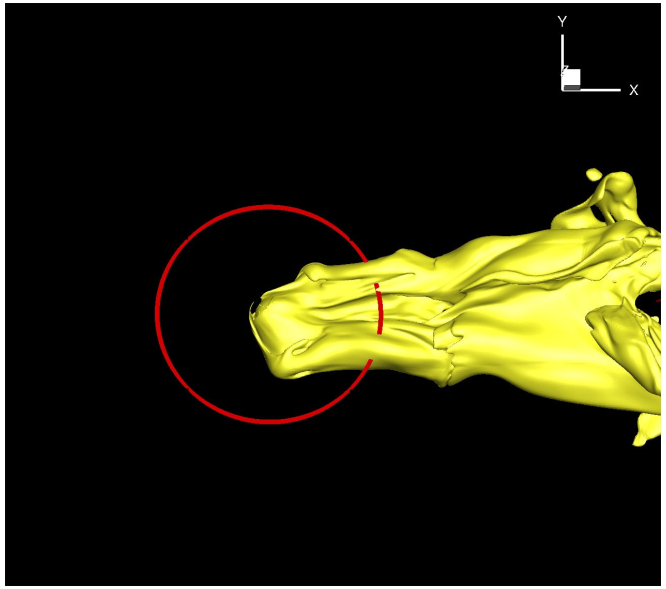


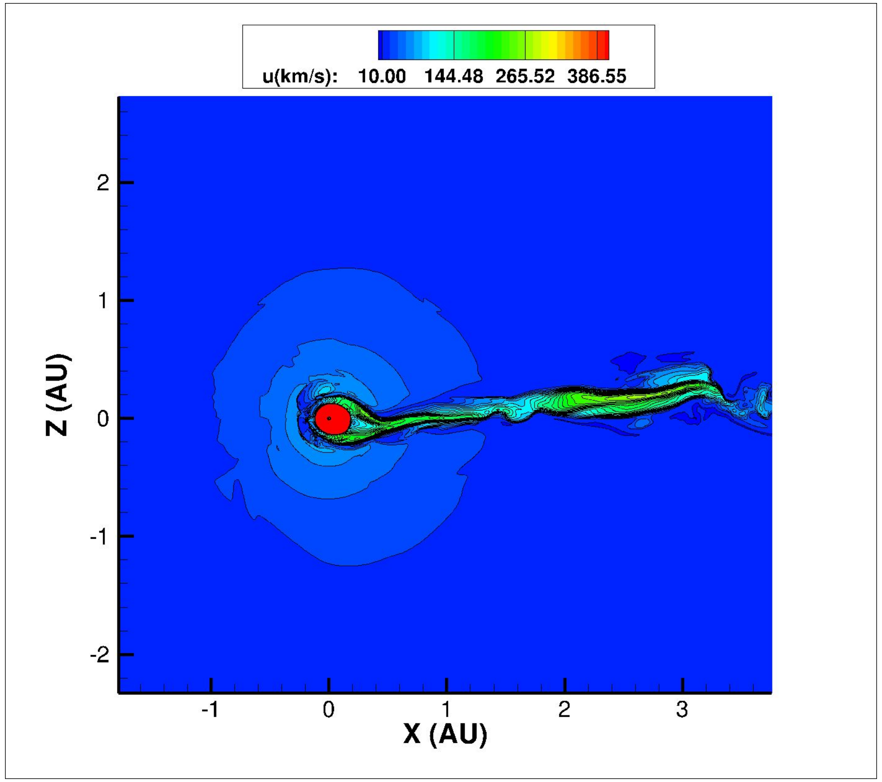


Opher, Loeb, & Peek (2024)

The heliosphere in the LxCC

- Much more complete helio model
  - Full 3D, mag fields
  - Completely neutral ISM
- ISM density ~3000 cm^{-3}
- Similar velocity to today
- Red circle is Earth's orbit
  - Completely exposed!
  - "De-screening"

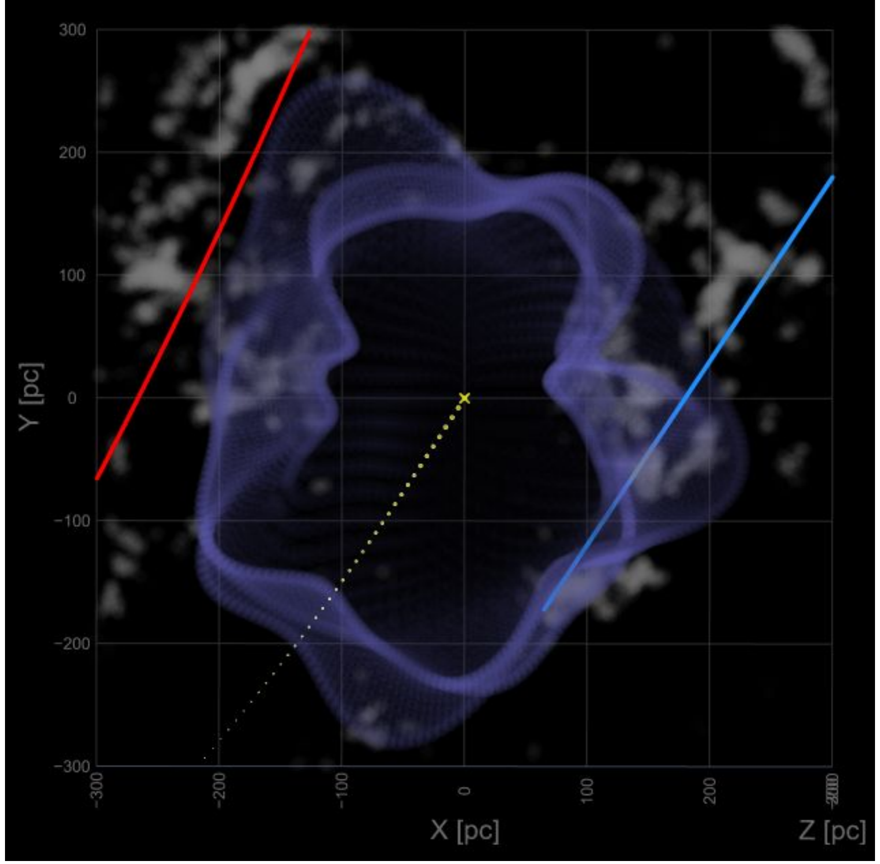


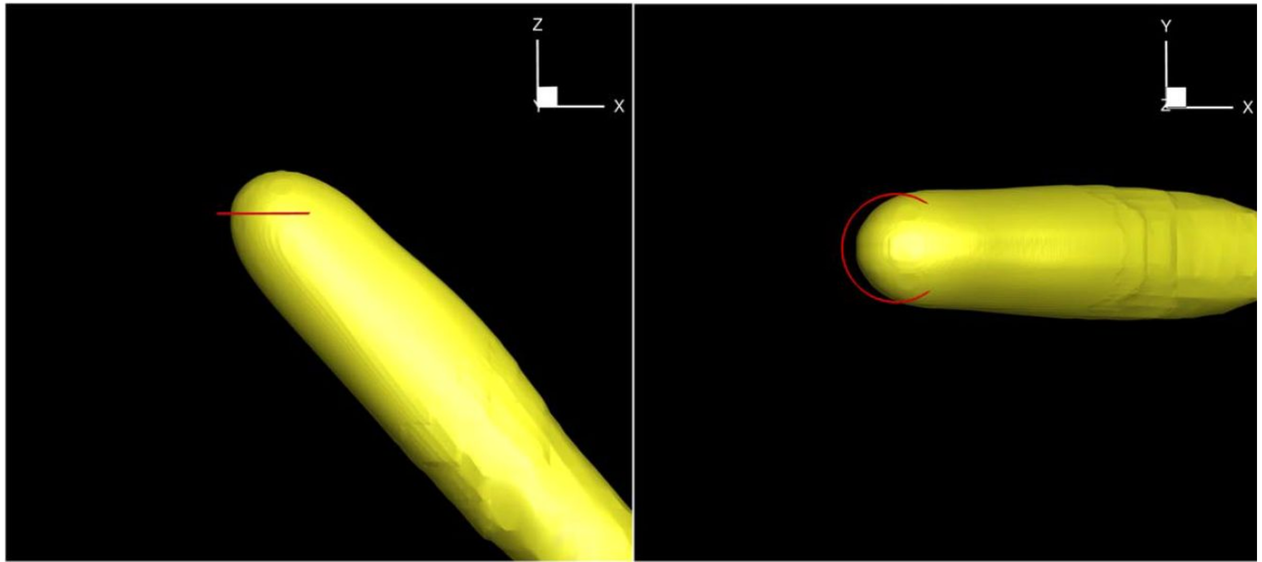


Opher, Loeb, & Peek (2024)

7-8 Myr ago

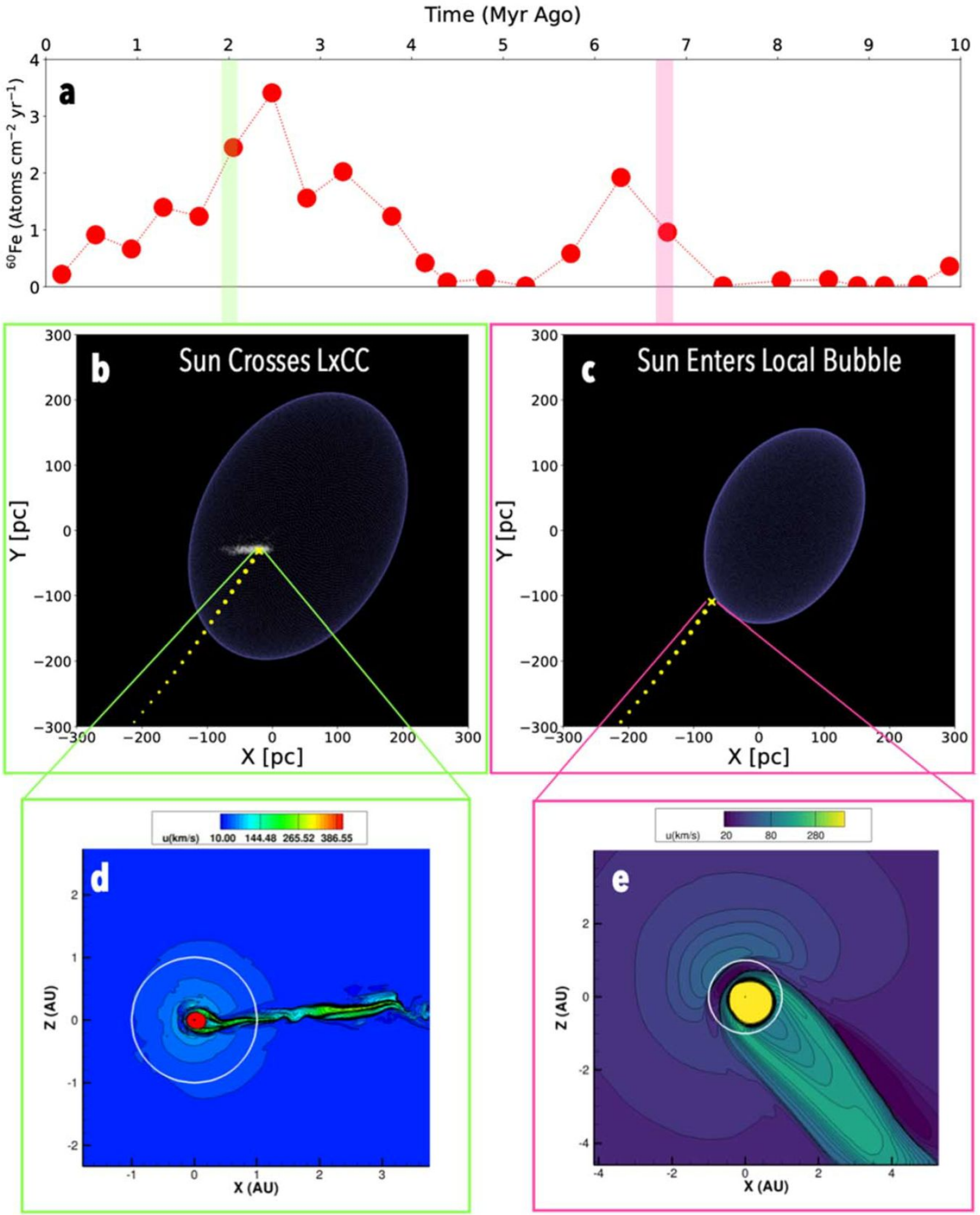
- Lines up with ^{60}Fe pulse
- Wall of the Local Bubble
- Local Bubble made by SN explosions starting ~15 Myr ago
- Dense clouds build up around edge
- Chance to expose Earth





Opher et al. (2024)

Connecting ocean floor sediment…

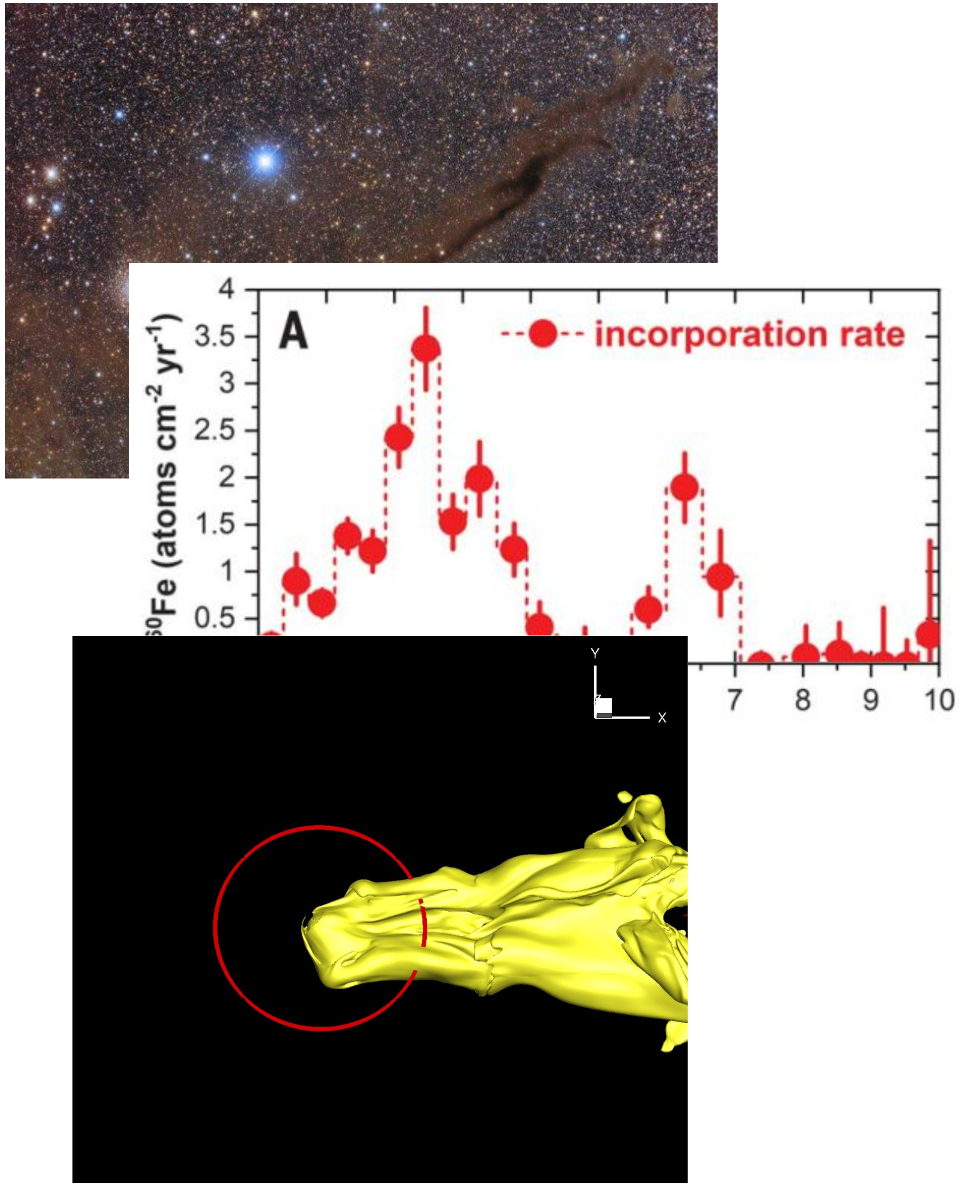


…to our habitable astrosphere

Opher et al. (2024)

Summary

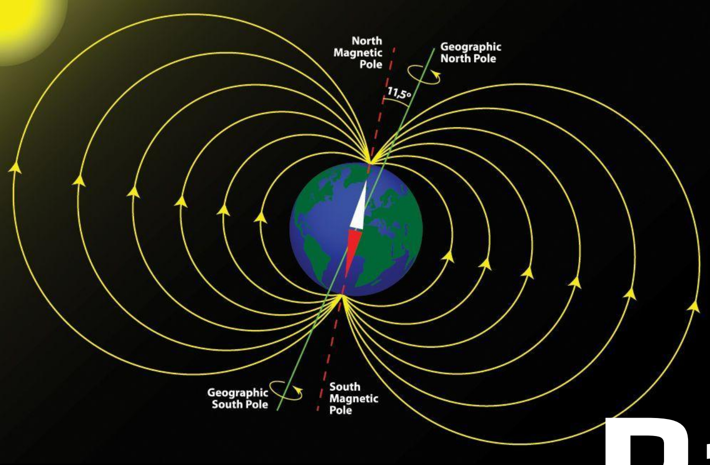
- **The heliosphere encountered extreme events 2-3 and 7-8 Myr ago**
  - And will again in the future!
- Discovered by measuring ^{60}Fe in ocean sediment/crusts
- Heliosphere was greatly compressed
  - Possibly exposed Earth directly to interstellar medium
- Always more to explore
  - Effects on other planets
  - Cosmic rays and interstellar dust transport
  - Other events?



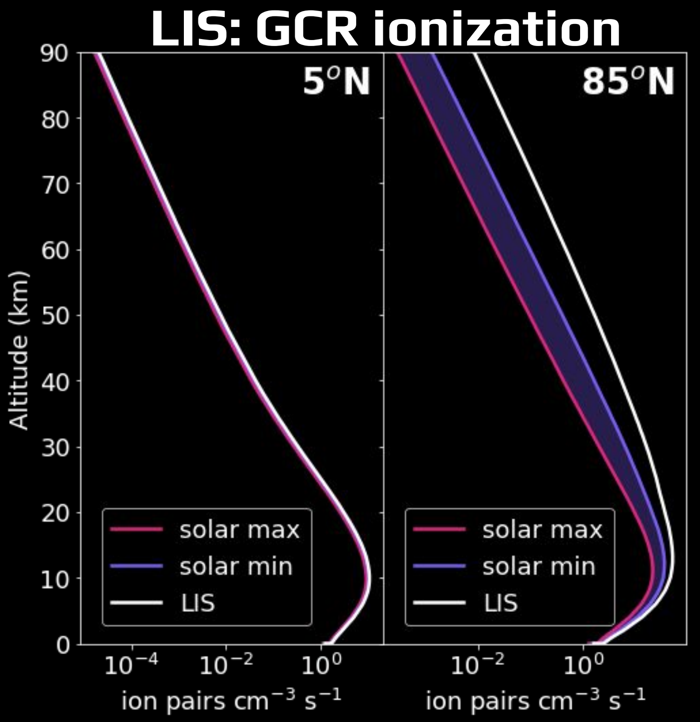
Next lecture: how do these events affect Earth’s atmosphere and climate?

Break time

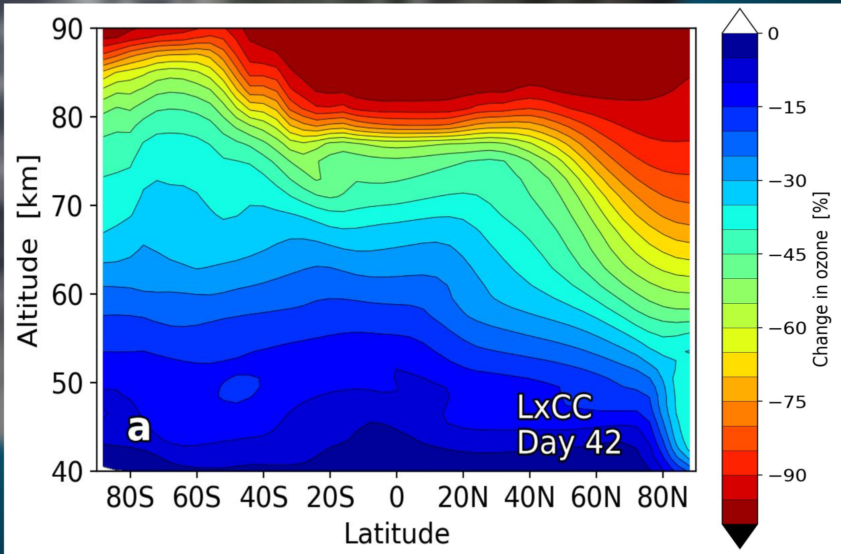
Meet back at 10:20



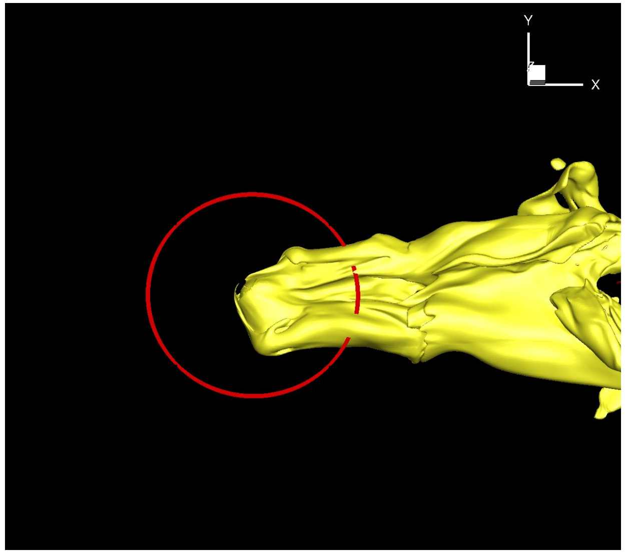
Paleo-heliosphere
Part II



Jesse Miller
Boston University
SHIELD summer school 2025



First lecture summary



- Heliosphere can get squashed
  - Supernovae or dense interstellar clouds
- Ignore supernovae, focus on cold cloud scenario
- And now: what happens to Earth?

Increased cosmic ray exposure

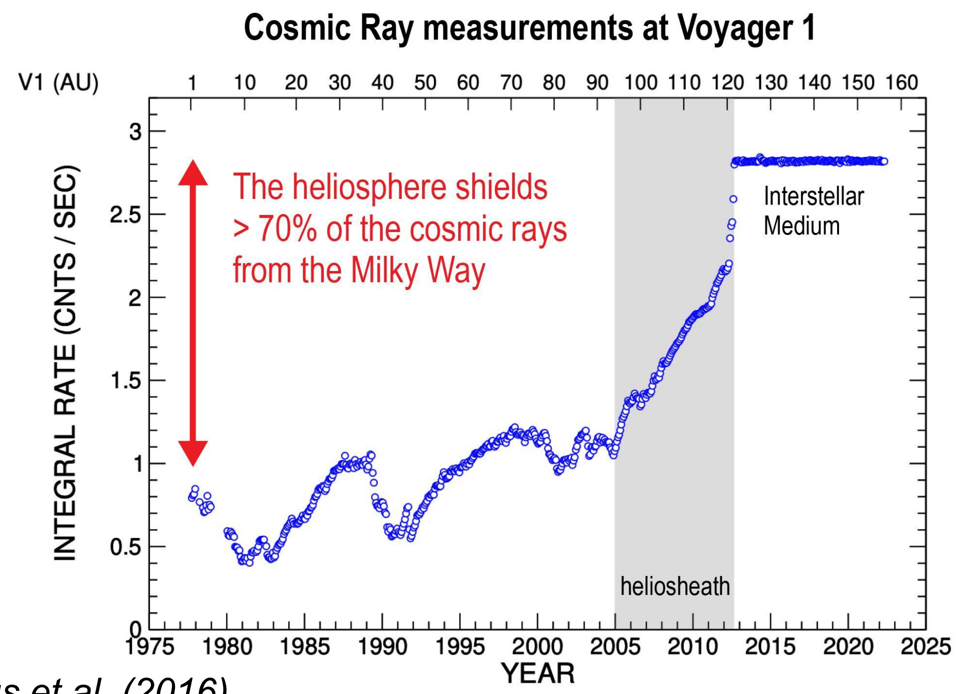
Led by Anna Nica

Direct hydrogen input

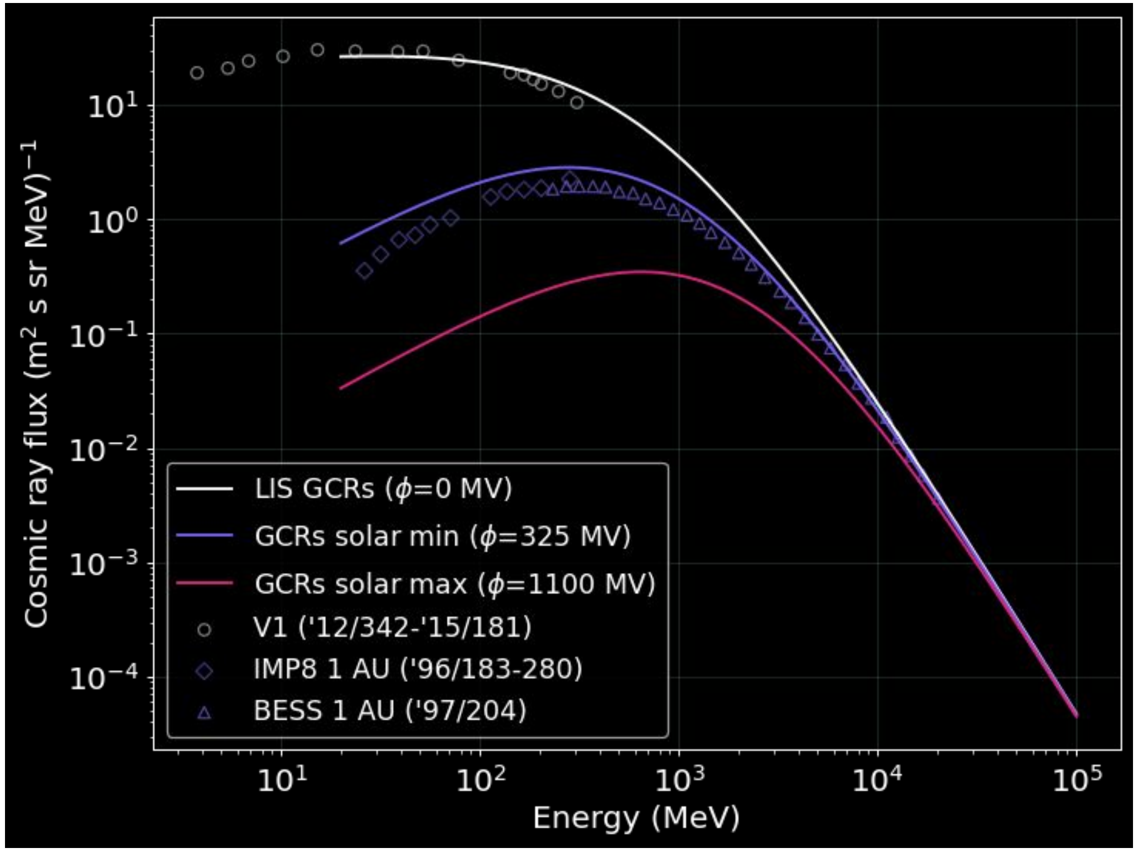
Led by yours truly

Our heliospheric shield

- Protects us from low-energy CRs
- Modulates <1 GeV
    - Depends on solar cycle



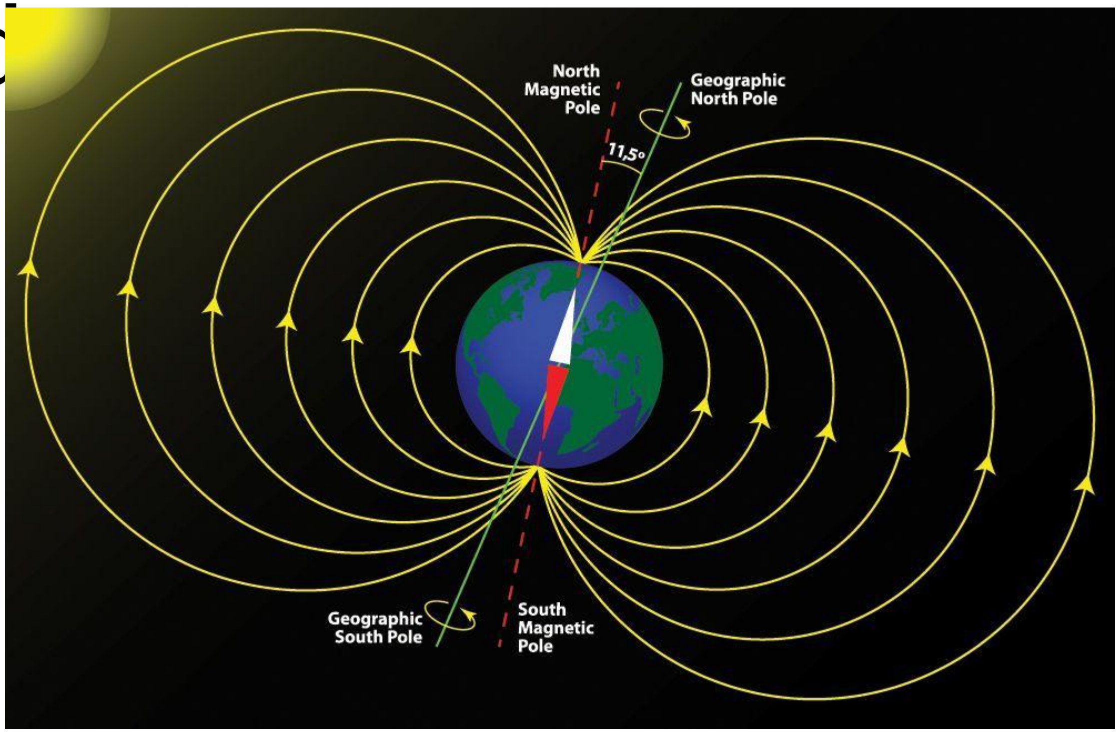
Cummings et al. (2016)

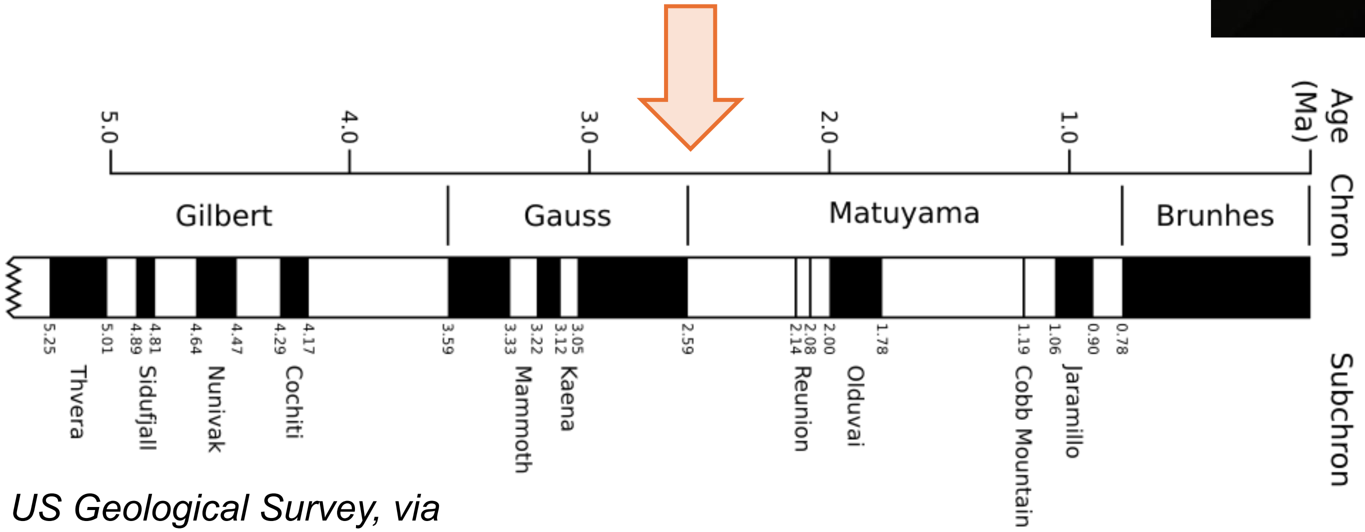


Nica et al. (submitted)

Our geomagnetic shield

- Approximately dipole
- At equator, blocks <10 GeV
- Can undergo reversals
    - Gauss-Matuyama reversal at 2.6 Mya

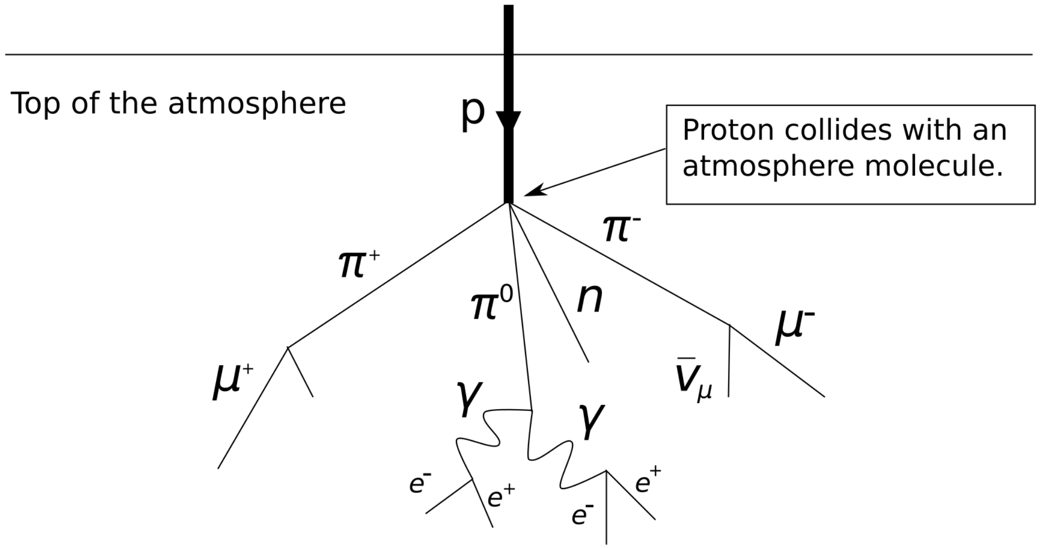


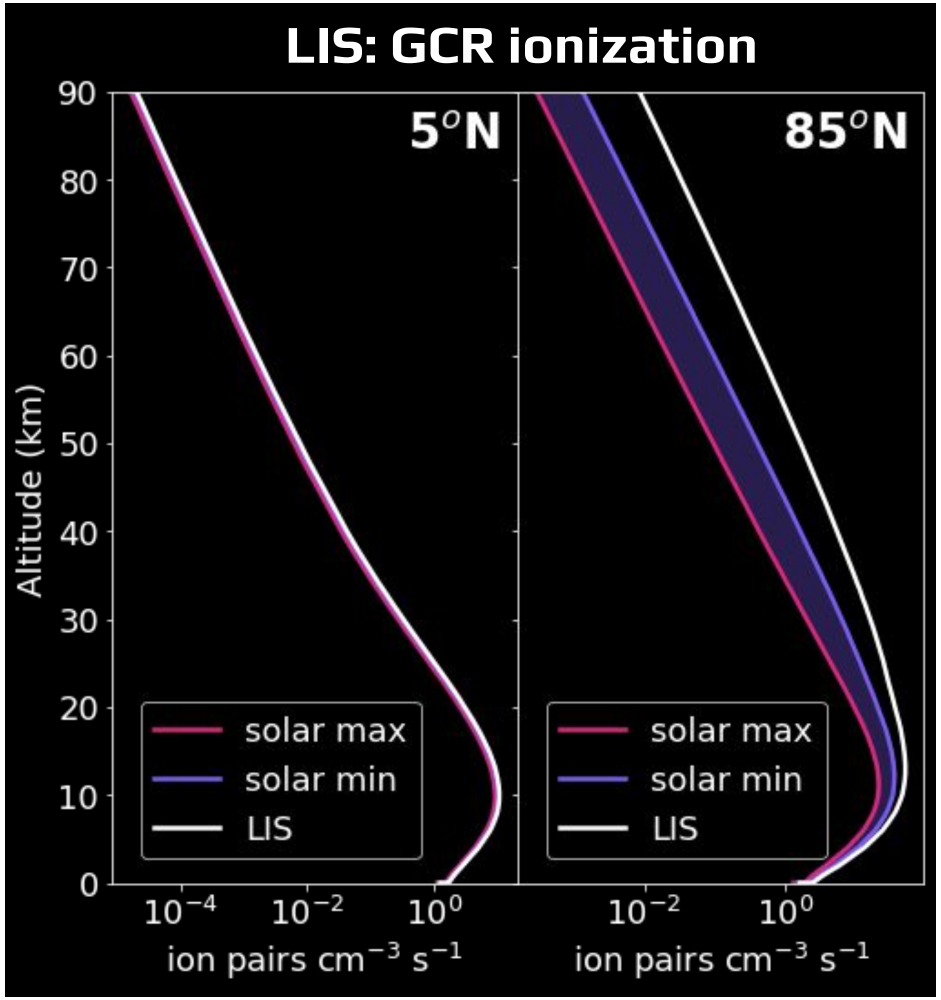


US Geological Survey, via Wikipedia

Cosmic rays interact with the atmosphere

- High-energy CRs generate a “shower”
- Ionize N_2
  - Primary component of atmosphere





Nica et al. (submitted)

Nitrogen compounds deplete ozone

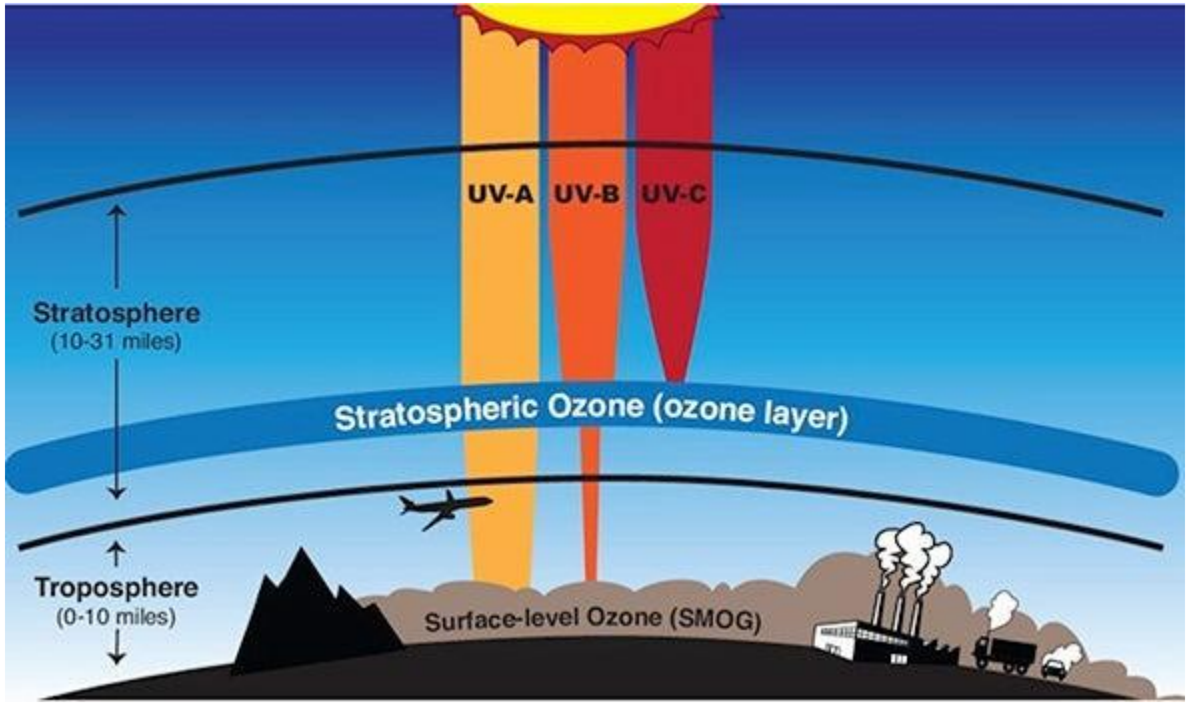
- Lots of NO_x compounds
  - $NO_x = N + NO + NO_2$
- Catalytically deplete ozone

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O \rightarrow NO + O_2$$

$$\text{net}: \quad O_3 + O \rightarrow O_2 + O_2$$

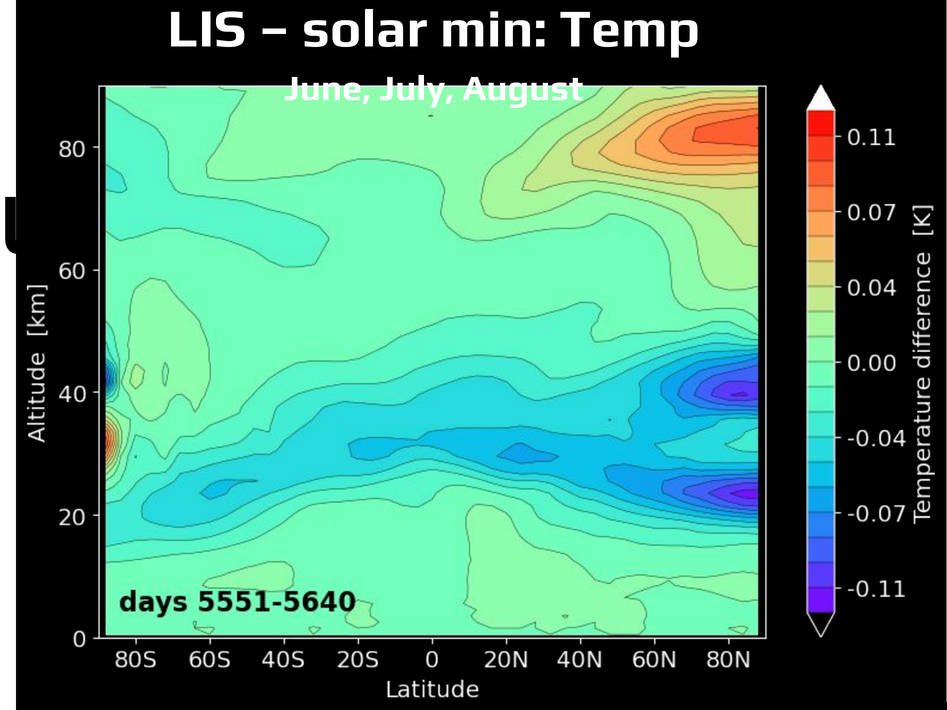
- But ozone is good at blocking UV

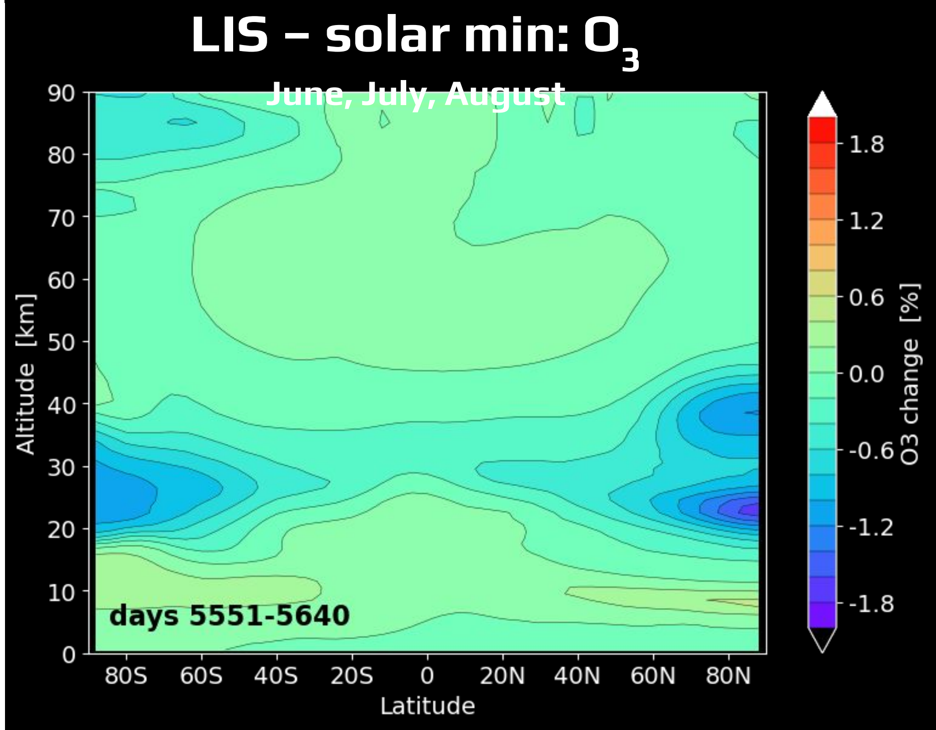


Radiation from the cold clou

- Run climate simulations with Local Interstellar Spectrum of CRs
- 1-2% ozone depletion in stratosphere
- Leads to 0.1 K decrease in temperature
- Possible geomagnetic field flip during crossing

- What would happen on the surface?

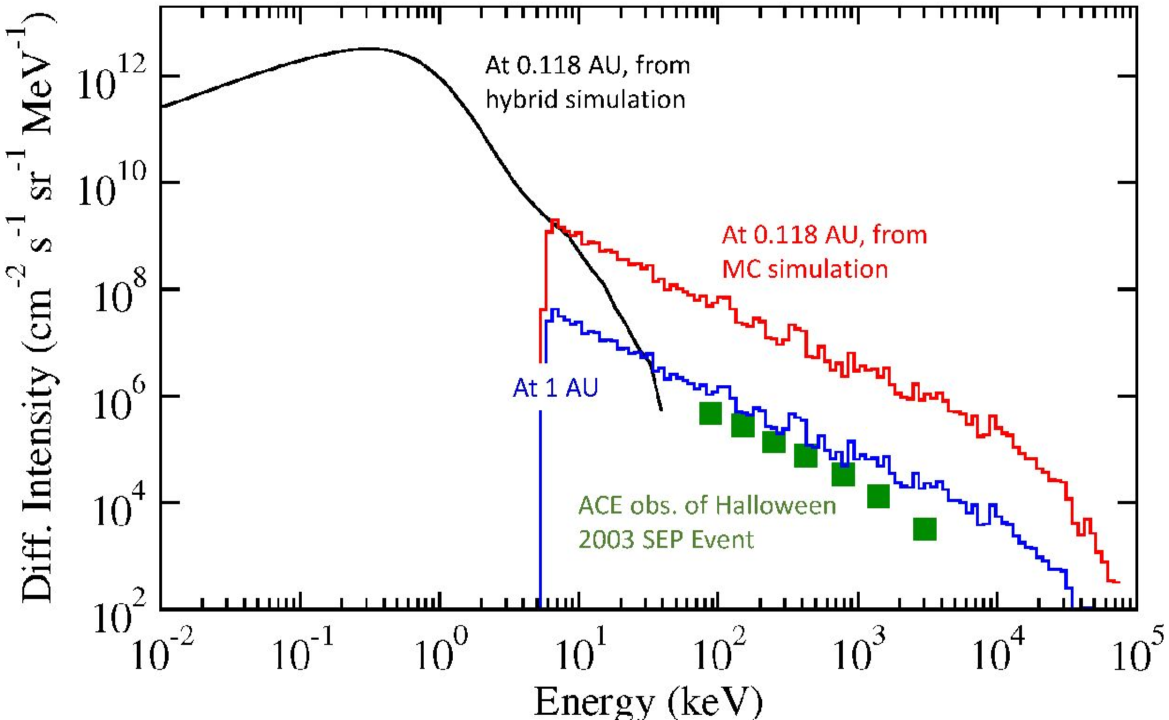




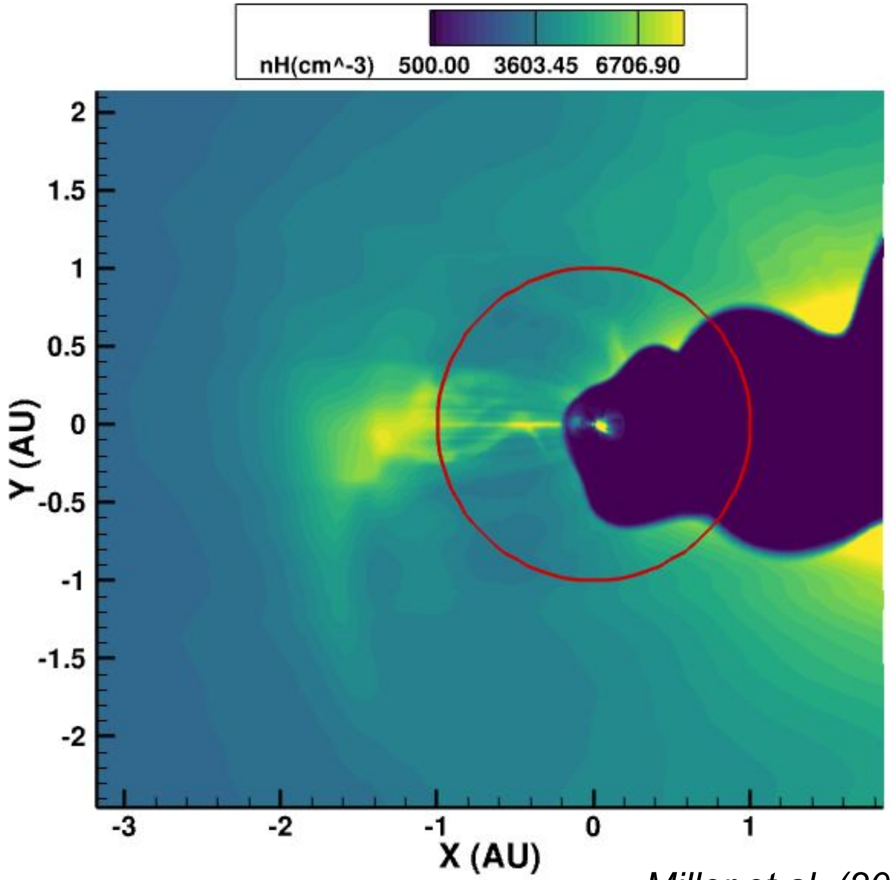
Nica et al. (submitted)

Heliospheric energetic particles

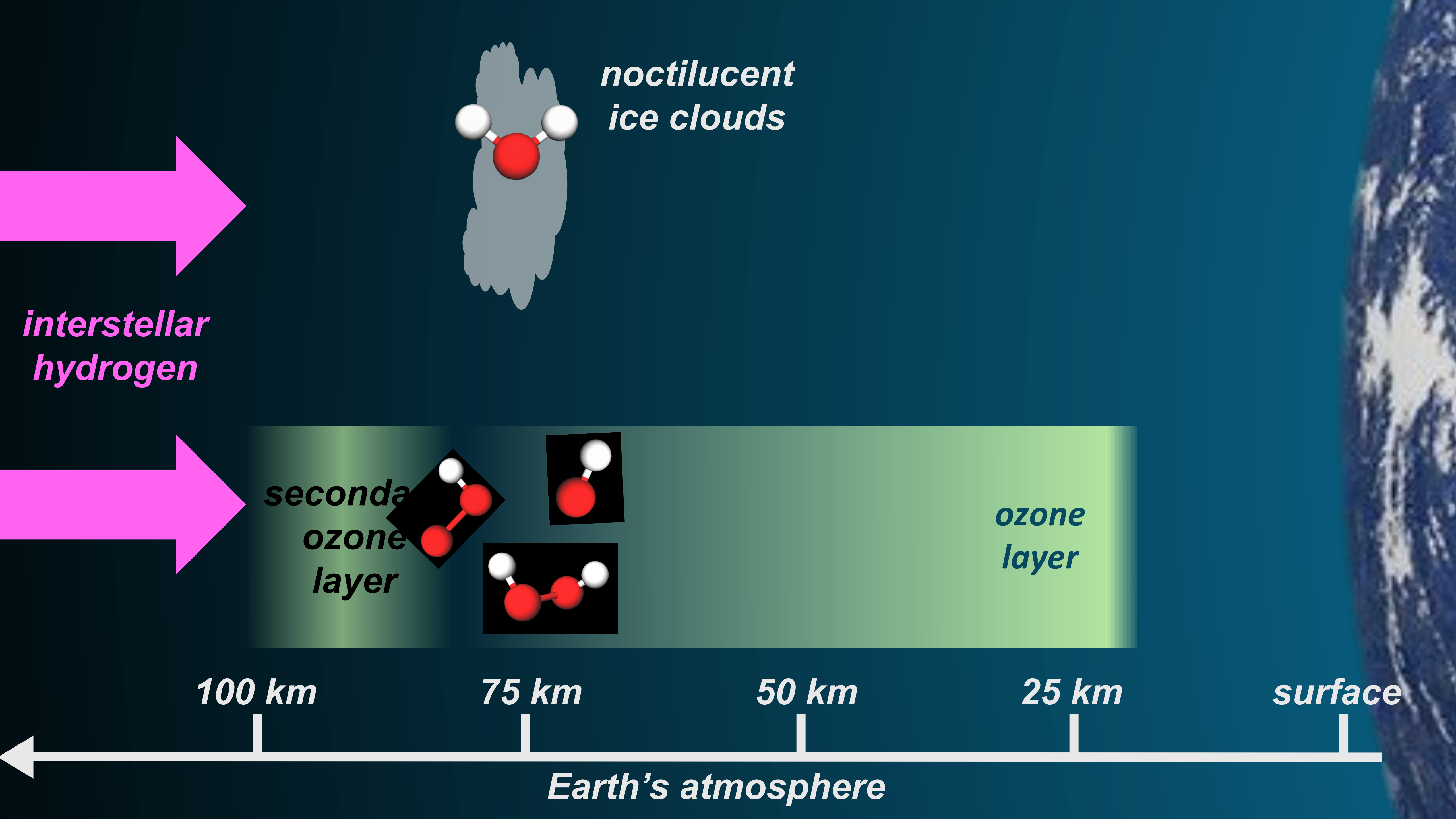
- Low energy, but *huge* intensity
- Only when Earth is inside heliosheath
  - A two-month-long SEP event!

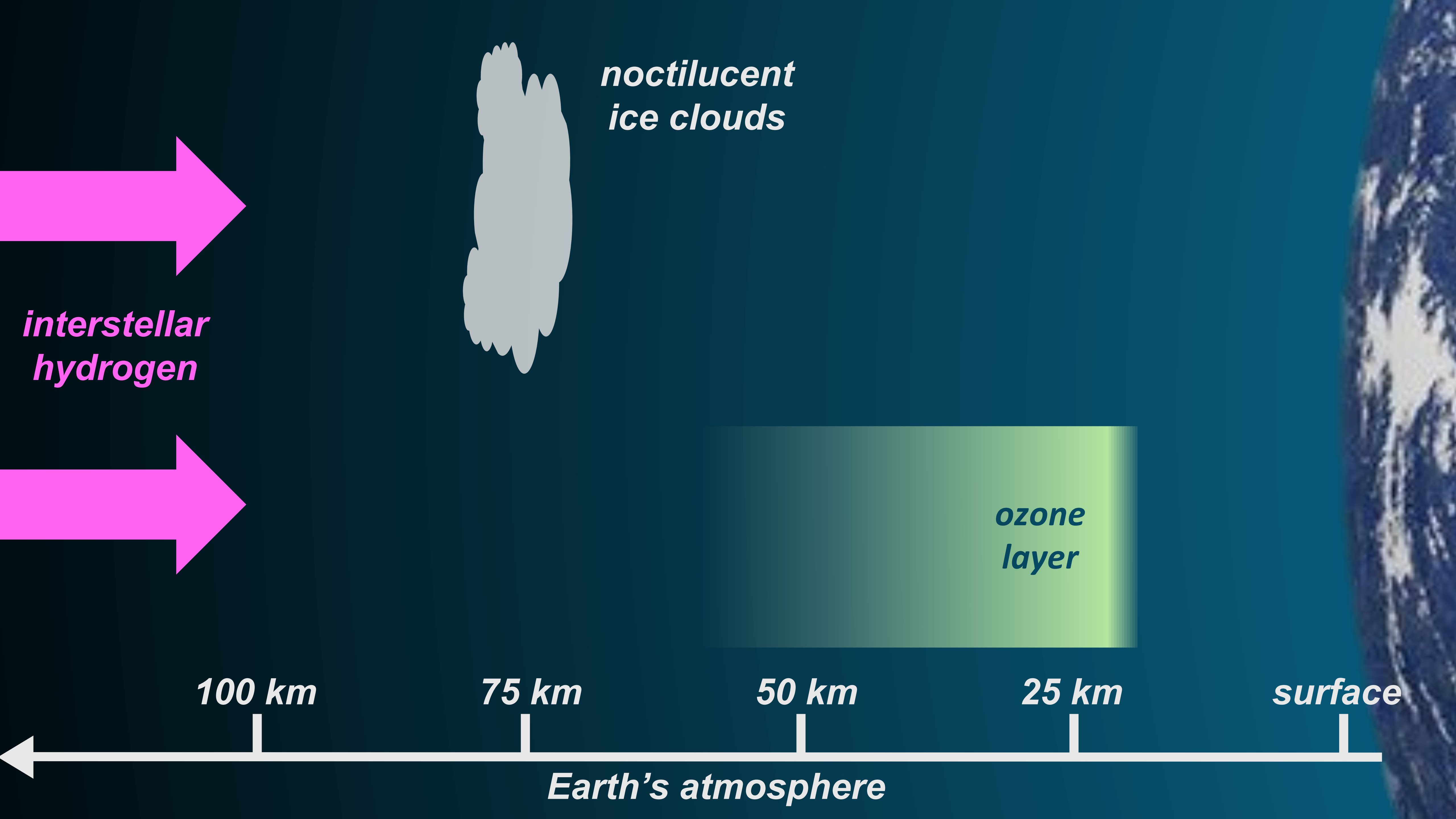


Opher et al. (submitted)



Miller et al. (2024)


noctilucent
ice clouds
interstellar
hydrogen
seconda
ozone
layer
ozone
layer
100 km
75 km
50 km
25 km
surface
Earth's atmosphere


noctilucent ice clouds
interstellar hydrogen
ozone layer
100 km
75 km
50 km
25 km
surface
Earth’s atmosphere

Interstellar hydrogen in the atmosphere

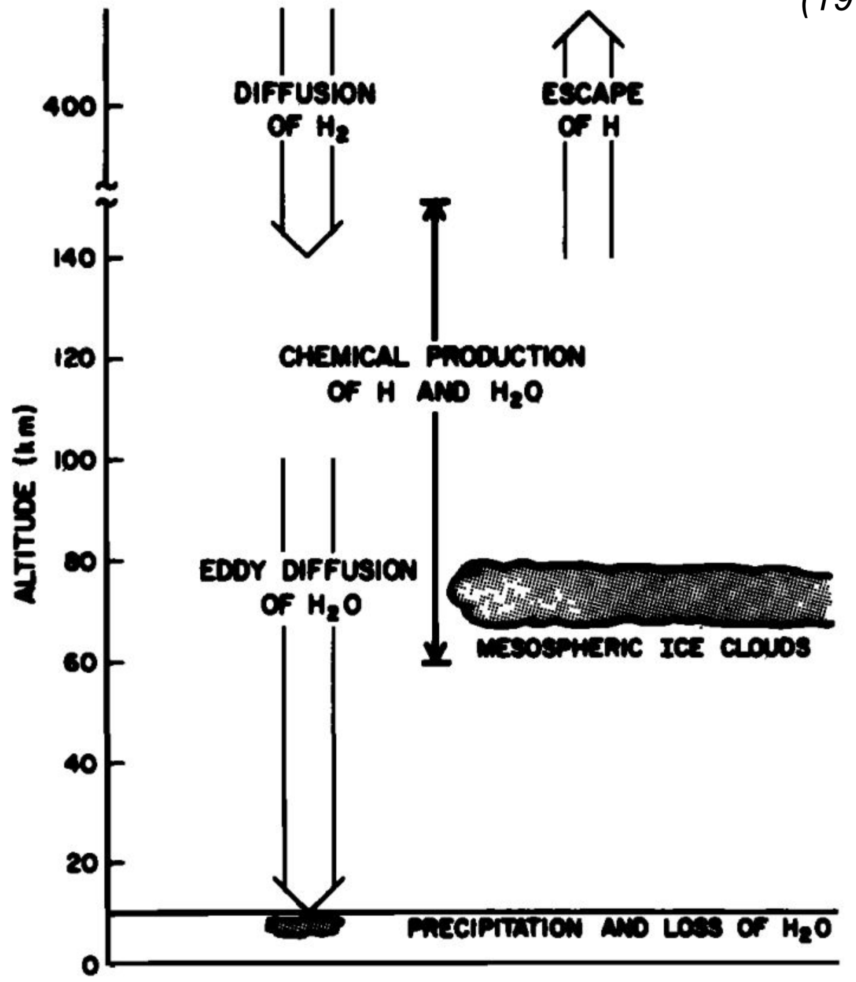
- H diffuses down through thermosphere
- Generates H_2O and HO_x

At 100 km, H_2O concentration is up to **570 ppm**!*

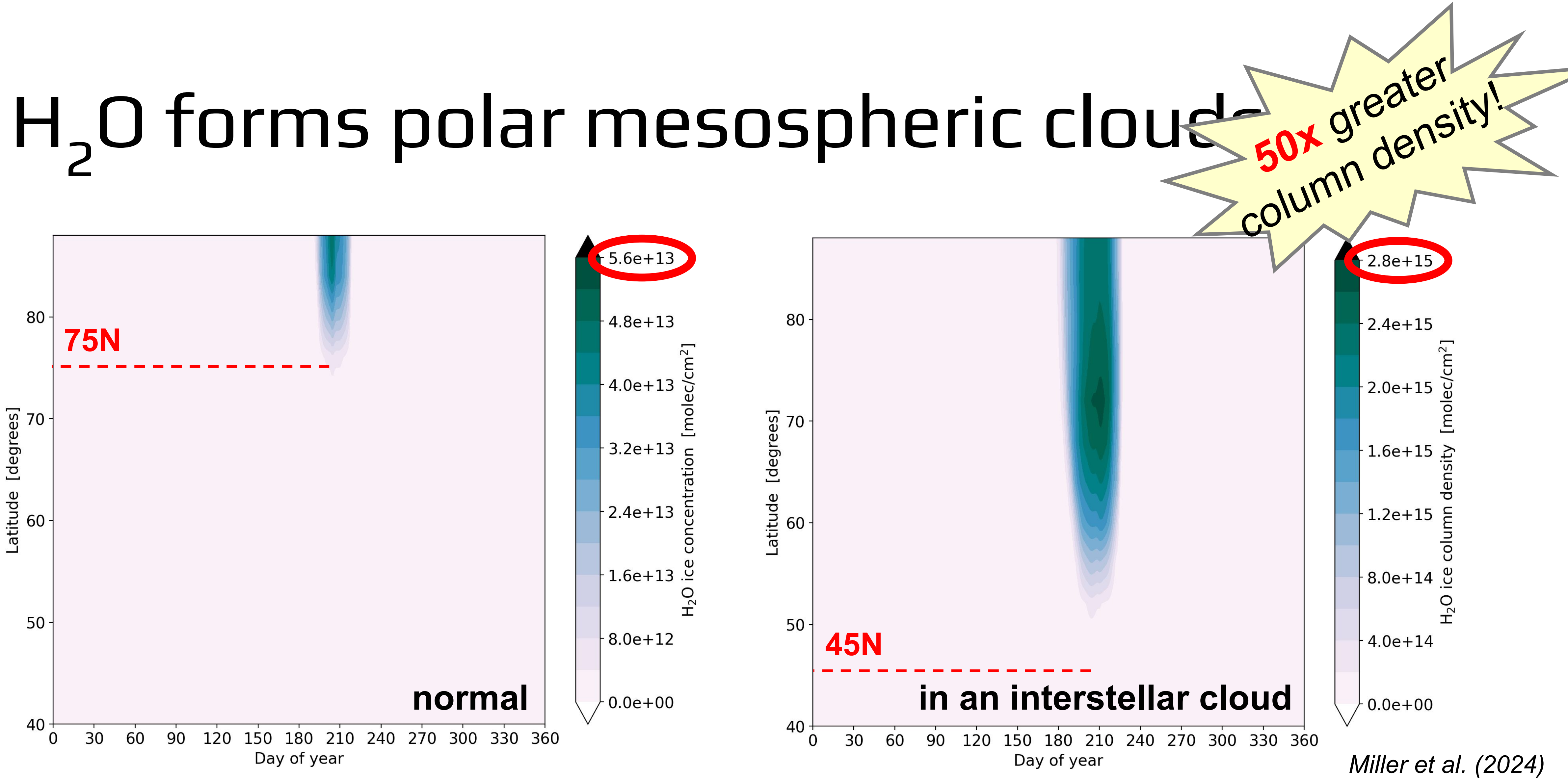
*Typically 1-10 ppm today

- First full atmospheric chemistry simulation
  - GSFC 2D chemistry-dynamics model
  - Pre-industrial conditions
  - Comes to equilibrium after ~20 years

McKay & Thomas (1978)



H_2O forms polar mesospheric clouds



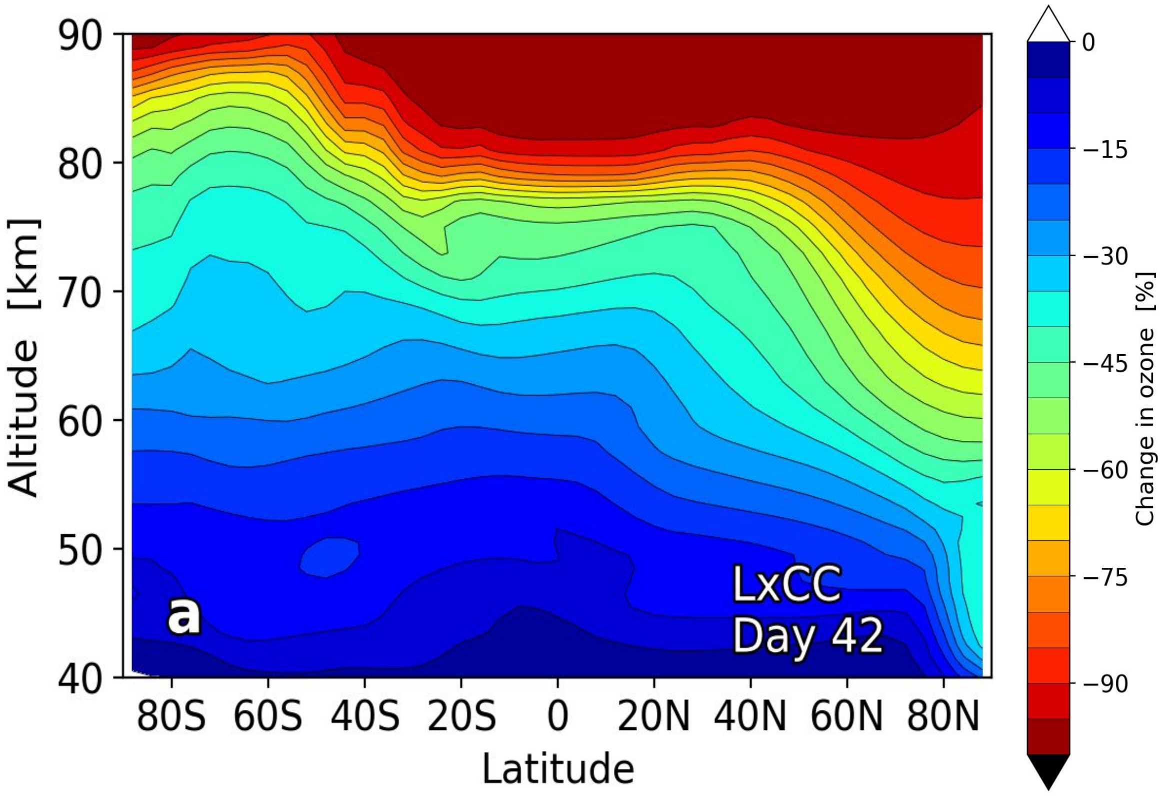
Miller et al. (2024)

- Thick PMCs block both sunlight and longwave radiation

HO_x depletes mesospheric ozone….

- HO_x depletes mesospheric ozone
  - Complete depletion above 80 km
- Strong seasonal effects in polar regions
- Decreases temperature by up to 10 K throughout mesosphere

Miller et al. (2024)



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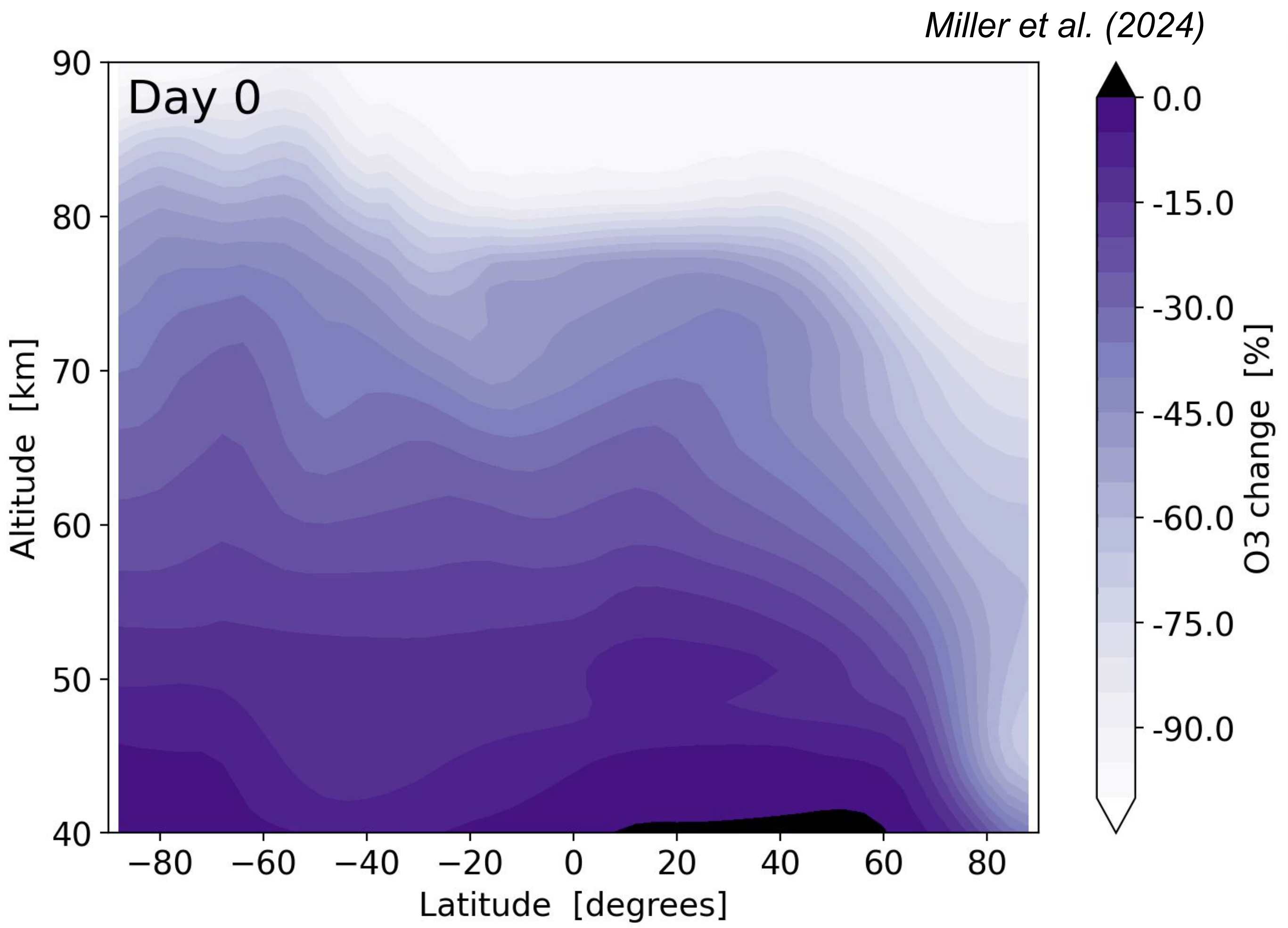
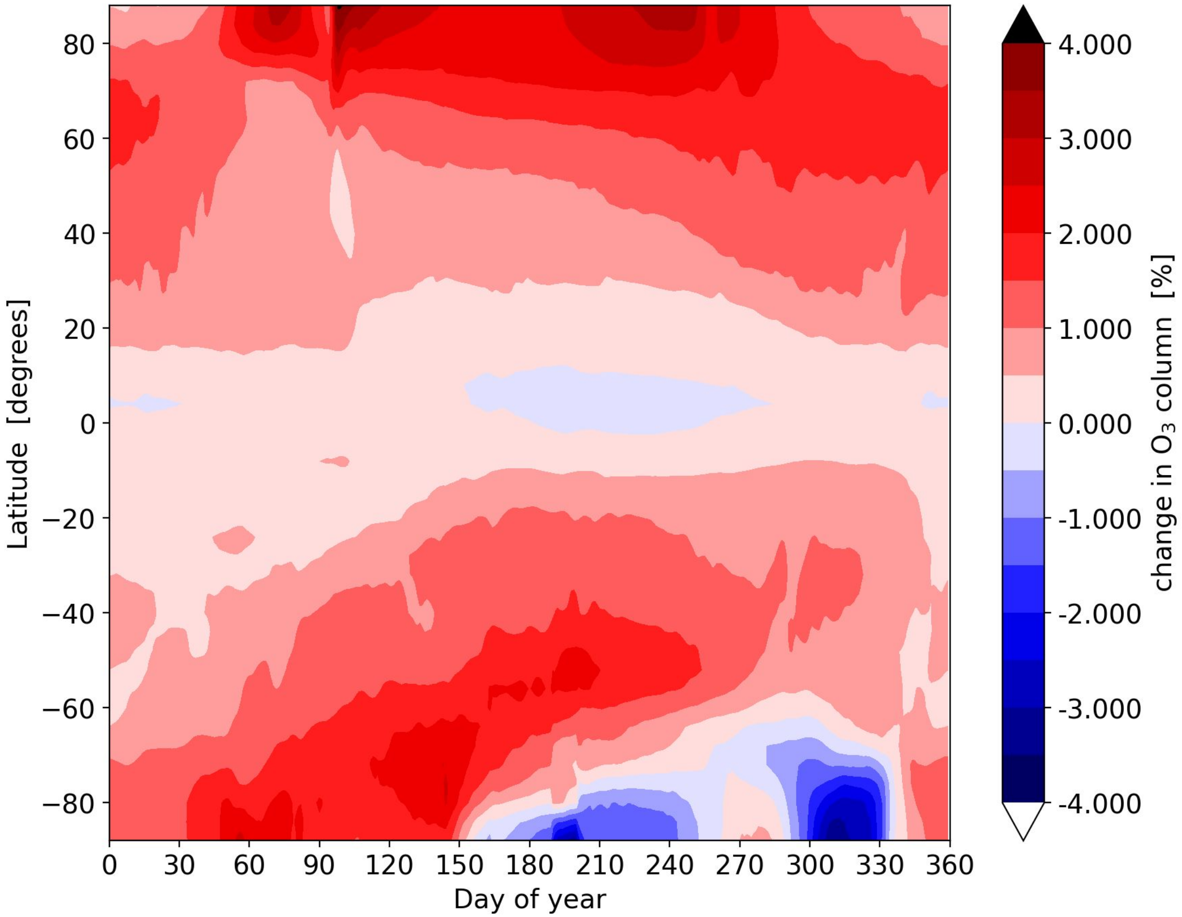


….but total ozone column is increased

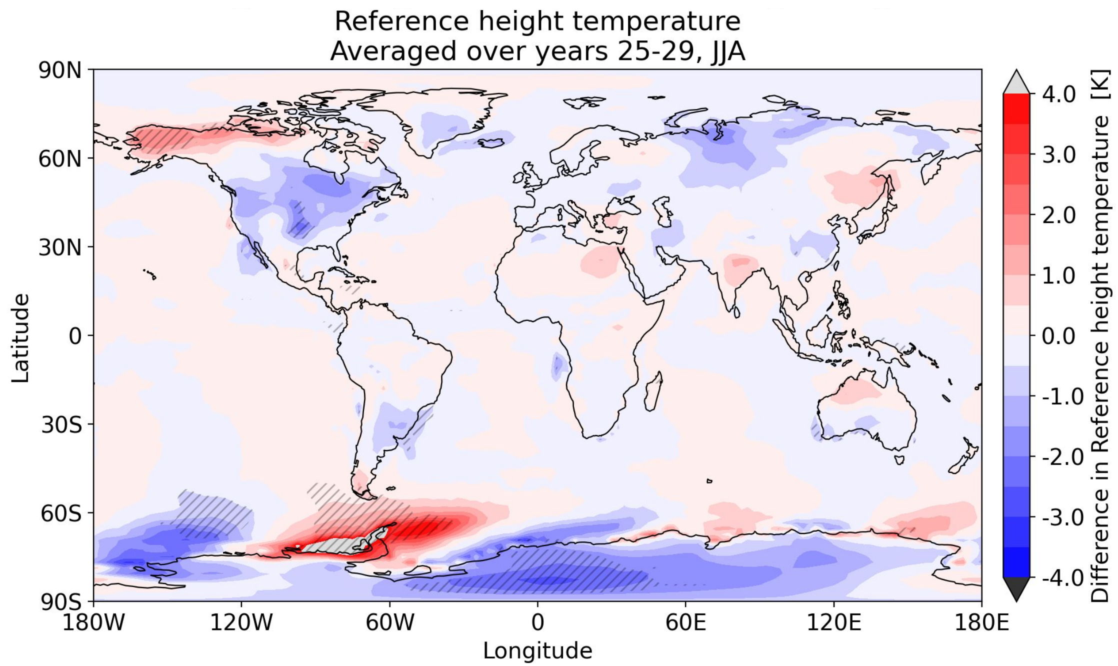
- Penetrating UV generates stratospheric ozone
- Total ozone column increases by several percent
  - Especially in polar regions
- Prior studies did not extend to stratosphere *(McKay & Thomas 1978; Yeghikyan & Fahr 2004)*
  - We find the opposite effect!

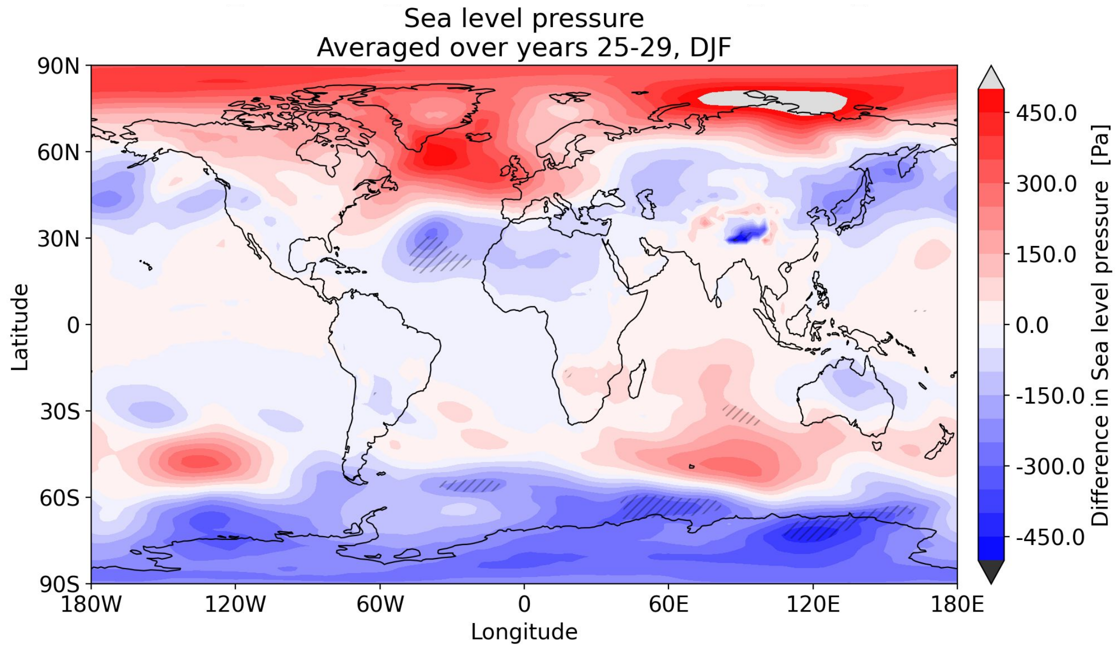
Miller et al. (2024)



Ongoing explorations

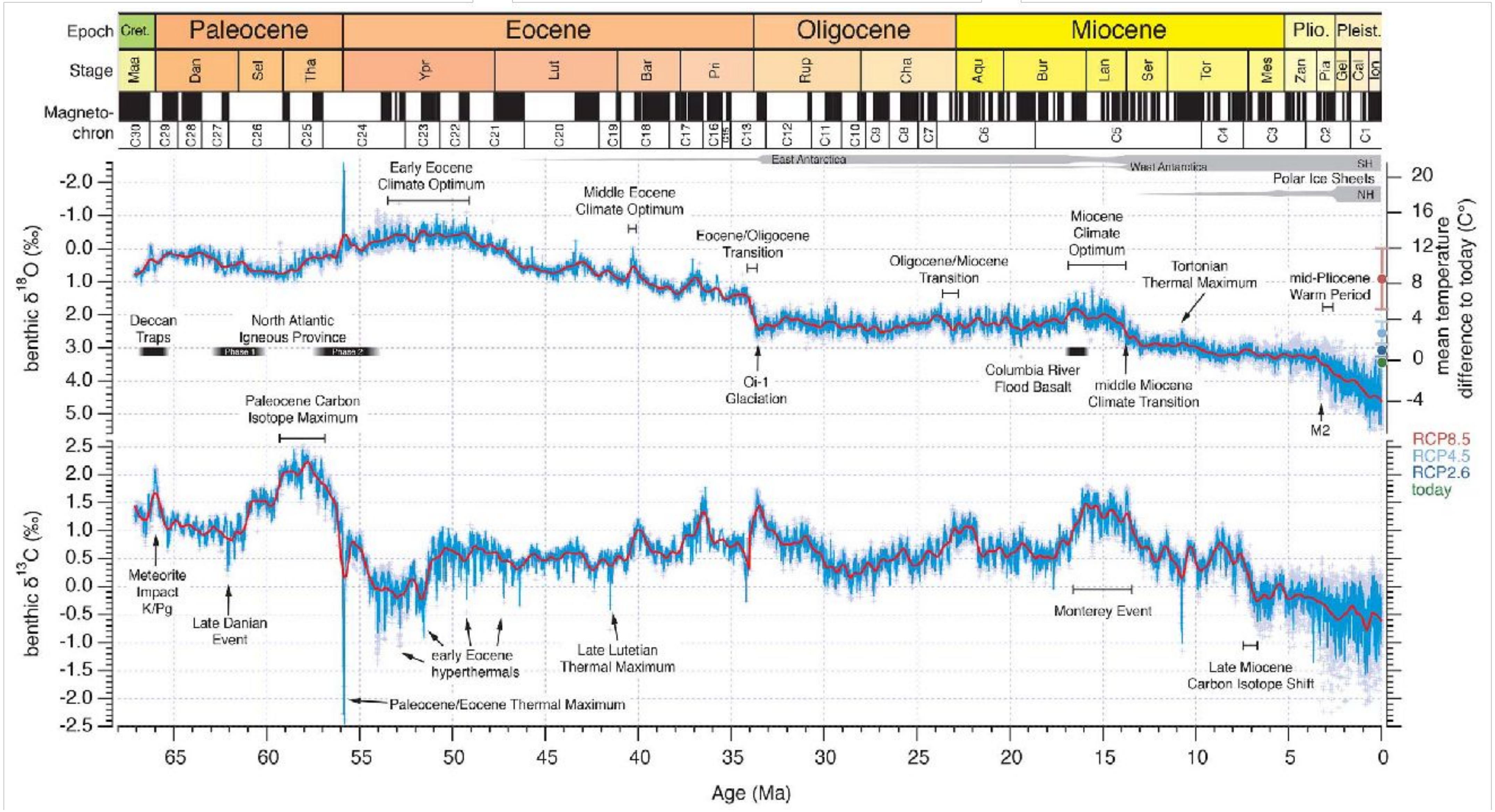
- More complex climate models
- Top: surface temperature anomaly
- Bottom: sea level pressure anomaly
- Other effects
  - Circulation, winds, polar vortices
  - Ozone
  - High-altitude polar clouds
  - And more!

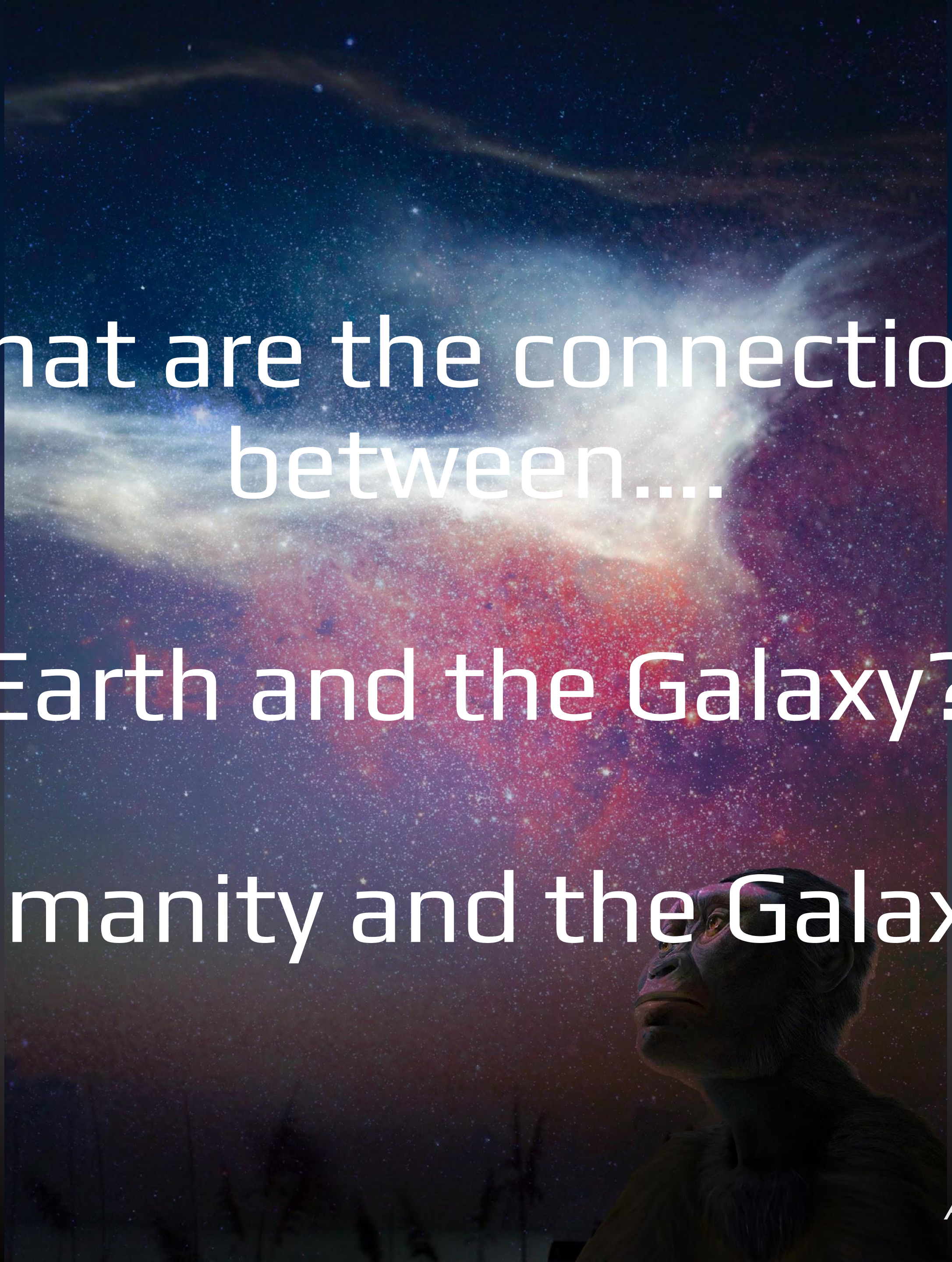




Miller et al. (in prep)

Temperature of Earth over 65 Myr





What are the connections between....

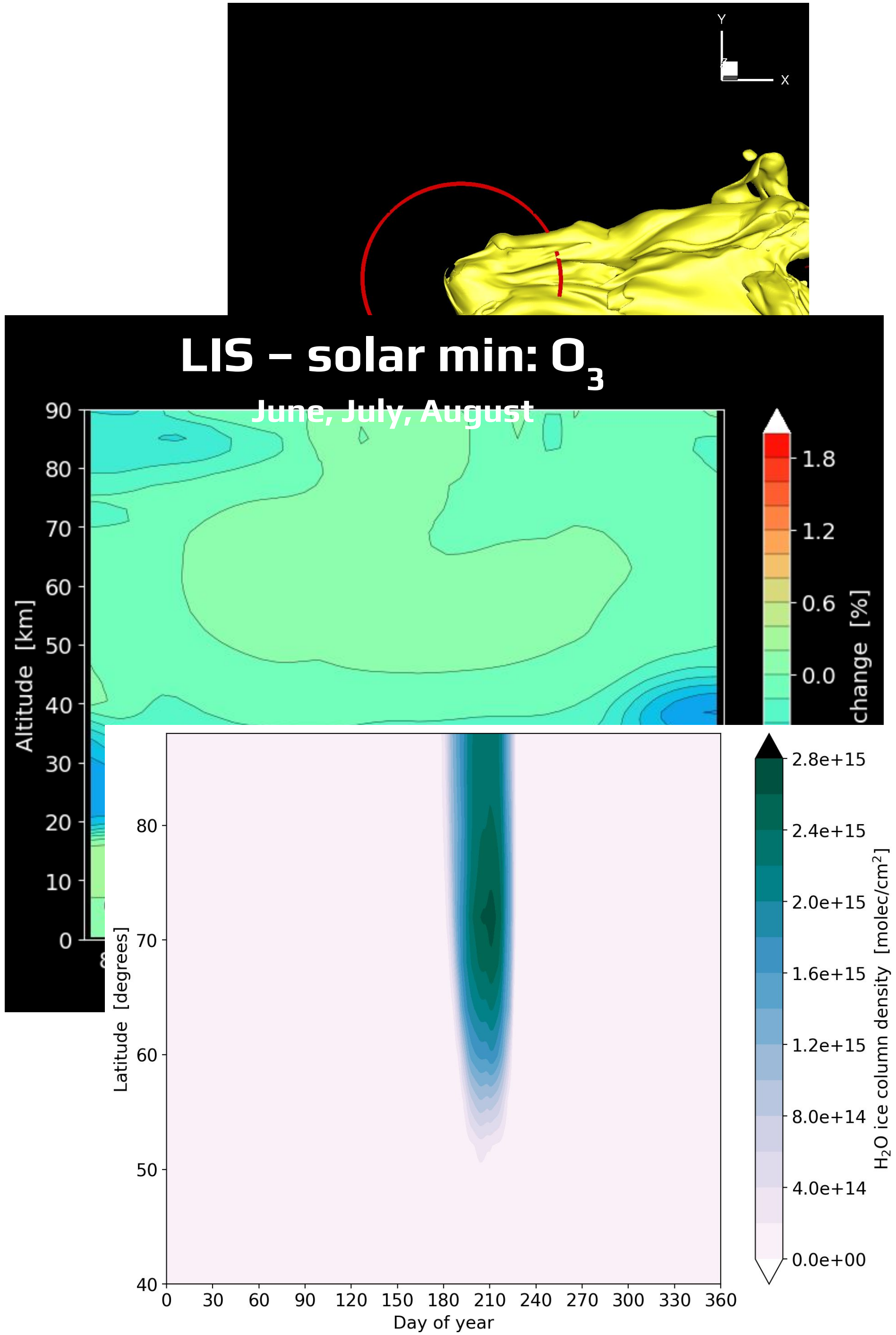
Earth and the Galaxy?

Humanity and the Galaxy?

Artist: Adam Hong

Summary

- **Exposure to interstellar clouds can affect Earth's climate**
- Increased cosmic rays -> ozone depletion
- Direct hydrogen accumulation
  - Increased cloud coverage
  - Ozone is complicated
- Lots more to do!



Jesse Miller
jesmill@bu.edu