



STARFORGE

The dynamics and outcome of star formation with jets, radiation, winds
and supernovae in concert

Paper: arXiv:2201.00882 (MNRAS accepted)

Our Galactic Ecosystem:
Opportunities and Diagnostics in the Infrared and Beyond
February 28 2022

Team:

Dávid Guszejnov (UT Austin)

Stella Offner (UT Austin)

Phil Hopkins (Caltech)

Claude-André Faucher-Giguère (Northwestern)

Anna Rosen (CfA)

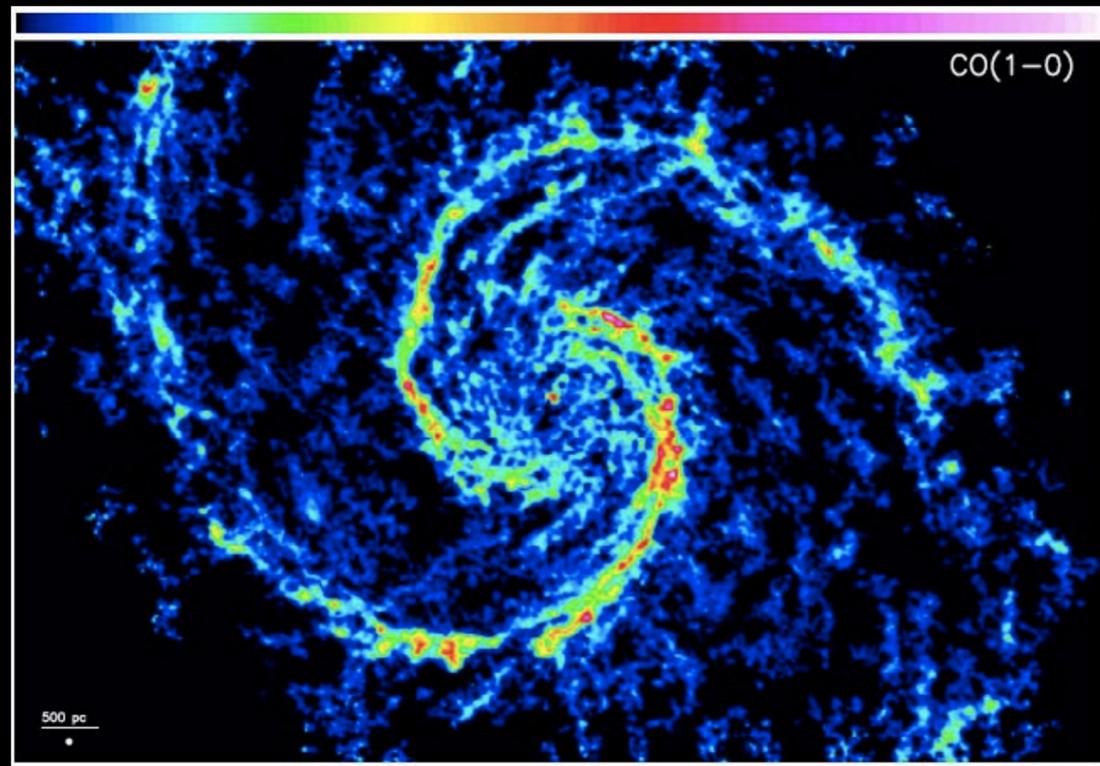
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Carnegie Observatories
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starforge.space

STAR FORMATION: I HAVE QUESTIONS 🤔

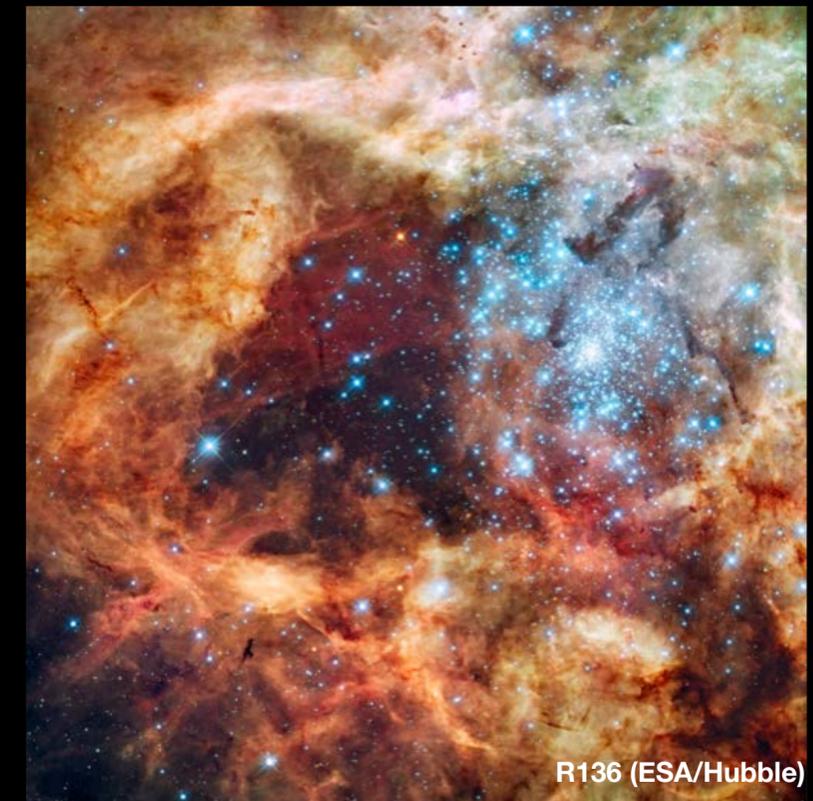
GMCs



CO (1-0) in M51: Schinnerer+13

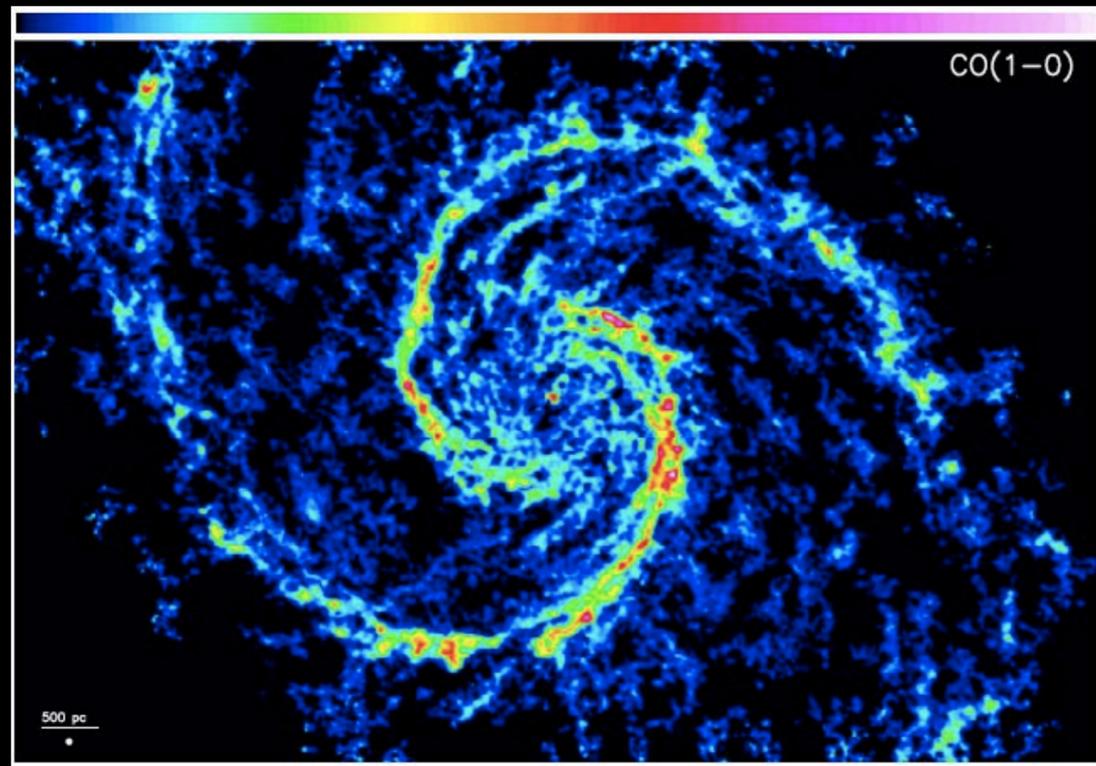
PHYSICS HAPPENS

Stars



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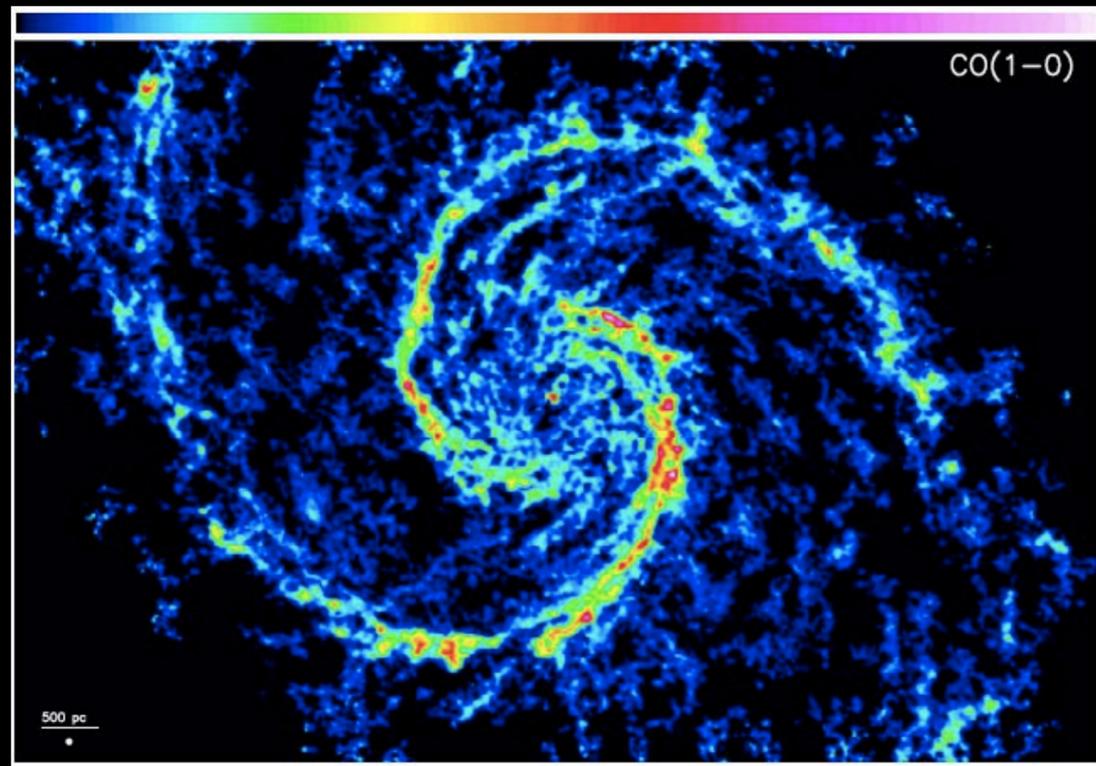
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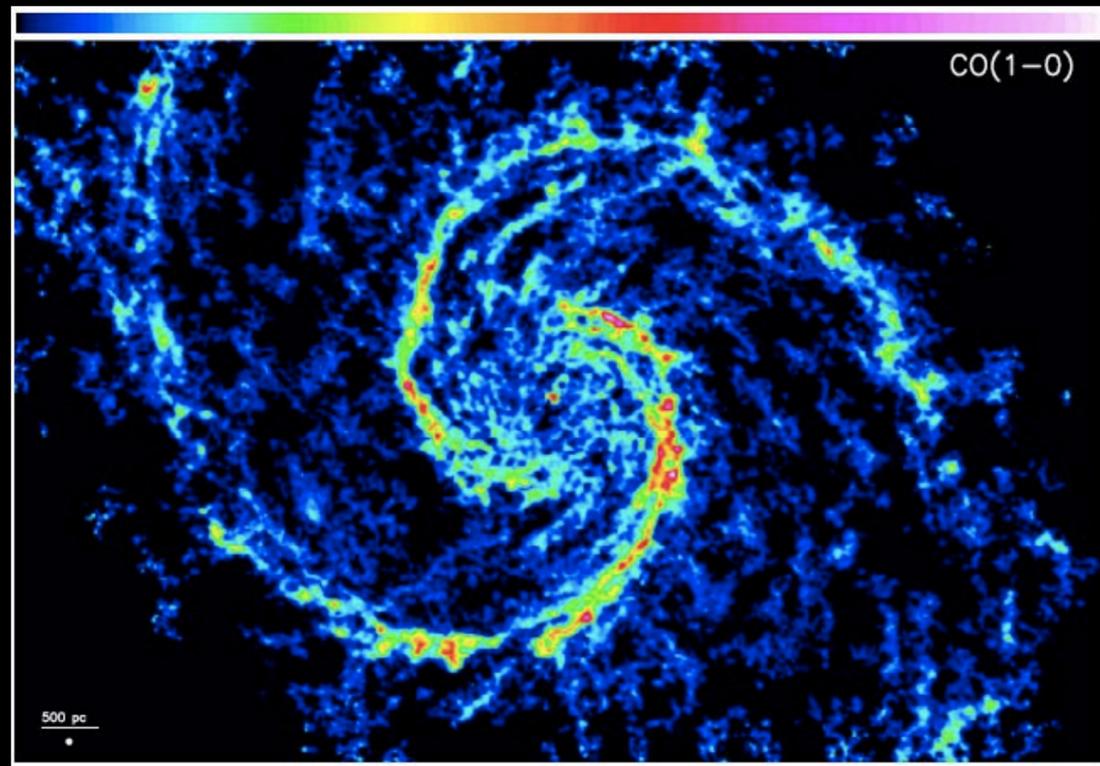
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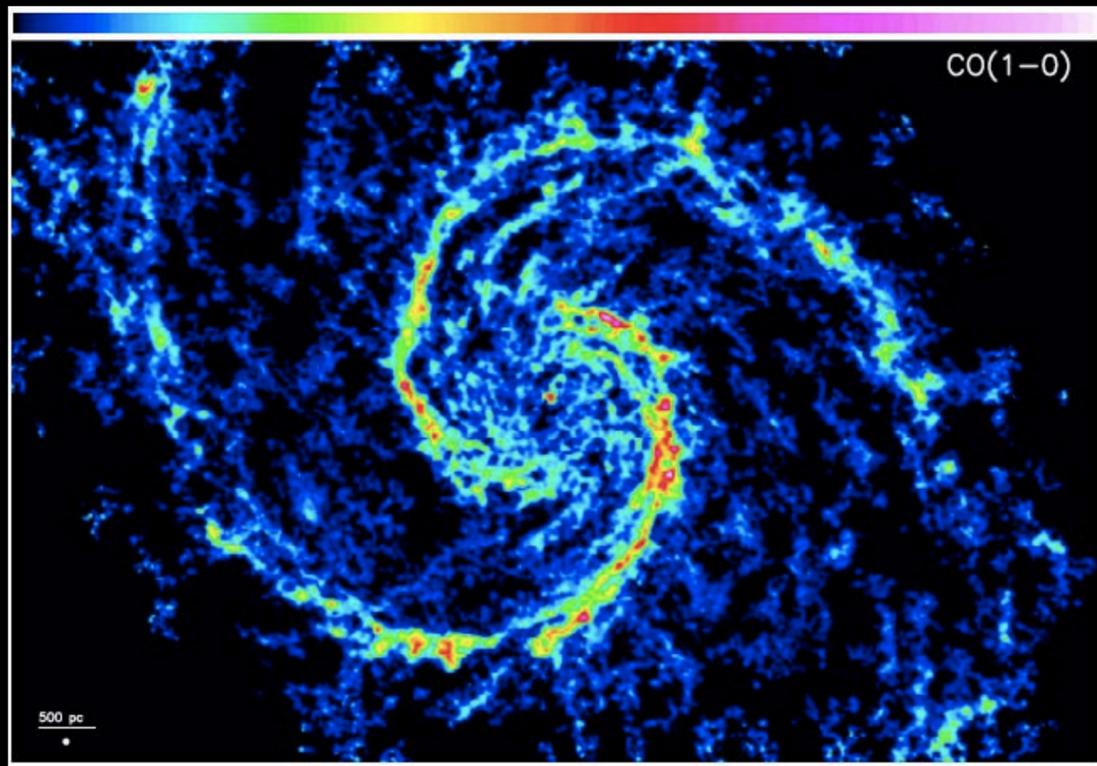
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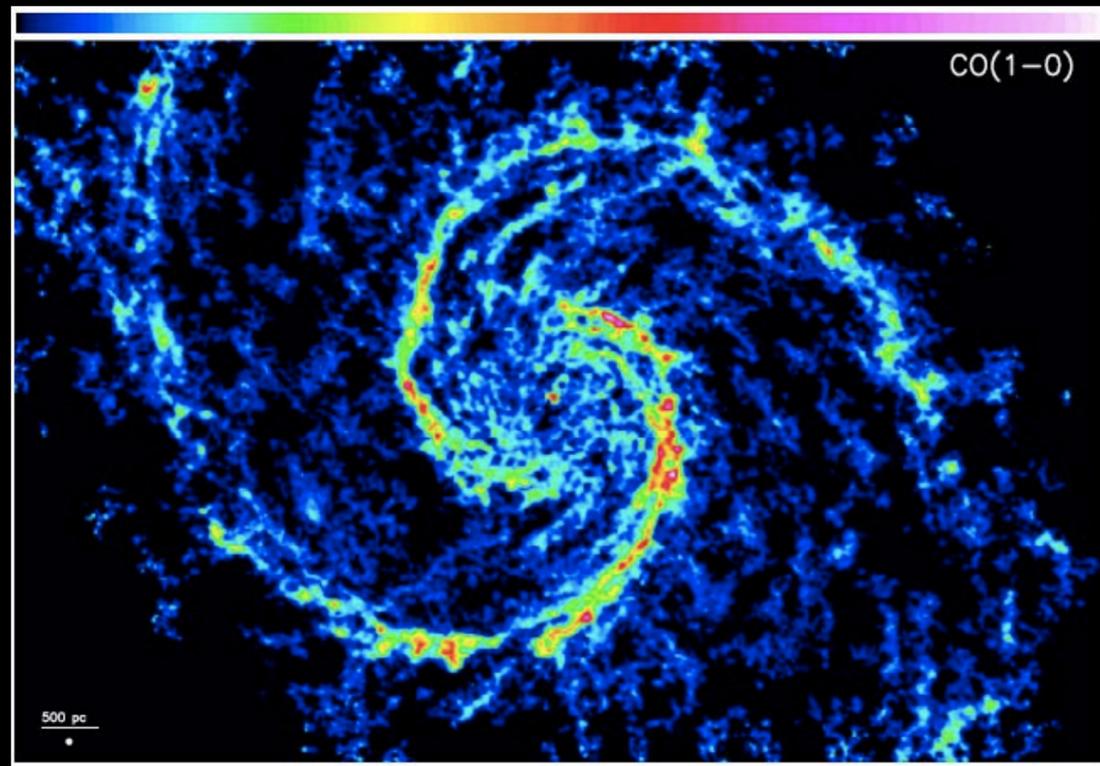
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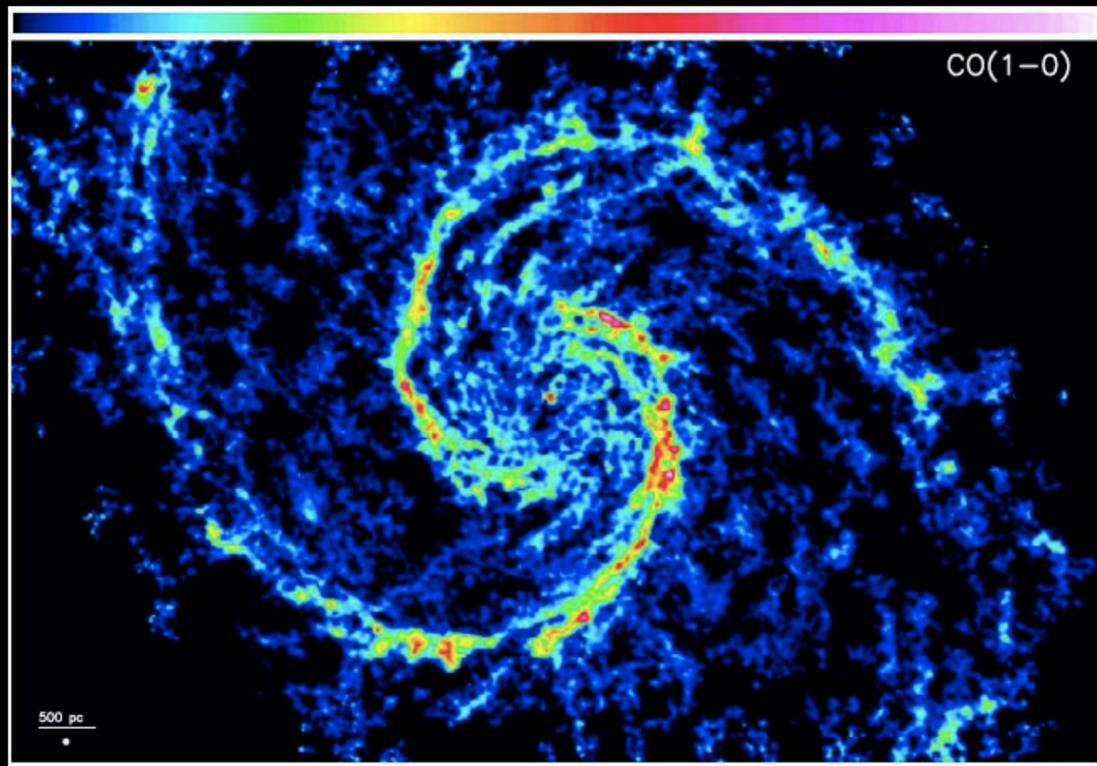
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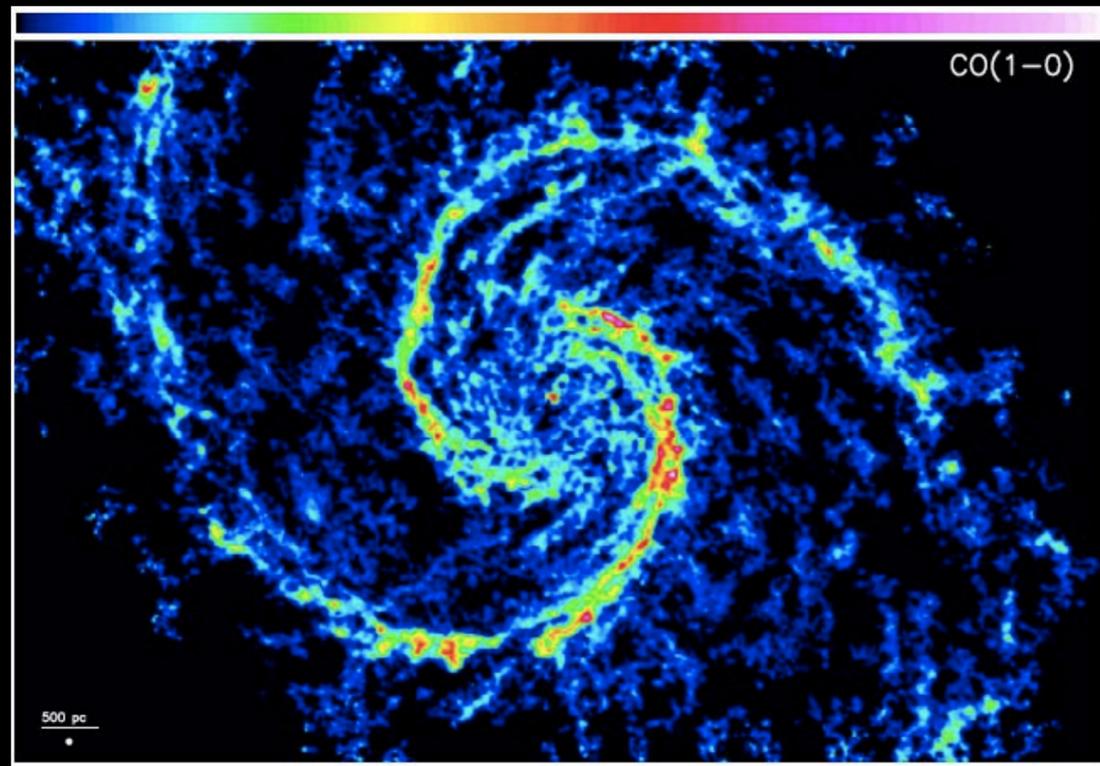
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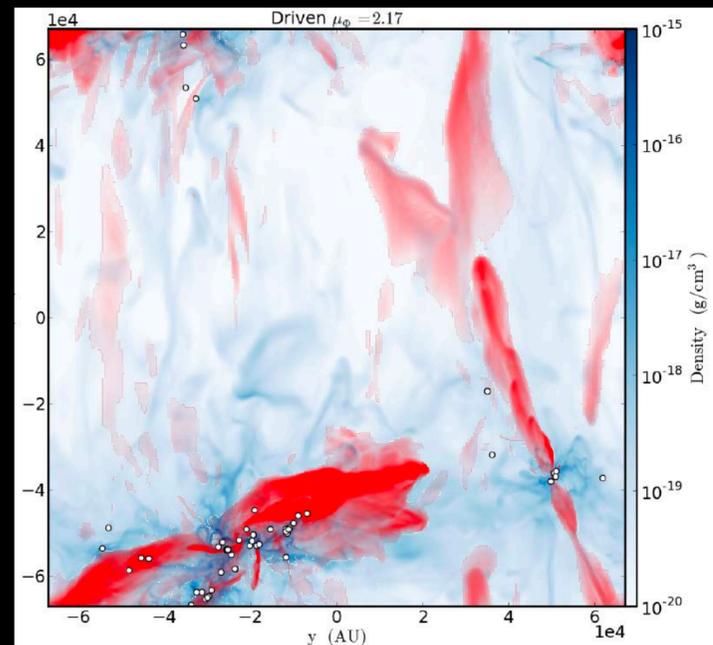
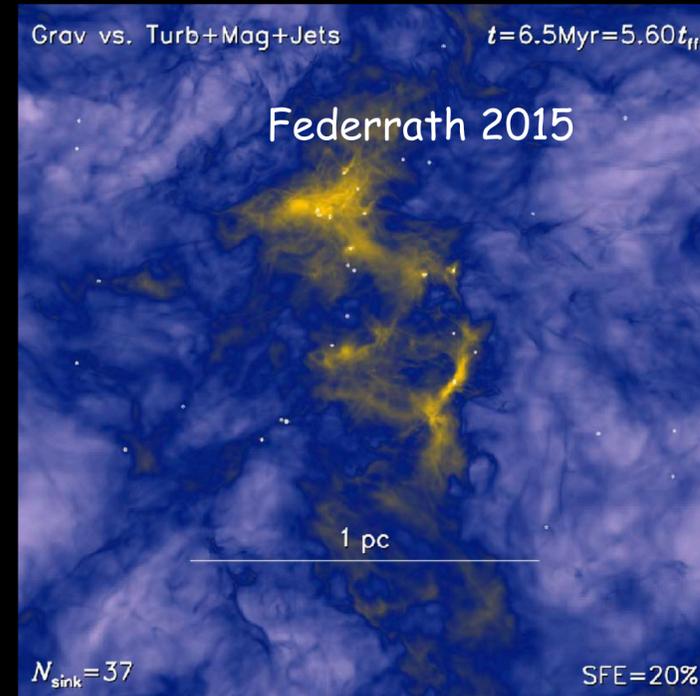
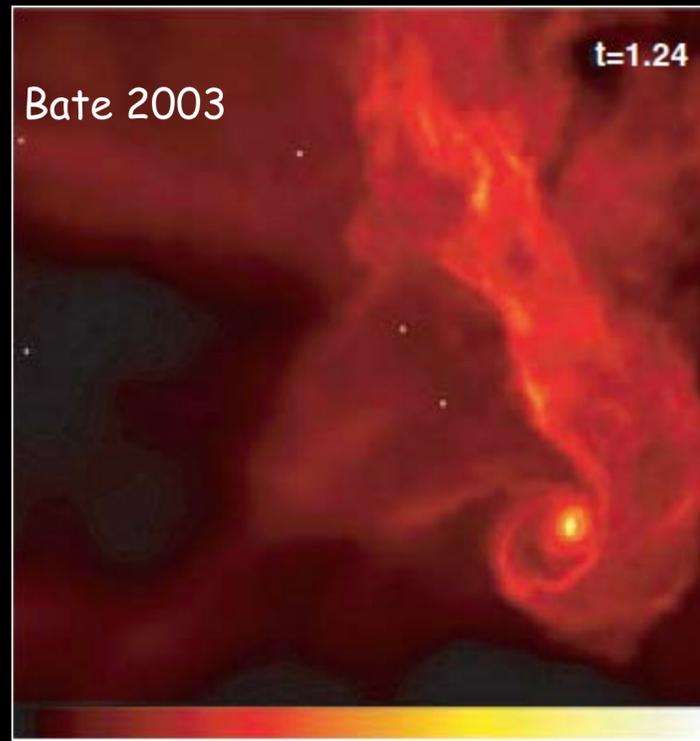


Simulating star formation

Simulating star formation

High-resolution boxes/clumps:

- Total gas mass $< 10^3 M_{\odot}$
- Sometimes IR radiation and/or protostellar jets

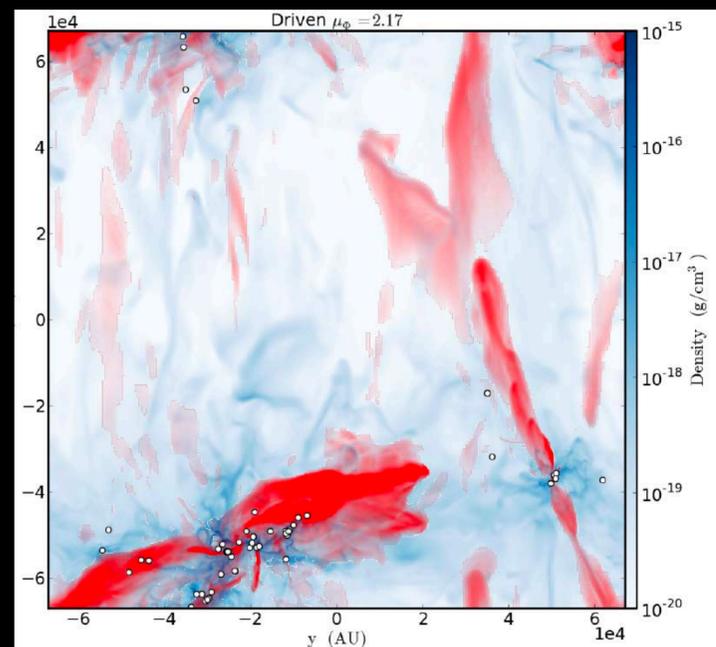
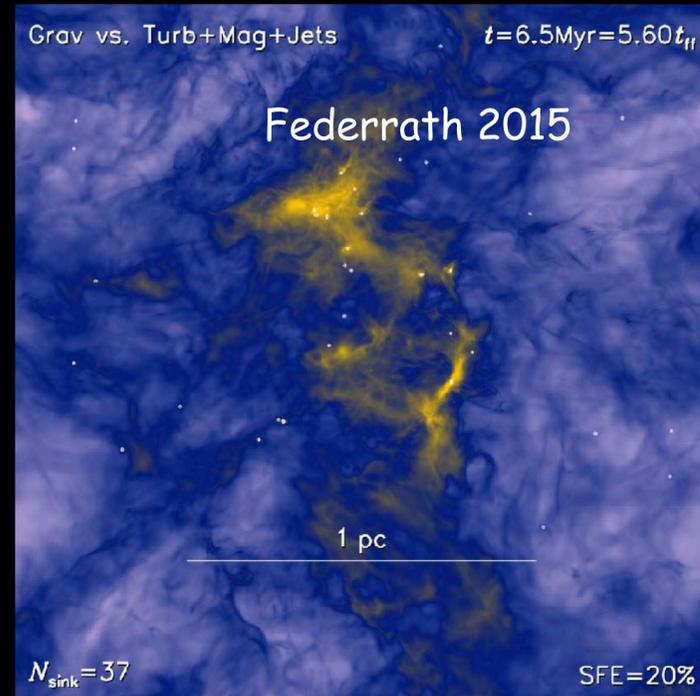
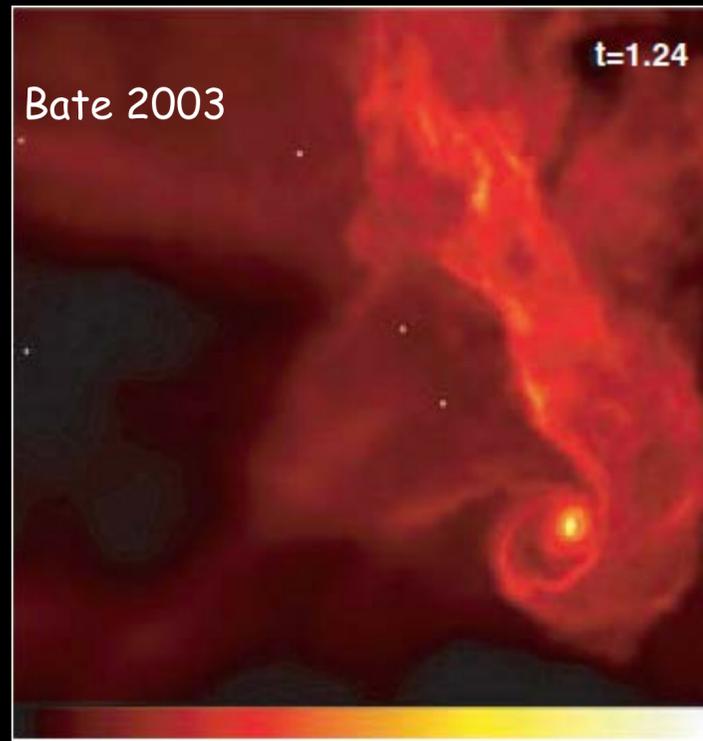


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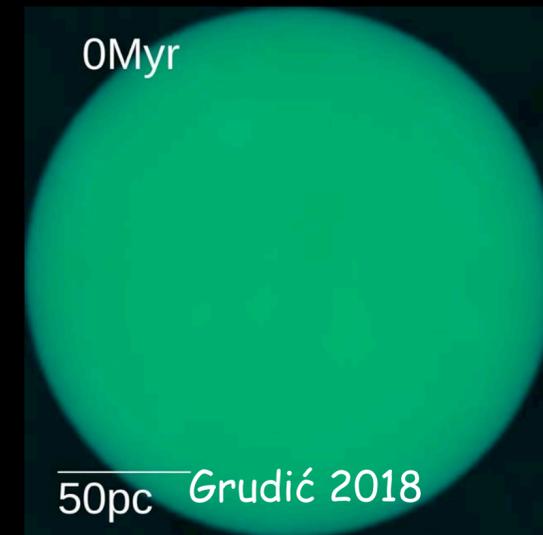
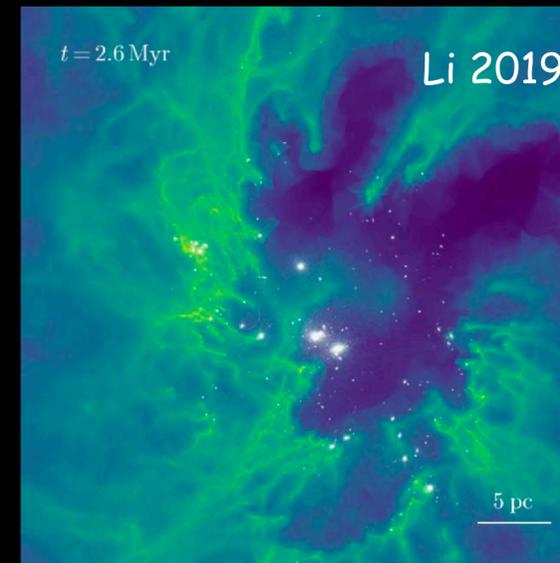
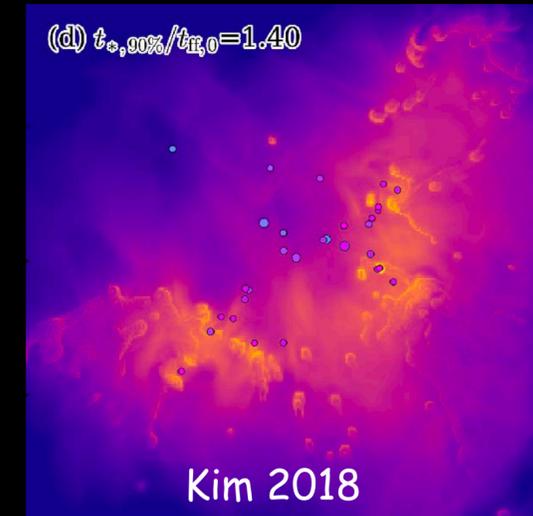
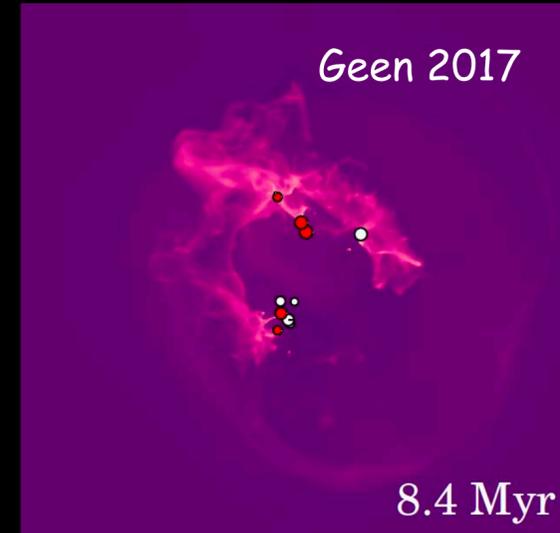
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Global GMC simulations that do not resolve the IMF:

- Can survey much larger masses (entire GMCs)
- Have included stellar radiation, winds, SN
- But can't resolve individual stars!

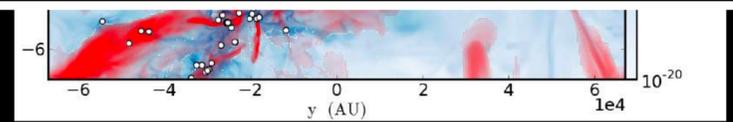
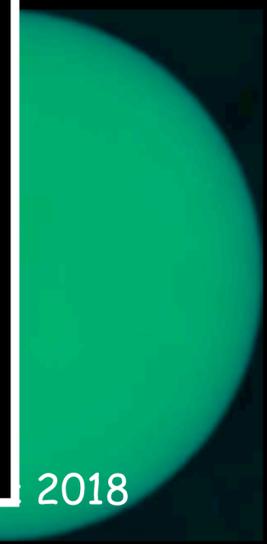
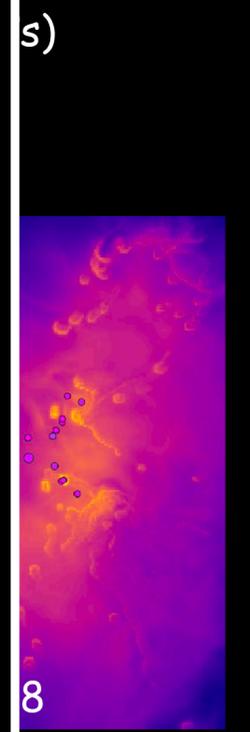
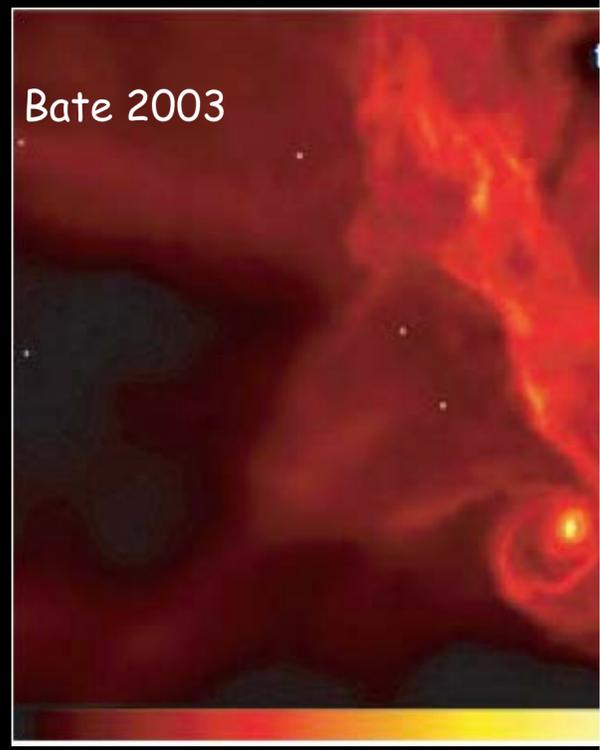


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Global GMC simulations that do not resolve the IMF:

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Wish-list for SF simulations with predictive power:



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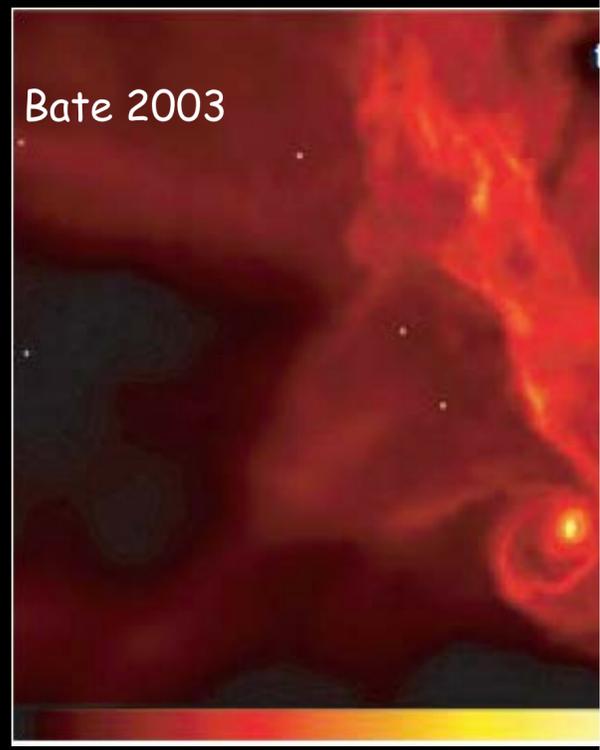
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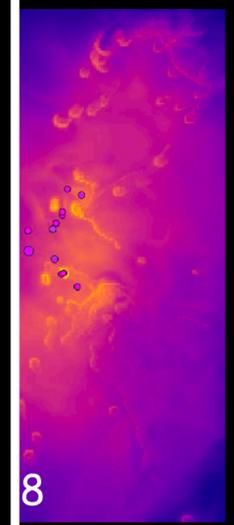
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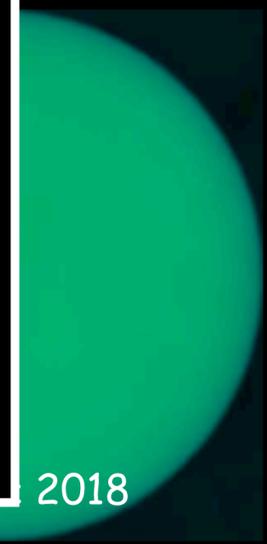
Wish-list for SF simulations with predictive power:
1. Forms individual stars self-consistently



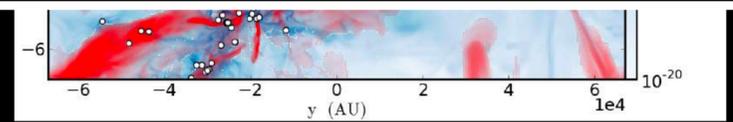
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2018



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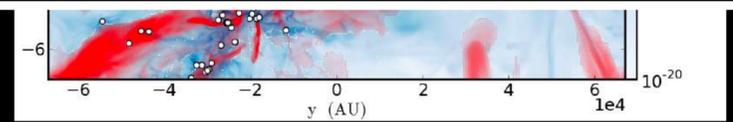
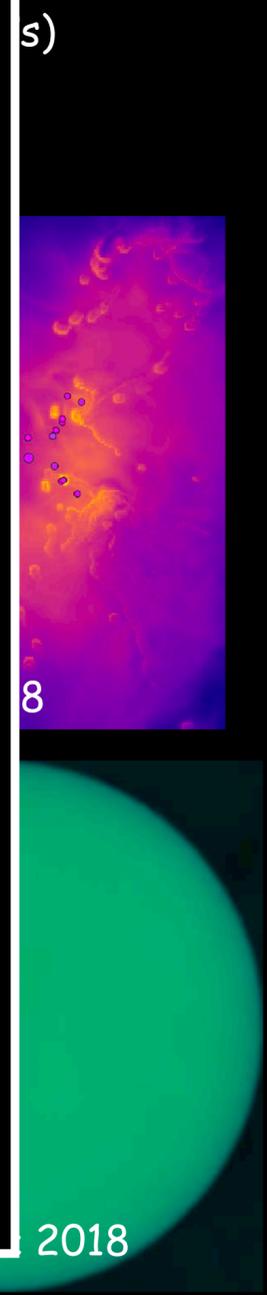
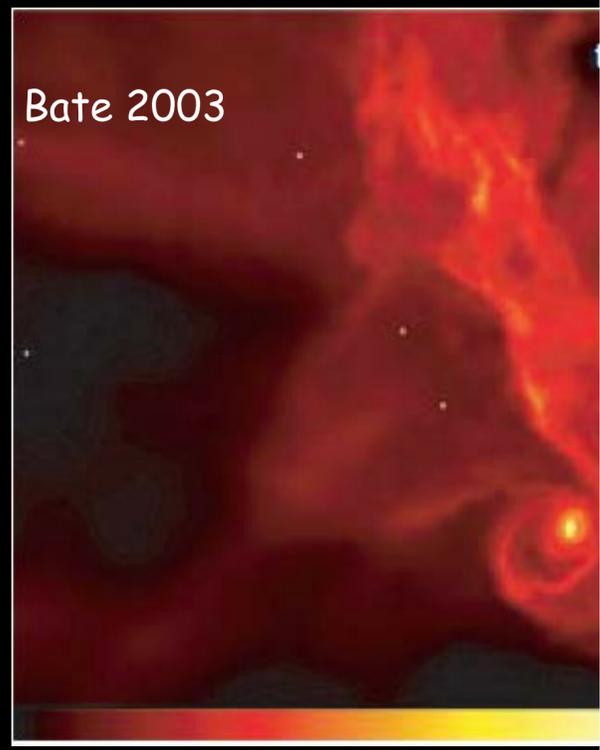
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Wish-list for SF simulations with predictive power:

1. Forms individual stars self-consistently
2. Includes all important feedback mechanisms



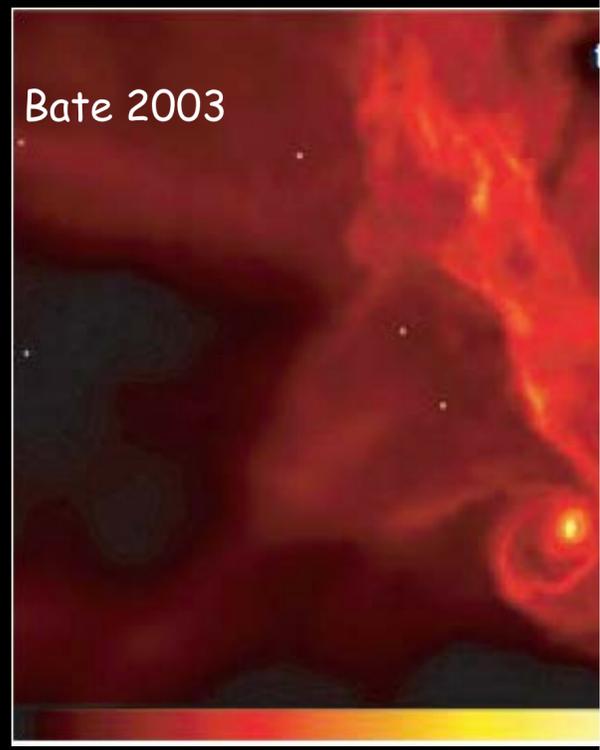
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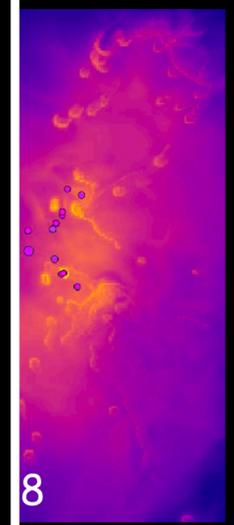
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- Wish-list for SF simulations with predictive power:**
1. Forms individual stars self-consistently
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 3. Can scale up to massive ($> 10^4 M_{\odot}$) GMCs

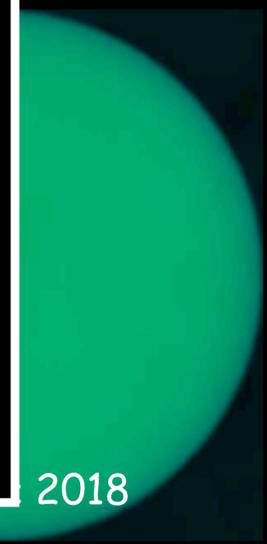


Bate 2003

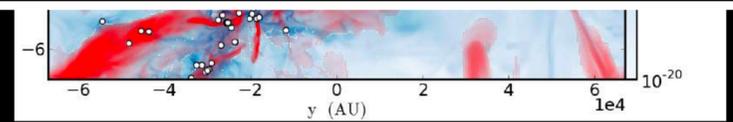
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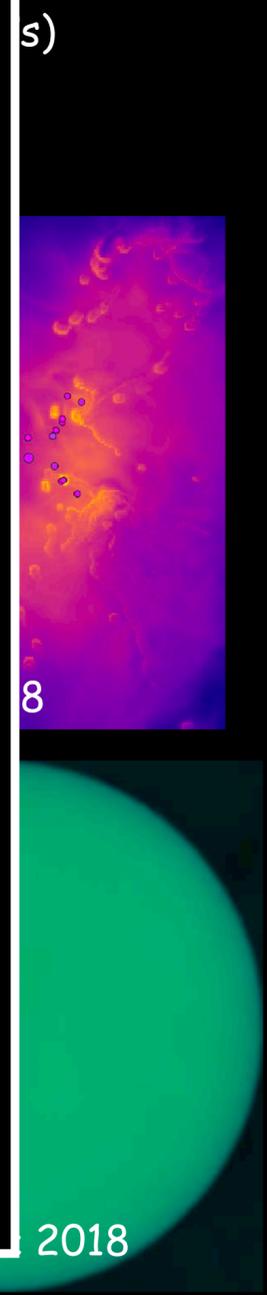
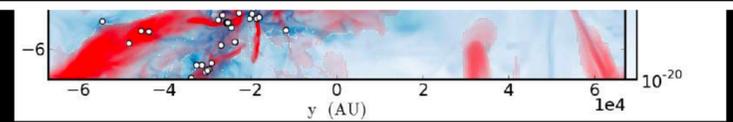
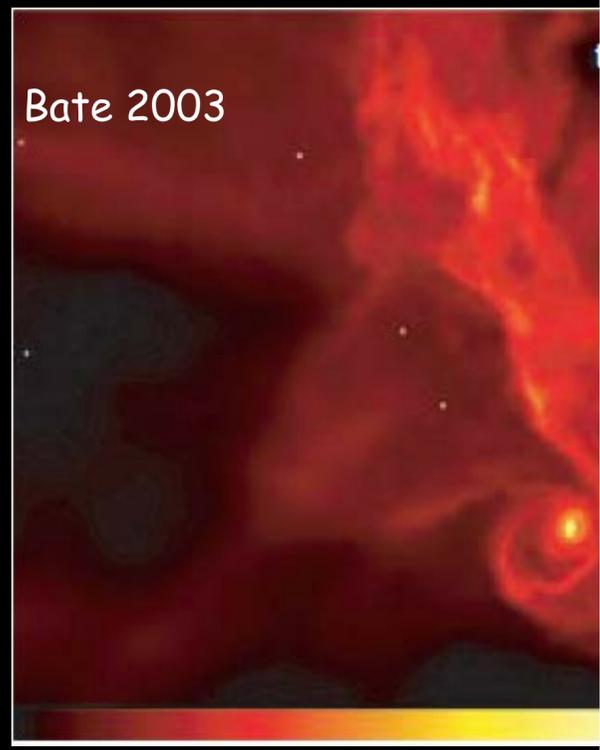
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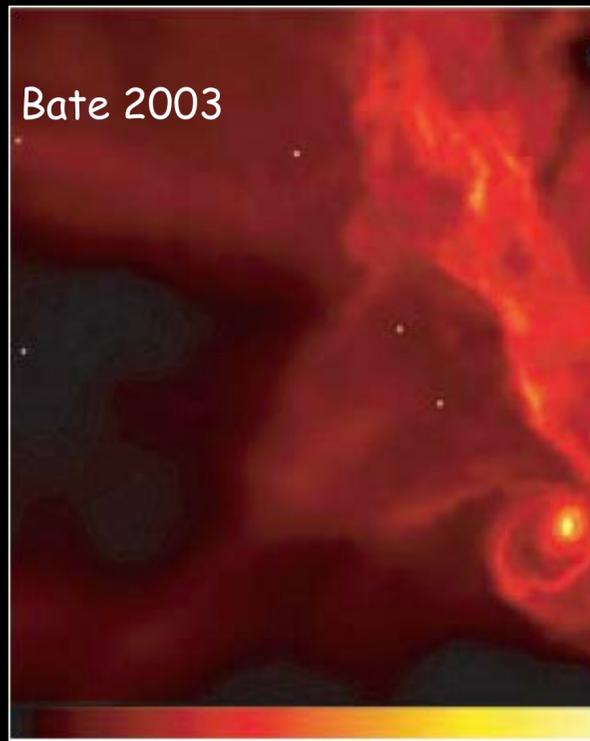
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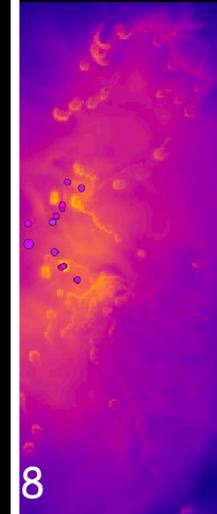
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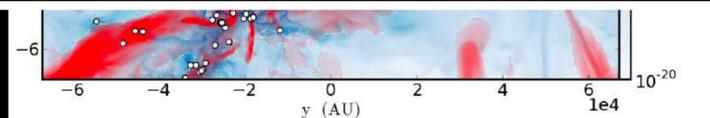
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2018



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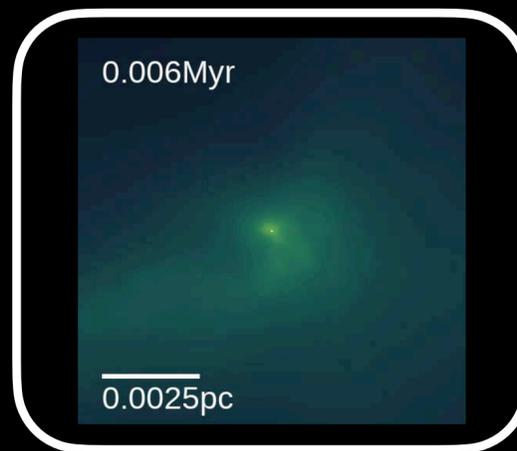


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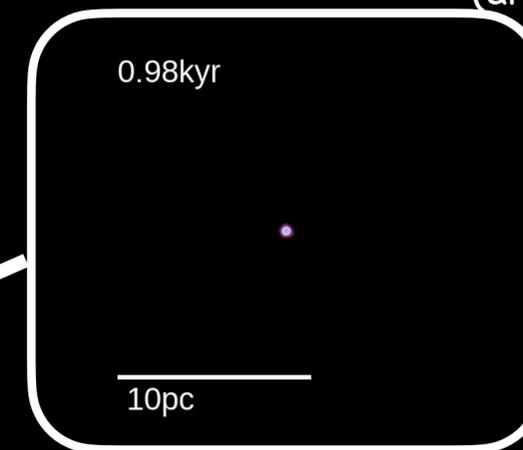


STARFORGE
methods paper
(arXiv:2010.11254)

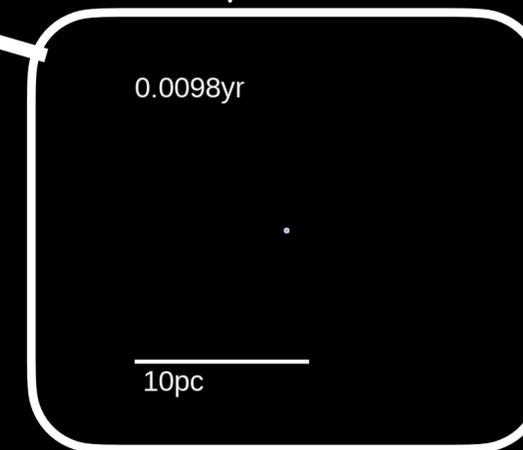
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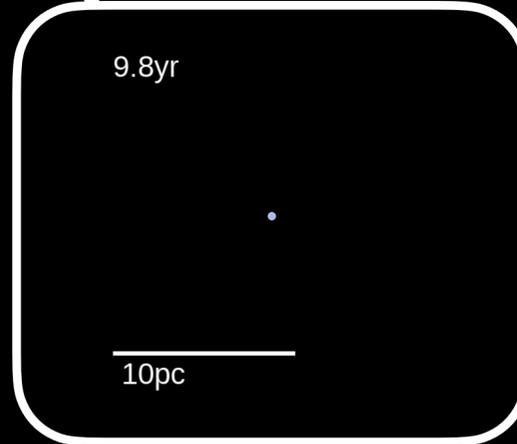
Radiation



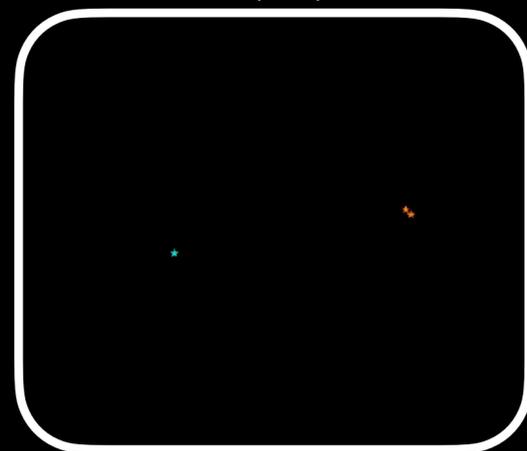
Supernovae



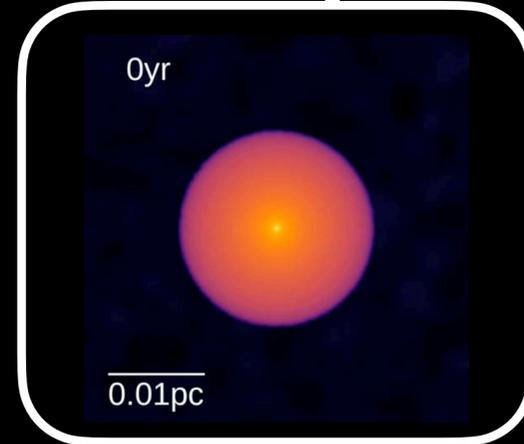
Stellar Winds



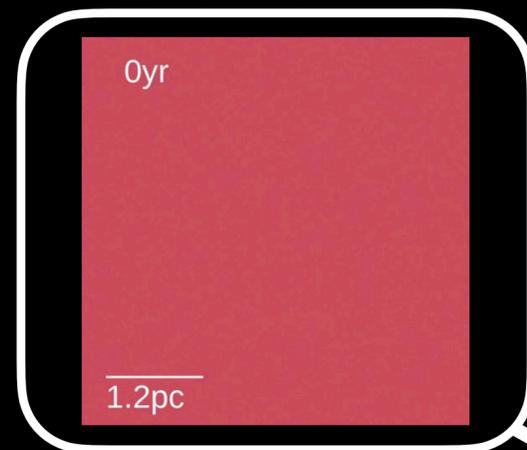
N-body dynamics



Jets

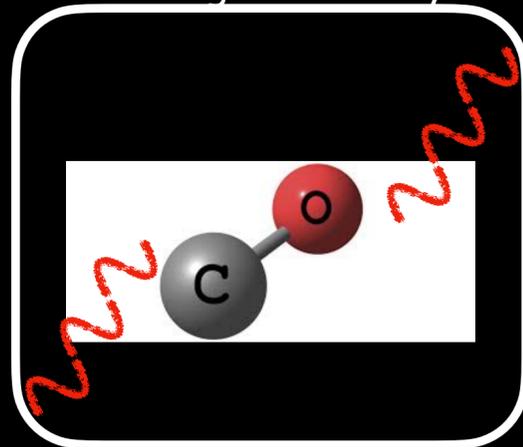


GIZMO MFM MHD



STARFORGE

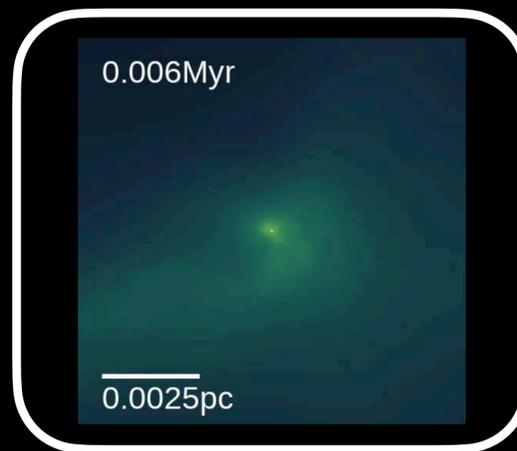
Cooling/Chemistry



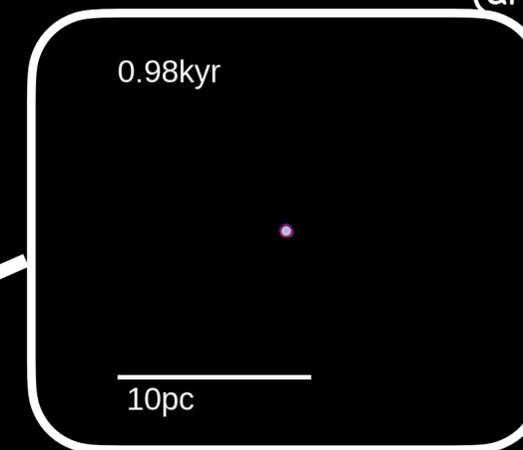


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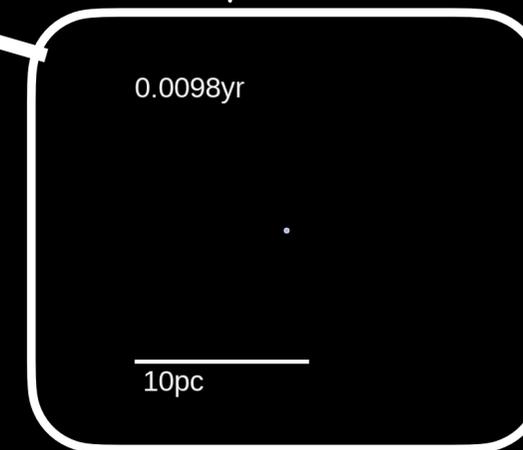
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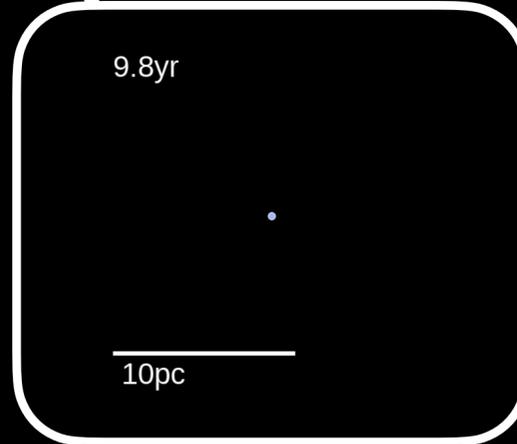
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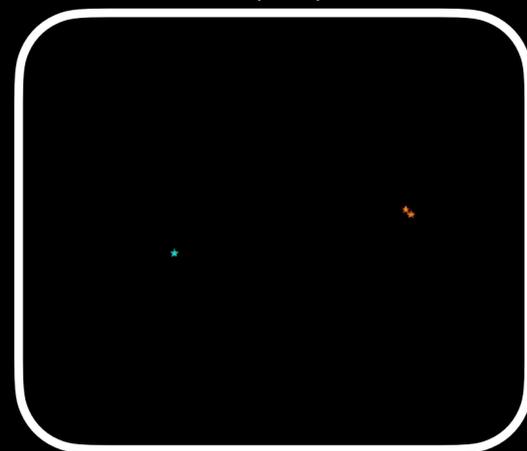
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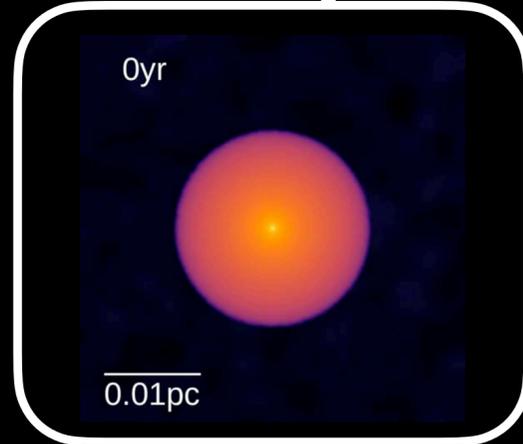
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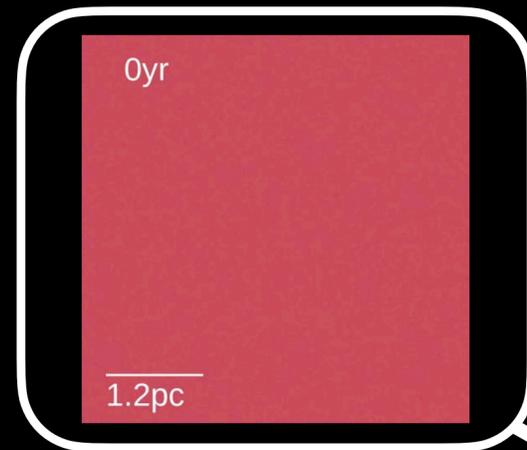
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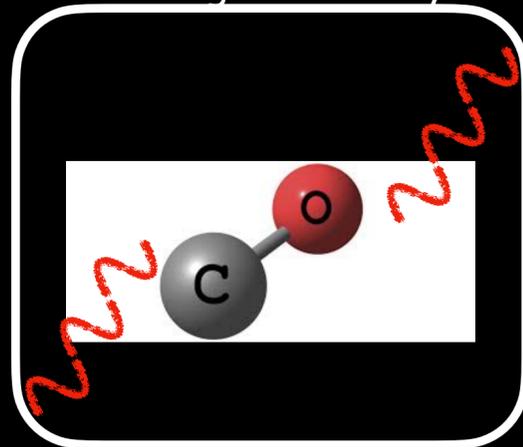
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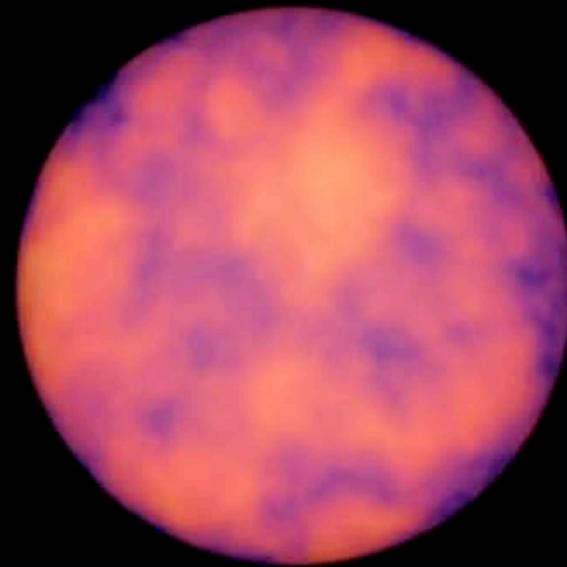
The Simulation

Full STARFORGE physics - Grudić et al. 2022 arXiv:2201.00882

<https://www.youtube.com/watch?v=LeX5e51UkzI>



4k 60fps version



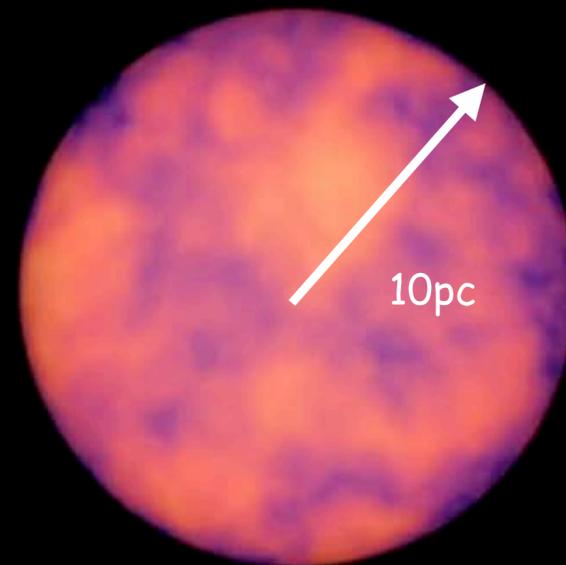
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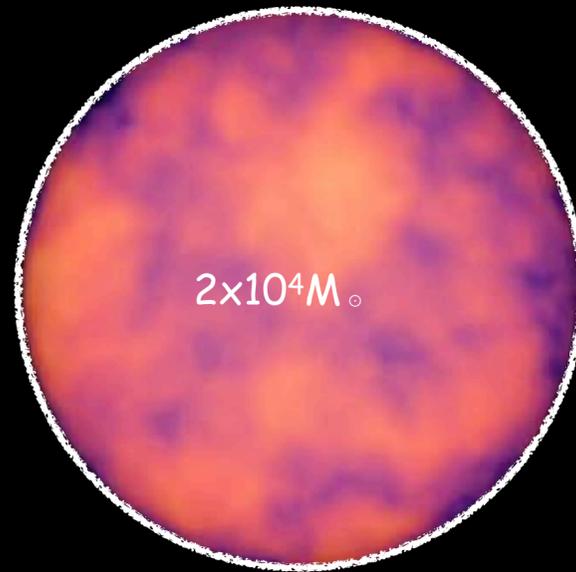
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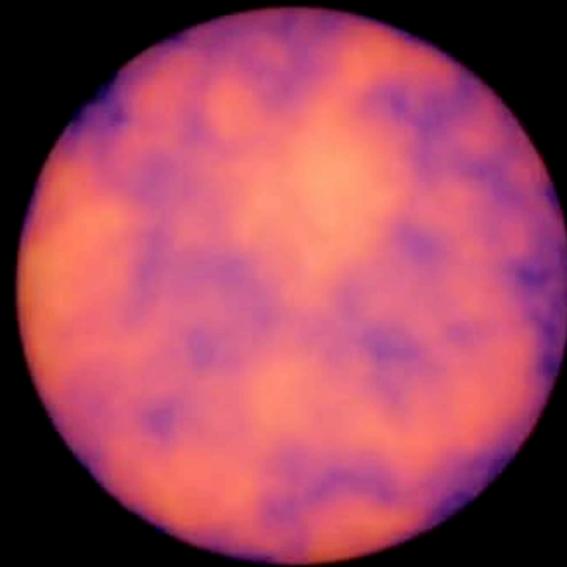
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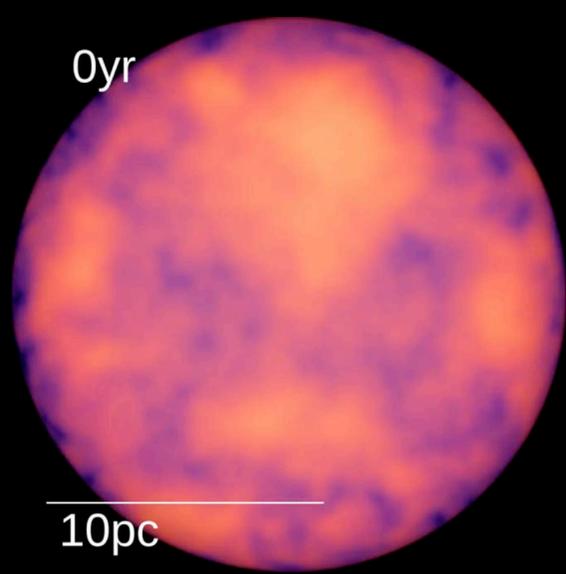
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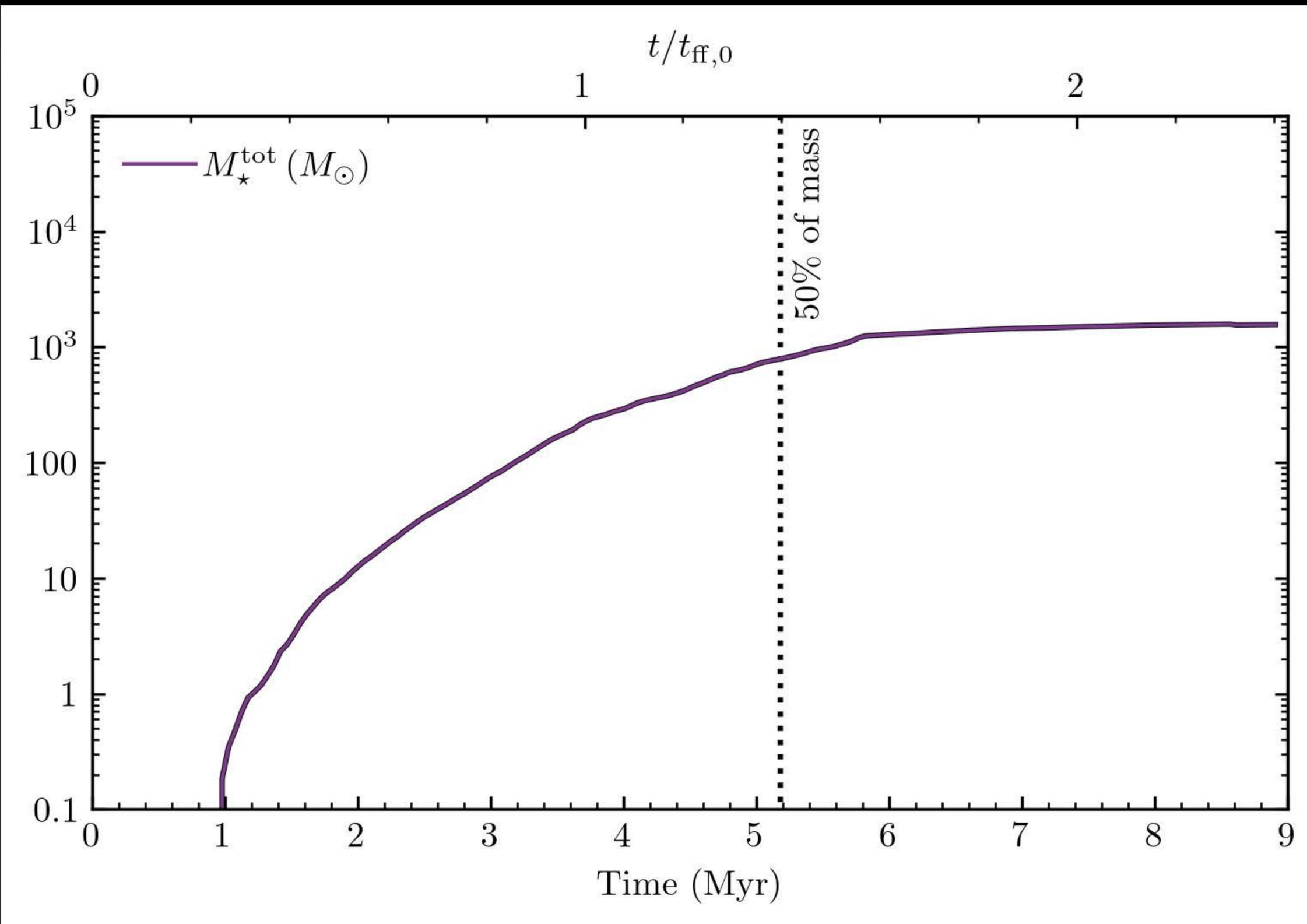


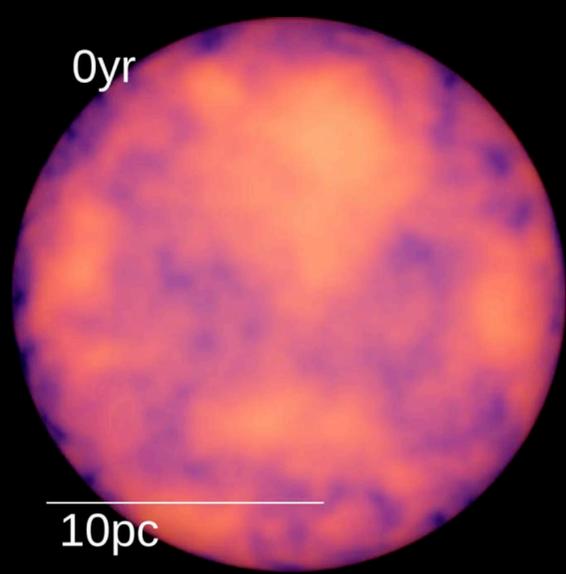
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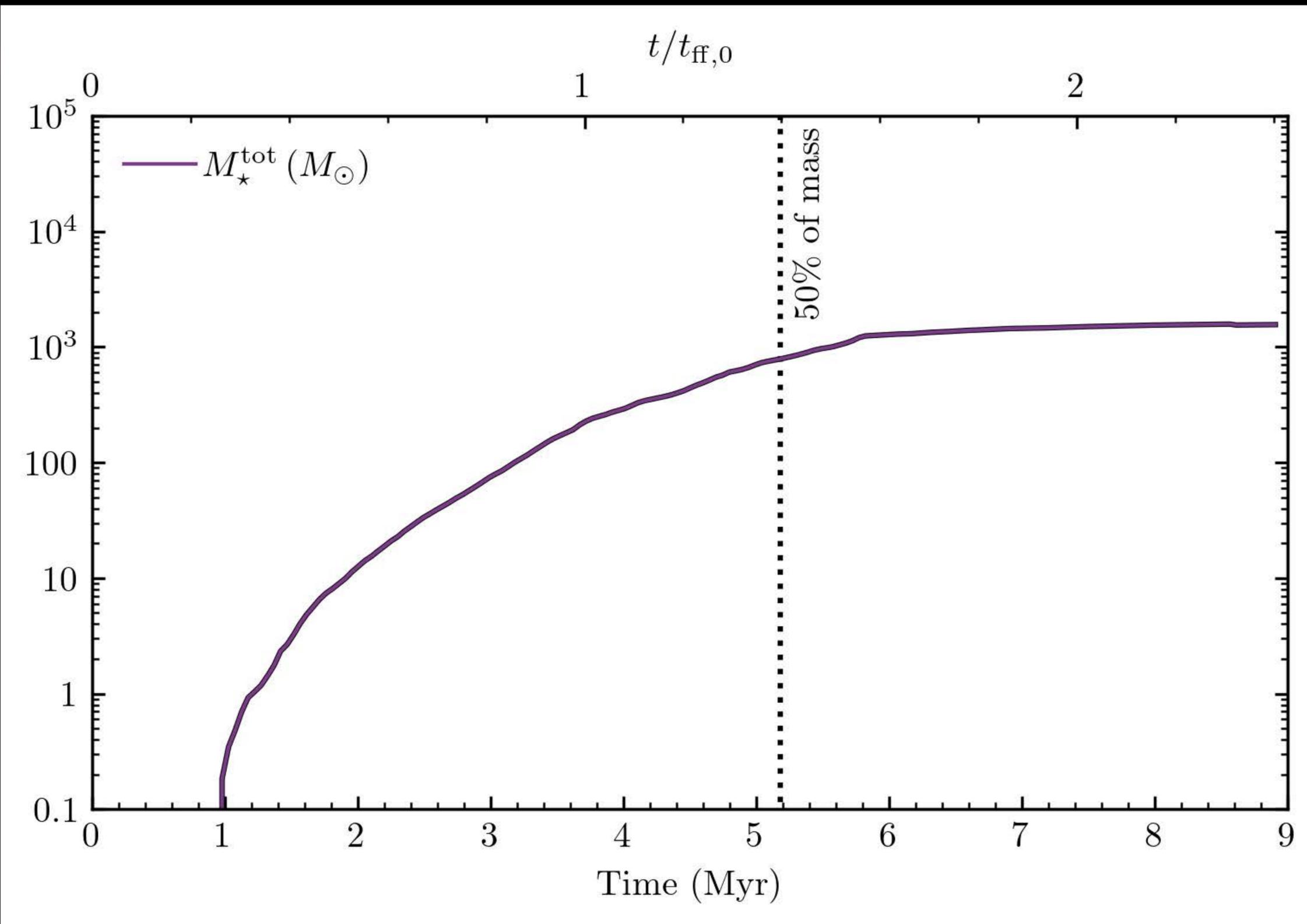


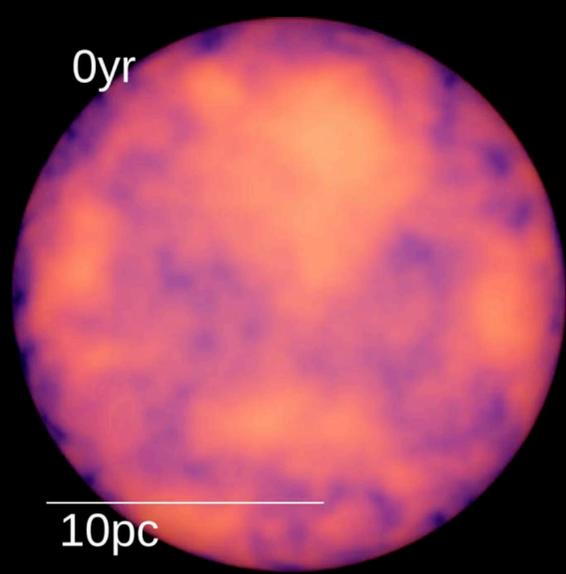
Star Cluster Evolution



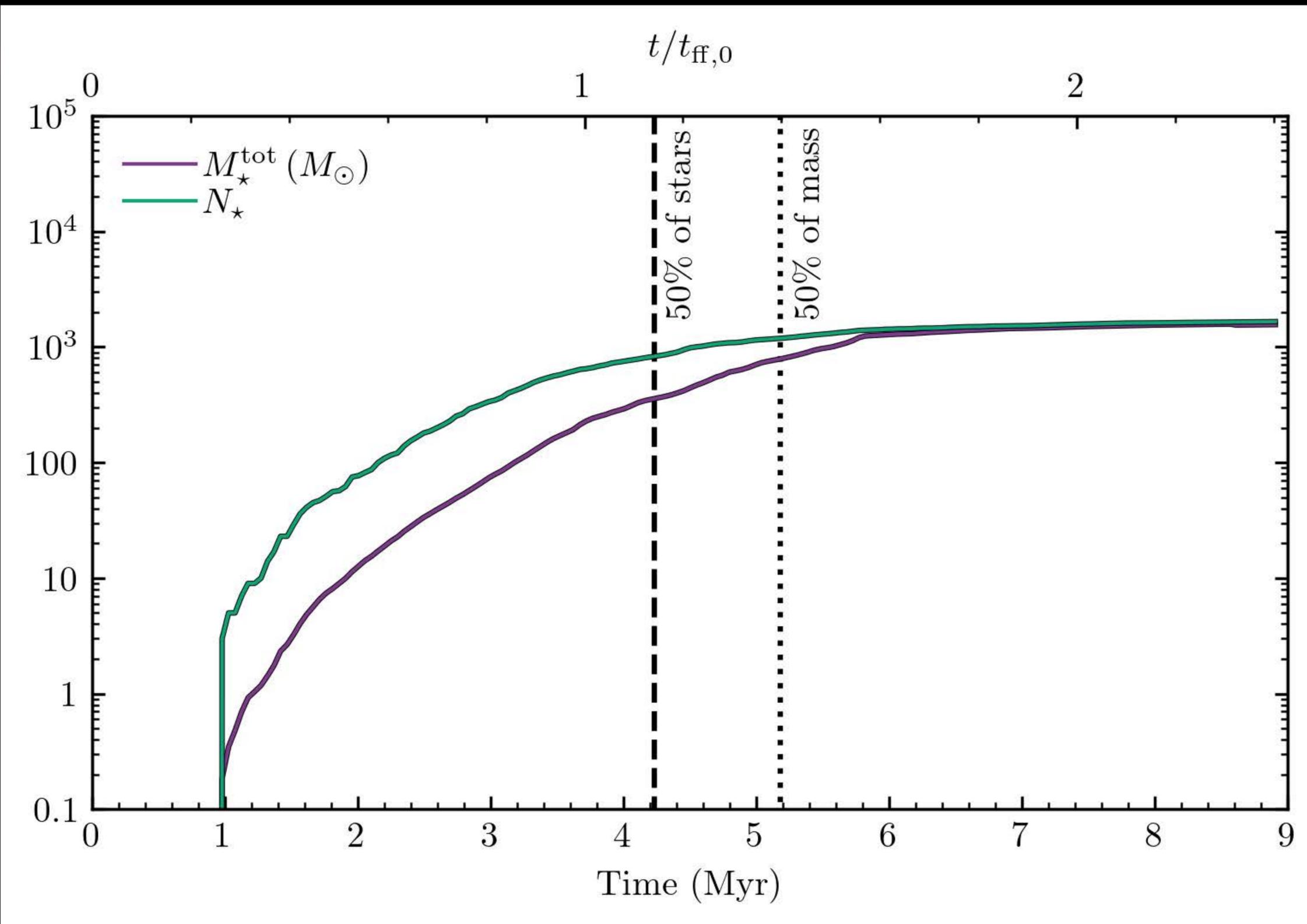


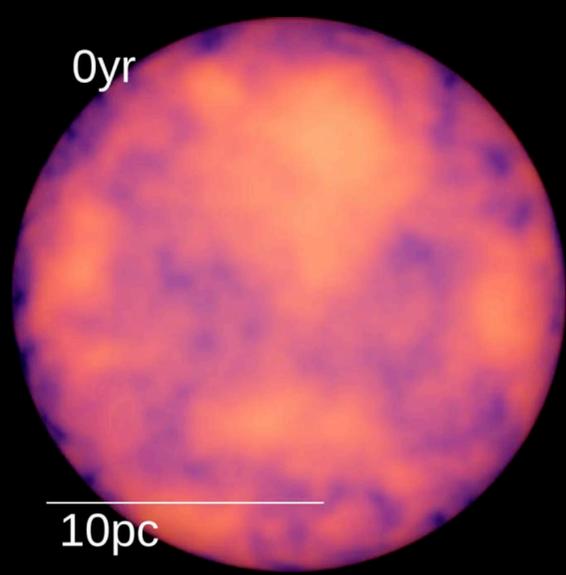
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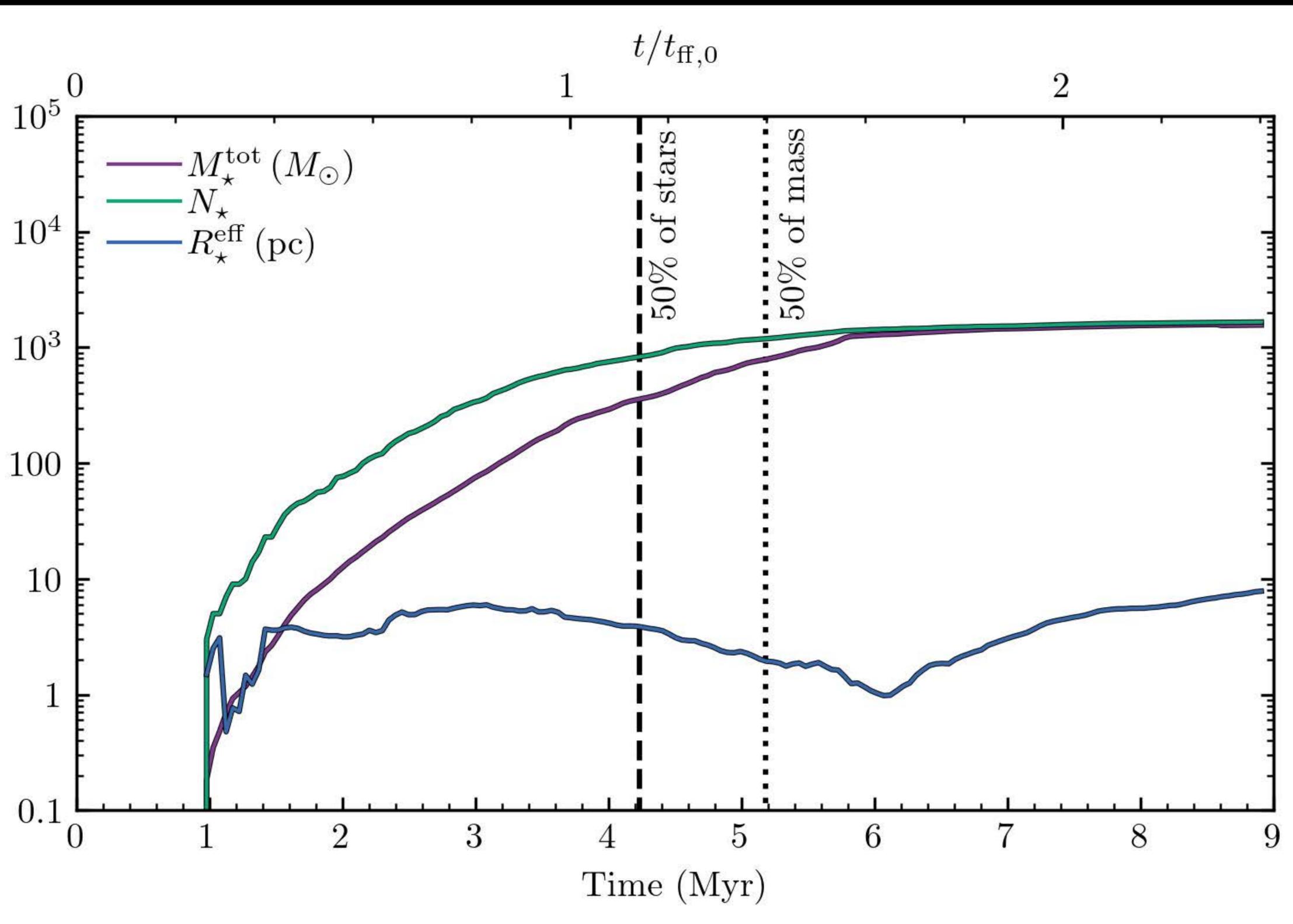


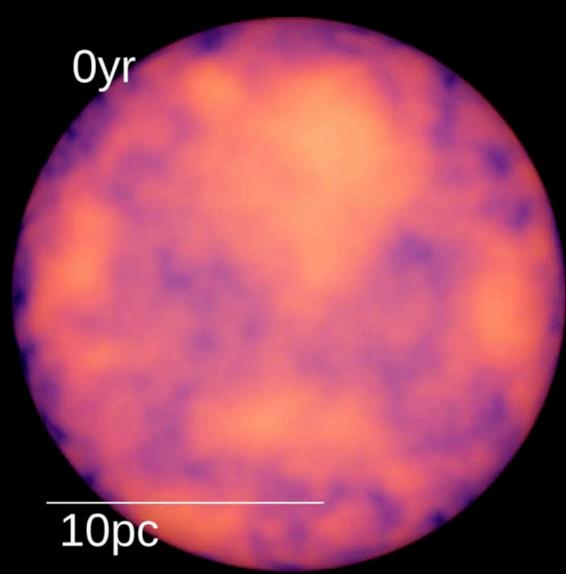
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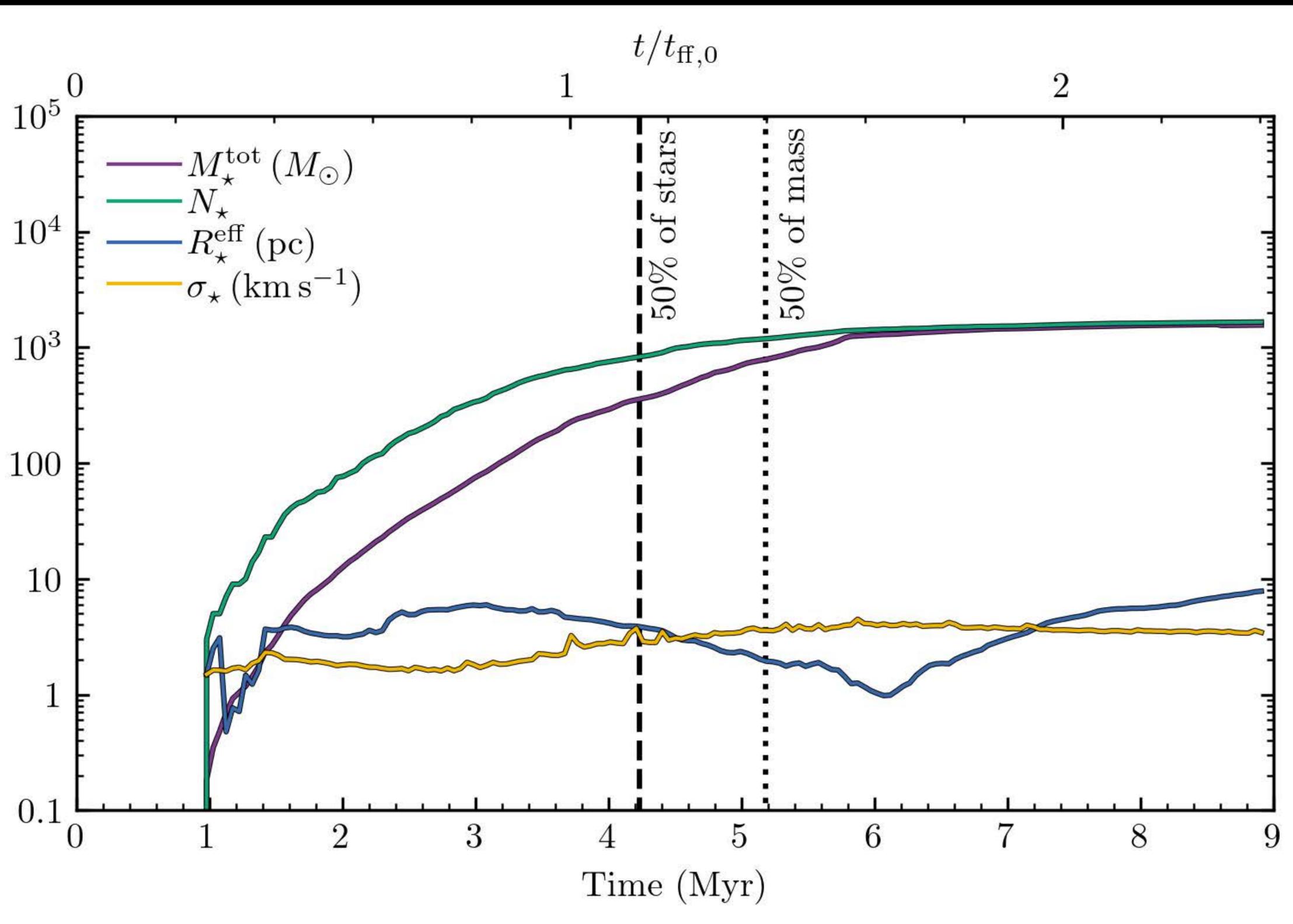


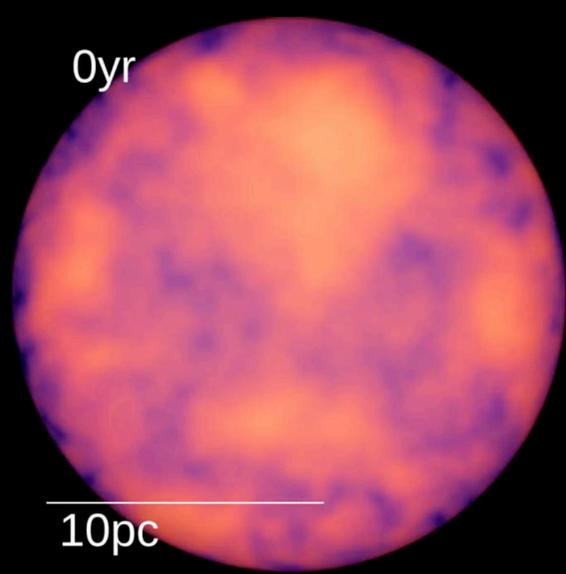
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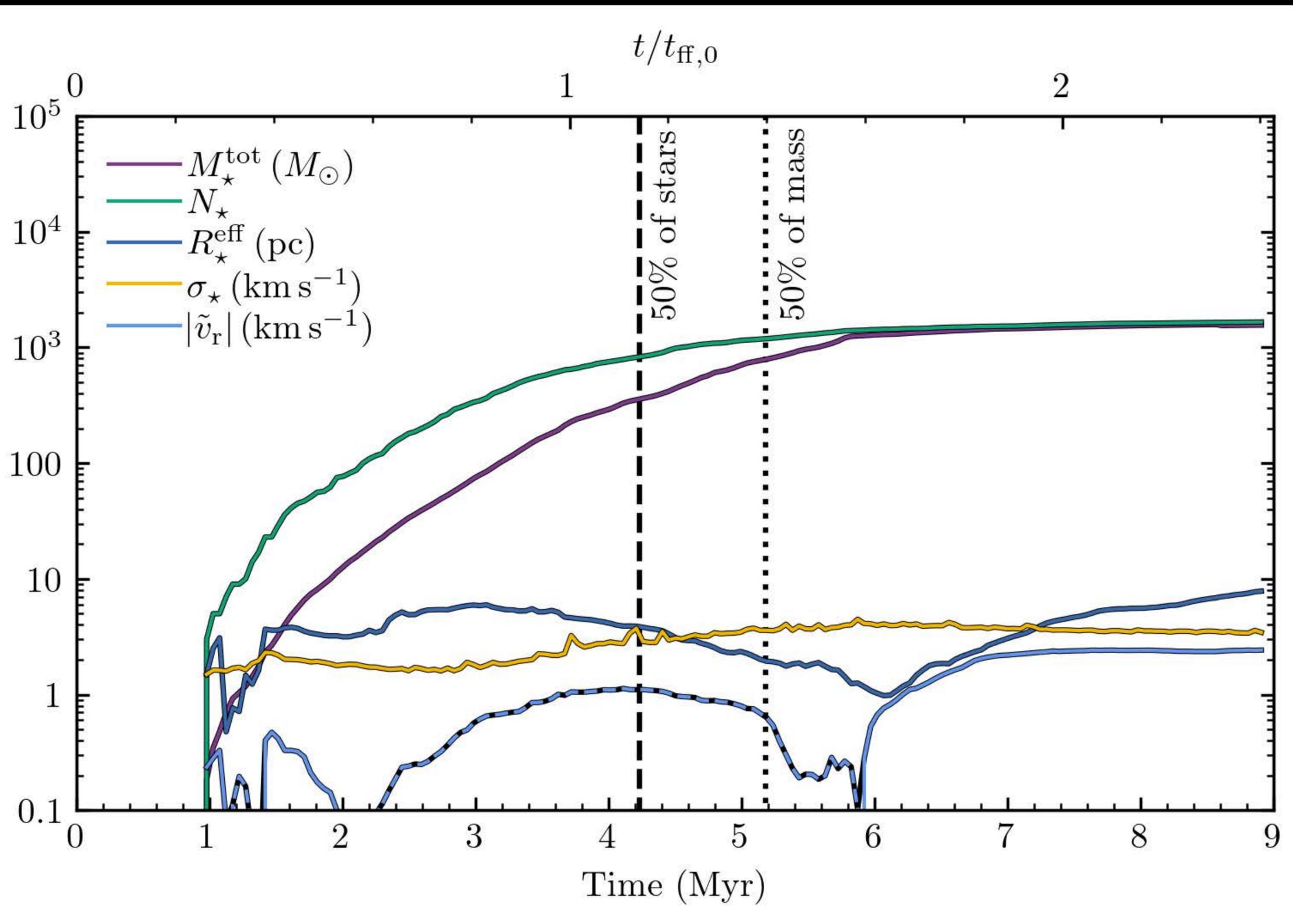


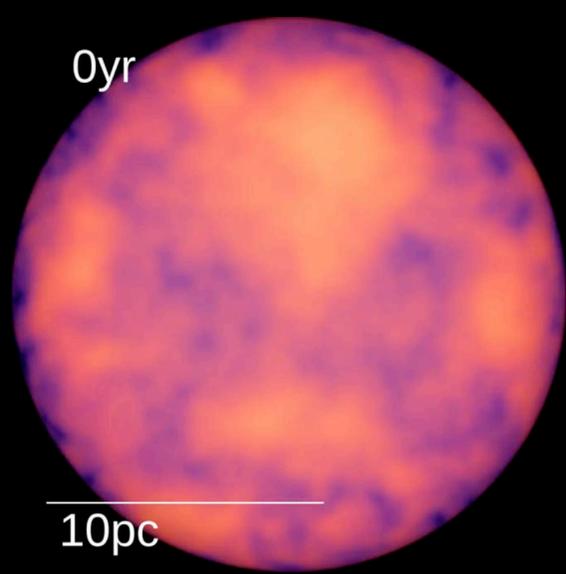
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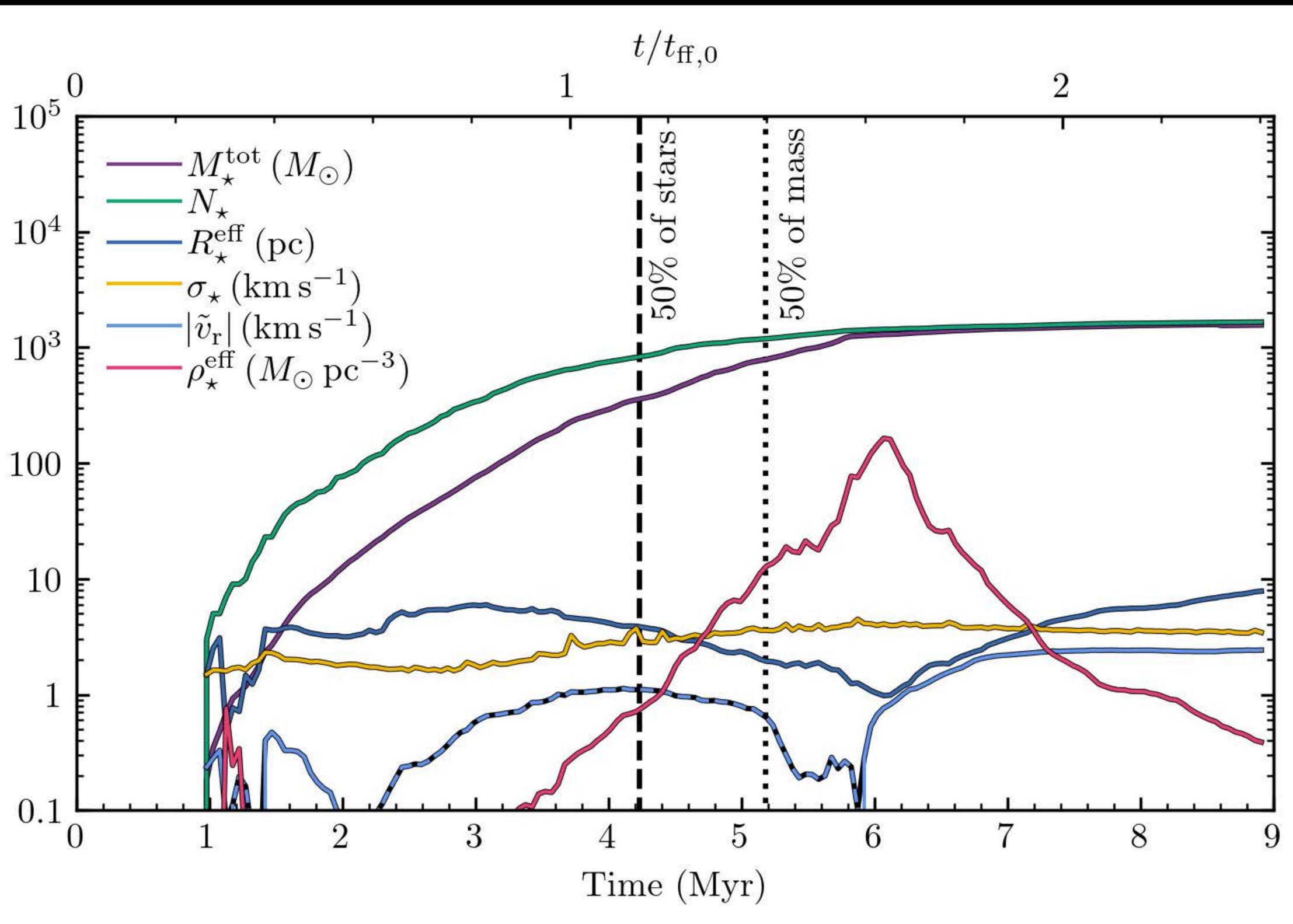


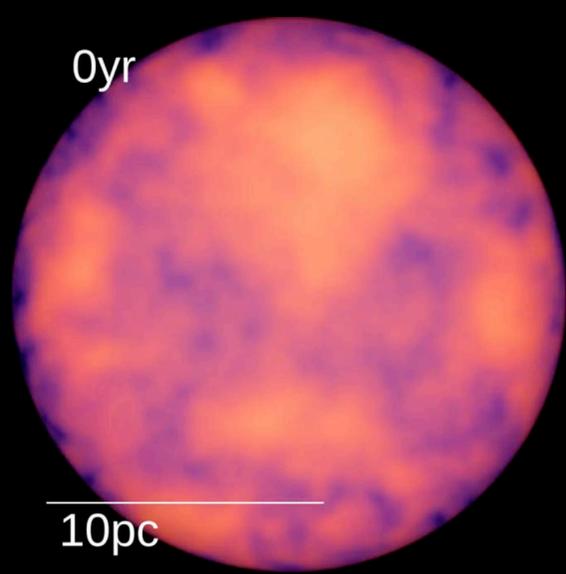
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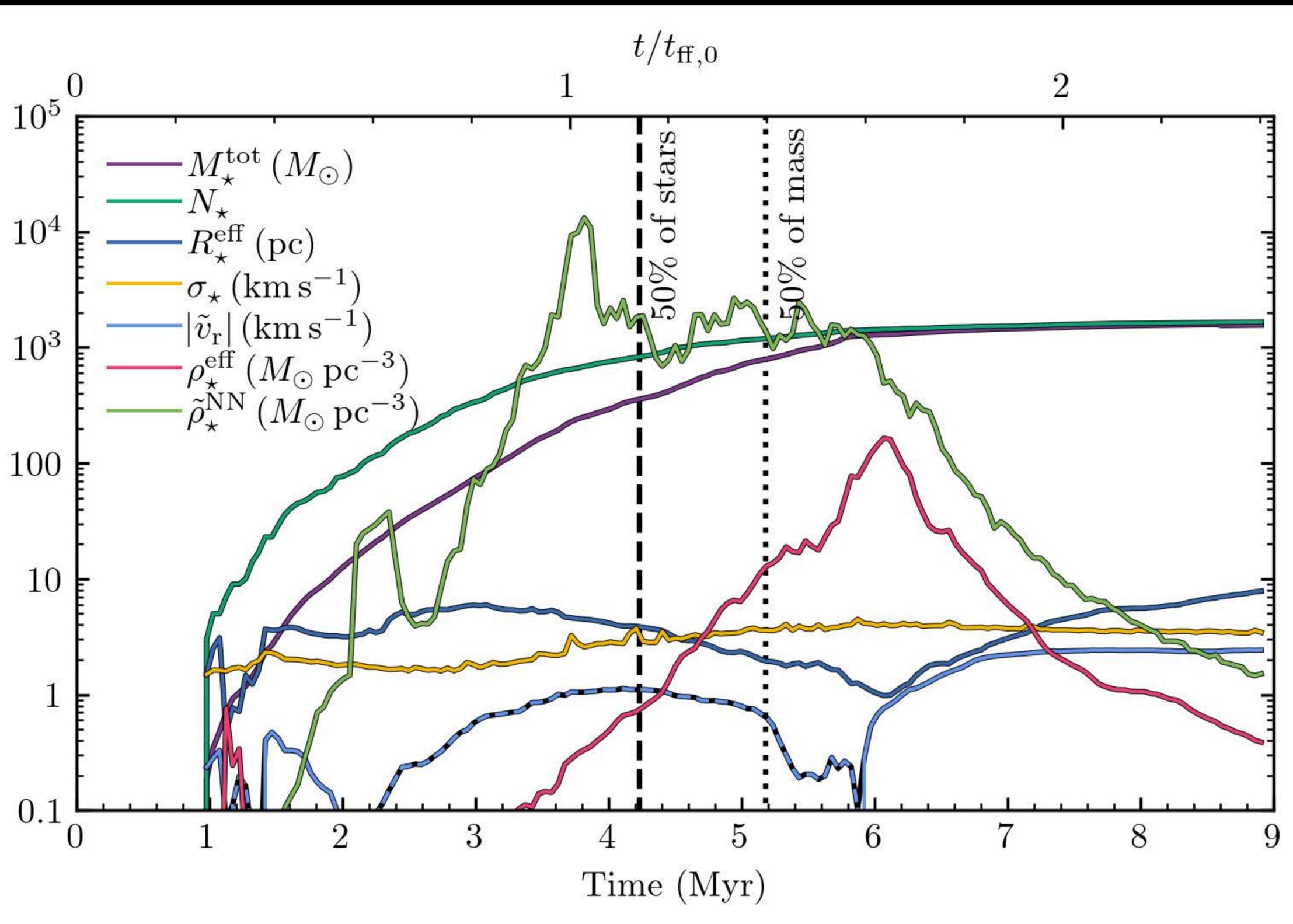


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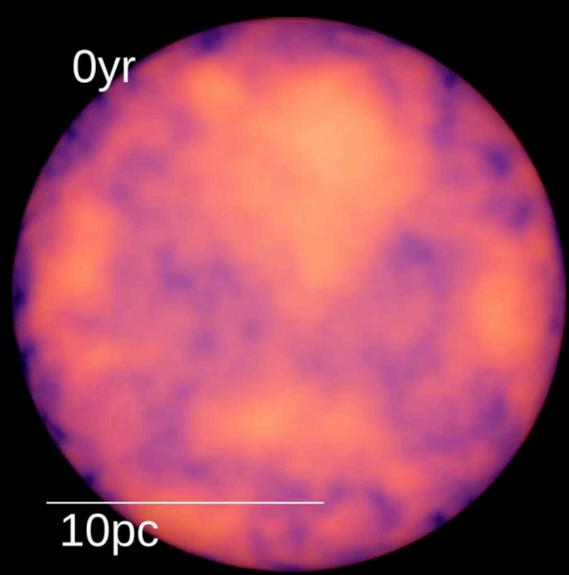


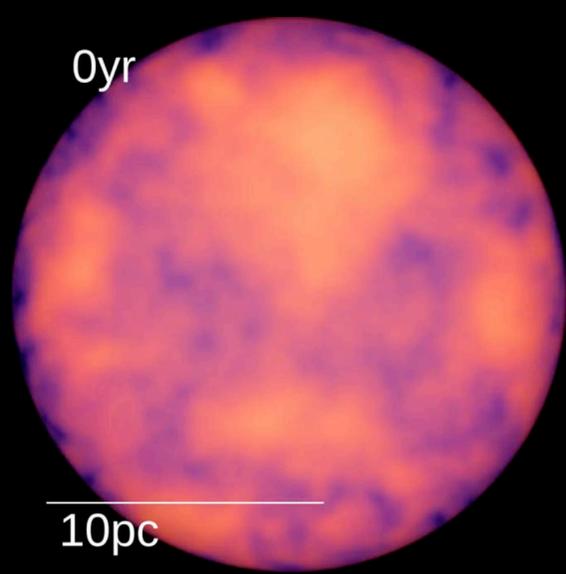


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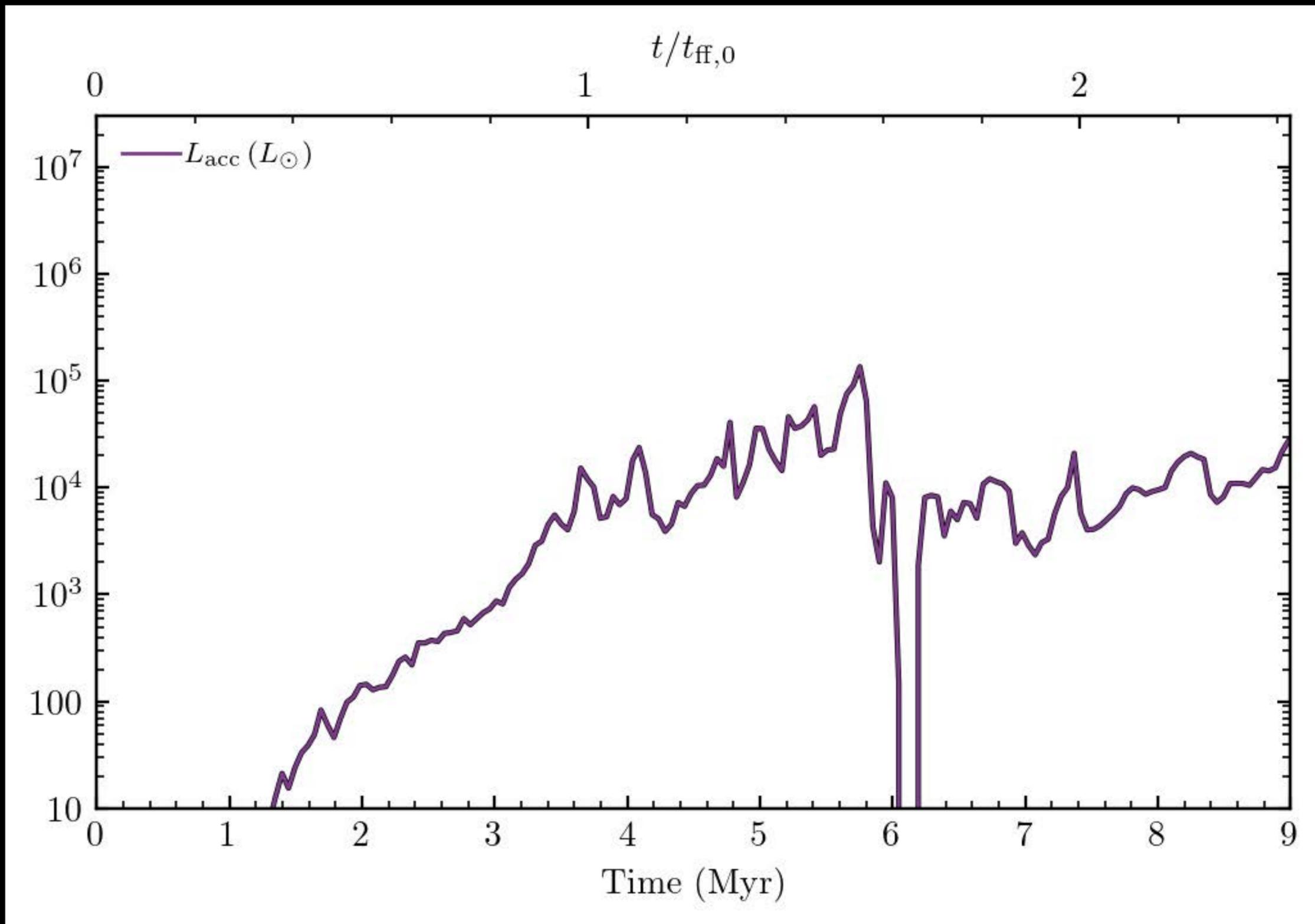


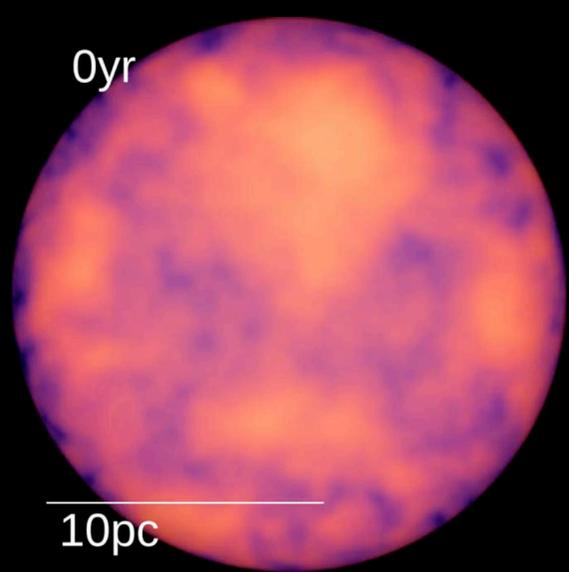
Feedback Evolution



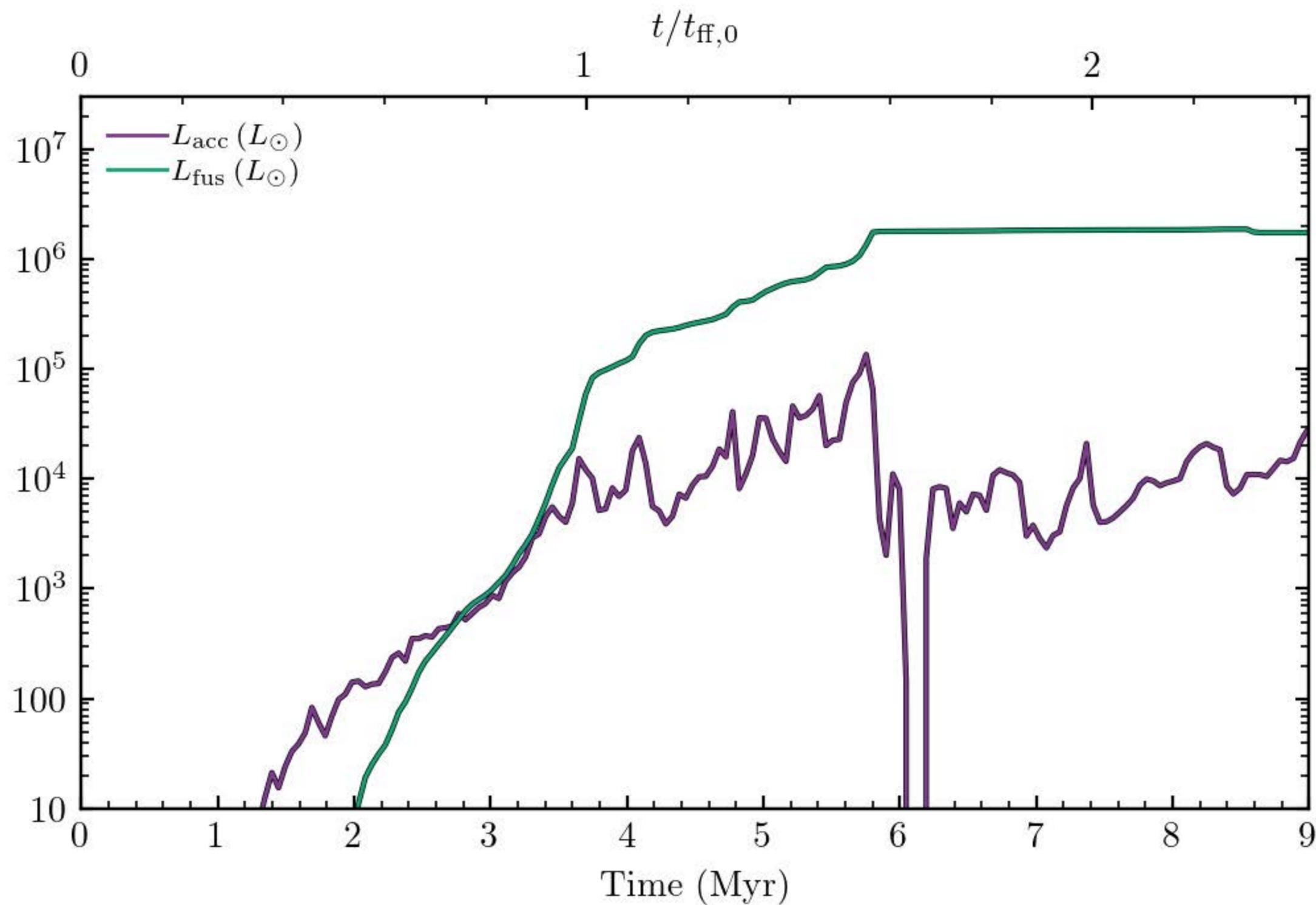


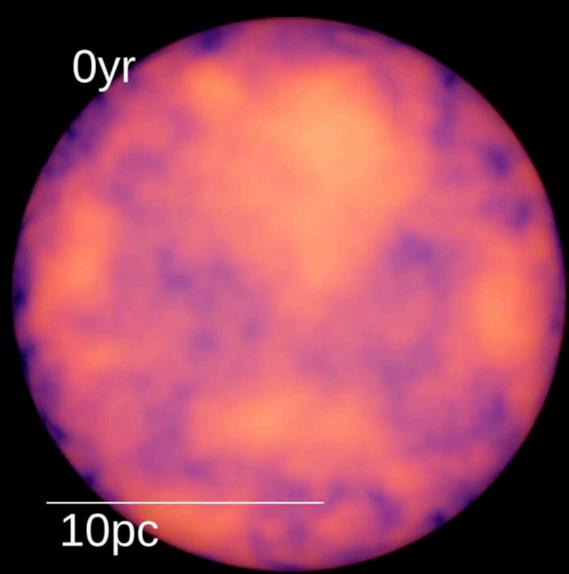
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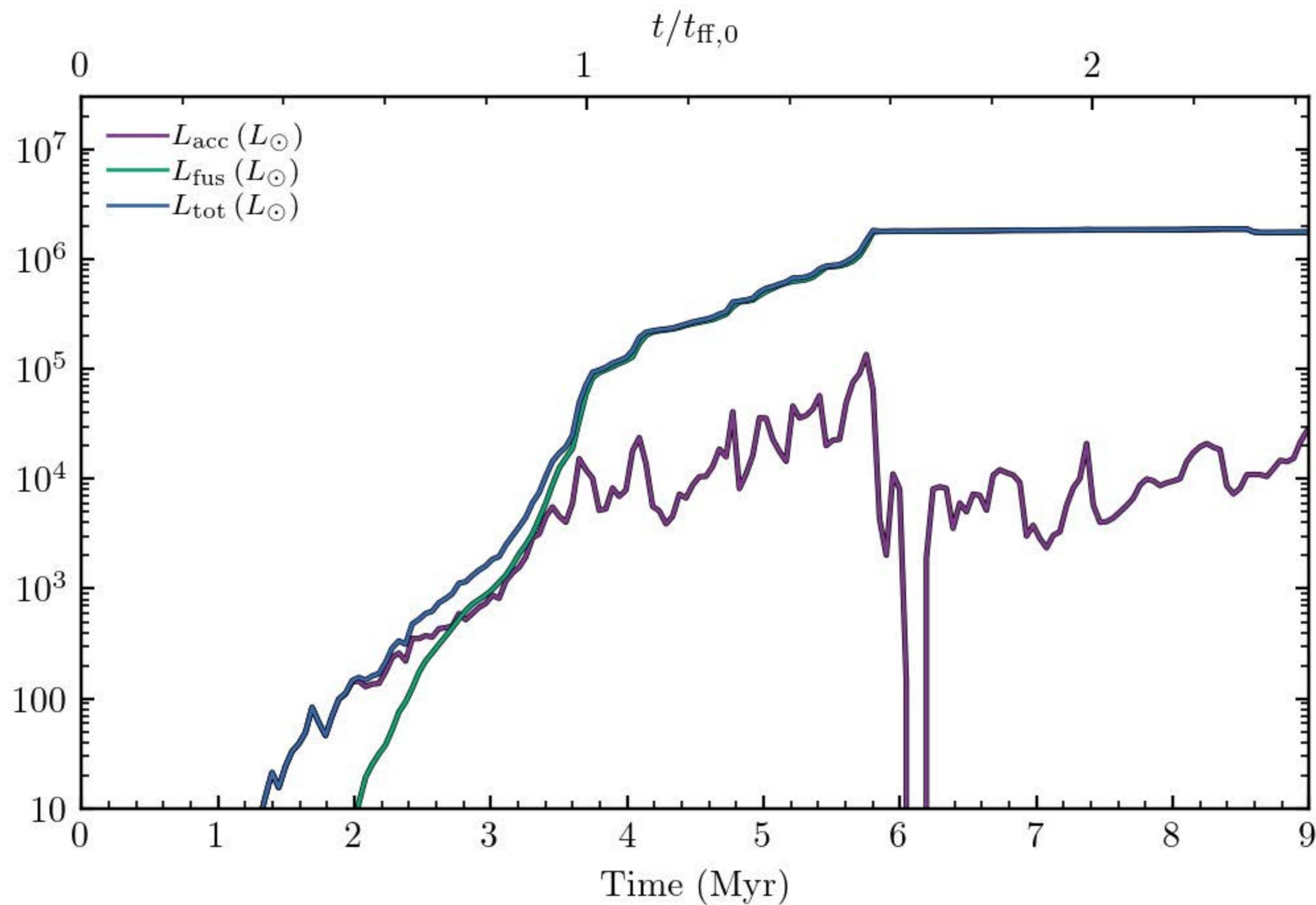


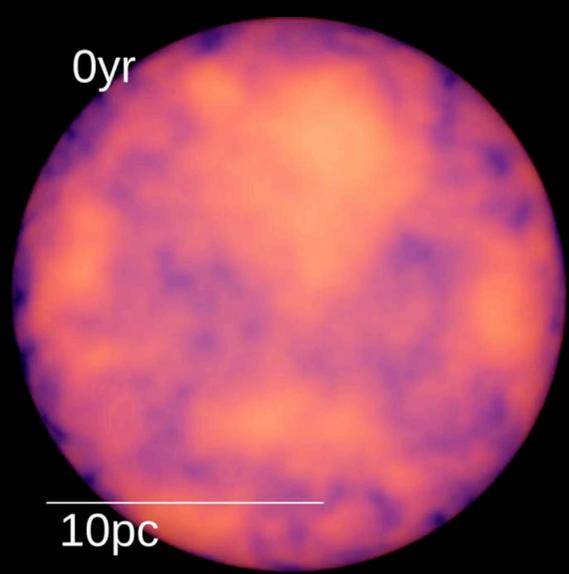
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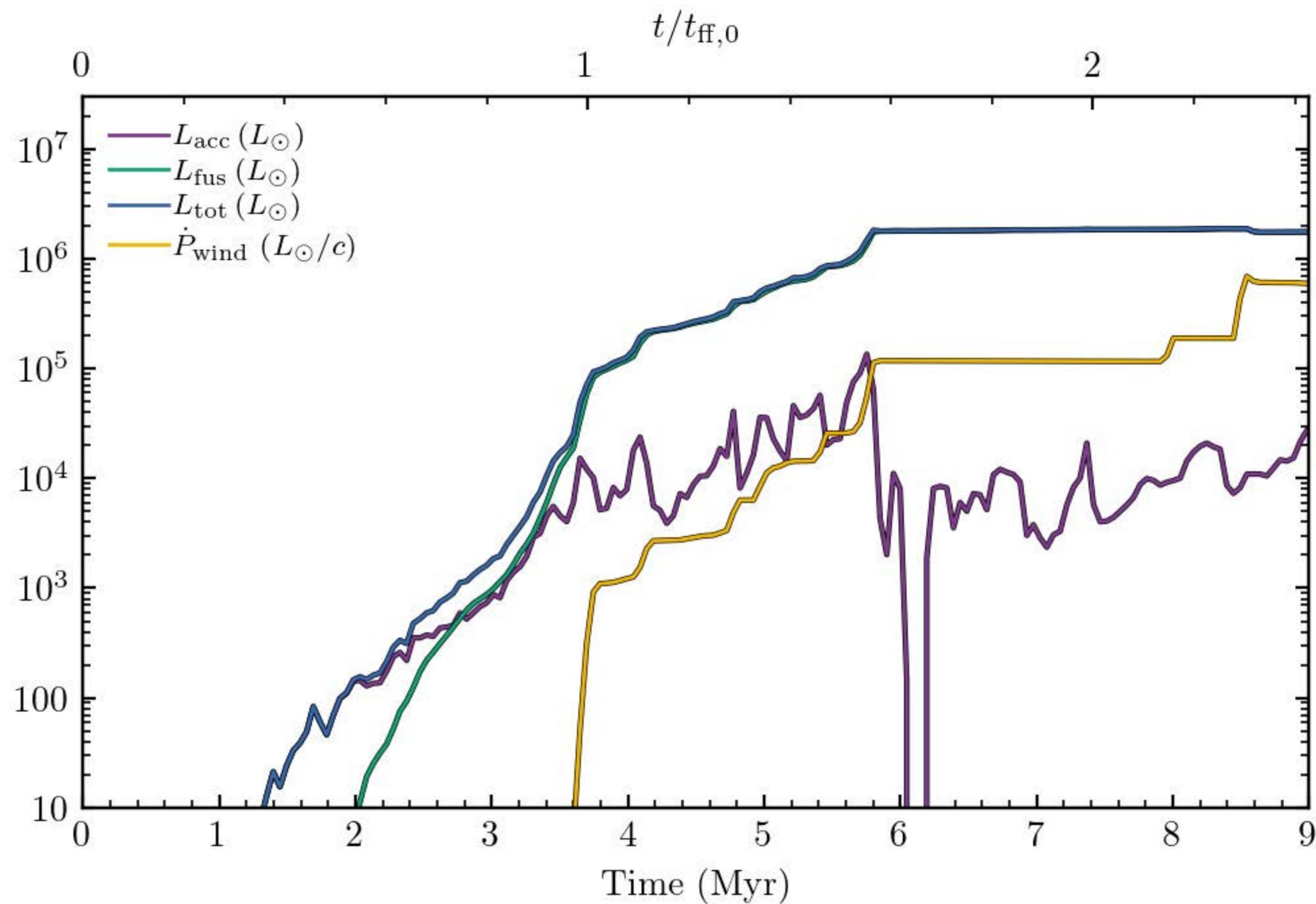


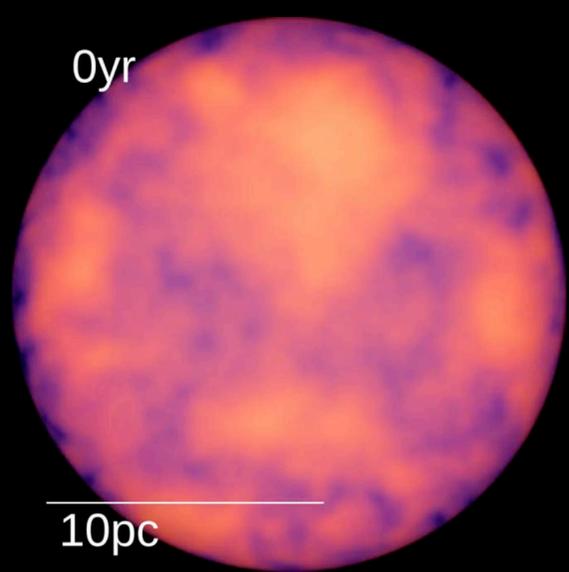
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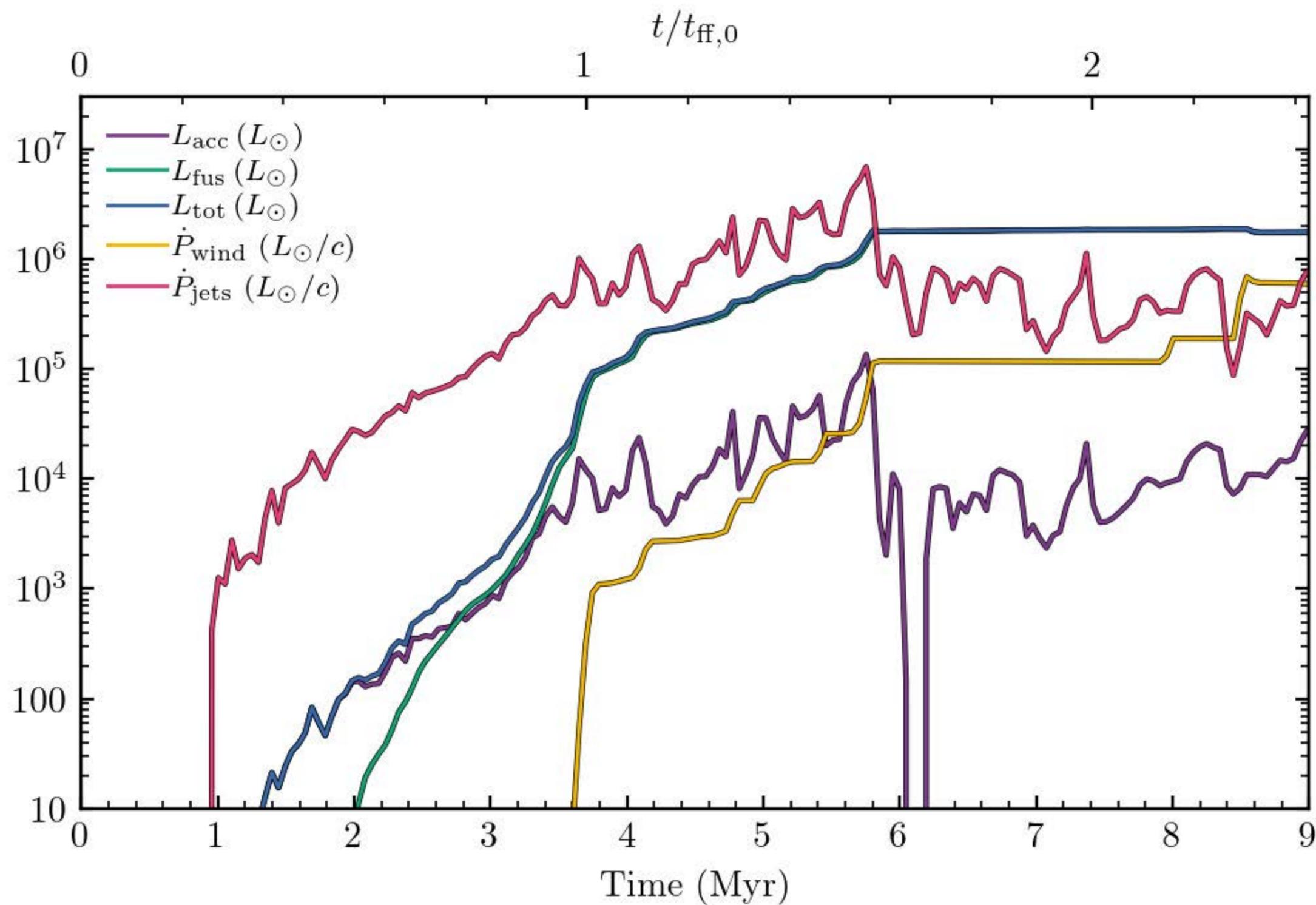


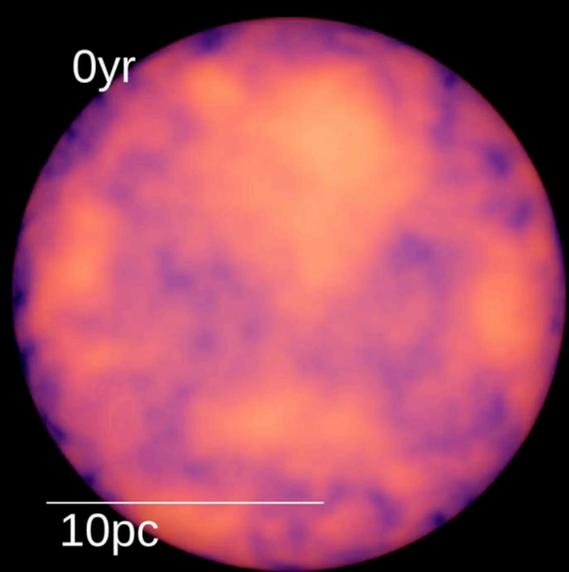
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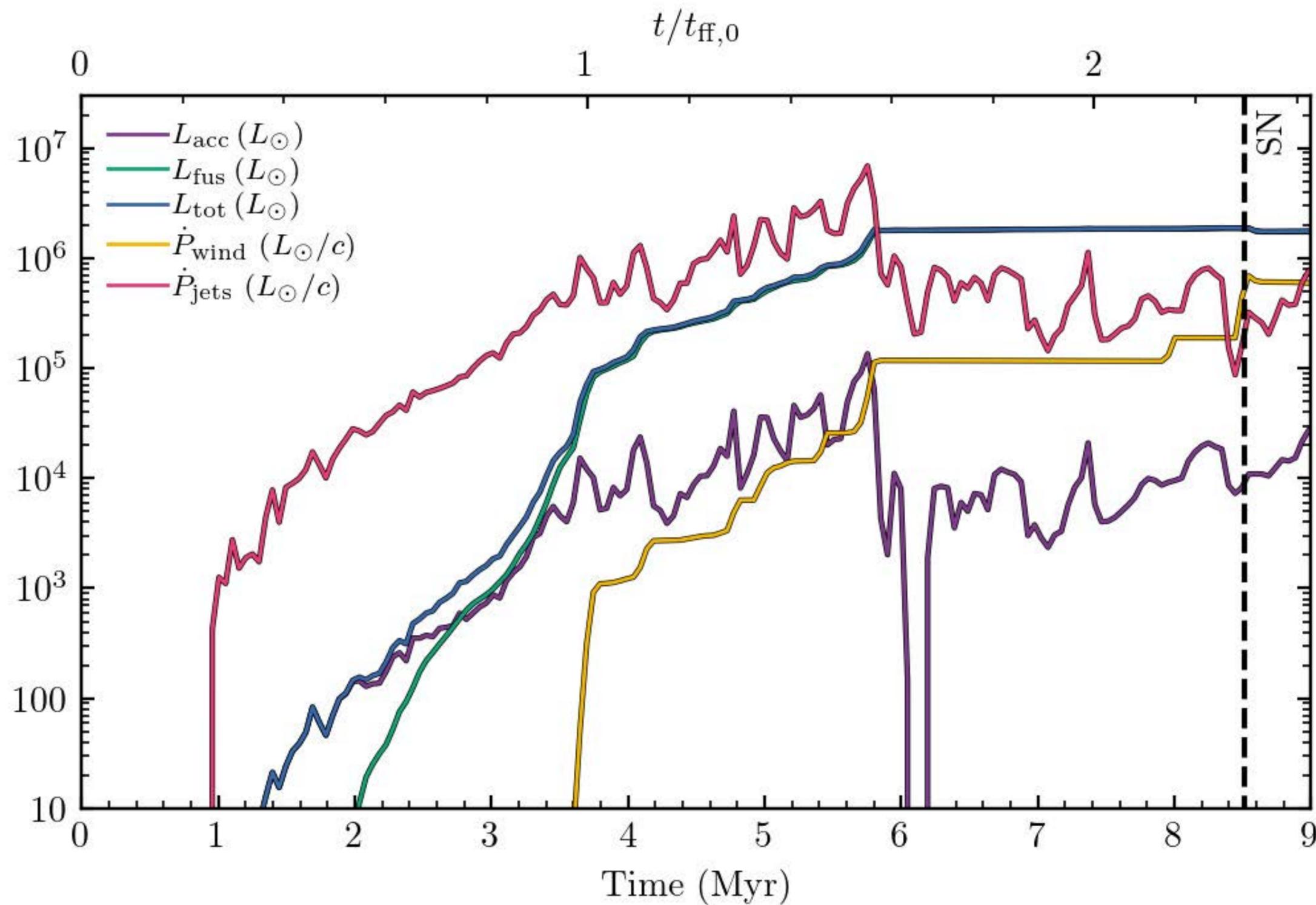


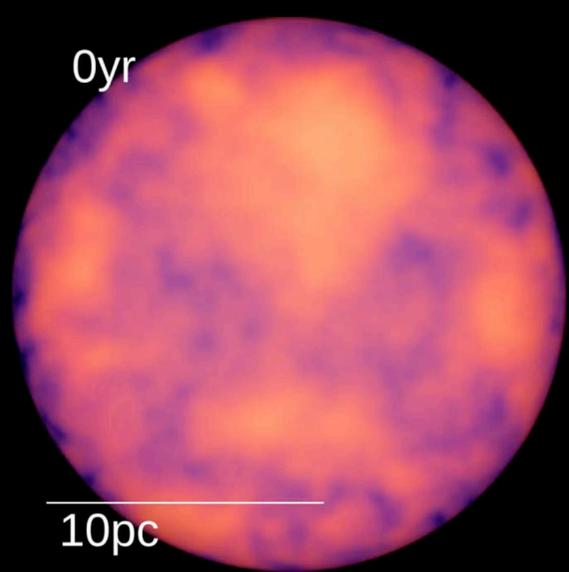
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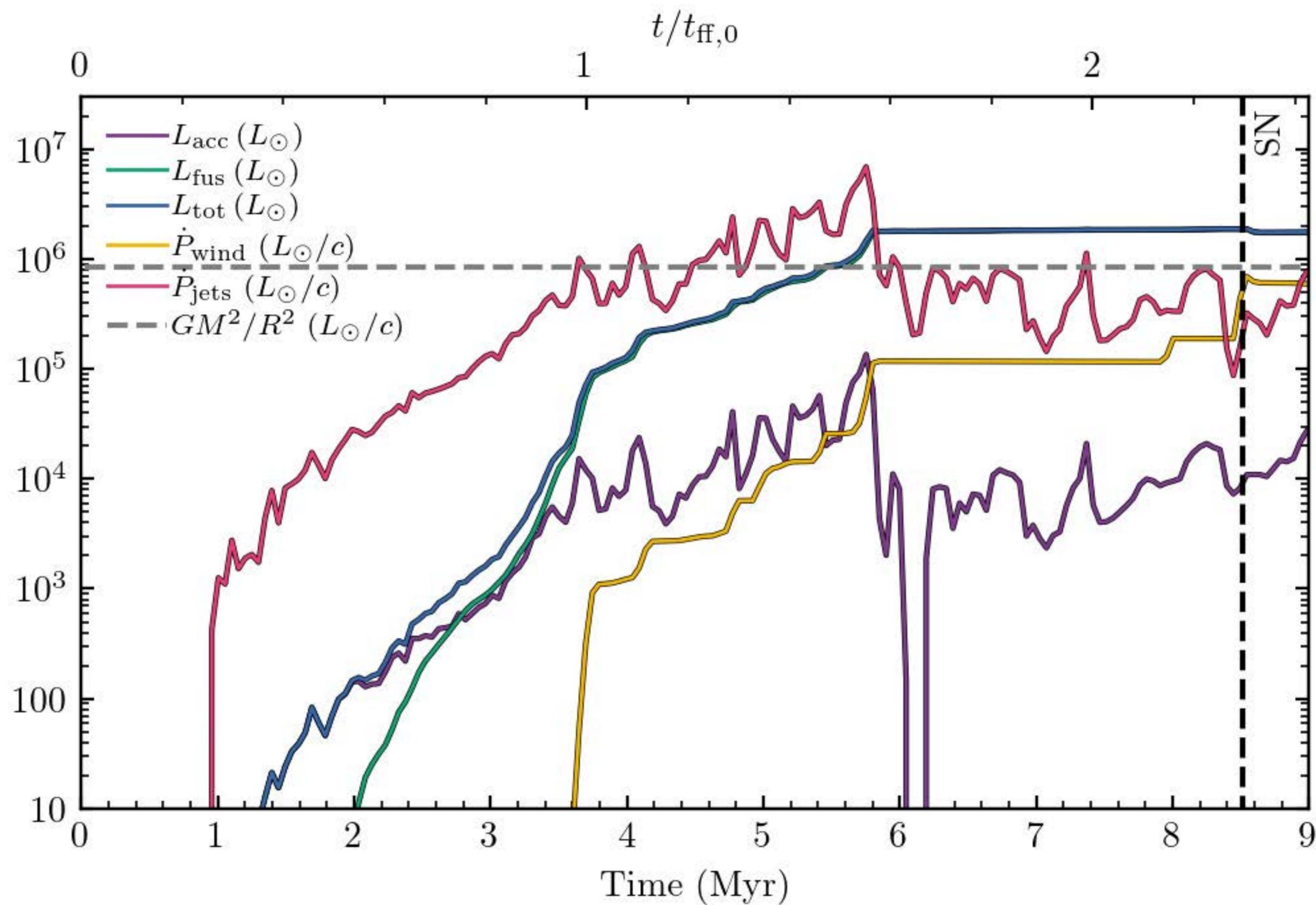


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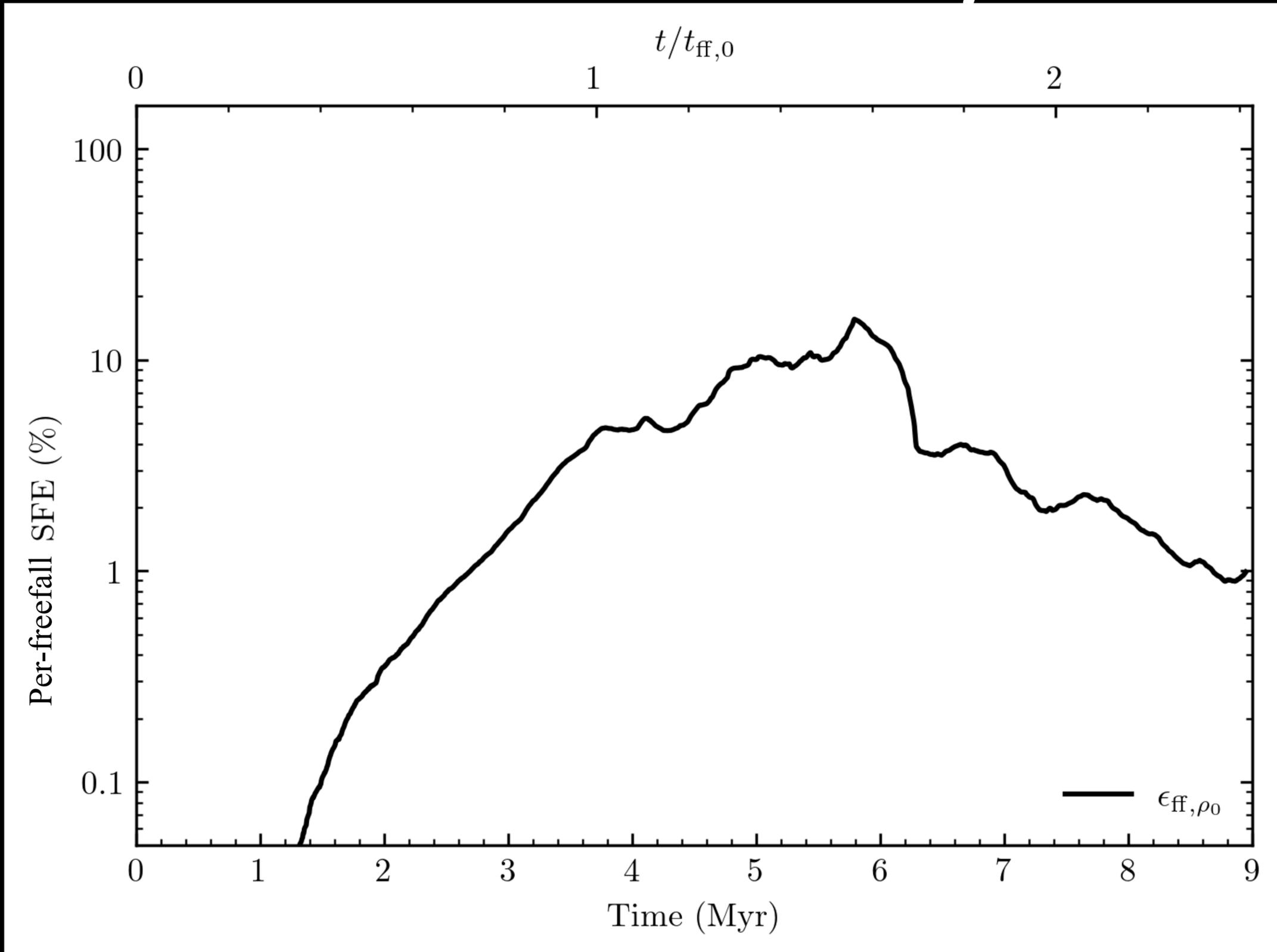


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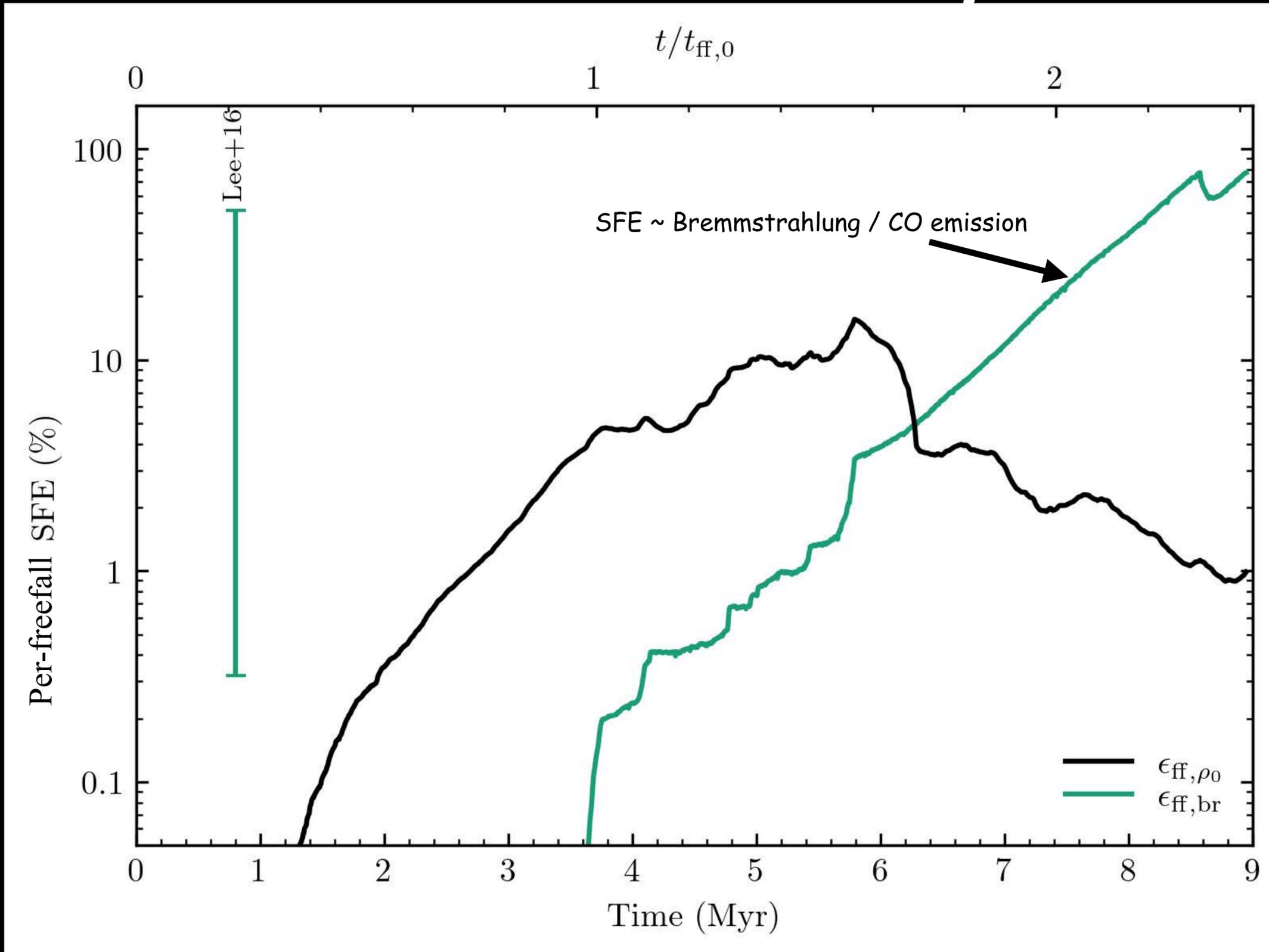


Star Formation Efficiency - ϵ_{ff}

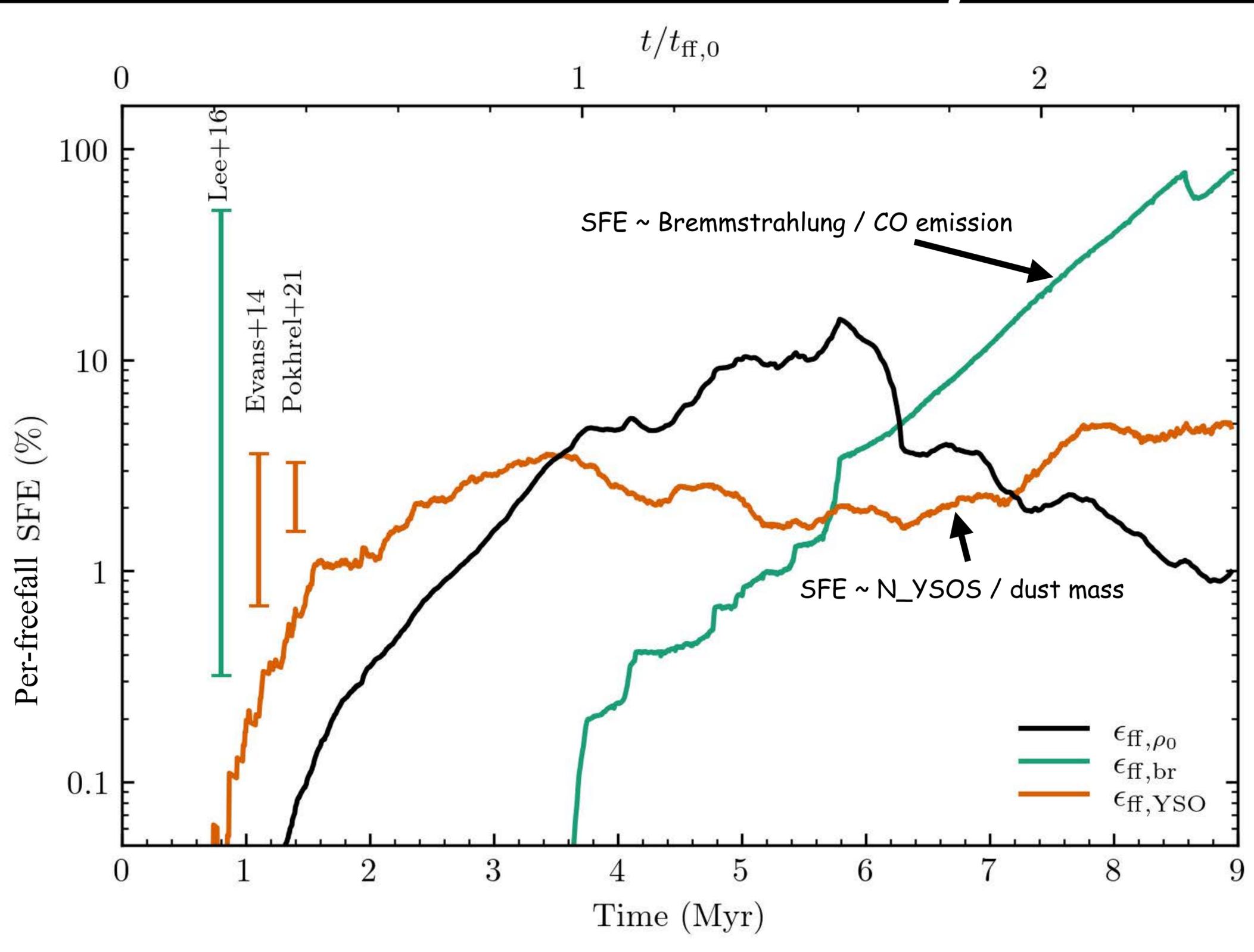
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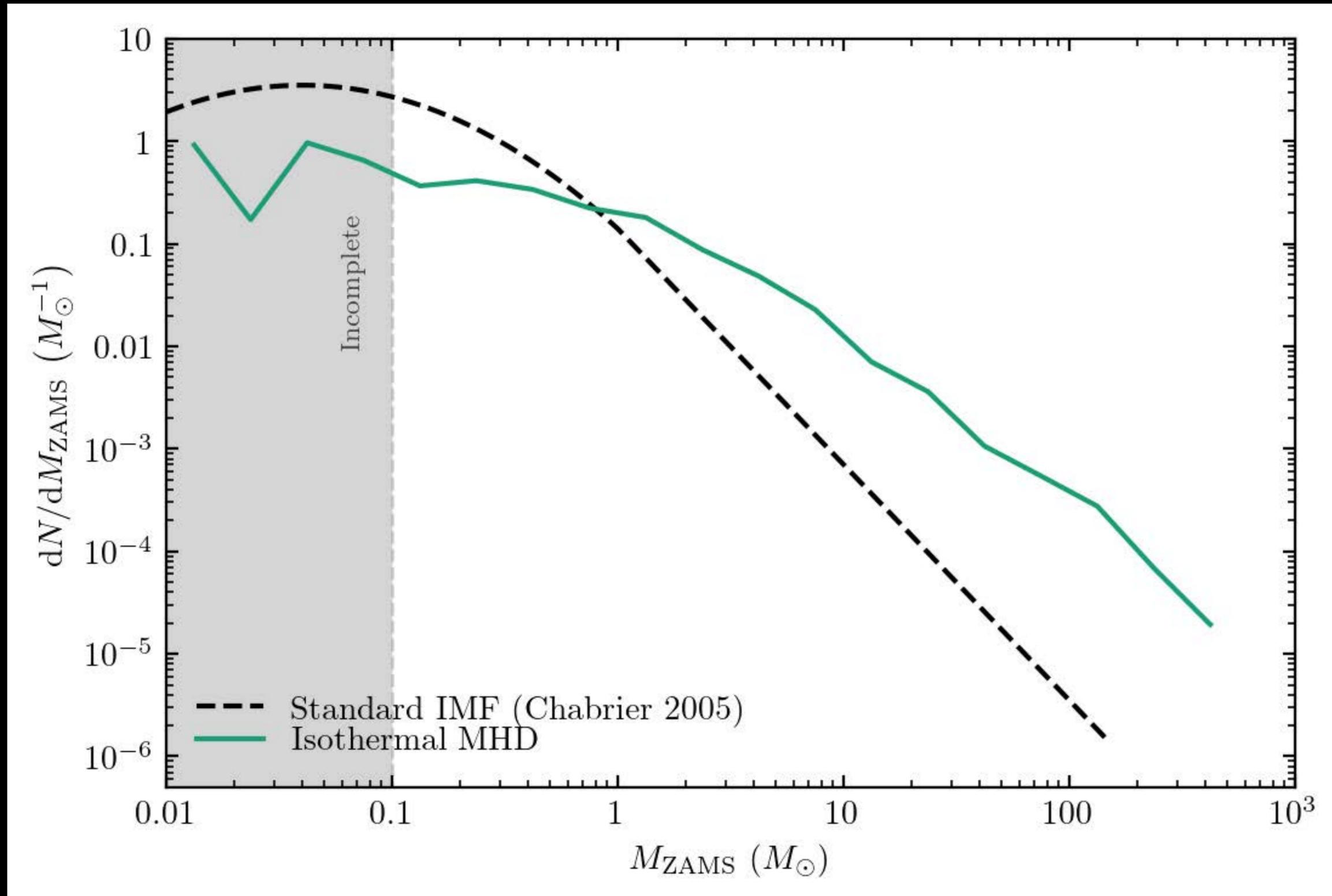


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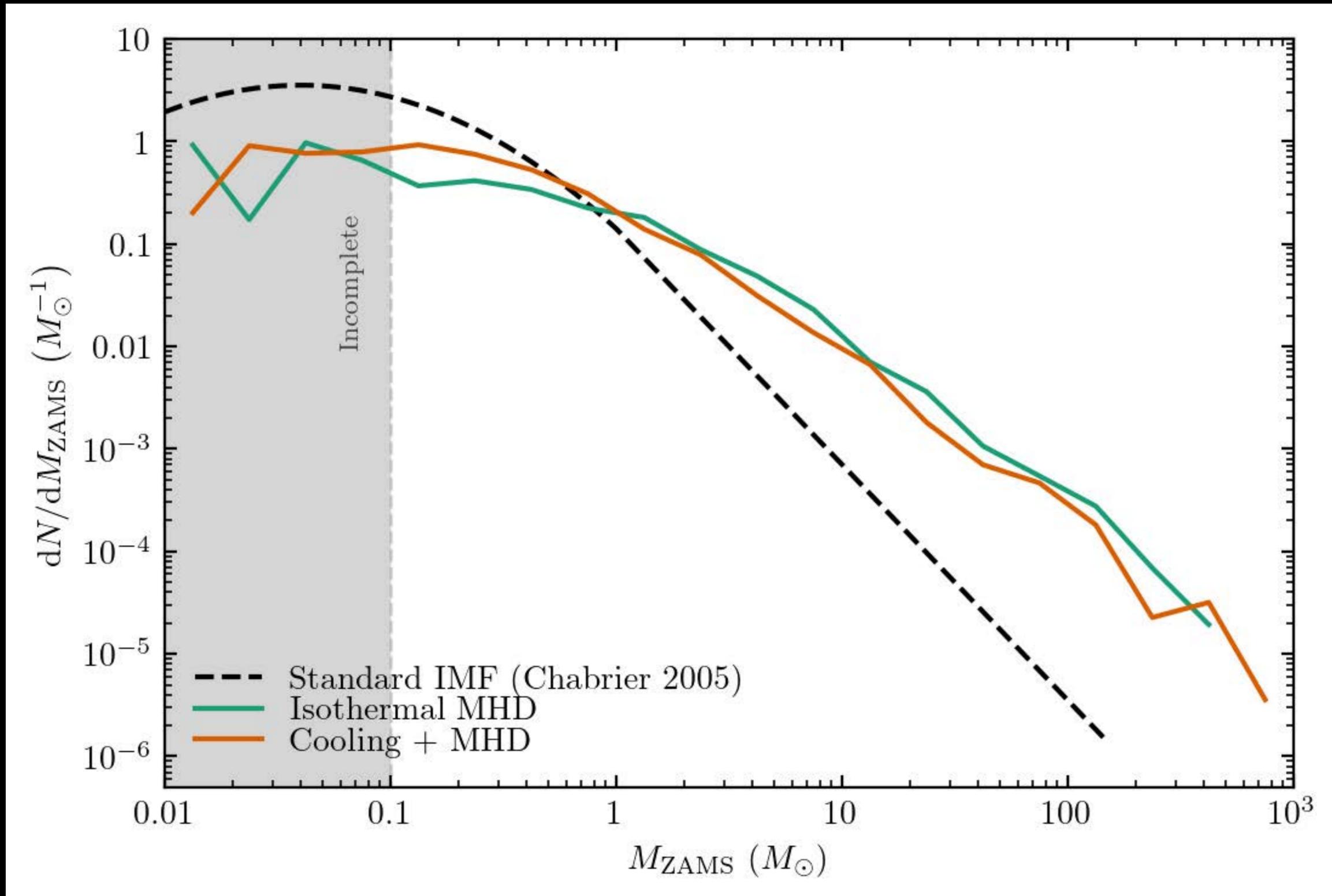


The Long Road to the IMF

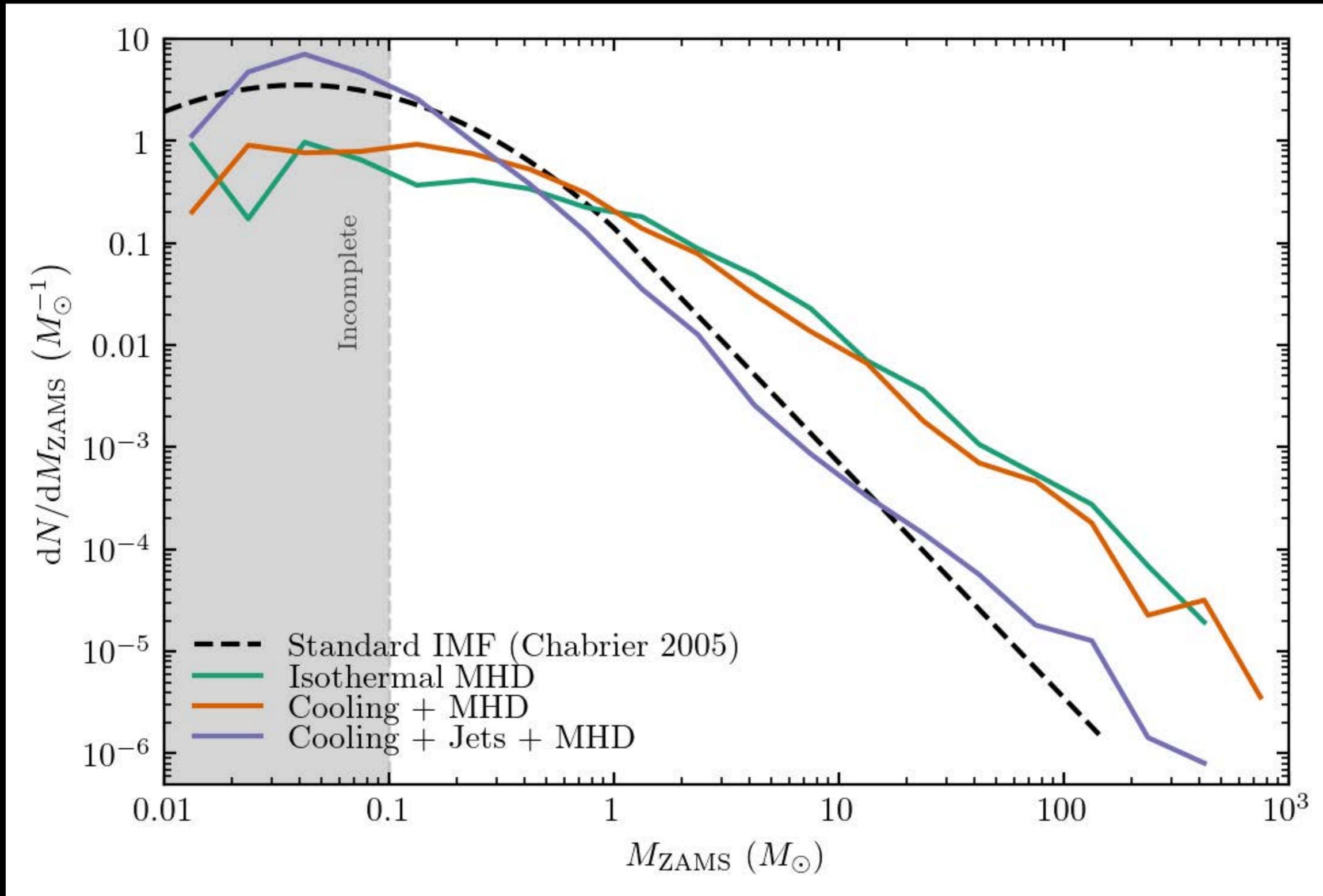
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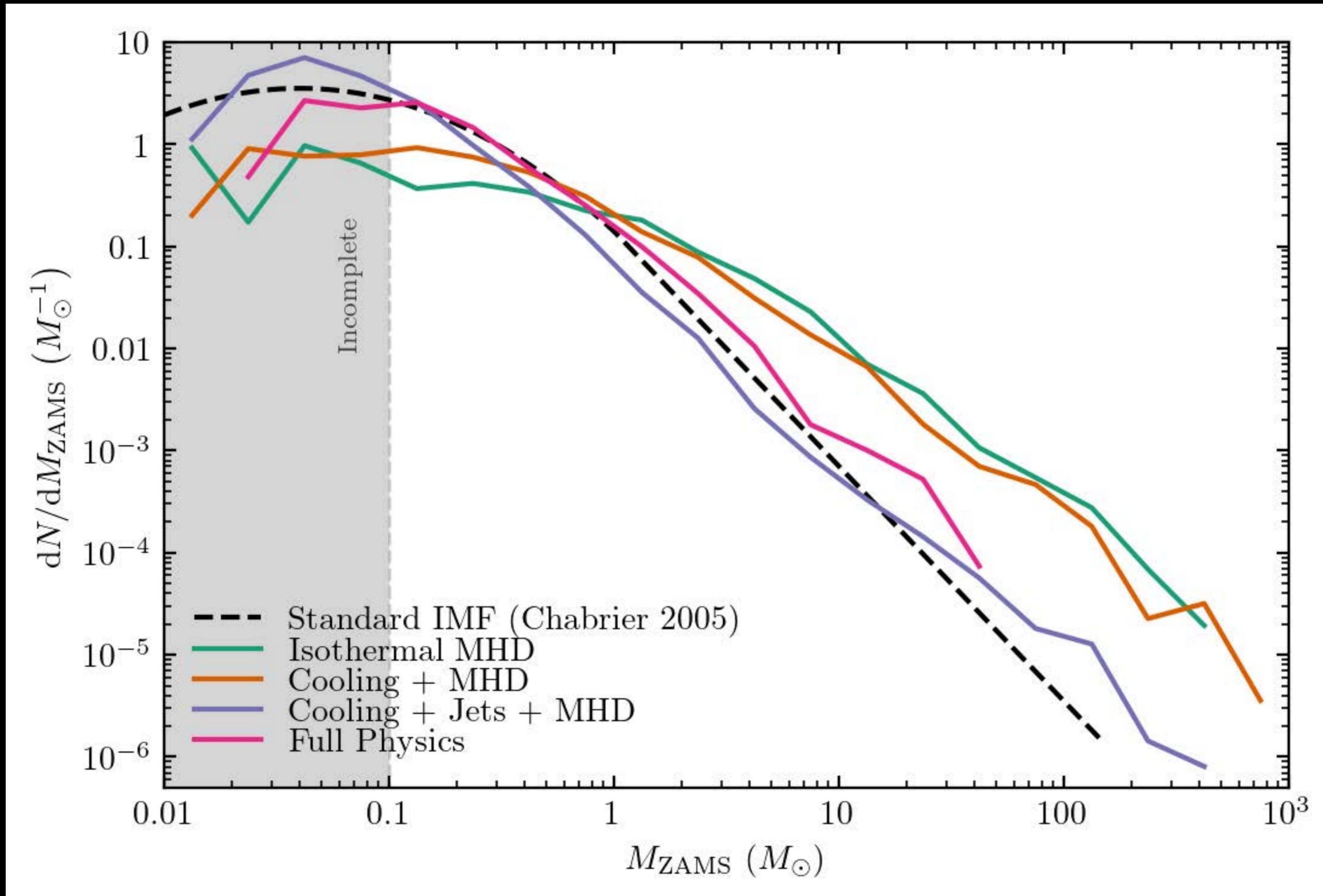
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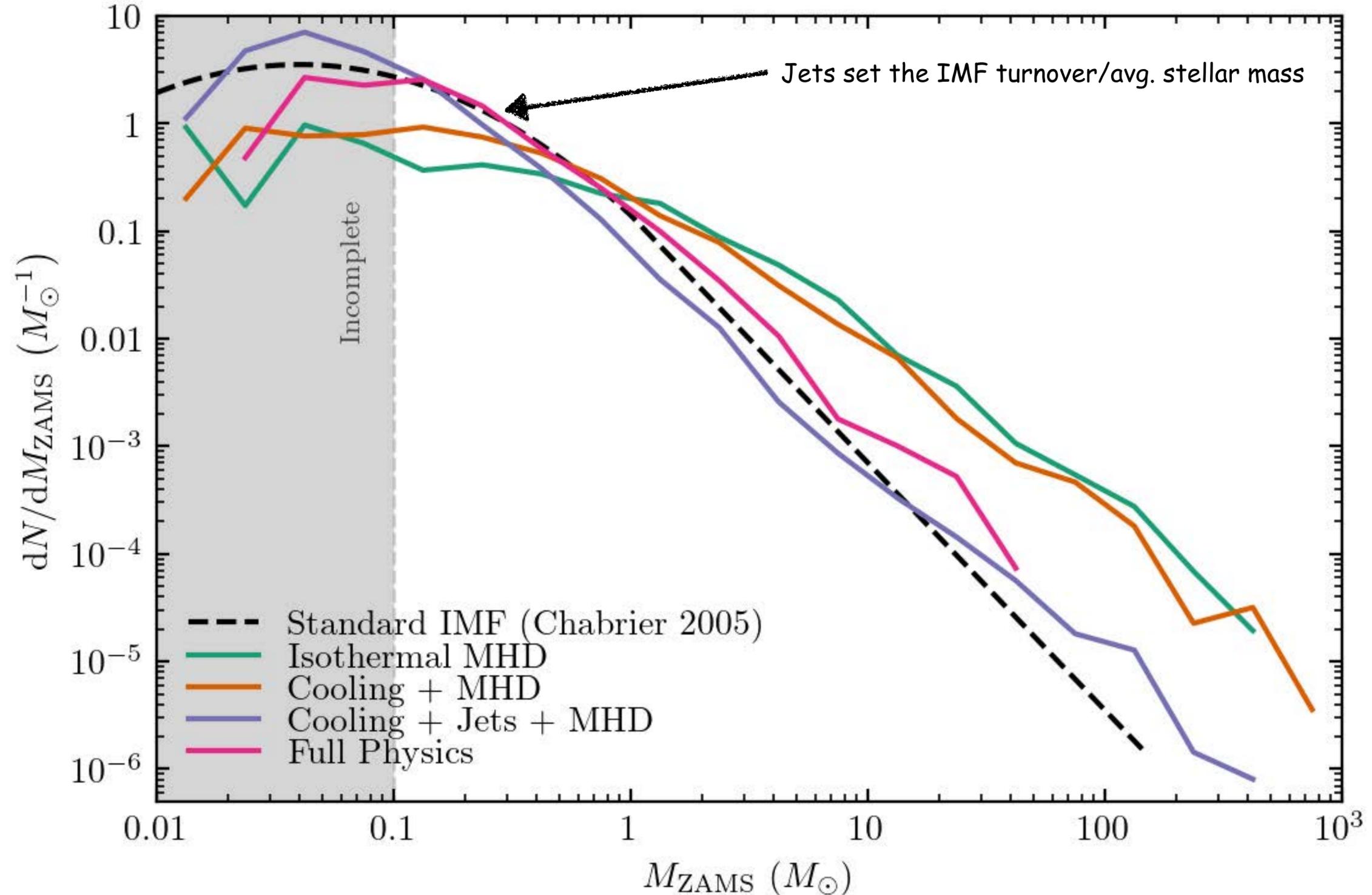
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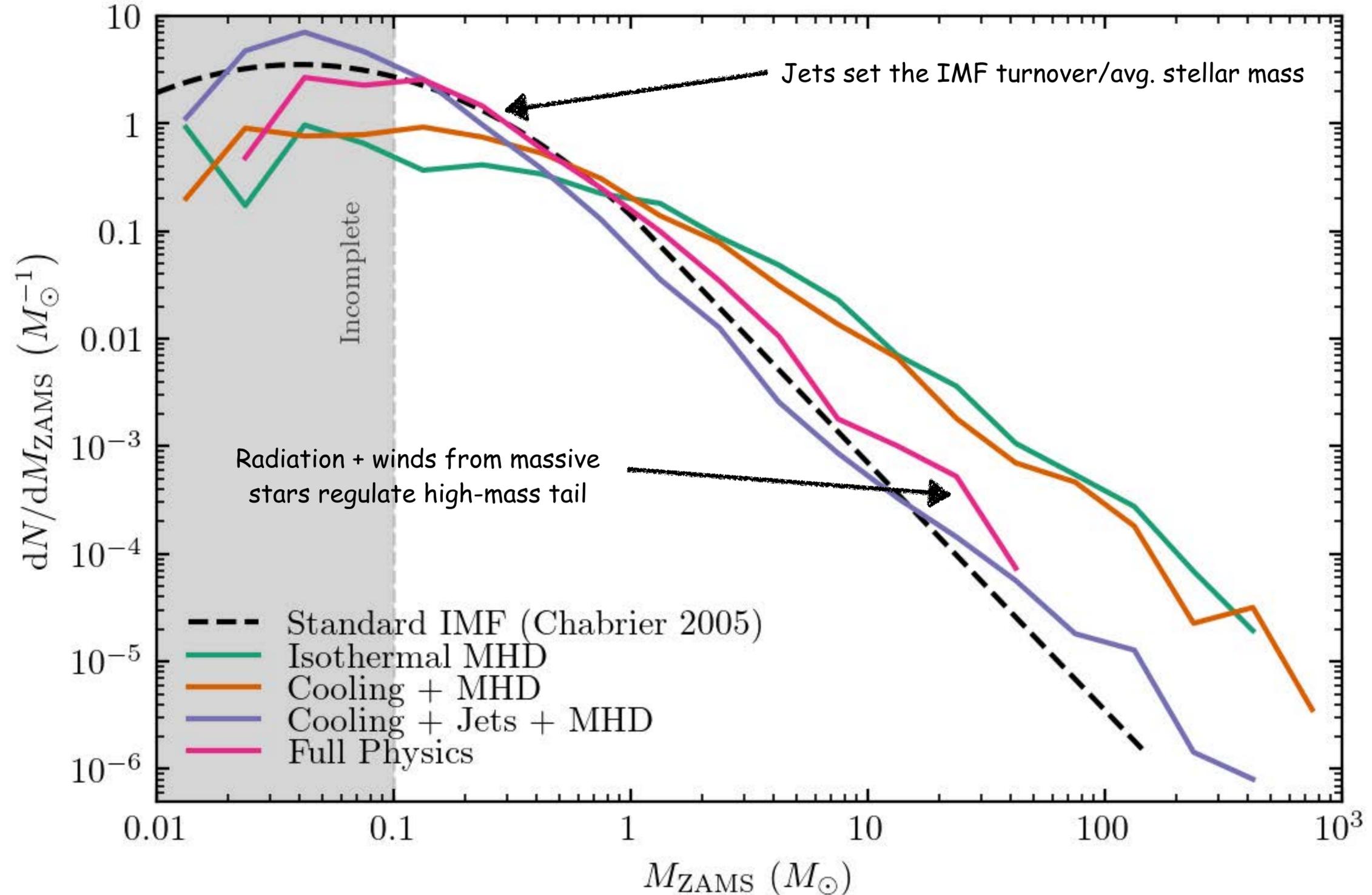
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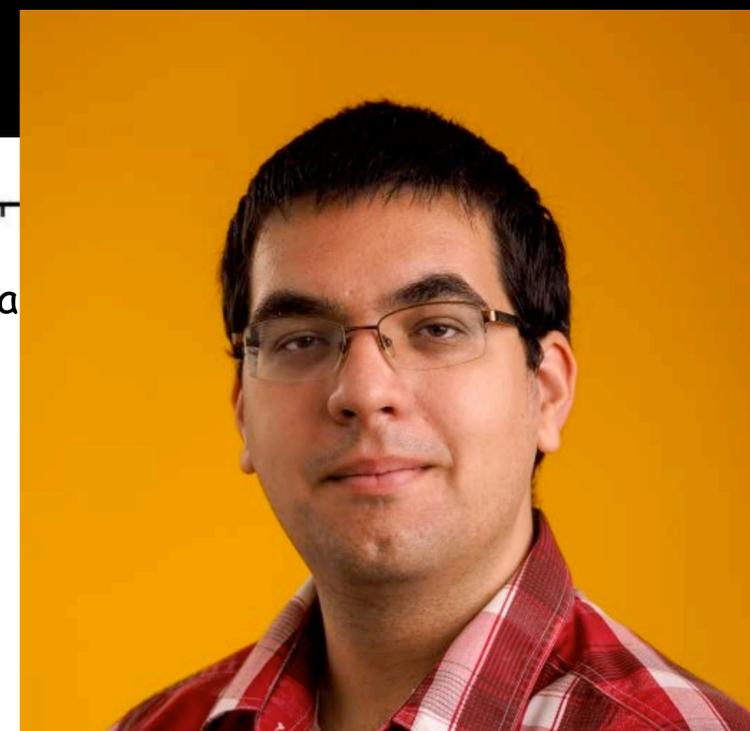
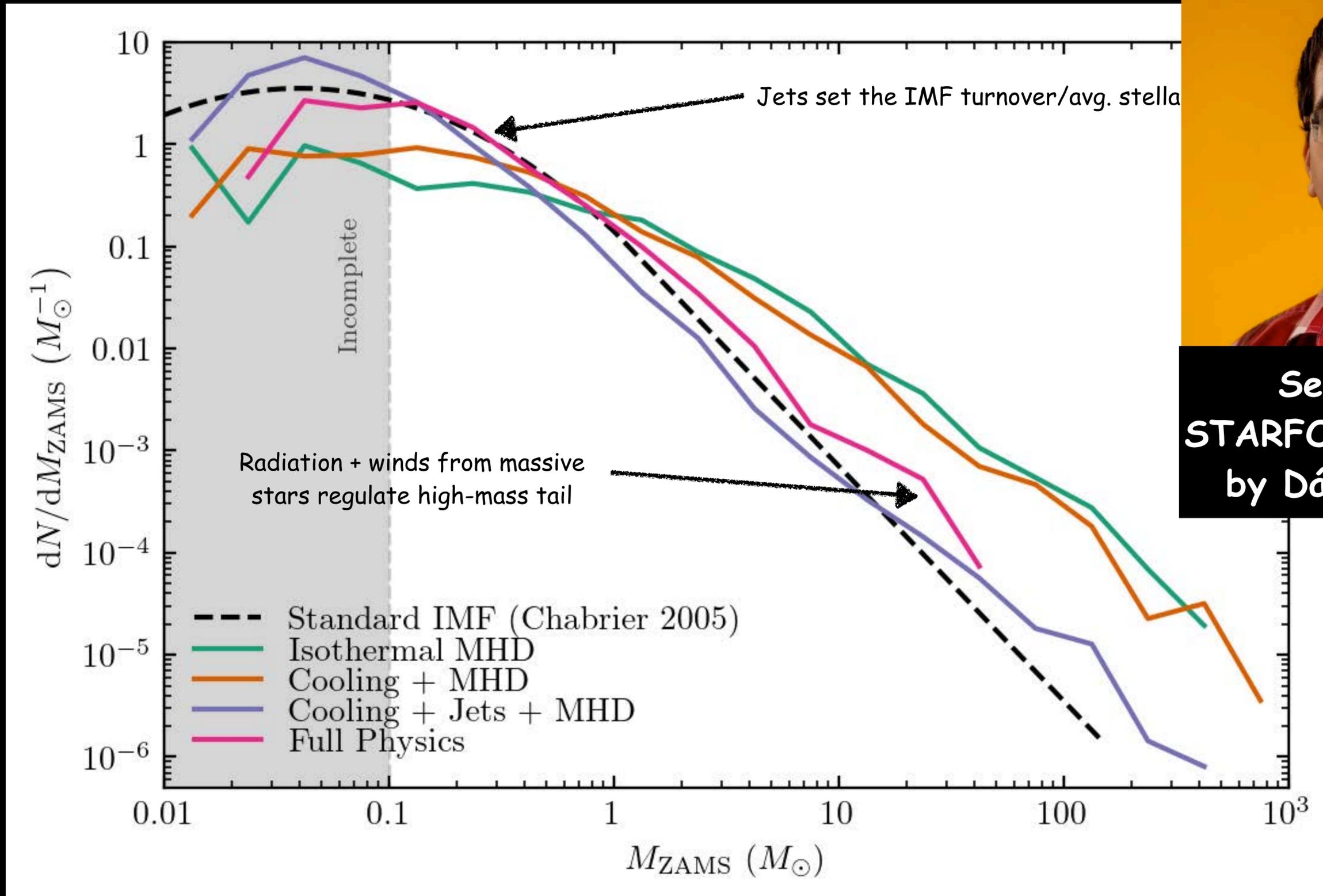
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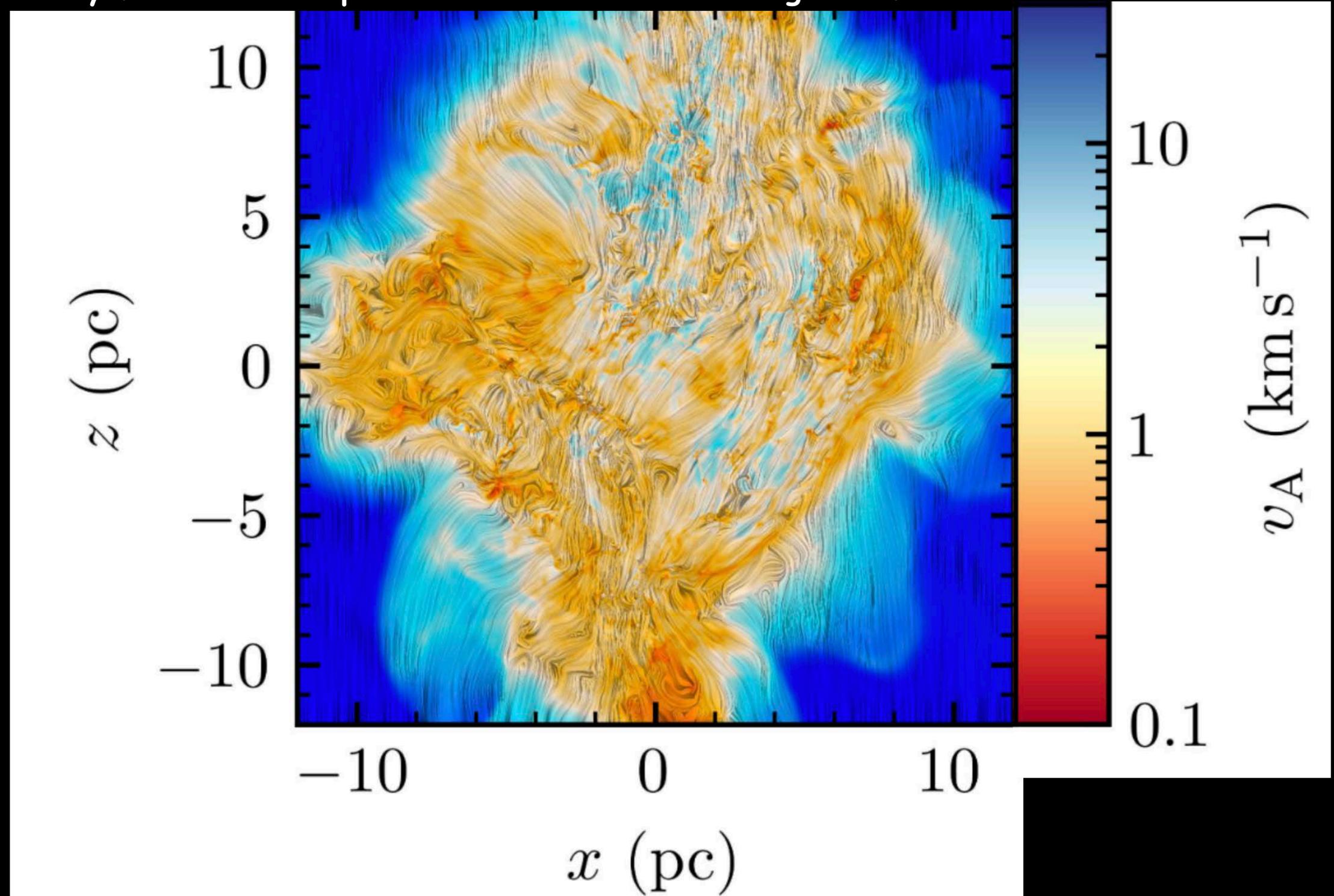
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See upcoming
STARFORGE IMF paper
by Dávid Guszejnov

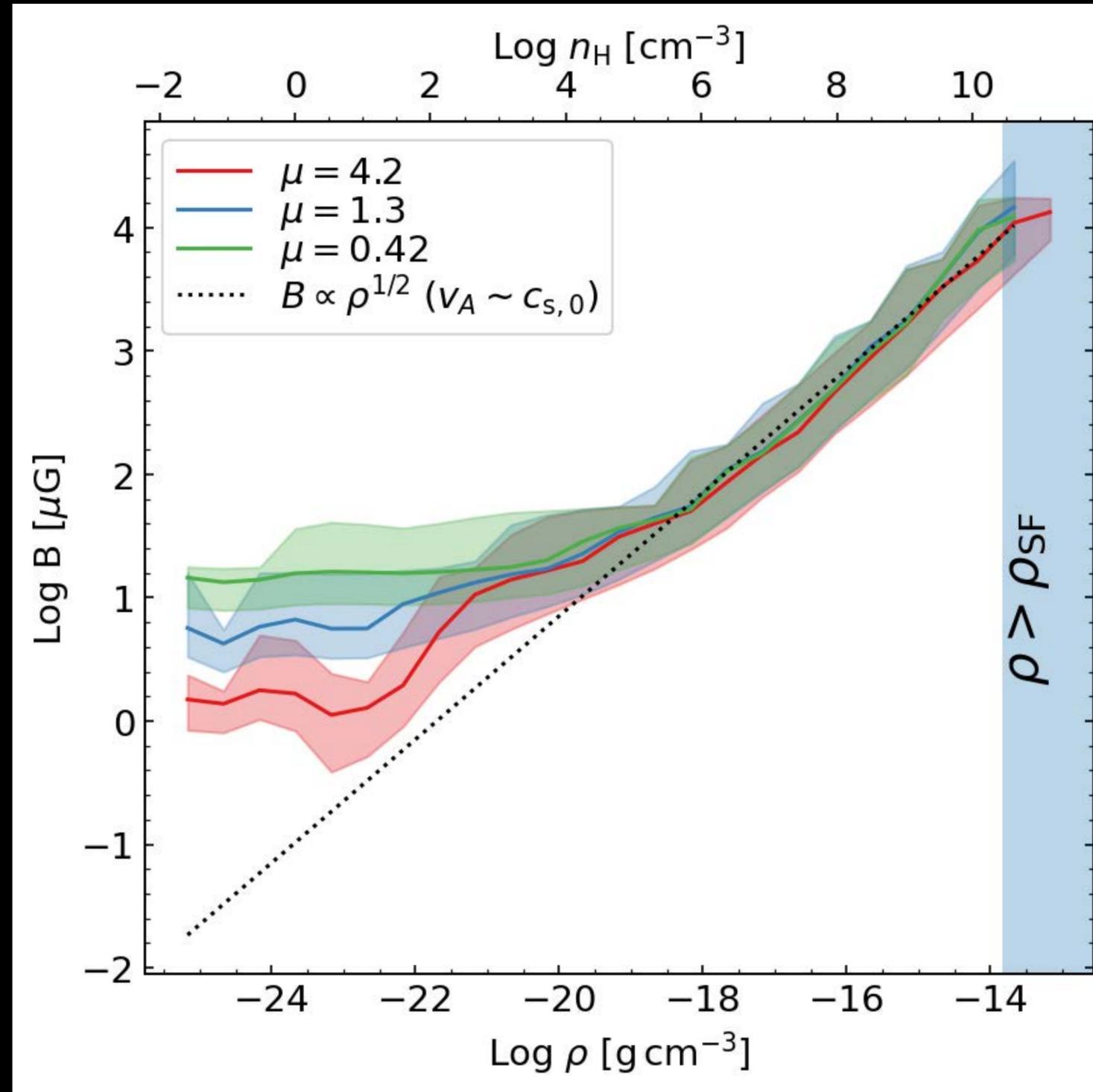
Magnetic fields in STARFORGE Simulations

Clearly feedback is important - but what about magnetic fields?

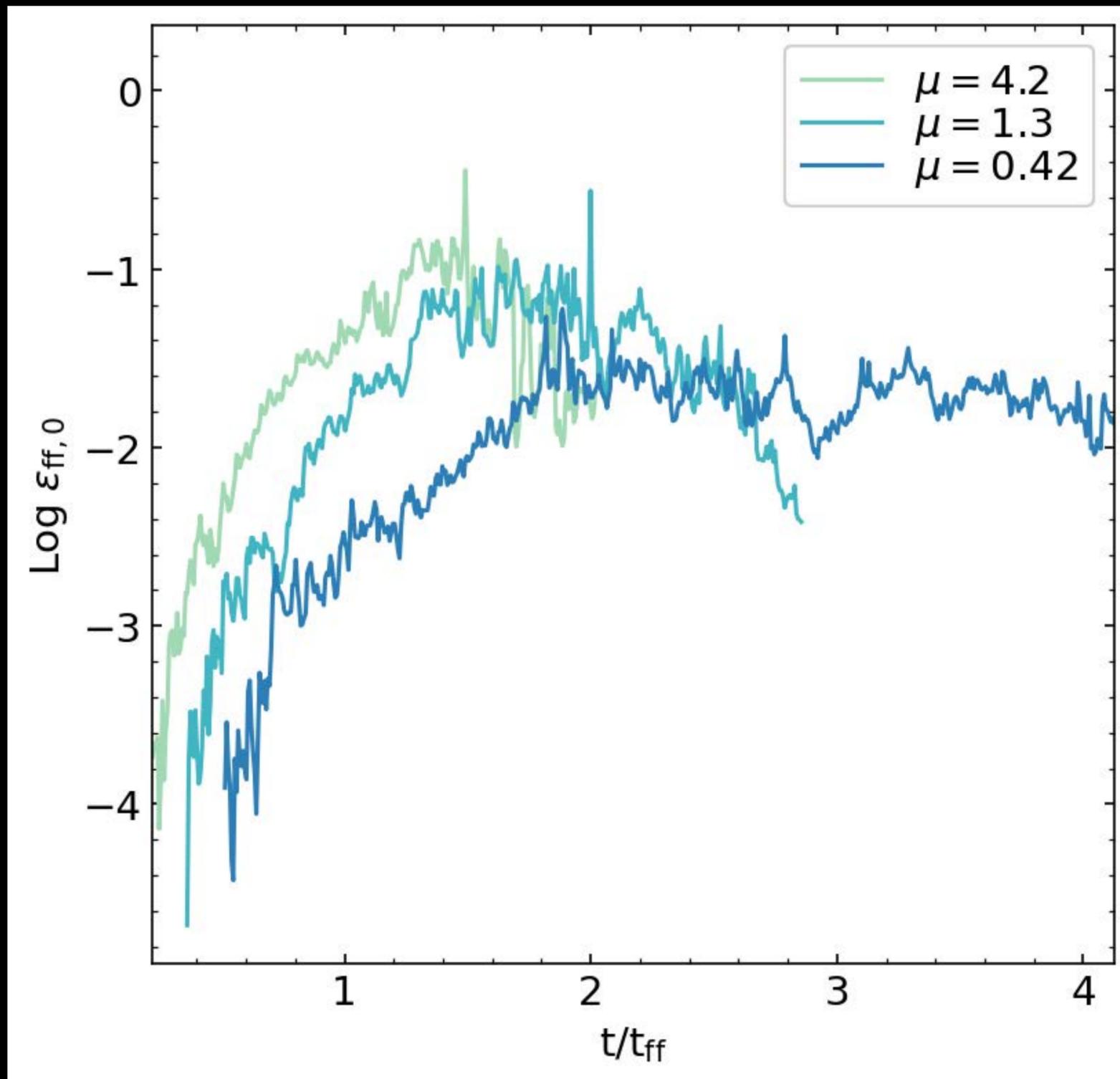


Magnetic field vs. density

B at high densities insensitive to low-density field strength - asymptotes to $v_A \sim c_s \sim 0.2 \text{ km s}^{-1}$ - see also Wurster+19, Guszejnov+20



Effect of magnetic fields on SFE

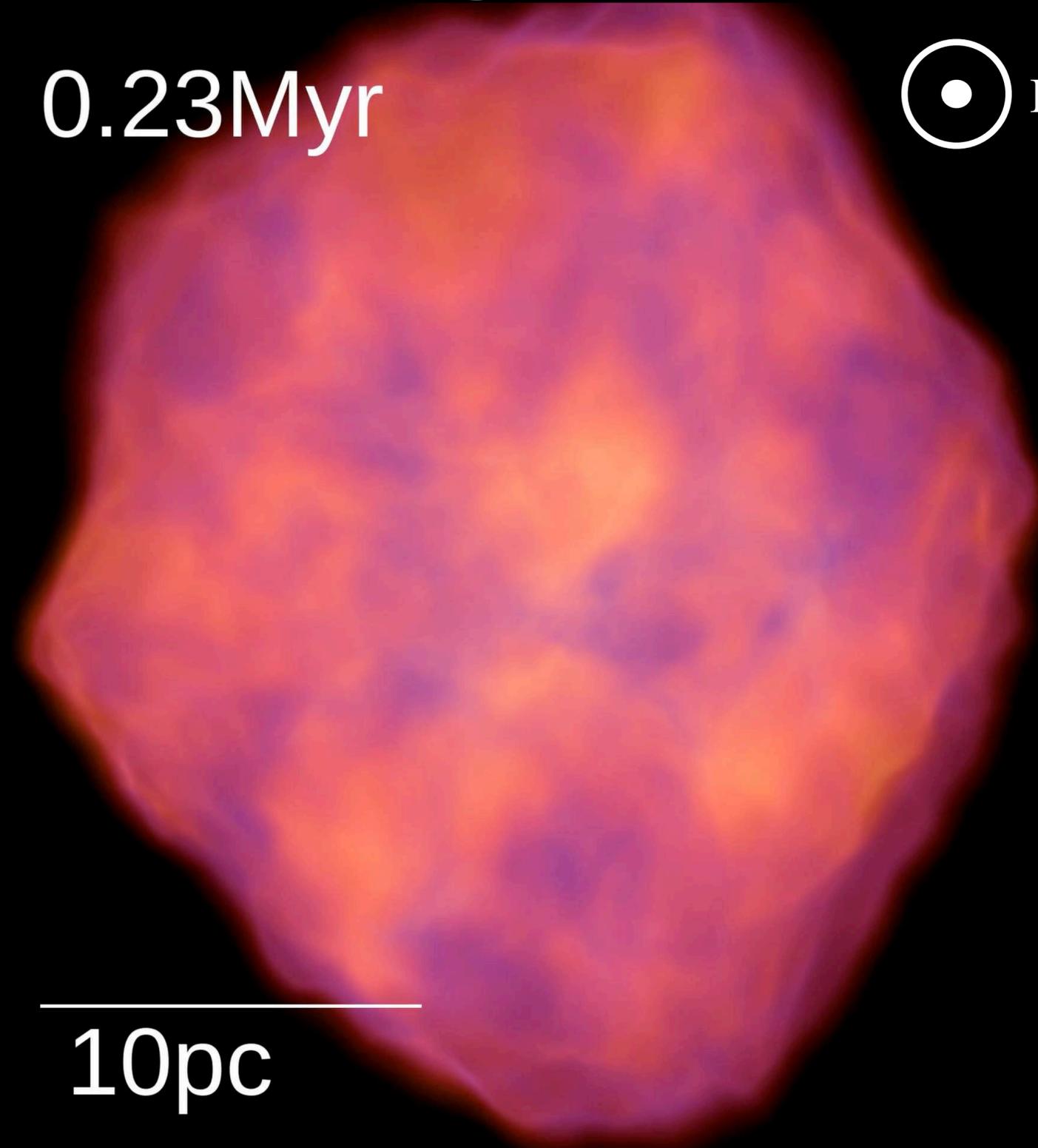


Many effects likely at work:

- Confinement of HII regions suppressing blowout? (e.g. Krumholz 2007)
- Anisotropic accretion → less massive SF → less feedback (e.g. Lee 2014)
- Suppression of fragmentation → slower SF → feedback less apt to “overshoot”

Star formation at high B ($20\mu\text{G}$; $\mu = 0.42$)

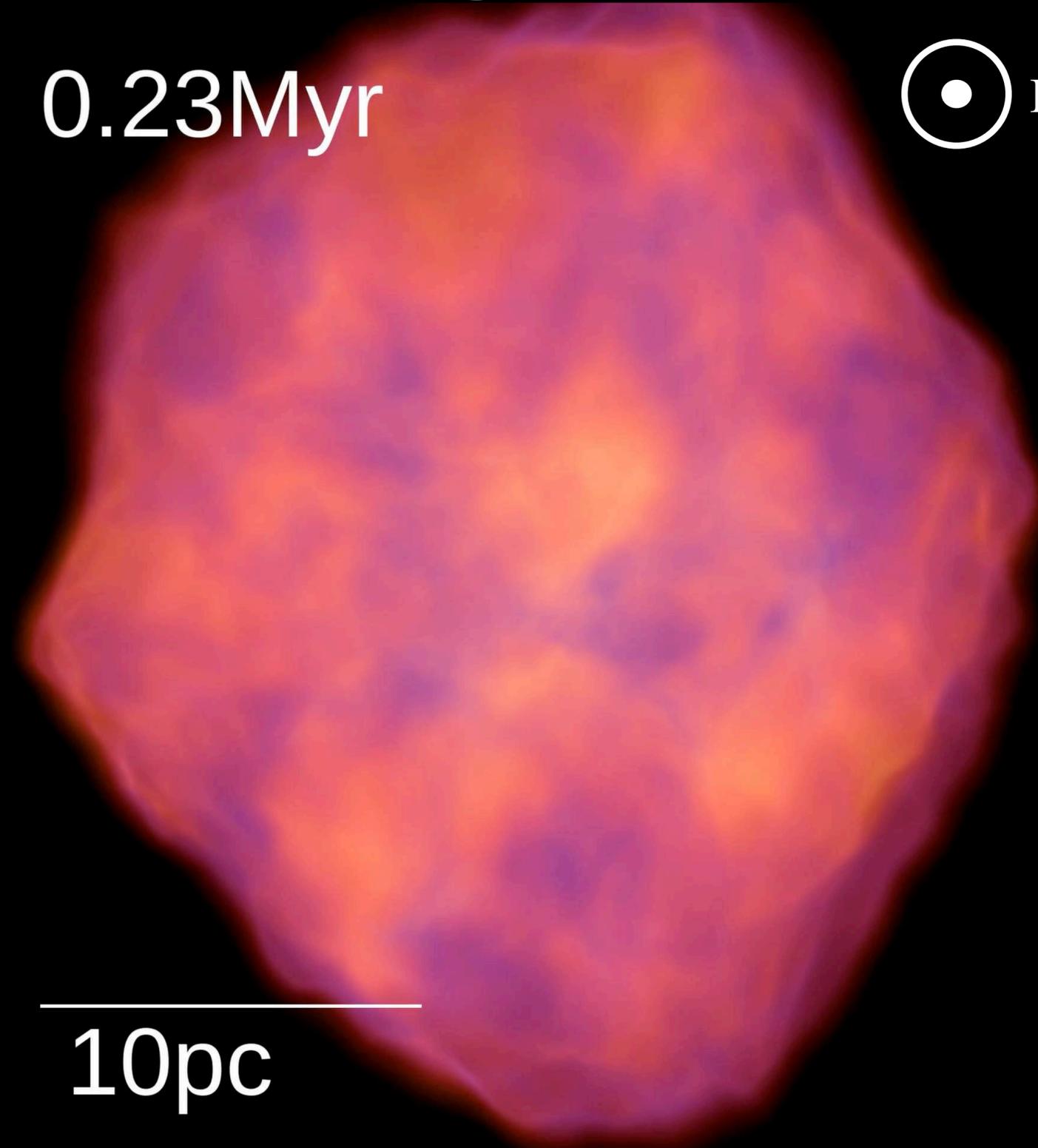
0.23Myr



10pc

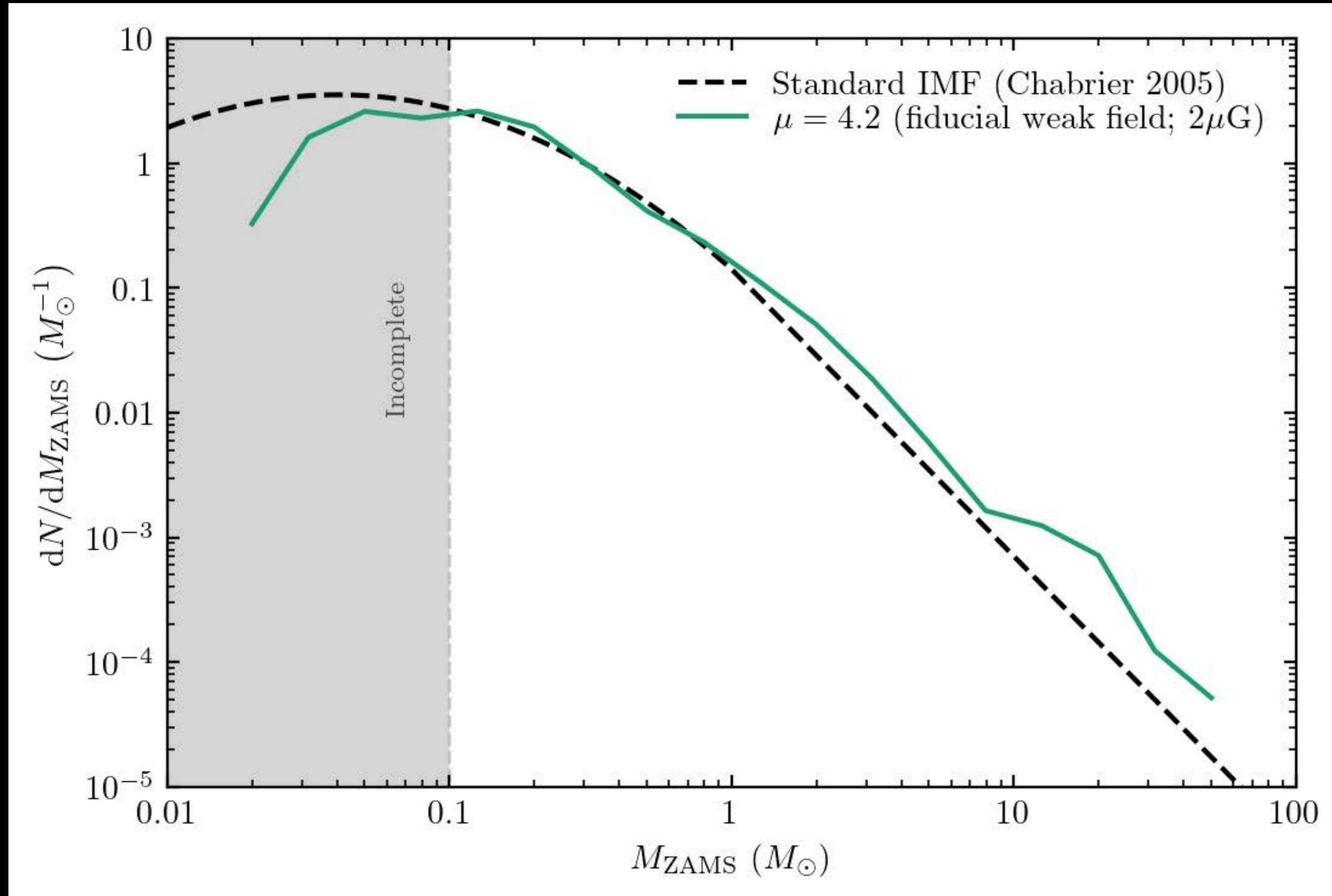
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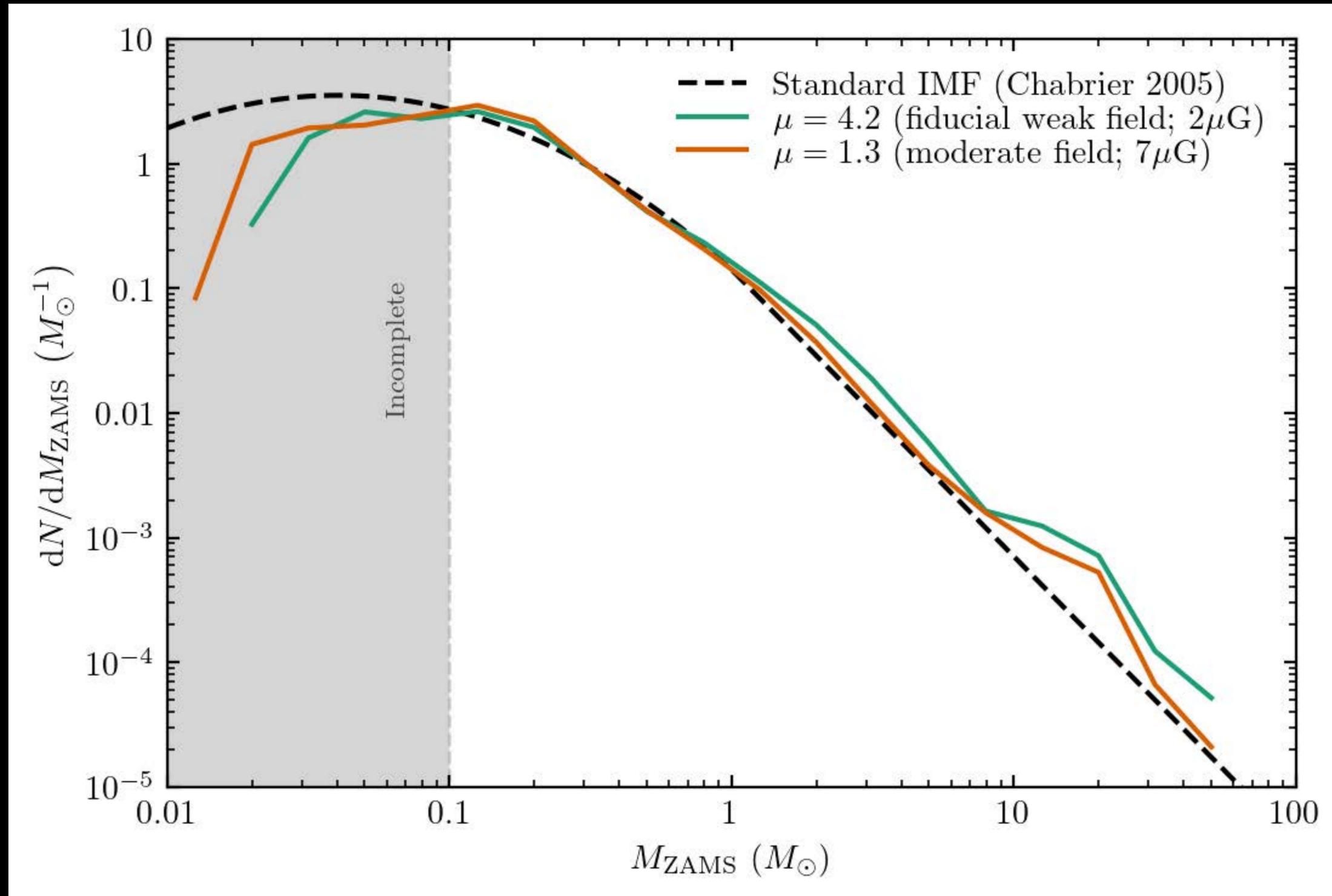


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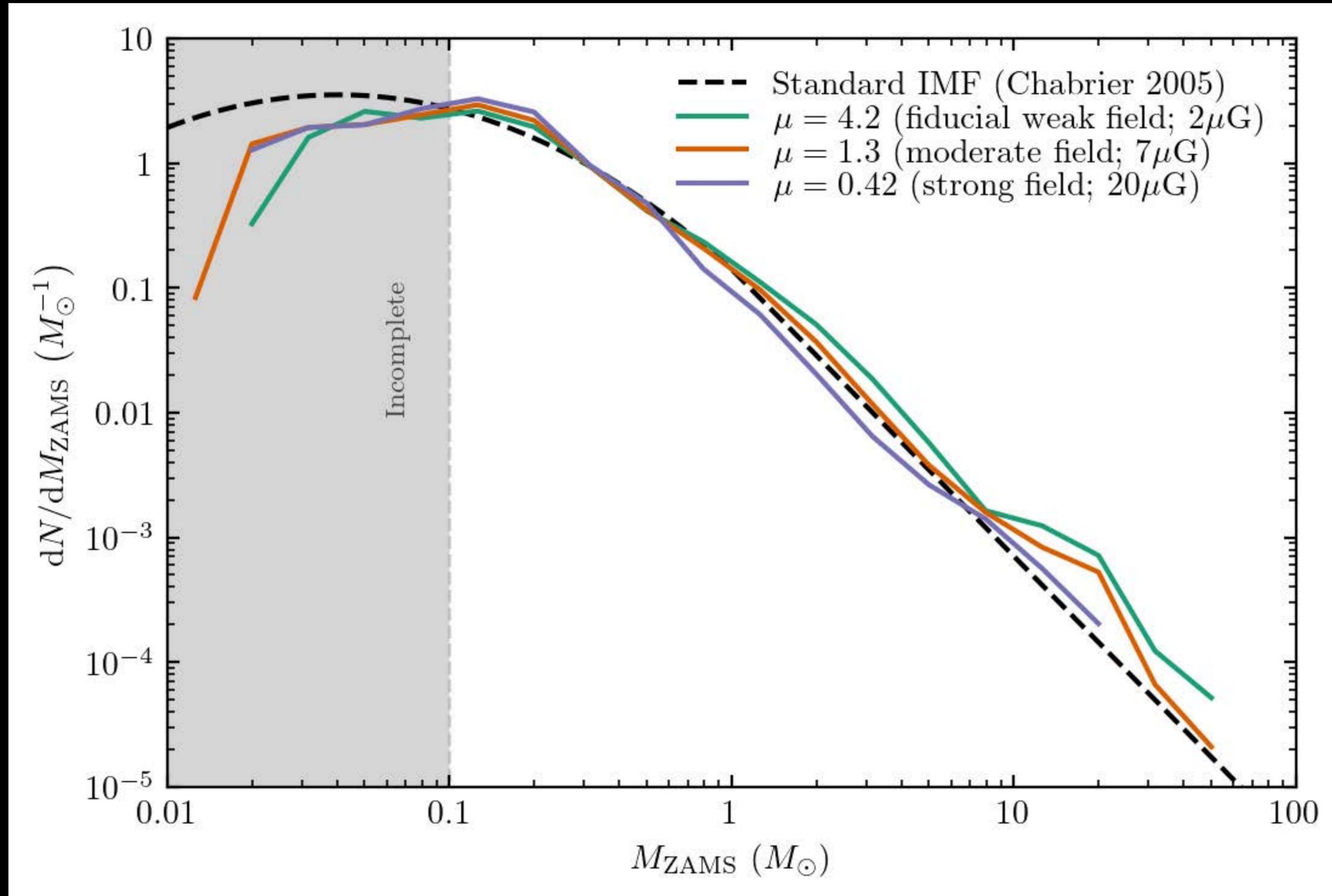
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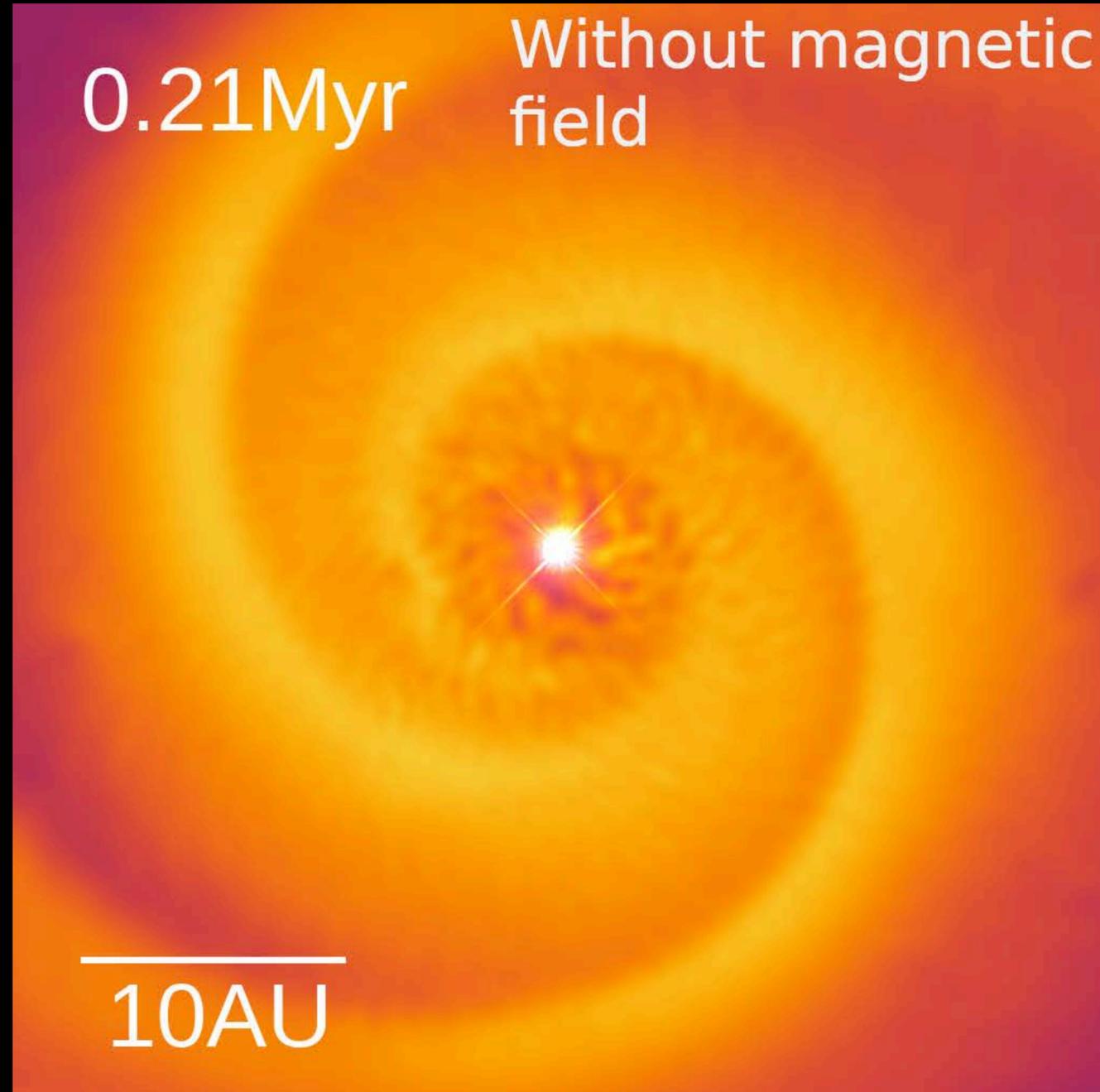


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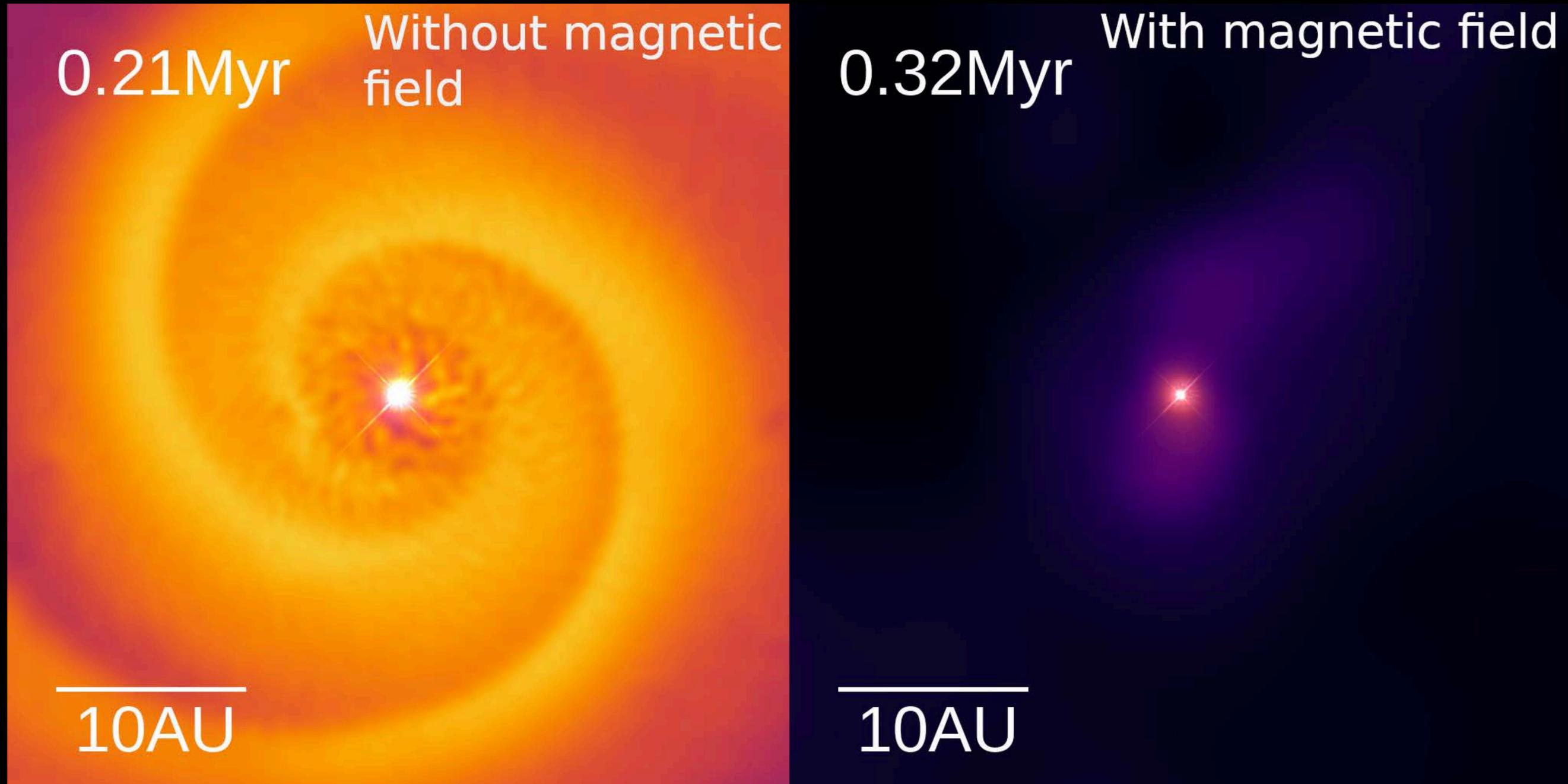
Where are the disks? 🤔

Very high-resolution ($10^{-5}M_{\text{sun}}$, $\sim 1\text{AU}$ resolution) MHD STARFORGE simulations that *should* resolve disks show a “braking catastrophe”

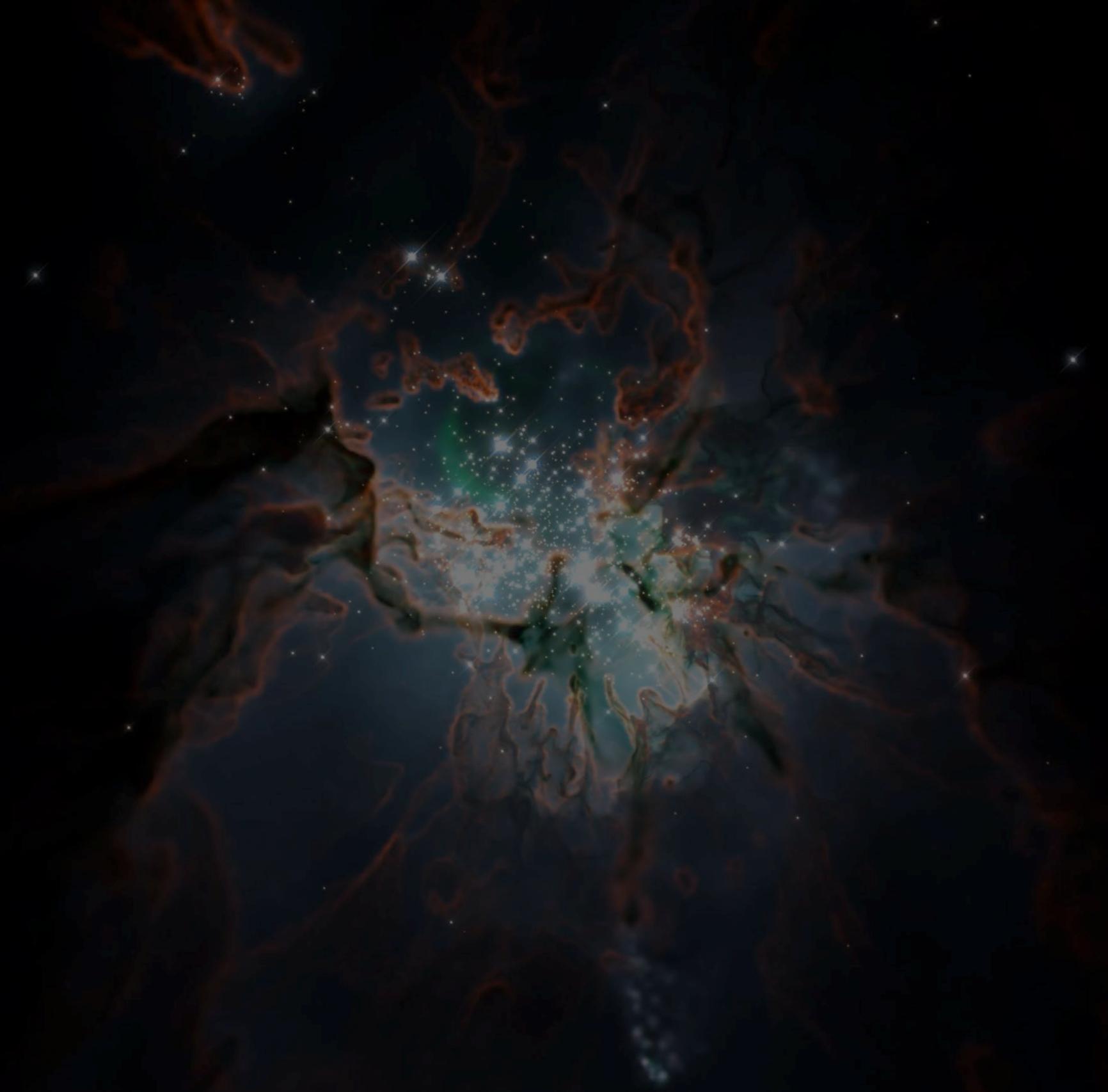


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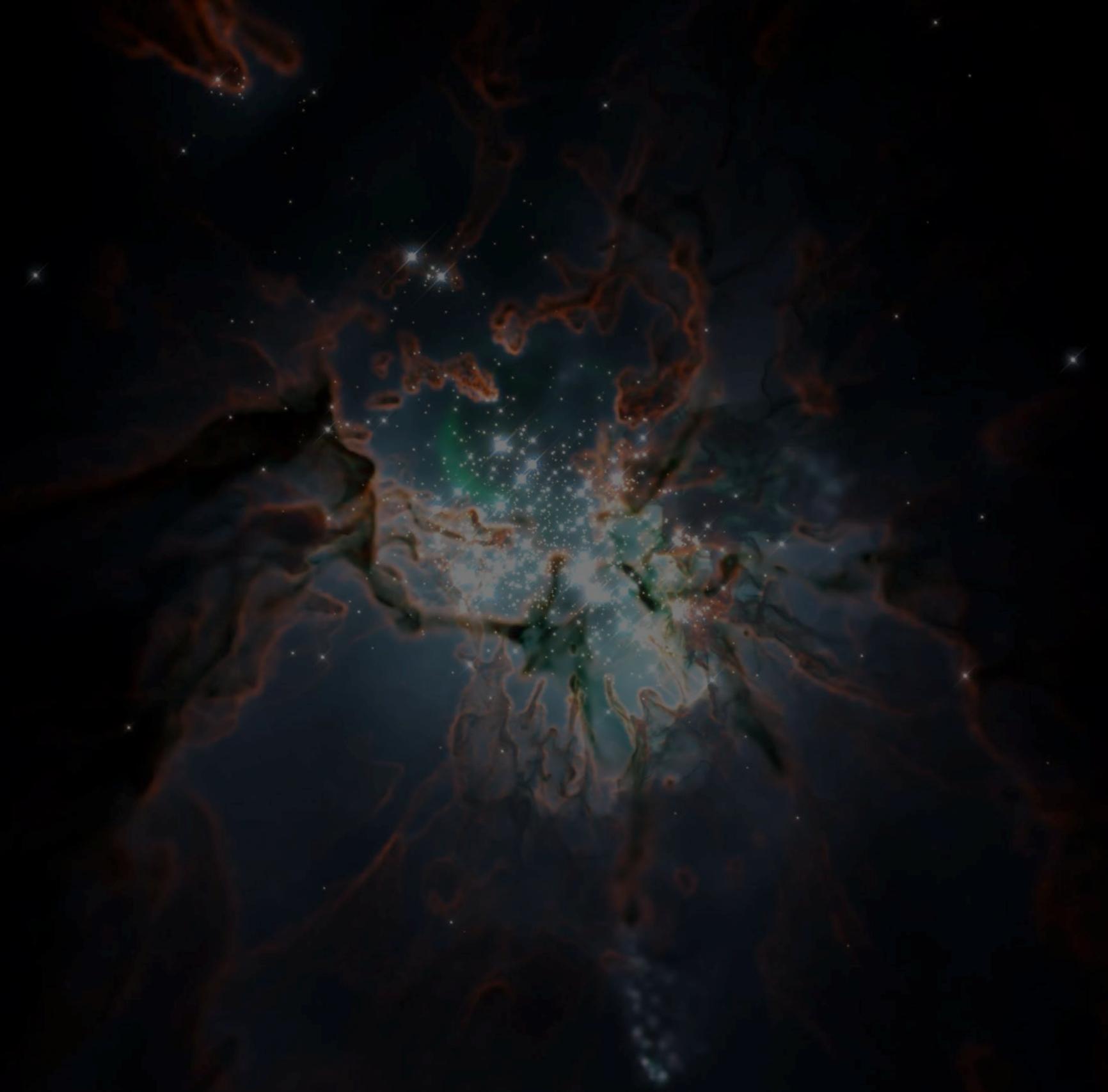
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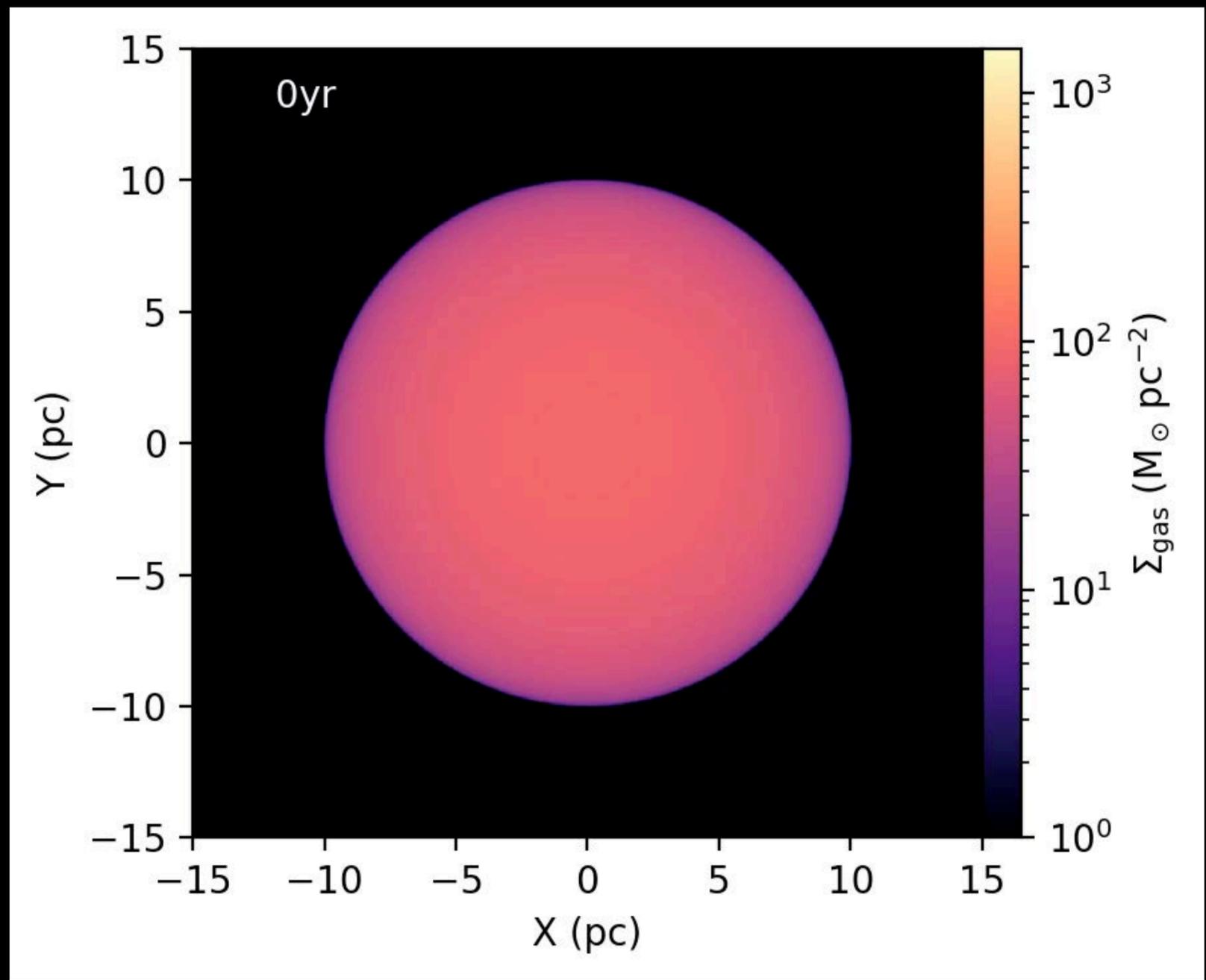
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GMC initial conditions: can we do better?

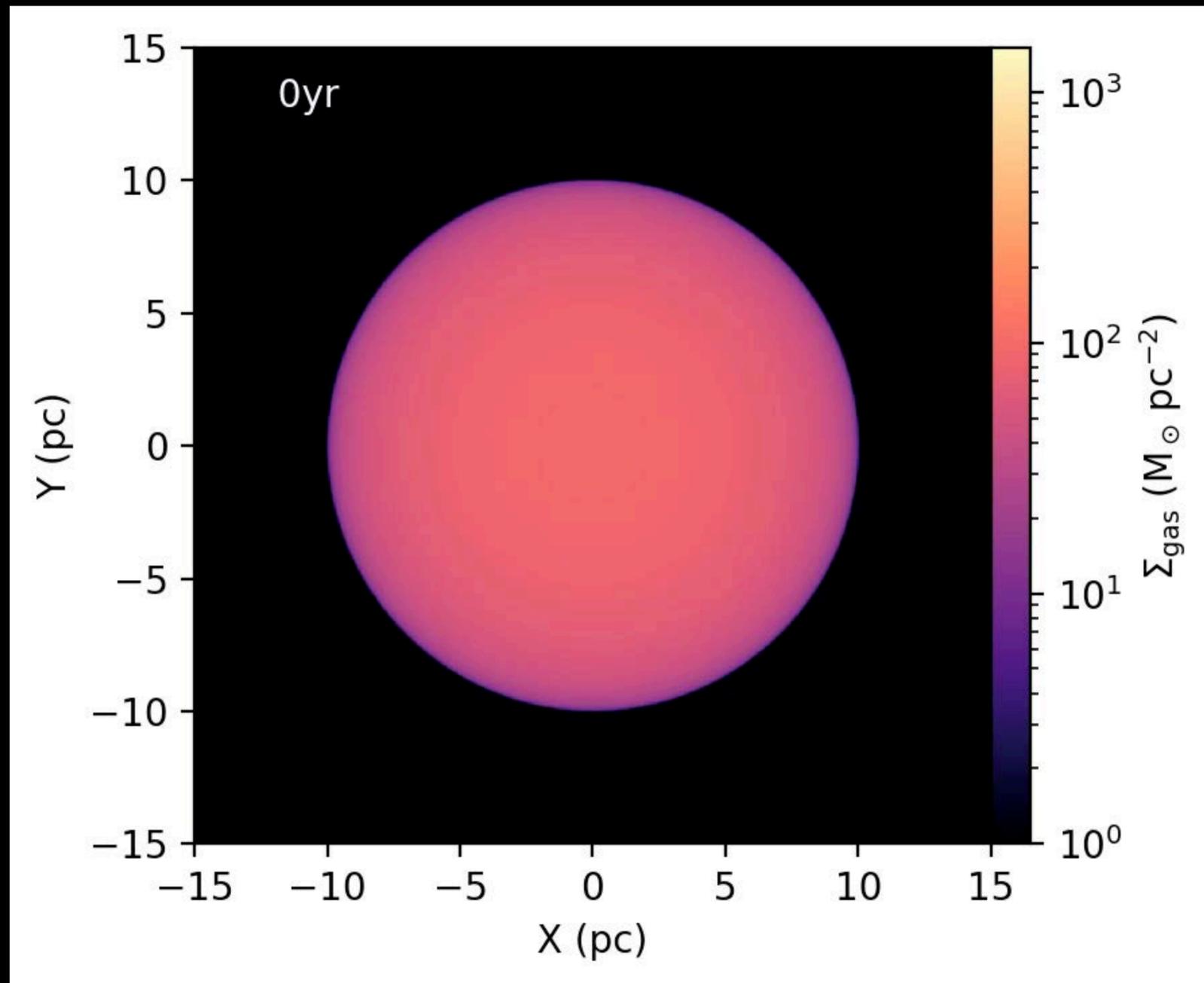
Lane, Grudić, et al. 2022 MNRAS. 510. 4767L



Henry Lane
Pennsbury High School, PA
↓
Caltech

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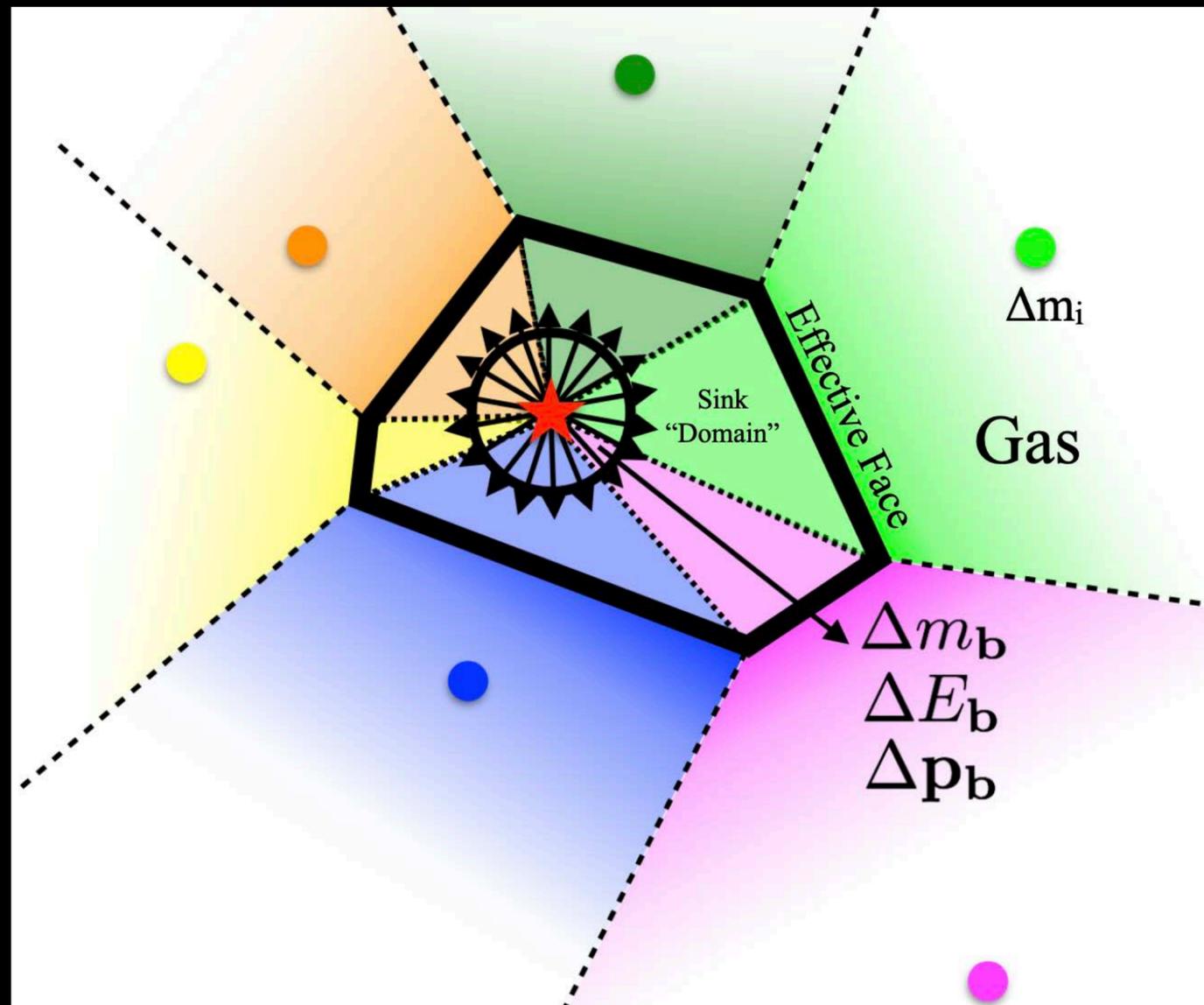


Caltech

Feedback Coupling Methods

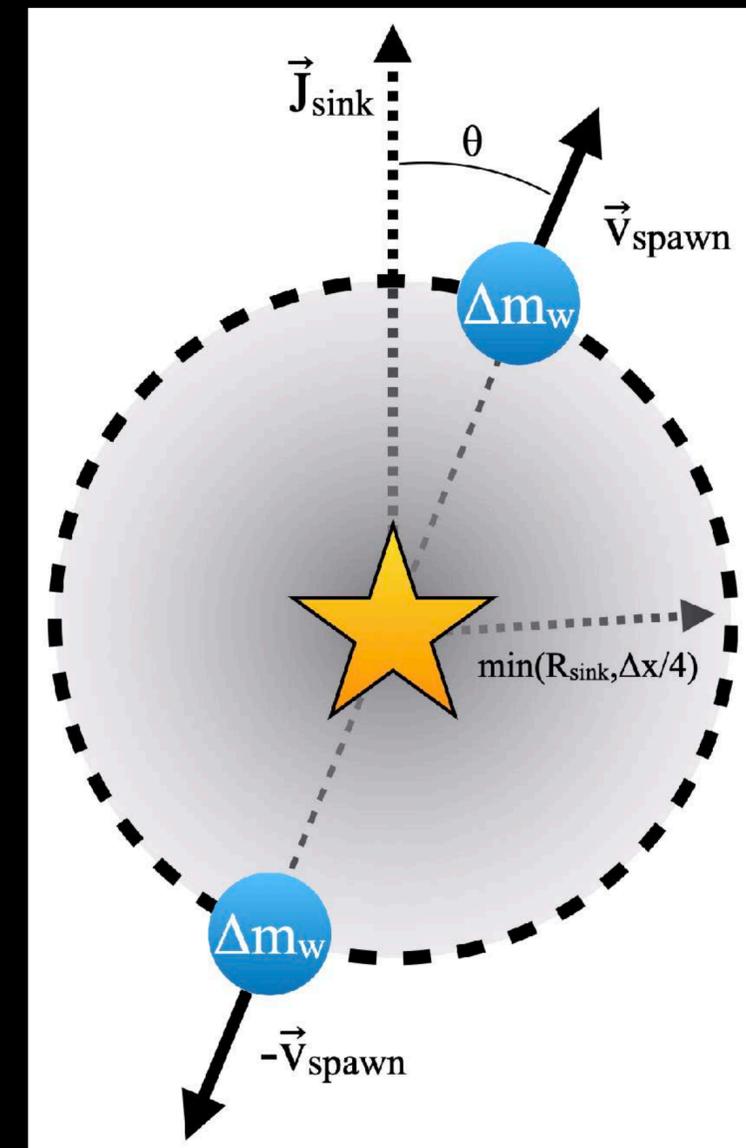
1. Local injection

Inject mass/momentum/energy into pre-existing cells conservatively



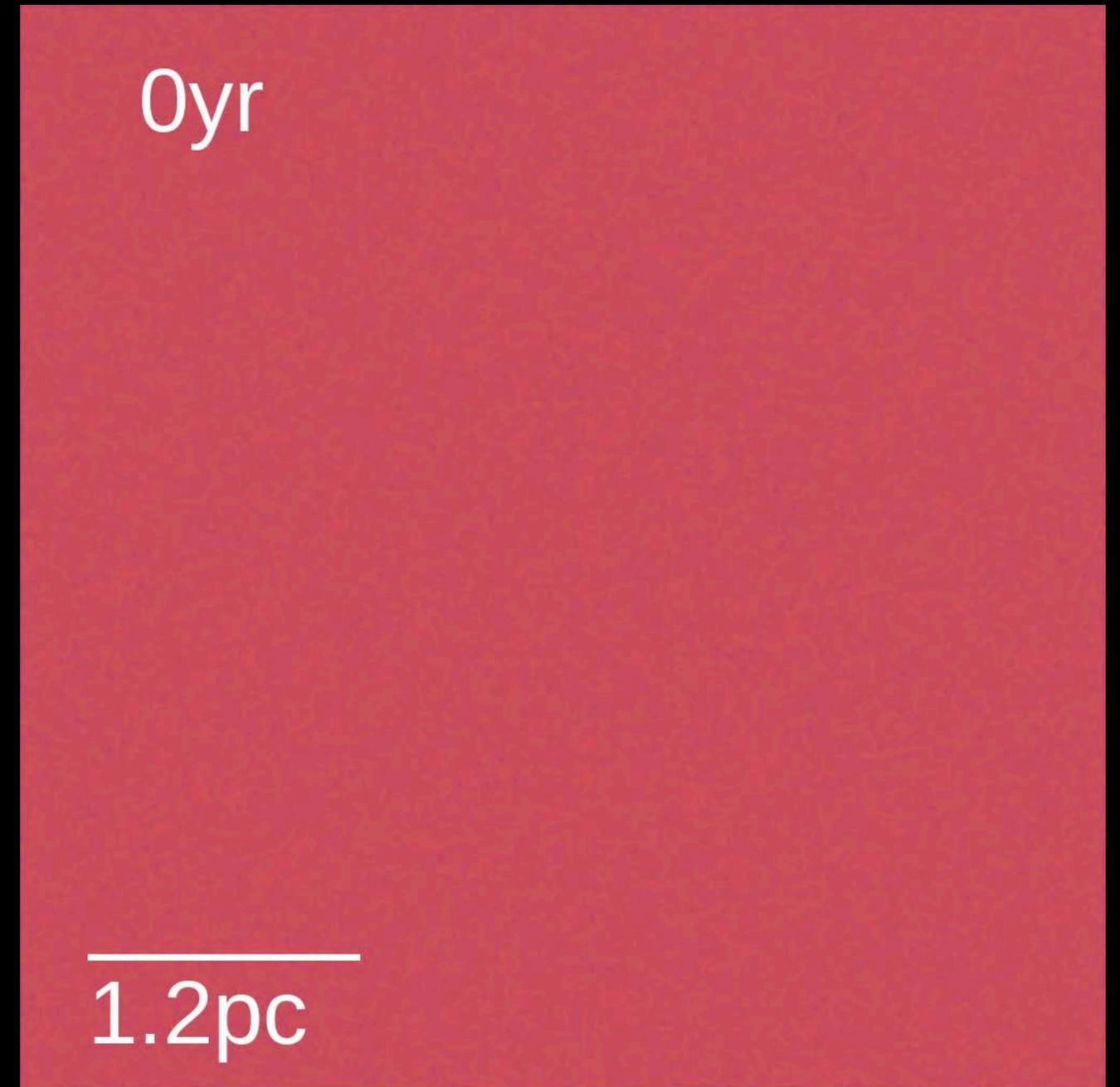
2. Cell spawning

Create new Lagrangian gas cells, still conserving COM/momentum to machine precision



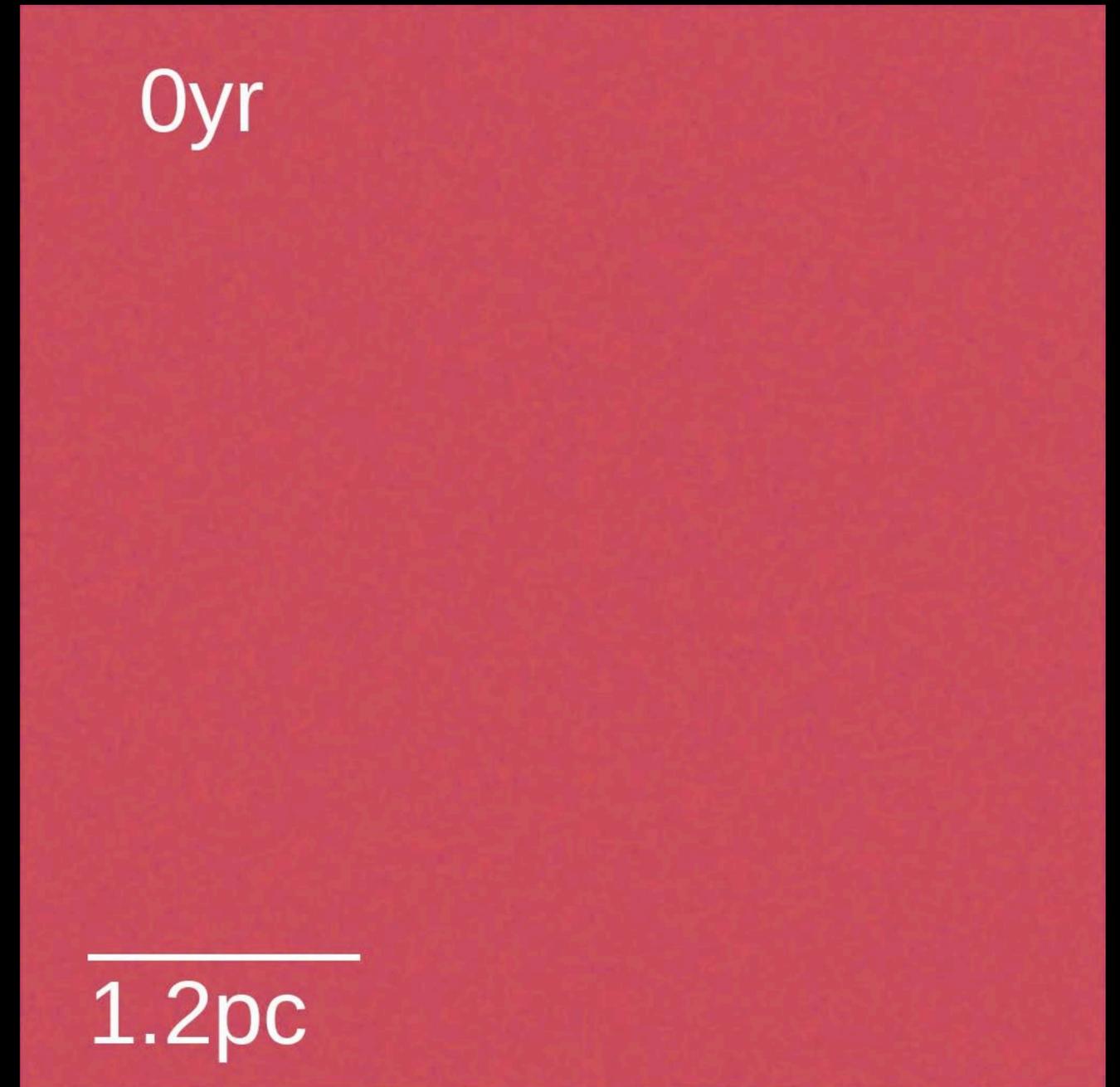
Meshless Lagrangian MHD with GIZMO

Mach 9 Supersonic MHD Turbulence



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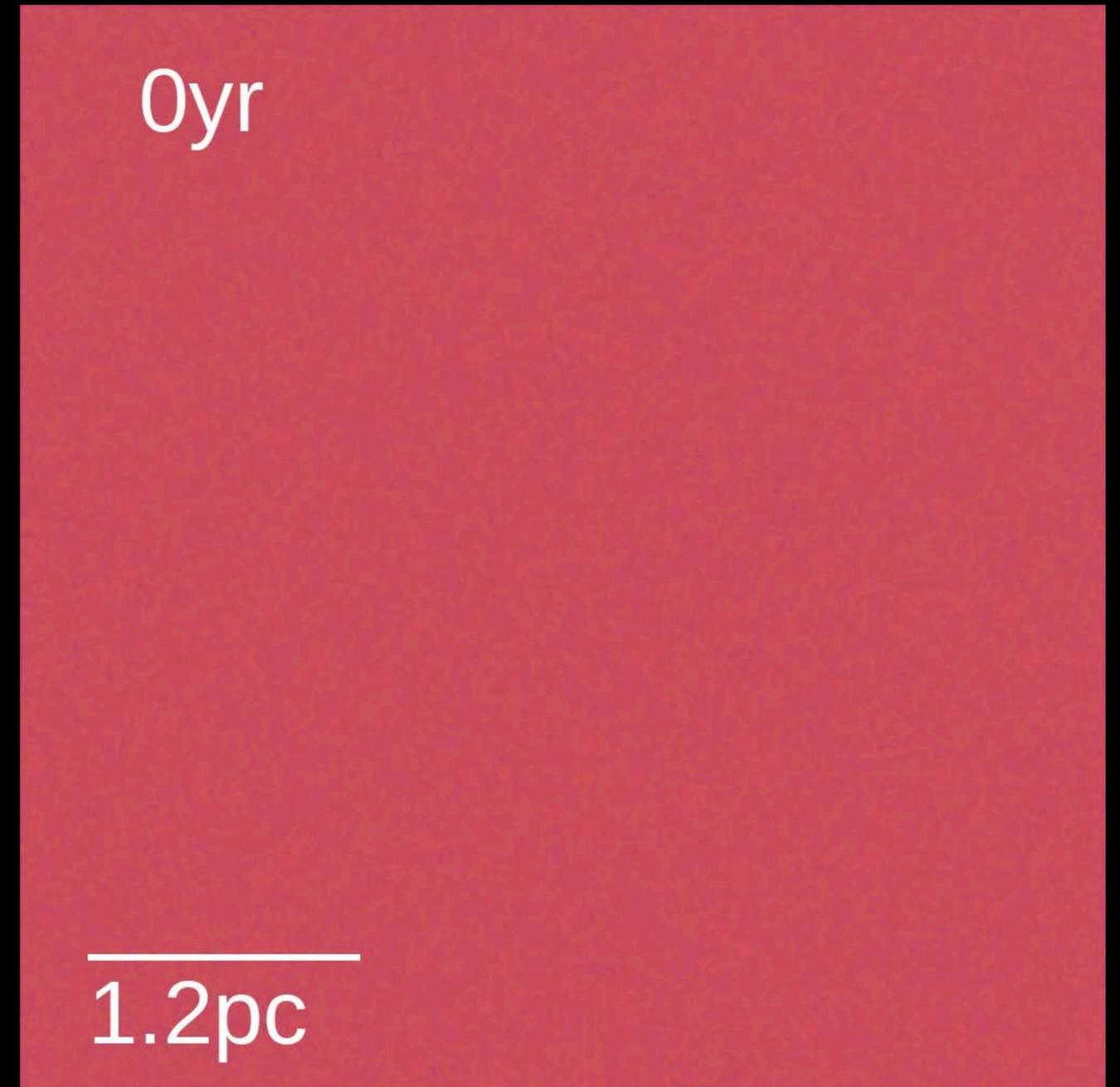
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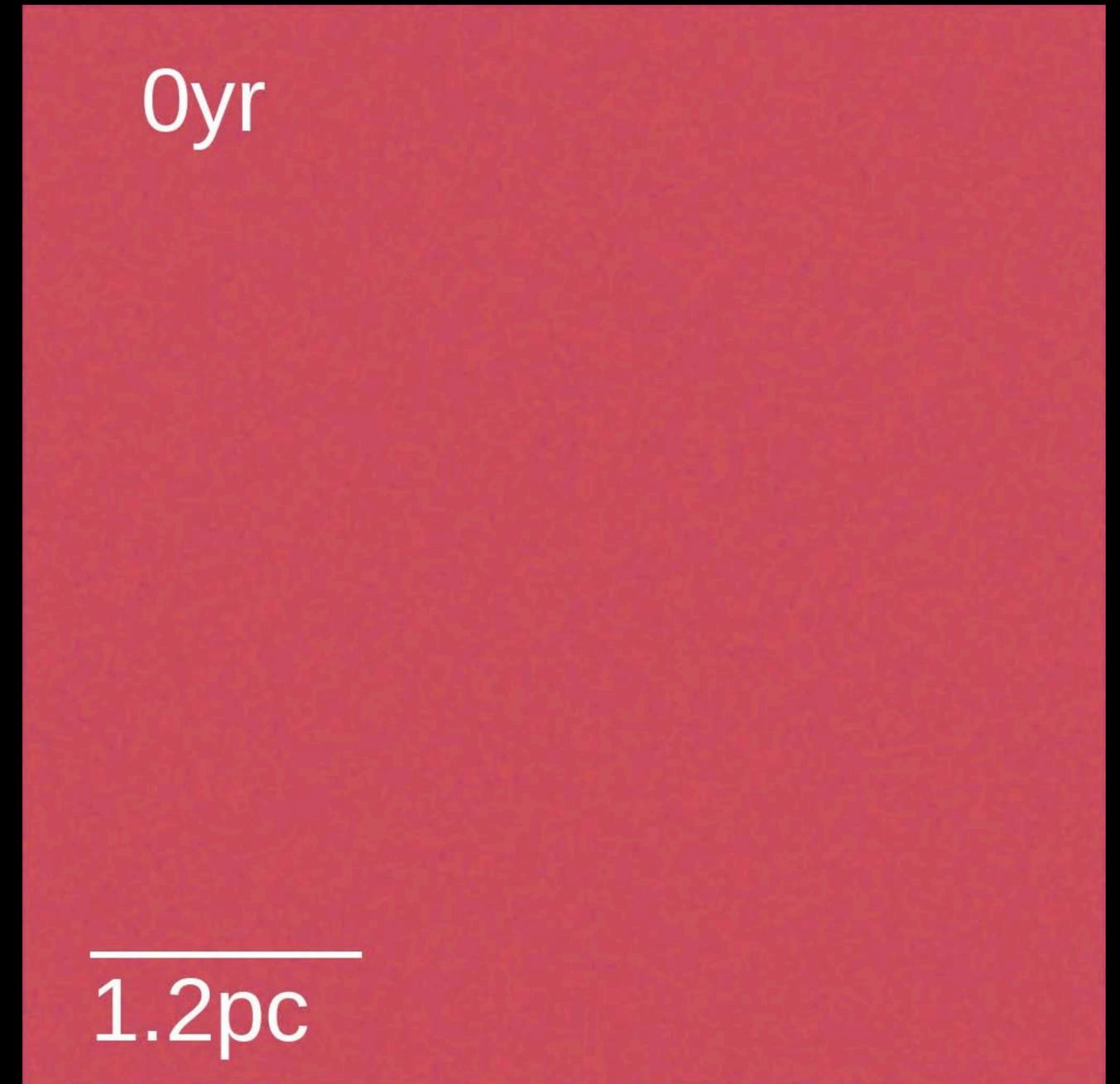


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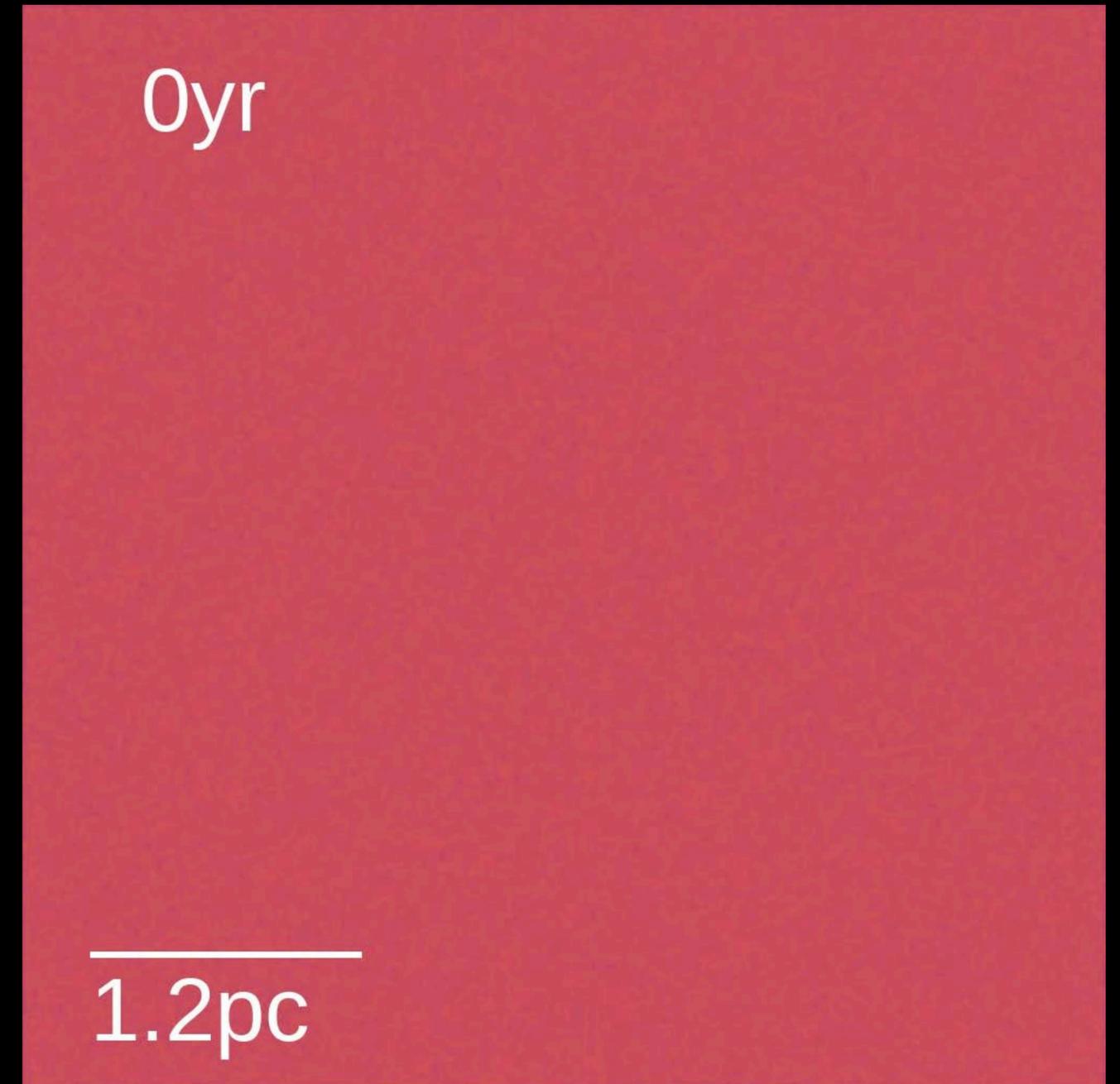


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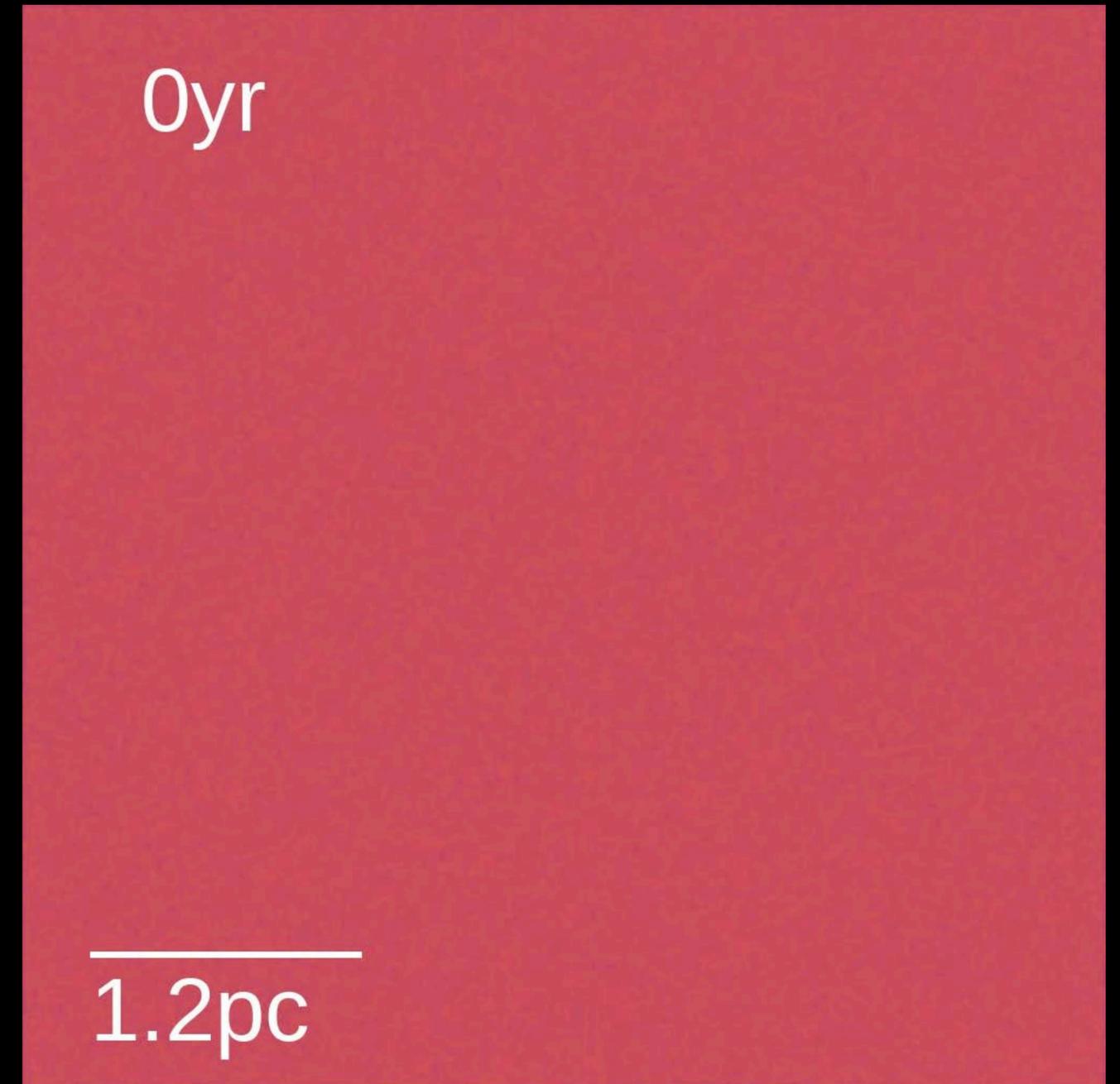


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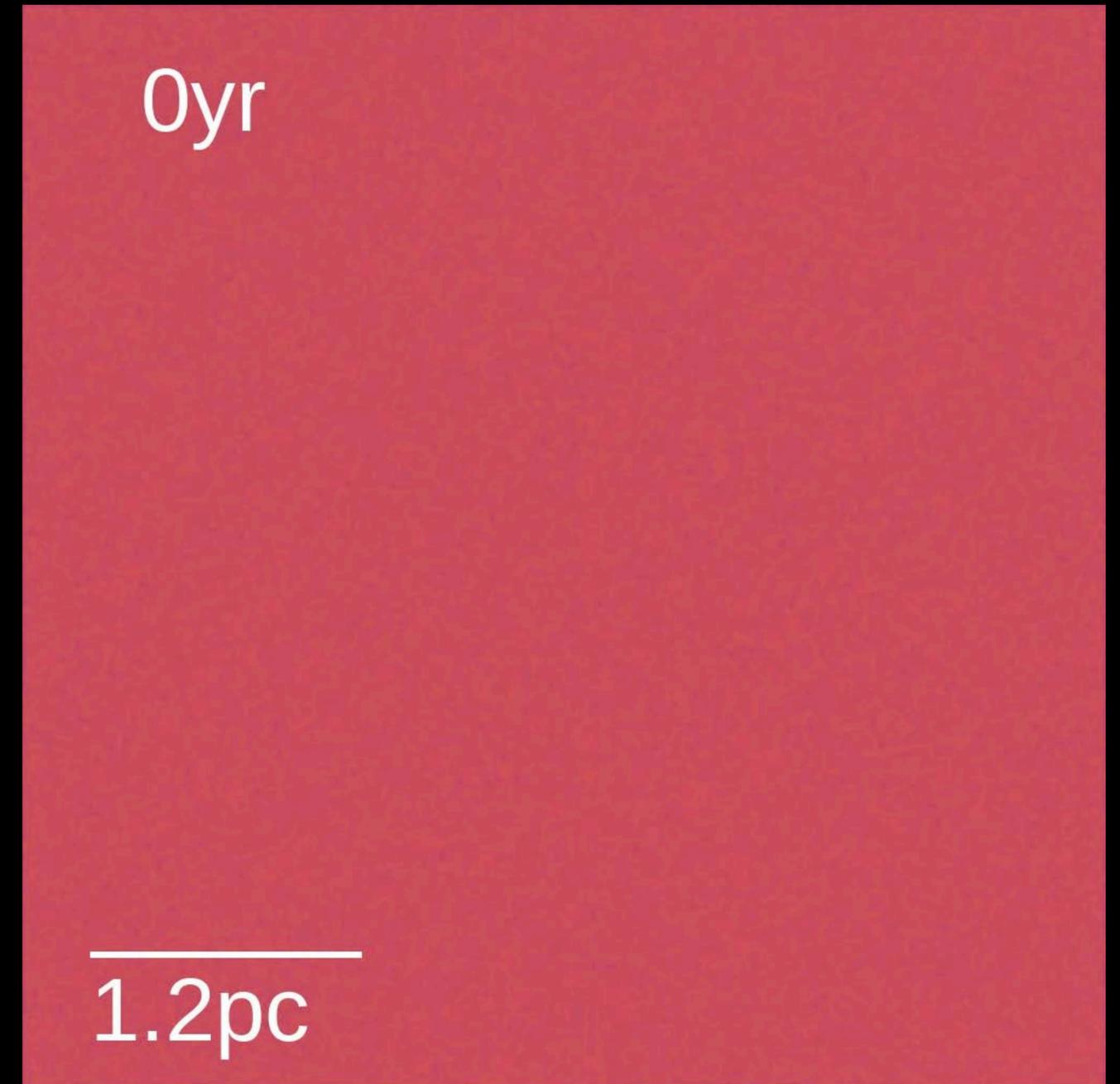


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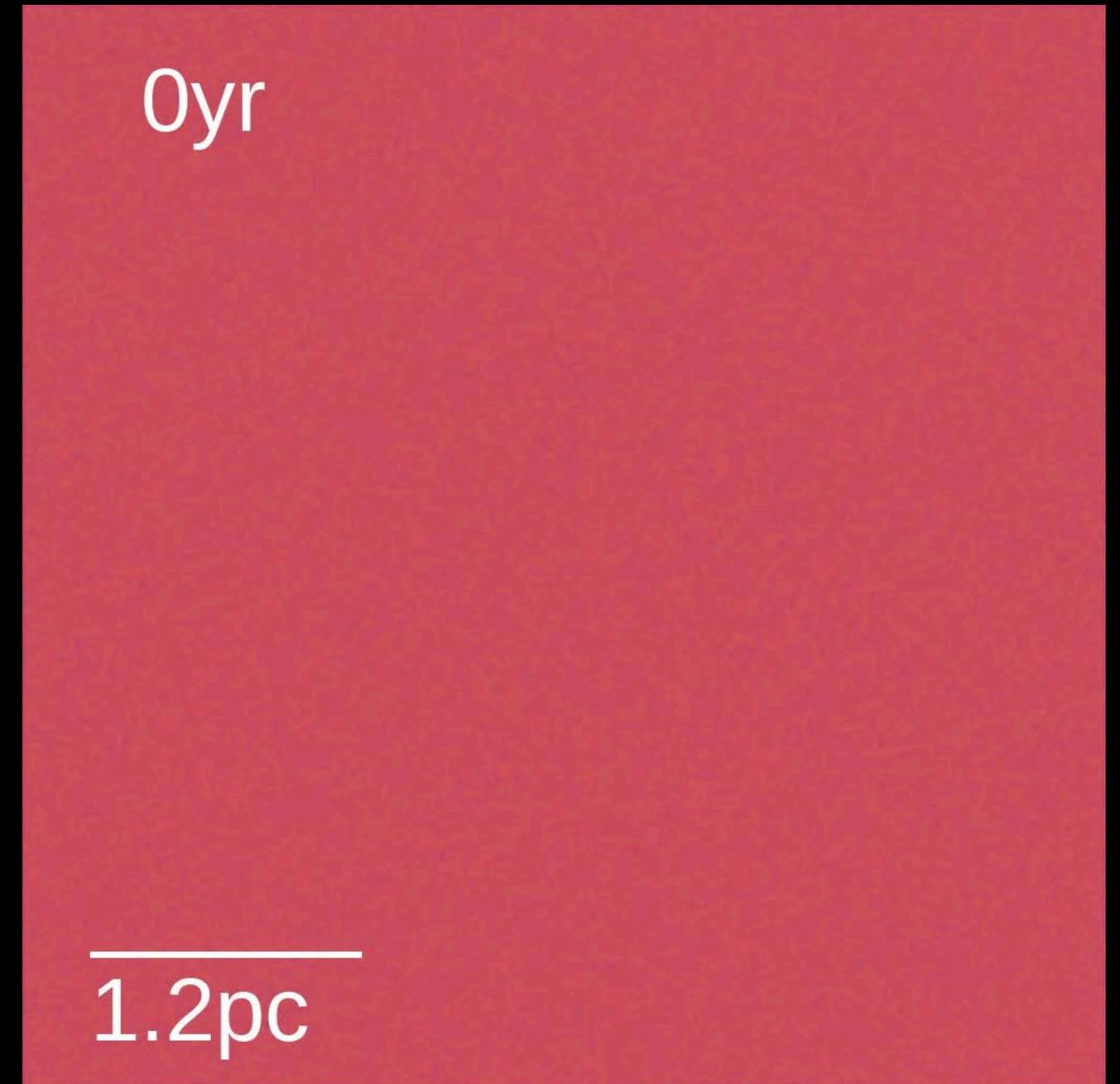


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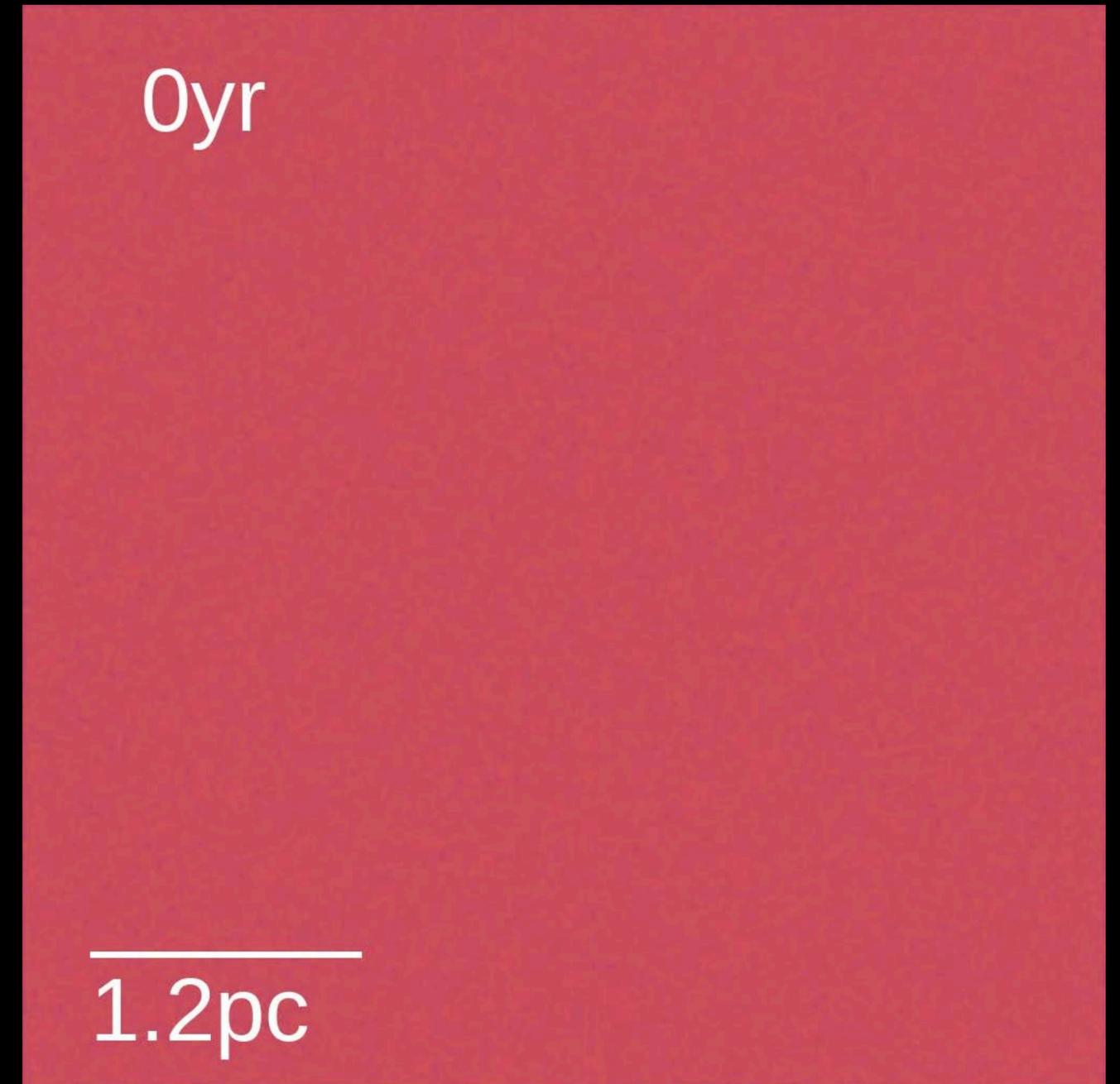


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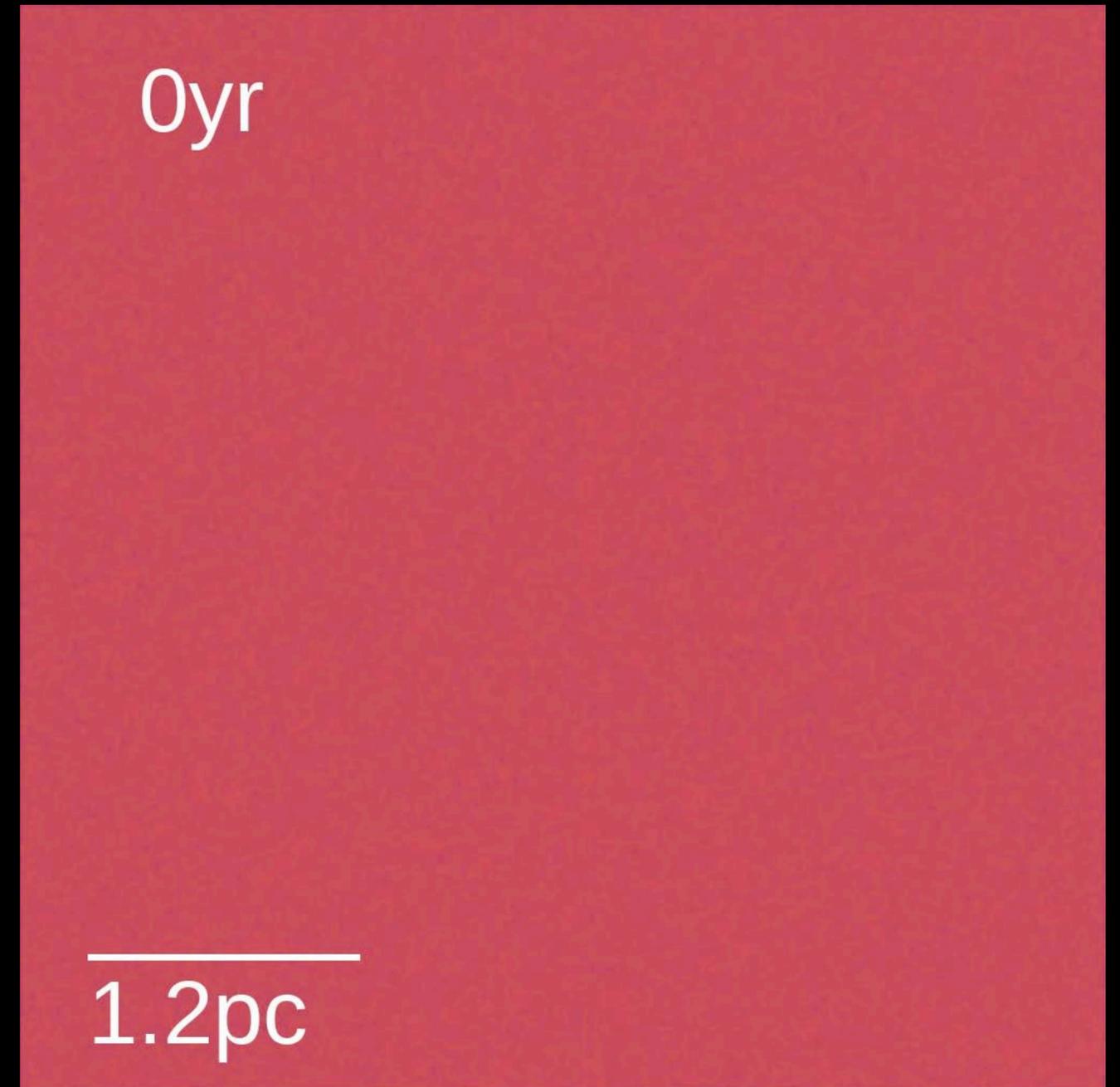


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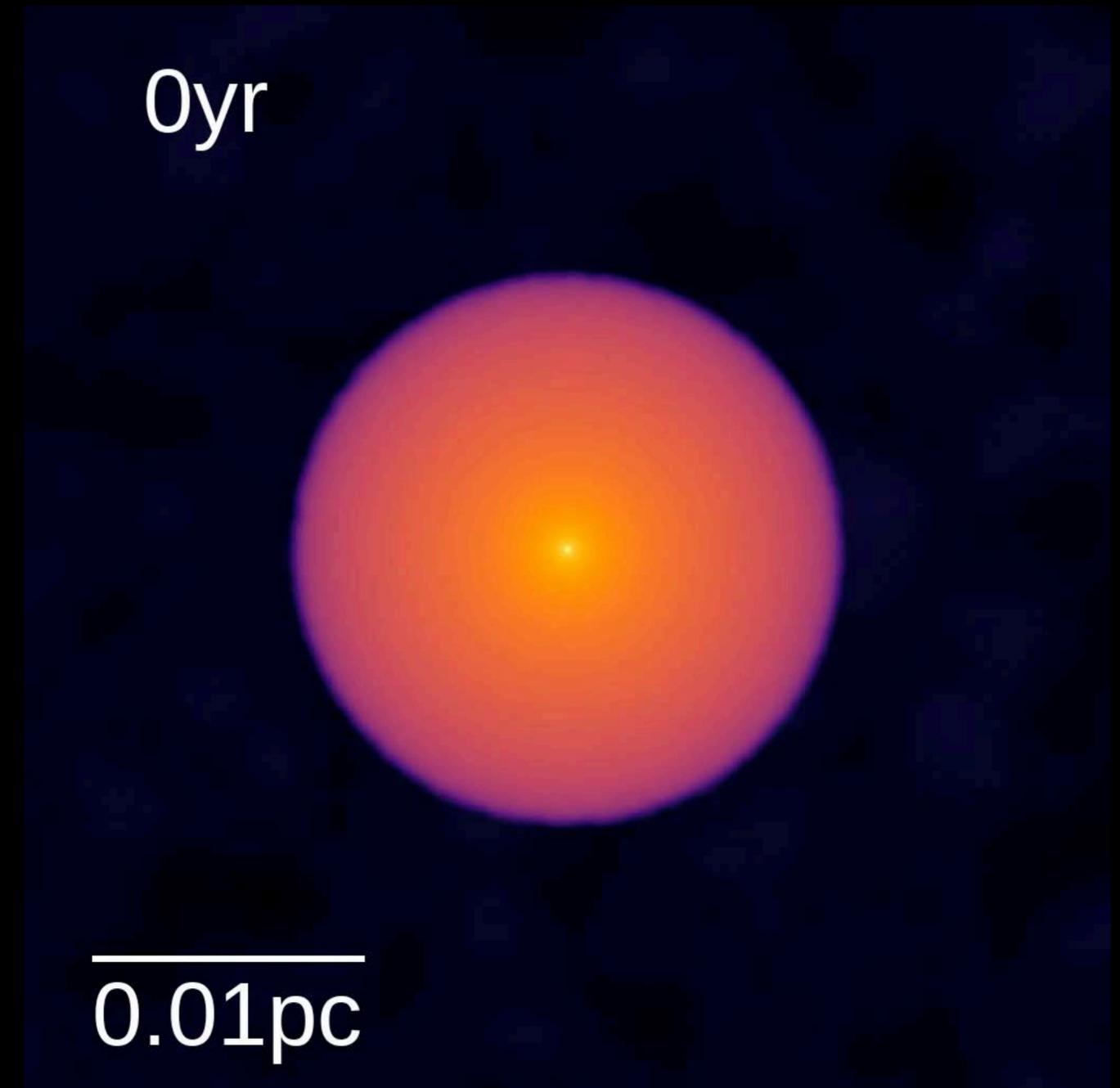
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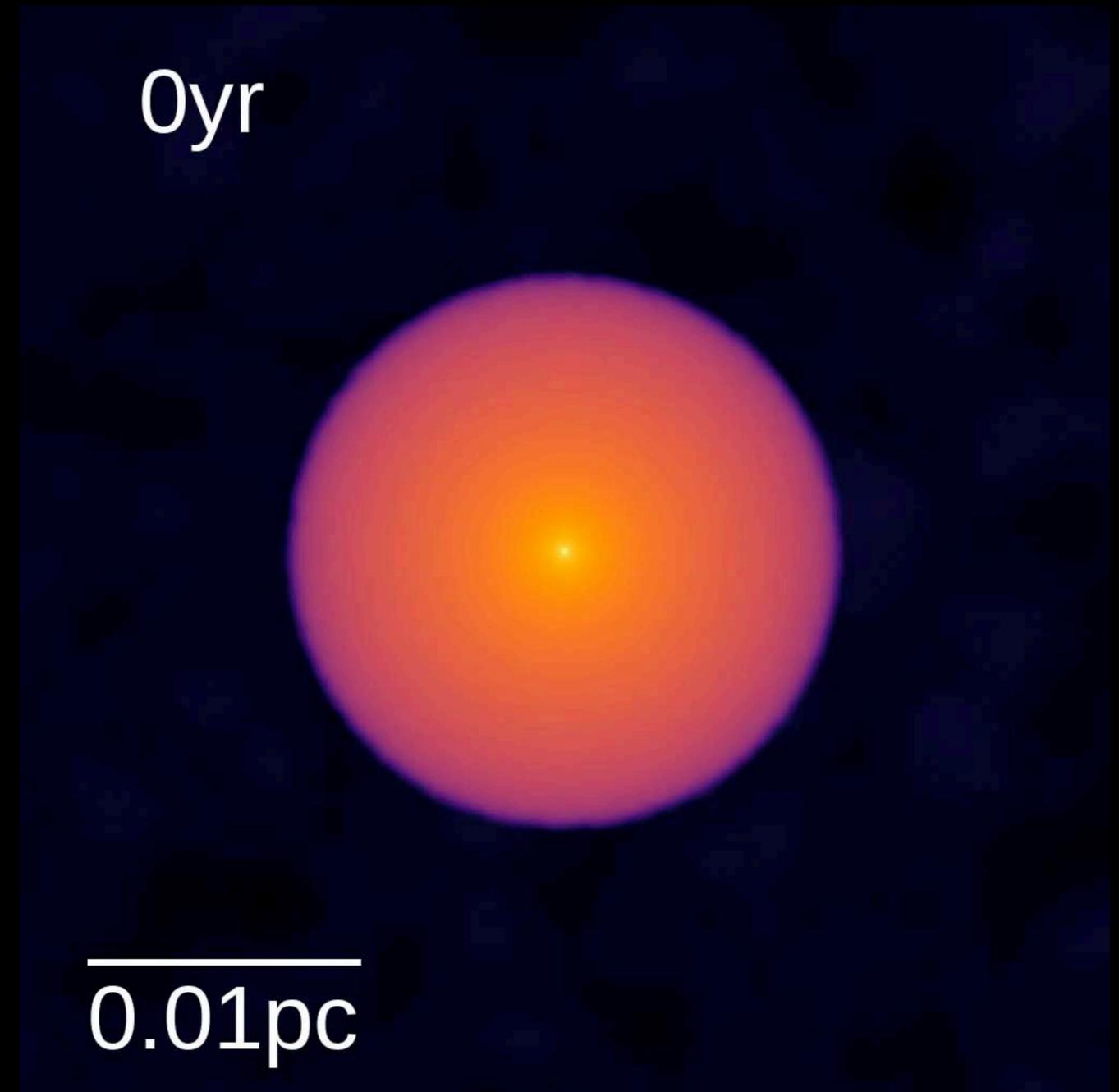
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- Jet launching powered by accretion onto the disk/protostar
- Very important for regulating stellar accretion, the IMF, SFE on <1pc scales (e.g. Rosen & Krumholz 2020, Guszejnov+2021MNRAS.502.3646G,)
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0.98kyr

Radiative transfer in 5 bands:

- LyC (13.6eV)
- Photoelectric ($8\text{-}13.6\text{eV}$)
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10pc

Solved with *GIZMO*'s M1 RMHD solver (Hopkins & Grudić 2018, Hopkins et al. 2020)

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