Aluminum-26 Enrichment in the Surface of Protostellar Disks Due to Protostellar Cosmic Rays

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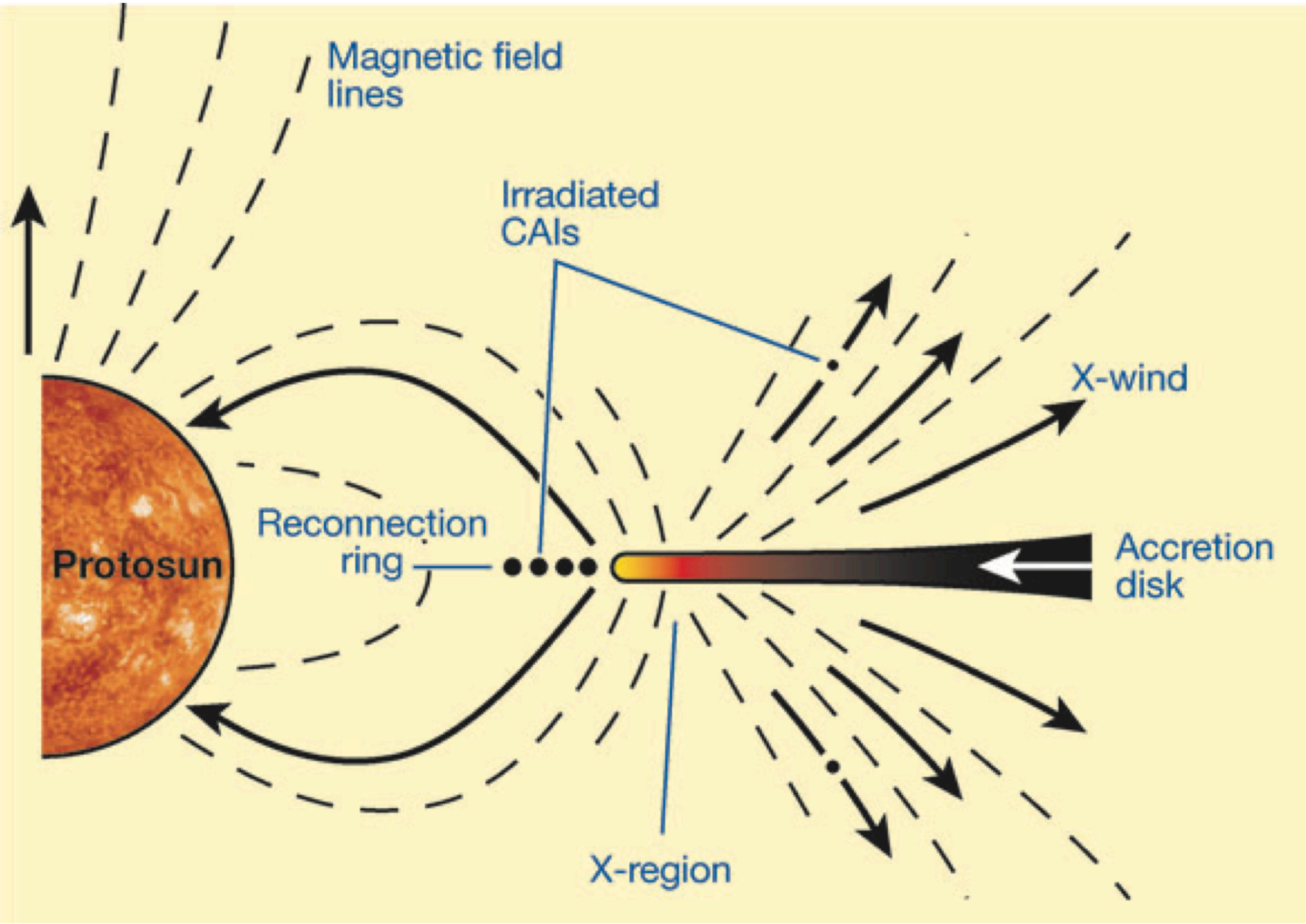
Observation: The early Solar System was enriched with short-lived radioactive nuclei (SLR), such as **Aluminium-26**, Iron-60, Beryllium-10, etc…

Question: Since they are short lived (order Myr), **how** and **where** was this enriched material produced, and **when** was it introduced into the early Solar System

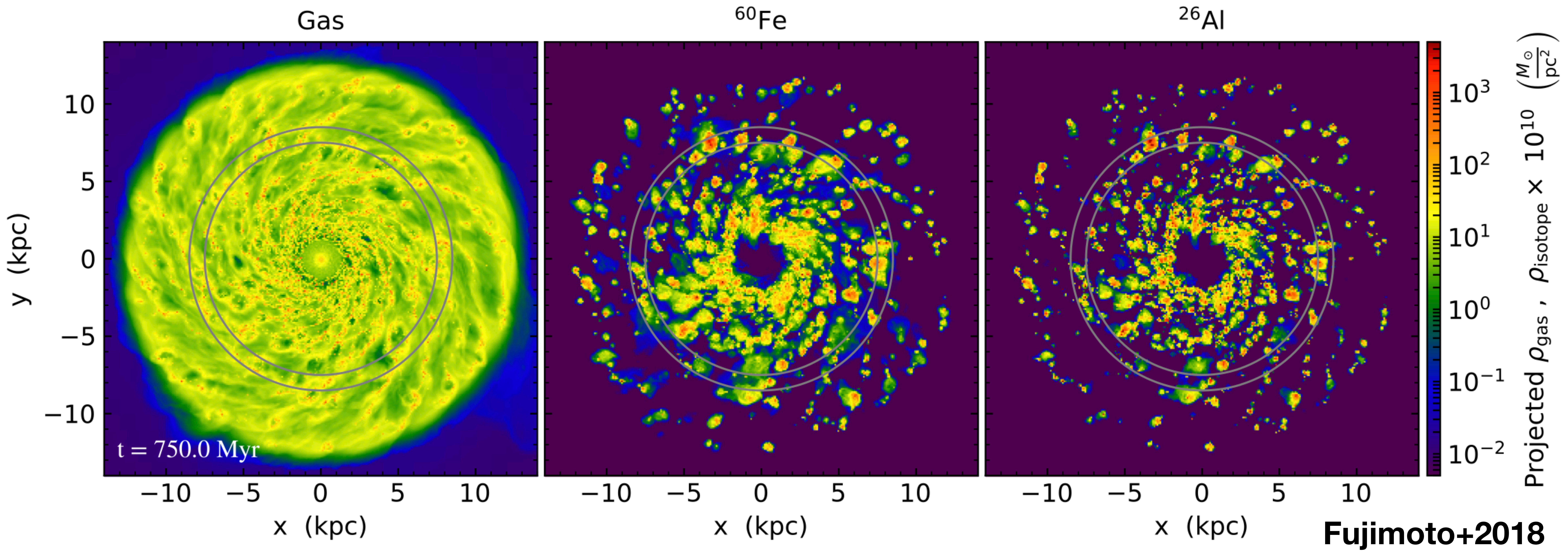
Aluminum-26 Enrichment - Internal



Scott 2007

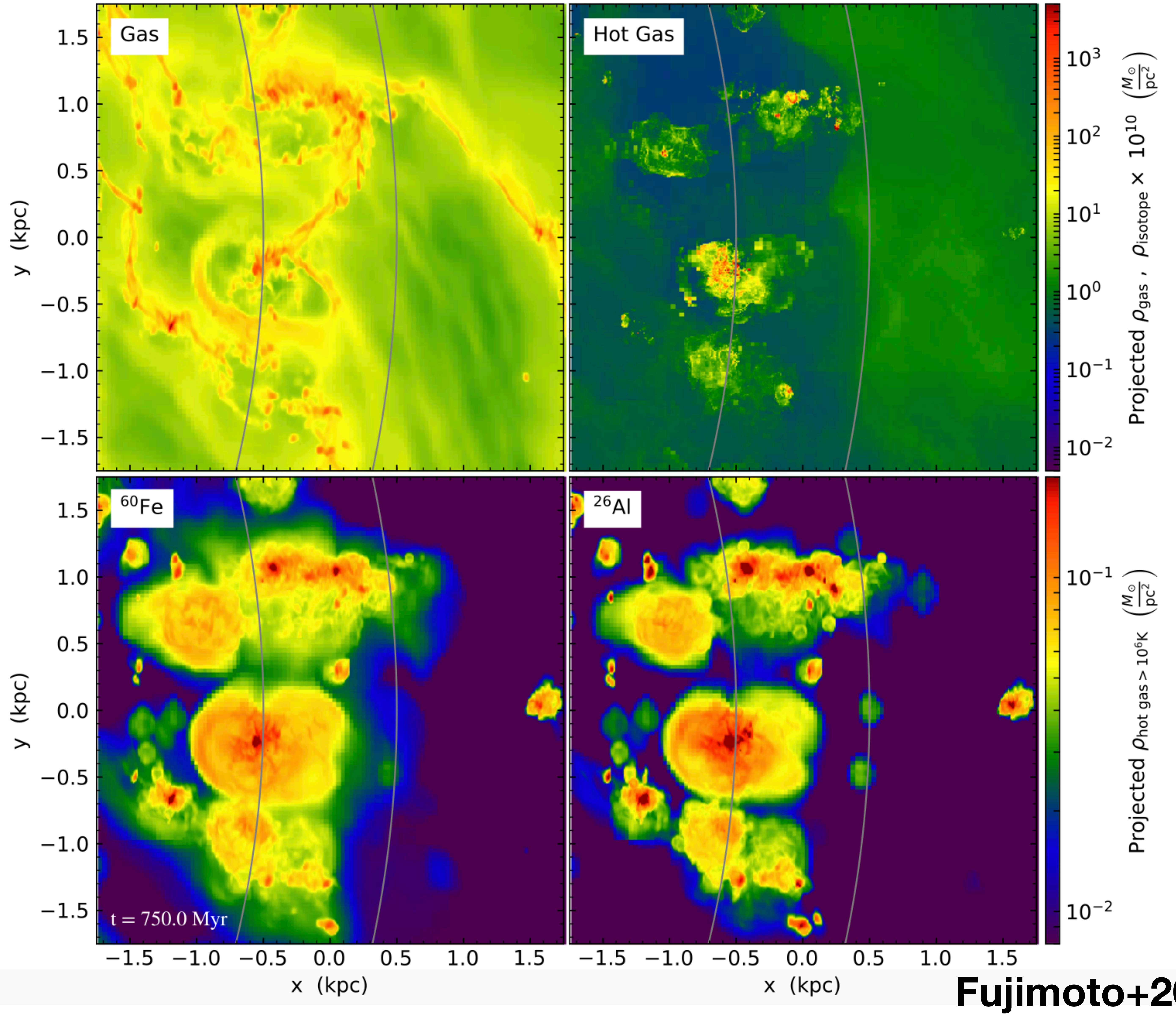
- Charged particle acceleration at magnetic field reconnection sites - Lee+1998, Gounelle+2001
  - Allows for a generic mechanism
  - Would impose heterogeneity in 26Al/27Al
- Issues:
  - The CR flux needed may not be supported by x-ray data
  - Requires enrichment in the accretion zone where there is little dust

Aluminum-26 Enrichment - External



Fujimoto+2018

Aluminum-26 Enrichment - External

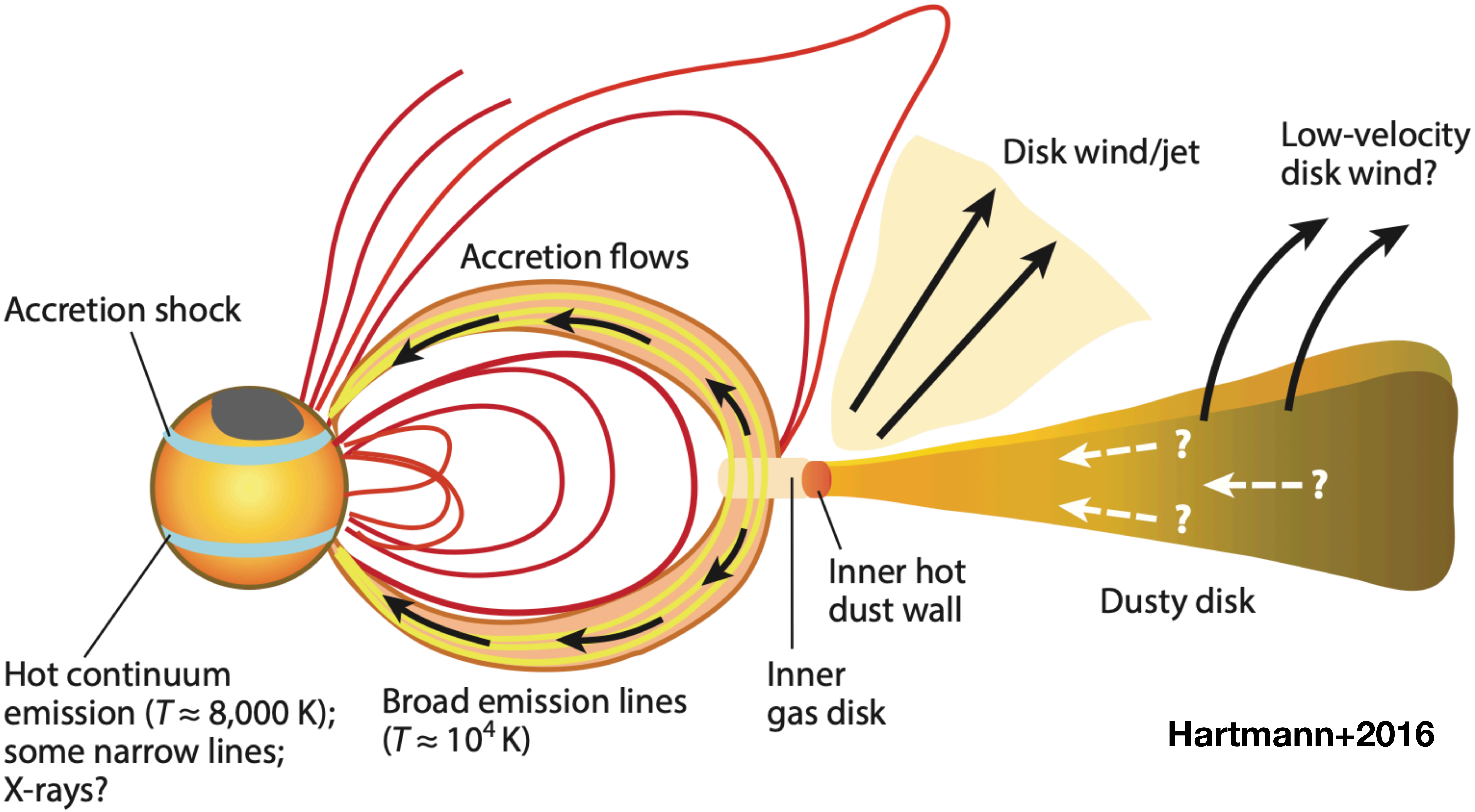


- **Fujimoto+2018 simulations include high-mass winds and SN as 26Al and 60Fe sources**
  - **Can reproduce the galactic distributions of 26Al**
  - **Can seed the disk with SLRs**
- **Issues:**
  - **Their simulations resolve at best 7 pc**
- **It is difficult for hot feedback gas to mix with cold molecular gas before SLR decay (See Seifried+2018)**
- **AGB stars have been proposed: very rare due to AGB star age**

Fujimoto+2018

Proposition: What if protostars could help produce 26Al in a general mechanism during the star formation process?

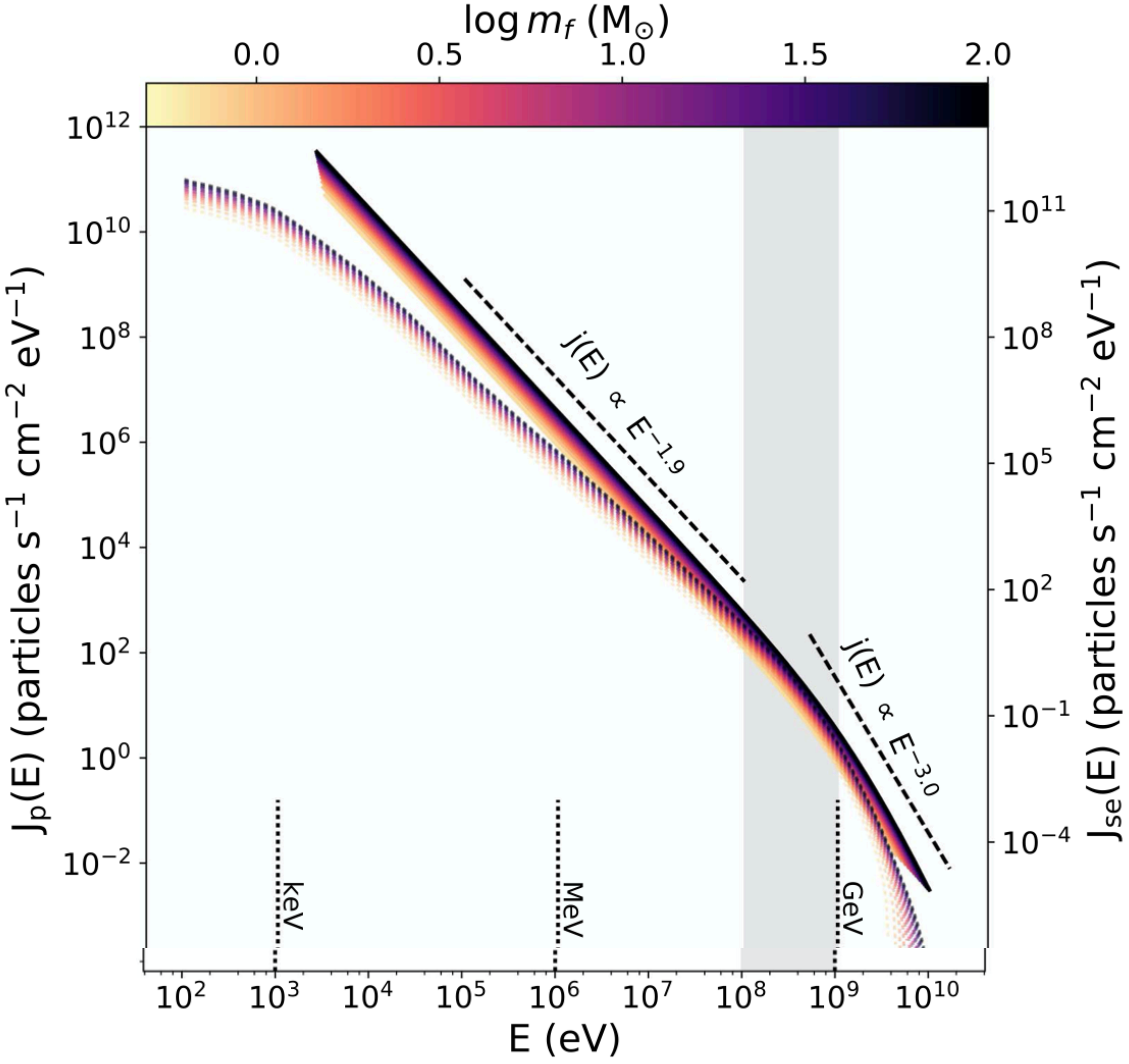
Site of Acceleration



Hartmann+2016

Cosmic Rays From Accretion Shocks

Gaches & Offner, 2018, ApJ 861



Example: Proton (solid) spectrum for 0.5 Msun protostar as a function of it’s final mass

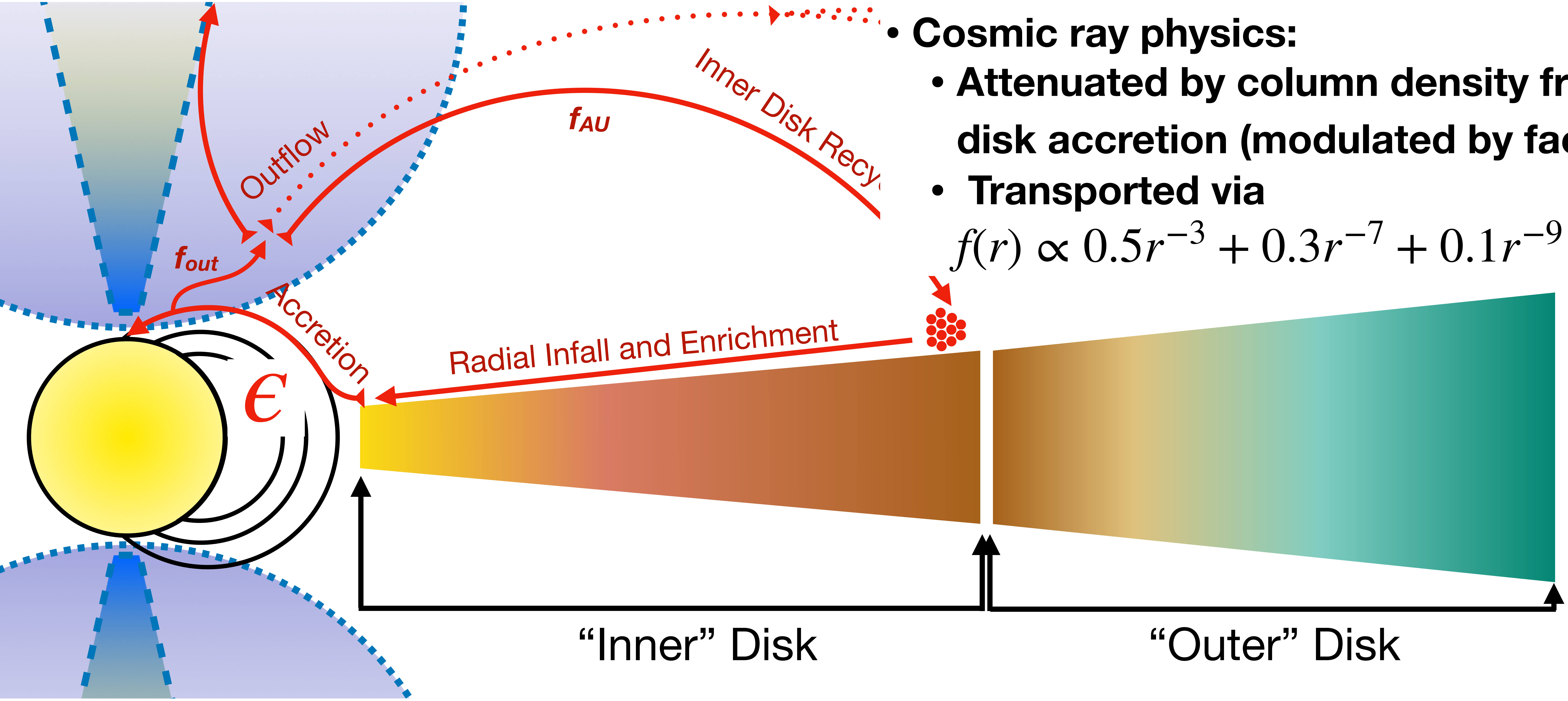
Assumes a Tapered-Turbulent Core accretion history (e.g. Offner & McKee 2011) to get accretion rate

Protostellar Disk 26Al Model

Protostellar Disk 26Al Model

- **Cosmic ray physics:**
  - **Attenuated by column density from disk accretion (modulated by factor ϵ)**
  - **Transported via**

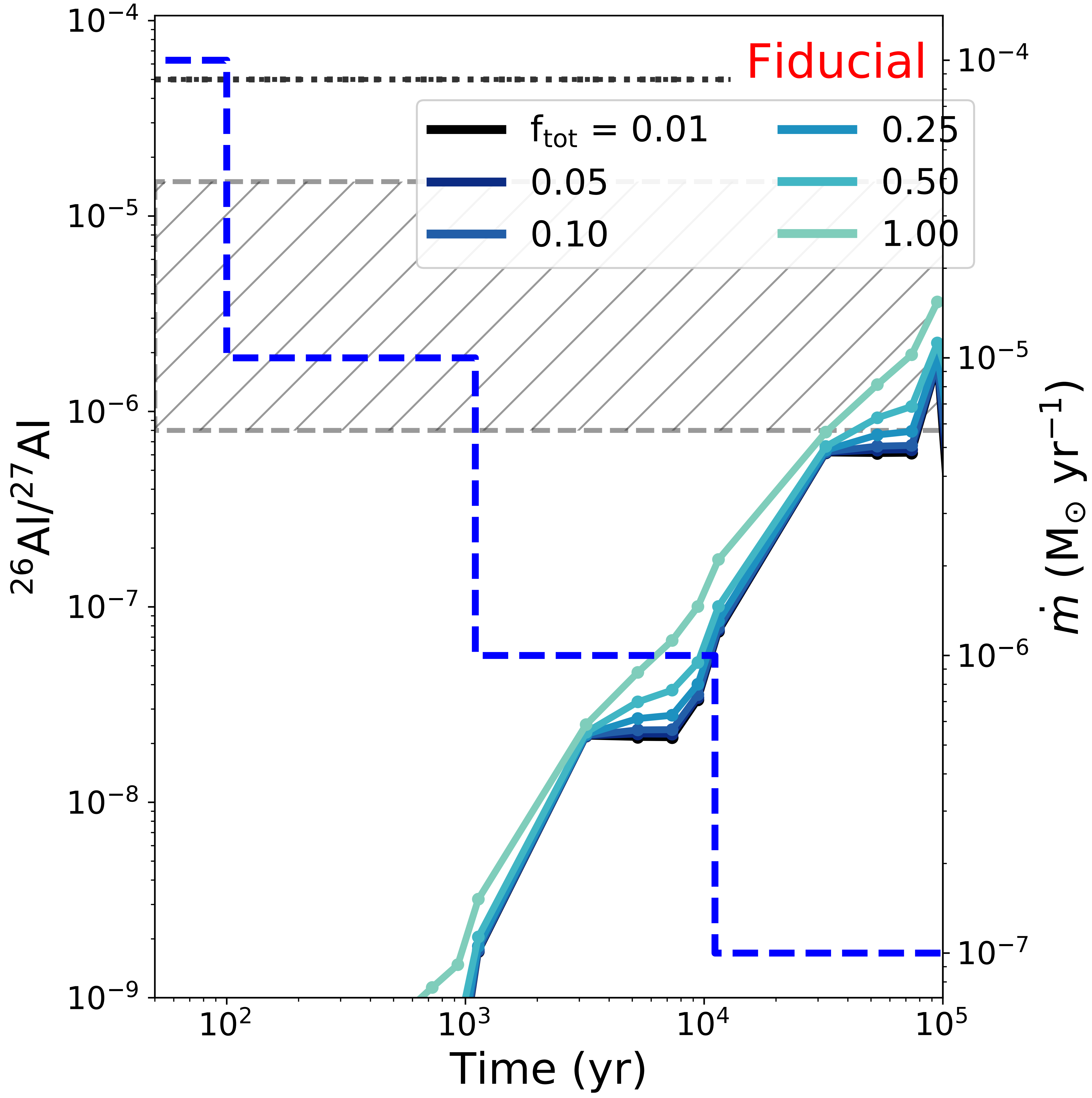
$$f(r) \propto 0.5r^{-3} + 0.3r^{-7} + 0.1r^{-9}$$



Results: Accretion Burst, $M_* = 0.9M_\odot$

Burst: 10^{-4} Msun/yr for 100 years, 10^{-5} for 1000 years, …

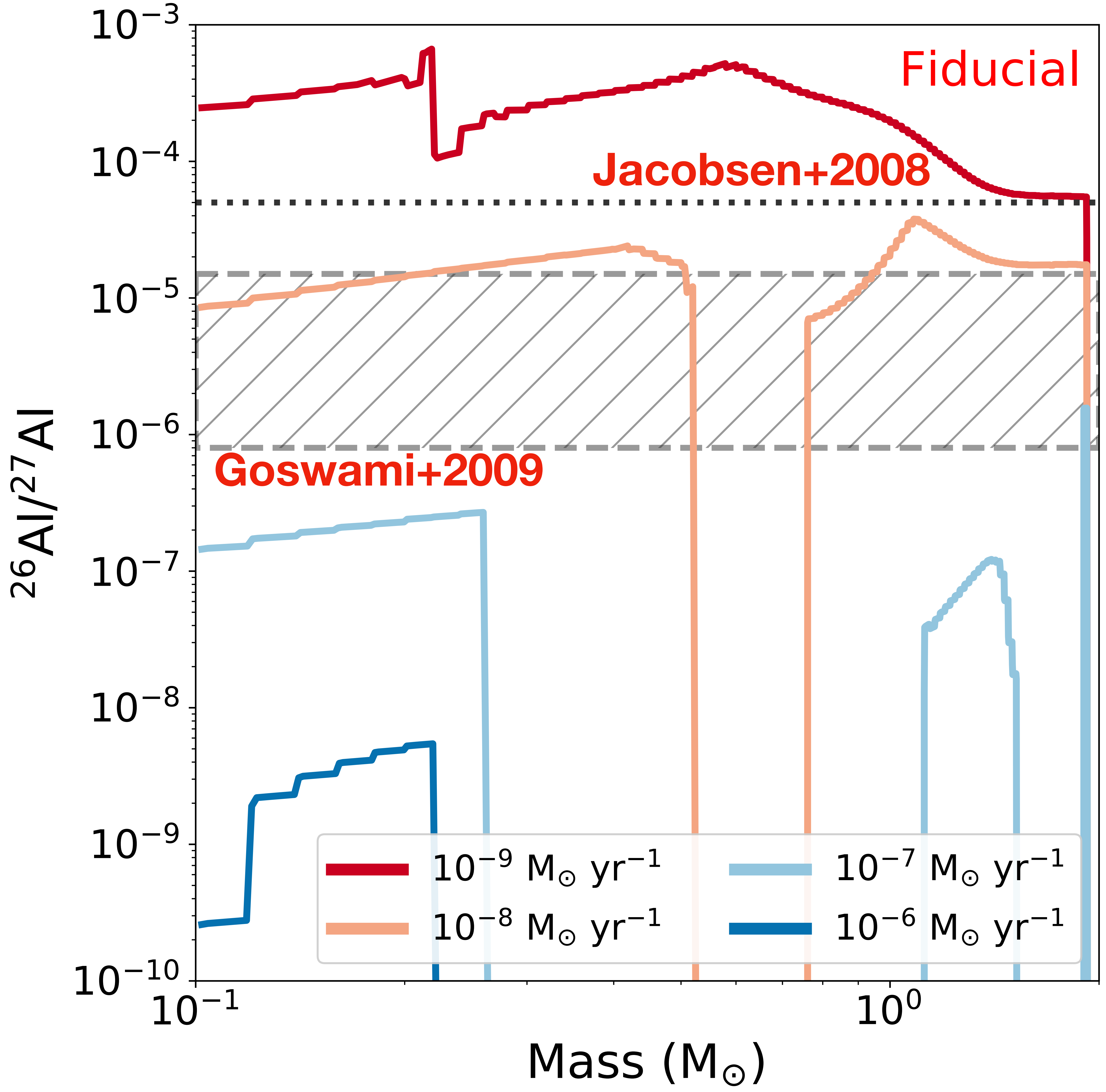
Fiducial model: $B_* = 10^3$G, $\epsilon = 0.1, f_{tot} = f_{AU} f_{out}$



- **No enrichment until the accretion rate drops to 10-6 Msun/yr**
  - **Higher accretion rates lead to larger radii and greater accretion - a double whammy!**
- **Can achieve lower limit enrichment ratios in Chondrules from Goswami+2006**

Results: Mass Evolution

Fiducial model: $B_* = 10^3$ G, $\epsilon = 0.1, f_{AU} = f_{out} = 0.1$

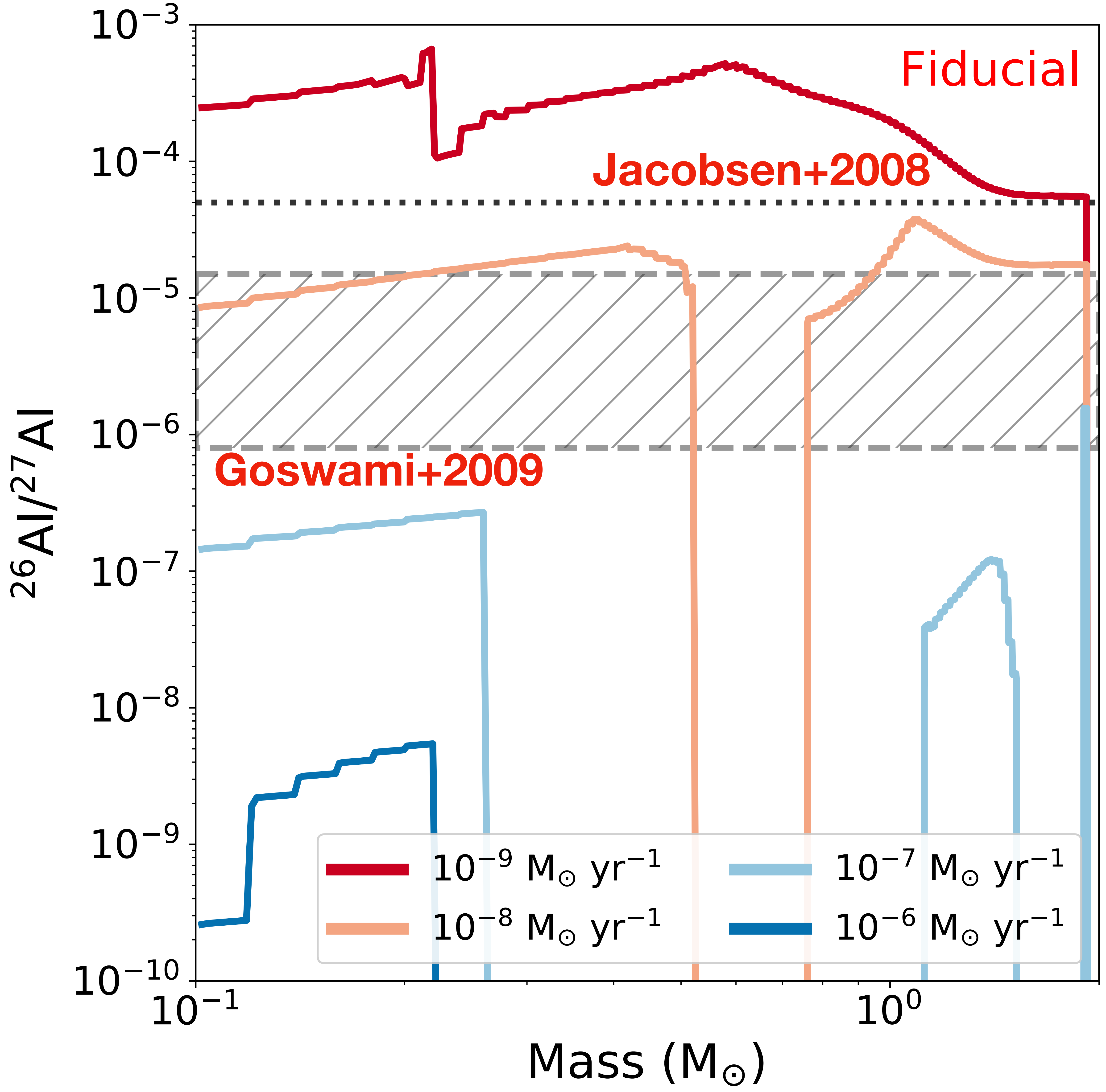


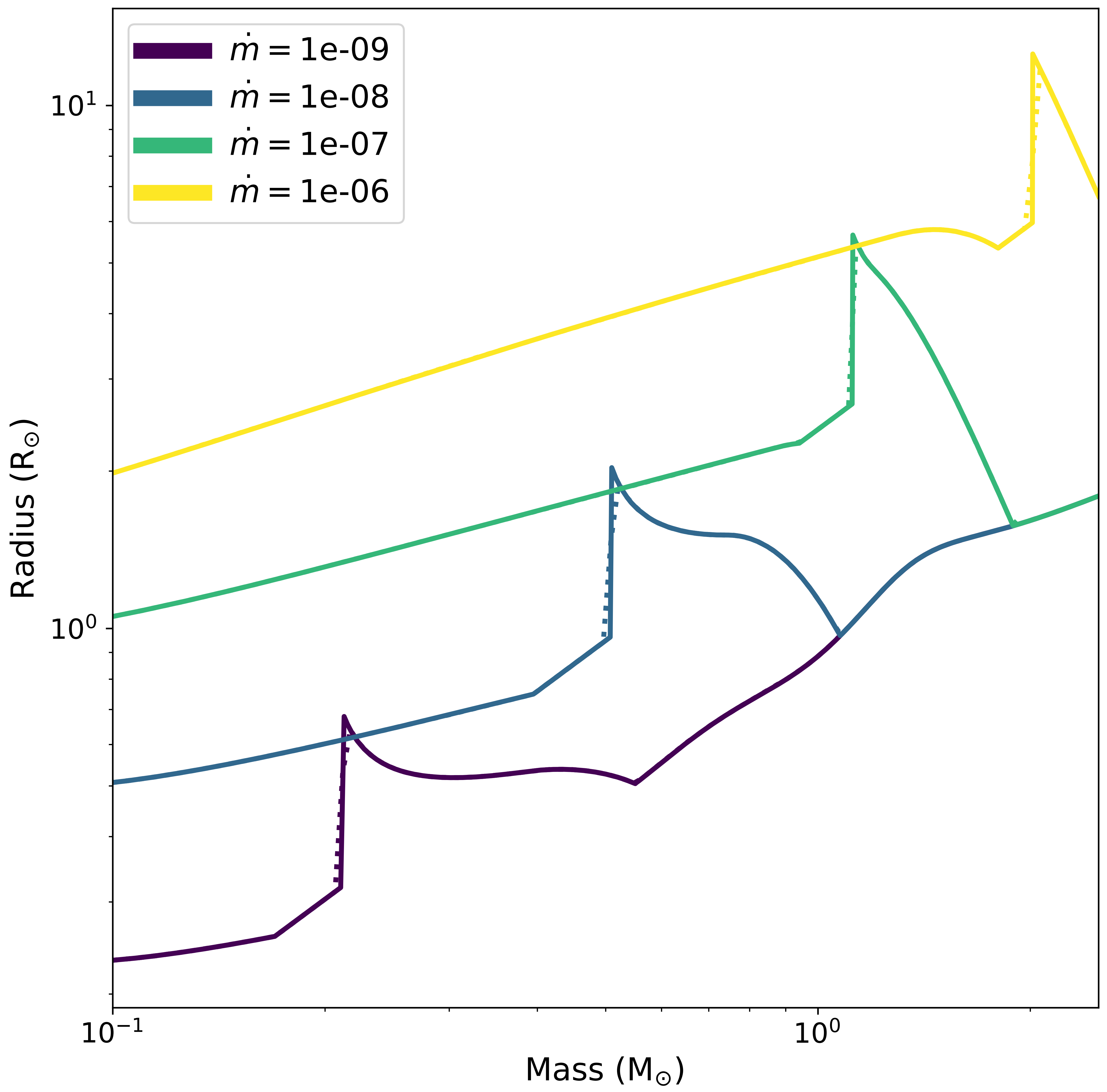
Start with a brown dwarf mass and evolve with constant accretion rate

- Models with low accretion rates can reproduce or exceed the CAI and Chondrule information
- **Note**: Where it goes to zero is due to the rapid loss from outflows and no generation due to large radii

Results: Mass Evolution

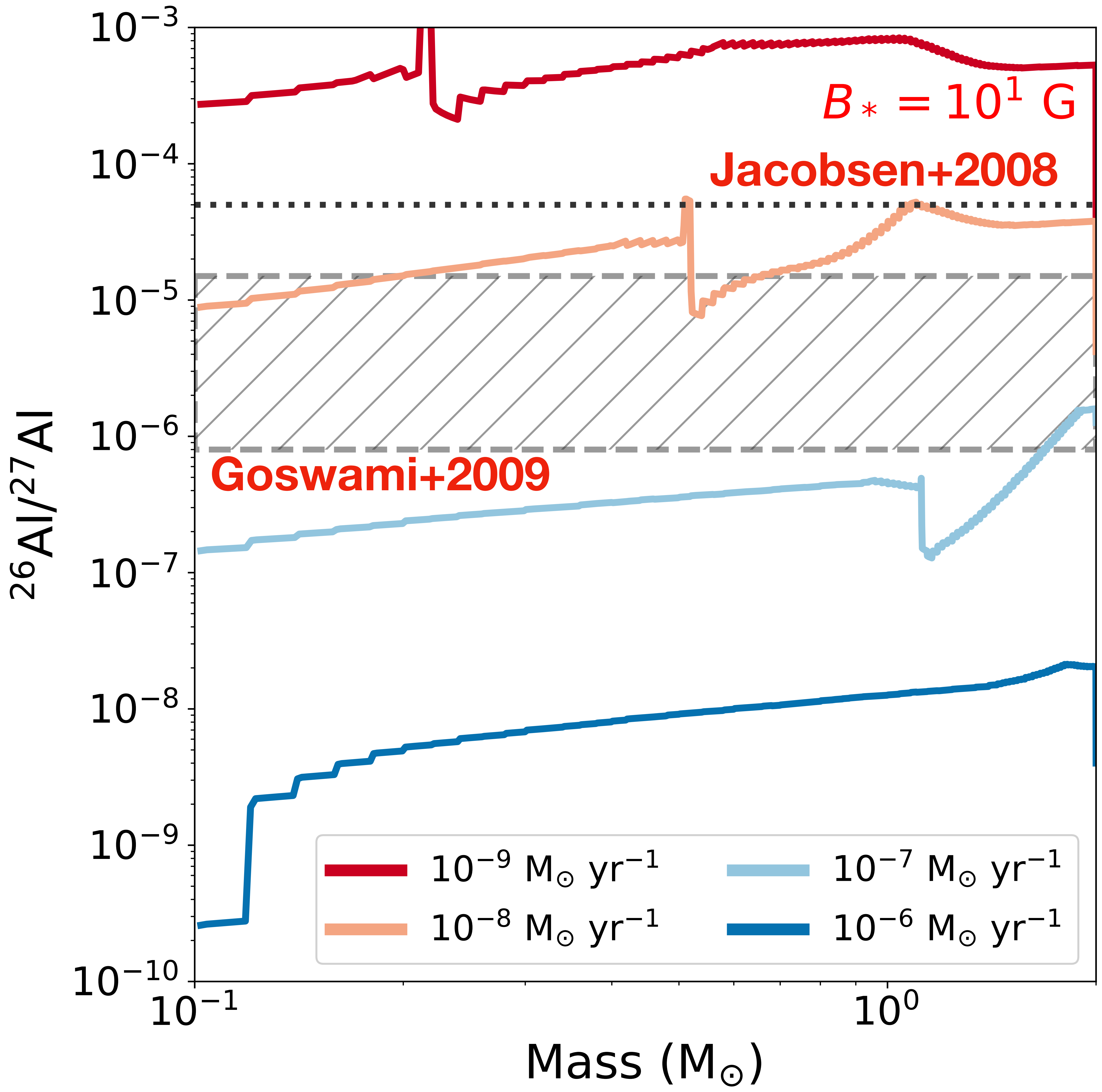
Fiducial model: $B_* = 10^3$ G, $\epsilon = 0.1$, $f_{AU} = f_{out} = 0.1$





Results: Mass Evolution

Low-B model: $B_* = 10^1$ G, $\epsilon = 0.1, f_{AU} = f_{out} = 0.1$

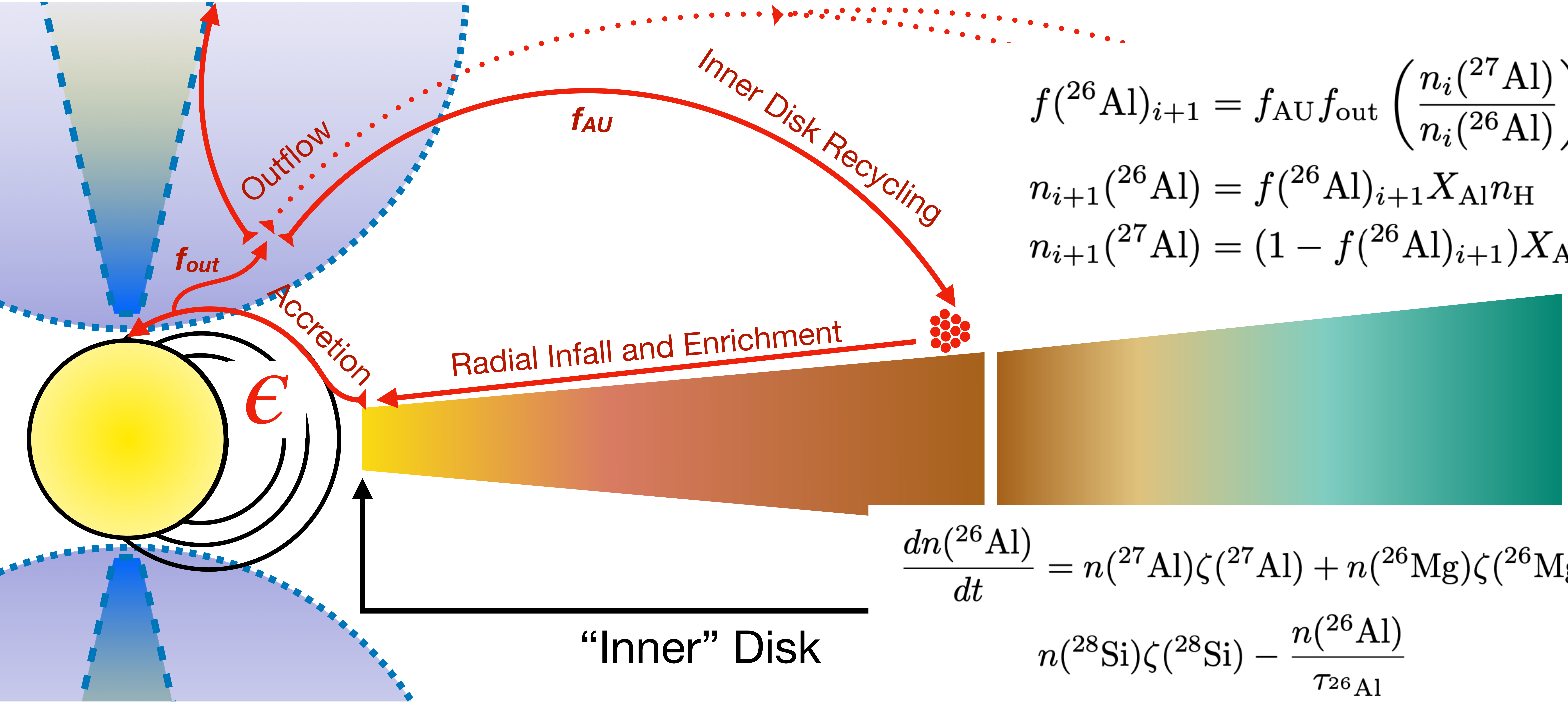


- Lower magnetic fields mean DSA is efficient for all protostellar radii
- Lower accretion rates are still dominant

Conclusions

1. In-situ irradiation by cosmic rays accelerated in protostellar accretion shocks is a **viable mechanism to produce Aluminum-26**.
2. **Accretion bursts are not a viable source**: a high accretion rate leads to a much larger radius and more attenuation
3. The model requires **low sustained accretion rates**, $\dot{m} < 10^{-7} M_{\odot} yr^{-1}$, due to the smaller radius and attenuation: **a general mechanism!**

Protostellar Disk 26Al Model



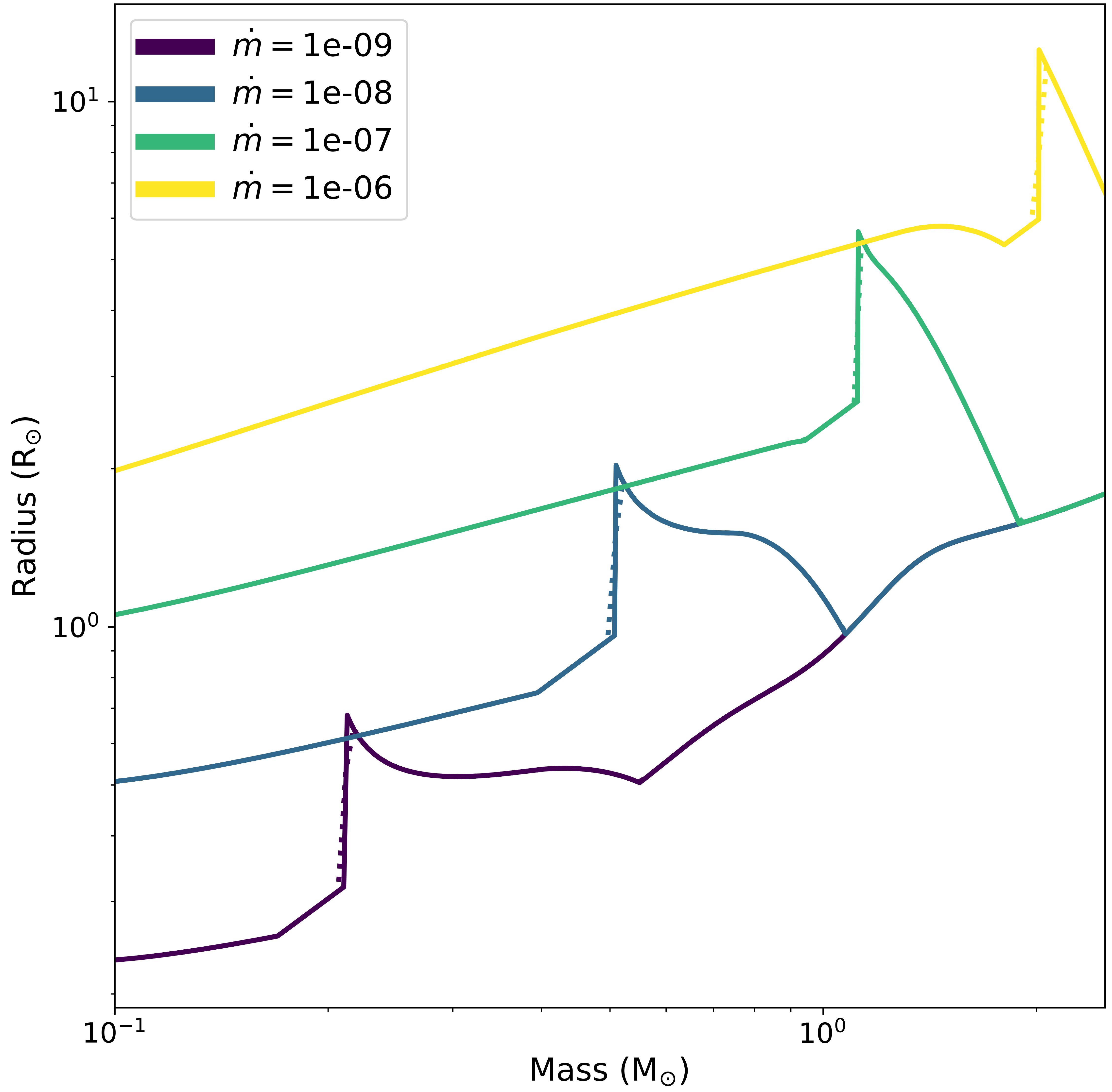
$$f(^{26}\mathrm{Al})_{i+1} = f_{\mathrm{AU}} f_{\mathrm{out}} \left(\frac{n_i(^{27}\mathrm{Al})}{n_i(^{26}\mathrm{Al})} \right)$$

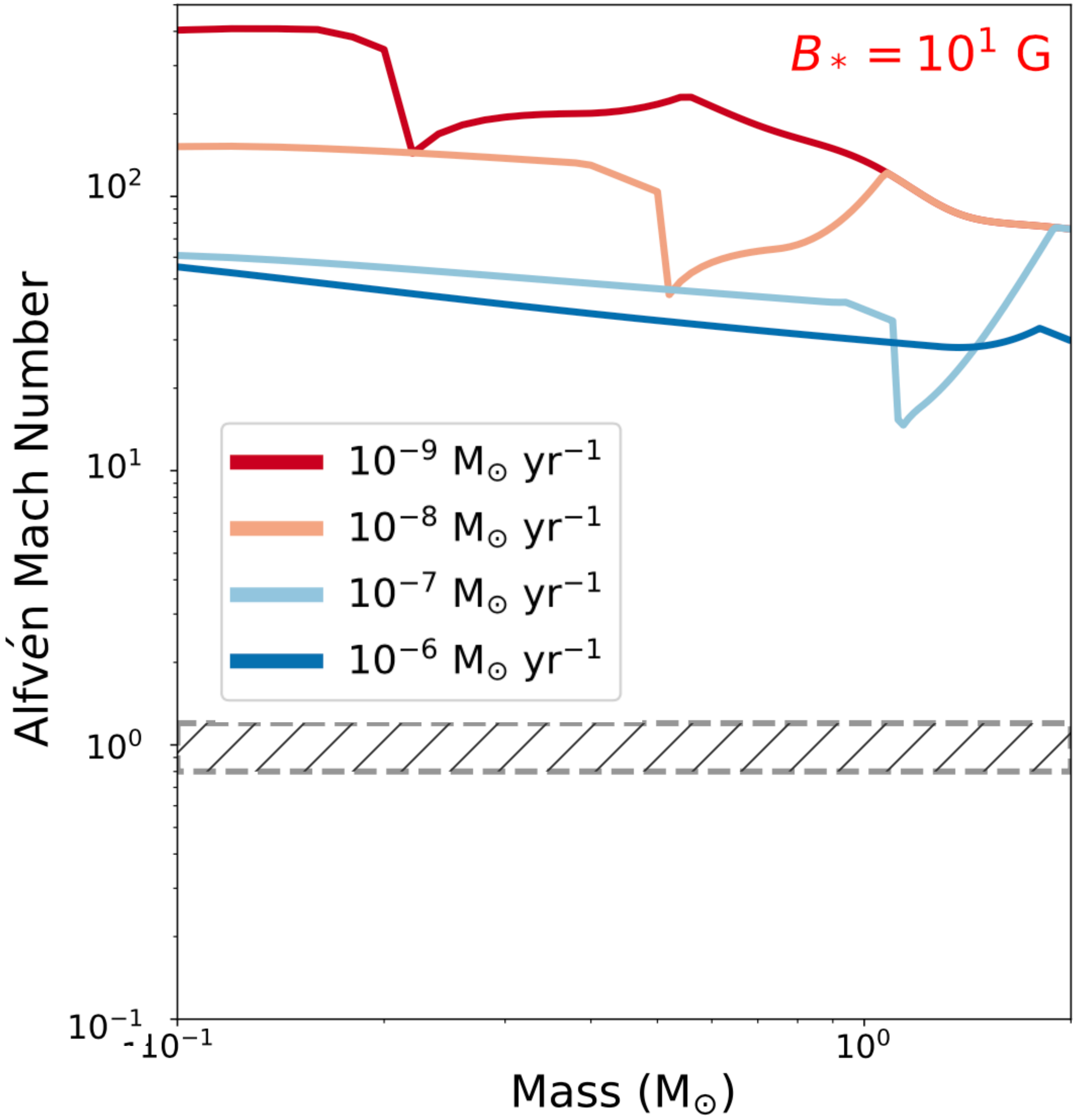
$$n_{i+1}(^{26}\mathrm{Al}) = f(^{26}\mathrm{Al})_{i+1} X_{\mathrm{Al}} n_{\mathrm{H}}$$

$$n_{i+1}(^{27}\mathrm{Al}) = (1 - f(^{26}\mathrm{Al})_{i+1}) X_{\mathrm{Al}} n_{\mathrm{H}}$$

$$\frac{dn(^{26}\mathrm{Al})}{dt} = n(^{27}\mathrm{Al})\zeta(^{27}\mathrm{Al}) + n(^{26}\mathrm{Mg})\zeta(^{26}\mathrm{Mg}) + n(^{28}\mathrm{Si})\zeta(^{28}\mathrm{Si}) - \frac{n(^{26}\mathrm{Al})}{\tau_{^{26}\mathrm{Al}}}$$

Protostellar Evolution + DSA Criterion





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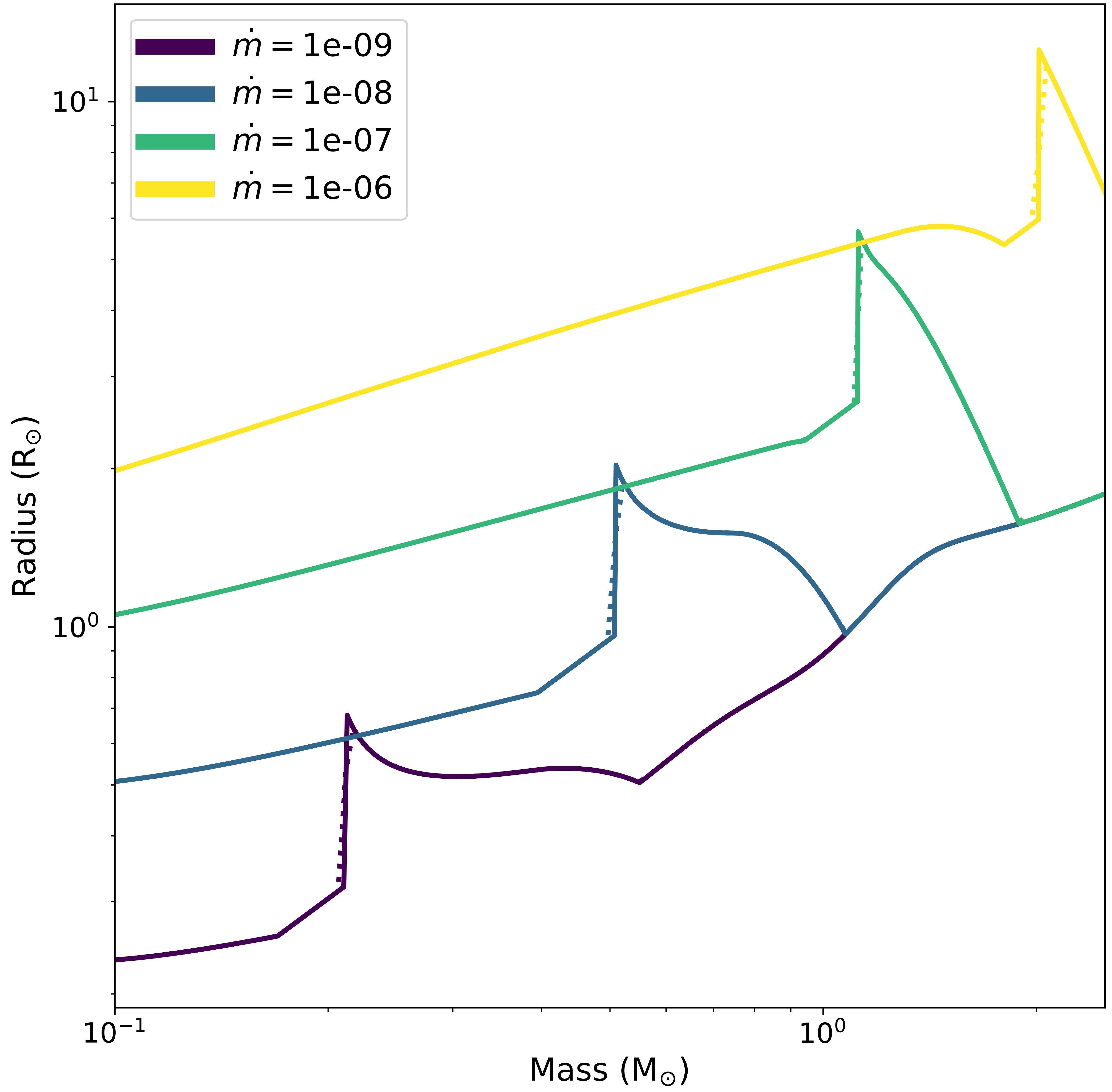

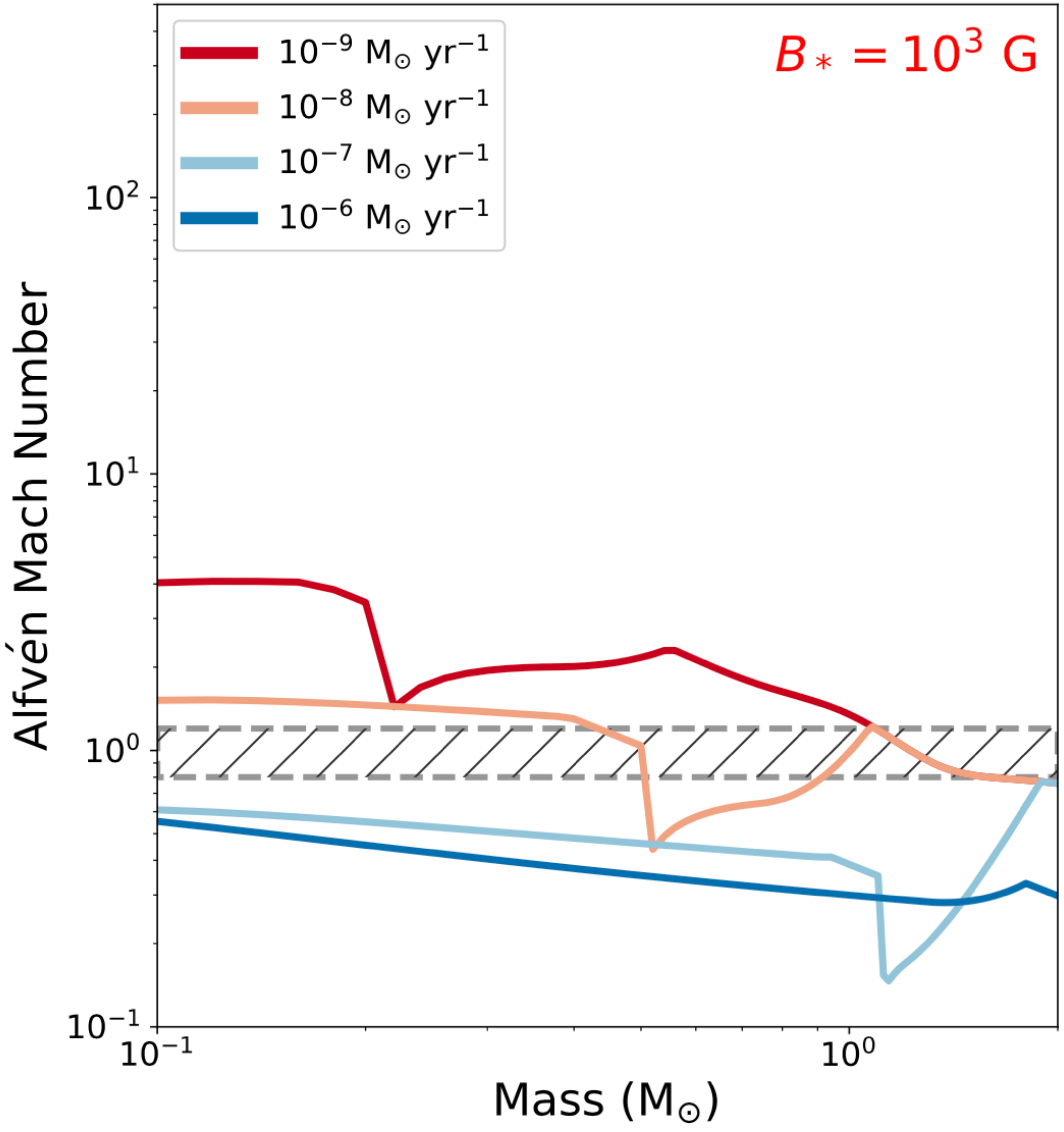

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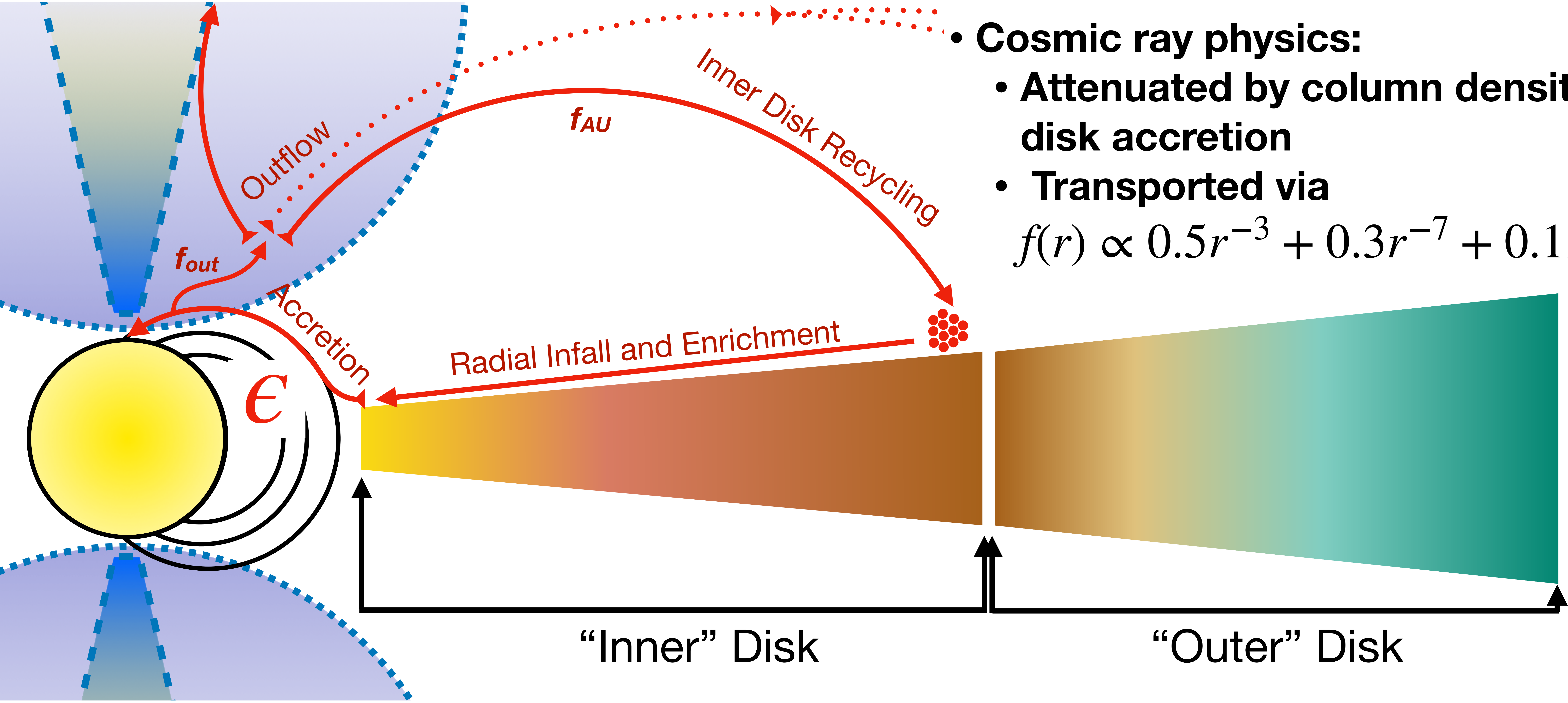

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