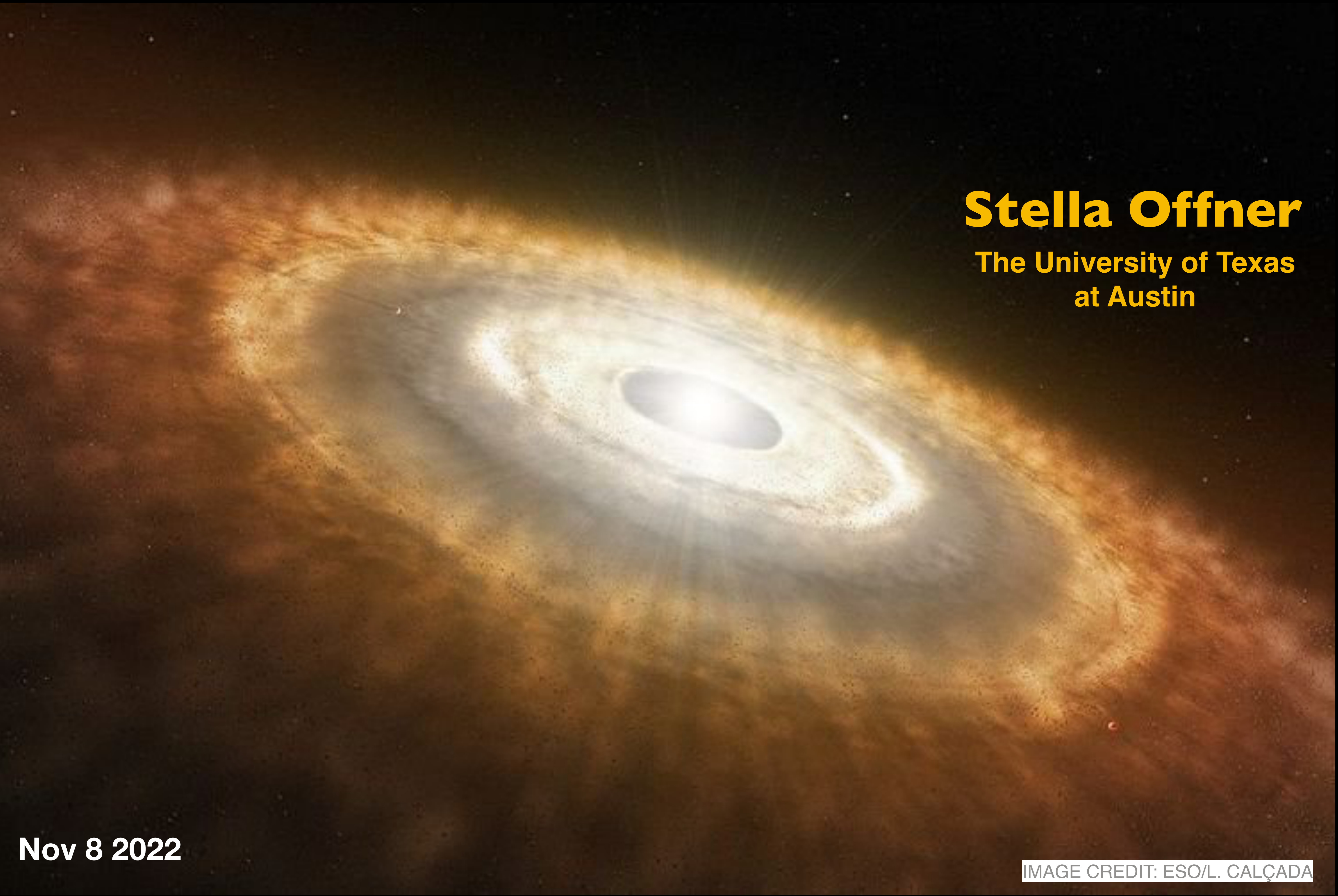
Impact of Cosmic-Ray Feedback on Protostellar Disks

Stella Offner

The University of Texas
at Austin

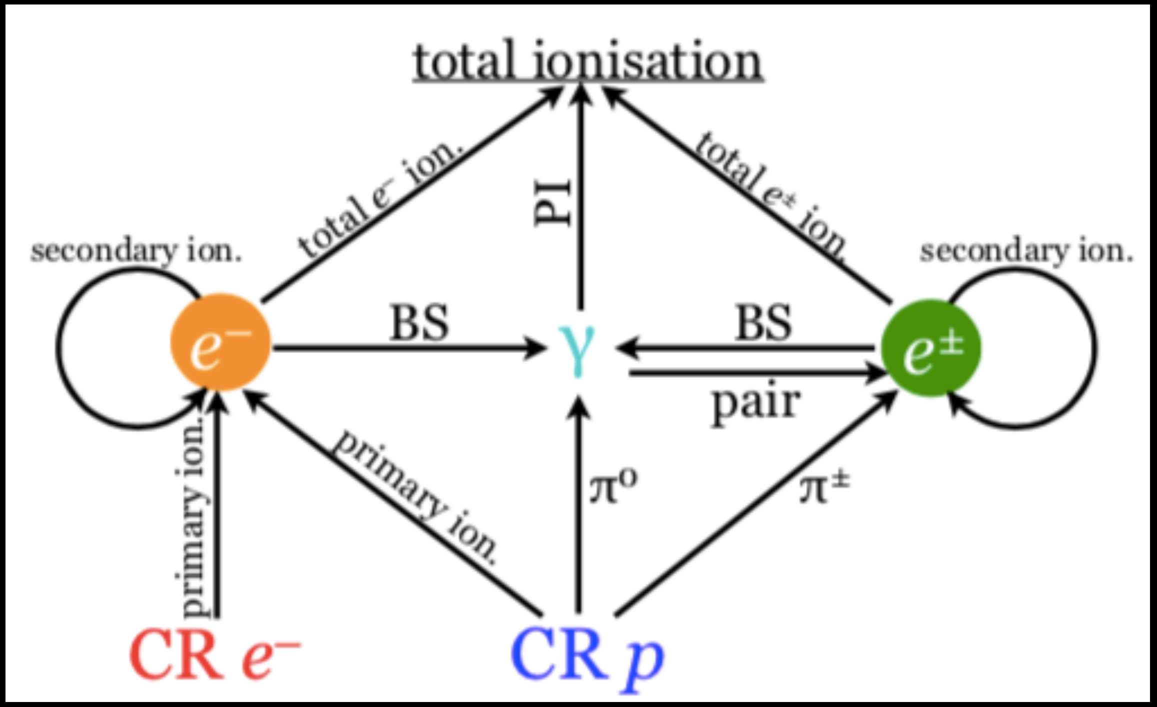


Nov 8 2022

IMAGE CREDIT: ESO/L. CALÇADA

Why care about Cosmic Rays in Star & Planet Formation?

ζ ionization rate parameter $[s^{-1}]$



Padovani et al. 2020, ISSI Review

Why care about Cosmic Rays in Star & Planet Formation?

ζ ionization rate parameter $[s^{-1}]$

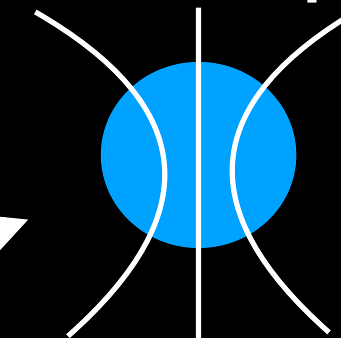
~ $10^{-16}\ s^{-1}$
Indriolo ea 2015

Disk evolution & Accretion

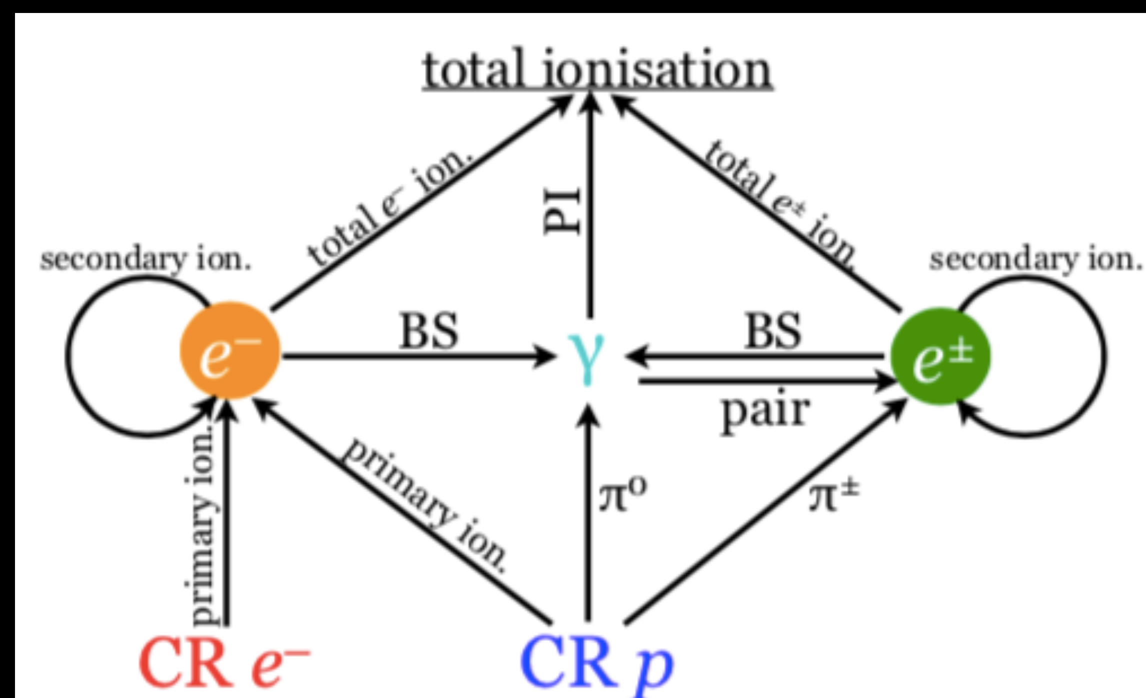
- angular momentum transport / MRI
- Planet formation

This Talk

Core Collapse



- Non-ideal magnetic effects
- angular momentum transport



Padovani et al. 2020, ISSI Review

Chemical Complexity

- origin of life
- habitability

Molecular Cloud Chemistry

- CO, C, C+ abundances (X-factor)
- Cloud temperatures

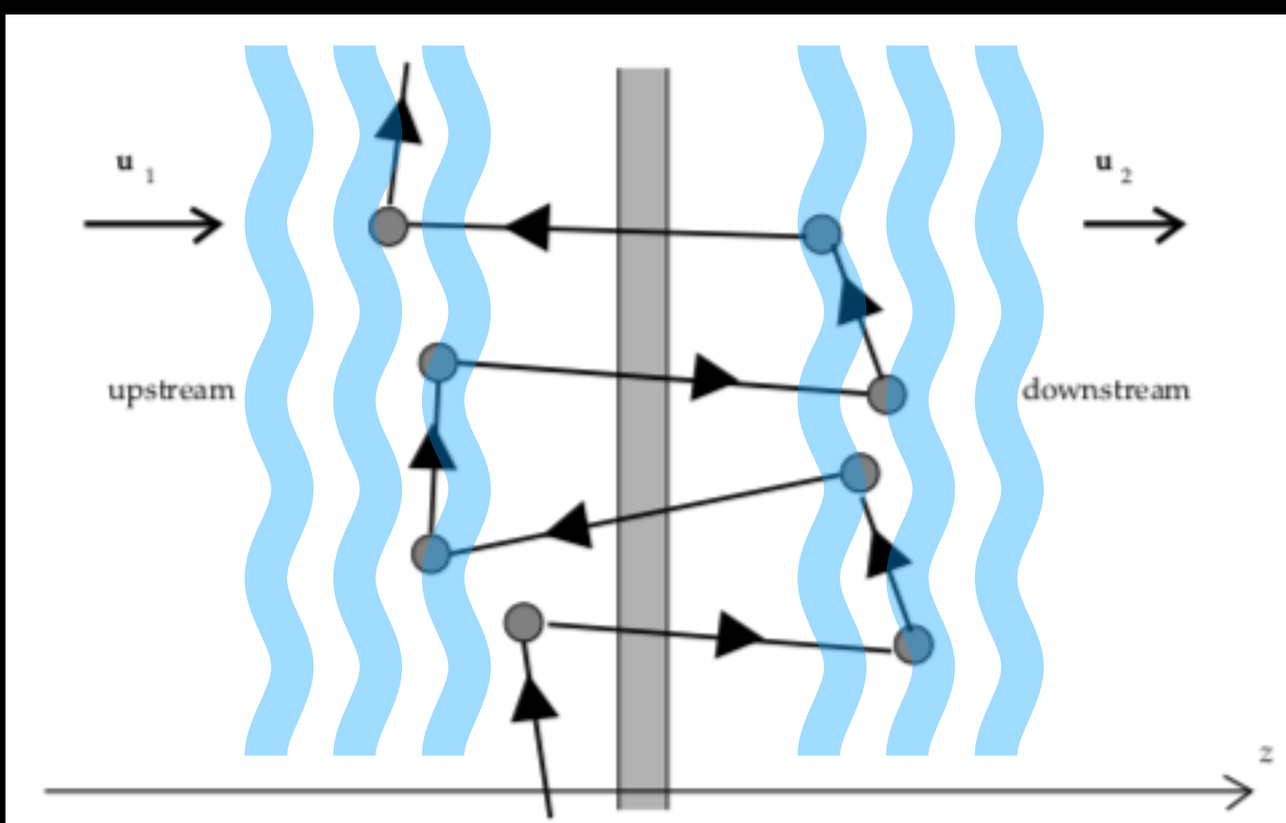
Cosmic-rays are not just produced by supernova shocks…

Image credit: NASA / CXC / RIKEN / NASA's Goddard Space Flight Center / T. Sato *et al* / DSS.

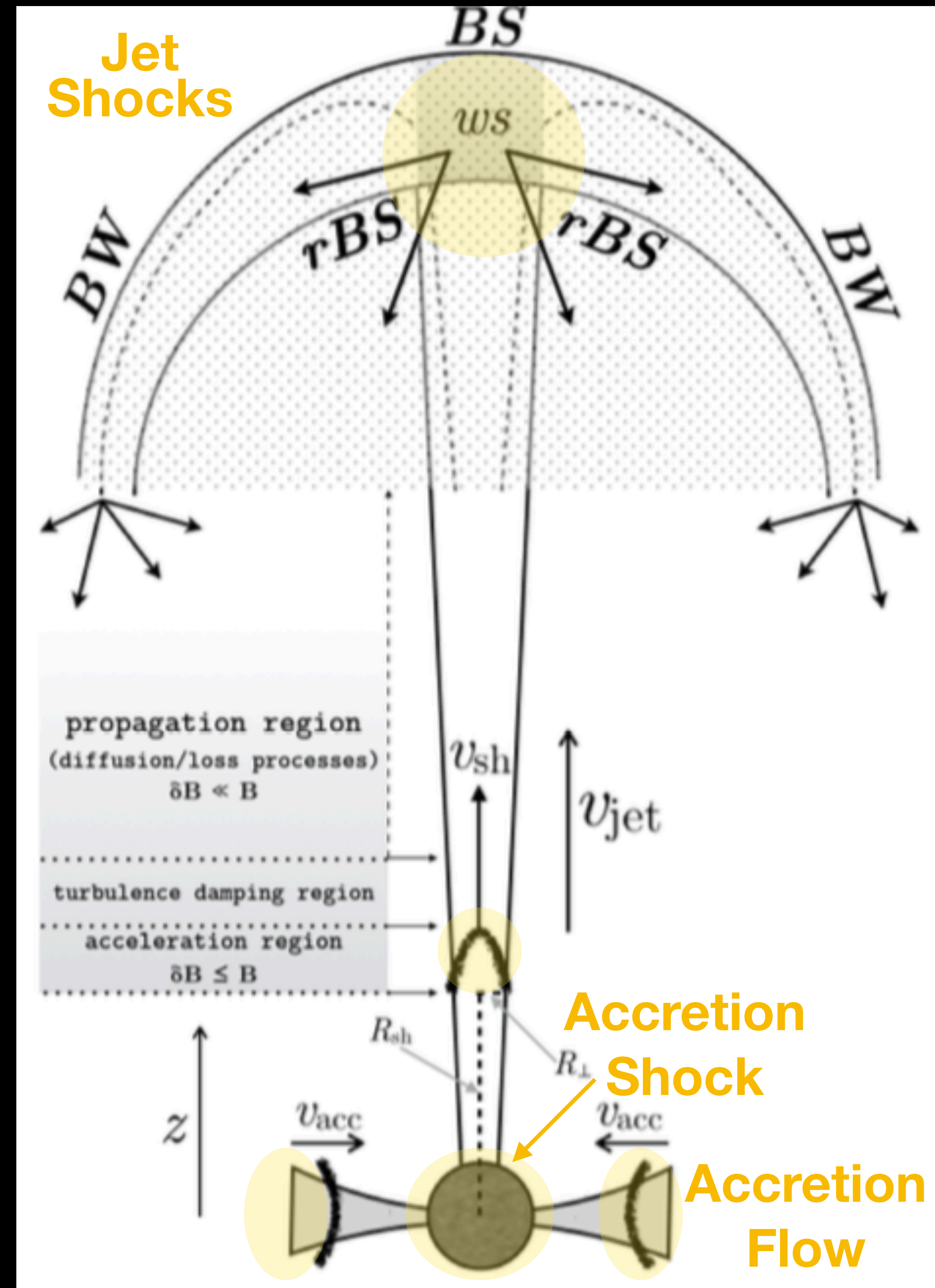
Protostars: Forges of Cosmic Rays

Accretion shocks and jets can accelerate CRs (Padovani et al. 2015, 2016)

First-Order Fermi Accereration or Diffusive Shock Acceleration



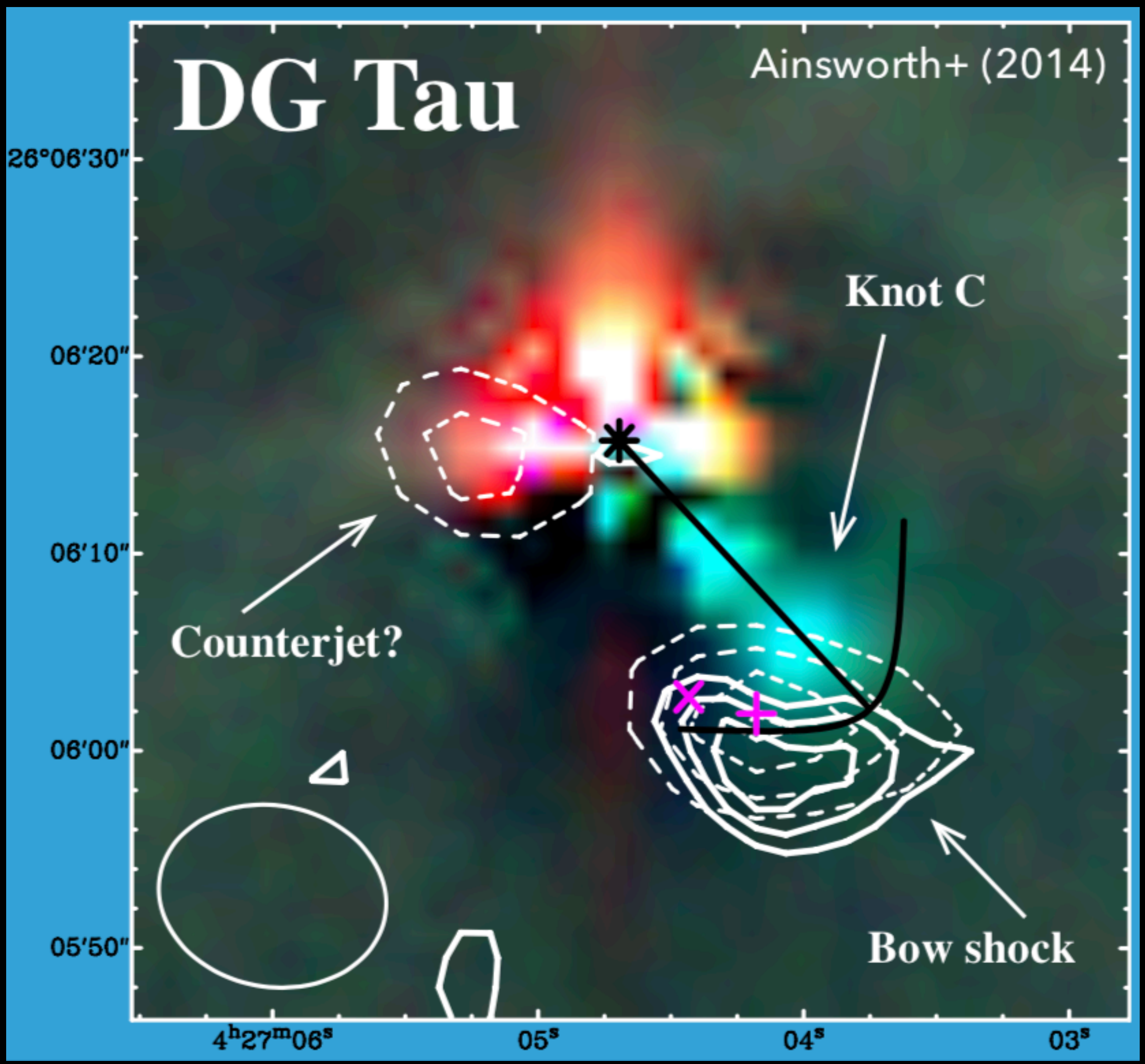
Melrose 2009



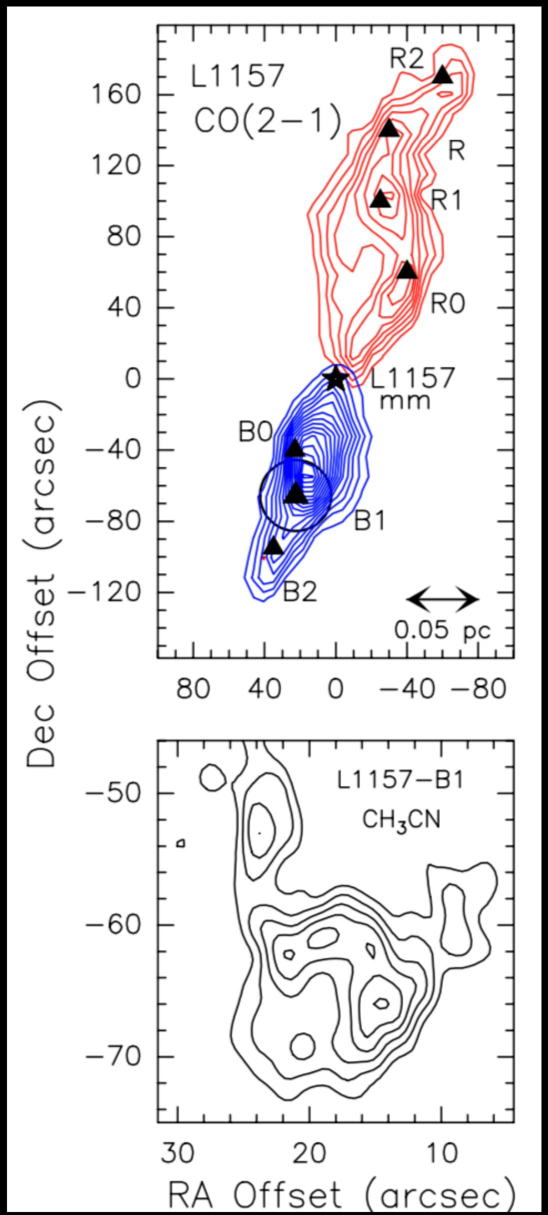
CRs are coming from inside the house (molecular clouds)!

Observational Evidence: Jets

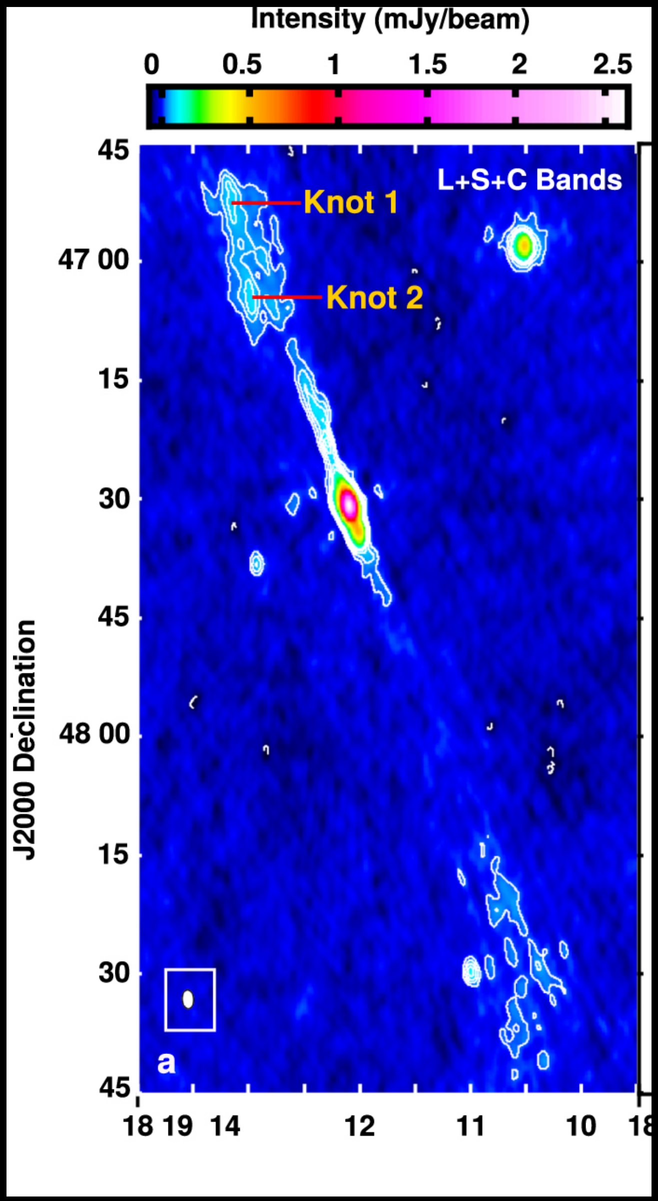
Non-thermal Synchrotron Emission is Observed in Protostellar Jets



Ainsworth ea 2014



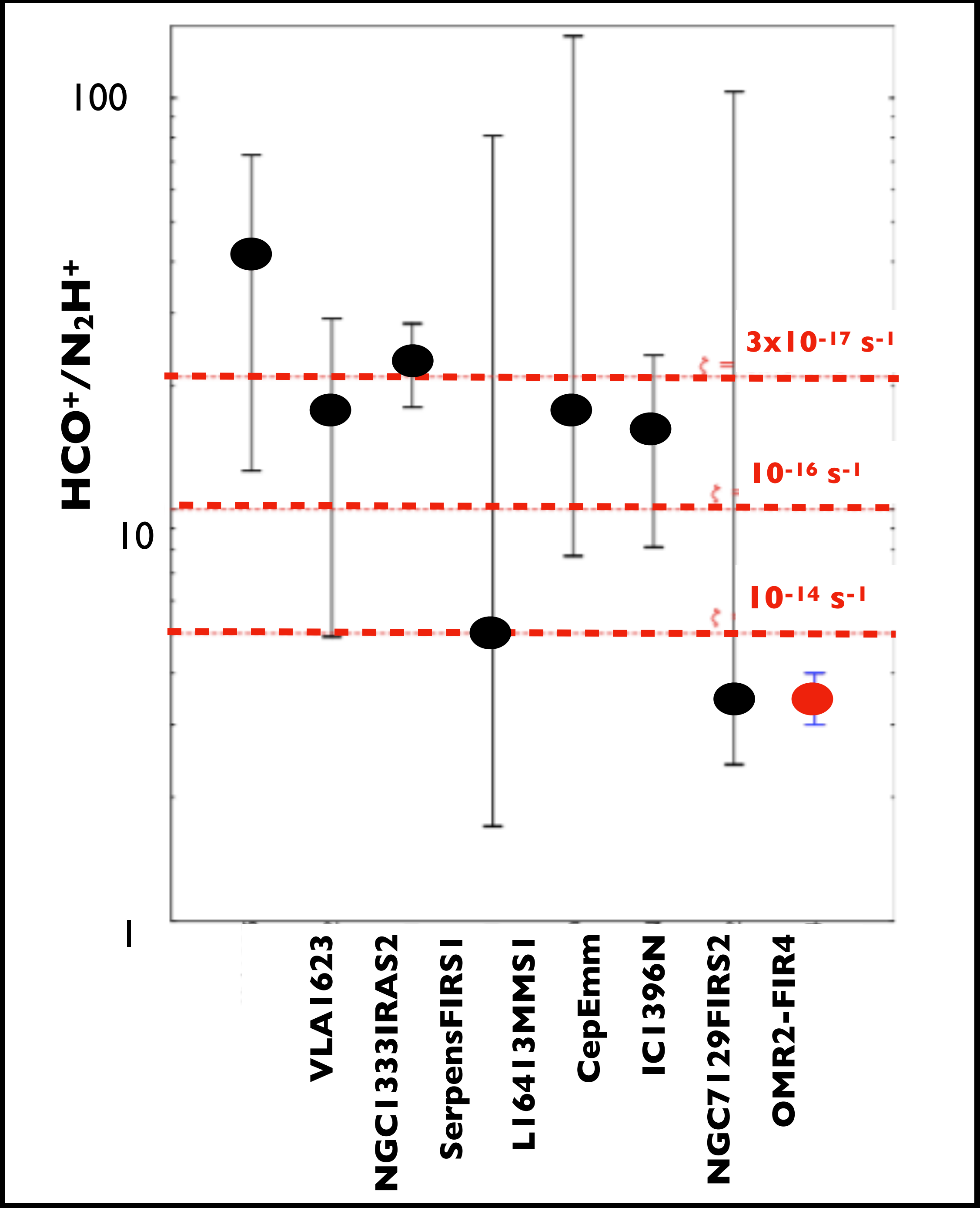
Podio ea 2014

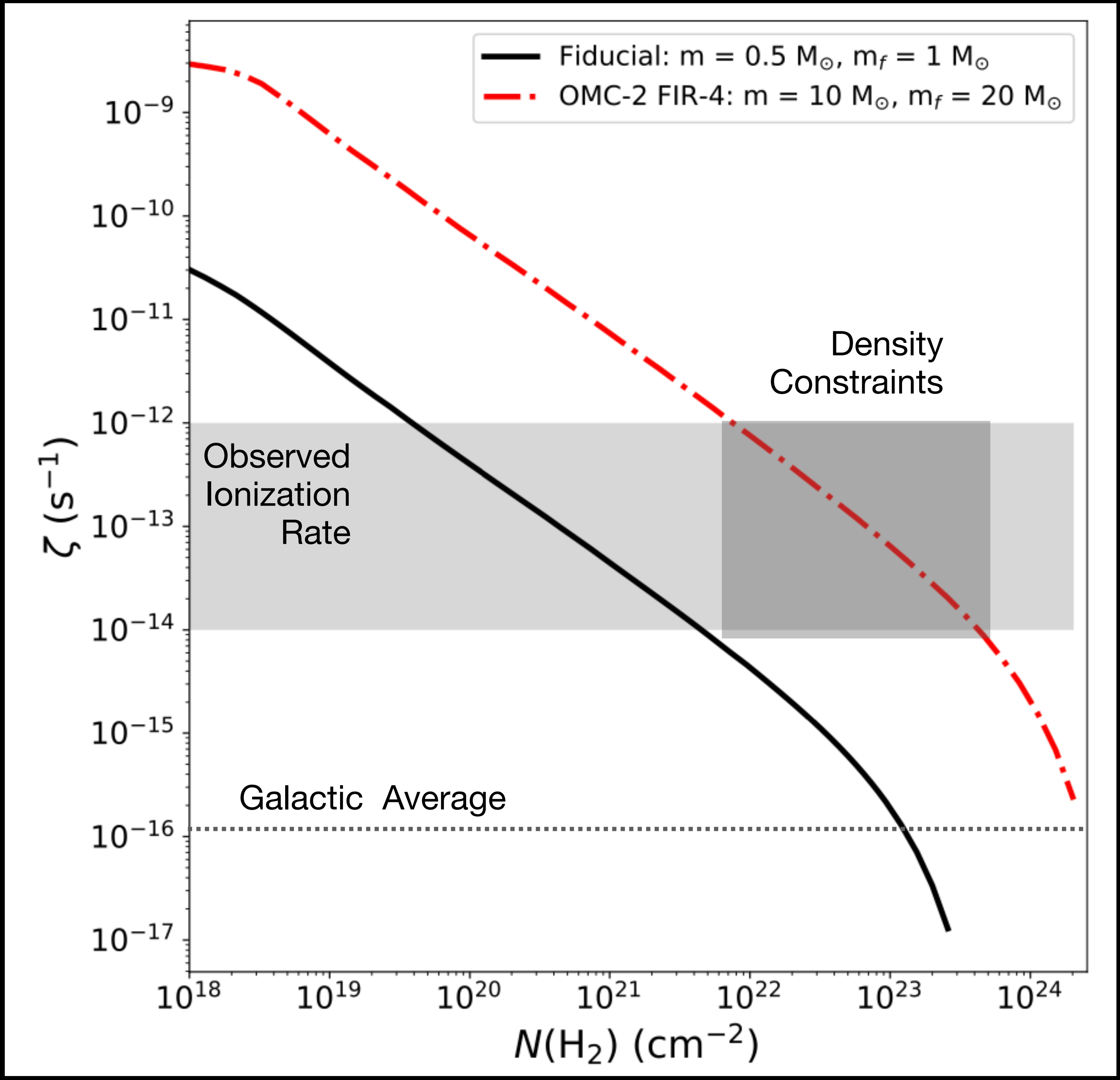


Rodriguez-Kamenetzky ea 2017

Observations Evidence: Protostars

OMC2-FIR4: Is a forming massive star with M*~10Msun





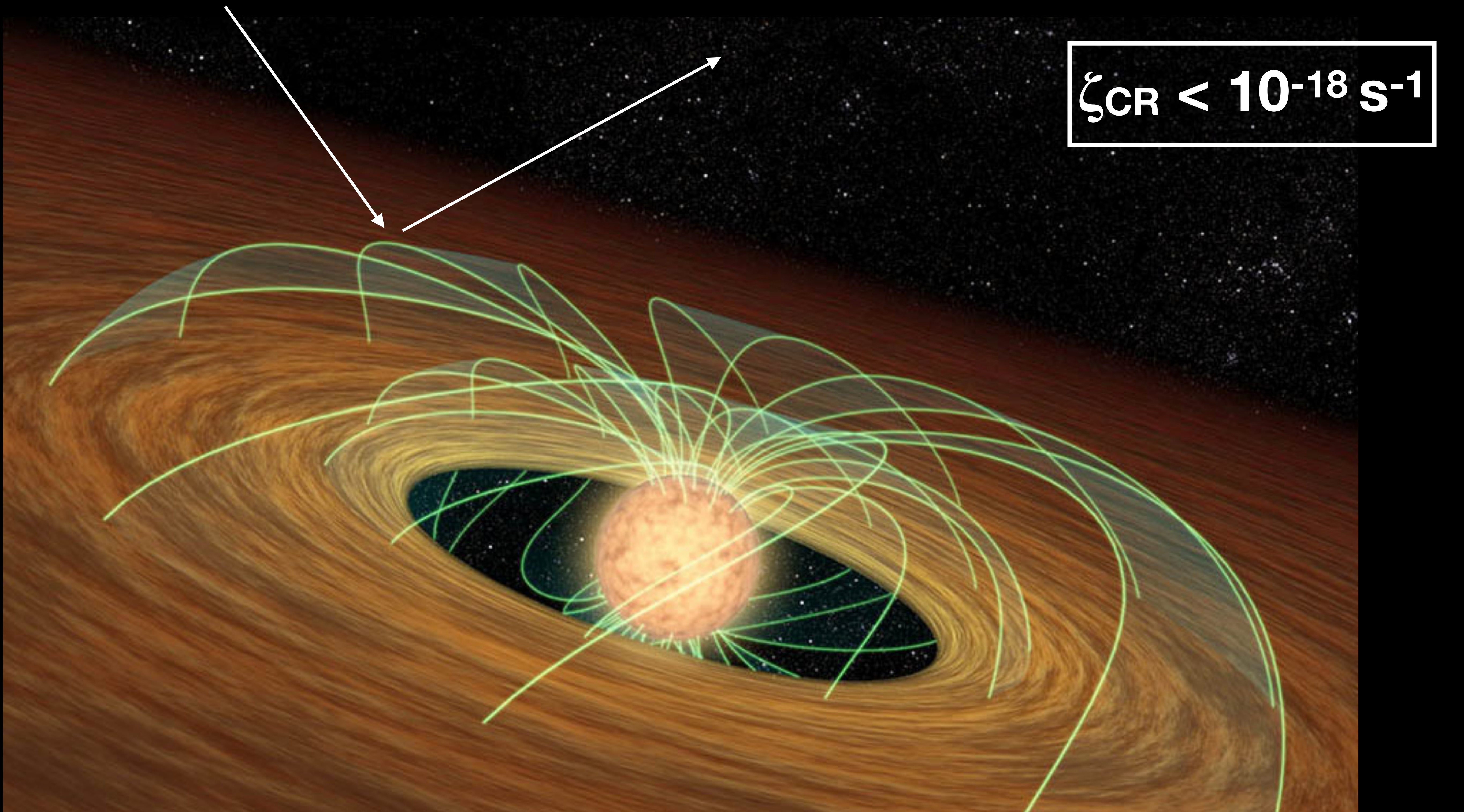
Favre et al. 2018 ($c-C_3H_2$)

Gaches & Offner 2018b, 2022

Also: Ceccarelli ea 2014 (HCO^+, N_2H^+), Fontani ea 2017 (HC_3N, HC_5N)

CRs Impact Disk Chemistry!

Galactic CRs are screened by stellar magnetic field (Cleeves ea 2013a)



CRs Impact Disk Chemistry!

Galactic CRs are screened by stellar magnetic field (Cleeves ea 2013a)

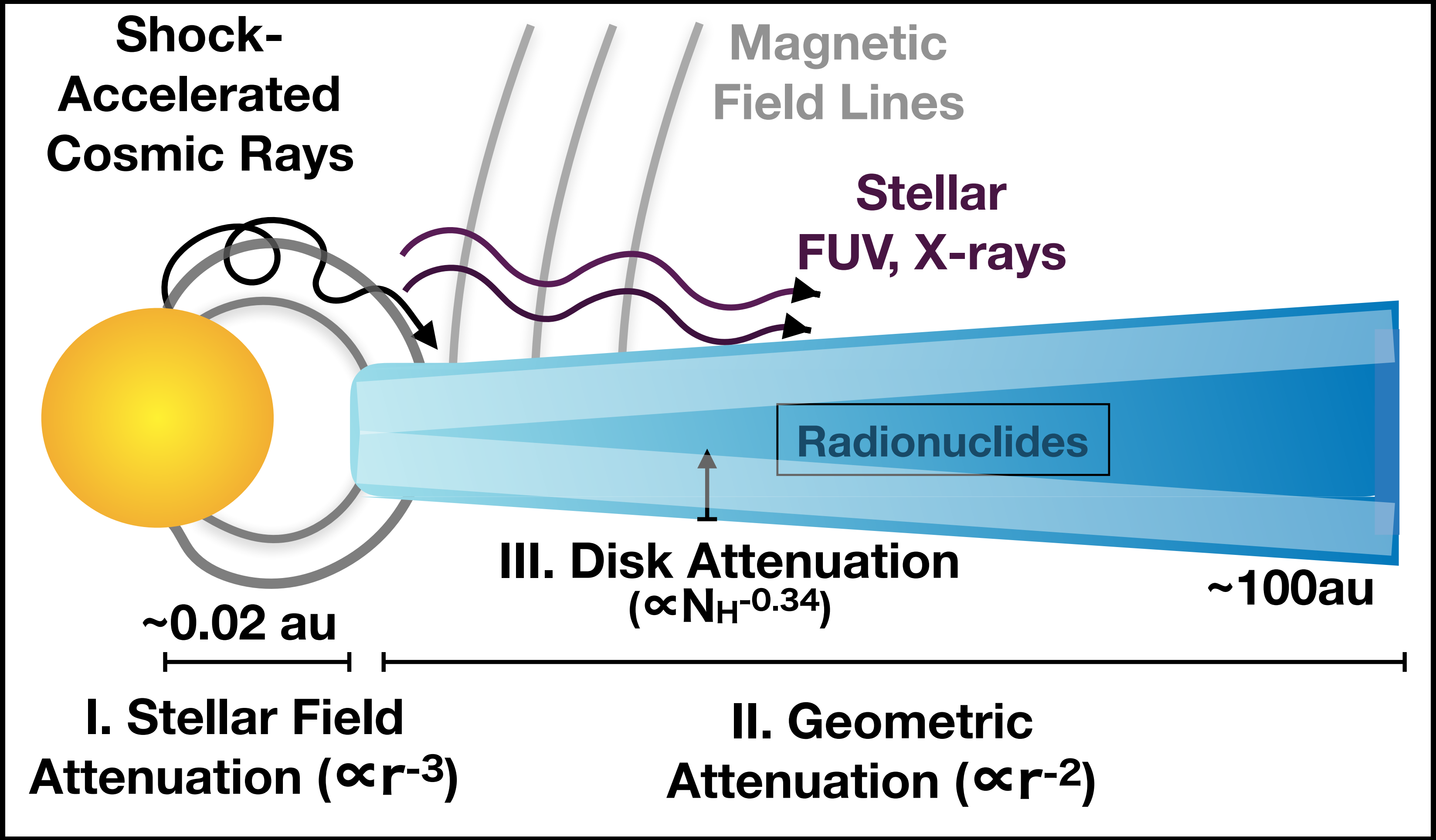
… but not ones accelerated locally.

CRs Impact Disk Chemistry!

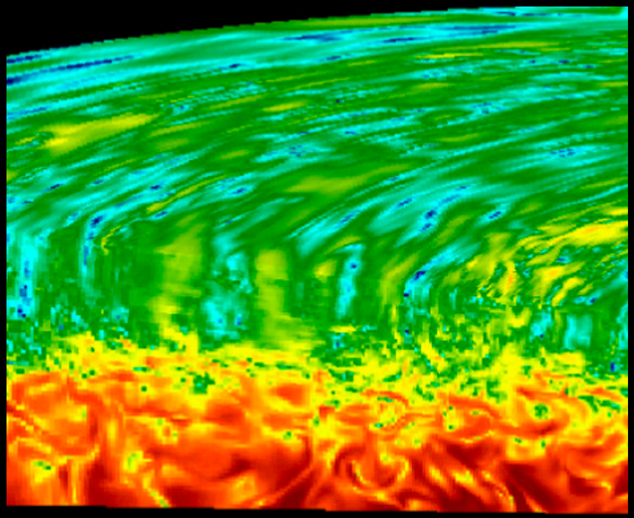
Galactic CRs are screened by stellar magnetic field (Cleeves ea 2013a)

… but not ones accelerated locally.

Offner et al. 2019



Magneto-Rotational Instability (MRI) Turbulence?

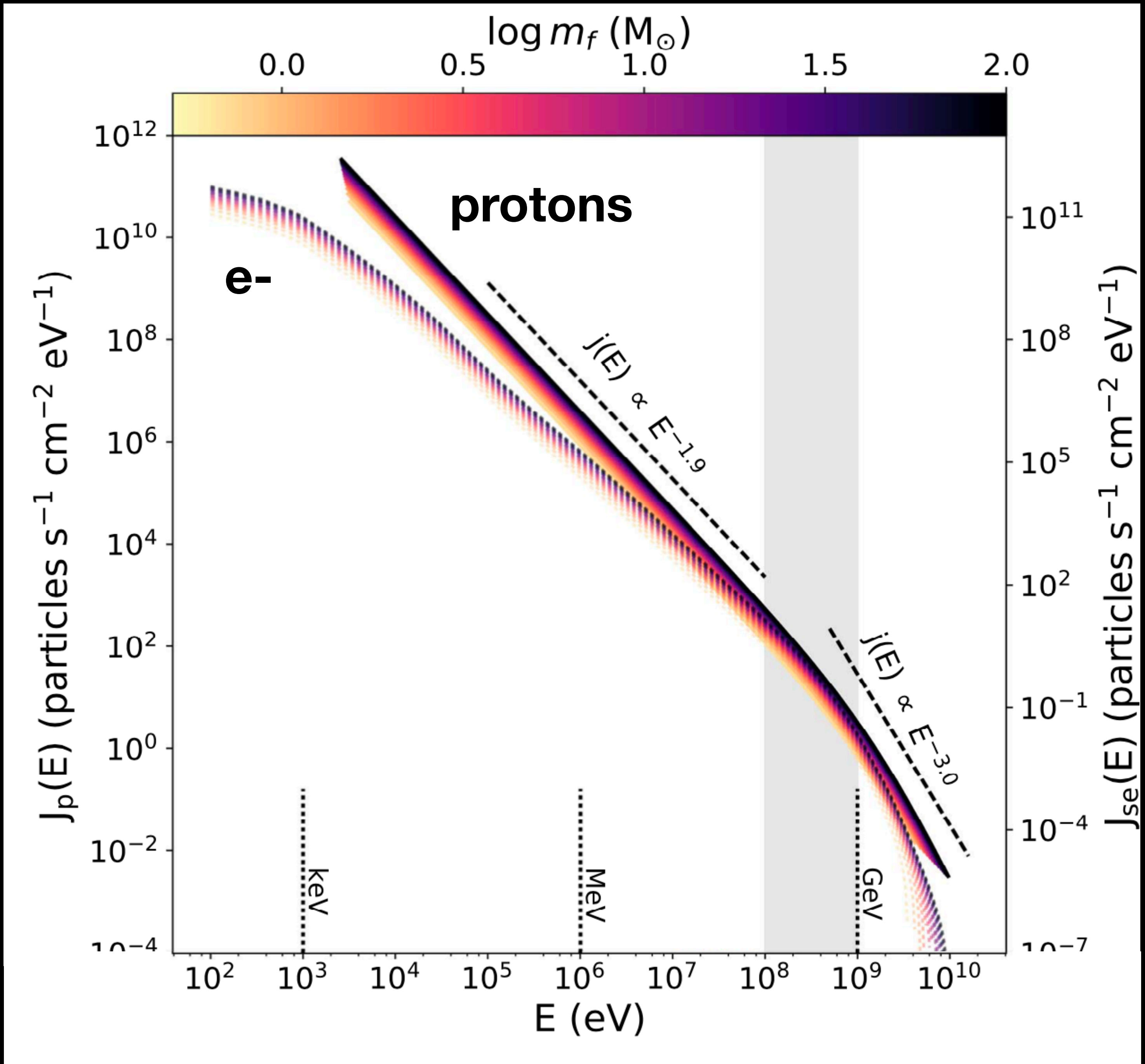


M Flock

Also: Ivlev et al. 2016, Rodgers-Lee ea 2017, Rab et al. 2017ab, Padovani et al. 2018

Protostars: Forges of Cosmic Rays

- **CRs accelerated at the shock by accretion shocks for different stellar masses.**
- **CR are low-energy: E < 20 GeV**
- **… low-energy CRs are primary cause of ionization**



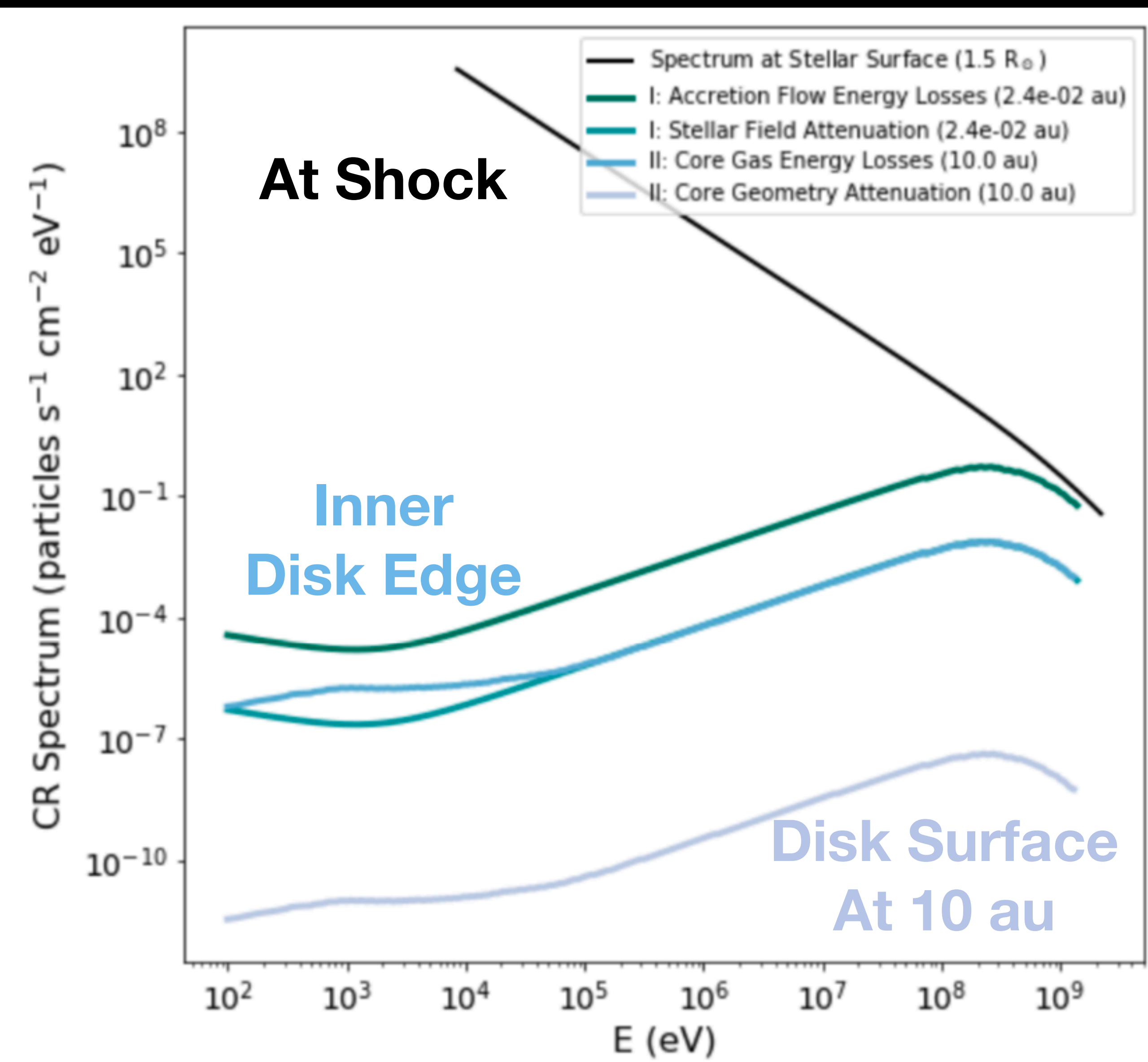
Model Parameters:

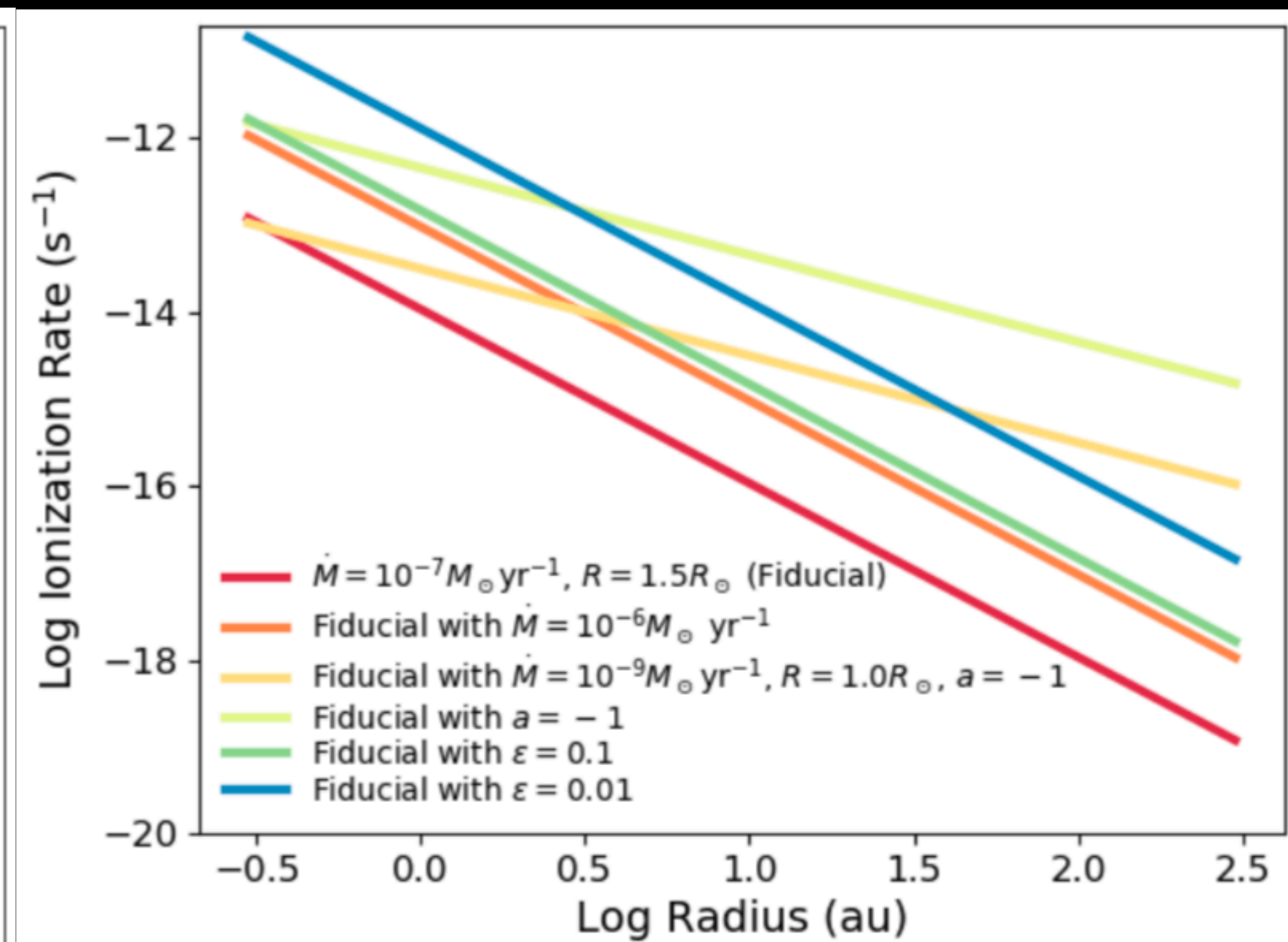
- Loss Function (Padovani ea 2016)
- B field
- Shock velocity
- Temperature
- Ionization fraction
- Accretion rate

Gaches & Offner 2018b

CR Spectrum & Ionization Rate At Disk Surface

Calculate attenuation of CR between the acceleration site and disk:

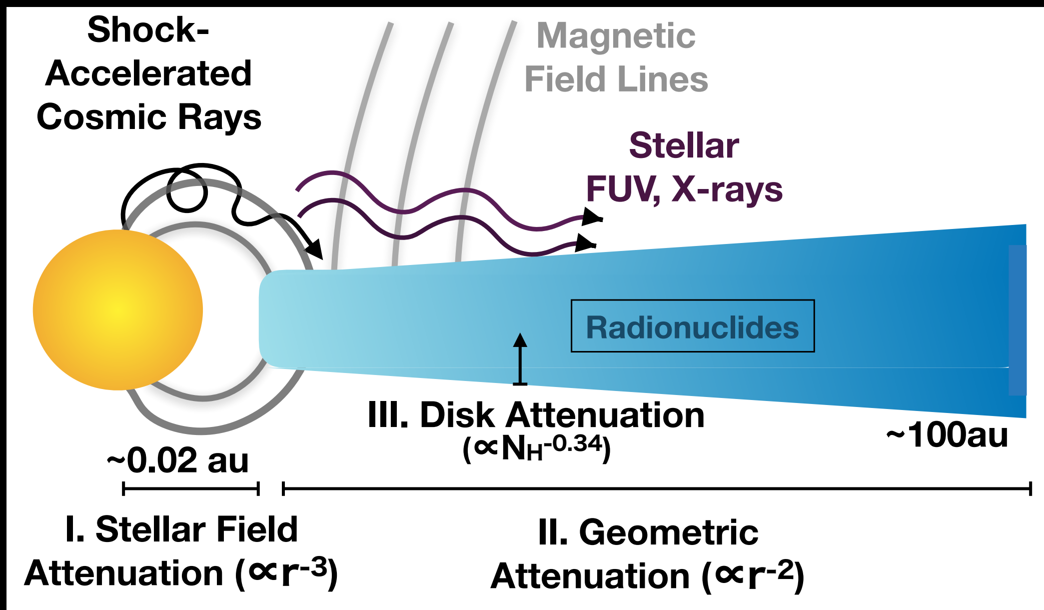




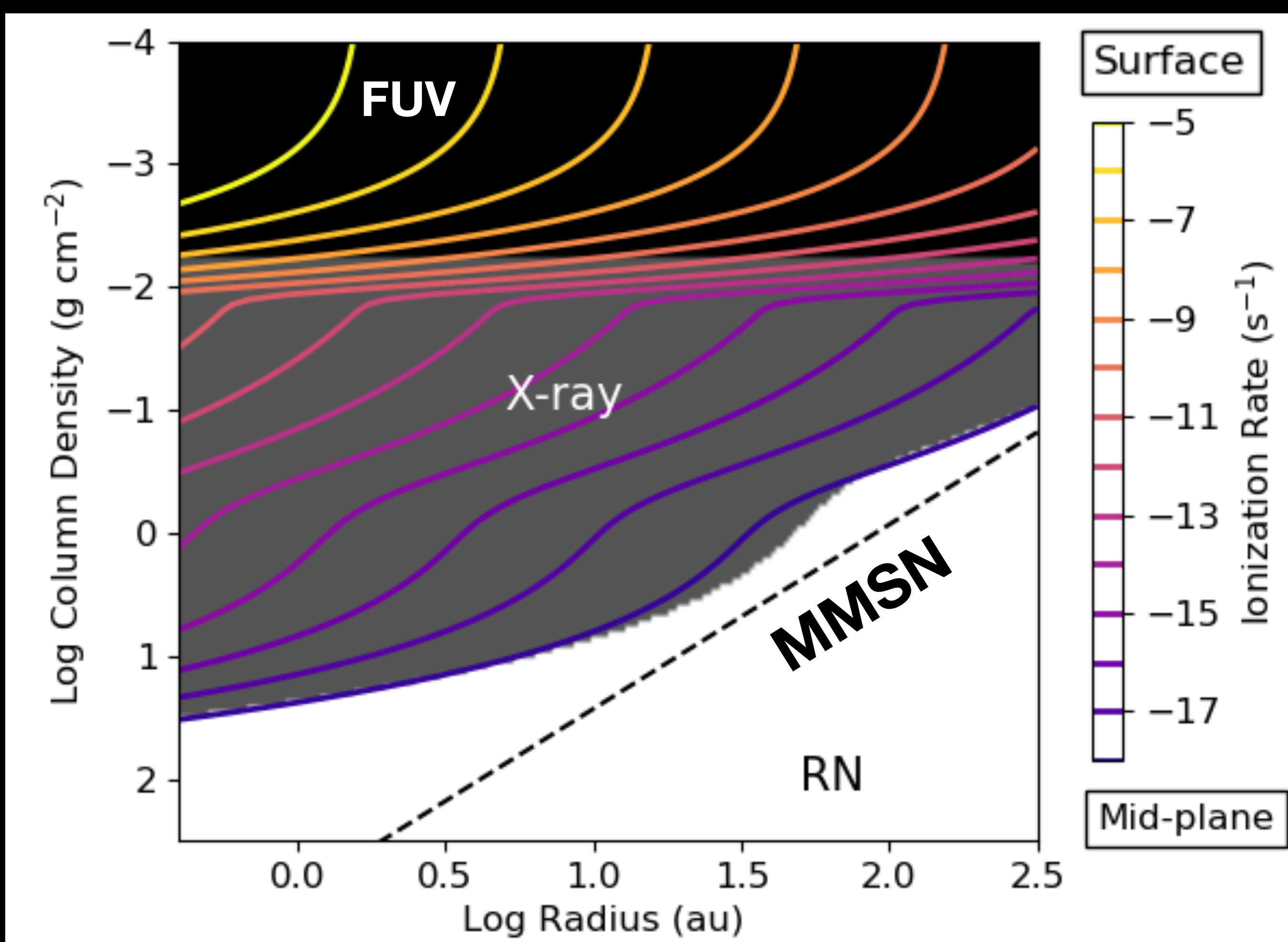
Offner et al. 2019

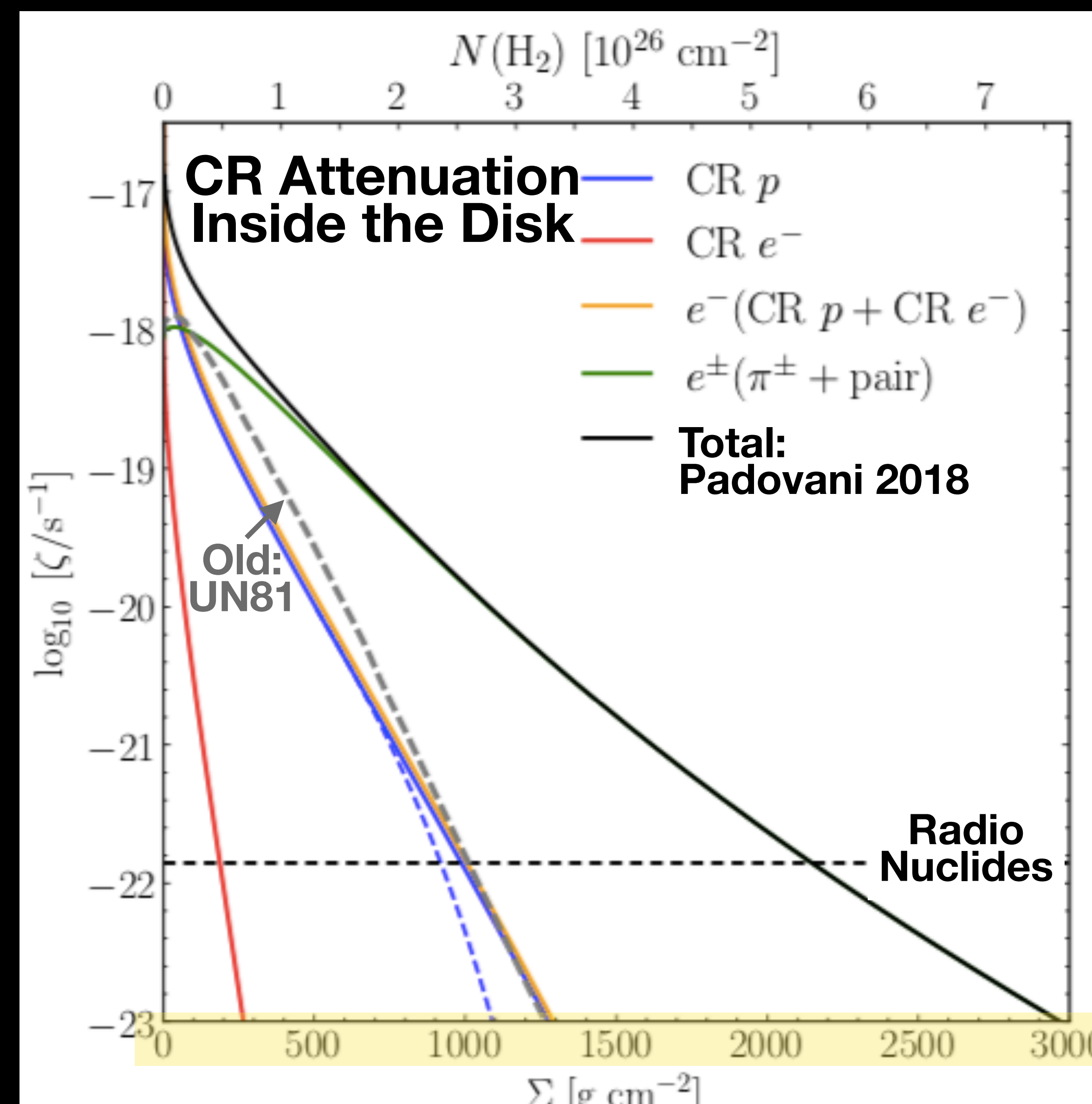
Fiducial Model

CRs Impact Disk Chemistry



- Analytic model for disk density and temperature
- Attenuate ionization rate following Padovani ea 2018:



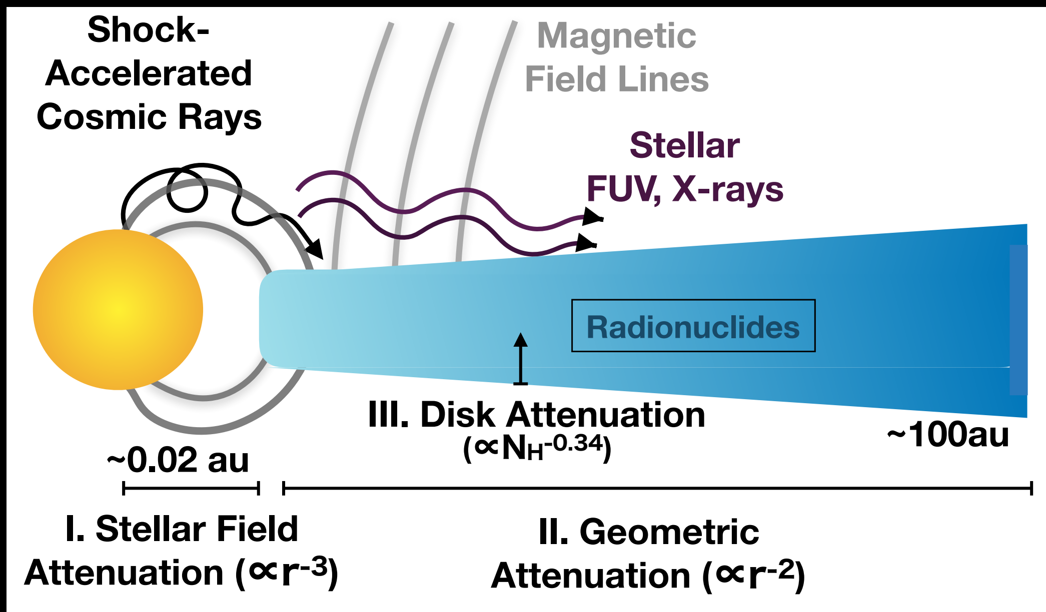


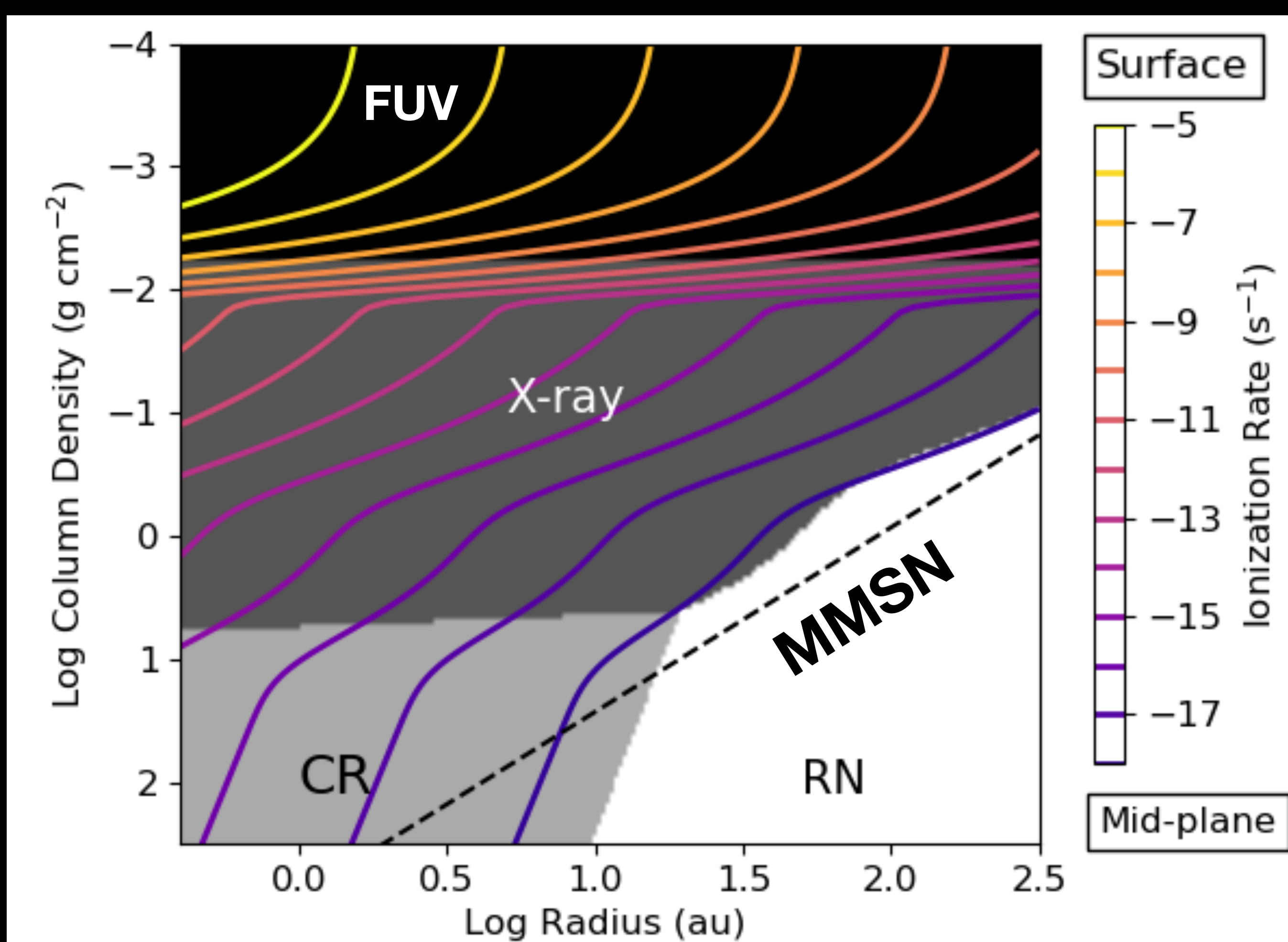
Offner et al. 2019

Padovani ea 2018, Padovani ea 2020, ISSI Review

CRs Mediate Disk Accretion

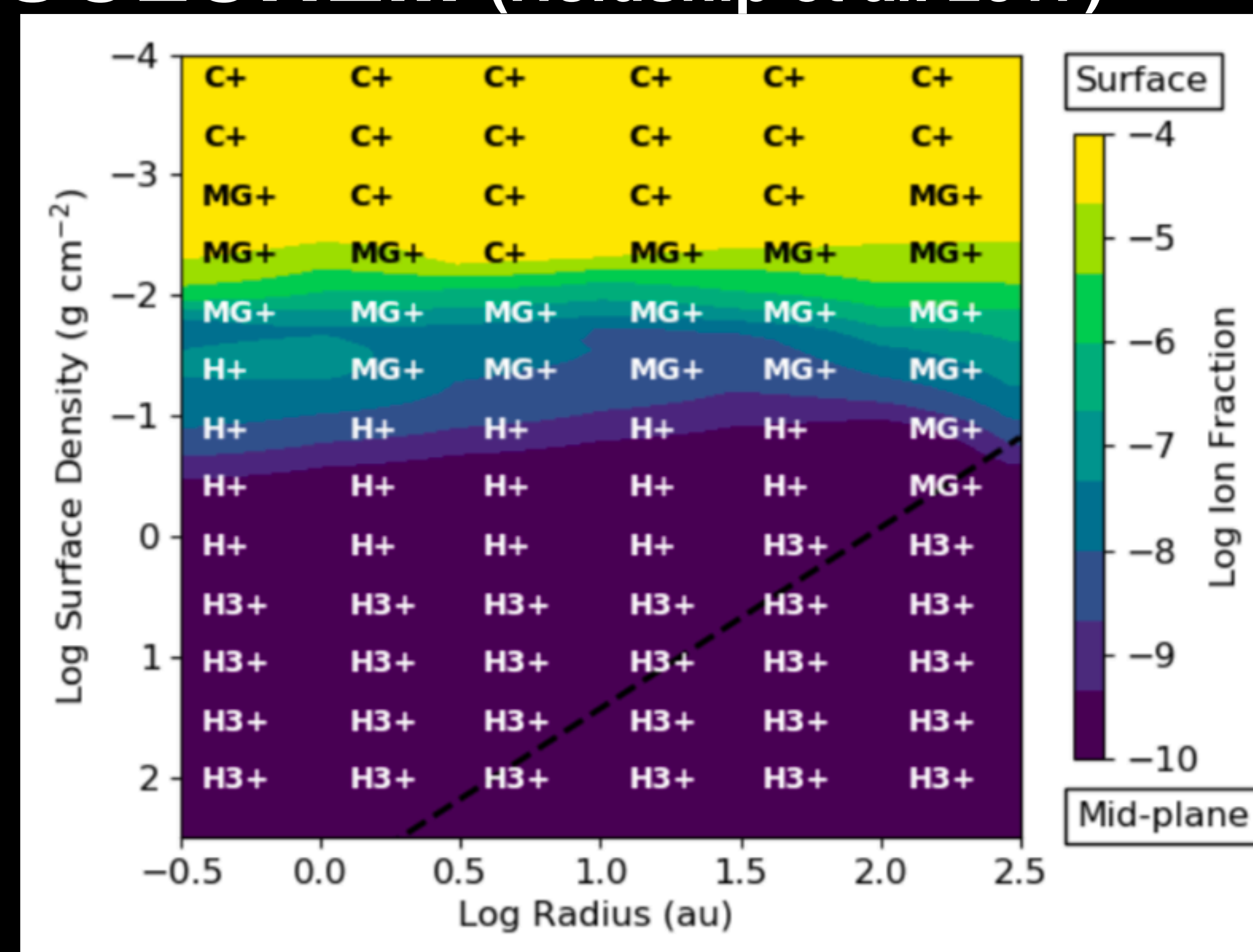
- CRs dominate ionization at disk mid plane, esp. <10au
- Impact depends on accretion rate, CR attenuation, B field coupling
- CRs shape disk chemistry





Offner et al. 2019

UCLCHEM (Holdship et al. 2017)

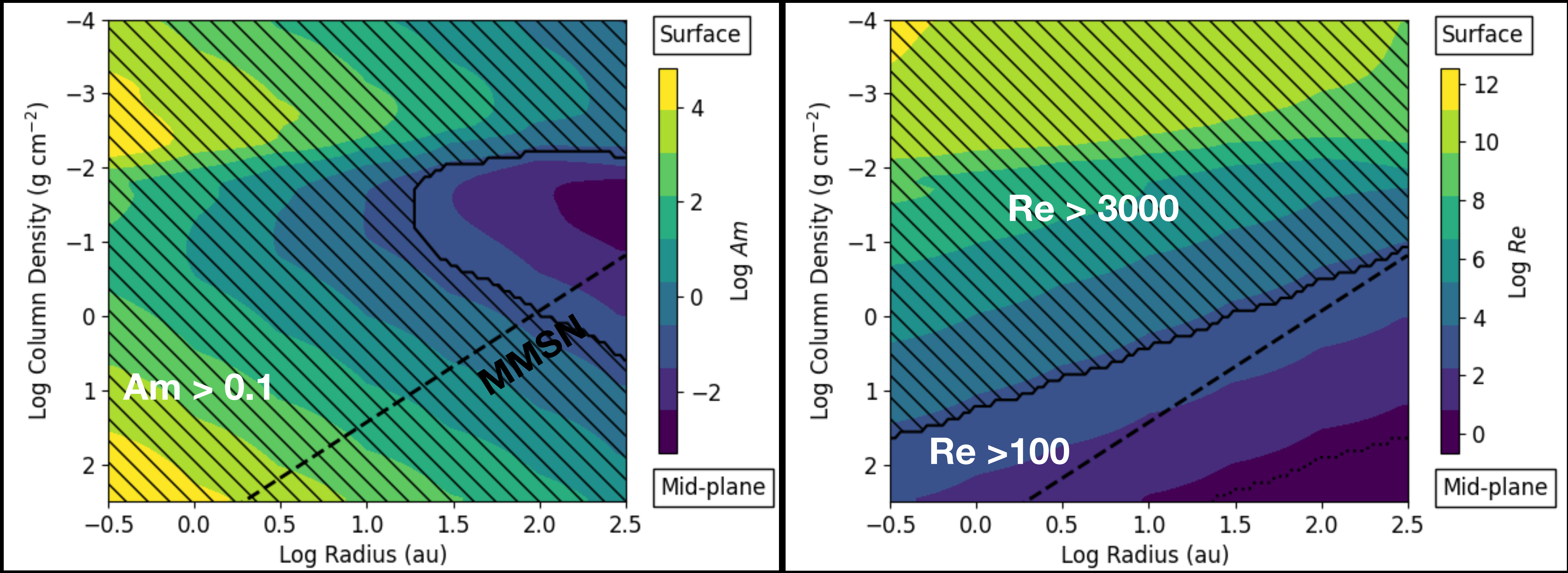


CRs Mediate Disk Accretion

- Estimate the MRI given the magnetic reynolds number (Re) and Ambipolar diffusion number (Am):

$$Am \equiv \frac{n_{\rm charge}\beta_{\rm in}}{\Omega},$$

$$Re \equiv \frac{c_s h}{D} \simeq 1\left(\frac{x_e}{10^{-13}}\right)\left(\frac{T}{100\rm K}\right)^{1/2}\left(\frac{a}{\rm AU}\right)^{3/2}$$

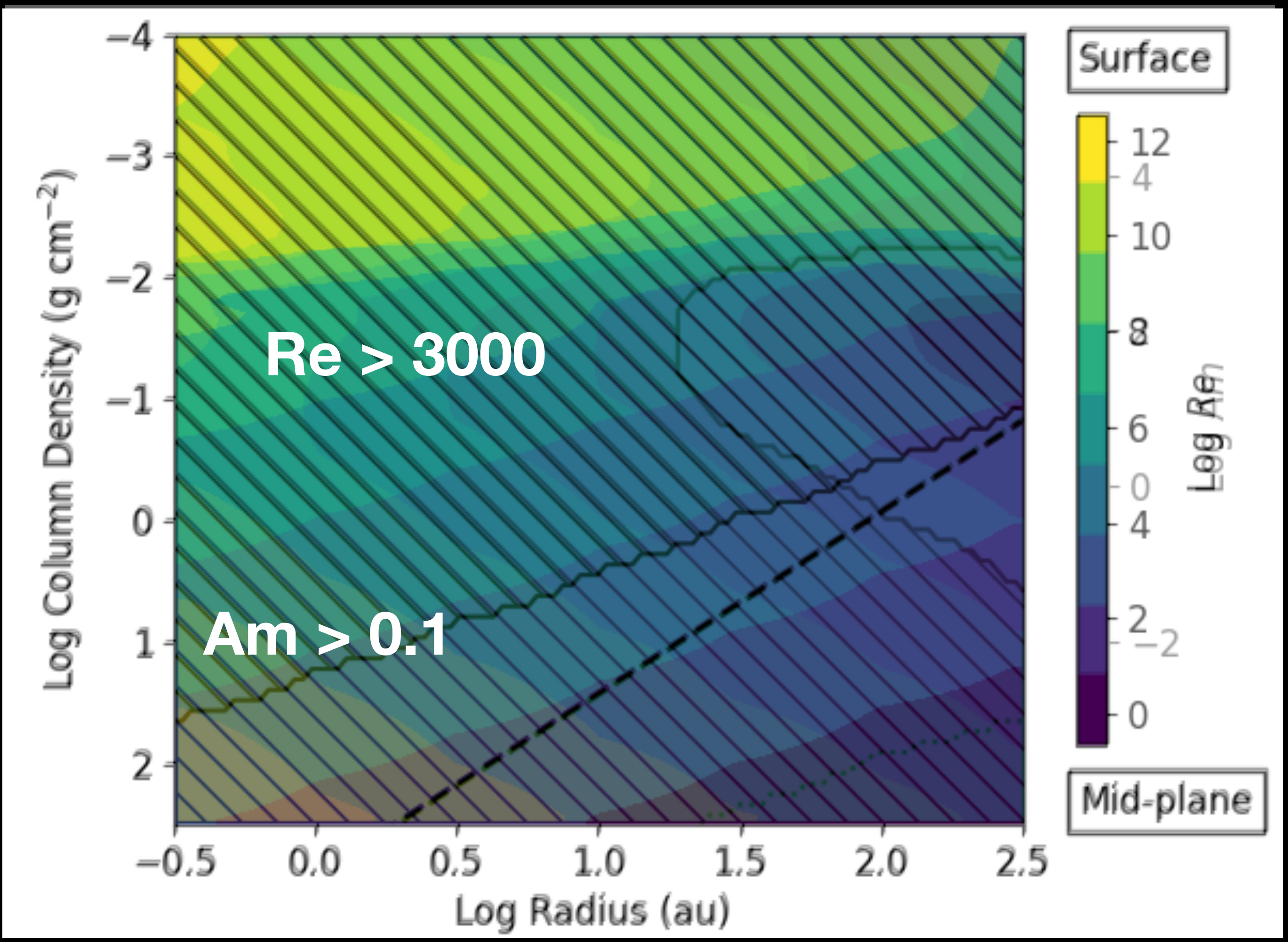


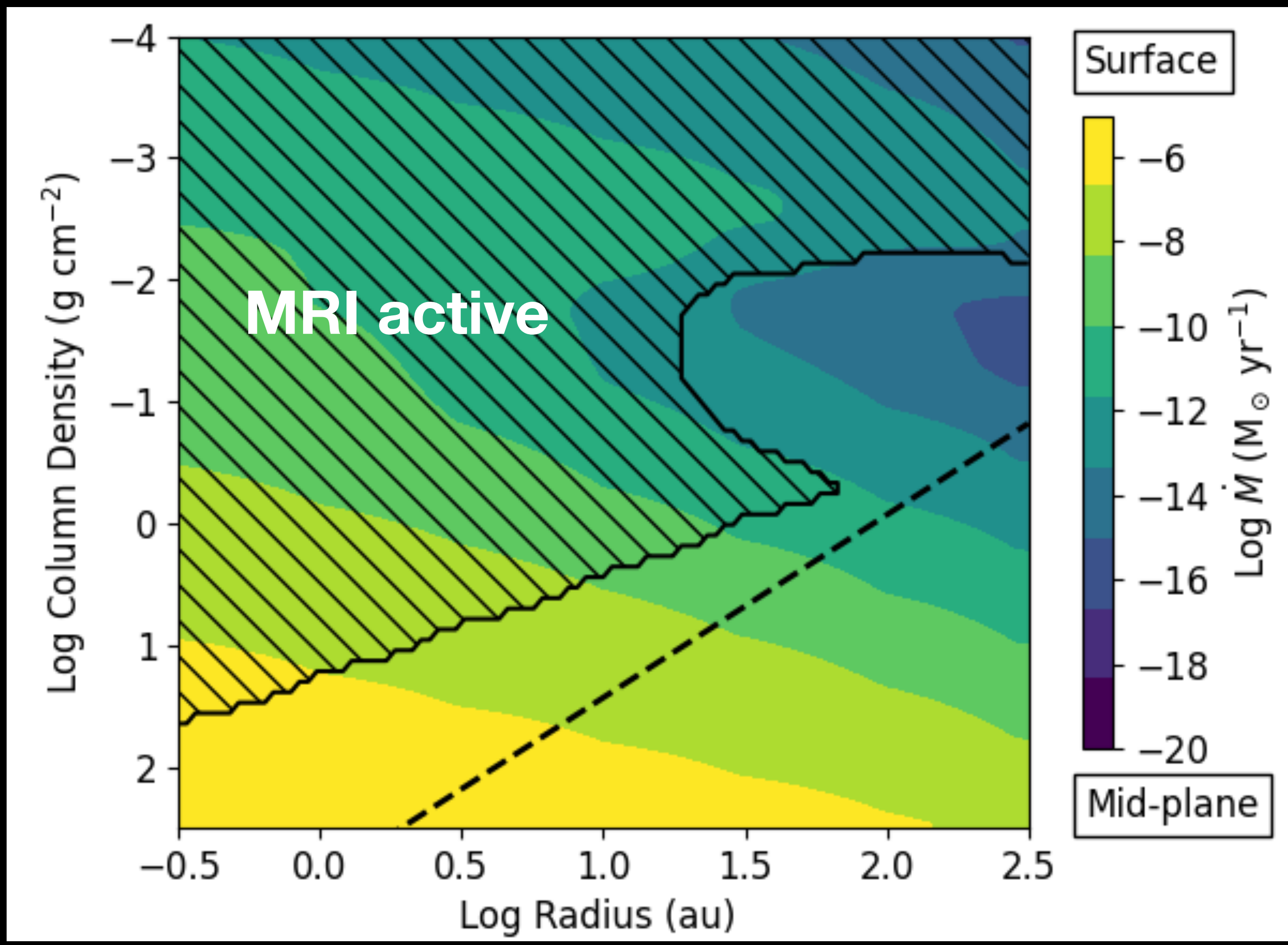
Offner et al. 2019 **with 2022 update**

Also: Bai & Goodman 2009, Perez-Becker & Chiang 2011, Cleeves et al. 2013

CRs Mediate Disk Accretion

- MRI is active but not too active…
- Fiducial case (mdot = 10^{-7} Msun/yr) MRI inactive at mid-plane — in agreement with observations (e.g., Flaherty et al. 2017)

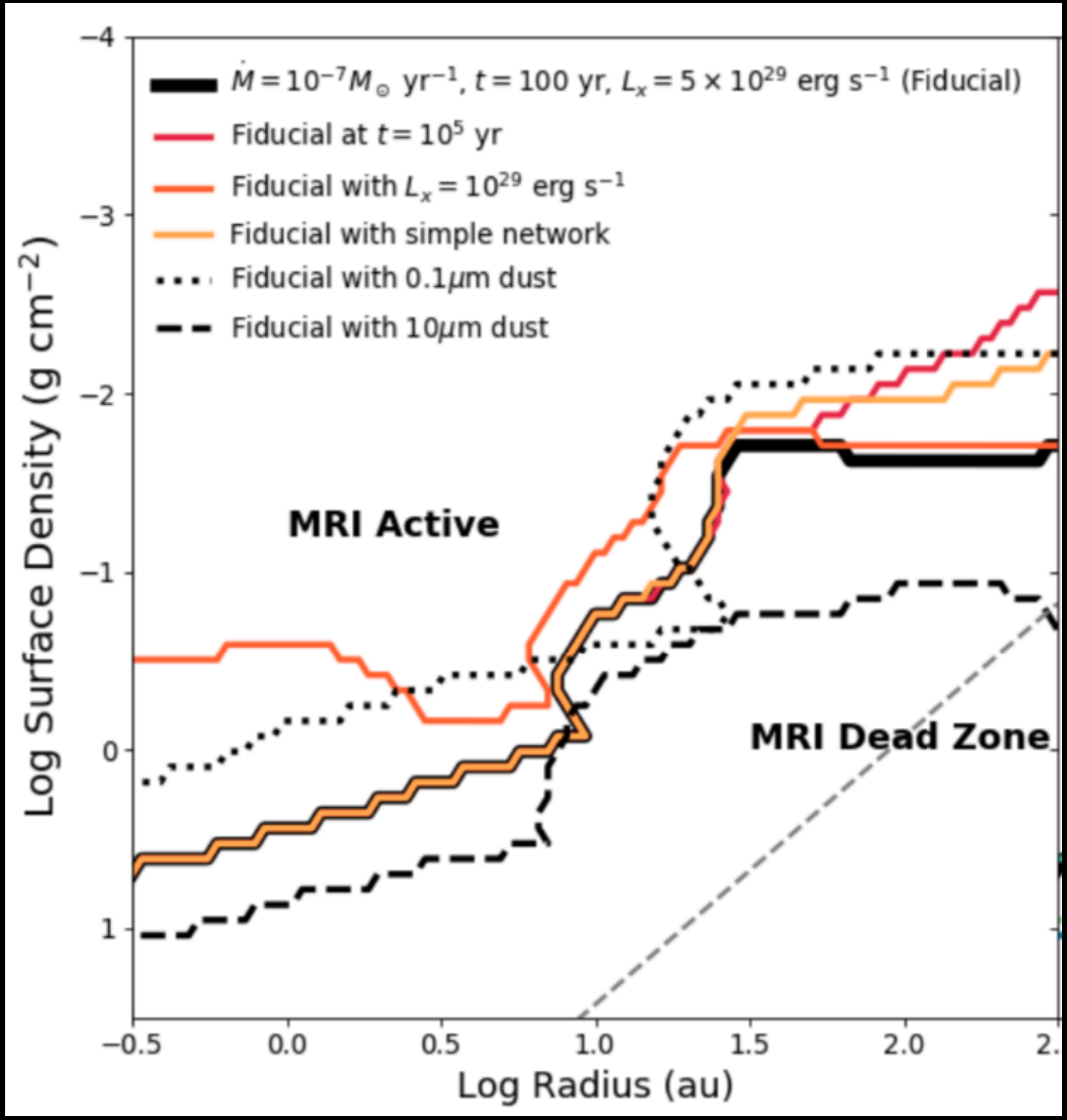




Offner et al. 2019 with 2022 update

Also: Bai & Goodman 2009, Perez-Becker & Chiang 2011, Cleeves et al. 2013

Dust Details Matter



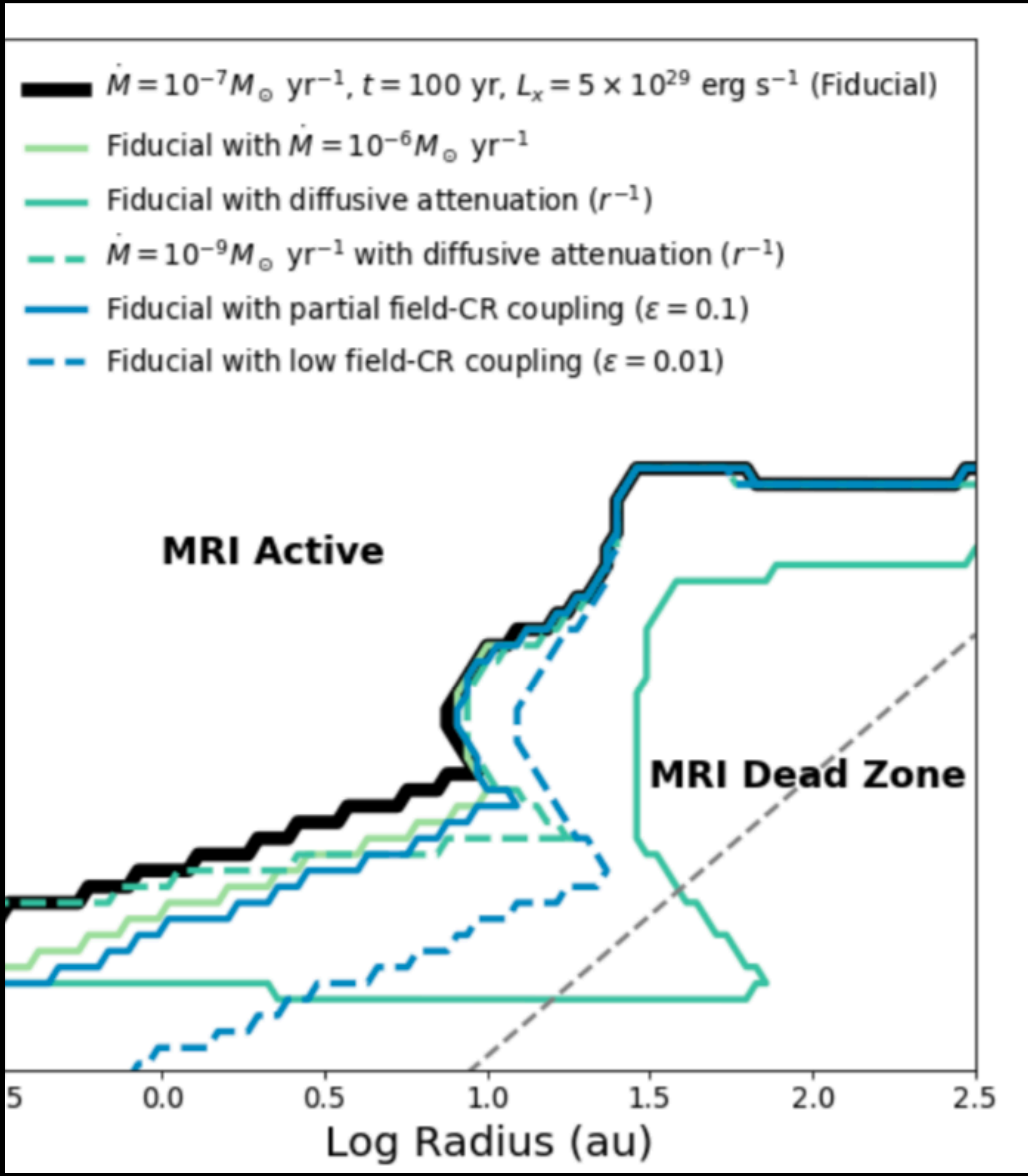
- MRI-active region is mostly independent of chemical network and time
- MRI region is larger for larger dust

Offner et al. 2019

Also: Bai & Goodman 2009, Perez-Becker & Chiang 2011, Cleeves et al. 2013

Transport and CR-B Field Coupling Matters

- MRI-active region increases for higher accretion (a little), diffusive attenuation ($\zeta \propto r^{-1}$) and low B-field coupling.

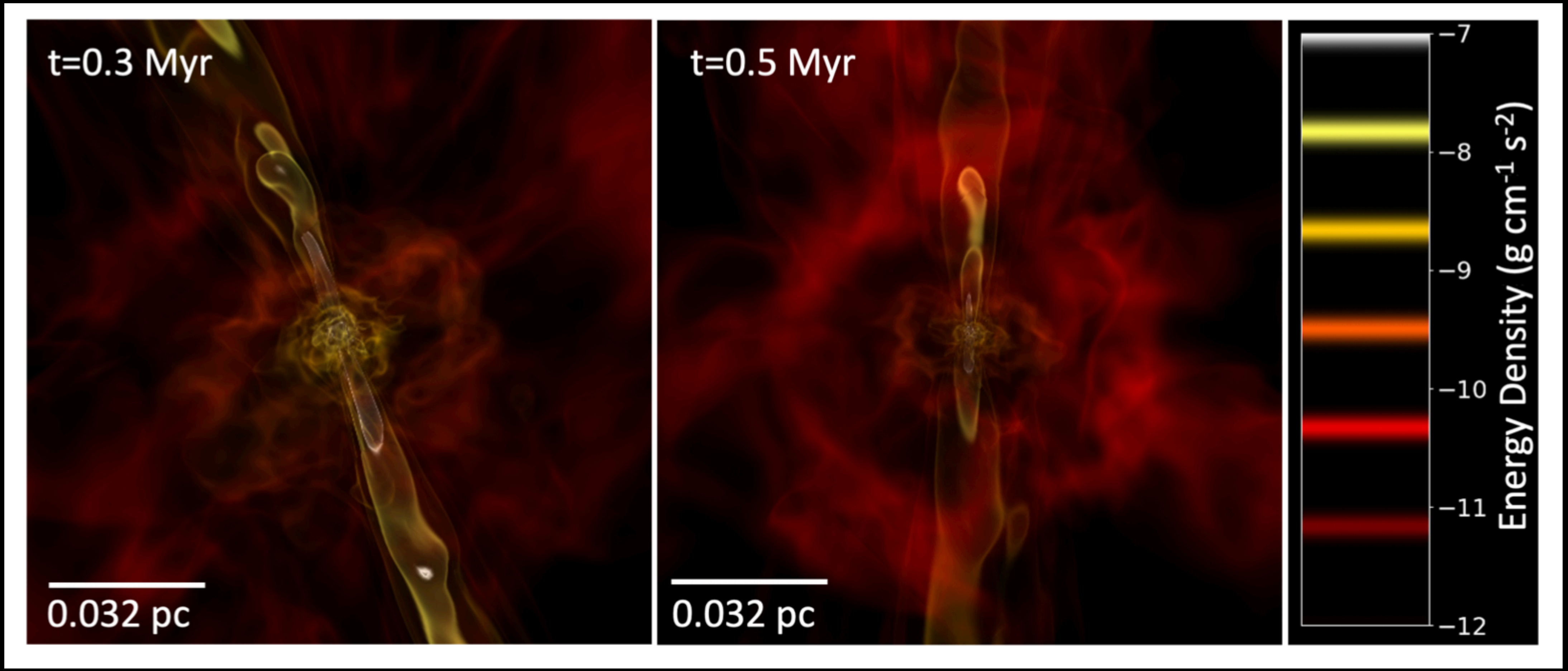


Offner et al. 2019

Also: Bai & Goodman 2009, Perez-Becker & Chiang 2011, Cleeves et al. 2013

What about ionization in the rest of the gas (outside the disk)?

CR Transport through Turbulent Dense Cores (Fitz-Axen ea 2021b)



Simulations of magnetized dense cores
Offner & Chaban 2017

\+

Model for CR Acceleration
Offner & Gaches 2018 / Padovani ea 2016

→

3D MonteCarlo CR Transport
Fitz-Axen ea 2021a

MC-CRT Method

1. Initialize particles with spectrum, random directions at source (protostar)
2. Propagate Δx along field line according to scattering length, where χ in [0,1] (Freyer ea 2007):

$$\Delta x = -\ln(\chi)\lambda_{\rm sc}.$$

$$\lambda_{\rm sc} = c(\gamma\beta)^{2-q} f(\beta_A) \frac{8}{\pi(q-1)\sigma^2 c k_{\rm min}} \left(\frac{c k_{\rm min}}{\Omega}\right)^{2-q}.$$

$f(\beta_A)$ = function of Alfven velocity
q=5/3 index of turbulent power spectrum
kmin = minimum wavenumber of mag. field
σ = magnitude of mag.field fluctuation

3. Apply energy losses

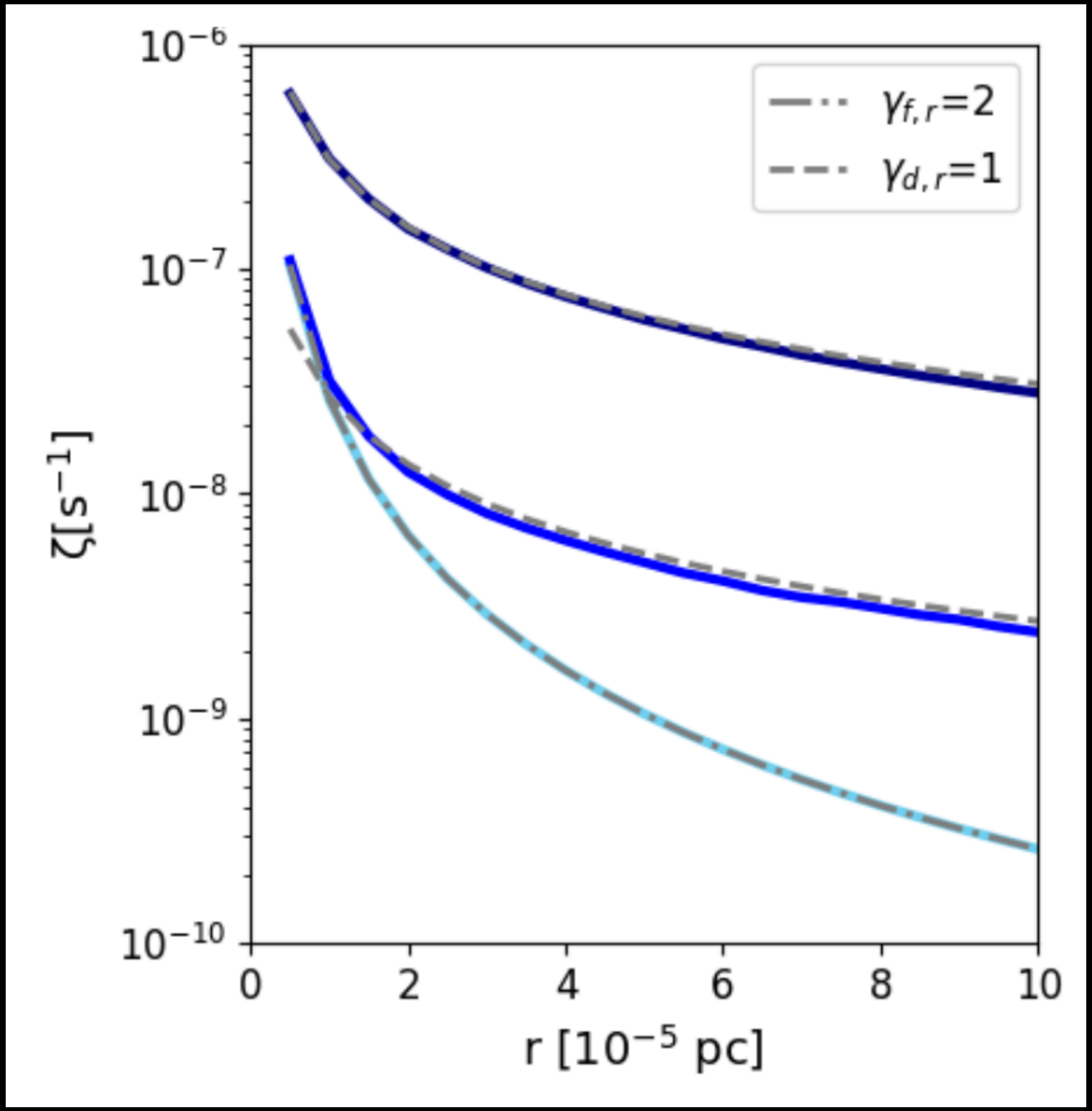
$$L(E) = \frac{1}{n(H_2)}\frac{dE}{dx} = \frac{1}{n(H_2)v}\frac{dE}{dt},$$

4. Calculate new direction, random number χ in [0,1]

$$\sigma^2 = (\frac{1}{b} - 1)^2,\ b = B_0/B_{\rm tot} \text{ where } B_{\rm tot} = B_0 + \delta B$$

$$\chi > b \rightarrow \text{sample randomly}, \chi < b \rightarrow \text{follow field } B_0$$

5. Repeat 2-4 until E below Emin or exit domain

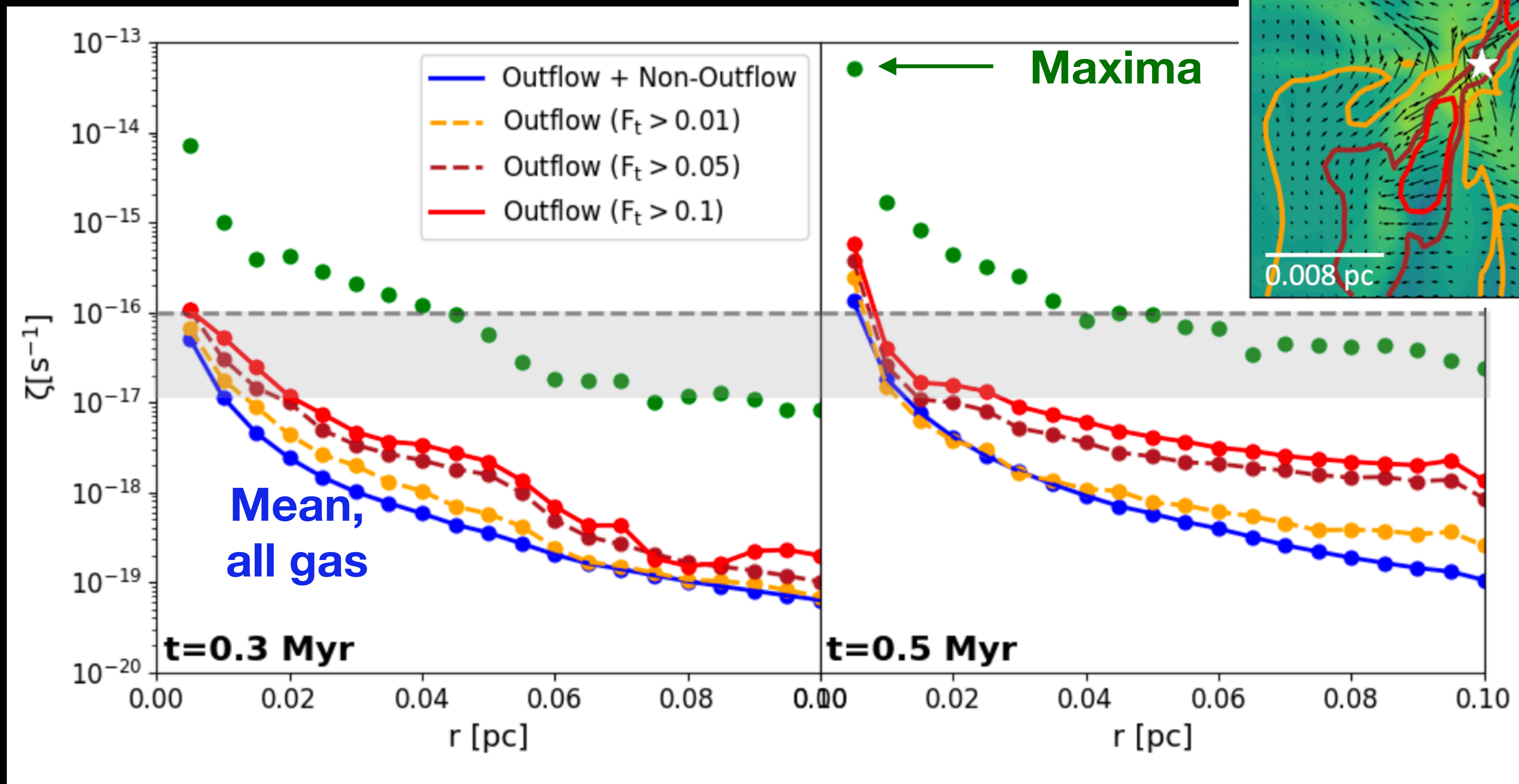


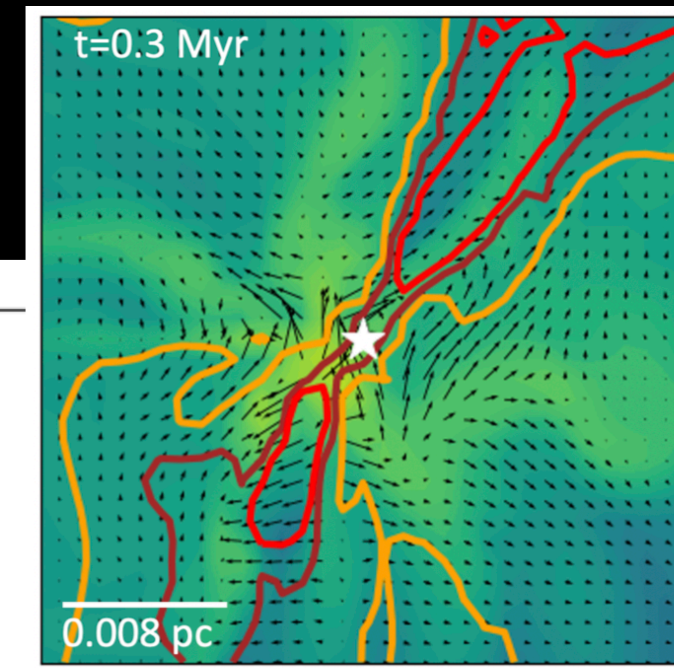
Code results compared to analytic solution for diffusion (always sample direction randomly) and free-streaming propagation (no direction changes); no losses

Fitz-Axen ea 2021a

CR ionization above ISM rate in the inner core

ζ

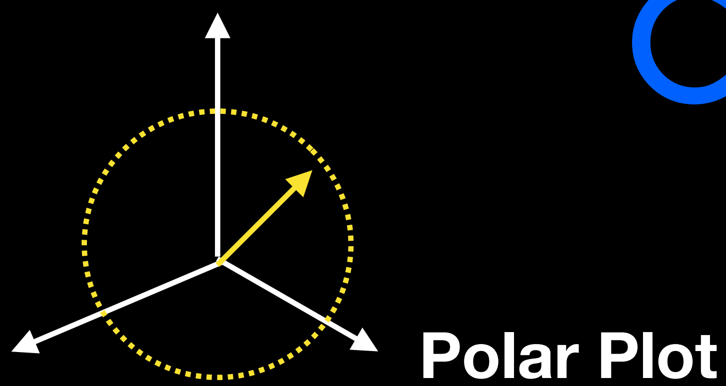


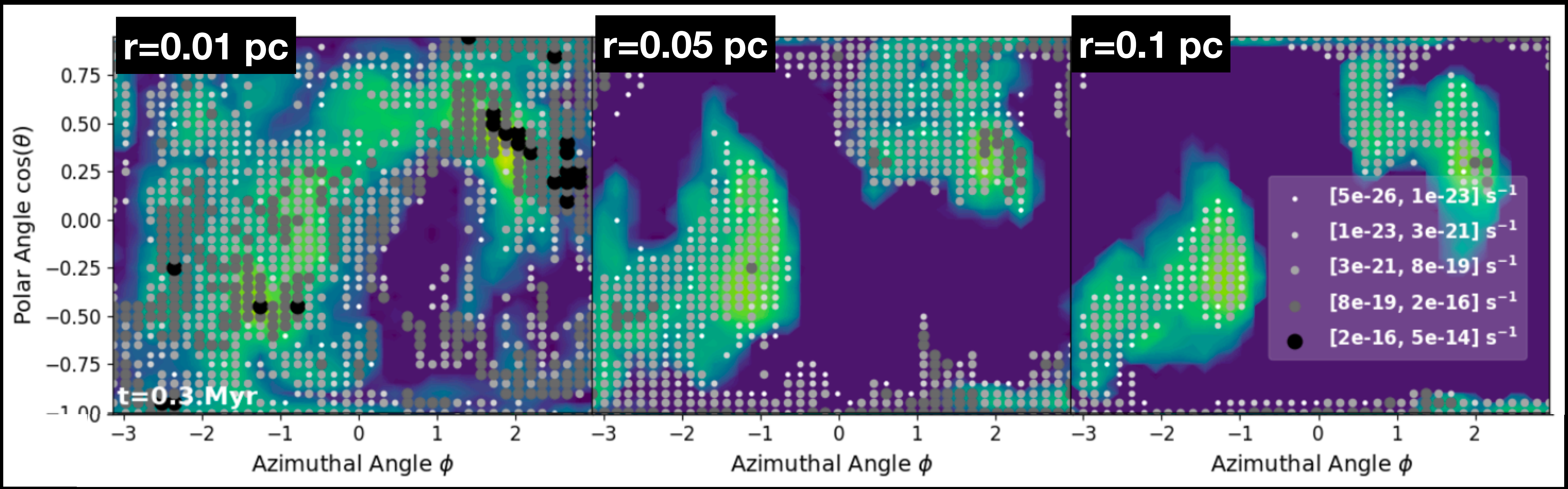


- CR ionization is highly non-uniform (see also Fraschetti ea 2018)
- CR ionization highest in the outflow by x 3-10 (density lower + magnetic collimation)
- CRs may leak out outflow cavity in a 'flashlight' effect

Fitz-Axen ea 2021b

CR Flashlight Effect

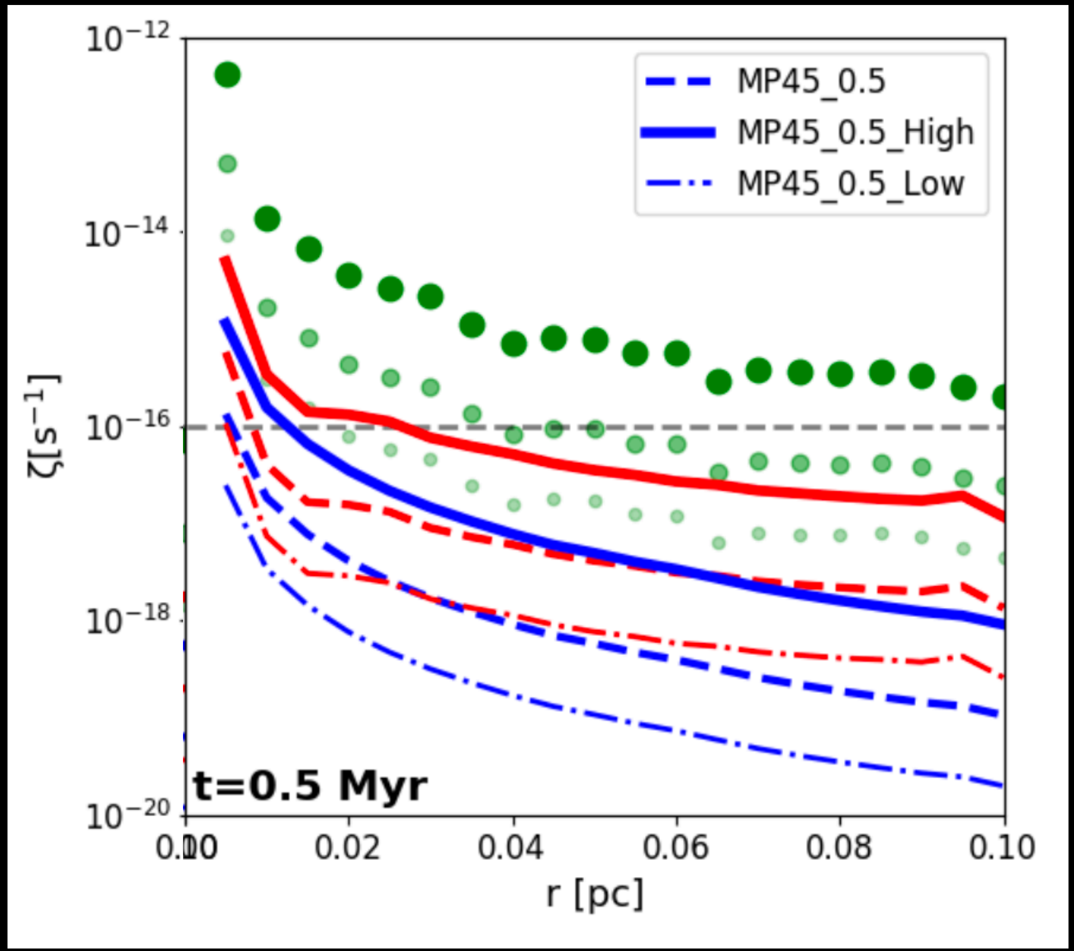




- CRs attenuate geometrically + loose energy while passing through denser core gas
- CRs flux remains high though the outflow cavity

Fitz-Axen ea 2021b

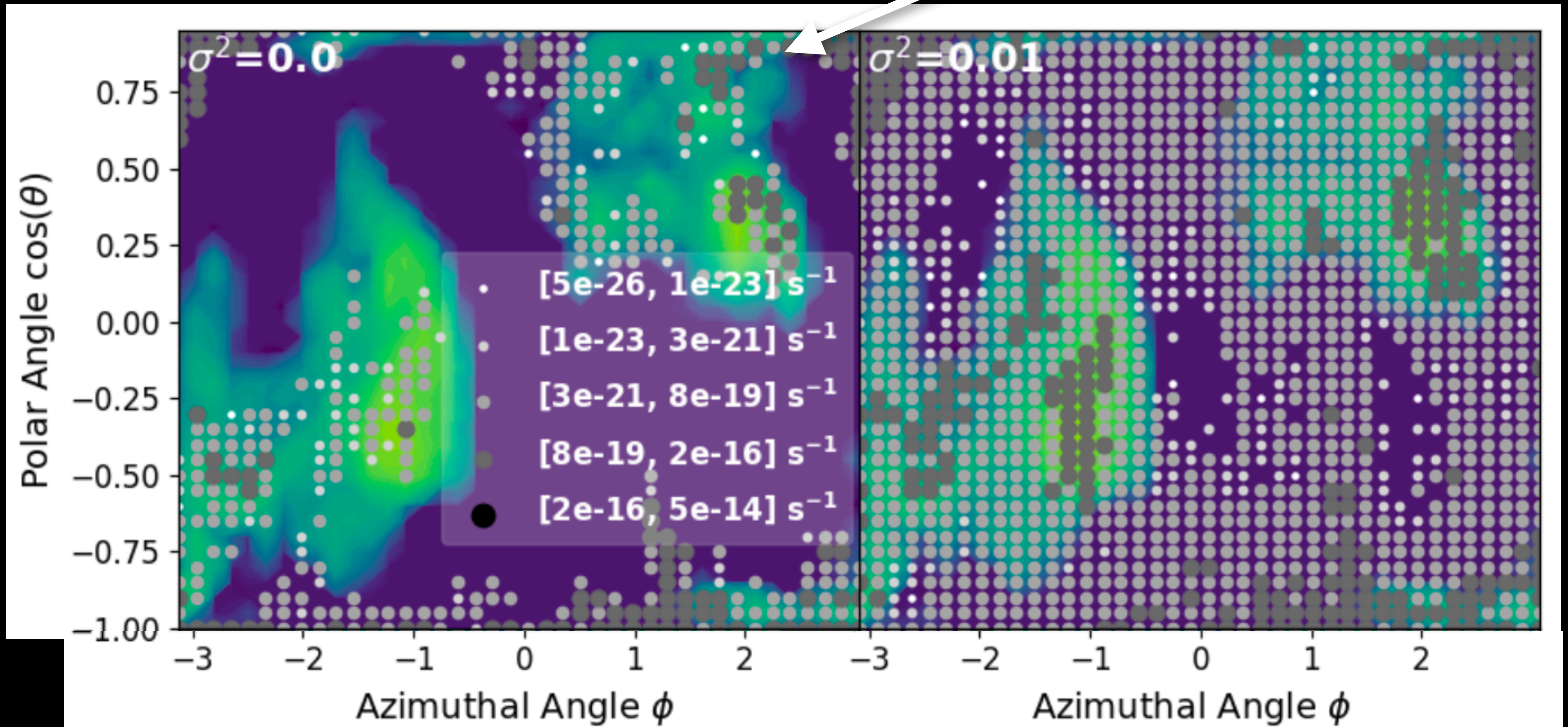
Parameters Matter



- Depends on acceleration model, e.g.:
  $\dot{m} = 10^{-7} - 10^{-5}\ \mathrm{M_\odot\ yr^{-1}}$
  $\eta = 10^{-6} - 10^{-4}$ (Shock acceleration efficiency)

- Depends on assumed random (turbulent) field component:
  $\sigma^2 = (\delta B/B_0)^2$

Streaming

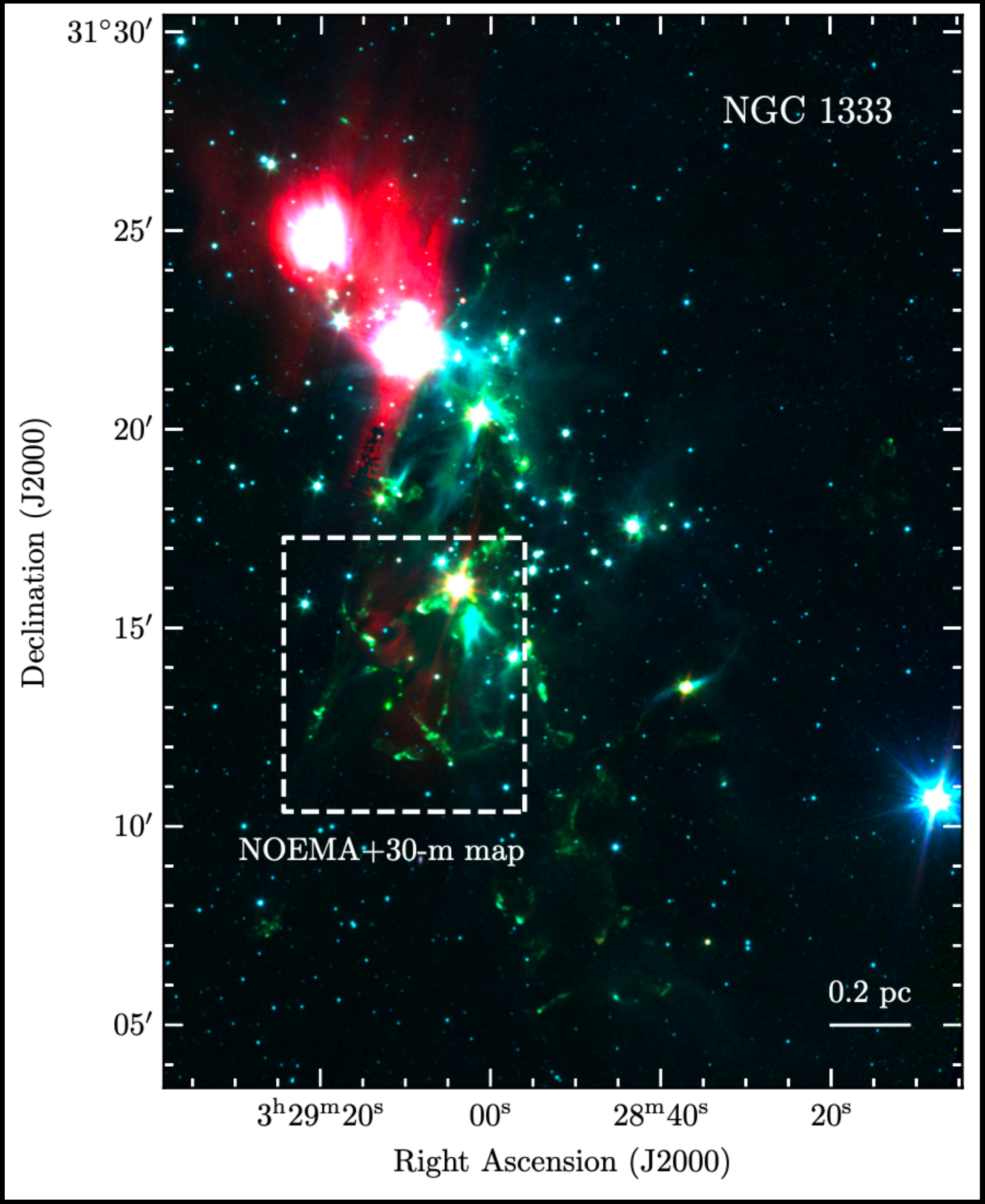


Some Turbulence (Partial diffusion)

Fitz-Axen ea 2021b

Observed Non-Uniform CR Ionization?

- See talk by Jaime Pineda (tomorrow) for map of spatial distribution of CR ionization rate



Pineda et al. in prep

What about the impact of CRs on galaxy scales?

"The CR ionization and gamma-ray budgets of star-forming galaxies" **Krumholz, Crocker & Offner sub (see arXiv tomorrow)**

- Use energy arguments, consider all sources of CR acceleration (SN, winds, jets/accretion, HII regions …)

$$\xi = 10^{-16} \left(\frac{t_{\rm dep}}{\rm Gyr} \right)^{-1} s^{-1} \rightarrow 2 - 5 \times 10^{-17} s^{-1}$$

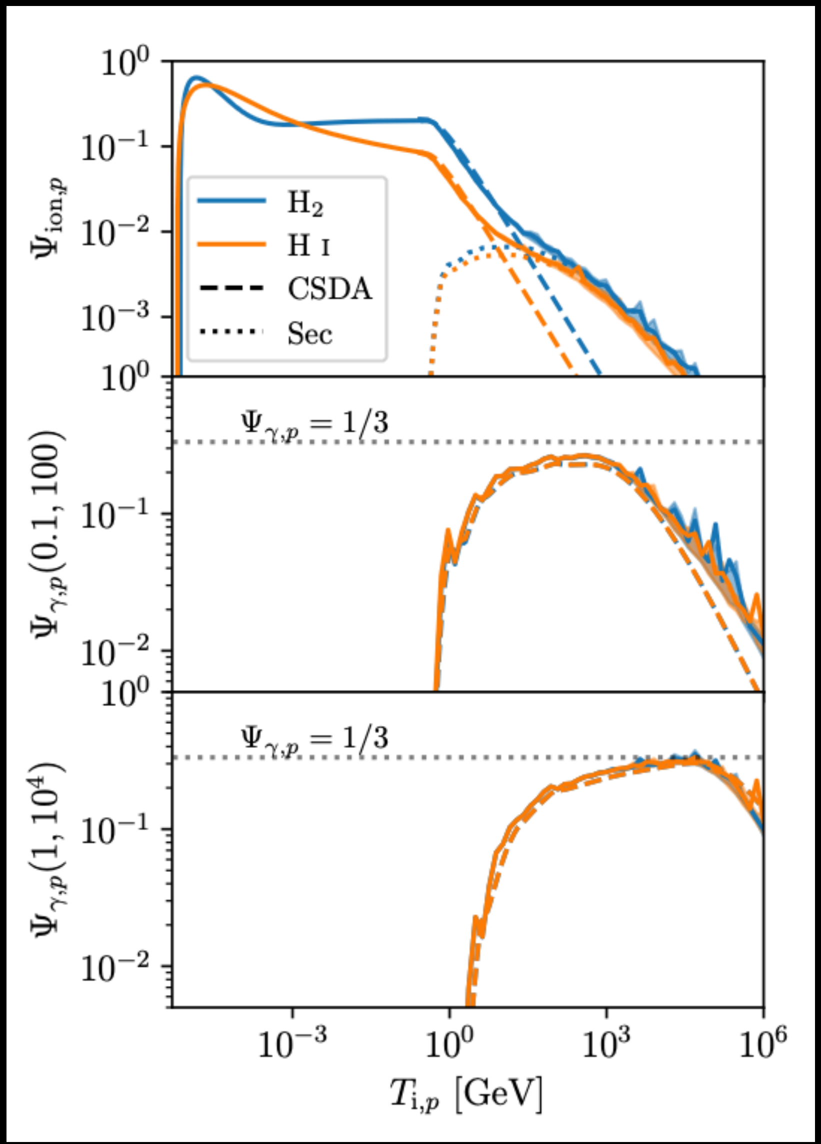
- 2-5 times lower than molecular obs. (e.g., Indriolo ea 2015), consistent with Voyager
- What if non-SNe CR feedback is local?

$$\xi_{\rm mc} = (0.75 + 0.47/f_{\rm mc}) \times 10^{-16} (t_{\rm dep}/{\rm Gyr})^{-1} s^{-1}$$

$$\rightarrow 1.7 - 5.5 \times 10^{-16} {\rm s}^{-1}$$

Ionization Efficiency

Gamma Ray Production Efficiency



Conclusions

★ Low-Energy CRs are accelerated “locally” in protostellar shocks and jets.

★ These CRs play a significant role in disk ionization and chemistry.

★ CR feedback dominates disk ionization rate <10 au for T Tauri disks; enhances region of active MRI.

★ Ionization in cores heterogeneous; locally accelerated CRs may leak out via outflow cavity.

★ Mean CR ionization in the MW is lower than the mean in molecular clouds due to SF CR feedback.