The ionising effect of low energy stellar cosmic rays in protoplanetary disks

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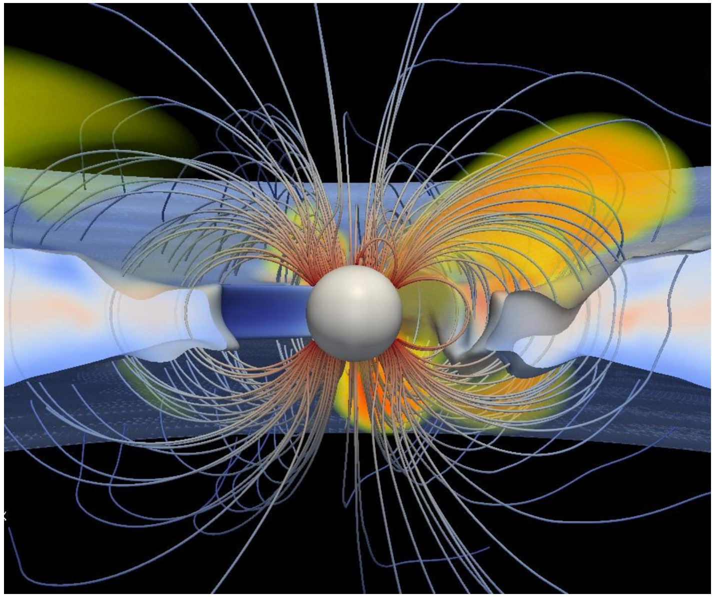
Angular momentum transport

Material loses angular momentum and accretes onto the young star....

If the mechanism is mediated by magnetic fields:

- Magneto-rotational instability (Balbus & Hawley, 1991, Rodgers-Lee et al, 2016)
- Magnetocentrifugally launched winds (Blandford & Payne, 1982)



www.astropa.unipa.it/progetti_ricerca/HPC/research.htm

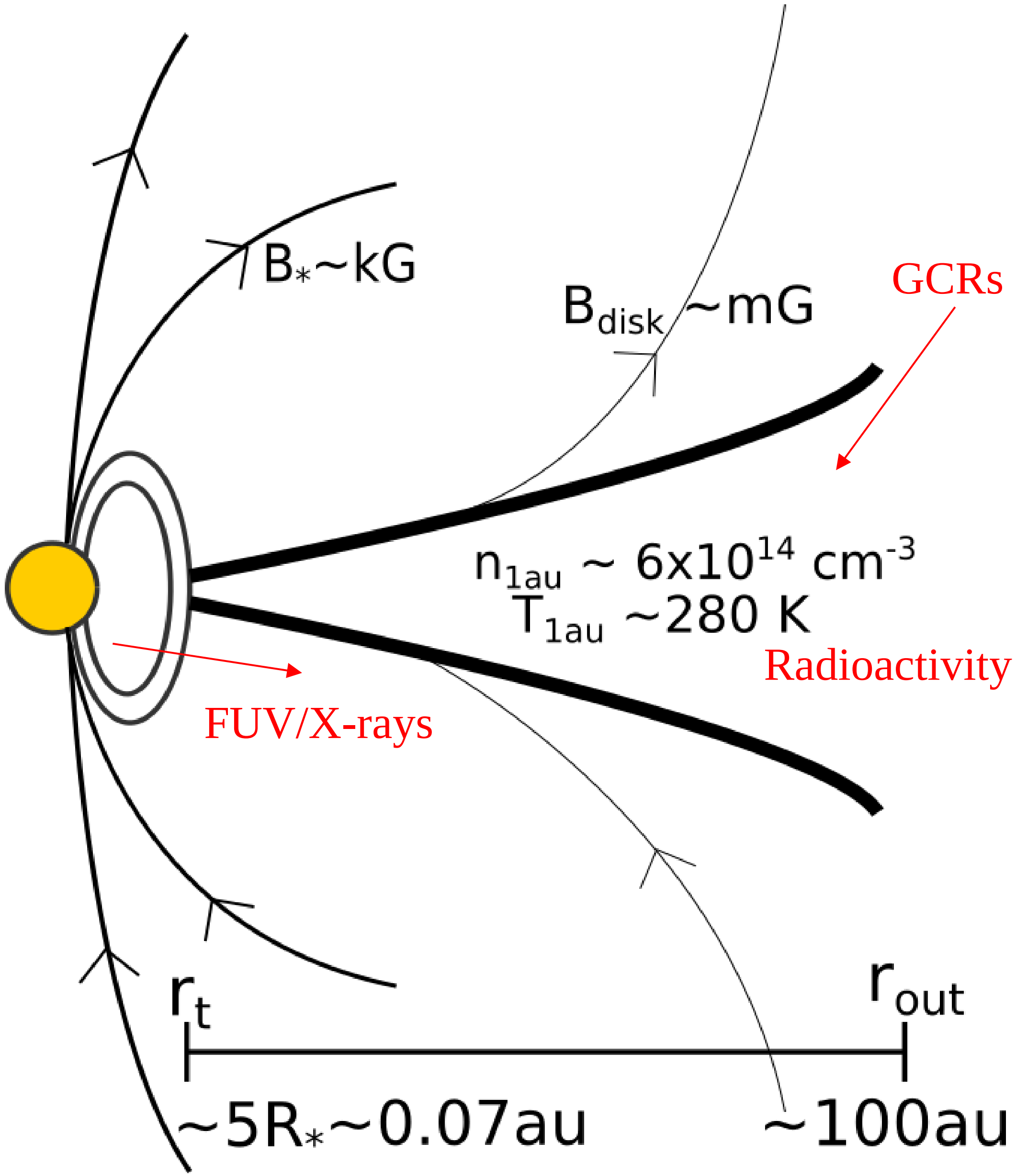
Both require a certain level of ionisation

Sources of ionisation

PPDs are *weakly ionised* by:

- Stellar X-rays/FUV
- Radioactivity
- Cosmic rays -

  Galactic



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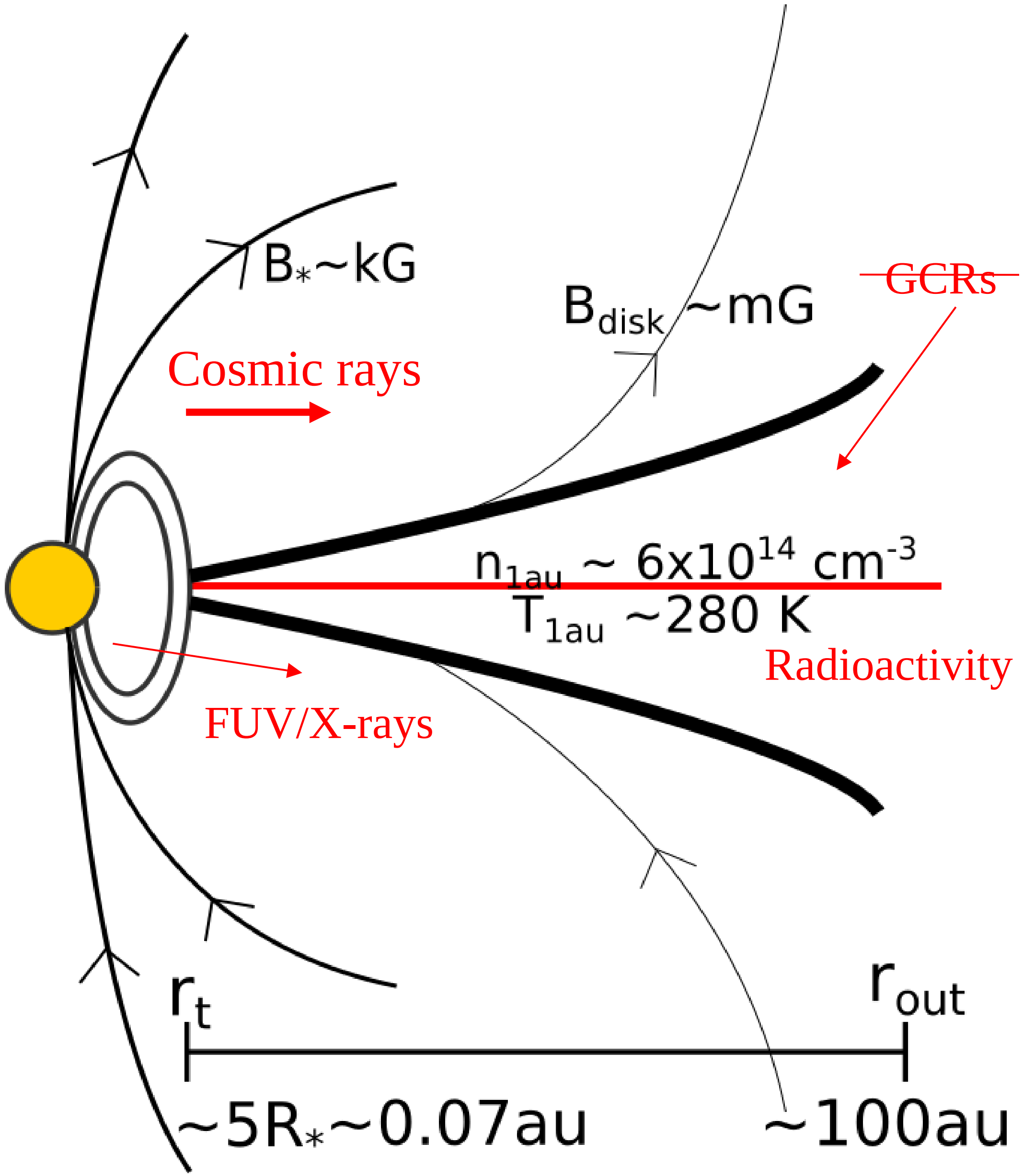
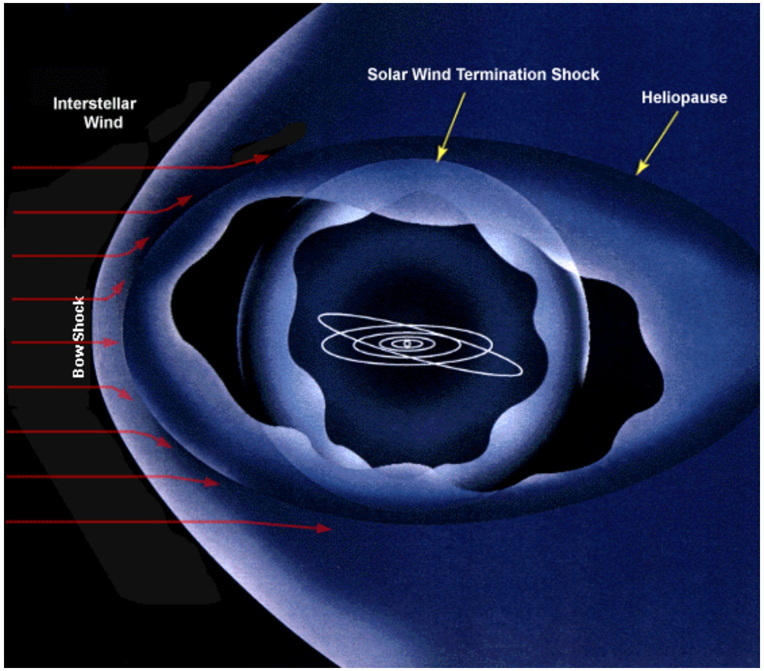
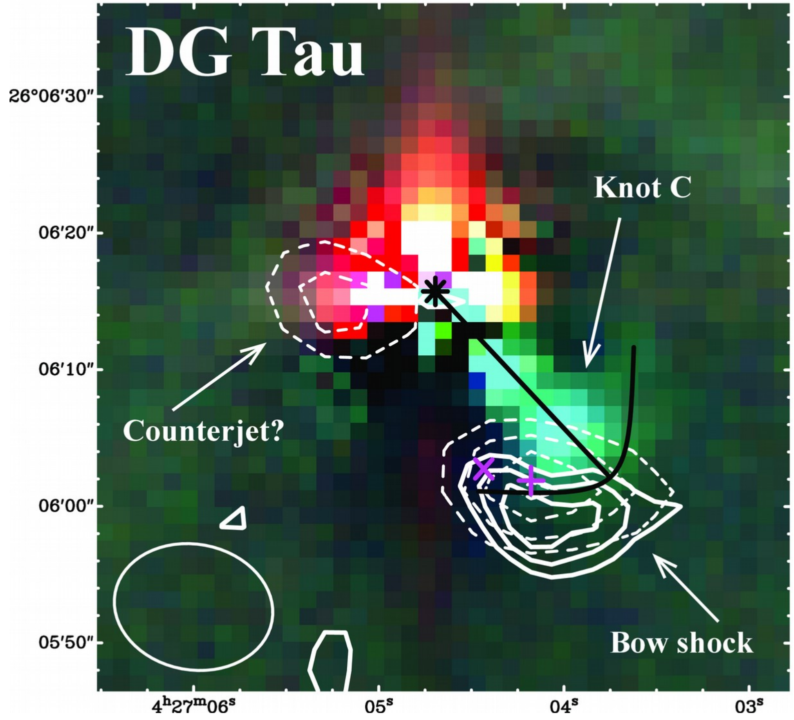


Recent clues...

- Suppression of galactic cosmic rays by stellar heliosphere (Cleeves et al., 2013)
- Acceleration sites (Padovani et al., 2015)
- Cosmic ray transport (Turner & Drake 2009, Rab et al. 2017, DRL et al. 2017, Fraschetti et al. 2018)





Ainsworth et al. (2014)

Observations:

- *Herschel* and $\mathrm{c-C_3H_2}$ observations (Ceccarelli et al., 2014, Favre et al., 2018)
- Non-thermal emission from DG Tau bow shock (Ainsworth et al., 2014)
- Radio flares (Forbrich et al., 2017)
- CO observations (Schwarz et al., 2018)

How to model cosmic rays

Propagation of cosmic rays:

- Can be treated as a diffusive process
- Simplest analytic model gives $\sim \frac{1}{r}$ distribution

X-rays give $\sim \frac{1}{r^2}$ distribution

CRs: More effective source of ionisation at large radii

Sites of acceleration: Inner edge of accretion disk, accretion shock, knots in jets...

Cosmic ray density from the young star

Solar x-ray luminosity (Peres et al 2002)

$$L_{\odot}^{\mathrm{X}} \sim 5 \times 10^{27} \mathrm{erg\,s^{-1}}$$

Solar cosmic rays (solar wind)

$$L_{\odot}^{\mathrm{CR}} \sim L_{\odot}^{\mathrm{SW}} \sim 1 \times 10^{27} \mathrm{erg\,s^{-1}}$$

YSOs are more magnetically active (Feigelson & Montemerle 1999)

$$L_{*}^{\mathrm{X}} \sim 1 \times 10^{29} \mathrm{erg\,s^{-1}}$$

$$L_{*}^{\mathrm{CR}} \sim L_{\odot}^{\mathrm{CR}} \frac{L_{*}^{\mathrm{X}}}{L_{\odot}^{\mathrm{X}}} \sim 1 \times 10^{28} \mathrm{erg\,s^{-1}}$$

Formulation & diffusion equation

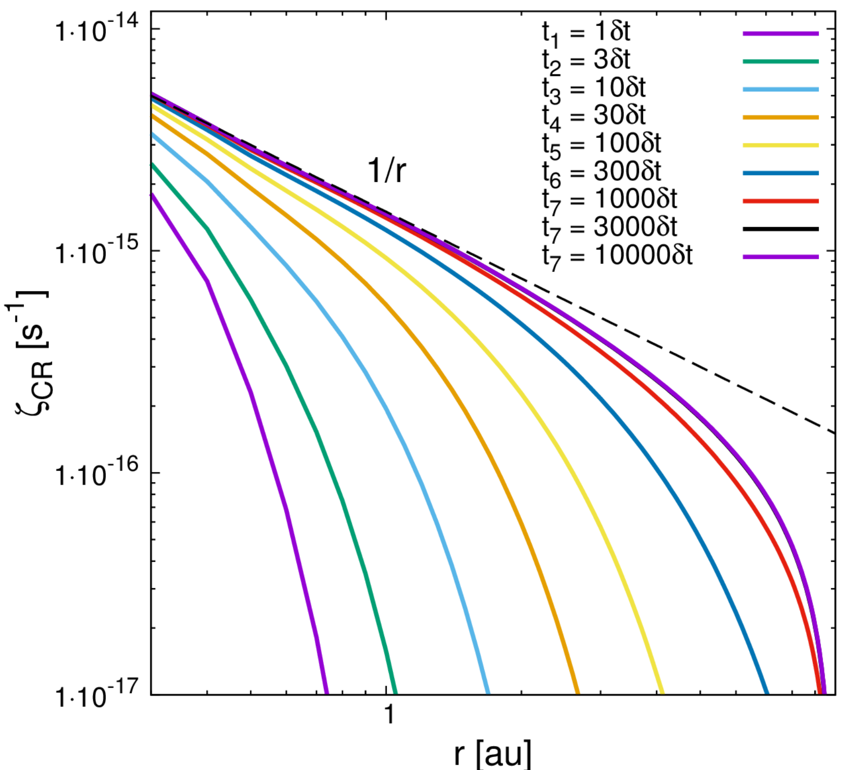
Calculate for ~GeV particles (minimally ionising but very abundant):

$$\frac{\partial n_{\rm CR}}{\partial t} = \nabla \cdot (D \nabla n_{\rm CR}) - \frac{n_{\rm CR}}{\tau} - \vec{v} \cdot \nabla n_{\rm CR} + Q$$

Steady-state

$$\frac{D(r,z)}{c} \propto \left(\frac{B}{\delta B}\right)^2 r_L$$

$$\frac{1}{\tau_{\rm GeV}(r,z)} = \frac{1}{E_{\rm GeV}} c\rho \left(\frac{dE_{\rm GeV}}{d\chi}\right)$$



Convert number density of cosmic rays to an ionisation rate:

$$\zeta_{\rm CR}(r,z) = 2.2 \times 10^{-18} {\rm s}^{-1} \frac{n_{\rm CR}(r,z)}{4 \times 10^{-10} {\rm cm}^{-3}}$$

Umebayashi & Nakano (1981)

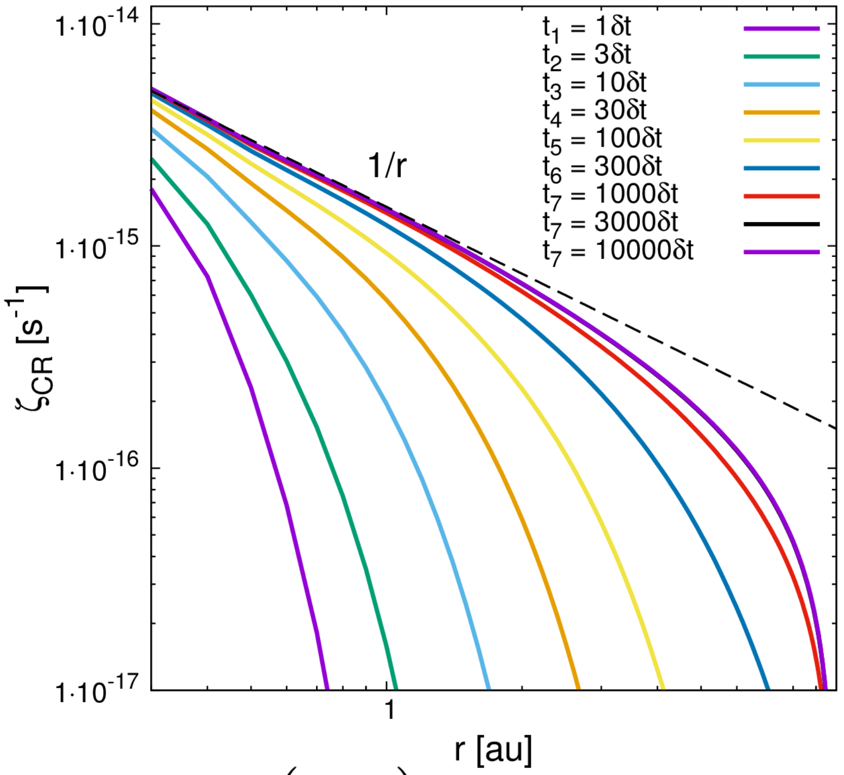
Formulation & diffusion equation

Steady-state

$$\frac{n_{\rm CR}}{\tau} = \nabla \cdot (D \nabla n_{\rm CR}) + Q$$

$$\frac{D(r,z)}{c} \propto \left(\frac{B}{\delta B}\right)^2 r_L$$

GeV particle in mG ~ 10^{-4} au
(gives lower limit for diffusion coefficient)



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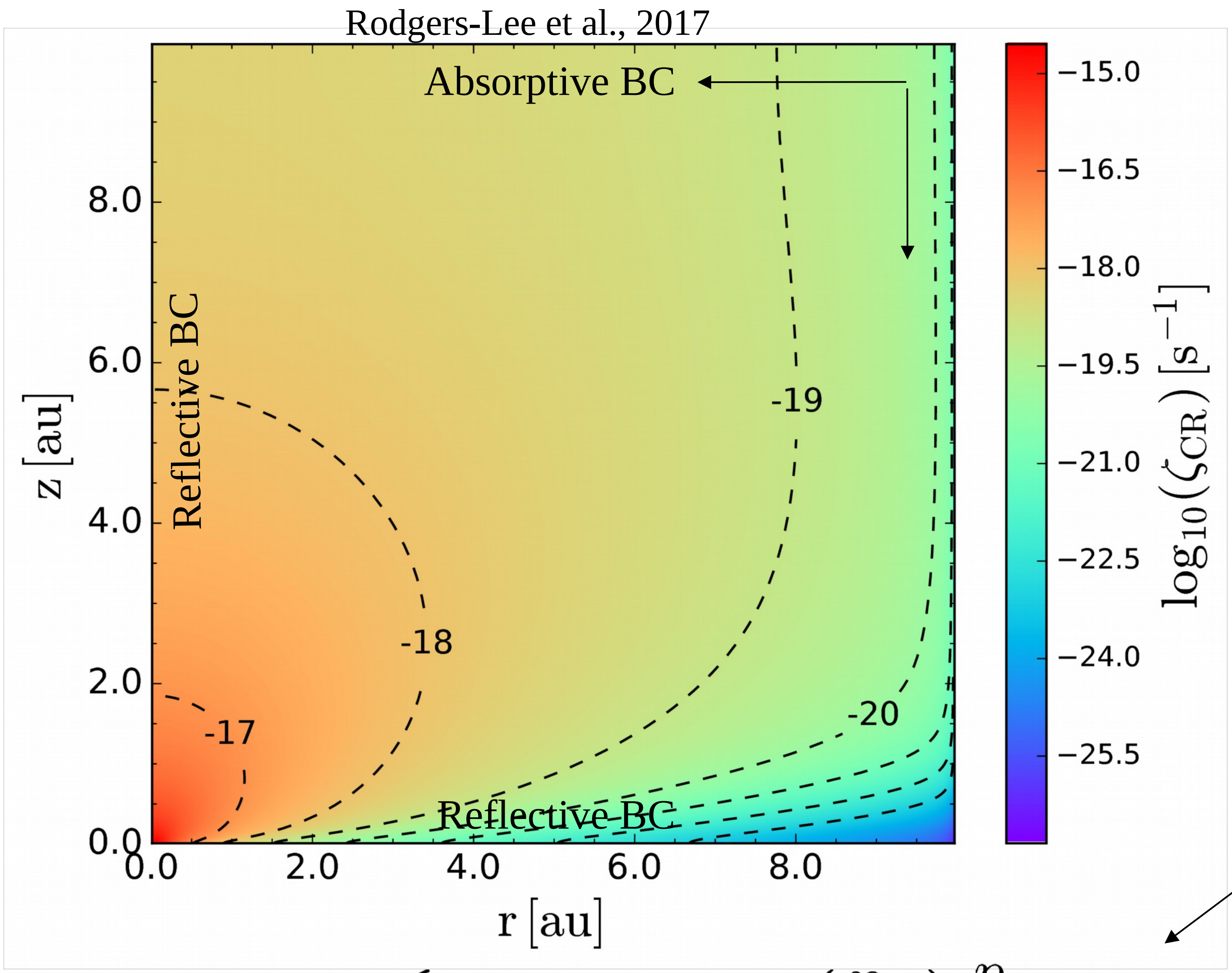
Numerical method

$$\frac{\partial n_{\rm CR}}{\partial t} = \nabla \cdot (D \nabla n_{\rm CR}) - \frac{n_{\rm CR}}{\tau} - \vec{v} \cdot \nabla n_{\rm CR} + Q$$

- Cylindrical coordinates
- Forward in time, centred in space scheme for diffusive term
- Lax-Wendroff scheme for the advective term (Lax & Wendroff, 1960)
- First order in time, second order in space
- Parallelised using MPI

Ionisation rate for fiducial run



Parameters:

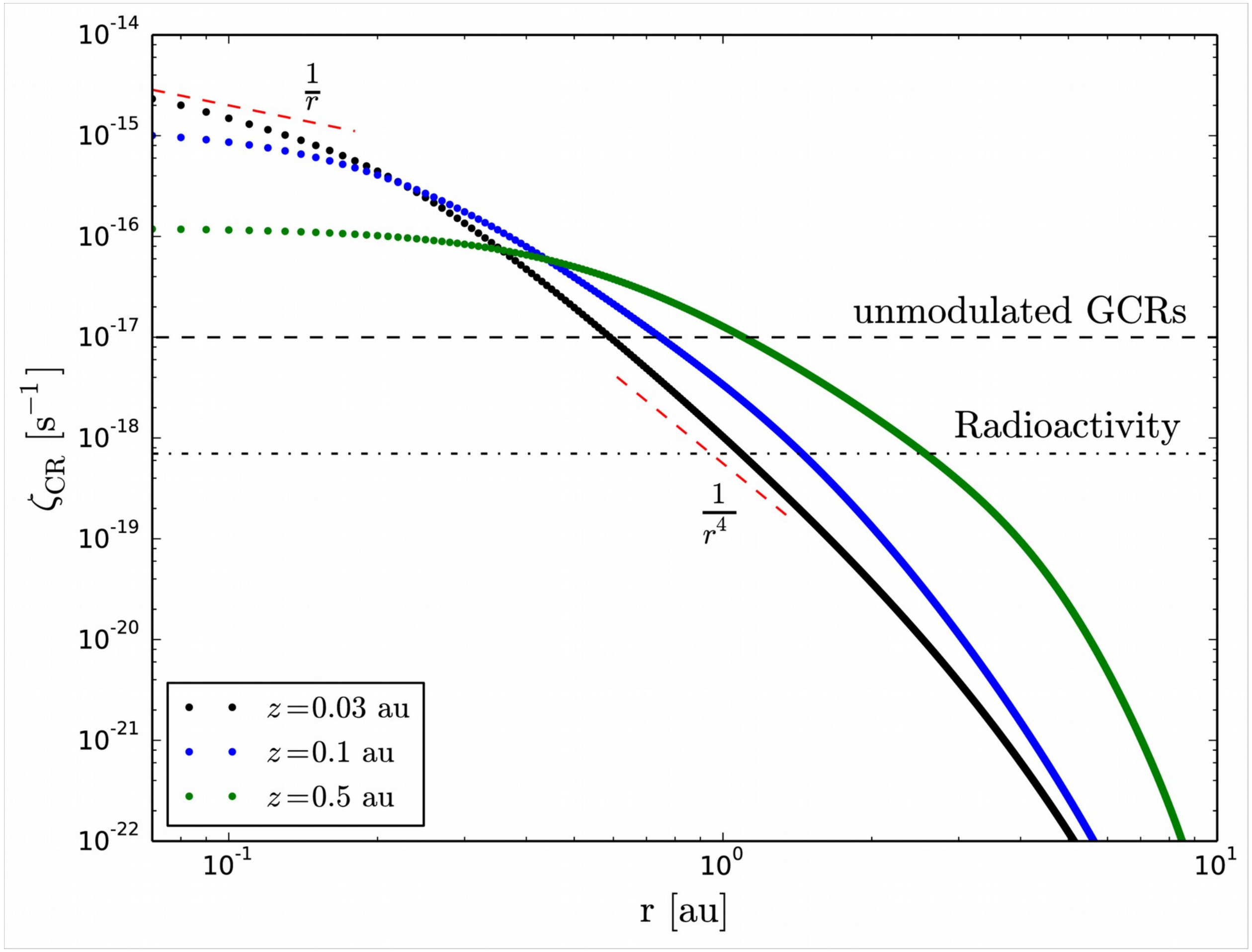
- Source of CRs at Alfven radius
- 2D axisymmetric
- 3 GeV CRs

$$\frac{D}{c} = 30 r_{\rm L}$$

$$\frac{1}{\tau(r,z)} \propto \rho(r,z)$$

$$\rho = \left\{ \rho_0 e^{-r_{\rm in}^2/r^2} \left(\frac{r_0}{r}\right)^p e^{-z^2/2H^2} + \rho_{\rm ISM} \right\}$$

Ionisation rate for fiducial run



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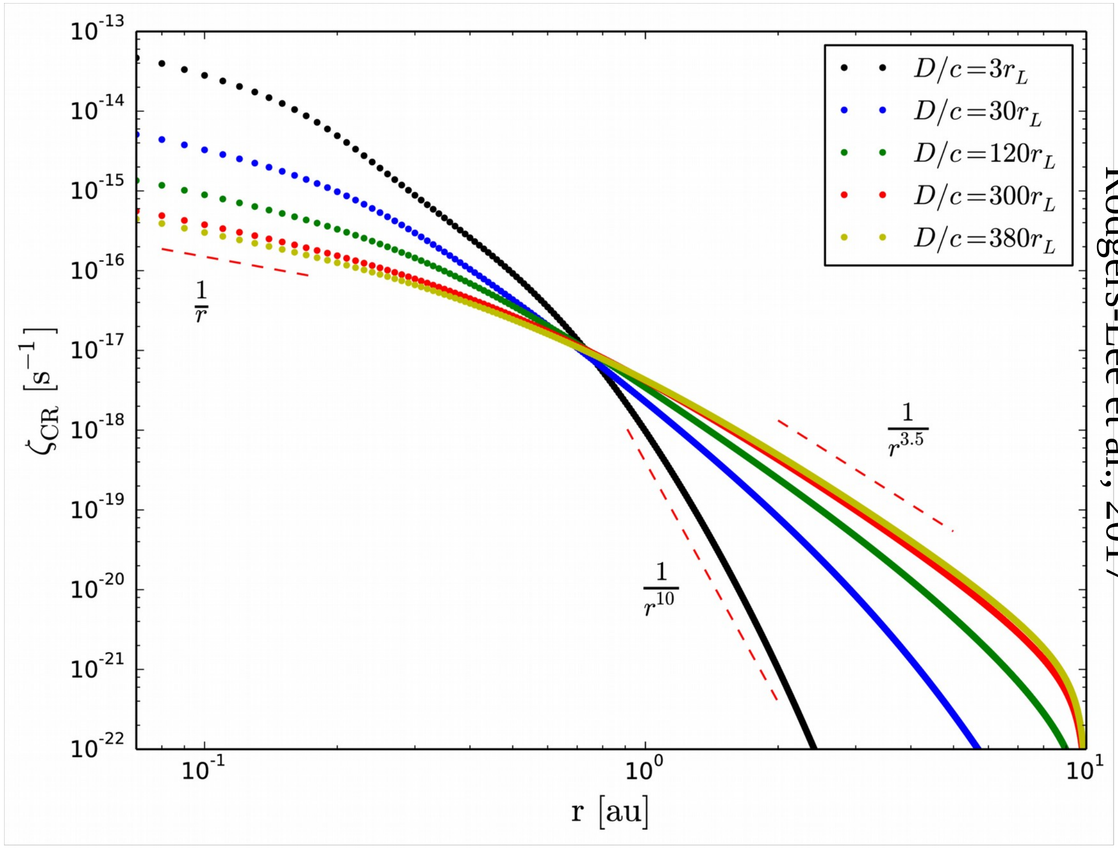
Ionisation rate - varying D(r,z)

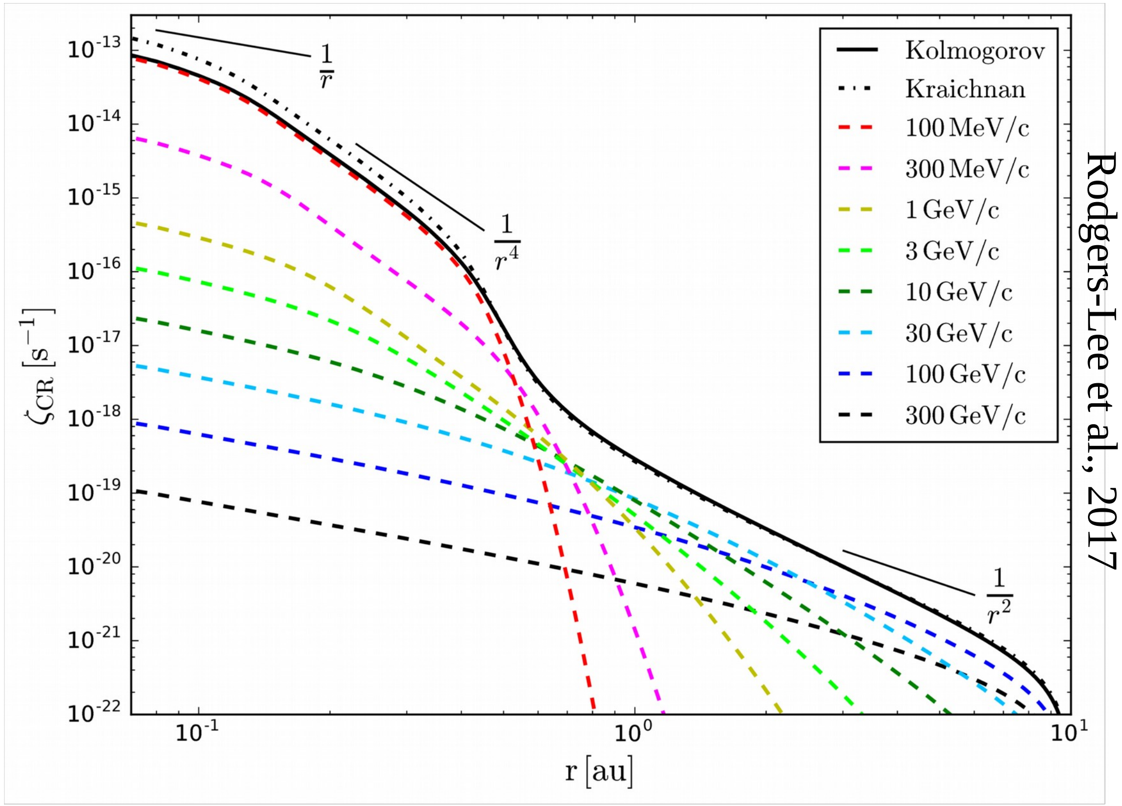


Rodgers-Lee et al., 2017

- Larger diffusion coefficients results in higher ionisation rates further out
- Higher than unmodulated ionisation rate from GCRs at ~1au
- Simulations are reaching steady state with the sink term

$$\frac{D}{c} = \eta_0 r_{\rm L}$$

Ionisation rate - energy dependence



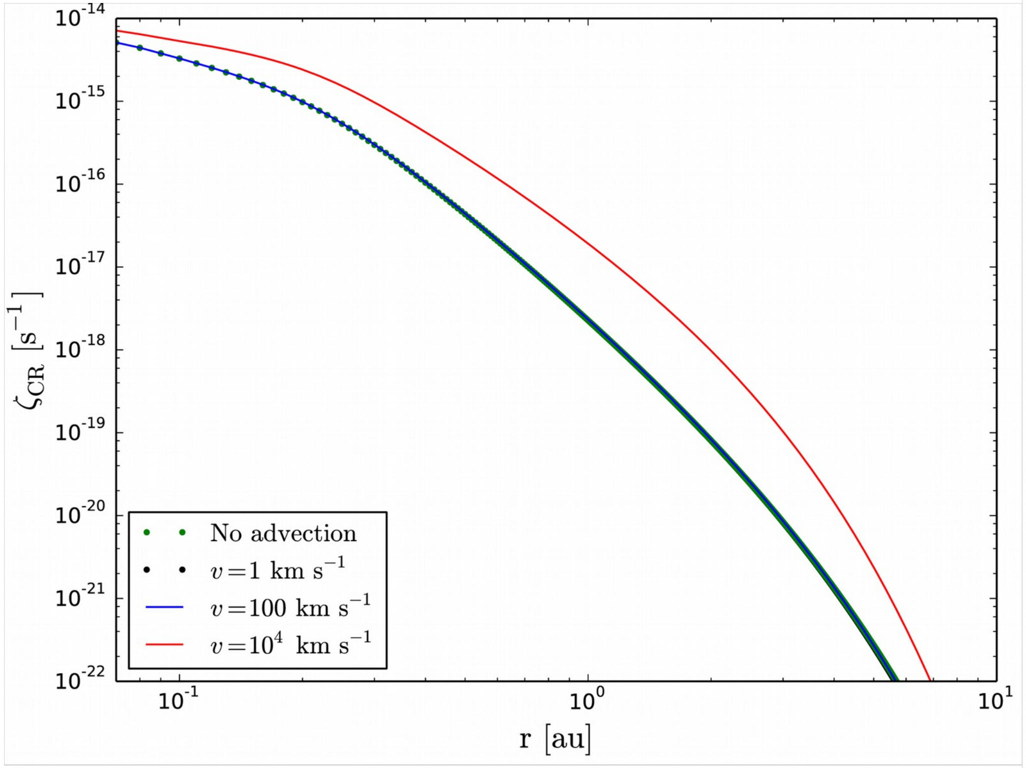
Rodgers-Lee et al., 2017

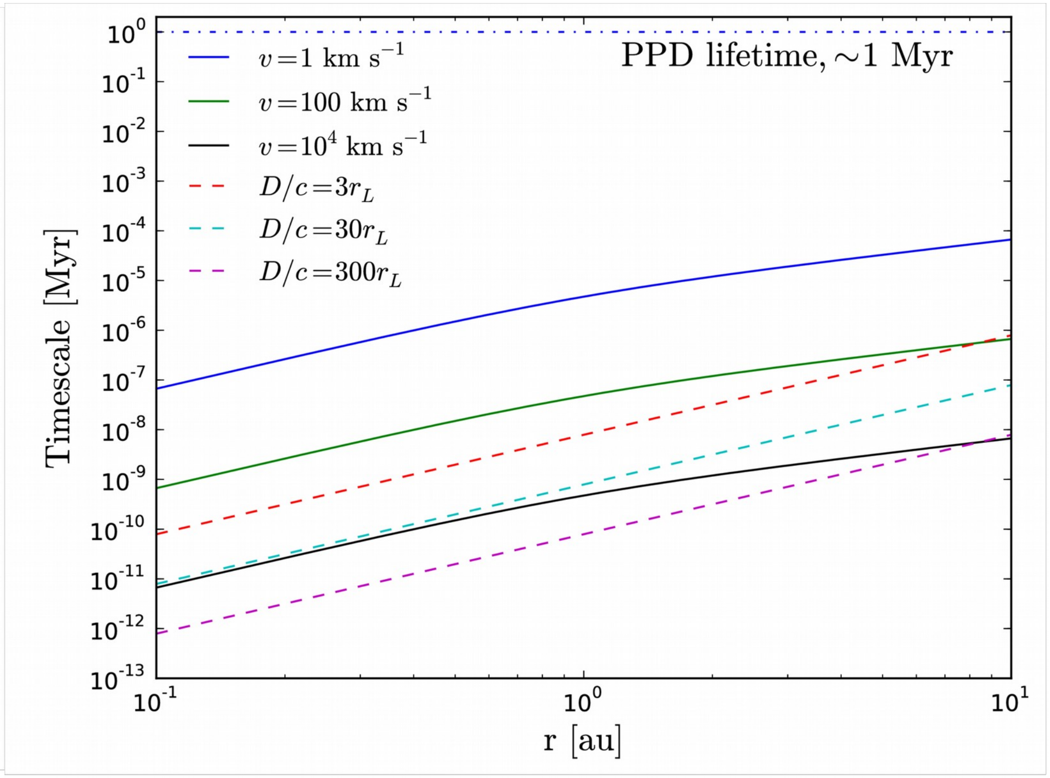
- Higher energies ionise further out
- Higher than unmodulated ionisation rate from GCRs at ~1au
- Uses small diffusion coefficient
- Higher energy CRs approach r^{-1} profile

$$\frac{D}{c} = \eta(p) r_L \qquad \eta(p) = \eta_0 \left(\frac{p}{p_0}\right)^{1-\gamma}$$

Turbulence spectrum

Influence of an advection term





$$v_r = v_0 \left(\frac{r_0}{r}\right)$$

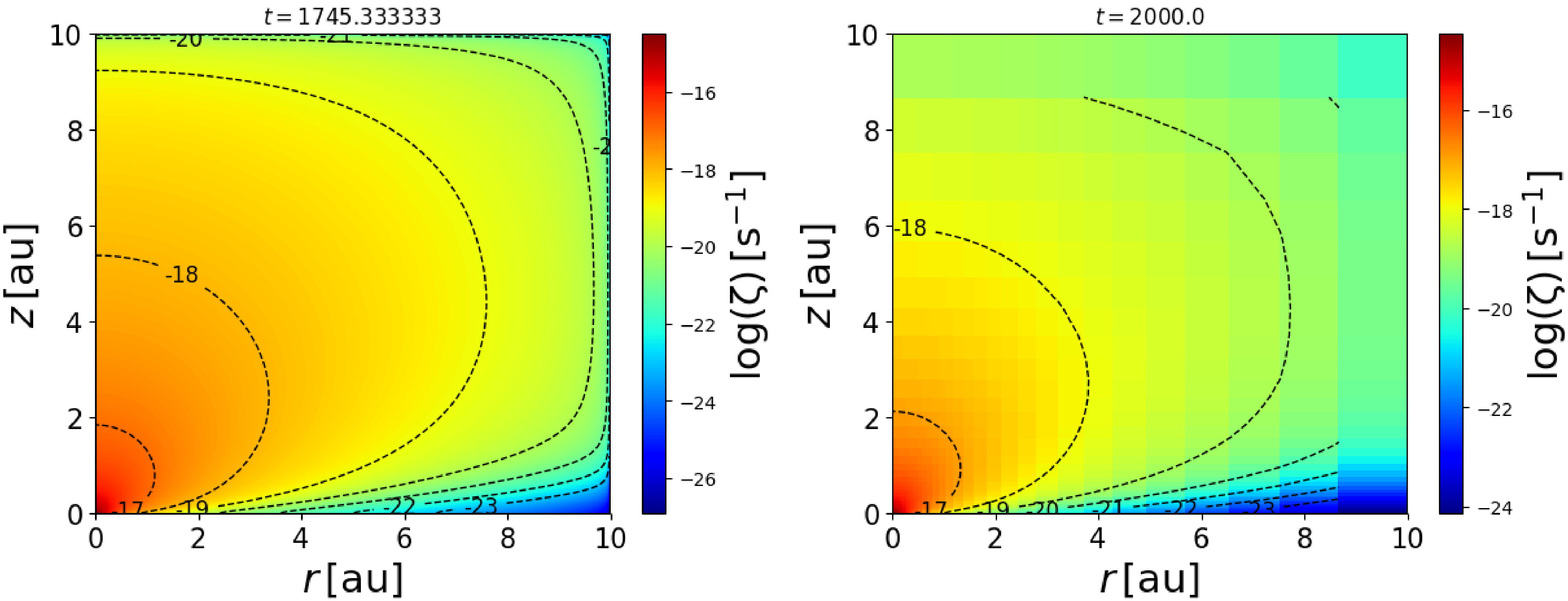
$$t_{\rm diff} = \frac{r^2}{D}, \quad t_{\rm adv} = \frac{r}{v}$$

No difference for physical velocities because diffusive timescale is shorter than advective timescale

Future/current work

$$\frac{\partial n_{\mathrm{CR}}}{\partial t} = \nabla \cdot (D \nabla n_{\mathrm{CR}}) - \frac{n_{\mathrm{CR}}}{\tau} - v \cdot \nabla n_{\mathrm{CR}} + Q + \nabla_p \cdot (D_p \nabla_p n_{\mathrm{CR}})$$

- Non-localised source of cosmic rays? (MRI turbulence Ross et al., 2018)
- Neutron contribution to cosmic ray energy loss rate (Kataoka et al., 2016)



Conclusions

- If low energy cosmic rays are to be an effective source of ionisation at r >1au in protoplanetary disks (at the midplane):
  - Large diffusion coefficients
  - High energy cosmic rays

$$\frac{D}{c} \sim 300 r_{\mathrm{L}}$$

$$E \gtrsim 30\,\mathrm{GeV}$$

- Canonical 1/r profile for diffusive processes is generally not recovered due to loss of CRs in the system (Rodgers-Lee et al., 2017)
- Similar results to Fraschetti et al., (2018) – for different reasons!
- Advective wind does not significantly deflect the cosmic rays

Thank you!

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