Modelling the Propagation of Cosmic Rays in Pre-stellar Cores and Shocks

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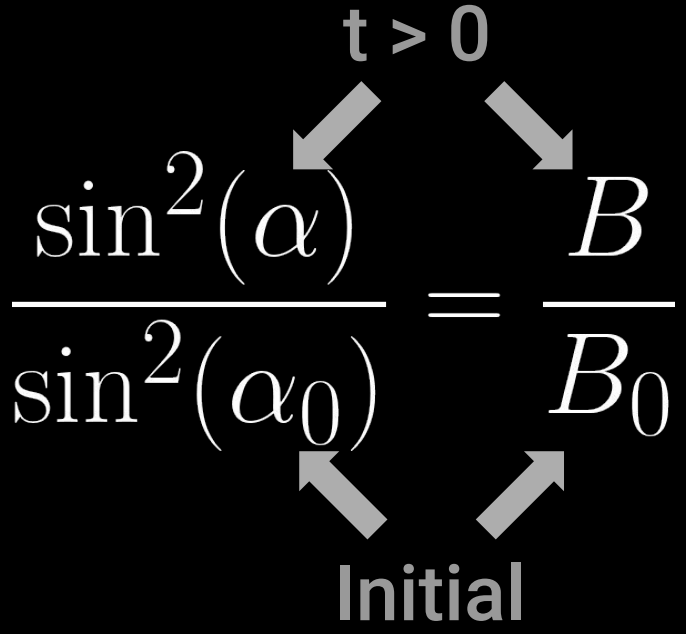
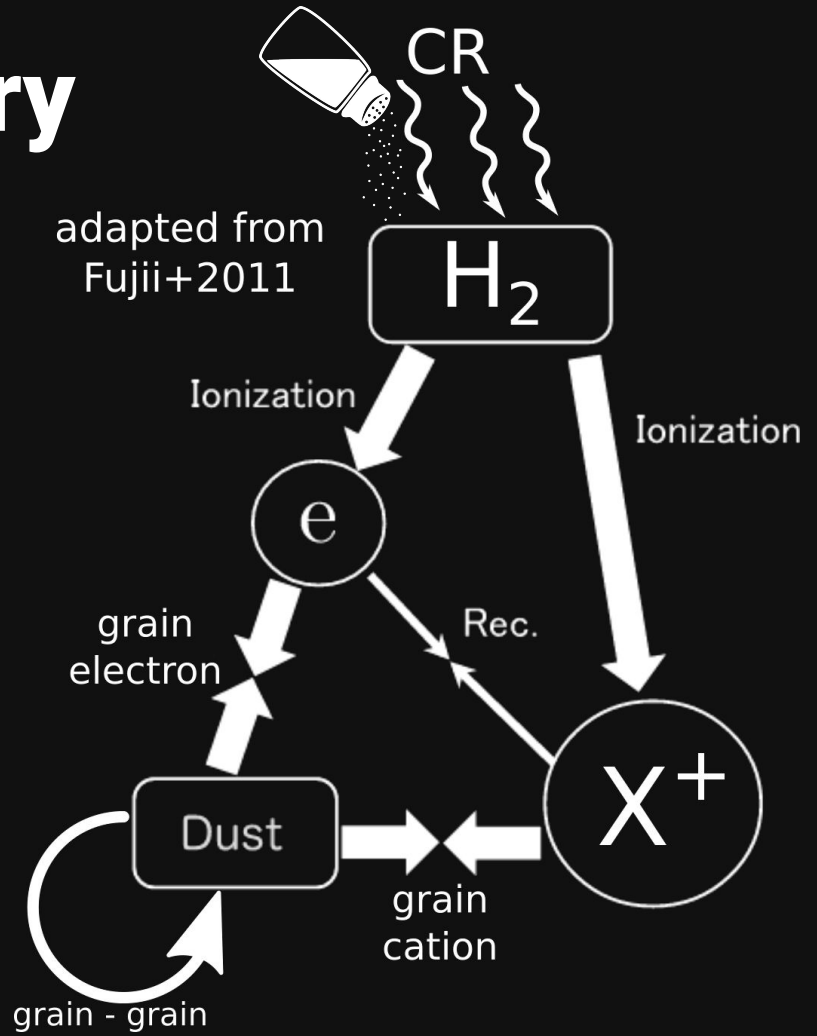
CRs follows magnetic field lines



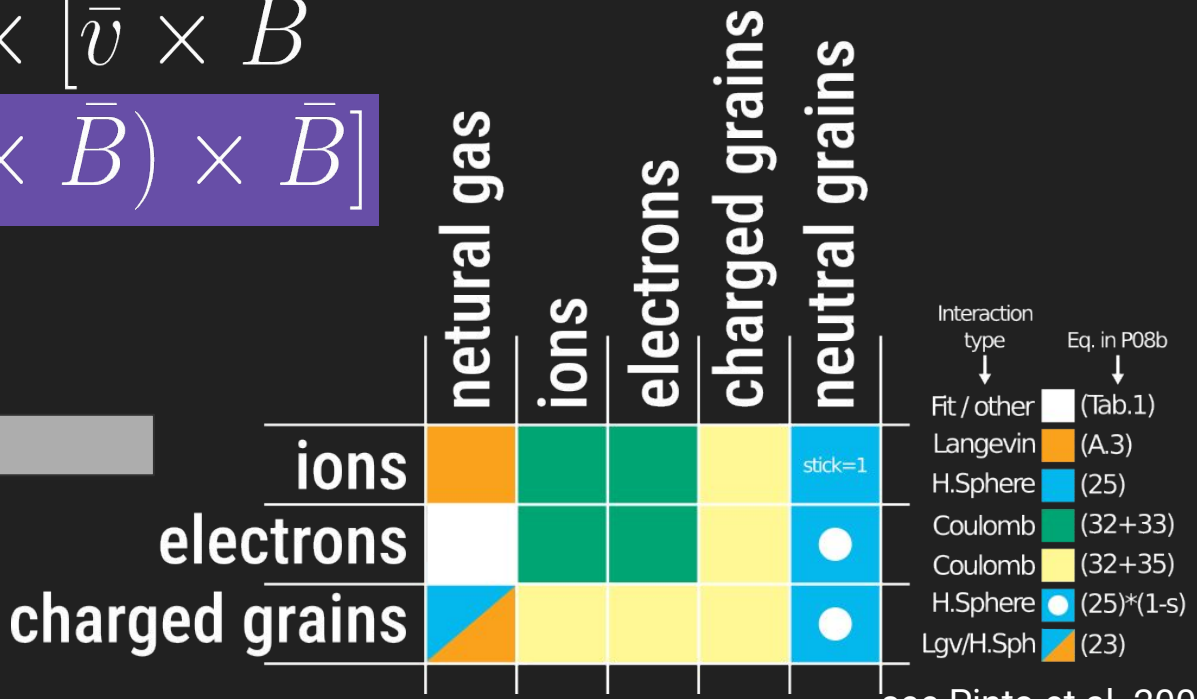
Chemistry



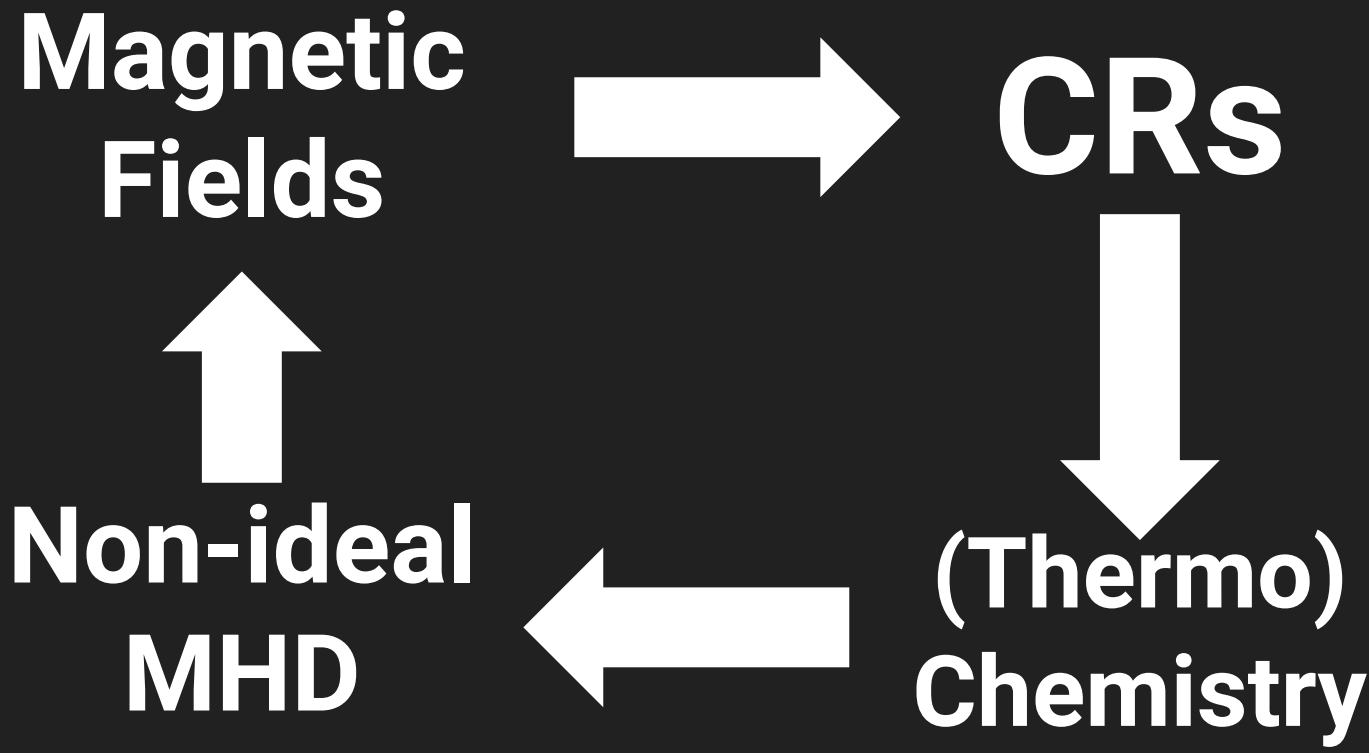
e.g. see talks Bialy, Geballe, Faure, Neufeld, …

Non-ideal MHD
(ambipolar diffusion)

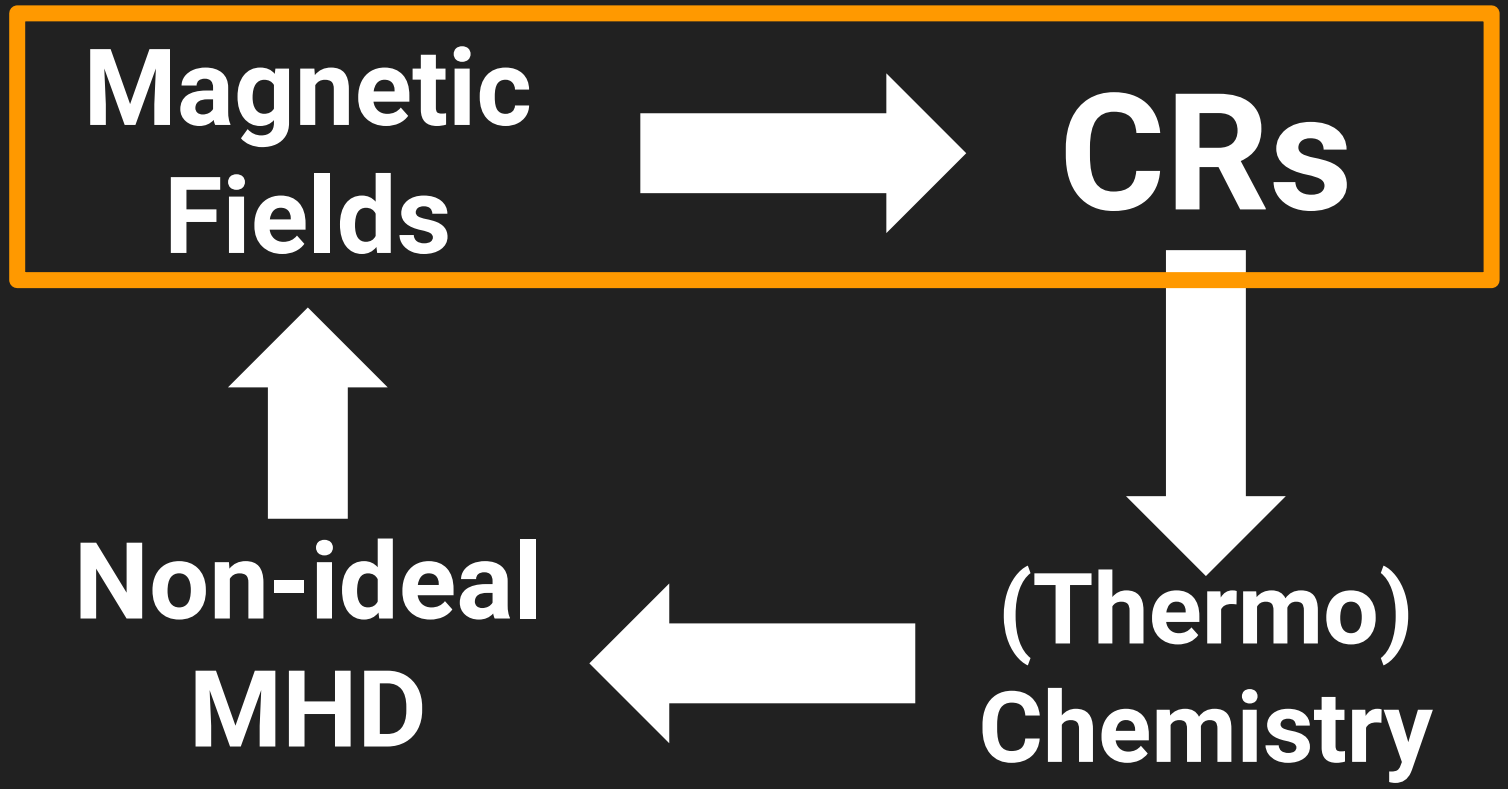
$$\partial_t \bar{B} = \nabla \times [\bar{v} \times \bar{B} - \eta(\bar{J} \times \bar{B}) \times \bar{B}]$$

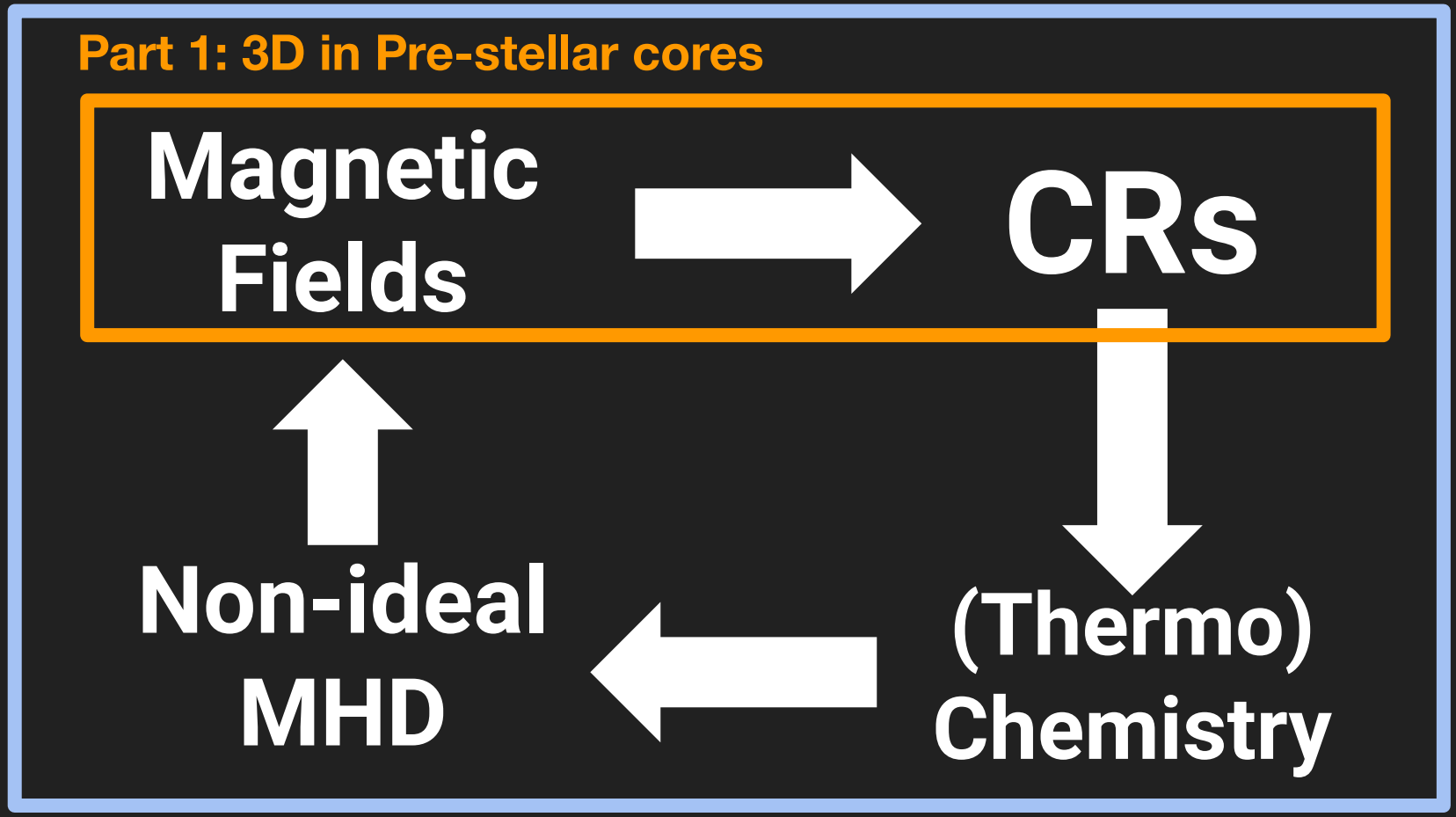


see Pinto et al. 2008a,b


Magnetic Fields
CRs
(Thermo) Chemistry
Non-ideal MHD

Part 1: 3D in Pre-stellar cores




Part 1: 3D in Pre-stellar cores
Magnetic Fields
CRs
(Thermo) Chemistry
Non-ideal MHD
Part 2: 1D in Shocks

PART 1

3D Propagation in Protostellar Cores

Grassi, Padovani, Galli et al. in prep.

Problem Geometry

MHD+AD 3D snapshot from Caselli+2019

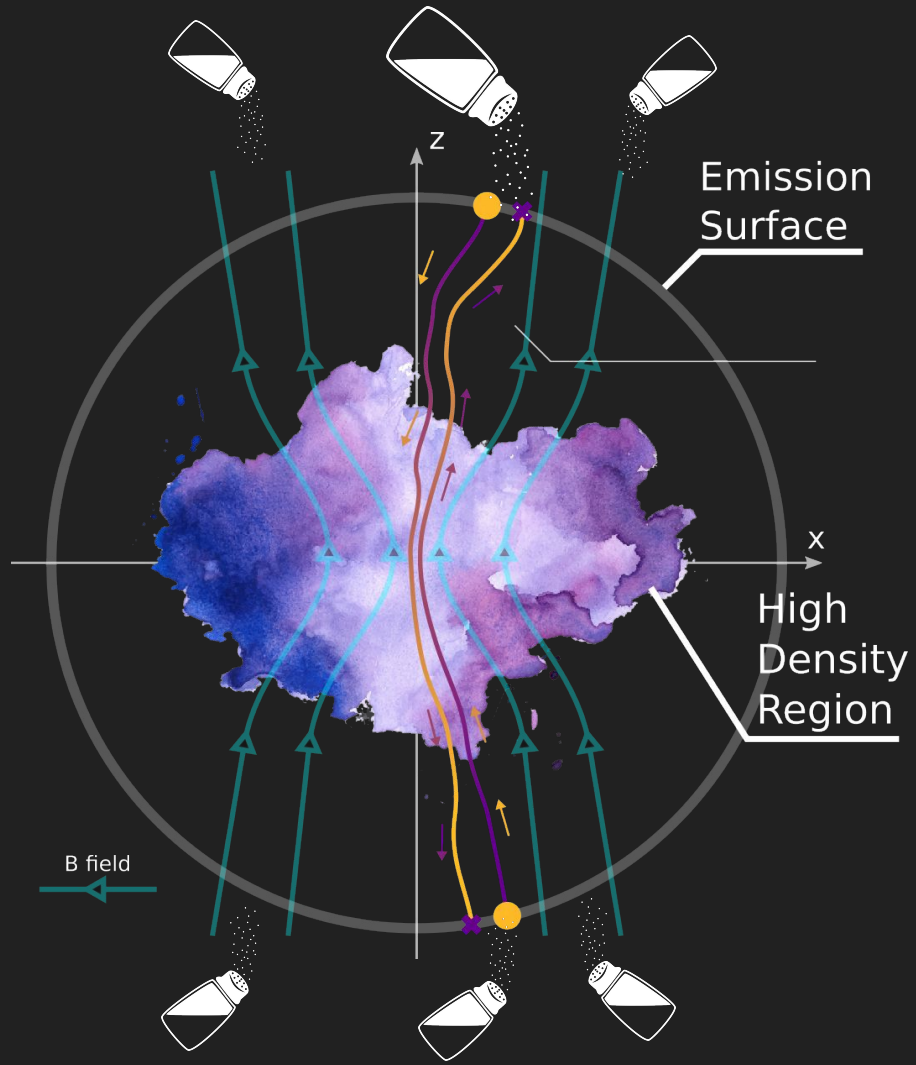
mass = 8.1 M_o

B_o = 14.8 μG

Turbulence = Mach 5

$\Omega = 4 \times 10^{-14}$

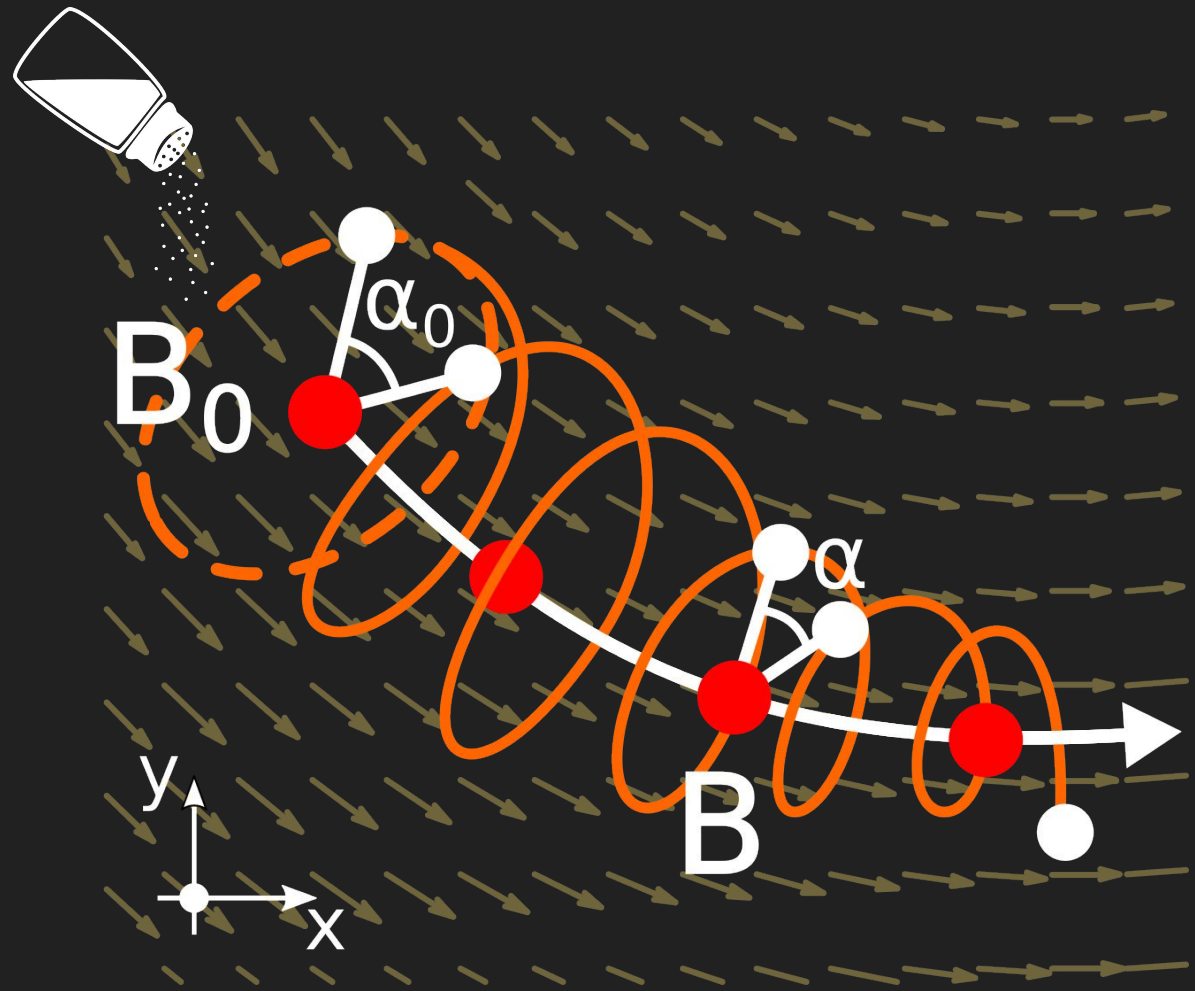
Peak density = 10^7 cm^{-3}



Effective Column Density

Monte Carlo sampling

cf. e.g. Fitz-Aixen 2021a,b

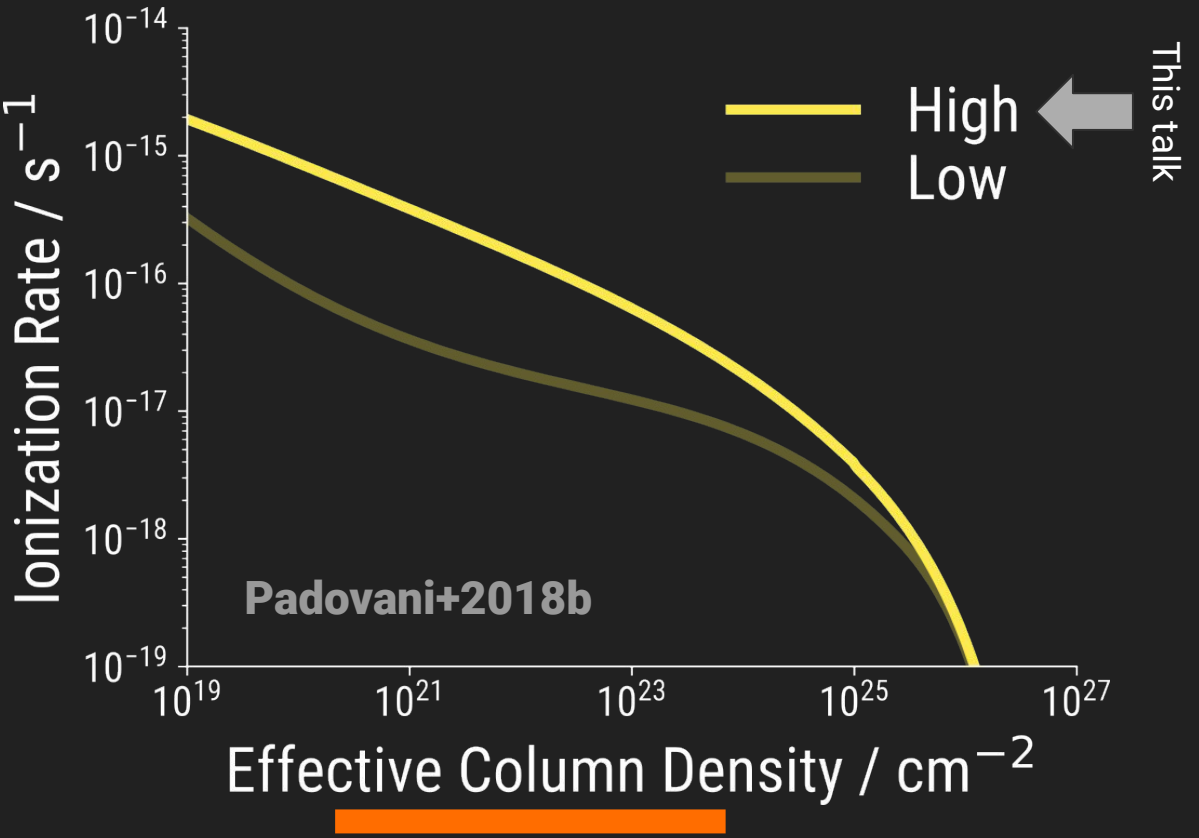


From

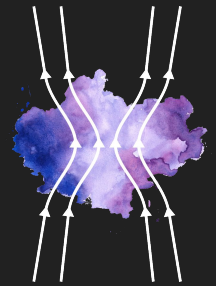
Effective Column Density

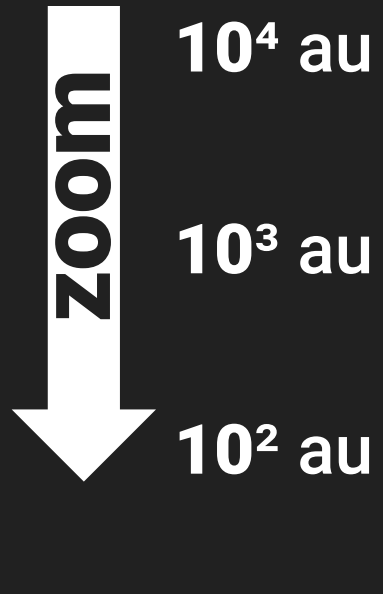
to

Ionization Rate

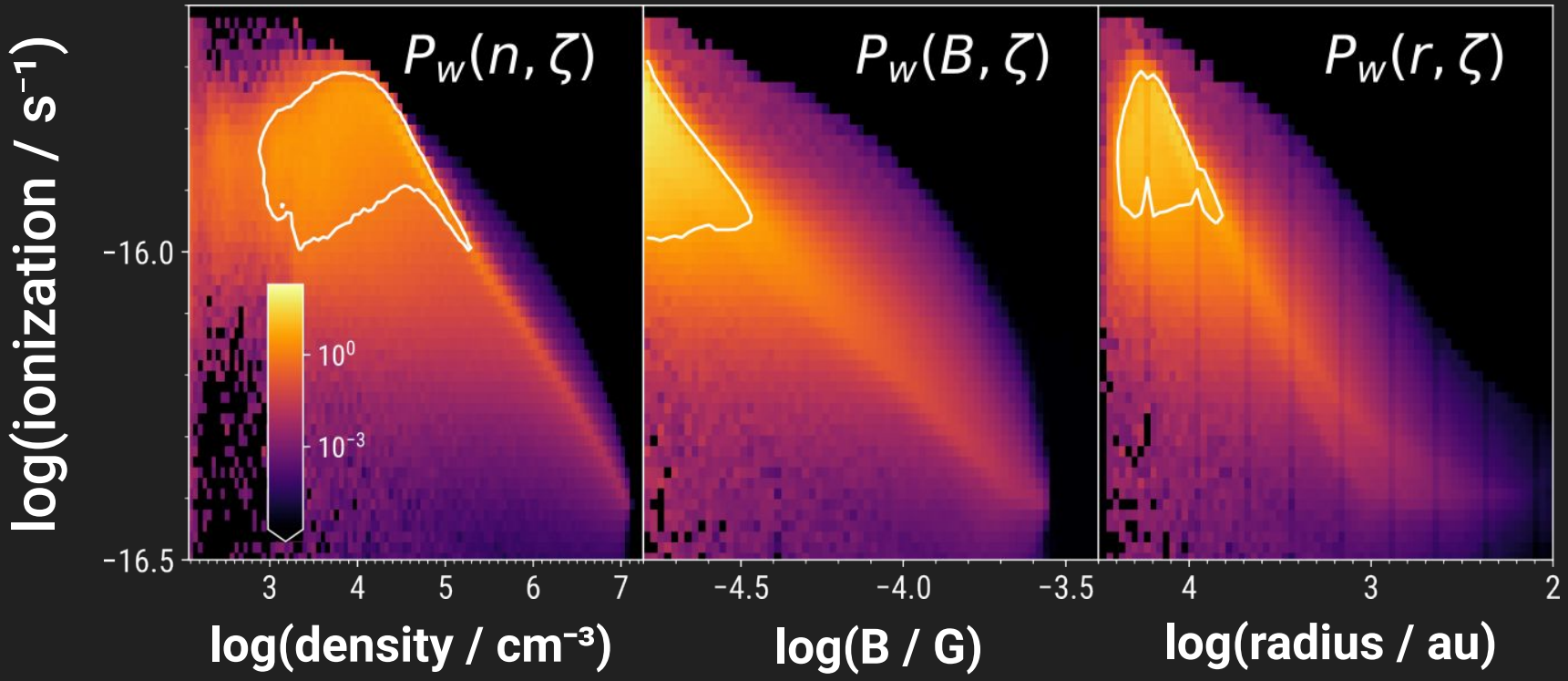


Projections





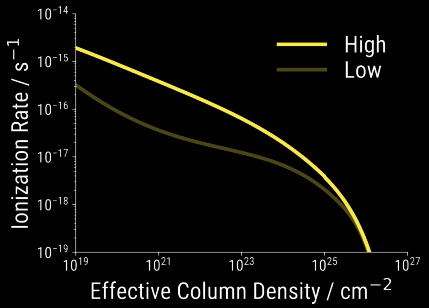
Mass-weighted probability density

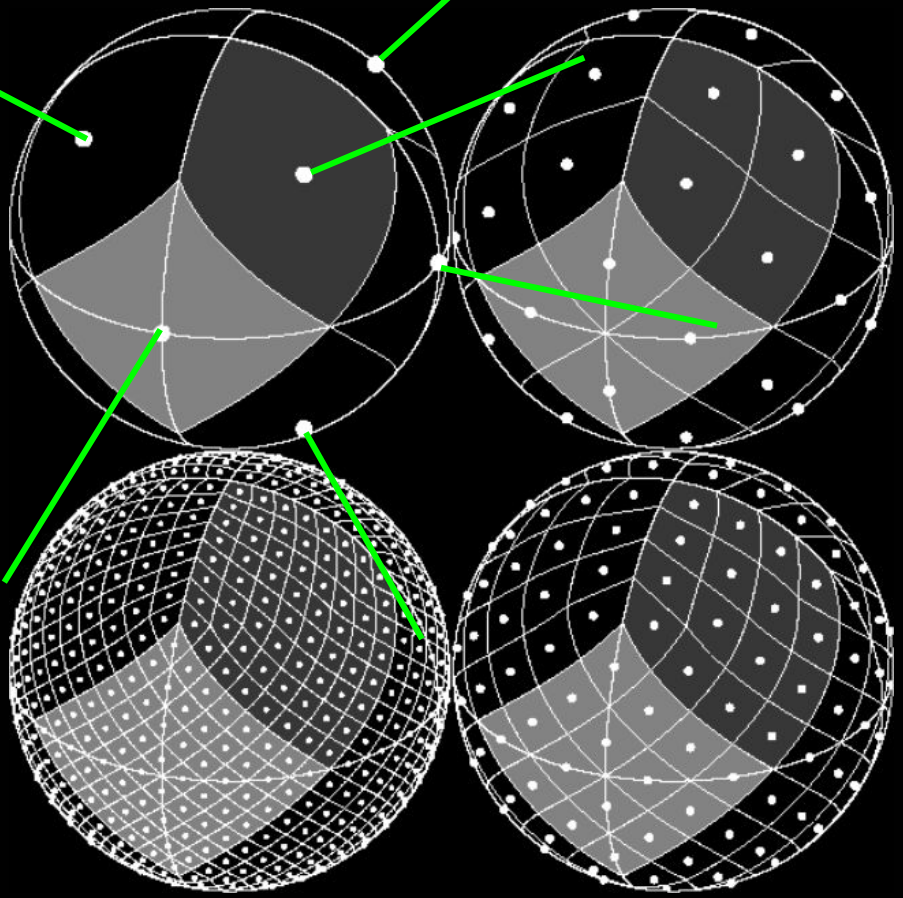


HEALPix

see Gaches, Bisbas & Bialy (2022)

$$N \propto \ln \left[\sum_{rays} e^{-2.5\,N_{rays}} \right]$$

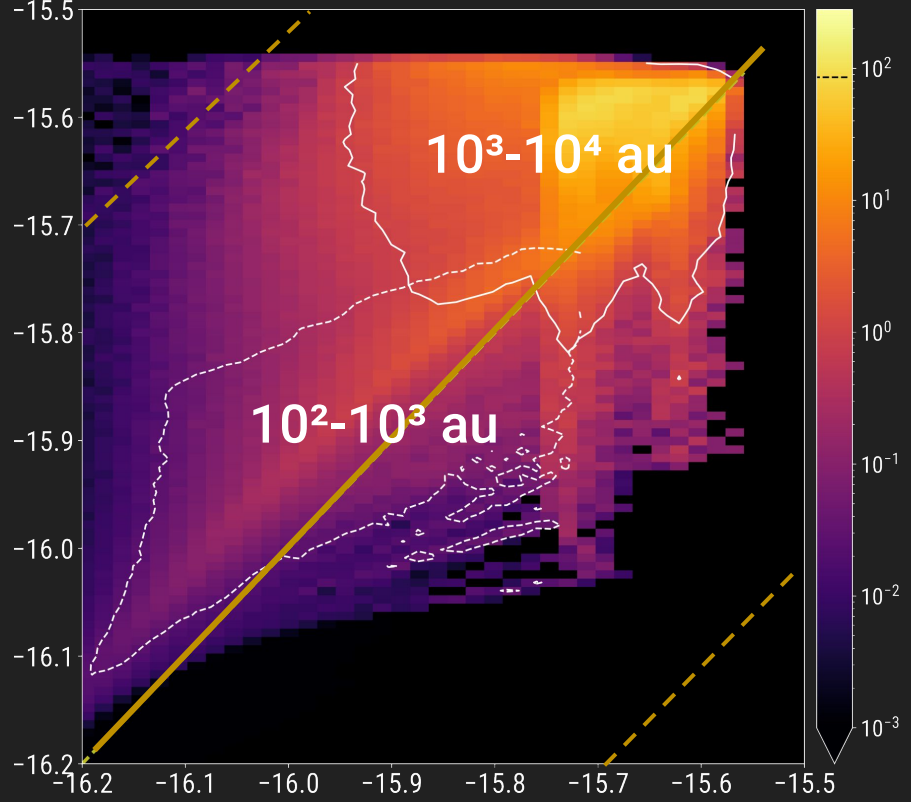




Mass-weighted statistics comparison

ionization
HEALPix
0/12

HEALPix less accurate, but much faster



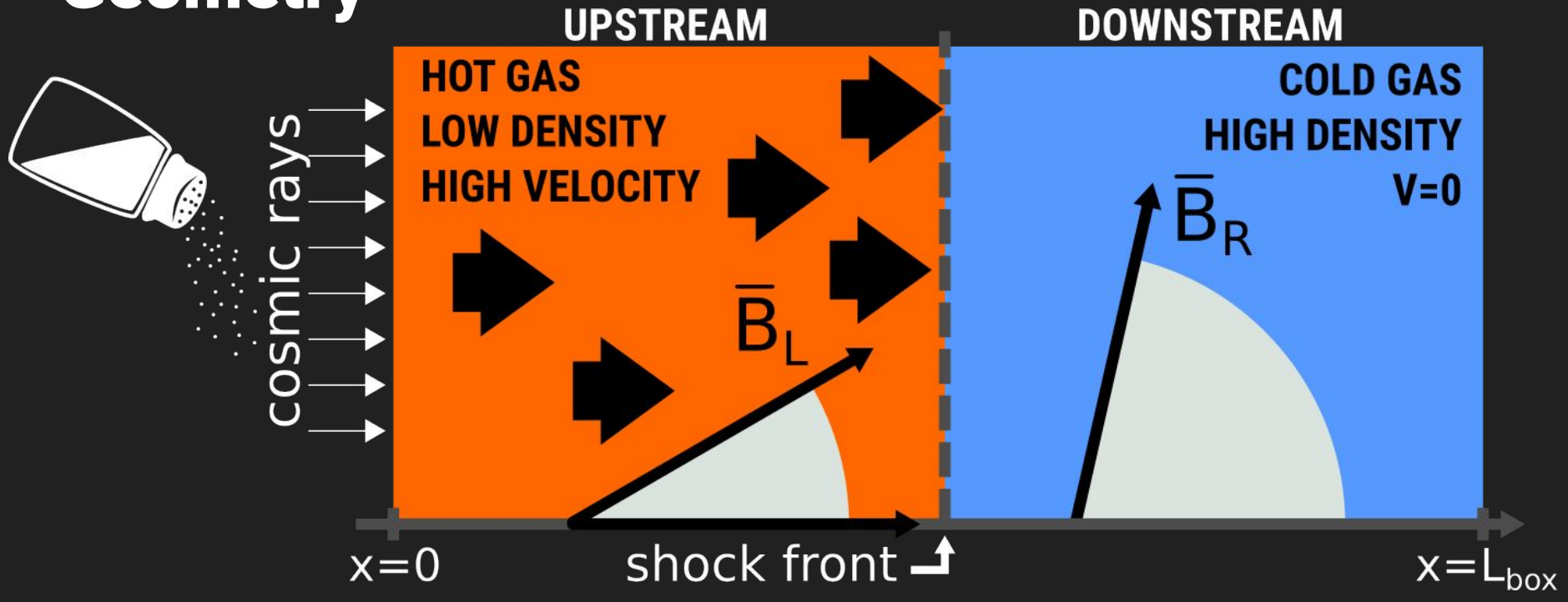
ionization THIS METHOD

PART 2

CRs in non-ideal MHD Shocks

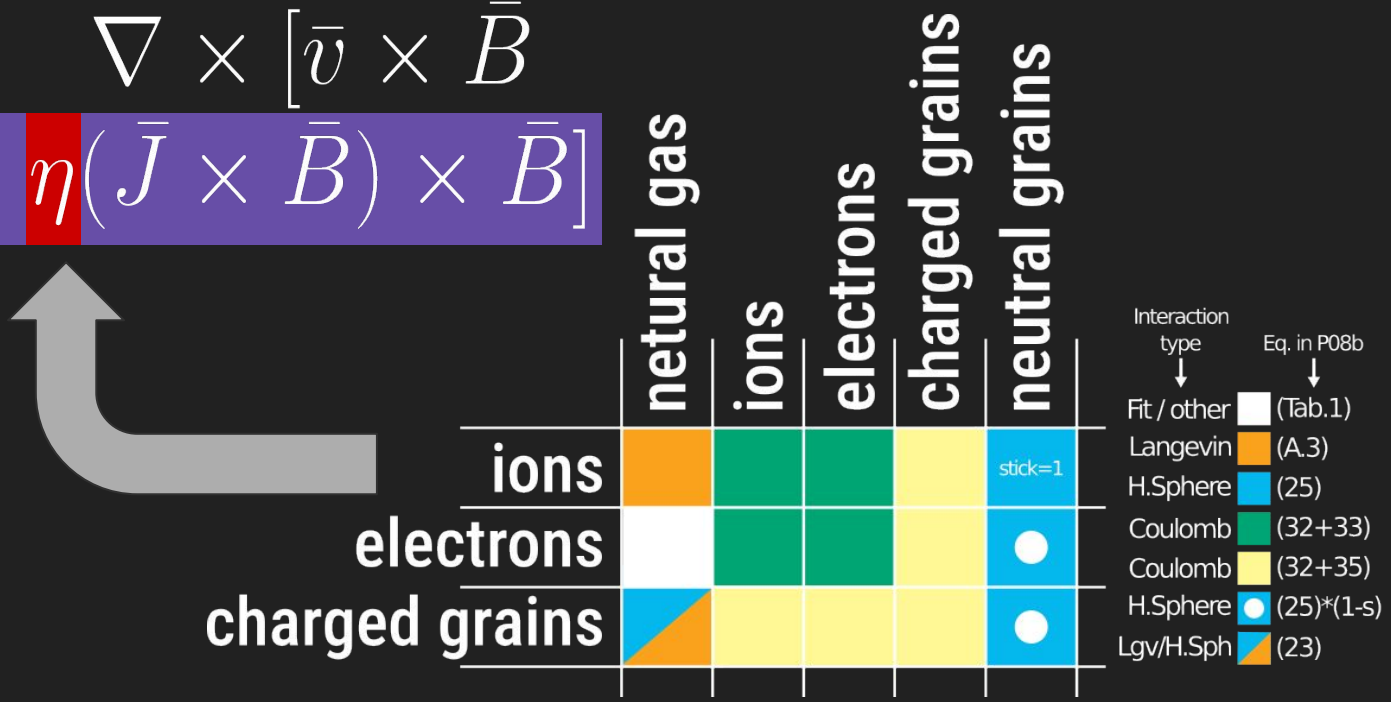
Grassi et al. (2019)

Problem Geometry



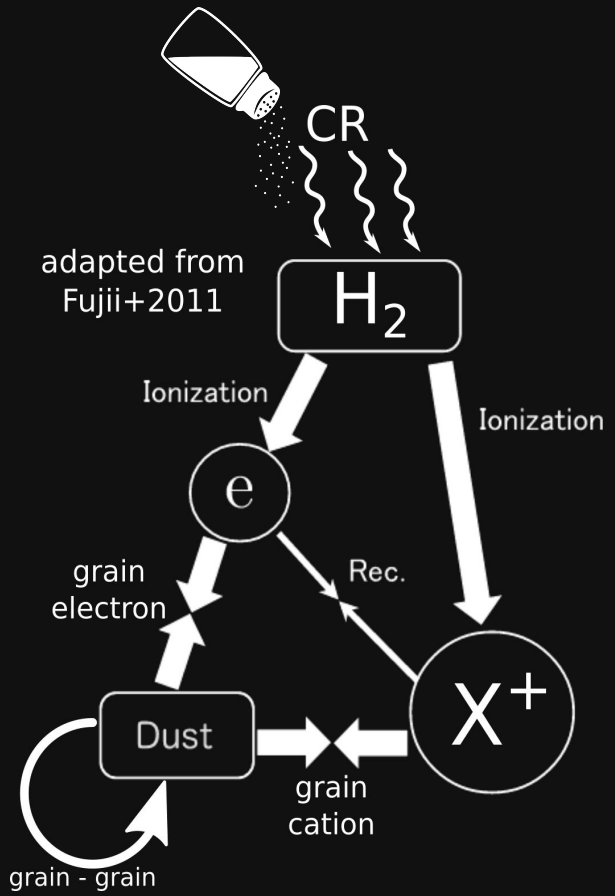
Non-ideal MHD
(ambipolar diffusion)

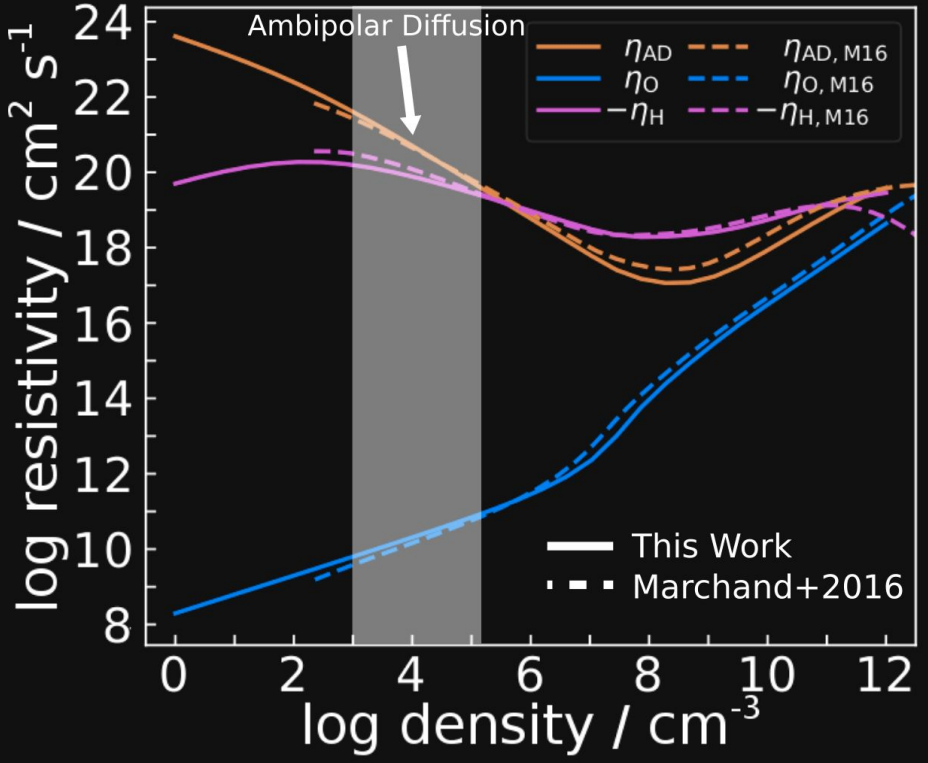
$$\partial_t \bar{B} = \nabla \times [\bar{v} \times \bar{B} - \eta(\bar{J} \times \bar{B}) \times \bar{B}]$$



see Pinto et al. 2008a,b

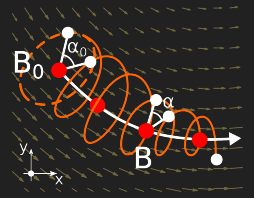
Chemistry and Ambipolar Diffusion





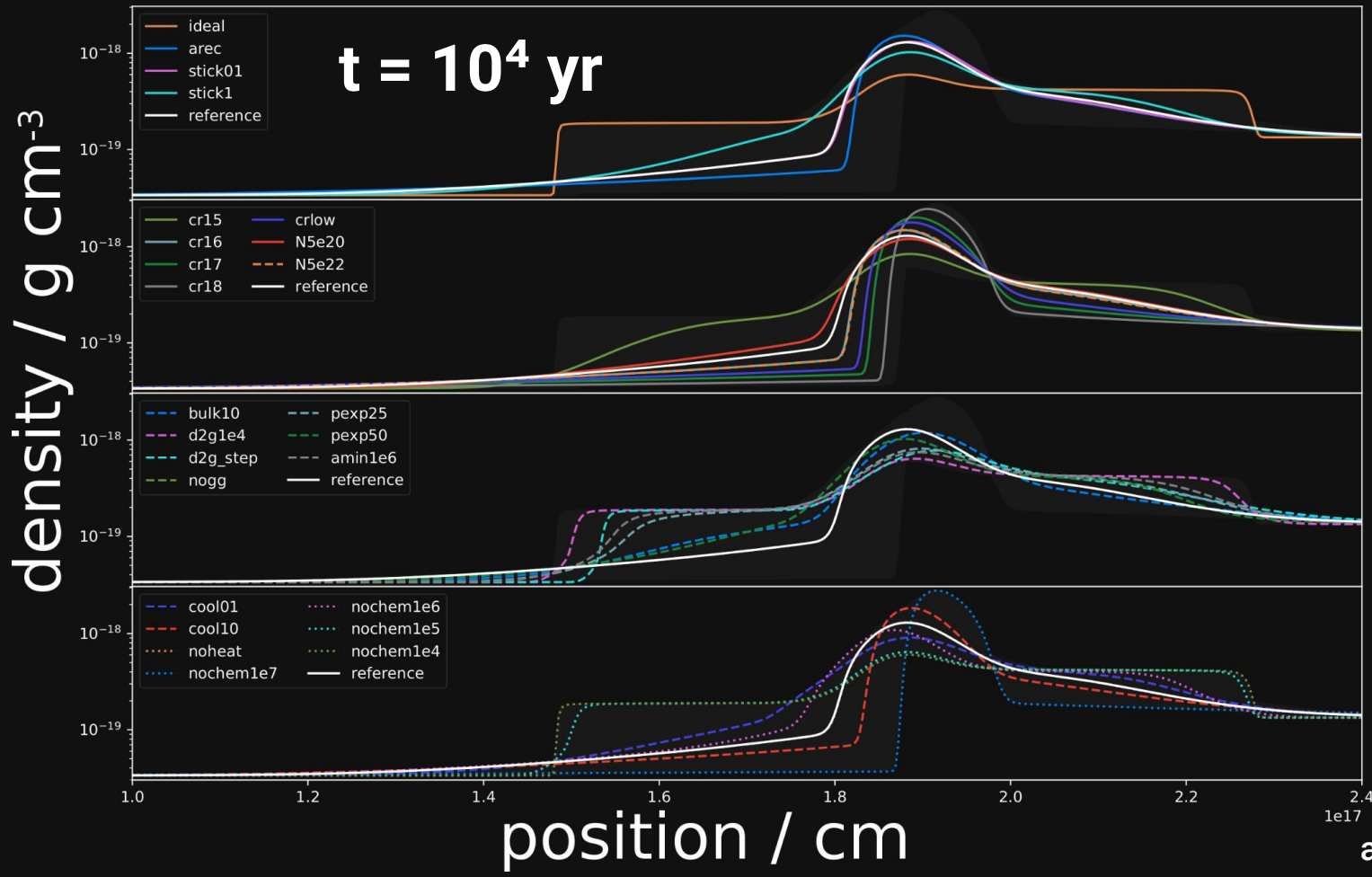
The Code: LEMONGRAB

- 1D + 3 components
- Fully-implicit & time-dependent
- Chemistry (gas+dust)
- CRs propagation
- Ambipolar diffusion
- Cooling/Heating (e.g. CR & AD)
- Open-source

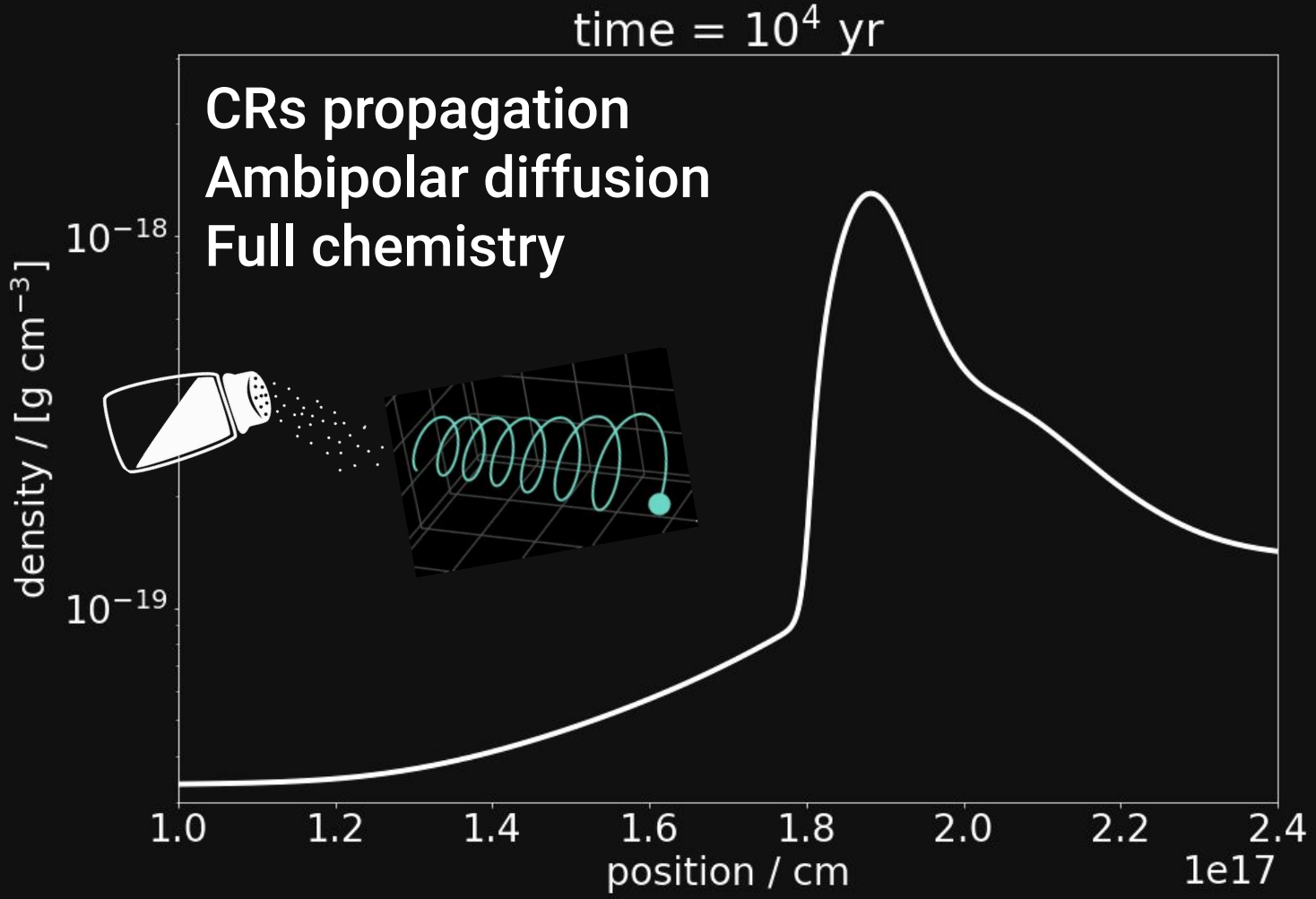


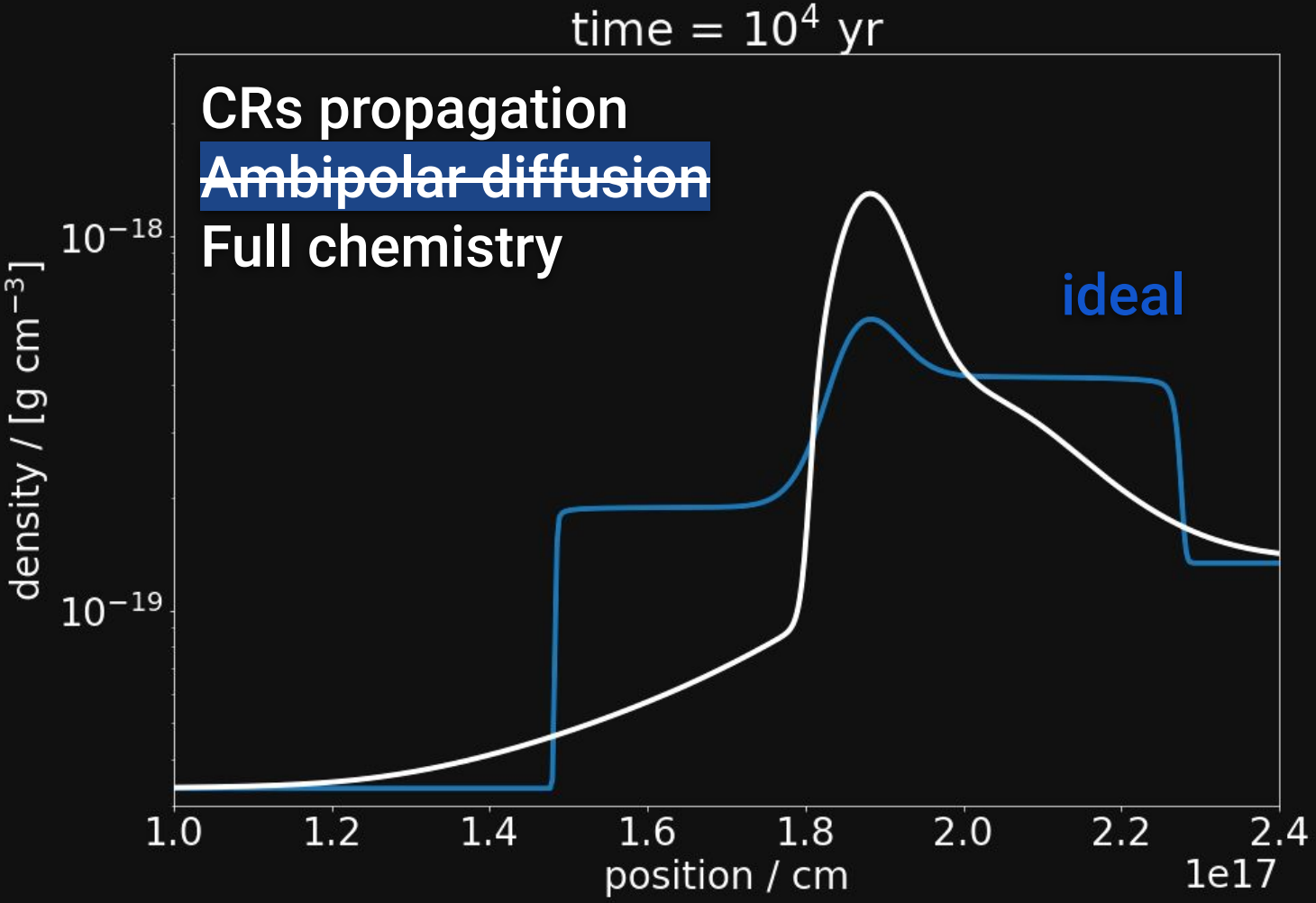
arXiv:1901.00504

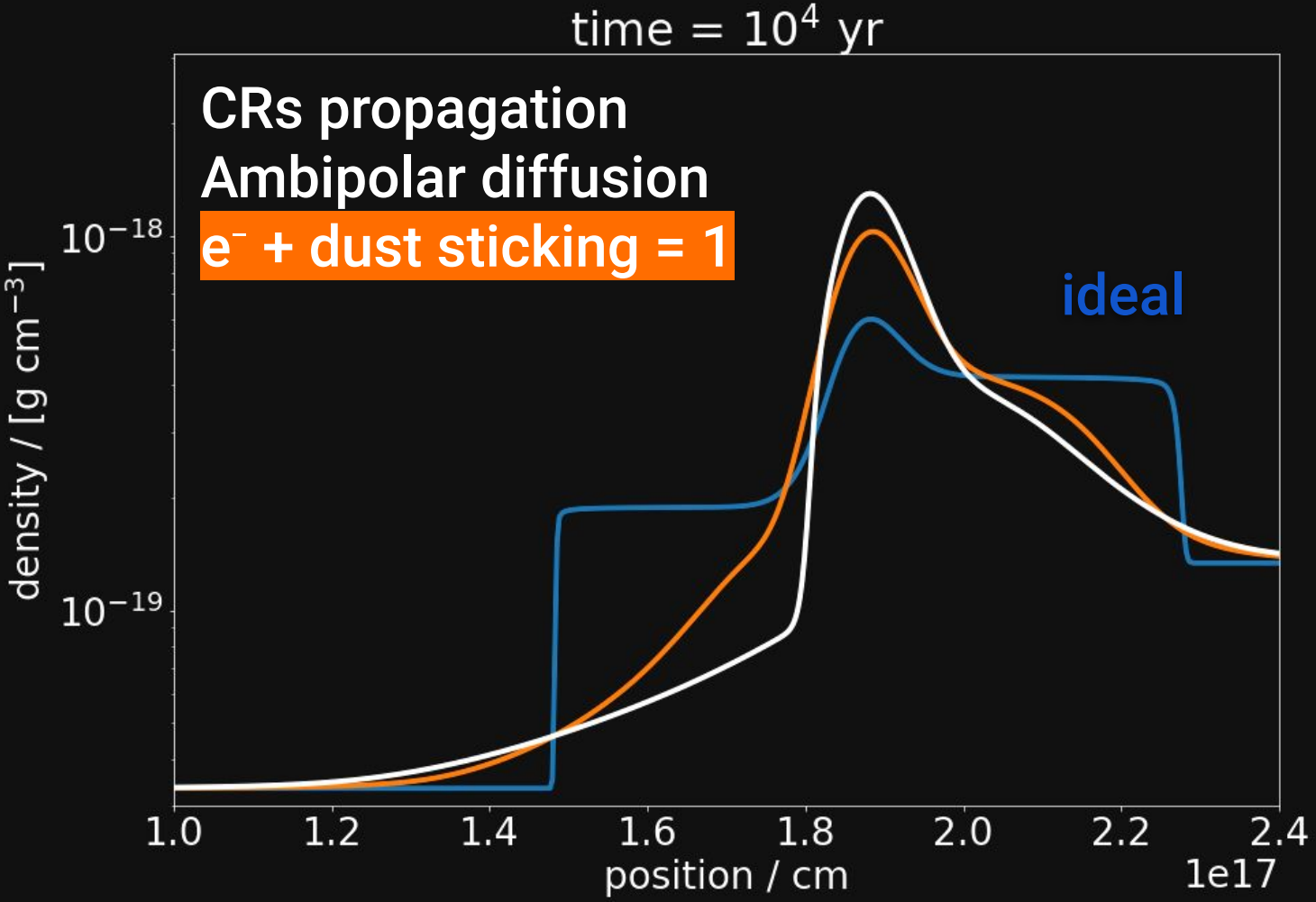
bitbucket.com/tgrassi/lemongrab

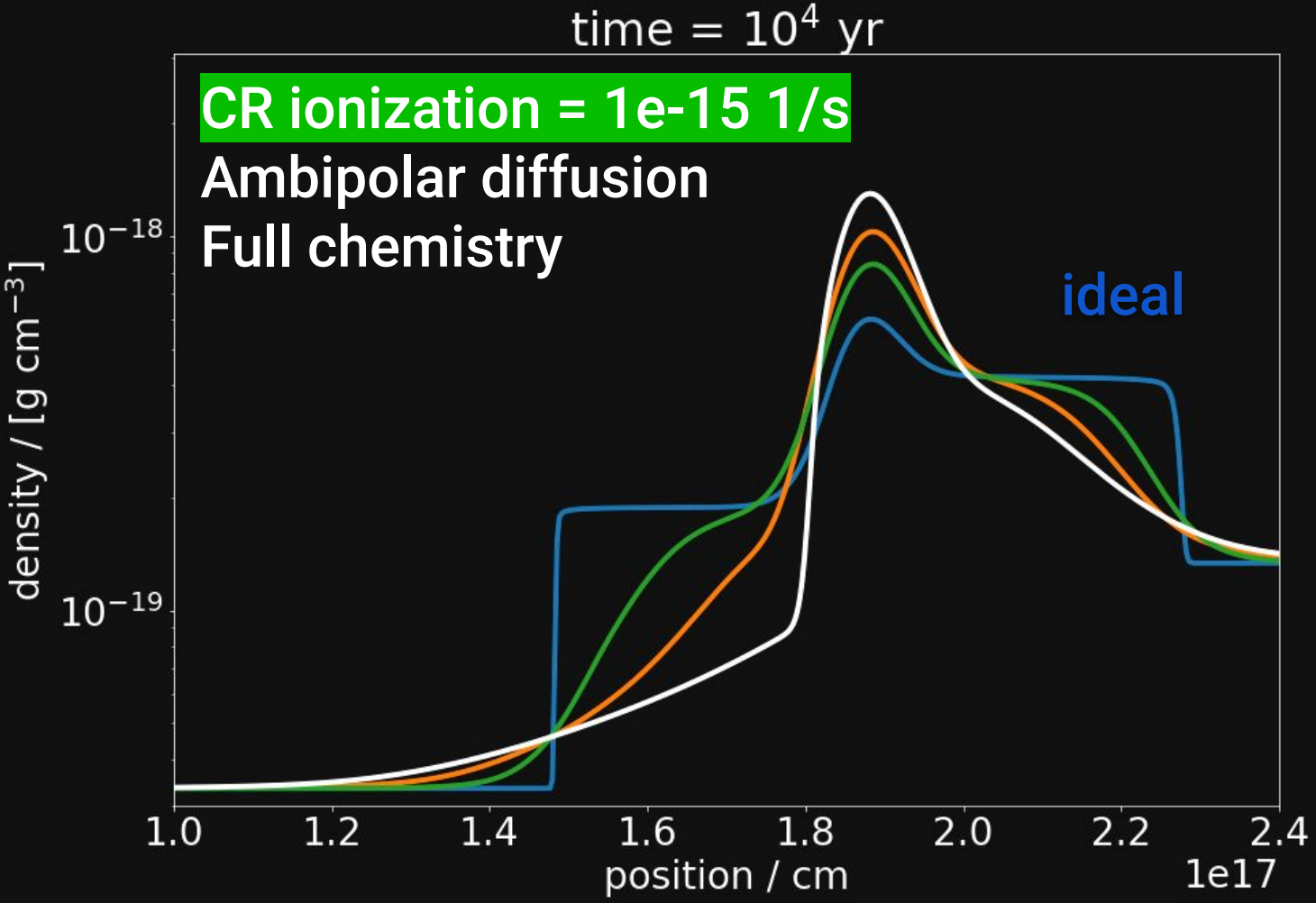


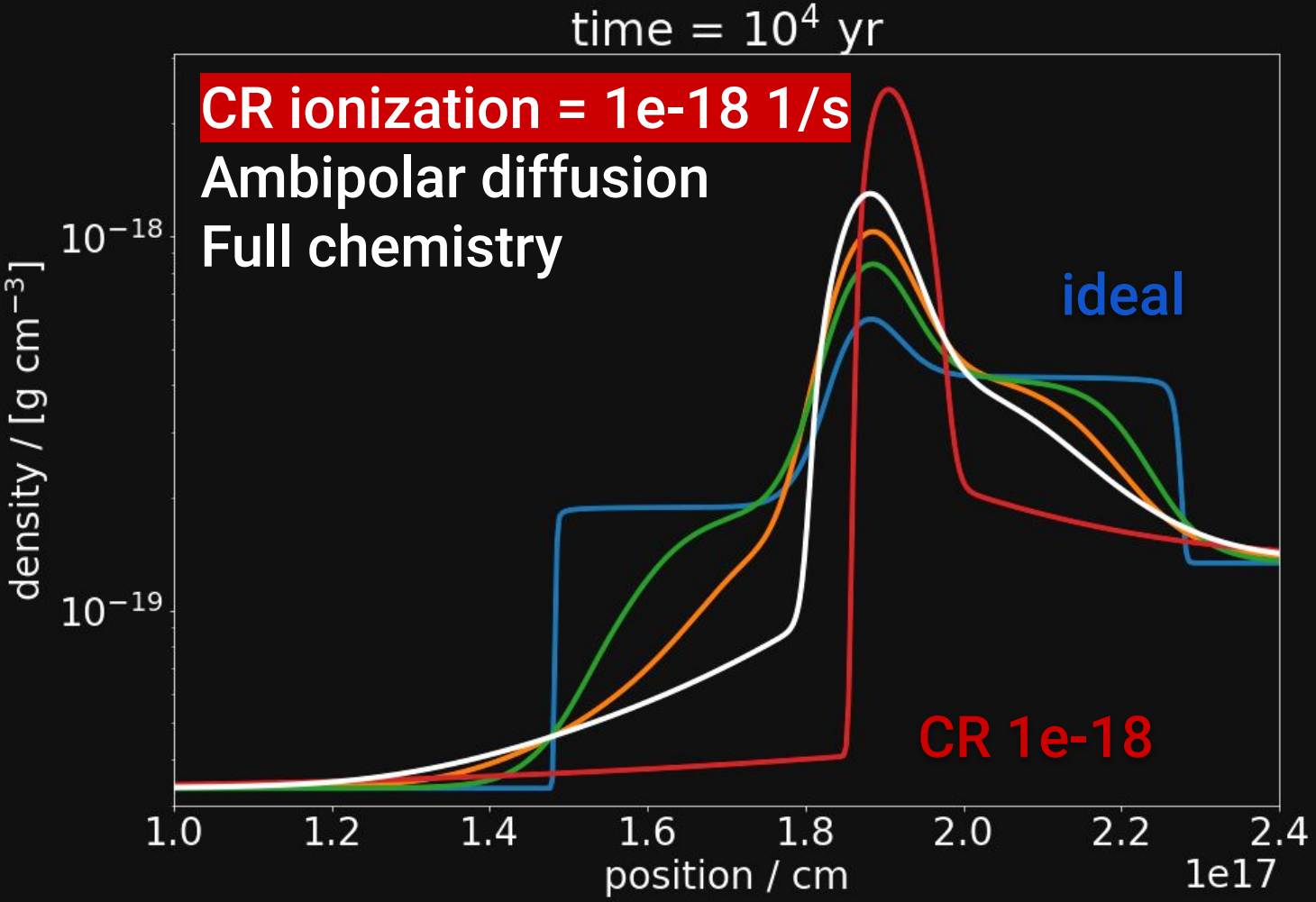
arXiv:1901.00504

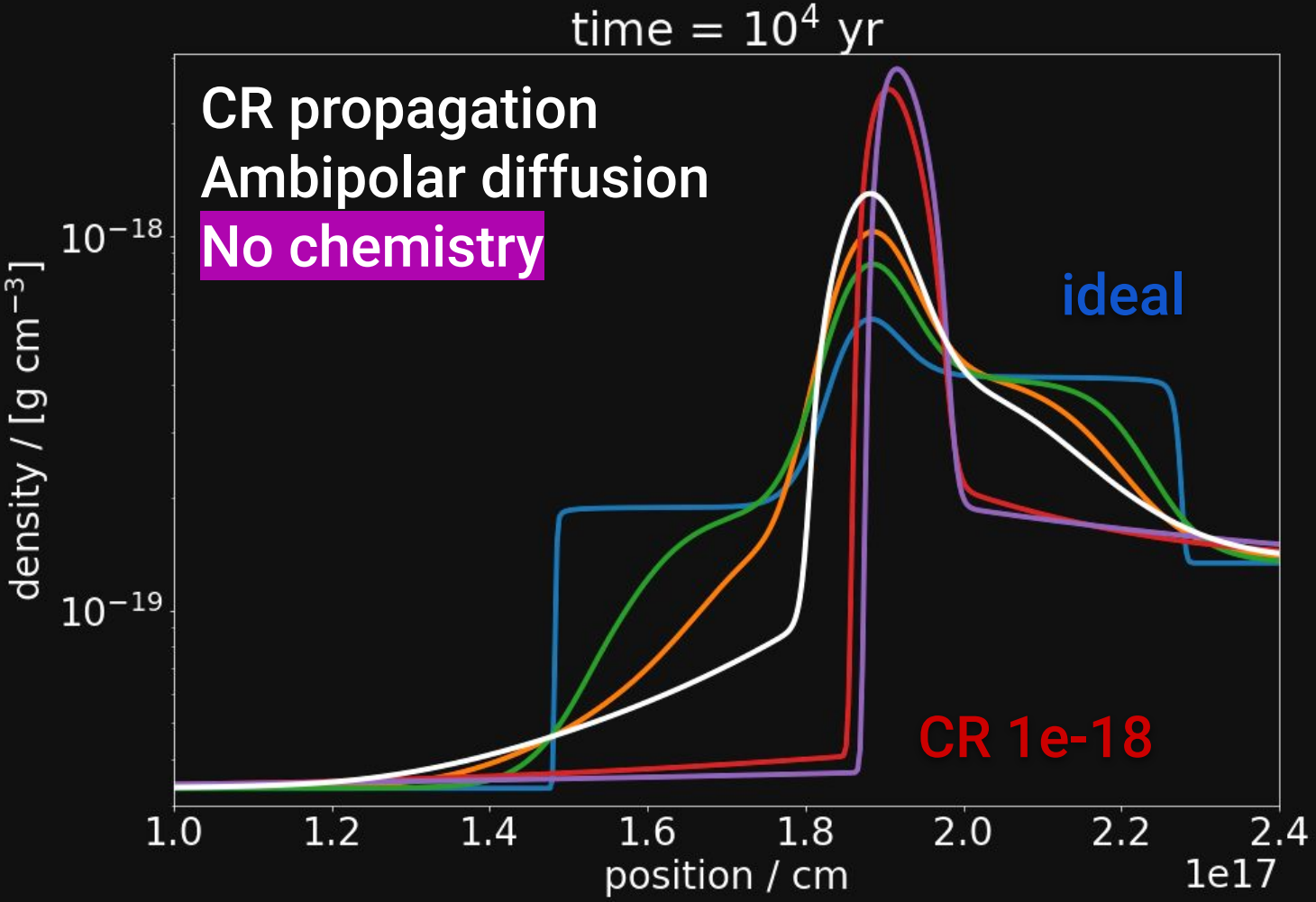

time = 10^4 yr
CRs propagation
Ambipolar diffusion
Full chemistry
density / [g cm^{-3}]
10^{-18}
10^{-19}
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
position / cm
1e17


time = 10^4 yr
CRs propagation
~~Ambipolar diffusion~~
Full chemistry
ideal
density / [g cm^{-3}]
10^{-18}
10^{-19}
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
position / cm
1e17


time = 10^4 yr
CRs propagation
Ambipolar diffusion
e^- + dust sticking = 1
ideal
density / [g cm^{-3}]
10^{-18}
10^{-19}
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
position / cm
1e17


time = 10^4 yr
CR ionization = 1e-15 1/s
Ambipolar diffusion
Full chemistry
ideal
density / [g cm^{-3}]
10^{-18}
10^{-19}
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
position / cm
1e17

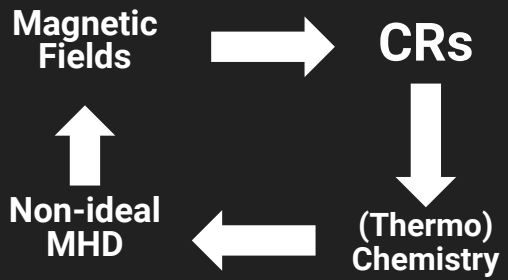

time = 10^4 yr
CR ionization = 1e-18 1/s
Ambipolar diffusion
Full chemistry
ideal
CR 1e-18
density / [g cm^{-3}]
10^{-18}
10^{-19}
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
position / cm
1e17


time = 10^4 yr
CR propagation
Ambipolar diffusion
No chemistry
ideal
CR 1e-18
density / [g cm^{-3}]
10^{-18}
10^{-19}
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
position / cm
1e17

Conclusions

Part 1: 3D in Pre-stellar cores

- Magnetic fields topology matters
- Monte Carlo is accurate but slow
- HEALPix works well (if simple topology)



Part 2: 1D in Shocks

- Microphysics matters
- Self-consistency matters
- Do not draw conclusions for case studies

- Muon detector original design: Spencer N. Axani (MIT)
- Project: cosmicwatch.lns.mit.edu
- Thanks to U.K. Radio Astronomy Association (UKRAA)
- Buy similar one on https://www.ukraa.com/store/products