The Role of Cosmic Rays in Isolated Disk Galaxies

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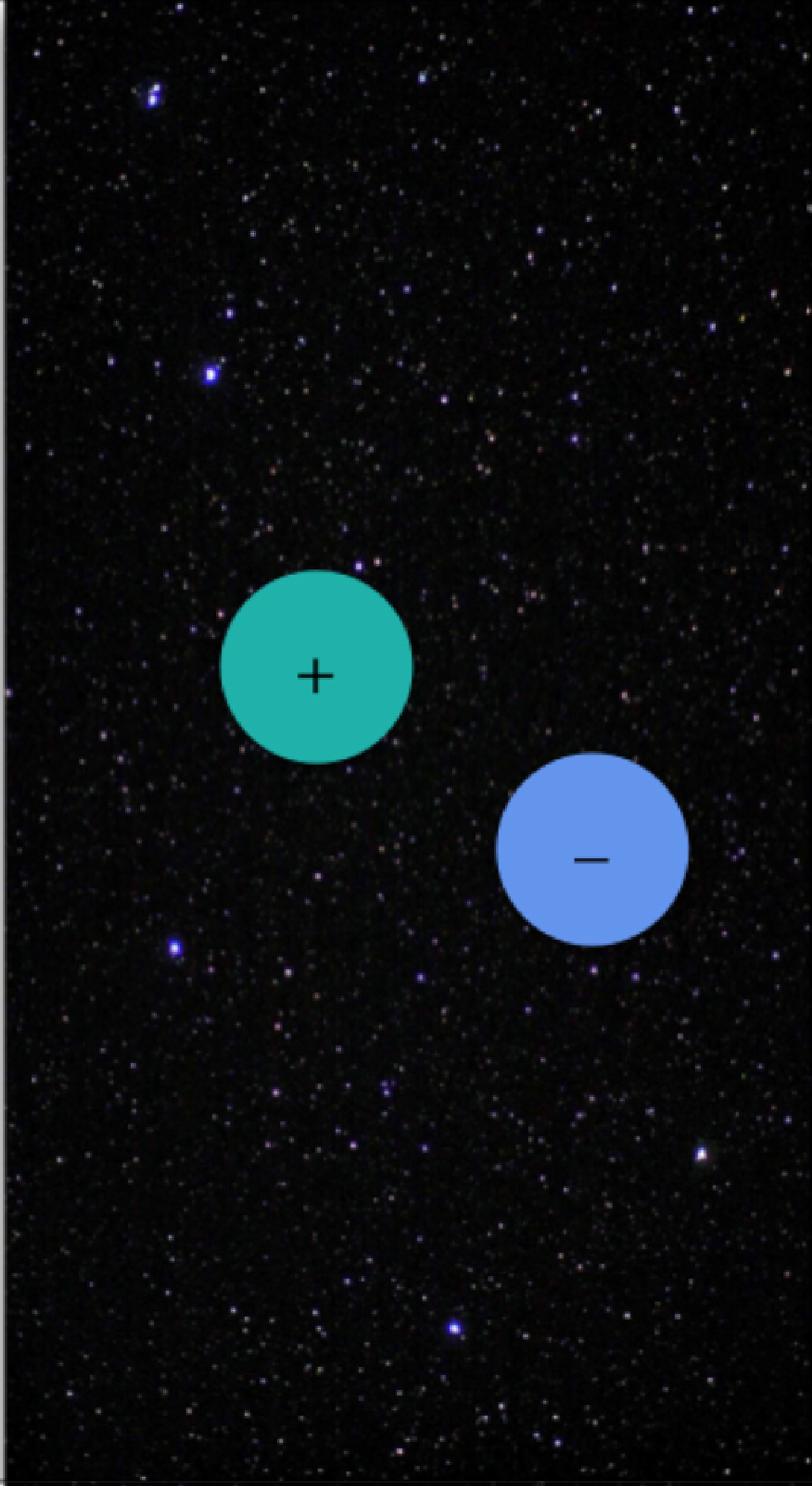
Outline

- Why it Matters (Background)
- Methods & Key Challenges
- Why Blue Waters?
- Preliminary Results
- Broader Impact

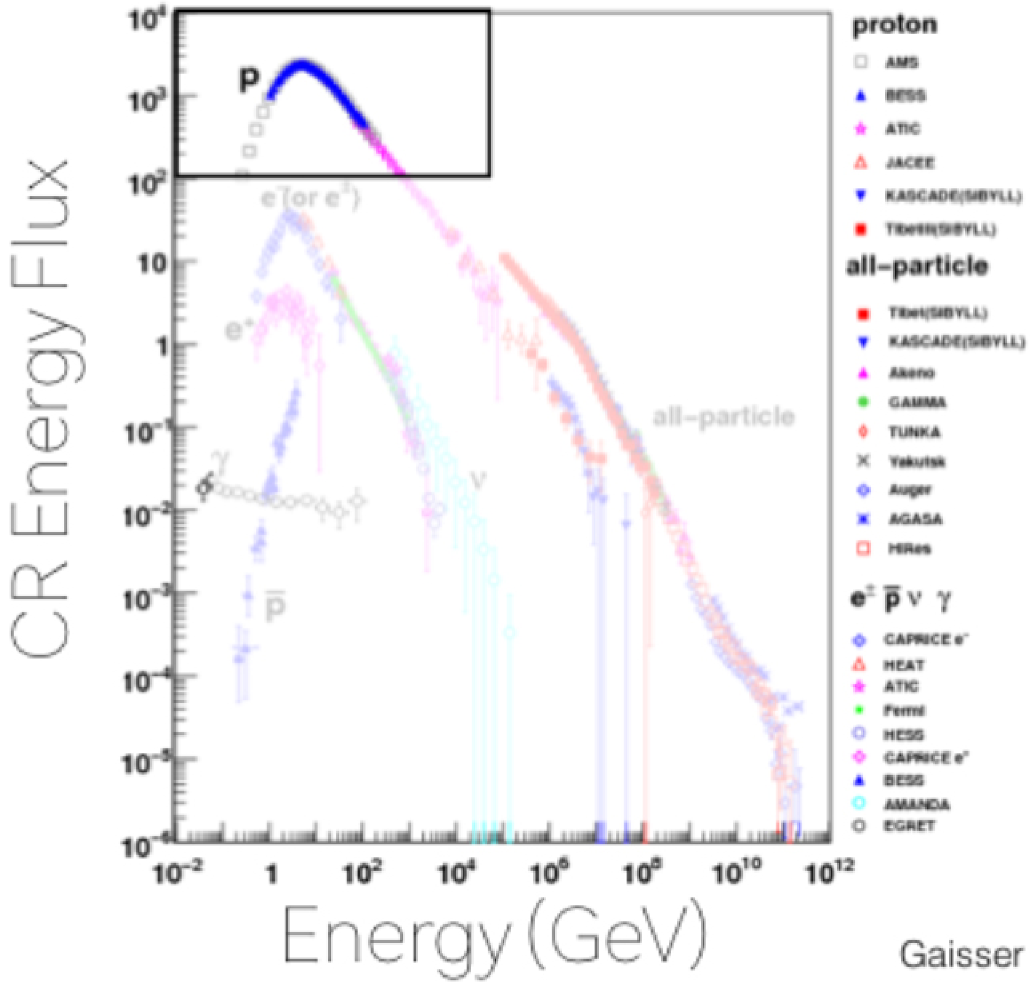
Cosmic Rays

- Charged particles (p+ , e-, etc.)

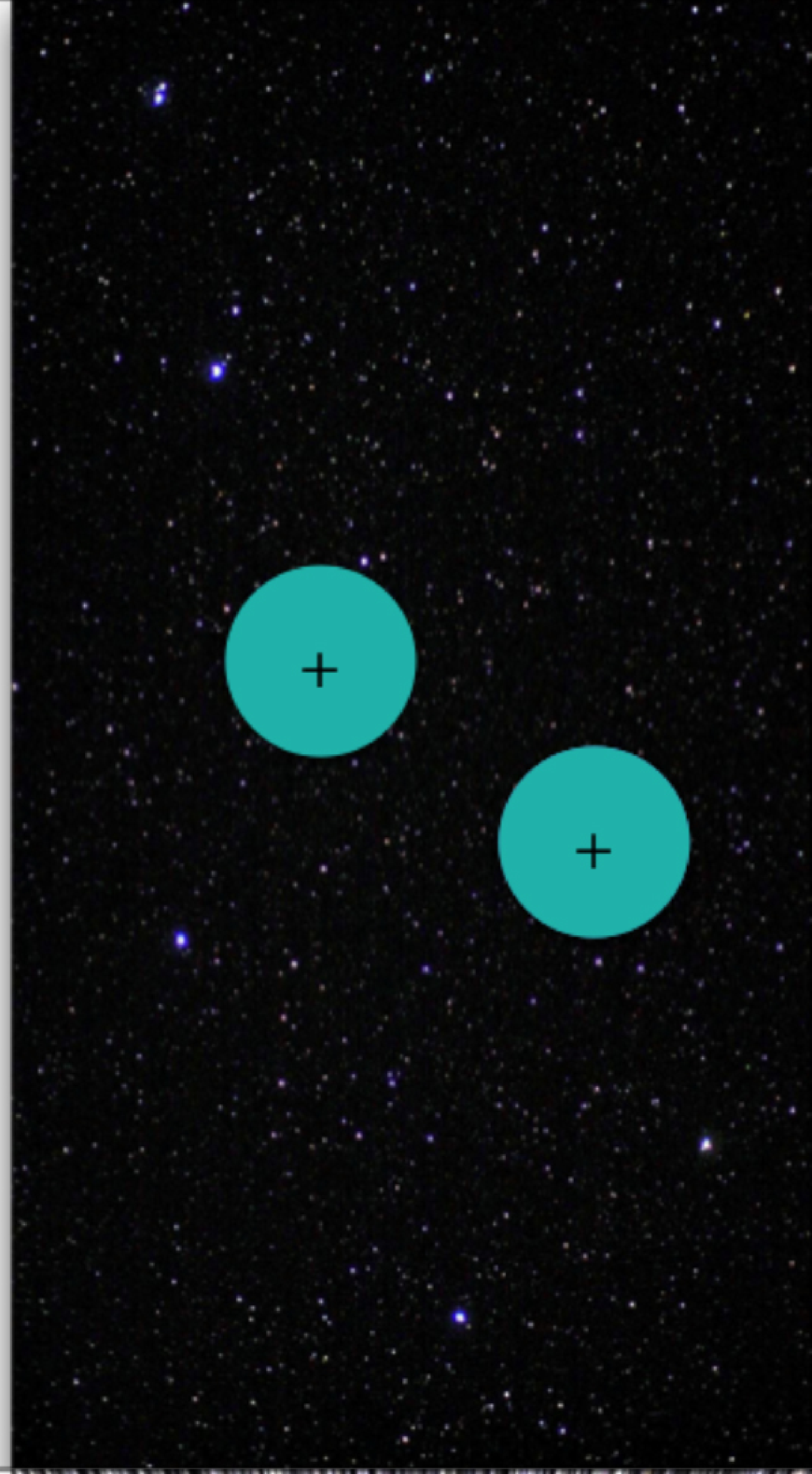


Cosmic Rays

- Charged particles (p+)

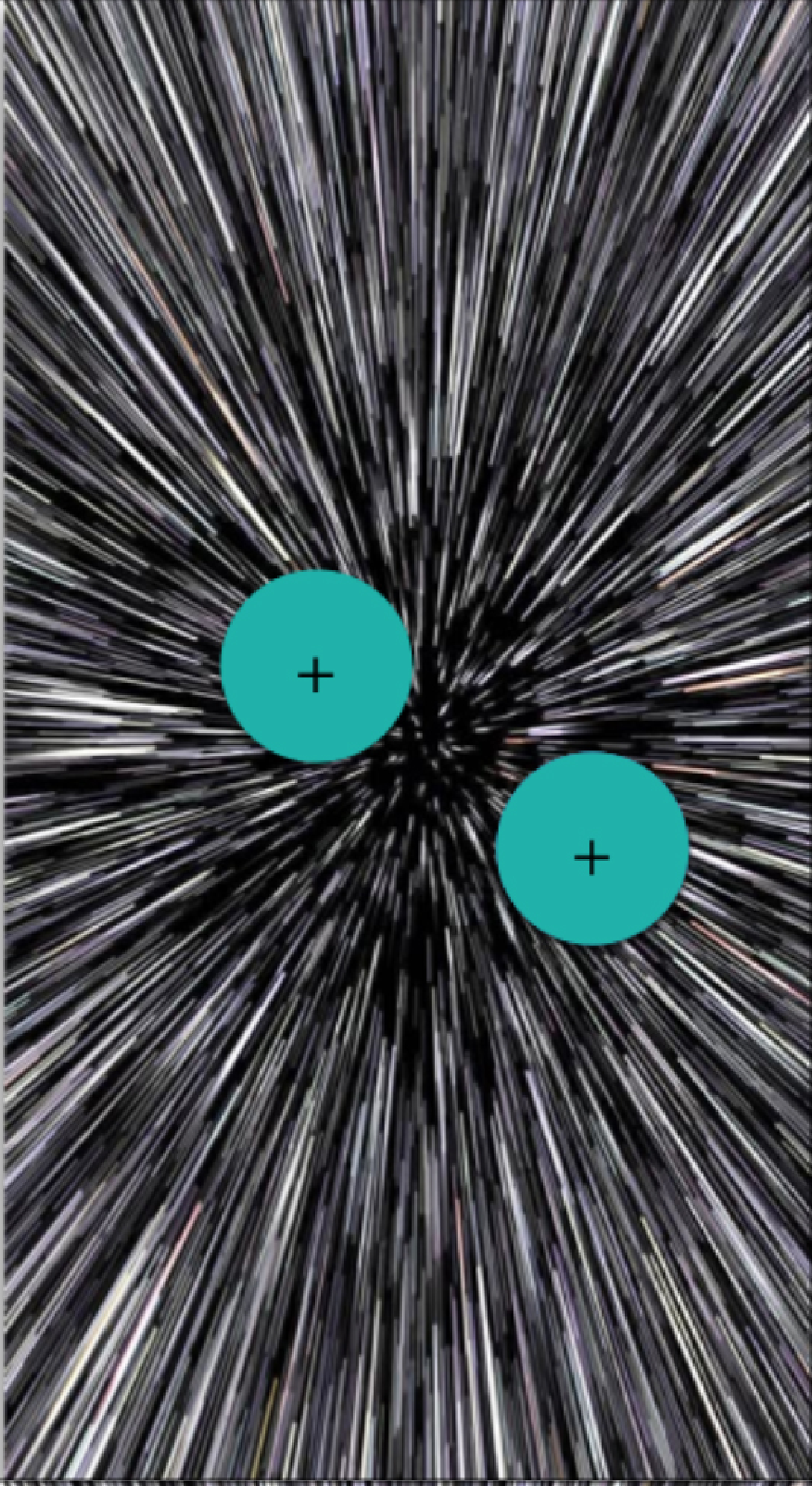


Gaisser 2006



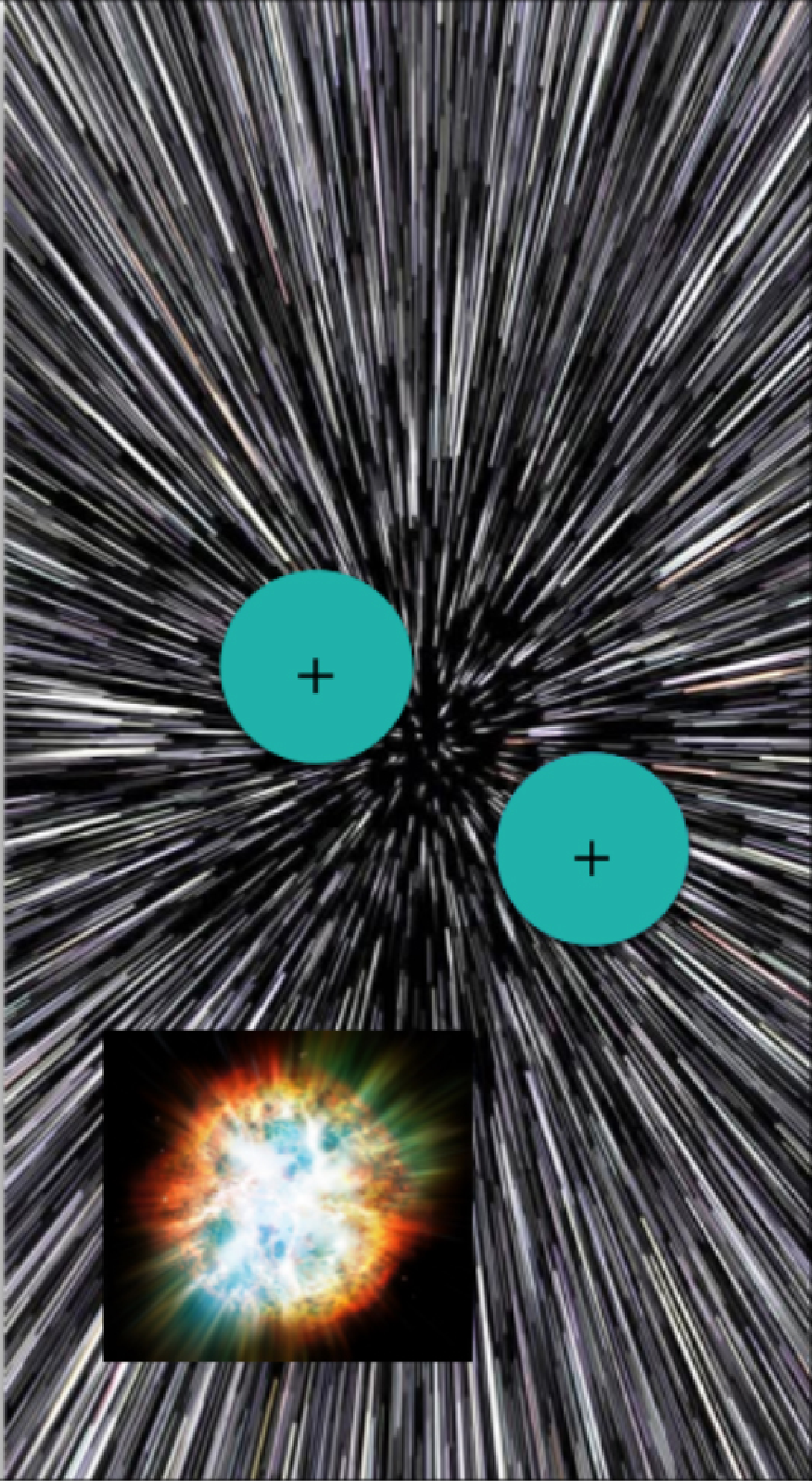
Cosmic Rays

- Charged particles (p+)
- Move at relativistic speeds



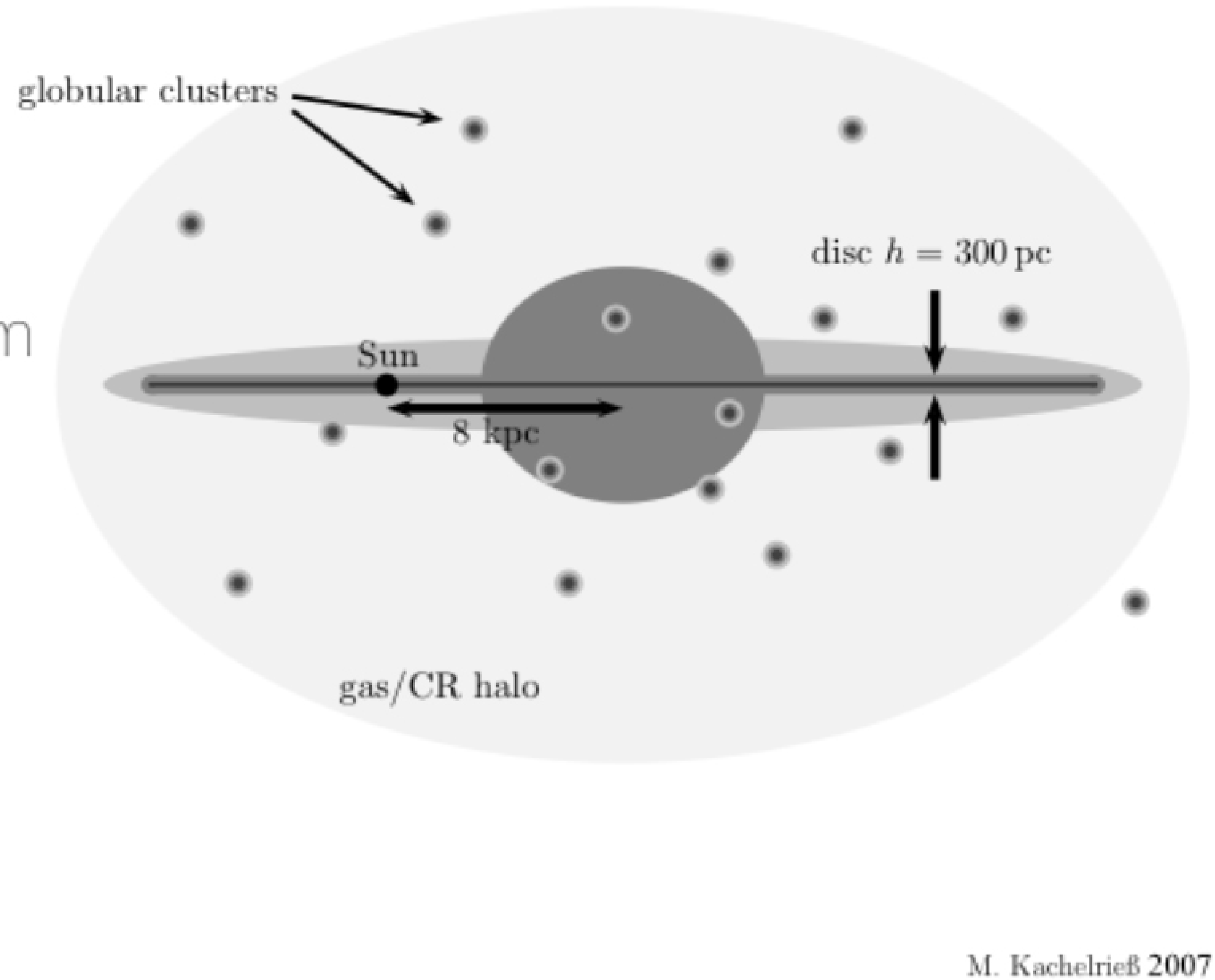
Cosmic Rays

- Charged particles (p+)
- Move at relativistic speeds
- Accelerated in shocks: supernovae, active galactic nuclei (AGN), quasars, gamma-ray bursts

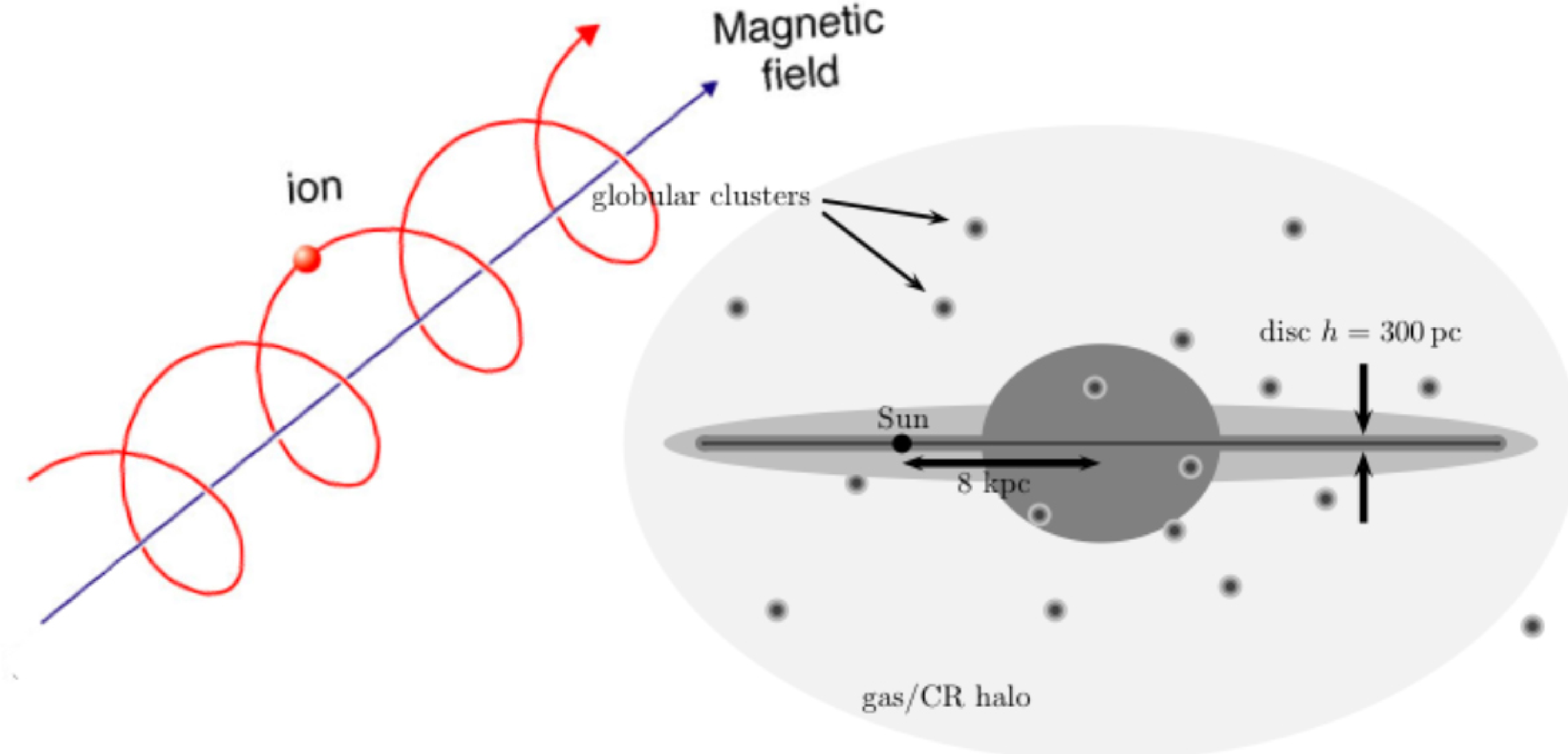


Propagation of Cosmic Rays

- Mean free path for CR collisions ~ 10 n Mpc ($10^{-4} < n < 10^{2}$ cm^{-3})
- Escape time of CRs from galaxy ~ 3×10^{7} years
- Must be some scattering mechanism present

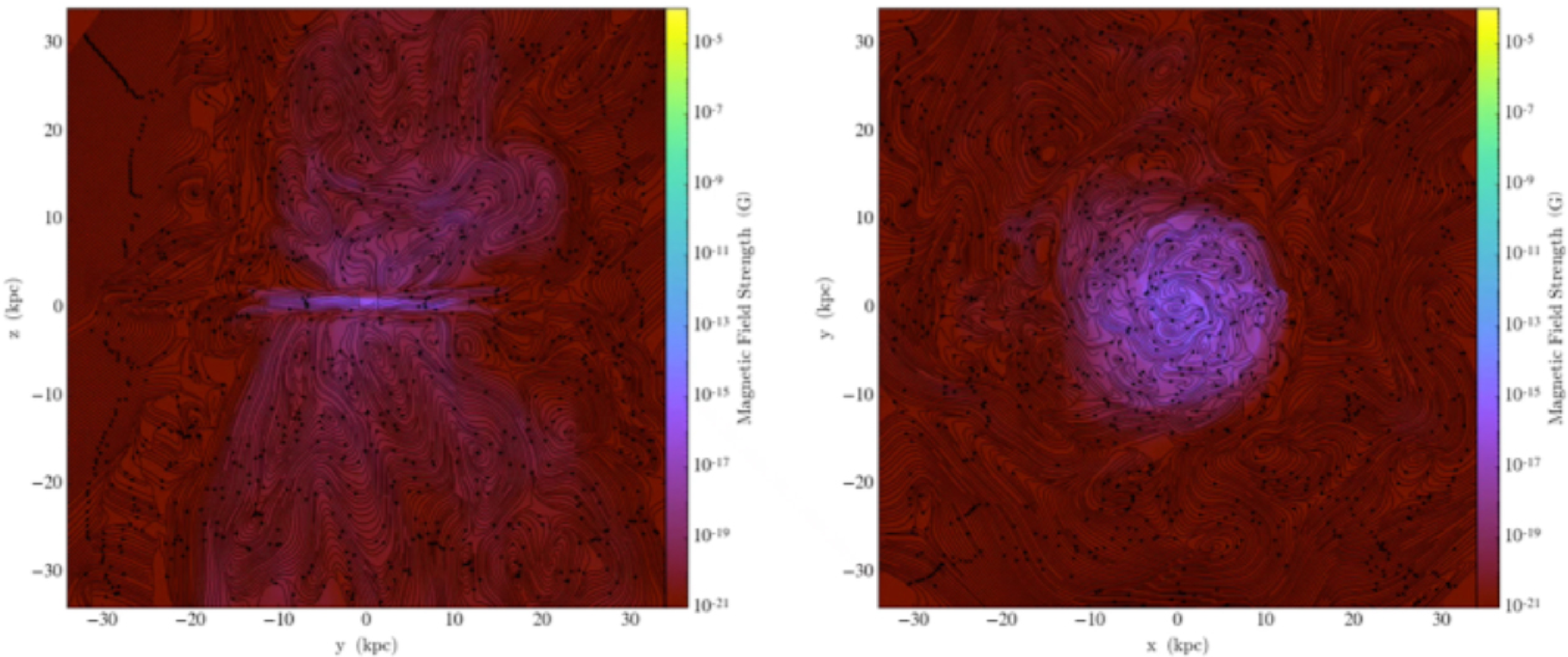


Propagation of Cosmic Rays



M. Kachelrieß 2007

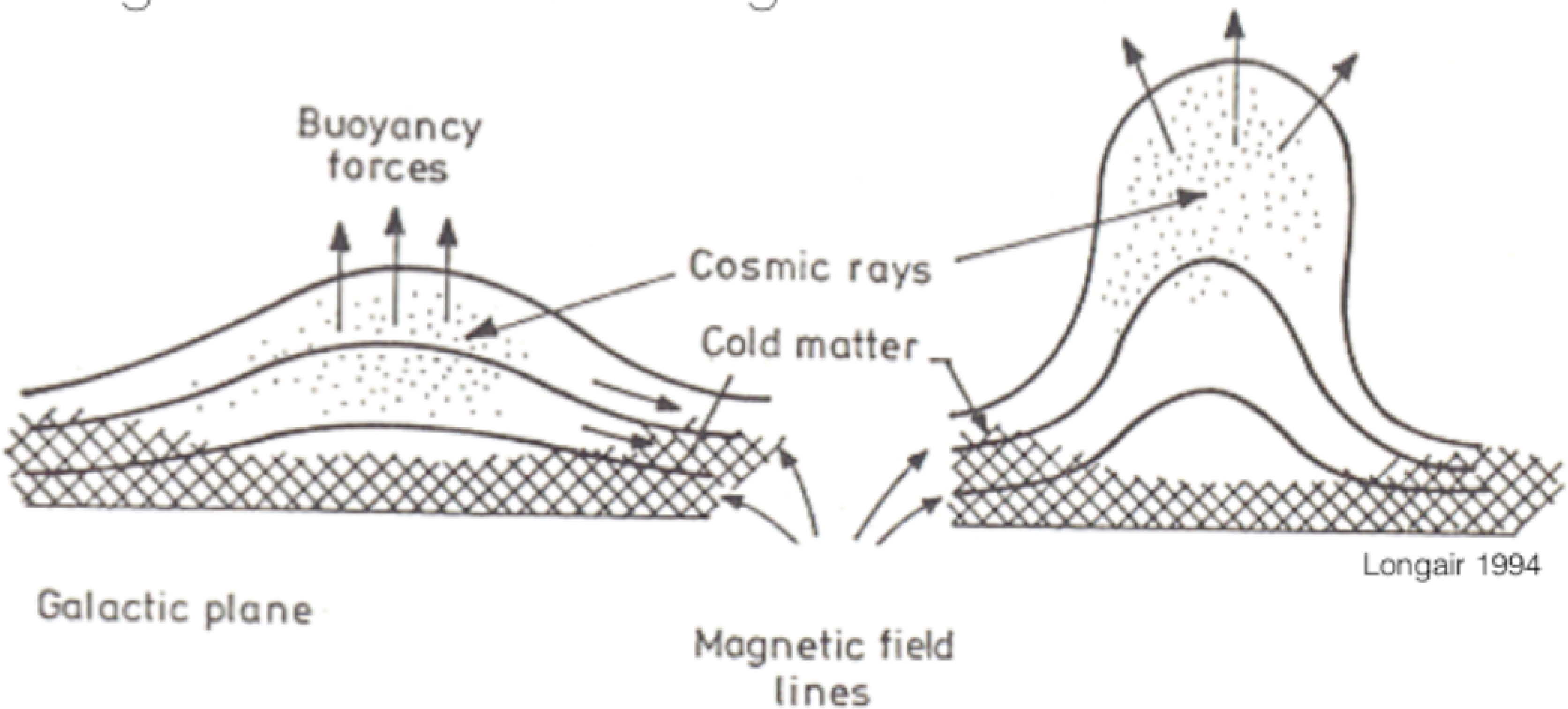
Galactic Magnetic Fields



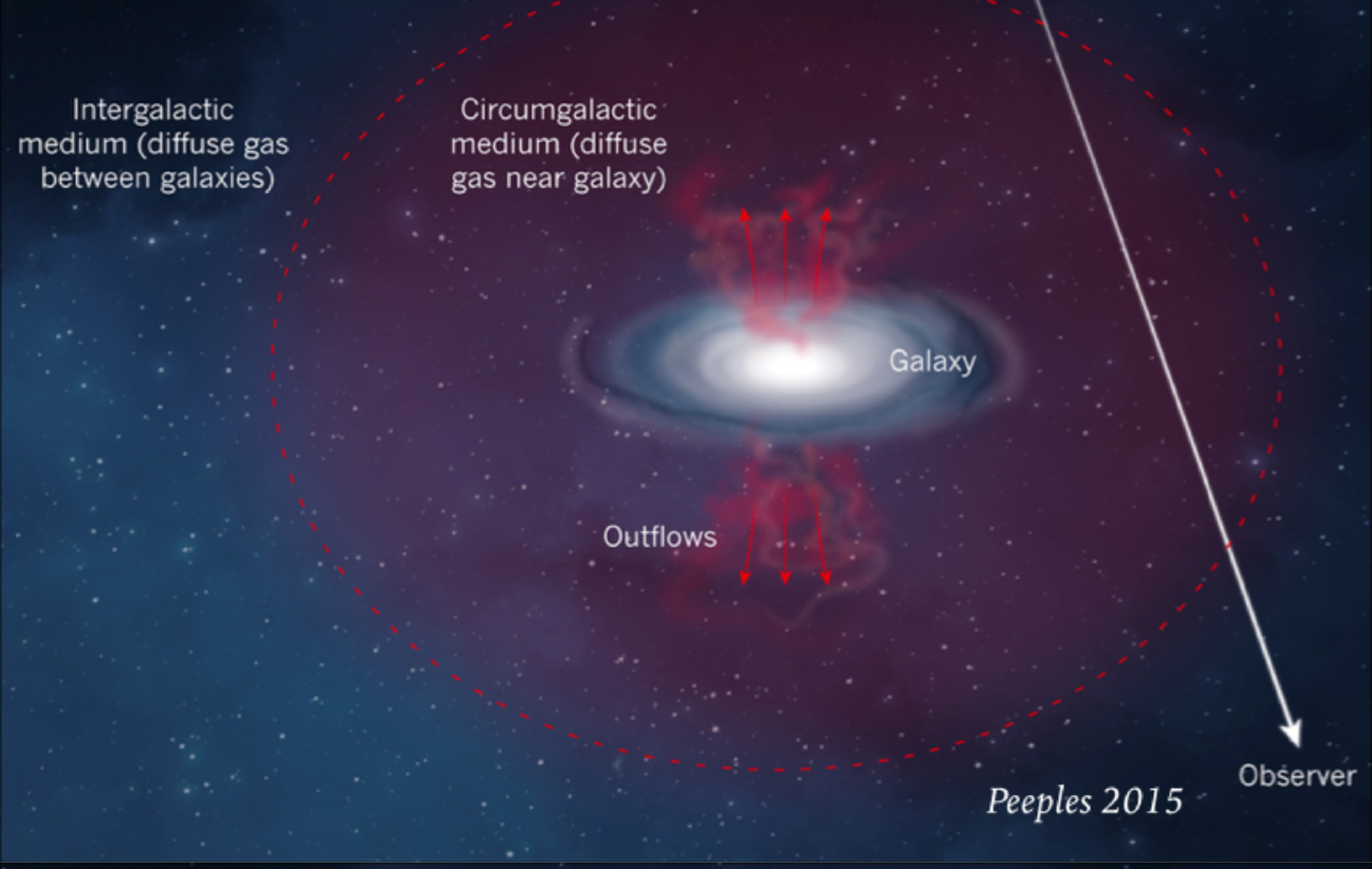
Butsky et al. 2017

CR Driven Dynamo

- dynamo converts kinetic energy into magnetic energy
- CRs create magnetic instabilities which grow the magnetic field and drive galactic winds



CIRCUMGALACTIC MEDIUM (CGM)



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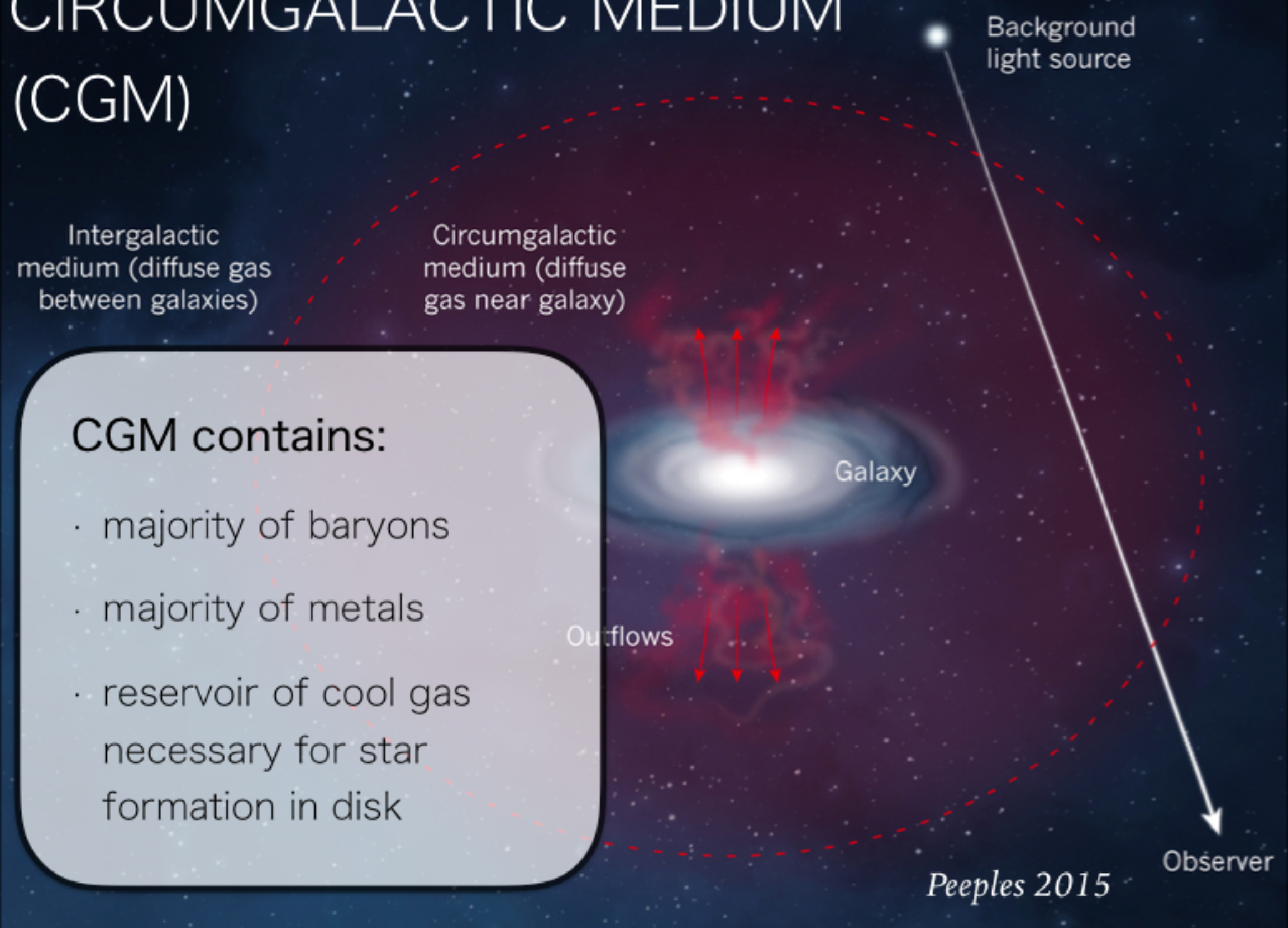
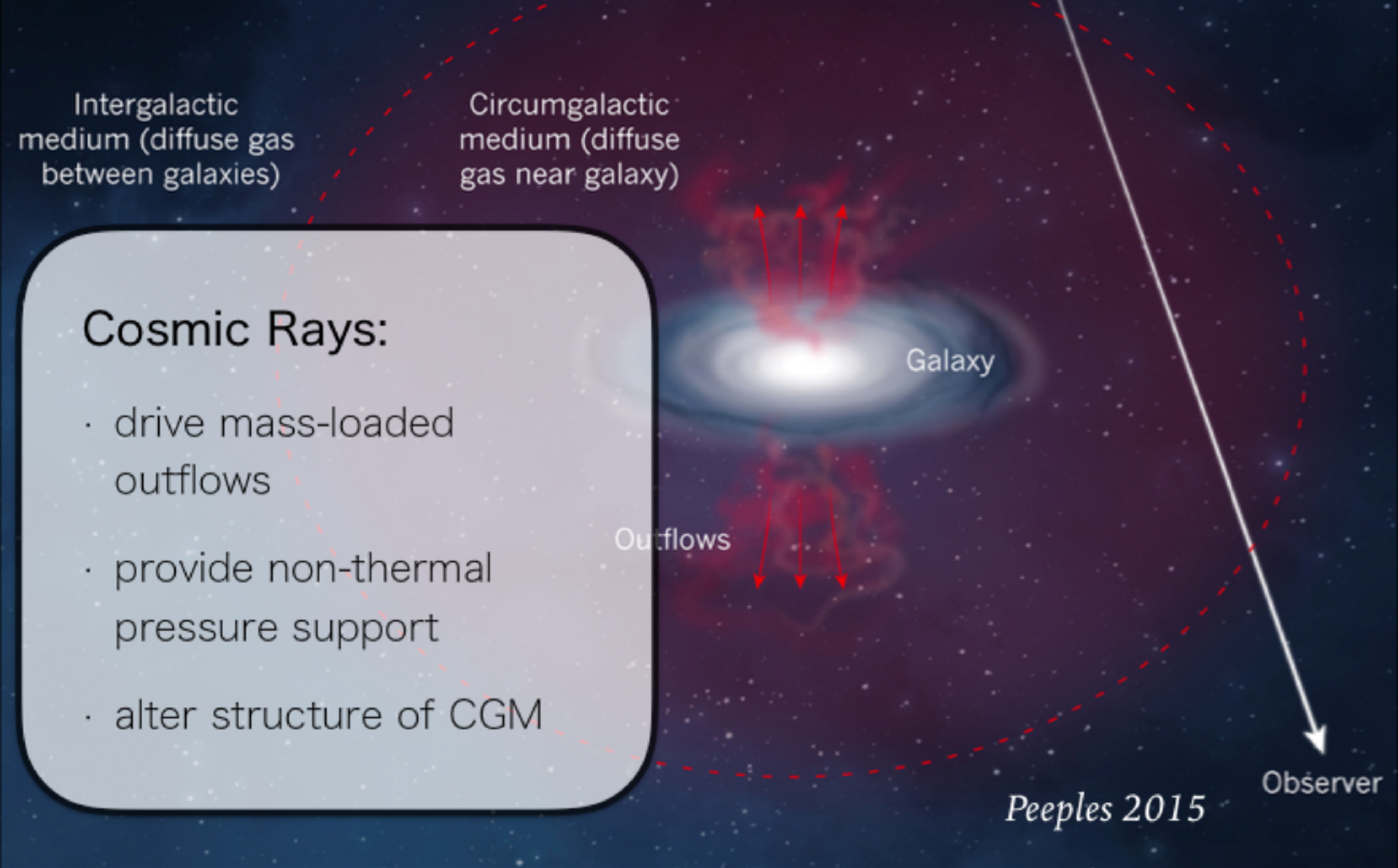


CGM contains:

- majority of baryons
- majority of metals
- reservoir of cool gas necessary for star formation in disk

Peeples 2015

CIRCUMGALACTIC MEDIUM (CGM)



Cosmic Rays:

- drive mass-loaded outflows
- provide non-thermal pressure support
- alter structure of CGM

Outline

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- **Methods & Key Challenges**
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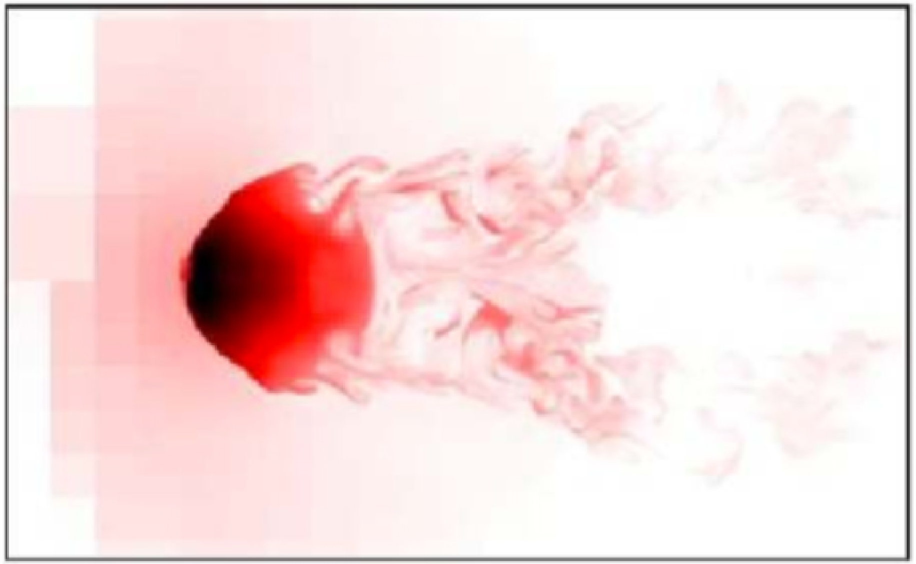
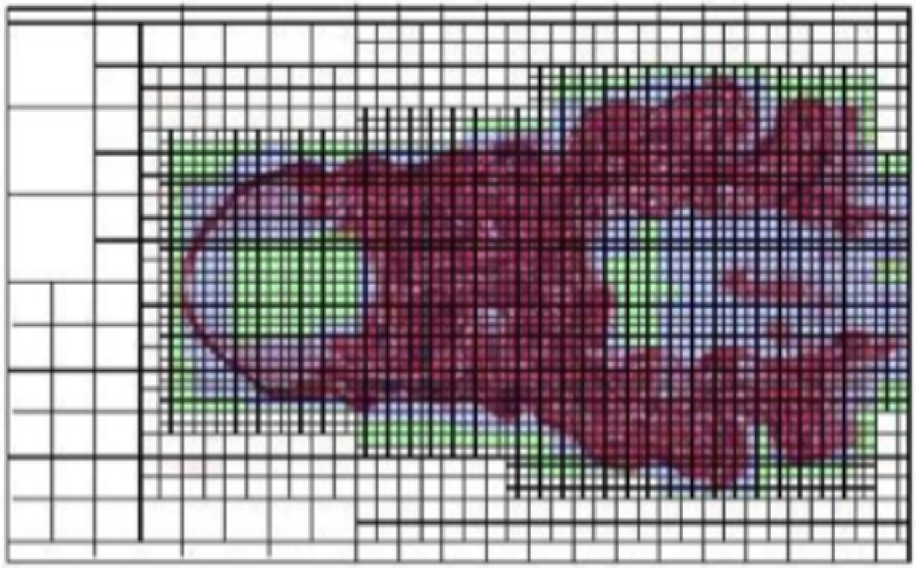
ENZO Basics

- Adaptive mesh grid code
- Simulate a fluid moving through cells
- Time evolution of conserved quantities governed by Euler's equations





Iapichino et al. 2008

Euler's Equations

1.

$$\frac{d\mathbf{U}}{dt} + \nabla \cdot \mathbf{F} = \mathbf{S}$$

density
velocity
B field
total energy
CR energy

change over time

flux through cell

source term

2. Numerically approximate solution using a Riemann solver

Adding CRs to the Equation

$$\mathbf{U} = \begin{pmatrix} \rho \\ \rho\mathbf{v} \\ \mathbf{B} \\ \epsilon \end{pmatrix}$$

density
velocity
B field
total energy

$$\mathbf{F} = \begin{pmatrix} \rho\mathbf{v} \\ \rho\mathbf{v}\mathbf{v}^{\mathrm{T}} + P\mathbf{1} - \mathbf{B}\mathbf{B}^{\mathrm{T}} \\ \mathbf{B}\mathbf{v}^{\mathrm{T}} - \mathbf{v}\mathbf{B}^{\mathrm{T}} \\ (\epsilon + P)\mathbf{v} - \mathbf{B}(\mathbf{v} \cdot \mathbf{B}) \end{pmatrix}$$

$$\mathbf{S} = \begin{pmatrix} 0 \\ \mathbf{0} \\ \mathbf{0} \\ 0 \end{pmatrix}$$

$$\boxed{\frac{d\mathbf{U}}{dt} + \nabla \cdot \mathbf{F} = \mathbf{S}}$$

Adding CRs to the Equation

$$\mathbf{U} = \begin{pmatrix} \rho \\ \rho\mathbf{v} \\ \mathbf{B} \\ \epsilon \\ \epsilon_{cr} \end{pmatrix}$$

density
velocity
B field
total energy
CR energy

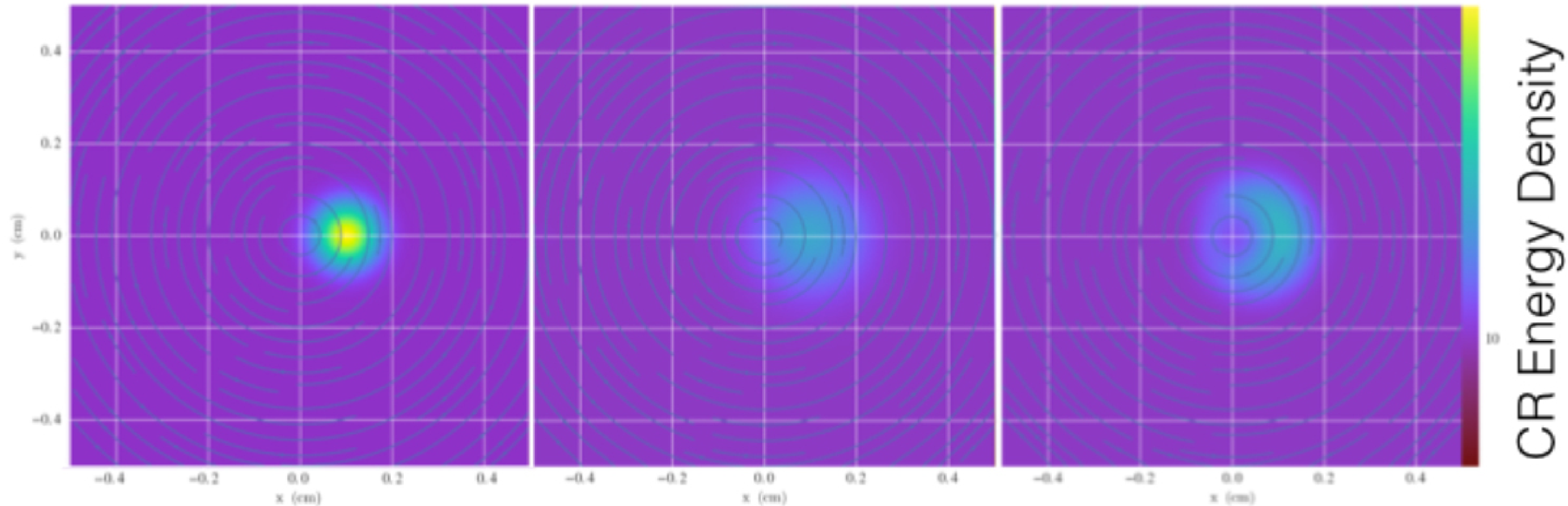
$$\mathbf{F} = \begin{pmatrix} \rho\mathbf{v} \\ \rho\mathbf{v}\mathbf{v}^{\mathrm{T}} + P\mathbf{1} - \mathbf{B}\mathbf{B}^{\mathrm{T}} \\ \mathbf{B}\mathbf{v}^{\mathrm{T}} - \mathbf{v}\mathbf{B}^{\mathrm{T}} \\ (\epsilon + P)\mathbf{v} - \mathbf{B}(\mathbf{v}\cdot\mathbf{B}) - \kappa_\epsilon \mathbf{b}(\mathbf{b}\cdot\nabla\epsilon_{cr}) \\ \epsilon_{cr}(\mathbf{v} + \mathbf{v}_{\mathrm{st}}) - \kappa_\epsilon \mathbf{b}(\mathbf{b}\cdot\nabla\epsilon_{cr}) \end{pmatrix}$$

CR diffusion

$$\mathbf{S} = \begin{pmatrix} 0 \\ \mathbf{0} \\ \mathbf{0} \\ 0 \\ -P_{cr}\nabla\cdot(\mathbf{v} + \mathbf{v_{st}}) \end{pmatrix}$$

$$\frac{d\mathbf{U}}{dt} + \nabla\cdot\mathbf{F} = \mathbf{S}$$

CR Diffusion



Initial CR overdensity

Isotropic diffusion

$$\nabla \cdot \kappa_\epsilon \nabla^2 \epsilon_{cr}$$

Anisotropic diffusion

$$\nabla \cdot [\kappa_\epsilon \mathbf{b}(\mathbf{b} \cdot \nabla \epsilon_{cr})]$$

Key Challenge: Time Stepping with CRs

- **Diffusion:** $t_D = \frac{\Delta x^2}{\kappa_{cr}}$

- **Courant:** $t_c = \frac{\Delta x}{c_f}$ $$c_f \propto \sqrt{\frac{\gamma_{cr} P_{cr}}{\rho}}$$

Key Challenge: Pick Two

"Short" Computational Time

Cosmic Rays

Magnetic Fields

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Why Blue Waters?

- Huge variation in simulation scale
- Each cell follows complex interaction rules
- Efficient parallelization
- Sufficient data storage
- Awesome support team!

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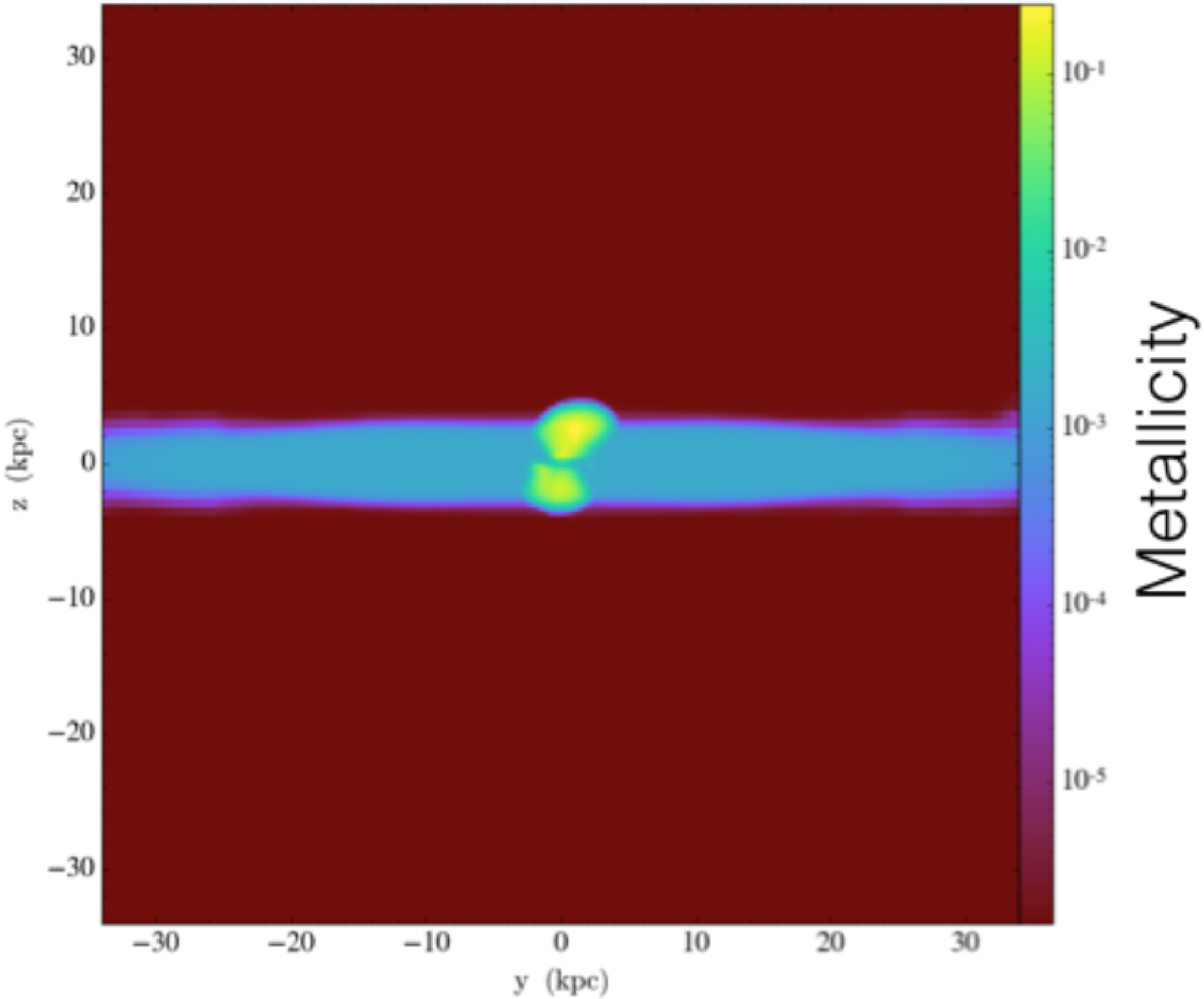
Preliminary Results: A (Short) Tale of Two Galaxies

- **Initial Conditions:**
  - AGORA isolated disk
  - Background magnetic field of 10^{-16} Gauss
  - 1 galaxy with uniform CR energy density of 10-3 erg/g
  - 1 galaxy with no CR physics
  - ~2000 core-hours to evolve 800 Myr

Circumgalactic Medium

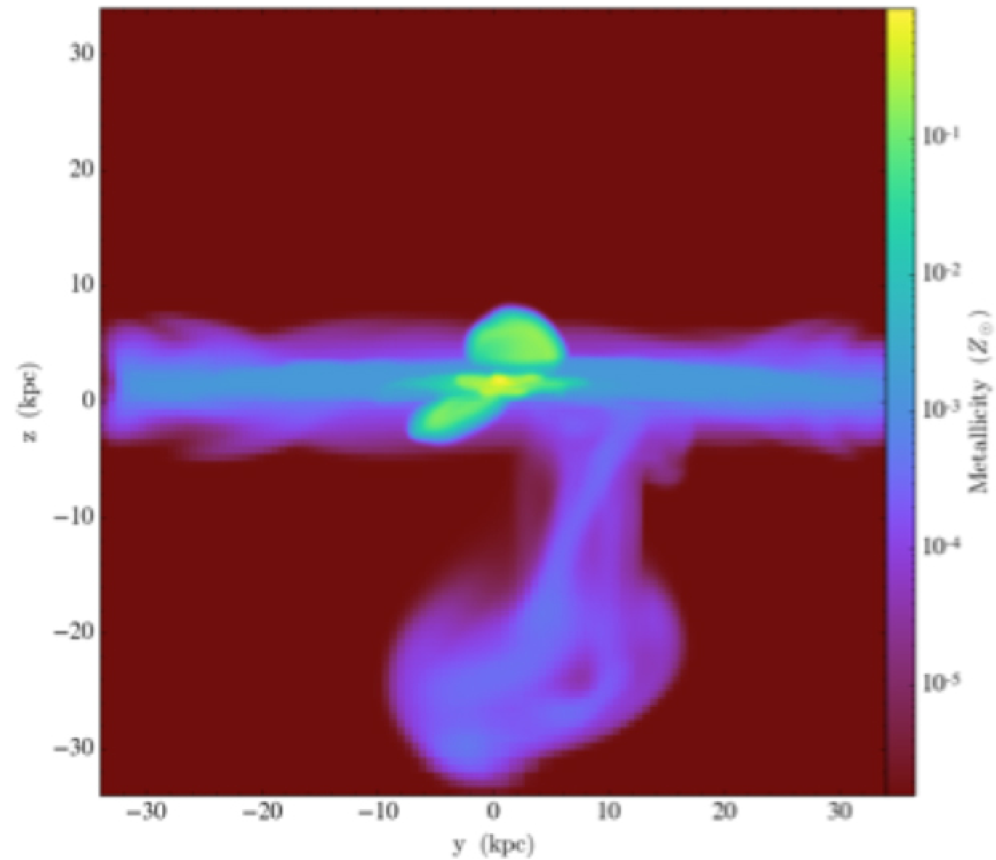


t = 3 Myr

- Metals* are produced by stars in disk
- Metallicity of halo traces galactic outflows

* metal = heavier than H or He

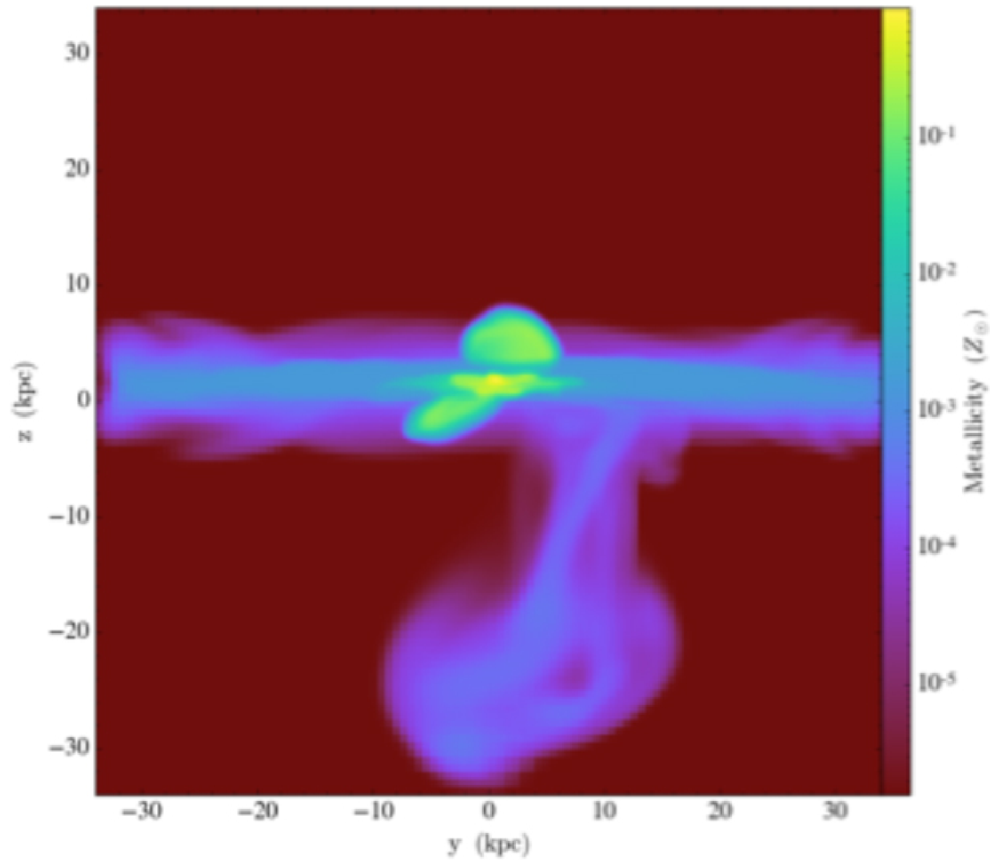
Circumgalactic Medium



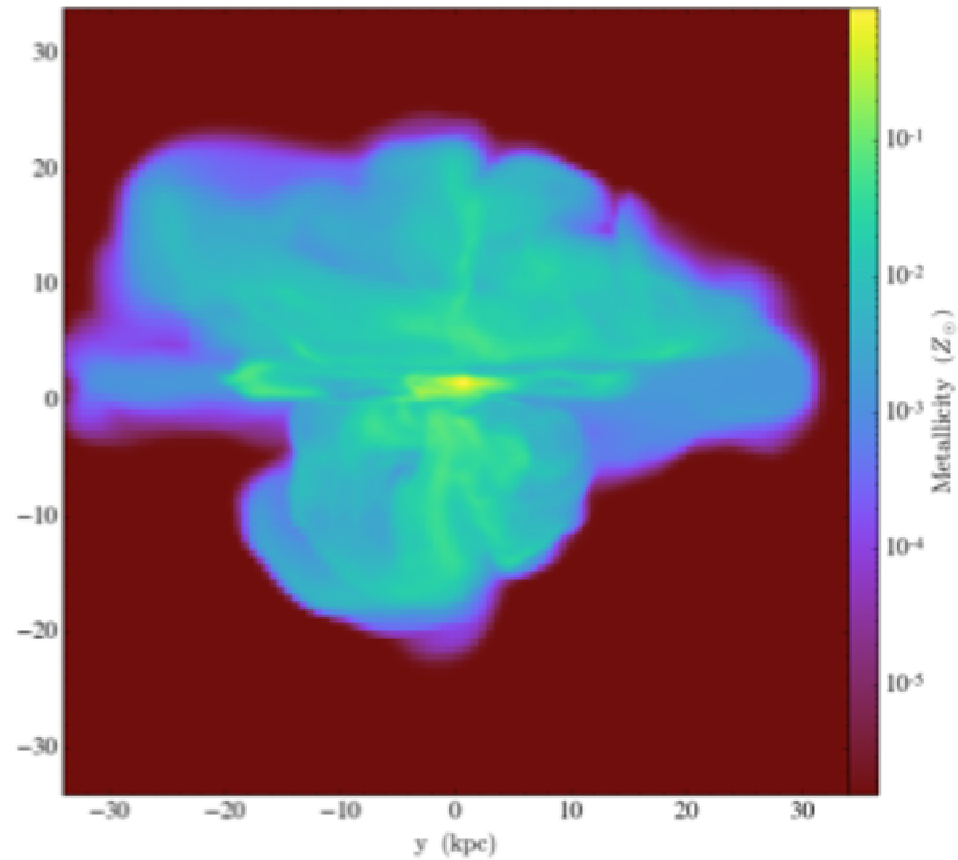
No CRs

t = 800 Myr

Circumgalactic Medium

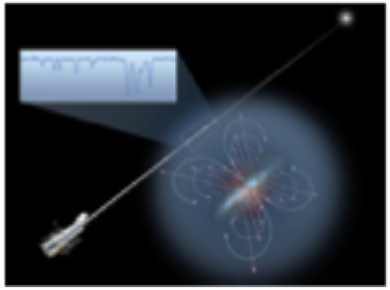


No CRs

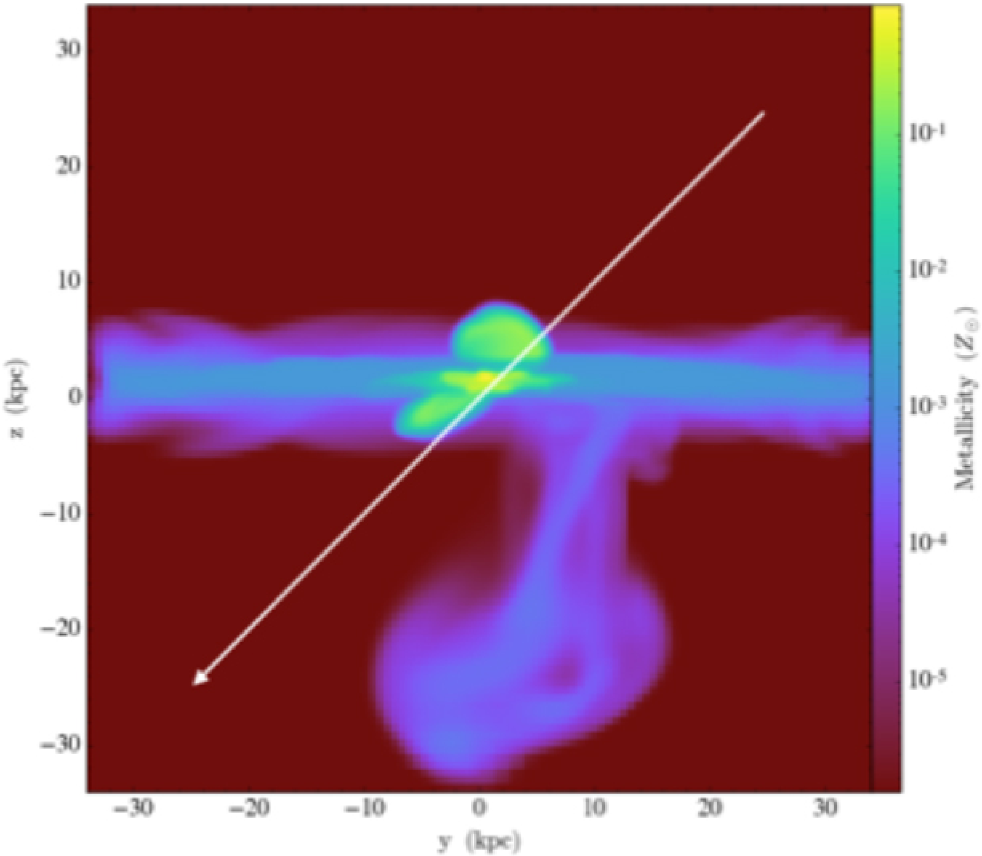


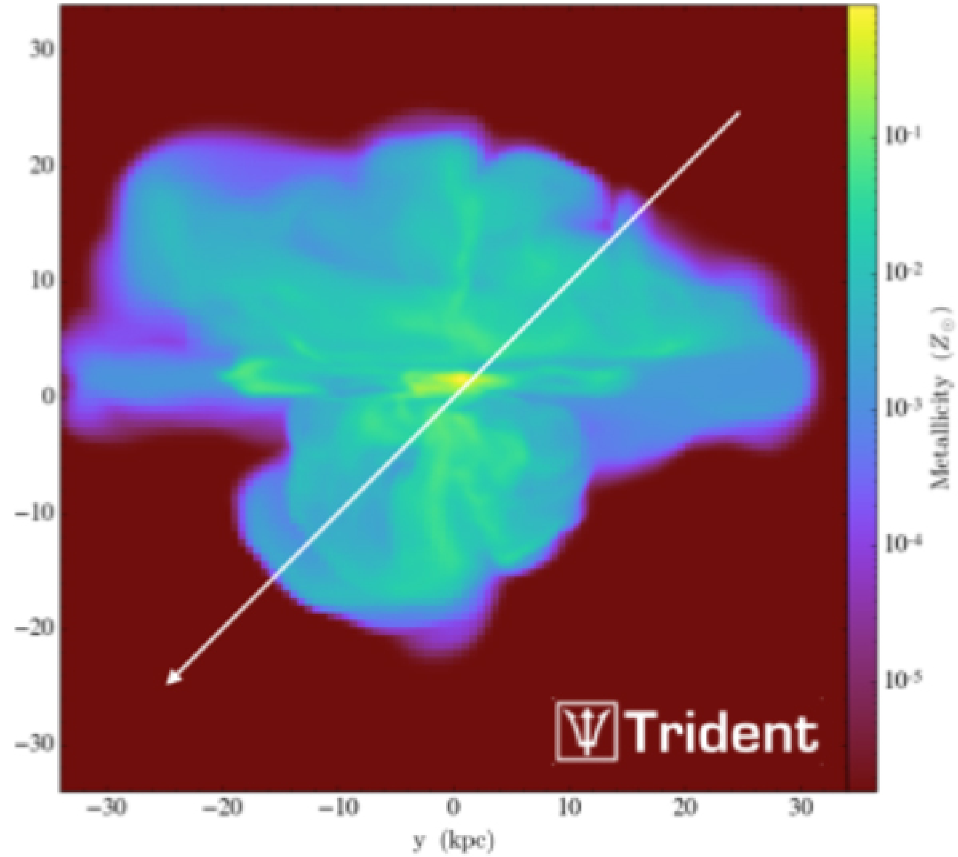
Includes CRs

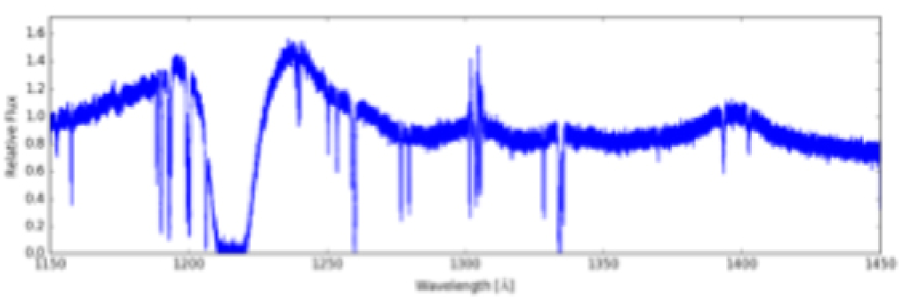
t = 800 Myr

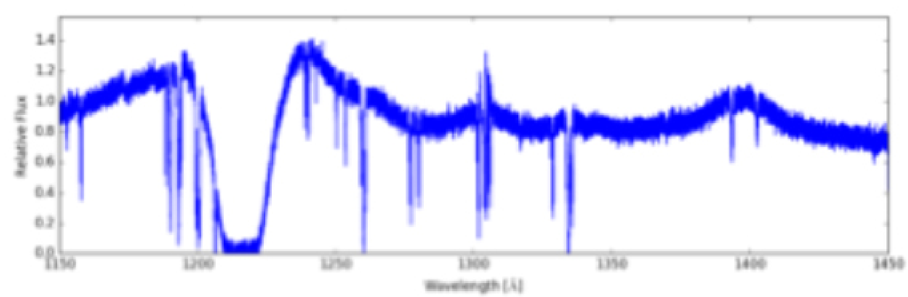


Hubble Space Telescope
Cosmic Origins Spectrograph

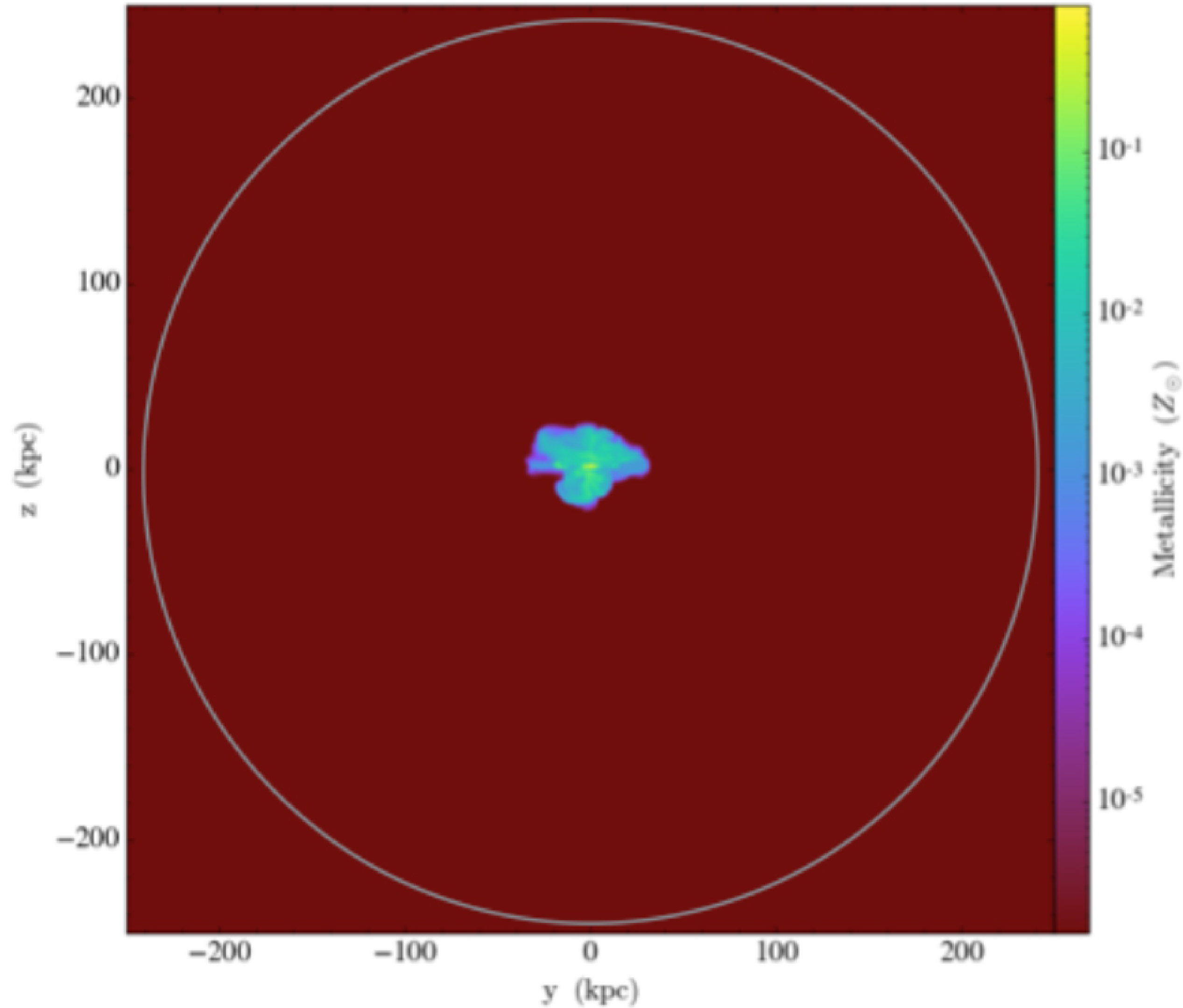








Circumgalactic Medium



Future Work:

- Evolve galaxies longer
- Dynamically important CRs
- Different mass galaxies
- Different diffusion coefficients / feedback

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- Results
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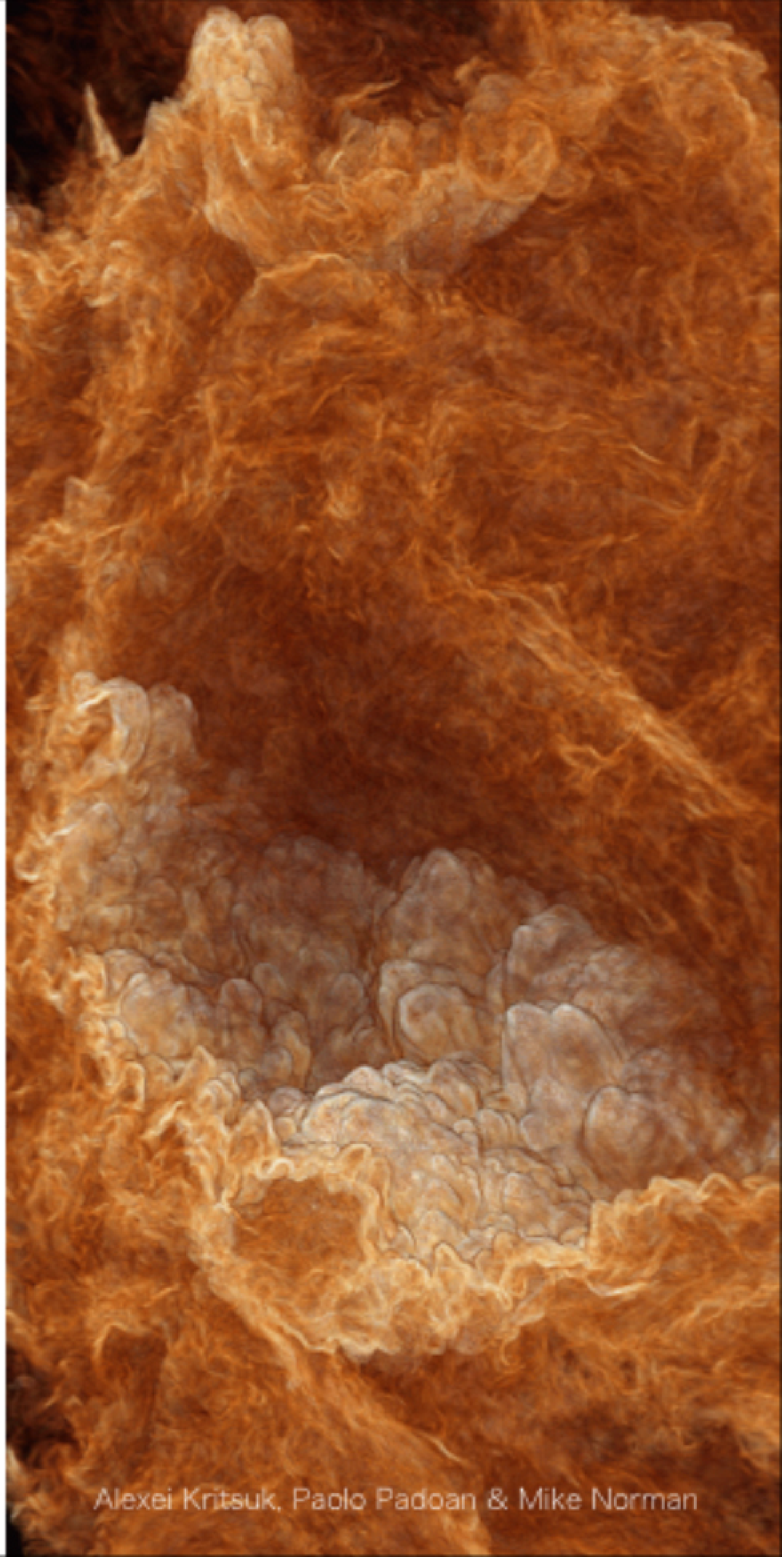
Broader Impact

- ENZO is a community-developed, publicly available code (enzo-project.org)
- Rich, multi-physics hydrodynamic astrophysical simulations
- Cosmic ray physics will be available for:
  - all HD and MHD solvers
  - all scales



Summary

- Understanding the structure of the CGM and the physical processes that govern its evolution is important for understanding galaxy evolution
- Cosmic rays drive large outflows and provide non-thermal pressure support which alter the structure and composition of the CGM
- Need magnetic fields and anisotropic diffusion to properly model CR behavior
- CR physics in ENZO compatible with MHD solvers
- Future work will use Blue Waters to run isolated galaxies with varying masses, feedback prescriptions, and CR diffusion coefficients
- We can compare our results to observations made with the HST COS-Halos instrument using synthetic spectra generated with Trident

Questions?