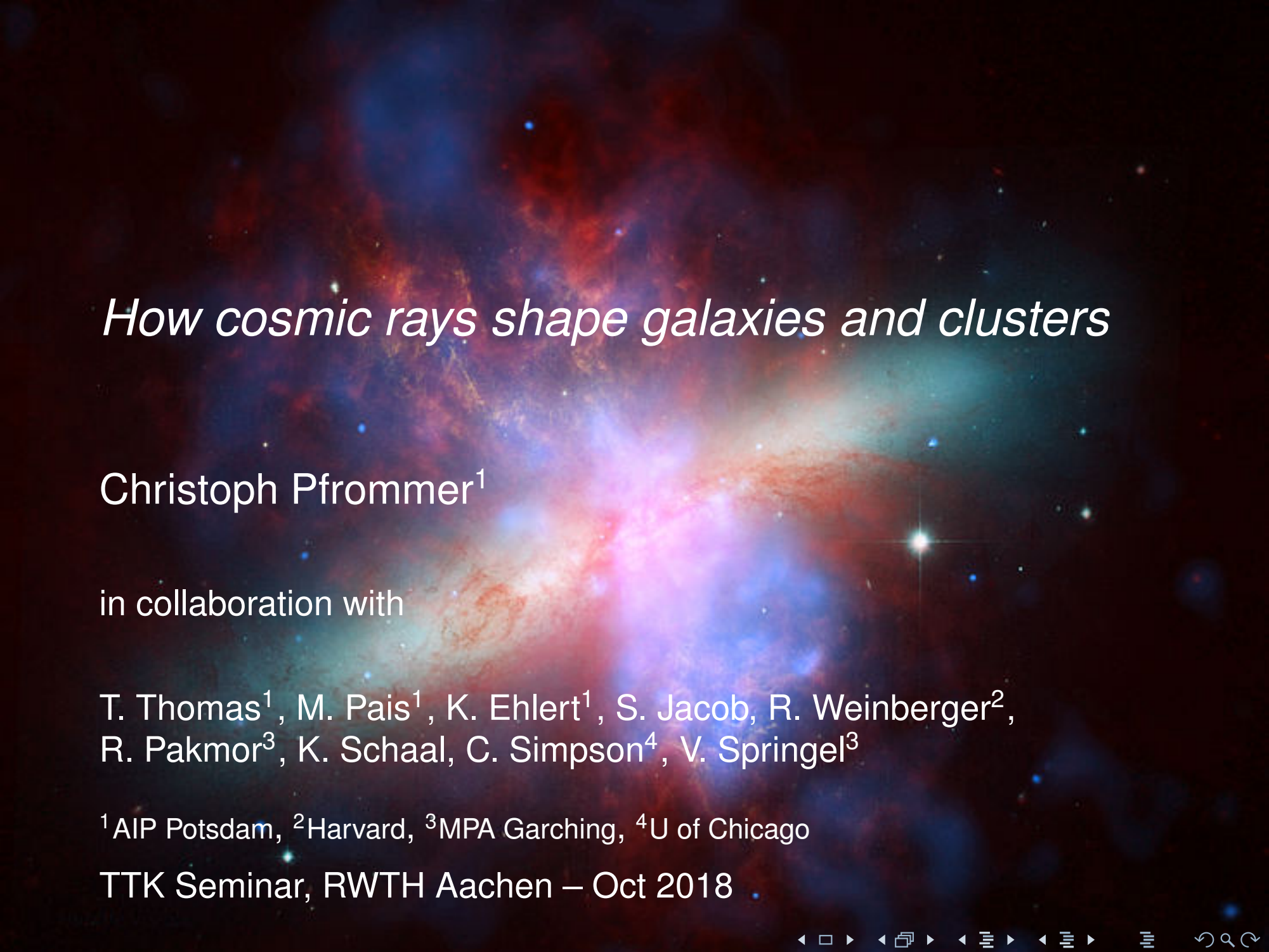


How cosmic rays shape galaxies and clusters

Christoph Pfrommer[1]

in collaboration with

T. Thomas[1], M. Pais[1], K. Ehlert[1], S. Jacob, R. Weinberger[2], R. Pakmor[3], K. Schaal, C. Simpson[4], V. Springel[3]

[1]AIP Potsdam, [2]Harvard, [3]MPA Garching, [4]U of Chicago

TTK Seminar, RWTH Aachen – Oct 2018

Outline

1. Introduction
   - Puzzles in galaxy formation
   - Particle acceleration
   - Cosmic rays
2. Galaxy formation
   - Modelling physics in galaxies
   - Supernova explosions
   - Galaxy simulations
3. Galaxy cluster evolution
   - Steady state models
   - AGN jet simulations
   - Conclusions



Outline

1. Introduction
   - Puzzles in galaxy formation
   - Particle acceleration
   - Cosmic rays
2. Galaxy formation
   - Modelling physics in galaxies
   - Supernova explosions
   - Galaxy simulations
3. Galaxy cluster evolution
   - Steady state models
   - AGN jet simulations
   - Conclusions

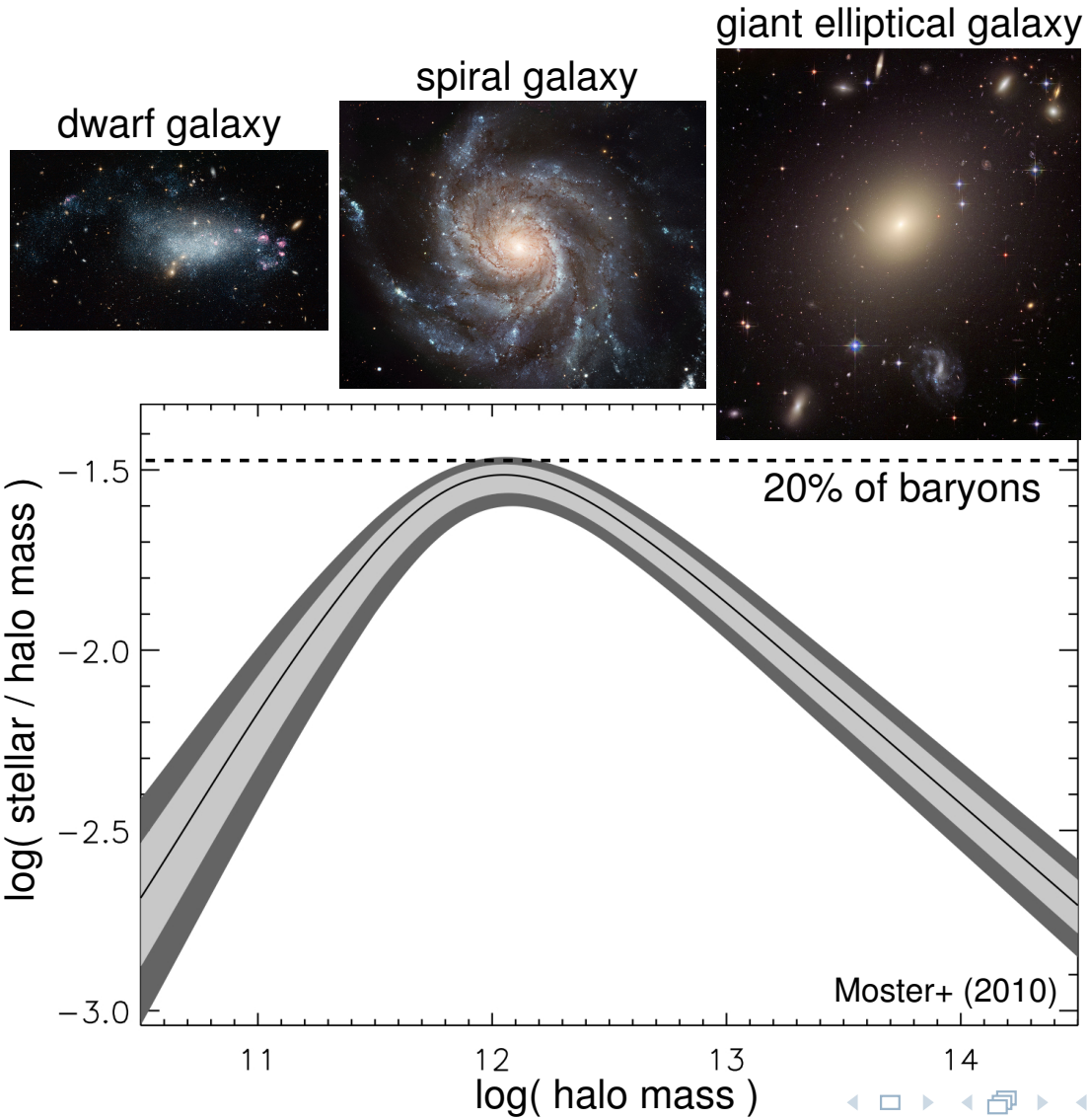
AIP

Puzzles in galaxy formation

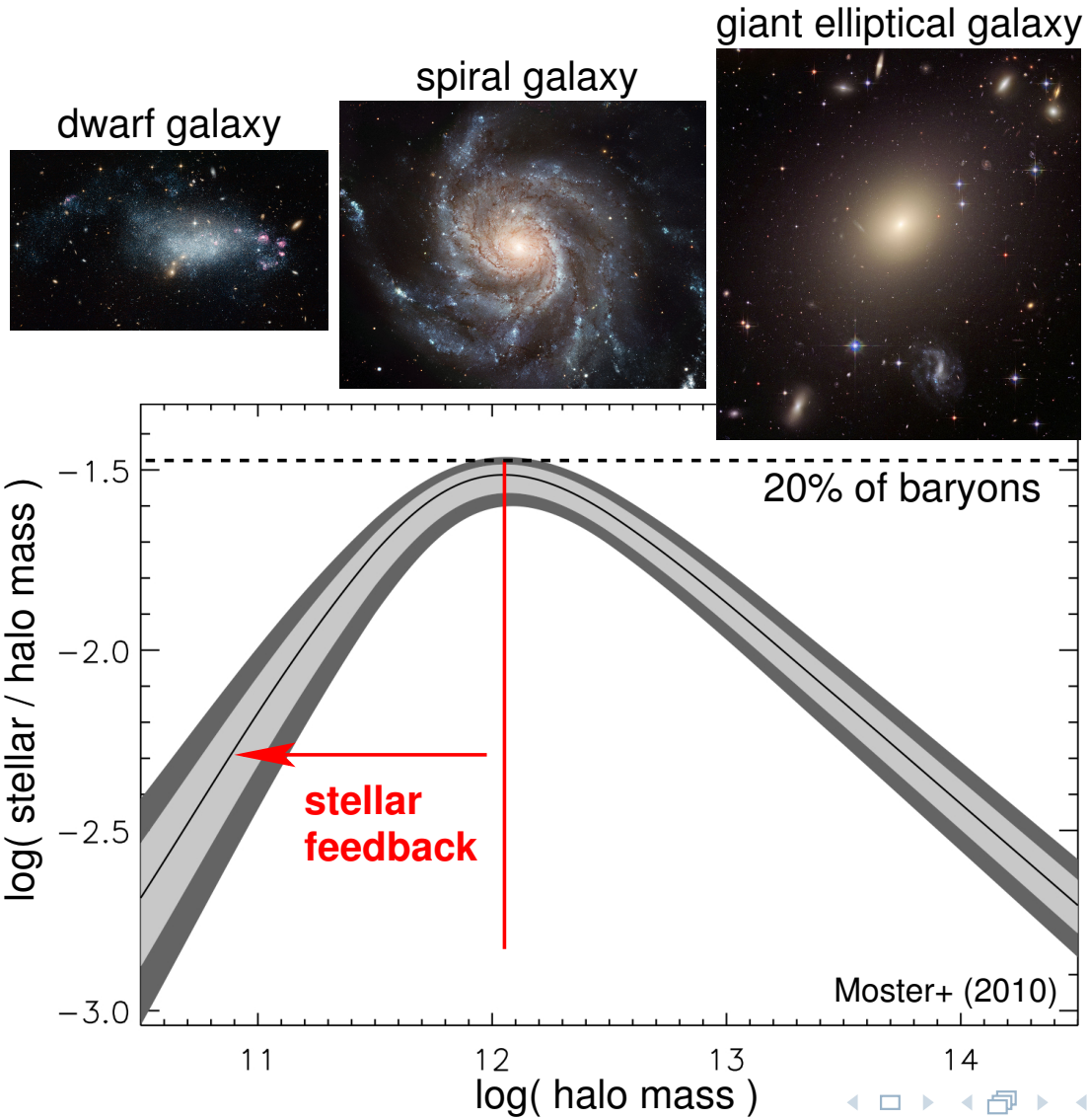




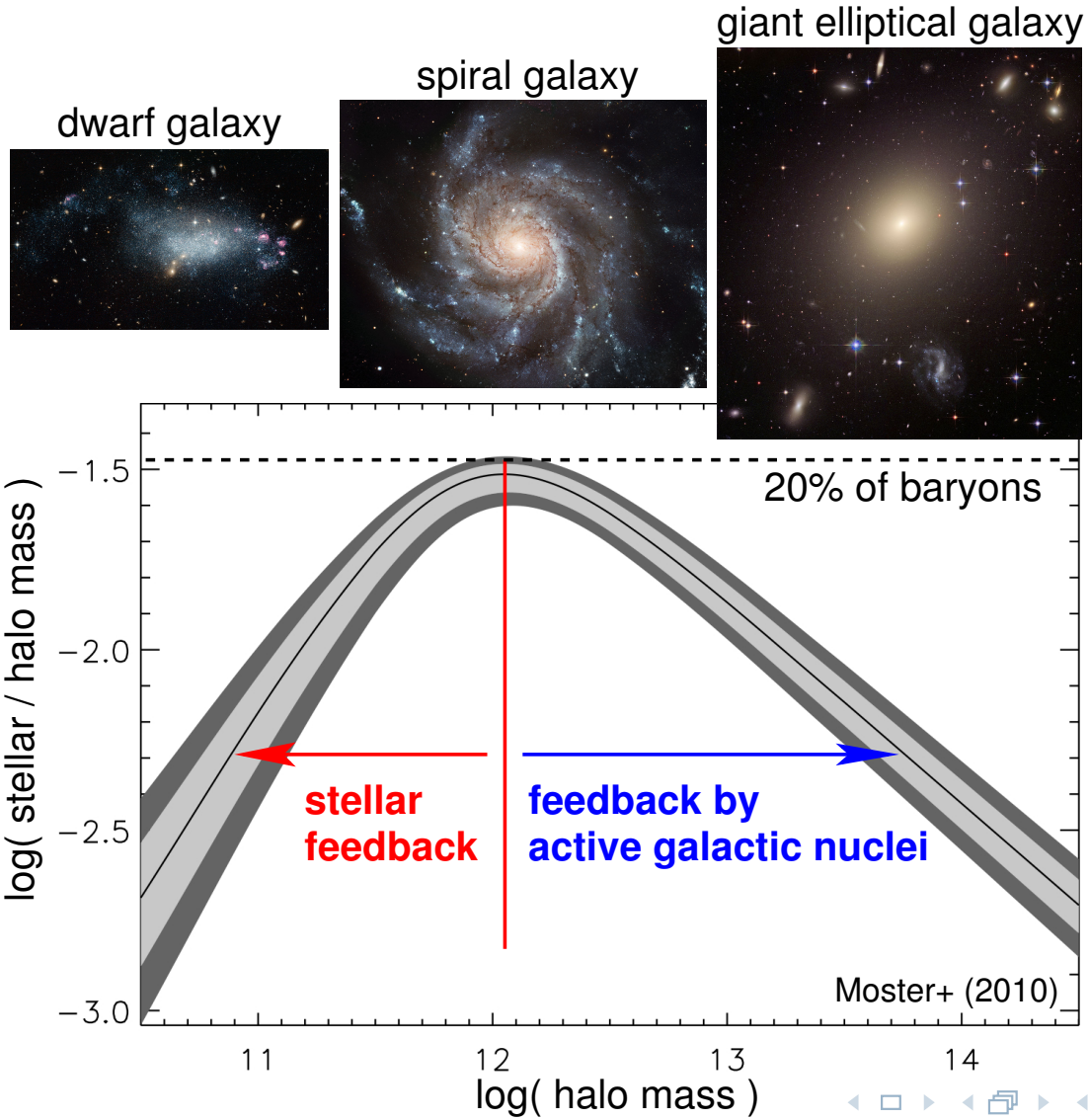
Puzzles in galaxy formation



Puzzles in galaxy formation



Puzzles in galaxy formation



Feedback

feedback n -s often attrib:

1. the return to the input of a part of the output of a machine, system, or process
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify this process

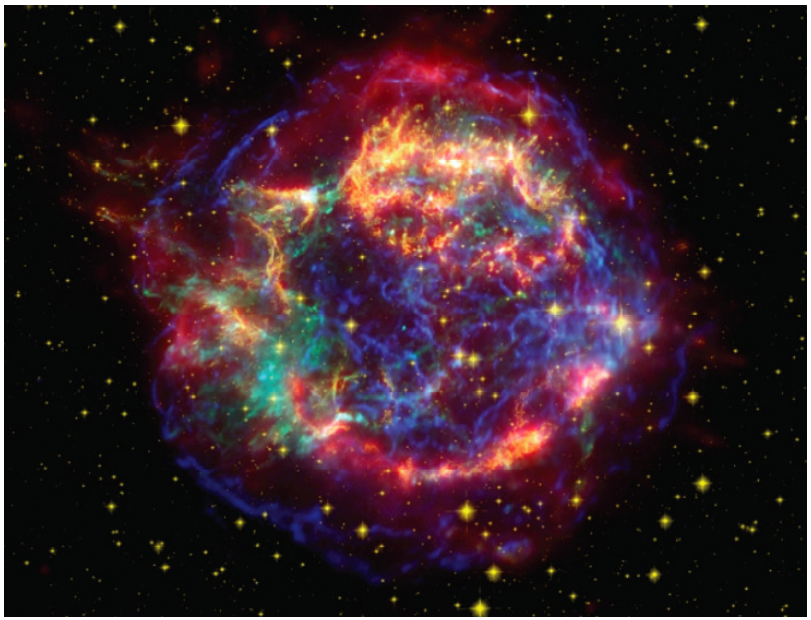
Feedback

feedback n -s often attrib:

1. the return to the input of a part of the output of a machine, system, or process
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify this process
3. the solution of all problems in galaxy formation



Feedback by galactic winds



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields

Feedback by galactic winds



super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds

AIP

Feedback by galactic winds



super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

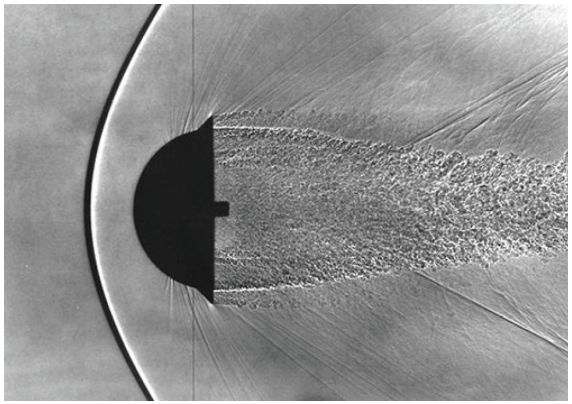
AIP

Shock waves

shock waves: sudden change in density, temperature, and pressure that decelerates supersonic flow.

thickness $\sim$ mean free path λ_{mfp}

in air, $\lambda_{mfp} \sim \mu$m,
on Earth, most shocks are mediated by collisions.





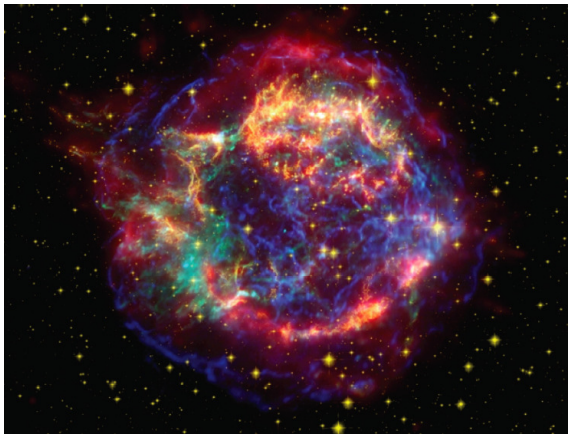
slide concept Spitkovsky

Shock waves

shock waves: sudden change in density, temperature, and pressure that decelerates supersonic flow.

thickness $\sim$ mean free path λ_{mfp}

in air, $\lambda_{\mathrm{mfp}} \sim \mu$m,
on Earth, most shocks are mediated by collisions.





clusters/galaxies, Coulomb collisions set λ_{mfp}:

$\lambda_{\mathrm{mfp}} \sim L_{\mathrm{cluster}}/10, \qquad \lambda_{\mathrm{mfp}} \sim L_{\mathrm{SNR}}$

Mean free path $\gg$ observed shock width!

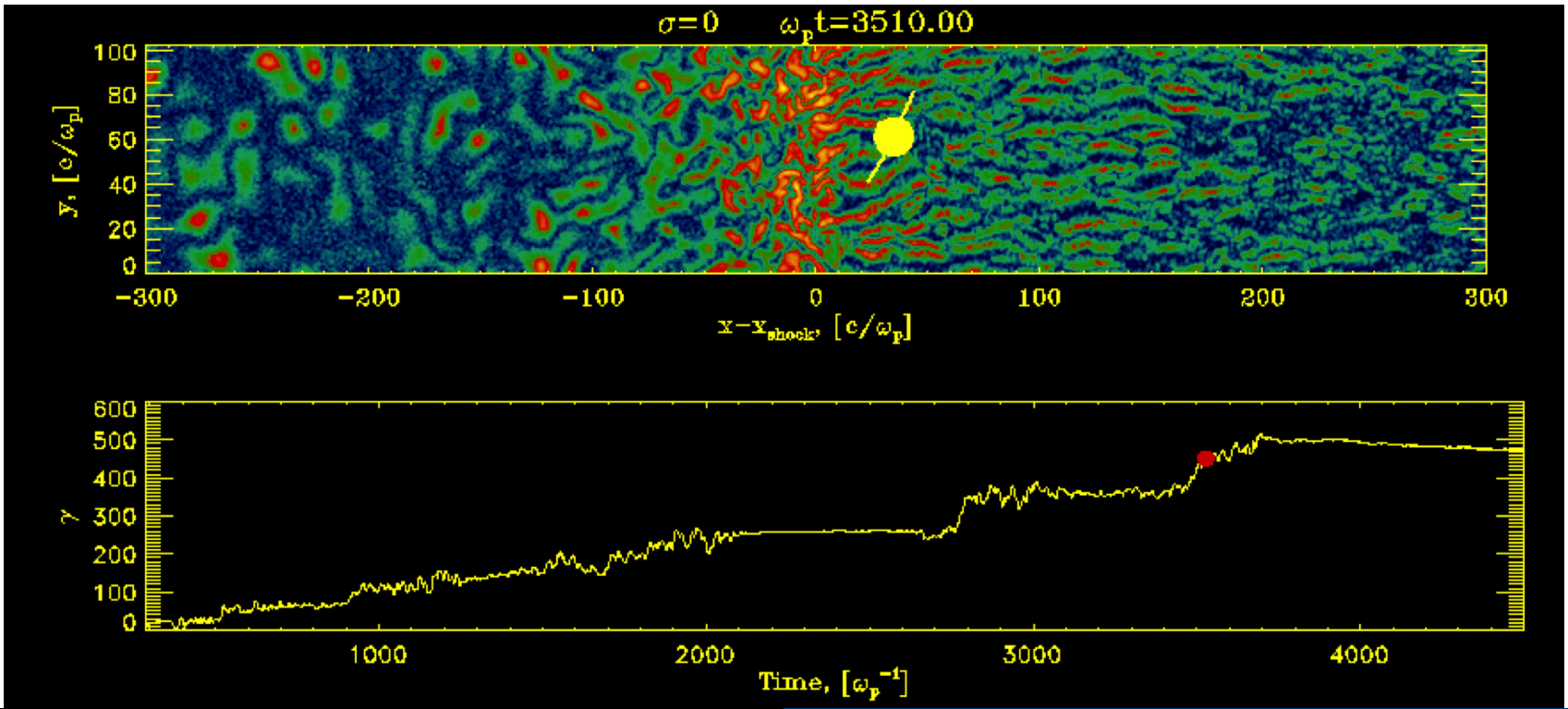
$\rightarrow$ shocks must be mediated without collisions, but through interactions with collective fields
$\rightarrow$ collisionless shocks

slide concept Spitkovsky

AIP

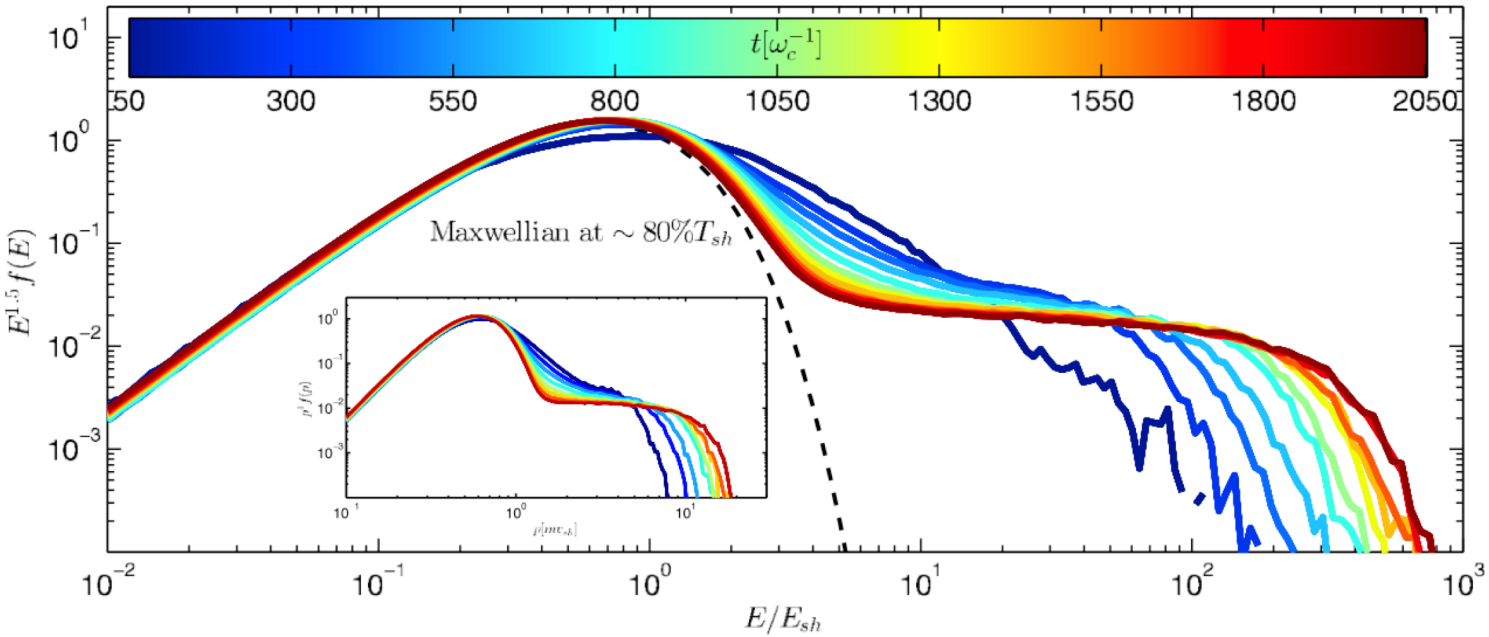
Particle acceleration at relativistic shock, $B_0 = 0$

- self-generated magnetic turbulence scatters particles across the shock
- each crossing results in energy gain – Fermi process
- movie below shows magnetic filaments in the shock frame (top), particle energy is measured the downstream frame (bottom): particle gains energy upon scattering in the upstream (Spitkovsky 2008)



Ion spectrum

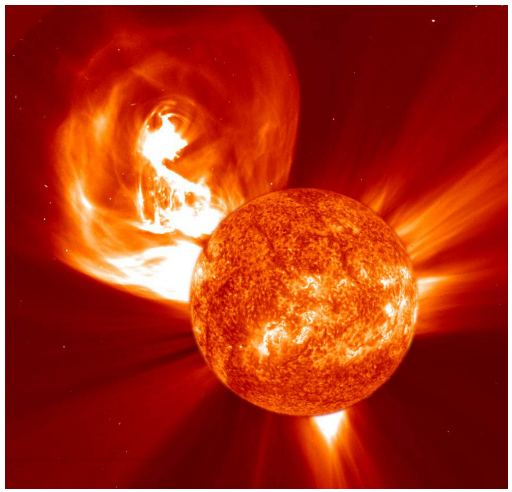
Non-relativistic parallel shock in long-term hybrid simulation



Caprioli & Spitkovsky (2014)

- quasi-parallel shocks accelerate ions
- particles gain energy in each crossing and have probability of leaving the Fermi cycle by being swept downstream → power-law spectrum
- maximum energy increases with time

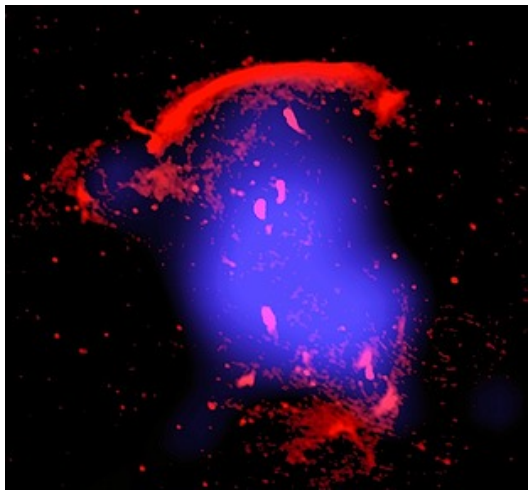
Astrophysical shocks



solar system shocks $\sim R_\odot$
coronal mass ejection (SOHO)



interstellar shocks $\sim$ 20 pc
supernova 1006 (CXC/Hughes)



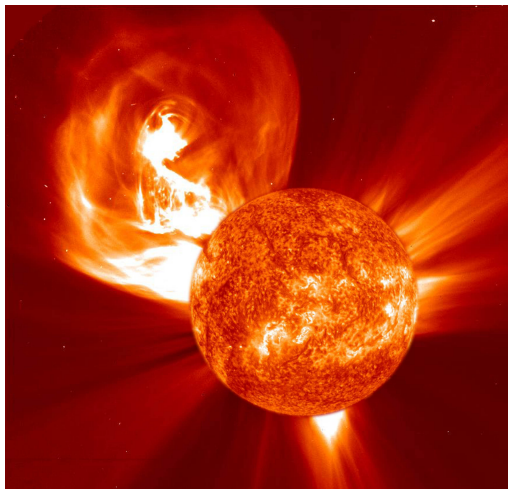
cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

AIP

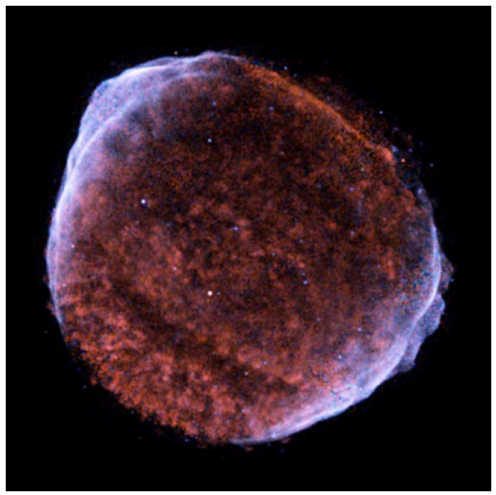
Astrophysical shocks

astrophysical collisionless shocks can:

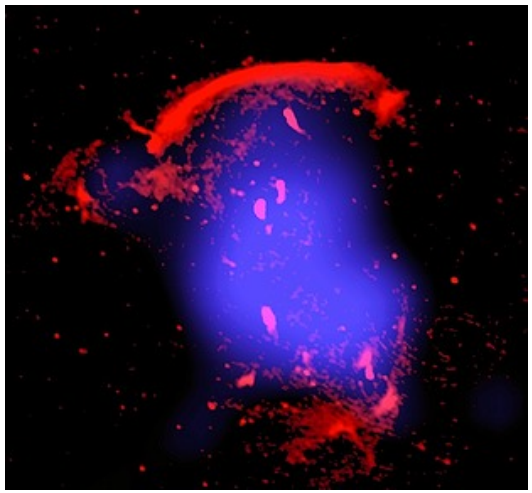
- accelerate particles (electrons and ions) $\rightarrow$ cosmic rays (CRs)
- amplify magnetic fields (or generate them from scratch)
- exchange energy between electrons and ions



solar system shocks $\sim R_\odot$
coronal mass ejection (SOHO)



interstellar shocks $\sim$ 20 pc
supernova 1006 (CXC/Hughes)



cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

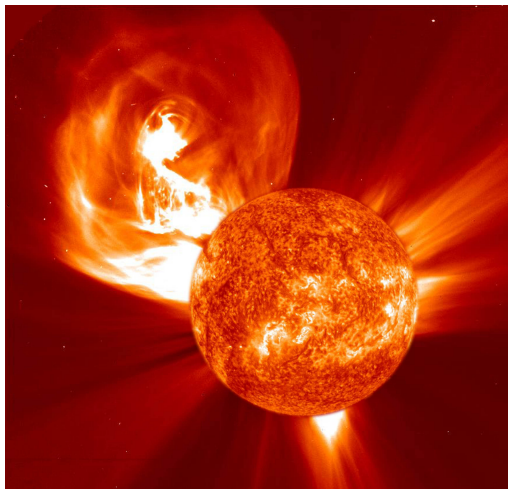
AIP

Astrophysical shocks

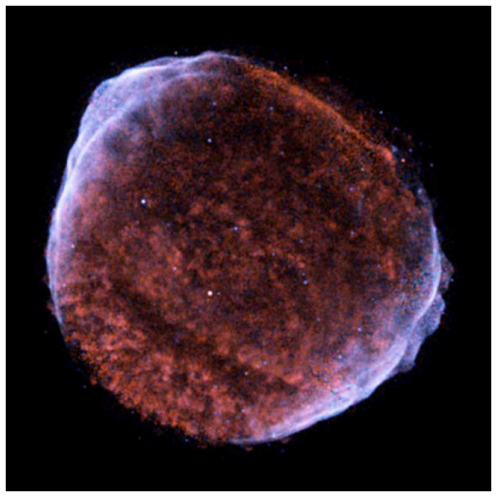
astrophysical collisionless shocks can:

- accelerate particles (electrons and ions) $\rightarrow$ cosmic rays (CRs)
- amplify magnetic fields (or generate them from scratch)
- exchange energy between electrons and ions

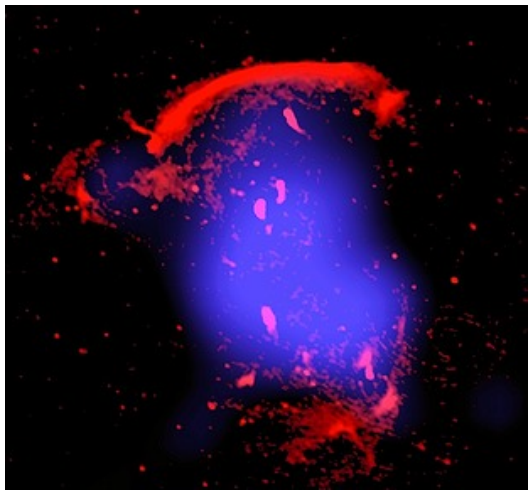
collisionless shocks $\Longleftrightarrow$ energetic particles $\Longleftrightarrow$ electro-magnetic waves



solar system shocks $\sim R_\odot$
coronal mass ejection (SOHO)



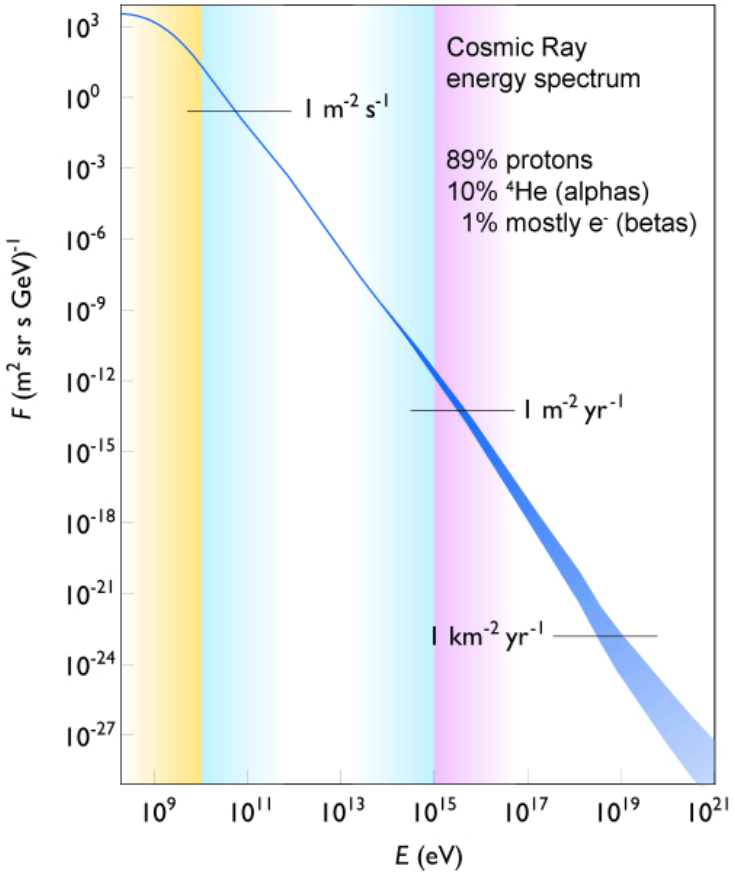
interstellar shocks $\sim$ 20 pc
supernova 1006 (CXC/Hughes)



cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

AIP

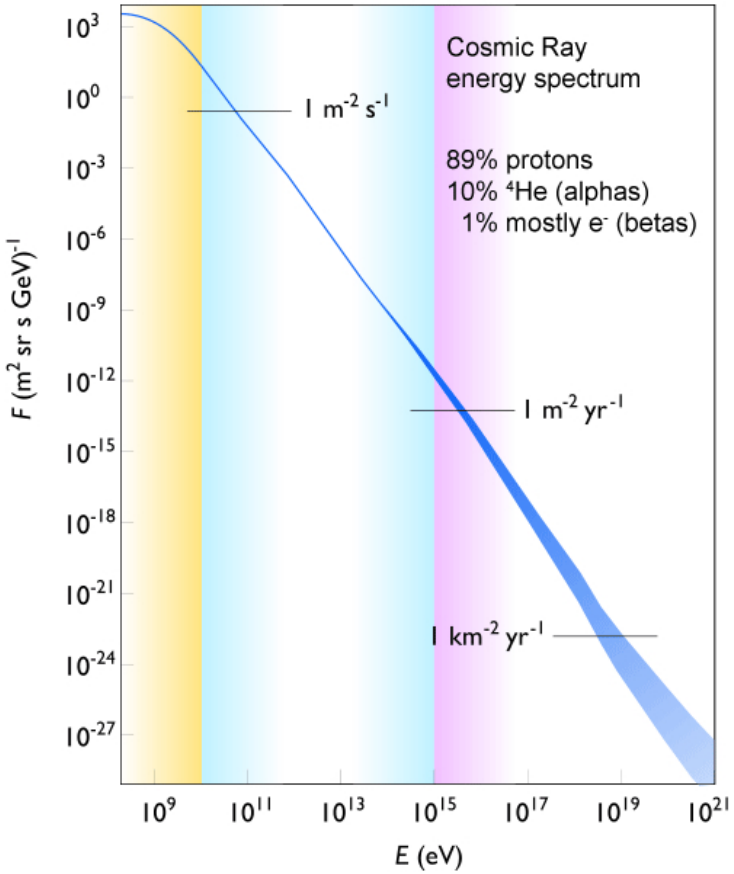
Galactic cosmic ray spectrum



data compiled by Swordy

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin

Galactic cosmic ray spectrum



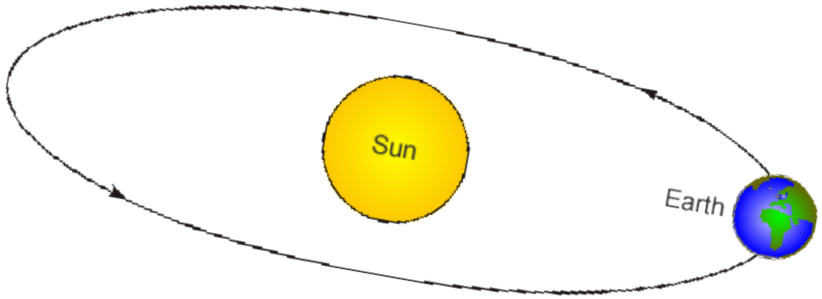
data compiled by Swordy

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

AIP

Cosmic ray feedback: an extreme multi-scale problem





Milky Way-like galaxy:

$$r_{\rm gal} \sim 10^4 \text{ pc}$$

gyro-orbit of GeV cosmic ray:

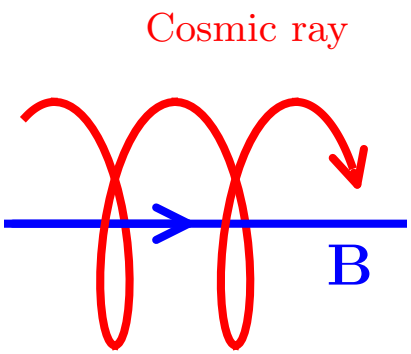
$$r_{\rm cr} = \frac{p_\perp}{e\,B_{\mu\rm G}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

$\Rightarrow$ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

Zweibel (2017), Jiang & Oh (2018), Thomas & CP (2018)

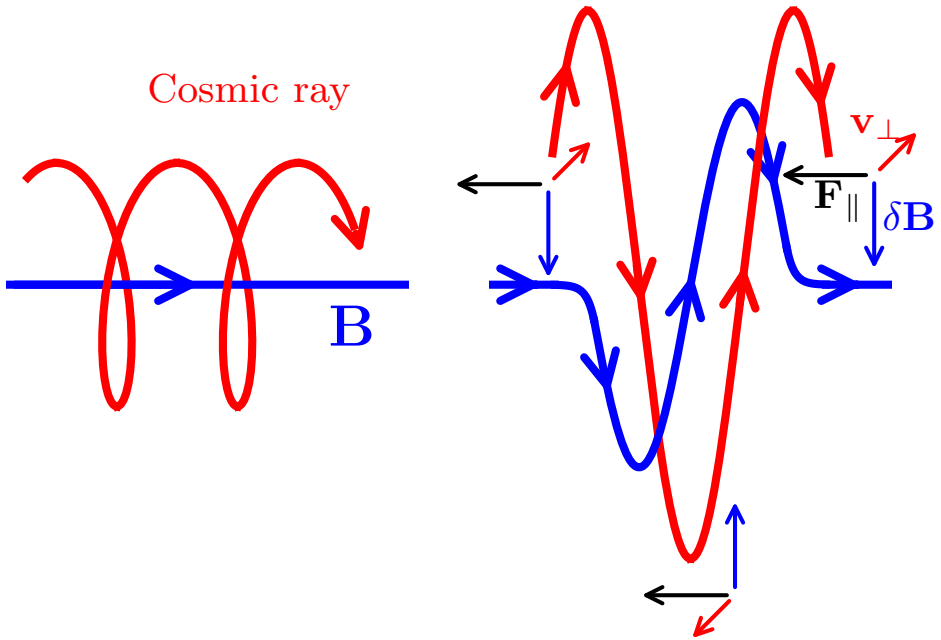
AIP

Interactions of CRs and magnetic fields



sketch: Jacob

Interactions of CRs and magnetic fields

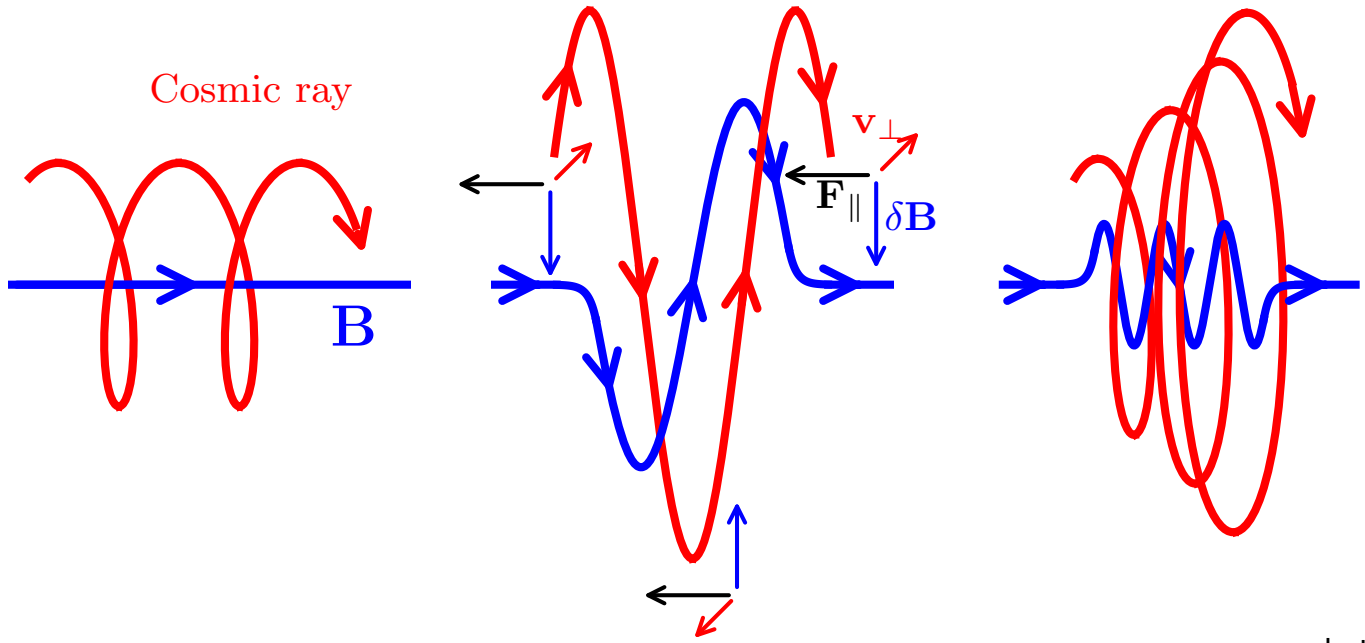


sketch: Jacob

- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$

  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

Interactions of CRs and magnetic fields



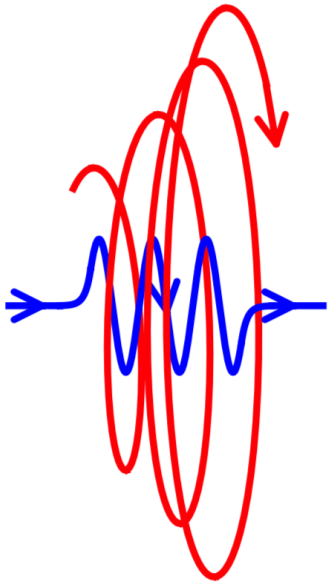
sketch: Jacob

- **gyro resonance:** $\omega - k_\parallel v_\parallel = n\Omega$

  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta

CR streaming and diffusion

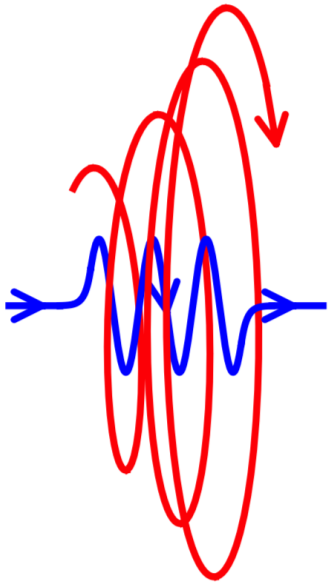
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{cr} > v_A$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_A$
  - wave damping: transfer of CR energy and momentum to the thermal gas



AIP

CR streaming and diffusion

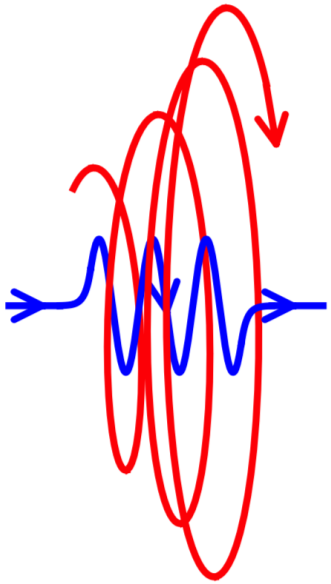
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{cr} > v_A$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_A$
  - wave damping: transfer of CR energy and momentum to the thermal gas



$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

CR streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{cr} > v_A$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_A$
  - wave damping: transfer of CR energy and momentum to the thermal gas



$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

weak wave damping: strong coupling $\rightarrow$ CR stream with waves
strong wave damping: less waves to scatter $\rightarrow$ CR diffusion prevails

AIP

CR transport (steady-state flux)

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)

CR transport (steady-state flux)

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas

$$\boldsymbol{v}_{\rm st} = \boldsymbol{v}_{\rm A} \frac{\bar{\nu}_+ - \bar{\nu}_-}{\bar{\nu}_+ + \bar{\nu}_-},$$

CR transport (steady-state flux)

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\rm st} = \boldsymbol{v}_{\rm A} \frac{\bar{\nu}_+ - \bar{\nu}_-}{\bar{\nu}_+ + \bar{\nu}_-}, \quad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di} \boldsymbol{b} \frac{\boldsymbol{b} \cdot \boldsymbol{\nabla} \varepsilon_{\rm cr}}{\varepsilon_{\rm cr}}, \quad \kappa_{\rm di} = \frac{c^2}{3(\bar{\nu}_+ + \bar{\nu}_-)}$$



CR transport (steady-state flux)

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\rm st} = \boldsymbol{v}_{\rm A}\,\frac{\bar{\nu}_+ - \bar{\nu}_-}{\bar{\nu}_+ + \bar{\nu}_-}, \quad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di}\boldsymbol{b}\,\frac{\boldsymbol{b}\cdot\boldsymbol{\nabla}\varepsilon_{\rm cr}}{\varepsilon_{\rm cr}}, \quad \kappa_{\rm di} = \frac{c^2}{3(\bar{\nu}_+ + \bar{\nu}_-)}$$

- energy equations with $\varepsilon = \varepsilon_{\rm th} + \rho v^2/2$:

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla}\cdot[(\varepsilon + P_{\rm th} \qquad)\boldsymbol{v}] \;=\; 0$$

CR transport (steady-state flux)

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\rm st} = \boldsymbol{v}_{\rm A}\,\frac{\bar{\nu}_+ - \bar{\nu}_-}{\bar{\nu}_+ + \bar{\nu}_-}, \quad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di}\boldsymbol{b}\,\frac{\boldsymbol{b}\cdot\boldsymbol{\nabla}\varepsilon_{\rm cr}}{\varepsilon_{\rm cr}}, \quad \kappa_{\rm di} = \frac{c^2}{3(\bar{\nu}_+ + \bar{\nu}_-)}$$

- energy equations with $\varepsilon = \varepsilon_{\rm th} + \rho v^2/2$:

$$\begin{aligned}
\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla}\cdot\left[(\varepsilon + P_{\rm th} + P_{\rm cr})\boldsymbol{v}\right] &= P_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} - \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr} \\
\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot\left[P_{\rm cr}\boldsymbol{v}_{\rm st} + \varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})\right] &= -P_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr}
\end{aligned}$$



CR transport (steady-state flux)

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\rm st} = \boldsymbol{v}_{\rm A}\,\frac{\bar{\nu}_+ - \bar{\nu}_-}{\bar{\nu}_+ + \bar{\nu}_-}, \quad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di}\boldsymbol{b}\,\frac{\boldsymbol{b}\cdot\boldsymbol{\nabla}\varepsilon_{\rm cr}}{\varepsilon_{\rm cr}}, \quad \kappa_{\rm di} = \frac{c^2}{3(\bar{\nu}_+ + \bar{\nu}_-)}$$

- energy equations with $\varepsilon = \varepsilon_{\rm th} + \rho v^2/2$:

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla}\cdot[(\varepsilon + P_{\rm th} + P_{\rm cr})\boldsymbol{v}] = P_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} - \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr}$$

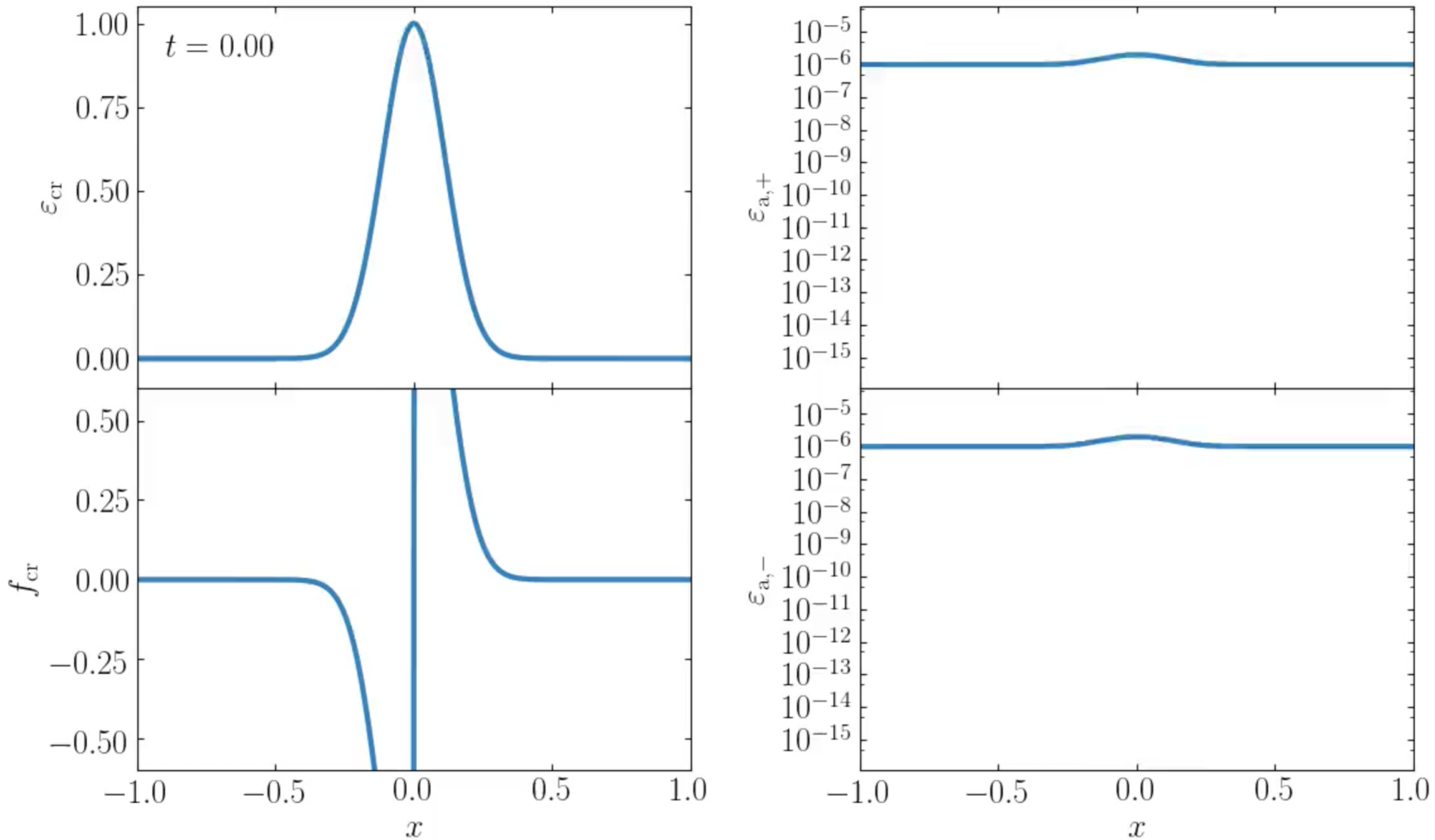
$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot[P_{\rm cr}\boldsymbol{v}_{\rm st} + \varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})] = -P_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr}$$

$$\Longleftrightarrow \quad \frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot[\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})] = -P_{\rm cr}\boldsymbol{\nabla}\cdot(\boldsymbol{v} + \boldsymbol{v}_{\rm st})$$



Non-equilibrium CR streaming and diffusion

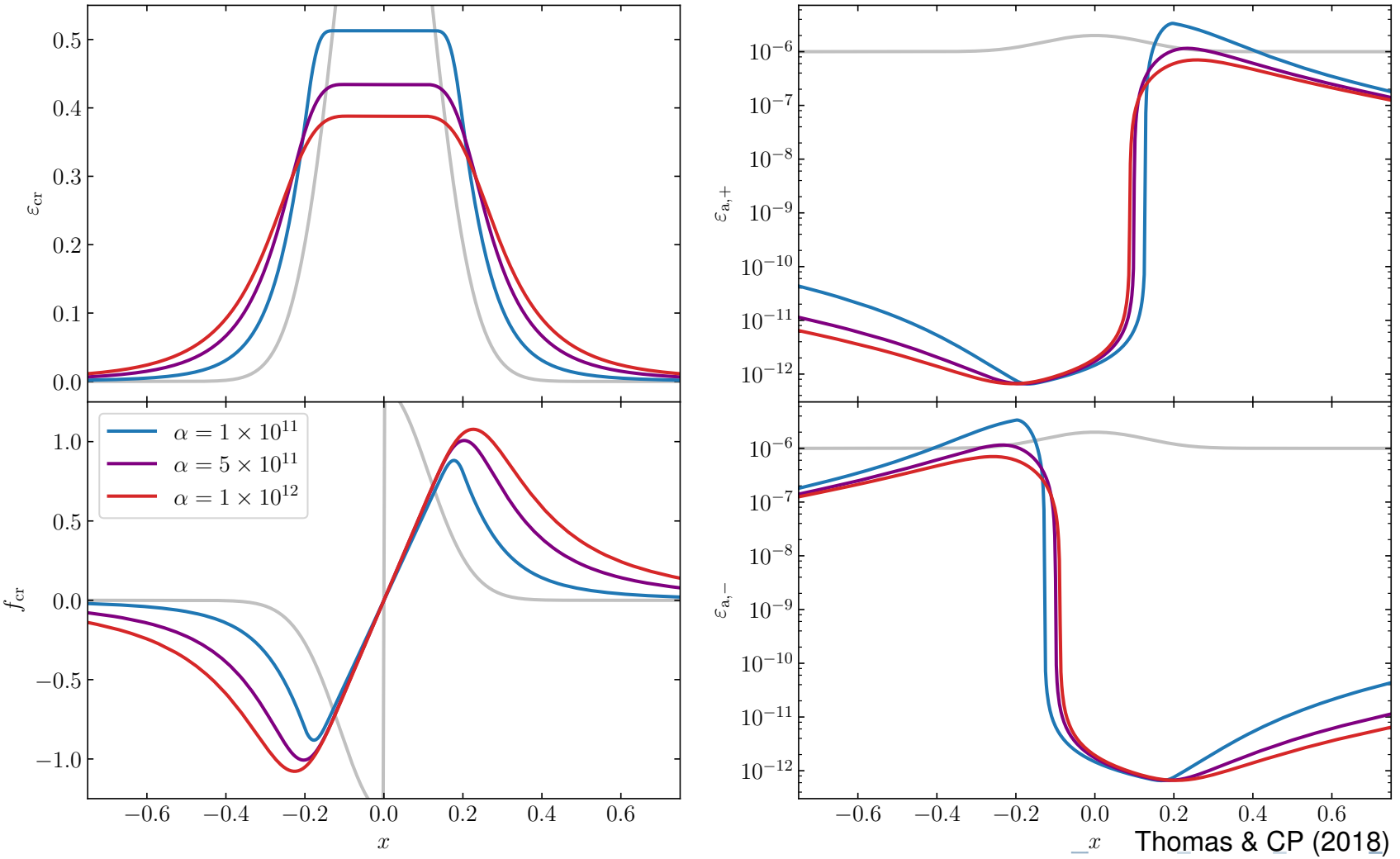
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

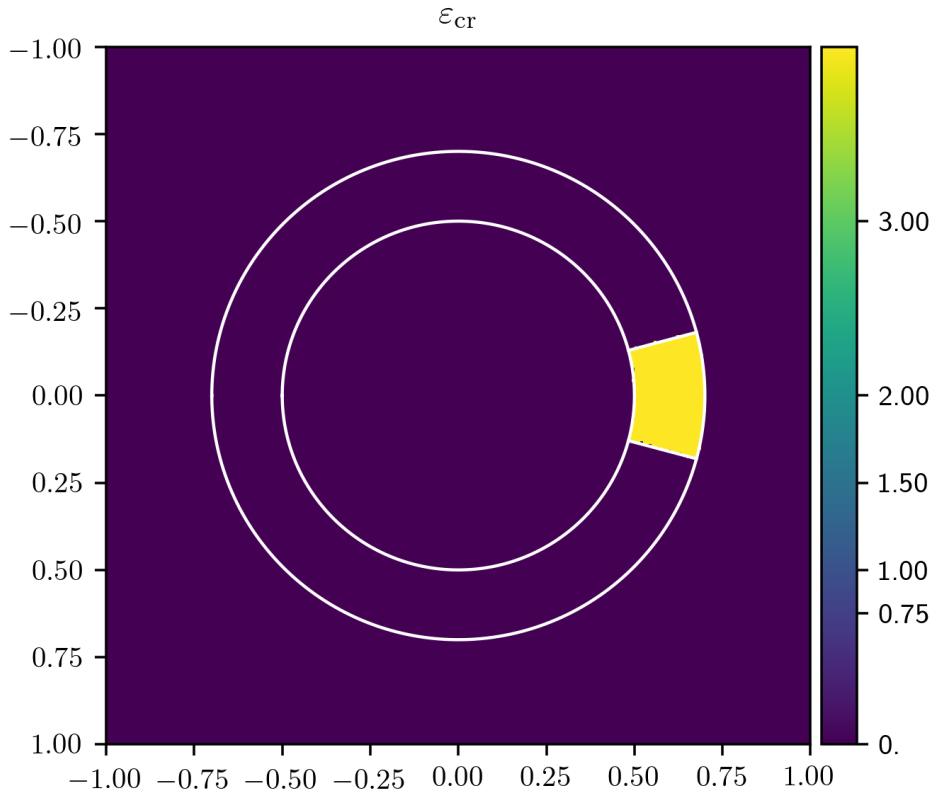


Thomas & CP (2018)

Anisotropic CR streaming and diffusion – AREPO

CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics

- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving



Thomas, Pakmor, CP (in prep.)

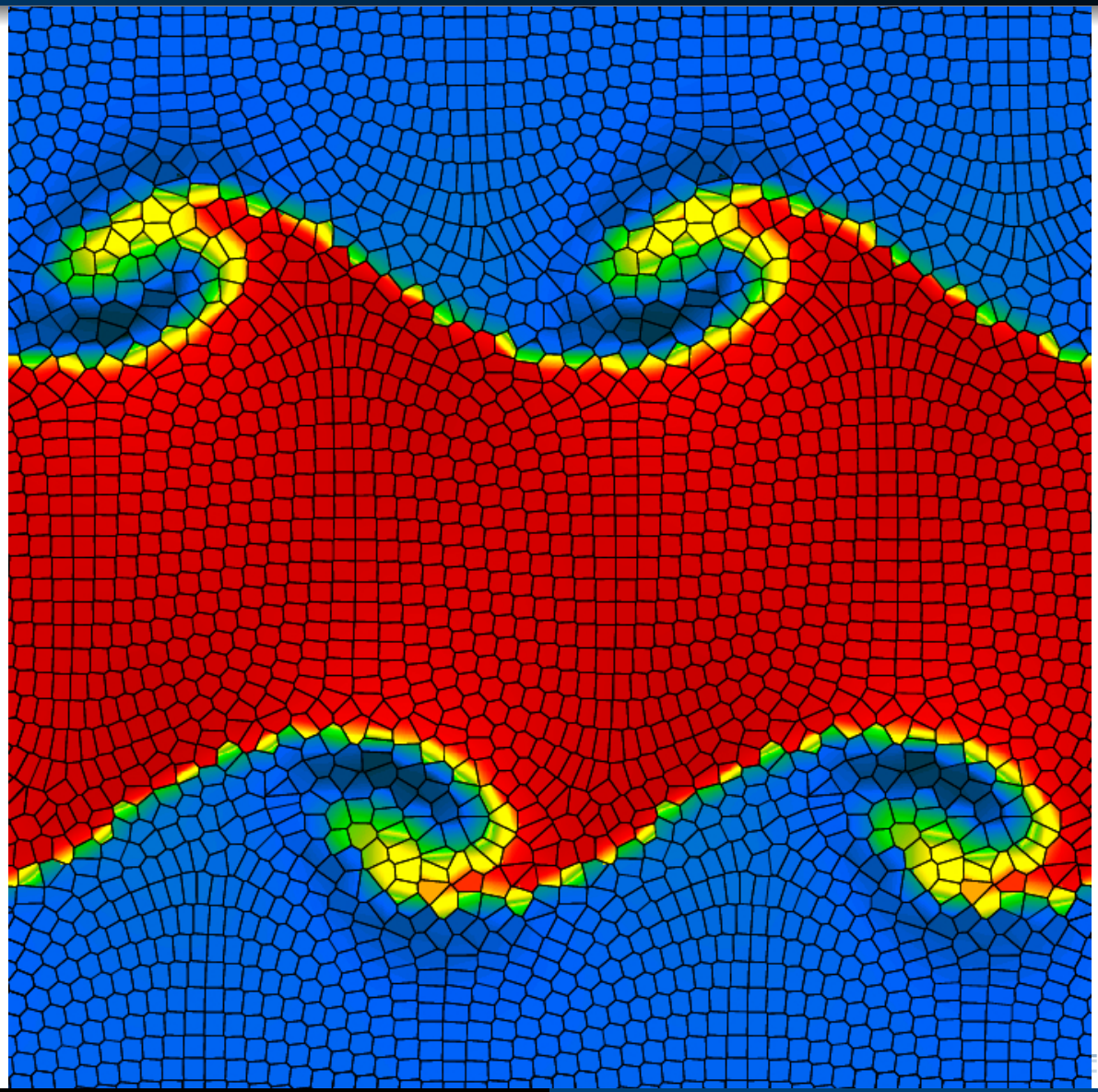
AIP

Outline

1. Introduction
   - Puzzles in galaxy formation
   - Particle acceleration
   - Cosmic rays
2. Galaxy formation
   - Modelling physics in galaxies
   - Supernova explosions
   - Galaxy simulations
3. Galaxy cluster evolution
   - Steady state models
   - AGN jet simulations
   - Conclusions



Cosmological moving-mesh code AREPO (Springel 2010)

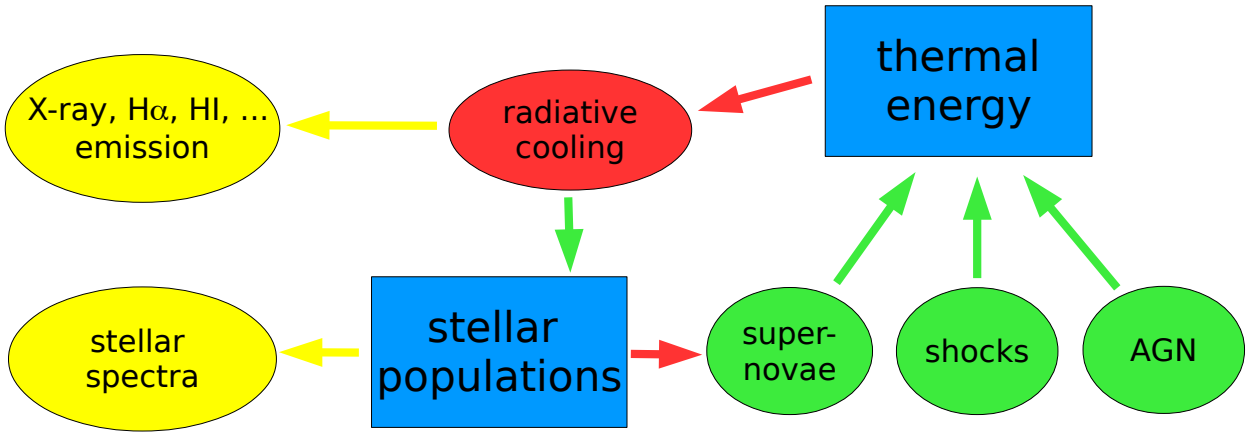


AIP

Simulations – flowchart

observables:

physical processes:



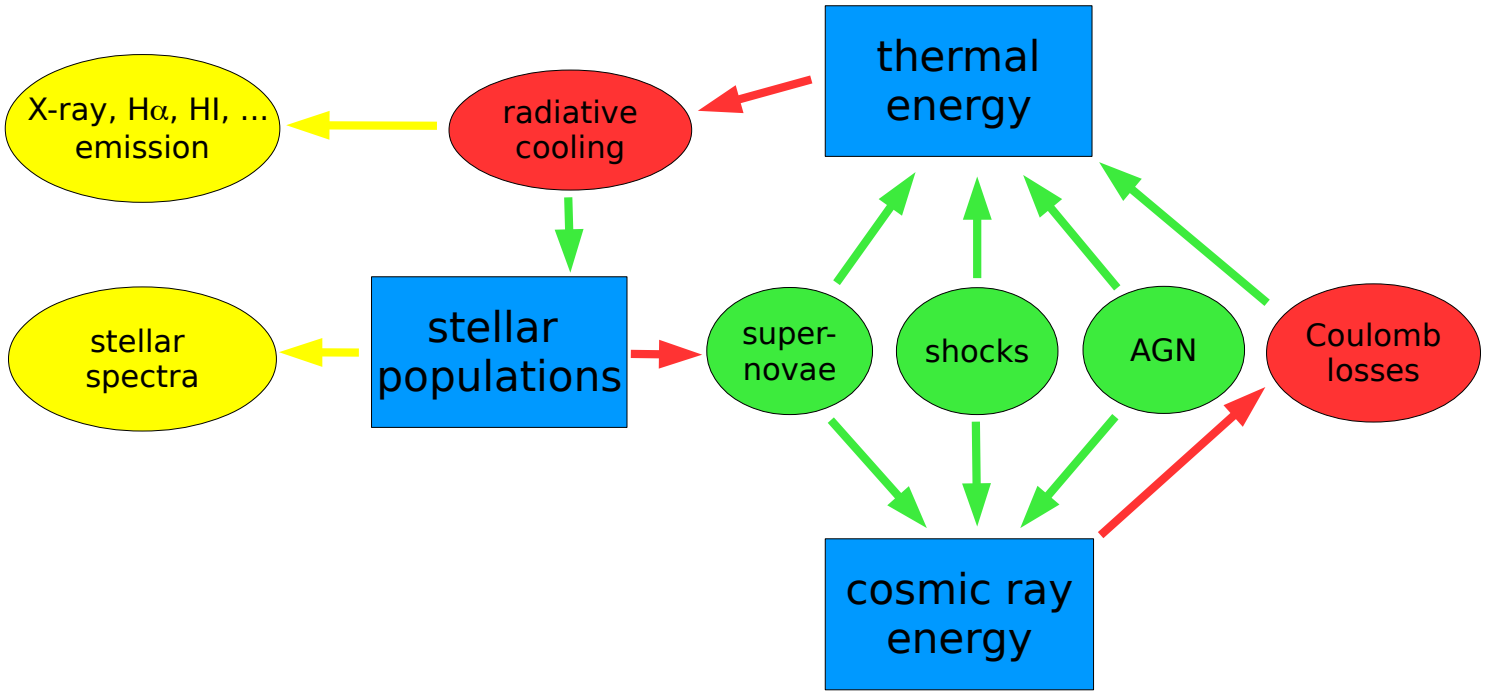
loss processes
gain processes
observables
populations

CP+ (2017a)

Simulations with cosmic ray physics

observables:

physical processes:

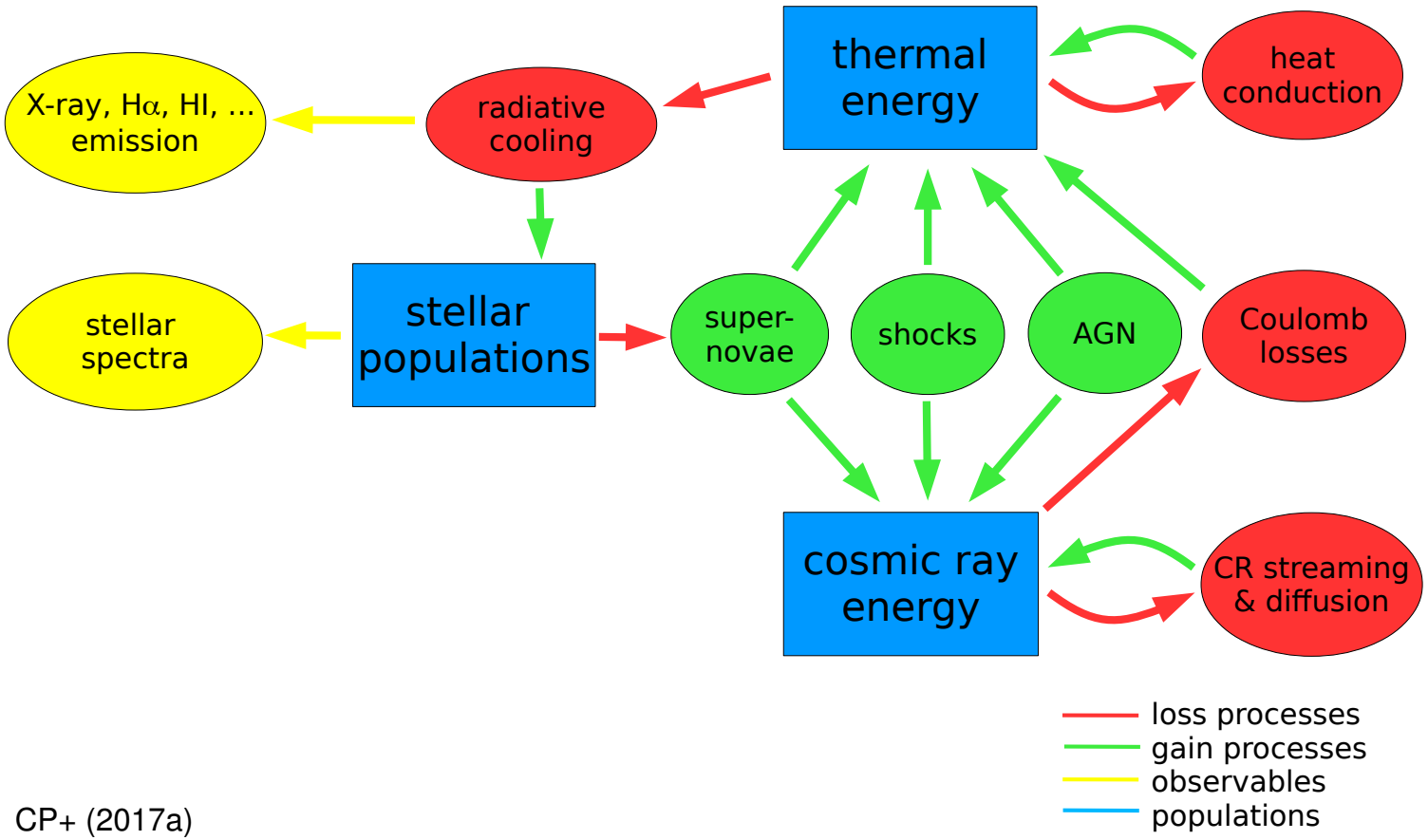


CP+ (2017a)

Simulations with cosmic ray physics

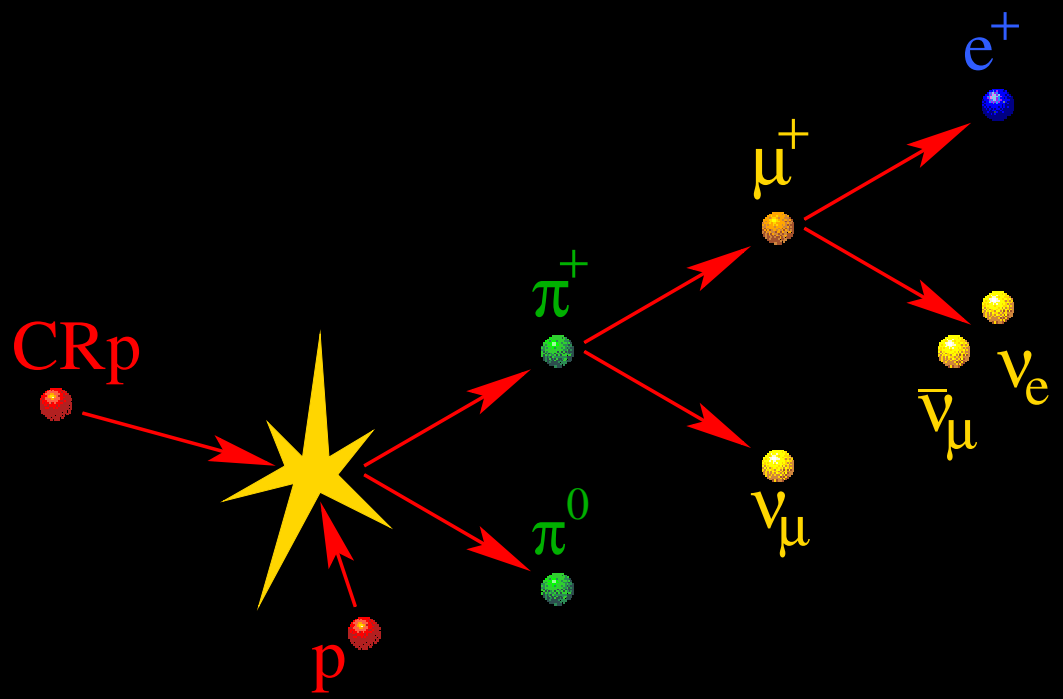
observables:

physical processes:

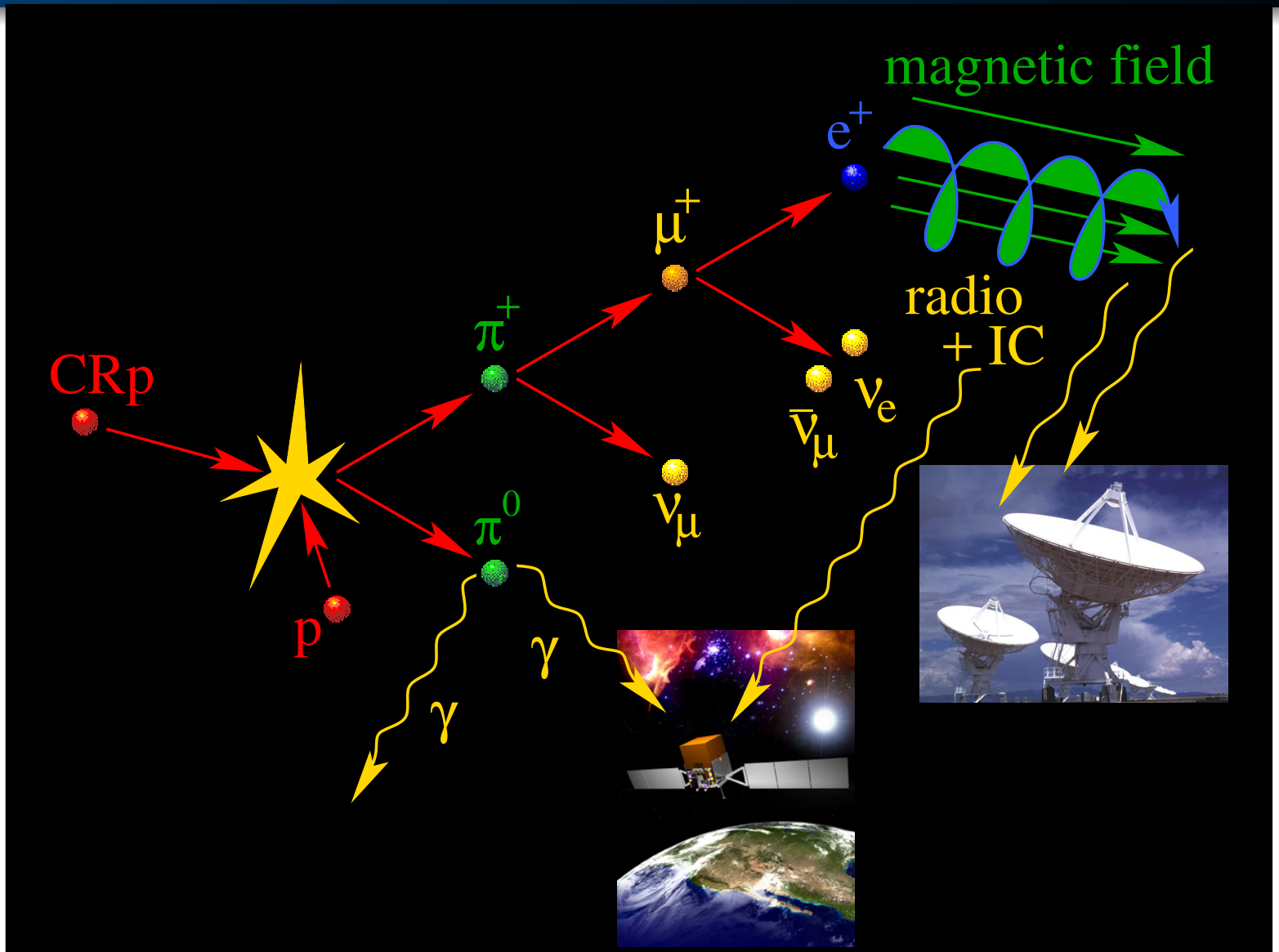


CP+ (2017a)

Hadronic cosmic ray proton interaction



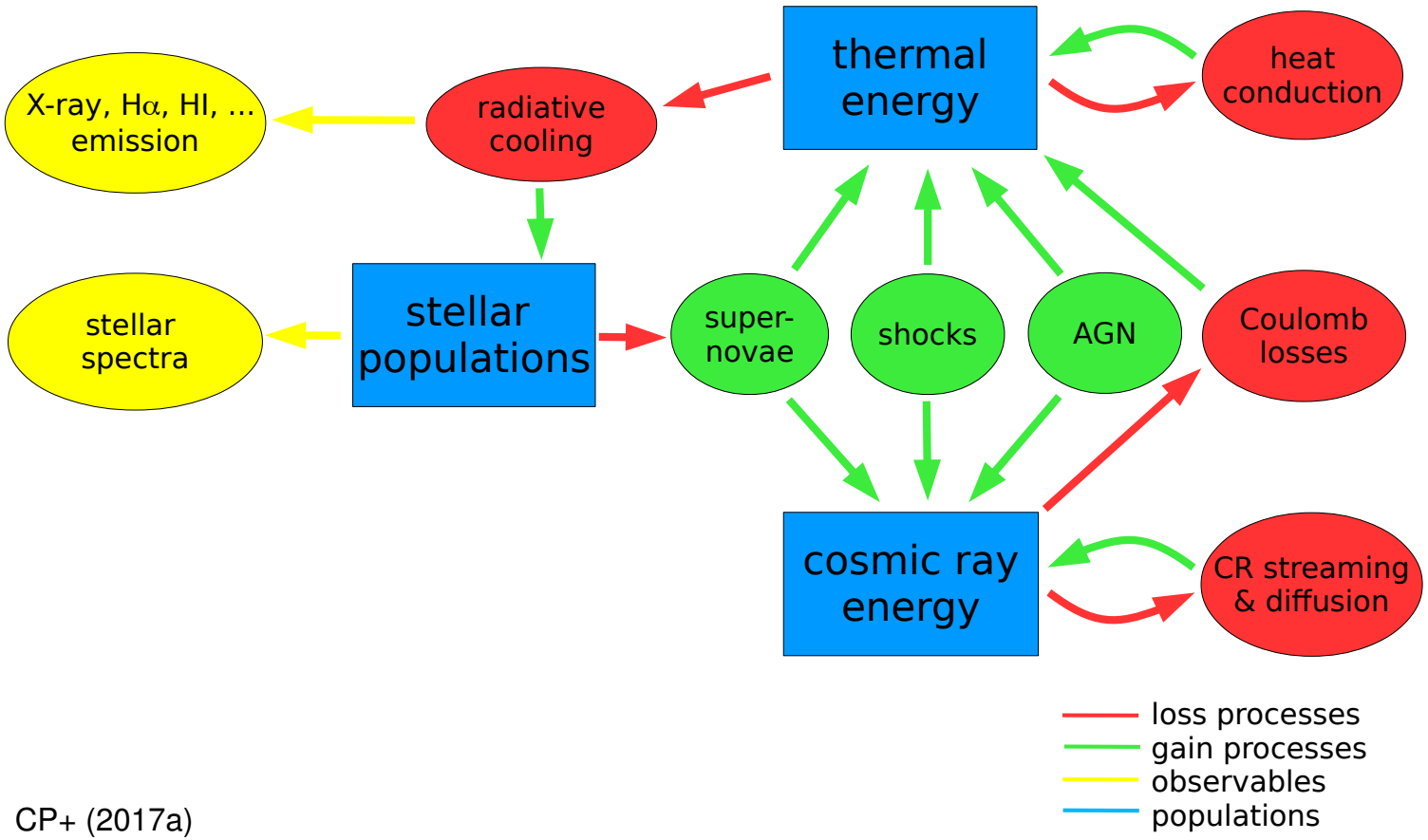
Hadronic cosmic ray proton interaction



Simulations with cosmic ray physics

observables:

physical processes:

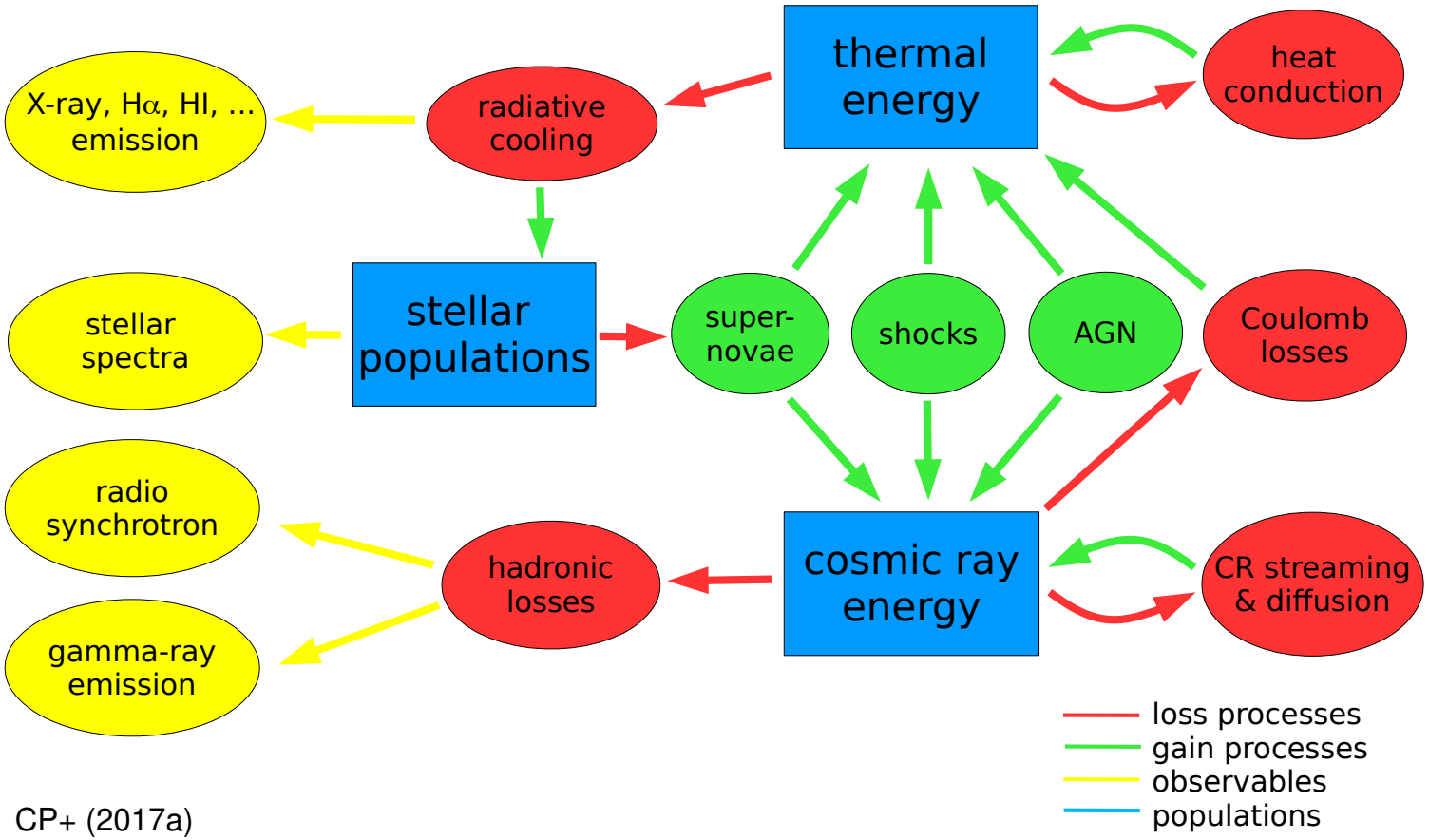


CP+ (2017a)

Simulations with cosmic ray physics

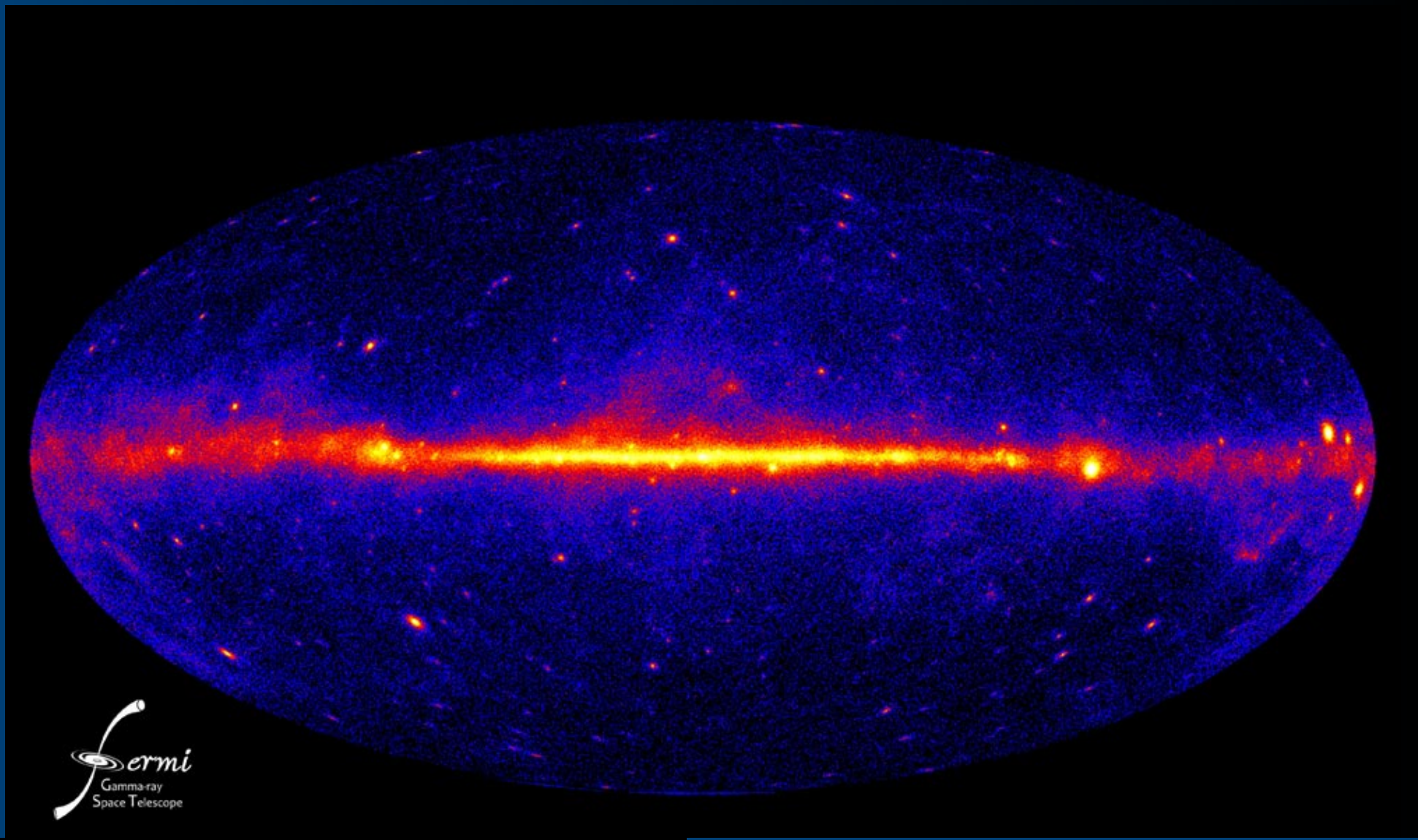
observables:

physical processes:



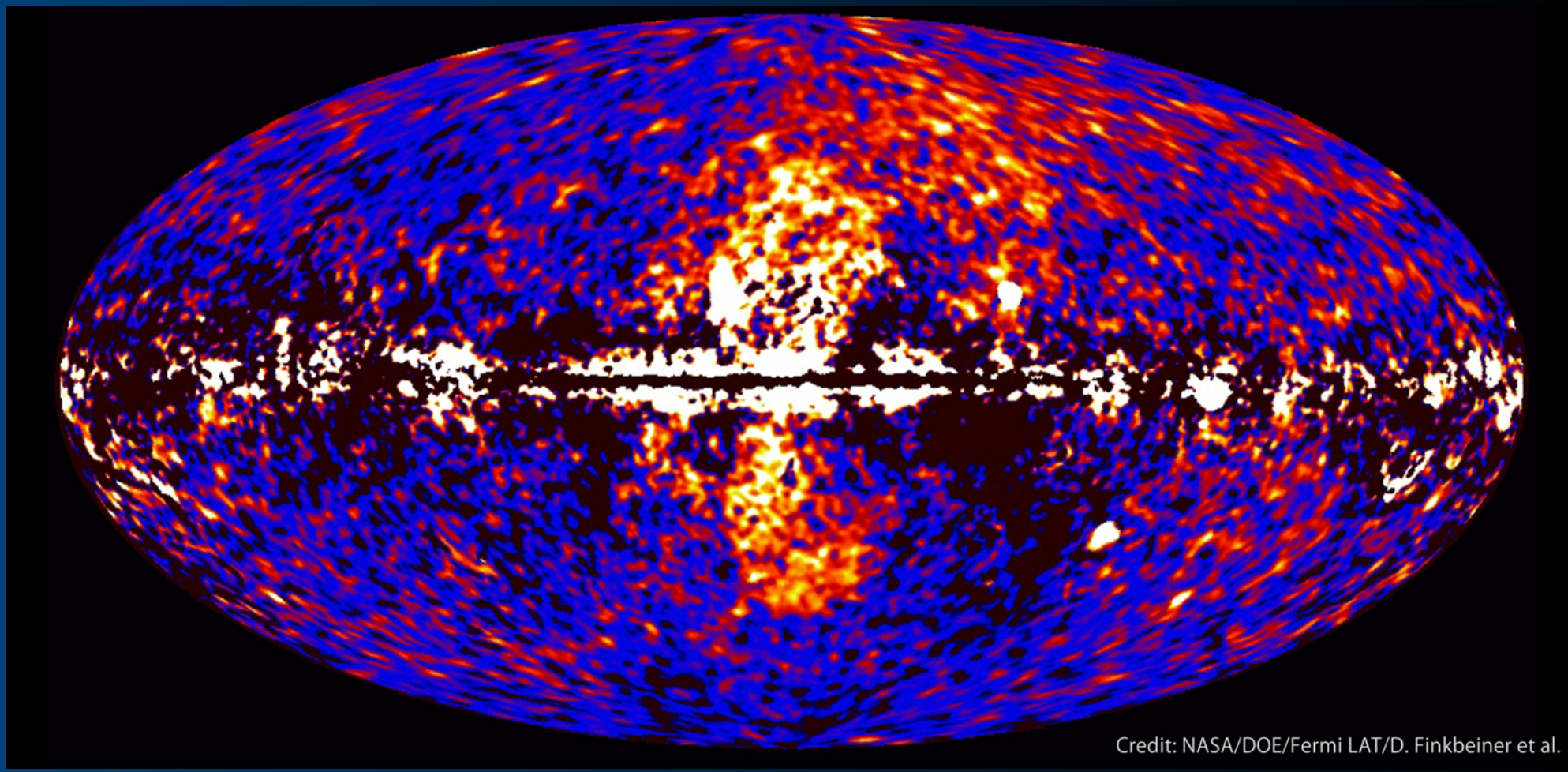
CP+ (2017a)

Gamma-ray emission of the Milky Way



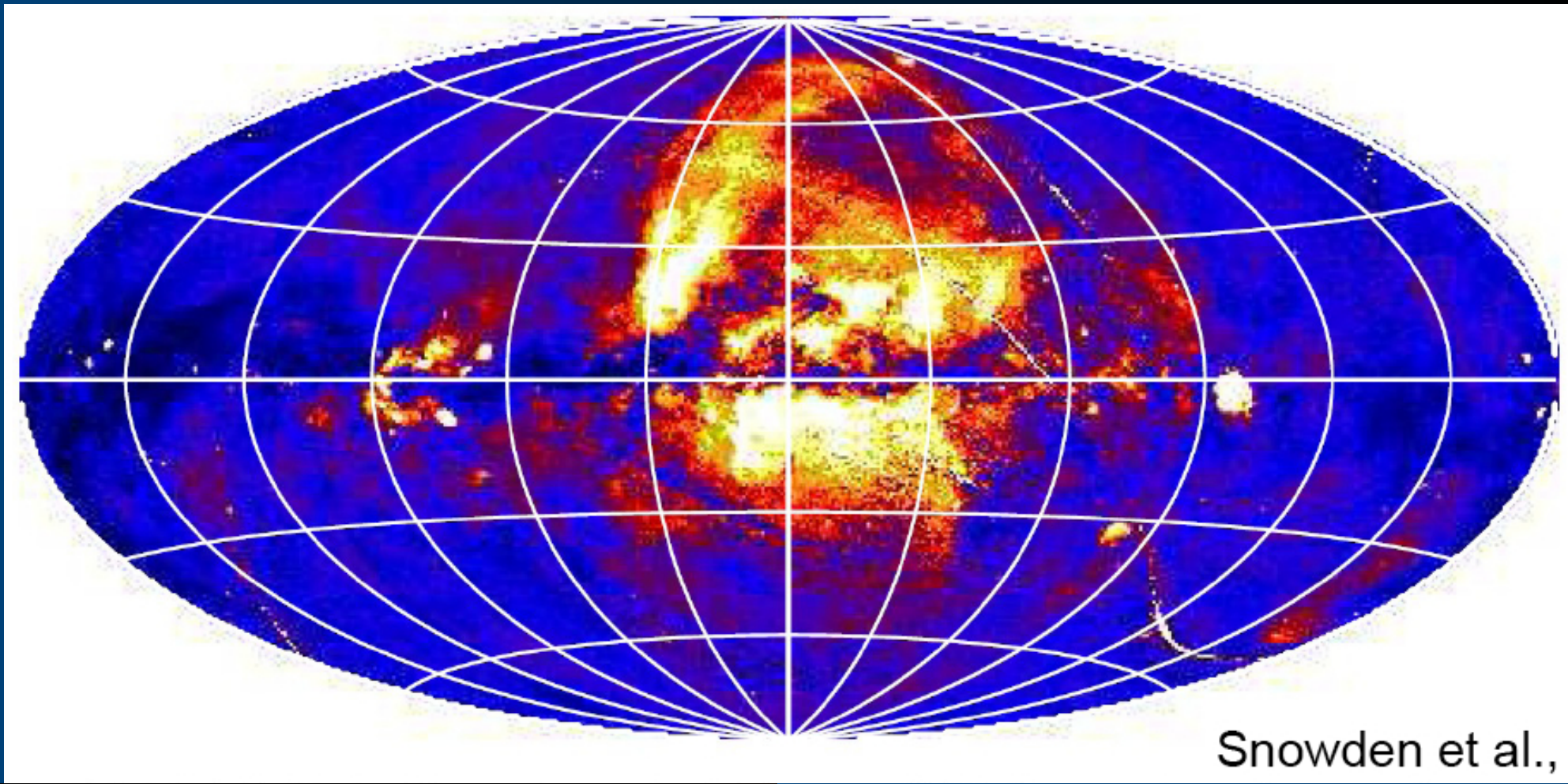
Galactic wind in the Milky Way?

Fermi gamma-ray bubbles

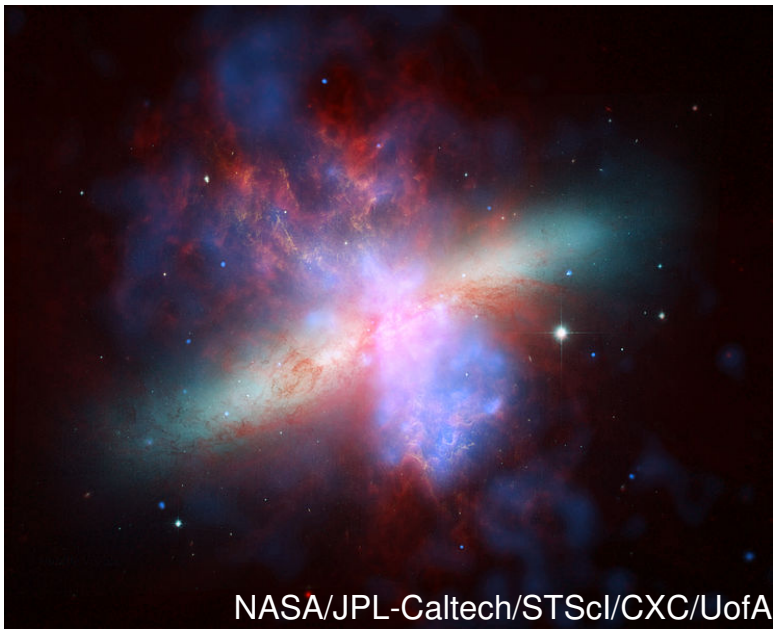


Galactic wind in the Milky Way?

Diffuse X-ray emission in our Galaxy



How are galactic winds driven?

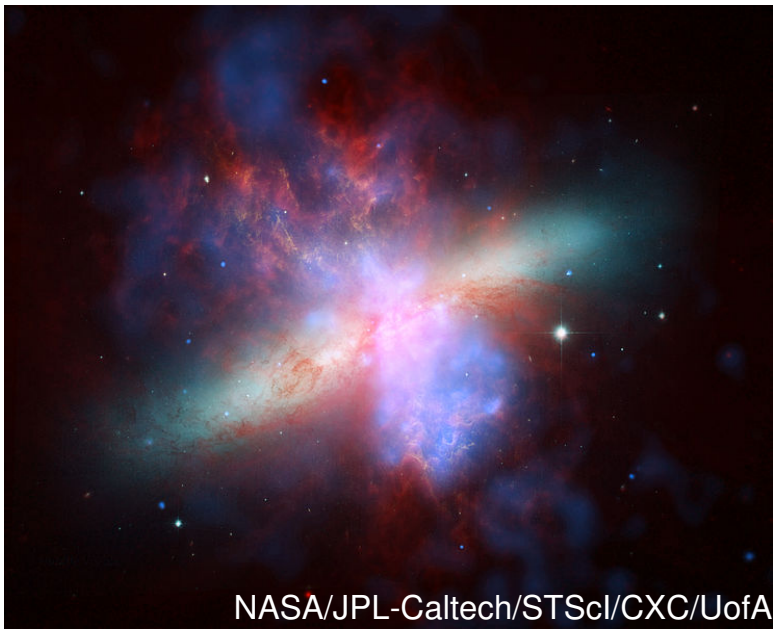


super wind in M82

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

AIP

How are galactic winds driven?



super wind in M82

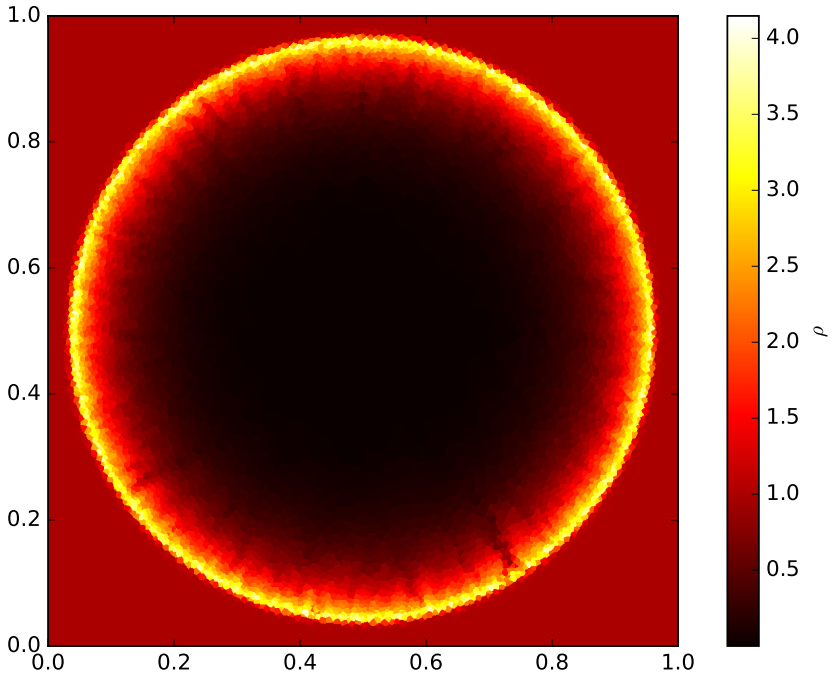
- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

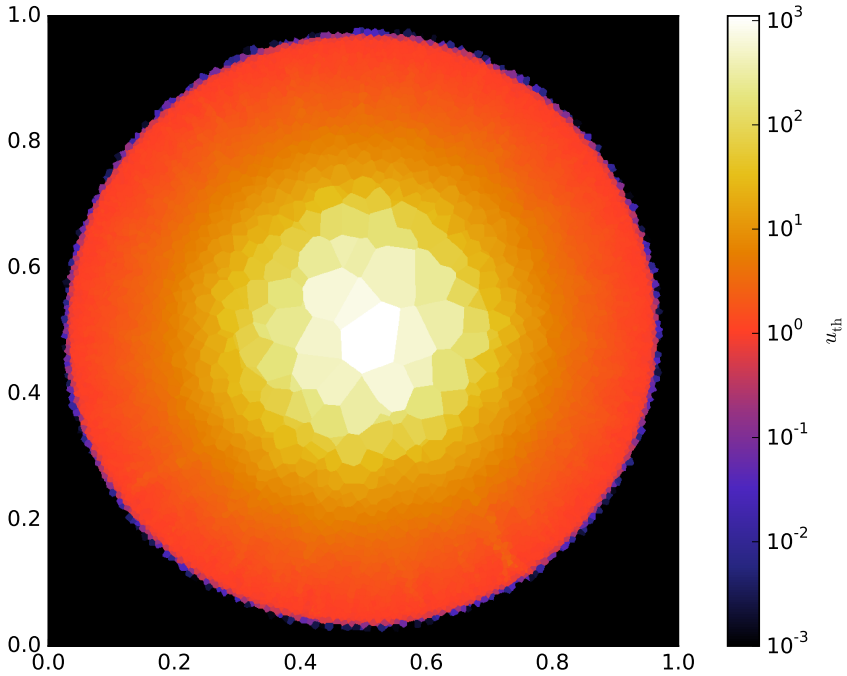
AIP

Sedov explosion

density



specific thermal energy

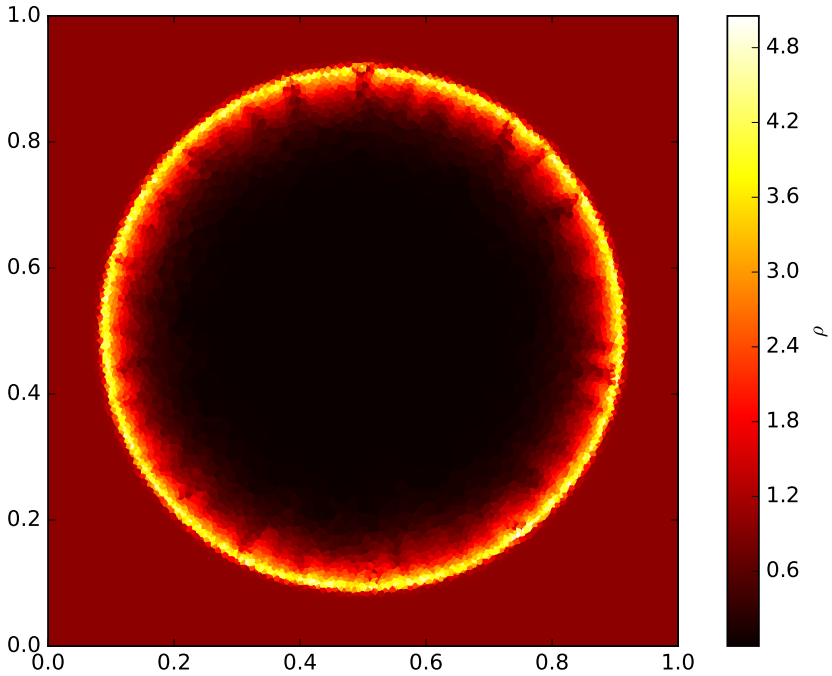


CP+ (2017a)

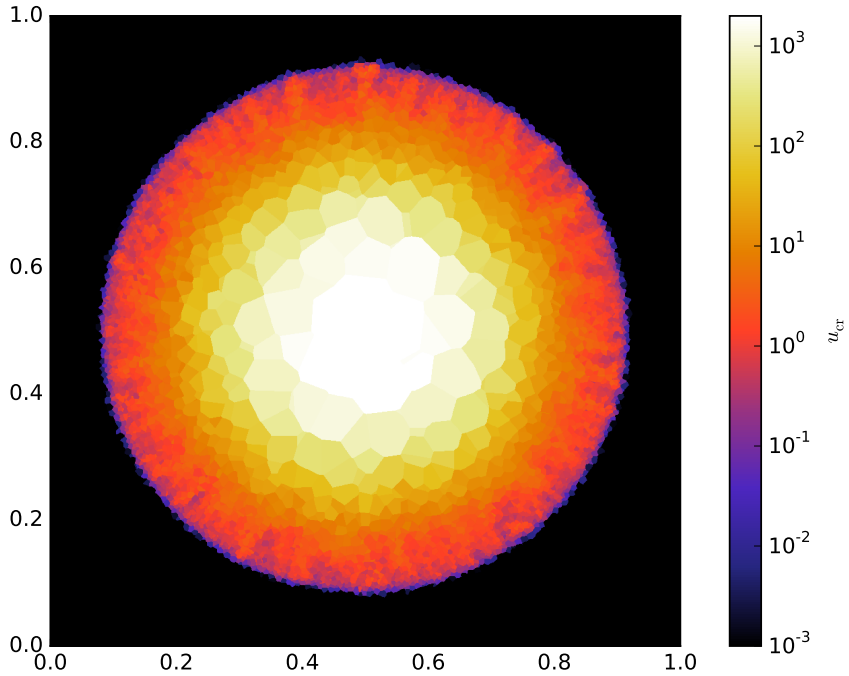
AIP

Sedov explosion with CR acceleration

density



specific cosmic ray energy

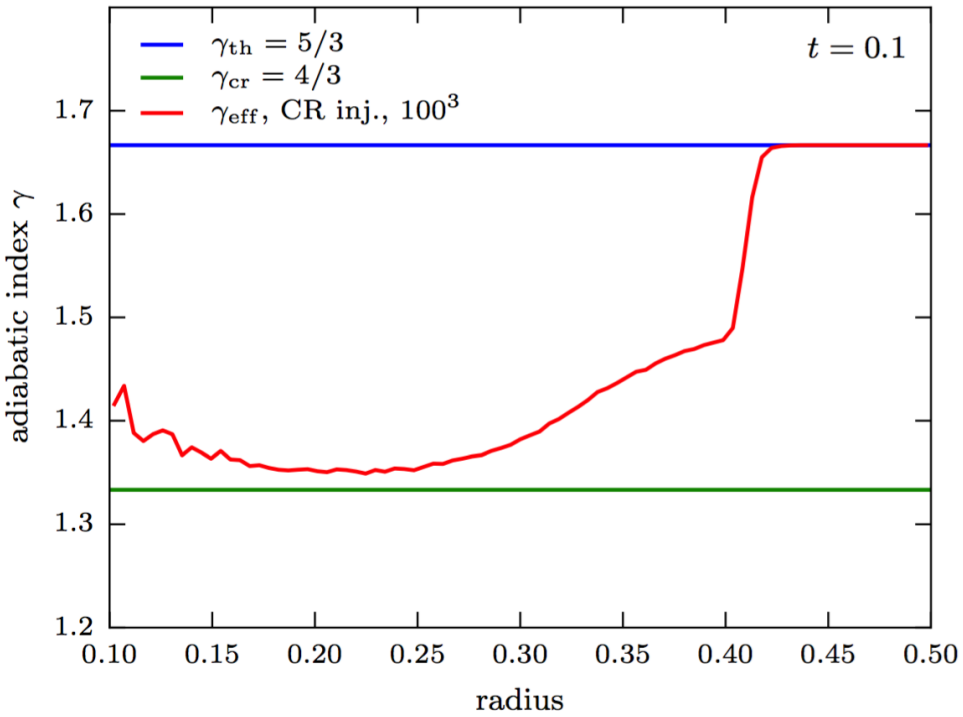


CP+ (2017a)

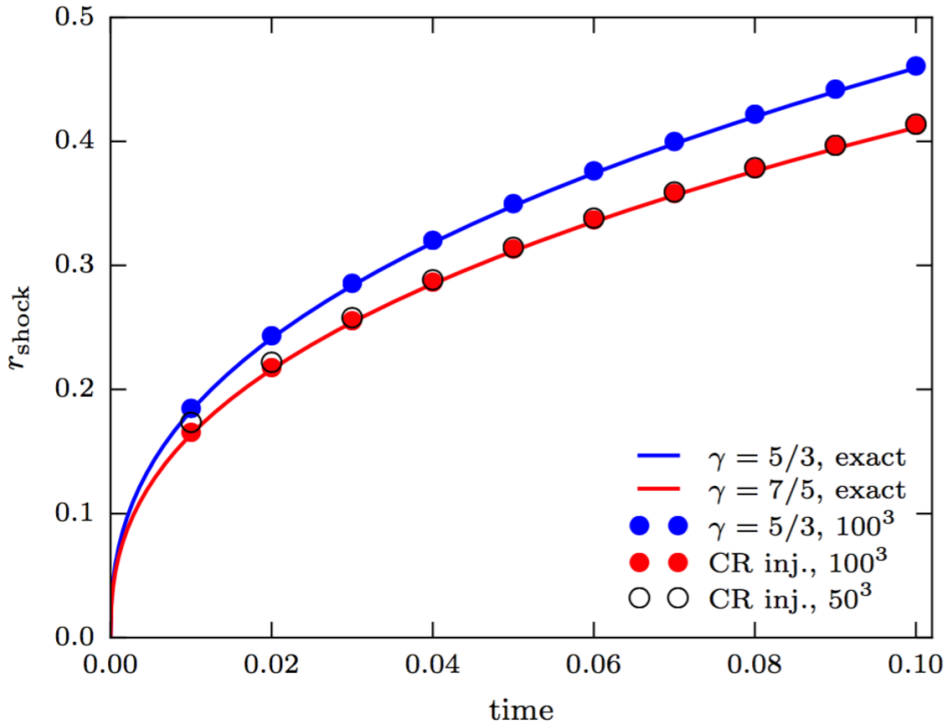
AIP

Sedov explosion with CR acceleration

adiabatic index



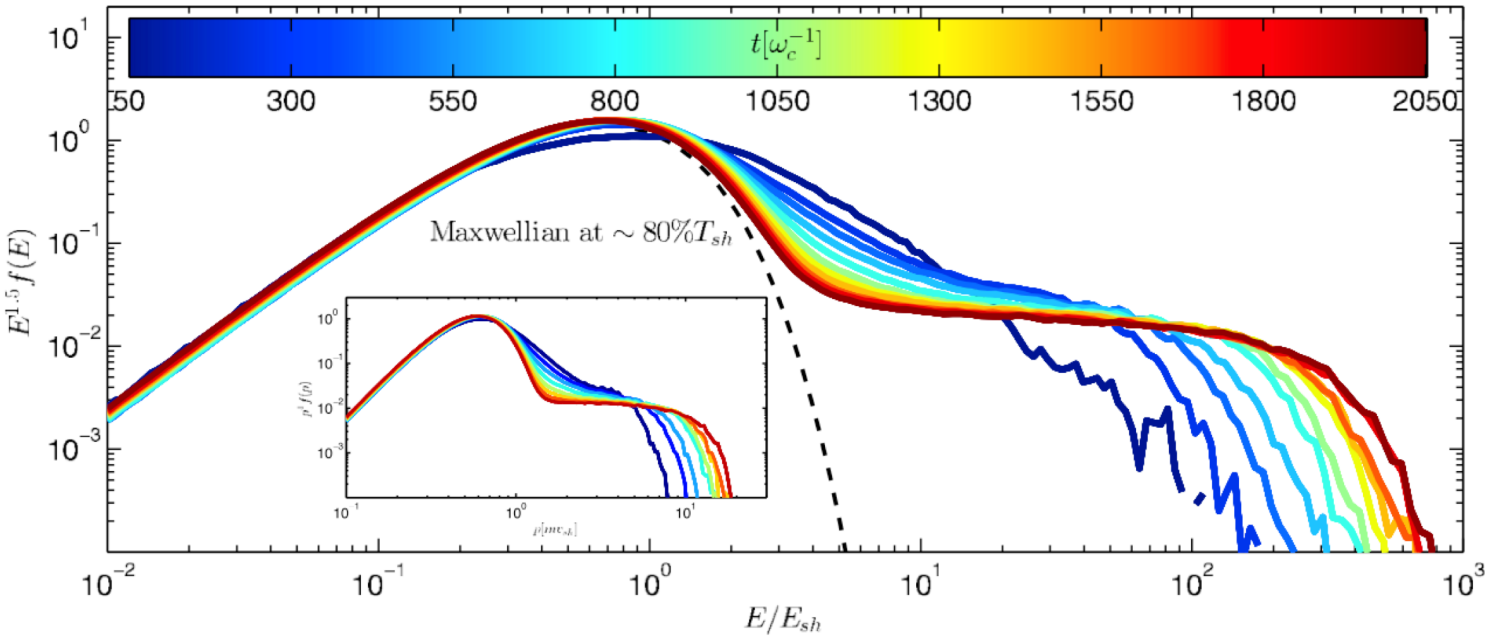
shock evolution



CP+ (2017a)

Ion spectrum

Non-relativistic *parallel shock* in long-term hybrid simulation



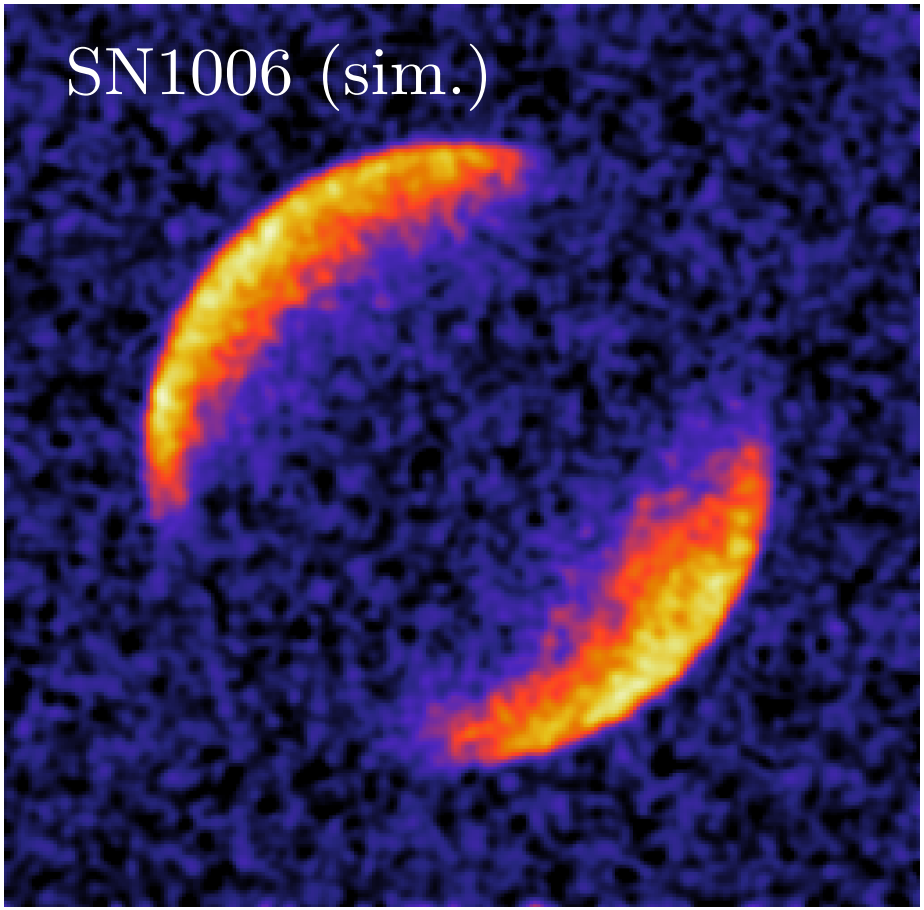
Caprioli & Spitkovsky (2014)

- quasi-parallel shocks ($\boldsymbol{B} \parallel \boldsymbol{n}_s$) accelerate ions
- quasi-perpendicular shocks ($\boldsymbol{B} \perp \boldsymbol{n}_s$) cannot
- model magnetic obliquity in AREPO simulations

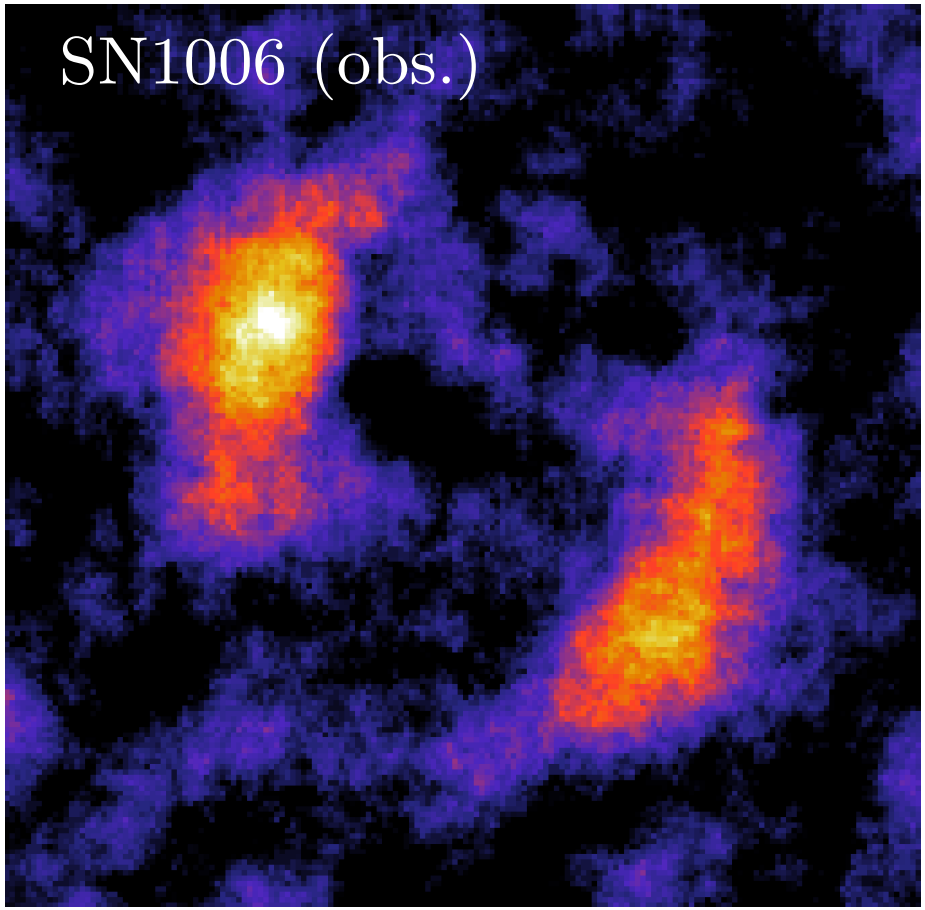
AIP

TeV γ rays from shell-type SNRs: SNR 1006

AREPO simulation



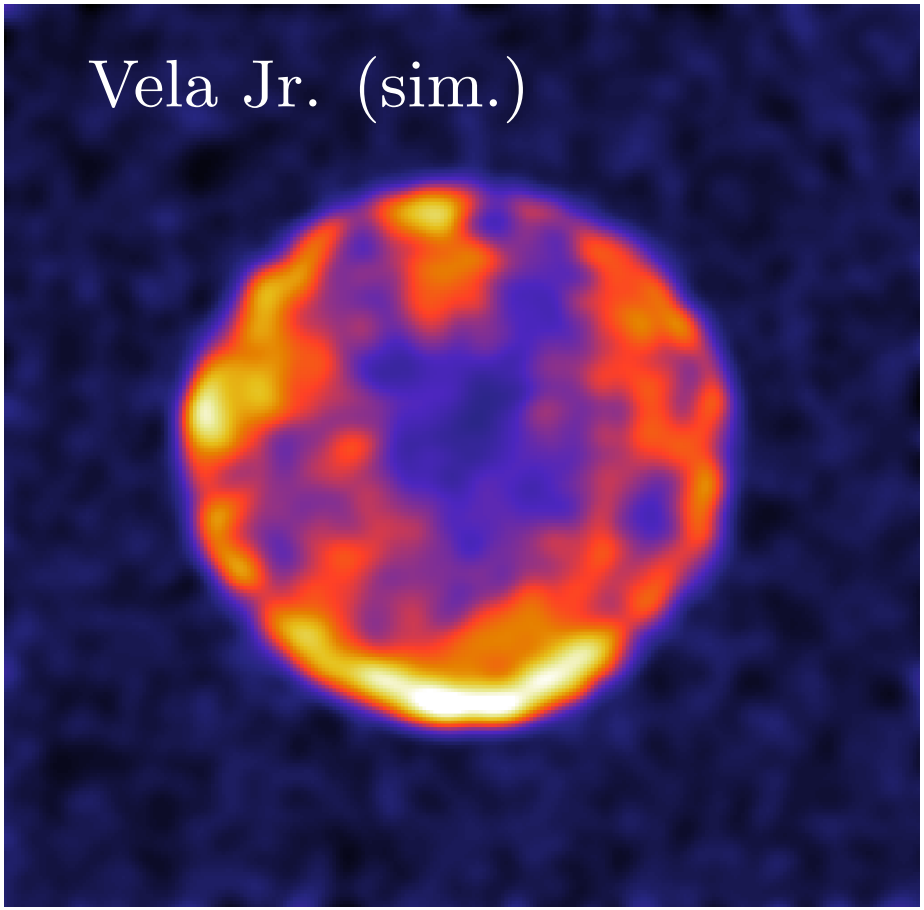
H.E.S.S. observation



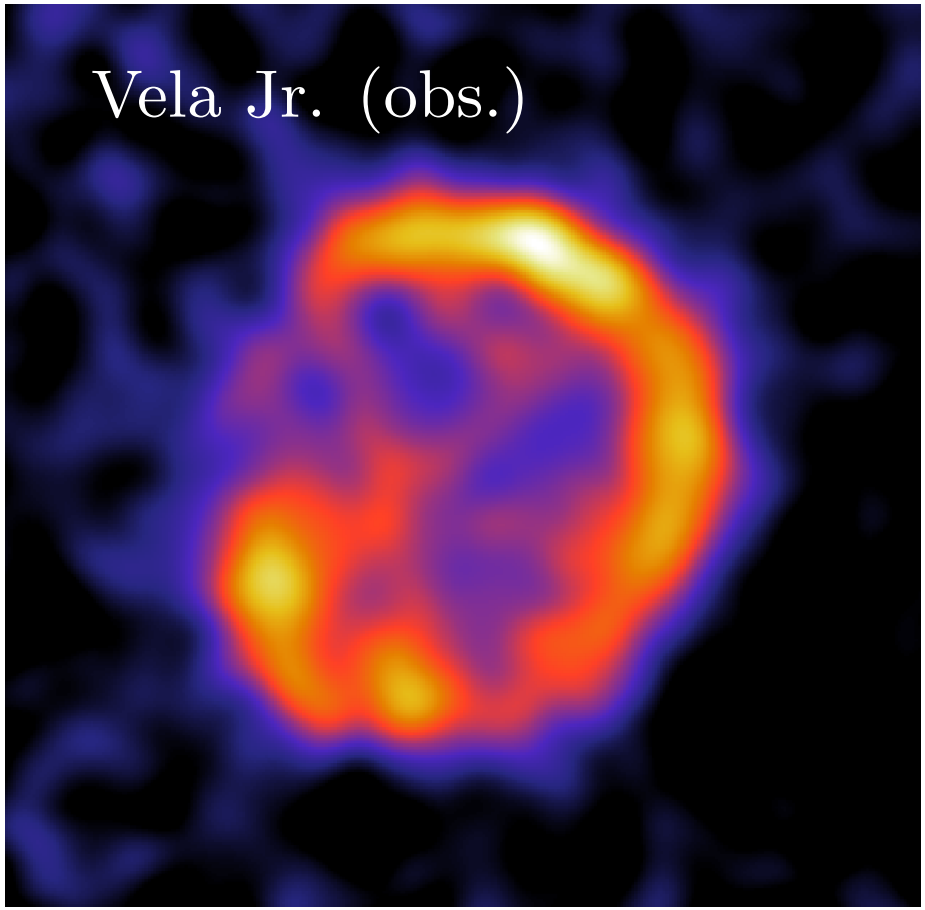
Pais, CP, Ehlert (2018)

TeV γ rays from shell-type SNRs: Vela Junior

AREPO simulation



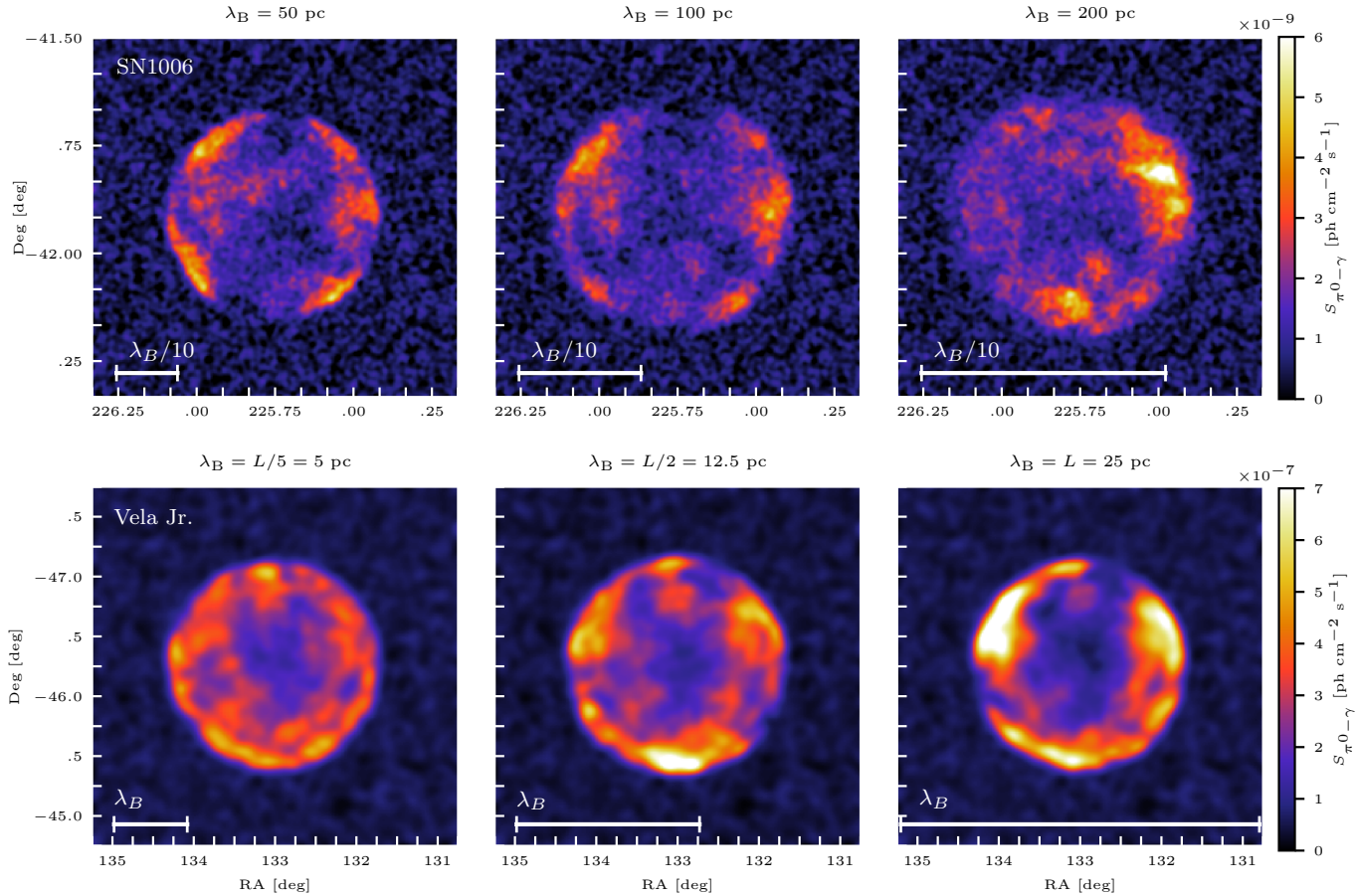
H.E.S.S. observation



Pais, CP, Ehlert (2018)

TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN1006 and Vela Junior

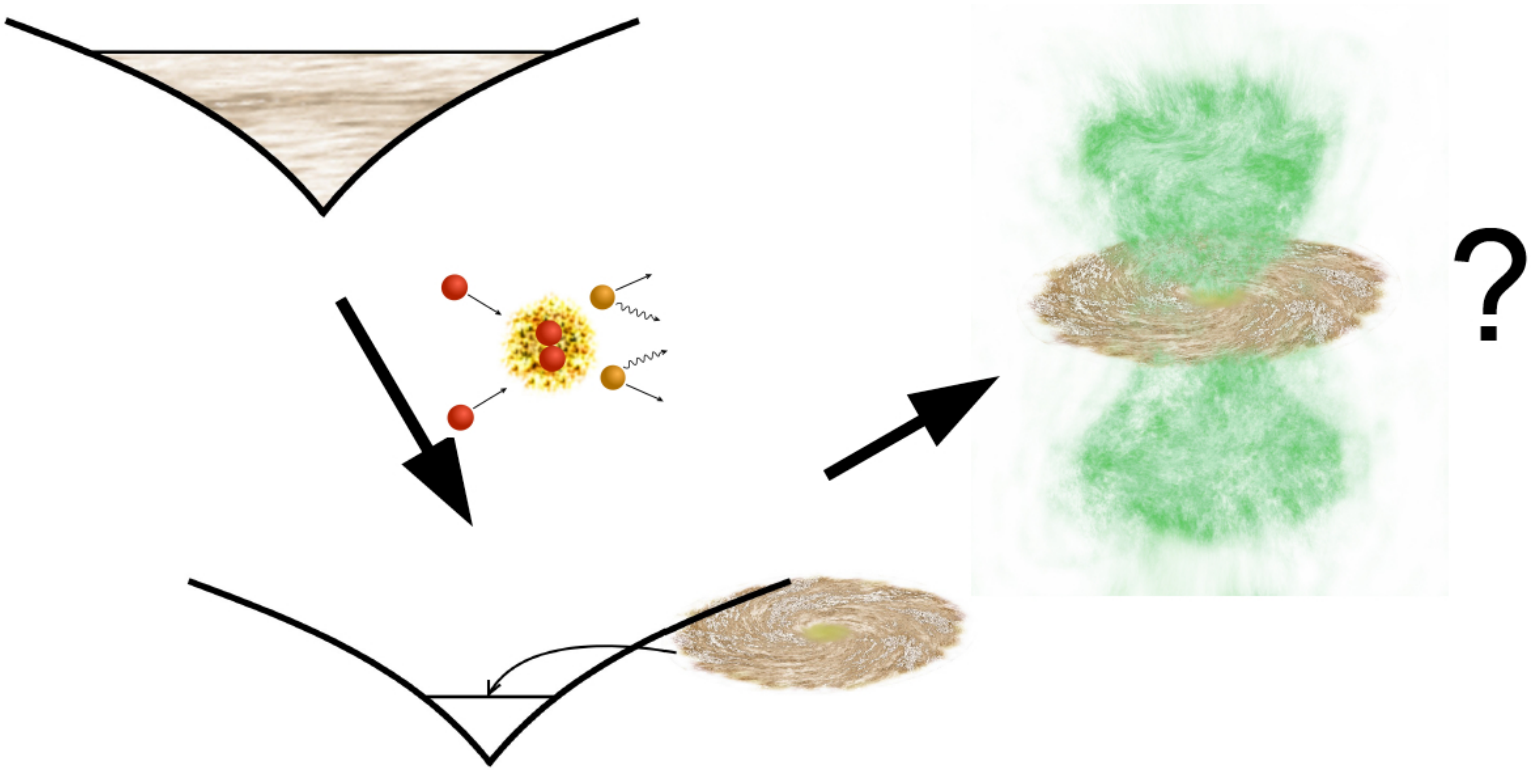


Pais, CP, Ehlert (2018)

SNR 1006: $\lambda_B > 200^{+10}_{-60}$ pc

Vela Junior: $\lambda_B = 8^{+15}_{-6}$ pc

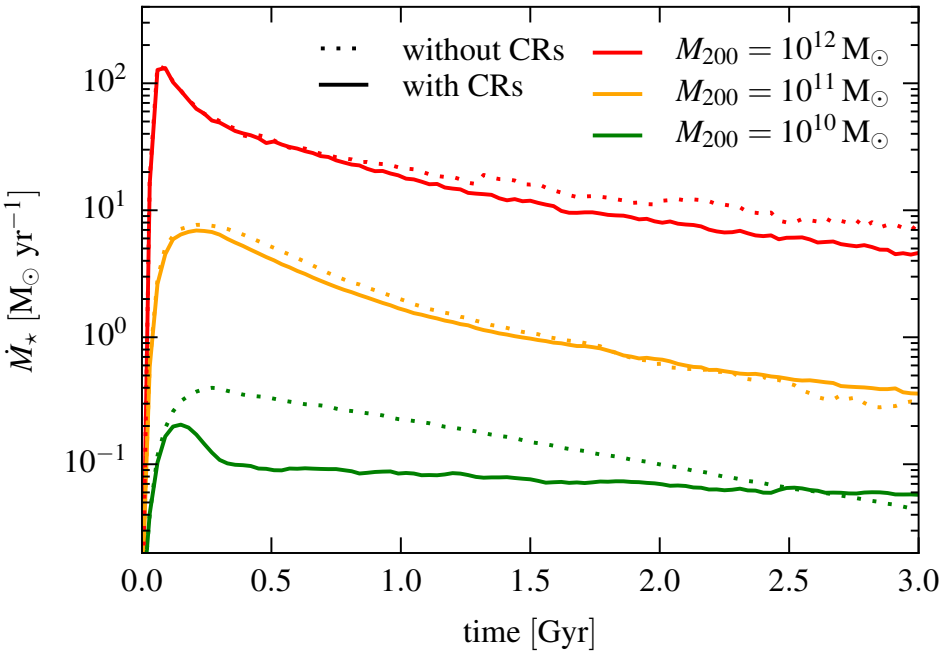
Galaxy simulation setup: 1. cosmic ray advection

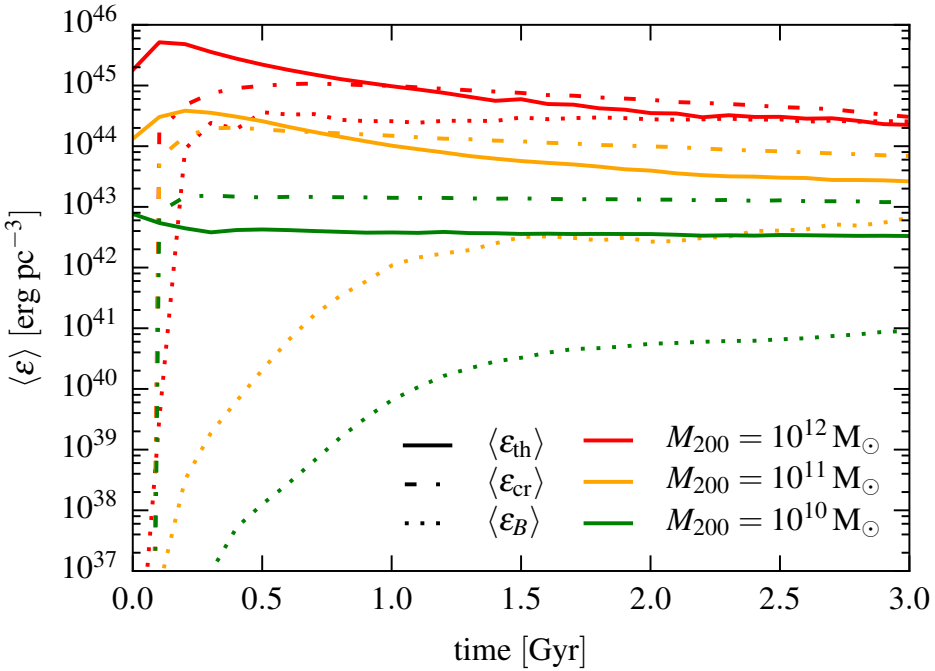


CP, Pakmor, Schaal, Simpson, Springel (2017a)
Simulating cosmic ray physics on a moving mesh

MHD + cosmic ray advection: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

Time evolution of SFR and energy densities

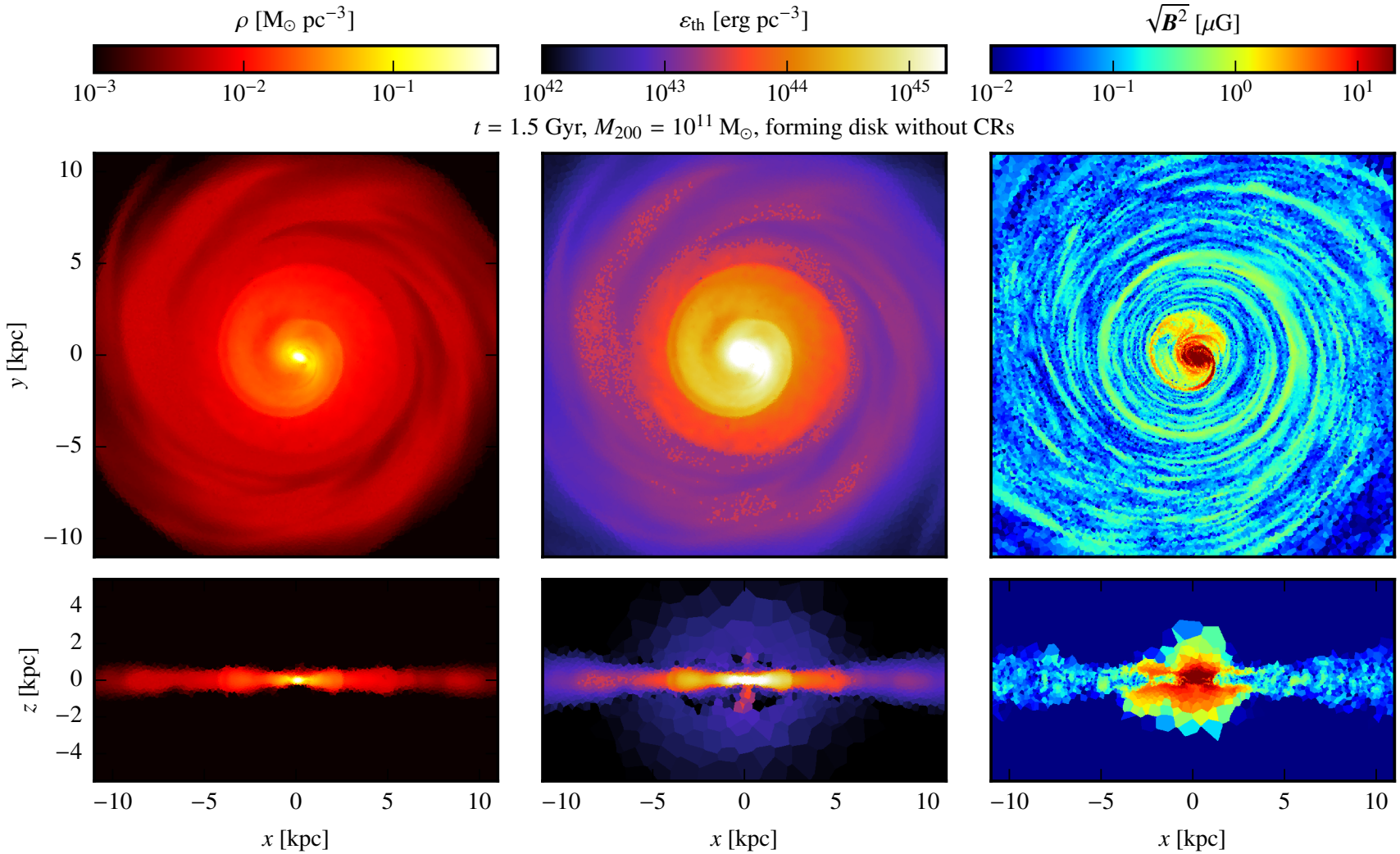




CP+ (2017a)

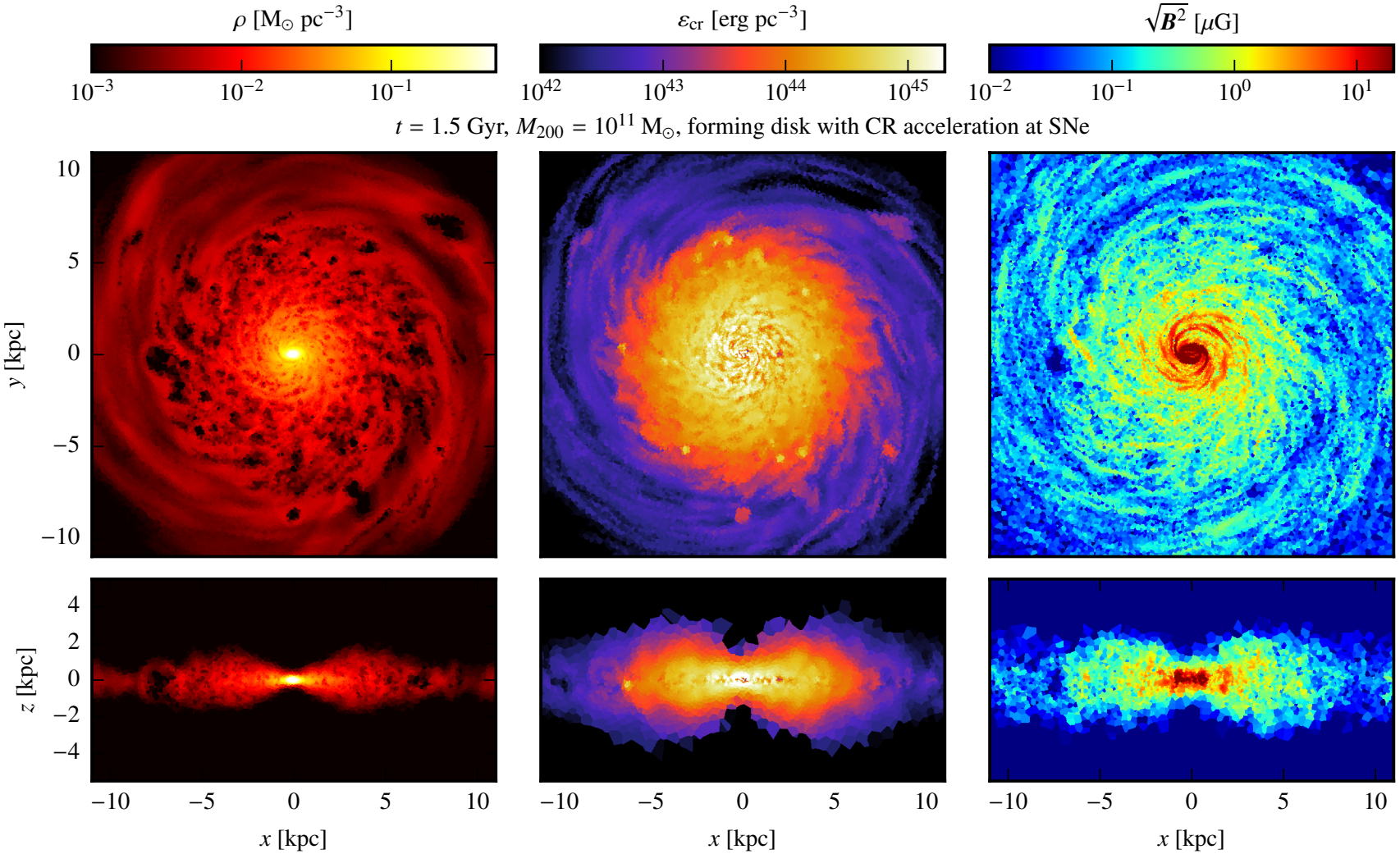
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



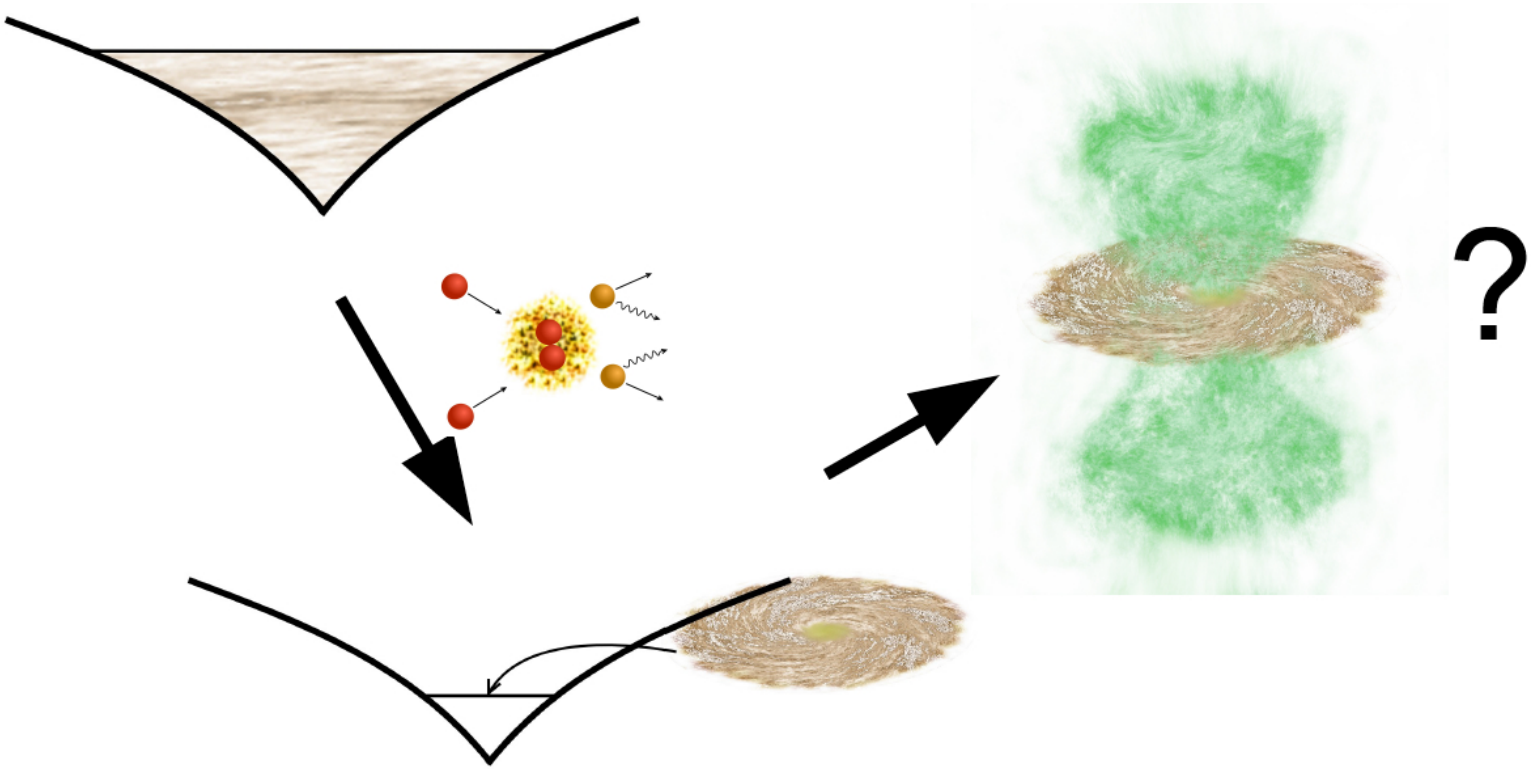
CP+ (2017a)

MHD galaxy simulation with CRs



CP+ (2017a)

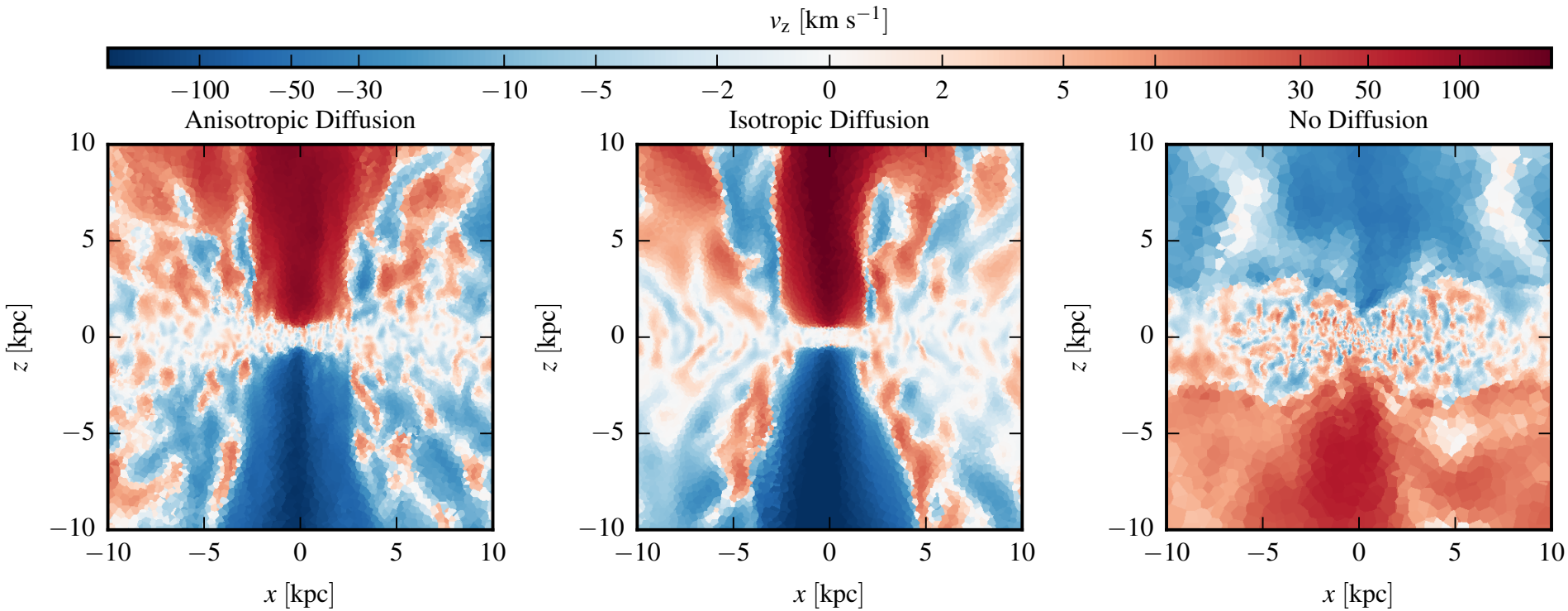
Galaxy simulation setup: 2. cosmic ray diffusion



Pakmor, CP, Simpson, Springel (2016)
Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies

MHD + CR advection + diffusion: $10^{11}\,M_\odot$

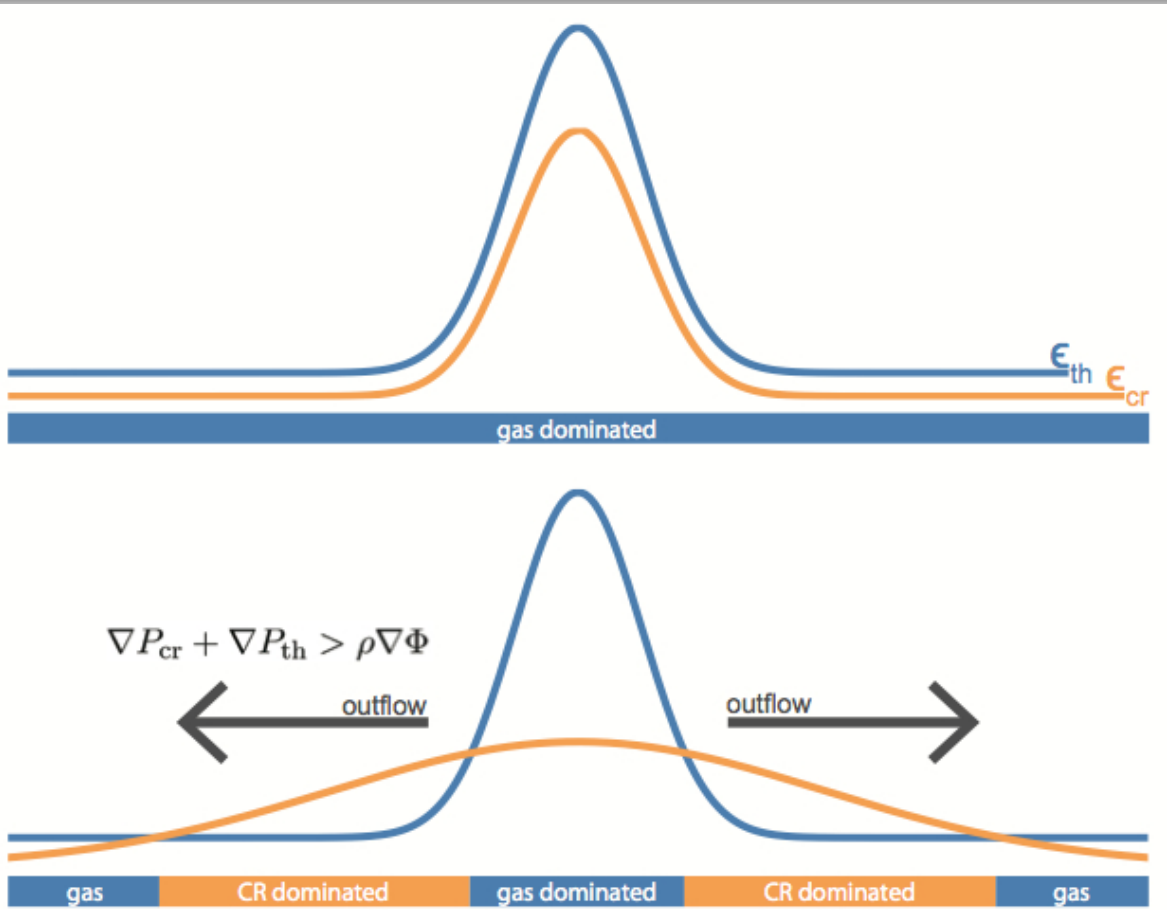
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

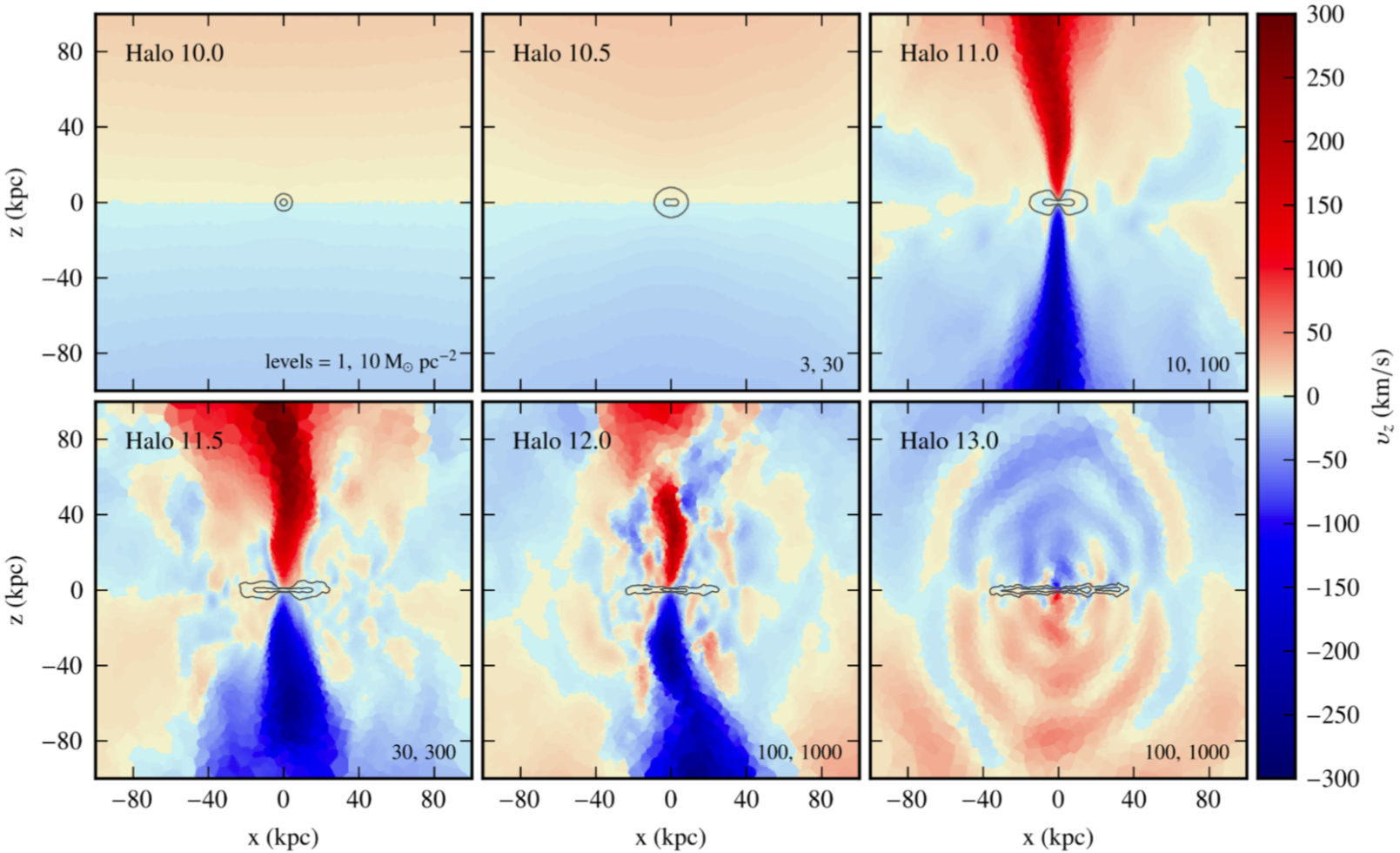
Cosmic ray driven wind: mechanism



CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

AIP

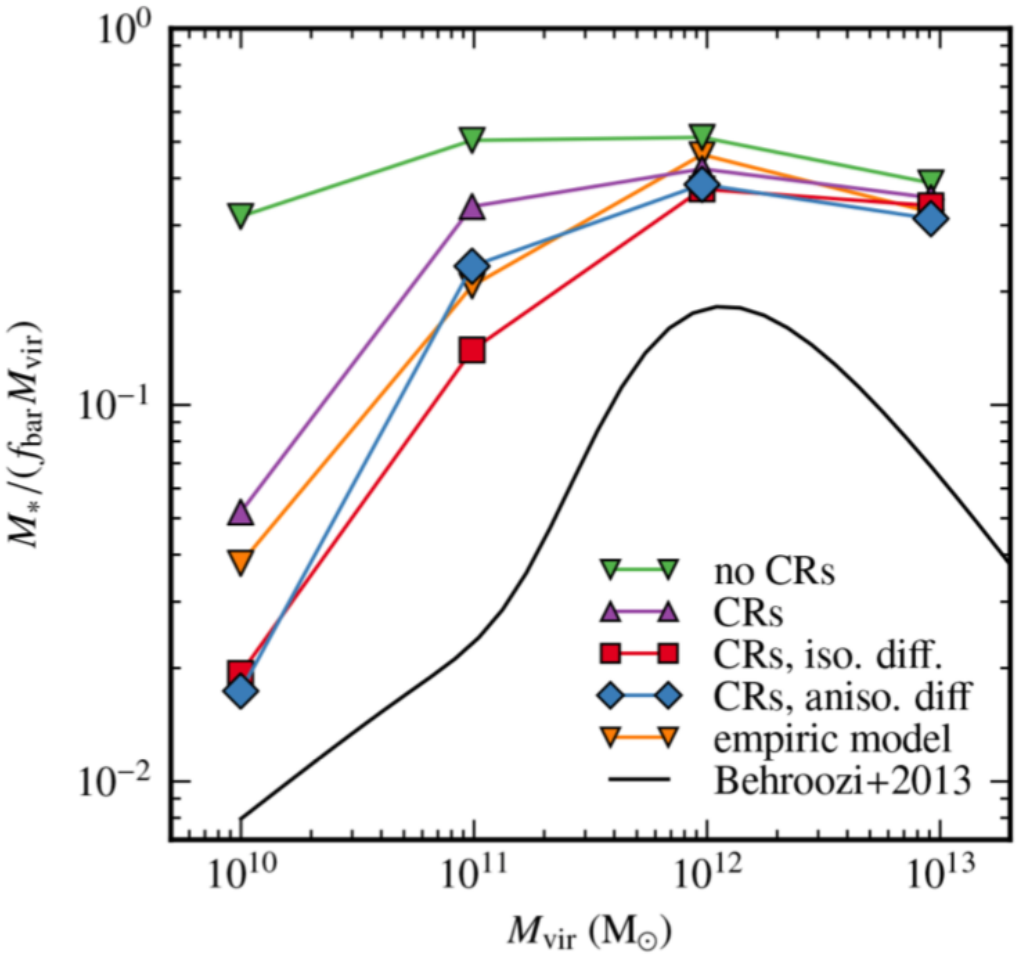
CR-driven winds: dependence on halo mass



Jacob+ (2018)

AIP

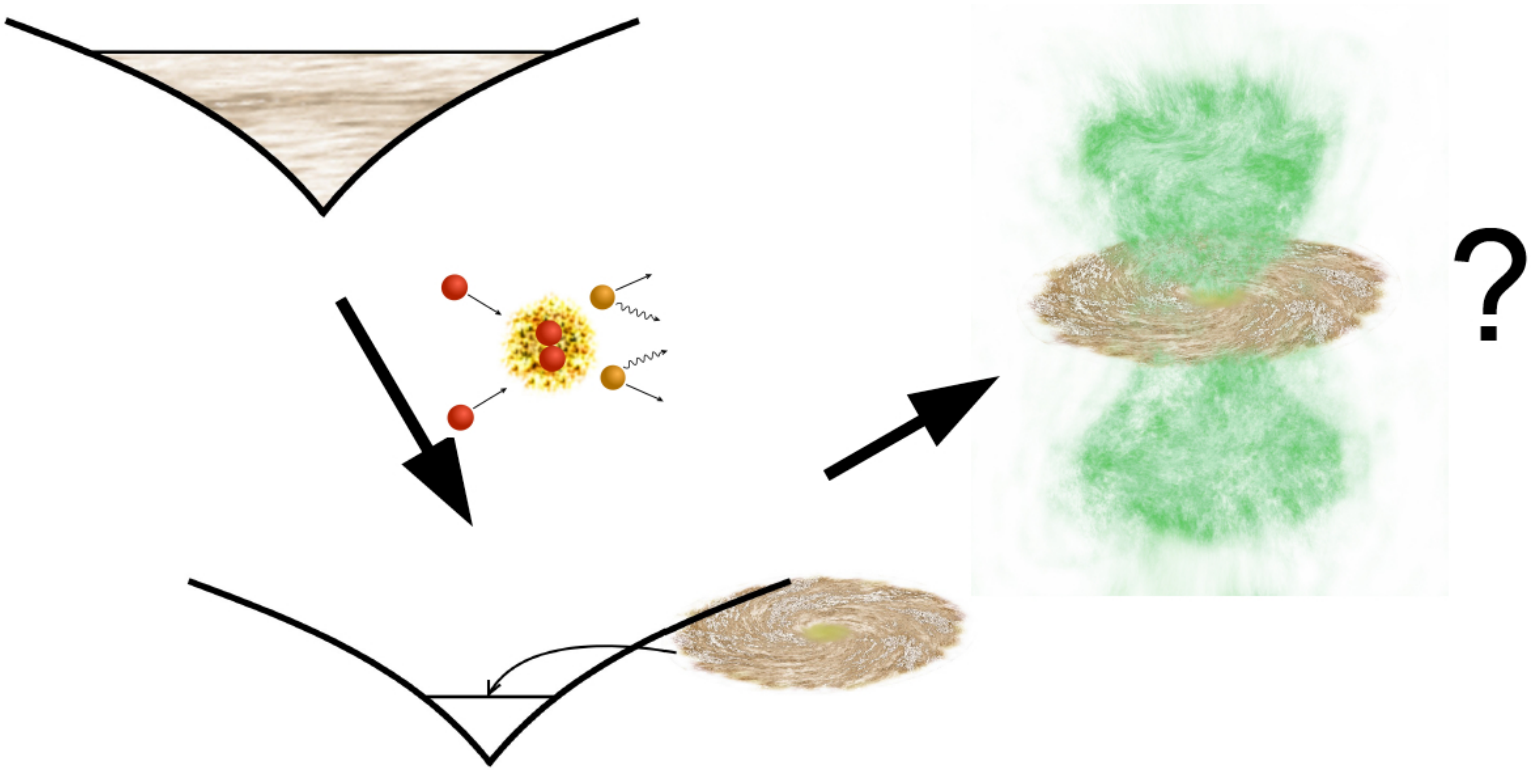
CR-driven winds: suppression of star formation



Jacob+ (2018)

AIP

Galaxy simulation setup: 3. non-thermal emission

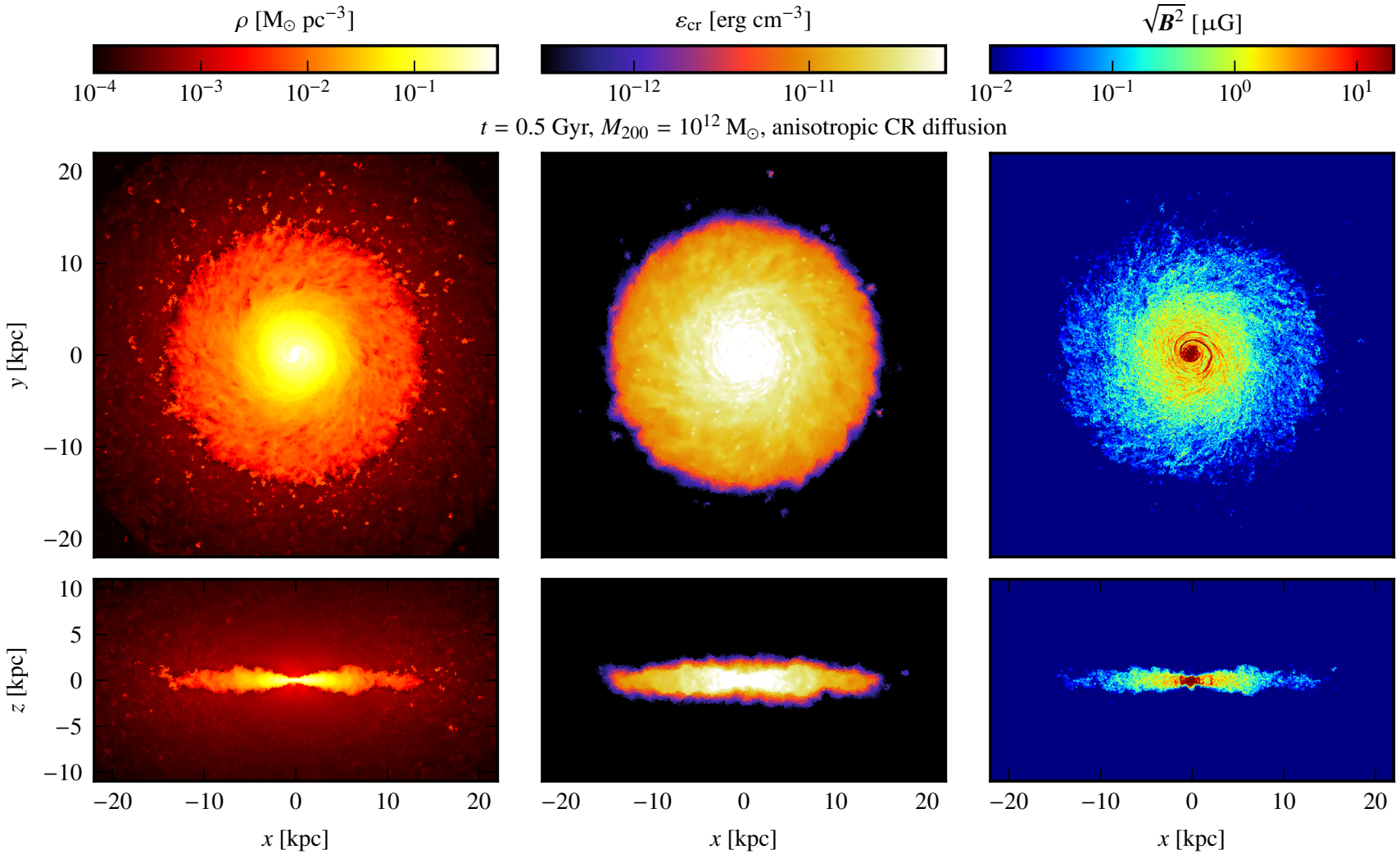


CP, Pakmor, Simpson, Springel (2017b, in prep.)
Simulating radio synchrotron and gamma-ray emission in galaxies

MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

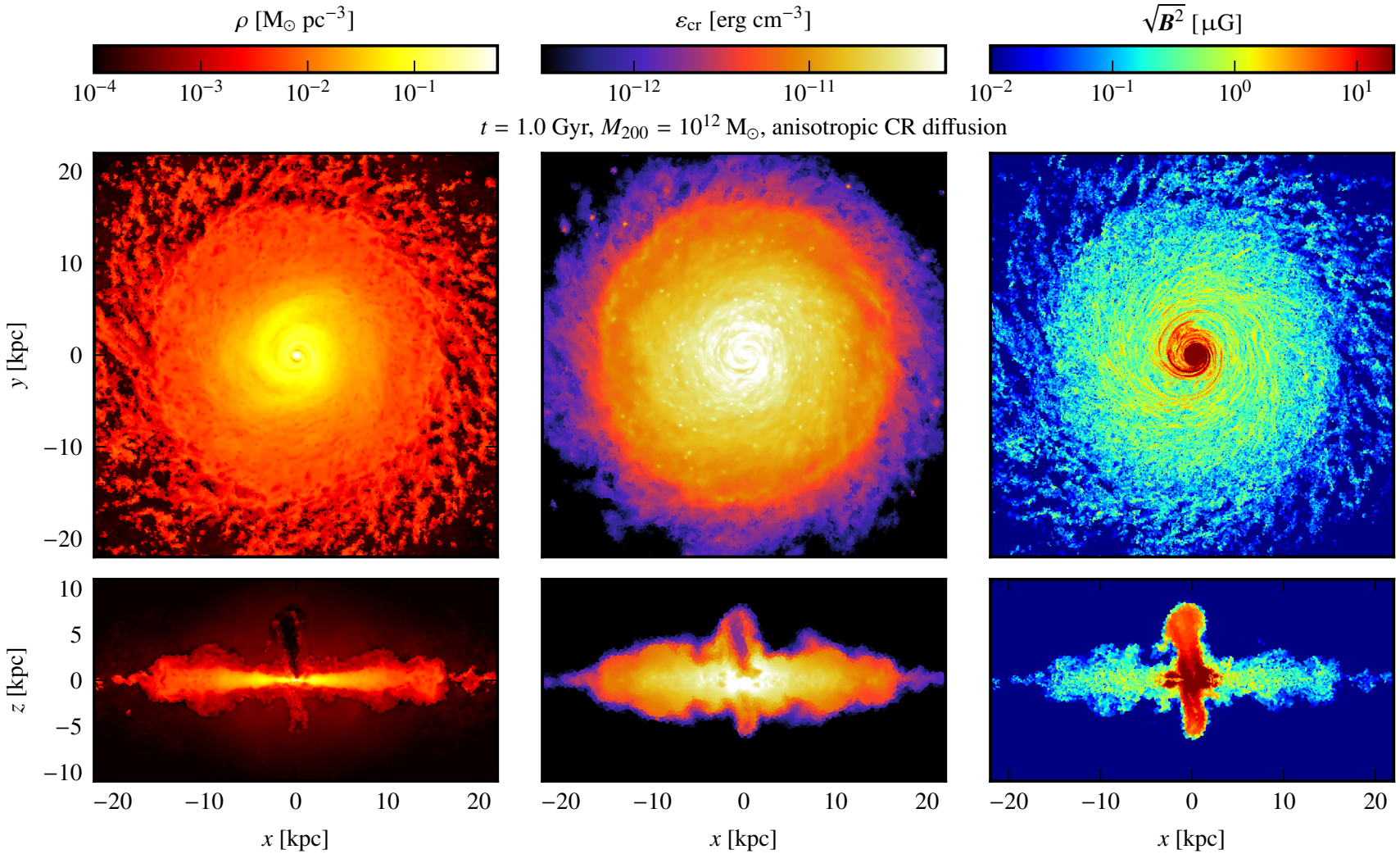
AIP

Simulation of Milky Way-like galaxy, $t = 0.5$ Gyr



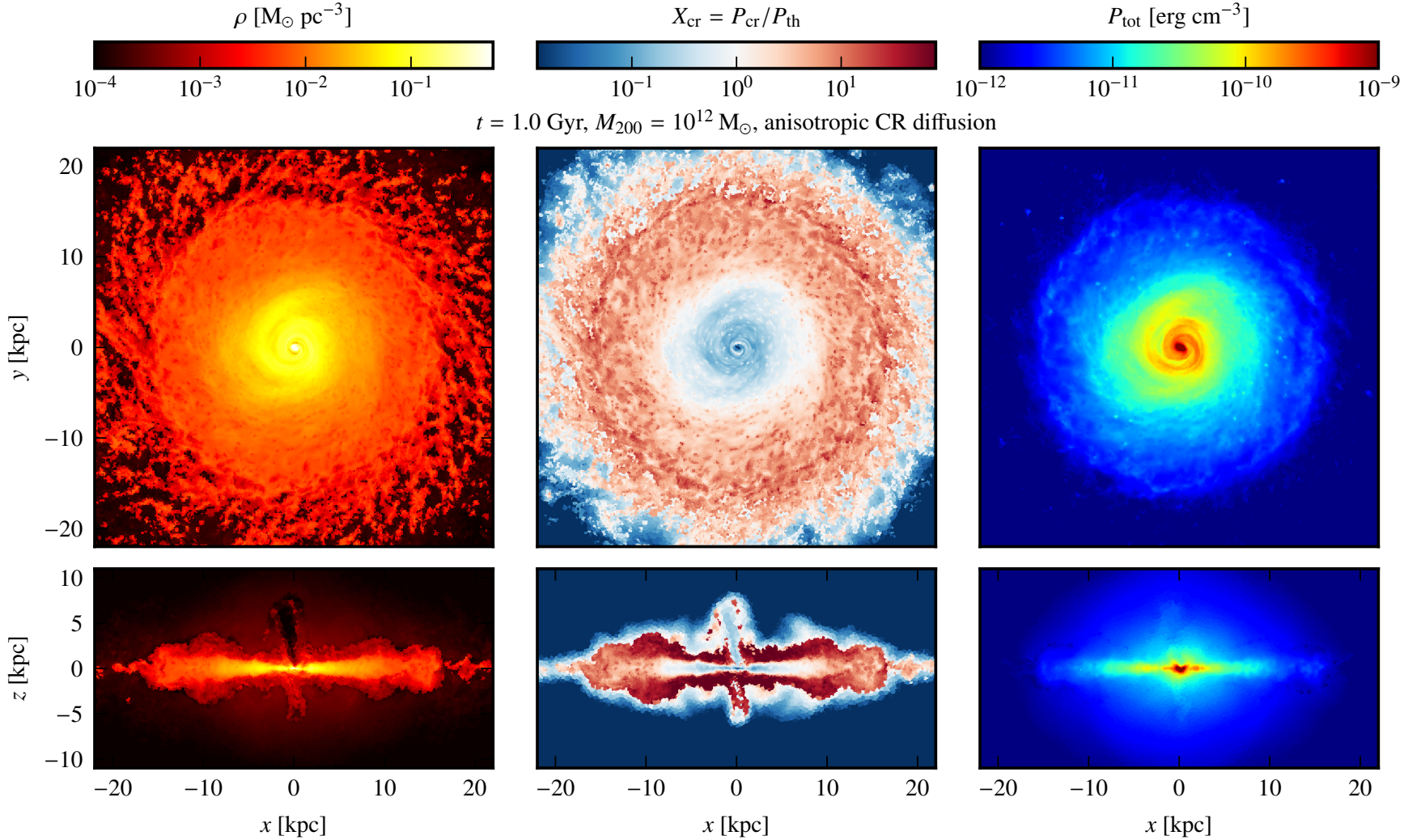
CP+ (2017b, in prep.)

Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr



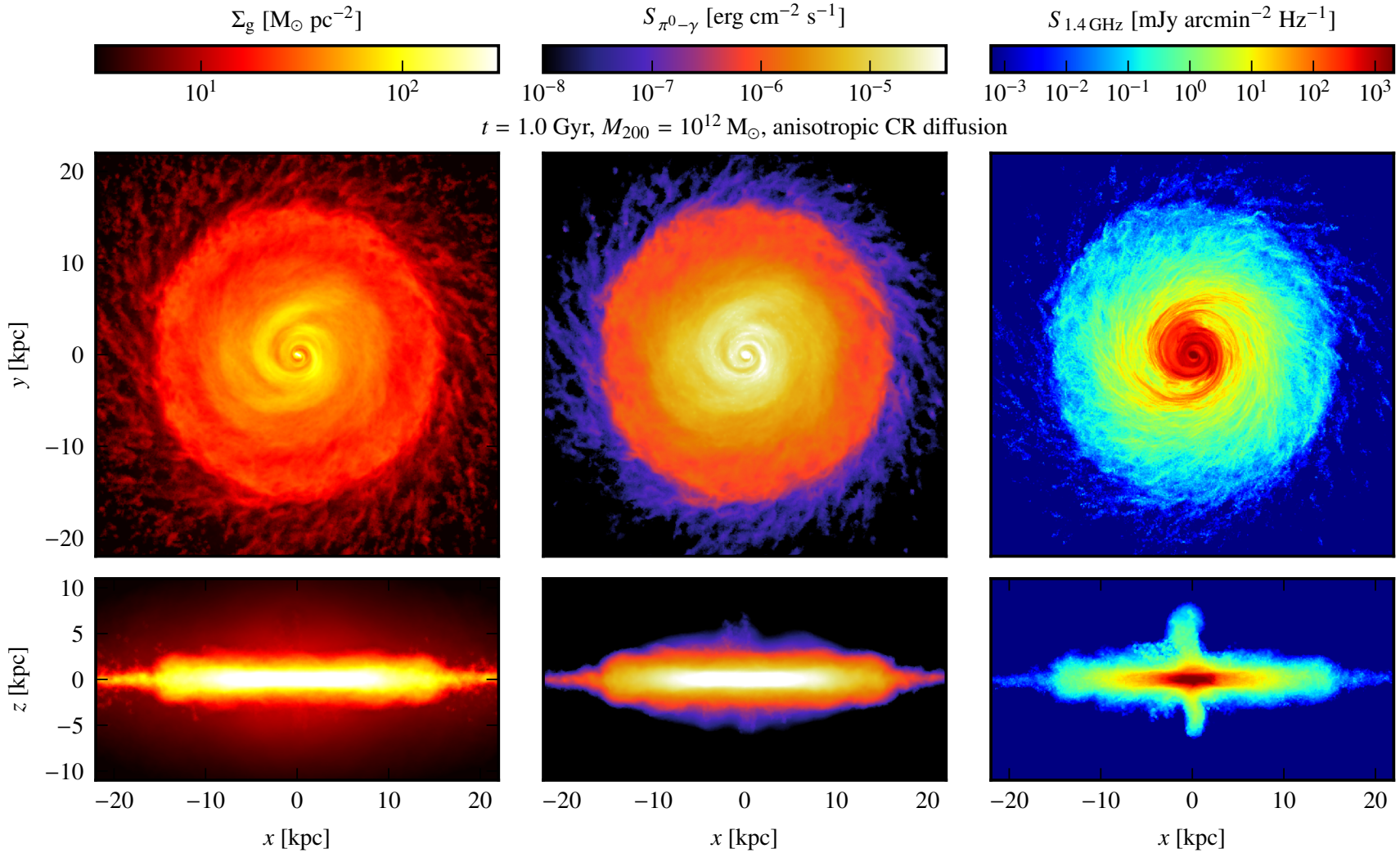
CP+ (2017b, in prep.)

Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr



CP+ (2017b, in prep.)

γ-ray and radio emission of Milky Way-like galaxy

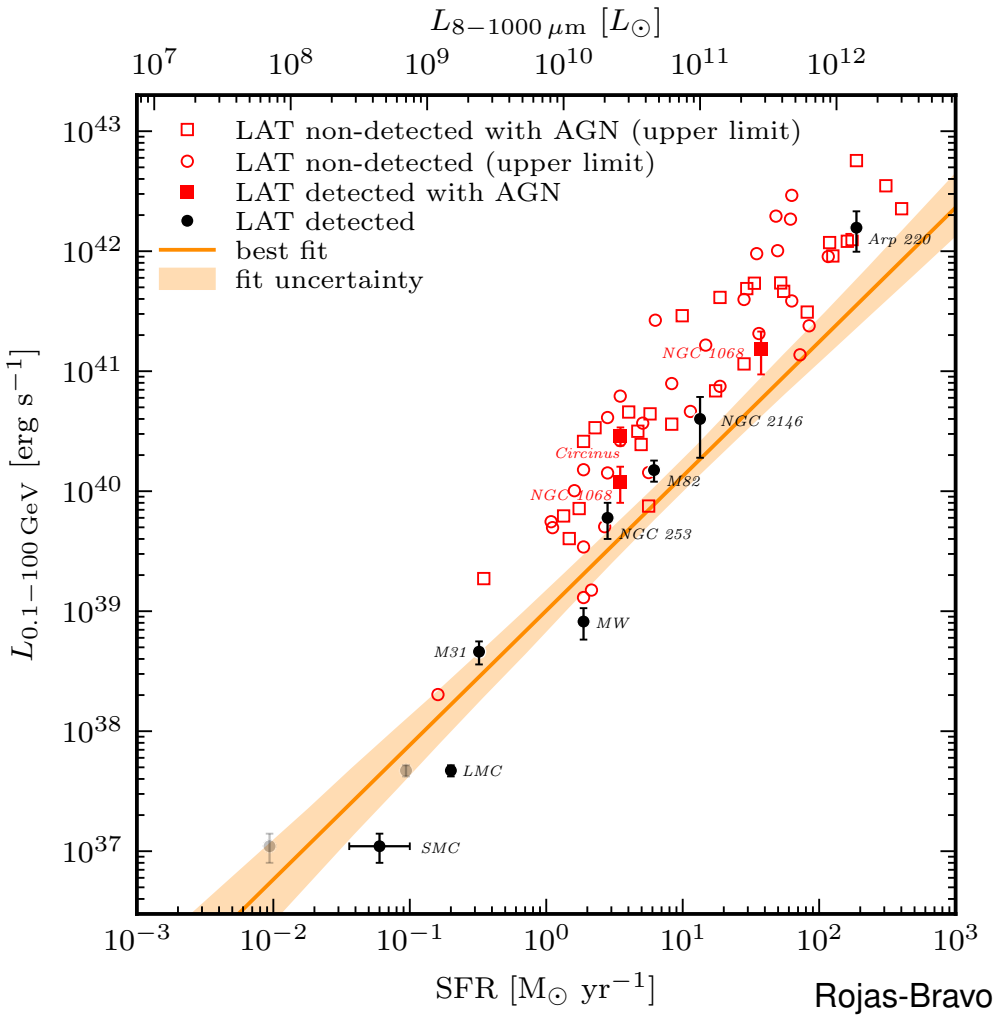


CP+ (2017b, in prep.)

AIP

Far infra-red – gamma-ray correlation

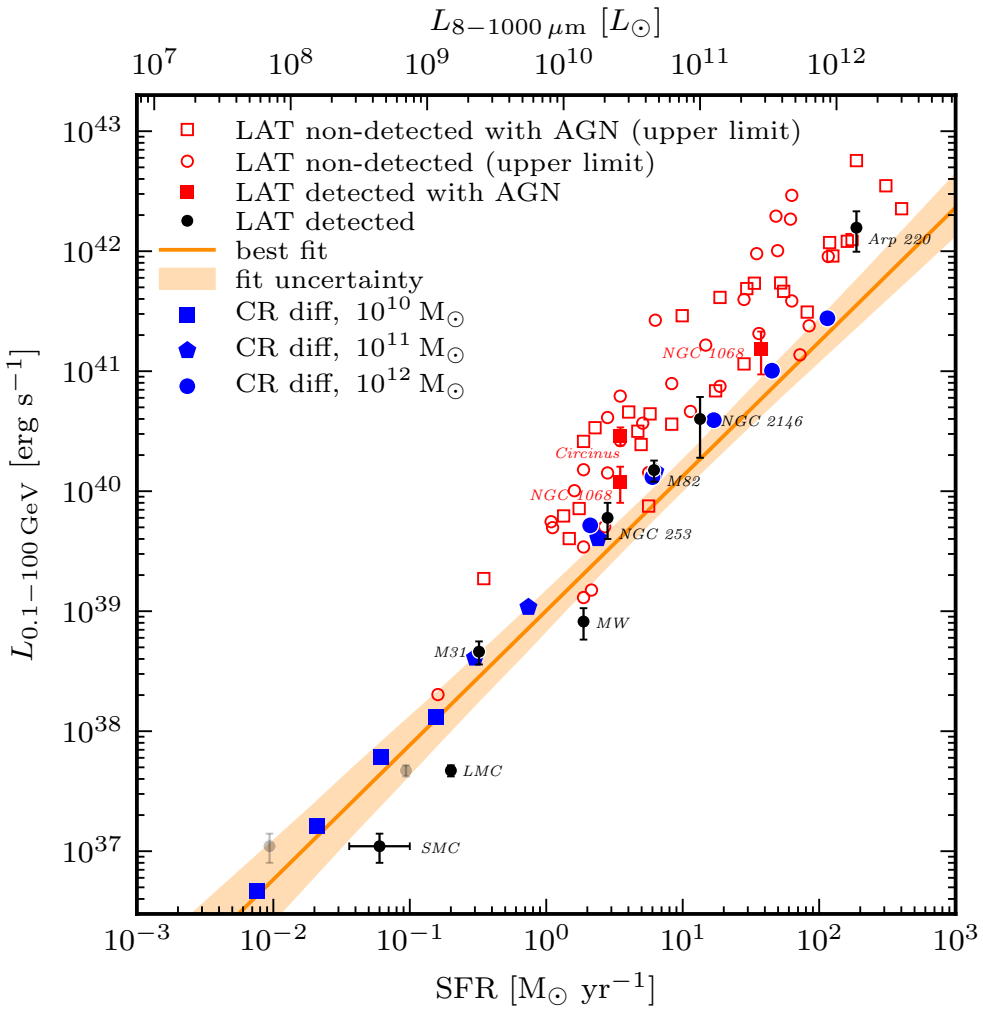
Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

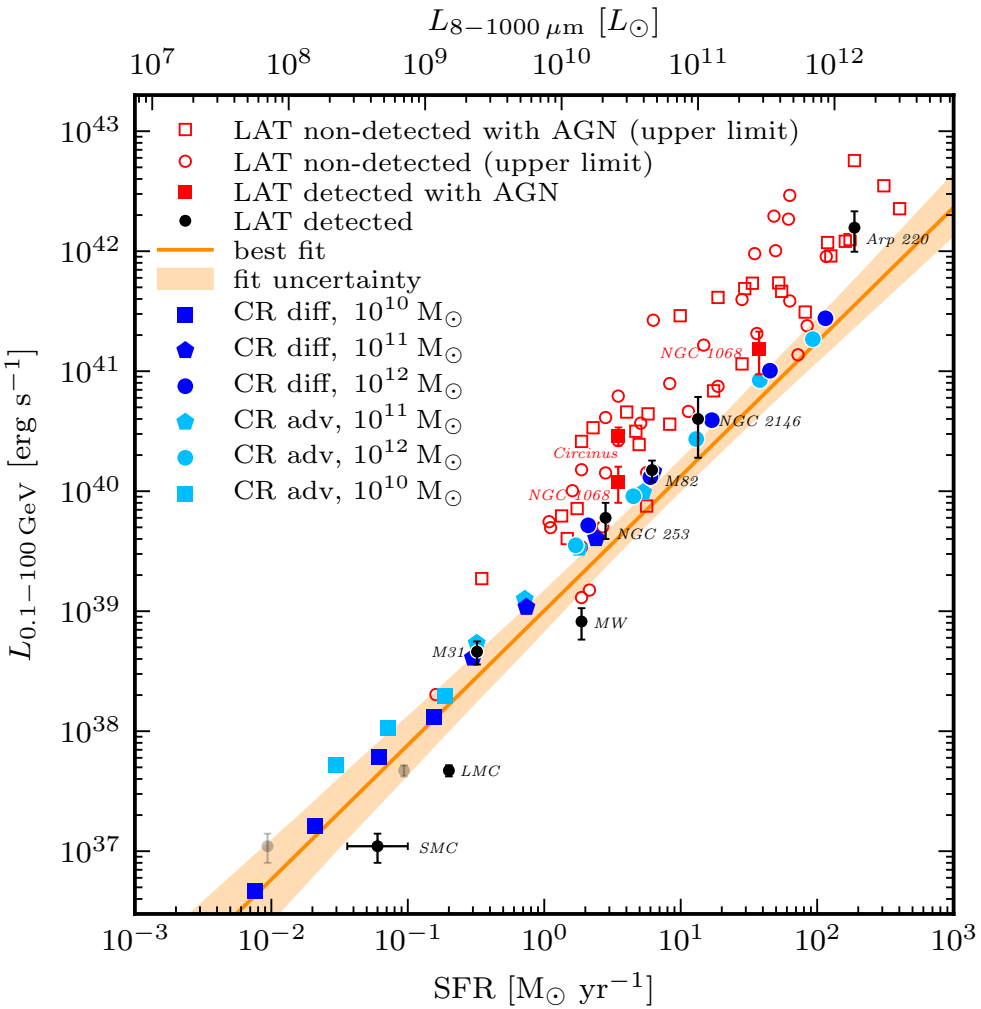
Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017b)

Far infra-red – gamma-ray correlation

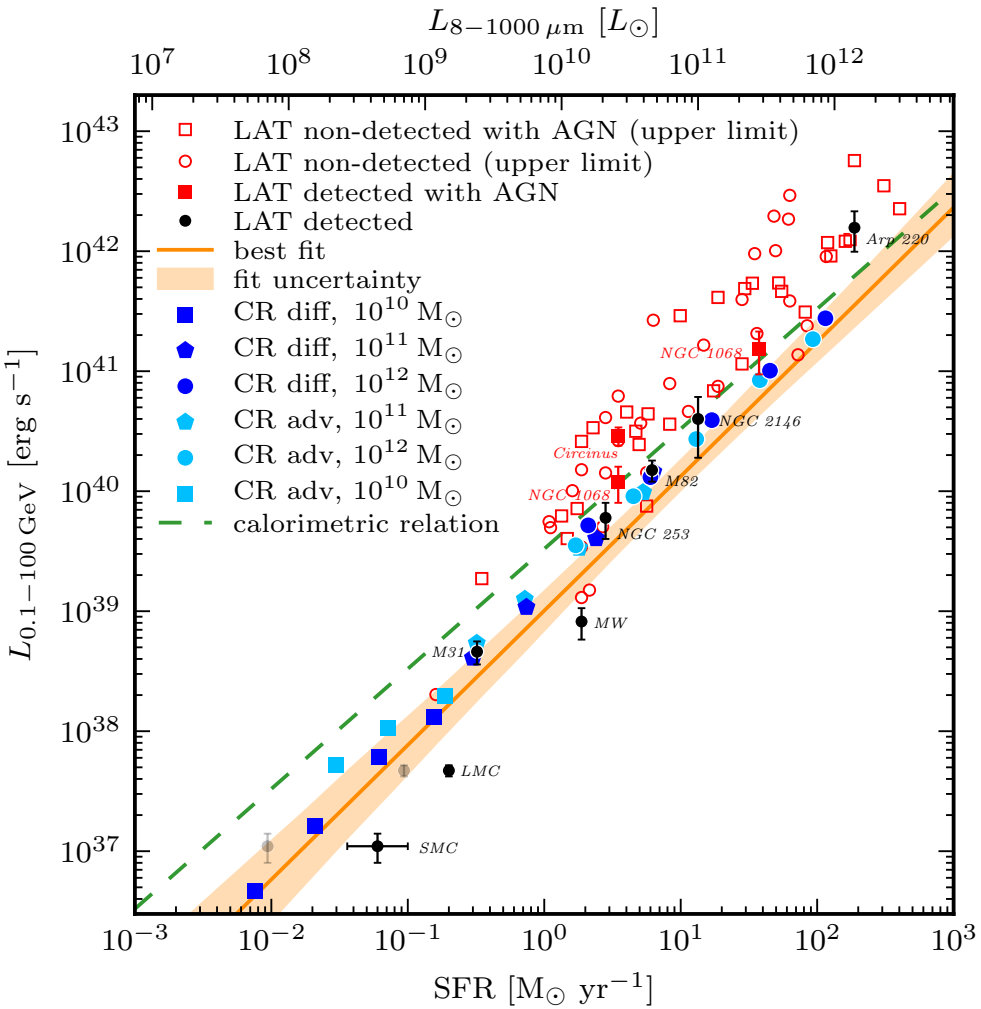
Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017b)

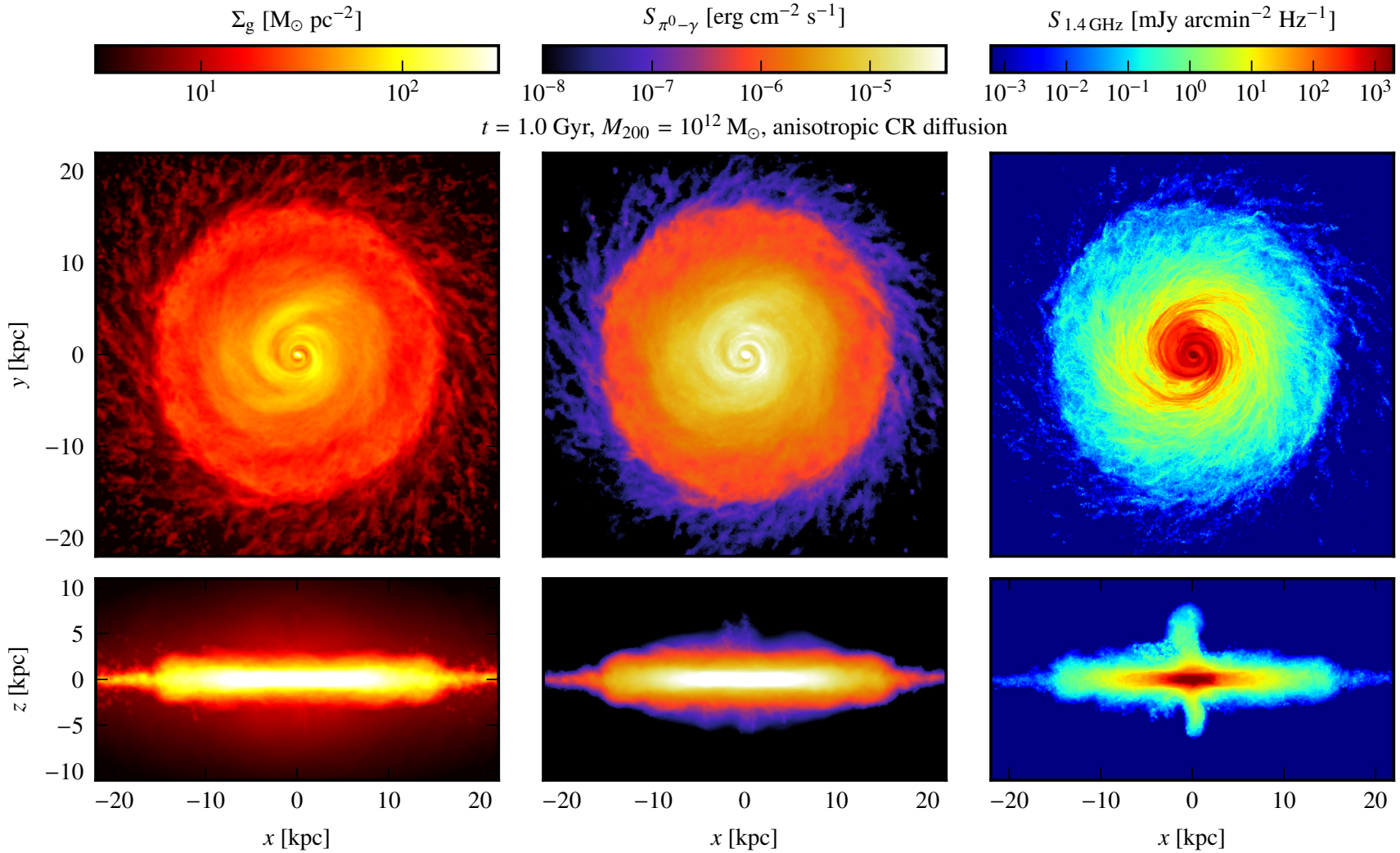
Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017b)

γ-ray and radio emission of Milky Way-like galaxy

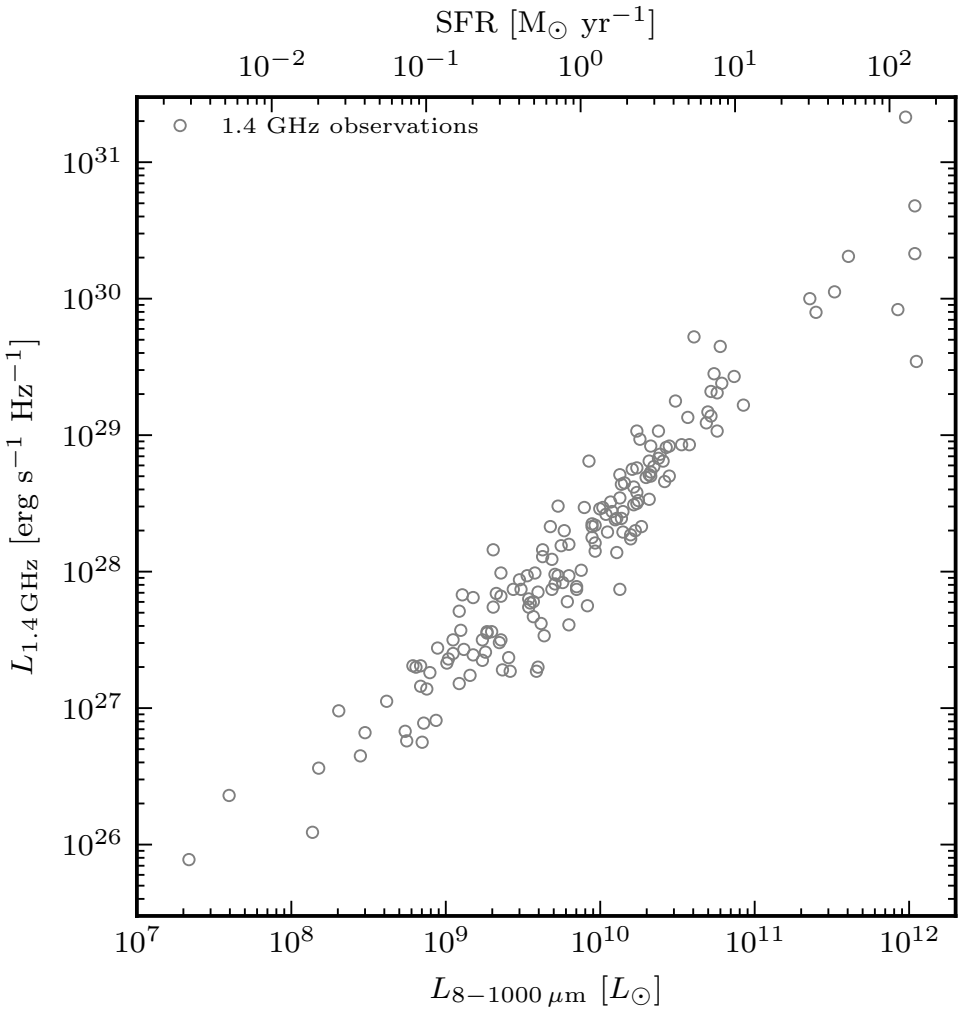


CP+ (2017b, in prep.)

AIP

Far infra-red – radio correlation

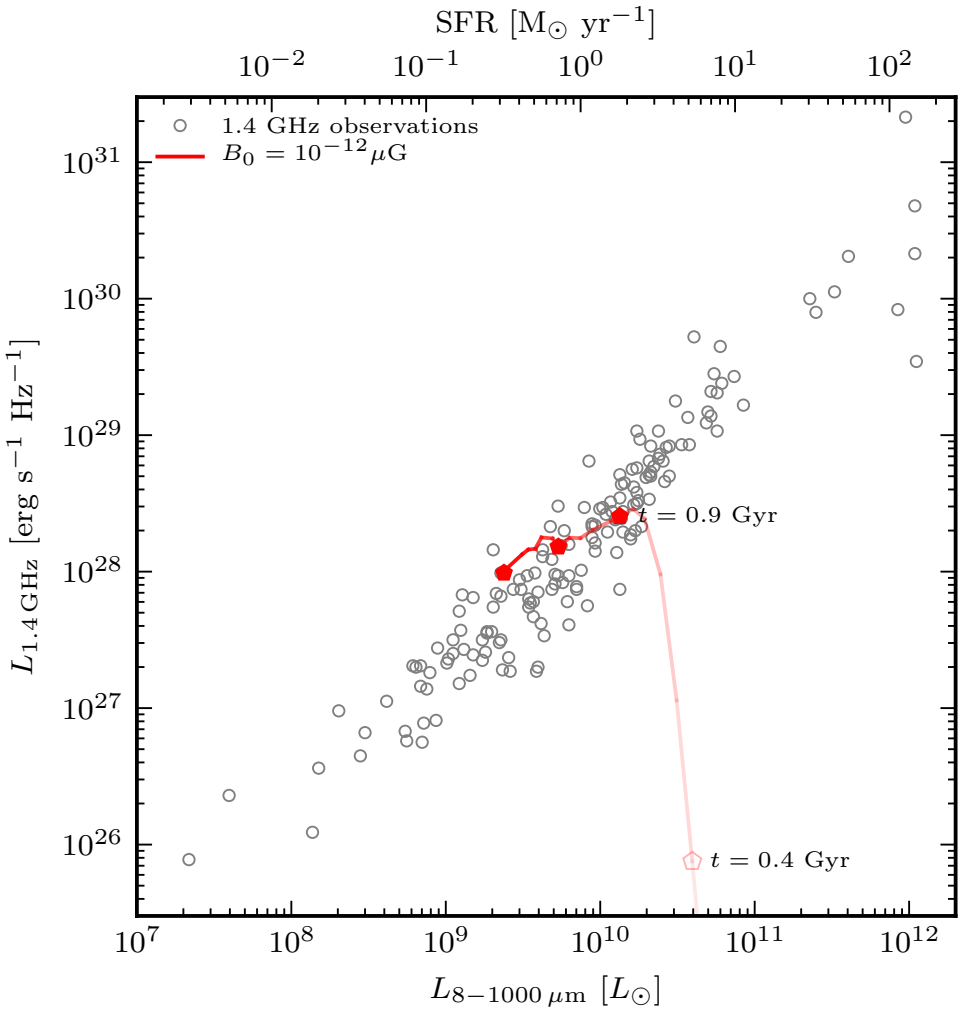
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

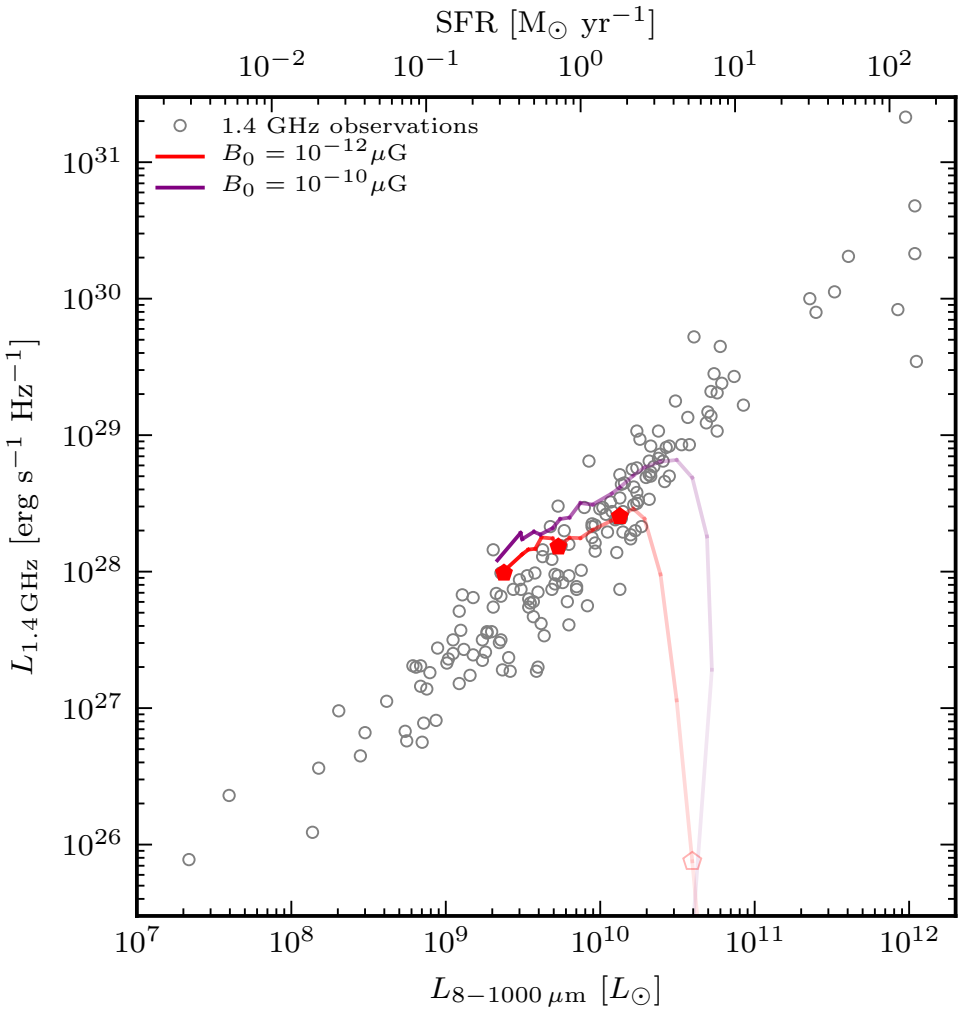
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

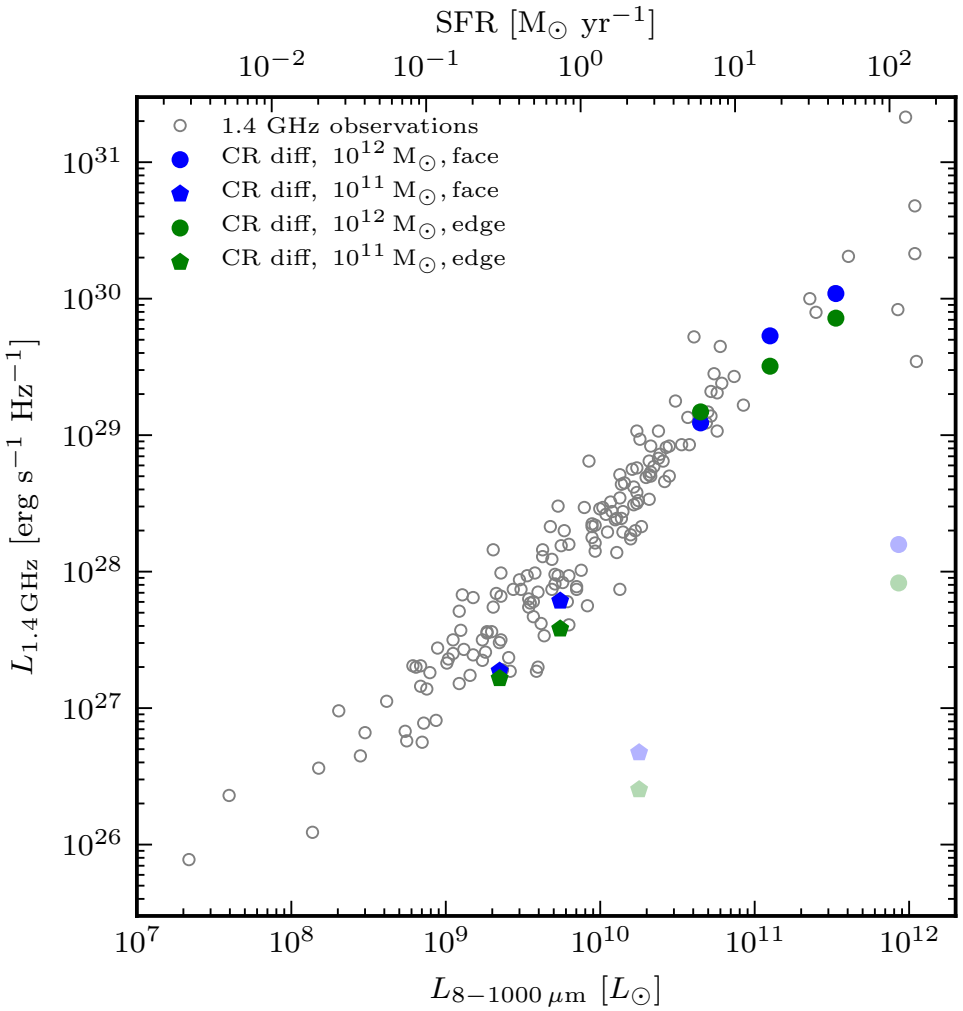
Universal conversion: star formation → cosmic rays → radio



Bell (2003)

Far infra-red – radio correlation

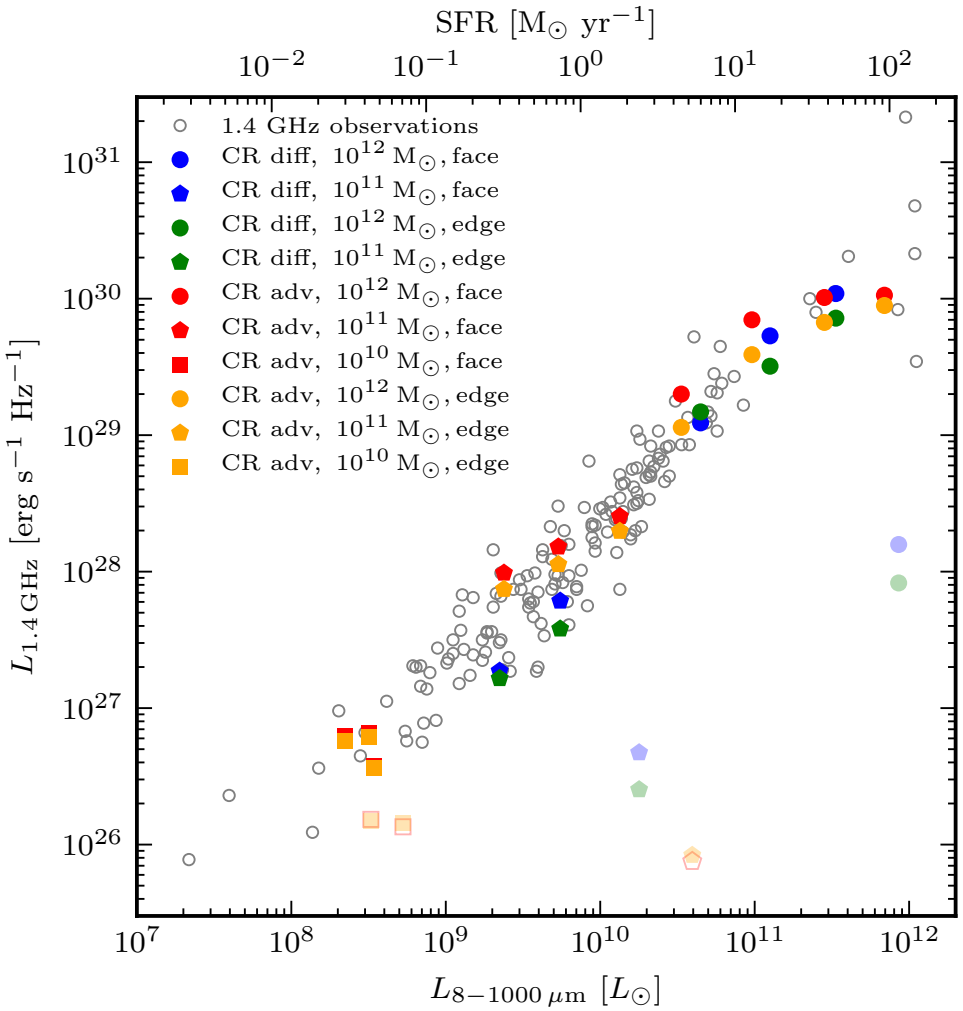
Universal conversion: star formation → cosmic rays → radio



CP+ (in prep.)

Far infra-red – radio correlation

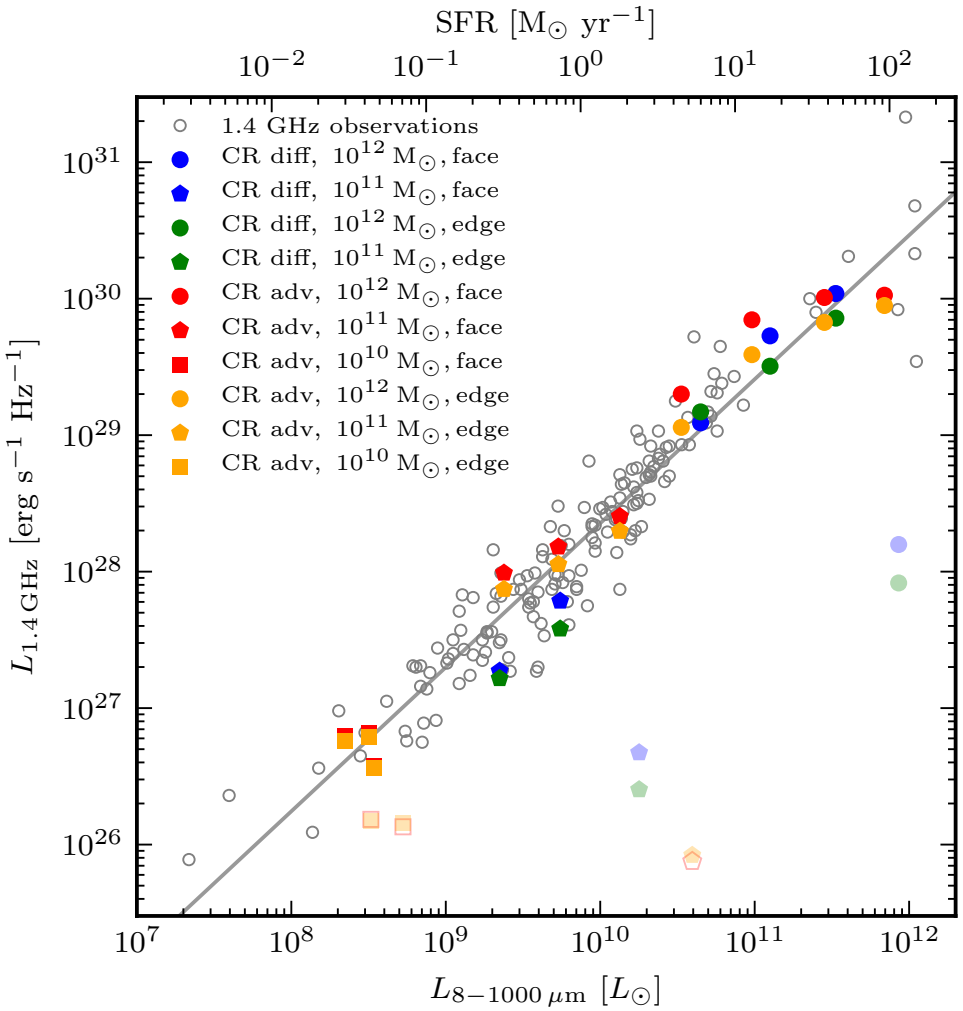
Universal conversion: star formation → cosmic rays → radio



CP+ (in prep.)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



CP+ (in prep.)

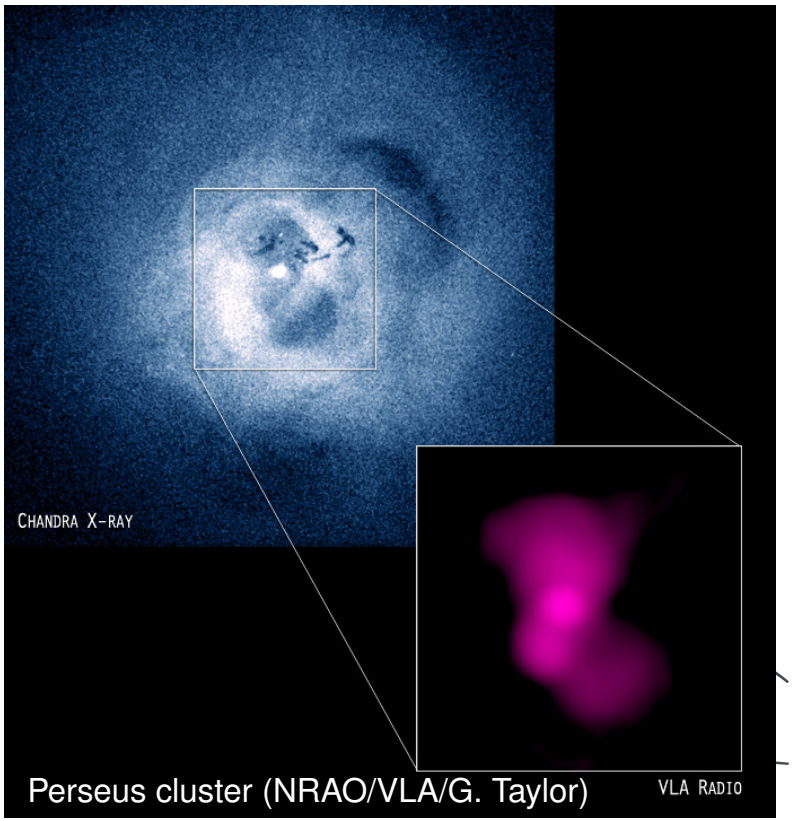
Outline

1. Introduction
   - Puzzles in galaxy formation
   - Particle acceleration
   - Cosmic rays
2. Galaxy formation
   - Modelling physics in galaxies
   - Supernova explosions
   - Galaxy simulations
3. Galaxy cluster evolution
   - Steady state models
   - AGN jet simulations
   - Conclusions



Feedback by active galactic nuclei

Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

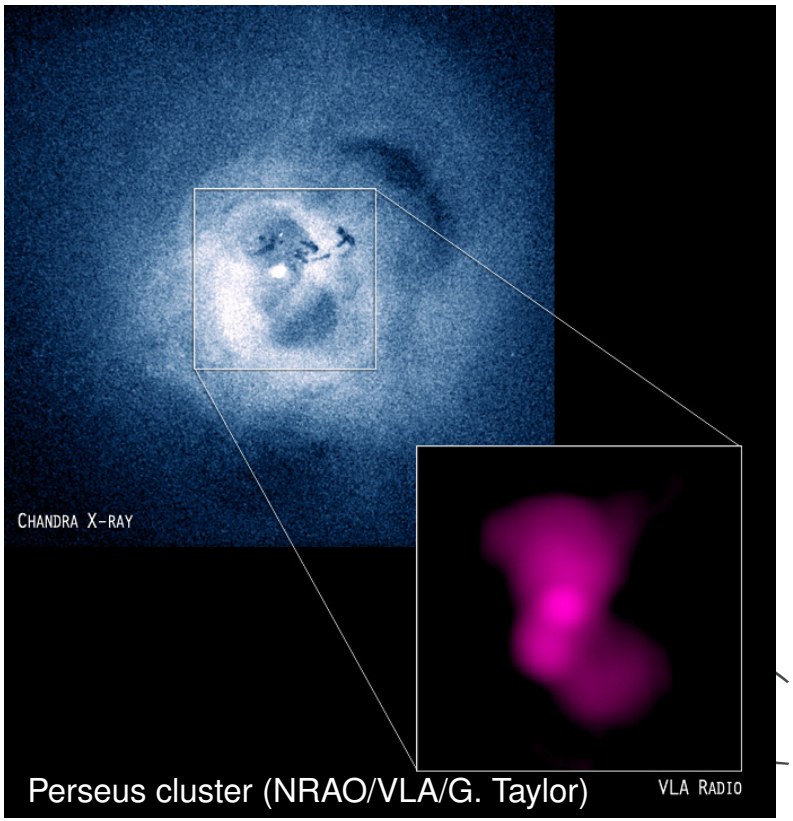


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling

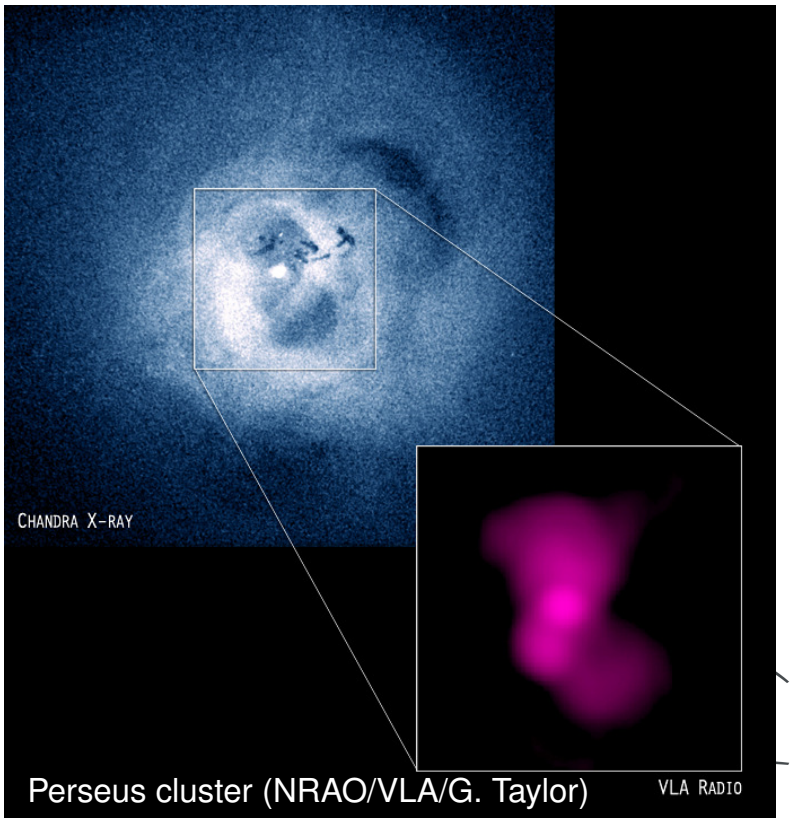


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling
- jet interaction with magnetized cluster medium $\rightarrow$ turbulence
- jet accelerates cosmic rays $\rightarrow$ release from bubbles provides source of heat

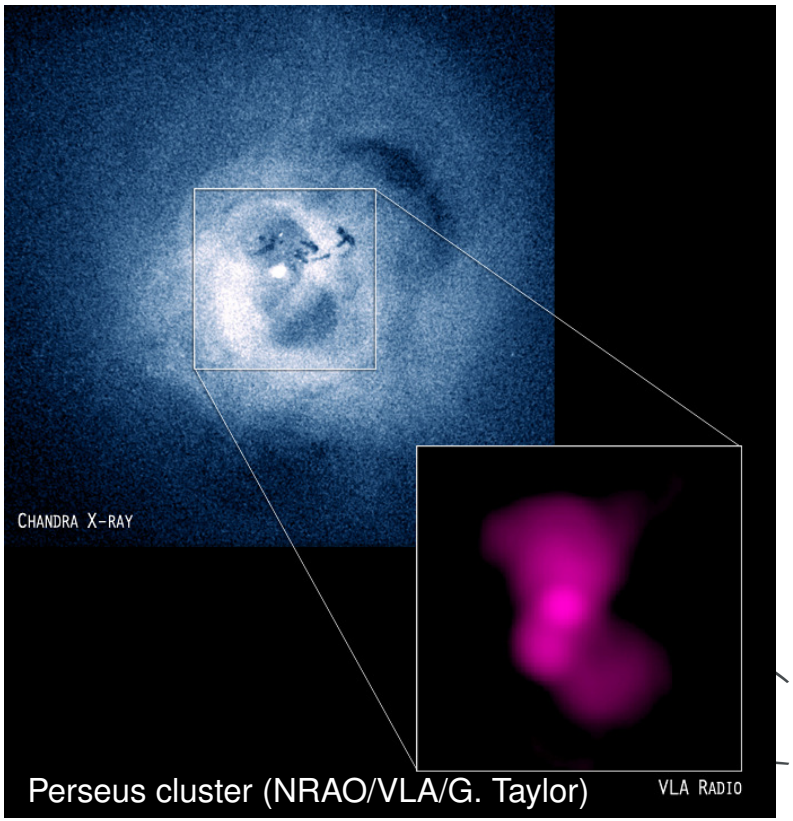


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

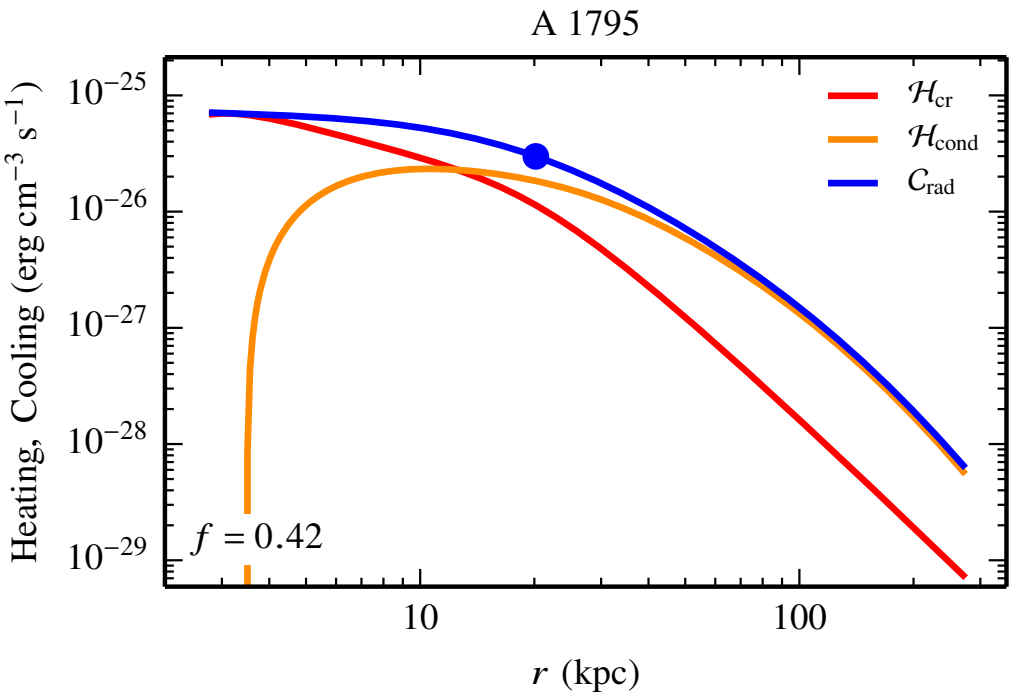
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

- Jacob & CP (2017a,b): study large sample of 40 cool core clusters
- spherically symmetric steady-state solutions where cosmic ray heating balances radiative cooling



Perseus cluster (NRAO/VLA/G. Taylor)

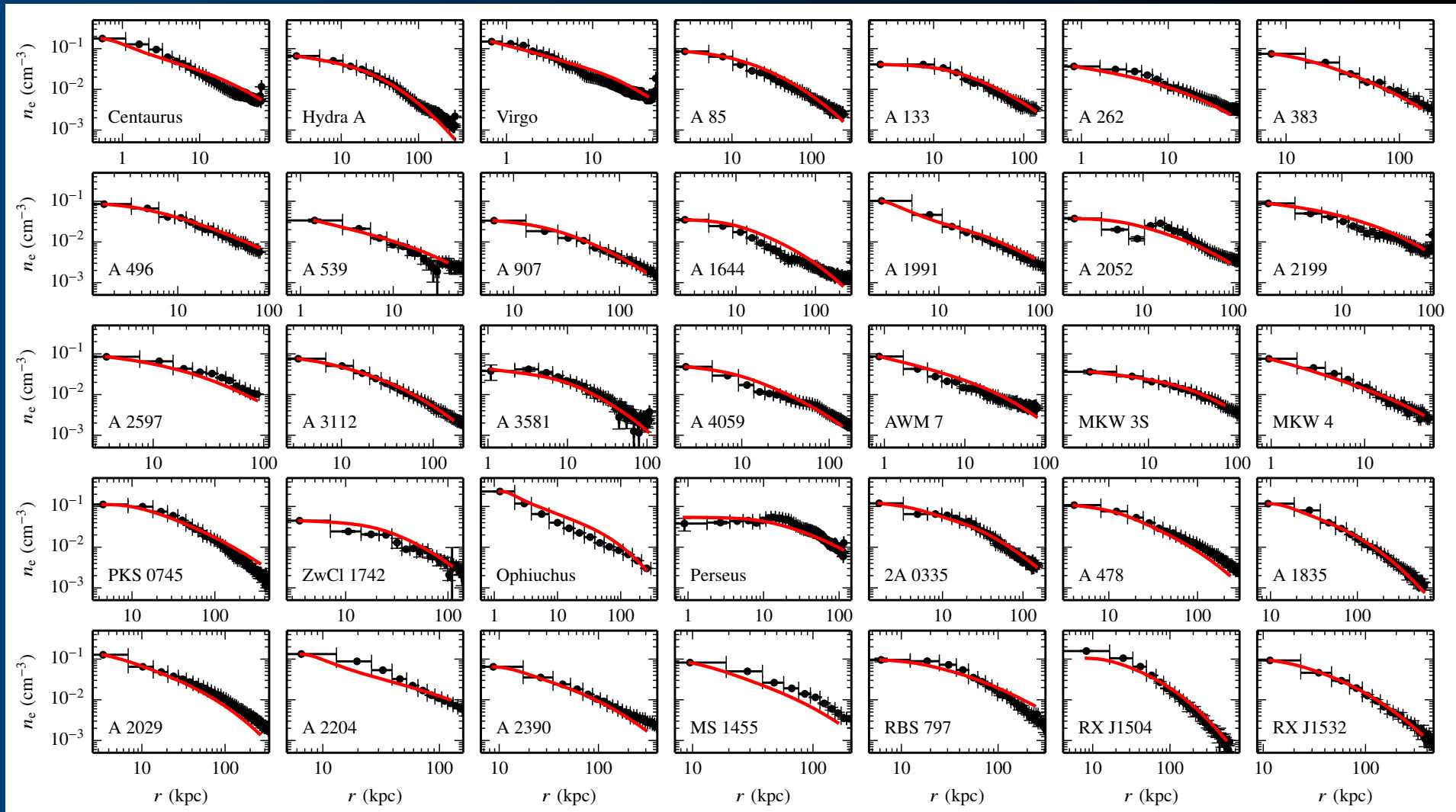
Case study A1795: heating and cooling



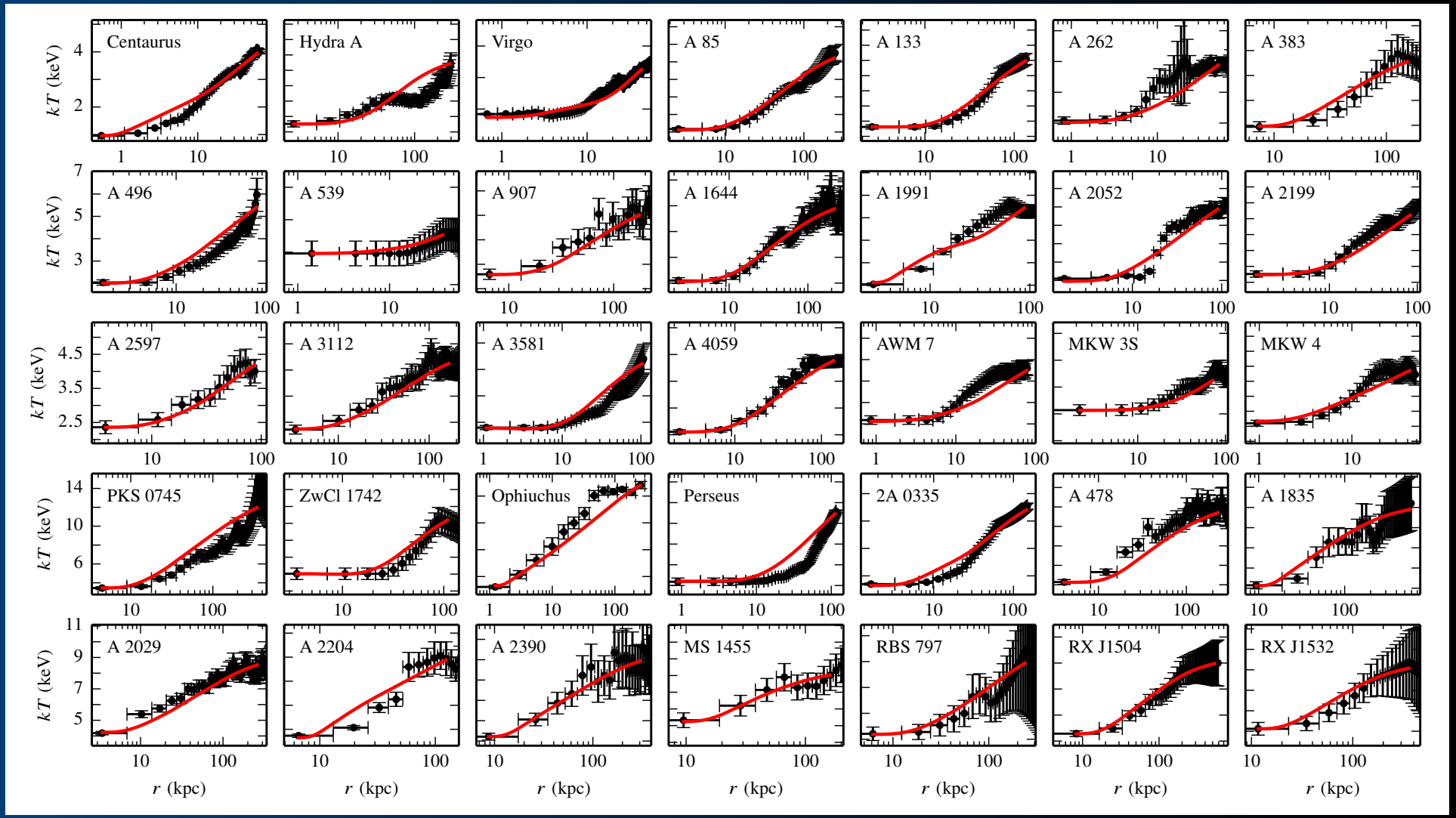
Jacob & CP (2016a)

- CR heating dominates in the center
- conductive heating takes over at larger radii, $\kappa = 0.42\kappa_{\rm Sp}$
- $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm cond} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of $1\,{\rm M}_\odot\,{\rm yr}^{-1}$

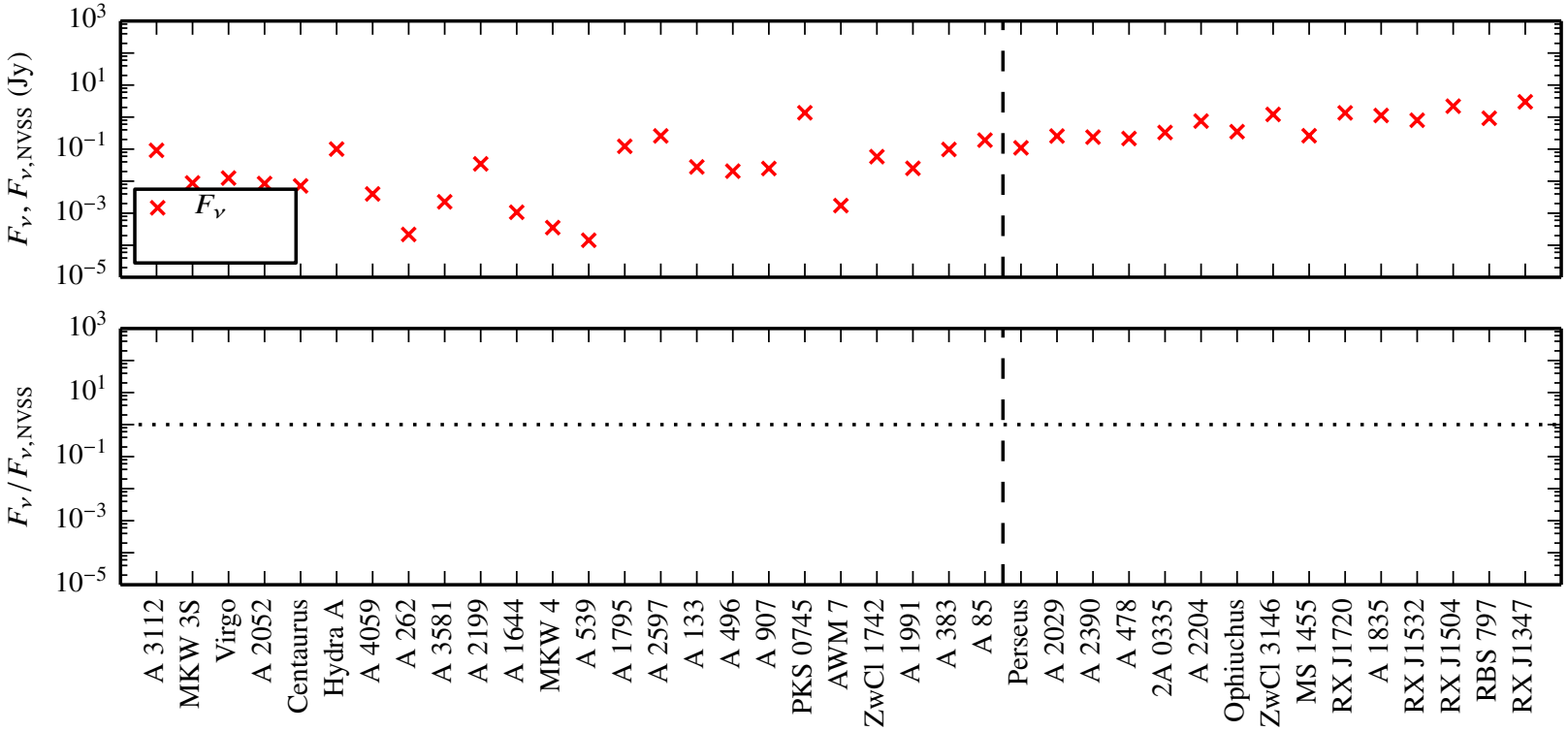
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

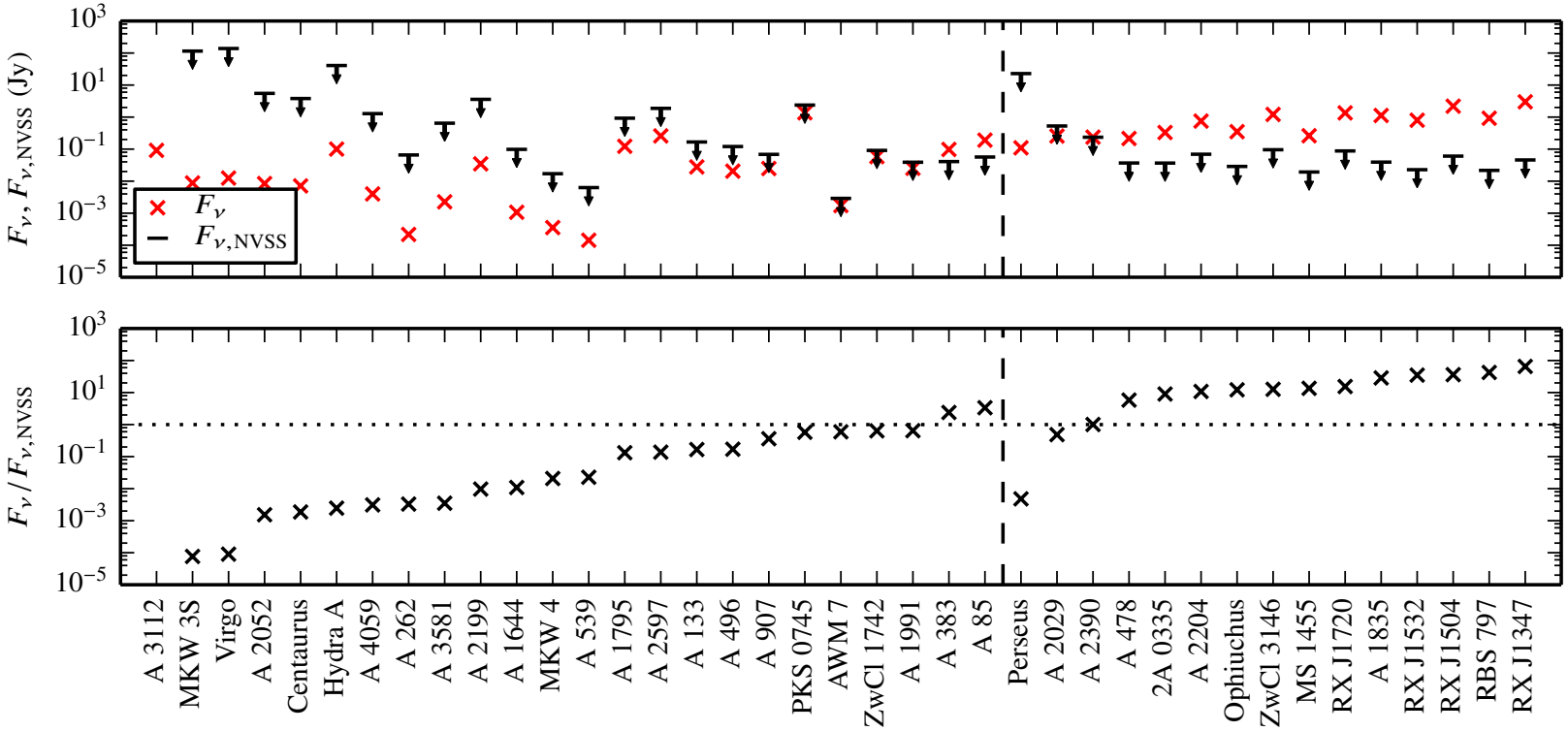


Hadronically induced radio emission



Jacob & CP (2017b)

Hadronically induced radio emission: NVSS limits



Jacob & CP (2017b)

- continuous sequence in $F_{\nu,\mathrm{pred}}/F_{\nu,\mathrm{NVSS}}$
- CR heating viable solution for non-RMH clusters
- CR heating solution ruled out in radio mini halos (RMHs)

AIP

How can we explain these results?

- self-regulated feedback cycle driven by CRs

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

↘

radio mini halo

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

↘

radio mini halo

↓

cluster cools and triggers AGN activity

←

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

↘

radio mini halo

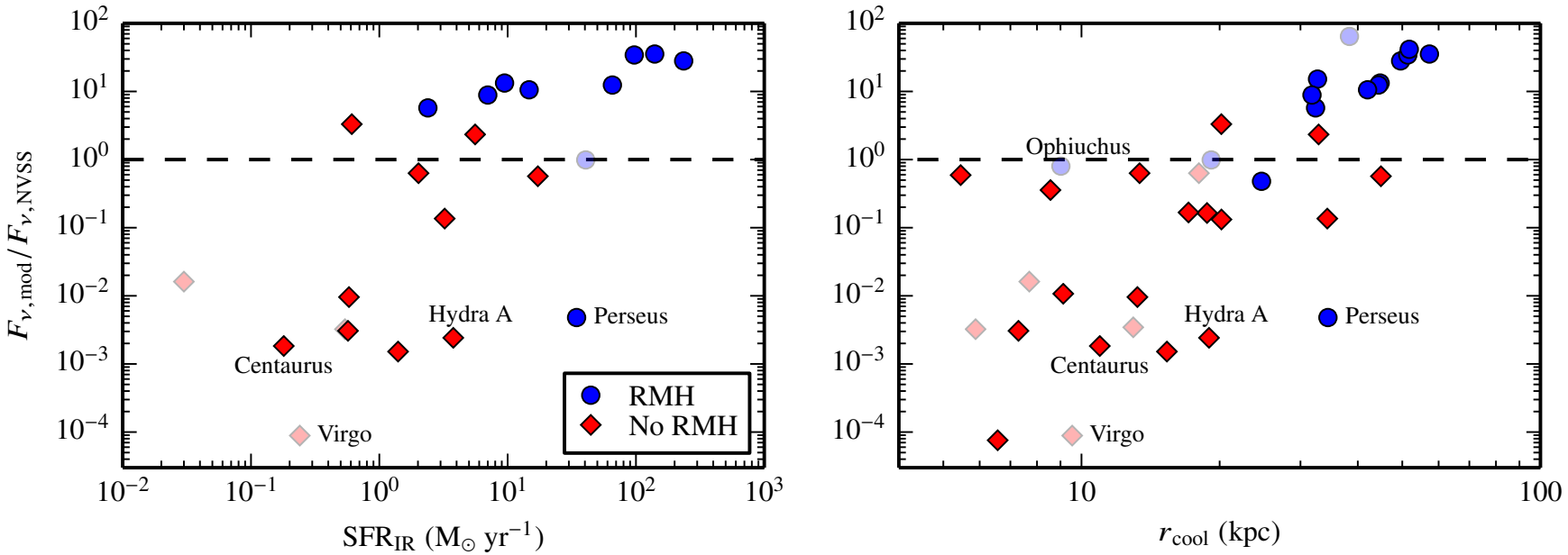
↓

cluster cools and triggers AGN activity

↑

AIP

Self-regulated heating/cooling cycle in cool cores

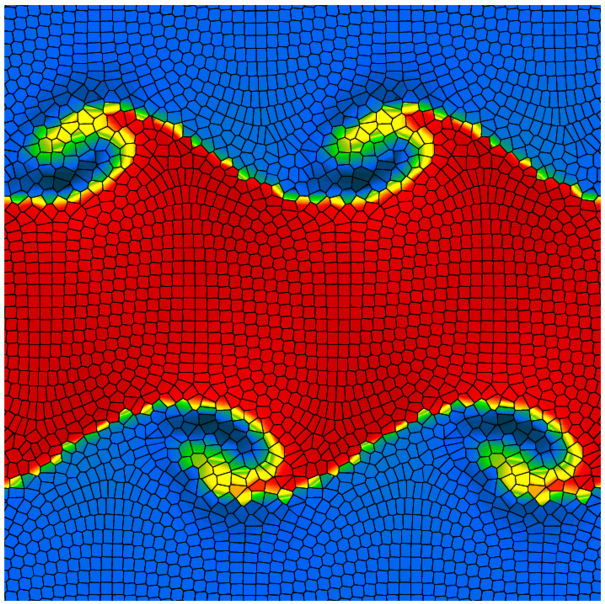


Jacob & CP (2017b)

possibly CR-heated cool cores vs. radio mini halo clusters:

- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance

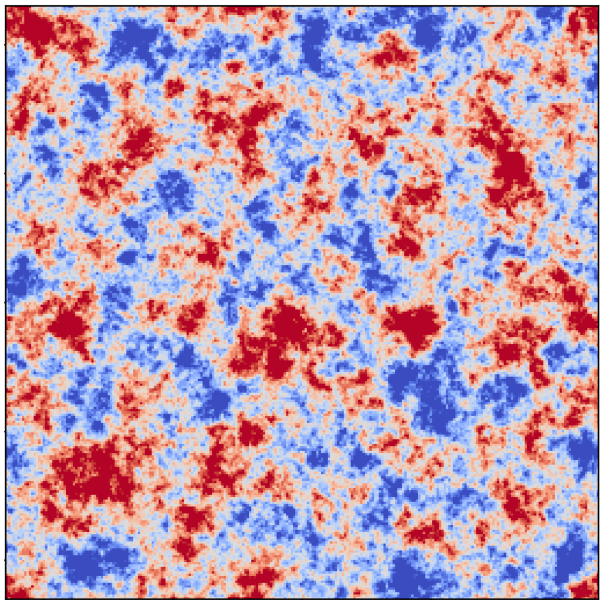
MHD jet simulations



AREPO: unstructured-mesh

- MHD moving-mesh code AREPO
- NFW cluster potential

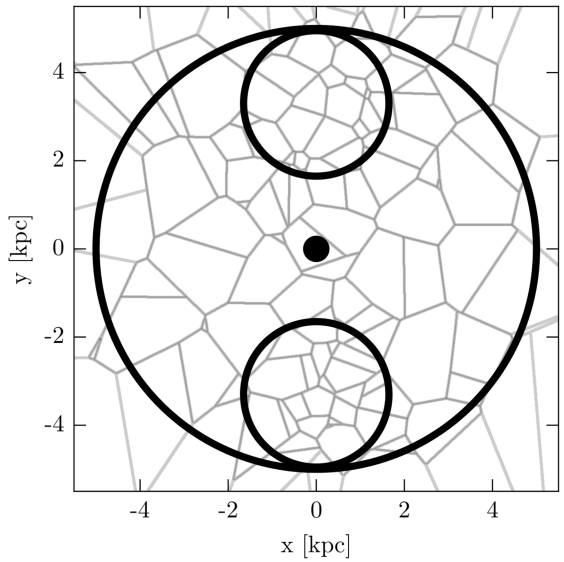
MHD jet simulations



initial magnetic field

- MHD moving-mesh code AREPO
- NFW cluster potential
- external turbulent magnetic field (Kolmogorov)

MHD jet simulations



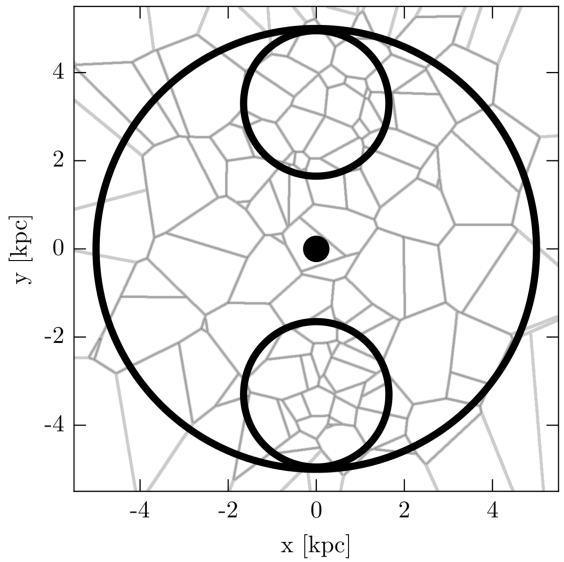
AREPO: jet injection region

(Weinberger+ 2017)

- MHD moving-mesh code AREPO
- NFW cluster potential
- external turbulent magnetic field (Kolmogorov)
- jet module
  - prepare low-density state in pressure equilibrium
  - inject kinetic energy, ***B***, and CRs
  - refine to sustain density contrast

AIP

Cosmic ray modelling

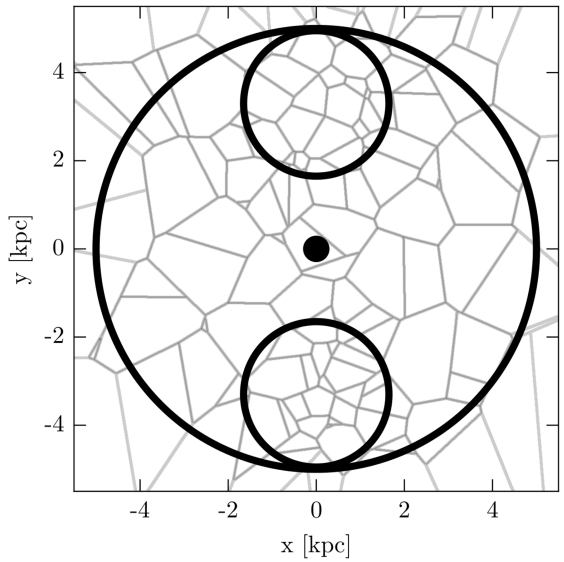


AREPO: jet injection region

(Weinberger+ 2017)

- subgrid CR acceleration:
  - reality: internal shocks
  - code: $E_{\mathrm{cr}}/E_{\mathrm{th}} \geq 0.5$

Cosmic ray modelling

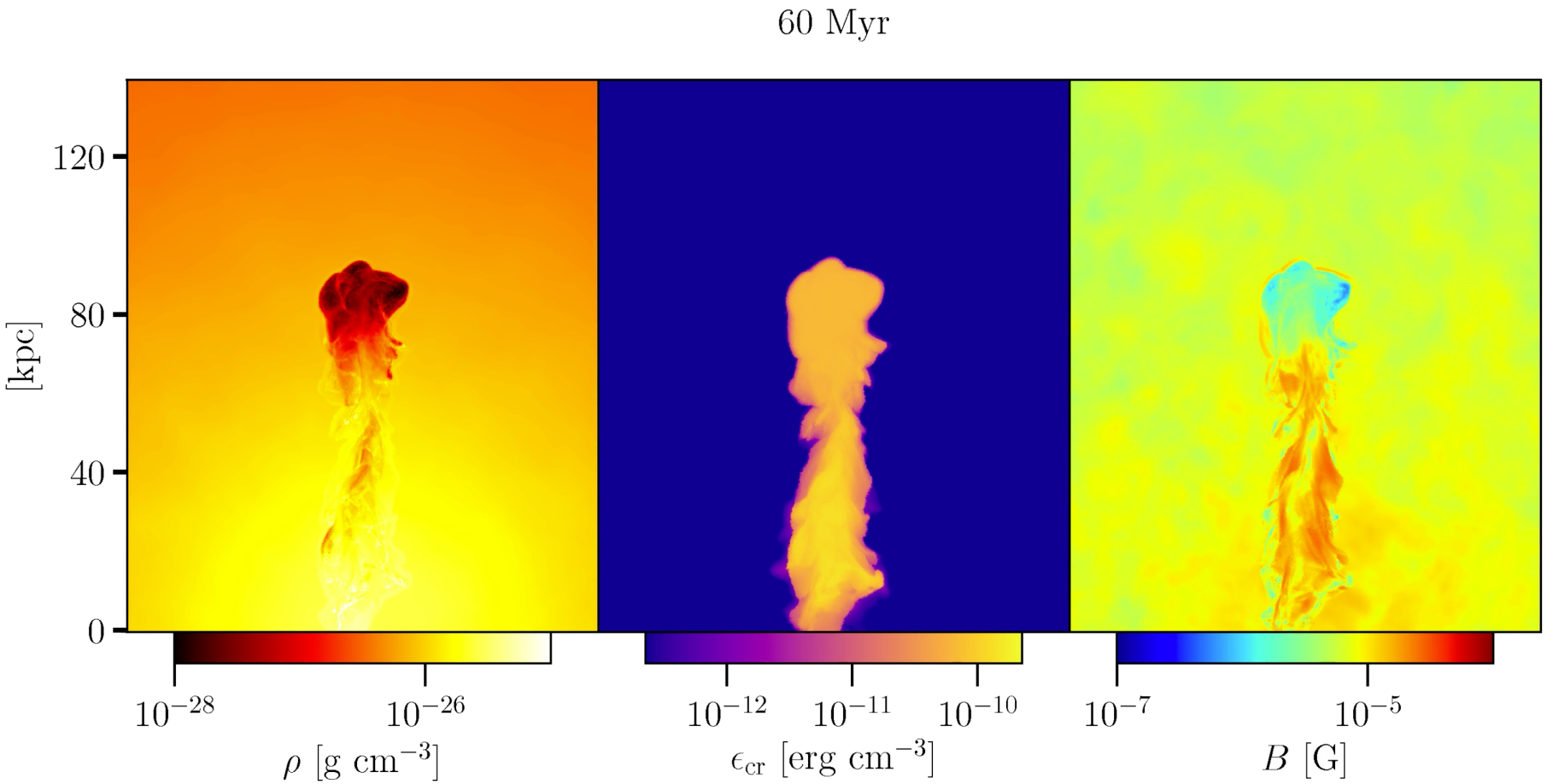


AREPO: jet injection region

(Weinberger+ 2017)

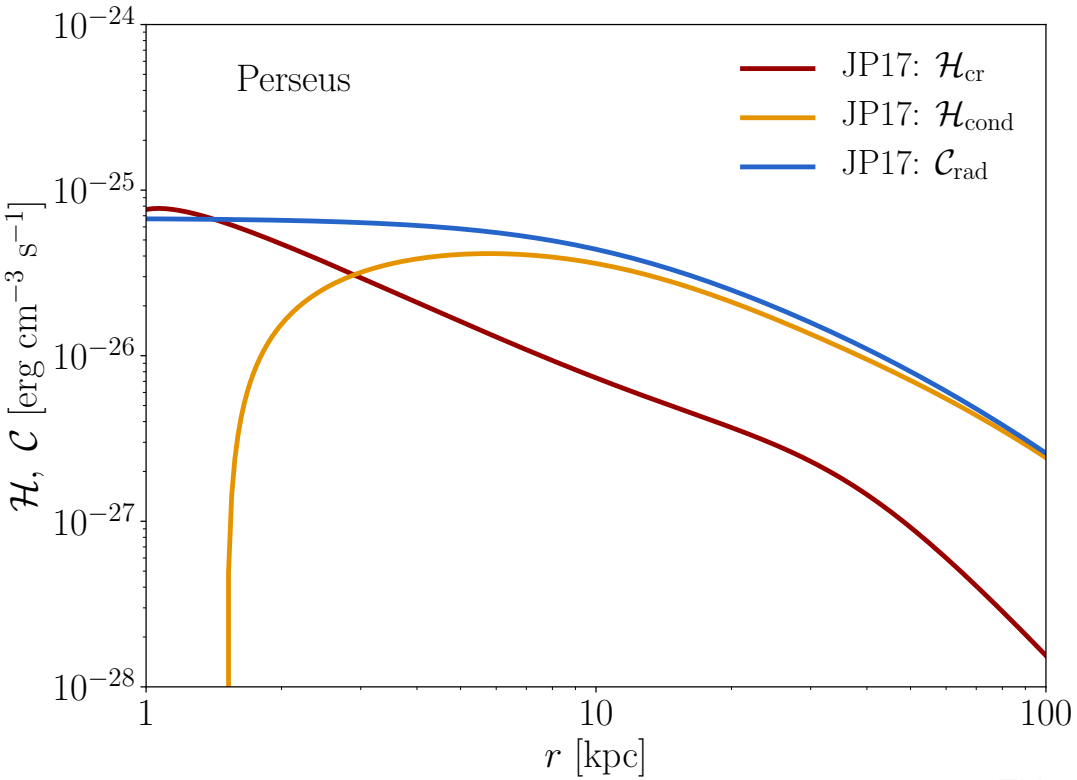
- subgrid CR acceleration:
  - reality: internal shocks
  - code: $E_{\rm cr}/E_{\rm th} \geq 0.5$
- CR transport:
  - CRs are advected
  - emulate CR streaming $\approx$ anisotropic CR diffusion & Alfvén cooling

Jet simulation: gas density, CR energy density, *B* field



Ehlert, Weinberger, CP+ (2018)

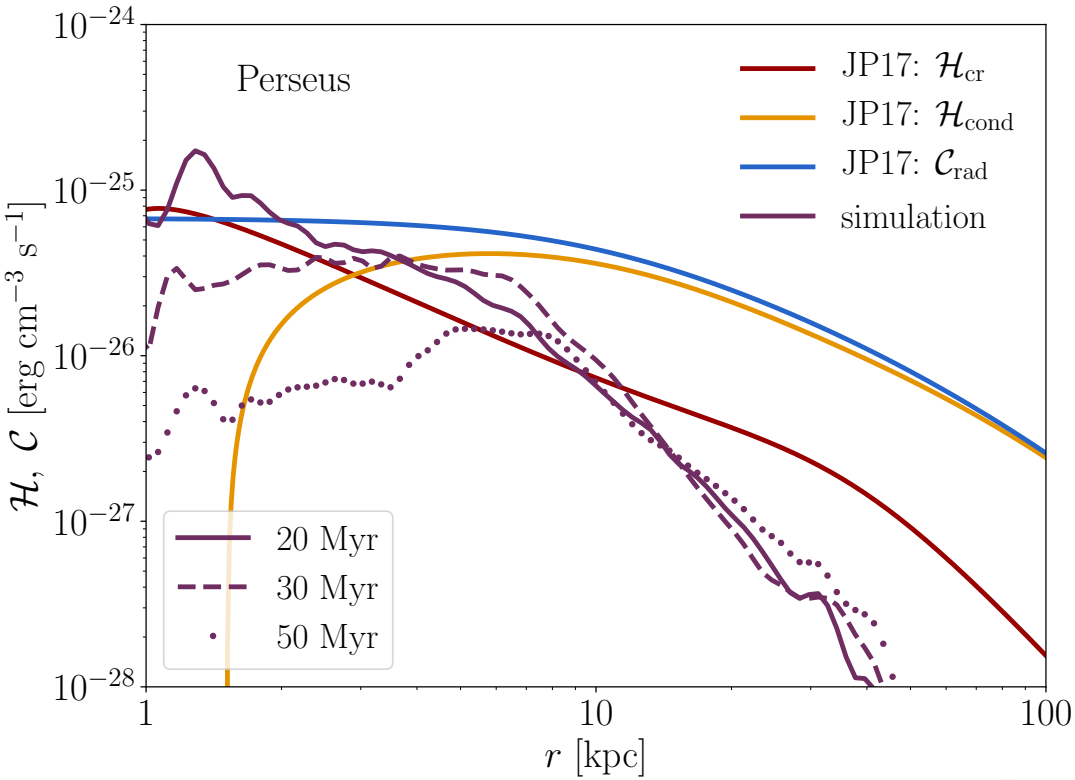
Perseus cluster – heating vs. cooling: theory



Ehlert, Weinberger, CP+ (2018)

- CR and conductive heating balance radiative cooling:
  $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

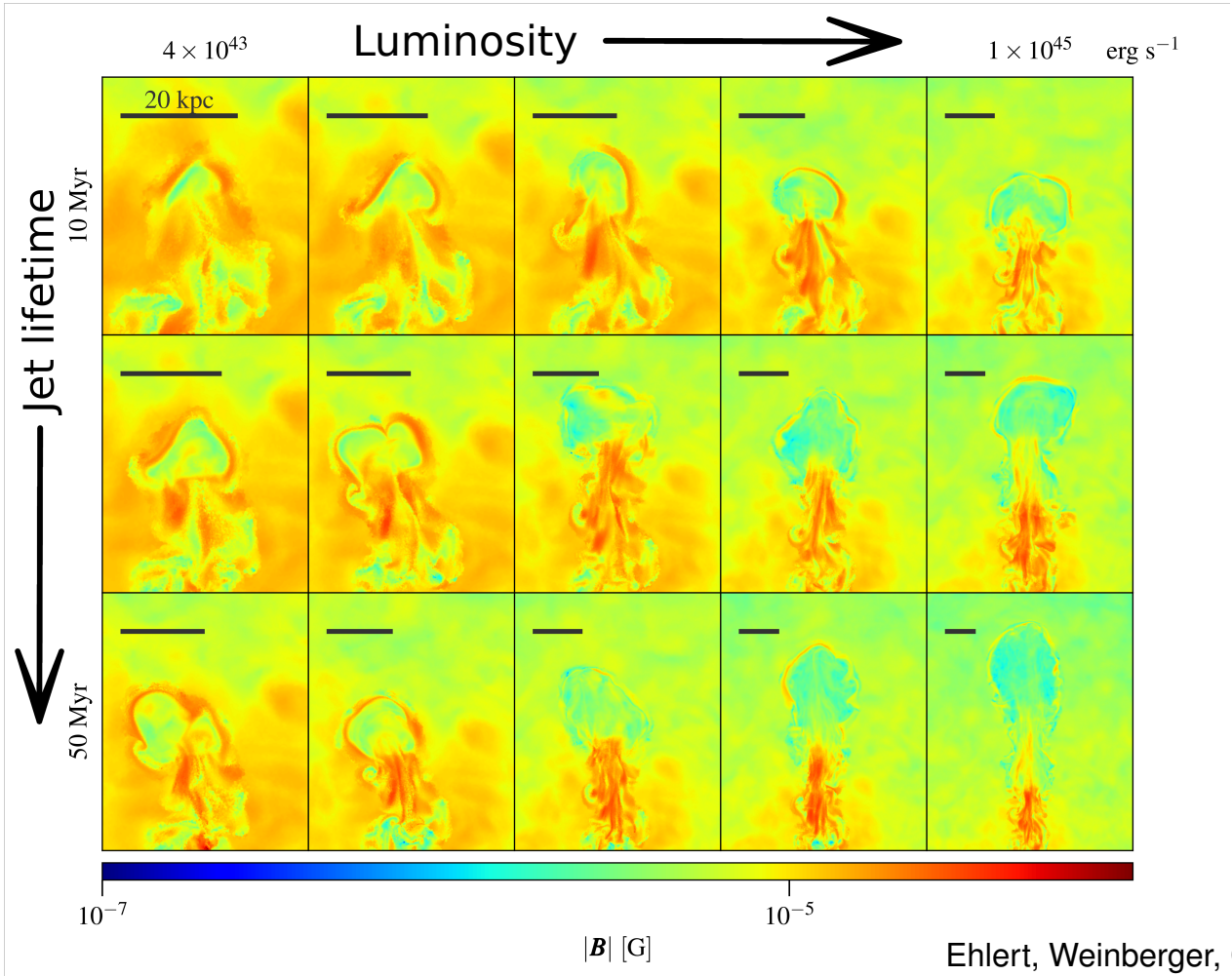
Perseus cluster – heating vs. cooling: simulations



Ehlert, Weinberger, CP+ (2018)

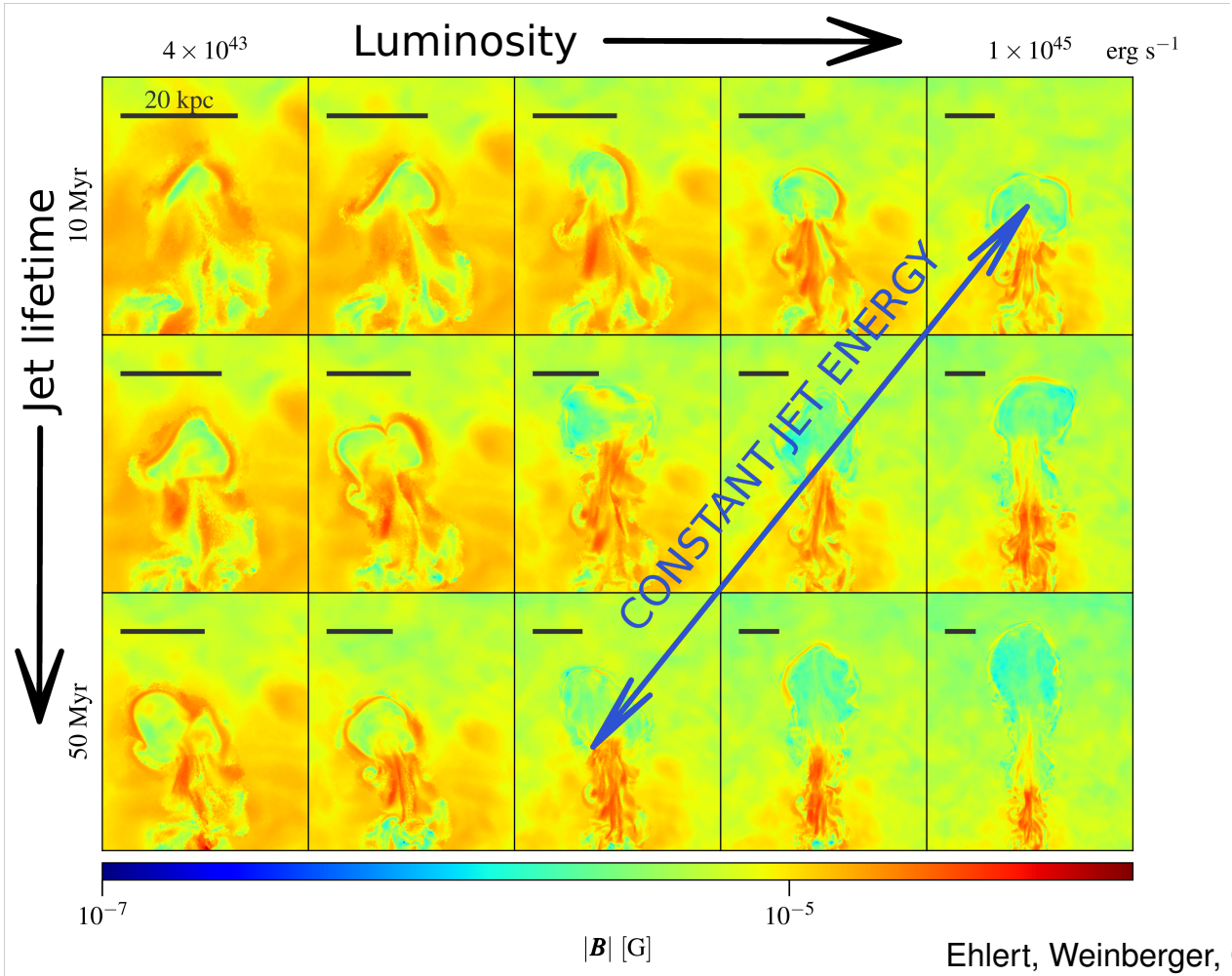
- CR and conductive heating balance radiative cooling:
  $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Magnetic field structure



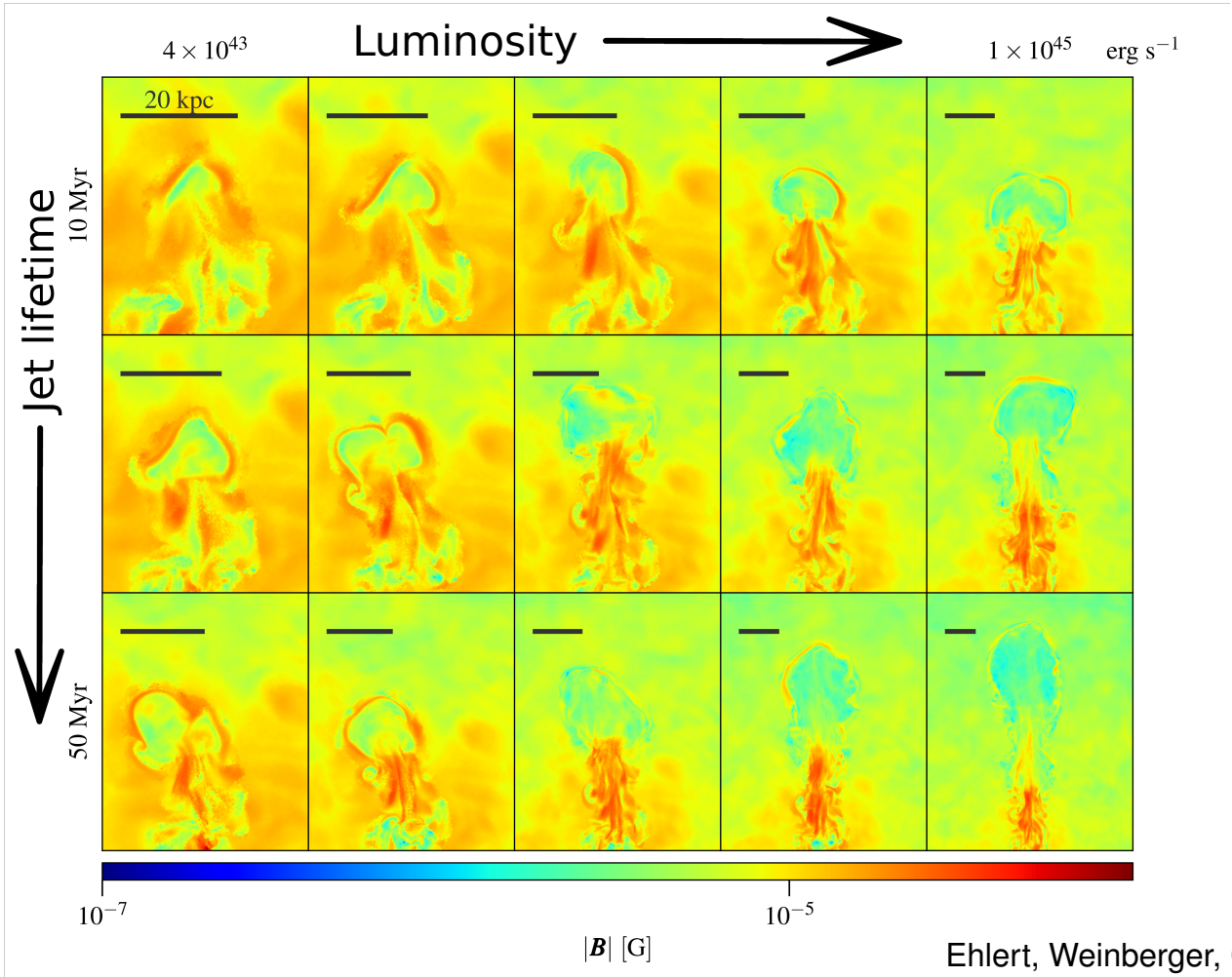
Ehlert, Weinberger, CP+ (2018)

Magnetic field structure



Ehlert, Weinberger, CP+ (2018)

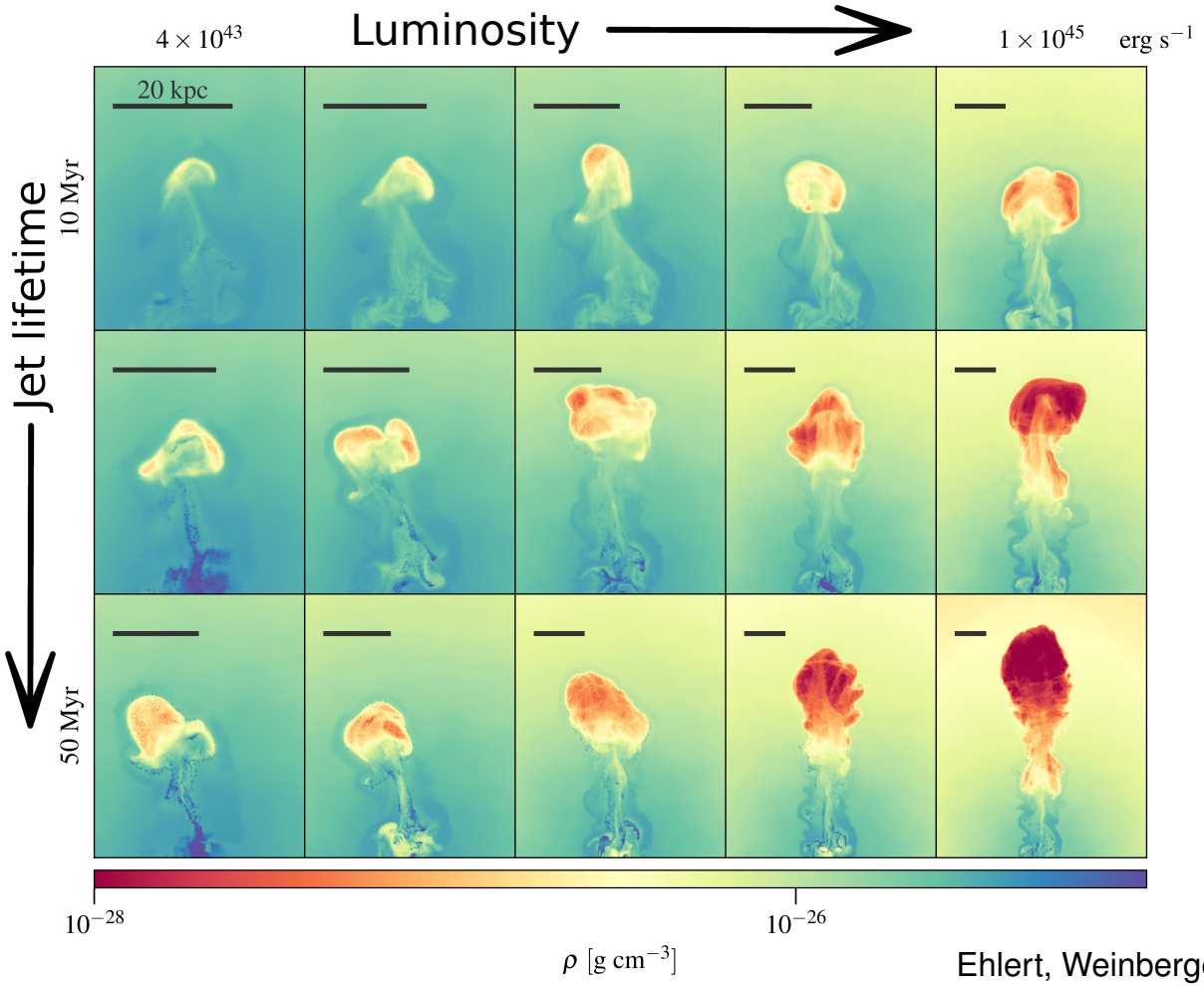
Magnetic field structure



Ehlert, Weinberger, CP+ (2018)

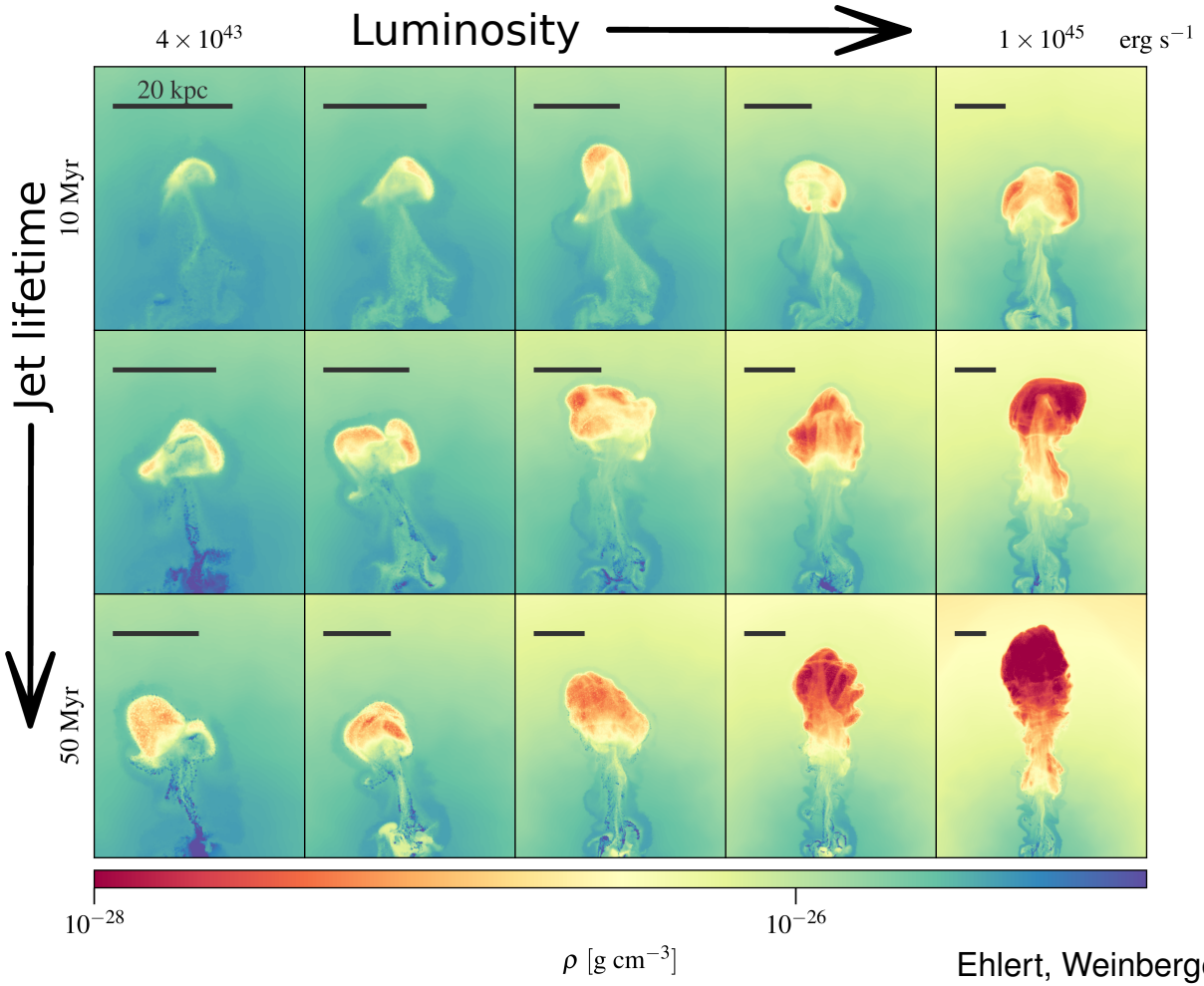
Magnetic enhancement and draping general feature

Jet morphology



Ehlert, Weinberger, CP+ (2018)

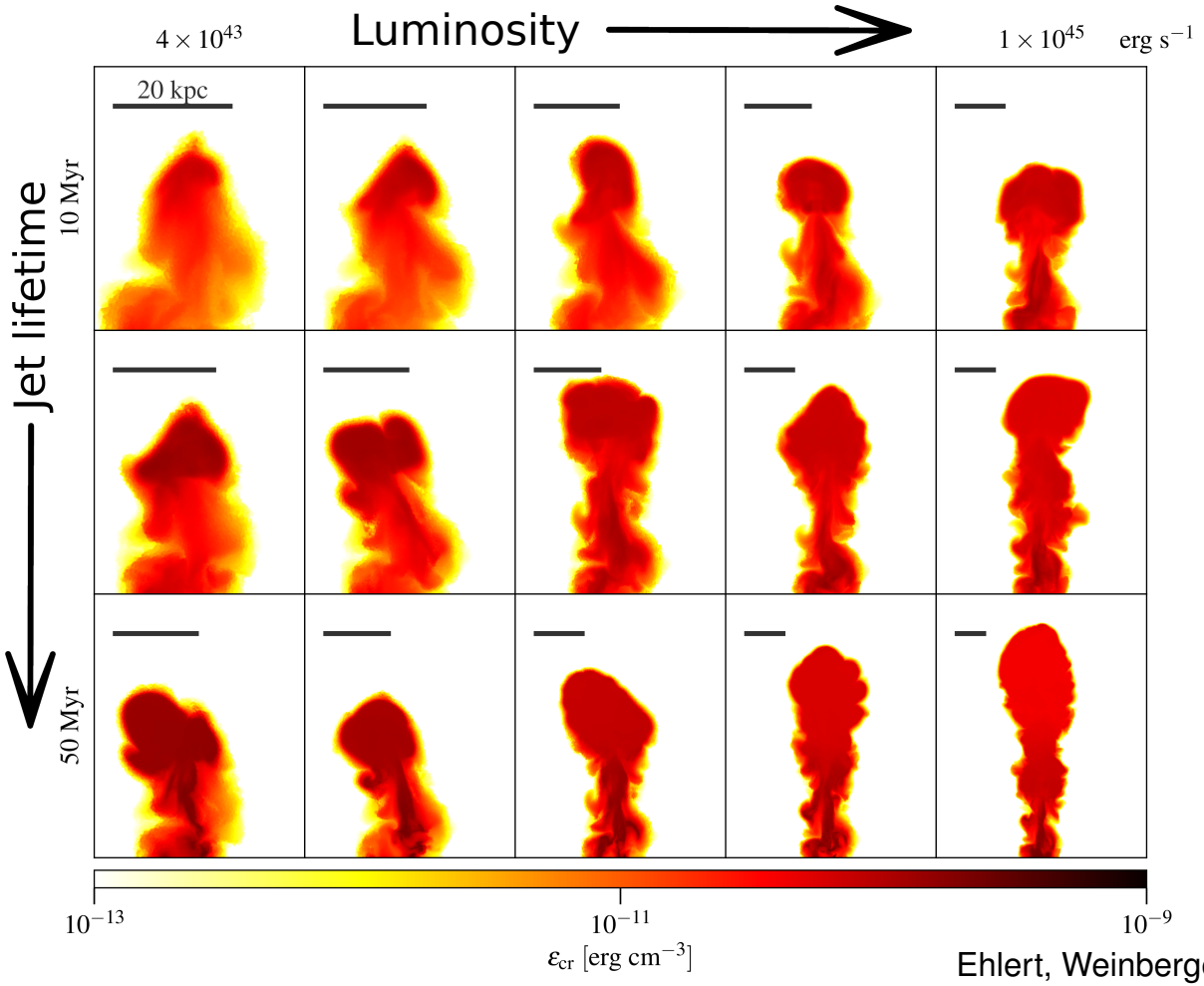
Jet morphology



Ehlert, Weinberger, CP+ (2018)

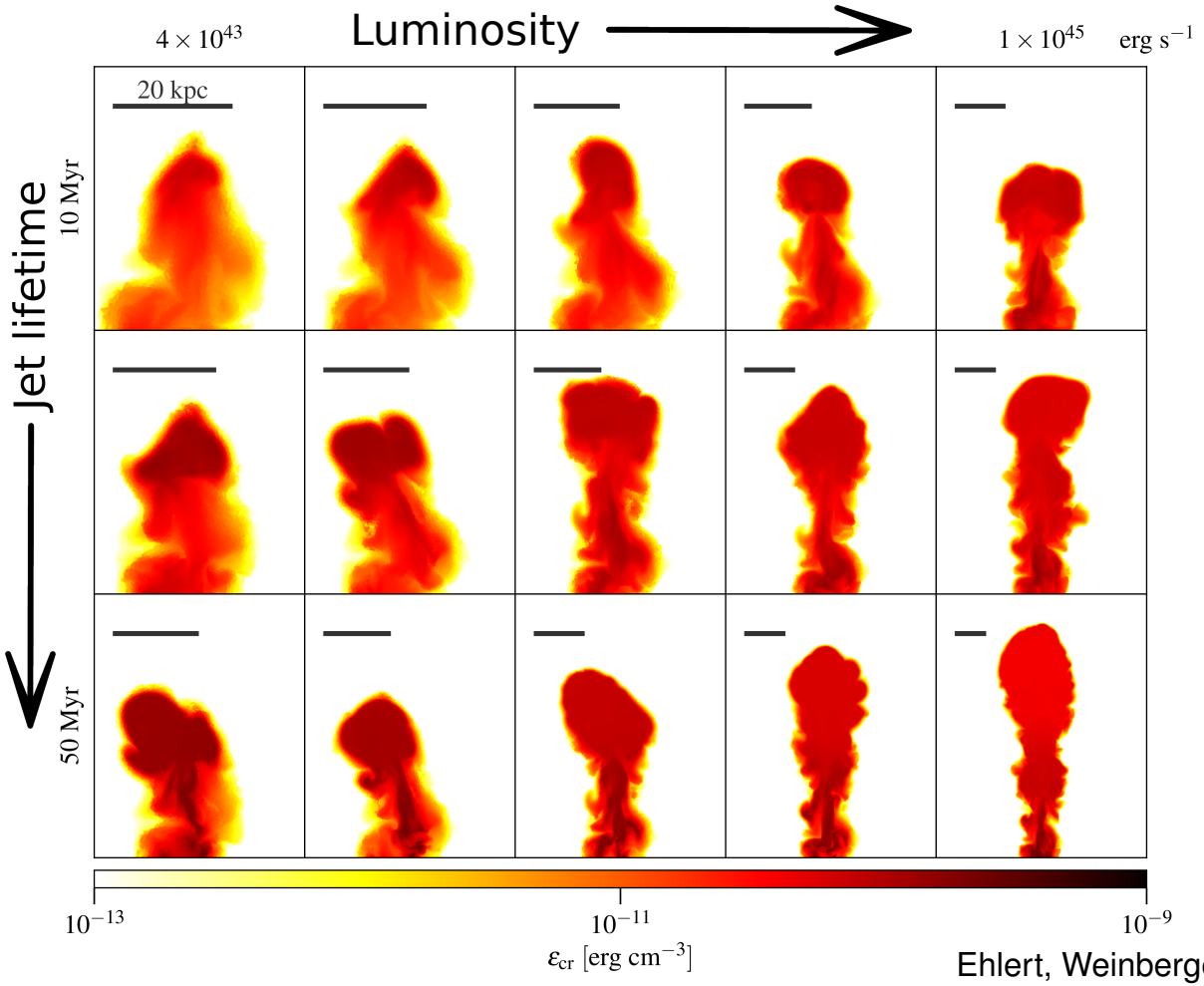
Low-energy/power jets mix more efficiently $\Rightarrow$ invisible in X-rays

CR distribution



Ehlert, Weinberger, CP+ (2018)

CR distribution



Ehlert, Weinberger, CP+ (2018)

CRs still present in low-energy/power jets

Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G



Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G
- $L_{\mathrm{FIR}} - L_{\gamma}$ and $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories
- MHD simulations of AGN jets: CR heating can solve the "cooling flow problem" in galaxy clusters



Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G
- $L_{\mathrm{FIR}} - L_{\gamma}$ and $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories
- MHD simulations of AGN jets: CR heating can solve the "cooling flow problem" in galaxy clusters

outlook: improved modeling of plasma physics, follow CR spectra, cosmological settings

need: comparison to resolved radio/γ-ray observations $\rightarrow$ **SKA/CTA**

AIP

CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtioN



This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No CRAGSMAN–646955).

Literature for the talk – 1

Cosmic ray acceleration and transport:

- Thomas, Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2018.
- Pais, Pfrommer, Ehlert, *Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants,* 2018b.
- Pais, Pfrommer, Ehlert, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics,* 2018a, MNRAS.

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, MNRAS.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.
- Jacob, Pakmor, Simpson, Springel, Pfrommer, *The dependence of cosmic ray driven galactic winds on halo mass,* 2018, MNRAS.

AIP

Literature for the talk – 2

Cosmic ray feedback in galaxy clusters:

- Ehlert, Weinberger, Pfrommer, Pakmor, Springel, *Simulations of the dynamics of magnetised jets and cosmic rays in galaxy clusters,* 2018.

Non-thermal radio and gamma-ray emission in galaxies:

- Pfrommer, Pakmor, Simpson, Springel, *Simulating Gamma-ray Emission in Star-forming Galaxies,* 2017b, ApJL.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating Radio Synchrotron Emission in Galaxies: the Origin of the Far Infrared–Radio Correlation,* in prep.

