Cosmic Rays in Galaxy Formation: Acceleration, Transport, and Feedback

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in collaboration with

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Astrolunch, Hebrew University, Jerusalem, Aug 2021

Outline

1. Introduction
   - Puzzles in galaxy formation
   - Galaxy formation paradigm
   - Cosmic ray acceleration
2. Cosmic ray transport
   - Wave-particle interactions
   - CR hydrodynamics
   - Radio harps
3. Supernovae and galaxy formation
   - Supernovae
   - Isolated galaxies
   - Cosmological galaxies

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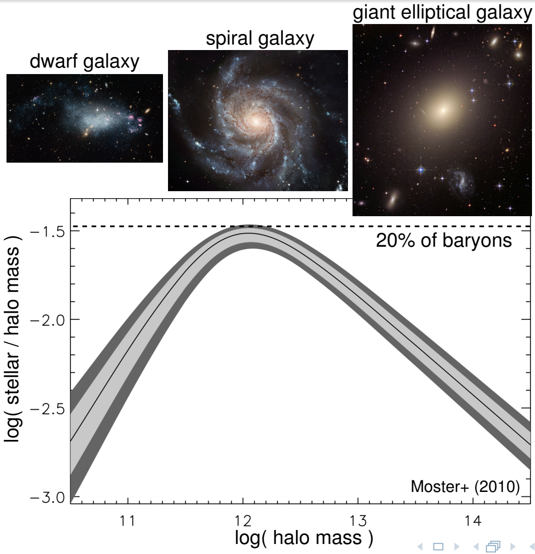
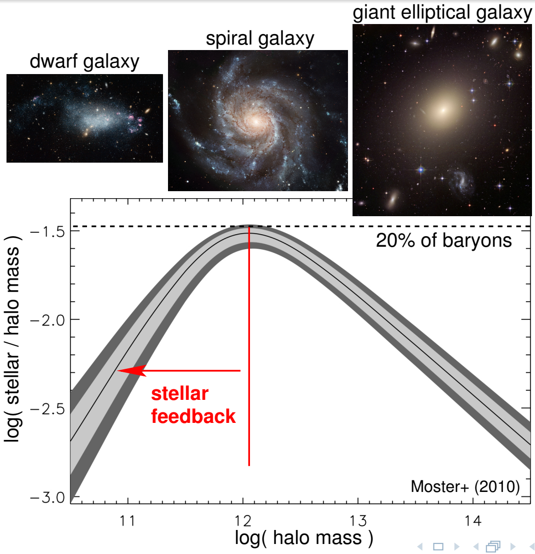
Puzzles in galaxy formation

Puzzles in galaxy formation



Puzzles in galaxy formation



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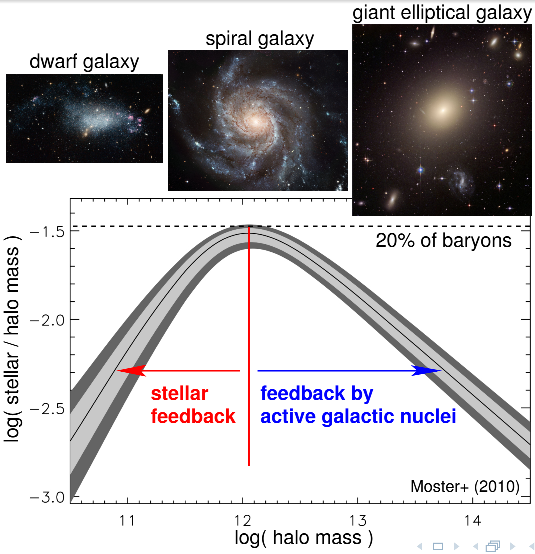
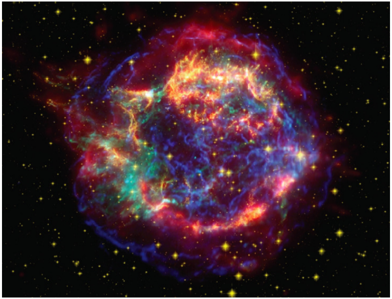


Feedback by galactic winds



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

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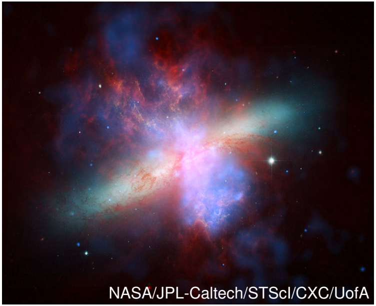
- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star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

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?
- pressure of cosmic rays (CRs) that are accelerated at supernova shocks?

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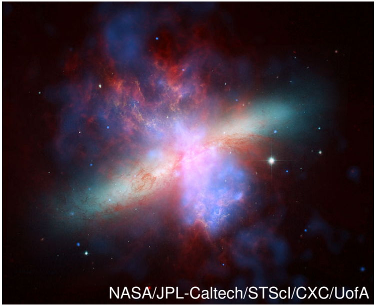

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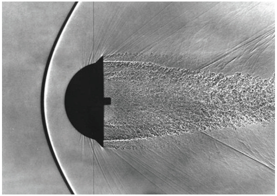
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

Shock waves

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

thickness $\sim$ mean free path $\lambda_{\rm mfp}$

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



slide concept Spitkovsky

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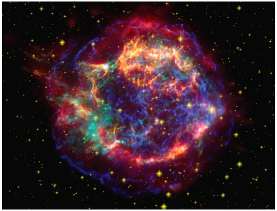

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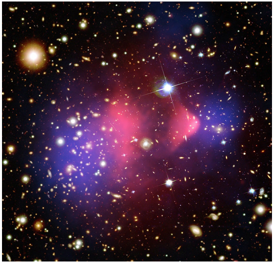


clusters/galaxies, Coulomb collisions set λ_{mfp}:
$\lambda_{\mathrm{mfp}} \sim L_{\mathrm{cluster}}/10,\qquad \lambda_{\mathrm{mfp}} \sim L_{\mathrm{SNR}}$

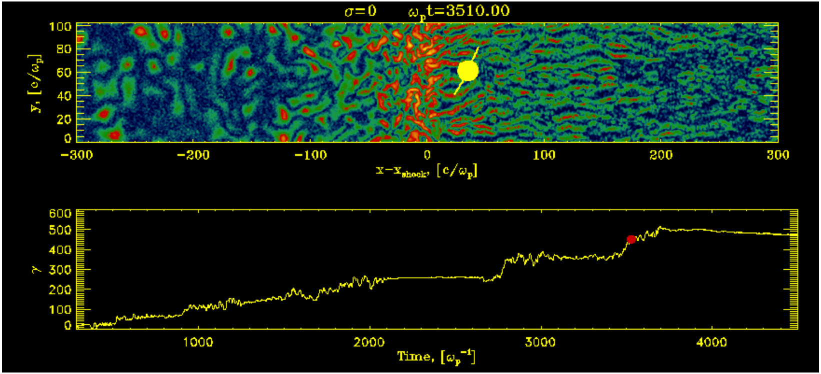
Mean free path $\gg$ observed shock width!

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

slide concept Spitkovsky

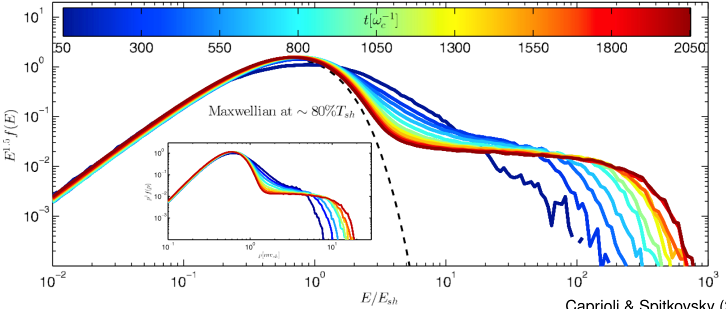
Particle acceleration at relativistic shock, $B_0 = 0$

- 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

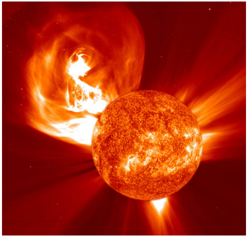
Non-relativistic parallel shock in long-term hybrid simulation



Caprioli & Spitkovsky (2014)

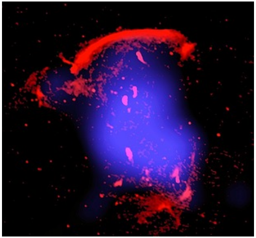
- quasi-parallel shocks accelerate ions
- particles gain energy in each crossing and have probability of leaving the Fermi cycle by being swept downstream $\rightarrow$ power-law spectrum
- maximum energy increases with time

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)

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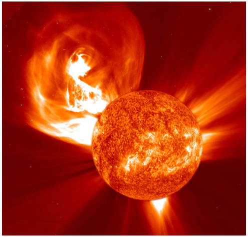
Astrophysical shocks

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



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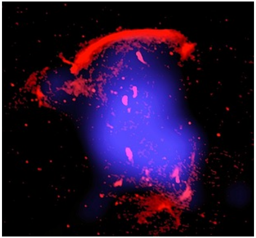

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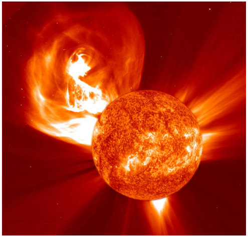
collisionless shocks $\Longleftrightarrow$ energetic particles $\Longleftrightarrow$ electro-magnetic waves



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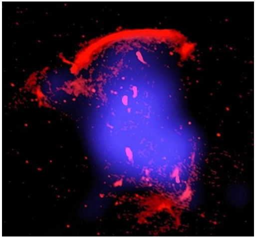

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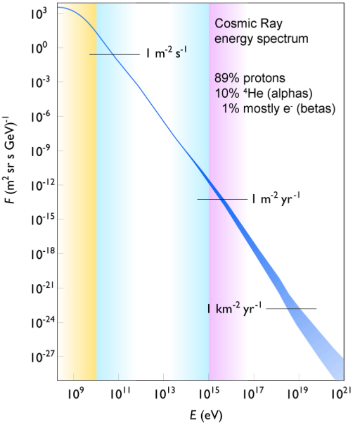
Galactic cosmic ray spectrum



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

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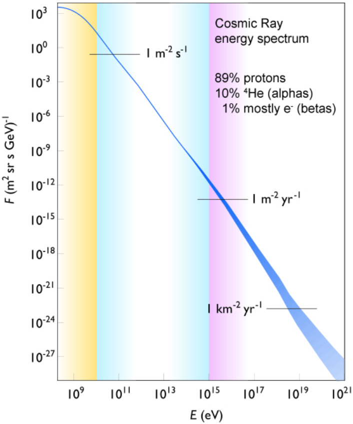

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- spans more than 33 decades in flux and 12 decades in energy
- “knee” indicates characteristic maximum energy of galactic accelerators
- CRs beyond the “ankle” have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence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

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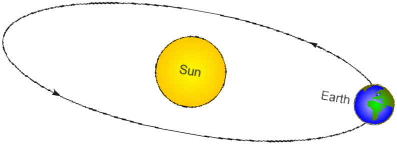
Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

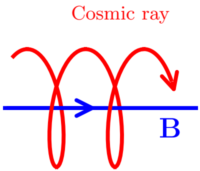
gyro-orbit of GeV cosmic ray:

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

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

Zweibel (2017), Jiang & Oh (2018), Thomas & CP (2019)

Interactions of CRs and magnetic fields



sketch: Jacob

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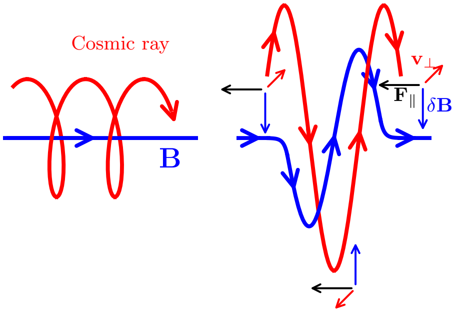

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  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

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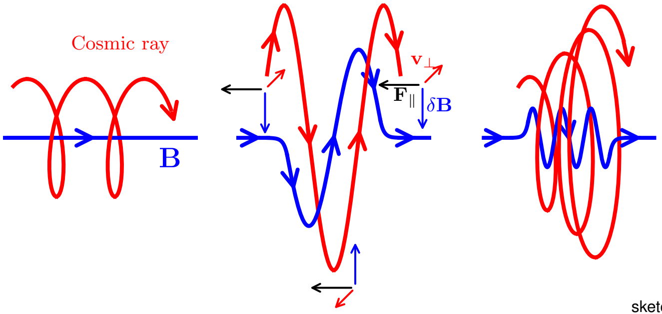

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- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$
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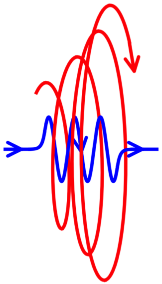
- CRs scatter on magnetic fields $\rightarrow$ isotropization of CR momenta

CR streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm a}$, 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 $\sim v_{\rm a}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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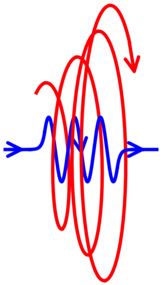

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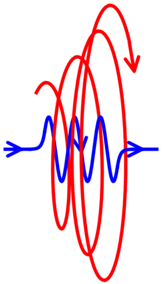
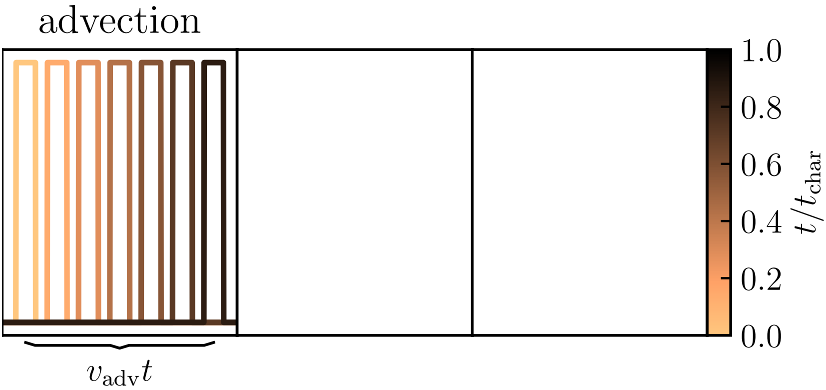


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

Modes of CR propagation



Thomas, CP, Enßlin (2020)

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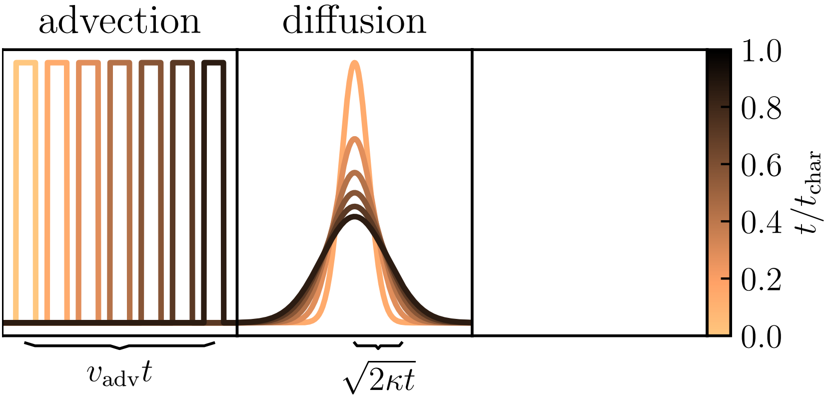

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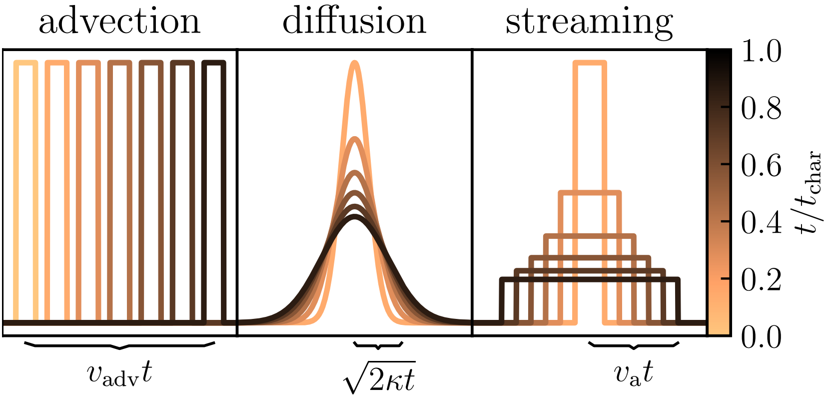

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CR vs. radiation hydrodynamics

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$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{f}_{\mathrm{cr}} = -\boldsymbol{w}_{\pm} \cdot \frac{\boldsymbol{bb}}{3\kappa_{\pm}} \cdot \left[\boldsymbol{f}_{\mathrm{cr}} - \boldsymbol{w}_{\pm}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\right] - \boldsymbol{v} \cdot \boldsymbol{g}_{\mathrm{Lorentz}} + S_{\varepsilon}$$

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Alfvén wave velocity in lab frame: $\boldsymbol{w}_{\pm} = \boldsymbol{v} \pm \boldsymbol{v}_{\mathrm{a}}$,
CR scattering frequency $\bar{\nu}_{\pm} = c^2/(3\kappa_{\pm})$

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- lab-frame equ's for radiation energy and momentum density, ε and $\boldsymbol{f}/c^2$
(Mihalas & Mihalas, 1984, Lowrie+ 1999):

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla}\cdot\boldsymbol{f} = -\sigma_{\rm s}\boldsymbol{v}\cdot\left[\boldsymbol{f} - \boldsymbol{v}\cdot(\varepsilon\mathbf{1}+\mathbf{P})\right] + S_{\rm a}$$

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- ***problem:*** *CR lab-frame equation requires resolving rapid gyrokinetics!*

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- ***solution:*** *transform in comoving frame and project out gyrokinetics!*

Alfvén-wave regulated CR transport

- comoving equ's for CR energy and momentum density (along $\boldsymbol{B}$), $\varepsilon_{\rm cr}$ and $f_{\rm cr}/c^2$, and Alfvén-wave energy densities $\varepsilon_{\rm a,\pm}$ (Thomas & CP 2019)

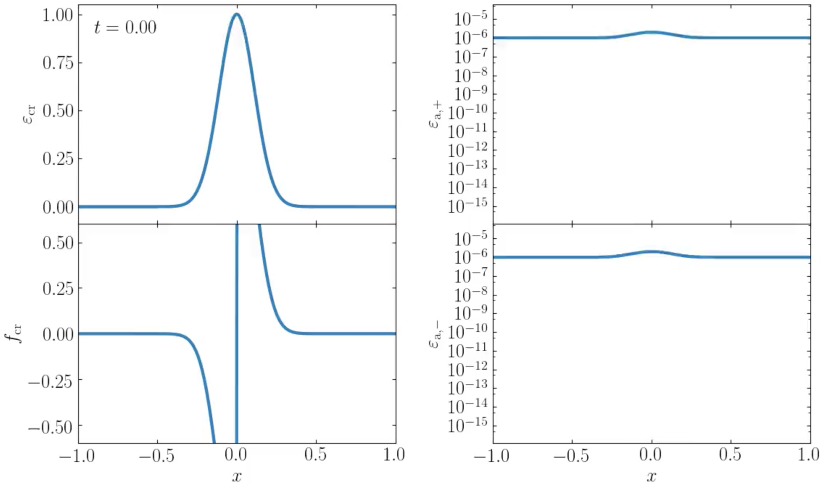
$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot[\boldsymbol{v}(\varepsilon_{\rm cr}+P_{\rm cr}) + \boldsymbol{b} f_{\rm cr}] = \boldsymbol{v}\cdot\boldsymbol{\nabla} P_{\rm cr} - \frac{v_{\rm a}}{3\kappa_+}[f_{\rm cr} - v_{\rm a}(\varepsilon_{\rm cr}+P_{\rm cr})] + \frac{v_{\rm a}}{3\kappa_-}[f_{\rm cr} + v_{\rm a}(\varepsilon_{\rm cr}+P_{\rm cr})],$$

$$\frac{\partial f_{\rm cr}/c^2}{\partial t} + \boldsymbol{\nabla}\cdot\left(\boldsymbol{v} f_{\rm cr}/c^2\right) + \boldsymbol{b}\cdot\boldsymbol{\nabla} P_{\rm cr} = -(\boldsymbol{b}\cdot\boldsymbol{\nabla}\boldsymbol{v})\cdot(\boldsymbol{b} f_{\rm cr}/c^2) - \frac{1}{3\kappa_+}[f_{\rm cr} - v_{\rm a}(\varepsilon_{\rm cr}+P_{\rm cr})] - \frac{1}{3\kappa_-}[f_{\rm cr} + v_{\rm a}(\varepsilon_{\rm cr}+P_{\rm cr})],$$

$$\frac{\partial \varepsilon_{\rm a,\pm}}{\partial t} + \boldsymbol{\nabla}\cdot[\boldsymbol{v}(\varepsilon_{\rm a,\pm}+P_{\rm a,\pm}) \pm v_{\rm a}\boldsymbol{b}\varepsilon_{\rm a,\pm}] = \boldsymbol{v}\cdot\boldsymbol{\nabla} P_{\rm a,\pm} \pm \frac{v_{\rm a}}{3\kappa_\pm}[f_{\rm cr} \mp v_{\rm a}(\varepsilon_{\rm cr}+P_{\rm cr})] - S_{\rm a,\pm}.$$

Non-equilibrium CR streaming and diffusion

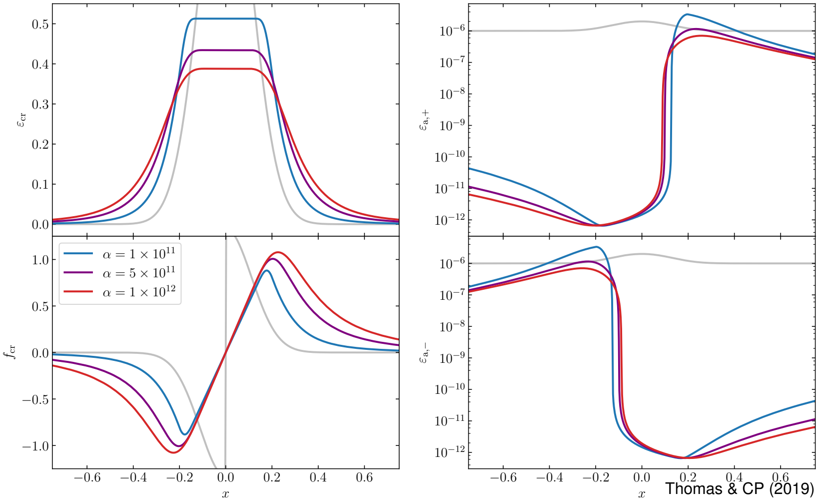
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

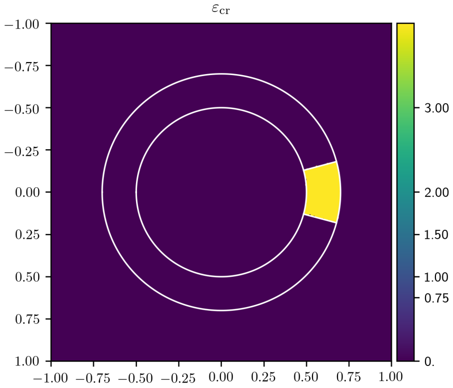


Thomas & CP (2019)

Anisotropic CR streaming and diffusion – AREPO

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

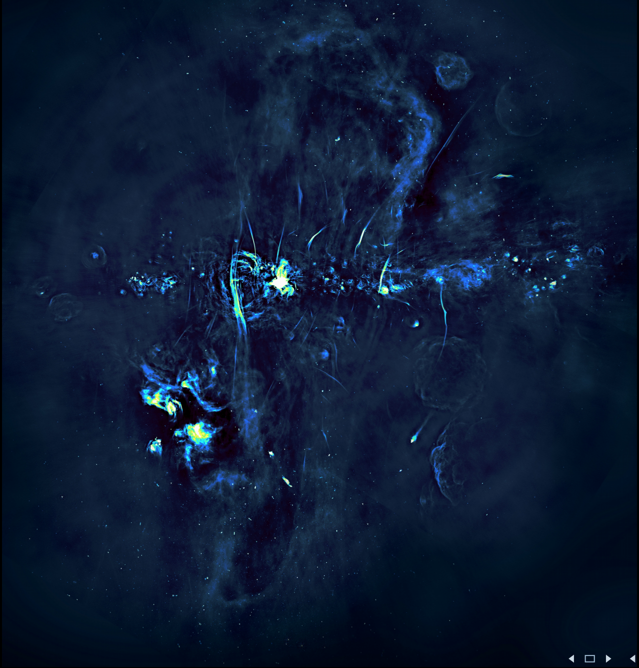
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving



Thomas, CP, Pakmor (2021), Thomas & CP (subm.)

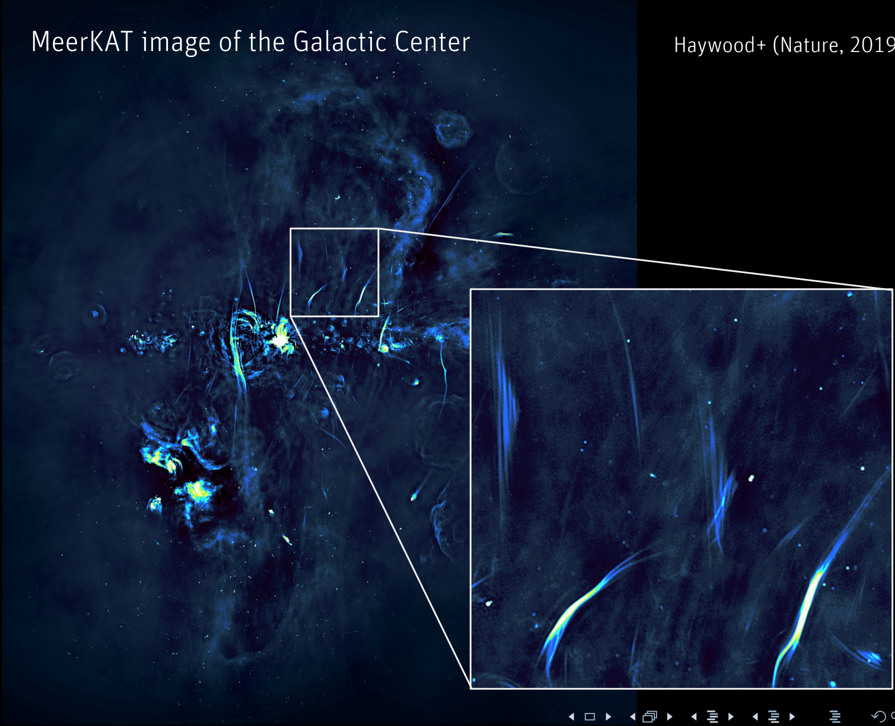
MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



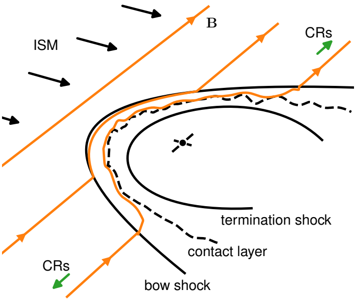
MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



Radio synchrotron harps: the model

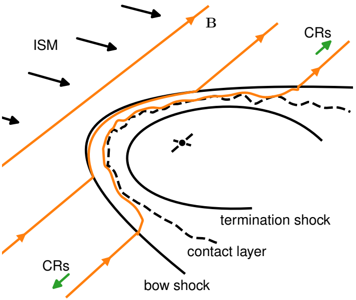
shock acceleration scenario



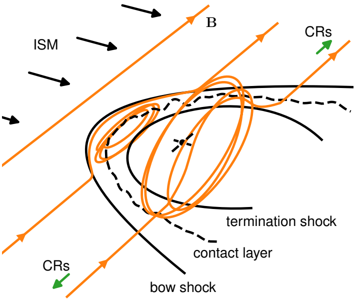
Thomas, CP, Enßlin (2020)

Radio synchrotron harps: the model

shock acceleration scenario



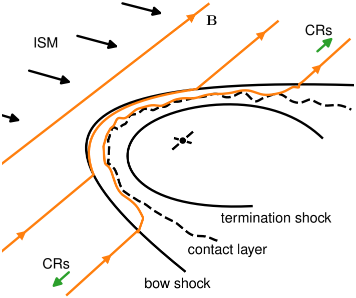
magnetic reconnection at pulsar wind



Thomas, CP, Enßlin (2020)

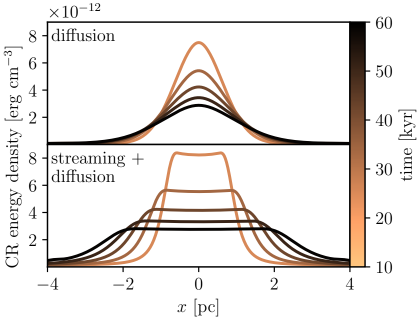
Radio synchrotron harps: the model

shock acceleration scenario

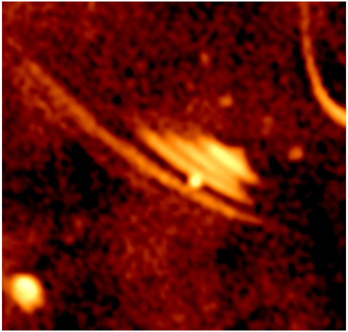


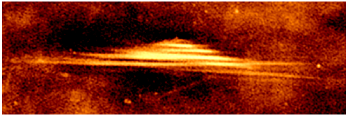
Thomas, CP, Enßlin (2020)

CR diffusion vs. streamig + diffusion



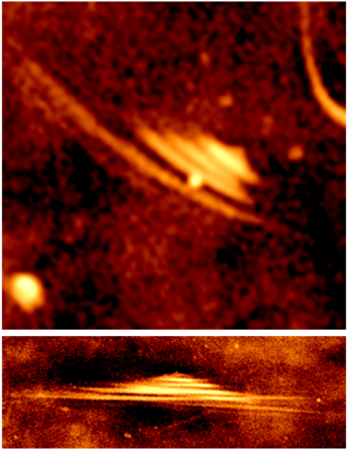
Radio synchrotron harps: testing CR propagation



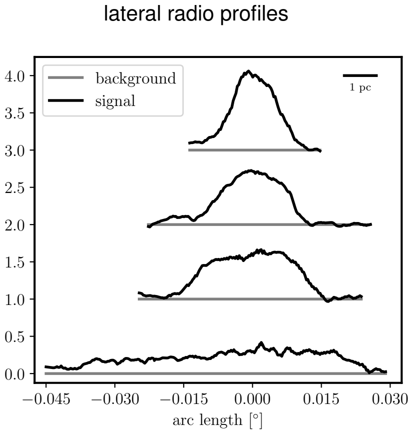


Haywood+ (Nature, 2019)

Radio synchrotron harps: testing CR propagation

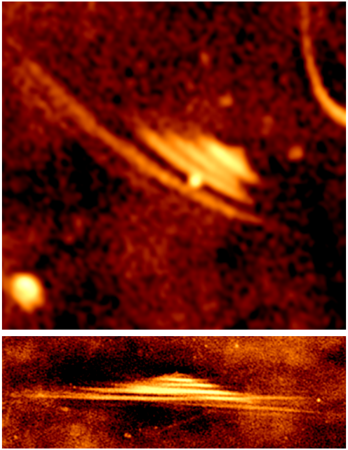


Haywood+ (Nature, 2019)

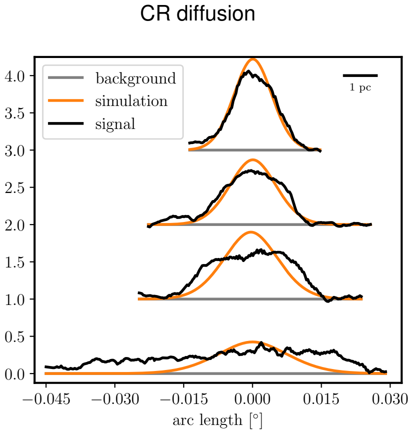


Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation

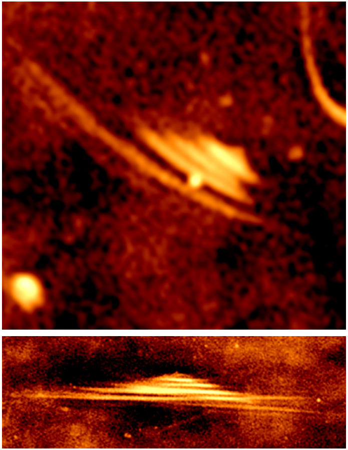


Haywood+ (Nature, 2019)

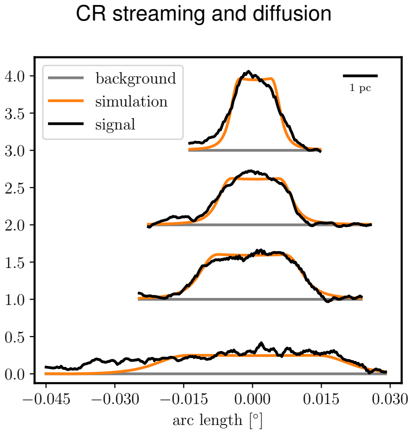


Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation



Haywood+ (Nature, 2019)

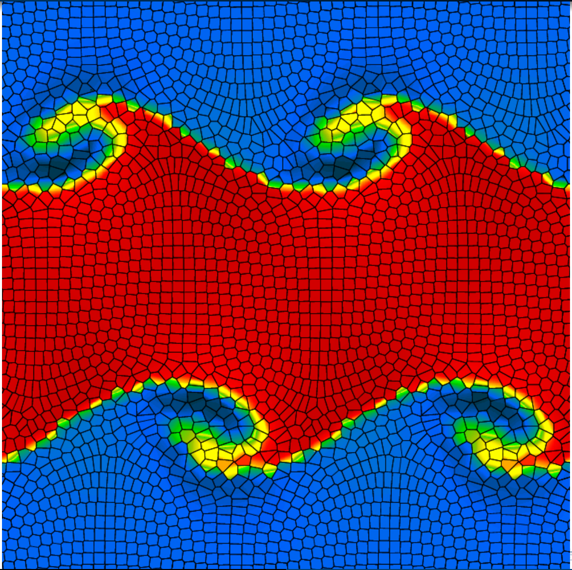


Thomas, CP, Enßlin (2020)

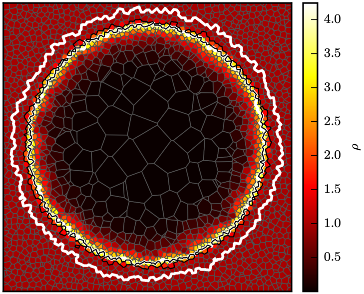
Outline

1. Introduction
   - Puzzles in galaxy formation
   - Galaxy formation paradigm
   - Cosmic ray acceleration
2. Cosmic ray transport
   - Wave-particle interactions
   - CR hydrodynamics
   - Radio harps
3. Supernovae and galaxy formation
   - Supernovae
   - Isolated galaxies
   - Cosmological galaxies

Cosmological moving-mesh code AREPO (Springel 2010)



Global MHD simulations of SNRs with CR physics

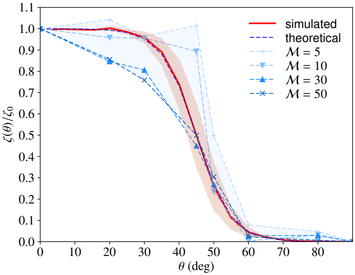


Mach number finder with CRs

CP+ (2017)

- detect and characterize shocks and jump conditions on the fly

Global MHD simulations of SNRs with CR physics

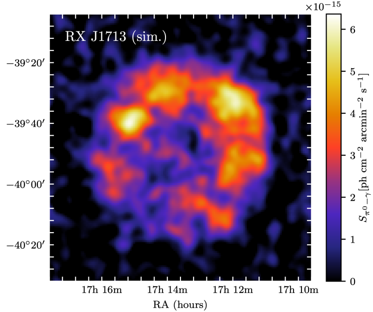


obliquity-dep. acceleration efficiency

Pais, CP+ (2018) based on
hybrid PIC sim.'s by Caprioli & Spitkovsky (2015)

- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B

Global MHD simulations of SNRs with CR physics

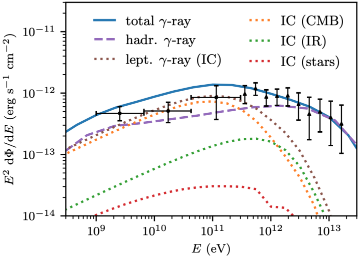


simulated TeV gamma-ray map

Pais & CP (2020)

- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B
- inject and transport CR protons $\Rightarrow$ dynamical back reaction on gas flow, hadronic emission

Global MHD simulations of SNRs with CR physics

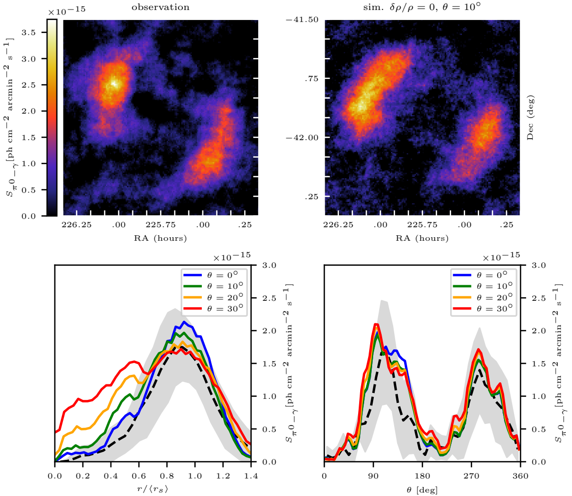


simulated gamma-ray spectrum

Winner, CP+ (2019, 2020)

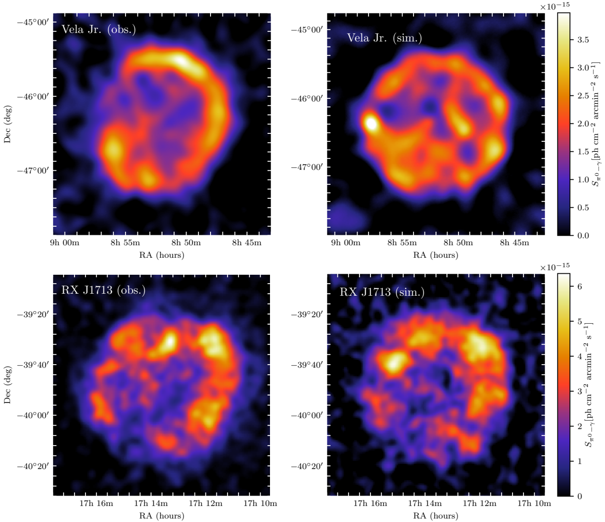
- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B
- inject and transport CR protons $\Rightarrow$ dynamical back reaction on gas flow, hadronic emission
- inject and transport CR electrons
- calculate non-thermal radio, X-ray, γ-ray emission

Hadronic TeV γ rays: SN 1006



Pais & CP (2020)

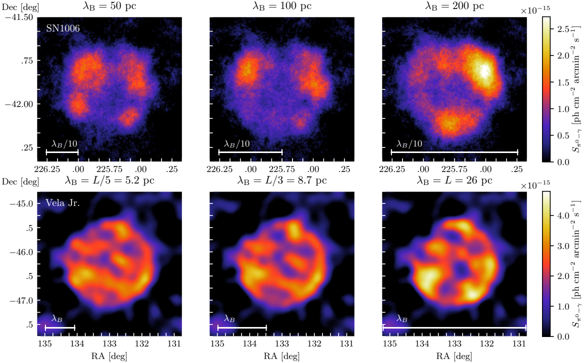
Hadronic TeV γ rays: Vela Jr. and RXJ 1713



Pais & CP (2020)

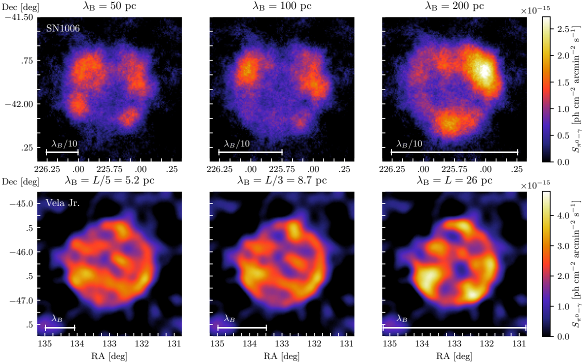
TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN 1006 and Vela Junior



TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN 1006 and Vela Junior

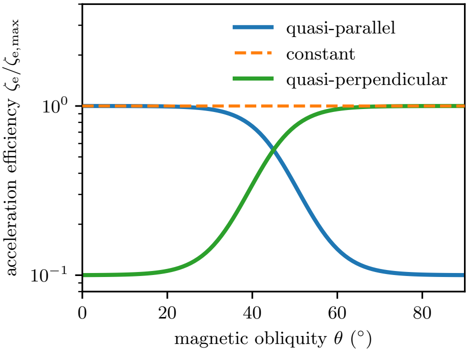


Pais, CP+ (2020)

$\Rightarrow$ Correlation structure of patchy TeV γ-rays constrains magnetic coherence scale in ISM:

SN 1006: $\lambda_B > 200^{+80}_{-10}$ pc Vela Junior: $\lambda_B = 13^{+13}_{-4.3}$ pc

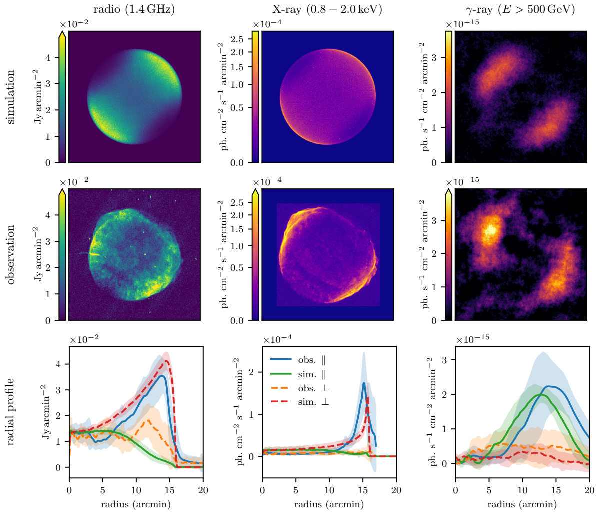
SN 1006: CR electron acceleration models



Winner, CP+ (2020)

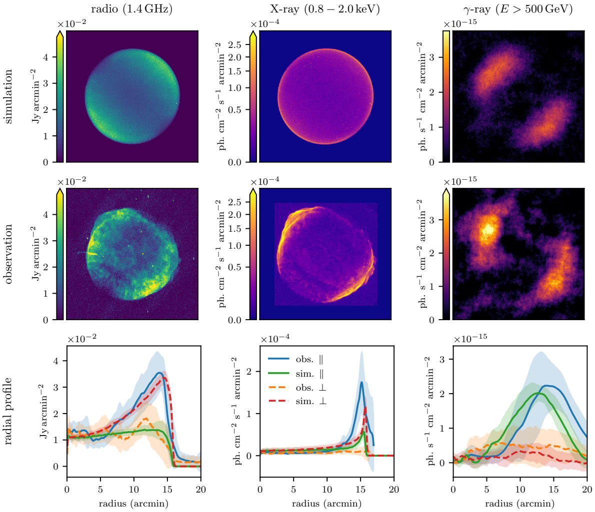
- different obliquity dependent electron acceleration efficiencies:
  1. preferred quasi-perpendicular acceleration (PIC simulations)
  2. constant acceleration efficiency (a straw man's model)
  3. preferred quasi-parallel acceleration (like CR protons)

CR electron acceleration: quasi-perpendicular shocks



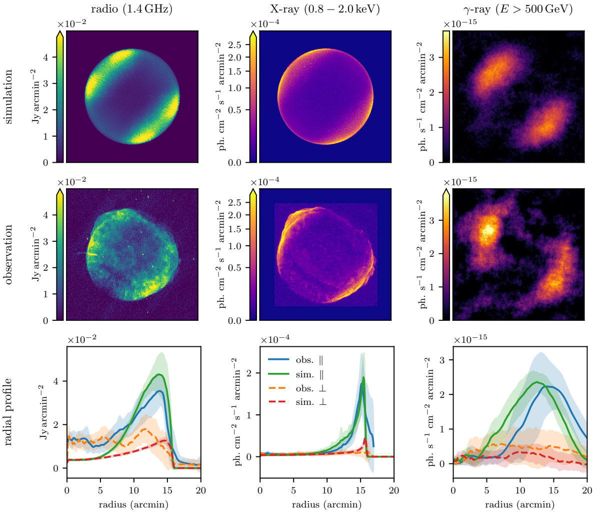
Winner, CP+ (2020)

CR electron acceleration: constant efficiency



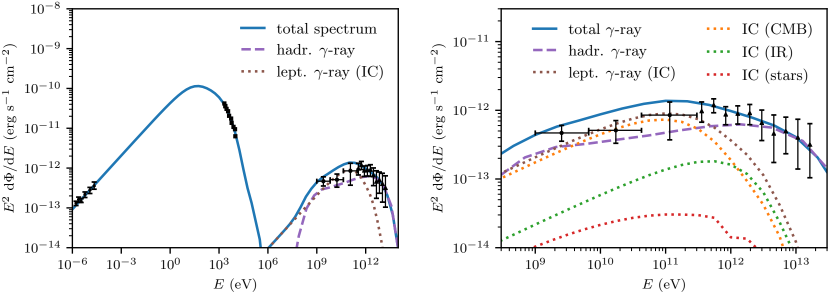
Winner, CP+ (2020)

CR electron acceleration: quasi-parallel shocks



Winner, CP+ (2020)

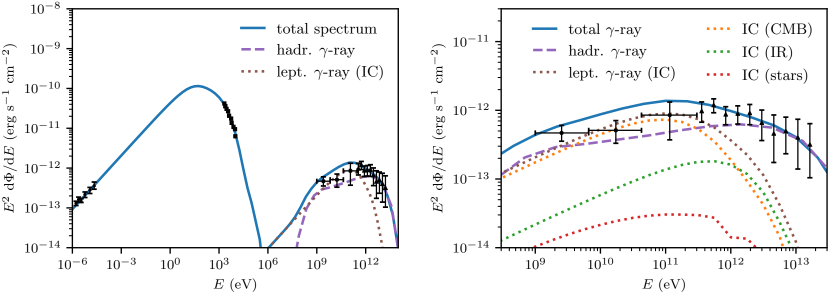
SN 1006: multi-frequency spectrum



Winner, CP+ (2020)

- quasi-parallel acceleration model fits multi-frequency spectrum

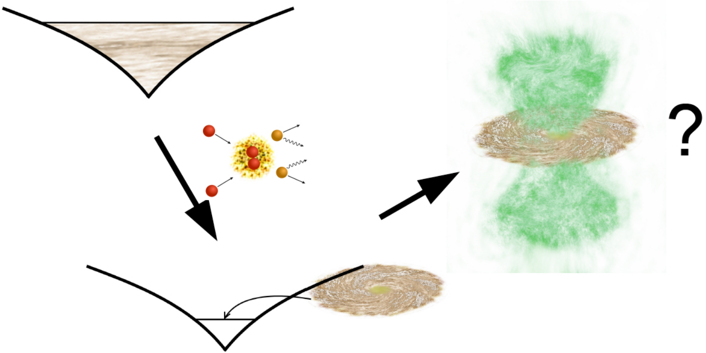
SN 1006: multi-frequency spectrum



Winner, CP+ (2020)

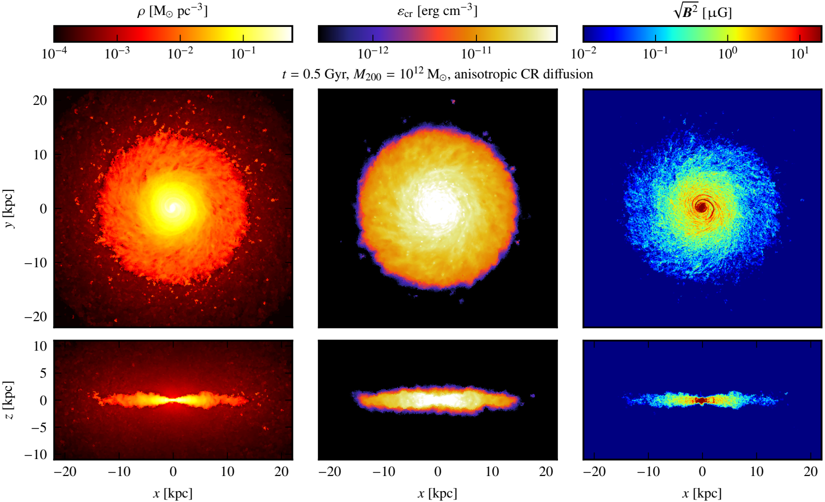
- quasi-parallel acceleration model fits multi-frequency spectrum
- GeV regime: leptonic inverse Compton dominates
- TeV regime: hadronic pion decay

1. Cosmic ray feedback in galaxy formation



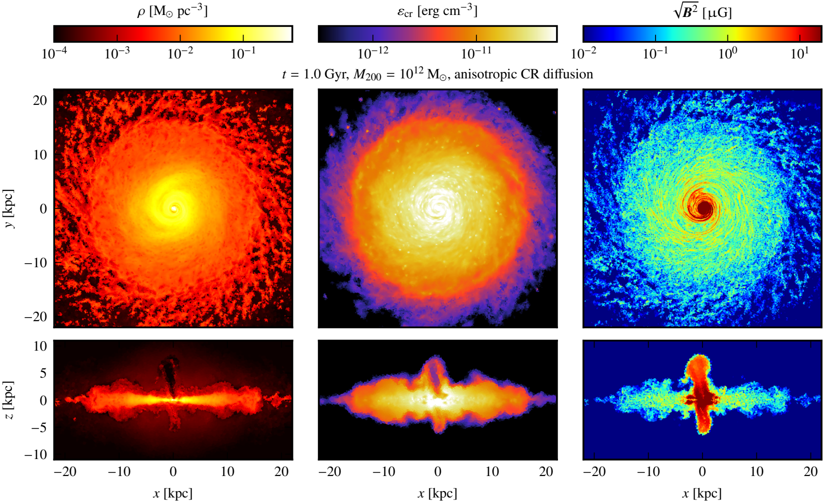
Pakmor, CP+ (2016), CP+ (2017b)
Galactic winds driven by CR diffusion in isolated disk galaxies
MHD + CR advection + anisotropic diffusion, $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

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



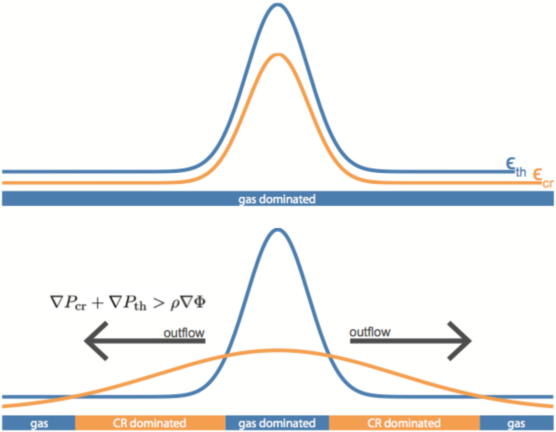
CP+ (2017b)

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



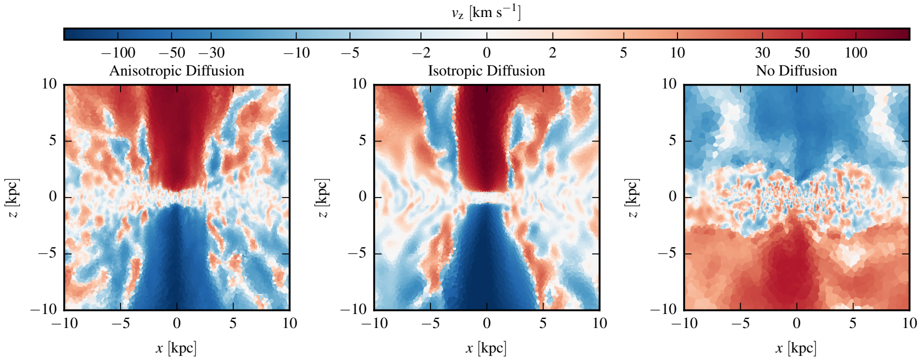
CP+ (2017b)

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), . . .

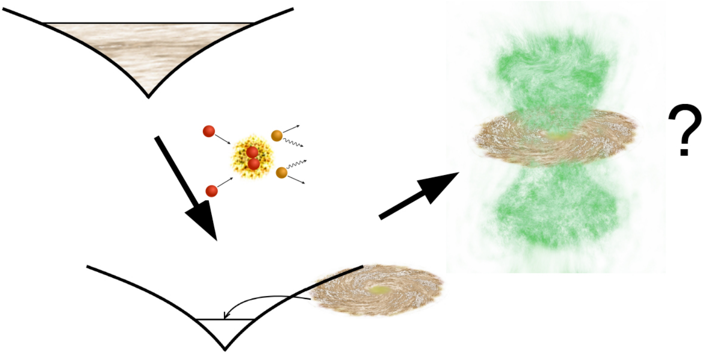
CR diffusion vs. advection



Pakmor, CP, Simpson, Springel (2016)

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

2. Cosmic rays and non-thermal emission



Werhahn, CP, Girichidis+ (2021)

Cosmic rays and non-thermal emission in simulated galaxies: I. & II.

MHD + CR advection + anisotropic diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ \mathrm{M}_\odot$

steady-state spectra of CR protons, primary & secondary electrons

Steady-state cosmic ray spectra

- solve the steady-state equation in every cell for each CR population:

$$\frac{f(E)}{\tau_{\mathrm{esc}}} - \frac{\mathrm{d}}{\mathrm{d}E}\left[f(E)b(E)\right] = q(E)$$

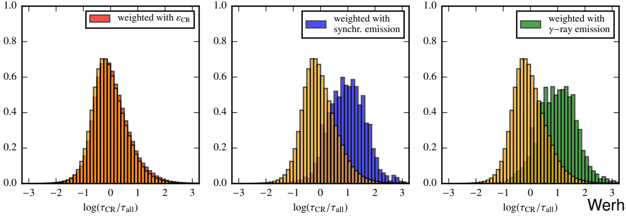
- protons: Coulomb, hadronic and escape losses (re-normalized to $\varepsilon_{\mathrm{cr}}$)
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\mathrm{ep}} = 0.02$)
  - secondaries

Steady-state cosmic ray spectra

- solve the steady-state equation in every cell for each CR population:

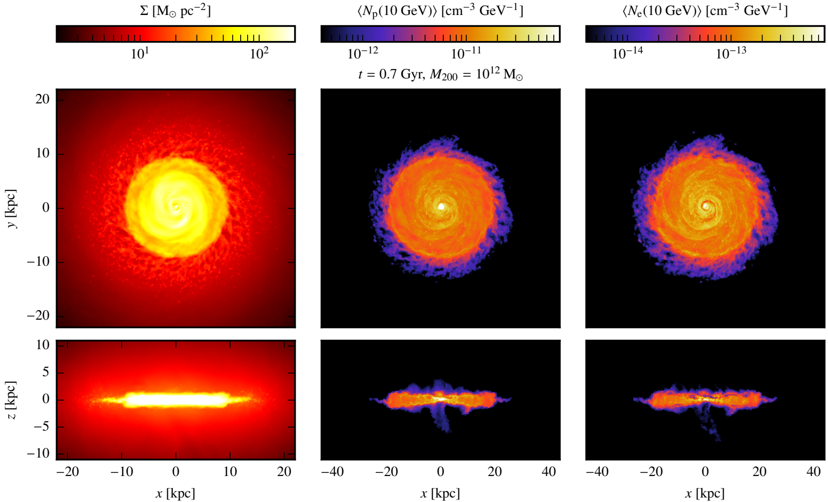
$$\frac{f(E)}{\tau_{\mathrm{esc}}} - \frac{\mathrm{d}}{\mathrm{d}E}\left[f(E)b(E)\right] = q(E)$$

- protons: Coulomb, hadronic and escape losses (re-normalized to $\varepsilon_{\mathrm{cr}}$)
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
    - primaries (re-normalized using $K_{\mathrm{ep}} = 0.02$)
    - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



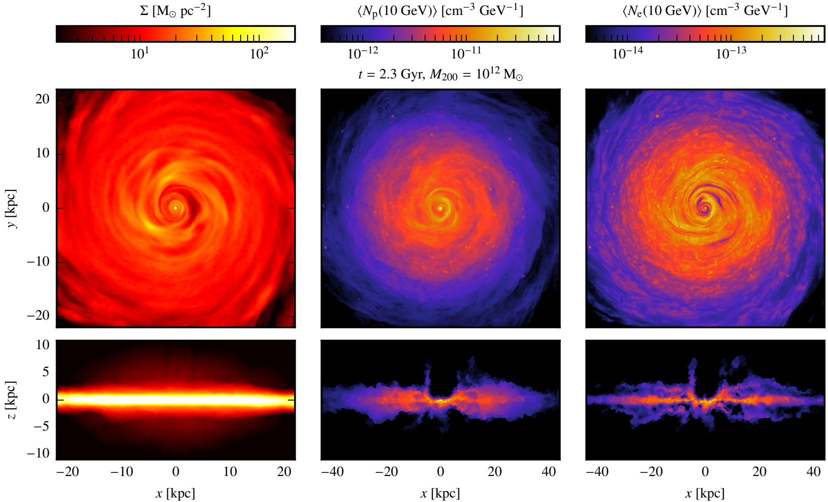
Werhahn+ (2021a)

From a starburst galaxy to a Milky Way analogy



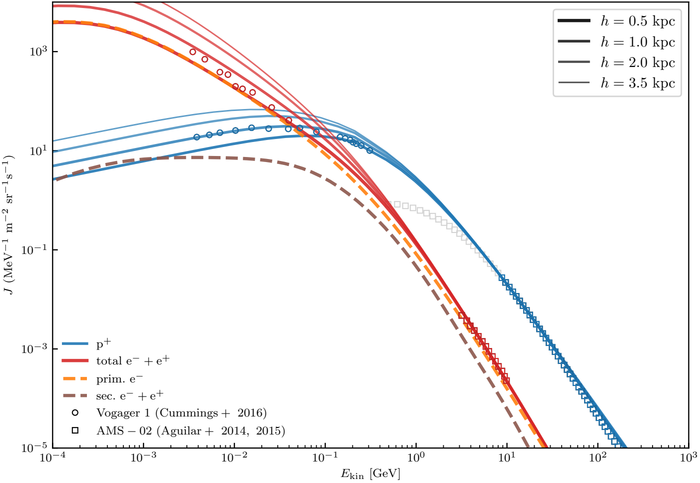
Werhahn, CP+ (2021)

From a starburst galaxy to a Milky Way analogy



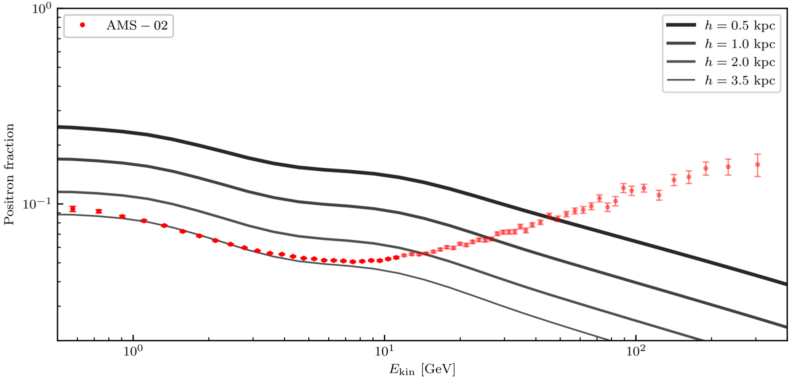
Werhahn, CP+ (2021)

Comparing CR spectra to Voyager and AMS-02 data



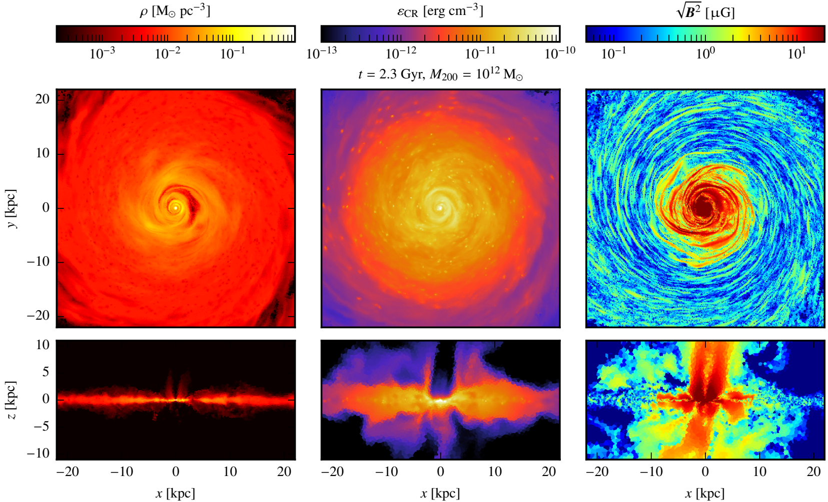
Werhahn, CP+ (2021)

Comparing the positron fraction to AMS-02 data



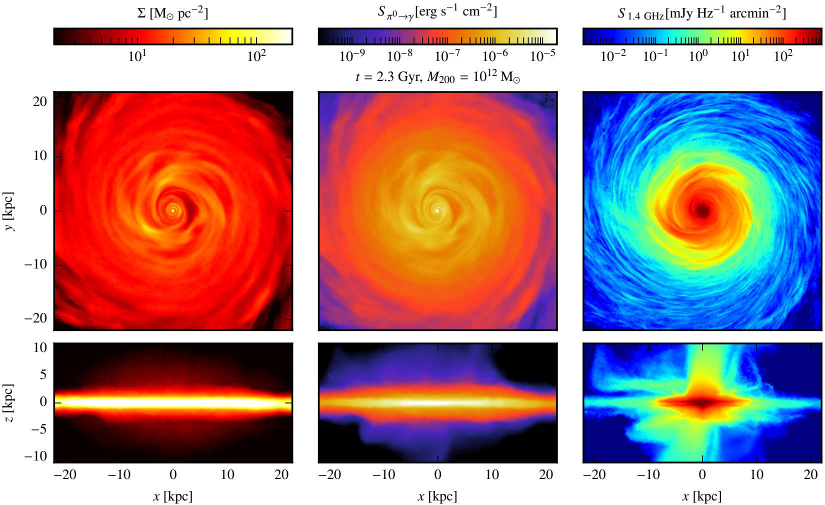
Werhahn, CP+ (2021)

Simulation of a starburst galaxy



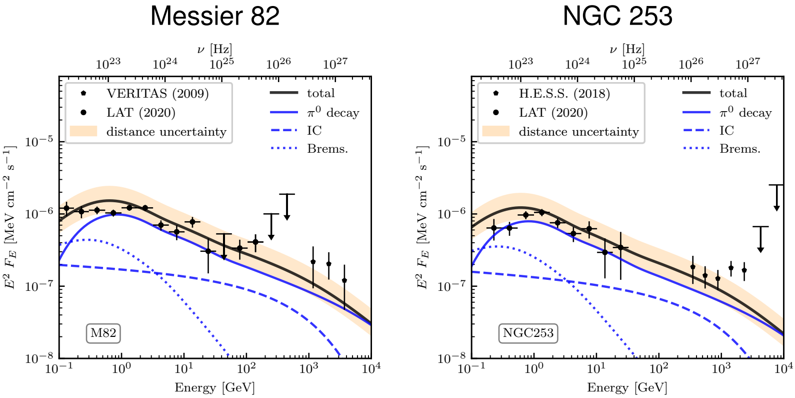
Werhahn, CP+ (2021)

Simulation of a starburst galaxy



Werhahn, CP+ (2021)

Gamma-ray spectra of starburst galaxies

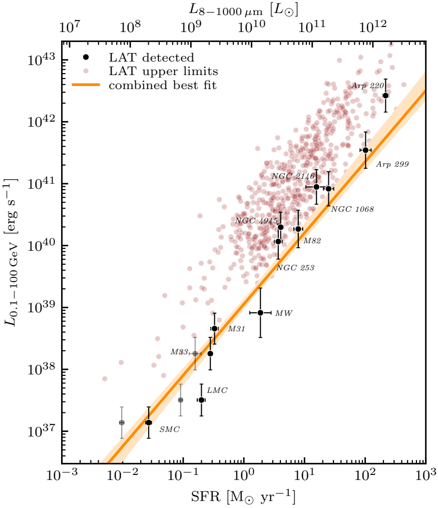


Werhahn, CP+ (2021)

- gamma-ray spectra in starbursts dominated by pion decay
- CR protons propagate in Kolmogorov turbulence: $\kappa \propto E^{0.3}$

Far infra-red – gamma-ray correlation

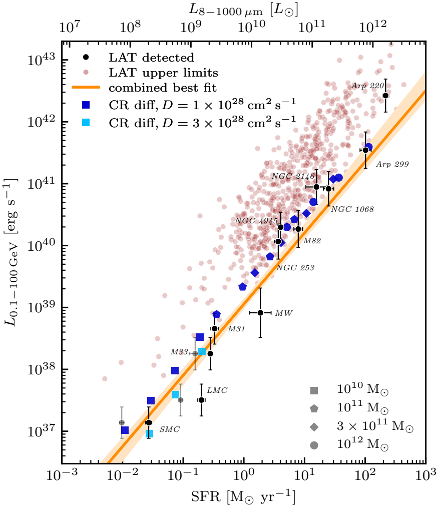
Universal conversion: star formation → cosmic rays → gamma rays



Ajello+ (2020)

Far infra-red – gamma-ray correlation

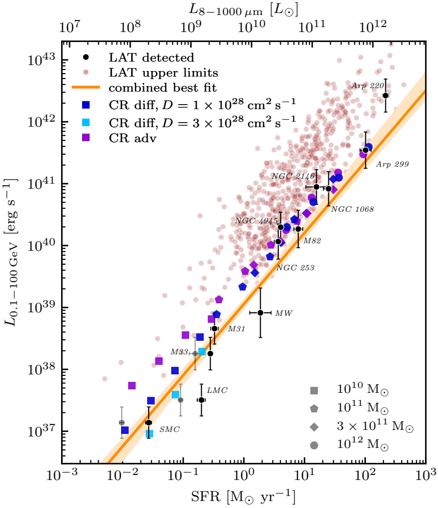
Universal conversion: star formation → cosmic rays → gamma rays



Werhahn, CP+ (2021)

Far infra-red – gamma-ray correlation

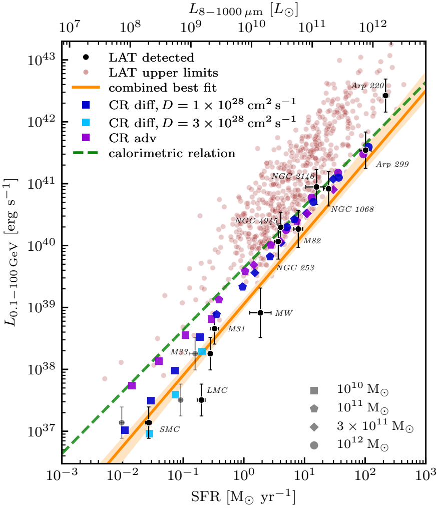
Universal conversion: star formation → cosmic rays → gamma rays



Werhahn, CP+ (2021)

Far infra-red – gamma-ray correlation

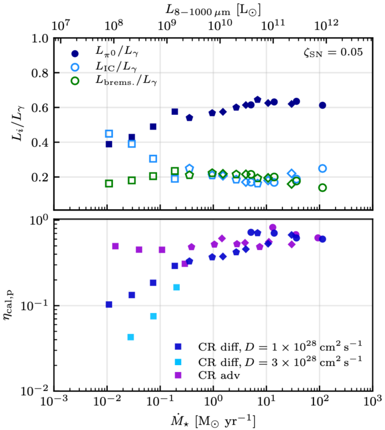
Universal conversion: star formation → cosmic rays → gamma rays



Werhahn, CP+ (2021)

Far infra-red – gamma-ray correlation

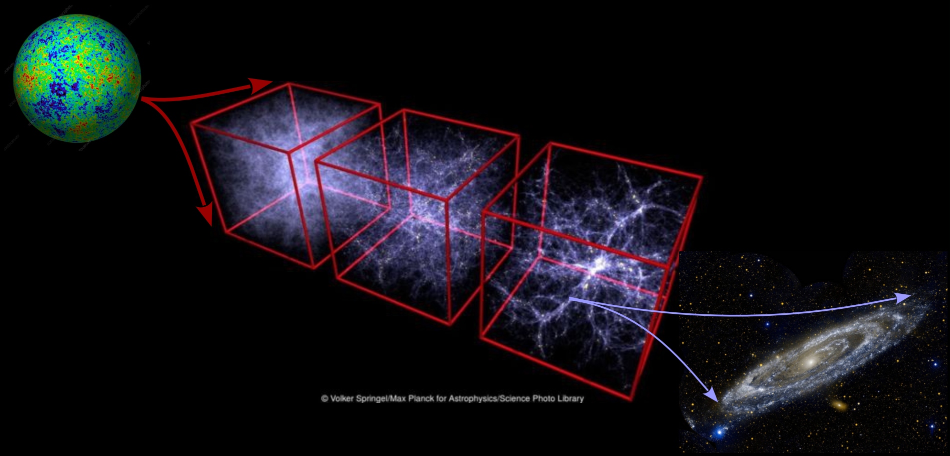
Hadronic vs. leptonic emission and calorimetric fraction across galaxy scales



Werhahn, CP+ (2021)

- pion decay dominates gamma-ray emission in starbursts
- leptonic component (primarily inverse Compton) dominates at low star formation rates
- calorimetric energy fraction in starbursts $\eta_{cal,p} \approx 0.5$: half of the energy available for CR feedback
- faster CR diffusion decreases calorimetric fraction at low star formation rates

3. Cosmological galaxy formation



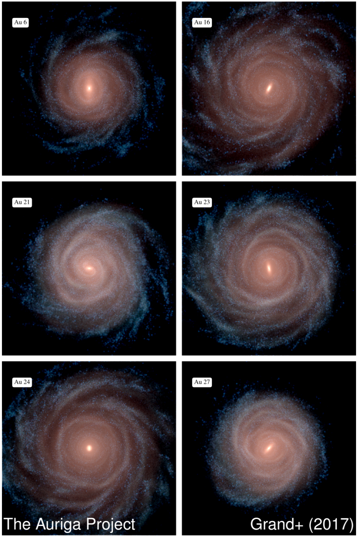
Cosmic rays in cosmological galaxy simulations

The galaxy formation model

- primordial and metal line cooling
- sub-resolution model for star formation (Springel+ 03)
- mass and metal return from stars to ISM
- cold dense gas stabilised by pressurised ISM
- thermal and kinetic energy from supernovae modelled by isotropic wind – launched outside of SF region
- black hole seeding and accretion model (Springel+ 05)
- thermal feedback from AGN in radio and quasar mode
- uniform magnetic field of 10^{-10} G seeded at $z = 128$

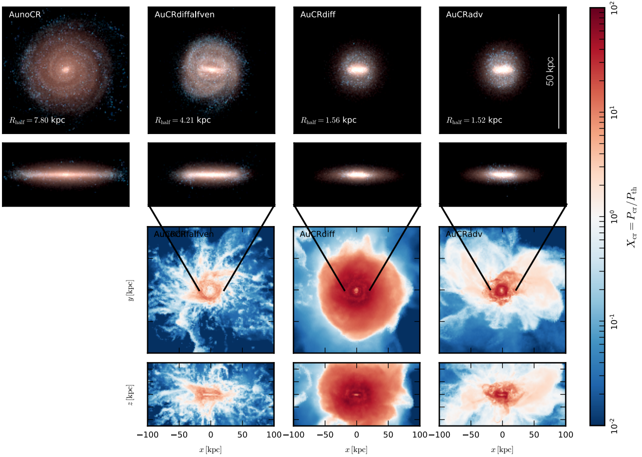
Simulation suite (Buck, CP+ 2020)

- 2 galaxies, baryons with $5 \times 10^4\,\mathrm{M}_\odot \sim 5 \times 10^6$ resolution elements in halo, 2×10^6 star particles
- 4 models with different CR physics for each galaxy:
  - no CRs
  - CR advection
  - + CR anisotropic diffusion
  - + CR Alfvén wave cooling



Cosmic rays in cosmological galaxy simulations

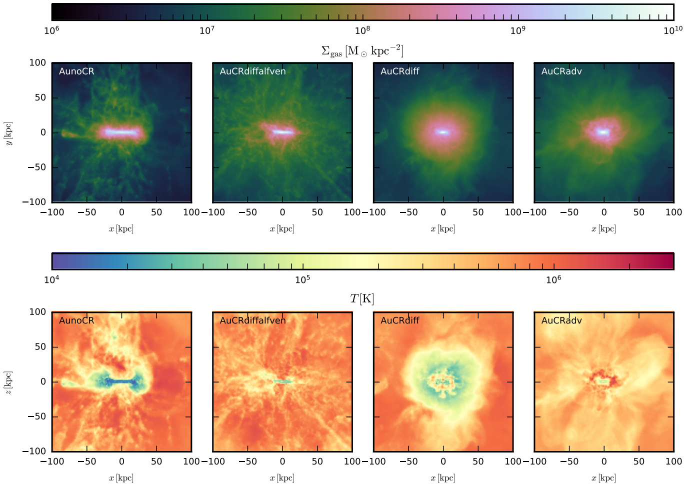
Auriga MHD models: CR transport changes disk sizes



Buck, CP, Pakmor, Grand, Springel (2020)

Cosmic rays in cosmological galaxy simulations

Auriga MHD models: CR transport modifies the circum-galactic medium



Buck, CP, Pakmor, Grand, Springel (2020)

Conclusions for cosmic ray physics in galaxies

CR hydrodynamics:

- moment expansion similar to radiation hydrodynamics
- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
- synchrotron harps: CR streaming dominates over diffusion

Conclusions for cosmic ray physics in galaxies

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CR acceleration and feedback in galaxy formation:

- global MHD simulations of SNRs constrain plasma physics of particle acceleration
- CR feedback drives galactic winds & slows down star formation
- 3D galactic emission models calibrate CR feedback and probe non-thermal physics
- CRs modify galaxy disk sizes and the circumgalactic medium

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).

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