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

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in collaboration with

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Astronomy Colloquium, University of Amsterdam, Mar 2022

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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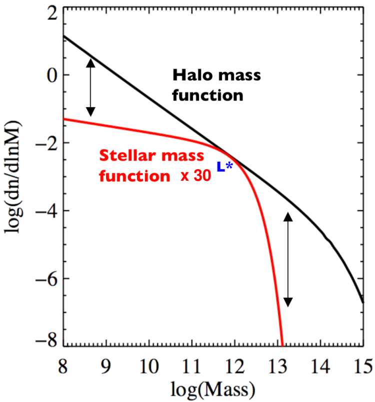
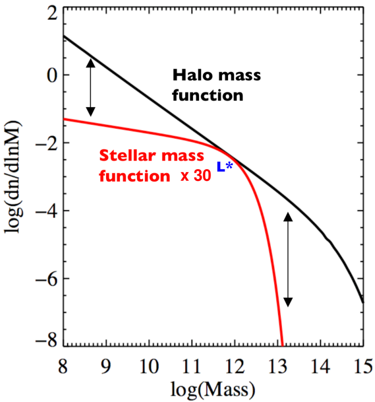
Puzzles in galaxy formation

Galaxy formation in dark matter halos

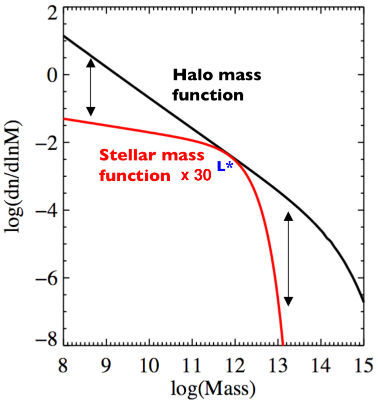


Galaxy formation in dark matter halos



- the number of galaxies in dark matter (DM) halos of mass $\gtrsim 10^{12}\,M_\odot$ is exponentially suppressed
  $\rightarrow$ some non-gravitational process introduces a new scale of galaxy formation

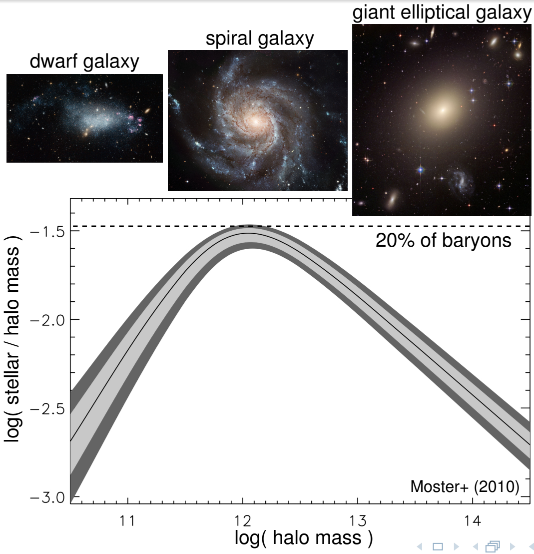
Galaxy formation in dark matter halos



- the number of galaxies in dark matter (DM) halos of mass $\gtrsim 10^{12}\,M_\odot$ is exponentially suppressed
  → some non-gravitational process introduces a new scale of galaxy formation
- discrepancy of the power-law slopes at the faint end
  → some process lowers the star conversion rate in smaller halos
  or the DM halo mass function is wrong (warm DM?)

AIP

Puzzles in galaxy formation



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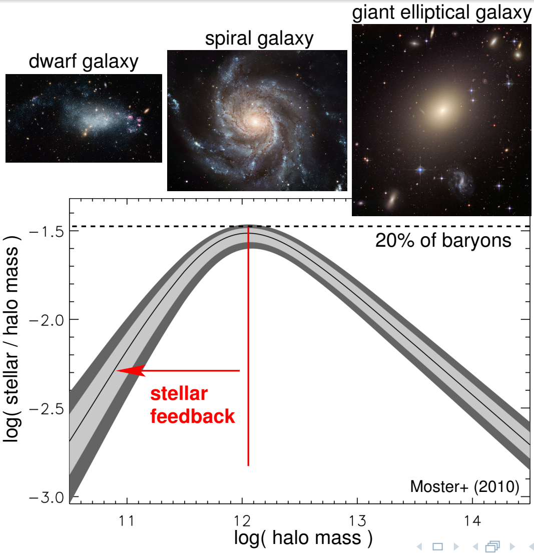
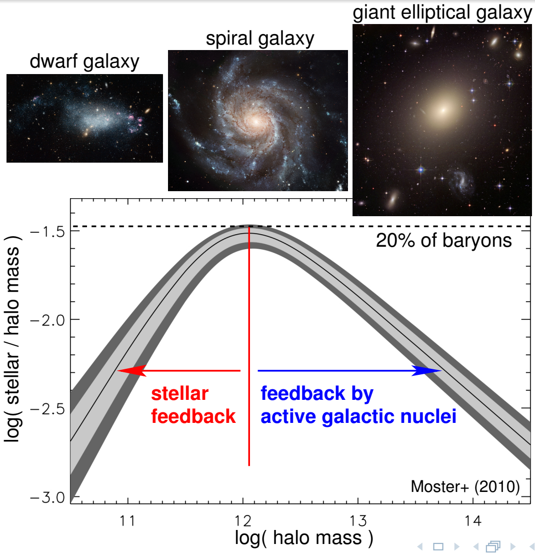
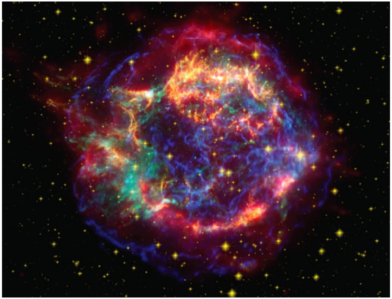


Puzzles in galaxy formation



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

Feedback by galactic winds

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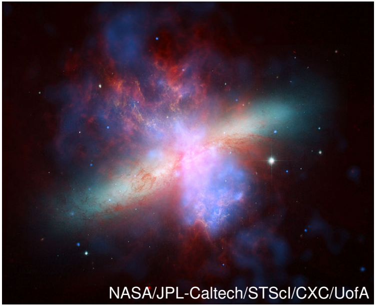
- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star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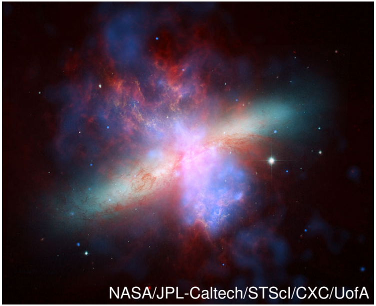

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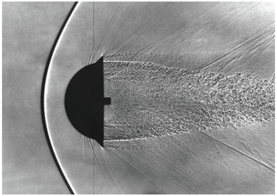
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

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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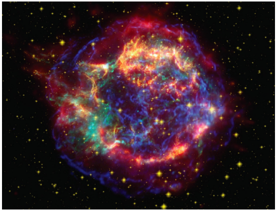

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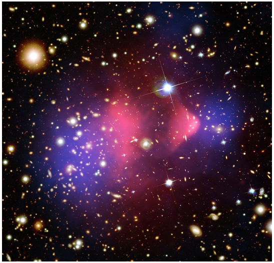

clusters/galaxies, Coulomb collisions set λ_{mfp}:
$\lambda_{\mathrm{mfp}} \sim L_{\mathrm{cluster}}/10, \qquad \lambda_{\mathrm{mfp}} \sim L_{\mathrm{SNR}}$

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

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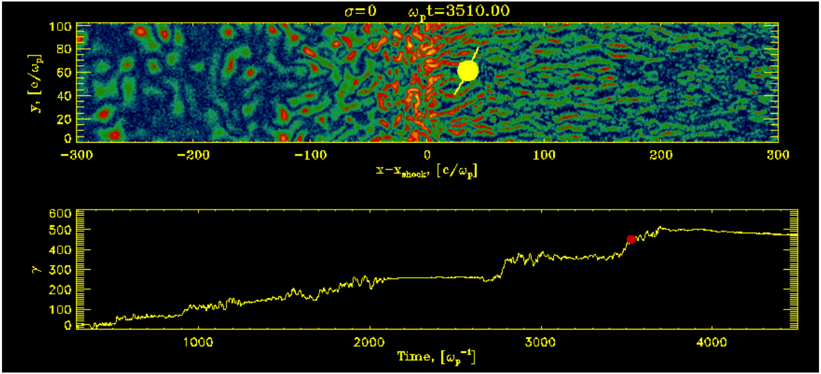
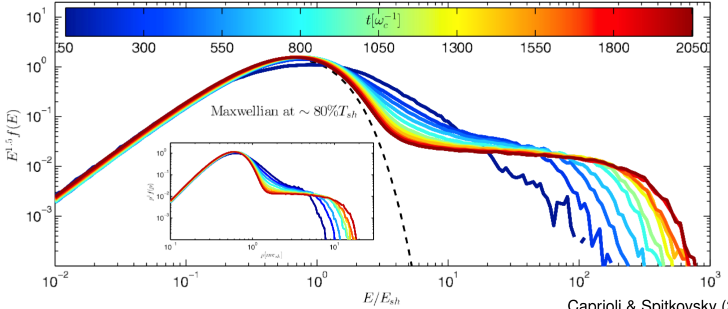
Particle acceleration at relativistic shock, $\boldsymbol{B}_0 = \mathbf{0}$

- 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

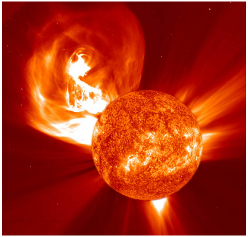
Non-relativistic parallel shock in long-term hybrid simulation



Caprioli & Spitkovsky (2014)

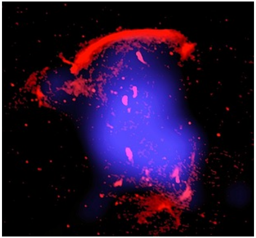
- quasi-parallel shocks accelerate ions
- particles gain energy in each crossing and have probability of leaving the Fermi cycle by being swept downstream → power-law spectrum
- maximum energy increases with time

Astrophysical shocks



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

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

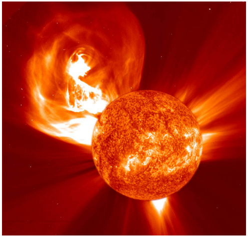


cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

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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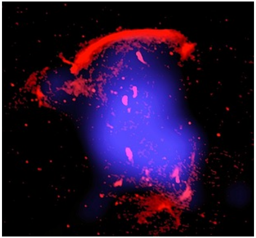

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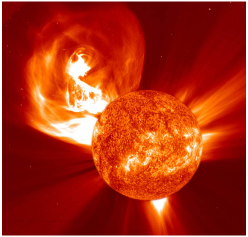
collisionless shocks $\Longleftrightarrow$ energetic particles $\Longleftrightarrow$ electro-magnetic waves



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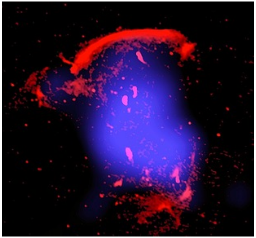

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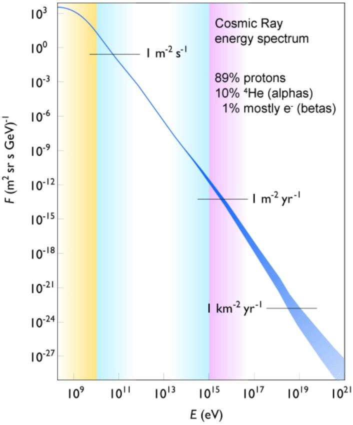
Galactic cosmic ray spectrum



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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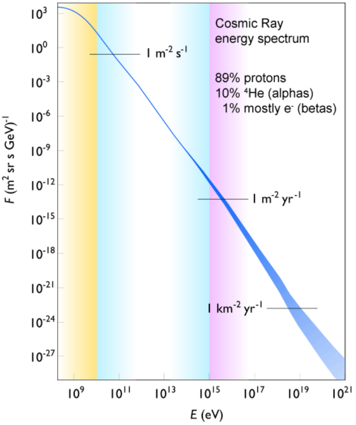

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- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence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

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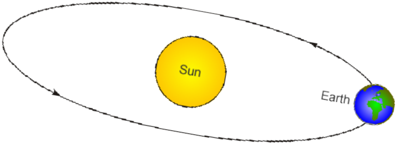
Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

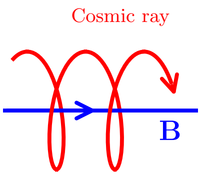
gyro-orbit of GeV cosmic ray:

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

$\Rightarrow$ 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 & CP

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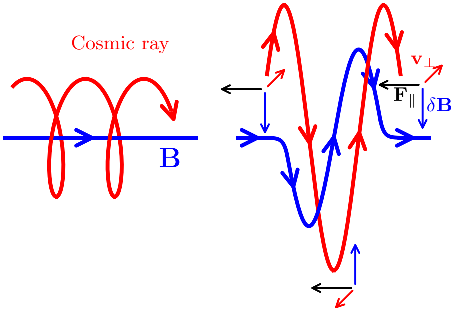

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  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

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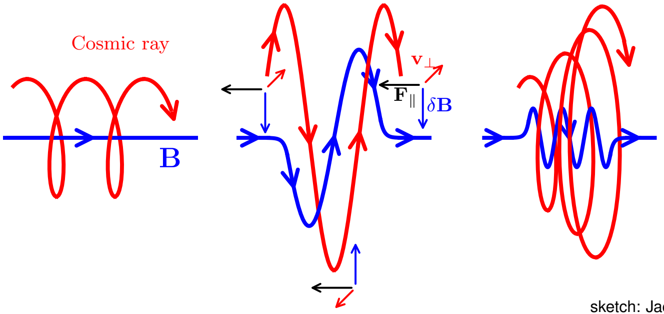

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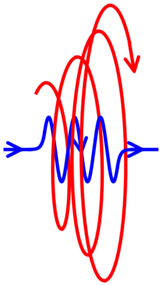
- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields → isotropization of CR momenta

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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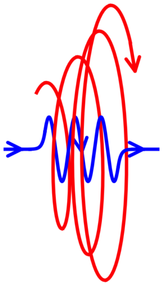

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

AIP

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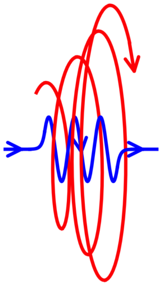
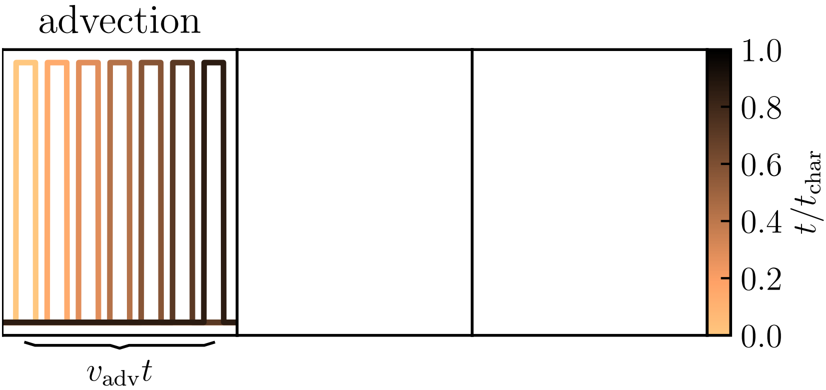


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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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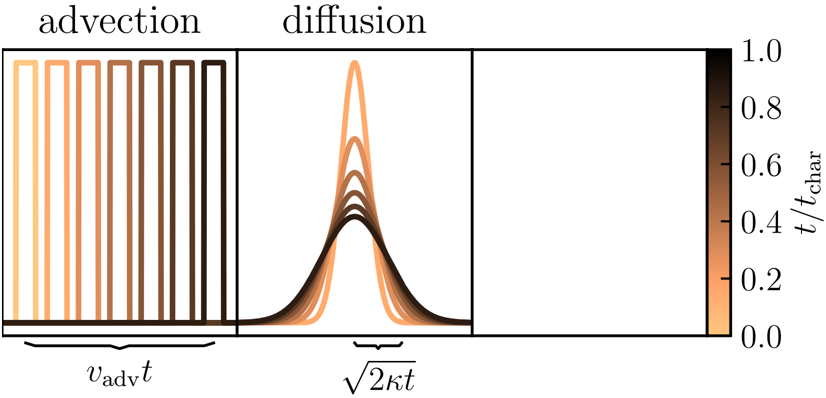

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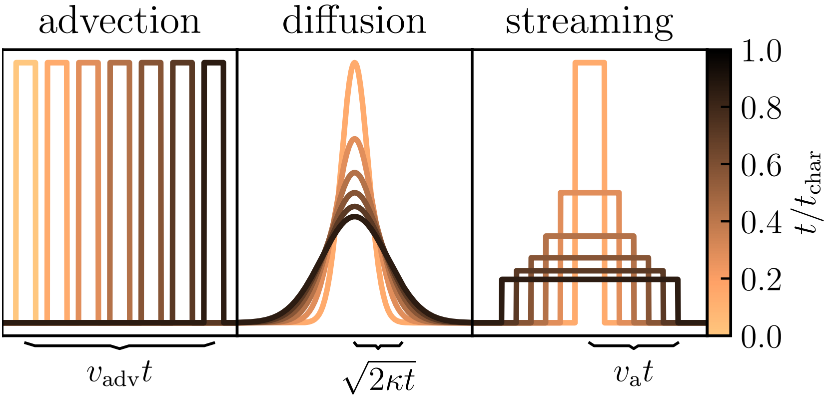

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CR vs. radiation hydrodynamics

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  derive two-moment equations from CR Vlasov equation (Thomas & CP 2019)

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- lab-frame equ's for CR energy and momentum density, $\varepsilon_{\mathrm{cr}}$ and $\boldsymbol{f}_{\mathrm{cr}}/c^2$

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

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Alfvén wave velocity in lab frame: $\boldsymbol{w}_{\pm} = \boldsymbol{v} \pm \boldsymbol{v}_{\mathrm{a}}$,
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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):

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

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

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  (Mihalas & Mihalas, 1984, Lowrie+ 1999):

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

$$\frac{1}{c^2}\frac{\partial \boldsymbol{f}}{\partial t} + \boldsymbol{\nabla}\cdot\mathbf{P} = -\sigma_{\mathrm{s}}\left[\boldsymbol{f} - \boldsymbol{v}\cdot(\varepsilon\mathbf{1} + \mathbf{P})\right] + S_{\mathrm{a}}\boldsymbol{v}$$

- ***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)

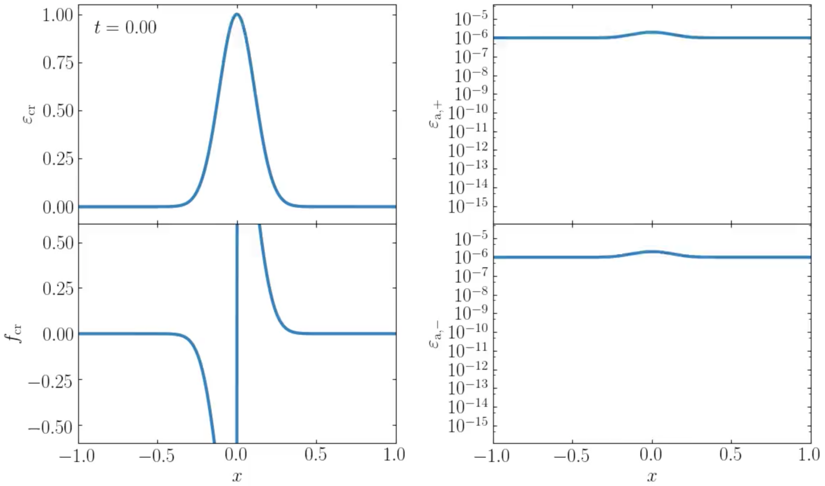
$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla} \cdot [\boldsymbol{v}(\varepsilon_{\rm cr} + P_{\rm cr}) + \boldsymbol{b} f_{\rm cr}] = \boldsymbol{v} \cdot \boldsymbol{\nabla} P_{\rm cr} - \frac{v_{\rm a}}{3\kappa_+}[f_{\rm cr} - v_{\rm a}(\varepsilon_{\rm cr} + P_{\rm cr})]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

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

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

Non-equilibrium CR streaming and diffusion

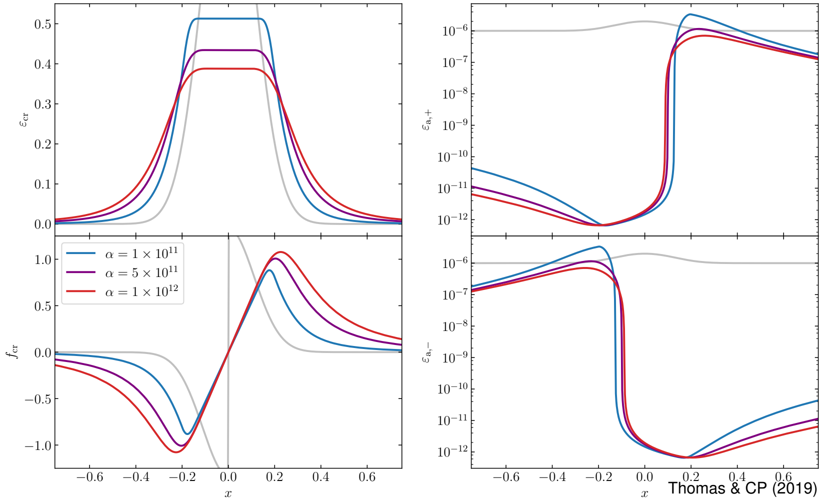
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

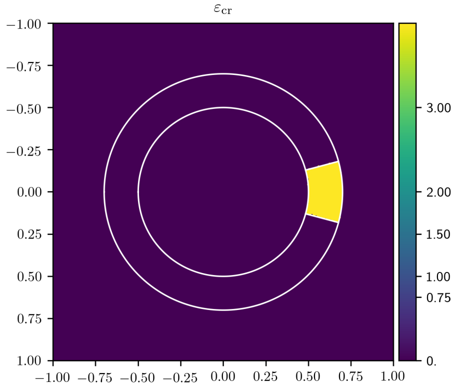


Thomas & CP (2019)

Anisotropic CR streaming and diffusion – AREPO

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

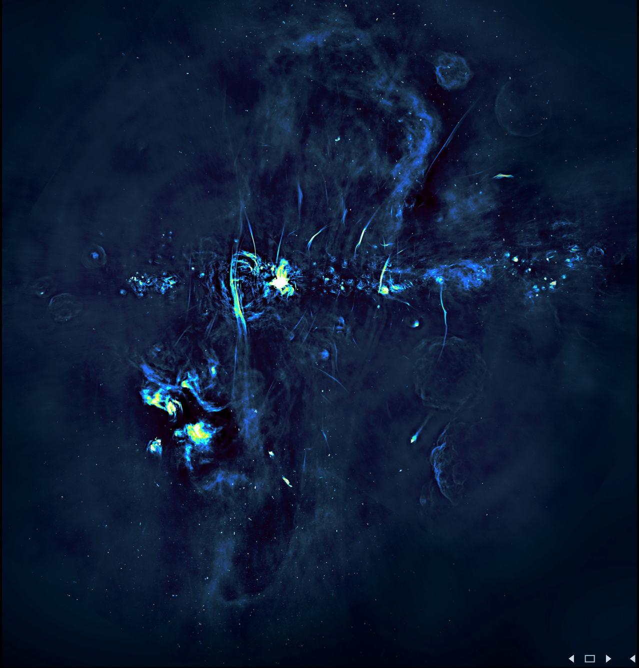
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving



Thomas, CP, Pakmor (2021), Thomas & CP (2022)

MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



MeerKAT image of the Galactic Center

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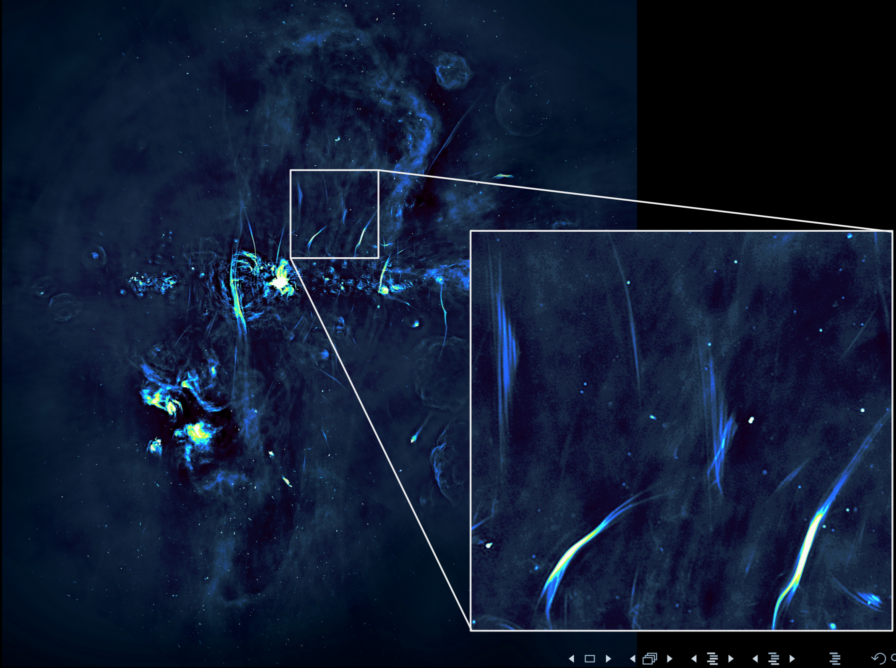
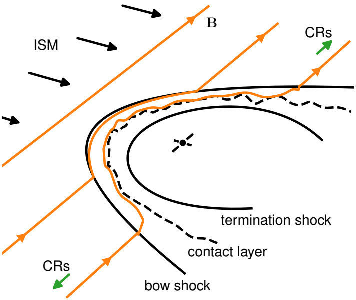


Radio synchrotron harps: the model

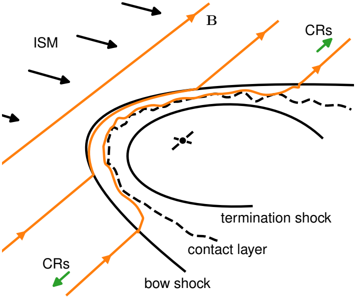
shock acceleration scenario



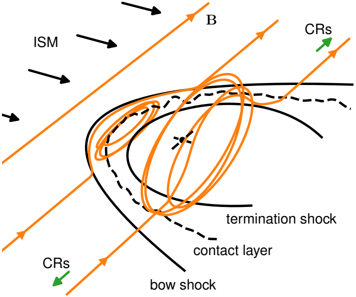
Thomas, CP, Enßlin (2020)

Radio synchrotron harps: the model

shock acceleration scenario



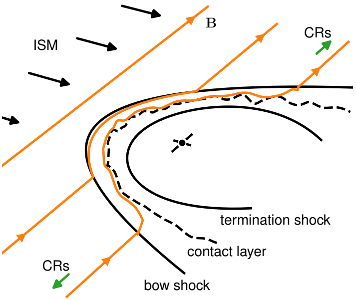
magnetic reconnection at pulsar wind



Thomas, CP, Enßlin (2020)

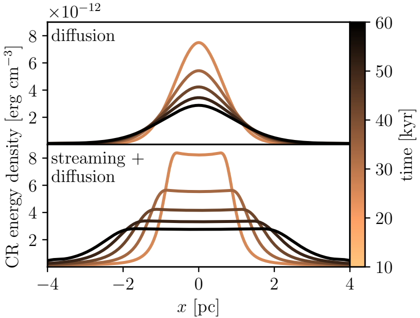
Radio synchrotron harps: the model

shock acceleration scenario

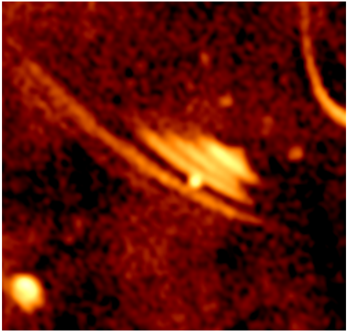


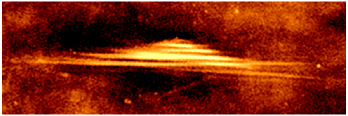
Thomas, CP, Enßlin (2020)

CR diffusion vs. streamig + diffusion



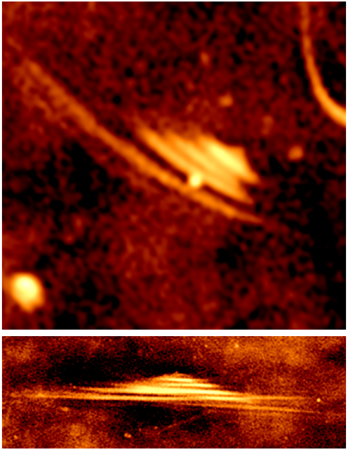
Radio synchrotron harps: testing CR propagation





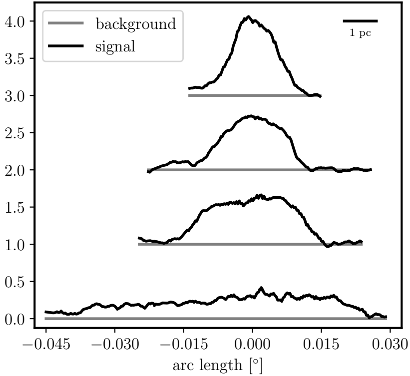
Haywood+ (Nature, 2019)

Radio synchrotron harps: testing CR propagation



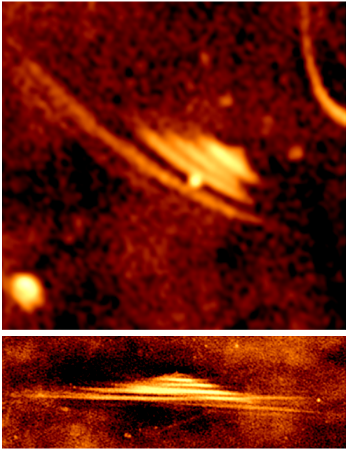
Haywood+ (Nature, 2019)

lateral radio profiles

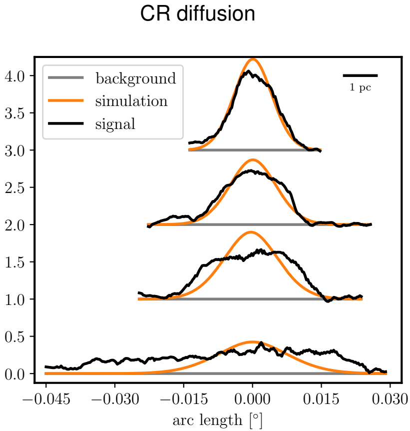


Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation

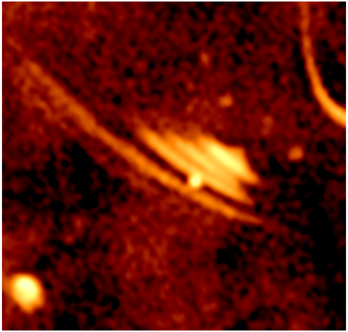


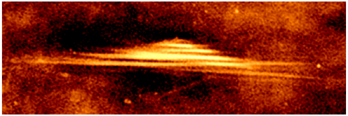
Haywood+ (Nature, 2019)



Thomas, CP, Enßlin (2020)

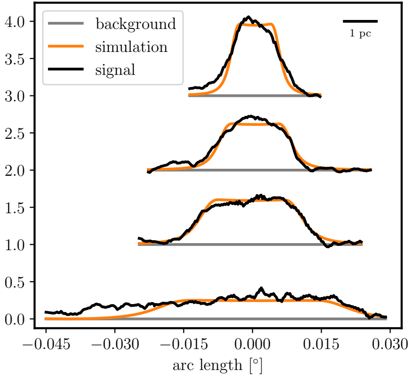
Radio synchrotron harps: testing CR propagation





Haywood+ (Nature, 2019)

CR streaming and diffusion

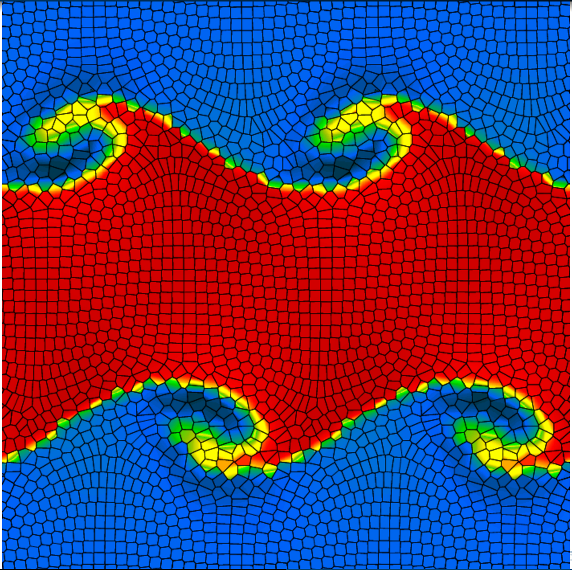


Thomas, CP, Enßlin (2020)

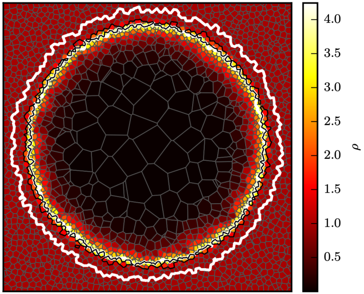
Outline

AIP

Cosmological moving-mesh code AREPO (Springel 2010)



Global MHD simulations of SNRs with CR physics

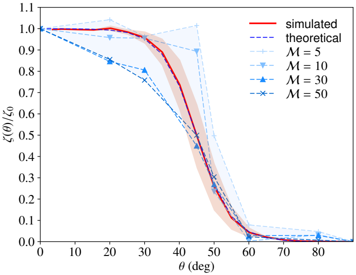


Mach number finder with CRs

CP+ (2017)

- detect and characterize shocks and jump conditions on the fly

Global MHD simulations of SNRs with CR physics

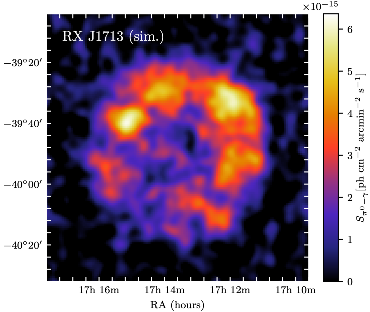


obliquity-dep. acceleration efficiency

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

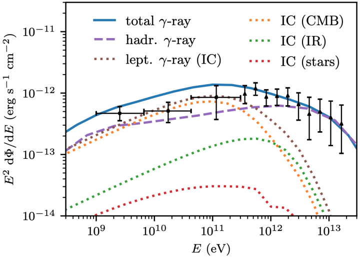


simulated TeV gamma-ray map

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

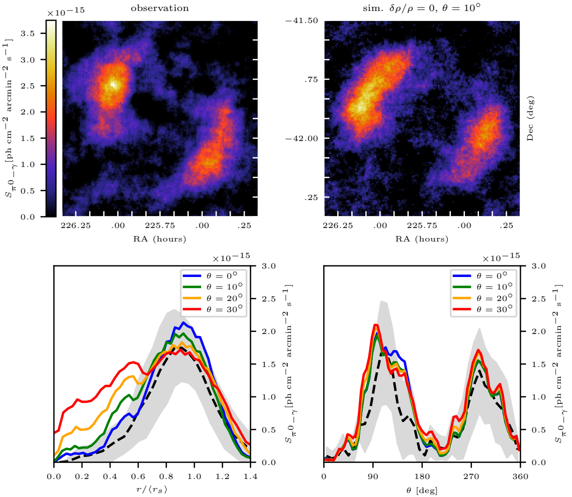


simulated gamma-ray spectrum

Winner, CP+ (2019, 2020)

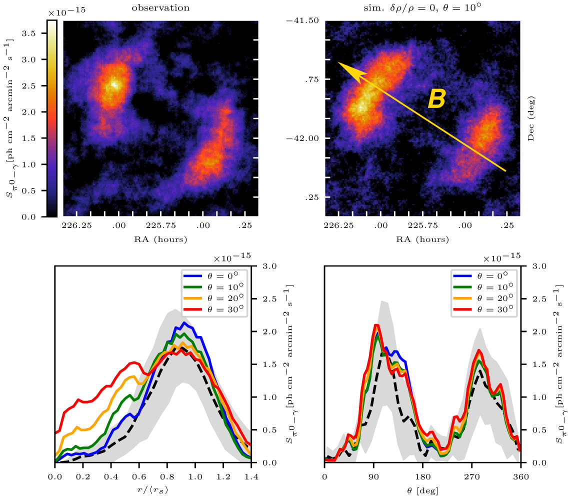
- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B
- inject and transport CR protons $\Rightarrow$ dynamical back reaction on gas flow, hadronic emission
- inject and transport CR electrons
- calculate non-thermal radio, X-ray,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

Hadronic TeV γ rays: SN 1006



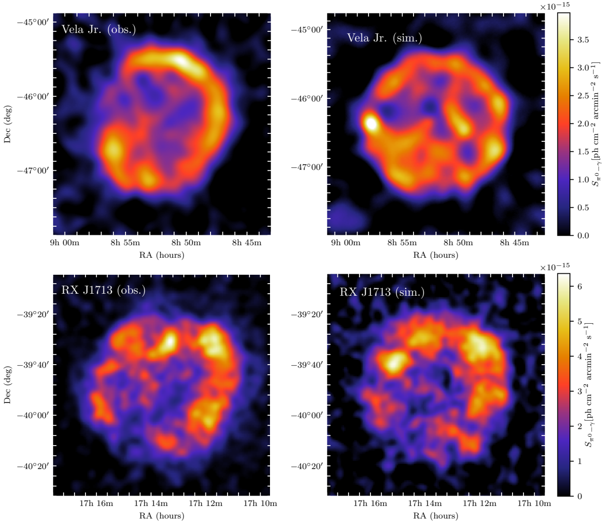
Pais & CP (2020)

Hadronic TeV γ rays: SN 1006



Pais & CP (2020)

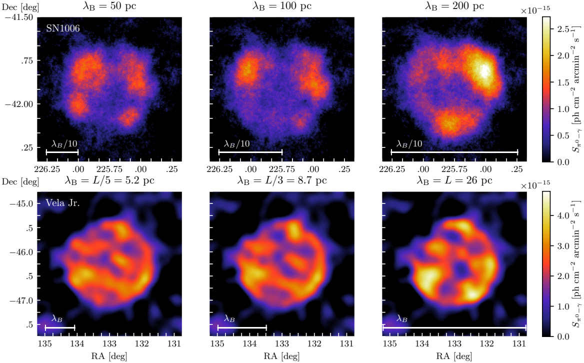
Hadronic TeV γ rays: Vela Jr. and RXJ 1713



Pais & CP (2020)

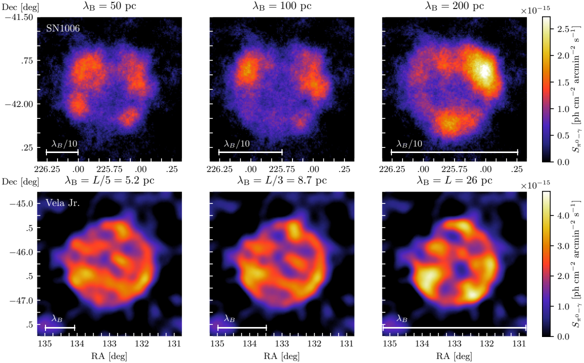
TeV γ rays from shell-type supernova remnants

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

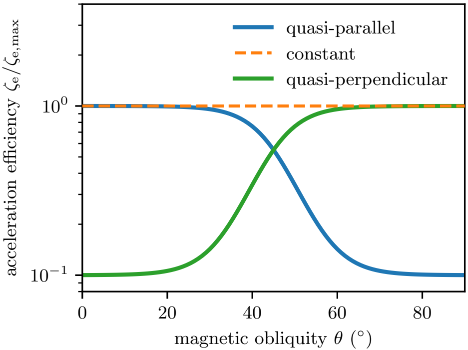


Pais, CP+ (2020)

$\Rightarrow$ 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

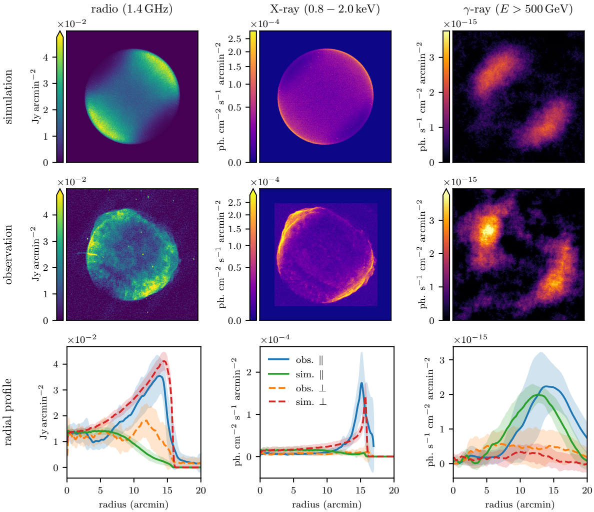
SN 1006: CR electron acceleration models



Winner, CP+ (2020)

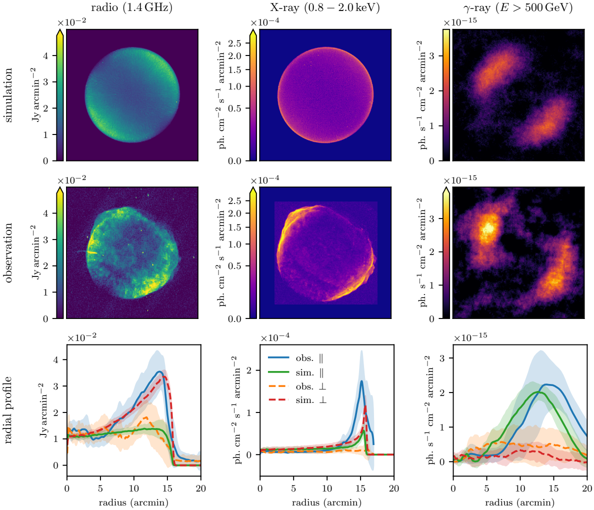
- different obliquity dependent electron acceleration efficiencies:
  1. preferred quasi-perpendicular acceleration (PIC simulations)
  2. constant acceleration efficiency (a straw man's model)
  3. preferred quasi-parallel acceleration (like CR protons)

CR electron acceleration: quasi-perpendicular shocks



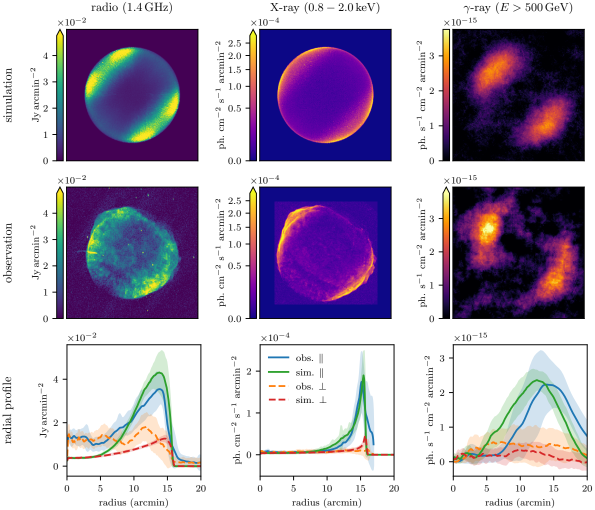
Winner, CP+ (2020)

CR electron acceleration: constant efficiency



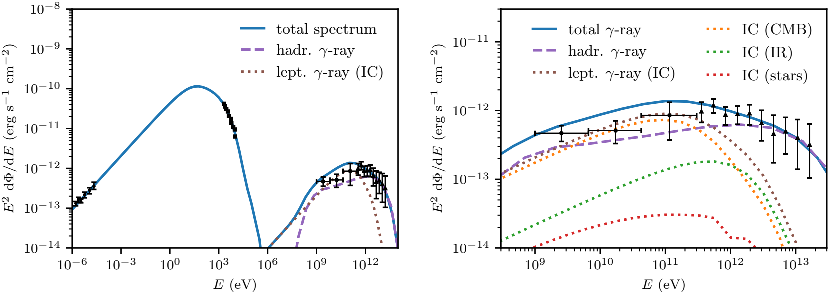
Winner, CP+ (2020)

CR electron acceleration: quasi-parallel shocks



Winner, CP+ (2020)

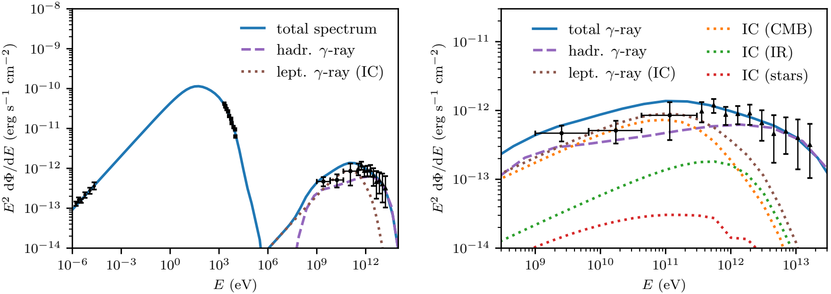
SN 1006: multi-frequency spectrum



Winner, CP+ (2020)

- quasi-parallel acceleration model fits multi-frequency spectrum

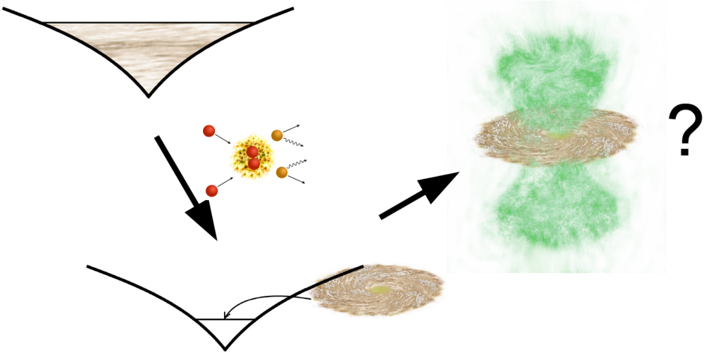
SN 1006: multi-frequency spectrum



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

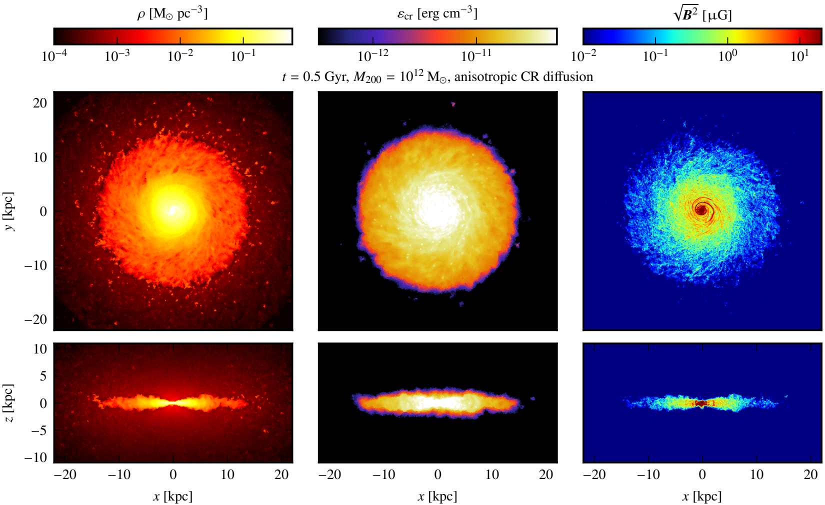


Pakmor, CP+ (2016), CP+ (2017b)

Galactic winds driven by CR diffusion in isolated disk galaxies

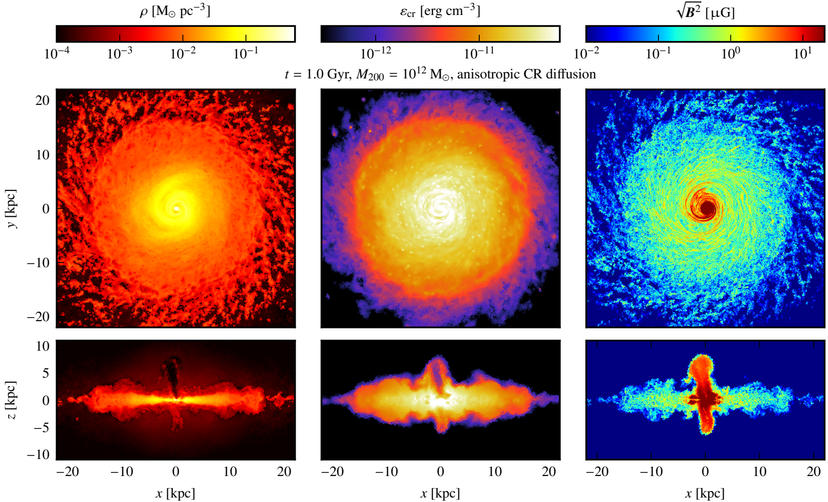
MHD + CR advection + anisotropic diffusion, $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

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



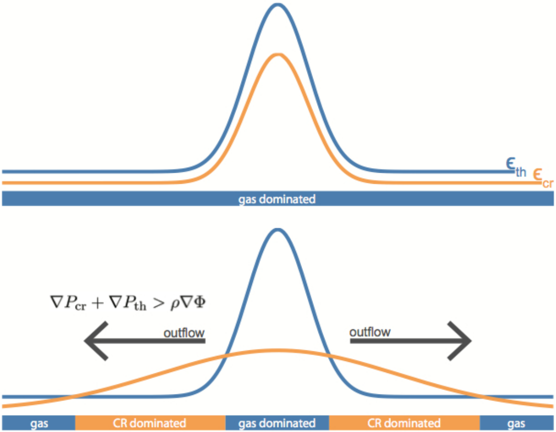
CP+ (2017b)

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



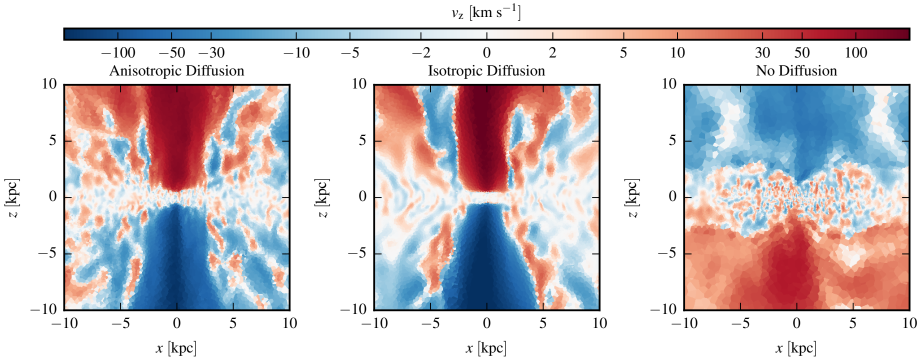
CP+ (2017b)

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

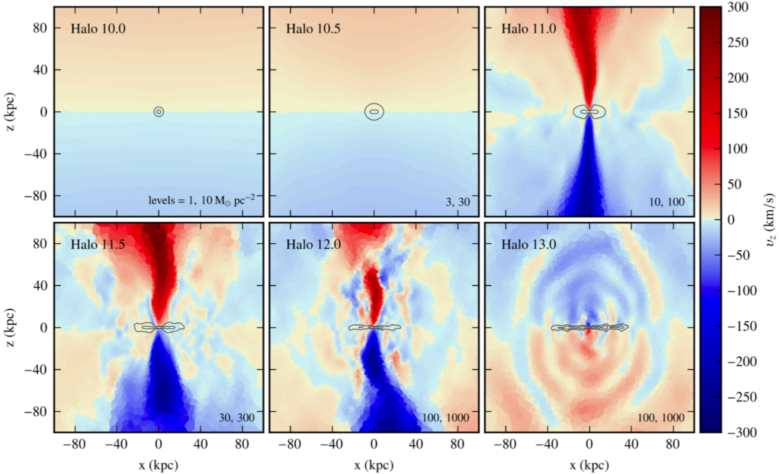


Pakmor, CP, Simpson, Springel (2016)

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

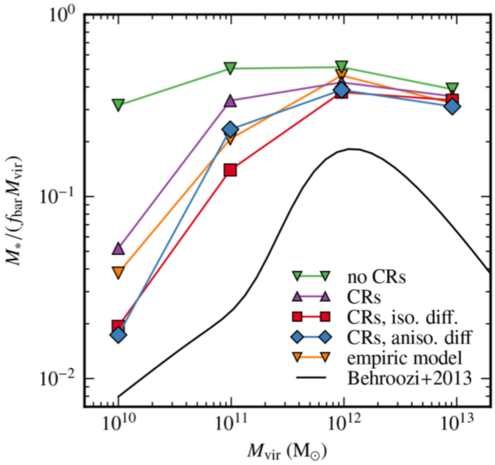
AIP

CR-driven winds: dependence on halo mass



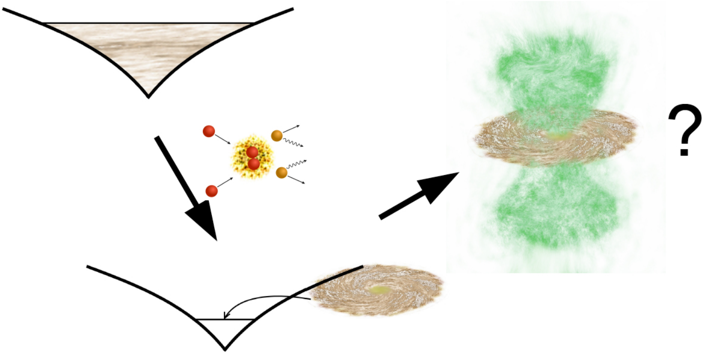
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

2. Cosmic rays and non-thermal emission



Werhahn, CP, Girichidis+ (2021a,b,c)
Cosmic rays and non-thermal emission in simulated galaxies
MHD + CR advection + anisotropic diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$
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:

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

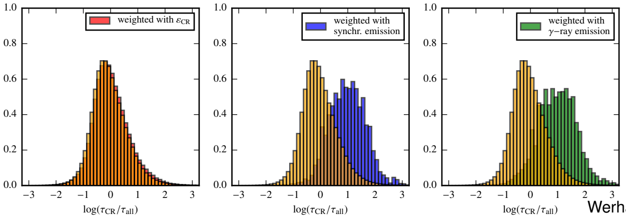
- protons: Coulomb, hadronic and escape losses (re-normalized to $\varepsilon_{\mathrm{cr}}$)
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\mathrm{ep}} = 0.02$)
  - secondaries

Steady-state cosmic ray spectra

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

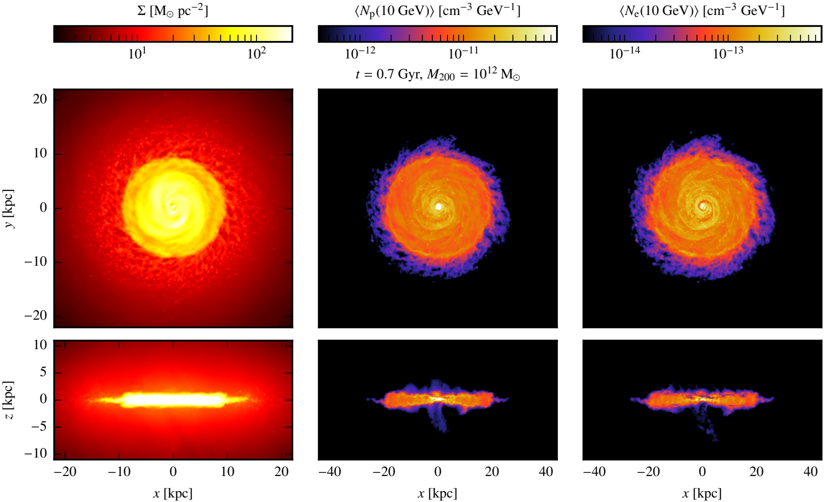
$$\frac{f(E)}{\tau_{\mathrm{esc}}} - \frac{\mathrm{d}}{\mathrm{d}E}\left[f(E)b(E)\right] = q(E)$$

- 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



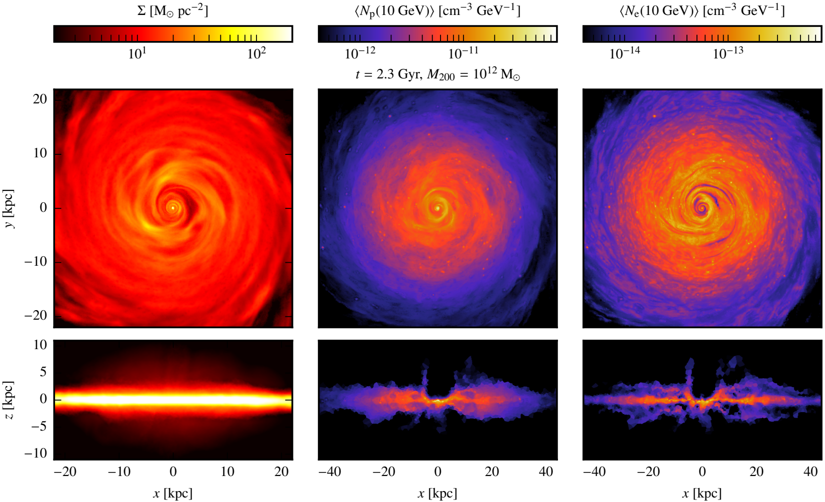
Werhahn+ (2021a)

From a starburst galaxy to a Milky Way analogy



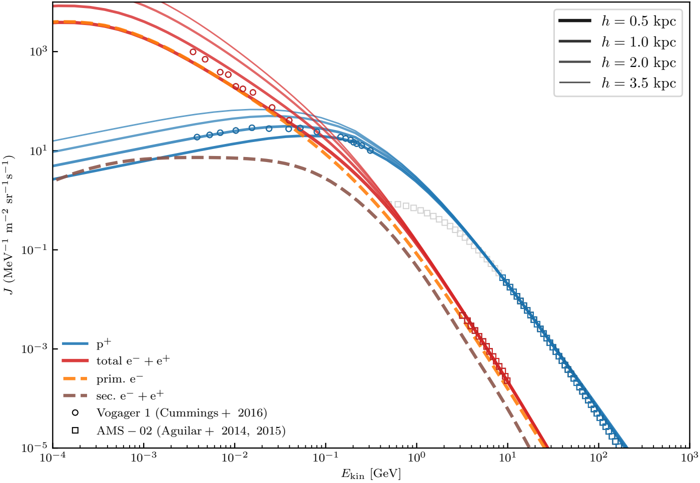
Werhahn, CP+ (2021a,b)

From a starburst galaxy to a Milky Way analogy



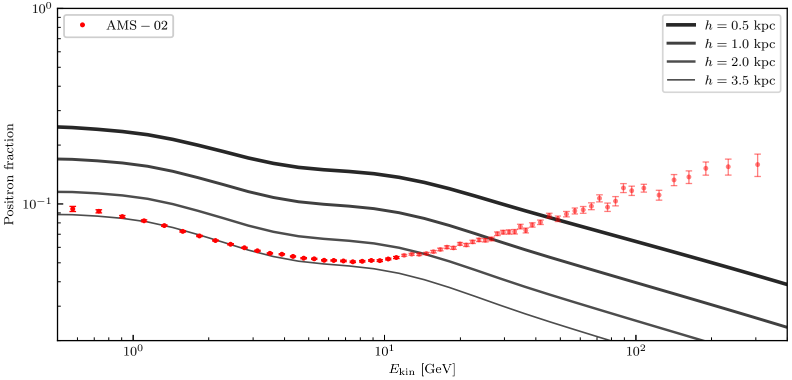
Werhahn, CP+ (2021a,b)

Comparing CR spectra to Voyager and AMS-02 data



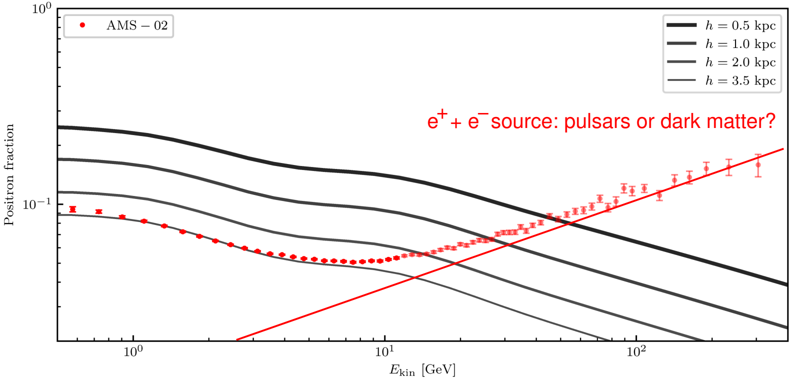
Werhahn, CP+ (2021a)

Comparing the positron fraction to AMS-02 data



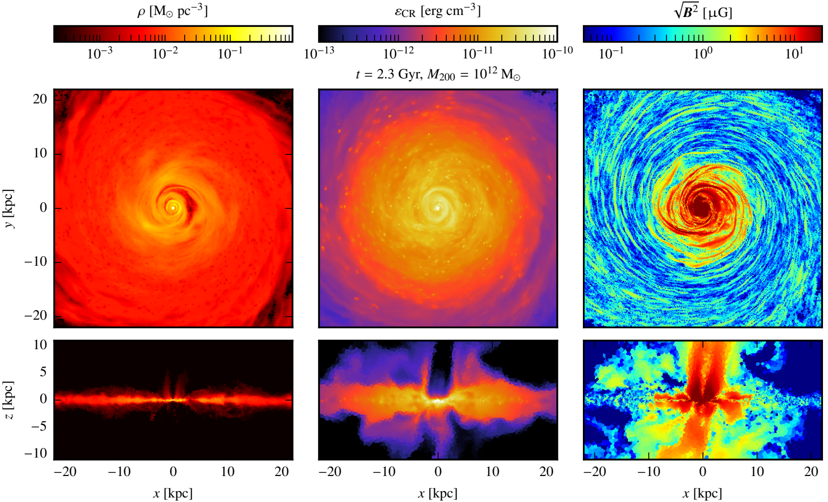
Werhahn, CP+ (2021a)

Comparing the positron fraction to AMS-02 data



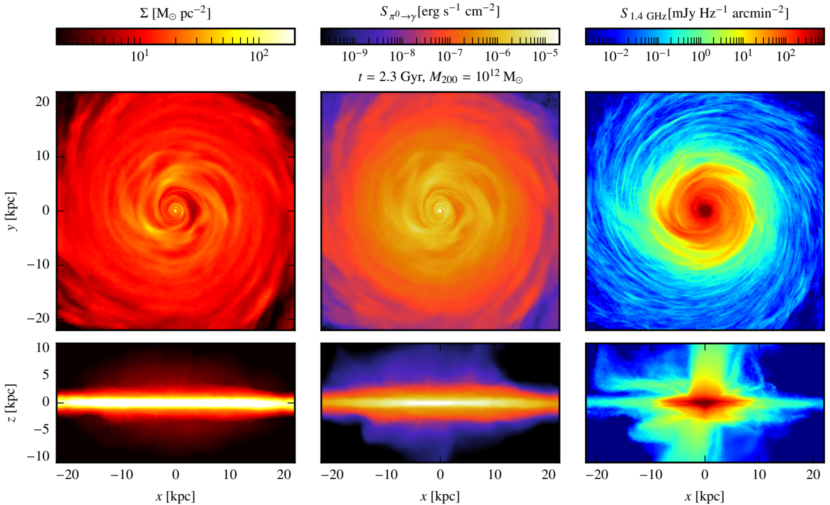
Werhahn, CP+ (2021a)

Simulation of a starburst galaxy



Werhahn, CP+ (2021b,c)

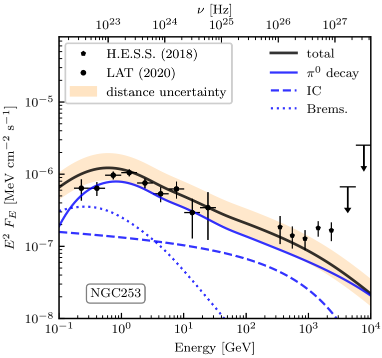
Simulation of a starburst galaxy



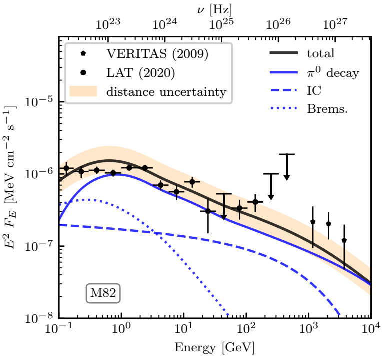
Werhahn, CP+ (2021b,c)

Gamma-ray spectra of starburst galaxies

NGC 253



Messier 82

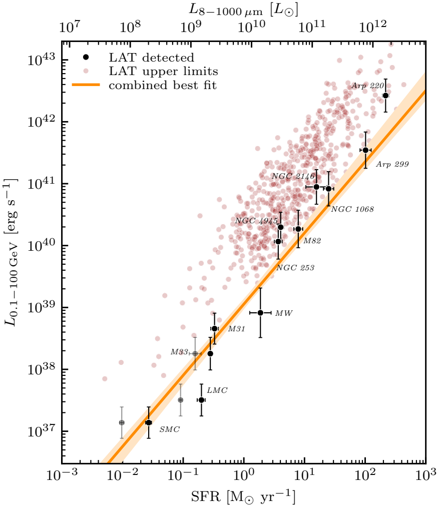


Werhahn, CP+ (2021b)

- 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

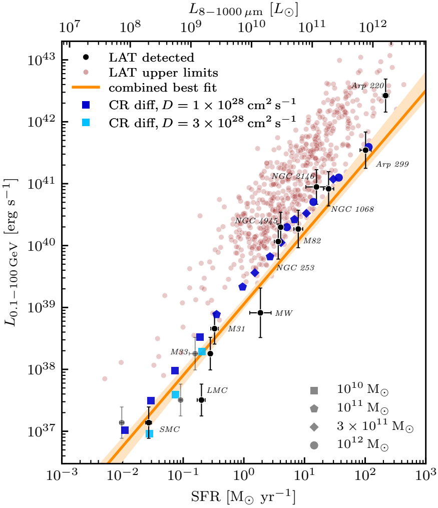
Universal conversion: star formation → cosmic rays → gamma rays



Ajello+ (2020)

Far infra-red – gamma-ray correlation

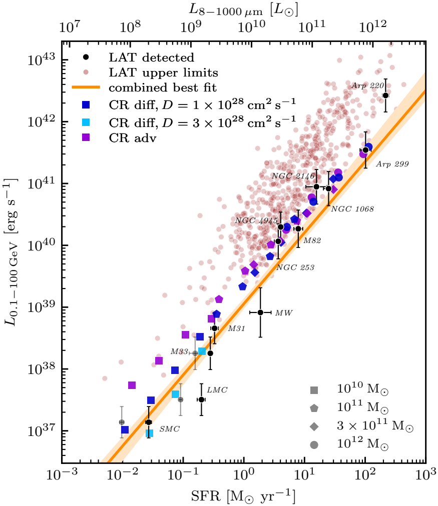
Universal conversion: star formation → cosmic rays → gamma rays



Werhahn, CP+ (2021b)

Far infra-red – gamma-ray correlation

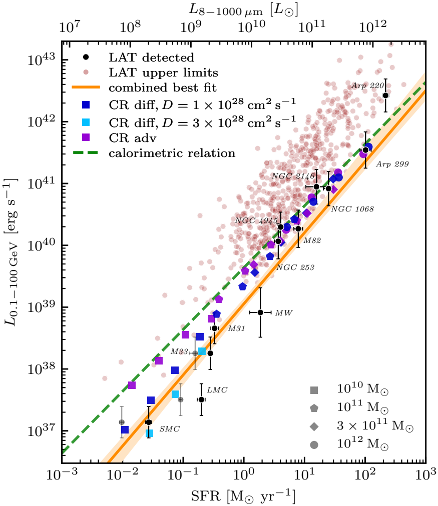
Universal conversion: star formation → cosmic rays → gamma rays



Werhahn, CP+ (2021b)

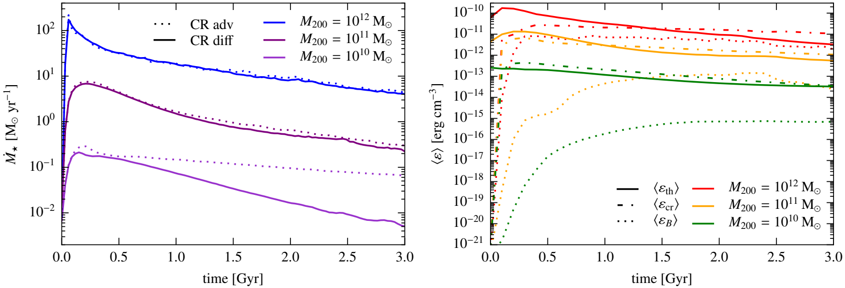
Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Werhahn, CP+ (2021b)

Time evolution of SFR and energy densities



CP, Werhahn+ (2022)

- 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

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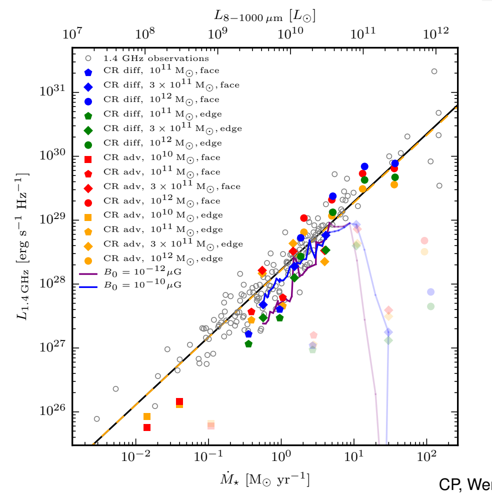
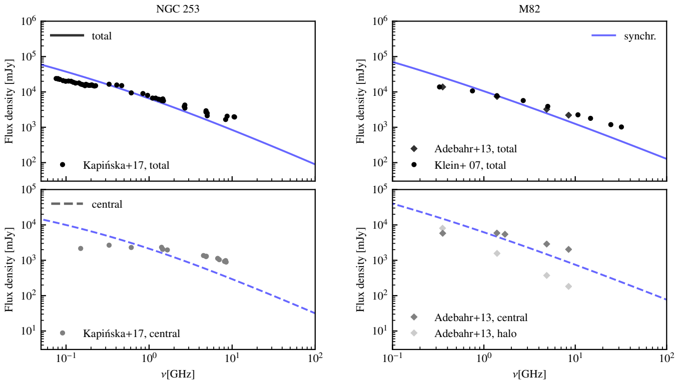
Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



CP, Werhahn+ (2022)

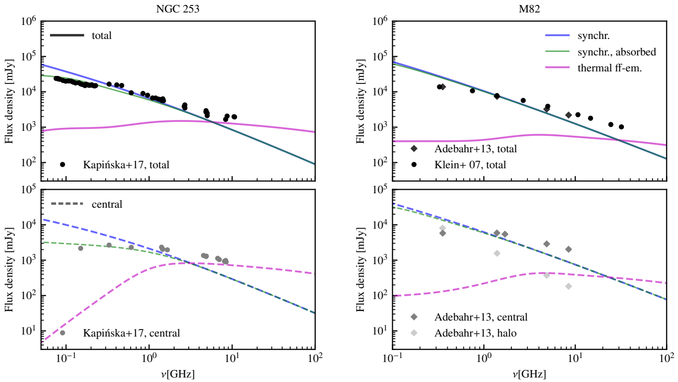
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)

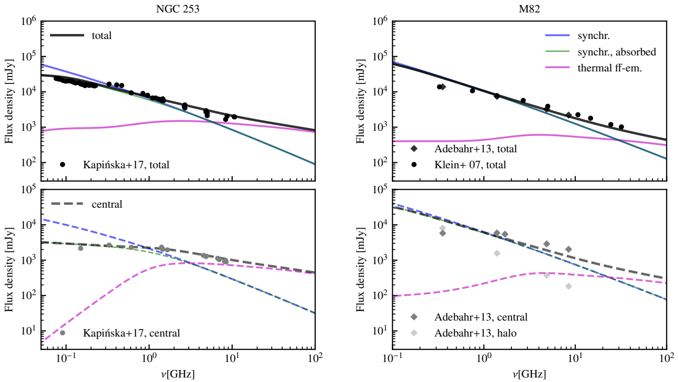
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν)

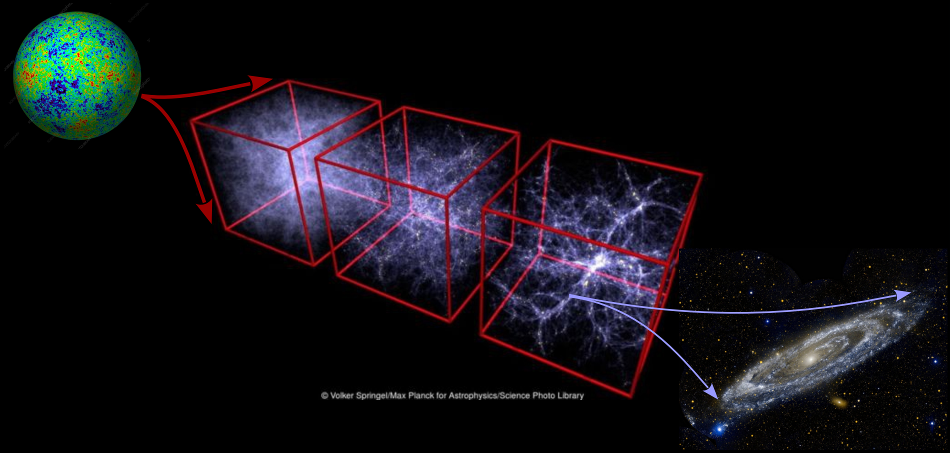
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν) required to match (total and central) spectra

3. Cosmological galaxy formation



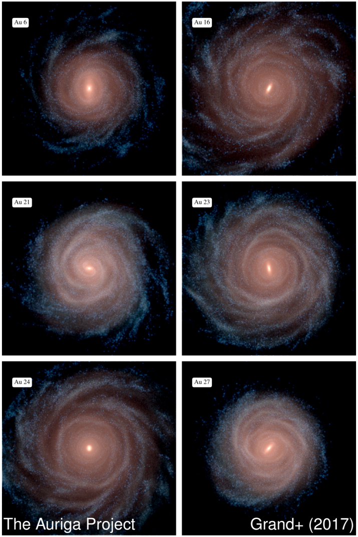
Cosmic rays in cosmological galaxy simulations

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 $z = 128$

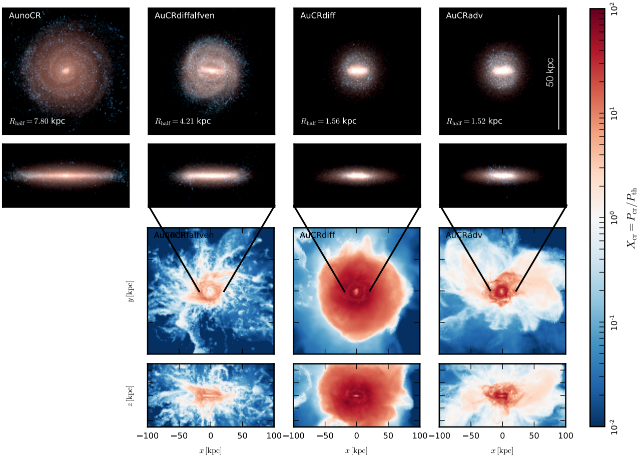
Simulation suite (Buck, CP+ 2020)

- 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

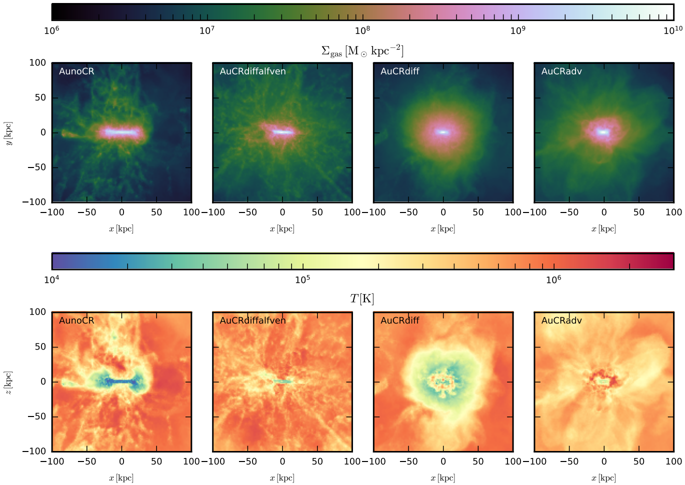
Auriga MHD models: CR transport changes disk sizes



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 match γ-ray and radio spectra, reproduce correlations with FIR and calibrate CR feedback
- CRs modify galaxy disk sizes and the circumgalactic medium

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

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