Cosmic rays — different species across the spectrum

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AIP Potsdam
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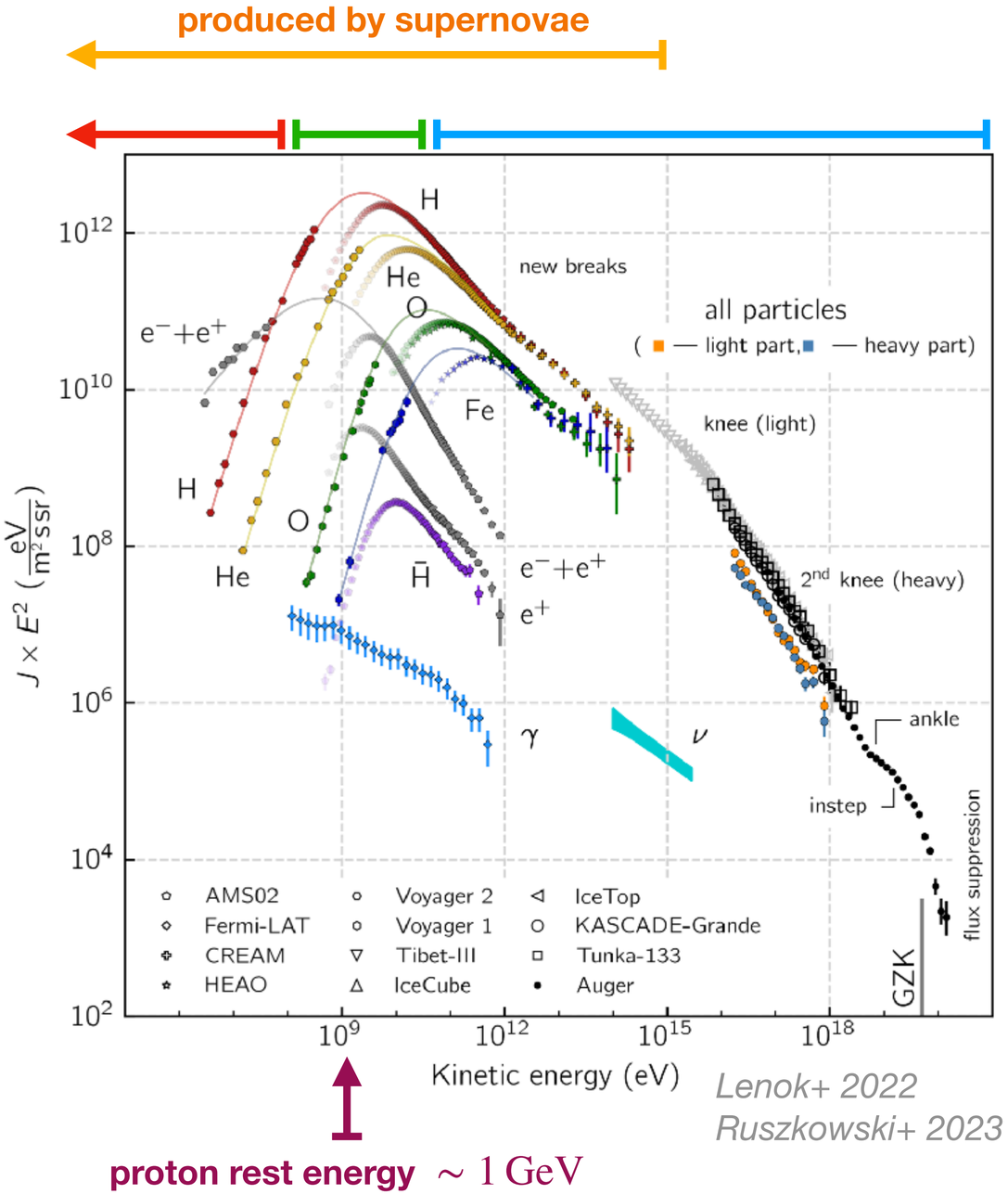
Cosmic ray facts

- no rays, but high energy particles $(p, e^+, e^-, \alpha \ldots)$
- **low-E CRs** *(Padovani+2020)*
  Large cross section with gas, strong losses
  heating of dense star forming regions
- **GeV CRs** *(Ferriere 2001, Ruszkowski & Pfrommer 2023)*
  Most of energy (weak losses)
  Dynamically relevant via pressure:
  similar E-densities: $e_{\rm cr} \sim e_{\rm kin} \sim e_{\rm therm} \sim e_{\rm mag}$
- **high-E CRs** *(Kotera&Olinto 2011)*
  Low integrated energy
  galactic ($E \lesssim 10^{15}\,$eV, SNe), *"knee"*
  extragalactic ($E \gtrsim 10^{15}\,$eV, AGN)
  important as **observational diagnostics**

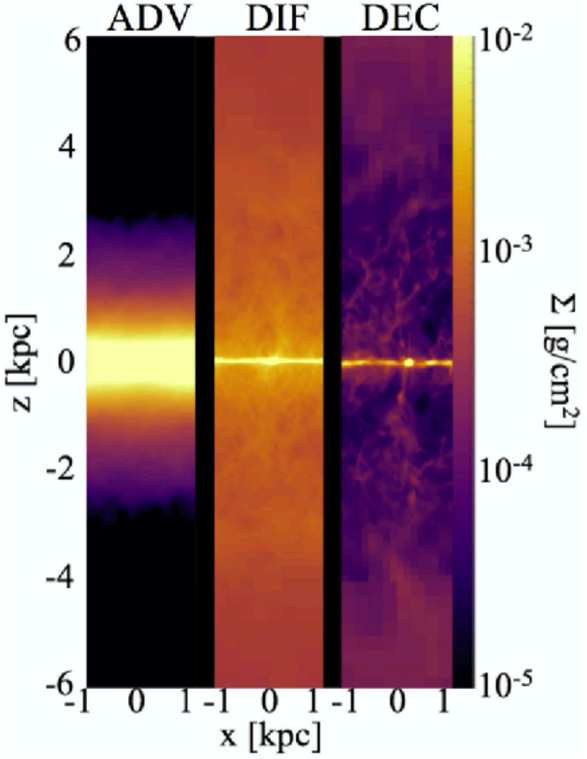


Lenok+ 2022
Ruszkowski+ 2023

proton rest energy $\sim 1\,$GeV

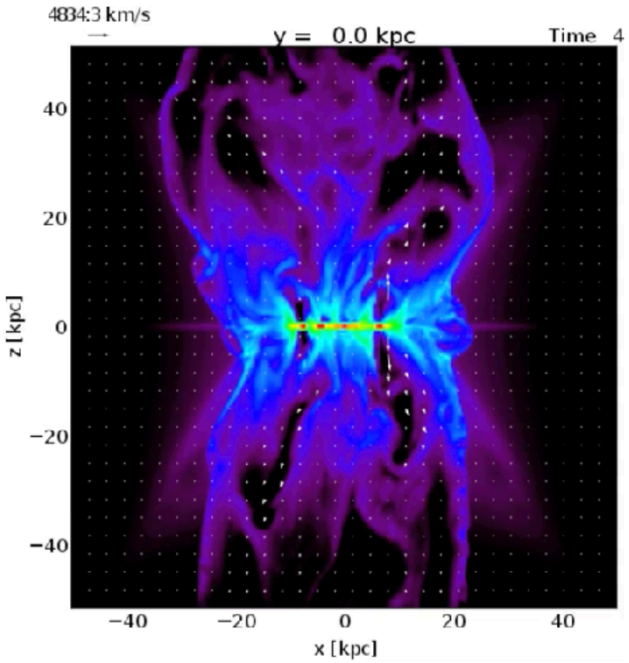
Different setups, similar conclusion

stratified boxes (ISM)



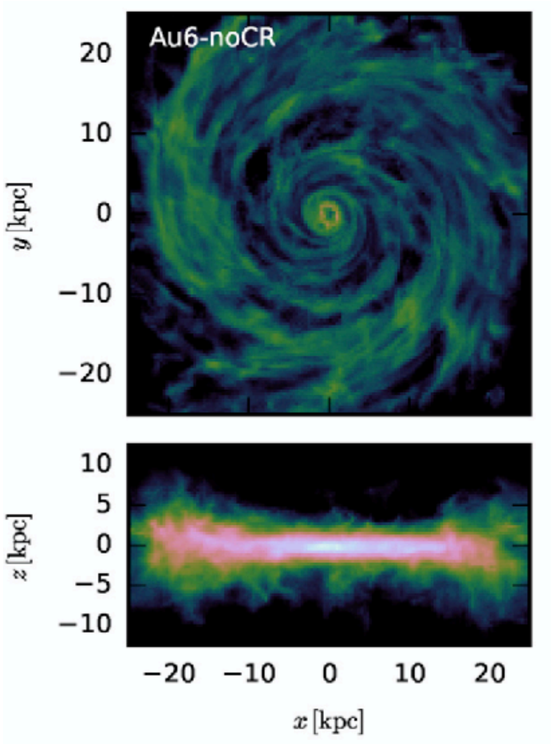
Hanasz+ 2003, Girichidis+ 2016,2018, Simpson+ 2016, Dubois+ 2016, Farber+ 2018, Armillotta+ 18,21,23 Commercon+ 2019, Butsky+ 2020, Rathjen+ 2021,2022, Armillotta+ 2024,2025, Sike+ 2024

isolated galaxies



Booth+ 2013, Ruszkowski+ 2017a, Pakmor+ 2016, Pfrommer+ 2017, Jacob+ 2018, Dashyan+ 2020, Semenov+ 2021, Girichidis+ 2022/24, Thomas+ 2021,2023, Farcy+ 2022, Nunez-Castineyra+ 2022, Peschken+ 2023, Kjellgren+ 2025

cosmological galaxies



Jubelgas+ 2008, Salem+ 2014, Chan+ 2018, Hopkins+ 2020/2021/2022, Buck+2020, Ji+2020, Böss+ 2023, Rodriguez Montero+ 2024, Ramesh+ 2025

CRs are good candidate to drive outflows / alter CGM! Details are complicated…

Current CR construction sites

Where are the main uncertainties

CR transport

- diffusion + streaming
- energy transfer
  $B \leftrightarrow \mathrm{CR} \leftrightarrow \mathrm{gas}$

Mateusz Ruszkowski
Lucia Armillotta
Timon Thomas

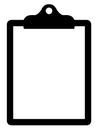
Brandon Sike
Karin Kjellgren

- theory: pen&paper, 70s
- bottom-up plasma physics models (PIC)

e.g. Holcomb+2019, Shalaby et al. 2021/2023, Lemmerz et al. 2024

spectrally resolved CRs

- cover full E-range
- E-dependent cooling, transport
- live spectrum $(t, \mathbf{x})$
- precise connection to observations
  - gamma rays
  - radio synchrotron



Nimatou Seydi Diallo
Daniel Karner

different species

- include
  - electrons
  - secondaries
  - unstable isotopes
- introduce CR clocks
- detailed comparison to Milky-Way

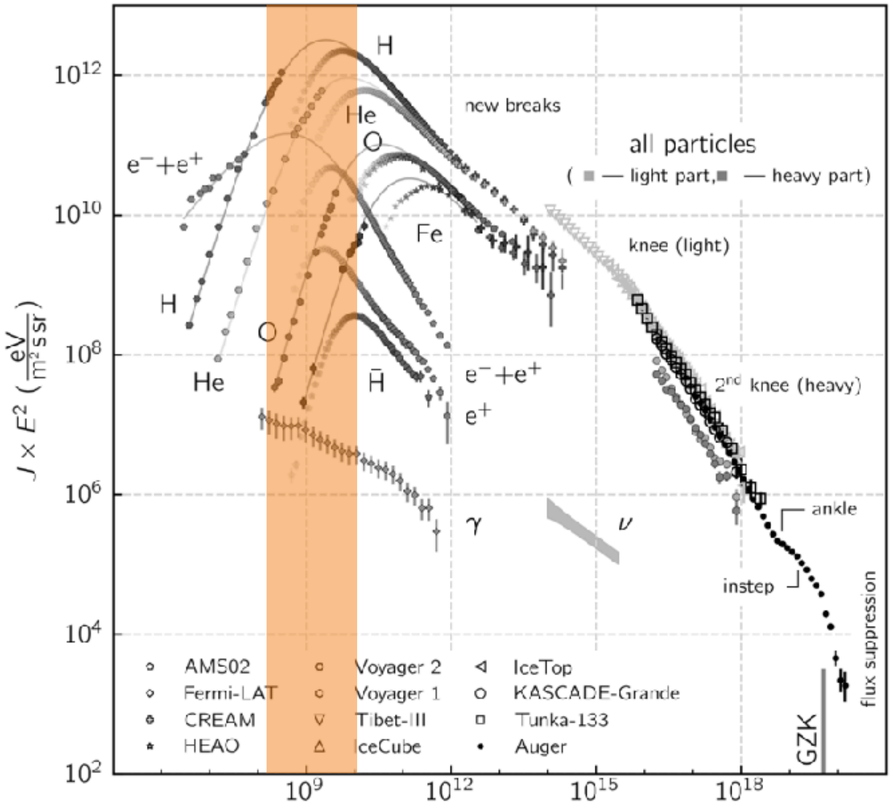
Allison Matthews

Ralf-Jürgen Dettmar

Grey approximation

assume universal spectrum

- total energy, dominated by GeV protons
- effective cooling+transport at GeV
- $P_{\mathrm{CR}} = (\gamma_{\mathrm{CR}} - 1) e_{\mathrm{CR}},\ \gamma_{\mathrm{CR}} = 4/3$



Full spectrum

temporally evolving spectrum

- investigate particle distribution fct.
- time evolution: Fokker-Planck eq.
  Skilling 1971, 1975a,b,c

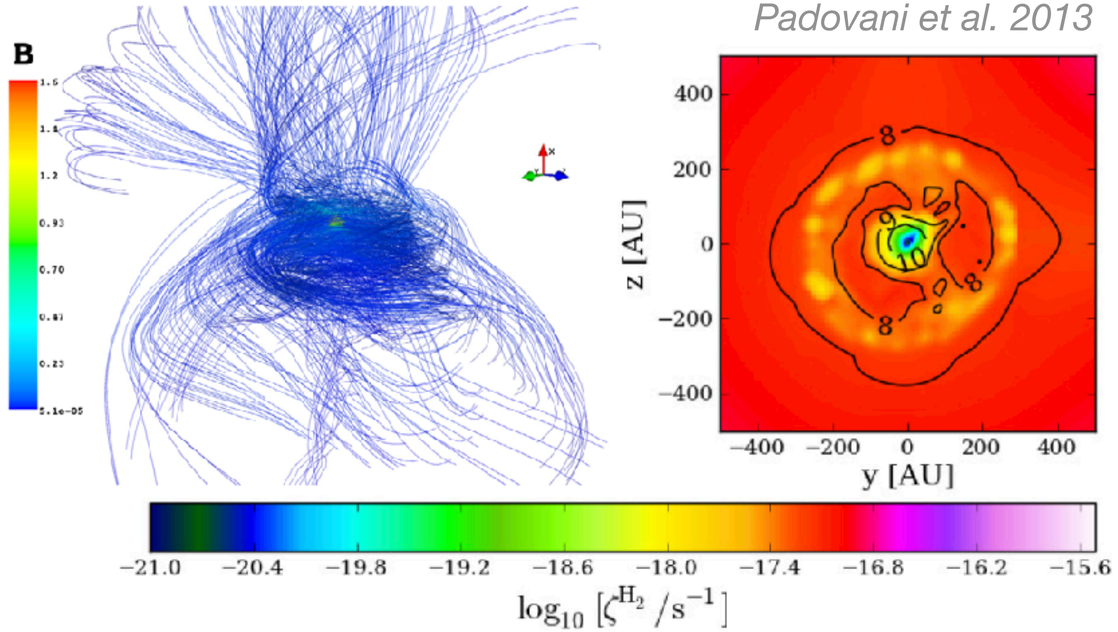
$$\frac{\partial f}{\partial t} = \underbrace{-\boldsymbol{u}\cdot\nabla f}_{\text{advection}} + \underbrace{\nabla\cdot\left(\mathsf{D}_{xx}\cdot\nabla f\right)}_{\text{diffusion}} + \underbrace{\frac{1}{3}(\nabla\cdot\boldsymbol{u})\,p\frac{\partial f}{\partial p}}_{\text{adiabatic process}} + \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(b_l f + D_{pp}\frac{\partial f}{\partial p}\right)\right]}_{\text{other losses and Fermi II acceleration}} + \underbrace{j}_{\text{sources}}$$

- transport, losses, sources: function p
  simple diffusion: $D(p) \propto p^{0.5}$

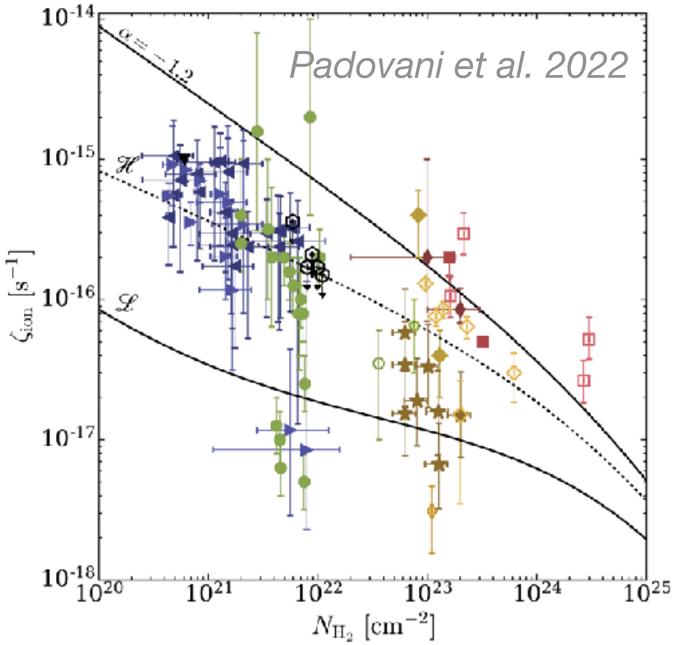
Low energy CRs - CR ionisation

review by Padovani+ 2020
see also Silsbee+ 2018, Seta+ 2018

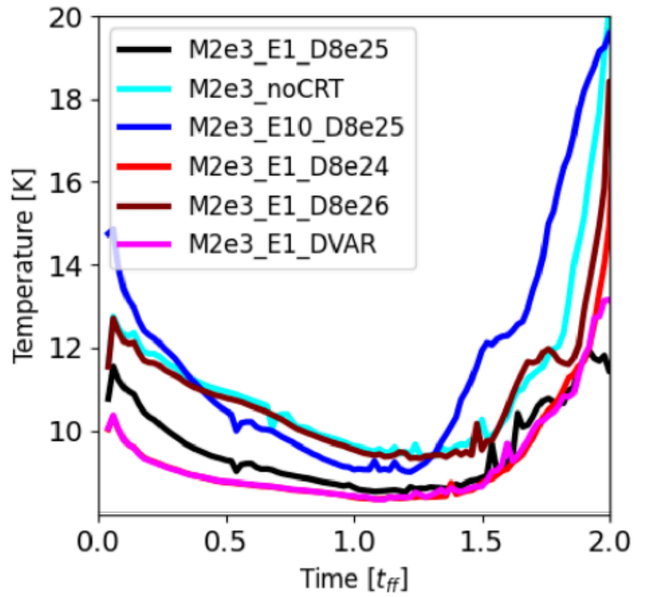
Padovani et al. 2013



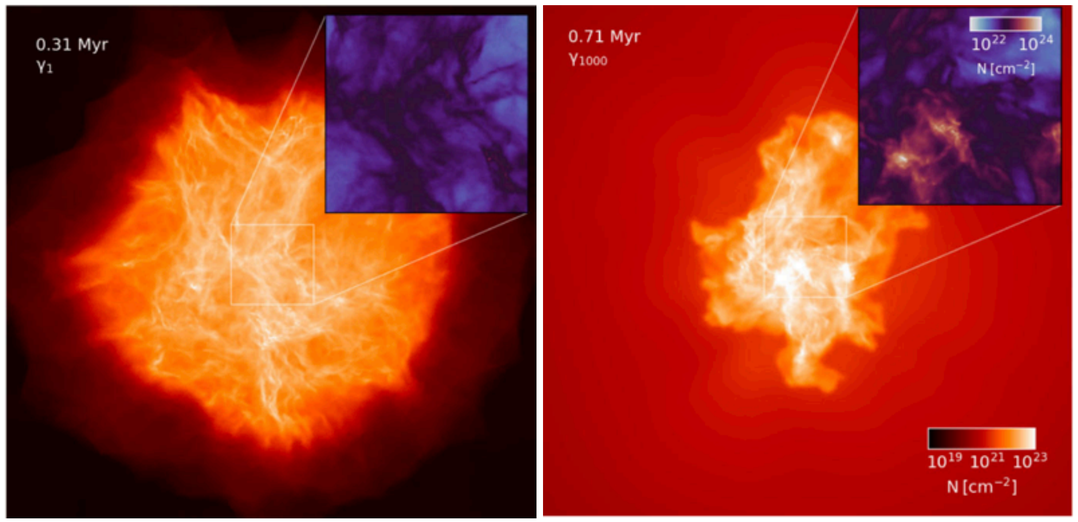
Padovani et al. 2022



Axen et al. 2024



Cusack+ 2025



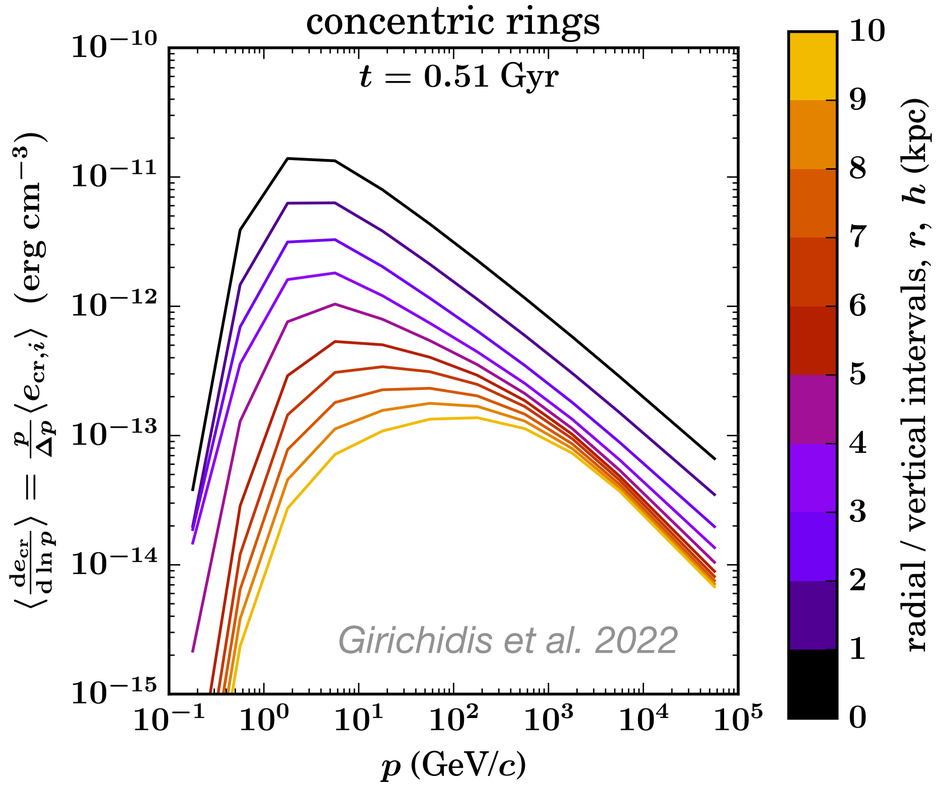
- CR ionisation rate: $10^{-18} - 10^{-14}\,\mathrm{s}^{-1}$
- low-E CR set temperature floor
- Impact on fragmentation and star formation *e.g. Brugaletta+PG+ 2025*

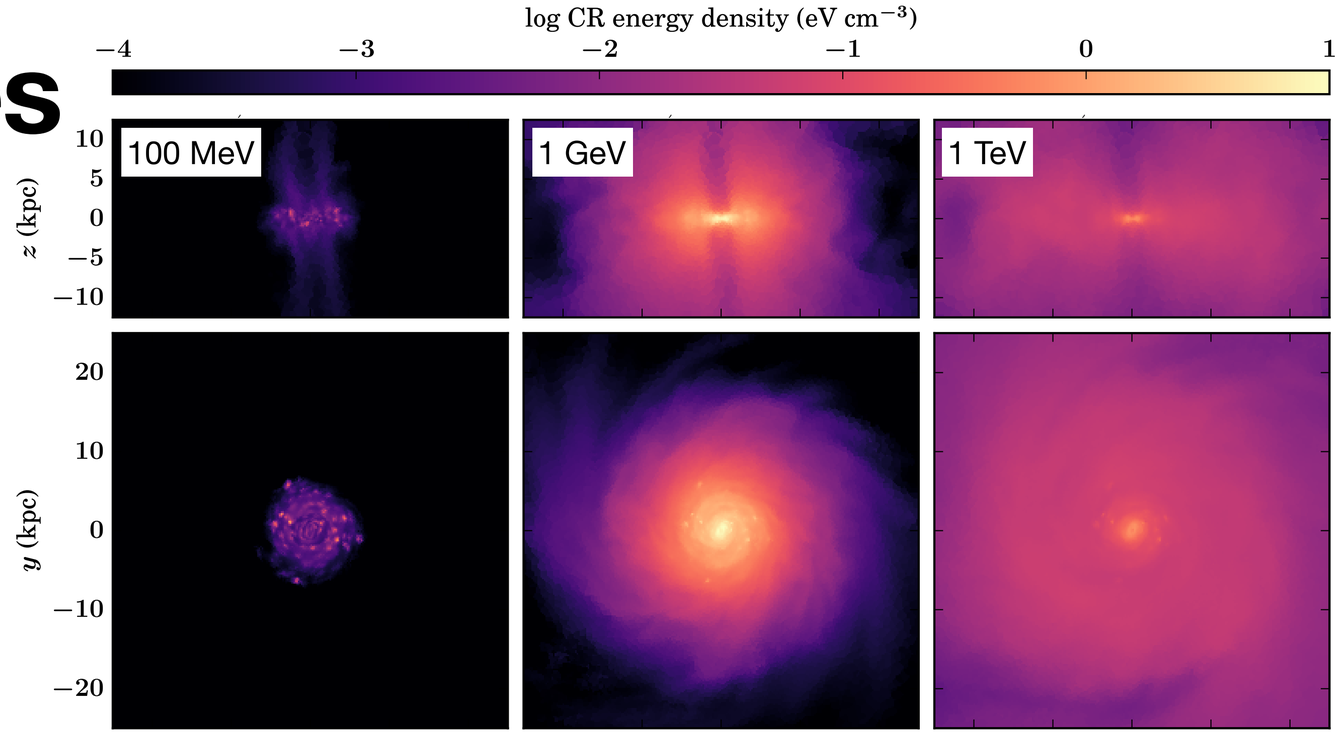
Spectral CR in galaxies

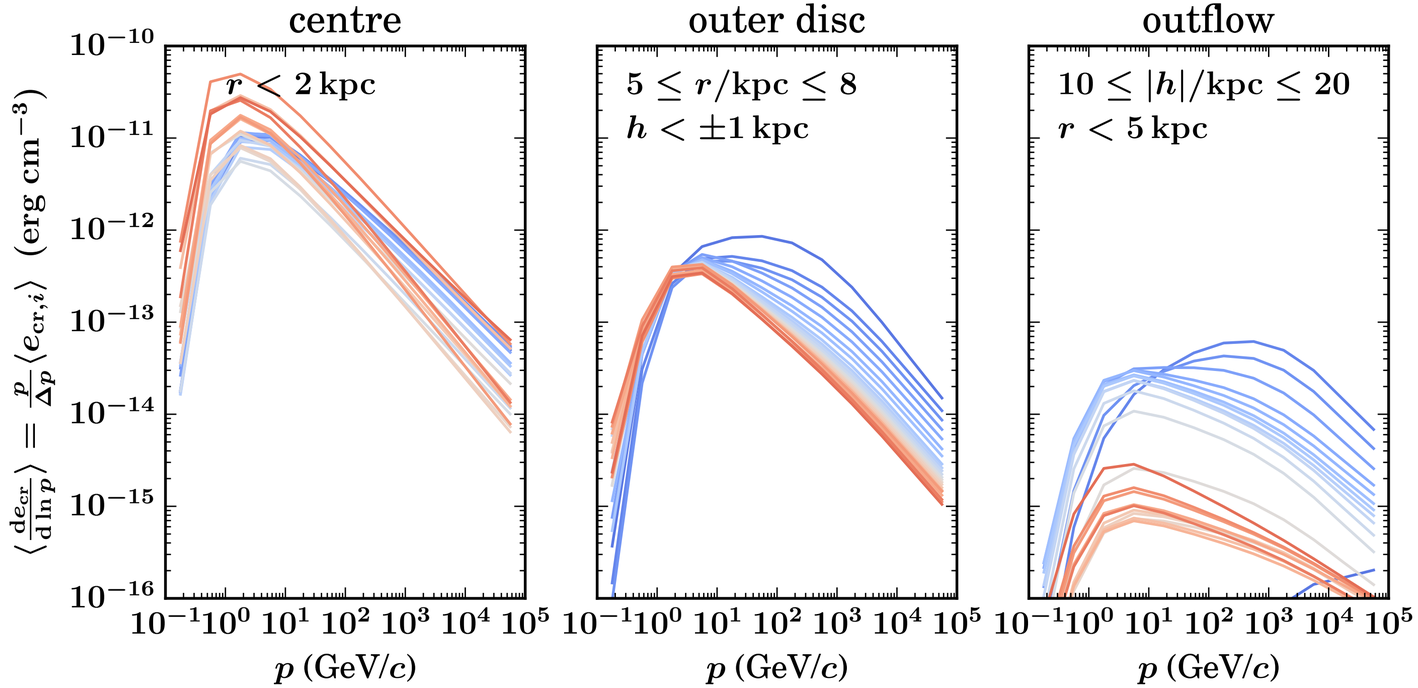
full spectrum in every cell

Arepo (Springel 2010, Weinberger+2020)
Arepo+CRs (Pakmor+2016, Pfrommer+2017)
CRSPEC (Girichidis et al. 2020,2022)

- high energy CR escape faster
  spectra at large distance: more high-E CRs
- larger distance -> lower total CR energy
- **no universal / steady state spectrum**

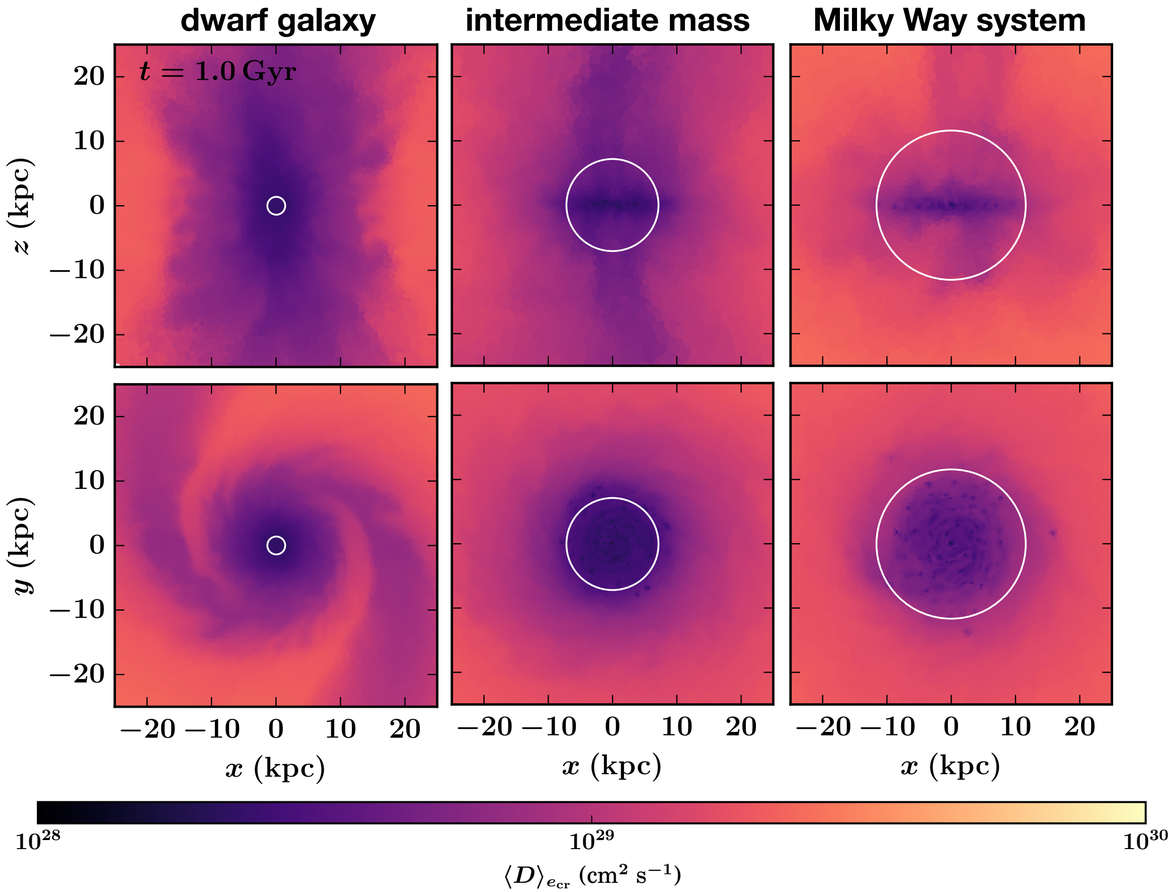






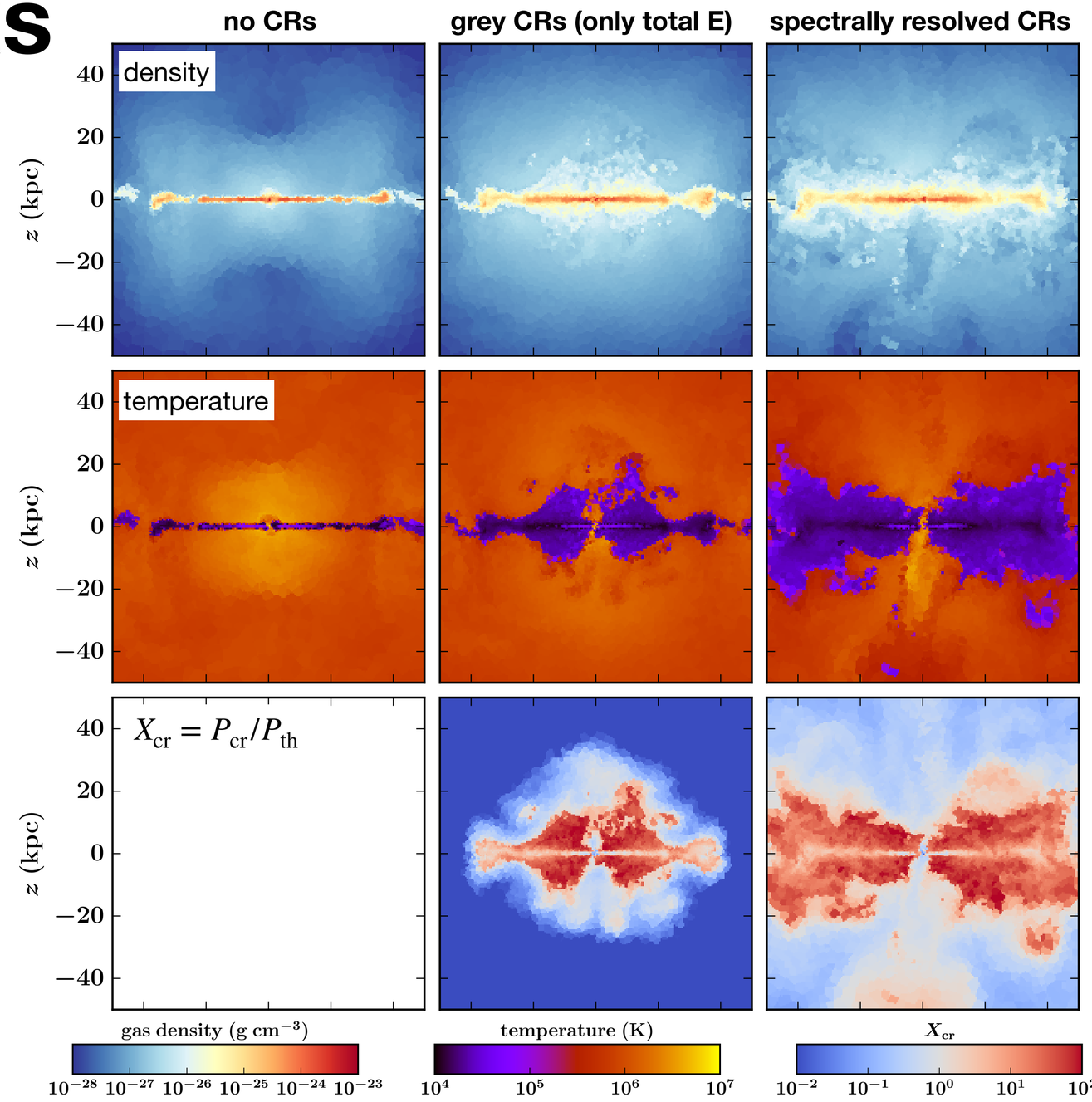
Spectrally resolved CRs

- variations in spectra ⇒ variations in diffusion
- large region of cold CGM, cold gal. fountain
- large region with CR dominated pressure



Milky Way model

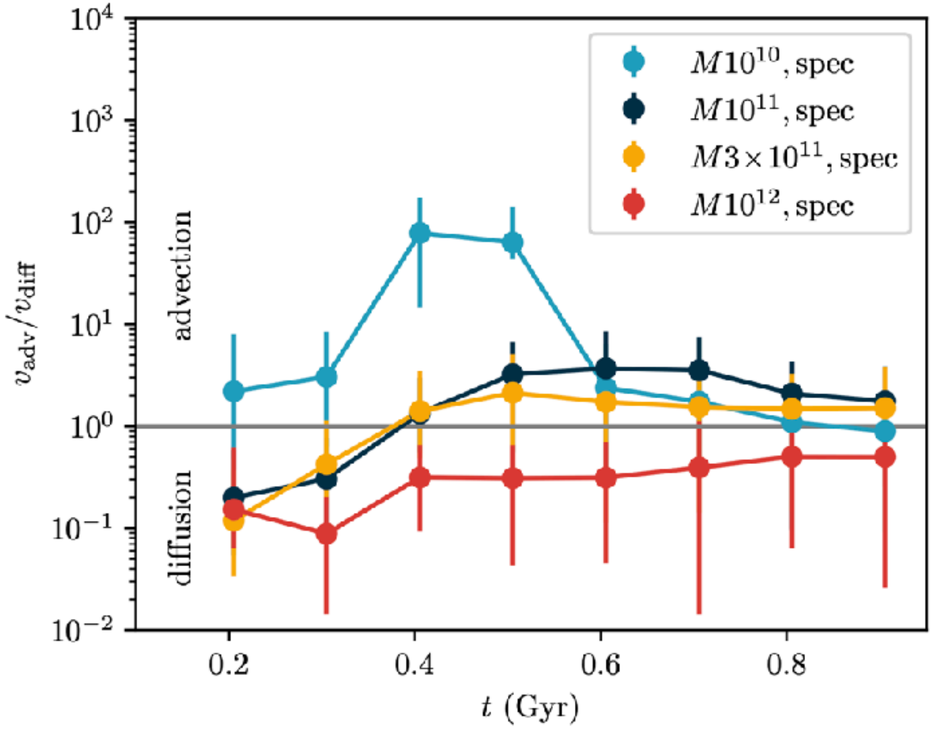
Girichidis et al. 2024



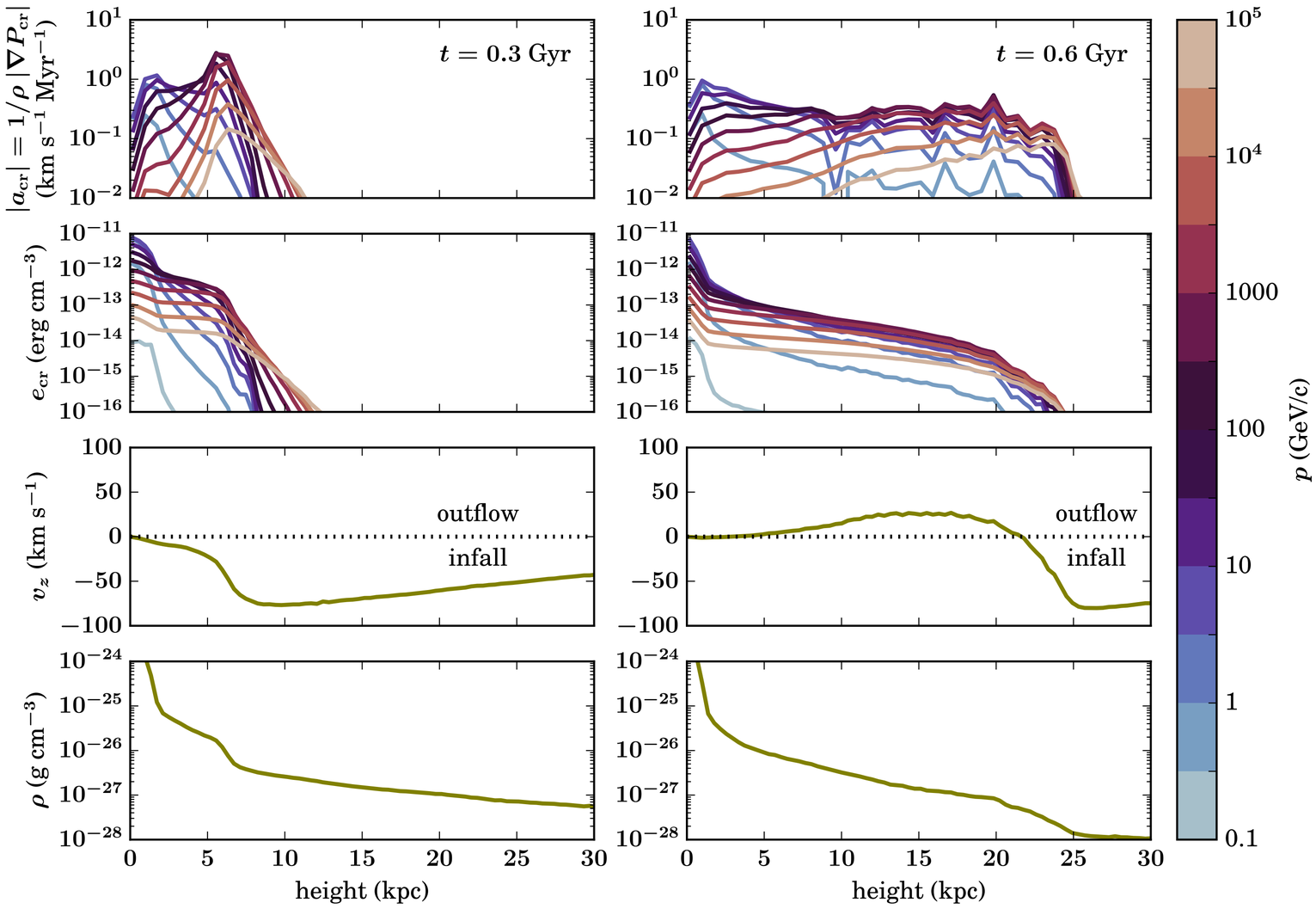
Advection vs. diffusion

- dwarfs:
  shallow potential, strong outflows
  dominated by advection

- Milky Way:
  deep potential, weak outflows
  dominated by diffusion



dwarf galaxy



Girichidis et al. 2024

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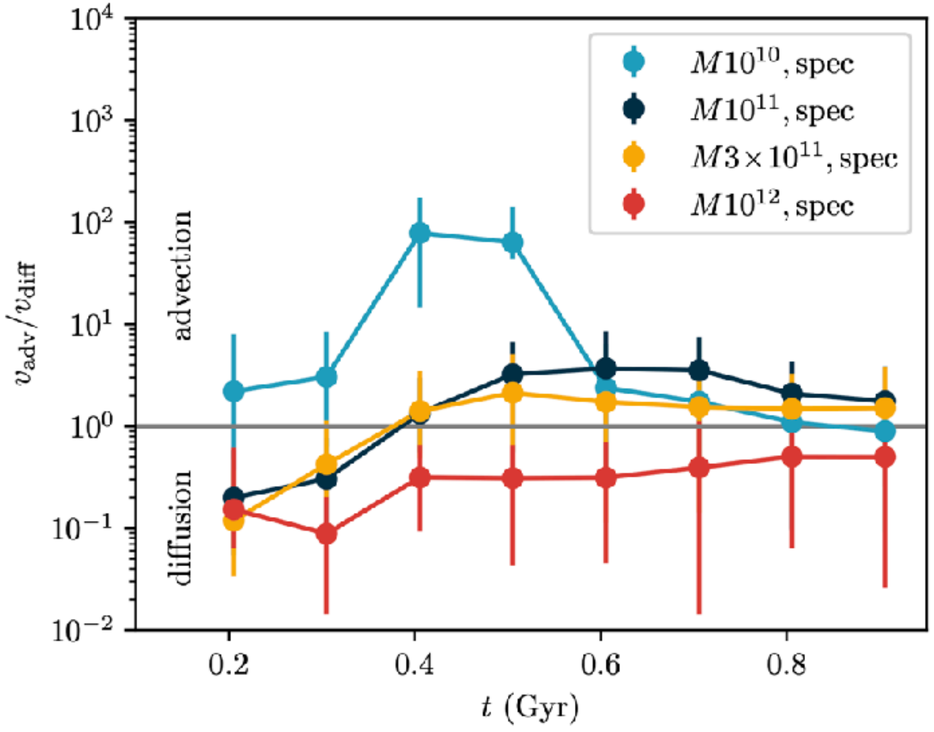
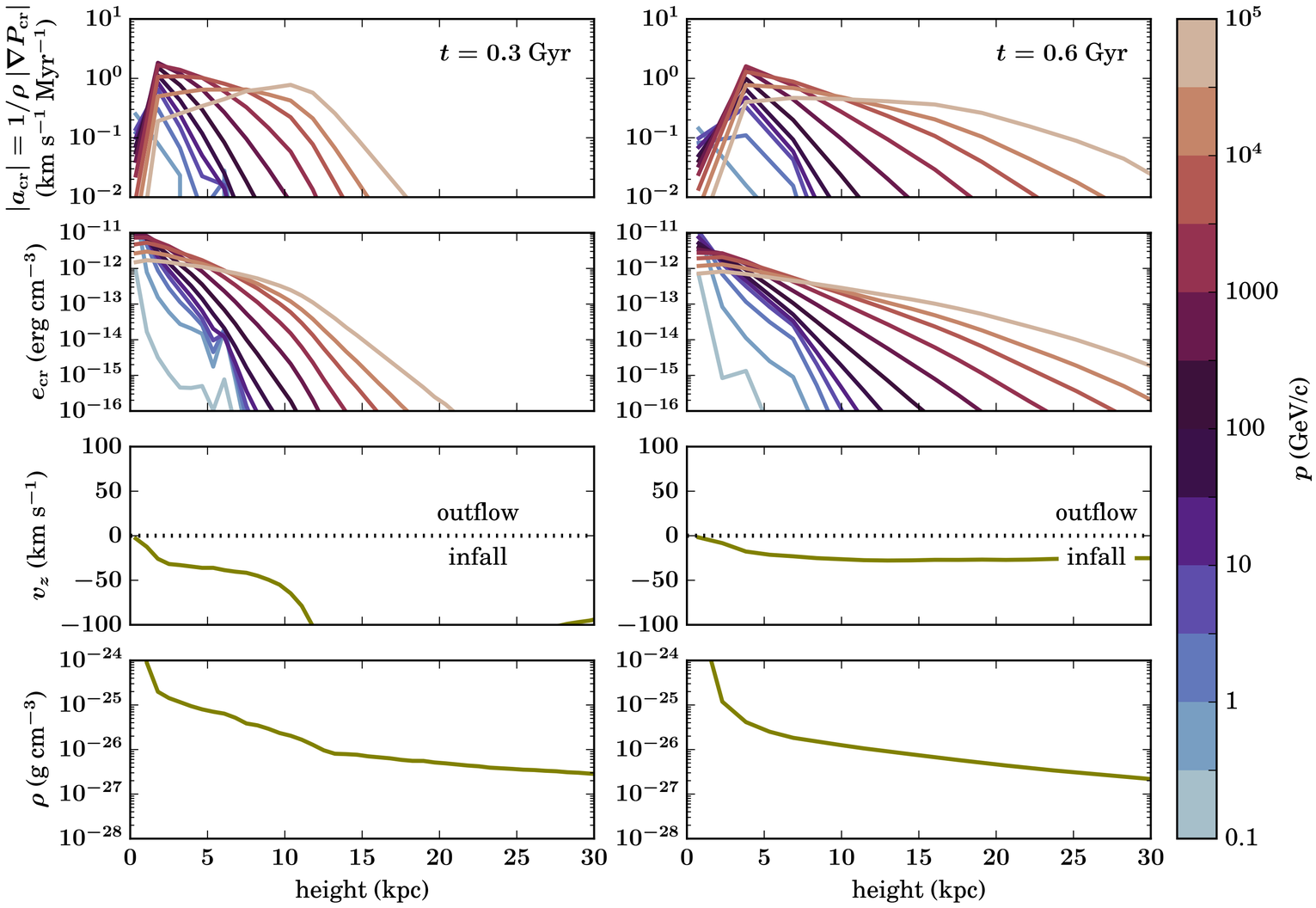


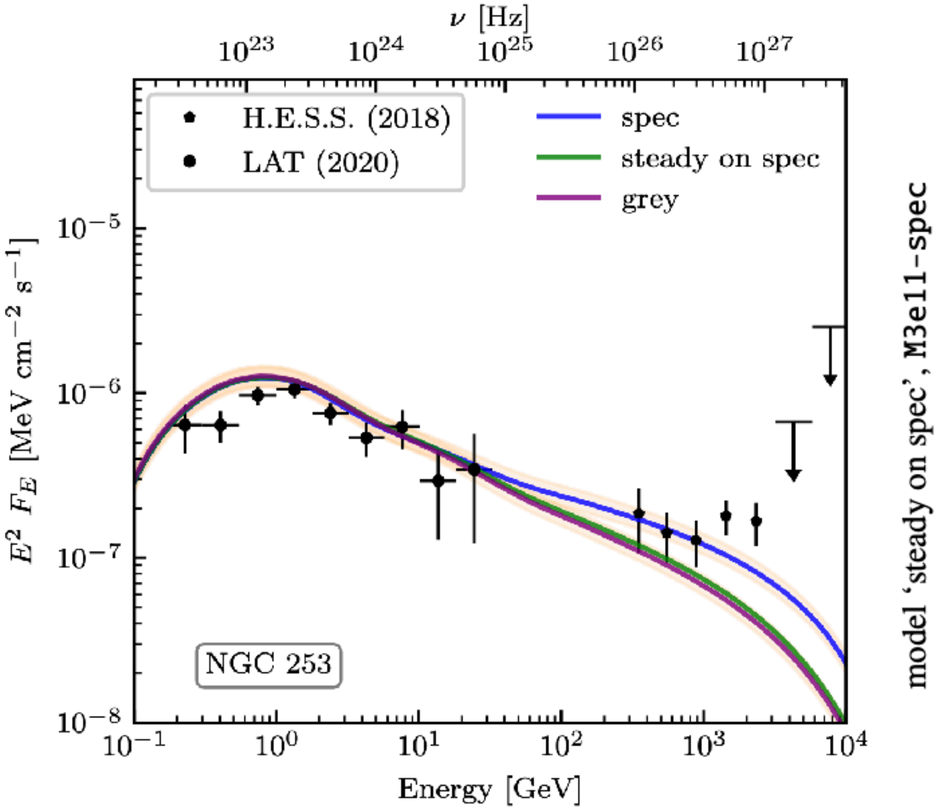
Milky Way

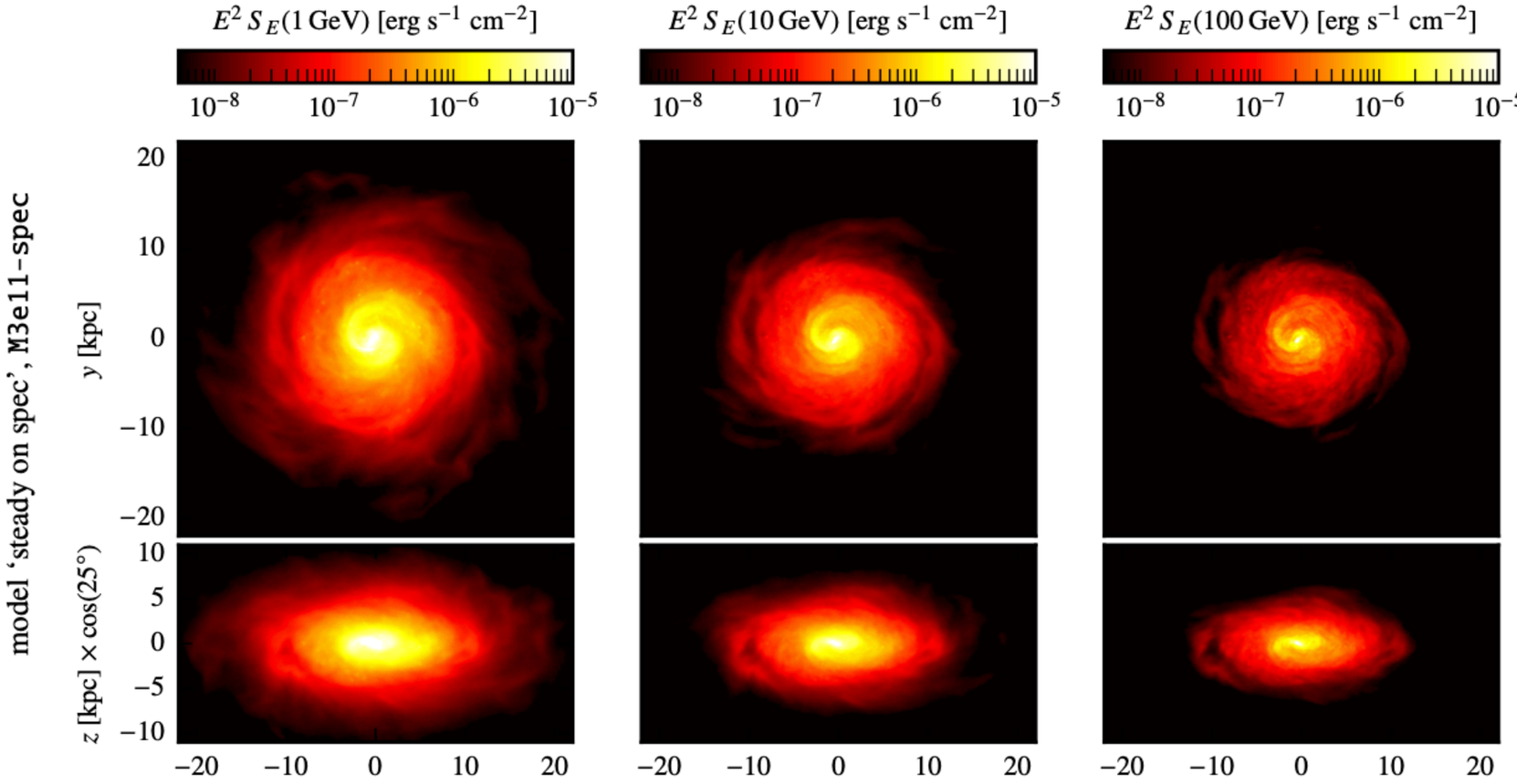


Girichidis et al. 2024

Connection to gamma rays

- Steady state vs. full spectrum *Werhahn+ 2021abc, 2023*
- Variations in Milky-Way models / Galactic center / Fermi bubbles *Kjellgren et al. 2025*





- spectral model: better fit to spectra

strong differences between energy ranges

Werhahn et al. 2023

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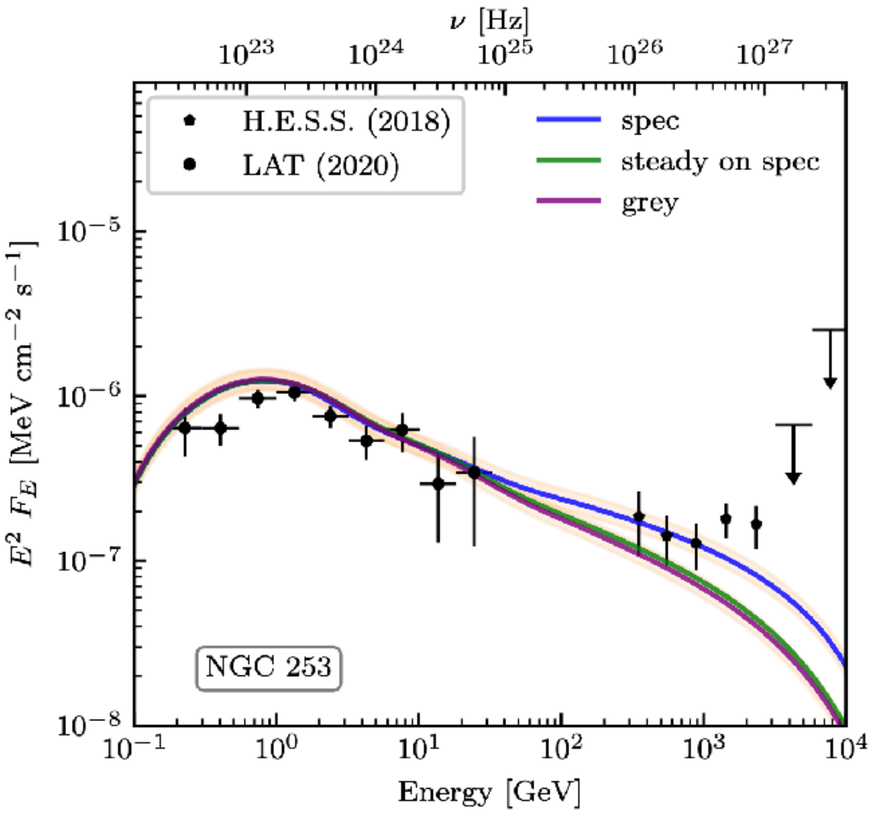

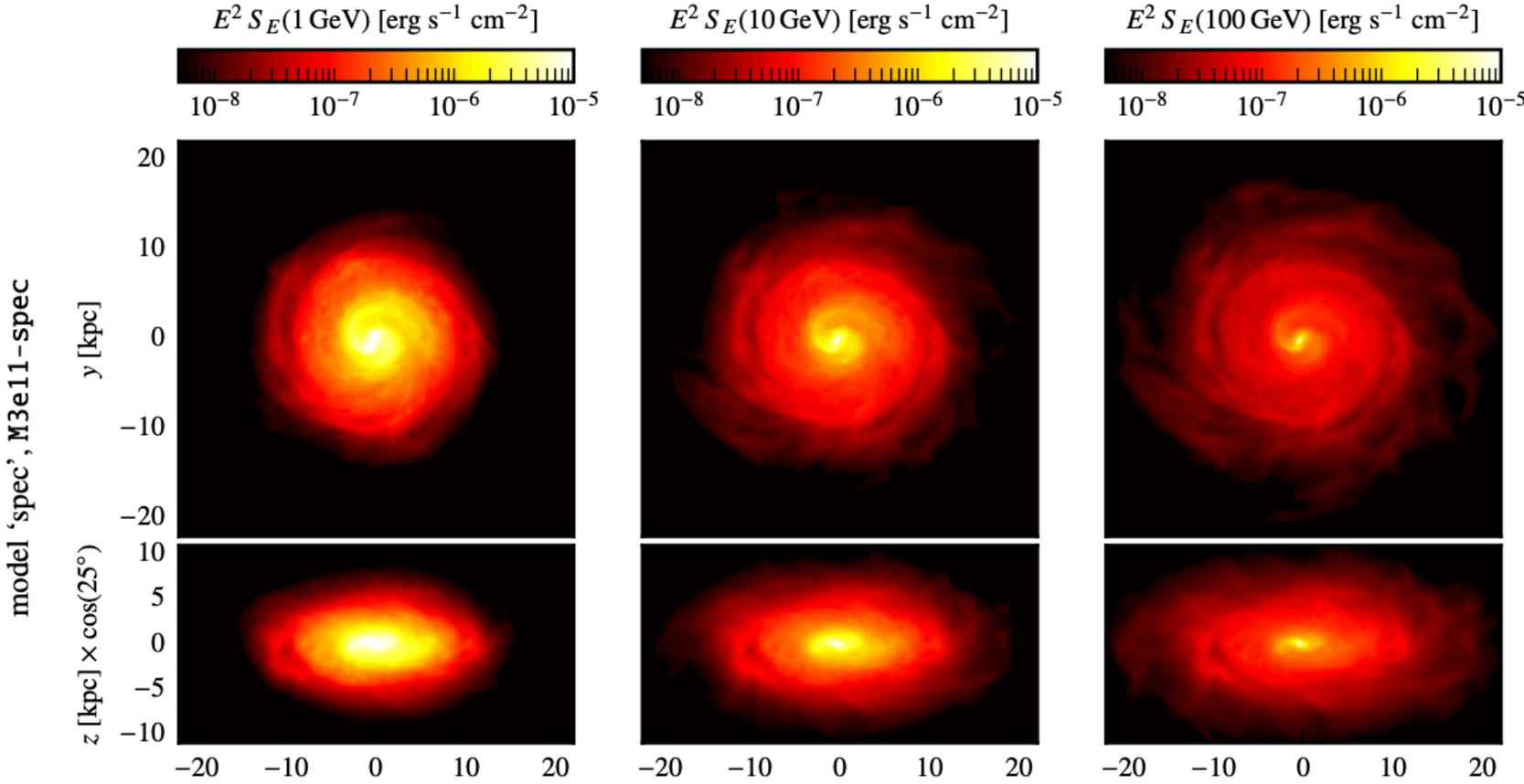

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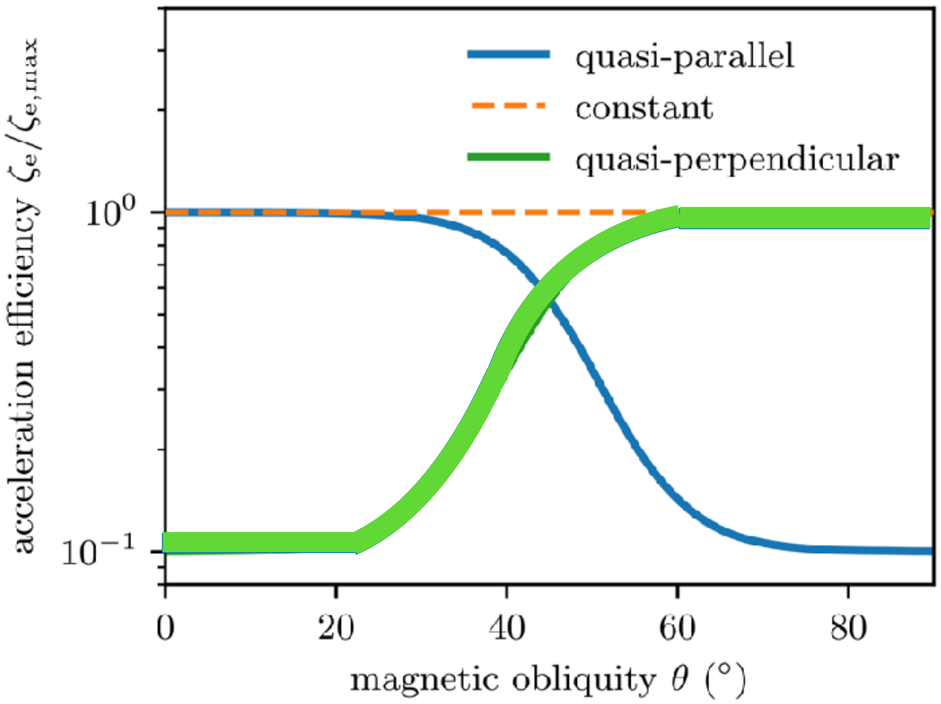
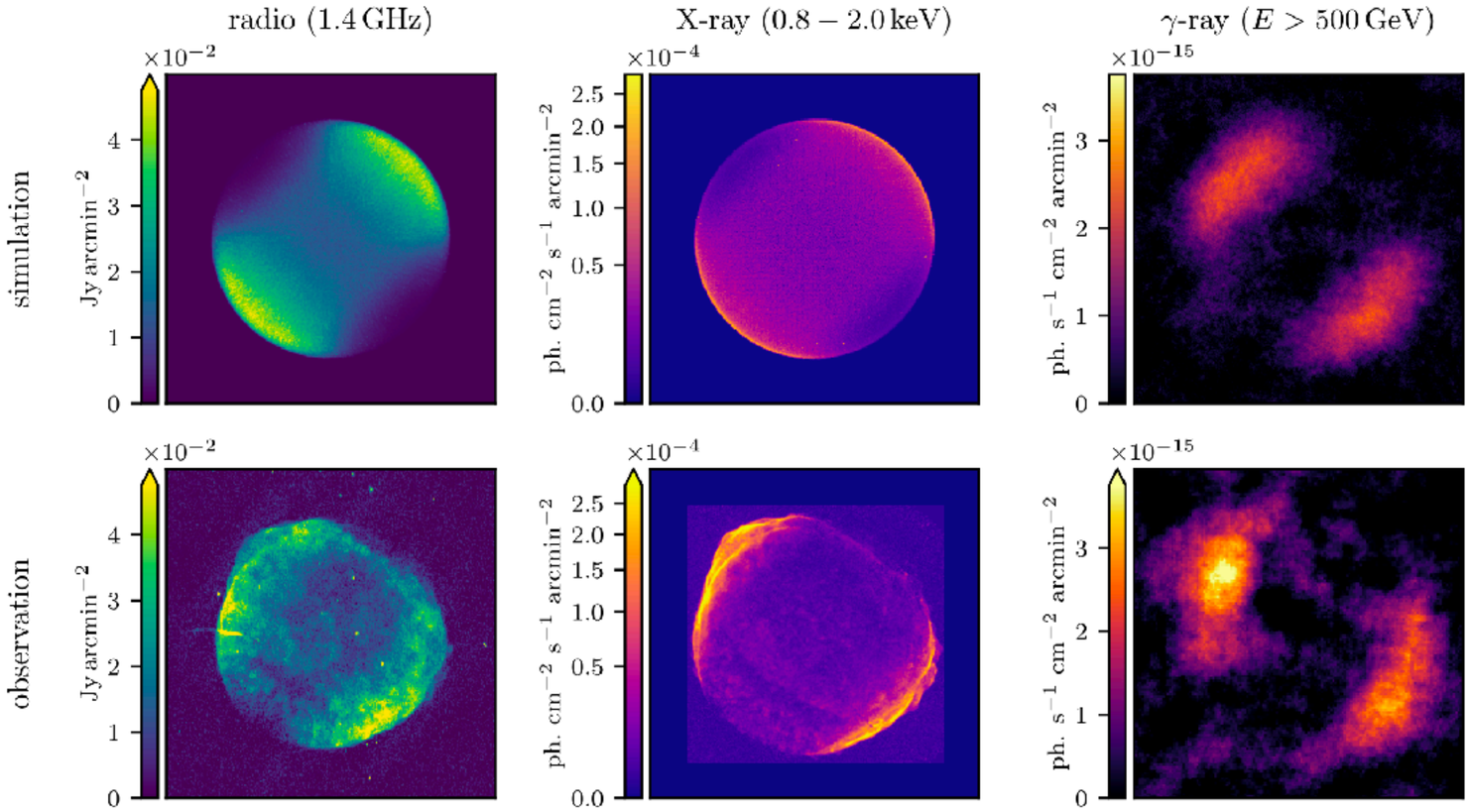
Werhahn et al. 2023

spectral CR electrons

- MHD sim of SN + electron tracers
- spectrally resolved CR electrons in post-processing

(Winner+PG+ 2019, 2020)





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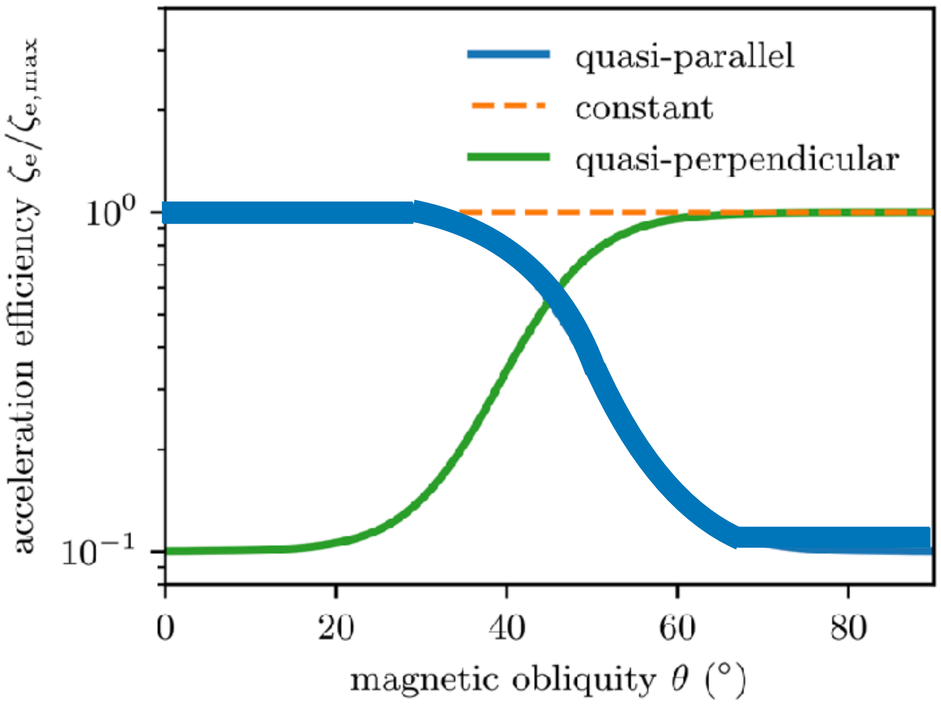

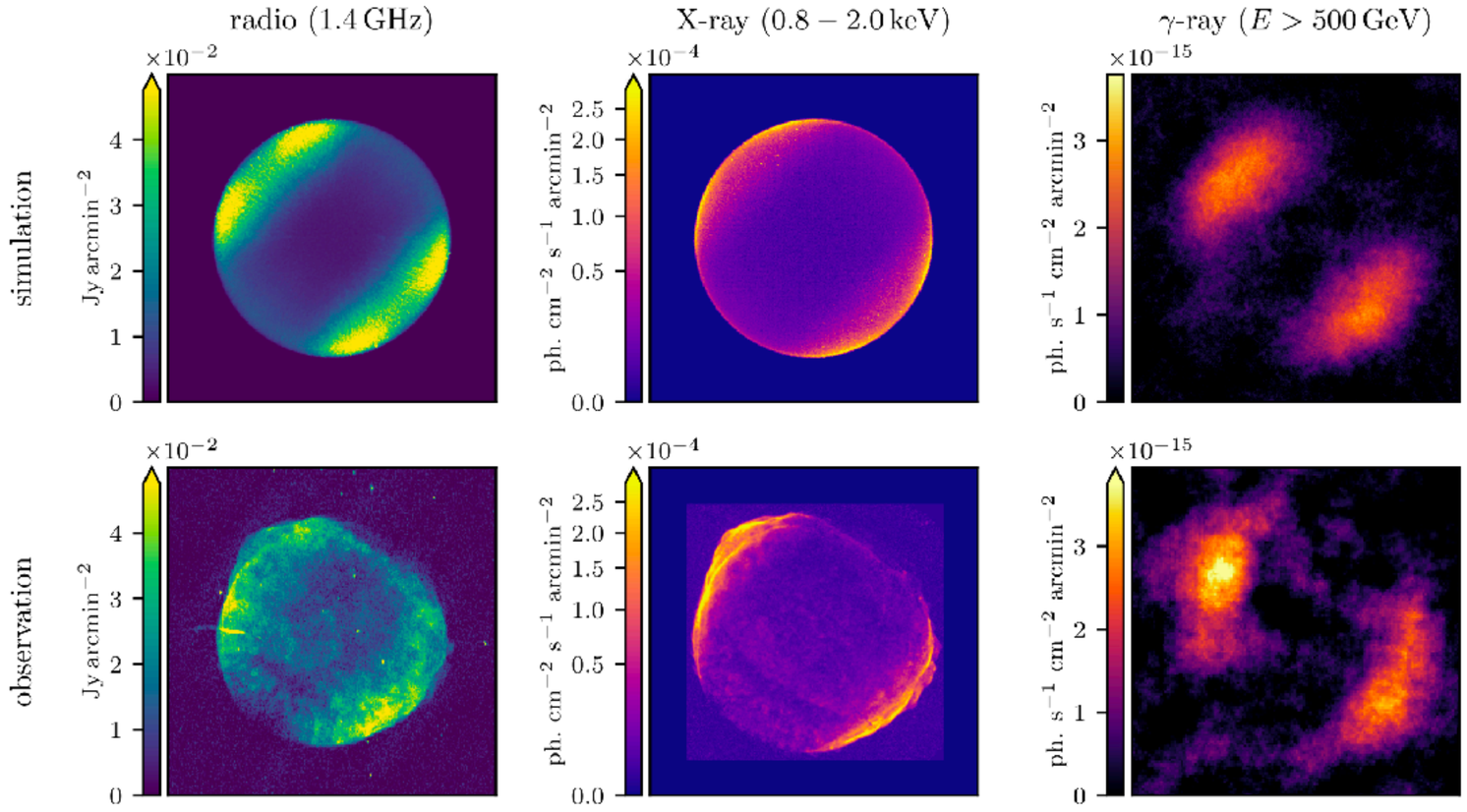

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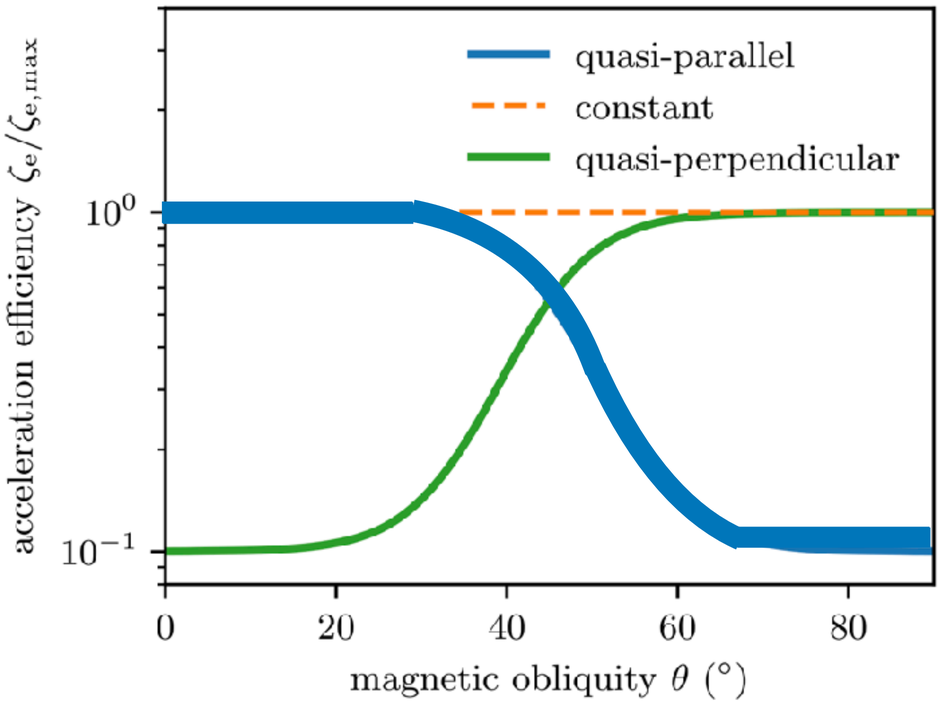
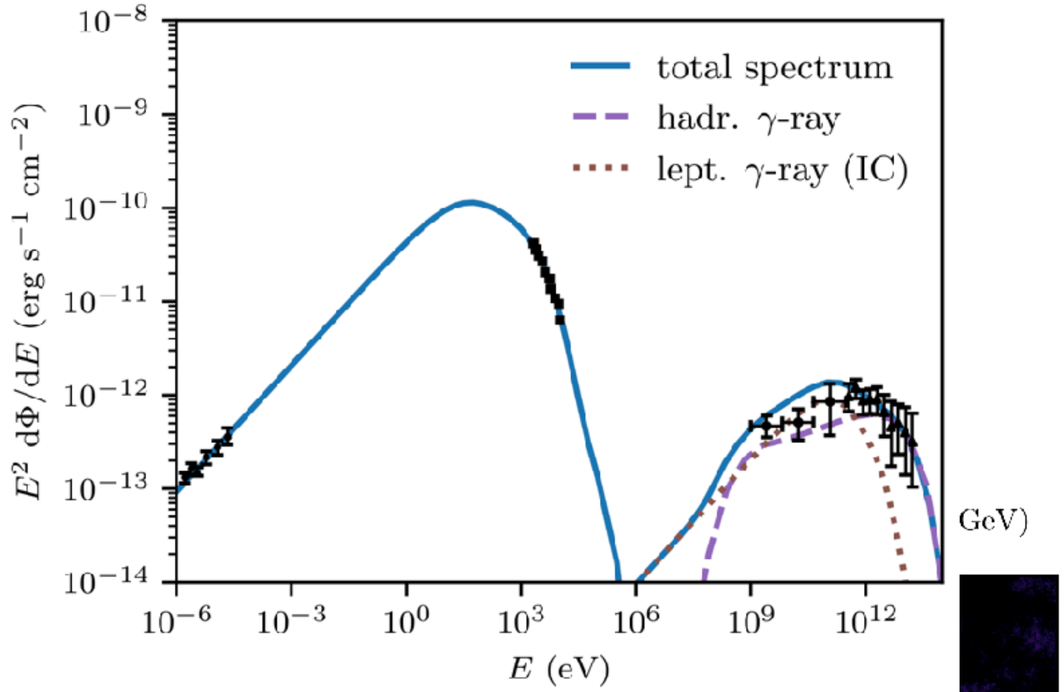
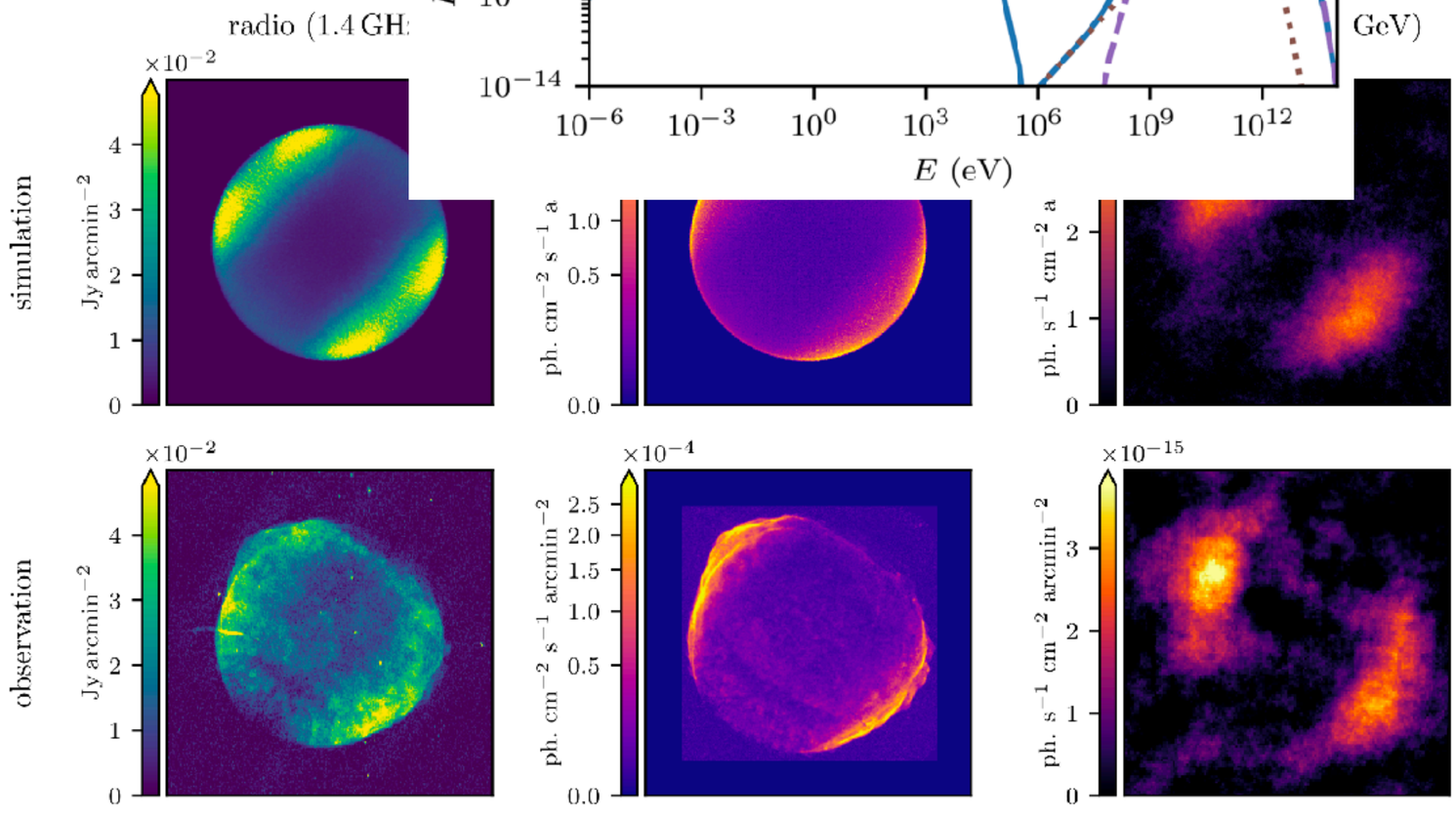


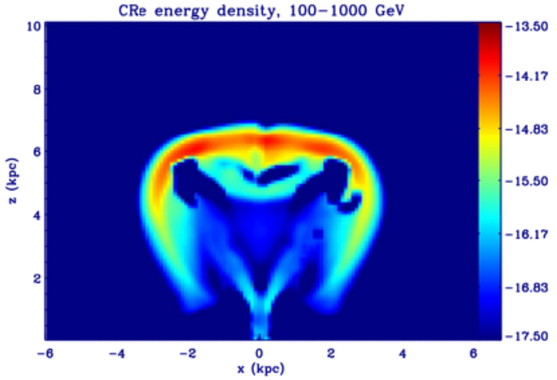




other spectrally resolved CR electrons

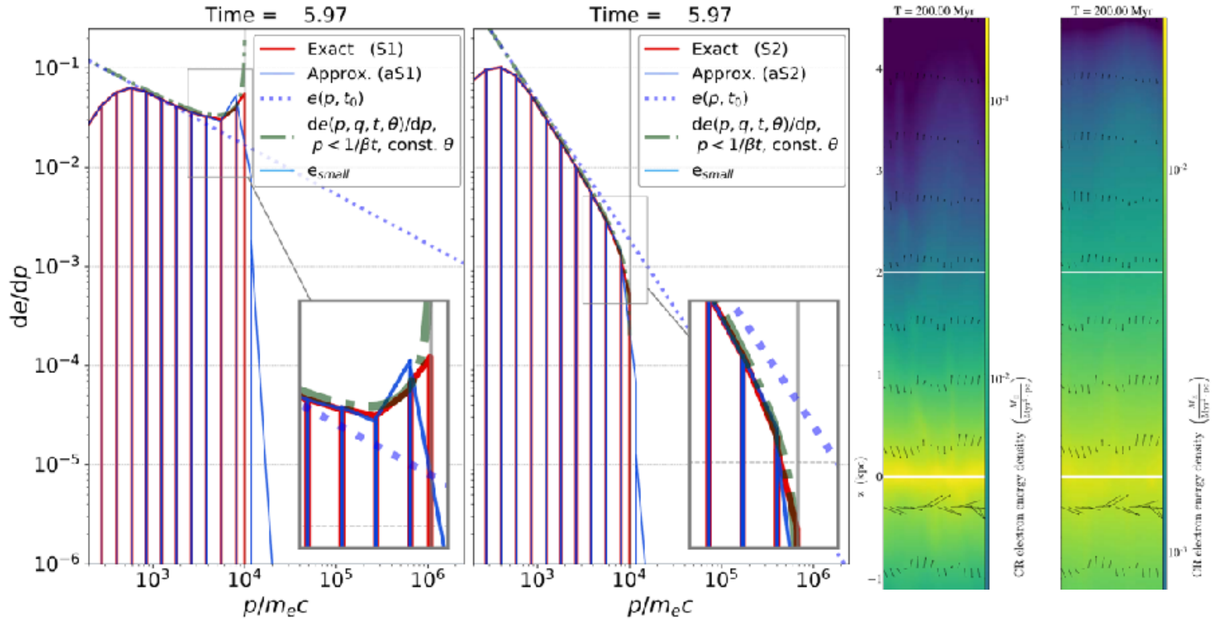
Yang+ 2017,2022

- AGN-driven Fermi Bubbles
- investigate advection vs. cooling spectral shape and energy distribution



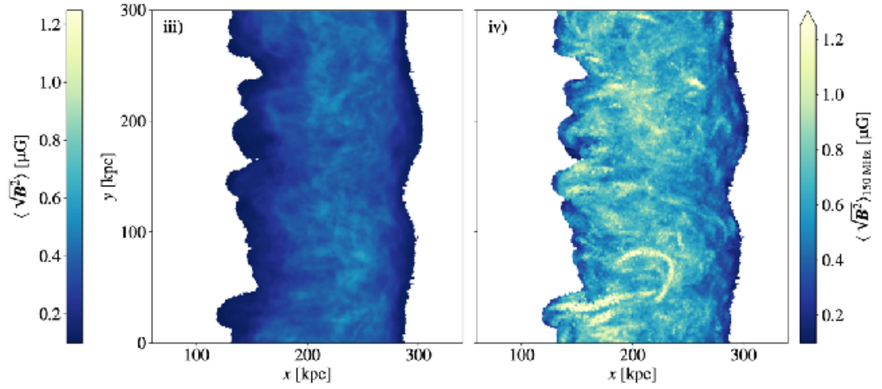
Ogrodnik+ 2021

- full Fokker-Planck+MHD solver

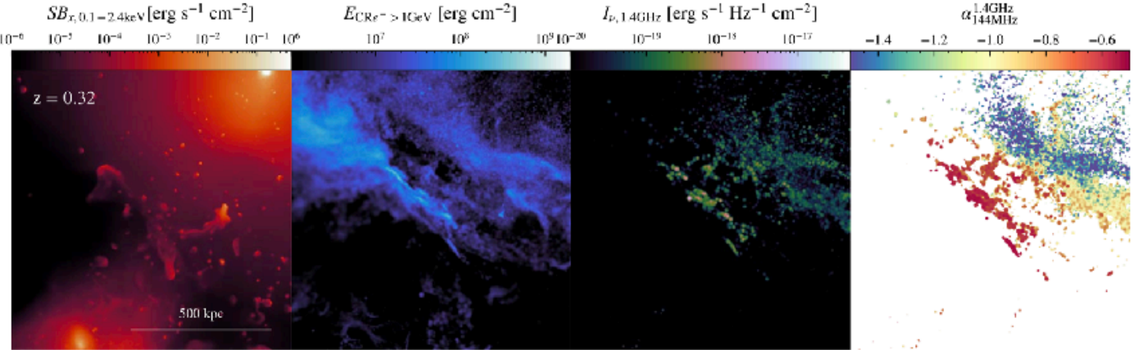


Whittingham et al. 2025

- Cosmo. shock: synthetic radio emission
- observed B field strength differs from MHD



- Radio relics: *Böss et al, 2023a,b*
- shock properties, variations in spectral index

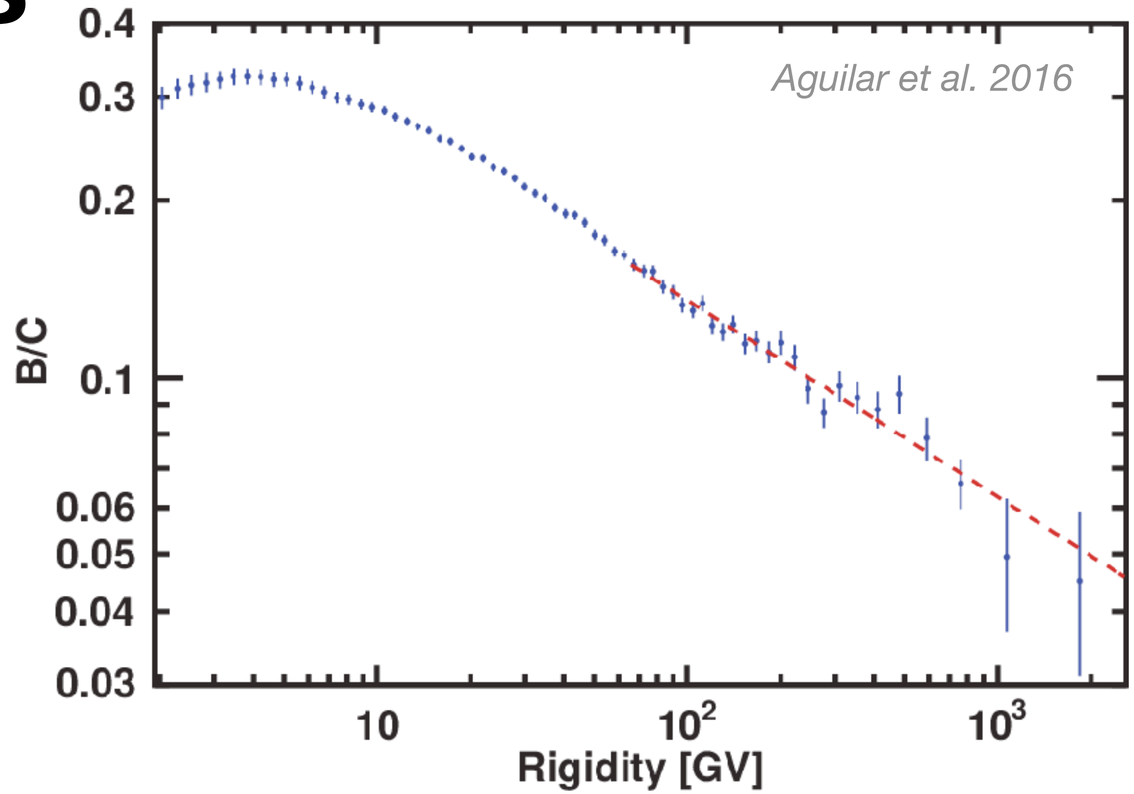


see reviews Strong+ 2007, Grenier+ 2015

Primaries to secondaries

example B/C ratio

- assume CRs are universally accelerated from ISM
- expect similar composition as in stars/ ISM (very abundant alpha elements!)
- but observed relative **over**abundance of light elements (e.g. B)
- B must be produced while travelling through ISM
- more B ⇒ longer residence time in ISM

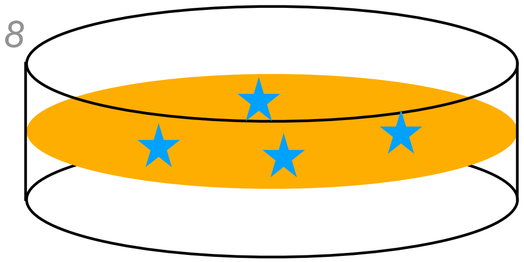


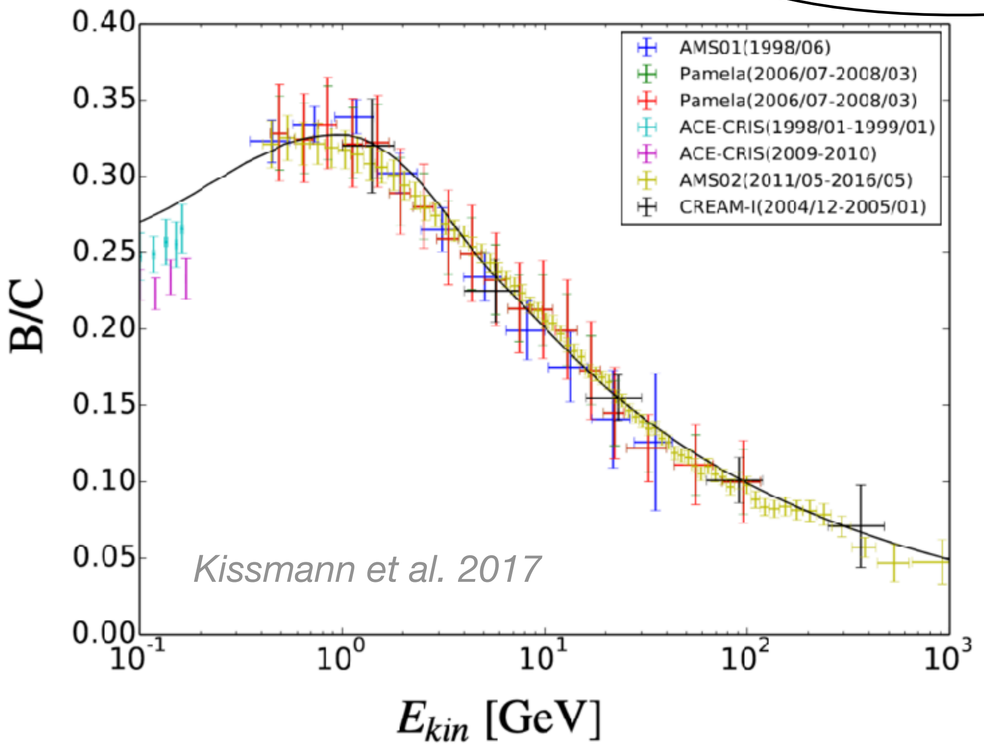
- B/C smaller for larger E
- rigidity $R = \frac{pc}{Ze}$, energy per charge
- CRs with high E escape faster

Secondaries in simulations

example B/C ratio

- many species in steady state
  GALPROP *Strong&Moskalenko 1998 ++++ (v57)*
  DRAGON2 *Evoli+2017,2018*
  PICARD *Kissmann+2014*

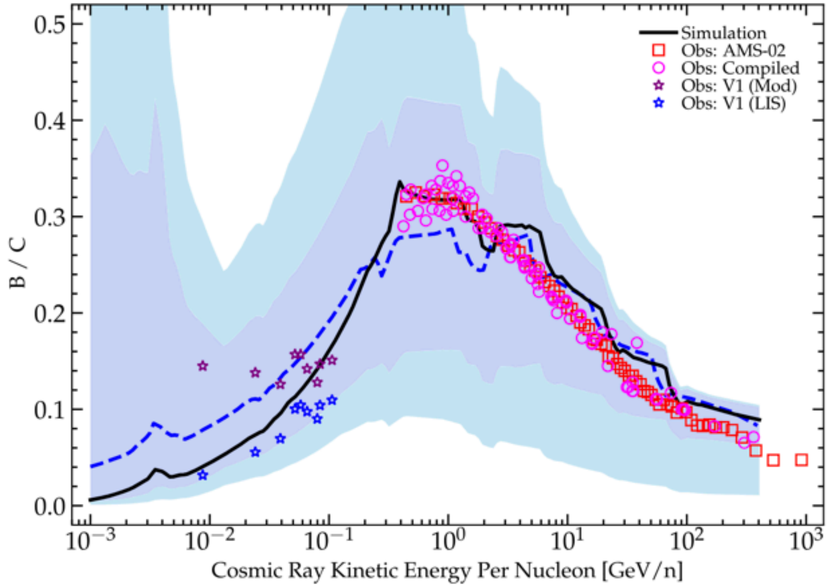




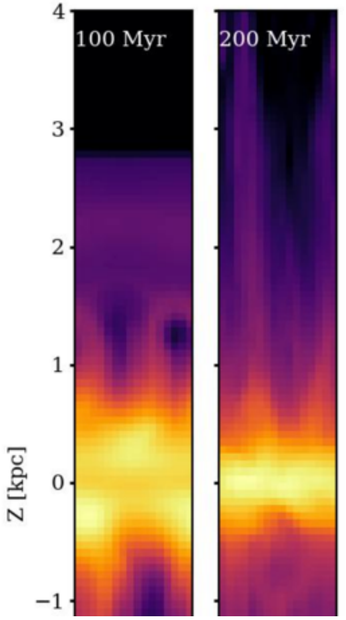
Kissmann et al. 2017

MHD cosmo. zoom

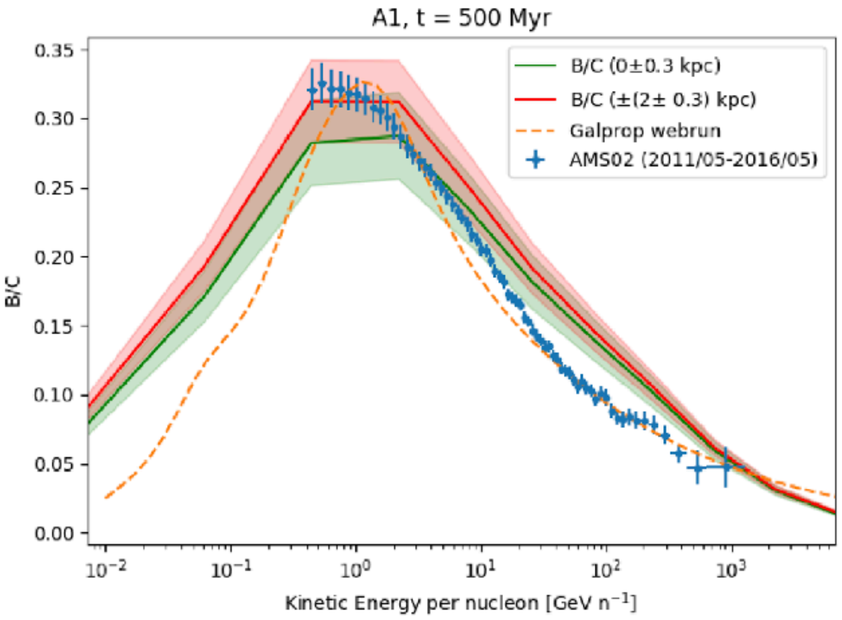
Hopkins et al. 2022



strat. box simulation

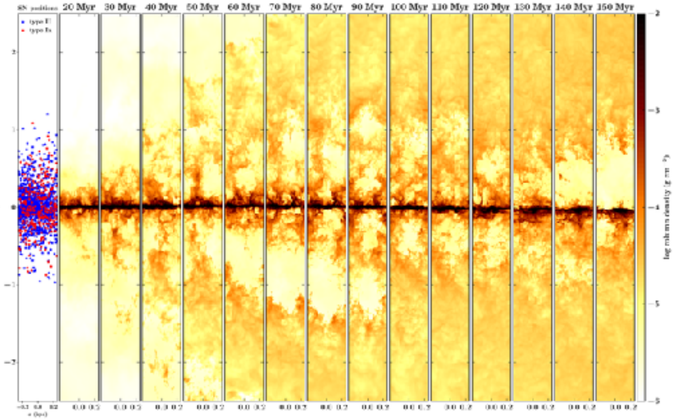


Baldacchino-Jordan+PG 2025

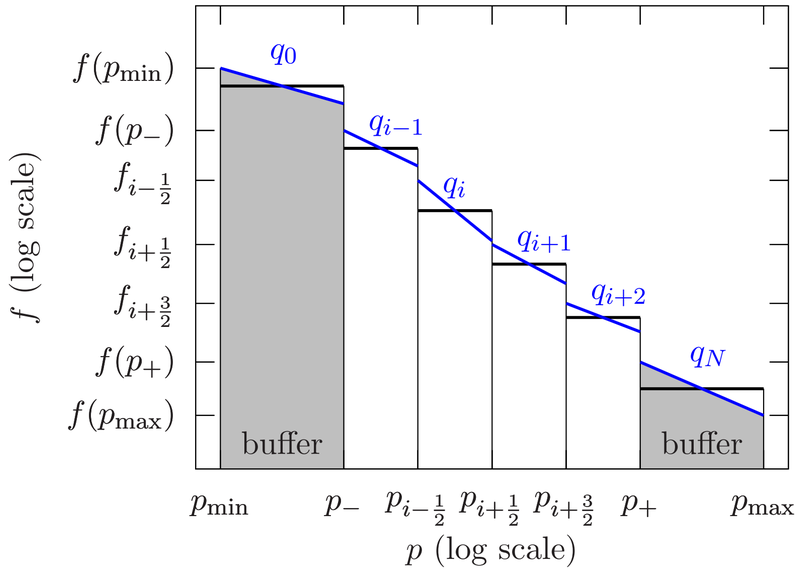


Take home points

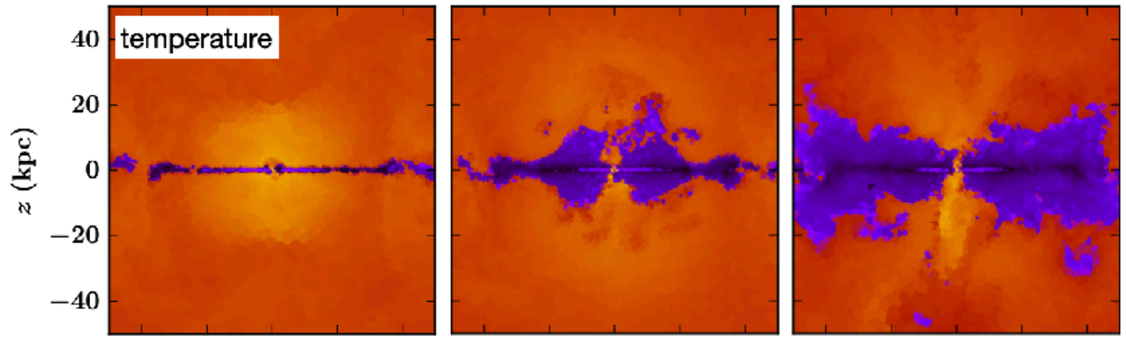
- CRs are important for outflows, details debated



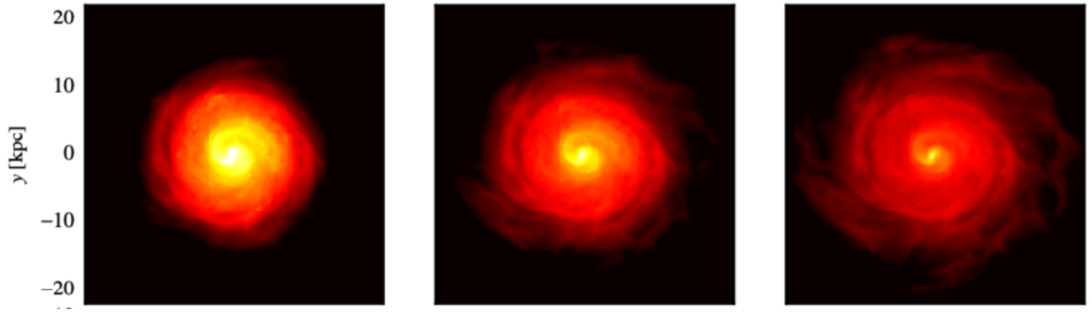
- (1) new plasma transport models (complex)
- (2) live CR spectra in ISM & galaxy sims



- proton spectra: different CGM / outflows



- proton spectra: better fit to γ-ray obs.



- CR e^- + secondaries: B/C ratio, clocks