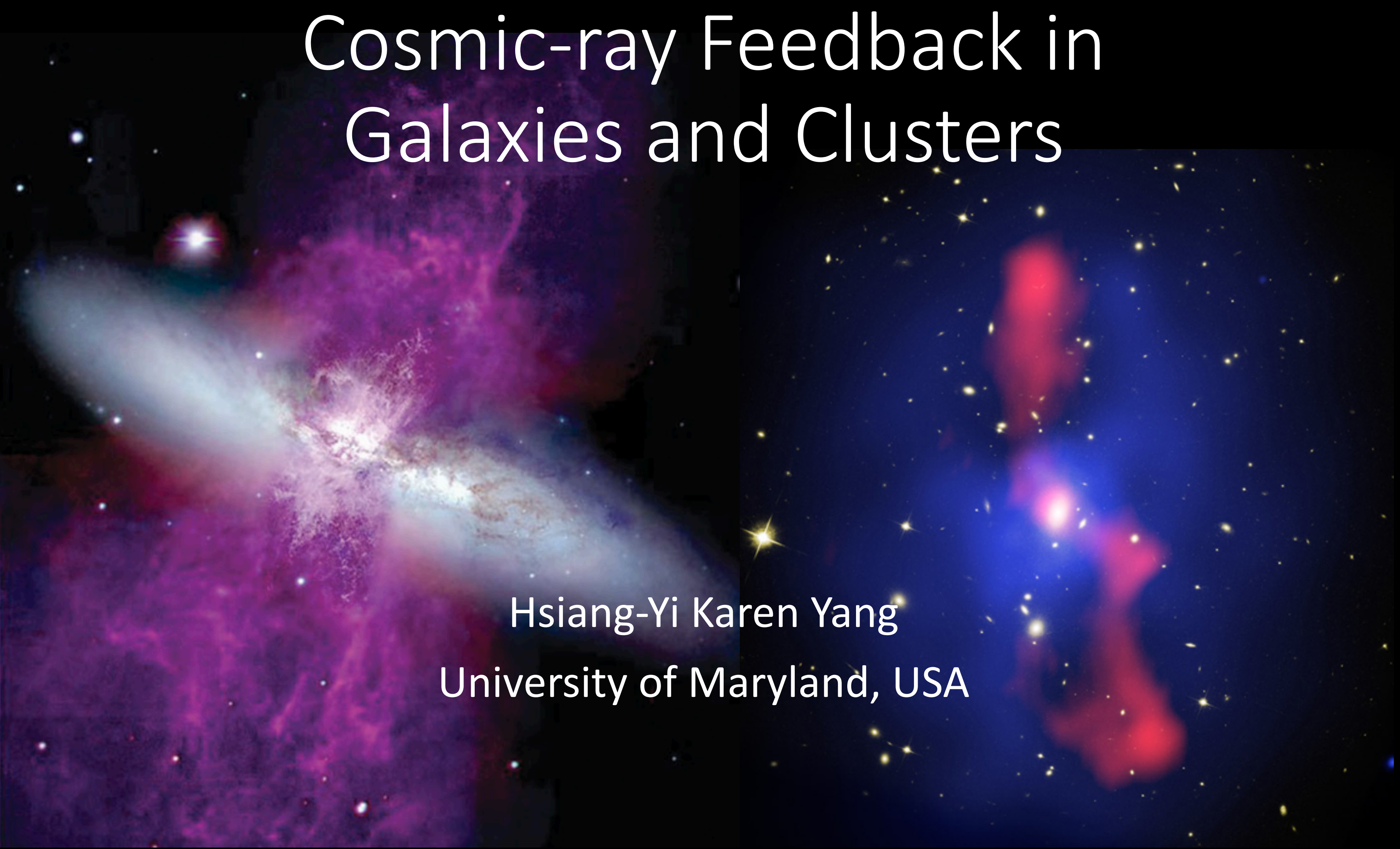
Cosmic-ray Feedback in Galaxies and Clusters



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Sep. 4, 2018 Potsdam Thinkshop Potsdam, Germany

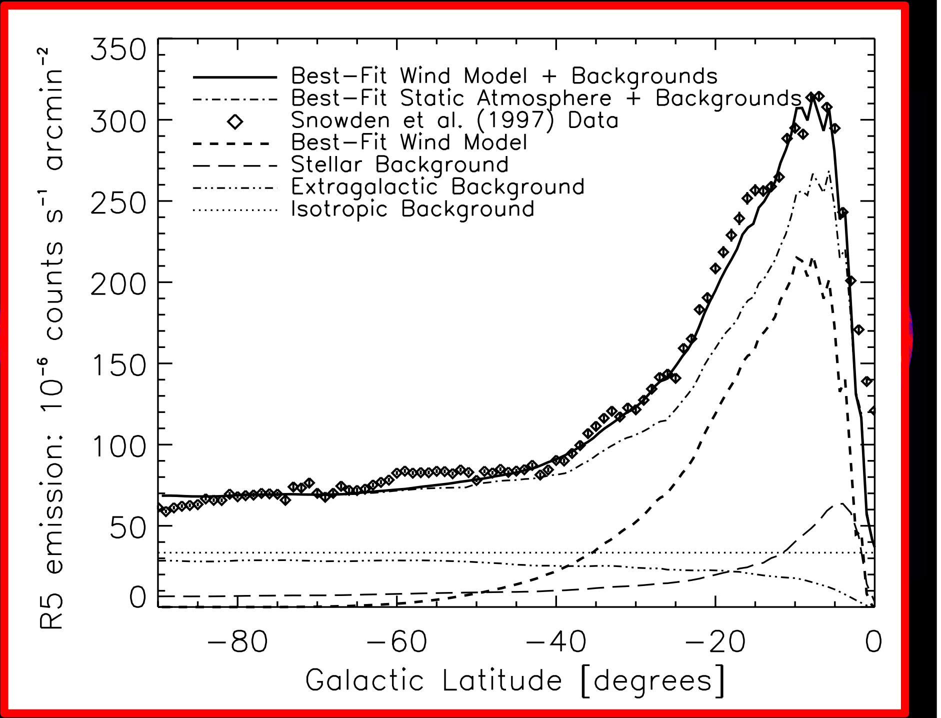
Cosmic rays (CRs) in galaxies vs. clusters

Nonthermal emission: hadronic (CRp); inverse-Compton, bremsstrahlung, synchrotron (CRe)

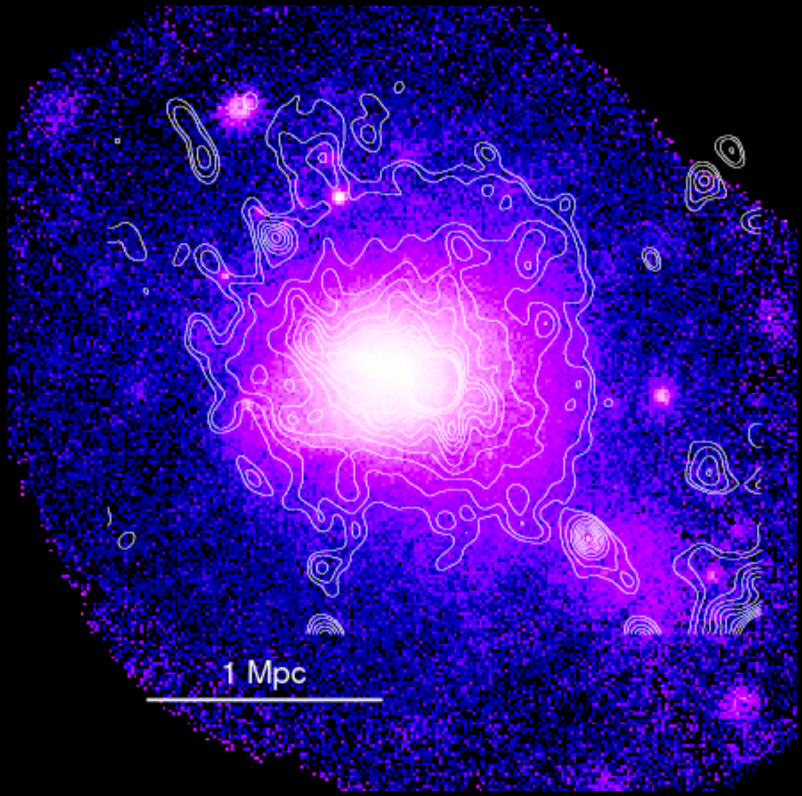
Acceleration by supernova explosions

$X_{CR} = P_{cr}/P_{th} \sim 1$

Winds in the MW (Everett+08)



Coma cluster (X-ray & radio)



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Acceleration by supernova explosions

$P_{CR}/P_{CR,MW}$ >~ 100! (VERITAS 2009)

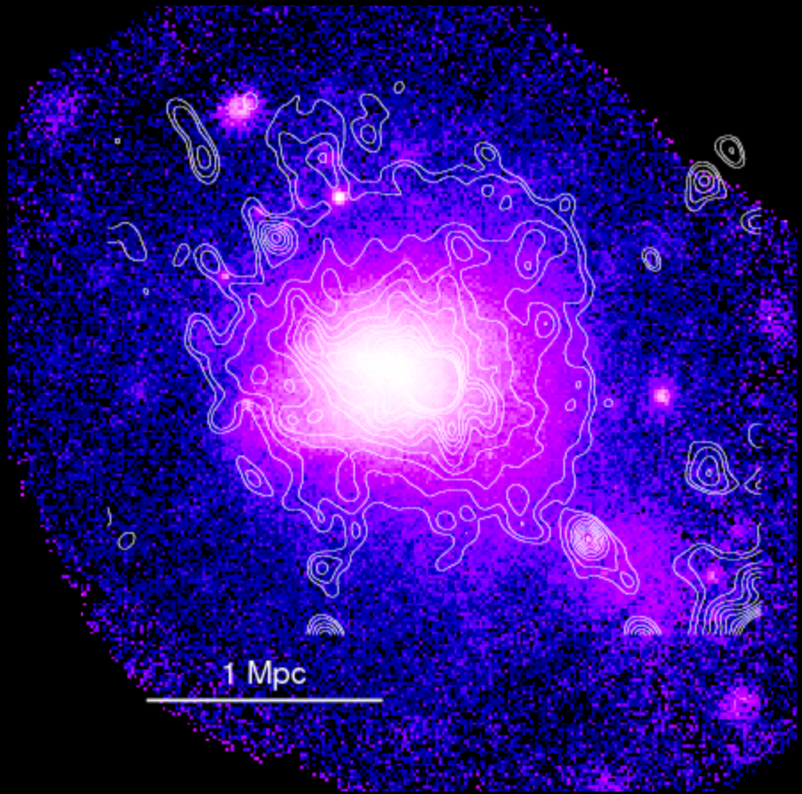
M82 (HST/WIYN)

How do CRs drive winds, affect SFRs, & the CGM?

Acceleration by structure formation shocks

X_{CR} <~ 10%

Coma cluster (X-ray & radio)



Cosmic rays (CRs) in galaxies vs. clusters

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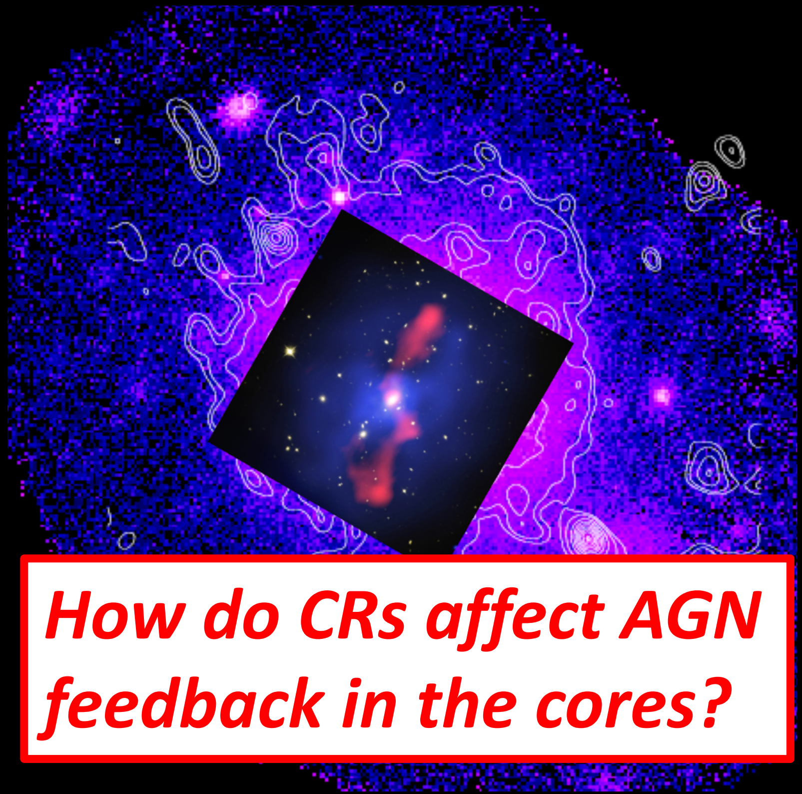
How do CRs drive winds, affect SFRs, & the CGM?

AGN injection

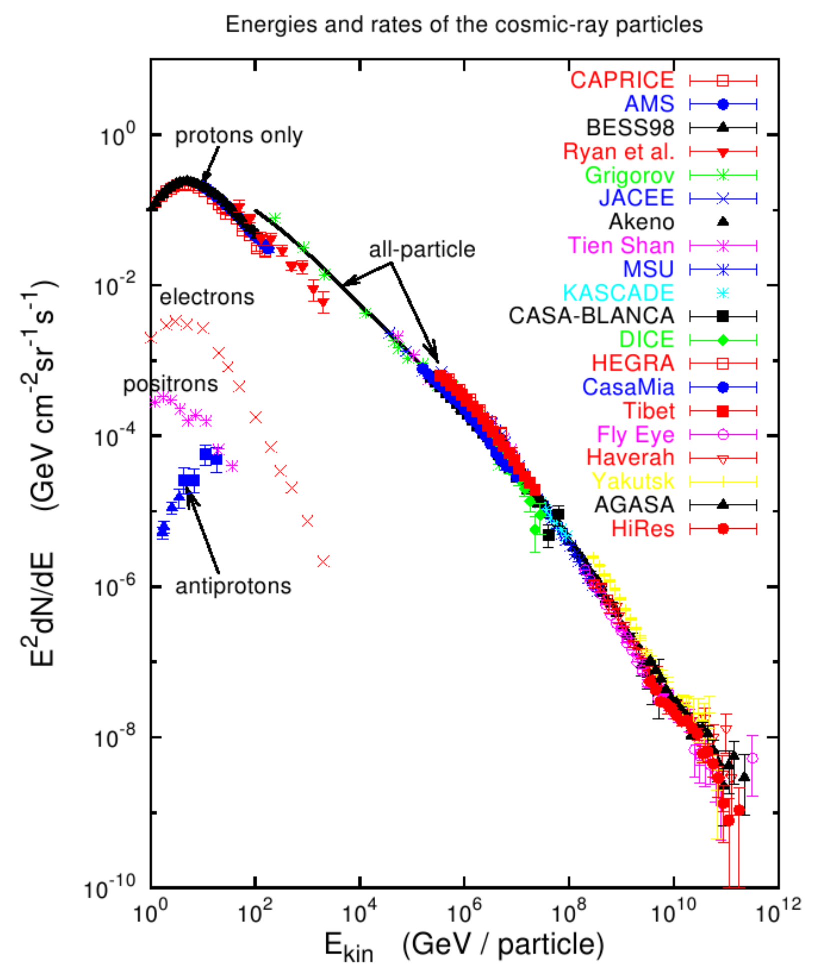
$X_{CR} <^{\sim} 10\%$, ***$X_{CR,jet} = ?$***

Coma cluster (X-ray & radio)



How do CRs affect AGN feedback in the cores?

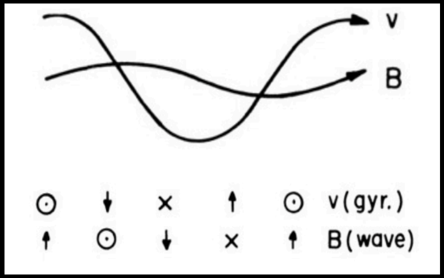
Properties of CRs in the Galaxy



- Mostly protons (n_i/n_e ~ 50-100)
- U_{CR} ~ 1eV cm^{-3} ~ U_B ~ U_{rad} ~ U_{th}
- Require ~10% of mechanical E_{SN}
- <E> ~ 3GeV
- Composition =>
  confinement time ~ 20 Myr
- Very isotropic =>
  well-scattered (λ_{mfp} ~ 1pc)

Self-confinement picture of CR transport

- Gyro-resonance scattering: $\boxed{k_{||} \sim \frac{1}{\mu r_L}}$



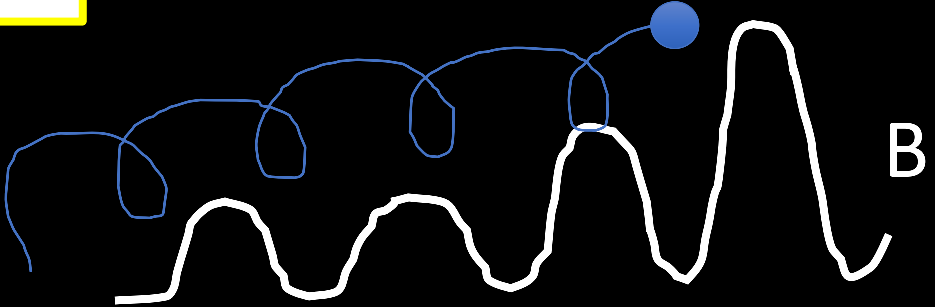
F = **v** x **B**

- Streaming instability (Kulsrud & Pearce, 1969):

  Anisotropy => wave growth => enhanced scattering

$$\boxed{\Gamma_{\rm CR}(k_\|) \sim \Omega_0 \frac{n_{\rm CR}(>\gamma)}{n_{\rm i}} \left(\frac{v_{\rm D}}{v_{\rm A}} - 1 \right)}$$

$\boxed{v_D > v_A}$



- Marginal stability: $v_D \sim v_A$

When waves are damped

$v_D \sim v_A$

streaming inhibited
(by perturbations)

$v_D > v_A$

fast streaming
(perturbations smoothed out)

Classical CR hydrodynamics

(see reviews by Zweibel 2013, 2017)

CRs stream down pressure gradient with v_A:

$$\boxed{\boldsymbol{v}_s = -\mathrm{sgn}(\hat{\boldsymbol{b}} \cdot \nabla e_{\mathrm{CR}})\boldsymbol{v}_{\mathrm{A}}}$$

$$\boxed{\frac{\partial(\varrho \boldsymbol{u})}{\partial t} = [\ldots] - \nabla P_{\mathrm{CR}}}$$

Momemtum transfer via pressure gradient

$$\boxed{\frac{\partial e_{CR}}{\partial t} = [\ldots] - \nabla \cdot \boldsymbol{F} + \nabla \cdot (\boldsymbol{\kappa} \cdot \nabla e_{\mathrm{CR}}) - H_{\mathrm{CR}}}$$

Streaming and diffusion

Heating via waves

$$\boxed{\boldsymbol{F} = (e_{\mathrm{CR}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{A}}, \ \ \kappa_{\|} \sim v^2/\nu}$$

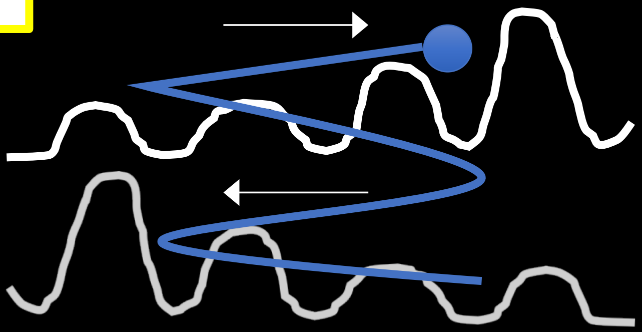
$$\boxed{H_{CR} = -v_A \cdot \nabla P_{CR}}$$

Alternative – *extrinsic turbulence* model

- Generalized CR hydrodynamics (Zweibel 2017):

$$\boldsymbol{v}_{\mathrm{D}} = \left(\frac{\nu_+ - \nu_-}{\nu_+ + \nu_-}\right)\boldsymbol{v}_{\mathrm{A}} \equiv f\boldsymbol{v}_{\mathrm{A}}, \text{where } f < 1$$

$$H_{\mathrm{CR}} = -f\boldsymbol{v}_{\mathrm{A}} \cdot \nabla P_{\mathrm{CR}}$$



- For balanced turbulence, f=0
  - -- CRs ***advect*** with gas, ***no wave heating***
  - -- ***Diffusion*** from B wandering or unresolved B

Simple but highly uncertain!!

Applications to CR-driven winds

- ***1D models & semi-analytical models:***

Ipavich 75, Breitschwerdt 91, 93, Zirakashvili+96, Everett+08, 10, Dorfi+12, Recchia+17, Samui+18, Mao+18

- ***3D hydro, isolated galaxies:***

Uhlig+12, Booth+13, Salem+14, Simpson+16, Wiener+17, Jacob+18

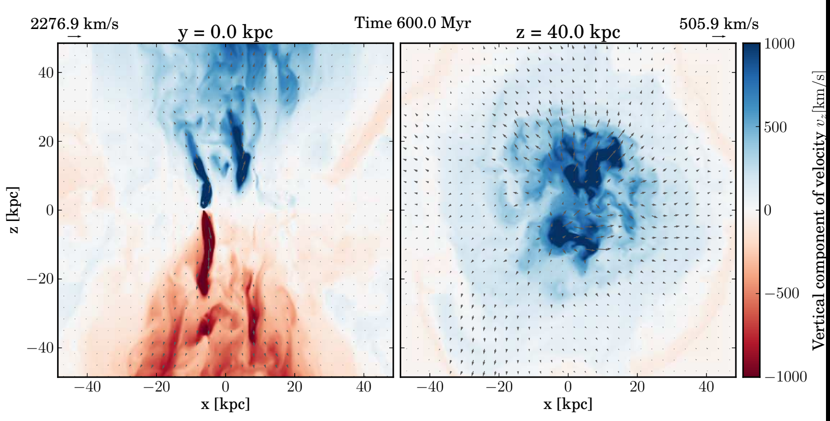
- ***3D MHD, galaxy patches or isolated galaxies:***

Hanasz+13, Pakmor+16, Girichidis+16, Ruszkowski+17, Butsky+18, Farber+18, Holguin+18

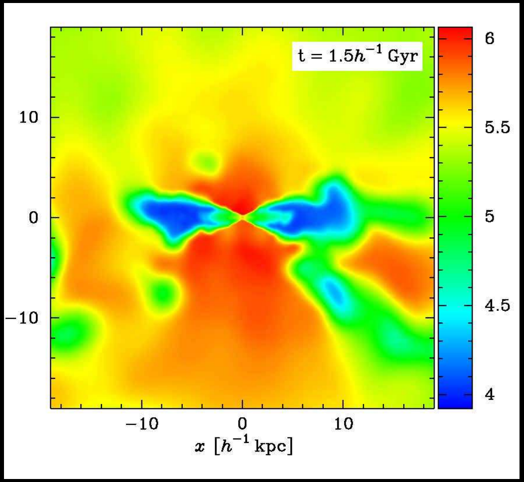
- ***3D cosmological hydro:***

Jubelgas+08, Wadepuhl+11, Salem+14, 16, Liang+16,

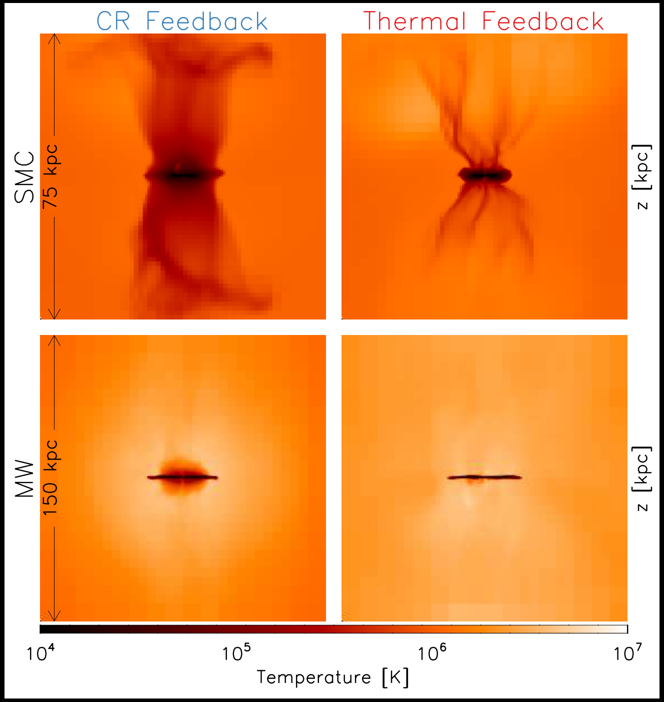
1. CRs can drive winds



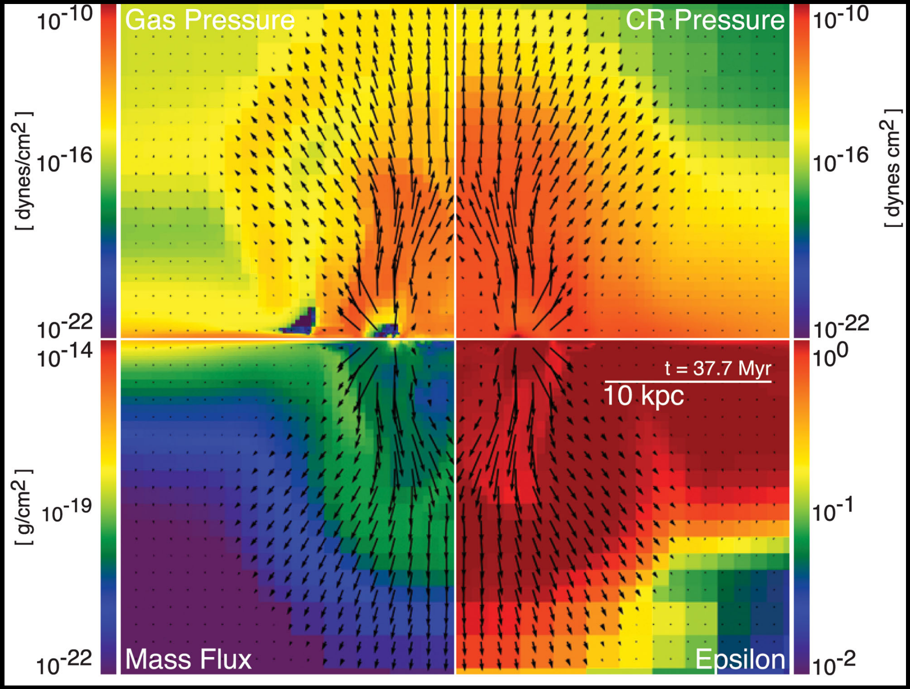
Hanasz+13



Uhlig+12

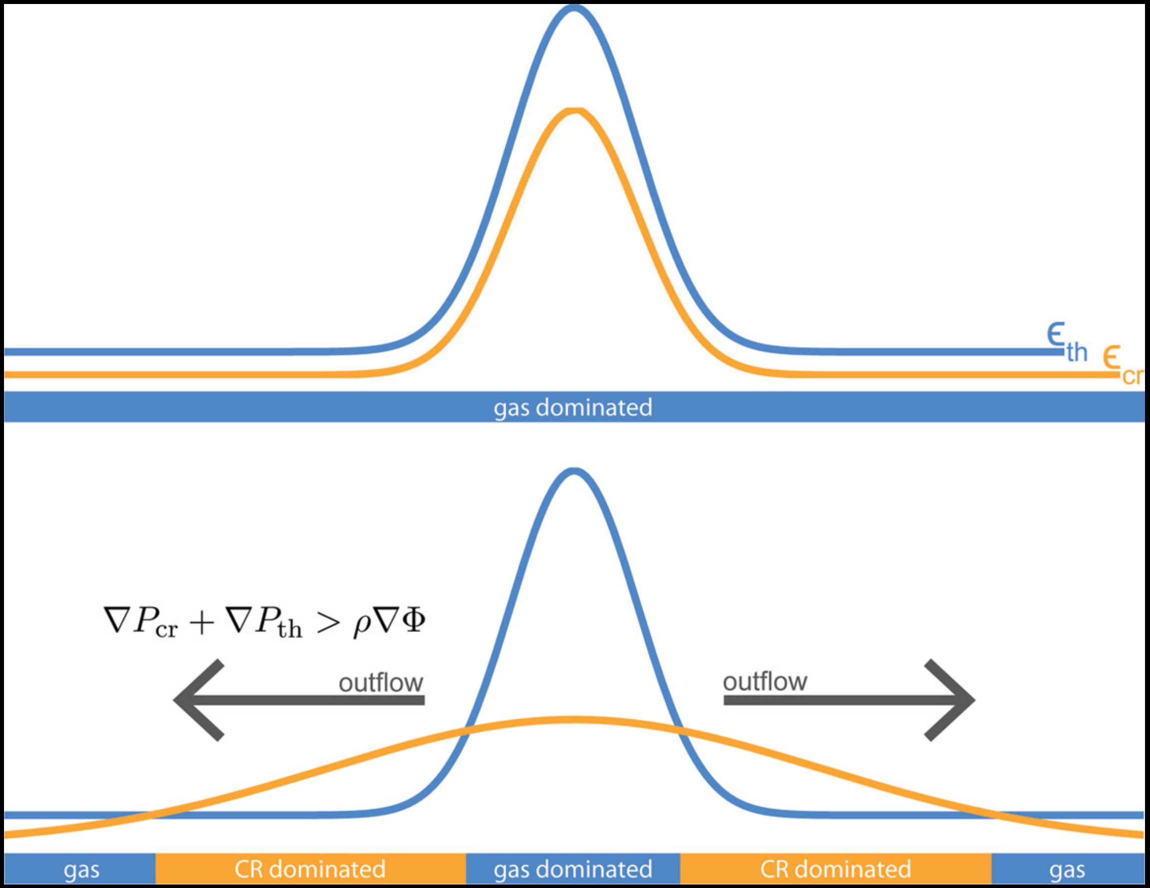


Booth+13



Salem+14

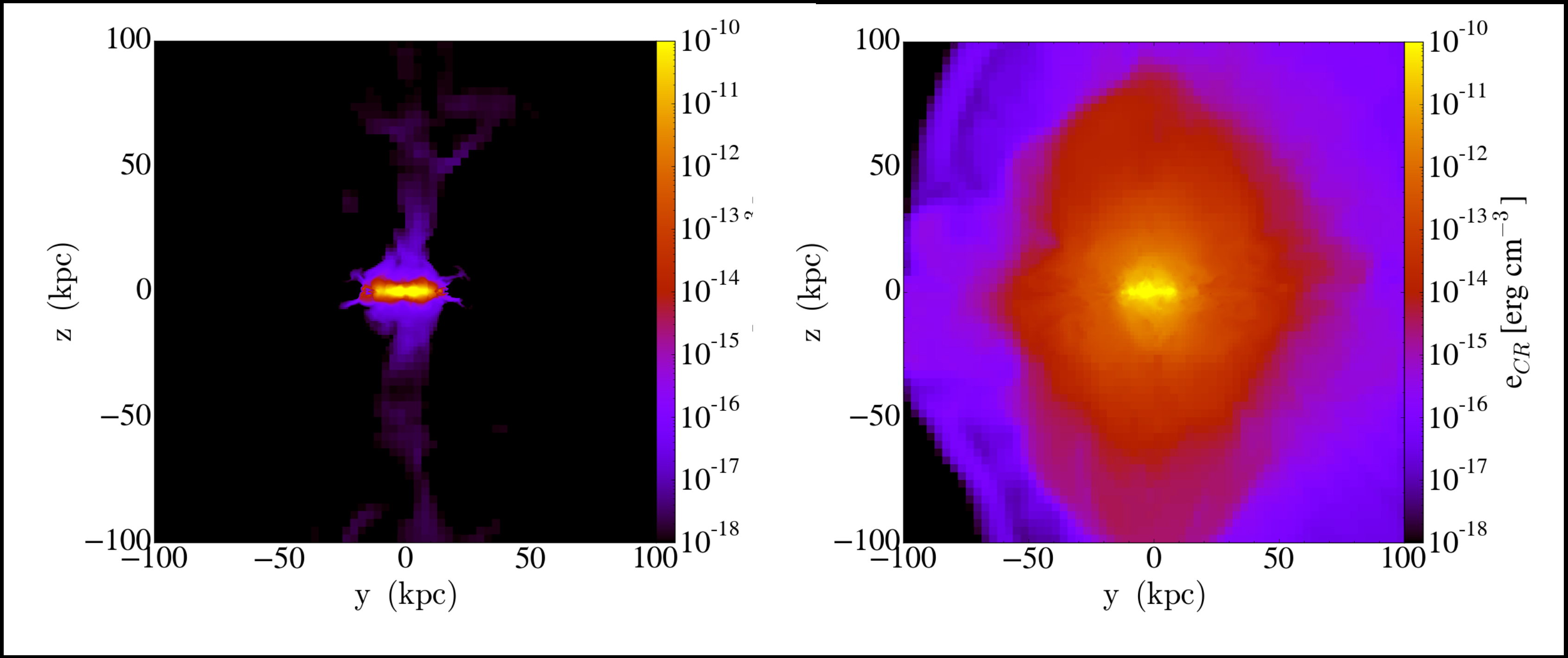
CRs drive winds by pressure gradients



Salem+14

No transport, no wind

(see also Salem+14, Girichidis+16, Simpson+16, Heintz+18)

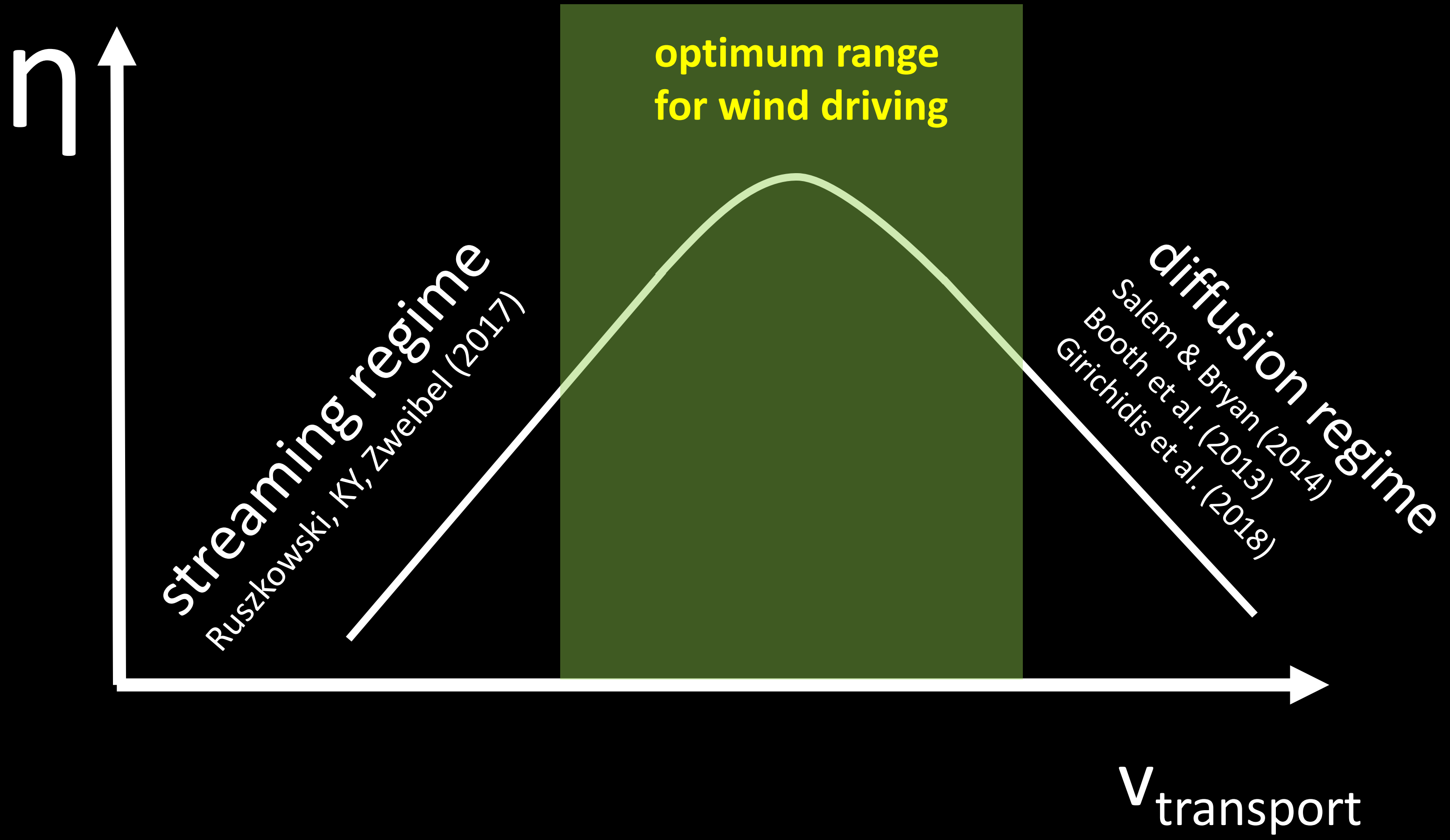


Advection only, no transport

Advection & transport

Ruszkowski, KY & Zweibel (2017)

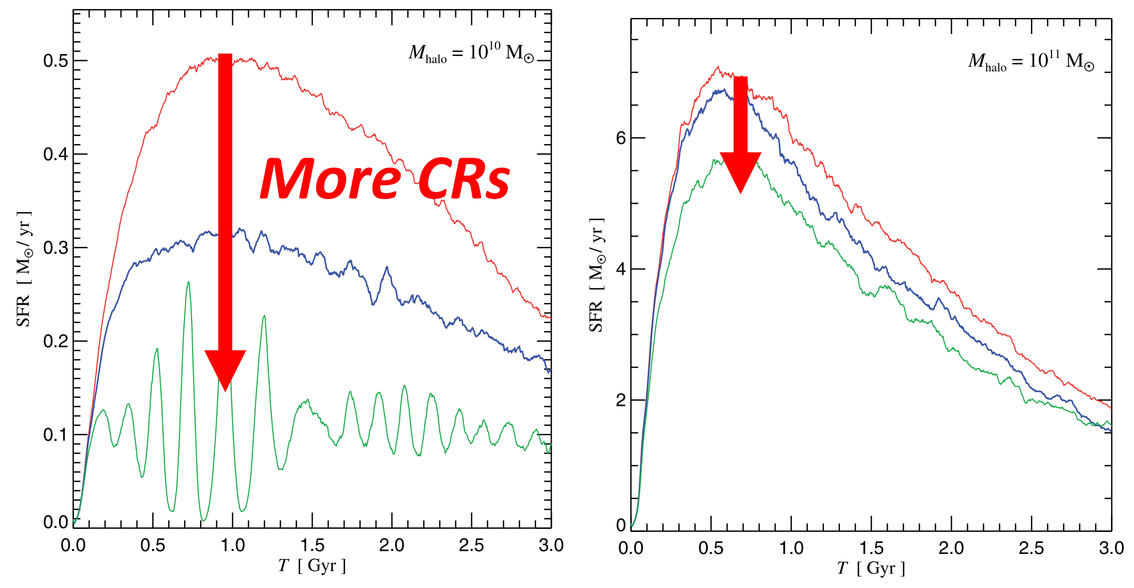
Mass loading depends on transport speed!



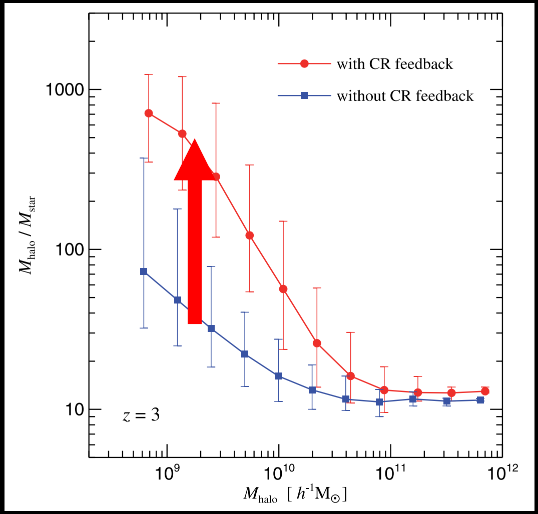
2. CRs can suppress star formation

(Jubelgas+08, Wadepuhl+11, Uhlig+12, Booth+13, Salem+14, Ruszkowski+17, Jacob+18)

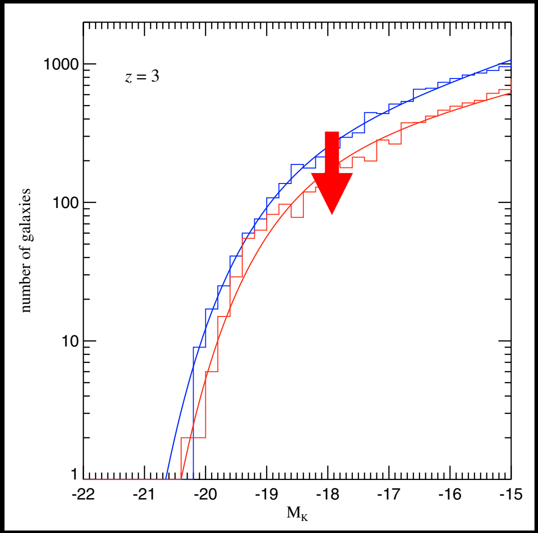
SFR vs. time



M/L ratio



Faint-end LF



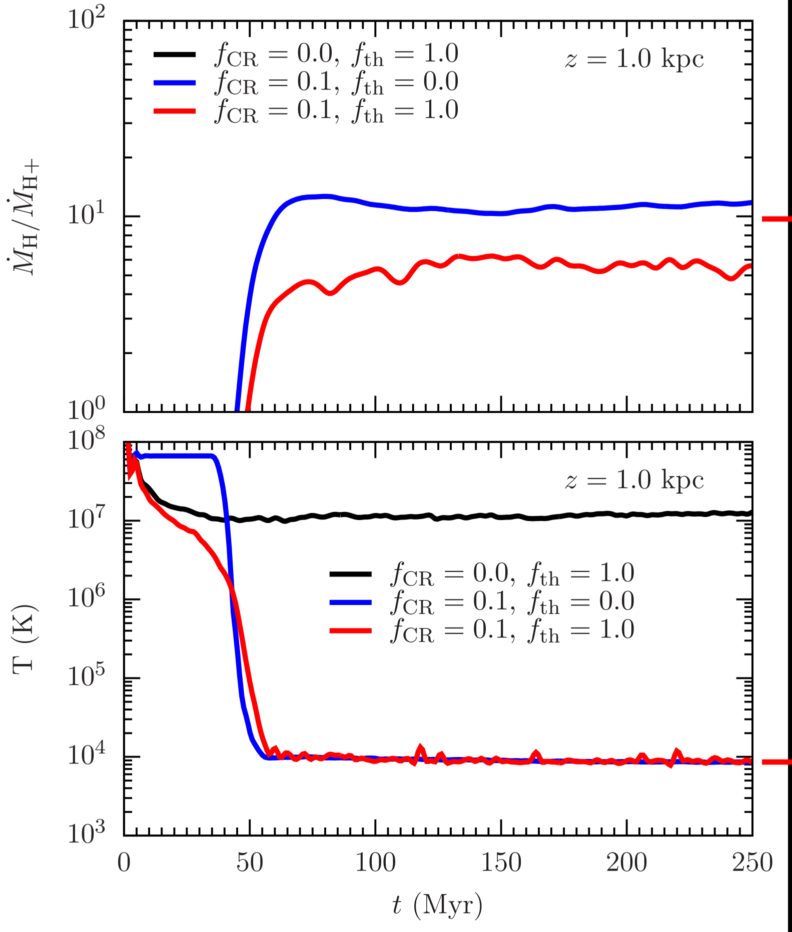
- ❖ SFRs suppressed due to CR pressure support against gravitational collapse
- ❖ More suppression for lower-mass halos

Jubelgas+08

3. CRs can affect wind properties

(Uhlig+12, Booth+13, Simpson+16, Samui+18, Butsky+18, Farber+18, Girichidis+18)

- CR winds are ***cooler (~1e4K), multi-phase, accelerated more gently***

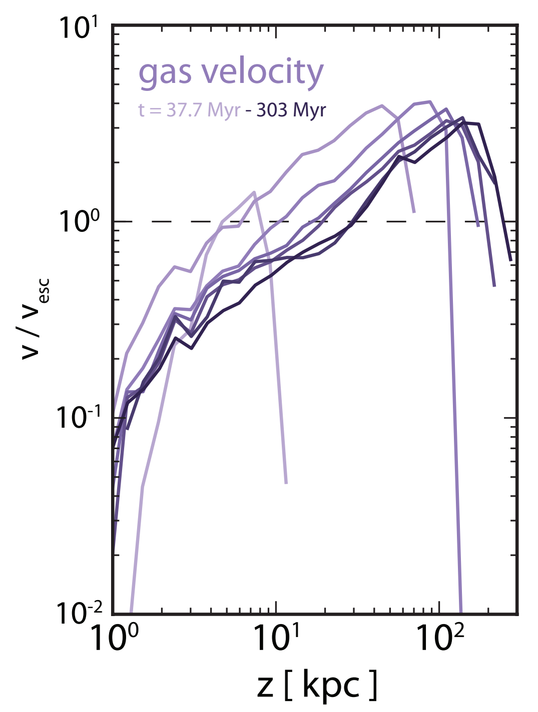


Girichidis+16

Higher atomic fraction

Cooler

V_w grows with z

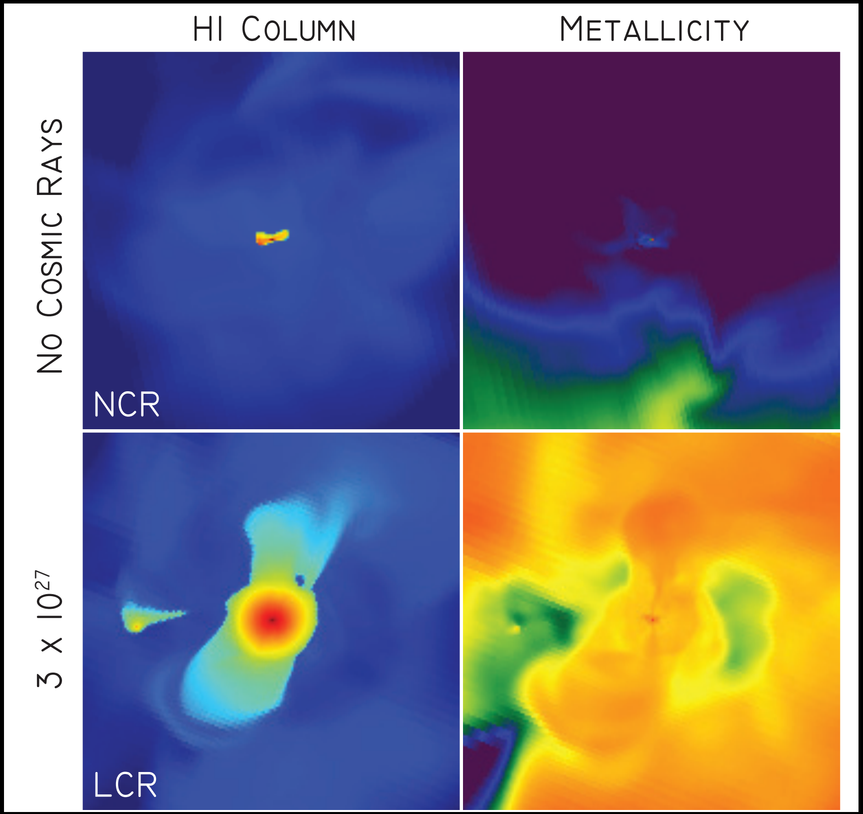


Salem+14

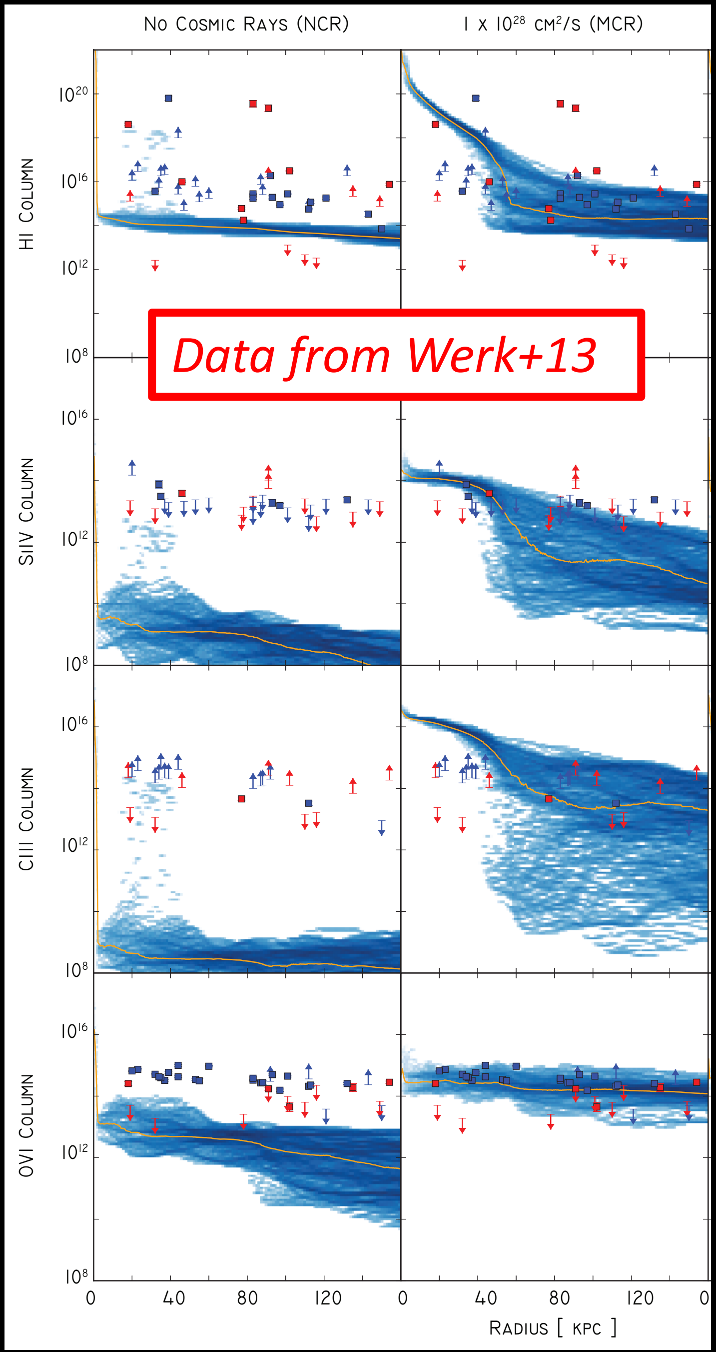
4. CRs can affect CGM properties

(see Liang+16, Butsky+18)

- CGM is ***cooler (<1e6K), metal-enriched (~0.1Z_{sun}), matches better with COS UV absorption lines***



Salem+16



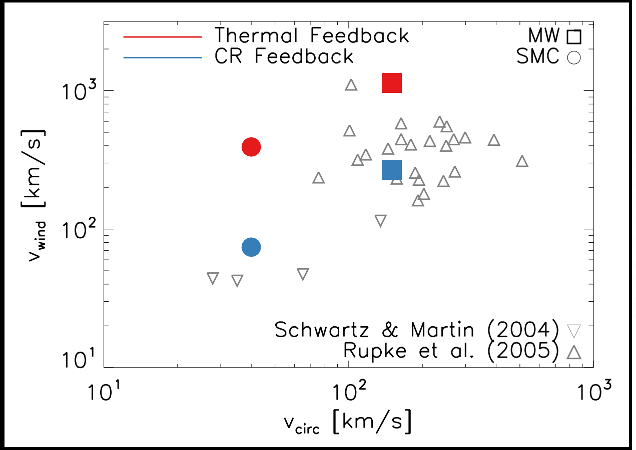
Data from Werk+13

Tests against the data

- Wind profiles (velocity, ionization, mass loss rate)
- v_{wind} vs. $v_{circ,}$ Mass loading vs. M_{halo}
- Galaxy scaling relations ($L\gamma$ vs. L_{FIR}, L_r vs. L_{FIR}, L_x-SFR, etc)
- CGM properties (profiles of columns & covering fractions)

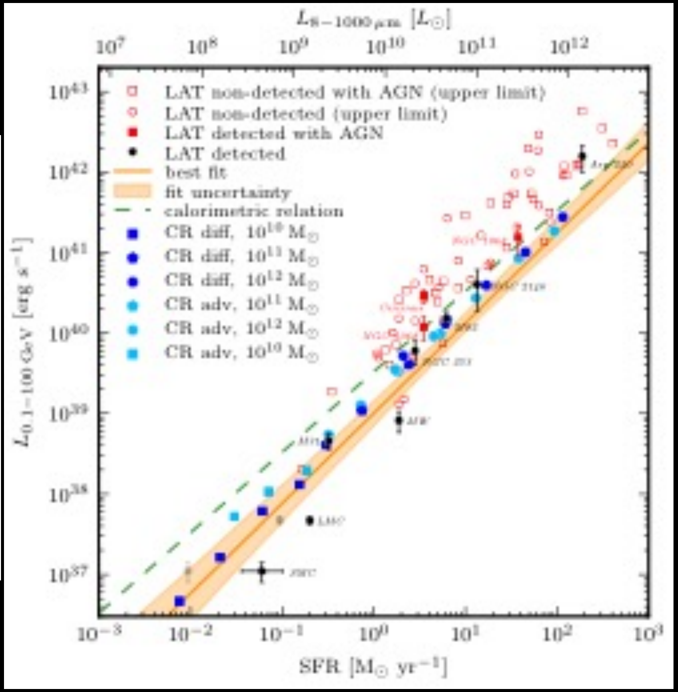
🟩	Consistent
🟨	Somewhat consistent
🟧	Potentially concerning
🟥	Inconsistent

v_{wind} vs. v_{circ}



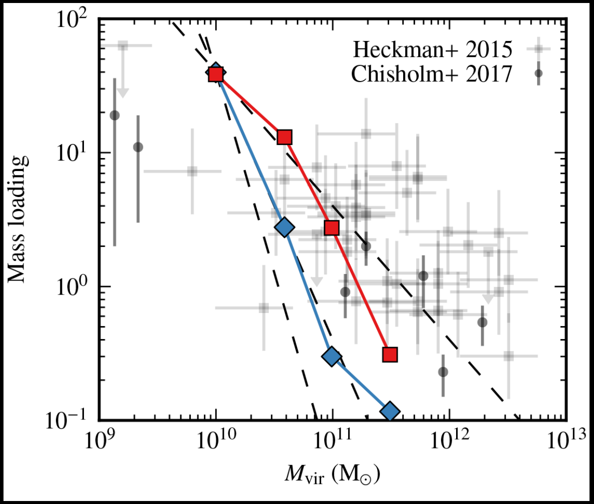
Booth+13

$L\gamma$ vs. SFR (L_{FIR})



Pfrommer+17

Mass loading vs. M_{halo}



Jacob+18, but see Mao+18

But the devil lies in the details…

- ***CR energy losses in dense environments*** (Jubelgas+08, Jacob+18)

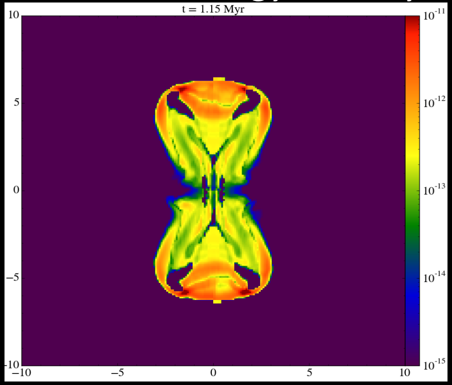
- ***Interaction between CRs & cold clouds*** (Everett+11, Wiener+18)

- ***Details about CR transport:***
  -- Isotropic vs. anisotropic diffusion (Pakmor+16, Jacob+18)
  -- Diffusion vs. streaming (Wiener+17, Butsky+18)
  -- Decoupling in cold, neutral medium (Farber+18).
  -- Spatial dependence of transport speed (Holguin+18)
  -- Energy dependent diffusion/streaming (?)

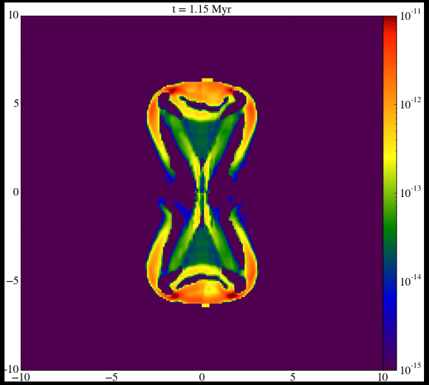
Simulating Fermi Bubbles with CR spectral evolution

(KY & Ruszkowski 2017)

Total CR energy density



CR energy density (>10 GeV)



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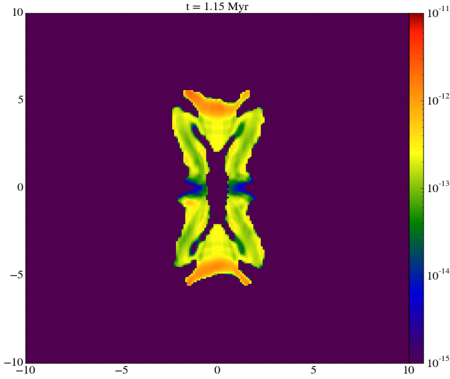

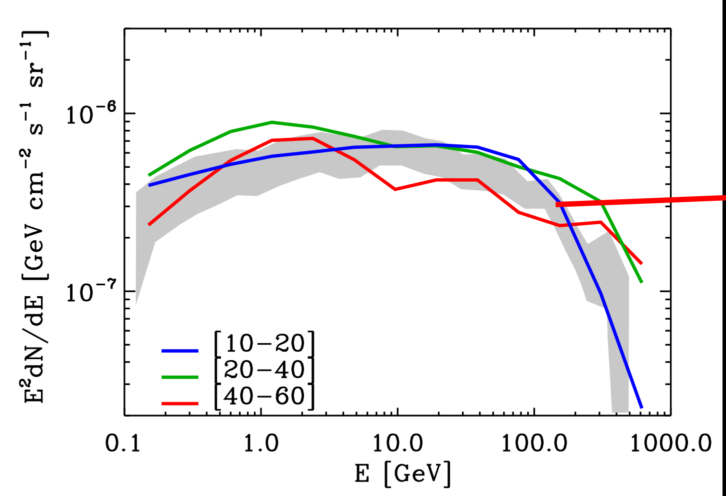

Simulated gamma-ray spectra in good agreement with data

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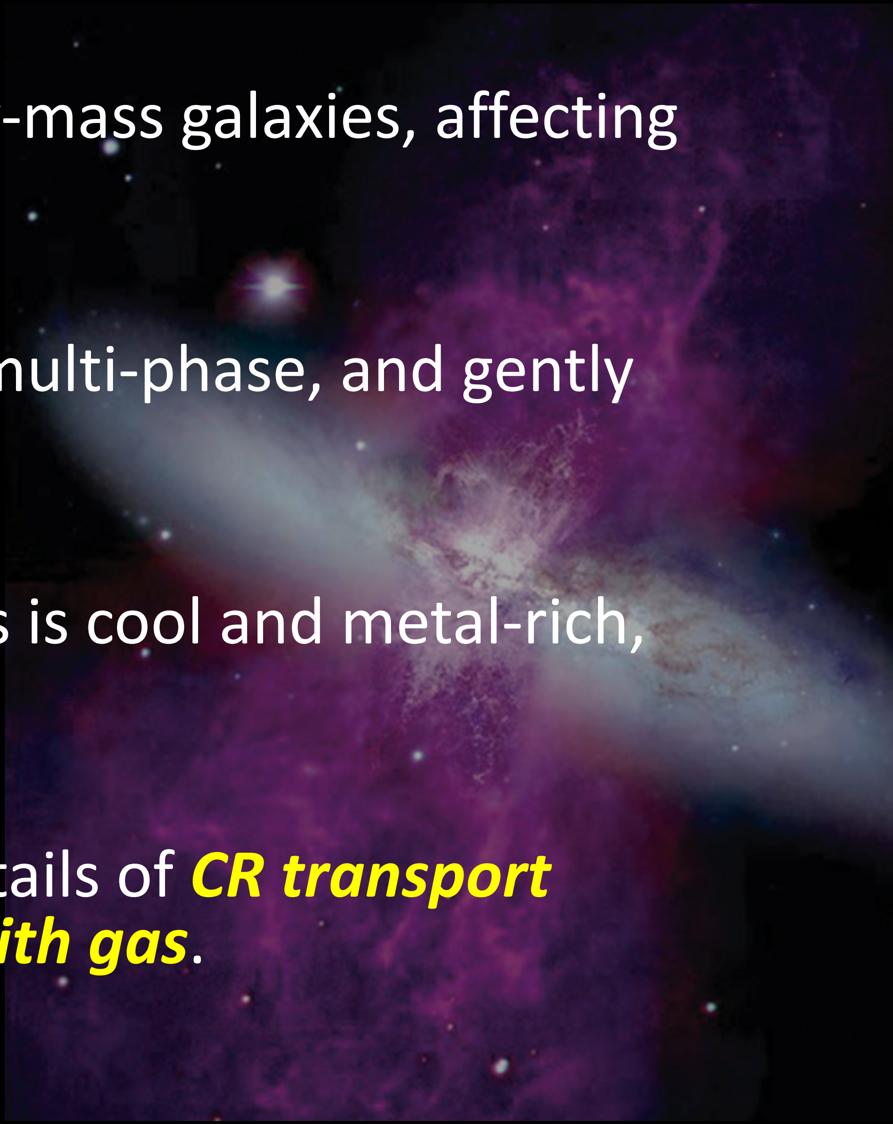
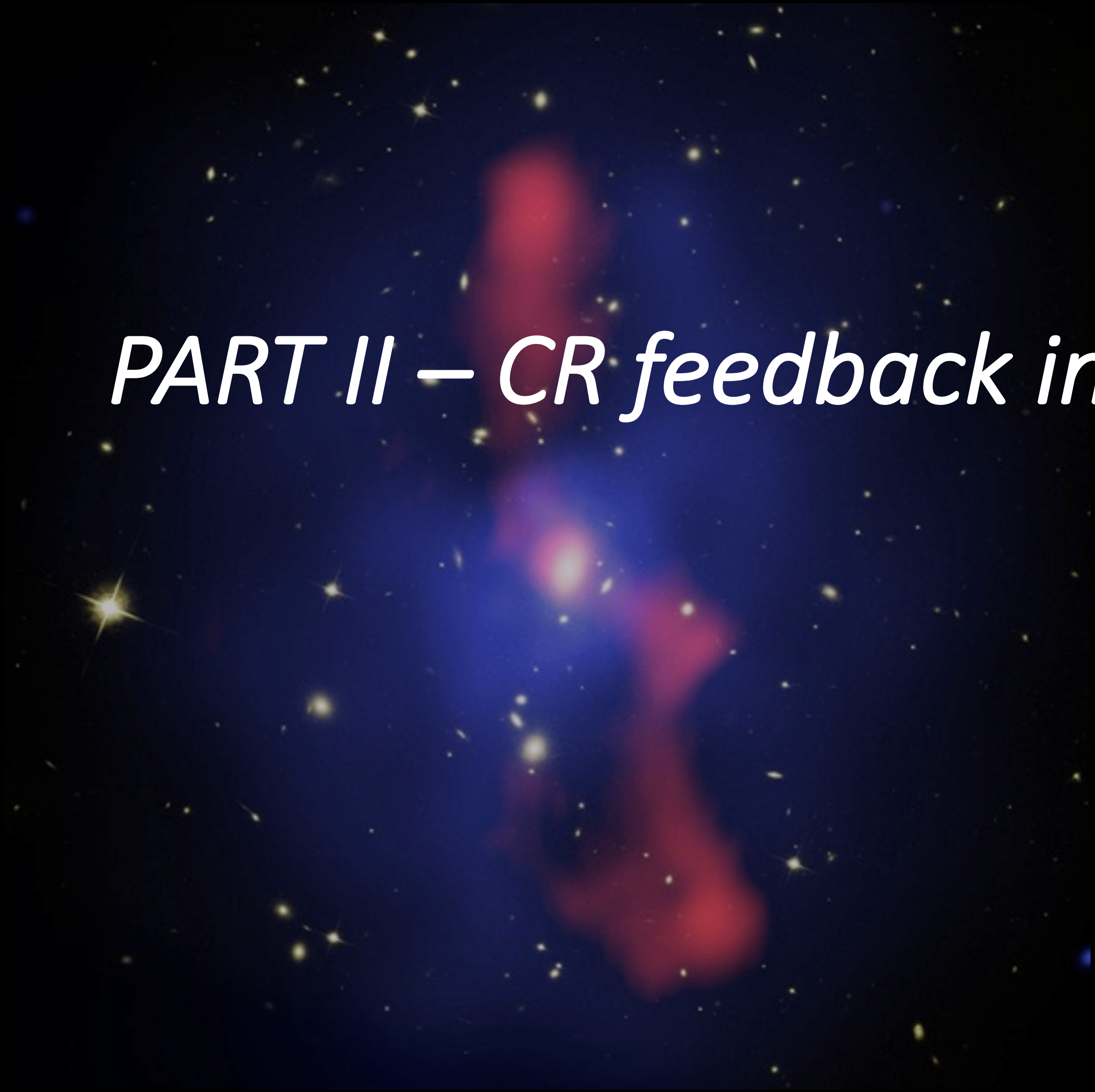
- ***Computational advancements*** (Dubois+16, Pakmor+16, Jiang+18, Thomas+18)

Talks: *C. Pfrommer, M. Ruszkowski, P. Girichidis & R. Pakmor*
Posters: *J. Wiener, T. Chan*

CR feedback in galaxies -- summary

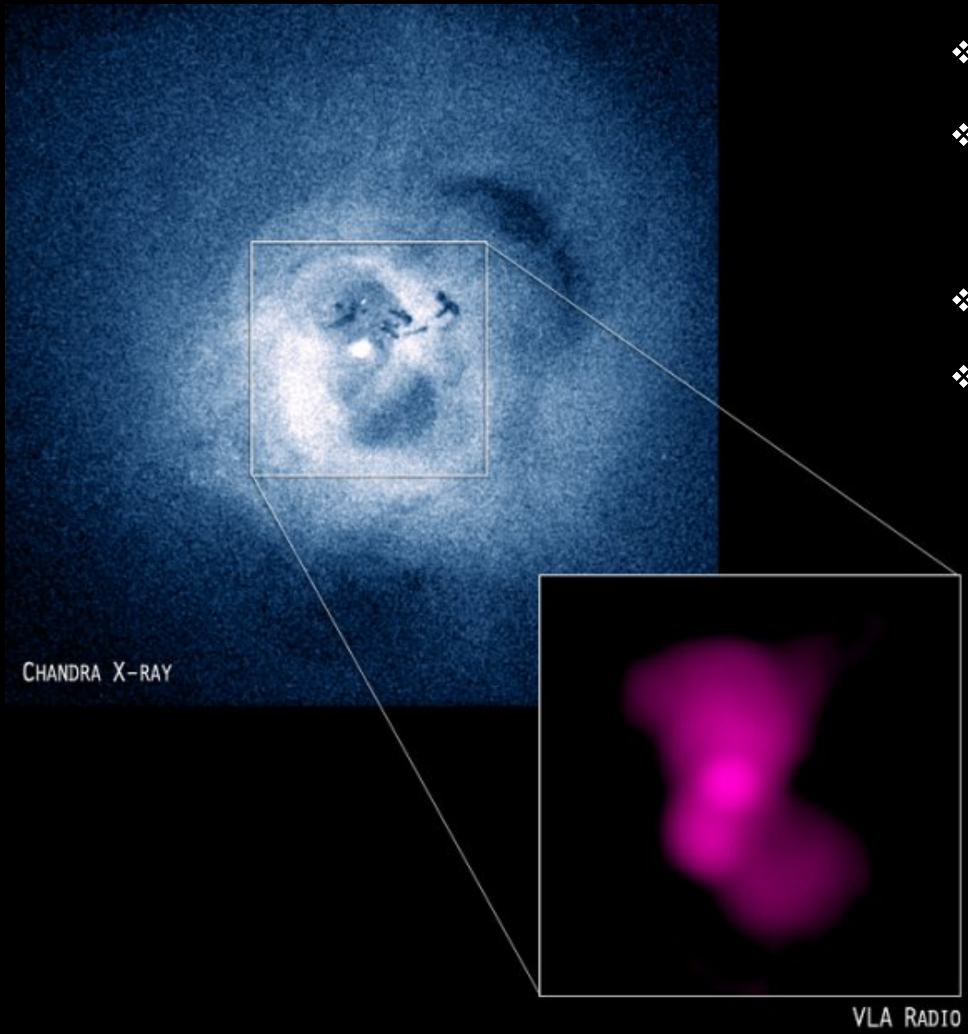


- CRs can suppress ***SFRs*** of low-mass galaxies, affecting faint-end LF & M/L ratios.
- CR-driven ***winds*** are cooler, multi-phase, and gently accelerated.
- The ***CGM*** including CR effects is cool and metal-rich, which matches the COS data.
- All the above depends on details of ***CR transport processes*** and ***interactions with gas***.

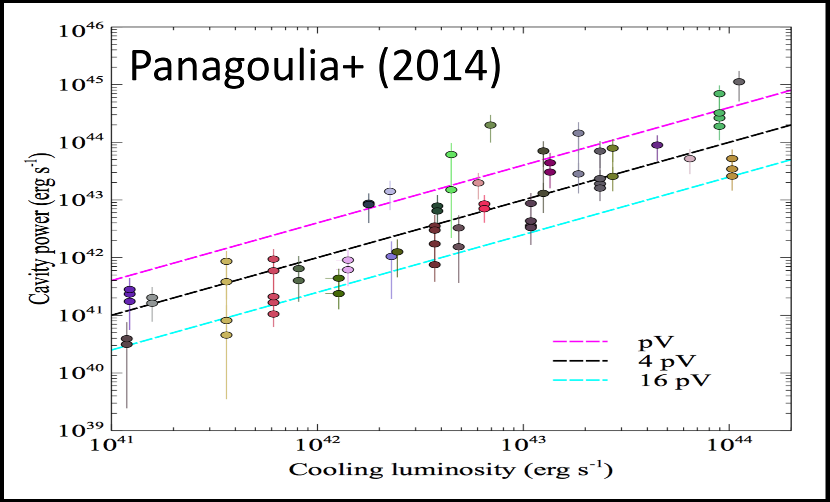


PART II – CR feedback in clusters

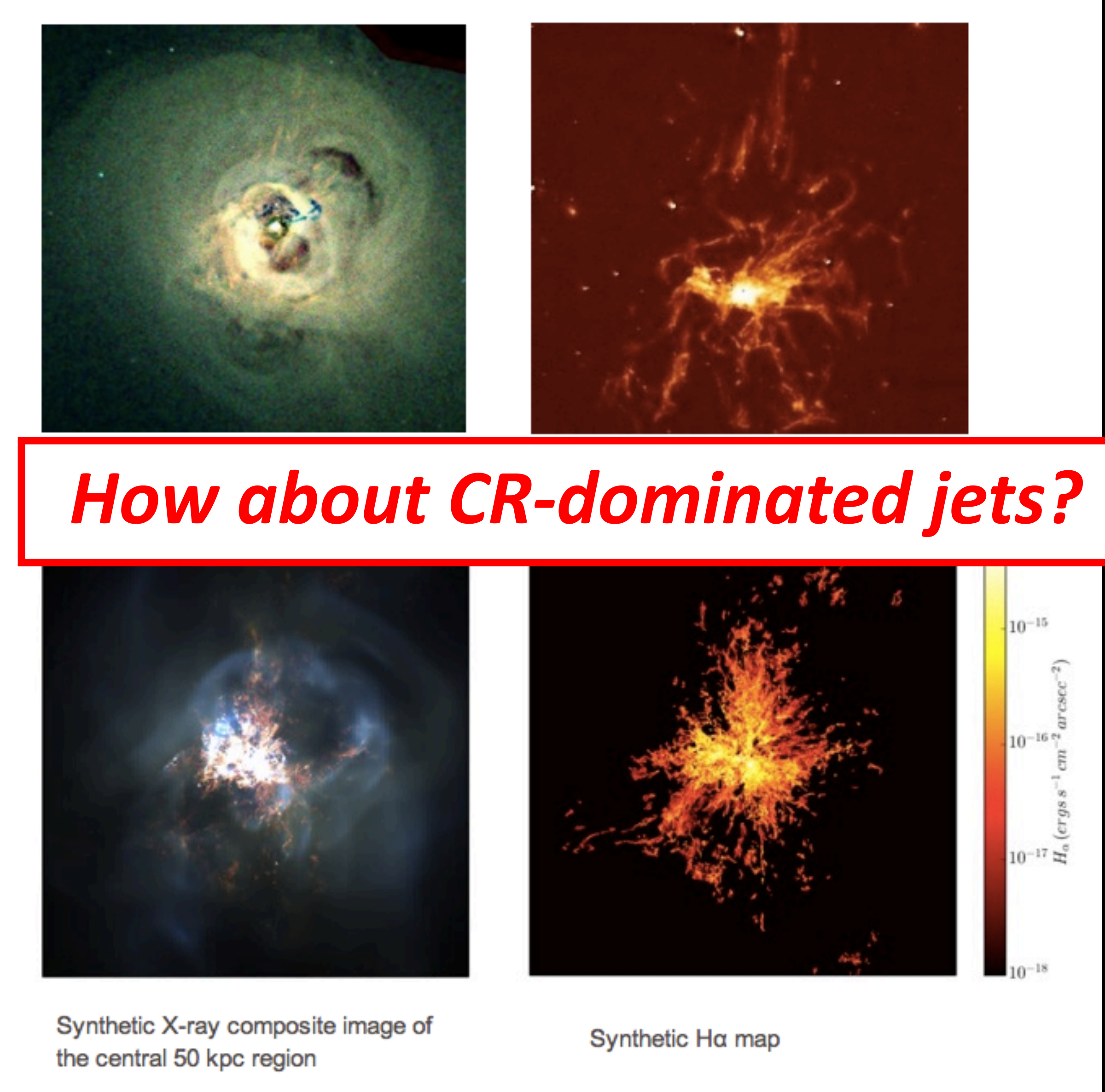
AGN feedback in Perseus cluster



- X-ray: intracluster medium (ICM)
- Composition of radio bubbles: thermal gas or ***CR protons***
- Cool-core (CC) clusters: $t_{cool} << t_H$
- Solution to the cooling-flow problem


Panagoulia+ (2014)

Success of hydro simulations of AGN feedback



Synthetic X-ray composite image of the central 50 kpc region

Synthetic Hα map

How about CR-dominated jets?

❖Self-regulation

Sijacki+07, Cattaneo+07, Booth+09, Dubois+10

❖Cold gas accretion + momentum-driven jets

Gaspari+11,12,15, Li+14,15,17, Prasad+15, KY+16ab, Meece+17

❖Local thermal instabilities

Pizzolato+05,10, McCourt+12, Sharma+12, Meece+15, Voit+15,17

Works on CR feedback in clusters

❖***1D models:***

Loewenstein+91, Guo+08, Pfrommer 13, Jacob+2016ab

❖***2D hydro, local simulations:***

Mathews+08, Guo+10

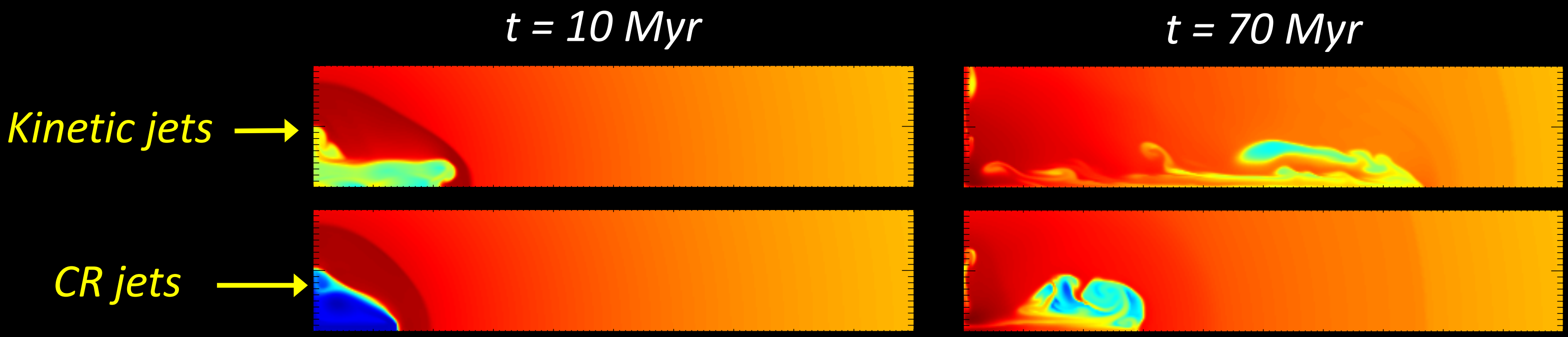
❖***3D hydro/MHD, local simulations:***

Weinberger+17, Bourne+17, Ehlert+18, KY+18

❖***3D hydro/MHD, global simulations:***

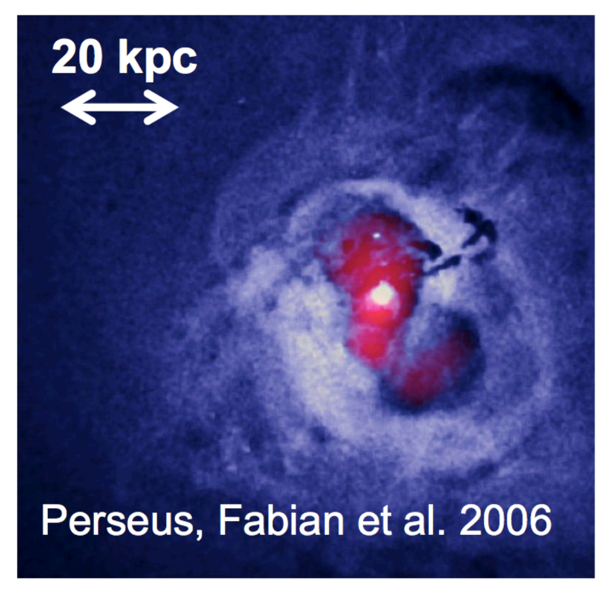
Sijacki+08, Ruszkowski+17

1. CR-jet inflated bubbles are "fatter"



Guo+10

- Slower CR jets allow CR pressure to expand laterally -> Larger cross section causes deceleration
- CR bubbles could more easily produced young cavities at the center of Perseus

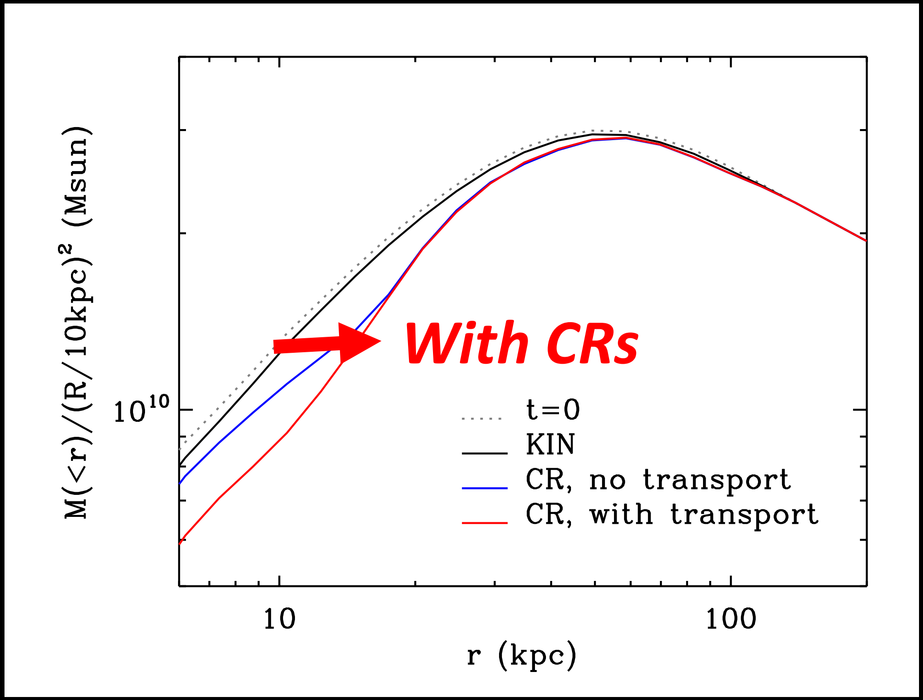


Perseus, Fabian et al. 2006

2. CR bubbles can expand the hot ICM

(see also Mathews+08)

Enclosed mass profiles



KY+18 (in prep.)

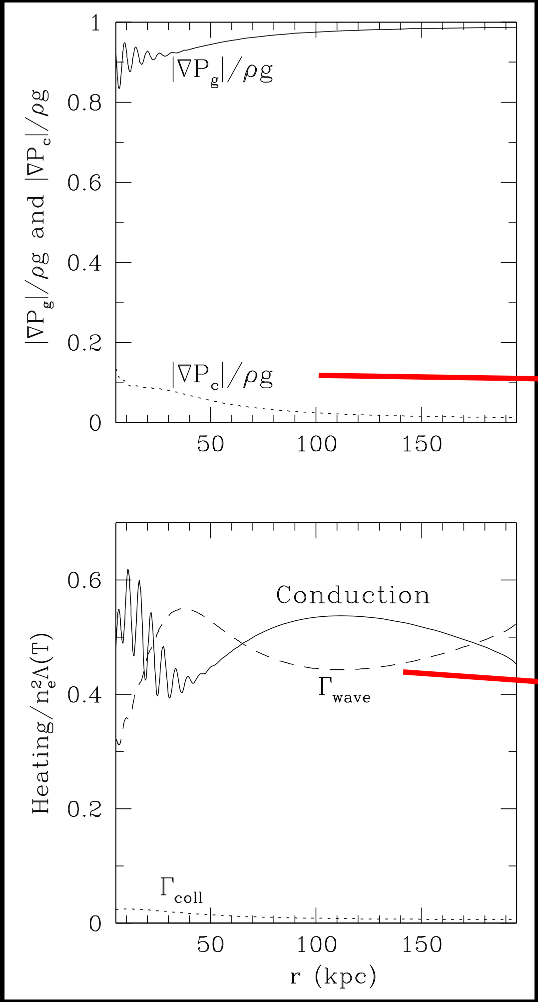
CRs can efficiently uplift the hot ICM because

-- CR bubbles have larger cross sections

-- ICM containing CRs is more buoyant

3. CR bubbles heat the ICM via Coulomb, hadronic & Alfven-wave heating

(**see also** Loewenstein+91, Pfrommer 13, Jacob+2016ab, Ruszkowski+17, Ehlert+18, KY+18)

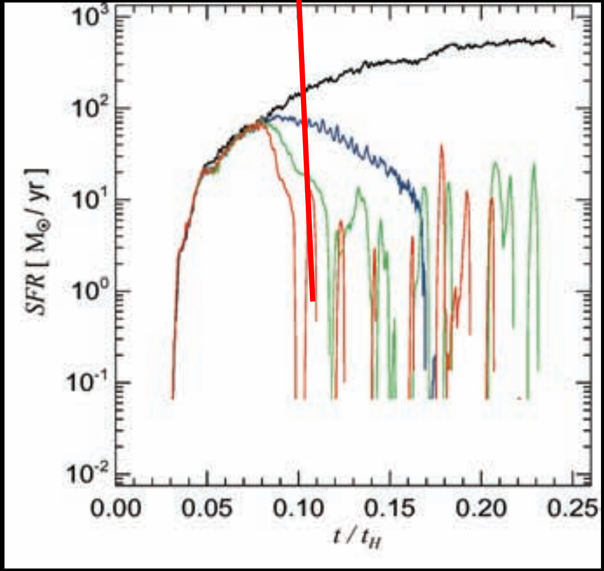


- CRs of <10% of P_{th} can provide significant heating

Xcr = Pcr/Pth < 0.1

Heating/cooling ~ 0.5

SFR suppressed by 100x

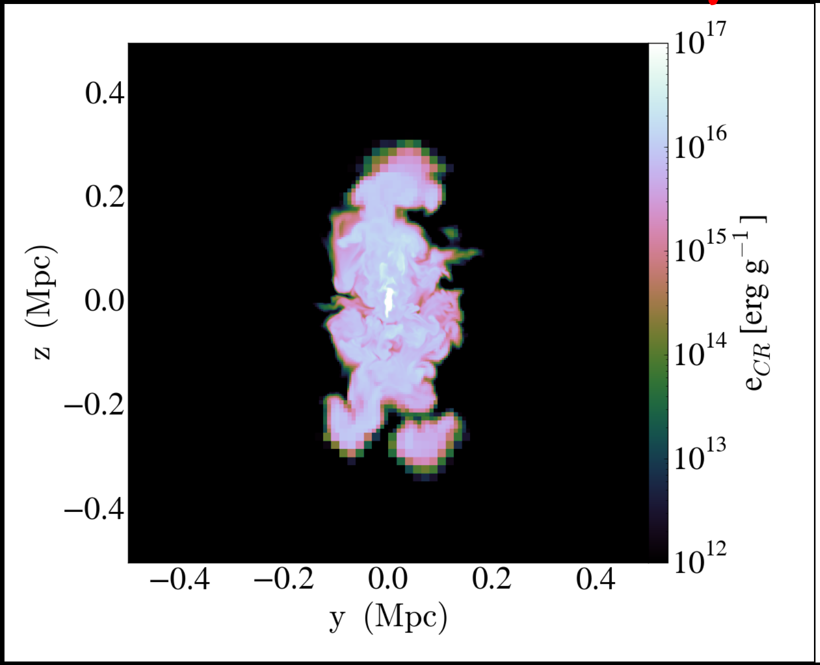


Guo+08

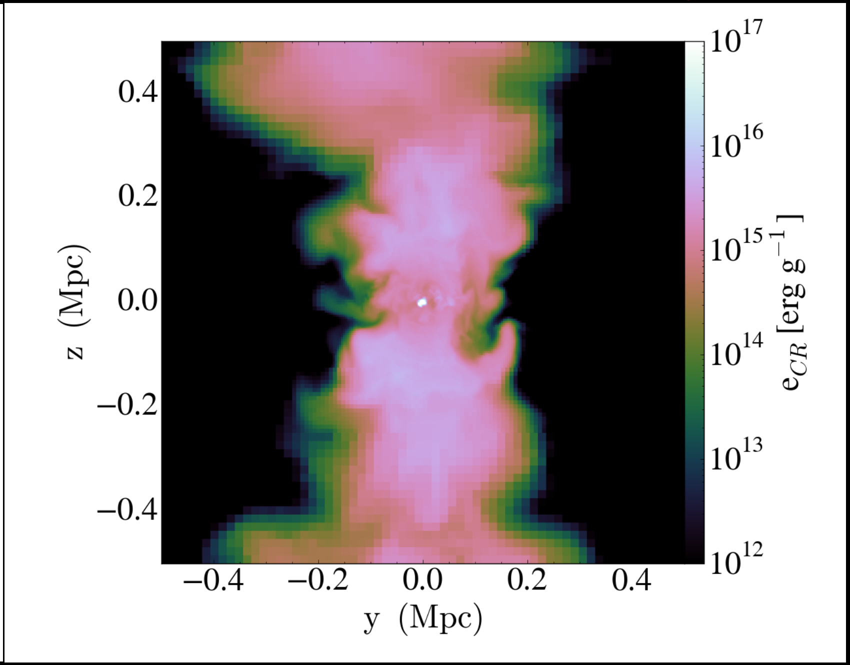
Sijacki+08

No transport, no heating

Advection only, no transport ✗



Advection & transport ✔



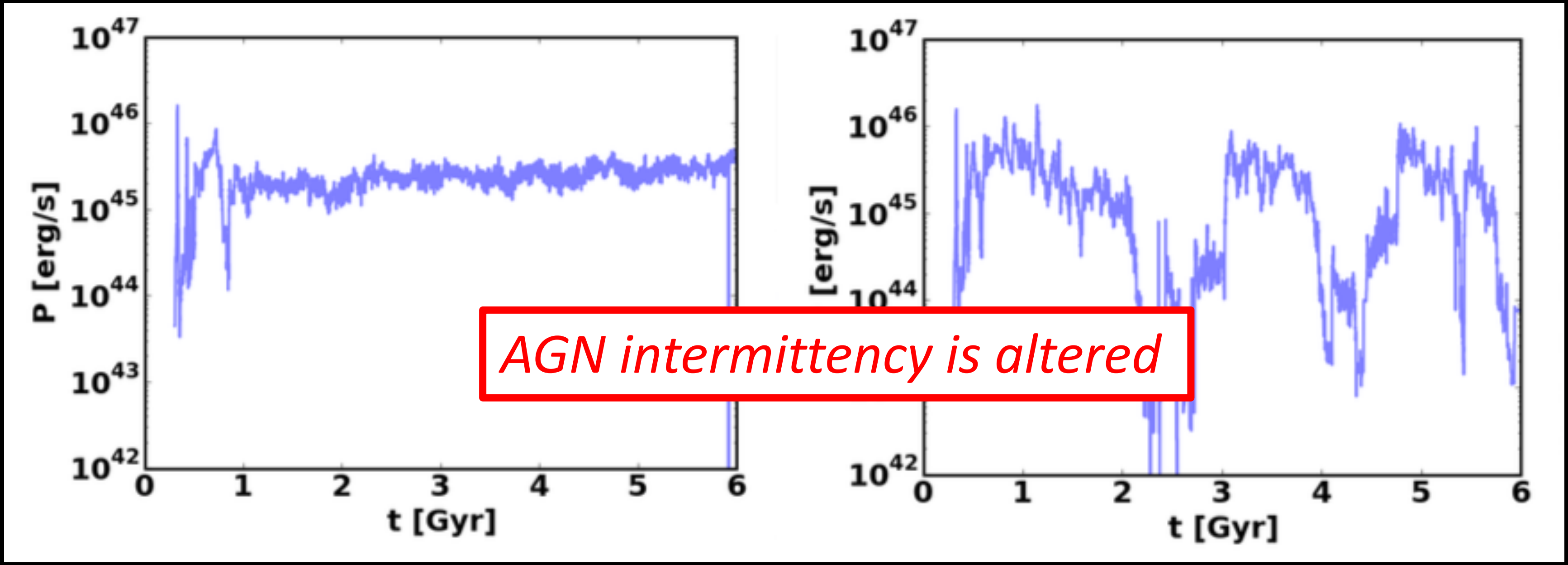
Ruszkowski, KY & Reynolds (2017)

- ❖ With transport, CRs can escape the bubbles and interact with ICM
- ❖ CR heating (Alfven-wave, Coulomb, hadronic) -> self-regulation

No transport, no heating

Advection only, no transport ✗

Advection & transport ✔

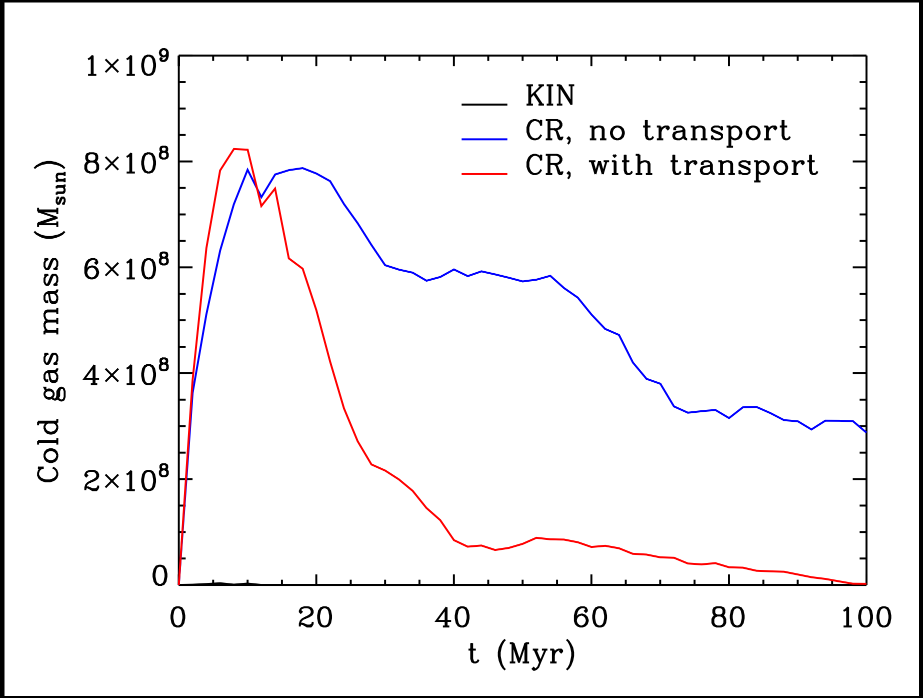


AGN intermittency is altered

Ruszkowski, KY & Reynolds (2017)

4. CR jet feedback affects evolution of cold gas

Mass of cold gas (T<5e5K) vs. time

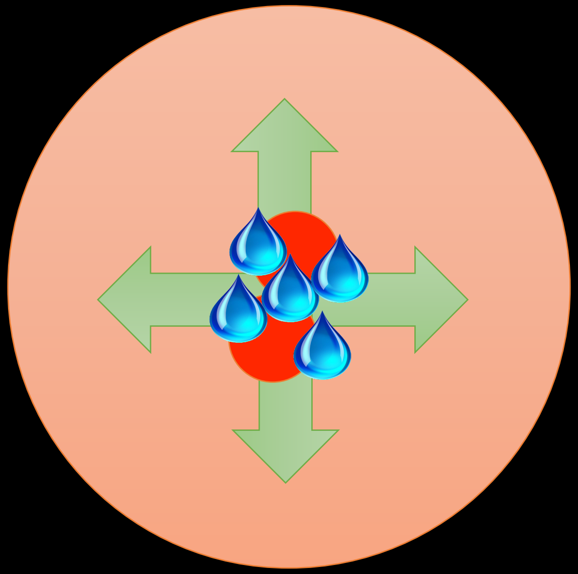


KY+18 (in prep.)

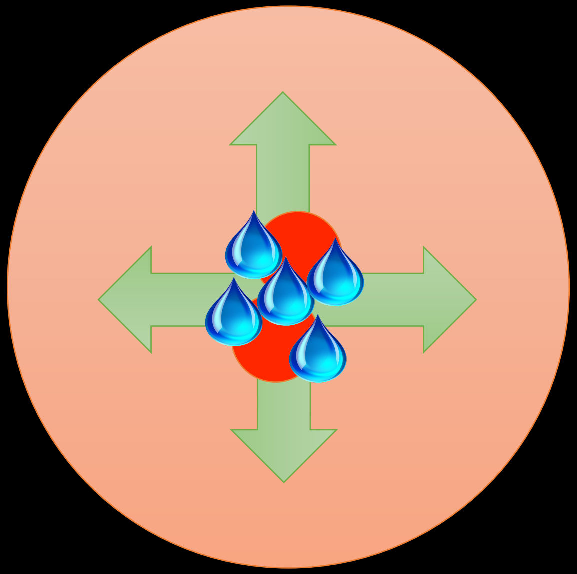
- Cold gas formed initially due to adiabatic cooling and slow heating
- With transport, amount of cold gas reduced due to CR heating

CR feedback in clusters -- summary

Kinetic jets

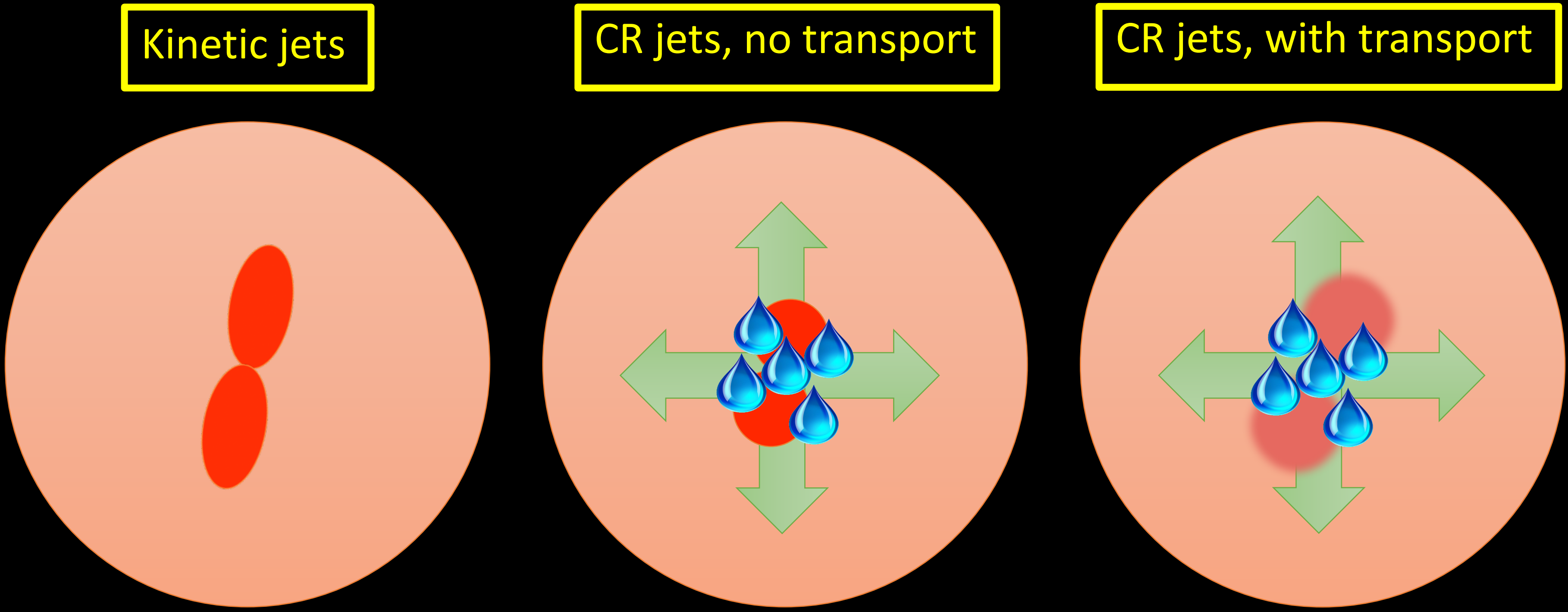


CR jets, no transport



CR jets, with transport

CR feedback in clusters -- summary



Kinetic jets

CR jets, no transport

CR jets, with transport

Successful

Failed to regulate

Successful

Less intermittent

More intermittent

Instantaneous bubble mixing (KY+16)

Gradual CR heating

Open questions

❖ ***Details of CR transport***

-- isotropic vs. anisotropic

-- streaming (self-confinement) vs. diffusion (extrinsic turbulence)

-- damping mechanisms (Wiener+13, 18)

-- energy dependence

❖ ***Nonthermal emission***

-- gamma-ray constraints from Fermi/MAGIC

-- connection to radio mini halos (Jacob+16ab)

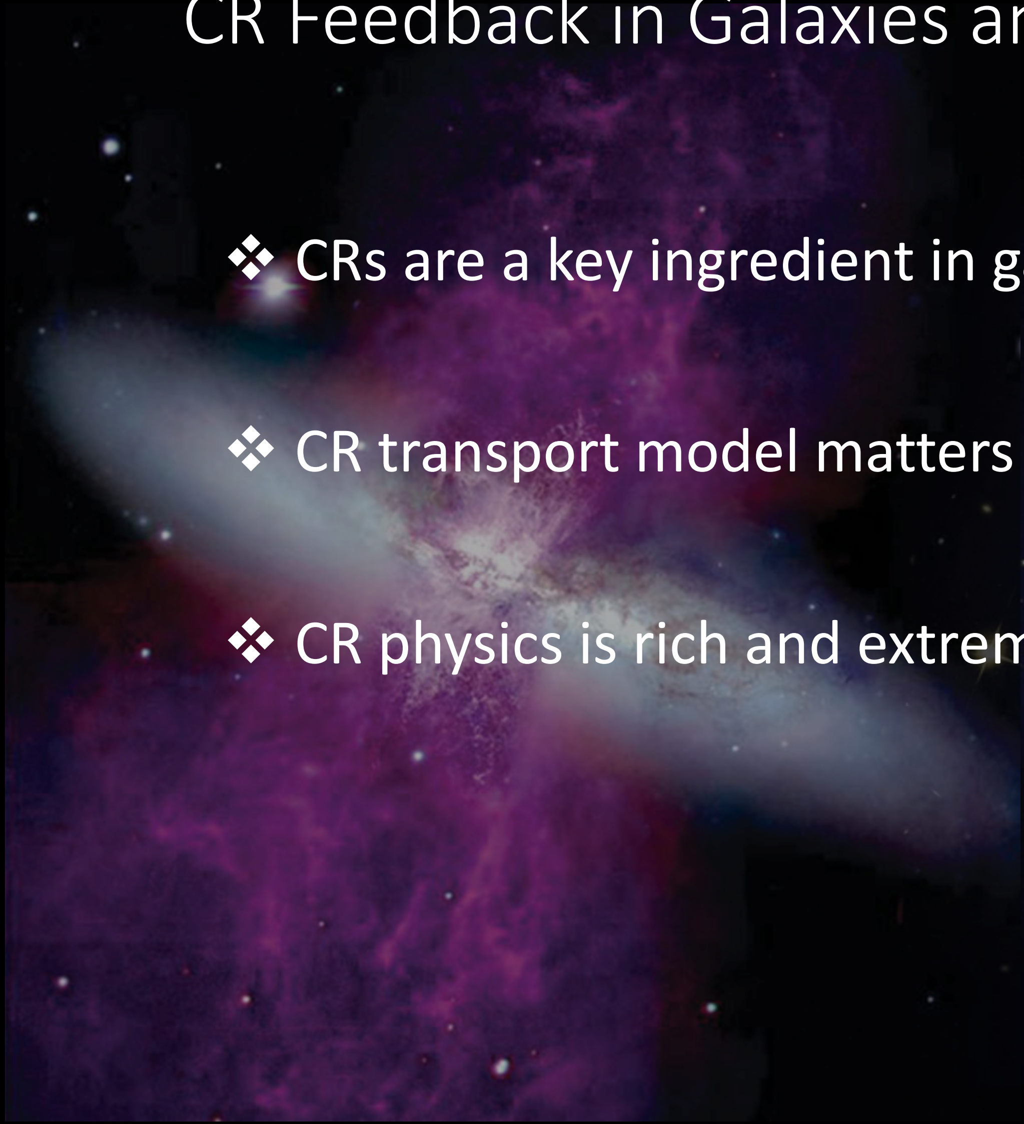
❖ ***How to distinguish CR bubbles from thermal bubbles obervationally?***

-- Sunyaev-Zel'dovich effect (Pfrommer+04, Sijacki+08, Abdulla+18)

-- Inverse-Compton scattering

-- ??

CR Feedback in Galaxies and Clusters -- summary



- CRs are a key ingredient in galaxy and cluster feedback
- CR transport model matters
- CR physics is rich and extremely multi-scale