Feedback in galaxy formation

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Competing Structure Formation Models, U of Iceland, Sep 2019

Outline

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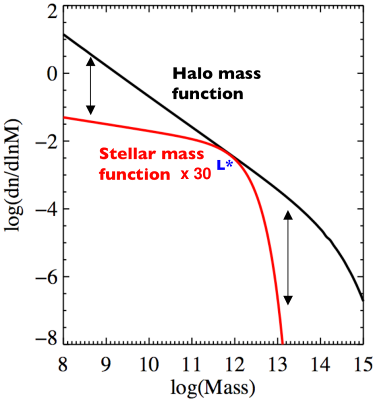
1. Feedback in cosmological simulations
   - Puzzles
   - Galactic winds
   - Feedback implementations

2. Physical feedback processes
   - Supernova feedback
   - Radiation feedback
   - Cosmic ray feedback

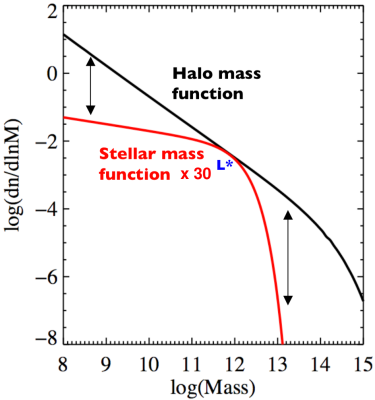
Galaxy formation

Galaxy formation in dark matter halos



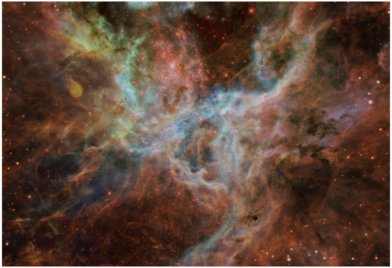
- the number of galaxies in dark matter (DM) halos of mass $\gtrsim 10^{12}\,\mathrm{M}_\odot$ is exponentially suppressed $\rightarrow$ non-gravitational (AGN) feedback introduces a new scale of galaxy formation

Galaxy formation in dark matter halos



- the number of galaxies in dark matter (DM) halos of mass $\gtrsim 10^{12}\,\mathrm{M}_\odot$ is exponentially suppressed
  $\rightarrow$ non-gravitational (AGN) feedback introduces a new scale of galaxy formation
- discrepancy of the power-law slopes at the faint end
  $\rightarrow$ feedback lowers the star conversion rate in dwarf halos
  $\rightarrow$ shallower halo mass function for WDM, SIDM, ...

Feedback by galactic winds



star forming region in Milky Way

- stellar feedback (proto-stellar jets, radiation feedback) regulates star formation in molecular clouds

Feedback by galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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NASA/JPL-Caltech/STScI/CXC/UofA

- stellar feedback (proto-stellar jets, radiation feedback) regulates star formation in molecular clouds
- galactic feedback (supernovae, radiation and cosmic rays) launches galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

Numerology

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$$E_{\rm bind} \sim M_{\rm gas} v_{\rm halo}^2 \sim \frac{G M_{\rm gas} M_{\rm halo}}{R_{\rm halo}} \propto M_{\rm halo}^{5/3}$$

  - giant molecular cloud (GMC):
    $M \sim 10^5\ M_\odot$, $R \sim 50$ pc $\quad\Rightarrow\quad E_{\rm bind} \sim 2\times10^{49}$ erg $< E_{\rm SN}$
  - Milky Way galaxy:
    $M_{\rm halo} \sim 10^{12}\ M_\odot$, $M_{\rm gas} \sim 10^{10}\ M_\odot$, $R \sim 1$ kpc
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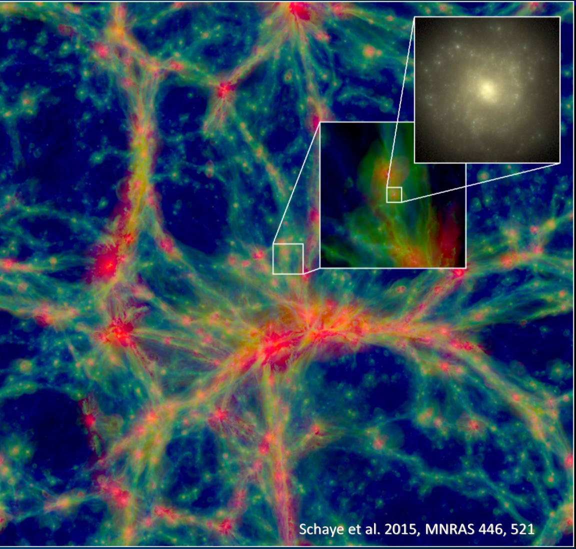
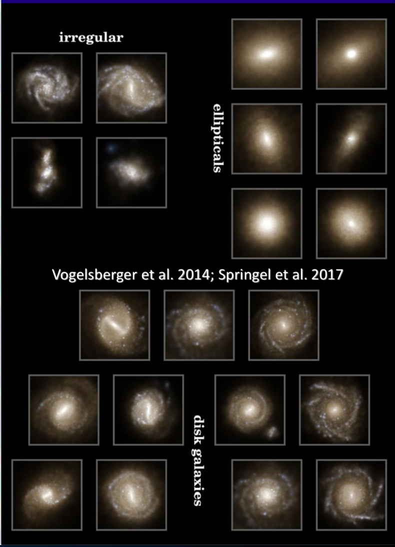
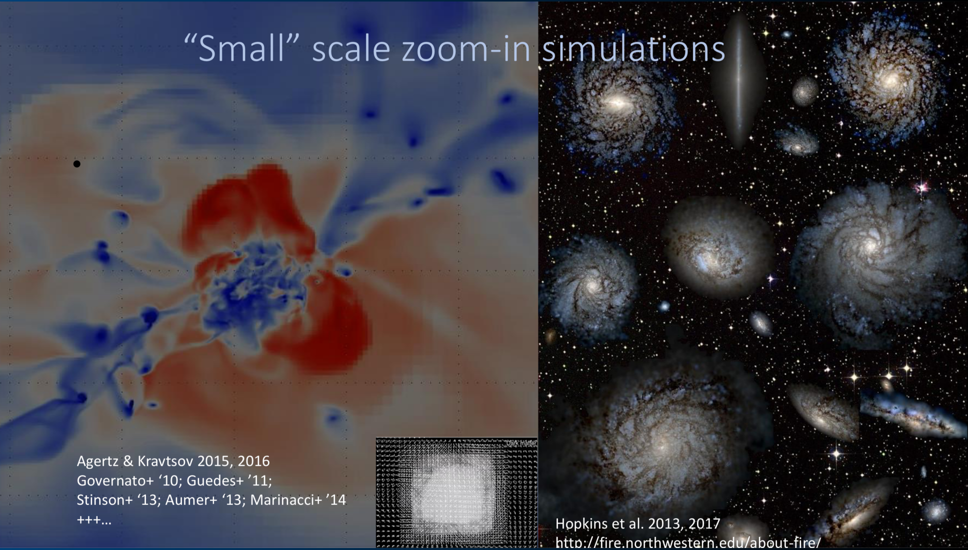
- for $\sim L_*$ galaxies, a single SN will not unbind the galaxy, but $E_{\rm gal} = e_{\rm SN} M_* = 10^{49}\,\mathrm{erg}\,\mathrm{M}_\odot^{-1} 10^{11}\mathrm{M}_\odot \sim 10^{60}\,\mathrm{erg} \sim E_{\rm bind}$

Large-scale galaxy formation simulations



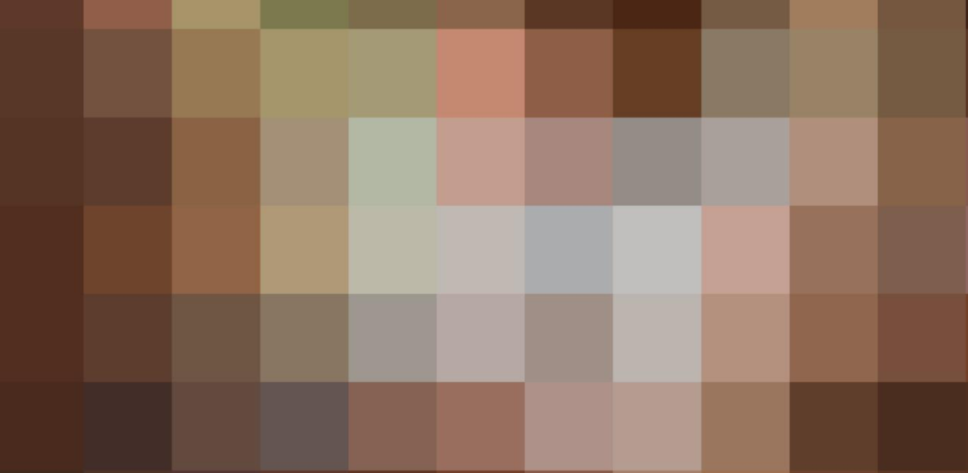


Zoom-in galaxy formation simulations



What is “small scales”?

In modern highest-resolution simulations the small-scale is this...



All of the current galaxy formation simulations can be thought of as “small-scale”, but they differ in how far down in resolution they push and how ISM and feedback is treated numerically

Feedback implementation in cosmological simulations

problem: injection of SN energy in dense SF regions is quickly radiated away

- Auriga/Illustris with Arepo (moving mesh):
  non-local injection of wind momentum outside SF region
  $\rightarrow$ launches galactic winds, excites ISM turbulence
  $n_{\mathrm{SF}} = 0.1\ \mathrm{cm}^{-3}$, quiescent SFH + bursts from accretion

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- Apostle/Eagle with Gadget (SPH), Horizon with Ramses (AMR):
  local injection of star-cluster energy ($T = 10^7$ K) or SN momentum:
  Sedov explosions $\rightarrow$ launches galactic winds, rises cooling time
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- NIHAO using Gasoline (SPH):
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- FIRE with Gizmo (Lagrangian meshless finite mass):
  local injection of momentum (mimicking radiation pressure)
  $\rightarrow$ launches explosive galactic winds
  $n_{\mathrm{SF}} = 500\ \mathrm{cm}^{-3}$, very bursty SFH

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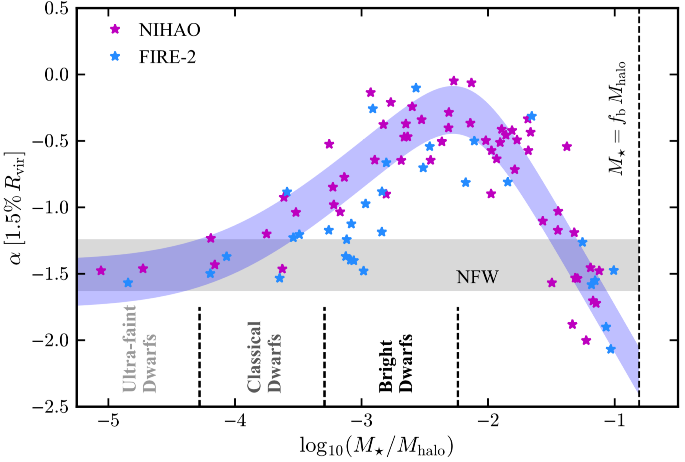
Halo response to galactic feedback

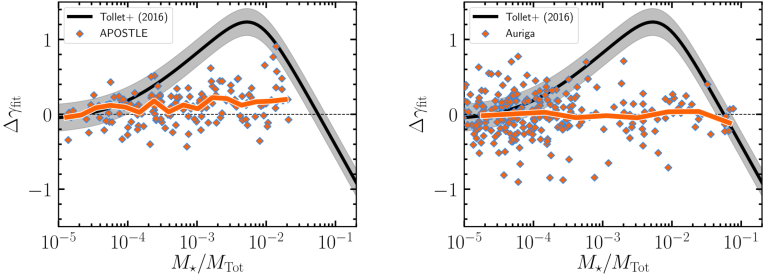
Inner DM slope **depends on** star formation efficiency (FIRE, NIHAO)



Di Cintio+ (2014), Chan+ (2015), Tollet+ (2016), figure from Bullock & Boylan-Kolchin (2017)

Halo response to galactic feedback

Inner DM slope **independent of** star formation efficiency (Auriga, Apostle)



Bose+ (2019)

- APOSTLE and AURIGA dwarfs display a similar diversity in their cumulative SFHs as observed Local Group dwarfs
- recurrent SF bursts are not sufficient to cause the formation of cores
- need to resolve multi-phase ISM gas flows and potential fluctuations to form cores (Pontzen & Governato 2012)

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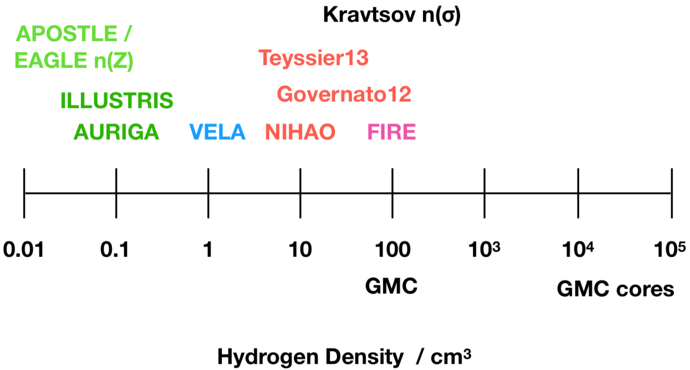
Star formation threshold in cosmological simulations



Current cosmological simulations lack predictive power

Halo response and star formation histories depend on choices of subgrid scale models

How can we obtain predictive power?

- what is the optimal resolution for modelling galaxy formation in cosmological context?
- which scales/process should be modelled and which should be “subgridded”?

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How can we obtain predictive power?

- what is the optimal resolution for modelling galaxy formation in cosmological context?
- which scales/process should be modelled and which should be "subgridded"?
- we want a numerical "effective theory" of the ISM
  - processes that separate well in scale from directly modelled processes in simulations can be modelled subgrid (e.g., star formation)
  - what about feedback processes?

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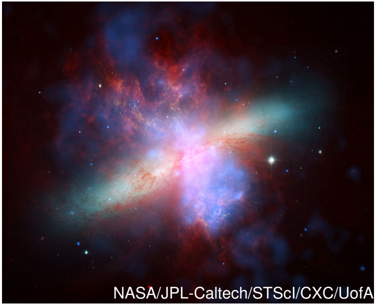
How are galactic winds really driven?



super wind in M82

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

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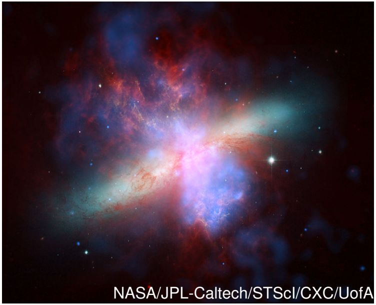

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observed energy equipartition between cosmic rays, thermal gas and magnetic fields
→ suggests self-regulated feedback loop with CR driven winds

Supernova feedback in the interstellar medium

the standard picture for isolated SN evolution:

1. free expansion: ends when $M_\text{swept} \sim M_\text{eject}$ ($t = 200$ yr, $R = 1$ pc)
2. adiabatic phase (energy-conserving Sedov phase): ends when radiative losses become important (10^{4-5} yr, $R = 30$ pc)
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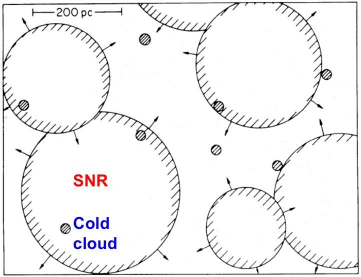
but: the standard picture is not applicable to galaxy formation:

- within 10^6 yr, another SN is likely to go off within 100 pc
- thus, within $\sim$ Myr every point in the ISM will have experienced a SN blastwave (McKee & Ostriker 1977)

$\rightarrow$ **feedback changes qualitatively**



Supernova feedback in the ISM

SILCC: **SI**mulating the **L**ife**C**ycle of molecular **C**louds

Stefanie Walch
Philipp Girichidis
Thorsten Naab
Andrea Gatto
Simon C. O. Glover
Richard Wünsch
Ralf S. Klessen
Paul C. Clark
Thomas Peters
Dominik Derigs
Christian Baczynski

Walch et al., 2015, MNRAS 454, 238
Girichidis et al., 2016, MNRAS 456, 3432

KS SN rate, random driving

Radiation feedback – 1

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$$\frac{dv}{dt} = -\frac{\nabla P}{\rho} - \nabla\Phi = 0$$

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- if pressure is dominated by radiation pressure associated with a radiation flux $\boldsymbol{F}_{\rm rad}$

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where κ is the opacity due to scattering and in the last step we have assumed $\kappa = \kappa_{\rm T} = \sigma_T/m_{\rm p}$, where $\sigma_{\rm T}$ is the Thomson scattering cross section for the electron and $m_{\rm p}$ is the proton rest mass

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- the luminosity of a source bounded by a surface S is

$$L_{\mathrm{s}} = \int_S \boldsymbol{F}_{\mathrm{rad}} \cdot d\boldsymbol{S} = \int_S \frac{c}{\kappa}\nabla\Phi \cdot d\boldsymbol{S} = \frac{c}{\kappa}\int_V \nabla^2\Phi dV = \frac{4\pi Gc}{\kappa}\int_V \rho dV,$$

  using Gauss' theorem and Poisson's equation.

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Radiation feedback – 2

- if radiation force of the source can be balanced by the gravitational weight of the surrounding gas distribution with mass $M_{\rm gas}(R)$, assumed to dominate over other matter components, the luminosity is given by

$$L_{\rm s} = \frac{4\pi G M_{\rm gas}(R) c}{\kappa}$$

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- if the central source is 1) a UV radiation emitting massive star powered by nuclear burning or 2) an AGN powered by an accreting supermassive black hole of mass $M_\bullet$ that are both accreting at their Eddington limit, then each object emits a luminosity

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- the mass of the GMC (for the star) or galaxy (for the AGN) that can be supported by radiation pressure from its central object is obtained by setting $L_{\mathrm{s}} = L_{\mathrm{Edd}}$:

$$M_{\mathrm{gas}}(R) = M_\bullet \, \frac{\kappa}{\kappa_{\mathrm{T}}}$$

$\Rightarrow$ we require $\kappa \gg \kappa_{\mathrm{T}}$ if radiation pressure is to have an appreciable impact on the gas of the GMC or the host galaxy!

Radiation feedback – 3

- **opacities:**
  - for Thomson scattering $\kappa_\mathrm{T} = \sigma_T / m_\mathrm{p} = 0.346\,\mathrm{cm}^2\mathrm{g}^{-1}$
  - at optical and UV frequencies, the dust opacity κ_D can reach values $\sim 10^3\,\mathrm{cm}^2\mathrm{g}^{-1} \gg \kappa_\mathrm{T}$ for a Milky Way with dust-to-gas ratio $f_\mathrm{D} \approx 0.01$

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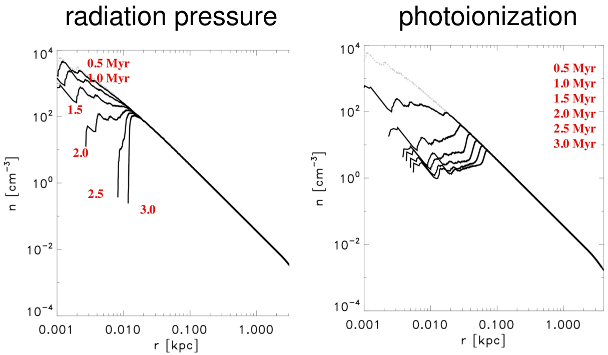
- in configurations in which dusty gas is optically thick also at infrared (IR) frequencies ($\tau_\mathrm{IR} > 1$), it is possible for the radiation force to exceed L_AGN/c, though at most by a factor of τ_IR
- in this regime, IR photons become trapped within the optically thick gas and must scatter multiple times before escaping:

$$\dot{p}_\mathrm{rad} = \frac{L_\mathrm{AGN}}{c}\tau_\mathrm{IR} \quad \text{implies} \quad \tau_\mathrm{IR} > 1$$

Radiation feedback – idealized experiments



Sales+ (2014), also Walch+ (2012), Rosdahl+ (2015), Raskutti+ (2017), Haid+ (2018)

- idealized radiative transfer experiments with Arepo
- radiation pressure has the capability for feedback, but is slower than photoionization!

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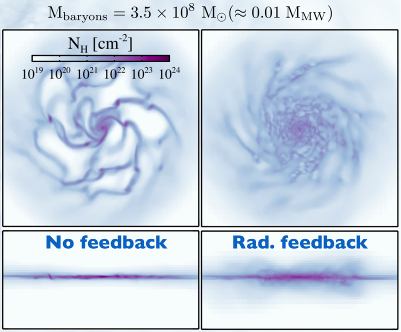
Radiation hydrodynamics simulations of disk galaxies

- significant effect from photoionisation in low-mass galaxies
- little effect at MW mass scale
- radiation pressure did nothing
- however: low optical depths $\rightarrow$ little boost from multi-scattering IR radiation:

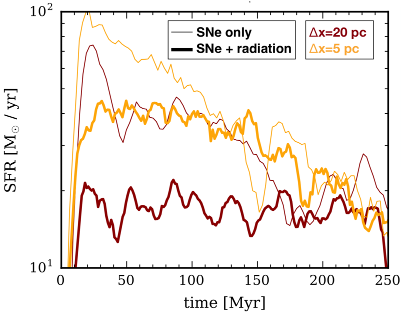
$$\dot{p}_{\mathrm{IR}} = \frac{L}{c}\tau_{\mathrm{IR}}$$



Rosdahl+ (2015)

RHD simulations of isolated compact ULIRG-like disks

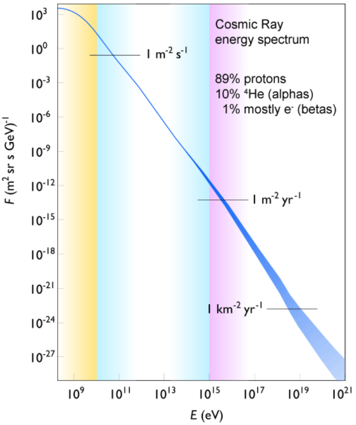
- multi-scattering IR radiation pressurises dense optically thick clumps → somewhat reducing star formation
- mildly stronger outflows in comparison to SN and photoionisation only
- but: the effect of IR weakens with increasing resolution → more IR escape channels with higher resolution?



DRAMA: Disks with RAdiation-MAtter interactions

Rosdahl+ (in prep.)

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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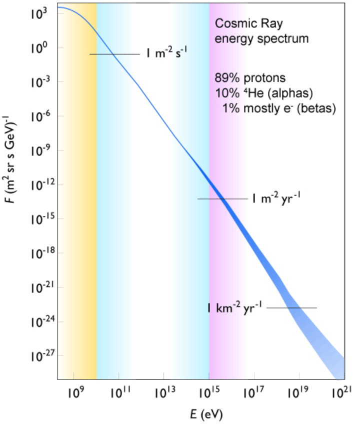

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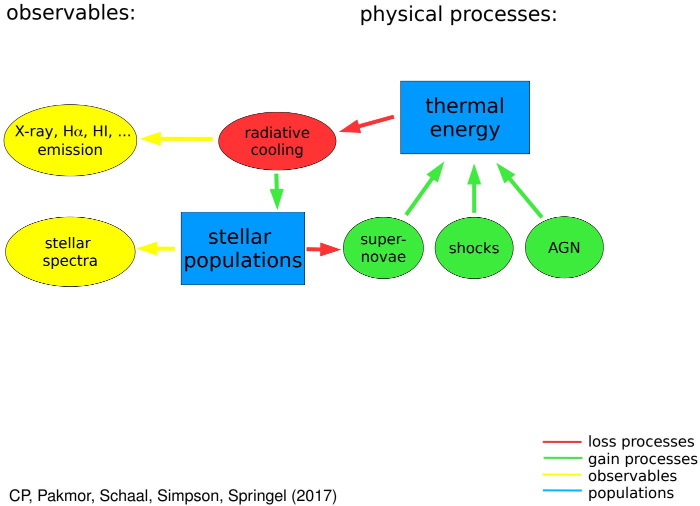
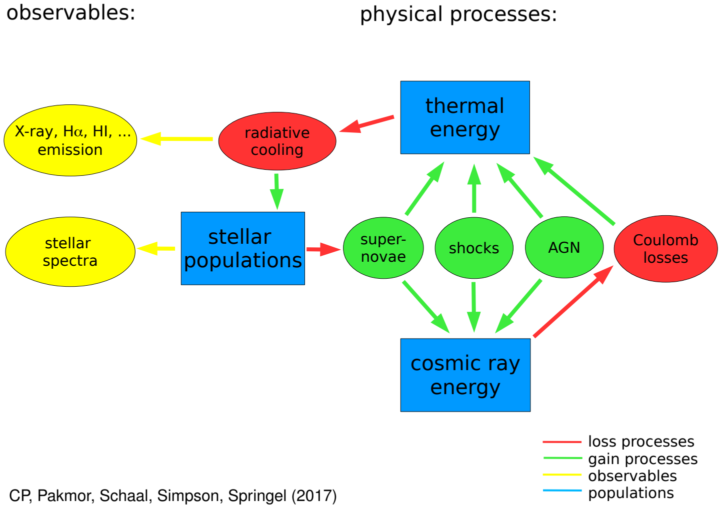
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

Simulations – flowchart



CP, Pakmor, Schaal, Simpson, Springel (2017)

Simulations with cosmic ray physics



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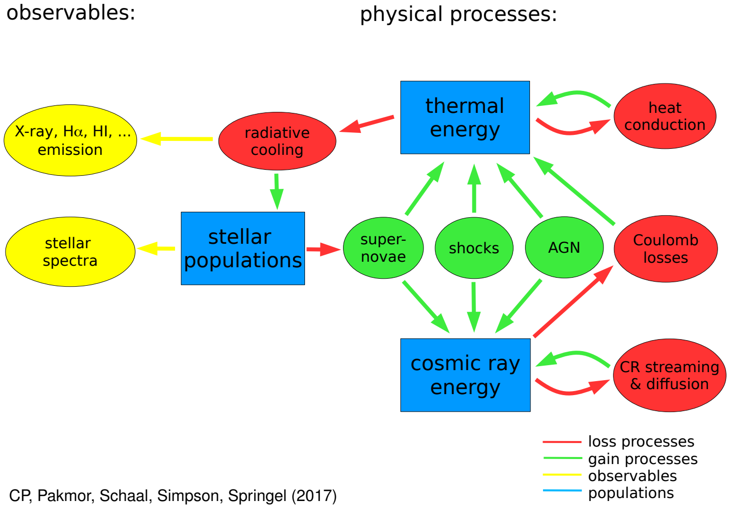

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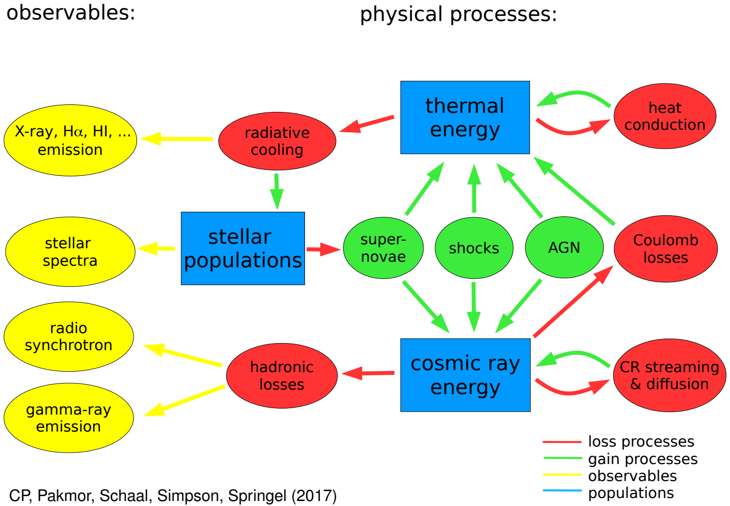
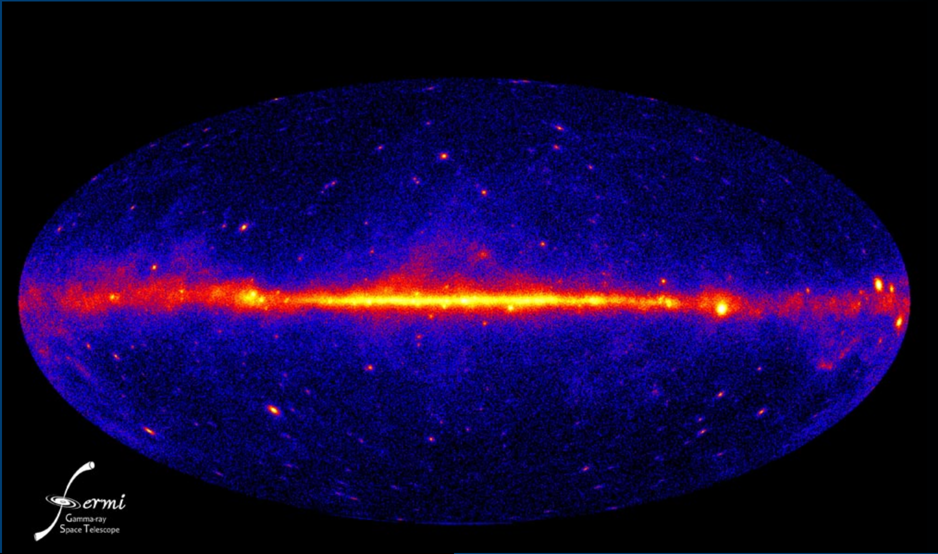


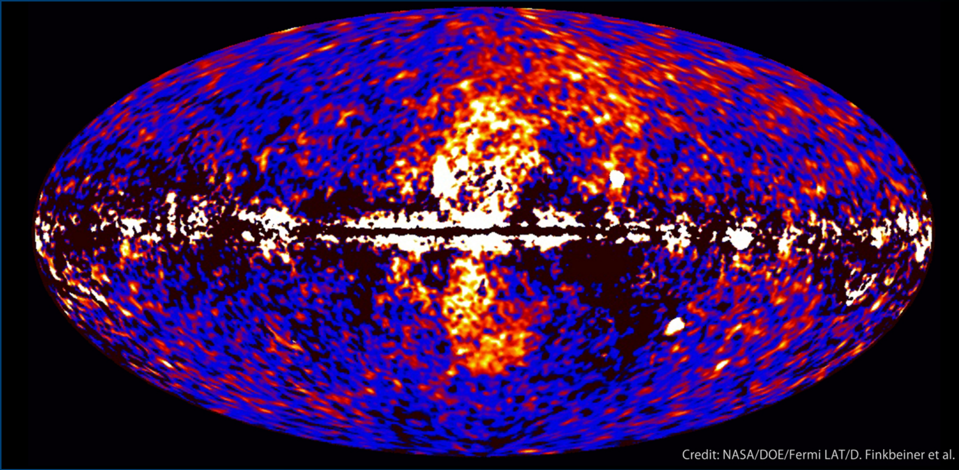
CP, Pakmor, Schaal, Simpson, Springel (2017)

Gamma-ray emission of the Milky Way

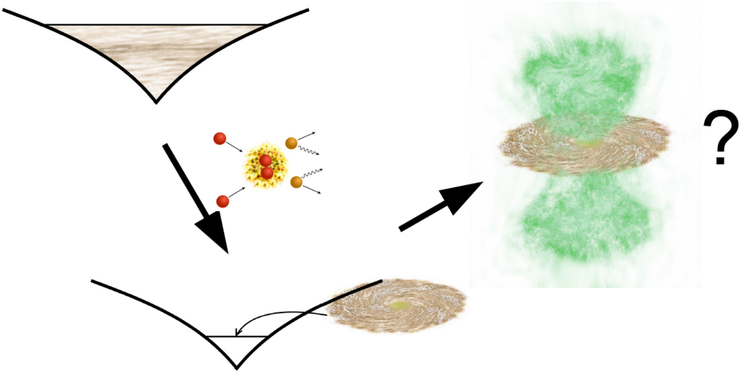


Galactic wind in the Milky Way?

Fermi gamma-ray bubbles



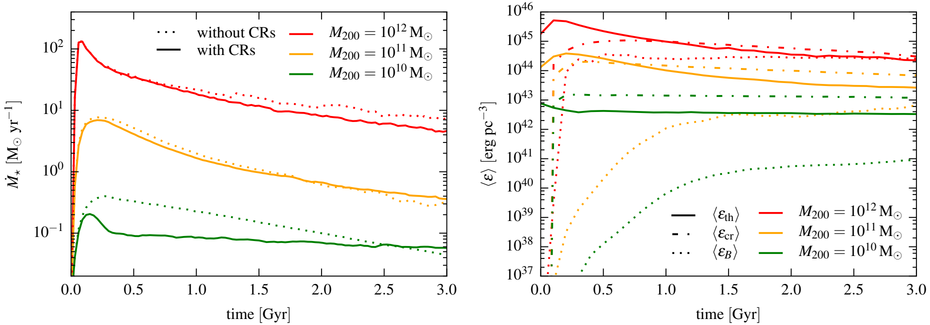
Galaxy simulation setup: 1. cosmic ray advection



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

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

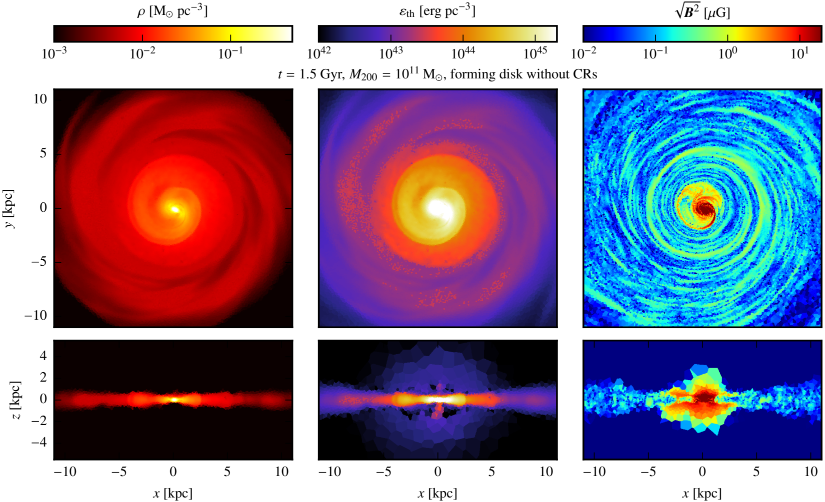
Time evolution of SFR and energy densities



CP, Pakmor, Schaal, Simpson, Springel (2017)

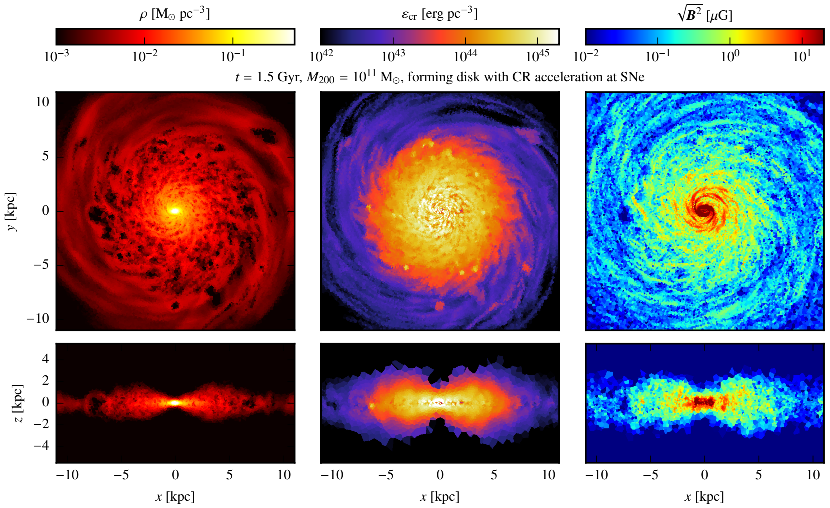
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



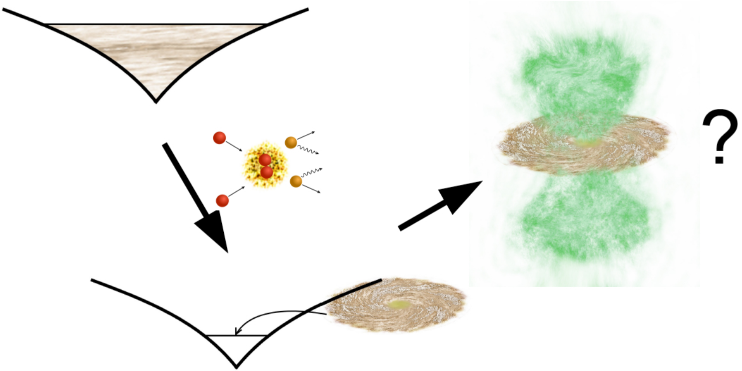
CP, Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



CP, Pakmor, Schaal, Simpson, Springel (2017)

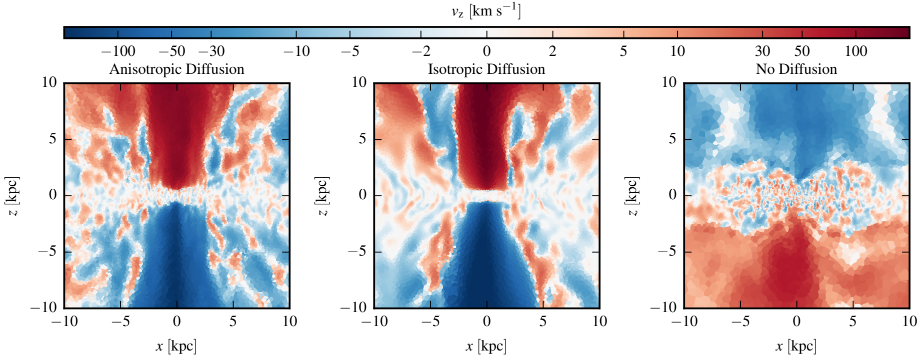
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

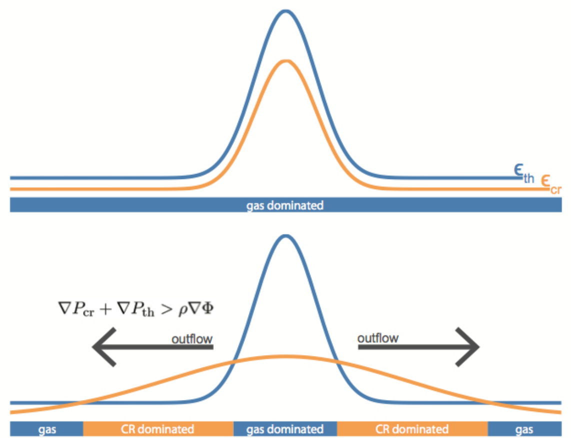
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

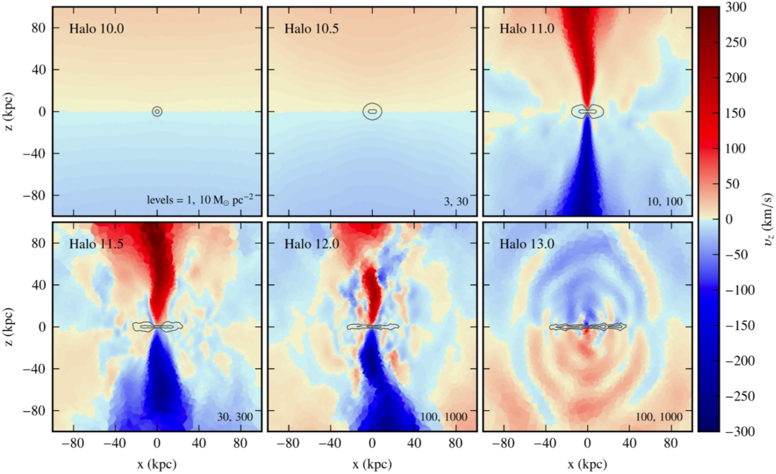
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



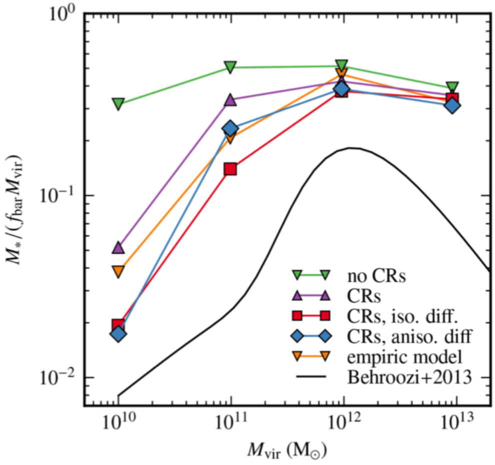
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

CR-driven winds: dependence on halo mass



Jacob+ (2018)

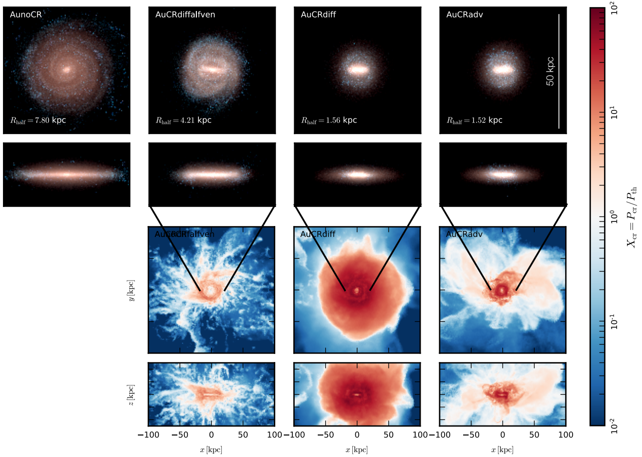
CR-driven winds: suppression of star formation



Jacob+ (2018)

Cosmic rays in cosmological galaxy simulations

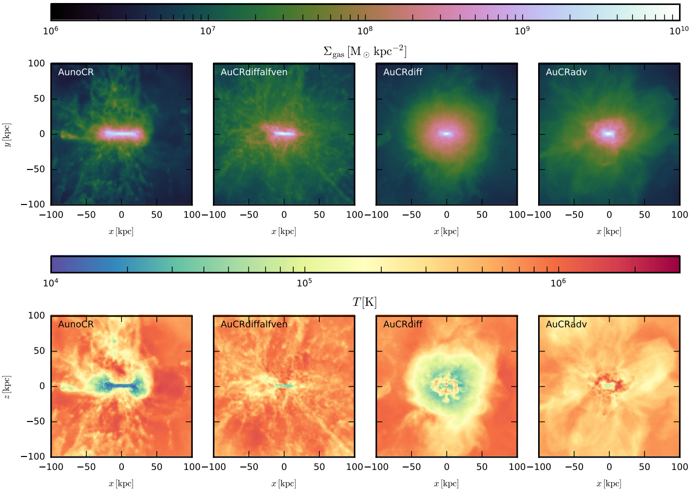
Auriga MHD models: CR transport changes disk sizes



Buck, CP, Pakmor+ (in prep.)

AIP

Cosmic rays in cosmological galaxy simulations
Auriga MHD models: CR transport modifies the circum-galactic medium



Buck, CP, Pakmor+ (in prep.)

Conclusions

- **stellar feedback reproduces observed galaxy properties**
  - galaxy formation is “inefficient” at low and high masses
  - cosmological simulations use subgrid models that depend on density thresholds for star formation, $n_{\rm SF}$
  - star formation histories (bursty vs. quiescent) and halo response (core vs. cusp) depend on $n_{\rm SF}$

AIP

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- **which physics provides stellar feedback?**
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AIP

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$\rightarrow$ **need all feedback variants at some time and mass scale!**