Galaxy formation

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Lecture *Cosmology and Galaxies*, Potsdam – July 2018

Outline

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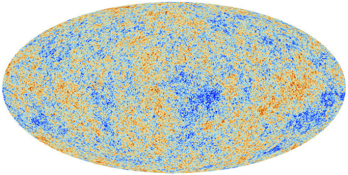
1. **Overview**
   - Puzzles in galaxy formation
   - Observations of feedback
   - Big picture
2. Stellar feedback
   - Supernova feedback
   - Radiation feedback
   - Cosmic ray feedback
3. Feedback by active galactic nuclei
   - Supermassive black holes
   - AGN jet feedback
   - Quasar feedback

Cosmological structure formation



ESA/Planck Collaboration (2013)

- small fluctuations in cosmic microwave background are initial conditions for structure formation

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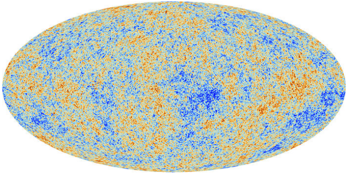

ESA/Planck Collaboration (2013)

dropping pebbles into the pond generates expanding waves that interfere with each other

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- galaxies and clusters form at sites of constructive interference of those primordial waves

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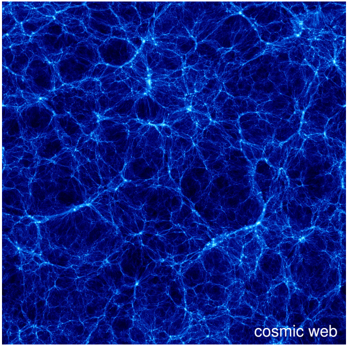

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- cosmic matter assembles in the "cosmic web" through gravitational instability
- galaxies form as "beats on a string" along the cosmic filaments
- galaxy clusters form at the knots of the cosmic web by mergers of galaxies and galaxy groups

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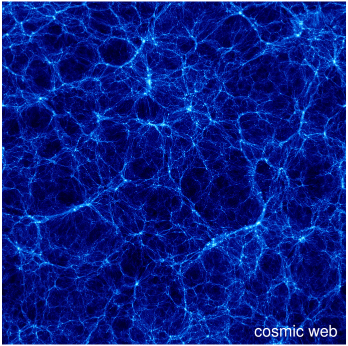

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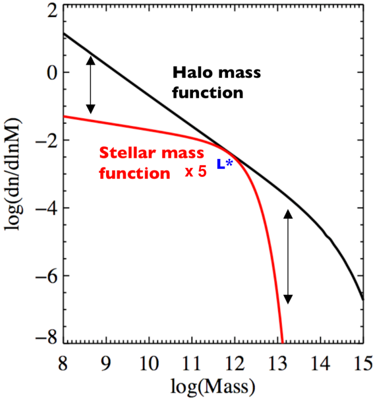
Galaxy formation

Galaxy formation in dark matter halos



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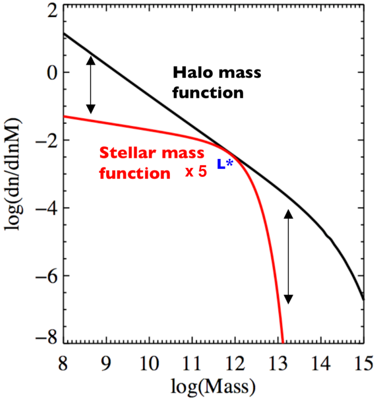
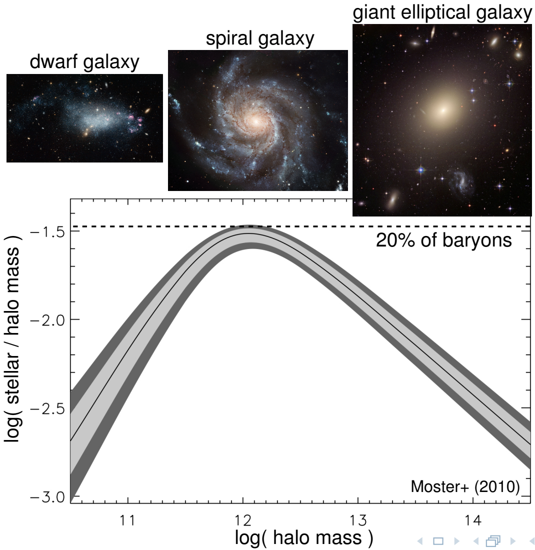
  $\rightarrow$ some non-gravitational process introduces a new scale of galaxy formation

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
  $\rightarrow$ some non-gravitational process introduces a new scale of galaxy formation
- discrepancy of the power-law slopes at the faint end
  $\rightarrow$ some process lowers the star conversion rate in smaller halos
  or the DM halo mass function is wrong (warm DM?)

Puzzles in galaxy formation



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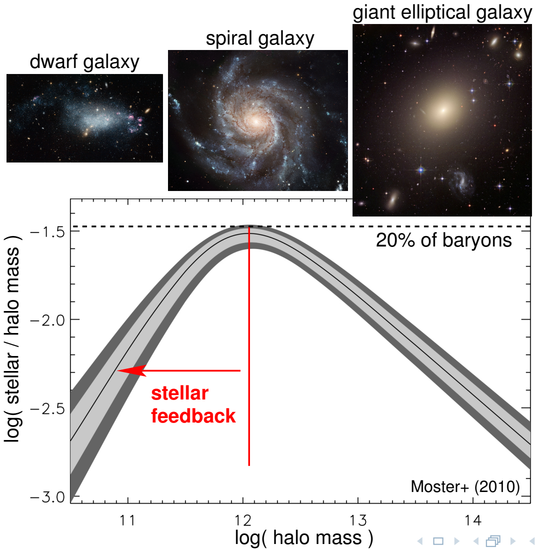

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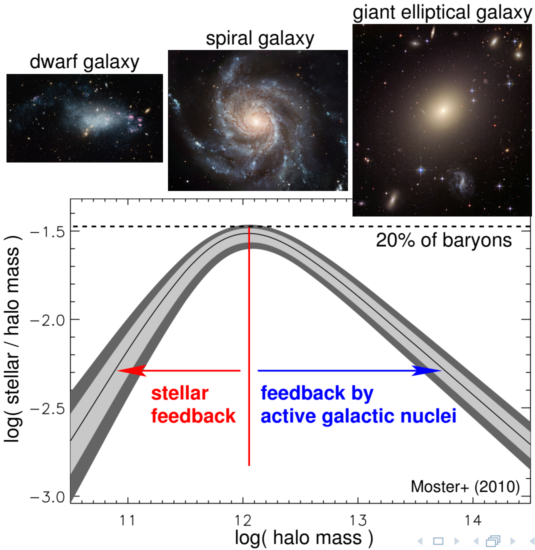

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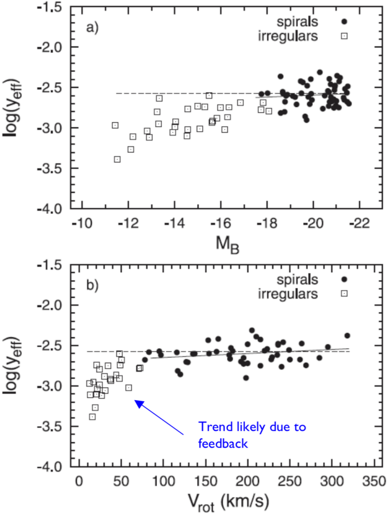
  - photoheating from UV background:
    reionization heats the intergalactic medium to $\sim 10^4$K
    - DM halos with a "virial temperature" less than 10^4K (~ 20 km s^{-1} at $z_{\rm reion}$) cannot retain any baryons
    - halos today with masses $< 10^{10}\,M_\odot$ should not contain baryons, including stars

Observational hints of feedback – 1

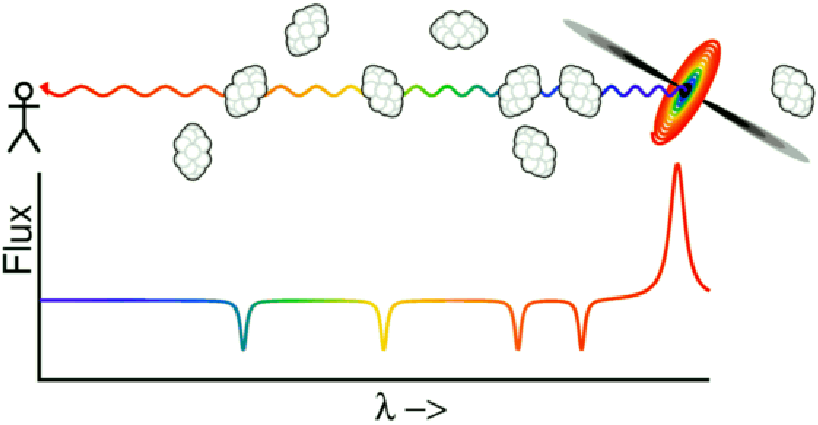


Pilyugin et al. 2004

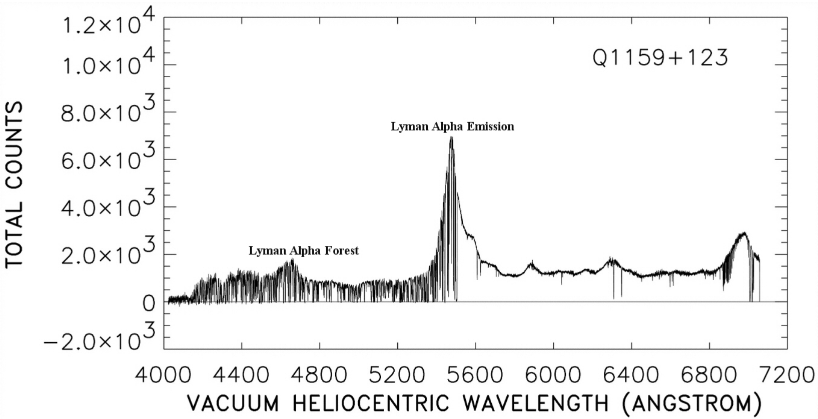
$$y_{\rm eff} \equiv \frac{Z_{\rm gas}}{\ln(1/f_{\rm gas})}$$

- the effective yield, $y_{\rm eff}$, equals the true nucleosynthetic yield for a closed box model of galactic chemical evolution
- $y_{\rm eff}$ is constant unless inflows and/or outflows are important
- lower values of $y_{\rm eff}$ in low-mass galaxies imply metal-enriched outflows

The Lyman-α forest

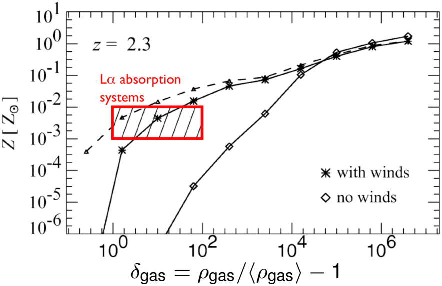


The observed Lyman-α forest



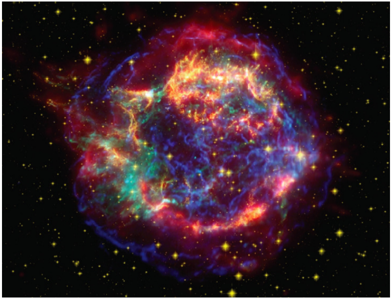
Observational hints of feedback – 2

- Lyman-α forest probes the importance of winds and feedback at high redshift ($z \sim 2$)
- moderate density regions of the Universe, e.g., the intergalactic medium (IGM) are metal-enriched: however there is no star formation in such regions
- metal-enriched winds can deposit metals into the IGM



Springel & Hernquist 2003

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

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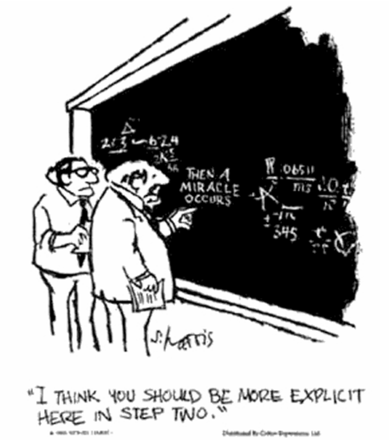

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- binding energy:

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

  - giant molecular cloud (GMC): $M \sim 10^5\,\mathrm{M}_\odot$, $R \sim 50$ pc $\quad\Rightarrow\quad E_{\rm bind} \sim 2\times10^{49}\,\mathrm{erg} < E_{\rm SN}$
  - Milky Way galaxy: $M_{\rm halo} \sim 10^{12}\,\mathrm{M}_\odot$, $M_{\rm gas} \sim 10^{10}\,\mathrm{M}_\odot$, $R \sim 1$ kpc $\Rightarrow\quad E_{\rm bind} \sim 10^{60}$ erg

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    $\Rightarrow \quad E_{\rm bind} \sim 10^{60}$ erg
- for $\sim L_*$ galaxies, a single SN will not unbind the galaxy, but $E_{\rm gal} = e_{\rm SN}\, M_* = 10^{49}$ erg $M_\odot^{-1} 10^{11} M_\odot \sim 10^{60}$ erg $\sim E_{\rm bind}$

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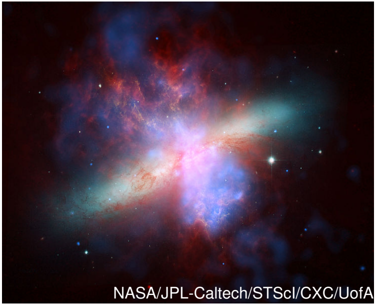
How are galactic winds driven?



super wind in M82

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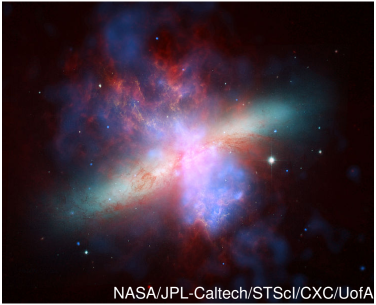

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observed energy equipartition between cosmic rays, thermal gas and magnetic fields
$\rightarrow$ suggests self-regulated feedback loop with CR driven winds

Supernova feedback in the interstellar medium

the standard picture for isolated SN evolution:

1. free expansion: ends when $M_{\rm swept} \sim M_{\rm eject}$ ($t = 200$ 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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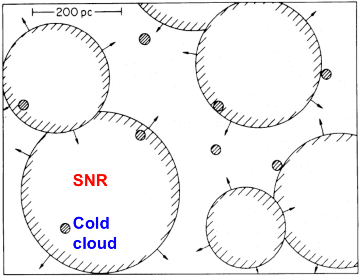
but: the standard picture is not applicable to galaxy formation:

- 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 on galactic scales

- star formation rate (SFR) $\dot{M}_* \sim \dfrac{M_\text{gas}}{t_\text{ff}} \propto n^{1/2}$
- total SN energy deposited into the gas is $E_\text{SN,tot}(t) \sim e_0 \dot{M}_* t_\text{rad}$, t_rad is comparable to the SN overlap time for the assumed SFR

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v_\mathrm{halo} &< 100\, f(E_\mathrm{SN}, e_0, g, \ldots)\ \mathrm{km\ s}^{-1}
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- galaxy-scale simulations: energy is dumped into the surrounding dense phase, which radiates the SN energy away instantly, and thus has little effect on the ISM → "cooling catastrophe", i.e., too many stars form
- high-resolution ISM simulations: clustered SNe can self-regulate the ISM, but are unable to drive galactic (super-)winds

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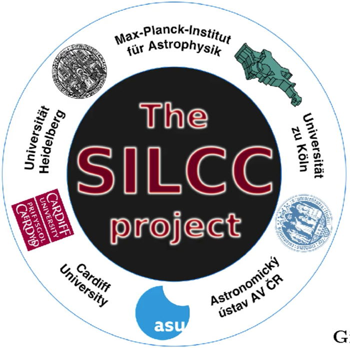
Supernova feedback in the ISM

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

- Euler's equation in hydrostatic equilibrium is

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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.

Radiation feedback – 2

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

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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 $L_{\rm s} = L_{\rm Edd}$:

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

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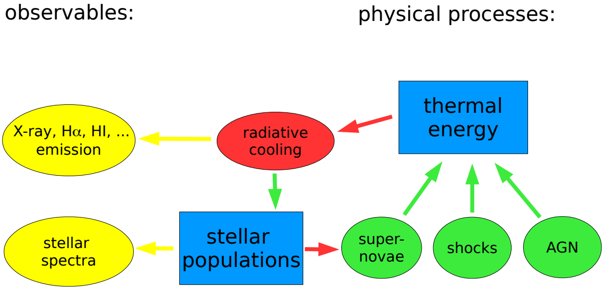
- in configurations in which dusty gas is optically thick also at infrared (IR) frequencies ($\tau_\mathrm{IR} > 1$), it is possible for the radiation force to exceed L_AGN/c, though at most by a factor of τ_IR
- in this regime, IR photons become trapped within the optically thick gas and must scatter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

$$\mathcal{F}_\mathrm{rad} = \tau_\mathrm{IR} L_\mathrm{AGN}/c \quad \text{implies} \quad \tau_\mathrm{IR} > 1$$

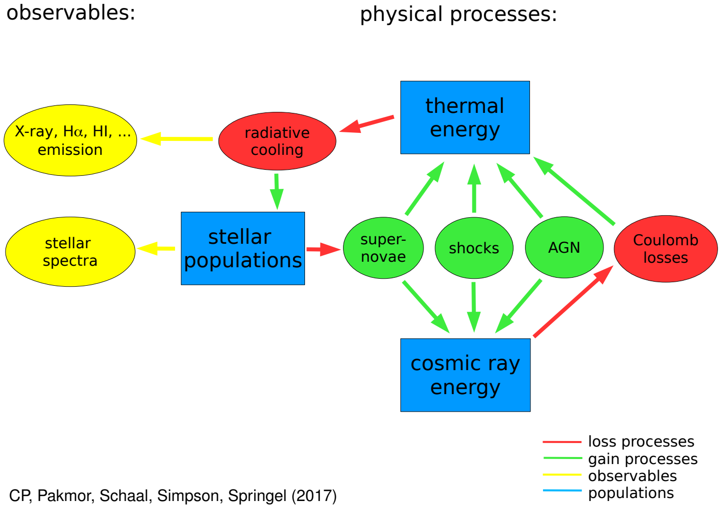
Simulations – flowchart



loss processes
gain processes
observables
populations

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

Simulations with cosmic ray physics



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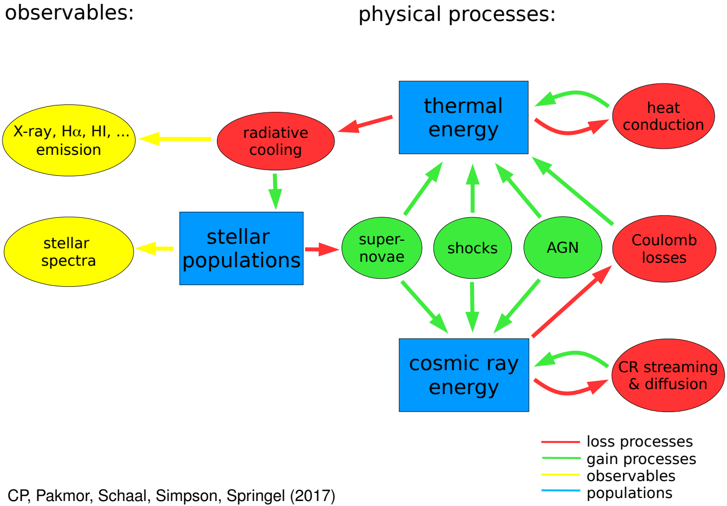

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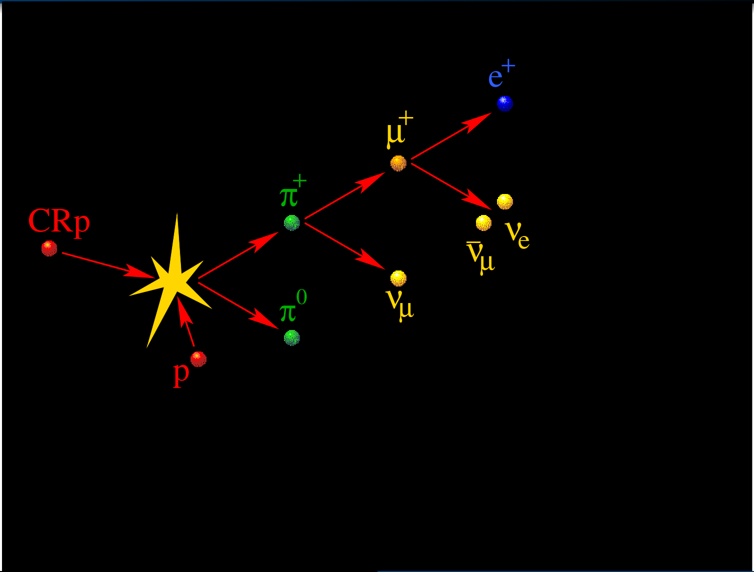
Hadronic cosmic ray proton interaction



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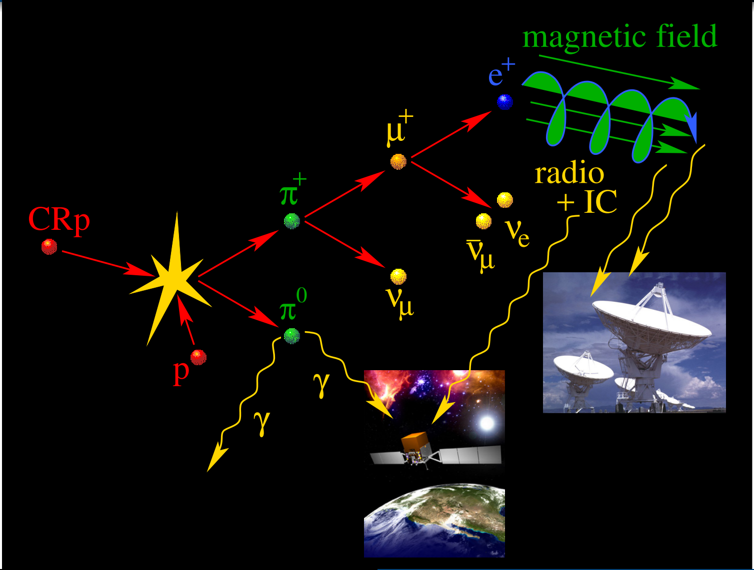
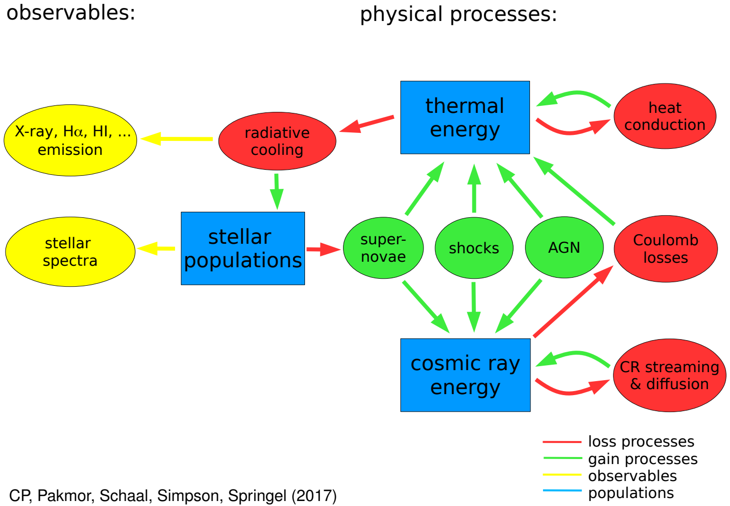


Simulations with cosmic ray physics

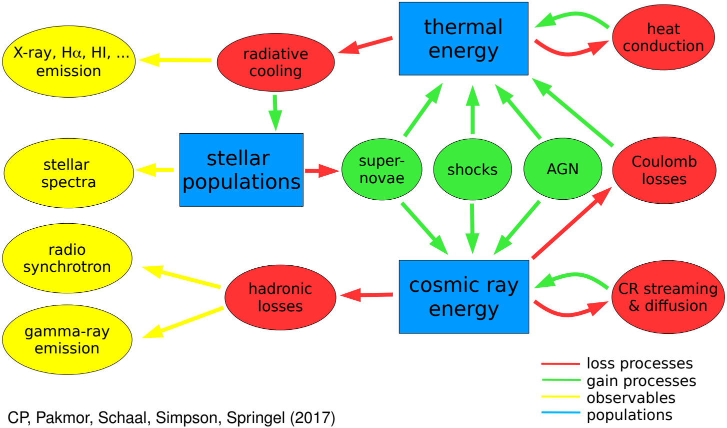


CP, Pakmor, Schaal, Simpson, Springel (2017)

Simulations with cosmic ray physics

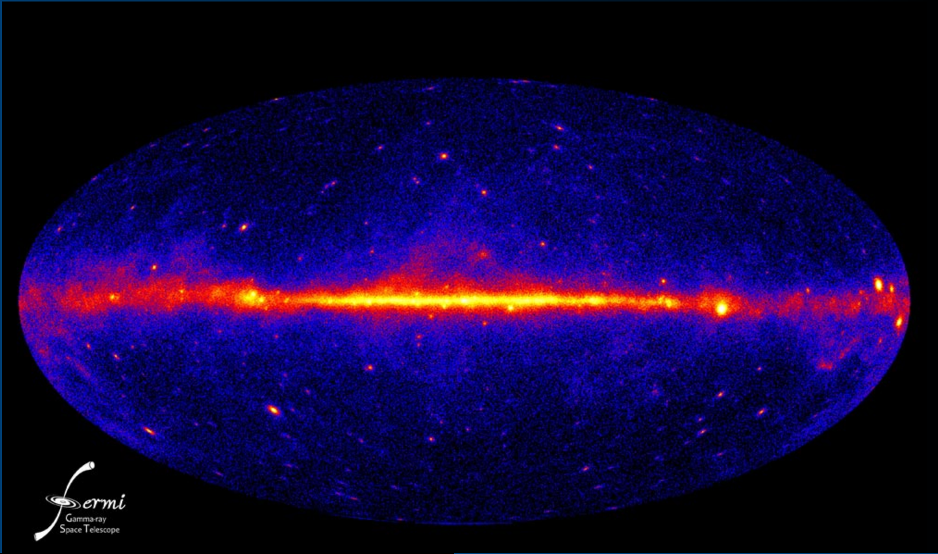
observables:

physical processes:



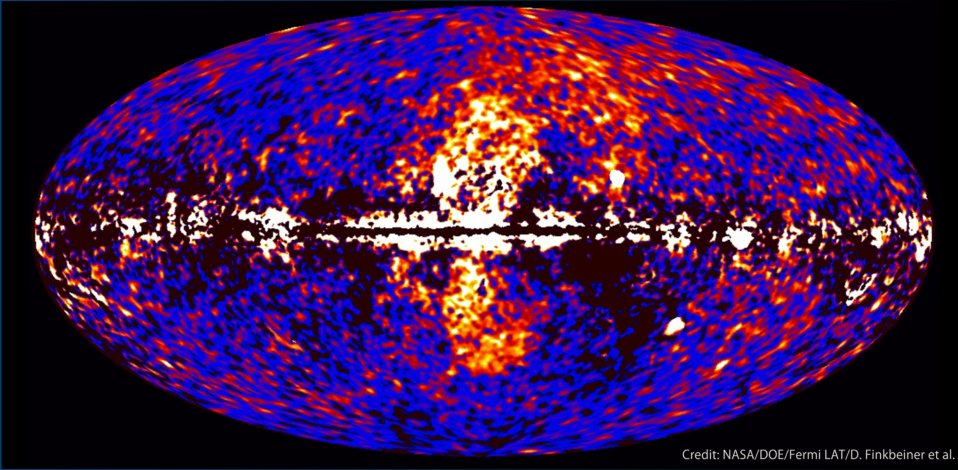
CP, Pakmor, Schaal, Simpson, Springel (2017)

Gamma-ray emission of the Milky Way



Galactic wind in the Milky Way?

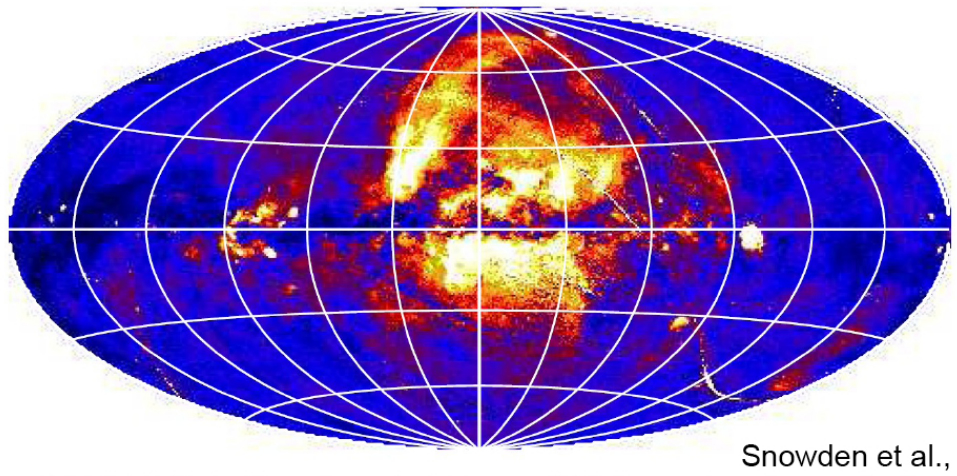
Fermi gamma-ray bubbles



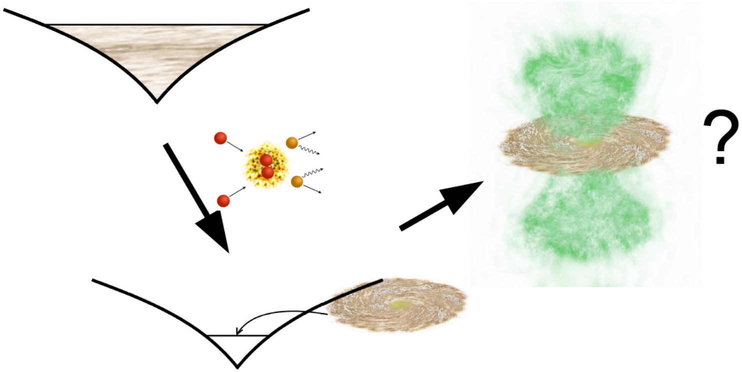
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Galactic wind in the Milky Way?

Diffuse X-ray emission in our Galaxy



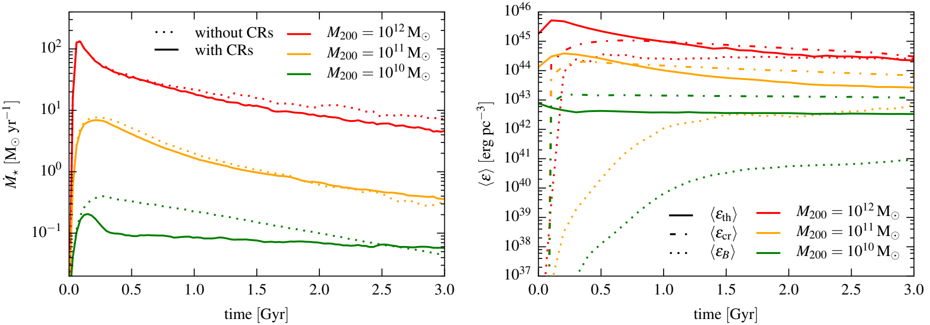
Galaxy simulation setup: 1. cosmic ray advection



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

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

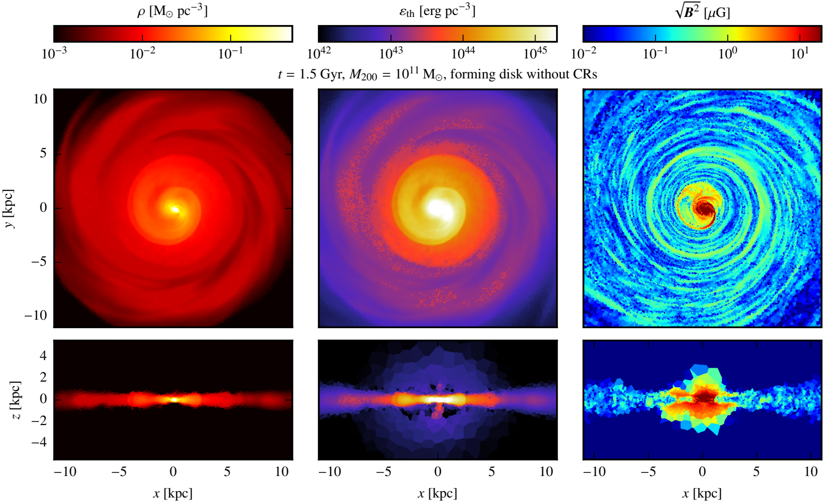
Time evolution of SFR and energy densities



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

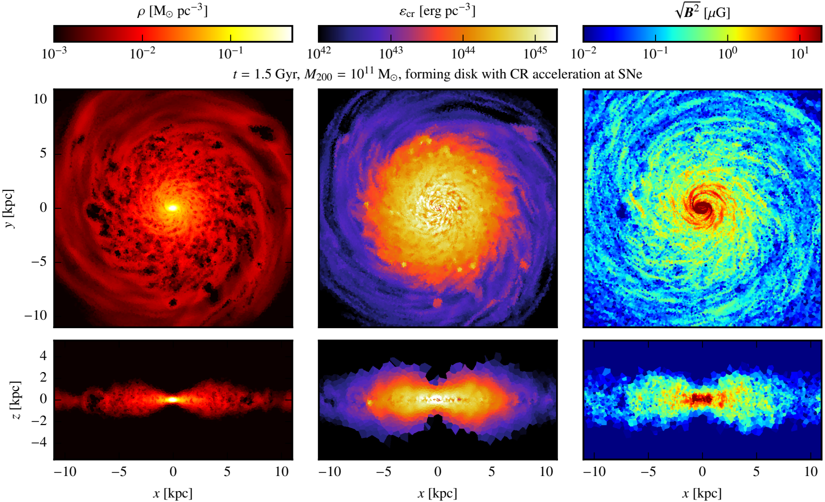
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



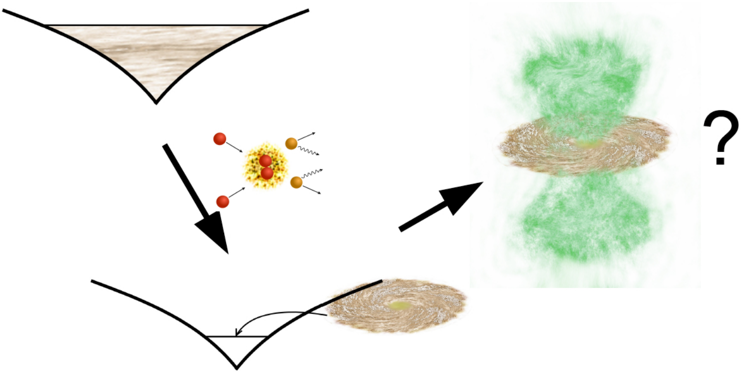
CP, Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



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

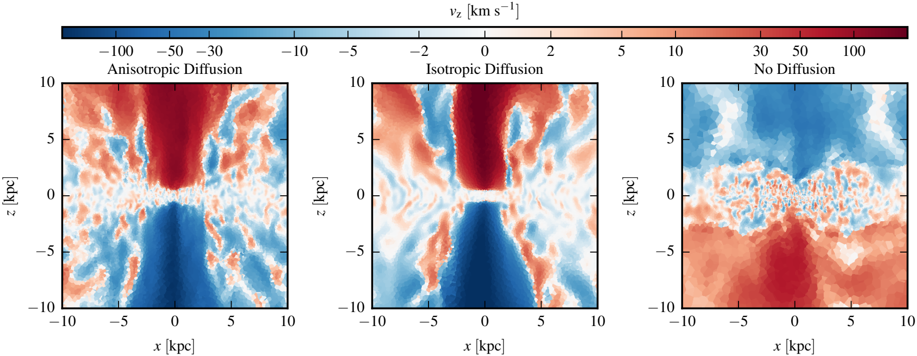
Galaxy simulation setup: 2. cosmic ray diffusion



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} $M_\odot$

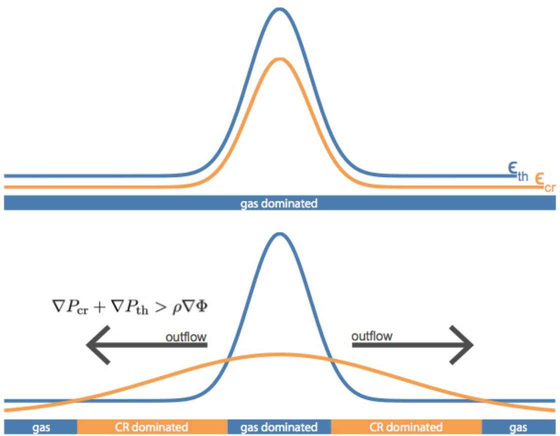
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

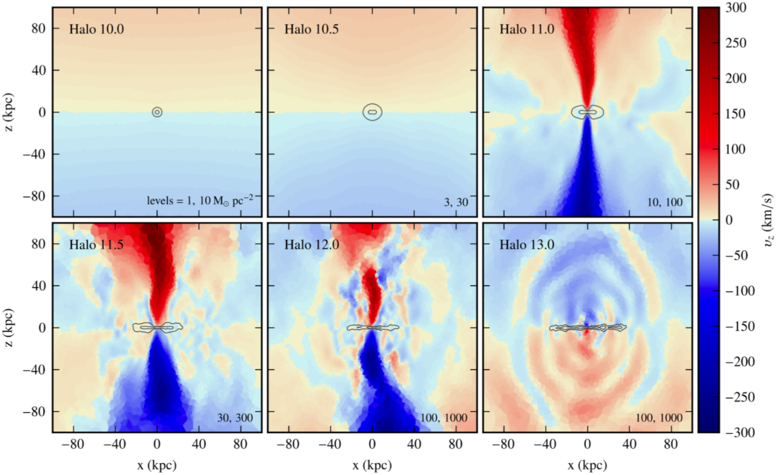
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



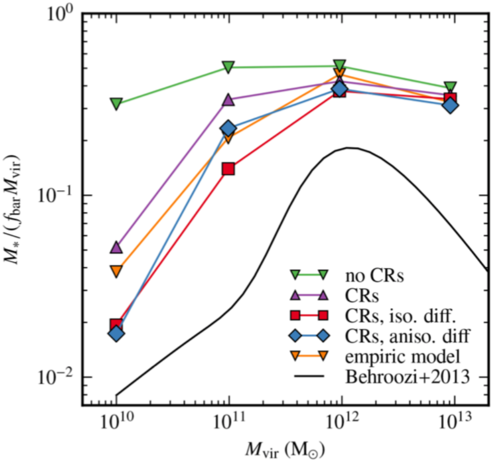
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

CR-driven winds: dependence on halo mass



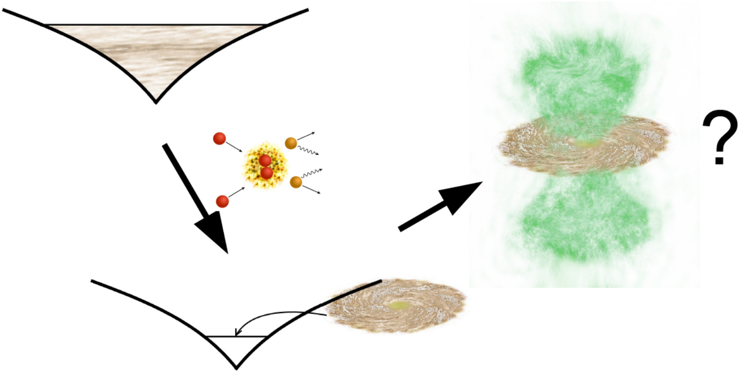
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

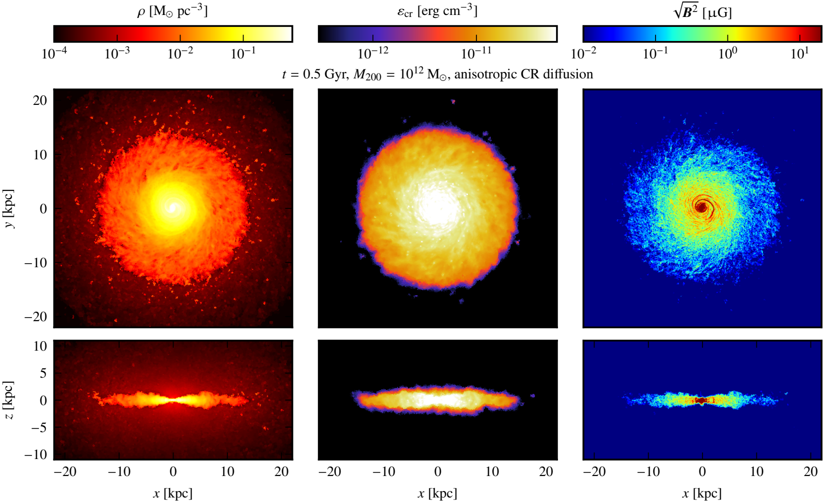
Galaxy simulation setup: 3. non-thermal emission



CP, Pakmor, Simpson, Springel (2017a,b)
Simulating radio synchrotron and gamma-ray emission in galaxies

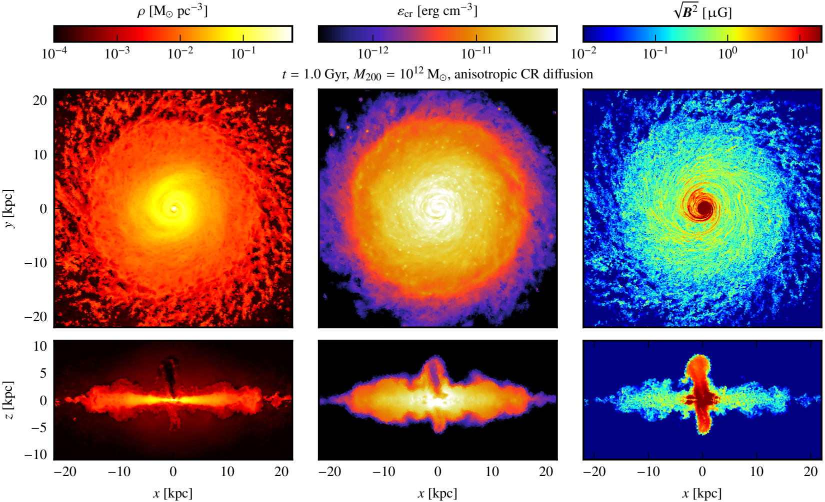
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

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



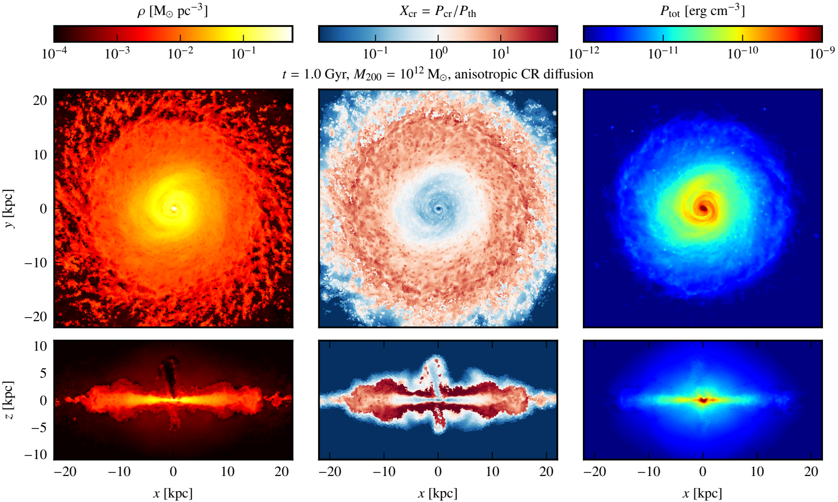
CP+ (2017a,b)

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



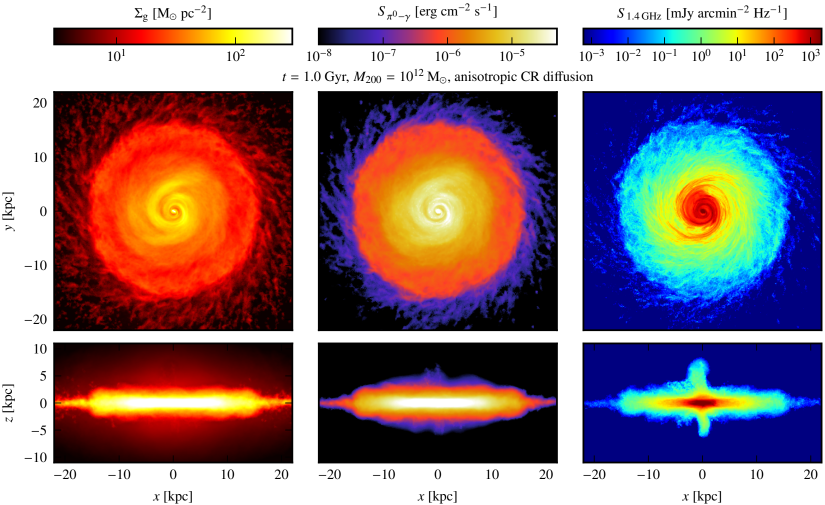
CP+ (2017a,b)

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



CP+ (2017a,b)

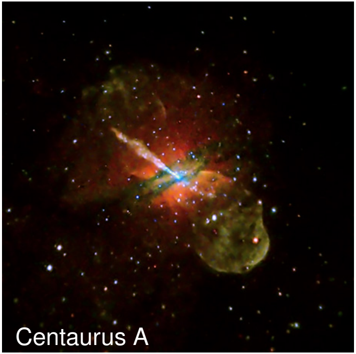
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017a,b)

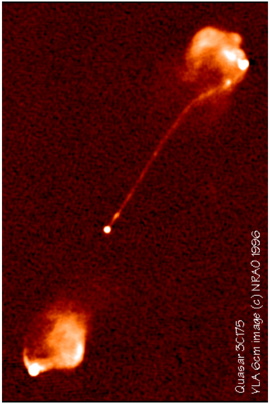
Outline

Active galactic nucleus (AGN)



- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets

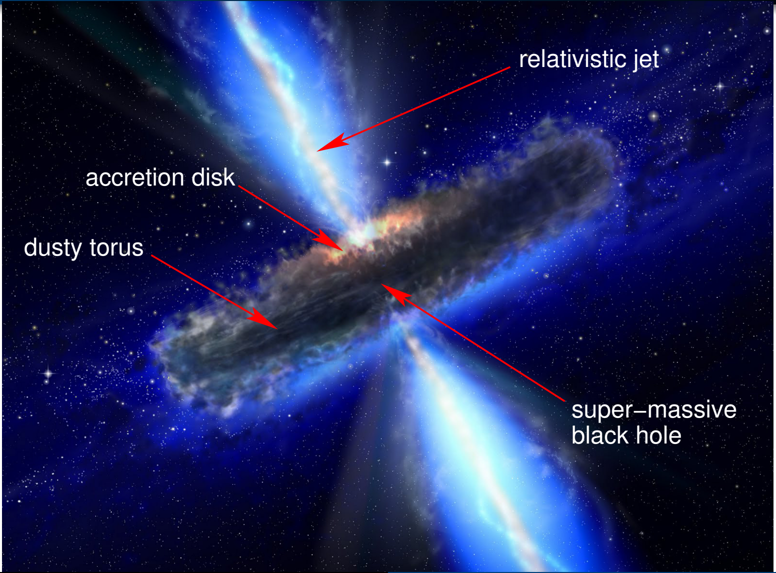
Active galactic nucleus at a cosmological distance



Quasar 3C175 at $z \simeq 0.8$:
jet extends 10^6 light years across

- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets
- AGNs are among the most luminous sources in the universe $\rightarrow$ discovery of distant objects

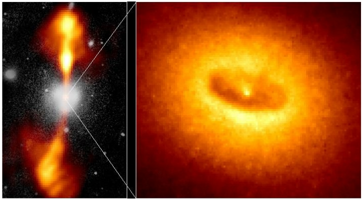
Unified model of active galactic nuclei



Accretion onto black holes (BHs)

- the radiative efficiency η relates the Eddington luminosity to the BH mass accretion rate:

$$L_{\mathrm{Edd}} = \eta \dot{M}_{\mathrm{Edd}} c^2 = \frac{4\pi G M_\bullet c m_{\mathrm{p}}}{\sigma_{\mathrm{T}}} \quad \Rightarrow \quad \dot{M}_{\mathrm{Edd}} = \frac{4\pi G M_\bullet m_{\mathrm{p}}}{\eta c \sigma_{\mathrm{T}}}$$



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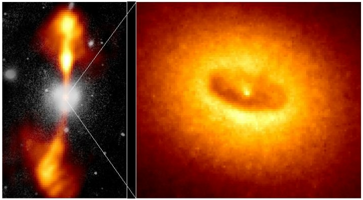
- **radiatively inefficient accretion** exhibits optically thin, geometrically thick disks and produces jets ($\epsilon \lesssim 0.01$):

$$\dot{M}_\bullet = \epsilon \dot{M}_{\mathrm{Edd}} = \frac{4\pi G \epsilon M_\bullet m_{\mathrm{p}}}{\eta c \sigma_{\mathrm{T}}} = \Gamma M_\bullet = 0.22\, \frac{\mathrm{M}_\odot}{\mathrm{yr}} \left(\frac{M_\bullet}{10^9\,\mathrm{M}_\odot}\right) \left(\frac{\epsilon}{0.01}\right) \left(\frac{\eta}{0.1}\right)^{-1}$$



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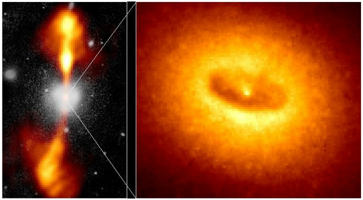

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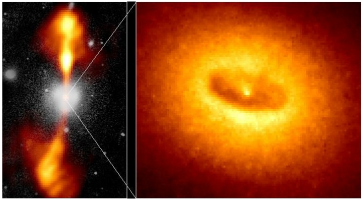
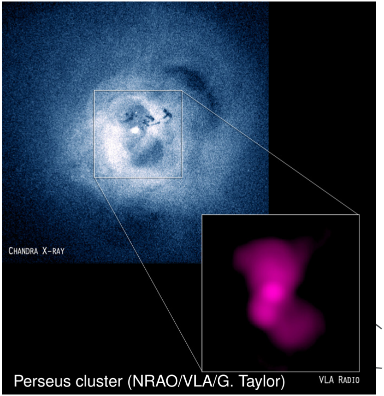
- **radiatively efficient BHs** accrete from optically thick, geometrically thin disks and shine as quasars
- BH mass accretion (Salpeter 1964):
$$\frac{{\rm d}M_\bullet}{{\rm d}t} = \Gamma M_\bullet \Rightarrow M_\bullet = M_0 {\rm e}^{\Gamma t}$$
- doubling time $t_2 = \dfrac{\ln 2}{\Gamma} = 3 \times 10^7$ yr



Feedback by black hole jets

Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**



Perseus cluster (NRAO/VLA/G. Taylor)

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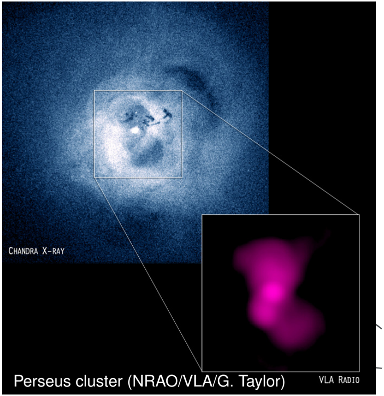

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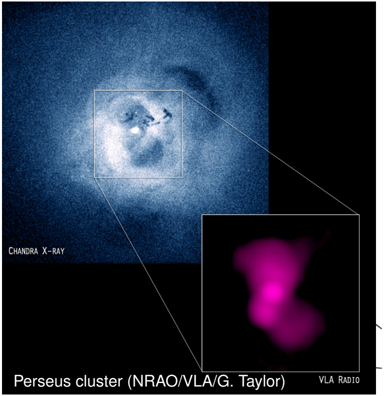
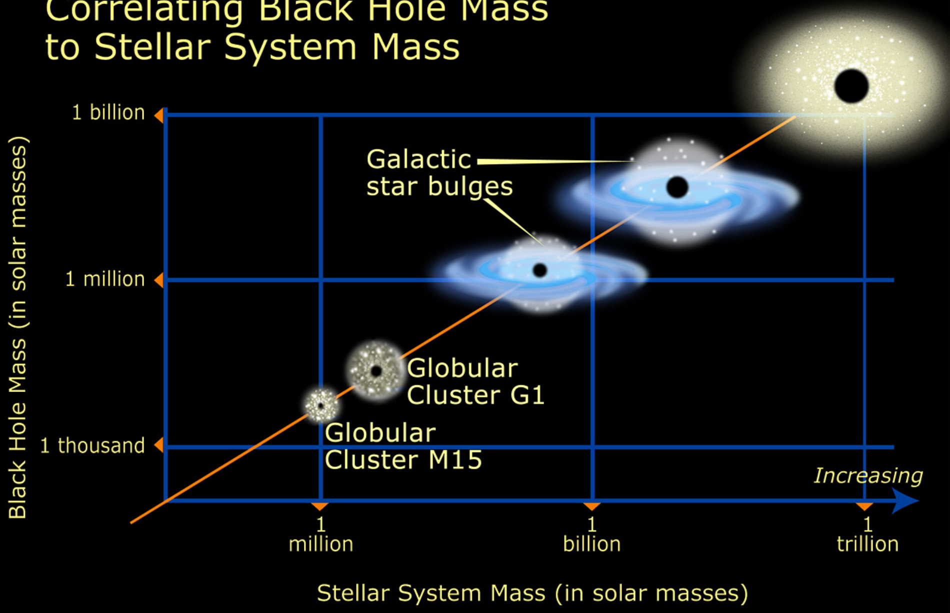
- self-regulated heating mechanism to avoid overcooling
- jet interaction with magnetized cluster medium $\rightarrow$ turbulence
- jet accelerates cosmic rays $\rightarrow$ release from bubbles provides source of heat



Perseus cluster (NRAO/VLA/G. Taylor)

Correlating Black Hole Mass to Stellar System Mass



AGN feedback – energetics

- gravitational binding energy of bulge: $E_{\rm grav} = M_{\rm bulge}\sigma^2$,
  $M_\bullet - \sigma$ relation: $M_\bullet \sim M_{\rm bulge}/500$
- available BH energy to be extracted is $E \sim 0.1 M_\bullet c^2$

AIP

AGN feedback – energetics

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- available BH energy to be extracted is $E \sim 0.1 M_\bullet c^2$
- it follows

$$\frac{E}{E_{\mathrm{grav}}} = 0.1\,\frac{M_\bullet}{M_{\mathrm{bulge}}}\left(\frac{c}{\sigma}\right)^2 \sim 200\left(\frac{300\ \mathrm{km/s}}{\sigma}\right)^2$$

$\rightarrow$ there is more than enough energy available for AGN feedback!

AGN feedback – thermodynamics

- relativistic jets displace the intracluster medium (ICM) at the location of the cavities, i.e. they do pdV work against the ICM, as well as supply internal energy to the cavities
- total energy required to create the cavity equals its enthalpy

$$H = U + PV = \frac{1}{\gamma_b - 1} PV + PV = \frac{\gamma_b}{\gamma_b - 1} PV = 4PV, \text{ with } \gamma_b = 4/3$$

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- only $1PV$ is directly available for mechanical work on the surroundings ($3PV$ is stored as internal energy); work done by 2 bubbles in one outburst

$$W = PV = 2\,\frac{4}{3}\pi r_b^3\, n_{\mathrm{ICM}} kT \sim 10^{59}\ \mathrm{erg}$$

with $r_b \sim 20\,\mathrm{kpc}$, $n_{\mathrm{ICM}} \sim 10^{-2}\,\mathrm{cm}^{-3}$, $kT \sim 3\ \mathrm{keV}$

AIP

AGN feedback – luminosity

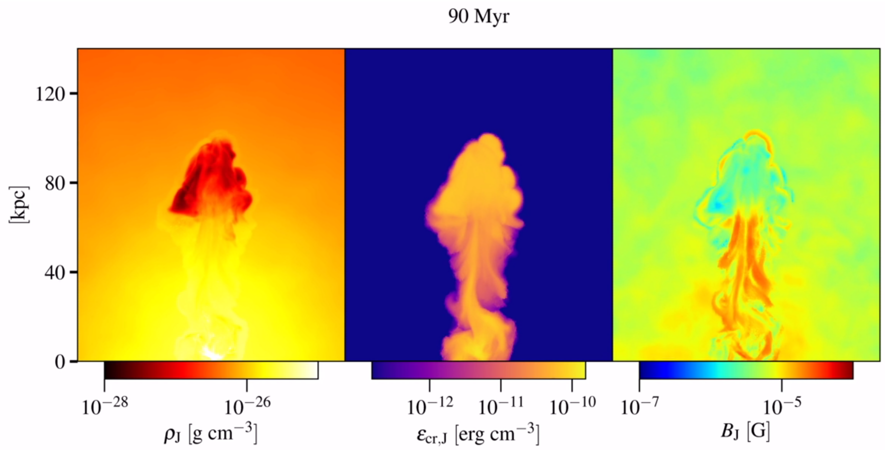
- energy release time scale is of order the sound crossing time $\sim$ buoyant rise time $\sim$ refill time of displaced bubble volume $\sim 3 \times 10^7$ yr
- AGN heating rate

$$L_{\mathrm{AGN}} \sim \frac{PV}{t_{\mathrm{buoy}}} \sim \frac{10^{59}\,\mathrm{erg}}{10^{15}\,\mathrm{s}} \sim 10^{44}\,\frac{\mathrm{erg}}{\mathrm{s}} \sim L_X$$

i.e. comparable to the X-ray luminosity

$\rightarrow$ necessary condition for balancing X-ray cooling losses and increasing the core entropy $K_e = kT/n_e^{2/3}$ of the ambient ICM!

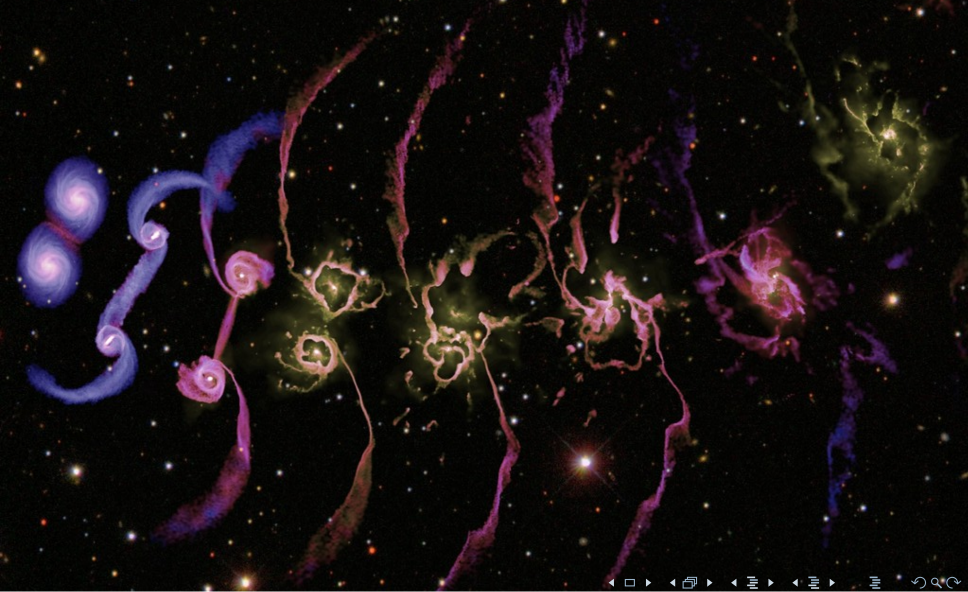
Jet simulation: gas density, CR energy density, *B* field



Ehlert, Weinberger, CP+ (2018)

Galaxy merger produces quasar feedback

(Springel+ 2005)



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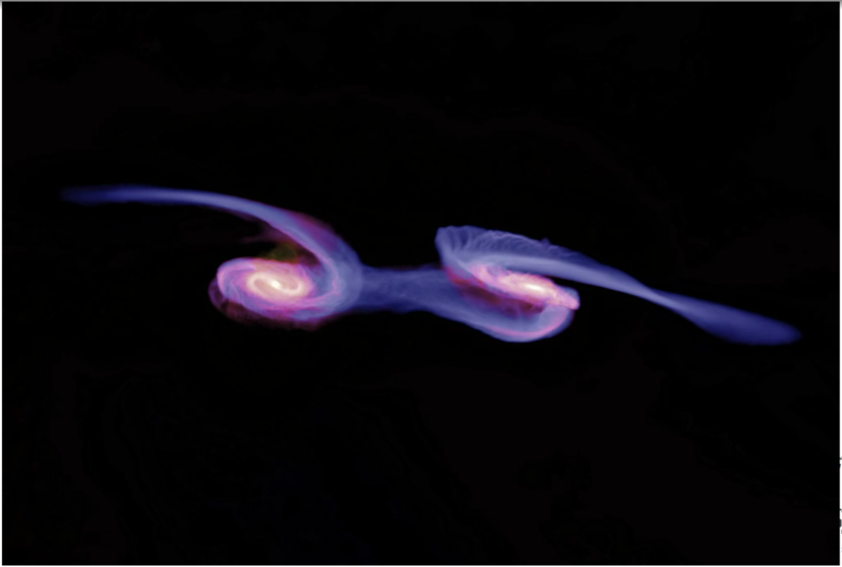

Conclusions

- there is ample evidence that energetic feedback takes place
  - galaxy formation is “inefficient” at both low and high masses
  - enriched IGM at $2 < z < 5$ indicates that feedback is occurring over a range of epochs
  - there are probably several forms of feedback operating over the full range of galaxy properties

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  - direct evidence for SN feedback comes from the MW
  - SN feedback still important at regulating SF in more massive systems
- AGN feedback is likely working in massive galaxies/clusters ($M > 10^{13} M_\odot$)
  - direct evidence for AGN jet feedback in clusters
  - direct evidence for quasar feedback is still missing