Toward a

AGN Feedback: Theory

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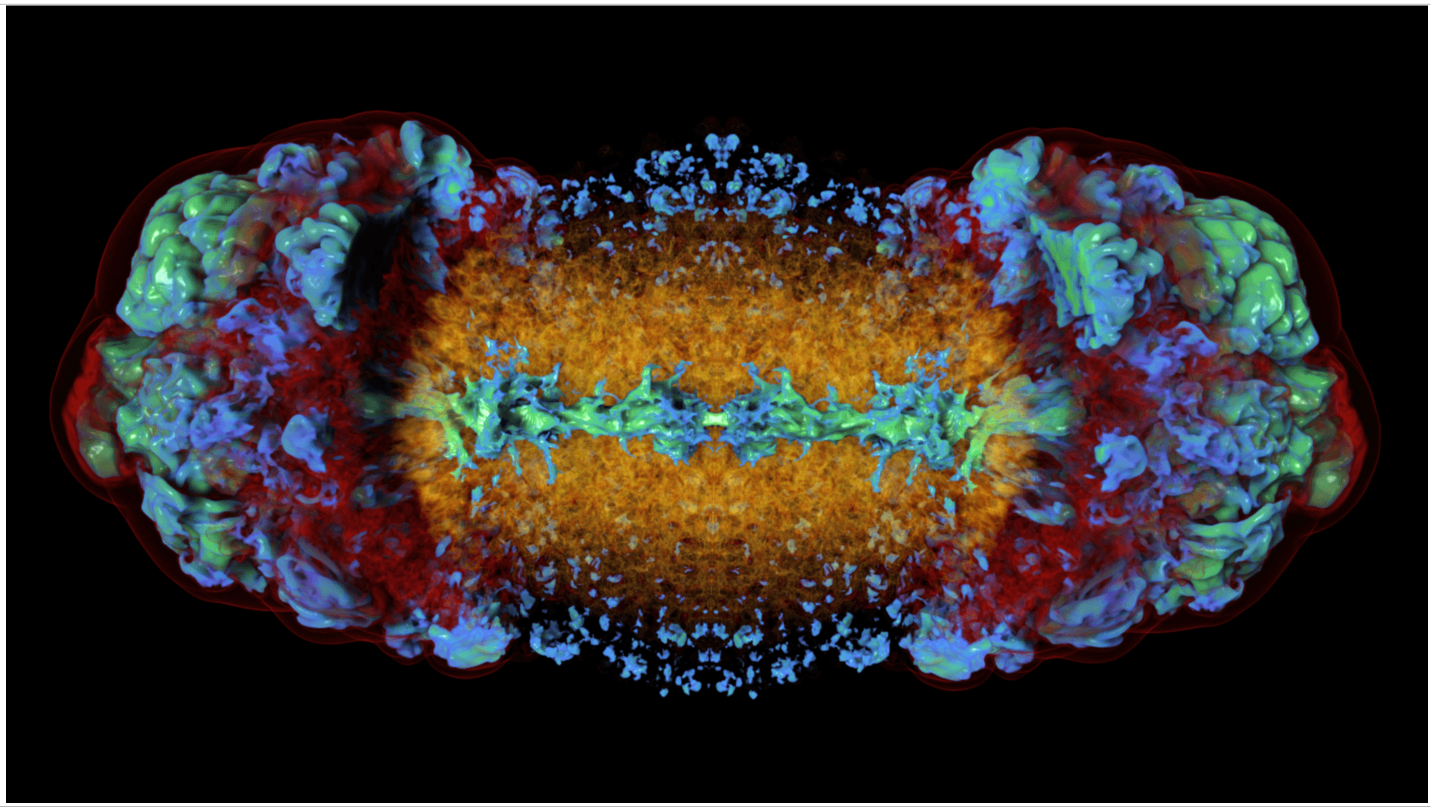

5th CSS/GPS Workshop, Rimini *May 29, 2015*

Types of AGN Feedback

- Quasar mode vs. Radio mode
- Establishment vs. Maintenance mode
- Energy-driven vs. Momentum-driven
- Negative vs. Positive
- Mechanical (Kinetic) vs. Radiation
  - Mechanical: Jets vs. Disc Wind
  - Radiation: Compton vs Dust-driven winds

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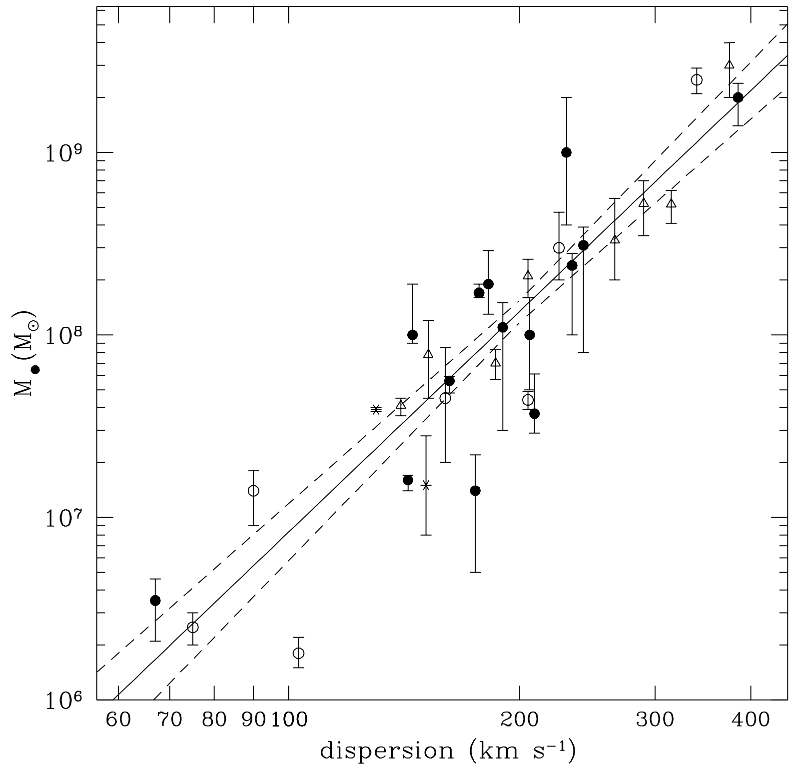
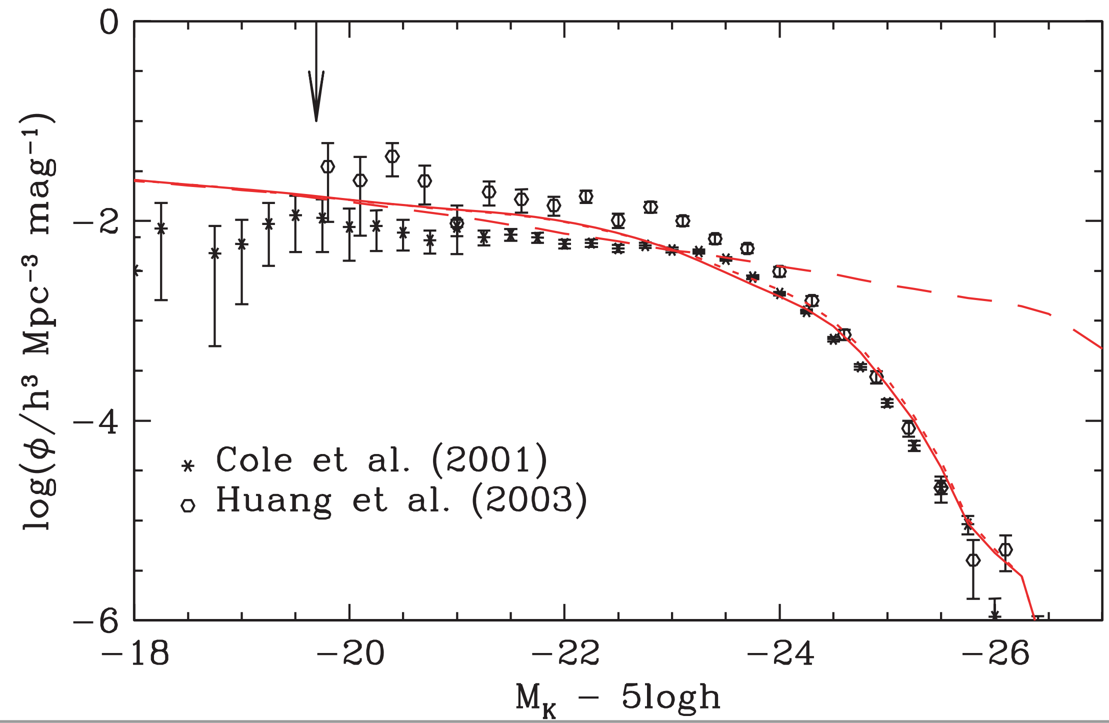
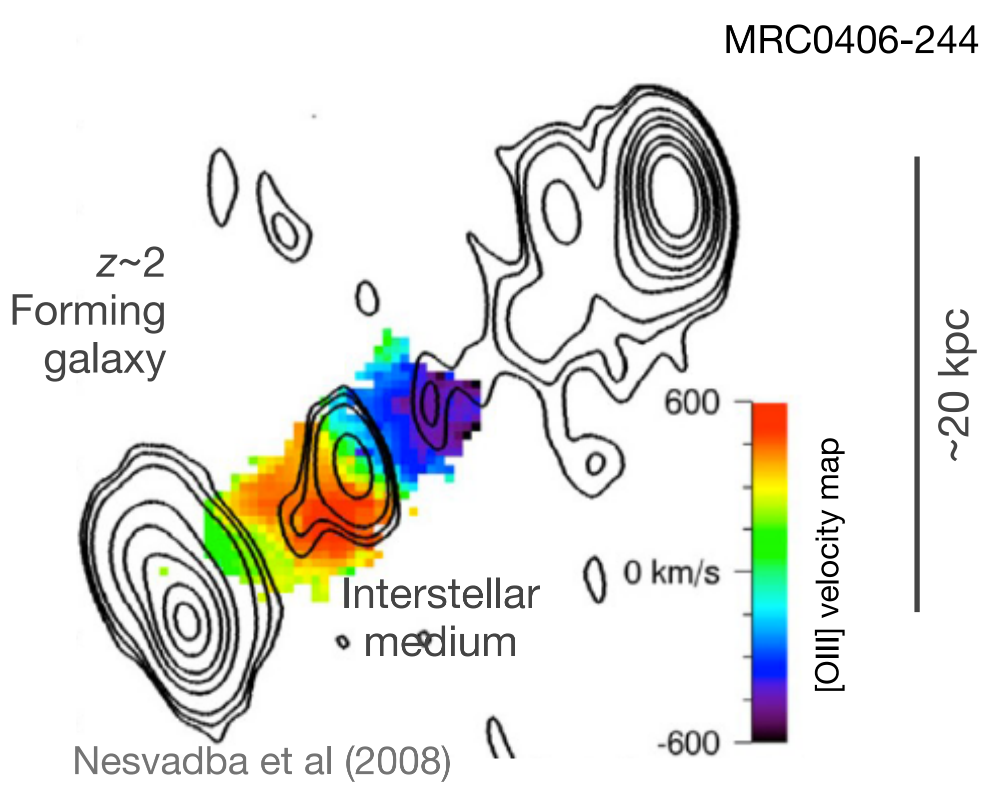
Quasar-mode or Radio-mode AGN Feedback

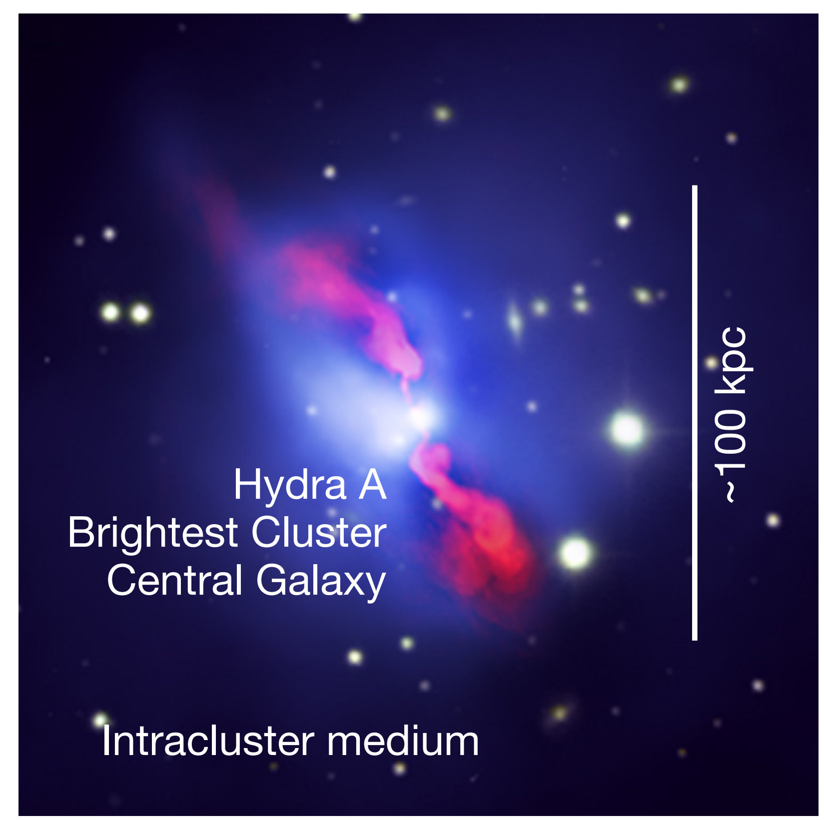




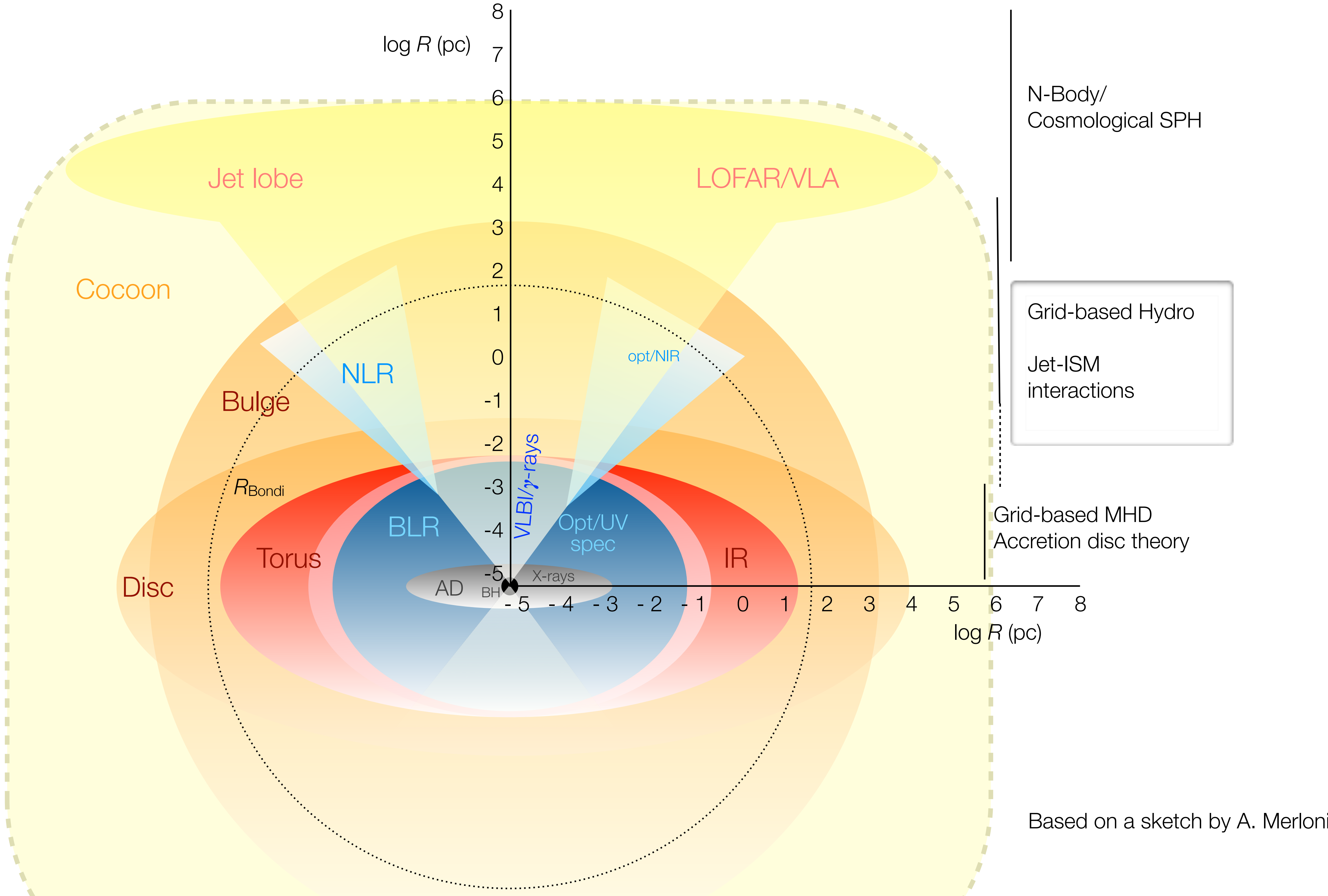
Quasar-mode AGN Feedback



Radio-mode AGN Feedback

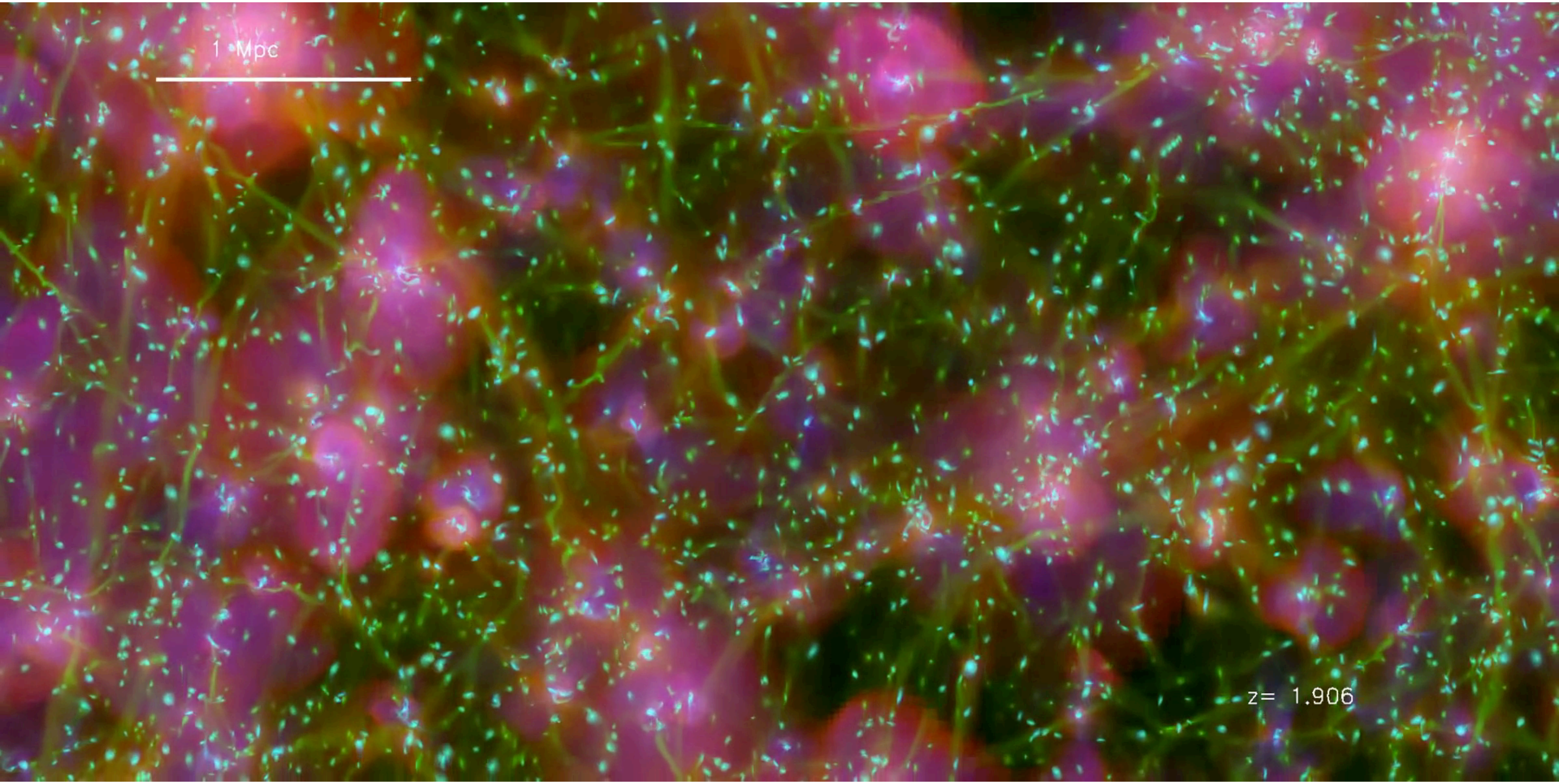


Logarithmic view of the AGN-galaxy system



Based on a sketch by A. Merloni

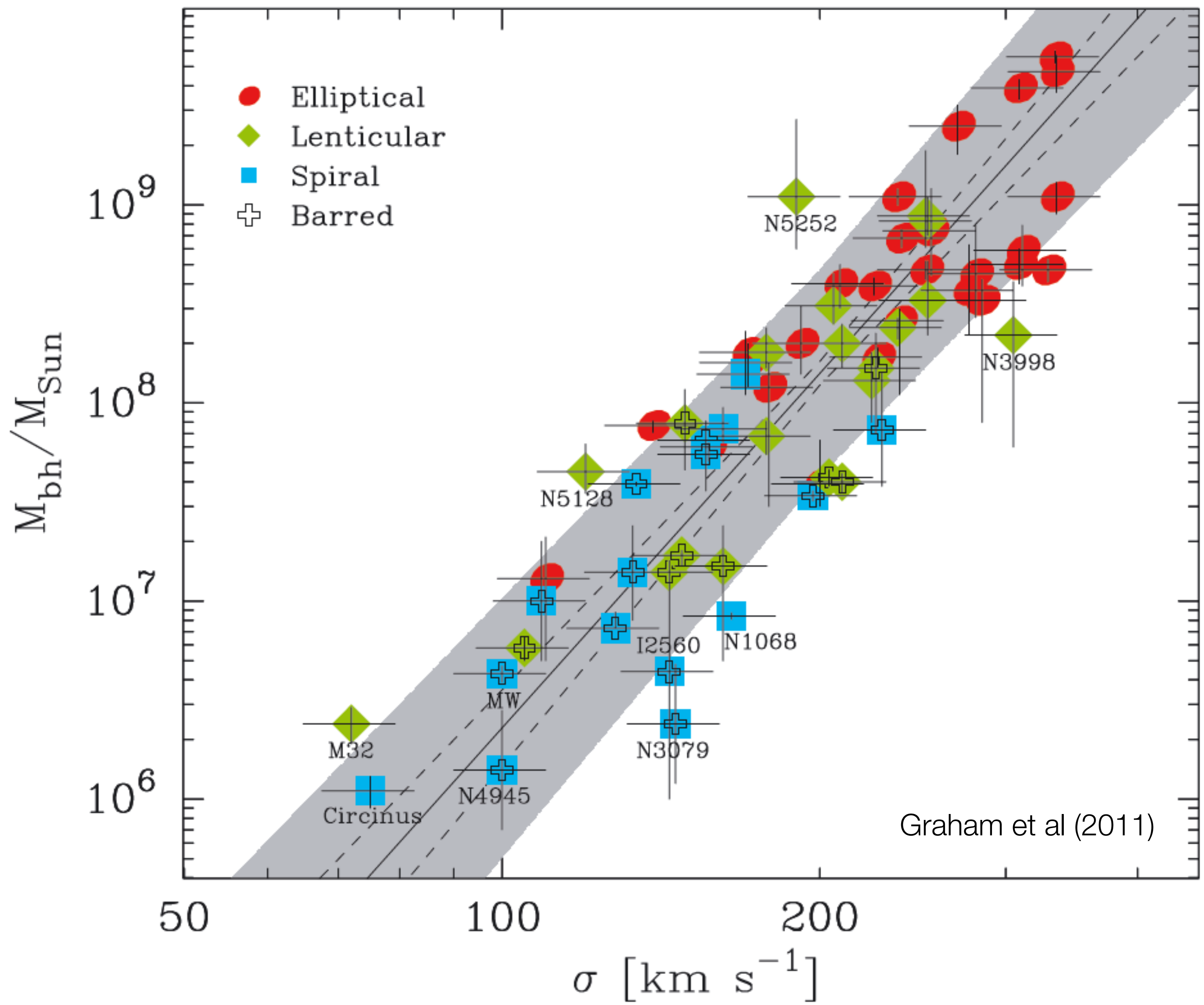
An example of a cosmological hydrodynamical simulation including AGN feedback: The Horizon Simulation (Dubois et al 2013, AMR code RAMSES, Teyssier, 2002)



http://www.horizon-simulation.org/

- 100 Mpc/h comoving volume
- 1024^3 dark matter particles
- Sub-grid models of star formation, SN and AGN feedback, metals (O, Fe, C, N, Mg, Si)
- The minimum cell size is ~1 kpc.

M-sigma relation *Black hole - Bulge Coevolution*



$$\log(M_{BH}/M_{\odot}) = (8.13 \pm 0.05) + (5.13 \pm 0.34) \log(\sigma / 200 \text{ km s}^{-1})$$

- Quasar(-mode) Feedback
  - Energy driven ($\sim\sigma^5$) (Silk & Rees 1998) or
  - Momentum driven ($\sim\sigma^4$) (Fabian 1999)

  outflows.
- Radiation regulated Bulge accretion (Umemura 2001)
- Non-causal. A scaling is a natural consequence of galaxy merging. (Jahnke & Maccio 2011)
- *What is the relative importance of each process?*

Key questions

- How is *M-σ* relation established and maintained?
- How is the star-formation rate affected by AGN Feedback?
    - How is star-formation inhibited?
      (Gas removal, Dispersion, Heating?)
    - How are outflows driven?
    - Can SF be enhanced by pressure trigged collapse?
- What is the efficiency of AGN Feedback and what does it depend on?

We find out with….

Hydrodynamic simulations

Jet/wind - Hot phase ISM - Cold phase ISM

Special relativistic conservation equations in the single fluid approximation

$$\frac{\partial D}{\partial t} + \frac{\partial D u^i}{\partial x^i} = 0;$$

$$\frac{\partial F^i}{\partial t} + \frac{\partial F^i u^j}{\partial x^j} + \frac{\partial p}{\partial x^i} = -\rho \frac{\partial \phi}{\partial x^i};$$

$$\frac{\partial E}{\partial t} + \frac{\partial F^i c^2}{\partial x^i} = \rho^2 \Lambda(T) - \rho \frac{\partial \phi}{\partial x^i} u^i;$$

$$D = \Gamma \rho$$

$$F^i = \rho w \Gamma^2 u^i / c^2$$

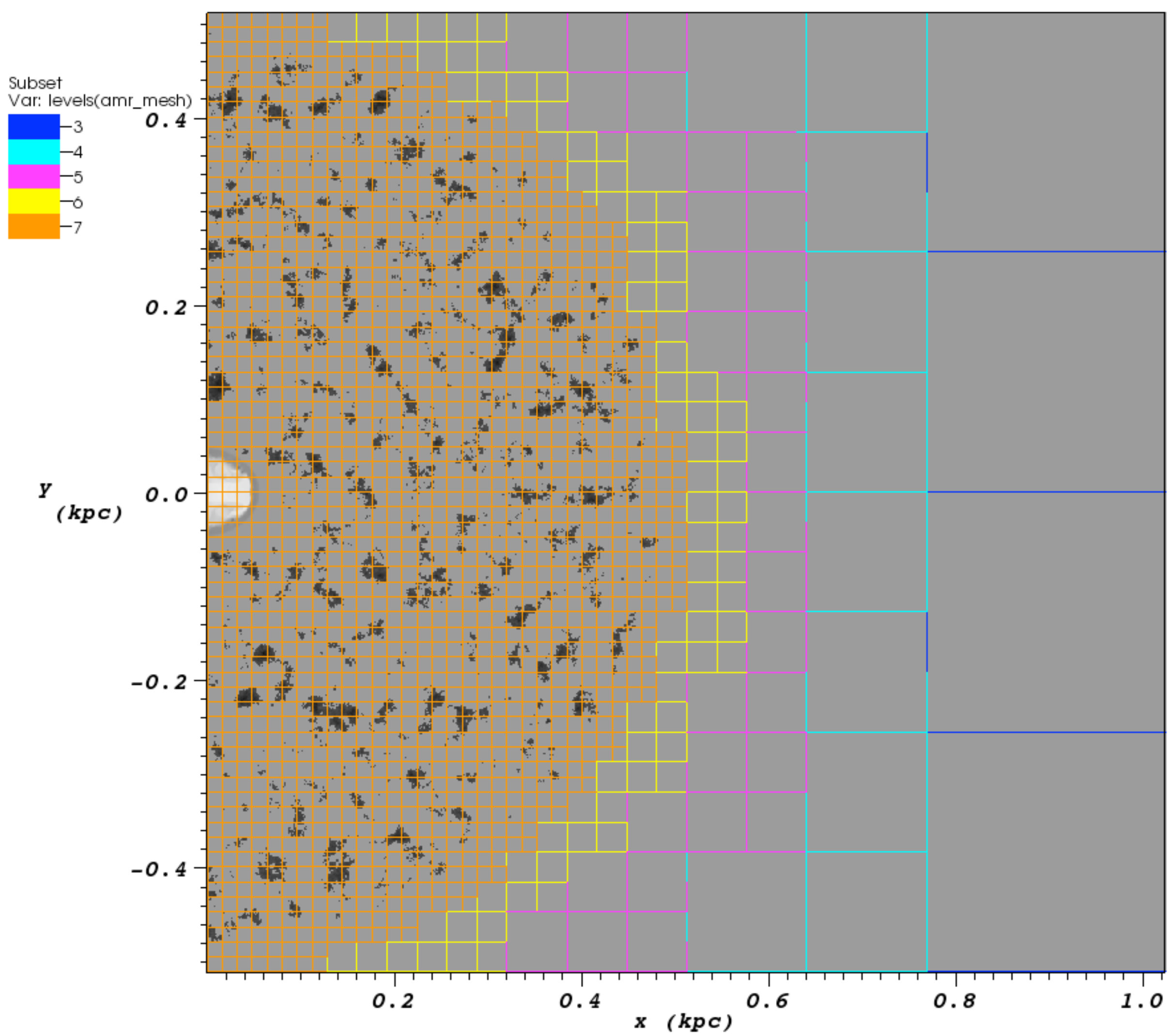
$$E = \rho w \Gamma^2 - p$$

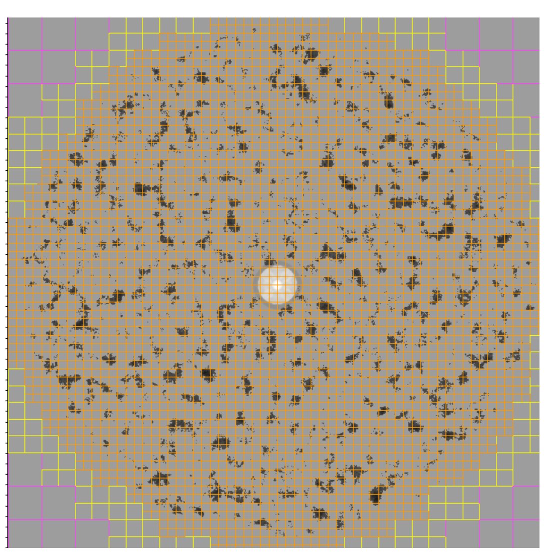
- Radiative cooling down to 10^4 K
- Taub equation of state
- Piecewise Parabolic Method (PPM)
- Characteristic Tracing
- Two-shock / HLLC hybrid Rieman solver

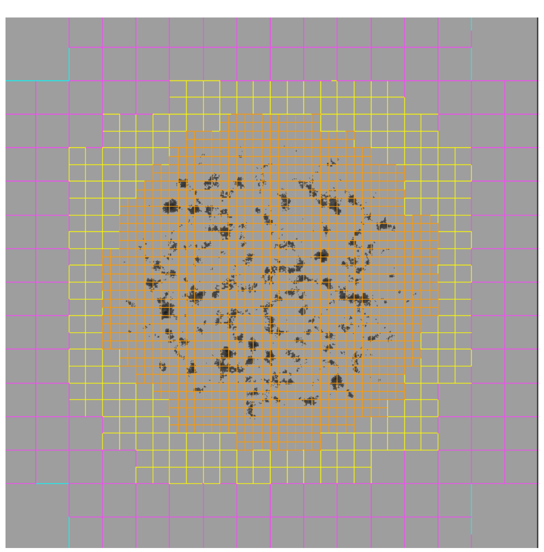
Future modifications

- Magnetic fields
- Self-gravity
- Radiation

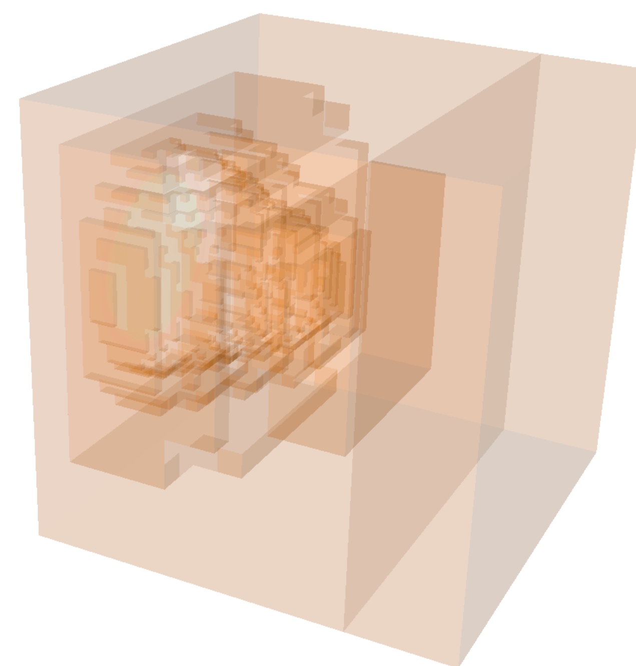
Simulation setup

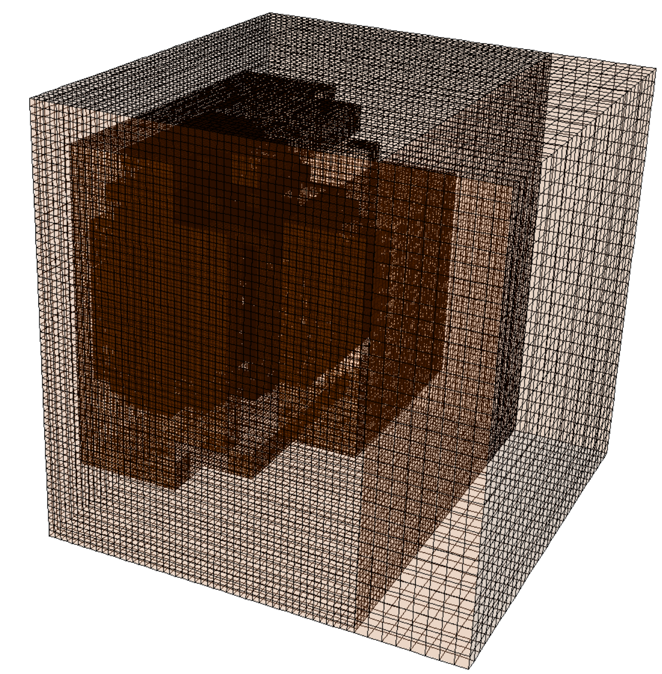






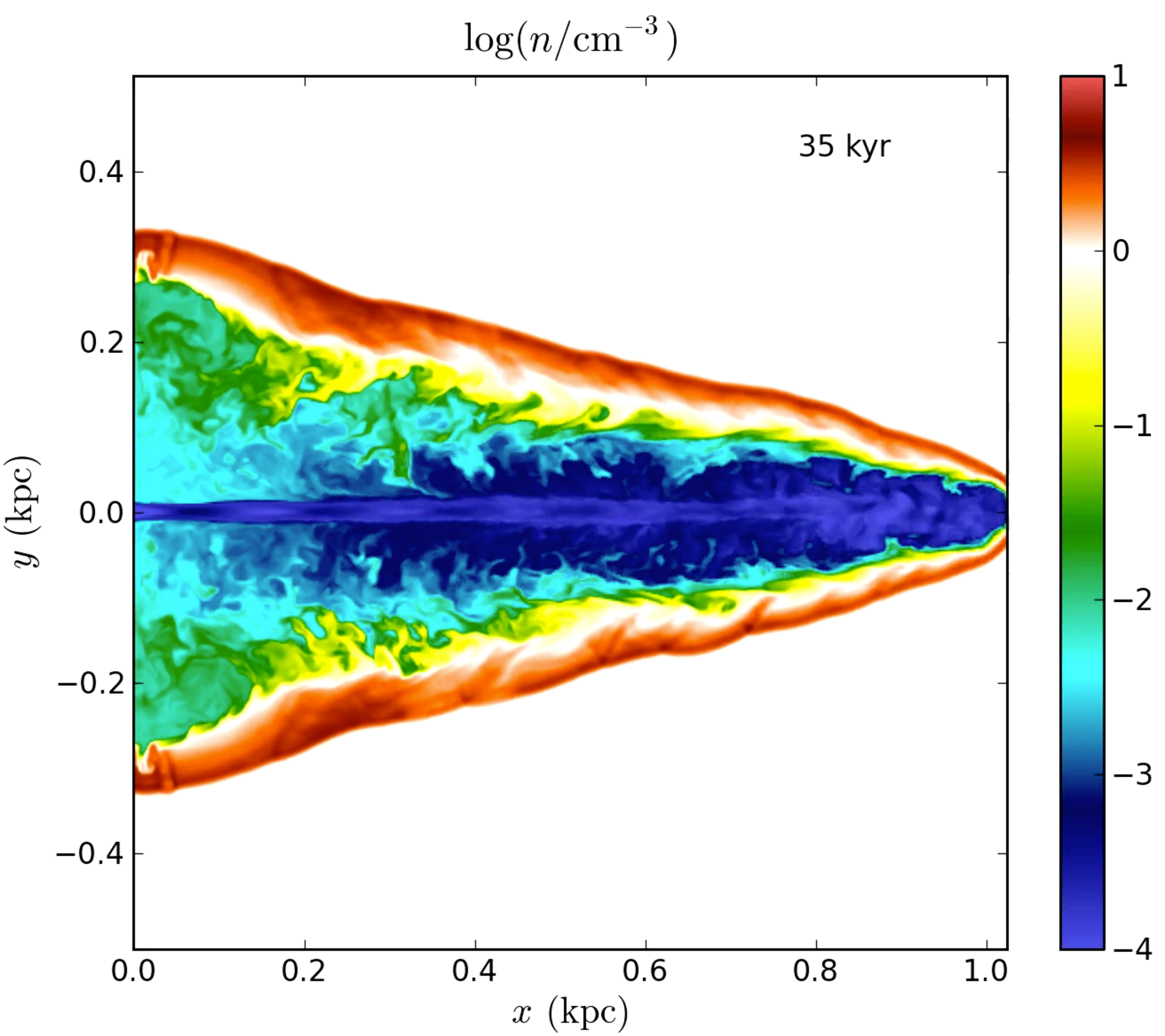
- Clumpy two-phase ISM
- Hemispherical isotropic distribution of clouds, representing bulges of protogalaxies, CCS, GPS sources
- Pressure equilibrium (except jet)
- x=0 reflective, others are reflective
- v = 0 everywhere, except at jet inlet

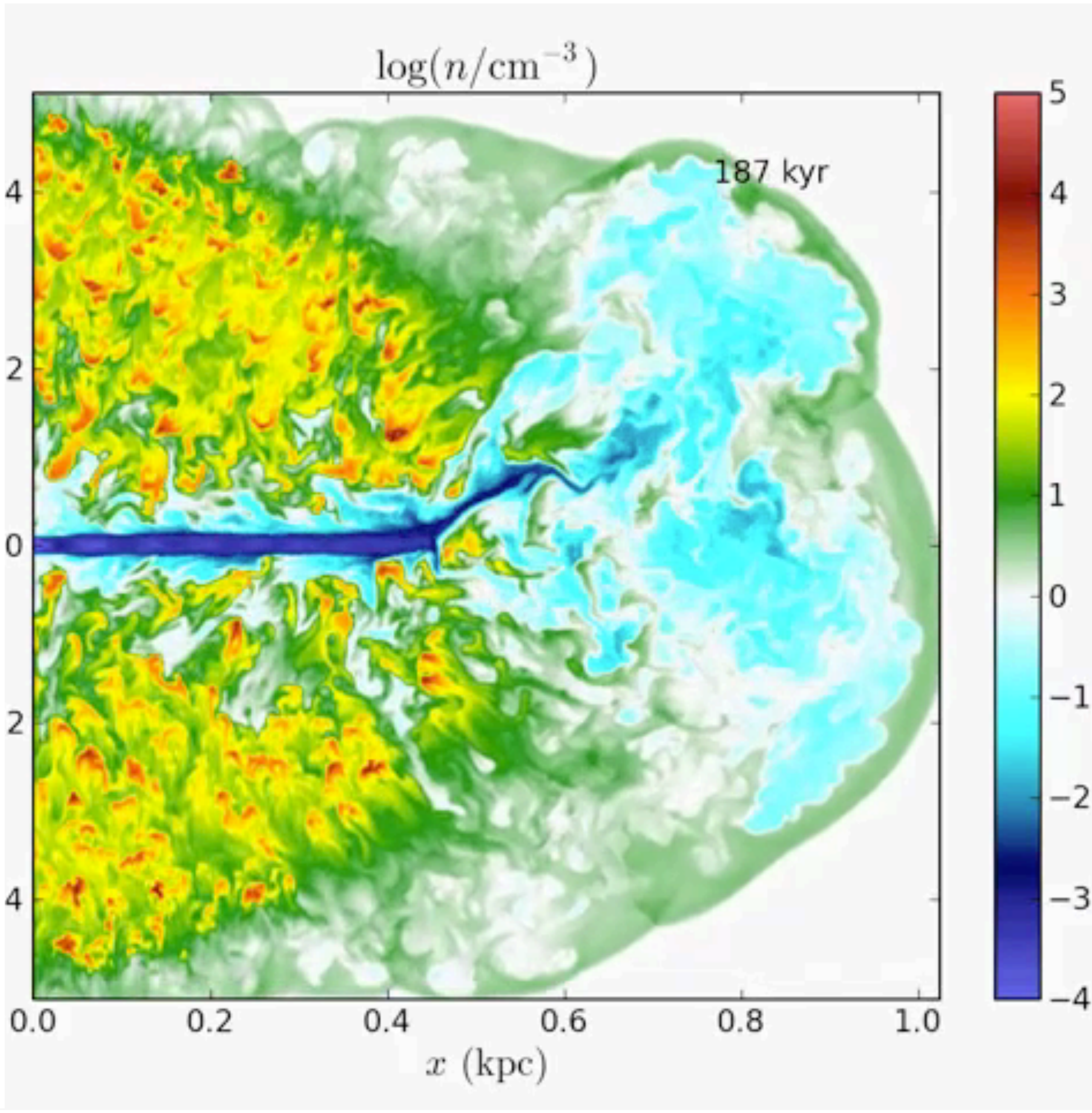




FLASH 3.2 with Paramesh AMR
PLUTO 4 with Chombo AMR

Quasar-mode feedback by AGN jets in gas-rich galaxies





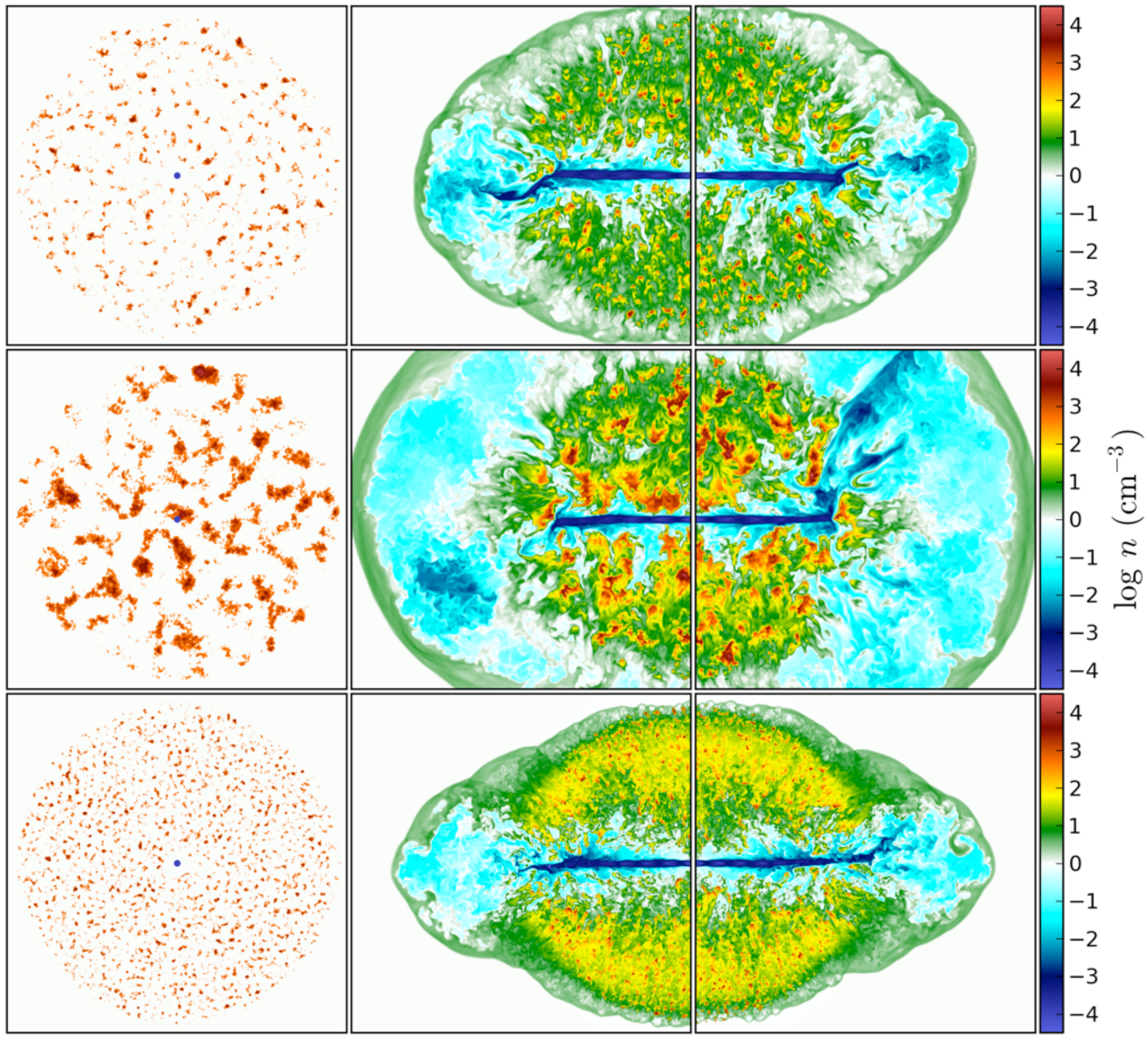
Γ=10, P=10^{45} erg s^{-1}, χ = mc^2/4p = 1

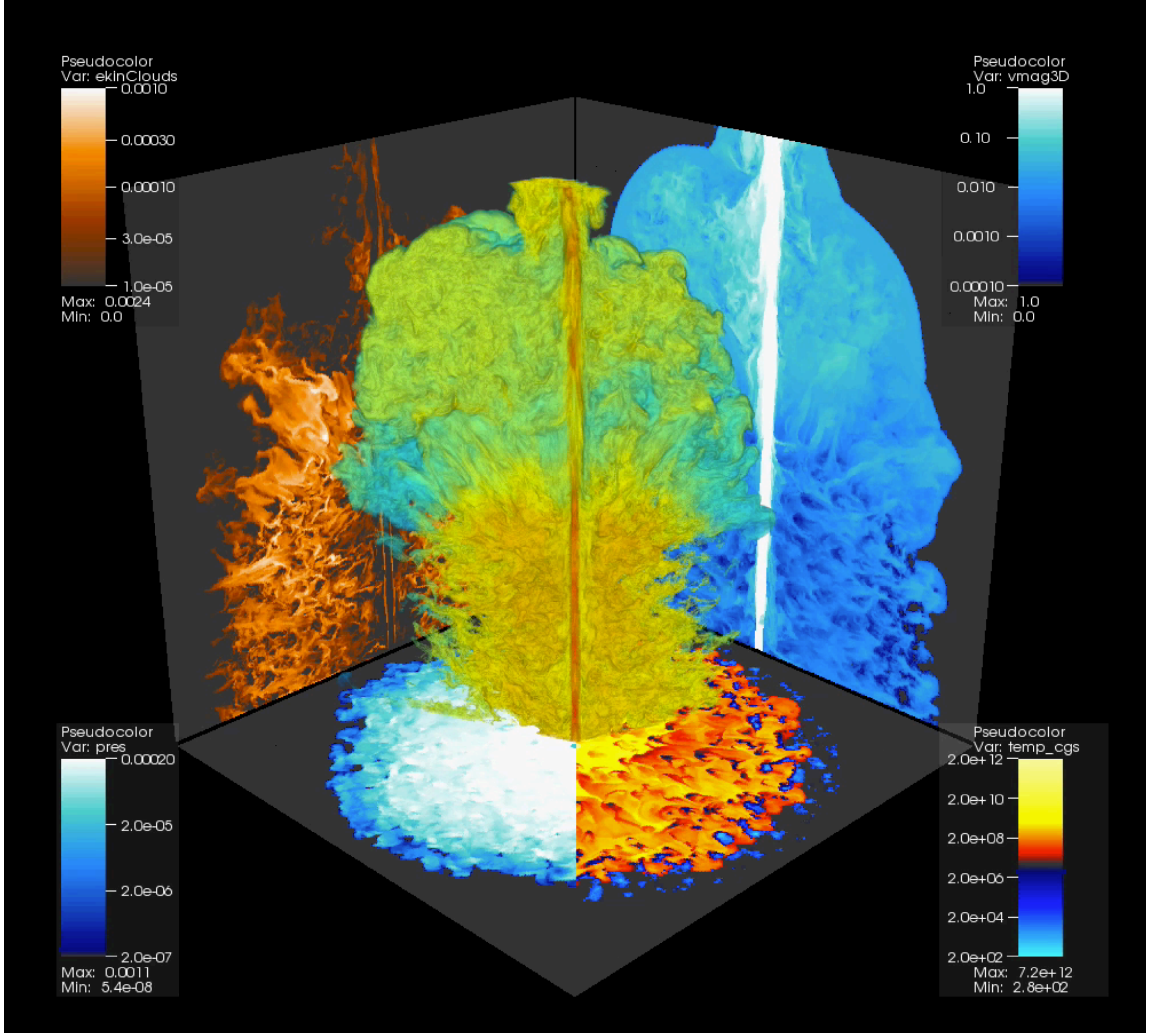
Quasar-mode feedback by AGN jets in gas-rich galaxies

$f_V = 0.027$
$R_{c,max}$~25 pc

$f_V = 0.053$
$R_{c,max}$~50 pc

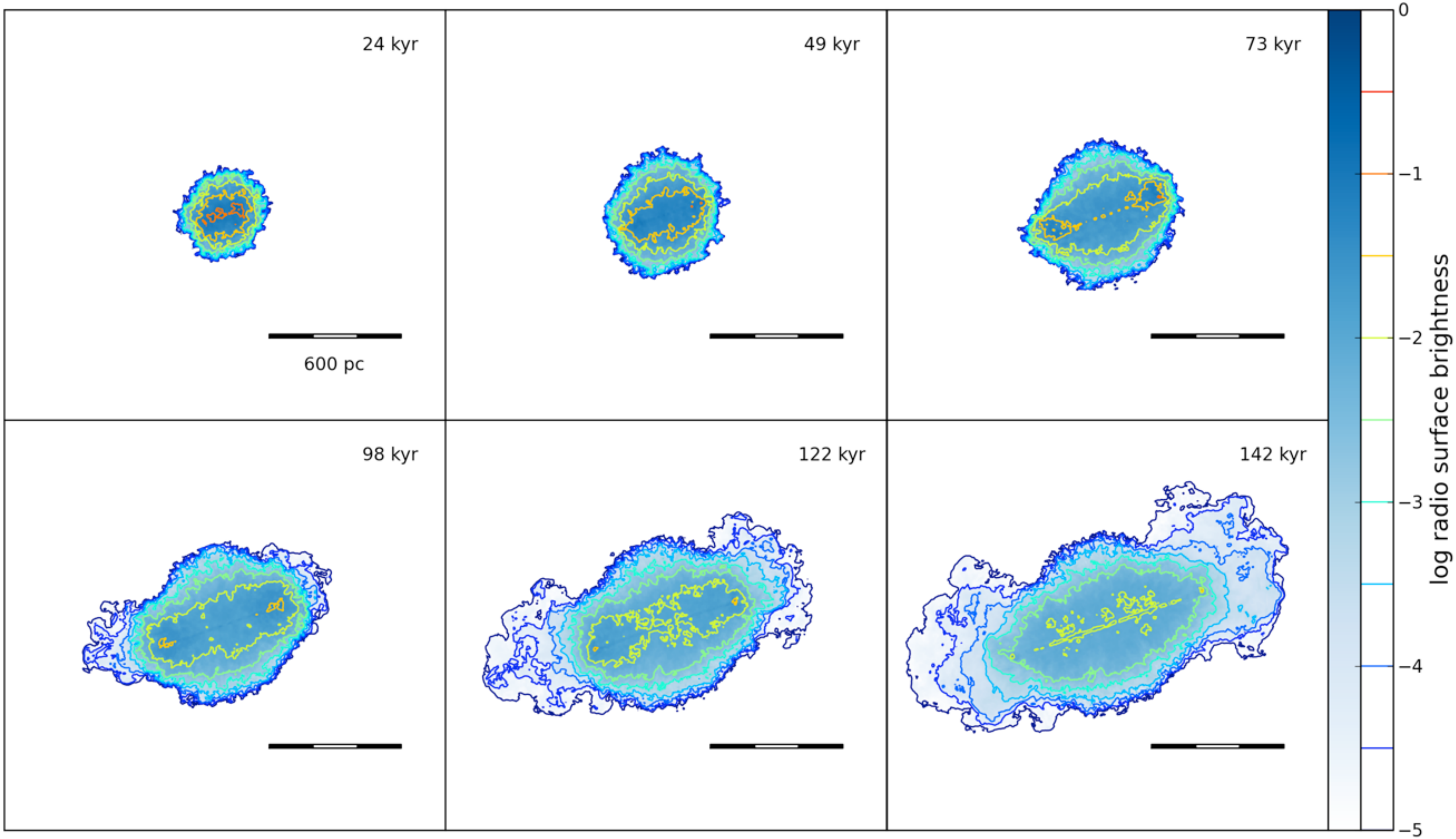
$f_V = 0.053$
$R_{c,max}$~10 pc





AGN Jet Feedback

Jet propagation
Energy deposition

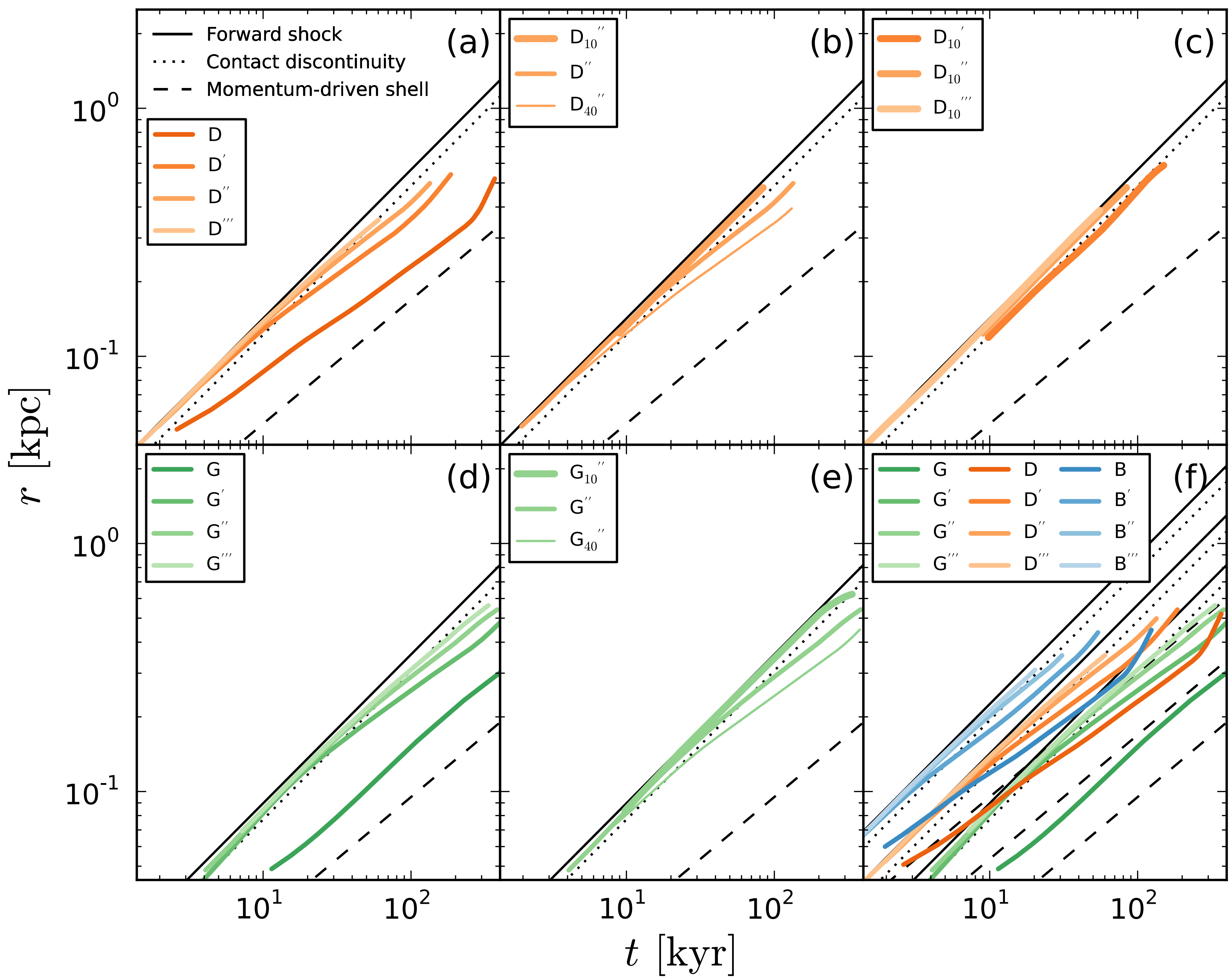


Synthetic radio images

Useful in comparisons to HzRG (e.g. GPS and CSS sources).

Energy- or Momentum-driven?

Bubble evolution - *Energy or momentum driven?*



Cosmological simulations are alright in employing energy driven outflows, especially in the limit of small cloud sizes and small filling factor.

Bubble expansion speed is ~1000-2000 km s^{-1}. How is warm phase material accelerated to comparable speeds within dynamical time of bubble?

Navier-Stokes (Newton's law) instantaenous momentum transfer + pressure gradient.

Integral of the pressure over the surface area bounding the cloud.

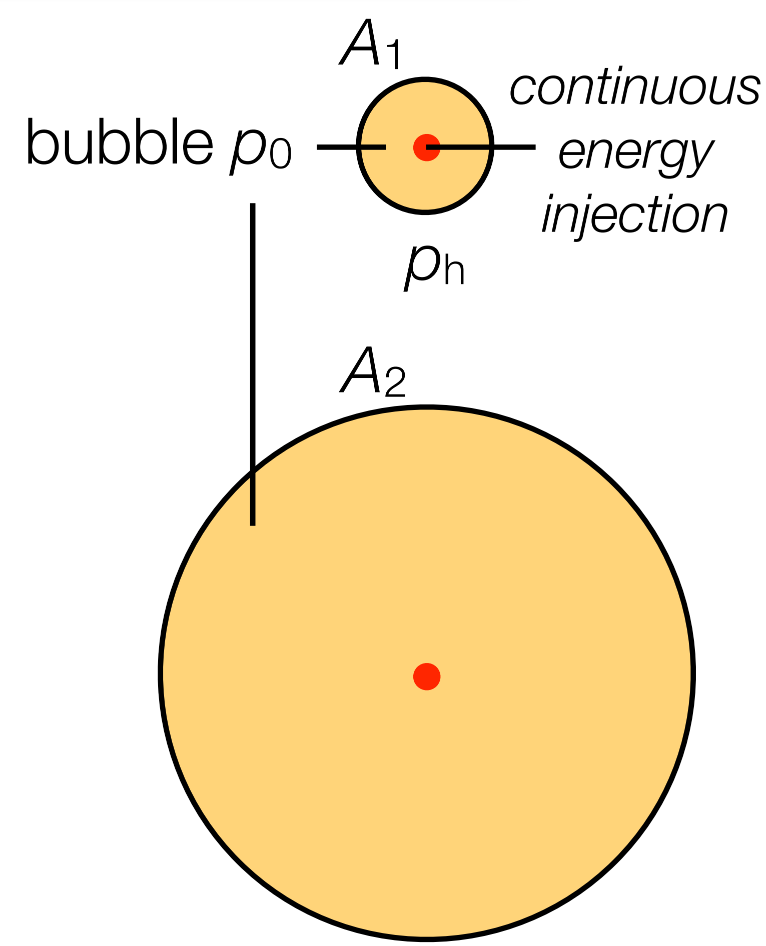
Mechanical advantage

Momentum budget

$$\frac{d}{dt}\int \rho v_i dV + \int \left[\frac{d}{dx_j}\left(\rho v_i v_j\right) + \frac{d}{dx_j} p\delta_{ij}\right] dV = 0$$

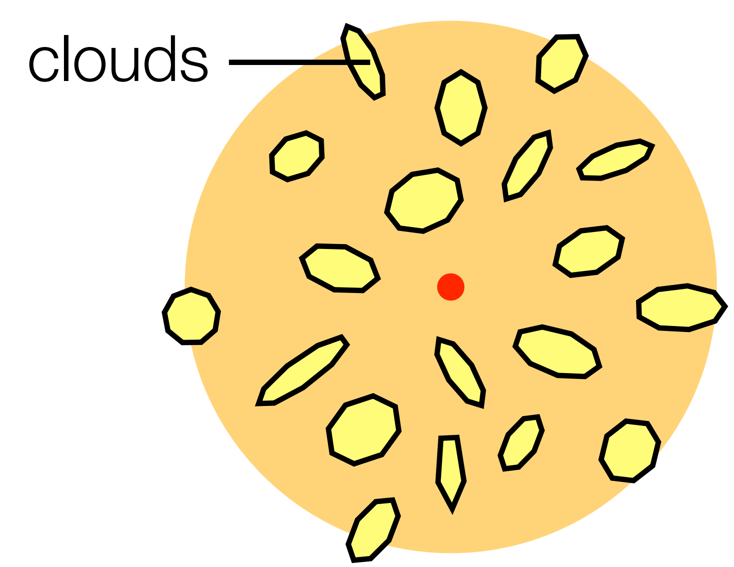
$$\frac{d}{dt}\int \rho v_i dV + \oint \left[n_j \rho v_i v_j + n_j p \delta_{ij}\right] dS = 0$$

Ram pressure Thermal pressure



Mechanical advantage = $\frac{A_2}{A_1}$

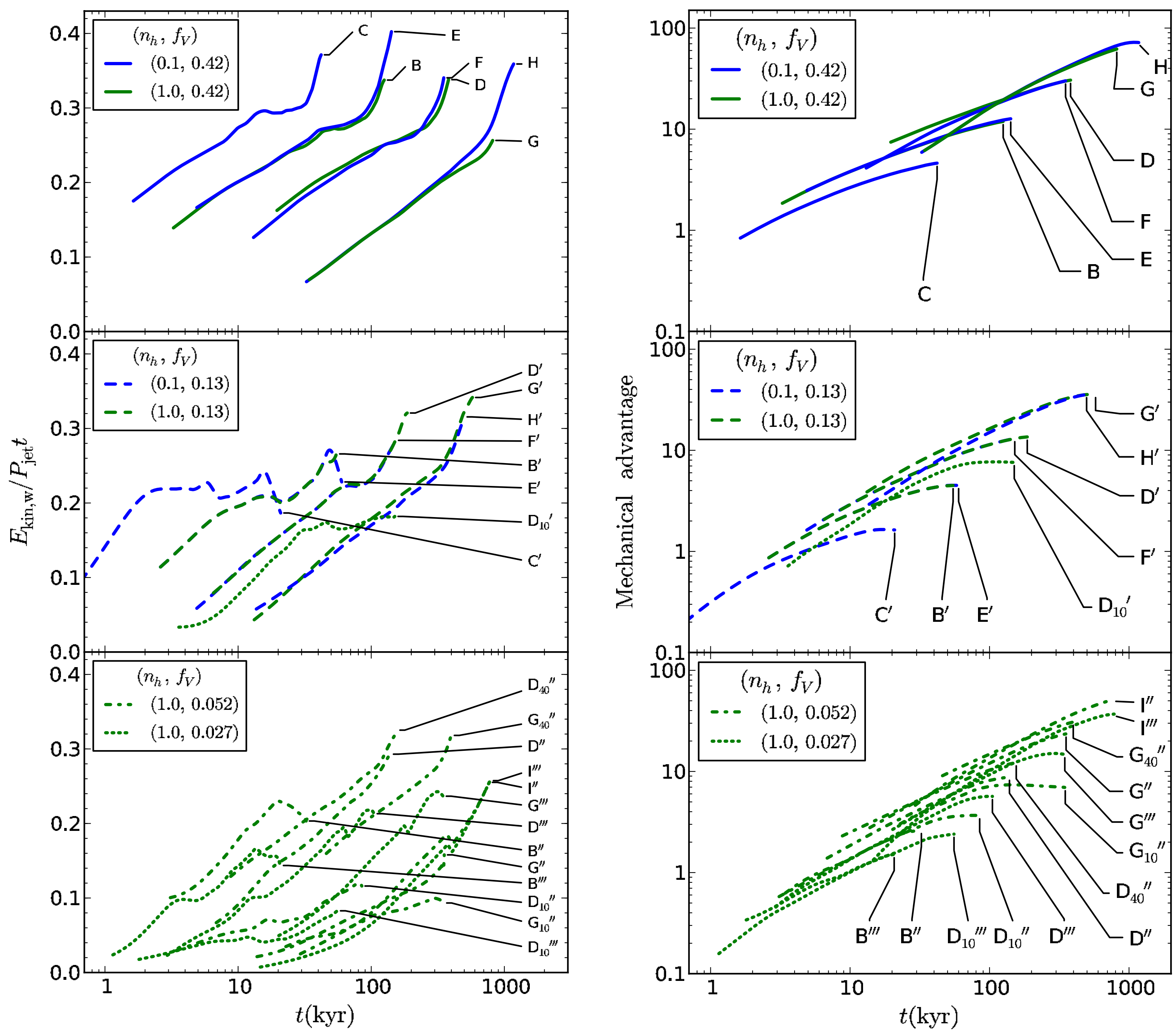
Analogous definition of mechanical advantage:
Ratio of integrated momenta



$$\frac{m_{\mathrm{clouds,tot}}}{m_{\mathrm{jet,tot}}} = \frac{\int \phi_w \rho \vec{v}\cdot\hat{r}dV}{\pi r^2 \Gamma^2 \beta^2 (\rho c^2 + p + \epsilon)\Delta t}$$

Mechanical advantange and Energy transfer

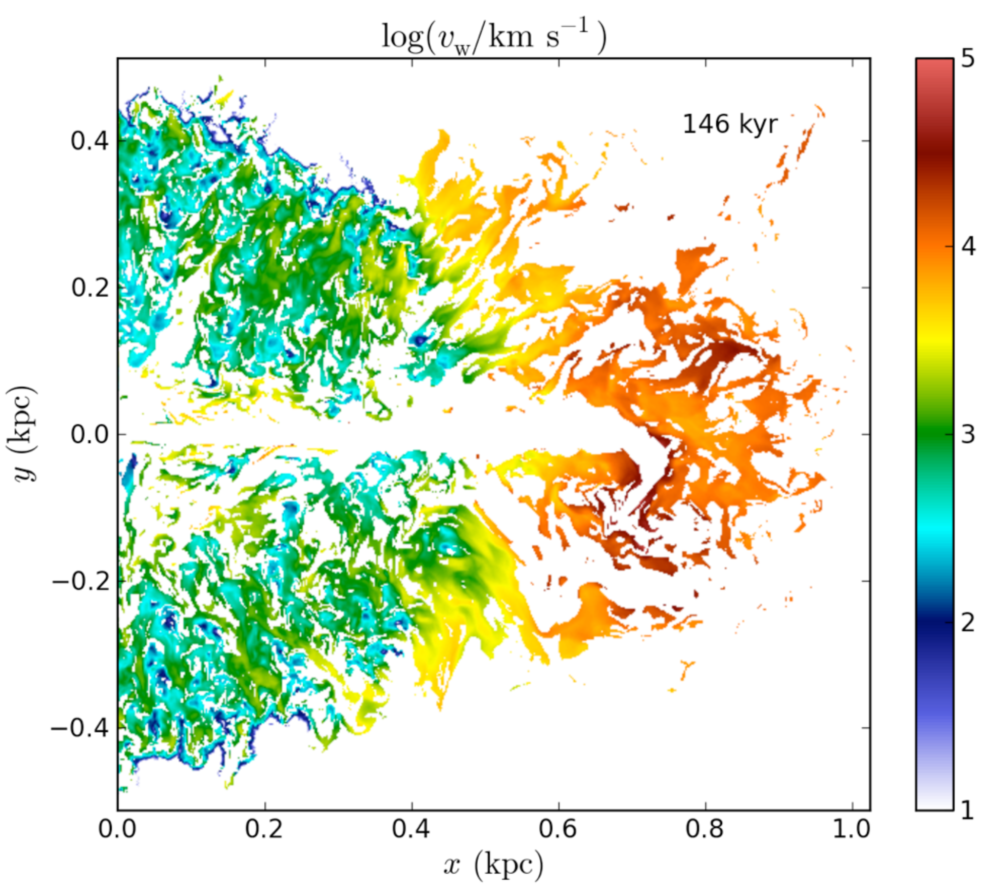
- Energy transfer from Jet to kinetic energy of clouds reaches 0.2-0.4 and rising.
- Mechanical advantage >> 1 , reaching 100

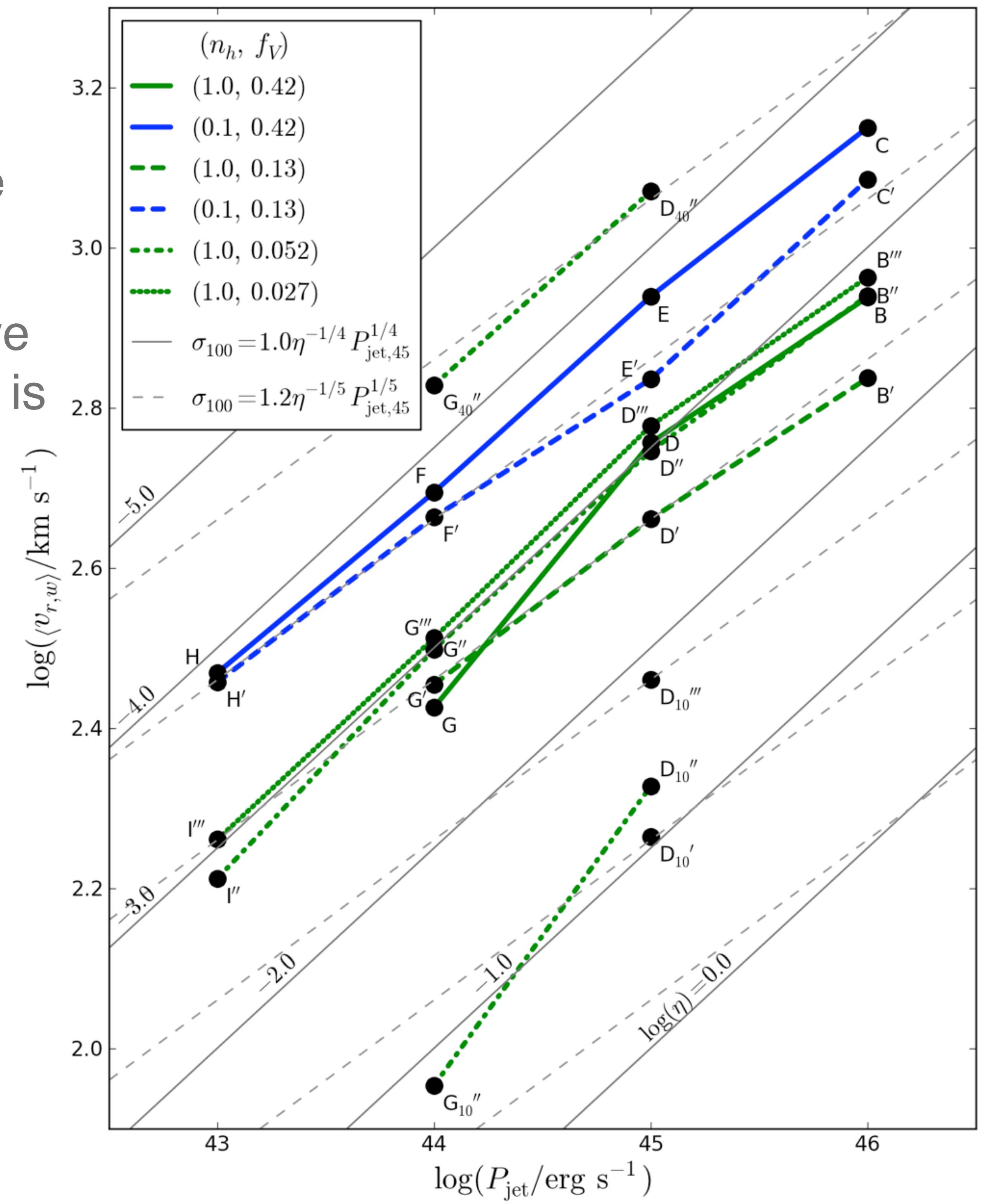


How strong (or efficient) is negative AGN feedback?

Negative Feedback *Outflow speeds and M-σ*

- Negative feedback depends on ISM properties and jet/wind parameters
- The more powerful the jet, the faster the outflows. ➡ *M-σ* scaling (Silk & Rees 1998).
- The gas dynamics is complicated, but we can make predictions of when feedback is efficient.



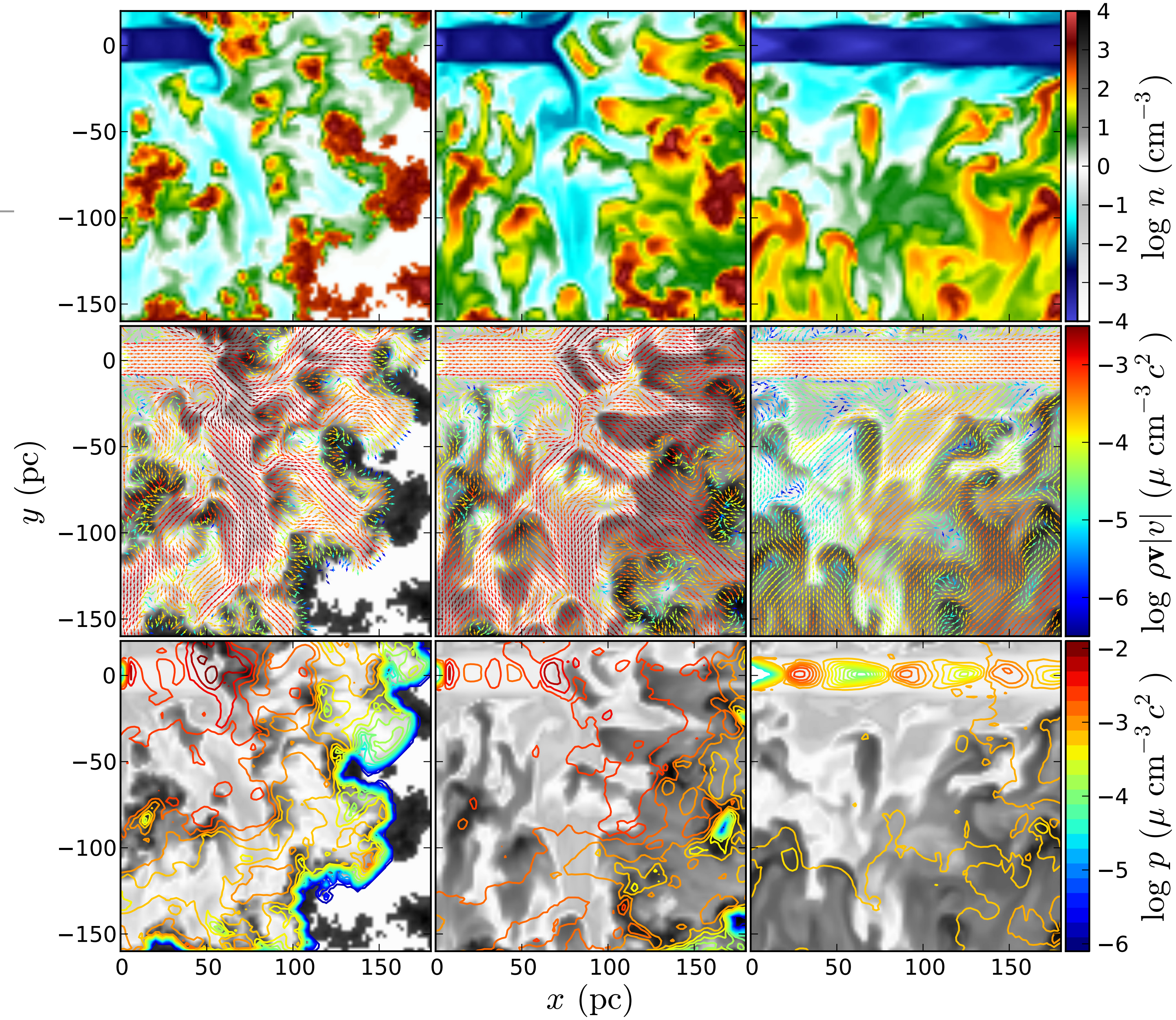


How does AGN Feedback work internally?

How is energy and momentum transferred?

The Inner Workings

- The channel flow remains at $\beta > 0.01$ within the kpc simulation domain.
- All channel flows have high densities $n > 0.1$ cm^{-3} due to turbulently entrained hot-phase material.
- Some channel flows are heavily mass loaded by cloud material ($n \gtrsim 10$ cm^{-3}).

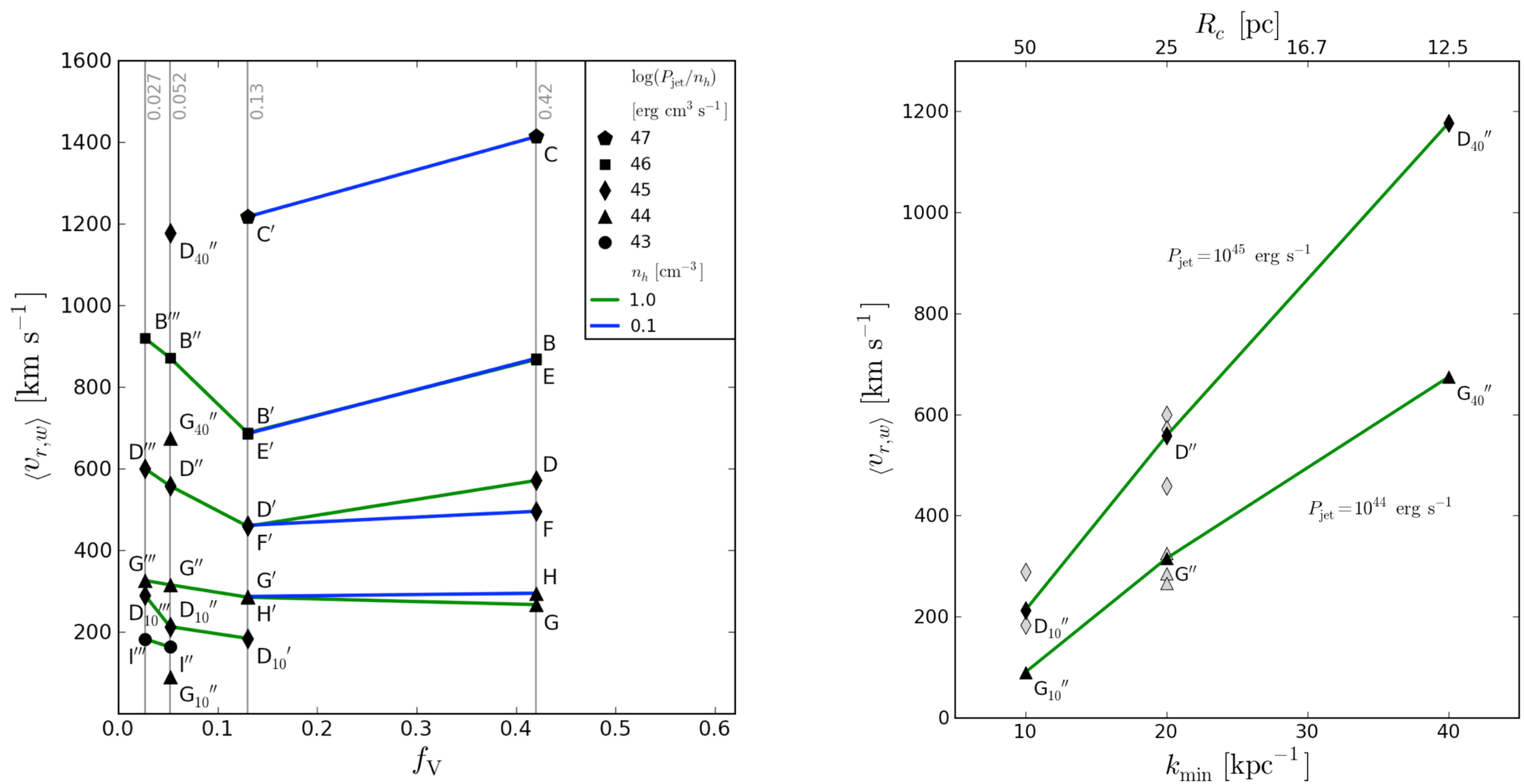


⇒ **Pressure gradients** at cloud interfaces are maintained mainly through high ram pressure channel flows.

⇒ Estimates of cloud acceleration timescales are less than bubble dynamical time.

AGN Feedback efficiencies

Dependence on filling factor and cloud sizes



- Surface area per unit mass exposed to ablation scales inversely with cloud radius.
- Confinement time of jet, and therefore, the time available for energy and momentum transfer is shorter in lower filling factor environments.

AGN Jet Feedback

Efficiencies

Reason for strong dependence of feedback efficiency on cloud size:

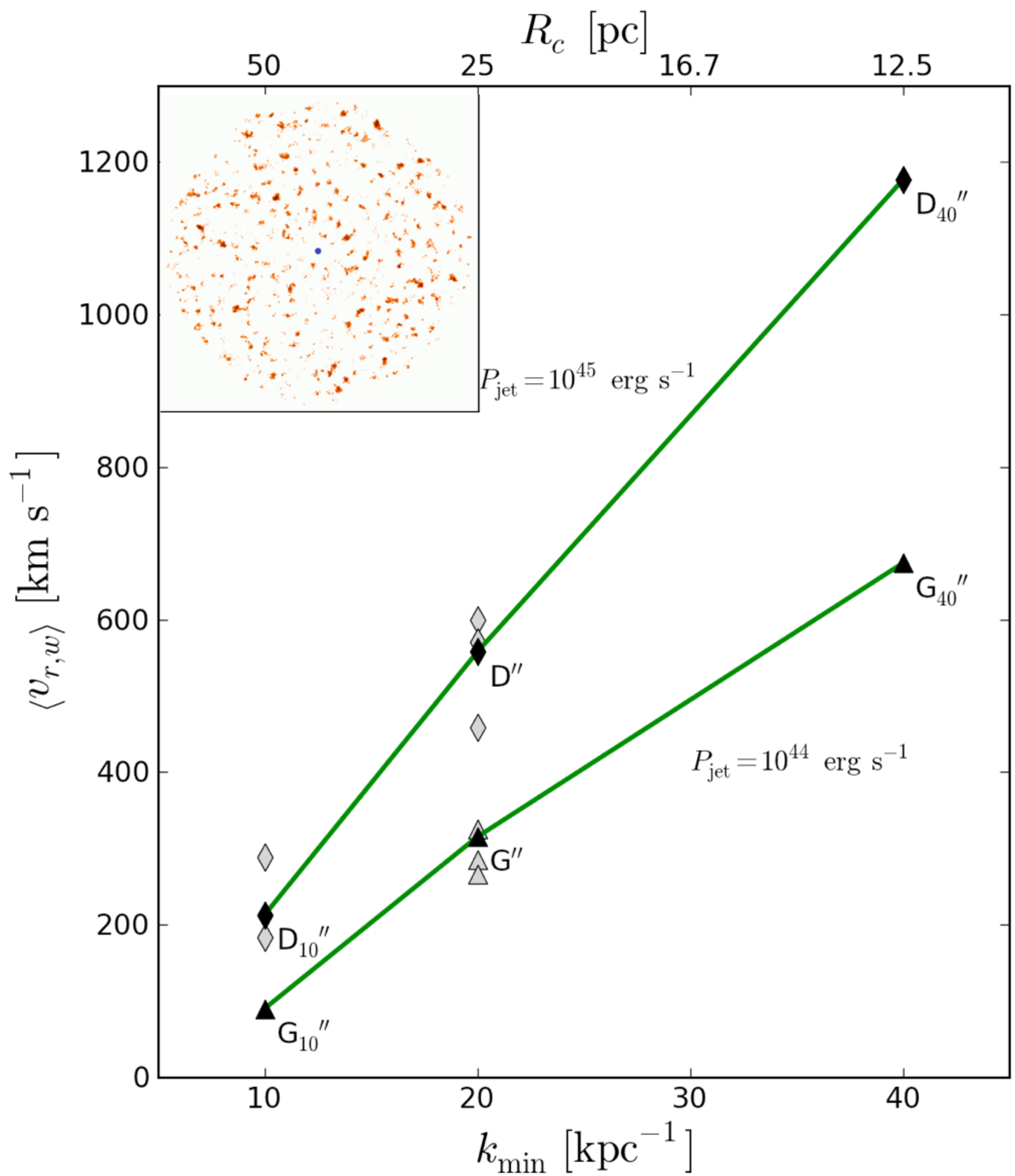
- View problem of jet propagation through galaxy as a (self-avoiding) random-walk/diffusion problem.
- We define an interaction depth:

$$\tau_{\rm jc} = (n_c R^2_{\rm c,max}) R_{\rm bulge}$$

$$N = f_V R^3_{\rm bulge} / R^3_{\rm c,max} = n_c R^3_{\rm bulge}$$

$$\tau_{\rm jc} = f_V (R_{\rm bulge}/R_{\rm c,max}) = f_V k_{\rm min}$$

Dependence on cloud sizes



AGN Jet Feedback

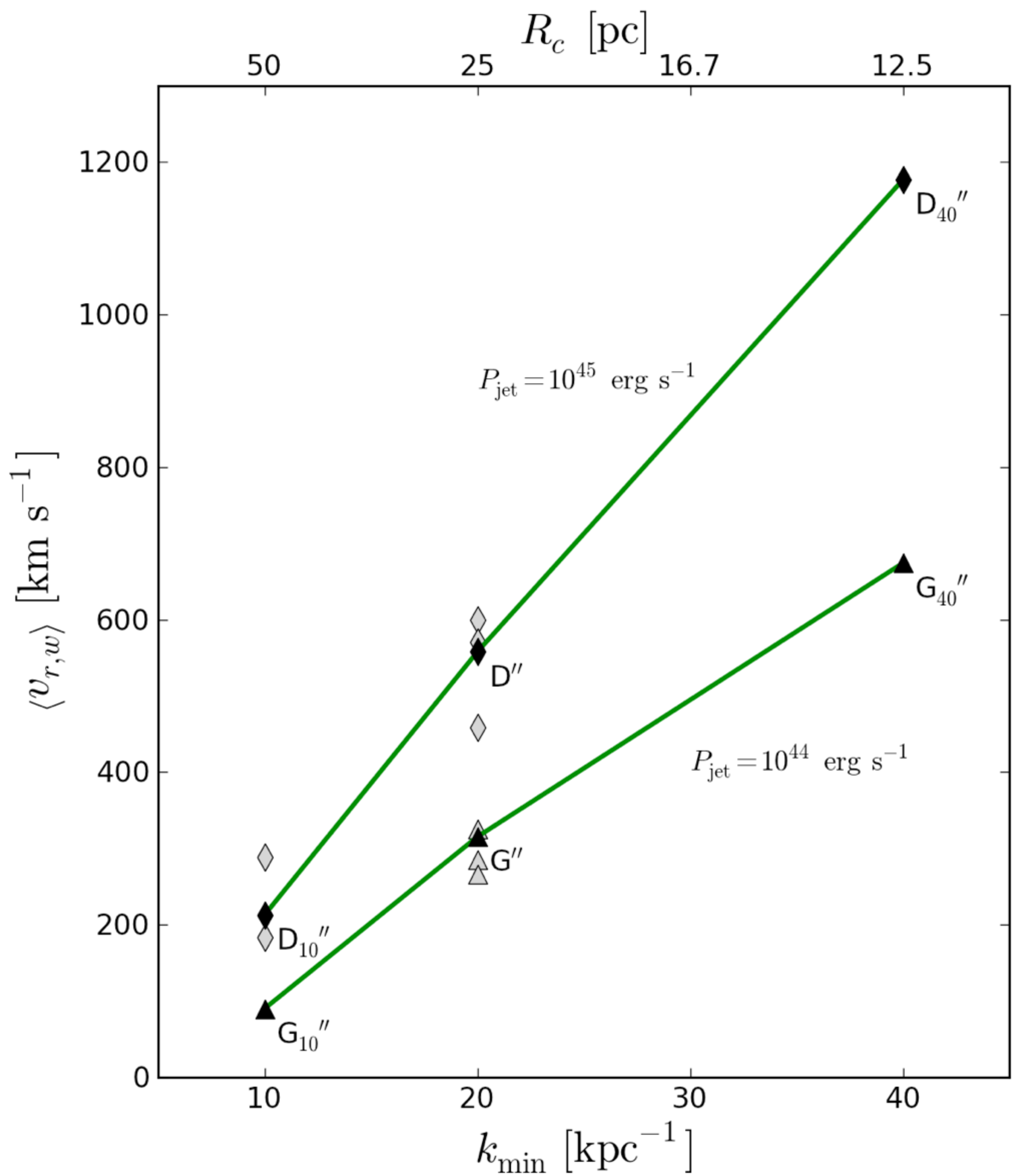
Efficiencies

Feedback efficiencies depend stronger on maximum cloud sizes than on filling factor

A galaxy with many small isolated clouds experiences efficient cloud dispersion compared to a galaxy with fewer but bigger cloud complexes.

Bigger cloud complexes may be more easily triggered to collapse.

Dependence on cloud sizes



Positive vs Negative Feedback.

Theoretical work on AGN induced star-formation

- **Kim et al (2012)** performed a (Toomre) stability analysis of a self-gravitating cold gas-rich disc confined by an external pressure (e.g. AGN induced)
  - The maximum instability growth rate is found to be enhanced by the external pressure by a factor $\sim(2p_{\rm ext}/p_{\rm disc})^{1/2}$
  - The characteristic wavelength of instabilities is reduced by $\sim 2p_{\rm ext}/p_{\rm disc}$.

- AGN (especially jets) can increase the external pressure **by a factor of 1000.**

- **Silk (2013)** proposed a **pressure regulated** (rather than density regulated) modified star-formation rate:

Mechanical advantage = $p_{\rm jet} / p_{\rm clouds}$

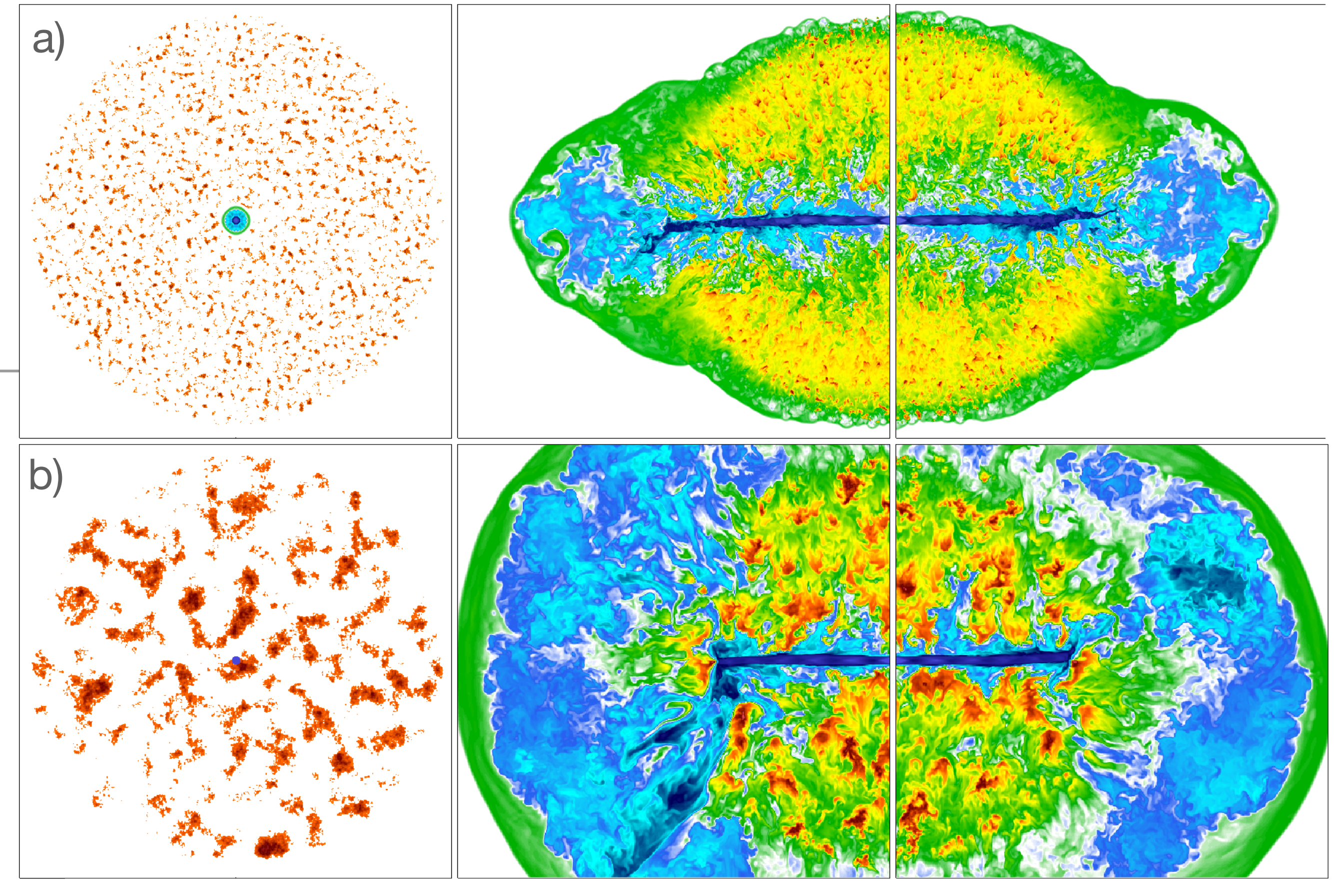
$$\dot{\Sigma}_*^{AGN} = \frac{\epsilon_{SN}}{\sigma_d}\Sigma_{gas}\sqrt{\frac{\pi G p_{AGN}}{f_g}} \qquad p_{\rm AGN} = f_p f_E \frac{L_E}{4\pi R^2 c}$$

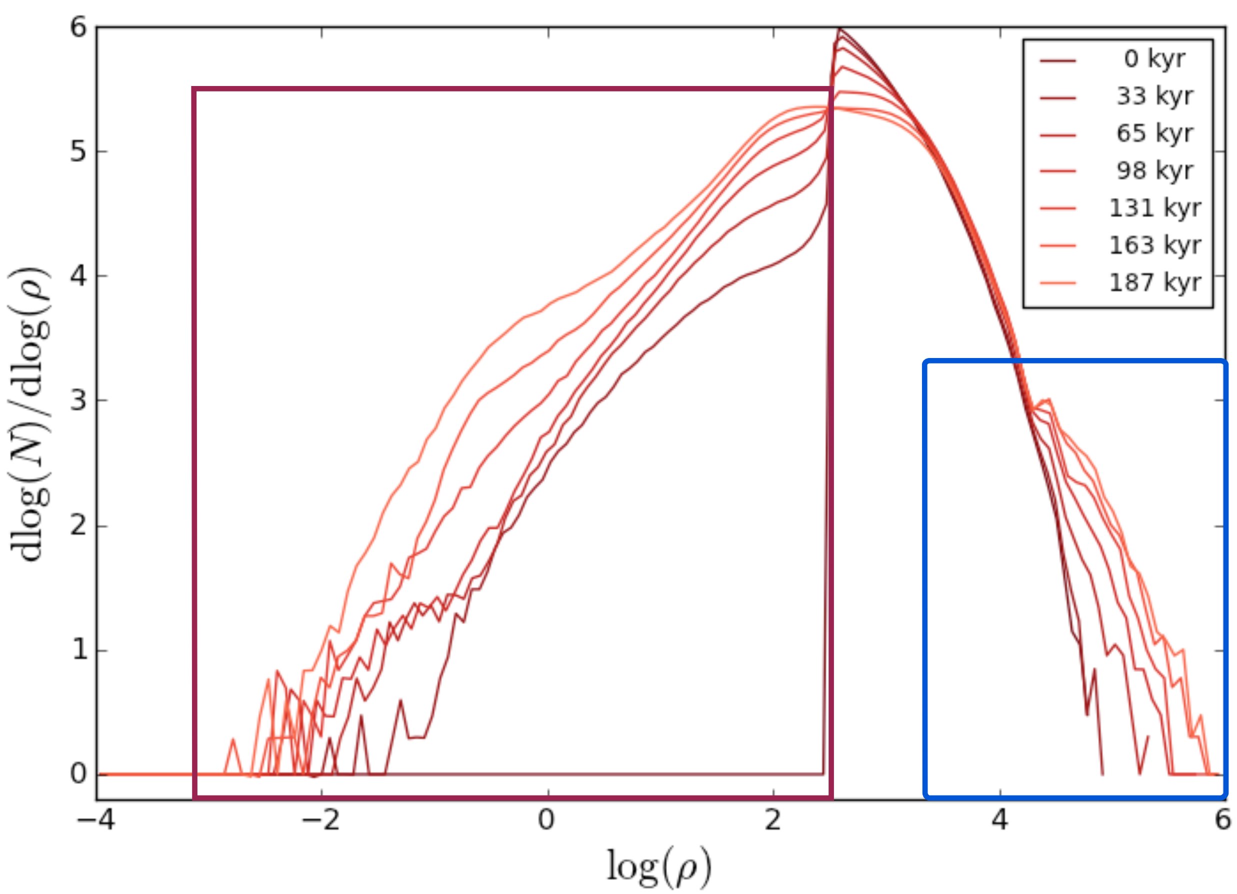
$L_{\rm AGN}/L_E$

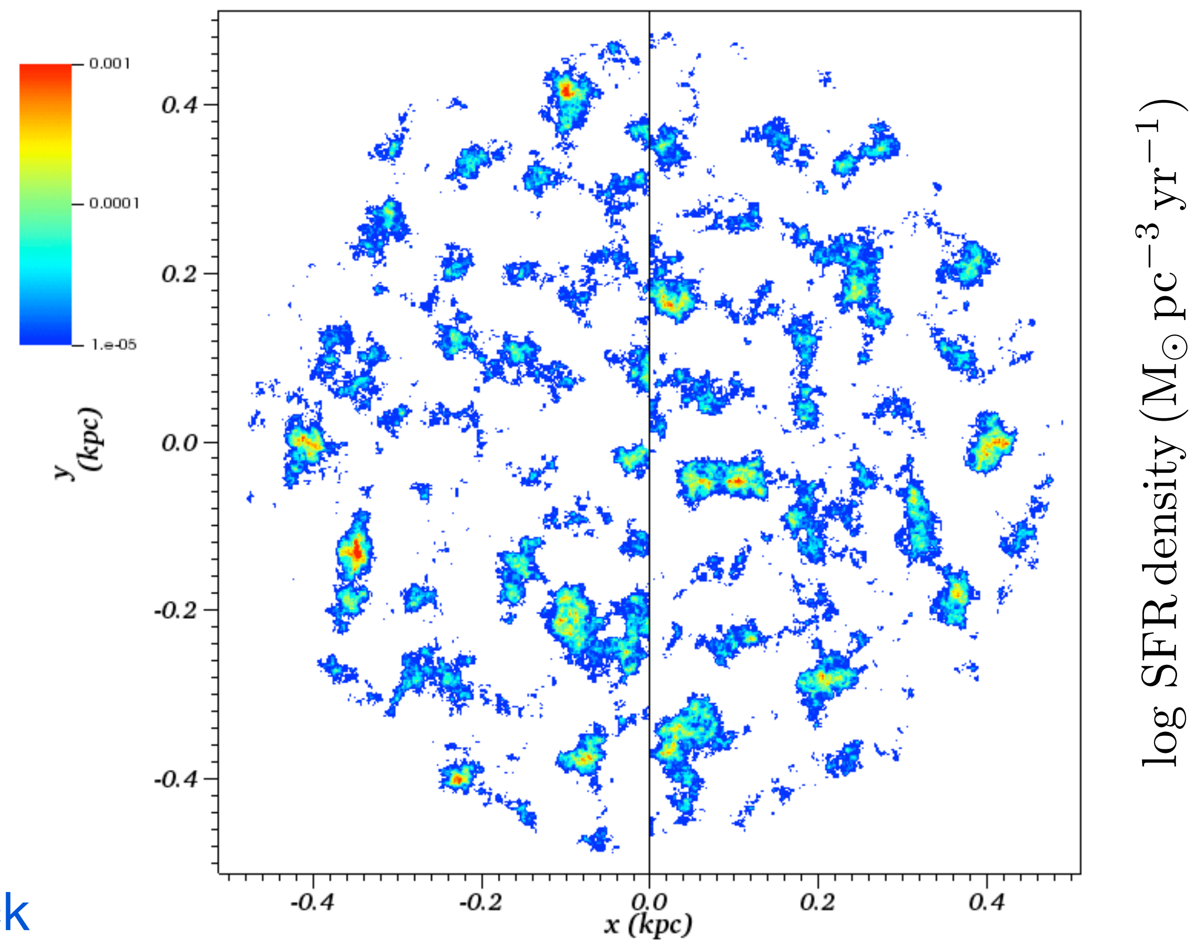
Negative vs Positive Feedback

- Competing effects:
  a) Cloud ablation
  b) Pressure-triggered collapse

  Evolution of density distribution



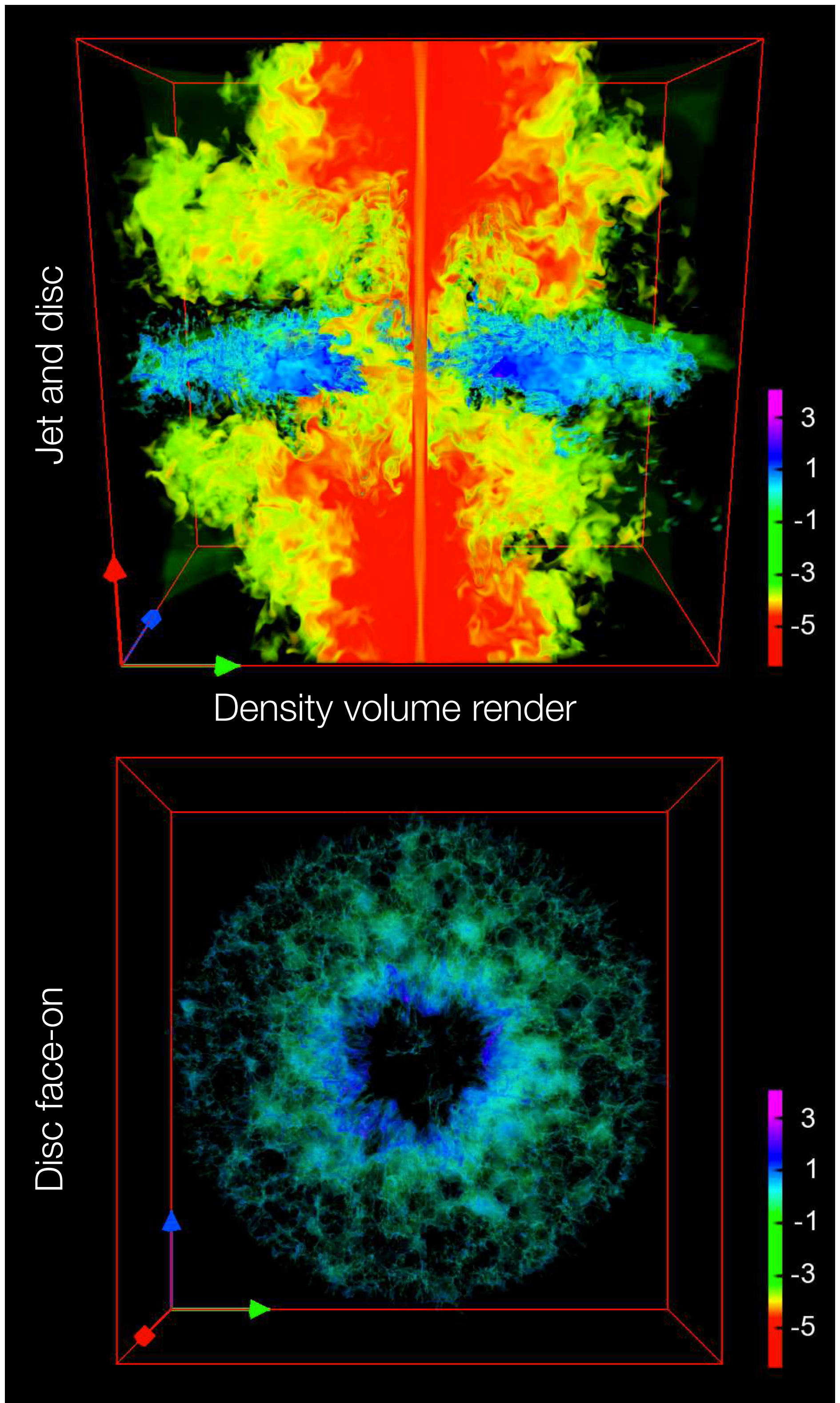


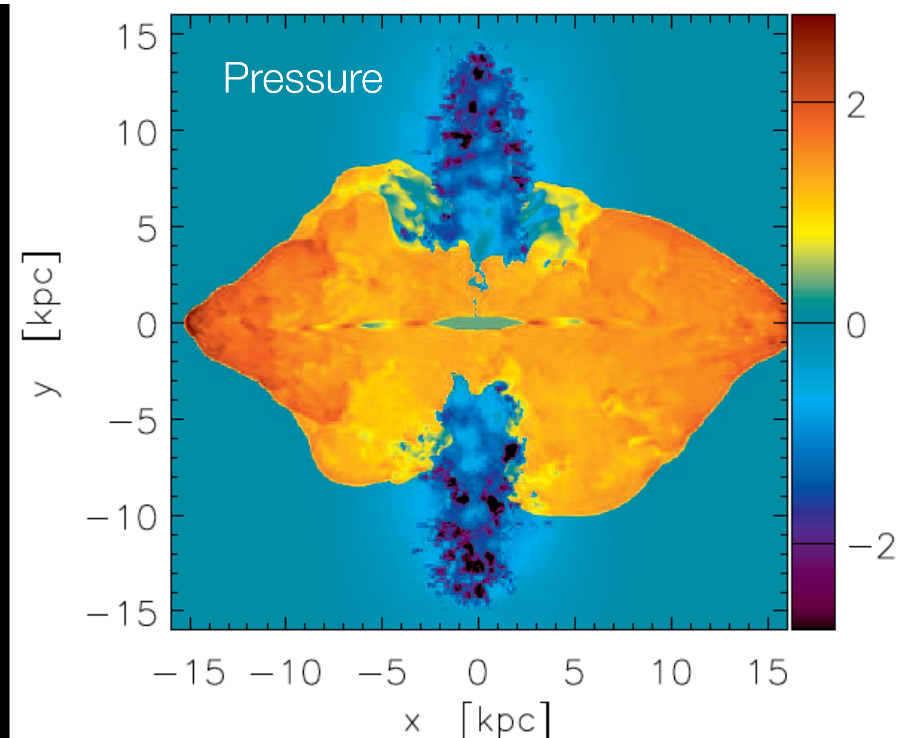


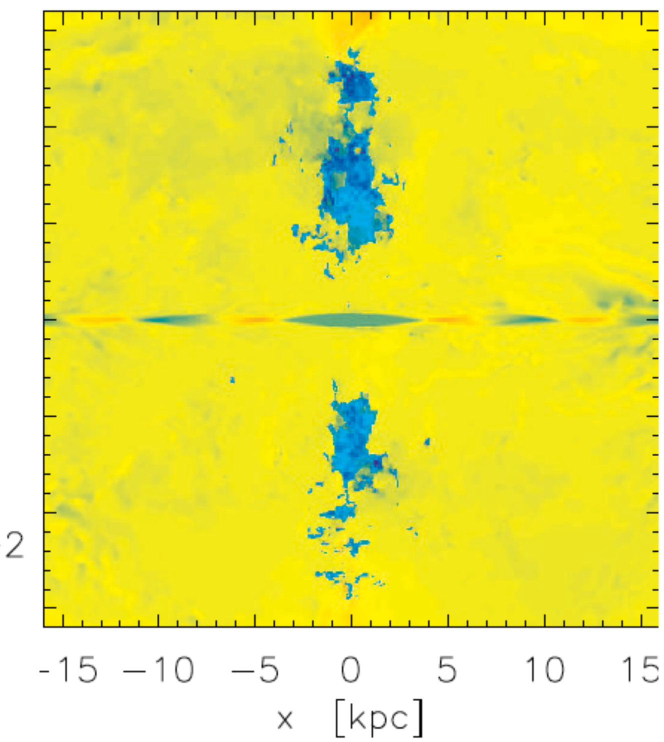
Negative Feedback
Dispersal・Heating・(Blowout)

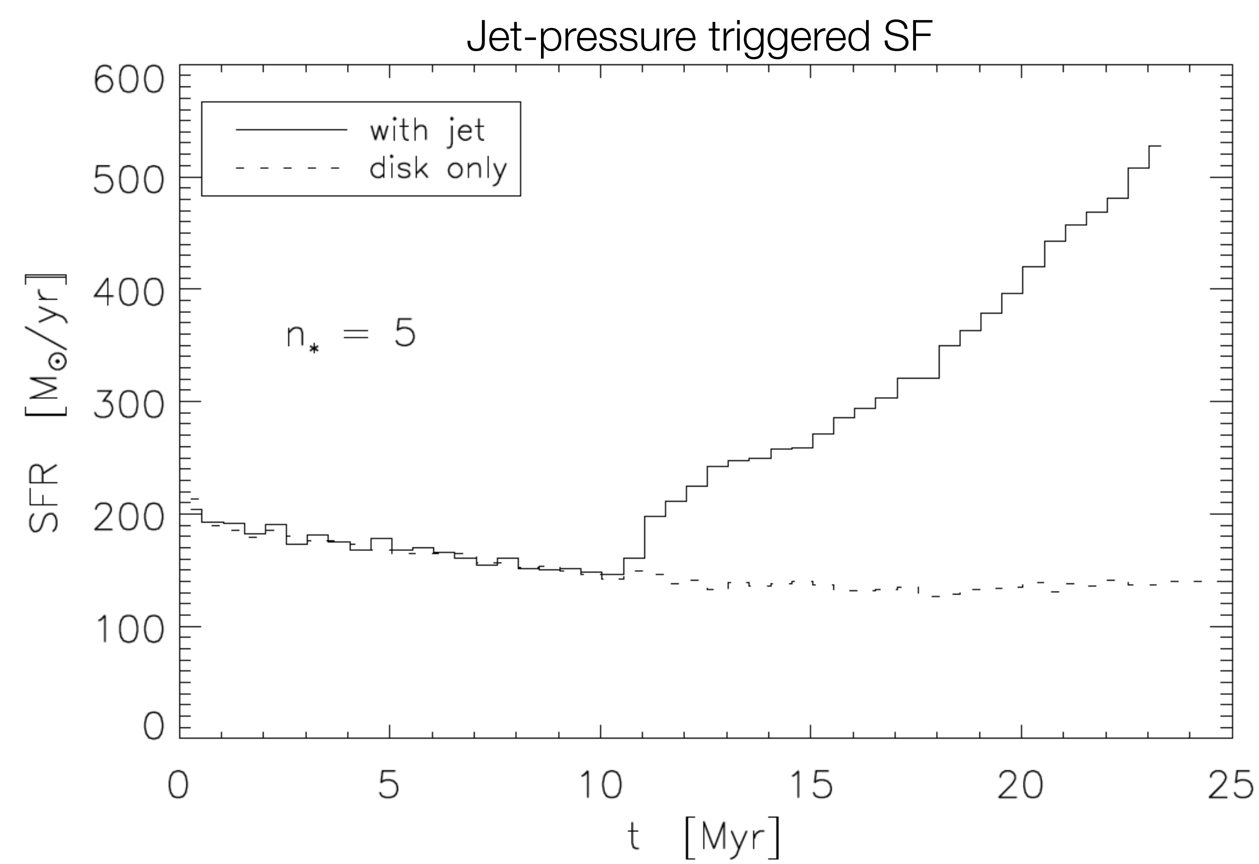
Positive Feedback
Coagulation・Pressurization・Shock compression

Positive Feedback through Jet-induced Star Formation in Disc Galaxies. Gaibler et al. (2011)



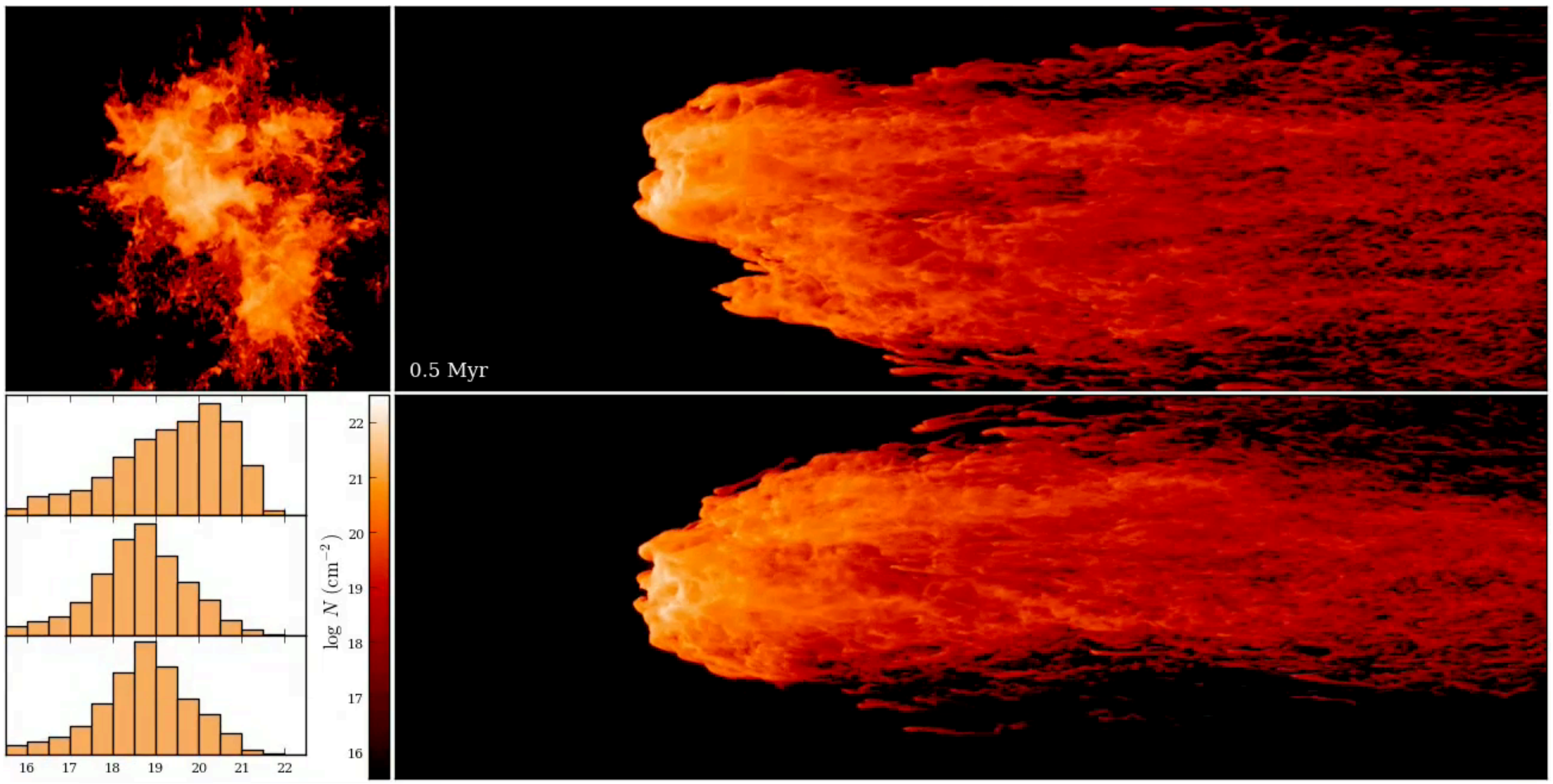






Cloud evolution in detail

The complexity of positive and negative feedback



Cooper et al. (2009)

- Star-formation can occur in galactic outflows. These would leave an imprint in stellar kinematics.
- A bottom up approach - starting from the simulation of individual coulds being blown out or compressed - is also needed to understand the averaged global effects of positive and negative feedback.

Summary

- Quasar mode (and radio-mode) feedback are ***Energy-driven***

- AGN jets and winds can accelerate ionized, neutral and molecular gas through ram-pressure to 100s~1000s km s^{-1}, as seen in observations. ➜ *Negative Feedback*
- Pressurization of clouds or the entire galactic disc by the AGN blown bubble can lead to enhanced star-formation in the galaxy. ➜ *Positive Feedback*
- ***Positive and negative always happen together***. It is the ratio of these and the locality of each which affects galaxy properties.

- The ***efficiencies*** of positive and negative feedback depend strongly on the properties of the ISM like, e.g. the size-distribution of clouds as well as the column density of the system. ***Positive feedback may be significant in gas rich disc galaxies at high redshift***.

- ***Quasar mode negative feedback (radiation and kinetic)*** *and* ***Positive feedback*** still need to be properly included in cosmological and semi-analytic modelling.

Movies shown in this talk can be found at http://www2.ccs.tsukuba.ac.jp/Astro/Members/ayw/research/agn_feedback/agn_feedback.html

Summary in images