Mass and Energy Budgets in Evolving Galaxies

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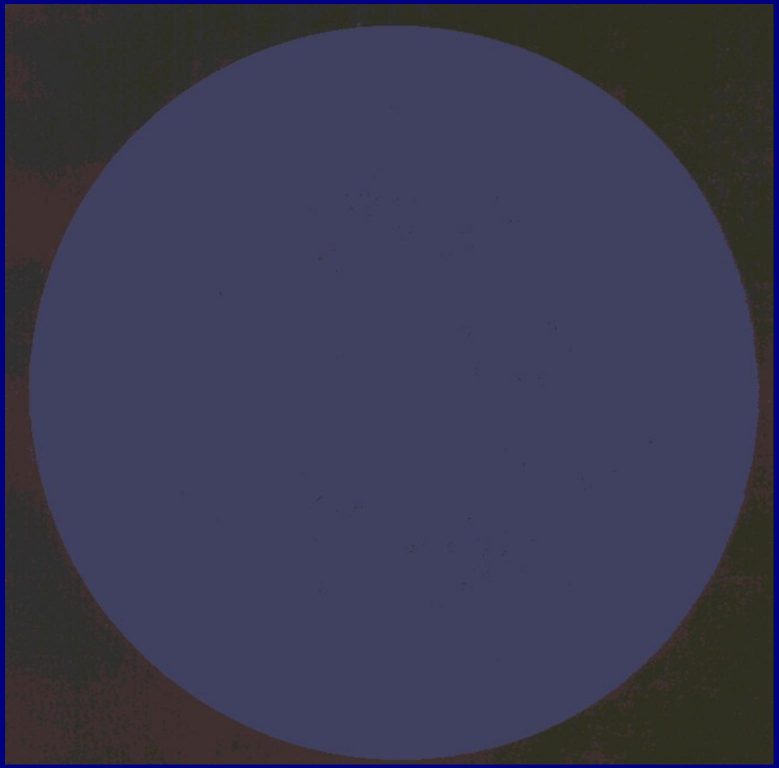
Why isolated galaxies are useful

- The purpose of scientific theories, or models, is to reduce nature complexity to the human mind level
- "Understanding" a natural phenomenon consists in being able to describe it with economical terms (Mach)
- Truly isolated galaxies may remain an asymptotic ideal state, but such an idealization is useful for separating what is intrinsic and extrinsic

FAQ

- Are mergers the main cause of
  - bars,
  - spirals,
  - warps,
  - asymmetries?
- Are spiral arms long-lived ?
- Are E's the best example of collisionless conservative system ?
- Can magnetic fields explain flat rotation curves ?
- ...

Objectives

- Re-check the principal physical ingredients in galaxies determining their global properties and evolution
- Reduction of galaxies to the simplest terms

How to order physical factors

Lagrange-Jacobi identity for physical systems

$$I = \sum_{i=1}^{N} m_i \vec{x}_i^2$$

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2\underbrace{E_{\text{kin}}}_{\geq 0} + \underbrace{E_{\text{grav}}}_{\leq 0} + 3\underbrace{\bar{P}V}_{\geq 0} \underbrace{-3P_{\text{ext}}V}_{\leq 0} + \underbrace{E_{\text{mag}}}_{\geq 0} + \ldots$$

- An equilibrium state is achieved when interacting energies are in balance
- The magnitudes of interacting energies allow to rank their importance
- Energy imbalances cause structural changes over typical time-scales

Example: Gas in a box

Without self-gravity and internal bulk motion, gas needs a confining pressure

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 3\underbrace{\bar{P}V}_{\geq 0}\underbrace{-3P_{\text{ext}}V}_{\leq 0}$$

- Equilibrium needs pressure equalization

Milky Way specific energies

$$e_{\mathrm{BH}} \approx 280 \frac{\mathrm{MeV}}{m_p}$$

$$e_{\mathrm{nuclear}} \approx 0.5 \frac{\mathrm{MeV}}{m_p}$$

Locked energies over dynamical time-scale

$$e_{\mathrm{rot}} \approx 210 \left(\frac{v_{\mathrm{rot}}}{200\,\mathrm{km}/s} \right)^2 \frac{\mathrm{eV}}{m_p}$$

Dominant interacting energy over dynamical time-scale

$$e_{\mathrm{star\,dis}} \approx 4.7 \left(\frac{\sigma}{30\,\mathrm{km}/s} \right)^2 \frac{\mathrm{eV}}{m_p}$$

$$e_{\mathrm{ISM}} \approx e_{\mathrm{mag}} \approx 0.52 \left(\frac{\sigma_{\mathrm{HI}}}{10\,\mathrm{km}/s} \right)^2 \frac{\mathrm{eV}}{m_p}$$

Magnetic energy is too small and of wrong sign to cause large rotation speeds

Some binding energies in the MW

$$|U_{\mathrm{GCBH}}| \approx 0.3\times 3\cdot 10^{6} M_{\mathrm{sun}} c^{2} = 1.6\cdot 10^{60}\,\mathrm{erg}$$

$$|U_{\mathrm{MW}}| \approx 2\cdot 10^{12} M_{\mathrm{sun}} v_{\mathrm{rot}}^{2} = 1.6\cdot 10^{60}\,\mathrm{erg}$$

$$|U_{\mathrm{pulsar}}| \approx 2\cdot 10^{8}\cdot 0.1\cdot 3\, M_{\mathrm{sun}} c^{2} = 1.1\cdot 10^{60}\,\mathrm{erg}$$

$$|U_{\mathrm{star}}| \approx 10^{11} \frac{G M_{\mathrm{sun}}^{2}}{R_{\mathrm{sun}}} = 3.8\cdot 10^{59}\,\mathrm{erg}$$

Interestingly these binding energies are similar

$$|E_{\mathrm{mag}}| \ll \frac{(100\,\mu\mathrm{G})^{2}}{8\pi}\pi(20\,\mathrm{kpc})^{2}(600\,\mathrm{pc}) \approx 10^{58}\,\mathrm{erg}$$

Magnetic energy is insufficient to play any global role

Isolated galaxy to 1st order

Since gravitational and kinetic energies dominate all the other forms of interacting energies

$$\frac{1}{2}\frac{d^2 I}{dt^2} \approx 2\underbrace{E_{\mathrm{kin}}}_{\geq 0}+\underbrace{E_{\mathrm{grav}}}_{\leq 0} = \underbrace{E_{\mathrm{kin}}}_{\geq 0}+\underbrace{E_{\mathrm{tot}}}_{\leq 0}$$

Characteristic time of system size change

$$\frac{1}{\tau^2} \approx \left|\frac{1}{\tau^2_{\mathrm{cross}}} - \frac{1}{\tau^2_{\mathrm{freefall}}}\right|$$

How to order evolution factors

The time-derivative of Lagrange-Jacobi identity indicates that quasi-equilibrium is maintained when interacting powers are in balance

$$\frac{d^2 I}{dt^2}(t+\delta t) = \underbrace{\frac{d^2 I}{dt^2}(t)}_{=0} + \delta t \frac{d^3 I}{dt^3}(t) + \ldots$$

$$= 2\delta t \frac{d}{dt}\left(2E_{\mathrm{kin}} + E_{\mathrm{grav}} + 3\bar{P}V - 3P_{\mathrm{ext}}V + E_{\mathrm{mag}} + \ldots\right) + \ldots$$

Milky Way powers

$$L_{\mathrm{star}} \approx 10^{11} L_{\mathrm{sun}} = 4 \cdot 10^{44} \,\mathrm{erg}/s$$

$$L_{\mathrm{dust}} \approx 0.3 \, L_{\mathrm{star}} = 1.2 \cdot 10^{44} \,\mathrm{erg}/s$$

$$L_{\mathrm{SN}\,\nu} \approx \frac{10^{53}\,\mathrm{erg}/s}{50\ \mathrm{yr}} = 6.3 \cdot 10^{43} \,\mathrm{erg}/s$$

$$L_{\mathrm{dyn\,max}} \approx \frac{v_{\mathrm{rot}}^{5}}{2G} = 2.4 \cdot 10^{43} \,\mathrm{erg}/s$$

$$L_{\mathrm{SN\,mech}} \approx \frac{10^{52}\,\mathrm{erg}/s}{50\ \mathrm{yr}} = 6.3 \cdot 10^{42} \,\mathrm{erg}/s$$

$$L_{\mathrm{SN\,light}} \approx \frac{10^{51}\,\mathrm{erg}/s}{50\ \mathrm{yr}} = 6.3 \cdot 10^{41} \,\mathrm{erg}/s$$

$$L_{\mathrm{infall}} \approx 1 \, M_{\mathrm{sun}}/\mathrm{yr}\, v_{\mathrm{rot}}^{2} = 2.5 \cdot 10^{40} \,\mathrm{erg}/s$$

The thermalization of light by dust may contribute to impact the disk comparably to SNe if only a few % is converted into mechanical energy.

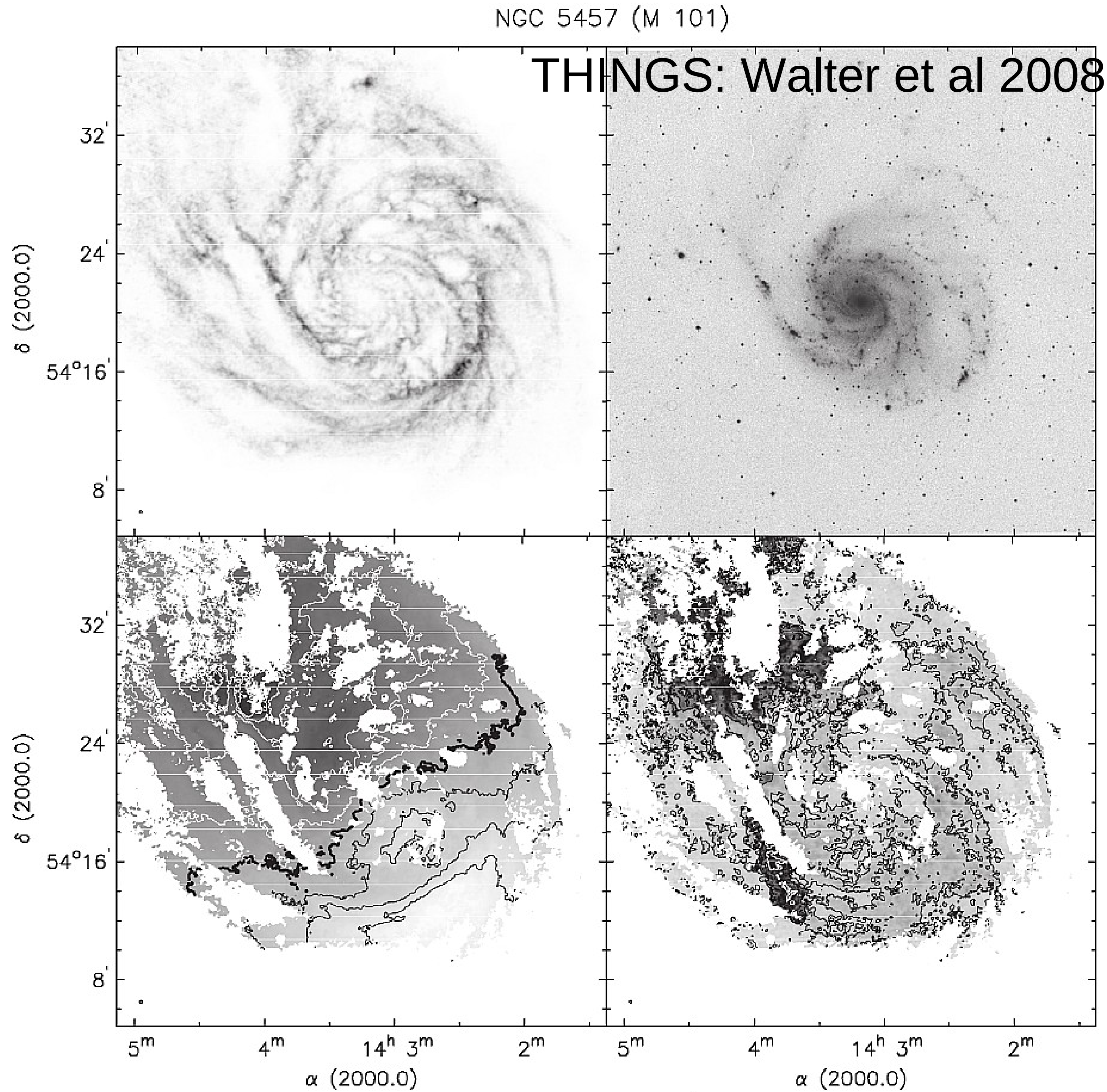


Figure 63. NGC 5457. Top left: integrated H I map (moment 0). Grayscale range from 0–510 Jy km s^{-1}. Top right: optical image from the digitized sky survey (DSS). Bottom left: velocity field (moment 1). Black contours (lighter grayscale) indicate approaching emission, white contours (darker grayscale) receding emission. The thick black contour is the systemic velocity ($v_{sys} = 226.4$ km s^{-1}), the iso-velocity contours are spaced bys $\Delta v = 25$ km s^{-1}. Bottom right: velocity dispersion map (moment 2). Contours are plotted at 5, 10, and 20 km s^{-1}.

Dynamics-dissipation feed-backs in disks

- Energy dissipation is essential for galaxy formation, dissipation cools disks until they reach the Safronov-Toomre threshold $Q = 1$
- Fierce dynamical reaction (spirals) heats the disk
- Result: disks stays marginally stable as long as dissipation acts
- Dissipation agents:
  - gas radiative cooling, coupled to dynamics via:
    - injection of kinematically cold stars by star formation
    - removal of kinematically hot stars by AGB mass loss

Dynamics-dissipation feed-backs

- This explains why disk galaxies have often spirals
- The main cause of spirals is not the disk perturber, but the intrinsic physics that makes the disk sensitive and strongly responsive.

Dynamics-dissipation feed-backs

- If dissipation cools in the disk plane, it should cool also random transverse motions:
  - The disk should become thin
  - The disk should become unstable according to the Araki's (1985) criterion $\sigma_z/\sigma_R > 0.3$

=> prediction :

- Warps can be produced as naturally as spirals for the same reason: strong dynamical response to dissipation-induced instability (Revaz & P 04)

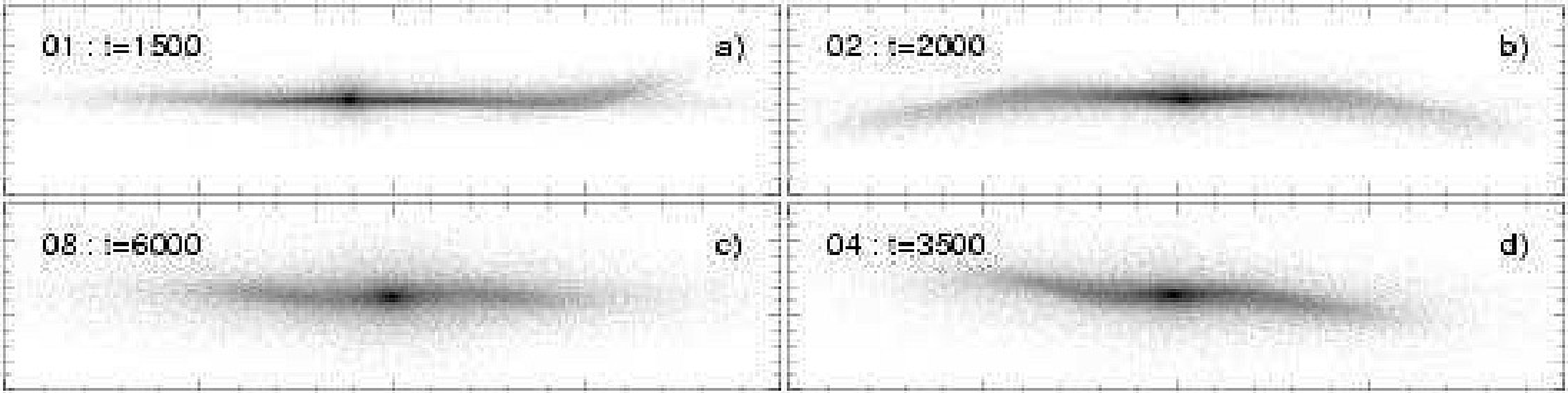
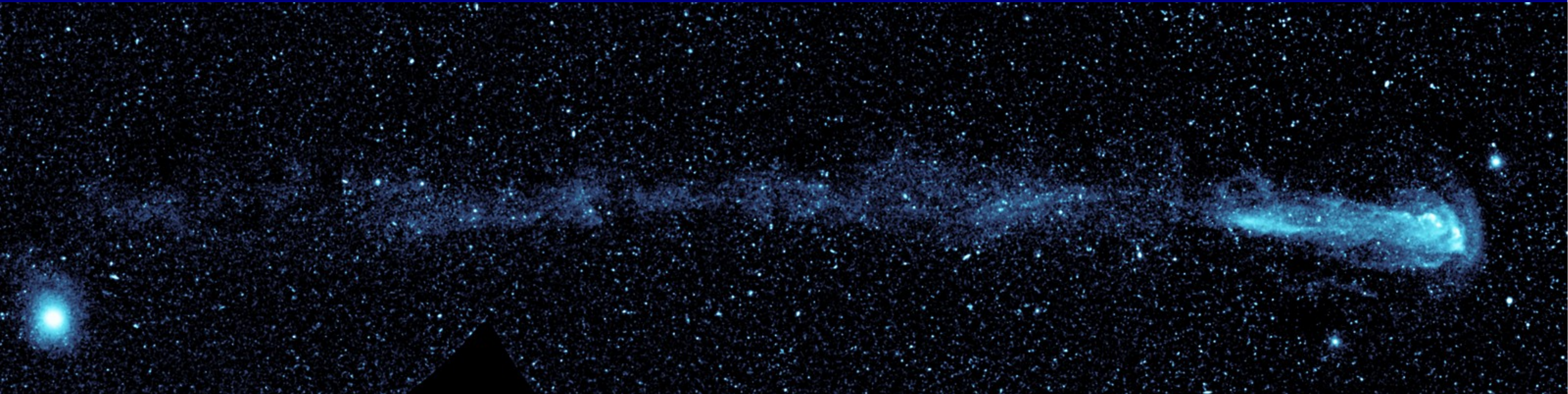


Fig. 4. Edge-on projections of the models 01, 02, 08, and 04. Times are indicated at the upper left. The box dimensions are 100 × 25 kpc2

- Like for spirals this marginal state explains why disk galaxies have often warps
- The main cause of warps is not the disk perturber, but the intrinsic physics that makes the disk strongly responsive.

Secular evolution of isolated ellipticals

- Most star evolve and terminate their life in the AGB and PN phases by ejecting their mass > 0.6 $M_{\odot}$
- Over several Gyr over 20 % of the initial stellar mass is returned into the ISM
- This process must occur in ellipticals as well
- Consequences for the whole E galaxy ?



Secular evolution of isolated ellipticals

- The ejected gas should deposit its kinetic energy $0.5\ M\ v^2$ in the ISM, but at least serves as receiver of the SNe mechanical energy
- When the cooling time of the hot gas in longer than the dynamical time, the global dynamical response to this added energy is to expand the galaxy and to cool the overall velocity dispersion

=> This suggests that E's might reach a critical state where the gas cooling time is comparable to the dynamical time

Conclusions

- The interplay between dynamics, dissipation and star formation and evolution is essential for understanding galaxies of all types, including E's
- Both spirals and warps can be seen as following the same intrinsic mechanism induced by the dynamics-dissipation coupling
- The energy exchanges in spirals is particularly effective because of their a marginal state of equilibrium
- Overall the collisionless conservative description is still valid over ~ 1Gyr, but not secularly

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