X-ray haloes and galaxy structure

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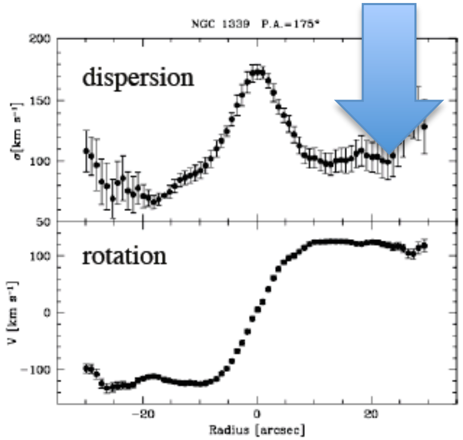
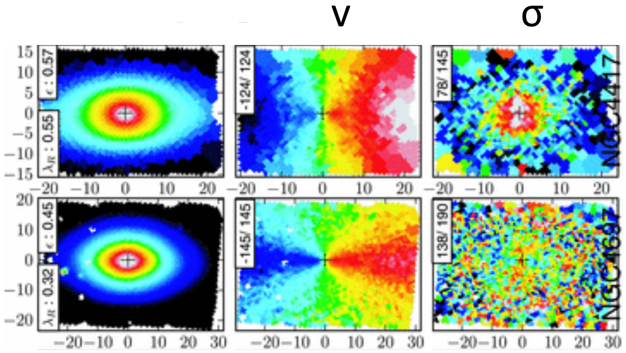
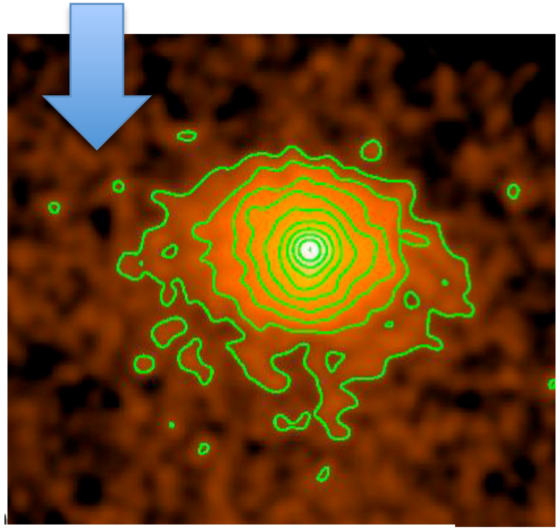
Effects of galaxy **shape** and internal **stellar kinematics** on the hot gas haloes (**L_X, T_X**) of **early-type** galaxies (ETGs)



kinematics along major axis

2D spectroscopy:





NGC1404: *Chandra* image

OUTLINE

1) observational motivations

2) expectations for L_X and T_X from purely energetic arguments

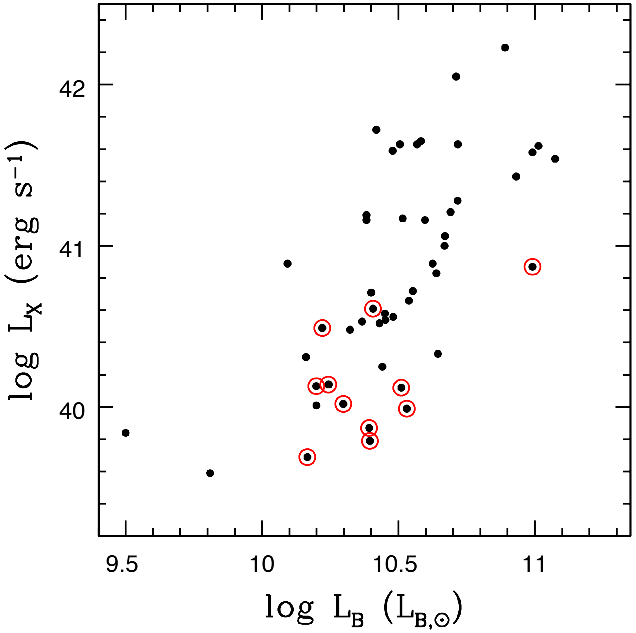
3) 2D **hydrodynamical simulations** for **realistic galaxy models**

4) results of simulations vs. observations

1) observational motivations

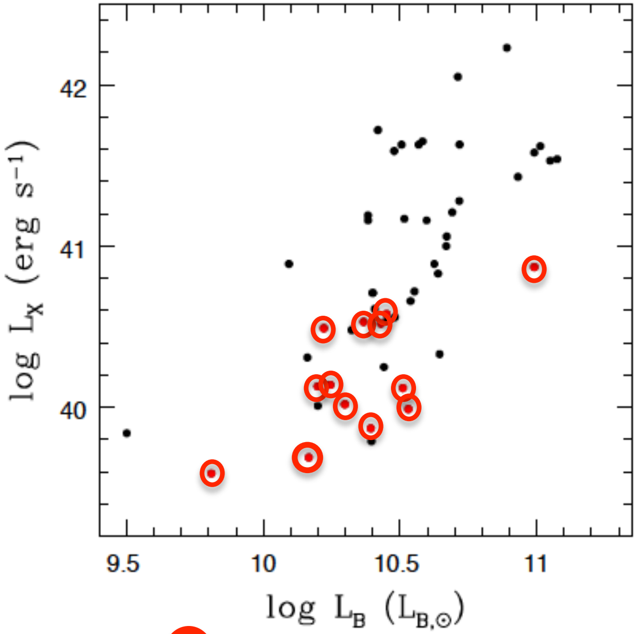
Observed relations with L_X

shape



● = high **flattening** (ε=1-b/a > 0.4)

internal stellar **kinematics**



● = $v_{rot}/\sigma_c > 0.5$

Pellegrini et al. 1997,
Pellegrini 2012

see also: Eskridge et al. 1995 for results from *Einstein*

see also Li et al. 2011 for a *Chandra* sample of S0 galaxies

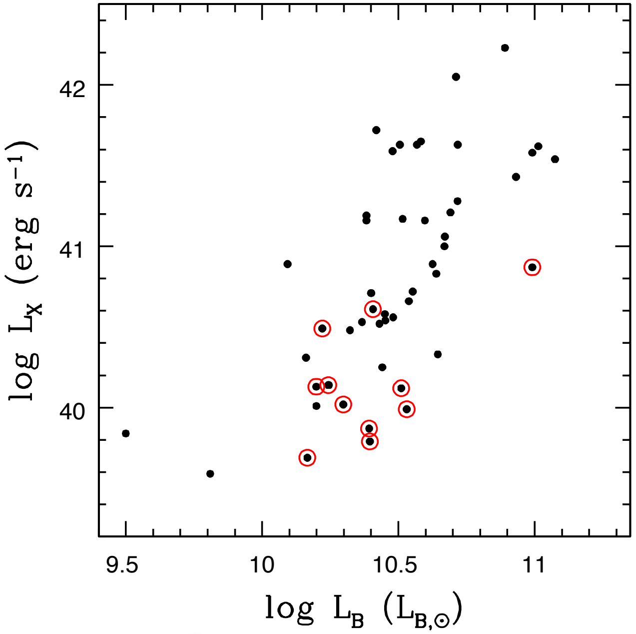
the hot gas content depends on the **shape** (ε) of the potential well and on the stellar **rotational support**

Which of the two exerts an influence on the hot gas?

How can shape and/or rotation affect L_X ?

Observed relations with L_X

shape



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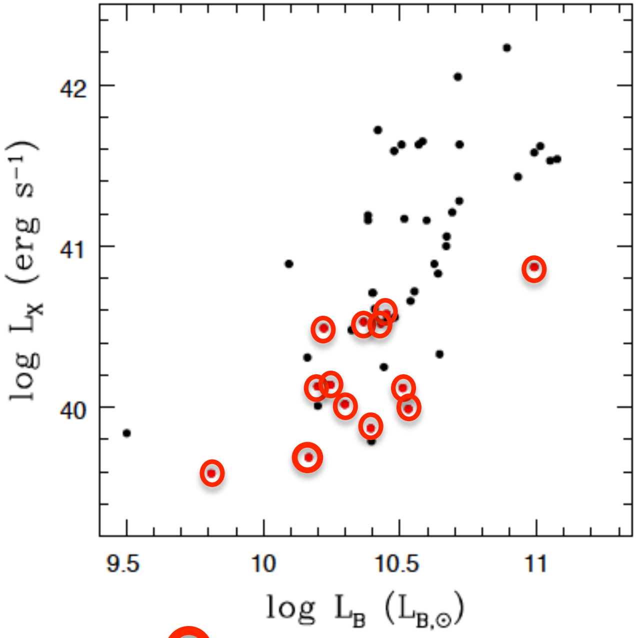
internal stellar **kinematics**

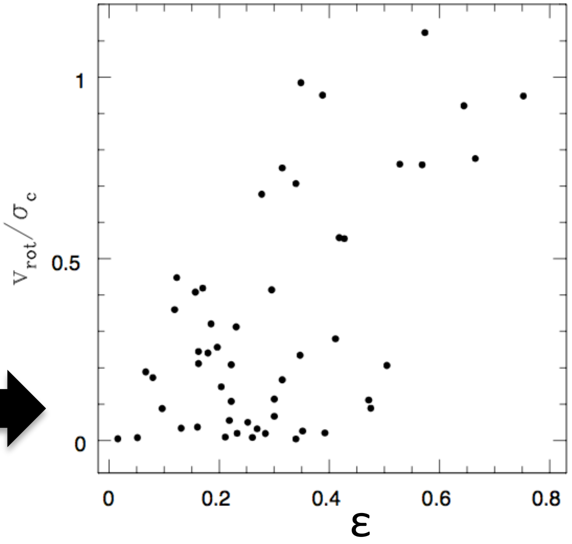


◉ = $v_{rot}/\sigma_c > 0.5$

Pellegrini et al. 1997,
Pellegrini 2012

➔difficult to **disentangle observationally purely rotational** from **purely flattening** effects

flatter systems possess, on average, ***higher rotation*** levels, and rotation can be found only in flat ETGs



MGE reconstruction of images

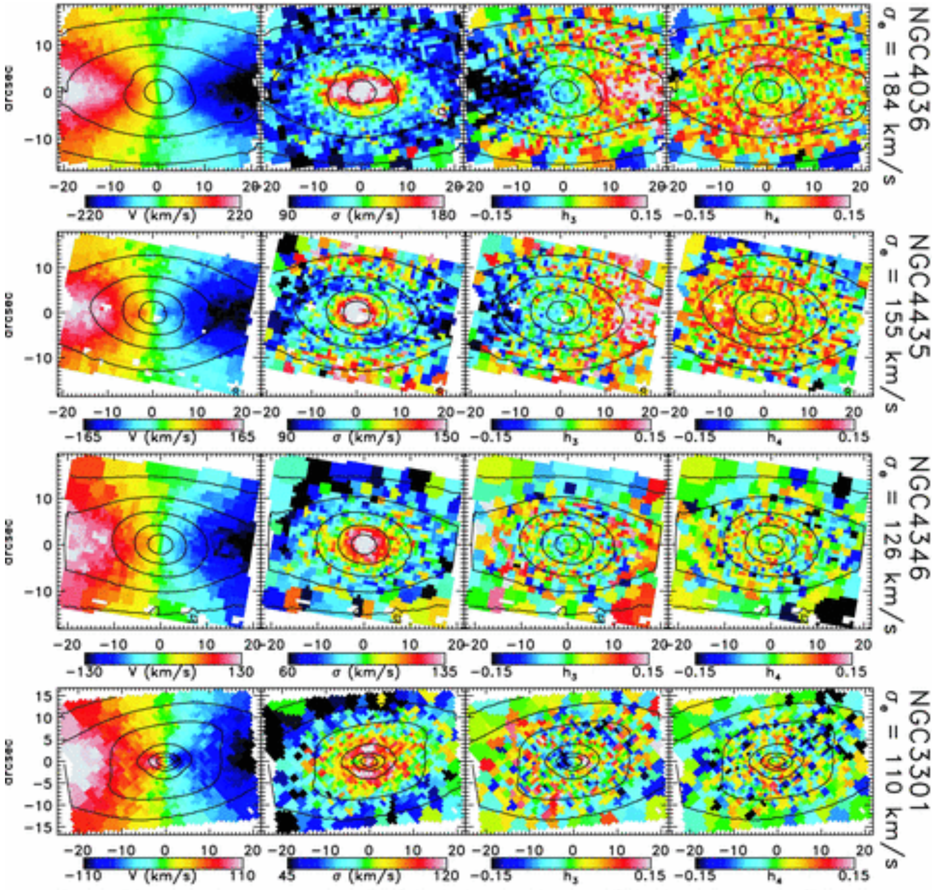
Cappellari et al. 2011

new optical data for shape and kinematics:

Atlas^{3D} project: volume-limited sample of 260 early-type galaxies (ETGs) :

D < 42 Mpc, morphologically selected
brighter than $M_K < -21.5$ mag
(stellar mass $M_\star \gtrsim 6 \times 10^9$ M$_\odot$)

Integral field spectroscopy
extraction of 2D stellar kinematics



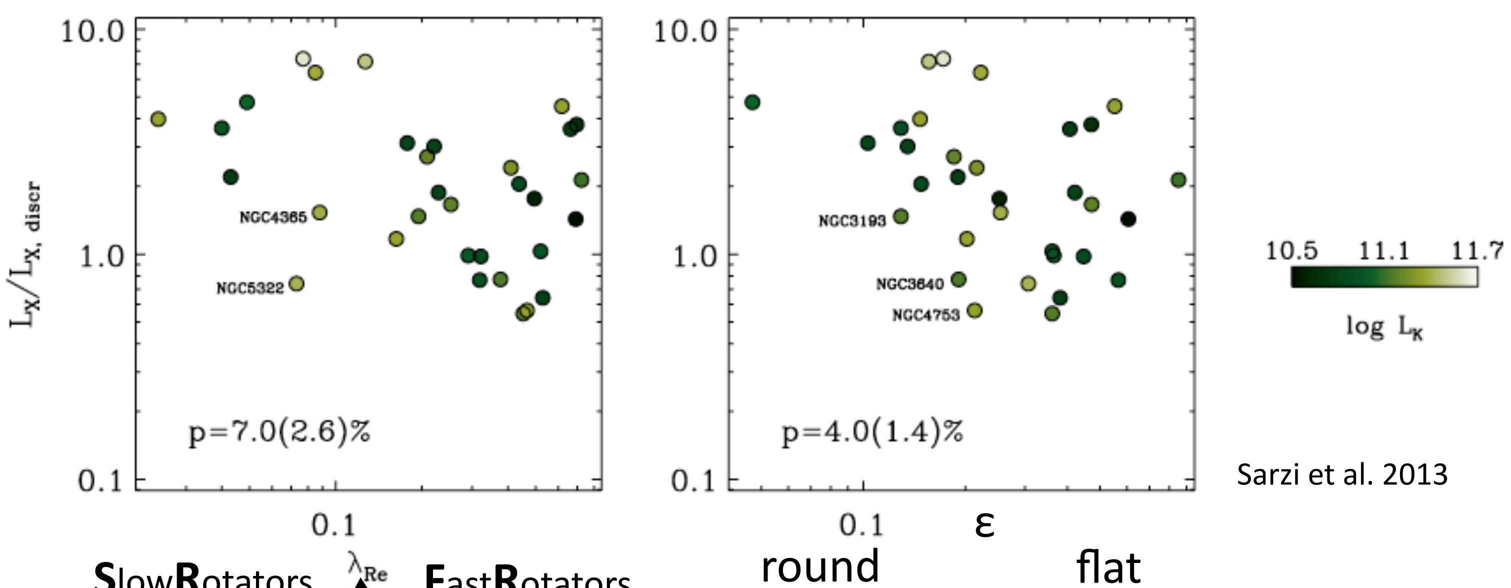
Emsellem et al. 2011

L_X and rotational properties/shape for the ETGs of the ATLAS^{3D} sample

(see also Dong-Woo's talk)

slowly rotating (SR) and **round** ETGs ➔ **larger L_X** on average than **flatter** and **fast-rotating** (FR) ones

total L_X (*ROSAT* and *Chandra*)



Slow**R**otators

Fast**R**otators

specific angular momentum

round

flat

apparent flattening

Sarzi et al. 2013

$L_{X,\,discr}$ = X-ray luminosity of the expected contribution from discrete sources only (X-ray binaries) α L_K

2) expectations for L_X and T_X from purely energetic arguments

Origin of the hot ISM: continuous mass loss from evolving stars (Red Giants, AGB, PNe, …)

The **rate of mass loss** :

$$\dot{M}_*(t) \sim 10^{-11}\, L_B(L_{B\odot})\, t(12\ \mathrm{Gyrs})^{-1.3} \qquad M_\odot/\mathrm{yr}$$

for a passively evolving stellar population, of age ~1 to over 10 Gyrs (~insensitive to the slope of the IMF).

Present rate ~0.1 - 1 $M_\odot$/yr .

Heating of the stellar mass losses:

$\dot{M}_*$ is **heated** to X-ray temperatures by thermalization of the kinetic energy

- ✓ of the stellar motions
- ✓ of the SNIa's ejecta

(Sarazin & White 87, 88; Loewenstein & Mathews 91; Ciotti et al. 91, David et al. 91, Parriott & Bregman 2011)

NOTE: the stellar **random** kinetic energy is *always* supplied to the ISM

the thermalization of the **ordered** kinetic energy depends on the **relative motion** between stars and ISM

(Pellegrini 2011, Posacki et al. 2013)

$$T_\sigma = \frac{\mu m_\mathrm{P}}{3 k_\mathrm{B} M_*} \int \rho_* \mathrm{Tr}(\boldsymbol{\sigma}^2)\mathrm{d}^3\mathbf{x}$$

$\boldsymbol{\sigma}^2$ velocity dispersion tensor

mass-weighted temperature for injected gas from thermalization of stellar **random** motions

$$T_\mathrm{rot} = \frac{\mu m_\mathrm{P}}{3 k_\mathrm{B} M_*} \int \rho_* \|\mathbf{u}_\mathrm{ISM} - \mathbf{v}\|^2 \mathrm{d}^3\mathbf{x}$$

v =stellar streaming velocity

$\mathbf{u}_\mathrm{ISM}$= gas velocity

mass-weighted temperature from thermalization of stellar **ordered** motions

- ✓ **Thermalization** of the **ordered** stellar motions: is it high or low?

  unknown “a priori”, it depends on kinematical properties of both stars and ISM

- ✓ **Binding energy** of the ISM:

  in **rotating** ETGs, is the ISM rotating as well? If so, it is *less bound* ➔more prone to an outflow?

  in **flat** ETGs, is the ISM binding energy *lower* than in spherical ETGs **of same L_B**?

  does this decrease make the hot halo more prone to an outflow?

➔ **realistic, state-of-the-art galaxy models**
+ hydrodynamical simulations

Posacki et al. 2013
Negri et al. 2014, MNRAS 439, 823
Negri et al. 2014, MNRAS submitted (eprint arXiv:1406.0008)

3) results from 2D hydrodynamical simulations for realistic galaxy models

hot gas flows behavior for a **large set** of state-of-the art galaxy models:

vary

- ✓ stellar mass (**M_***, L_B)
- ✓ intrinsic flattening (**ε**)
- ✓ internal kinematics (**galaxy flattening supported by ordered rotation or by tangential anisotropy**)
- ✓ distribution of dark matter

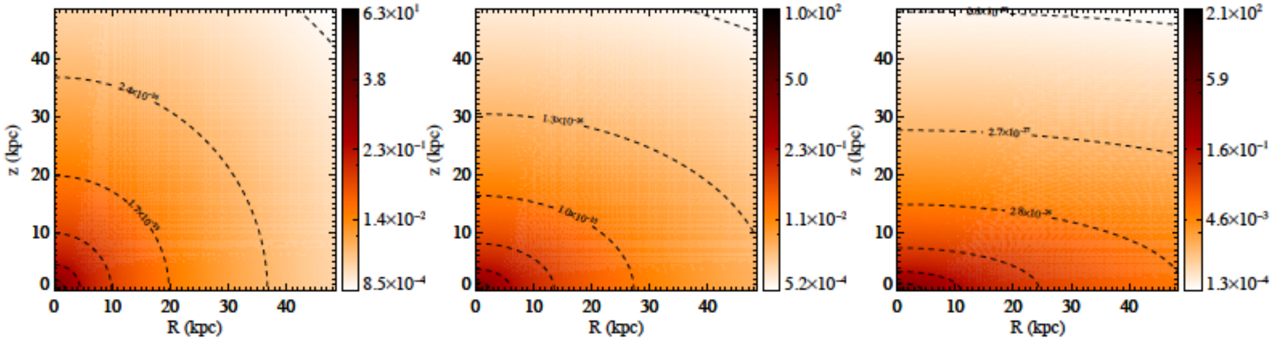
The galaxy structure. 1

Axisymmetric (oblate) stellar distribution + **spherical** NFW or Einasto dark matter halo

de Vaucouleurs (1948) law, generalized for **ellipsoidal** axisymmetric distributions:

$$\rho_*(R,z) = \rho_0 \xi^{-0.855} \exp(-\xi^{1/4}), \qquad \xi = b^4 \sqrt{R^2 + (z/q)^2}/R_e$$

Stellar projected density for $q = 1, 0.6, 0.3$ corresponding to **E0**, **E4**, **E7**



Flattening procedure (*at fixed L_B*):
a spherical E0 "progenitor" model ➔ **2 flat descendants**, for each fixed shape (***q***):
one "FO-built" – same R_e when viewed FACE-on ➔ *more concentrated* (gas more bound)
one "EO-built" – same (circularized) R_e when viewed EDGE-on ➔ *less concentrated* (gas less bound)

Stellar & dark halo parameters:

(L_B, R_e, σ_e) lie on the **Faber-Jackson** and **size–luminosity** relations for 10^5 ETGs in the SDSS (Desroches et al. 2007)

stellar mass-to-light ratios for a 12 Gyr old stellar population with a Kroupa initial mass function (Maraston 2005)

$M_h(<R_e)/M_{tot}(<R_e) <1$ as from stellar dynamics and gravitational lensing studies (e.g., Cappellari et al. 2006, Gerhard et al. 2001, Treu & Koopmans 2004)

The galaxy structure. 2

Gravitational force and velocity fields from solving the **Poisson** and the **Jeans equations** with a code built on purpose:

$$\frac{\partial \rho_\star \sigma^2}{\partial z} = -\rho_\star \frac{\partial \Phi_{tot}}{\partial z},$$

$$\frac{\partial \rho_\star \sigma^2}{\partial R} + \rho_\star \frac{\sigma^2 - \overline{v_\varphi^2}}{R} = -\rho_\star \frac{\partial \Phi_{tot}}{\partial R}$$

Stellar motions in the azimuthal direction are split into velocity dispersion and ordered rotation via the Satoh (1980) decomposition: $\overline{v_\varphi} = k\sqrt{\overline{v_\varphi^2} - \sigma^2}$ that gives:

$$\sigma_\varphi^2 \equiv \overline{v_\varphi^2} - \overline{v_\varphi}^2 = k^2\sigma^2 + (1-k^2)\overline{v_\varphi^2}$$

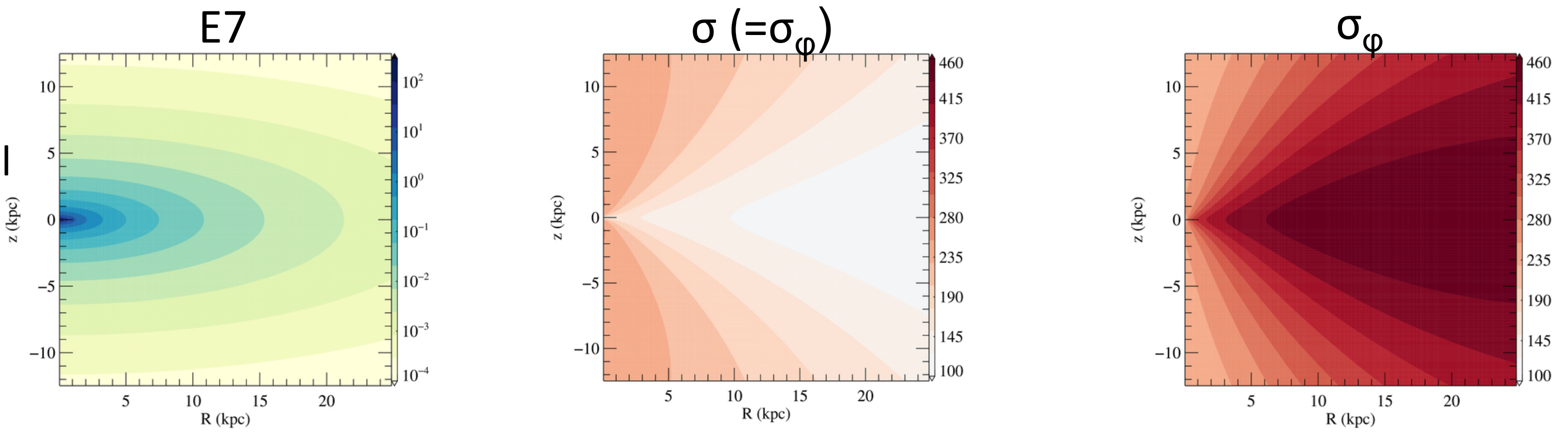
2 CLASSES
OF
MODELS

➔

VD models: k = 0, **no ordered velocity** (shape due to σ_φ)

IS (isotropic rotator) models: k = 1 (**shape wholly explained by rotation**)

Meridional sections


E7

σ (=σ$_\varphi$)

σ$_\varphi$

stellar density

IS

VD

The hydrodynamical equations

(with sources of mass, energy, momentum)

velocity of bulk flow

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\boldsymbol{u}) = \dot\rho_{\rm SN} + \dot\rho_* \equiv \dot\rho,$$

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho\,(\boldsymbol{u}\cdot\nabla)\,\boldsymbol{u} = -\nabla p - \rho\nabla\Phi_{\rm tot} + \dot\rho\,(\boldsymbol{v}-\boldsymbol{u}),$$

$$\frac{\partial E}{\partial t} + \nabla\cdot(E\boldsymbol{u}) = -p\nabla\cdot\boldsymbol{u} - \mathscr{L} + \dot\rho_{\rm SN}\frac{u_s^2}{2} + \frac{\dot\rho}{2}\left[||\boldsymbol{v}-\boldsymbol{u}||^2 + {\rm Tr}(\boldsymbol{\sigma}^2)\right],$$

$\boldsymbol{v} = v_\varphi \mathbf{e}_\varphi$ streaming velocity

$\boldsymbol{\sigma}^2$ velocity dispersion tensor

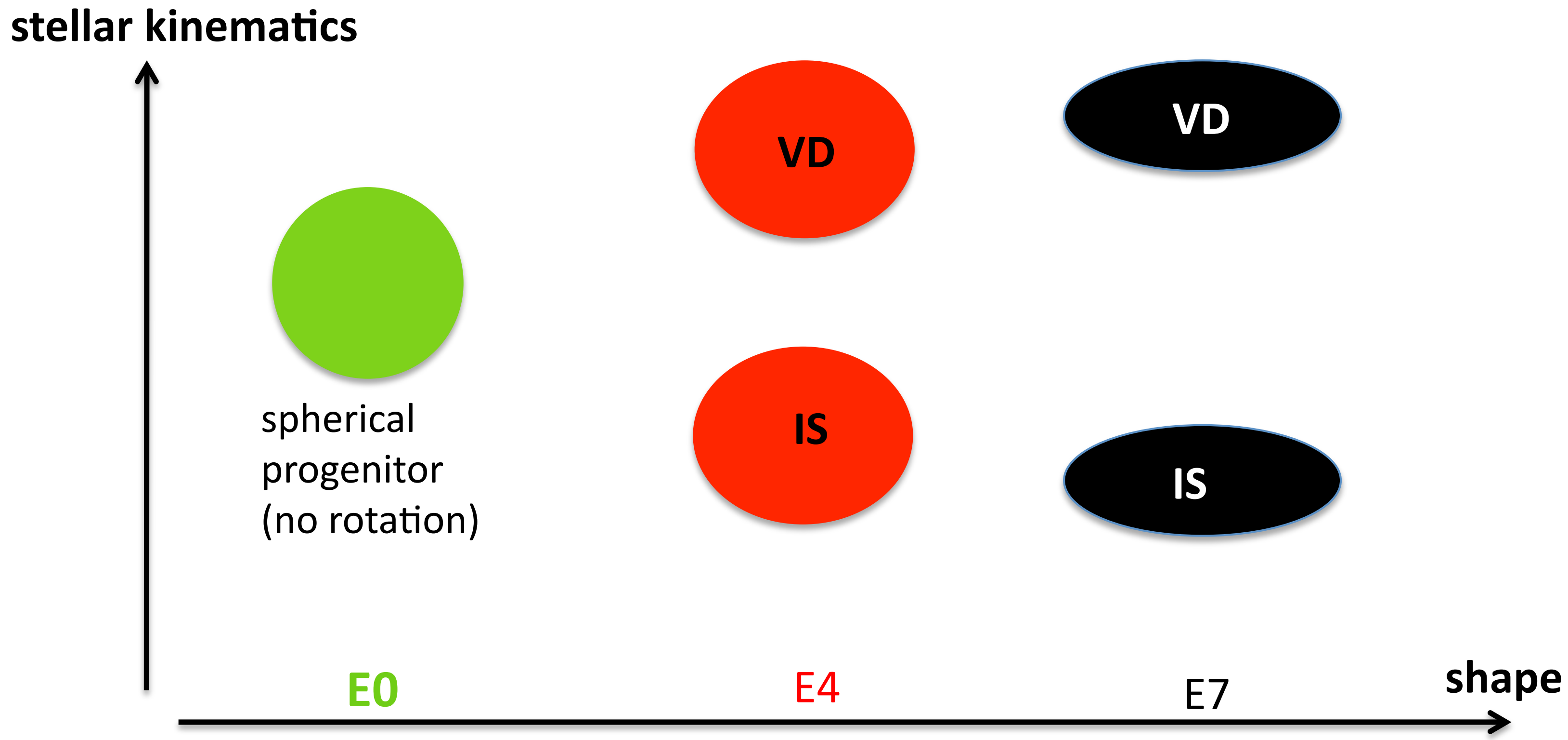
$\Big\}$ for the stars

it is also the streaming velocity of injected gas

hydro 2D code ZEUS-MP 2 in cylindrical coordinates (480x960 logarithmically spaced gridpoints)

resolution of 90 pc in the central 10 kpc
flow evolution followed for 11 Gyr

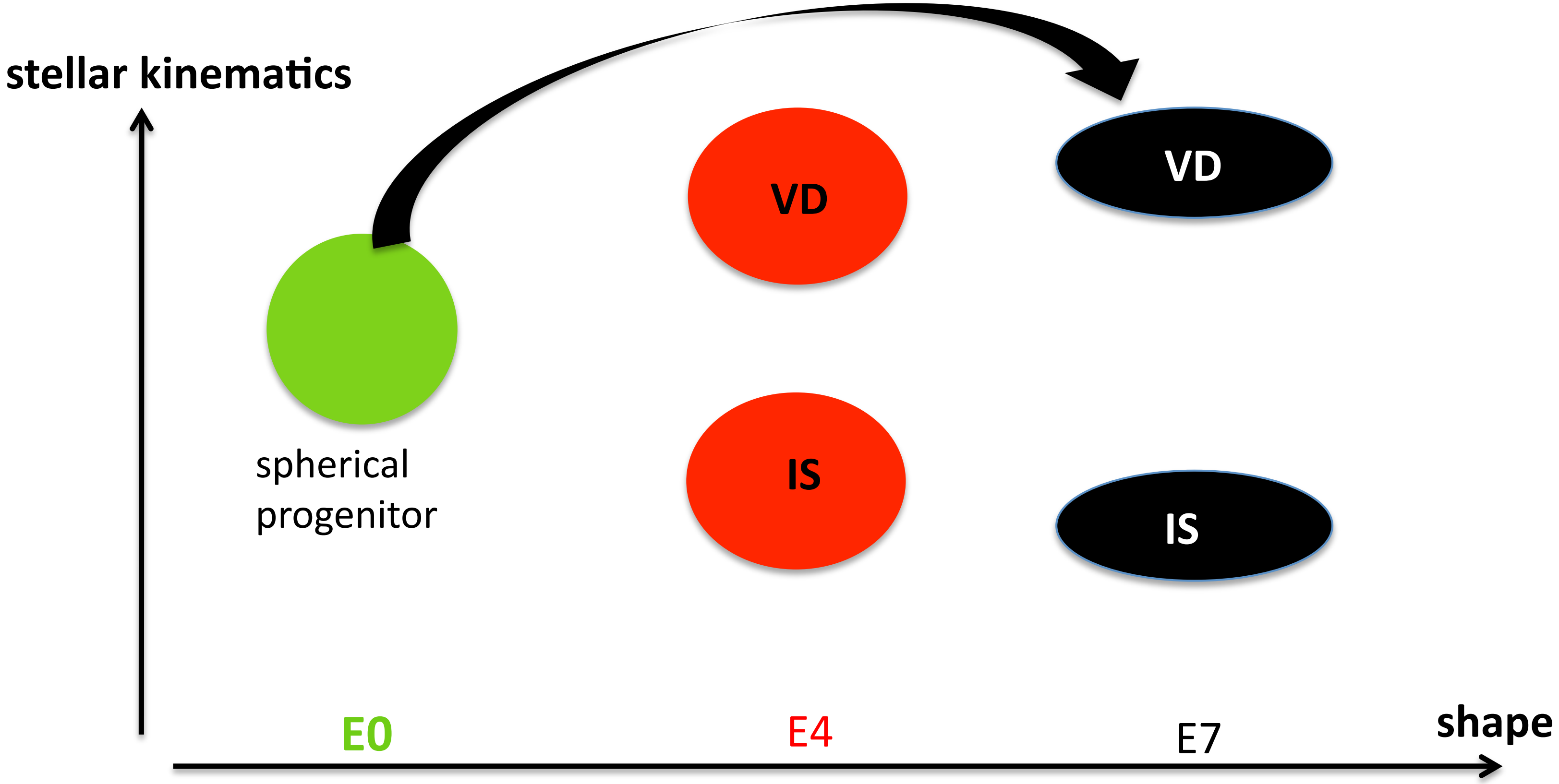
for each fixed L_B, hydro simulations explore the parameter space in two "directions":



At each L_B : 9 models = 1 progenitor + 8 descendants (4 FO-built and 4 EO-built)

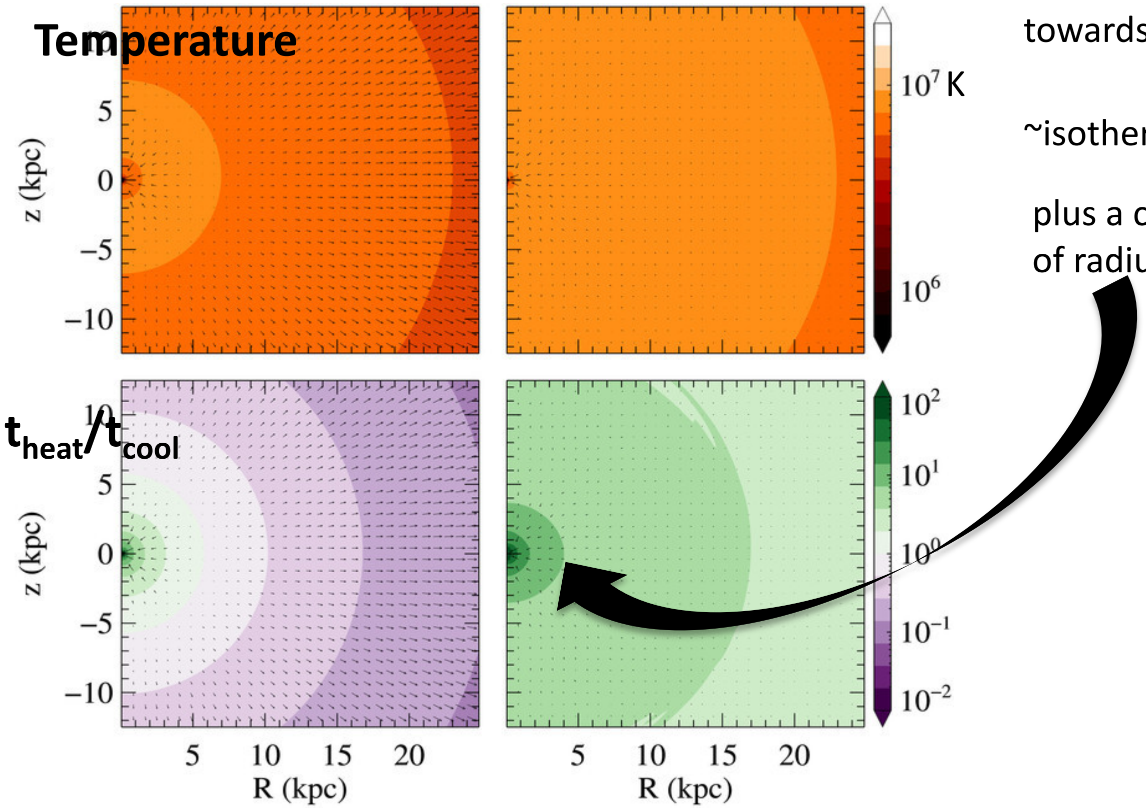
1^{st} experiment: change of *shape* in a fully VD supported model

large $L_B=6\text{x}10^{10}L_{B,\odot}$ fixed



smooth maps (meridional sections) of hydrodynamical quantities
low flow velocities + central, small cooling core

Spherical (E0)



t=2.4 Gyr t=13 Gyr

lack of centrifugal support ➔ **the ISM flows directly** towards the galactic center

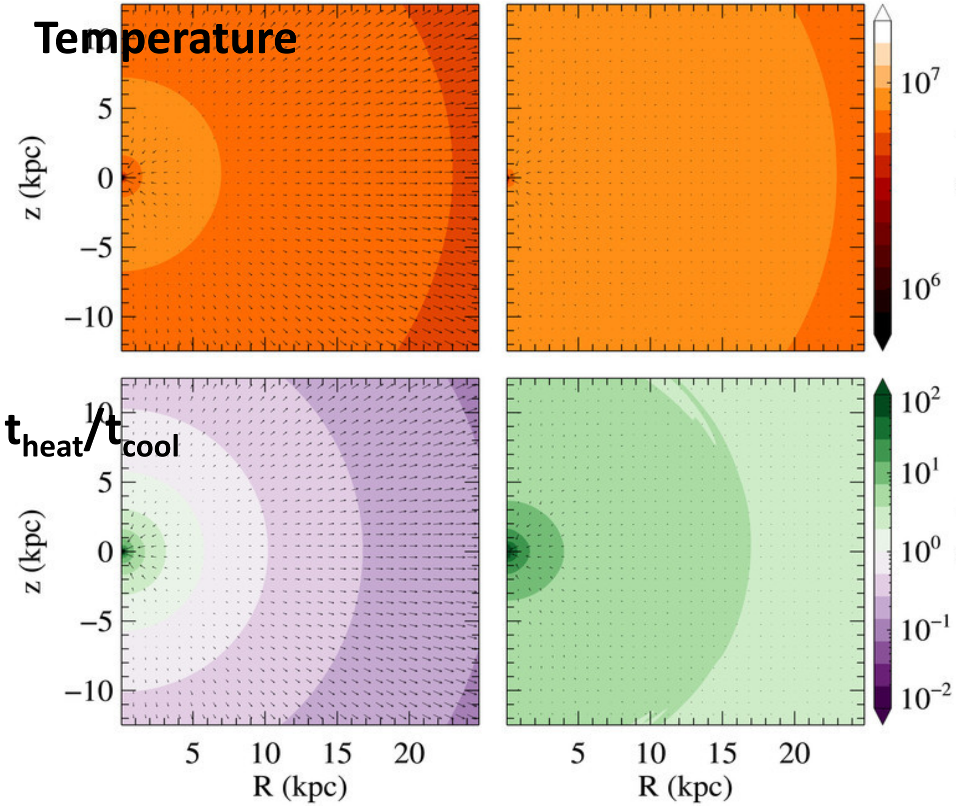
~isothermal (T ≃ 5 ×10^6 K) hot halo

plus a central cooling region
of radius ≃ 5 kpc

Green ➔ **cooling** gas
purple ➔ **heating** regions

Arrows: meridional **ISM velocity** field;
longest arrows = 127 km/s

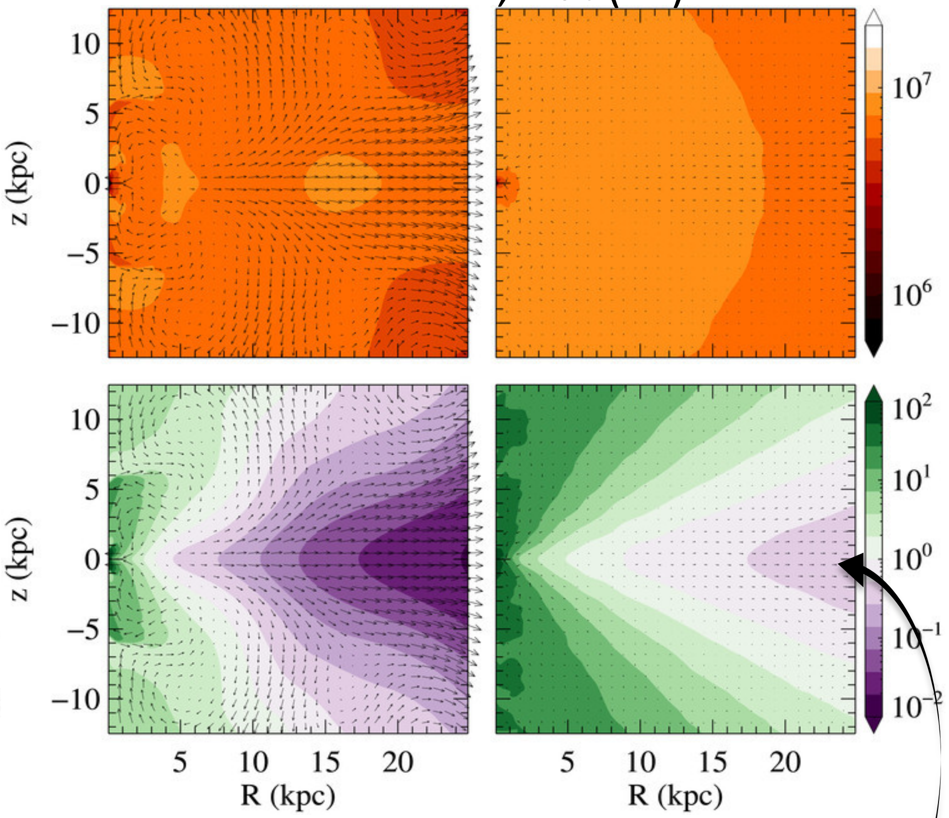
Spherical (E0)



t=2.4 Gyr

t=13 Gyr

VD, Flat (E7)



t=2.4 Gyr

t=13 Gyr

➔ concentrated heating on the equatorial plane (white and purple regions) ➔ **equatorial outflow**

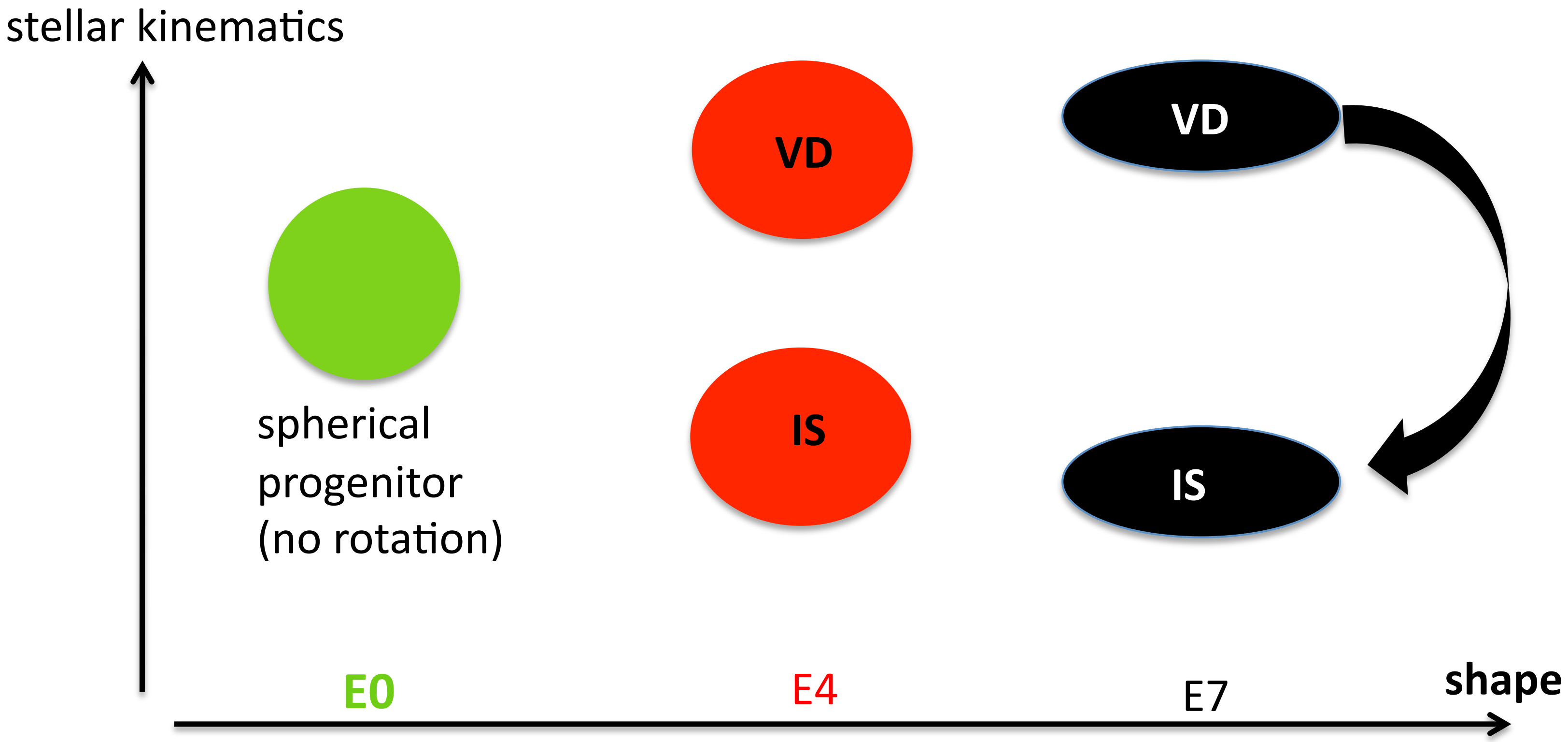
SMALL effect of flattening on :

L_X – slightly reduced (both for EO-built and FO-built cases)

T_X – variations within 10-15%

2nd experiment: change of kinematics

large $L_B=6\times10^{10}L_{B,\odot}$ fixed



stellar kinematics

VD

IS

VD

IS

spherical
progenitor
(no rotation)

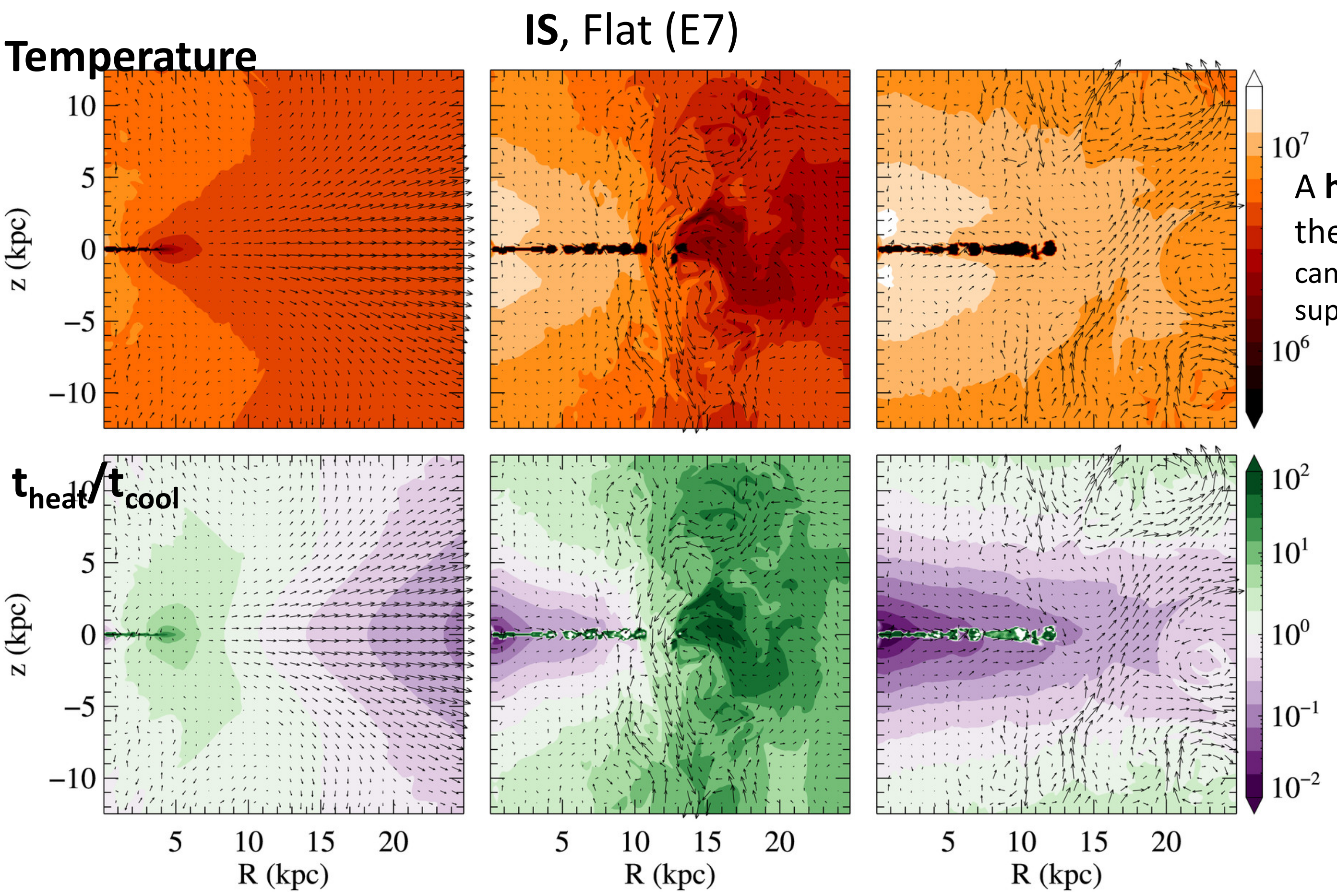
E0

E4

E7

shape

large effects: angular momentum conservation ➔ **a rotationally supported,** thin, dense **cold disc forms**
complex flow pattern (e.g., meridional motions) / instabilities



IS, Flat (E7)

Temperature

t_{heat}/t_{cool}

t = 2.4, 8.7, 13 Gyr

A **hot, rarefied** zone surrounds the cold disc:

cannot be replenished by inflowing gas, supported by angular momentum

*L_X is **reduced** in rotating models:*

- the gas cools on a disk before entering the galactic core region ➔ ΔΦ reduced;
- the center is less dense than in VD models

L_X reduction not due to the onset of galactic winds, but to **redistribution** of the gas inside the galaxy

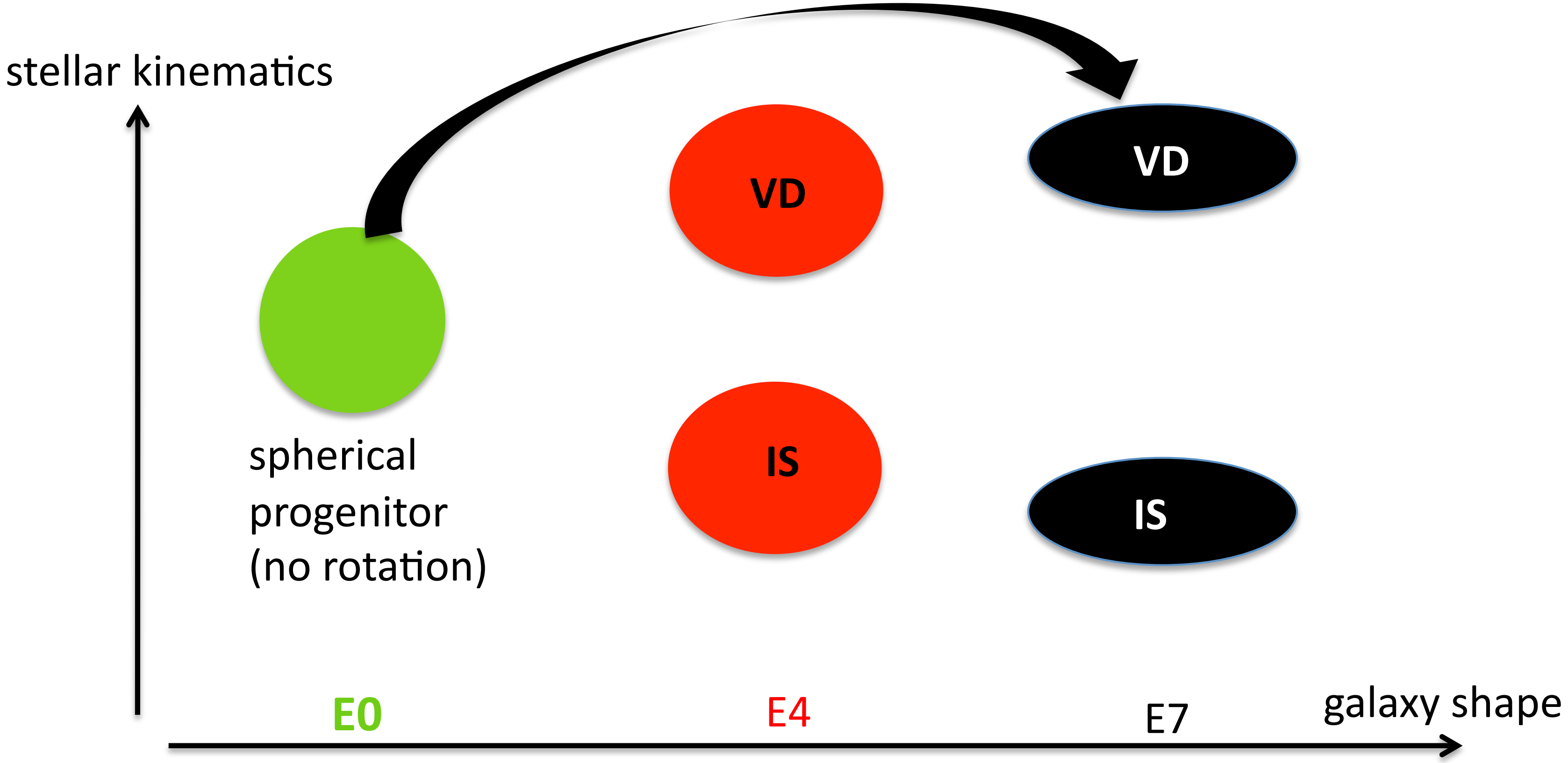
*T_X is **reduced** in rotating models:*

- thermalization of ordered stellar motion is low (the ISM tends to rotate as the stellar body)
- more important gas cooling
- lower density in central (hottest) regions

Lower mass ETGs: a change of shape or rotation can induce a *transition to a global wind*

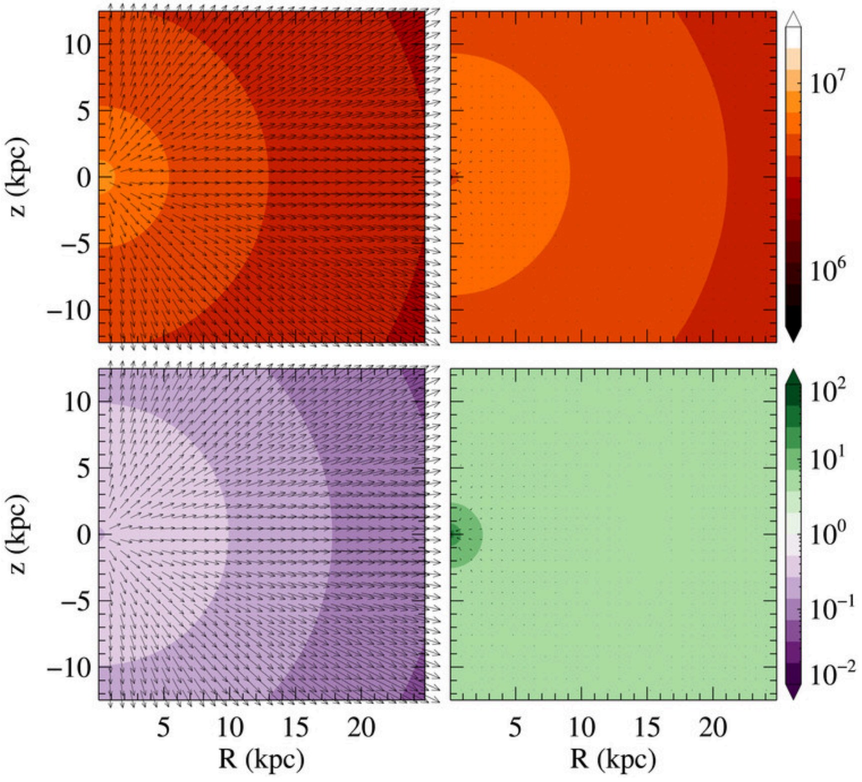
3rd experiment: change of shape

low $L_B=2.7\times10^{10}L_{B,\odot}$ fixed



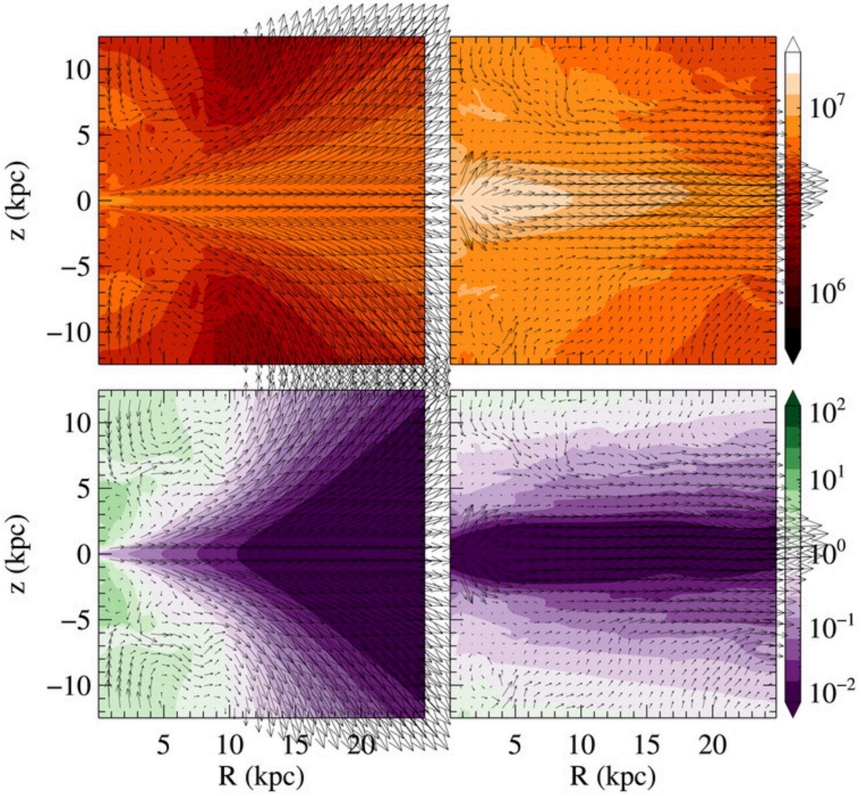
change of the flow status:

strong **equatorial degassing** at late times


Spherical (E0)

t=2.4 Gyr

t=13 Gyr


VD, Flat (E7)

t=2.4 Gyr

t=13 Gyr

L_X drops to very low values

T_X larger than expected from trend of non-wind models (reduced cooling + thermalization of meridional motions)

The effect of flattening (and rotation) is **mass-dependent**

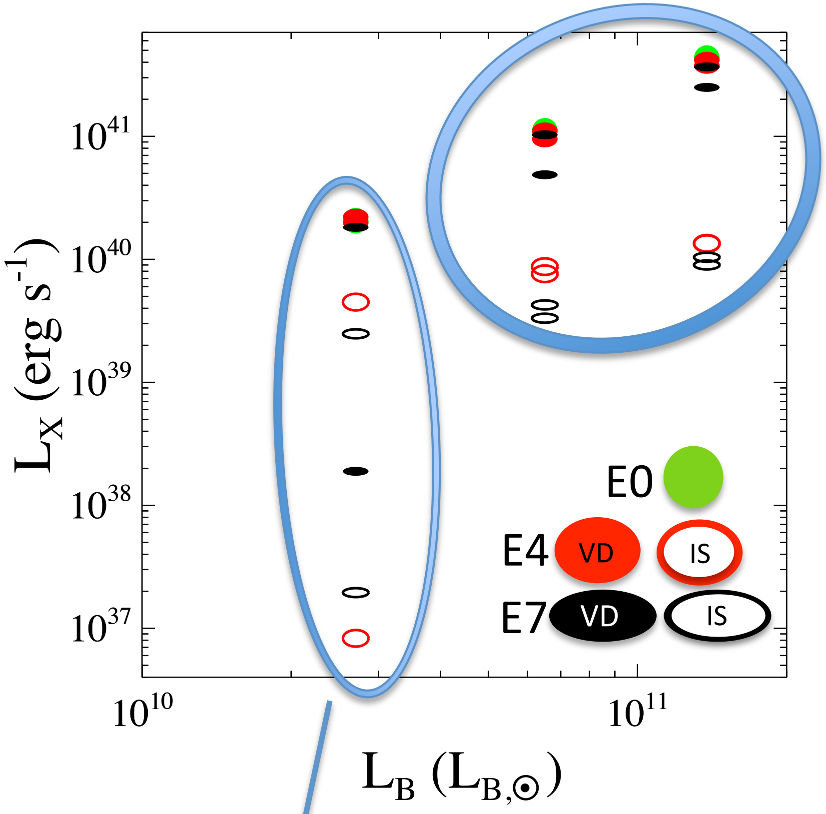
$L_X - L_B$

4) simulation results vs. observations

$T_X - \sigma$

$L_X - T_X$

NFW



At medium-to-high L_B:

small L_X difference for even large variations of the **shape**
weak increase of L_X as the ETG gets rounder

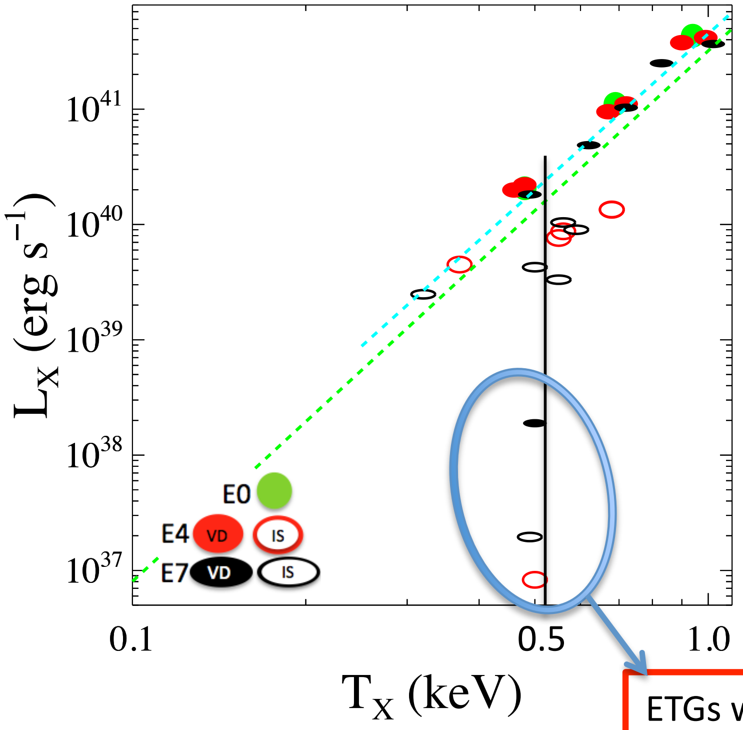
large L_X difference between IS and VD models of same shape
angular momentum prevents the gas from accumulating in the central regions, where a hot, low density atmosphere creates

At low L_B:

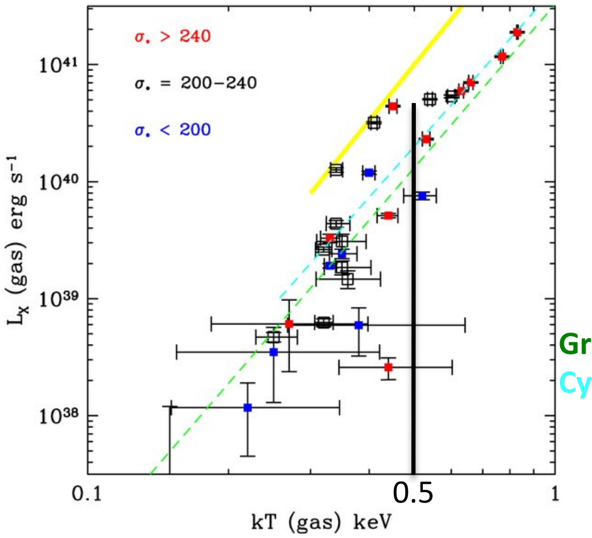
high sensitivity of the flow **to changes in galaxy structure**
➔ flattening and/or rotation can produce the **transition** to a global wind (low L_X)
➔ large L_X variation

at low galactic masses, systematic trends in L_X
cannot be predicted

NFW models



ETGs where outflow/wind important:
L_X low, T_X larger than expected



Green line: all ETGs
Cyan line: $L_X > 10^{39}$ erg/s only

Boroson et al. 2011

Scatter in L_X becomes large at $kT_X < 0.5$ keV:

high sensitivity of flow phase to shape/kinematics variations, at lower galaxy masses

Conclusions

✓ Dynamical modeling ➔ flattening (at fixed L_B) can increase or lower the depth of the potential well

✓ Simulations ➔ the **ISM rotation field** is **similar** to that of the **stellar** component

➡ low thermalization of the stellar ordered motions
the rotating ISM is less bound (reduction of the "effective" potential)

✓ Simulations ➔ **shape and rotation are important** in determining L_X and T_X.

Their effect is a function of galactic mass:

in **low** mass ETGs: flattening and rotation **both favor global winds** ➔ large decrease of L_X

in **high** mass ETGs : **shape has a minor** impact on L_X (slight decrease) and T_X (<15% variation)
rotation reduces significantly L_X and T_X

at any fixed $L_B > 3\text{x}10^{10}$ $L_{B,\odot}$ (σ_{e8}>200 km/s)
rotating ETGs are **colder** and **X-ray fainter** (the more so the flatter they are, i.e., the more rotating they can be)

rotation is the main driver of X-ray evolution ➔ anti-correlations of L_X and T_X with galaxy flattening **is a by-product**.

In progress: black hole feedback, starformation