The influence of AGN feedback on quiescent and star-forming galaxies

L. Ciotti
(Dept. Physics and Astronomy - Univ. of Bologna)

In collaboration with J.P. Ostriker and, among others:
G. Novak, D. Proga, S. Pellegrini, A. Negri,
F. Yuan (and his group), Z. Gan, L. Ho, etc.

"The co-evolution of galaxies and their central regions"
Dali − China (November 5-10, 2018)

1. Facts
2. Model(s) properties
3. Summary

1. EMPIRICAL FACTS ABOUT MASS & ENERGY BUDGETS of ETGs

ETGs ARE **NOT** “DEAD” OBJECTS **EVEN WHEN ISOLATED**
(=no merging)

Stellar evolution: INTERNAL MASS & ENERGY SOURCES

Mass

$$\dot{M}_*(t) \simeq 1.5 \times 10^{-11} L_{\rm B} t_{15}^{-1.3} \quad M_\odot {\rm yr}^{-1}$$

$$\Delta M_* \approx 0.1 - 0.3 M_*$$

- The rate in the past was HIGHER
- The returned total mass scales LINEARLY with M*

Energy

$$L_{\rm SN}(t) = 1.015 \times 10^{31} h^2 \vartheta_{\rm SN} \eta_{\rm SN} \frac{L_{\rm B}}{L_{\rm B\odot}} \left(\frac{t}{13.7\,{\rm Gyr}}\right)^{-s} \quad {\rm erg\,s^{-1}}$$

If unstopped, medium-to-large ETGs UNAVOIDABLY (from **Faber-Jackson** relation) develop a ``Cooling Flow'' (or some of its variants, e.g. Ciotti, D'Ercole, Pellegrini, Renzini 1991 - Pellegrini & Ciotti 1998 – etc.) with enormous mass accretion in the central regions.

Low mass galaxies are ruled by SNIa

X-ray observations of hot galactic halos do agree with the previous picture

Cooling flow problem reinforced by the

DISCOVERY OF SMBHs

SMBHs of Mbh ~ 0.001 M* are found at the center of ETGs/Bulges, ~ 100 times **SMALLER** than the gas made available from stellar evolution.

MASS PROBLEM: NEGATIVE FEEDBACK REQUIRED!

THE ISSUE IS NOT THE ENERGETICS

but HOW the released energy **INTERACTS** WITH THE ISM:

Lbh ~ 10^46 erg/s [accretion of 1 Msun/yr]
Lgrav ~ 10^41 erg/s [ejection of 1 Msun/yr from the galaxy]

Long-term project with J.P. Ostriker (since 1991 + collaborators) on radiation-hydrodynamical numerical simulations of

PHYSICALLY BASED AGN FEEDBACK in ETGs

MACER_code: see Zhiyuan Yao/Feng Yuan talk
Bologna_Code: Ciotti-Ostriker-Negri-Pellegrini

SMBH accretion and feedback are SELF-DETERMINED

1D-models (mainly historical!)

•Spherically symmetric, self-consistent dynamical models for the stars + DM halo + SMBH (Magorrian – Kormendy&Ho). Constraints from Fundamental Plane

•SNIa + Stellar winds from old stellar population+thermalization

•Star formation: SNII + Stellar winds from new population+thermalization

$$\dot{\rho}_* = \frac{\eta_{\rm form}\rho}{\tau_{\rm form}} \qquad \tau_{\rm form} = \max(\tau_{\rm cool}, \tau_{\rm dyn})$$

Self-determined SMBH accretion rate and emitted Lbh

Radiative feedback equations of radiative transfer in spherical symmetry are solved for the X-ray, UV, IR radiation. In this way we compute

ISM Heating & Cooling photoionization, Compton, line and free-free mechanisms

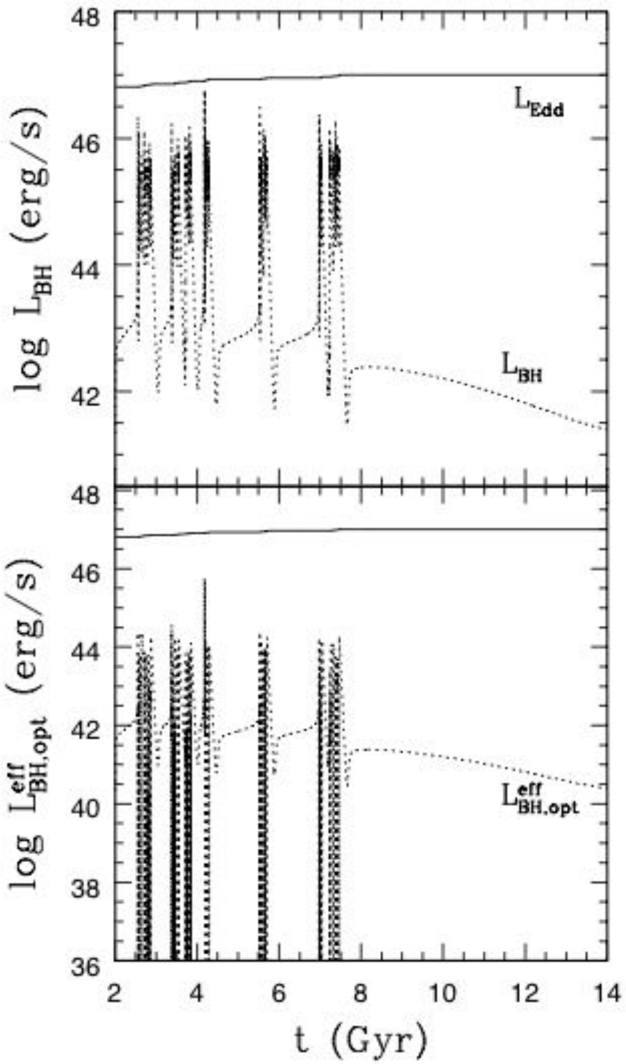
Radiation Pressure: on the ISM (photoionization, electron scattering) + DUST (grain formation, destruction & mixing times taken into account).

Mechanical Feedback: conical nuclear wind (BAL) [QUALITATIVE: spherical symmetry and absence of angular momentum]

Recurrent phases of a "dead" ETG

1. Stellar evolution produces gas
2. Cold shell ~ kpc (beginning of Cooling Flow catastrophe)
3. BURST: accretion on SMBH ➔ feedback ➔ Shock waves (& star formation) in the ISM ➔ clearing of inner regions
4. Hot & low luminosity steady accretion
5. Fresh gas accumulates over the galaxy body ➔ new cycle (more and more time needed)…. until SNIa take over
6. Final outflow phase, hot & low lumin. steady accretion

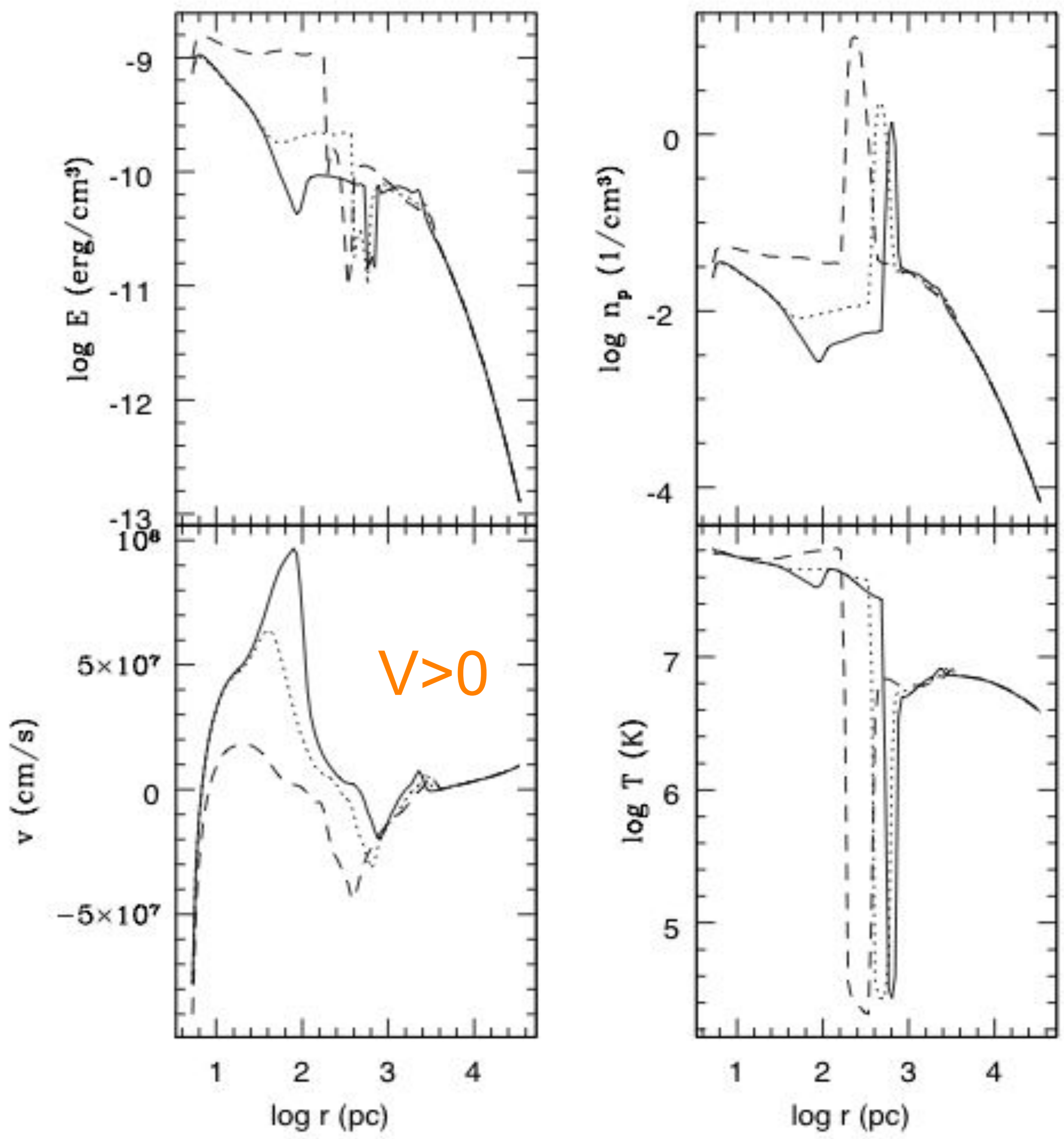
Luminosities



M*= 3 10^11 Msun
Lb= 5 10^10 Lsun
Re= 6.9 kpc
Central vel.disp. = 260 km/s

Bolometric accretion luminosity

Hydrodynamics

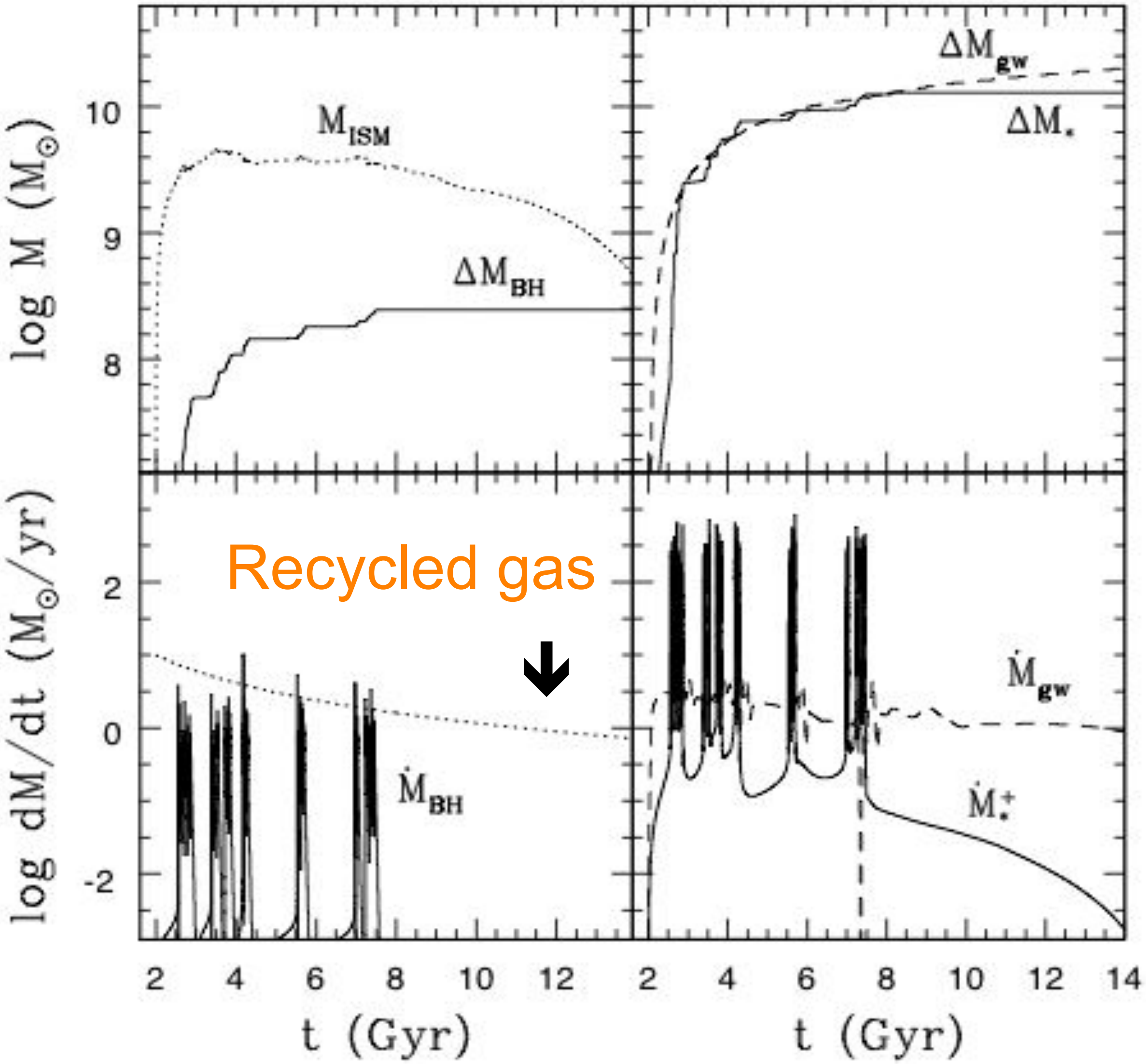


In each BURST EVENT (~ 10^7 yrs) series of direct and reflected shocks are launched and cooled, BH accretes in bursts

In the cold shells, vigorous star formation

A final event stops the sequence, kills star formation and cycle restarts

Mass Budgets



CO ApJ 2007

THE ASTROPHYSICAL JOURNAL, 665:1038–1056, 2007 August 20
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RADIATIVE FEEDBACK FROM MASSIVE BLACK HOLES IN ELLIPTICAL GALAXIES: AGN FLARING AND CENTRAL STARBURST FUELED BY RECYCLED GAS

LUCA CIOTTI[1] AND JEREMIAH P. OSTRIKER[2,3]
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ABSTRACT

INDUCED
&
SUPPRESSED
star
formation

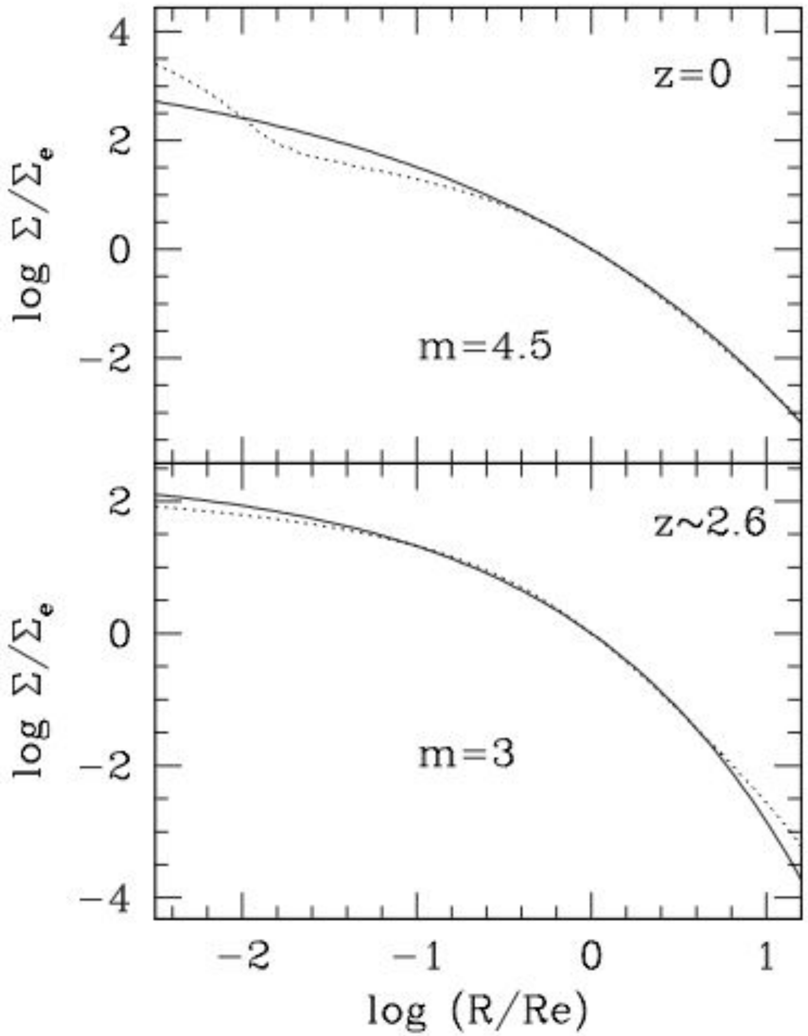
Due to **induced** star formation,
Sersic index increases
central extra-light
~300pc scale

Sersic fit

(solid: initial condition)

$$\Sigma(R) = \Sigma_0 \mathrm{e}^{-b(m)(R/R_\mathrm{e})^{1/m}}$$

$$b(m) = 2m - 1/3 + 4/(405m)$$



Sersic index increases

central extra-light

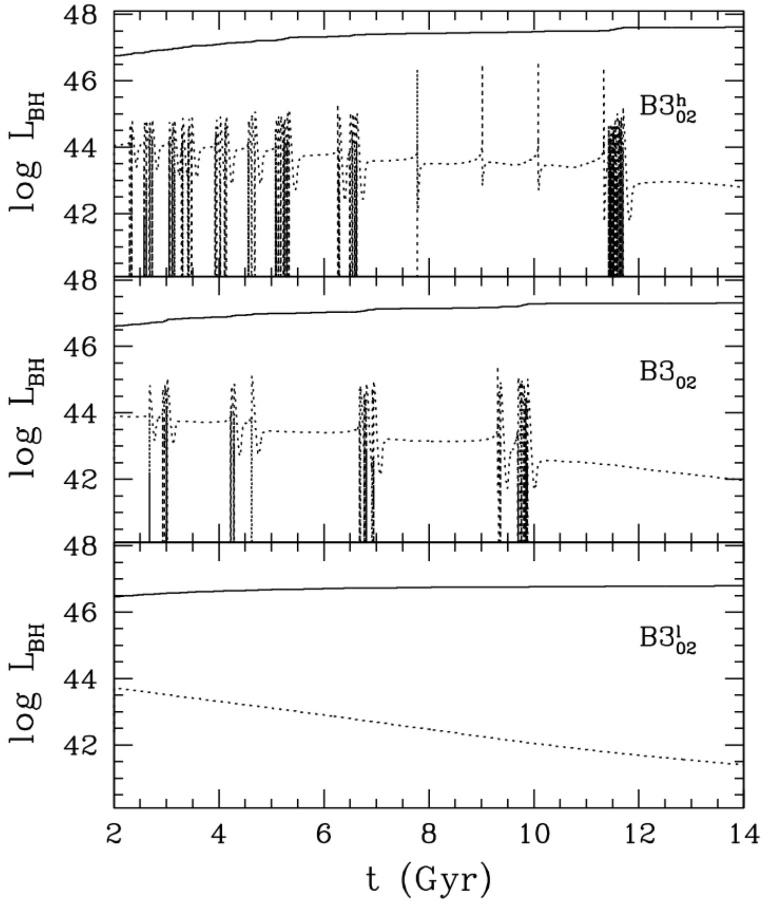
~300pc scale

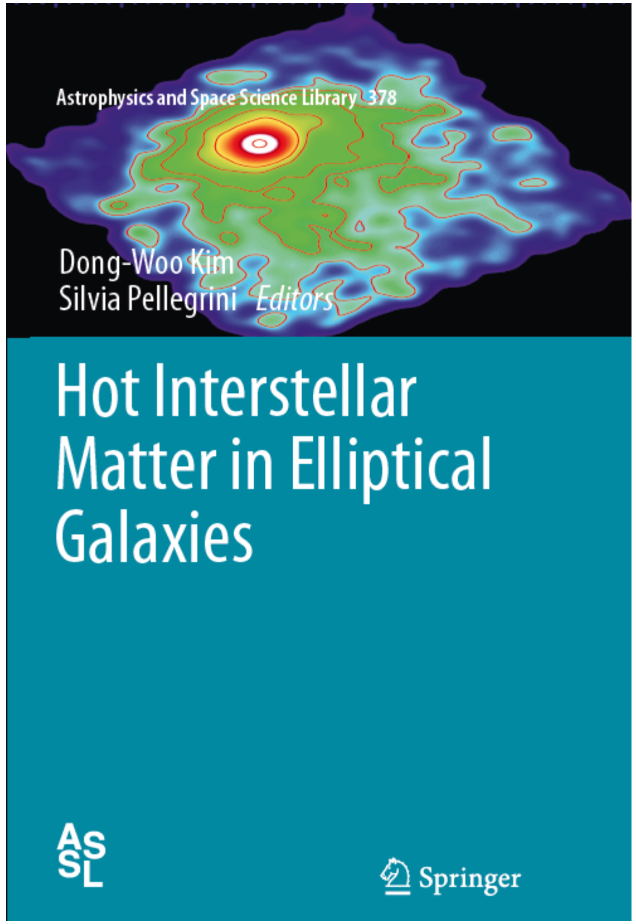
See Kormendy et al. ApJS 182, 2009

Strong dependence of activity on the galaxy potential well (SNIa)

AGN feedback in elliptical galaxies: numerical simulations

Luca Ciotti and Jeremiah P. Ostriker





Vel. Disp. = 280 (top) – 260 (midle) – 240 (bottom) km/s

2D-models

Starting from the preliminary studies (2011, 2012, with Novak and Proga)
on 2D feedback,
we are now running 2D hydro simulations with MACER and the Bologna_Code

• Realistic dynamical modeling of the galaxies
(multi-component Jeans, flattening, rotation, from

MACER: Ciotti, L., Ziaee Lorzad, A. 2018 & 2019 MNRAS

Bologna_code: JASMINE code

• Spatial resolution from ~pc scale to ~ 250 kpc, over Hubble time

Main References of recent works

A. MACER

Gan, Z., Yuan, F., Ostriker, J.P., Ciotti, L., Novak, G. 2014 ApJ

Li, Y-P., Yuan, F., Mo, H., Yoon, D., Gan, Z-M., Ho, L.C., Wang, B., Ostriker, J.P, Ciotti, L. 2018 ApJ

Yoon, D.S., Yuan, F., Gan, Z.-M., Ostriker, J.P., Li, Y-P., Ciotti, L. 2018 ApJ

Gan, Z., Ciotti, L., Ostriker, J.P., Yuan, F. 2018 ApJ

Gan, Z., Choi, E., Ostriker, J.P., Ciotti, L. 2018 ApJ (in preparation)

B. Bologna Code

Negri, A., Ciotti, L., Pellegrini, S. 2014 MNRAS, 439

Negri, A, Posacki, S., Pellegrini, S., Ciotti, L. 2014 MNRAS, 445

Negri, A., Pellegrini, S., Ciotti, L., 2015 MNRAS, 451

Ciotti, L., Pellegrini, S., Negri, A., Ostriker, J.P. 2017 ApJ, 835

Pellegrini, S., Ciotti, L., Negri, A., Ostriker, J.P. 2018 ApJ, 856

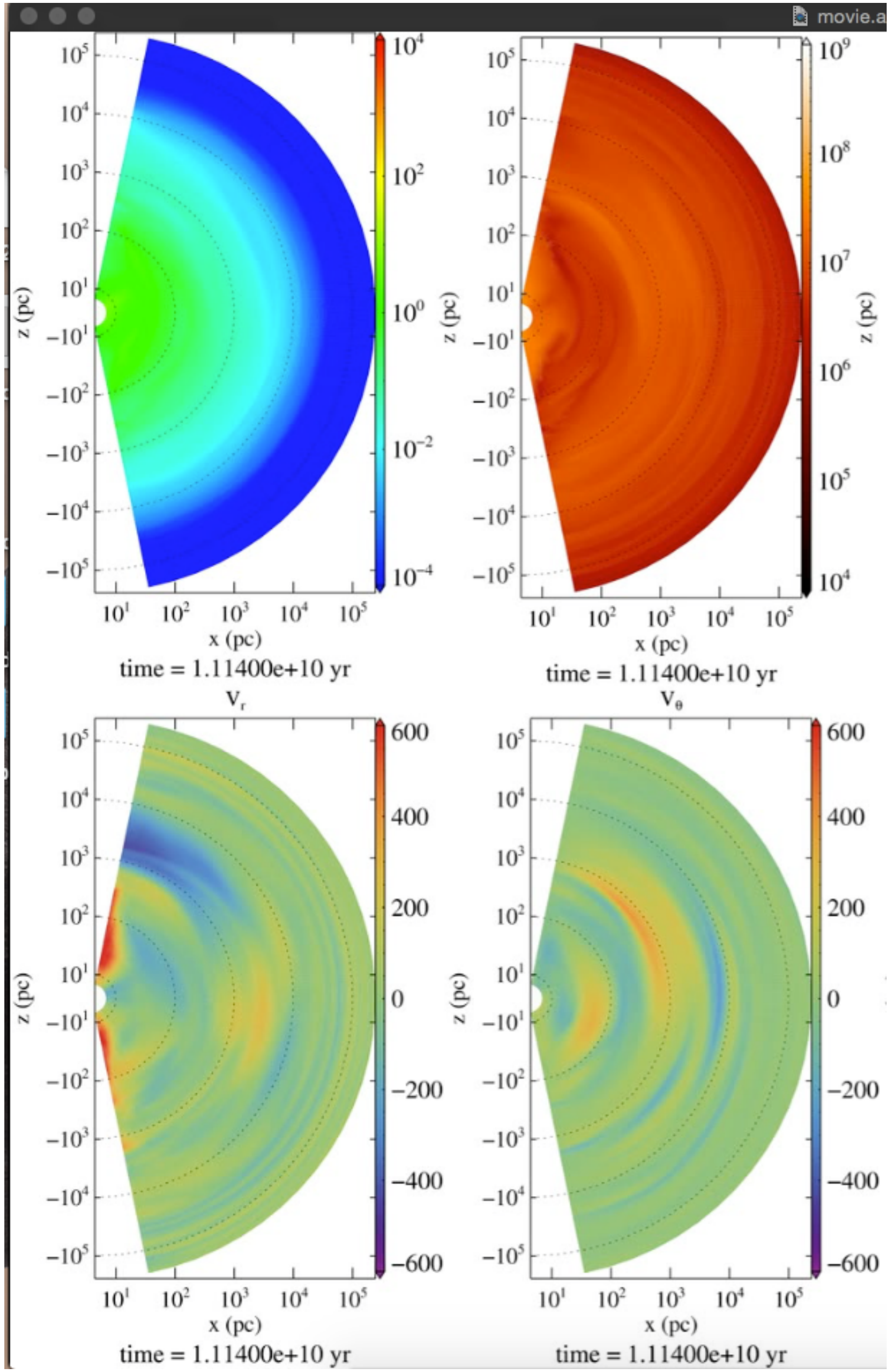
C. Bondi theory (analytical)

Korol, V., Ciotti, L., Pellegrini, S. 2016 MNRAS, 460

Ciotti, L., Pellegrini, S. 2017 & 2018 ApJ

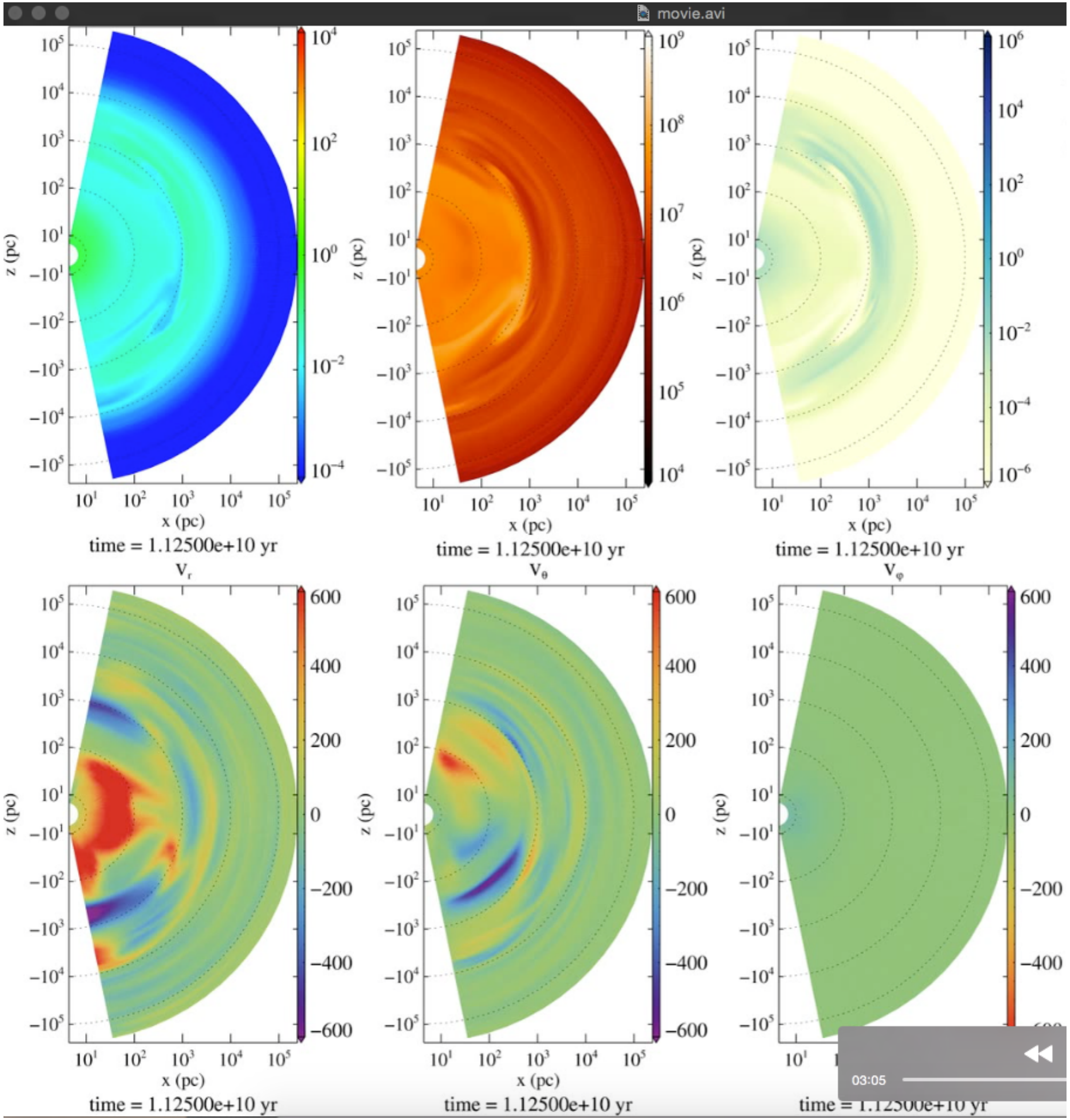
ISM density

Temperature

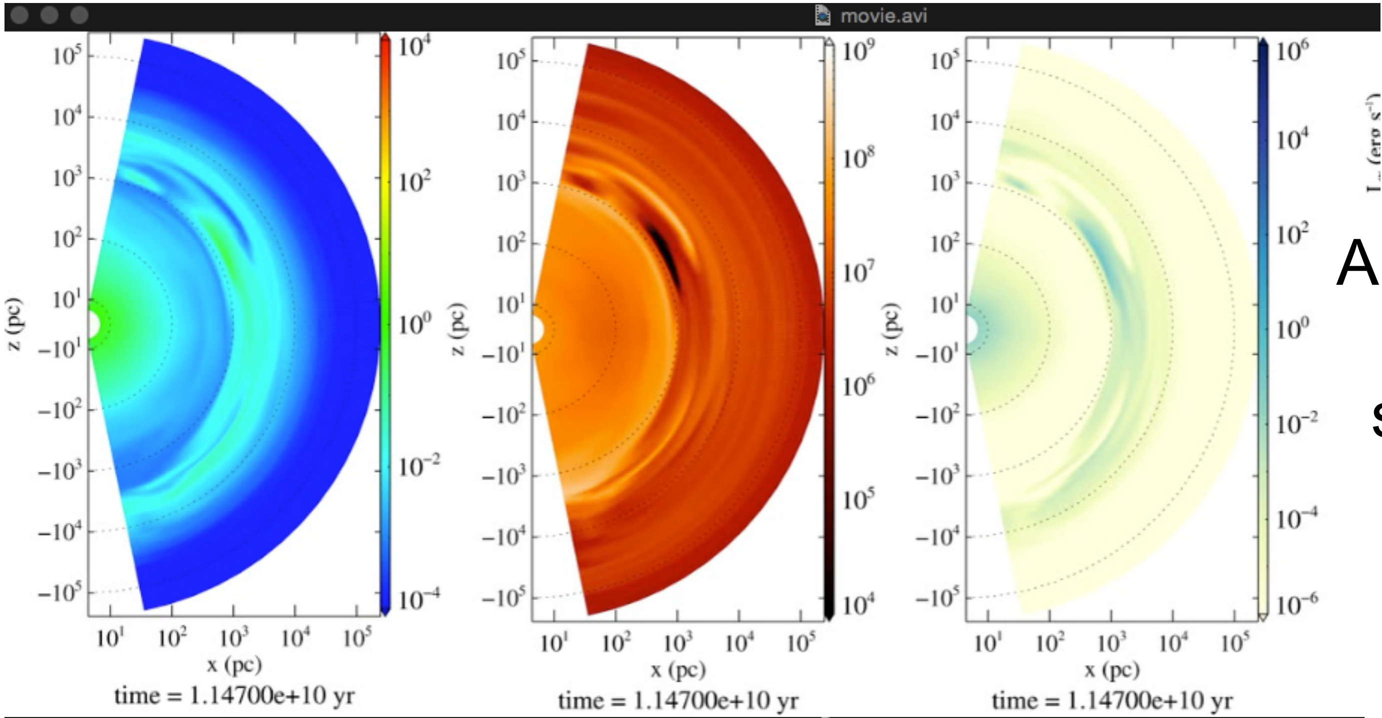


E4 galaxy
250 km/s
central
vel. disp.

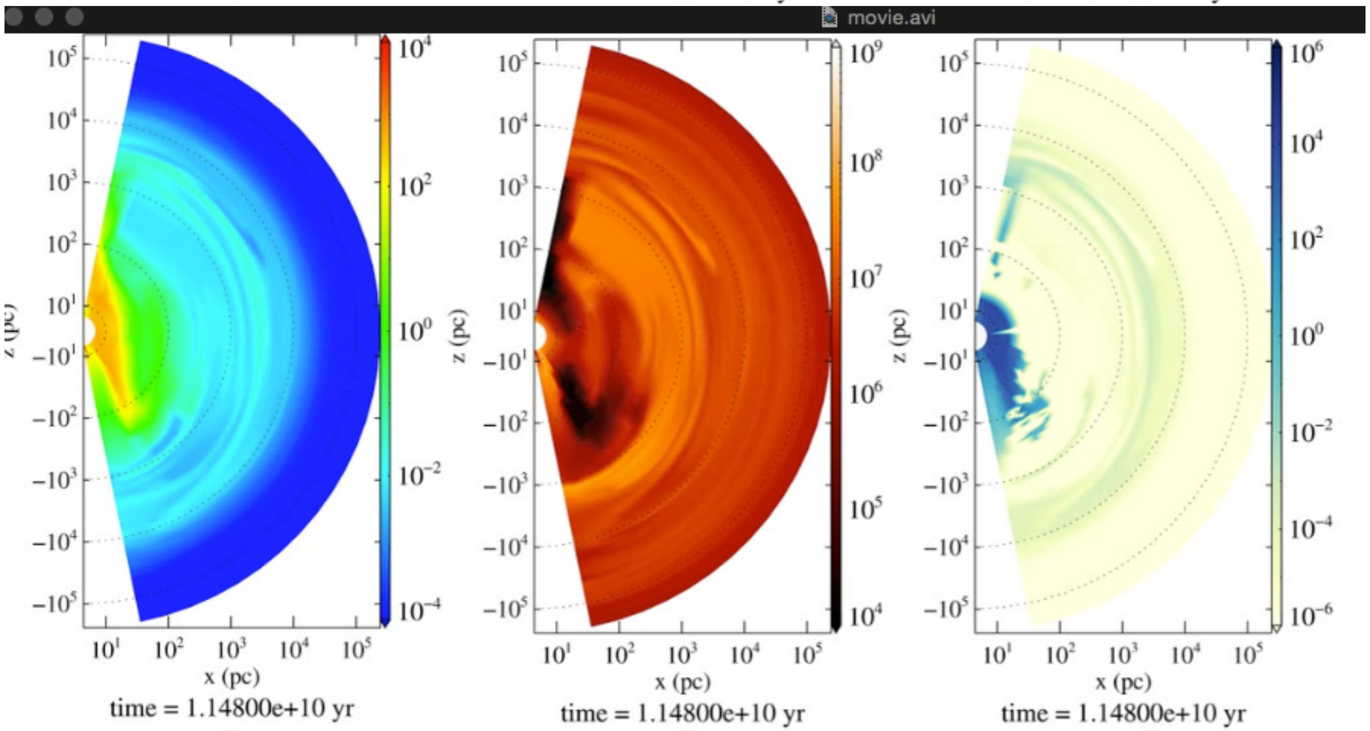
Conical jet
produced
by
mechanical
feedback



Hot bubble & star formation in shell RT instabilities



Another example of hot bubble, cold star forming shell

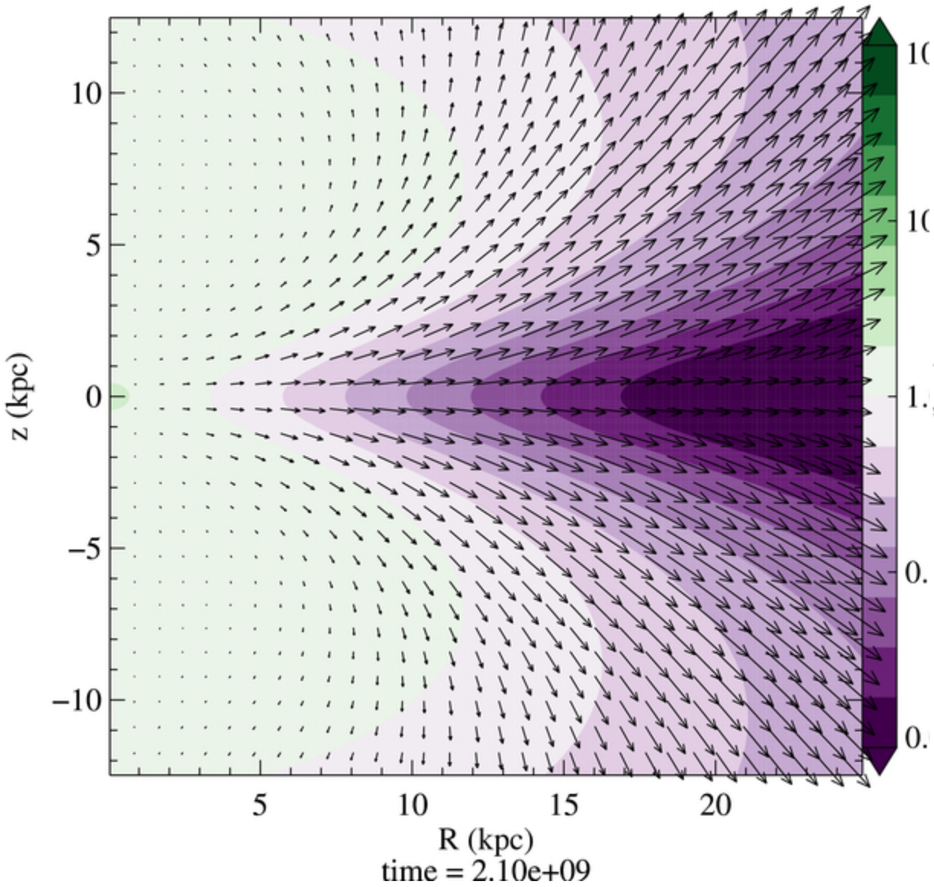


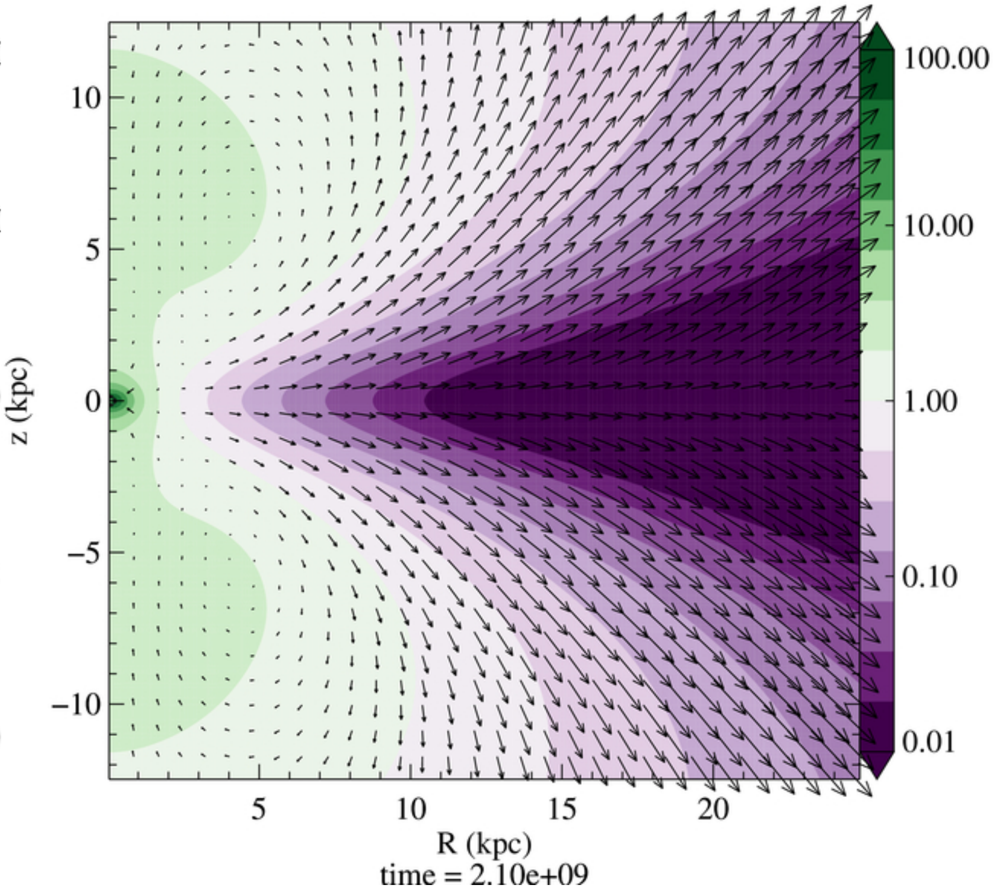
In this accretion event, instead concentrated star formation

IN THESE SIMULATIONS NO SUBSTANTIAL
GALAXY ORDERED
ROTATION WAS ALLOWED

HOWEVER

ISM evolution in realistic ETG models with different internal kinematics (BUT NO AGN feedback) shows that star formation is strongly dependent NOT ONLY on the depth of the galactic potential well, but also on
INTERNAL STELLAR KINEMATICS
at fixed galaxy structure

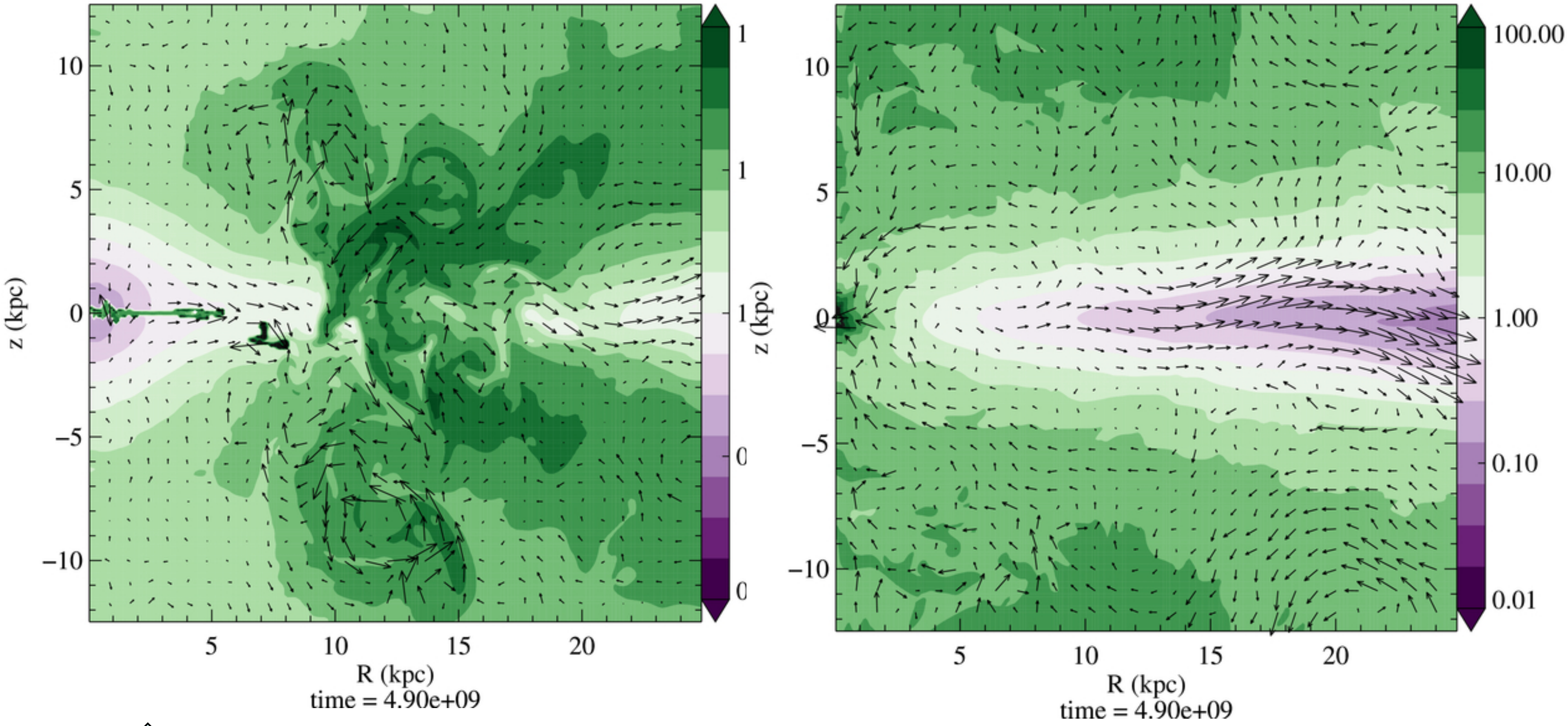




Isotropic Rotator

Velocity Dispersion Supported

Initial time, density (green=high)



z (kpc)
R (kpc)
time = 4.90e+09
z (kpc)
R (kpc)
time = 4.90e+09
100.00
10.00
1.00
0.10
0.01

Cold DISK

Currently working on the implementation of
cold gaseous disk
Q self-regulated evolution

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MACER IMPROVED: AGN FEEDBACK COMPUTED IN ROTATING EARLY-TYPE GALAXIES AT HIGH RESOLUTION

ZHAOMING GAN[1], LUCA CIOTTI[2], JEREMIAH P. OSTRIKER[3], FENG YUAN[1]
[1]Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China
[2]Department of Physics and Astronomy, University of Bologna, via Piero Gobetti 93/2, 40129 Bologna, Italy and
[3]Department of Astronomy, Columbia University, 550 W, 120th Street, New York, NY 10027, USA
Draft version September 11, 2018

Competition[*] between star formation and instability
(approx > Gyr time scale for instability)

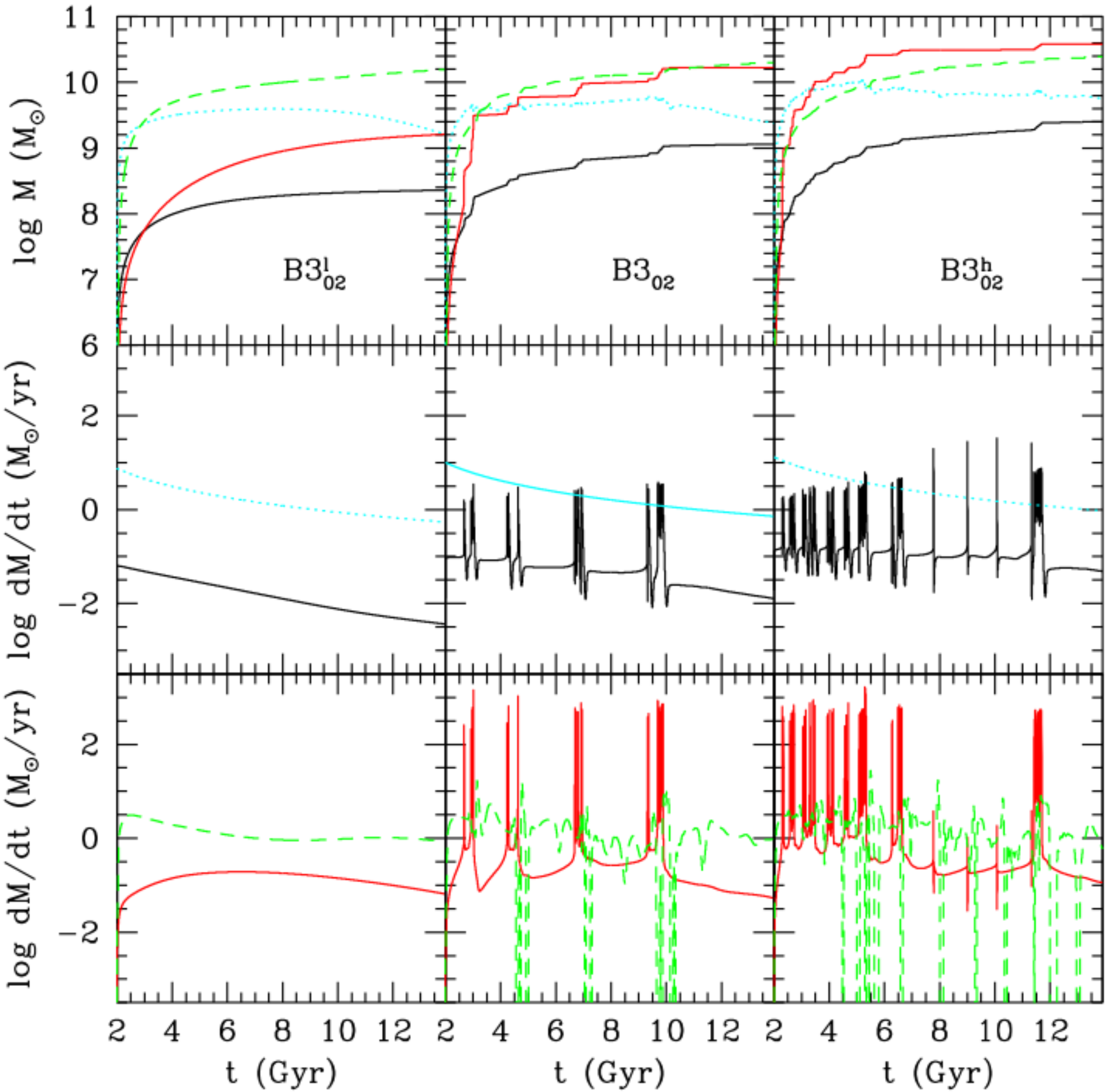
3. SUMMARY

- Radiative + mechanical AGN feedback is effective in maintaining "small" SMBH mass (increase ~ 2)
- Accretion highly non-stationary (short duty-cycle), interplay between global & local scales.
- Source of "fuel" proportional to M*, stellar mass losses decline with cosmic time, specific heating increases, activity declines
- QSO activity can be independent of merging
- **Bursting star formation** (in shells, INDUCED & SUPPRESSED), production of nuclear cusps
- Importance of detailed ETGs structure/internal kinematics (ROTATION) on accretion.

Additional Material

Mass budgets

Red: stars
Black: BH
Cyan: SSP
Green: G.W.



Name	$L_{\rm B}$ ($10^{11} L_{rmB\odot}$)	$R_{\rm e}$ (kpc)	M_* ($10^{11} M_\odot$)	$M_{\rm h}$ ($10^{11} M_\odot$)	$\sigma_{\rm e8}^{\rm VD}$ (km s^{-1})	$f_{\rm DM}$	c
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$EO4^{180}$	0.18	3.26	0.81	16.20	160	0.62	41
$EO7^{180}$	0.18	3.26	0.81	16.20	137	0.73	41
$EO4^{210}$	0.32	4.57	1.54	30.80	187	0.62	35
$EO7^{210}$	0.32	4.57	1.54	30.80	155	0.66	35
$EO4^{250}$	0.65	7.04	3.35	67.00	223	0.63	28
$EO7^{250}$	0.65	7.04	3.35	67.00	184	0.67	28
$EO4^{300}$	1.38	11.8	7.80	160.00	267	0.66	22
$EO7^{300}$	1.38	11.8	7.80	160.00	221	0.68	22

	name (1)	M_{bh} (10^8 $M_\odot$) (2)	$l_{0.5}$ - (3)	D (%) (4)	t_L (Gyr) (5)	M_* (10^9 $M_\odot$) (6)	SFR ($M_\odot/yr$) (7)	t_M (Gyr) (8)	r_M (kpc) (9)	
	E4 180	0.946	0.118	5.106	4.563	1.451	0.036	5.383	9.087	✓
	E7 180	0.859	0.118	4.734	3.269	0.721	0.013	4.664	10.23	✓
	E4 210	3.068	0.030	1.602	5.044	7.760	0.277	5.248	1.678	✓
	E7 210	2.582	0.031	1.171	4.834	6.482	0.132	5.222	1.678	✓
	E4 250	9.628	0.042	2.943	5.084	17.02	0.313	4.972	2.440	✓
	E7 250	8.232	0.039	2.181	5.243	15.57	0.437	5.239	2.294	✓
	E4 300	30.912	0.059	3.429	5.919	34.26	1.025	5.036	4.220	✓
	E7 300	28.045	0.050	3.030	5.915	30.99	2.947	5.163	4.759	✓
No Feedb.	E4 180	8.621	–	–	–	2.359	0.245	5.346	1.466	0
	E4 210	29.694	–	–	–	5.394	0.259	5.694	0.426	0
	E4 250	87.515	–	–	–	11.542	0.532	5.715	0.426	0
	E4 300	228.95	–	–	–	24.576	1.237	5.881	0.496	0

As in 1D simulations

MORE star formation when AGN feedback is present

New stars in a kpc-size region

SMBHs remains "small"

Bulk of injected mass -> SNIa-AGN assisted galactic wind