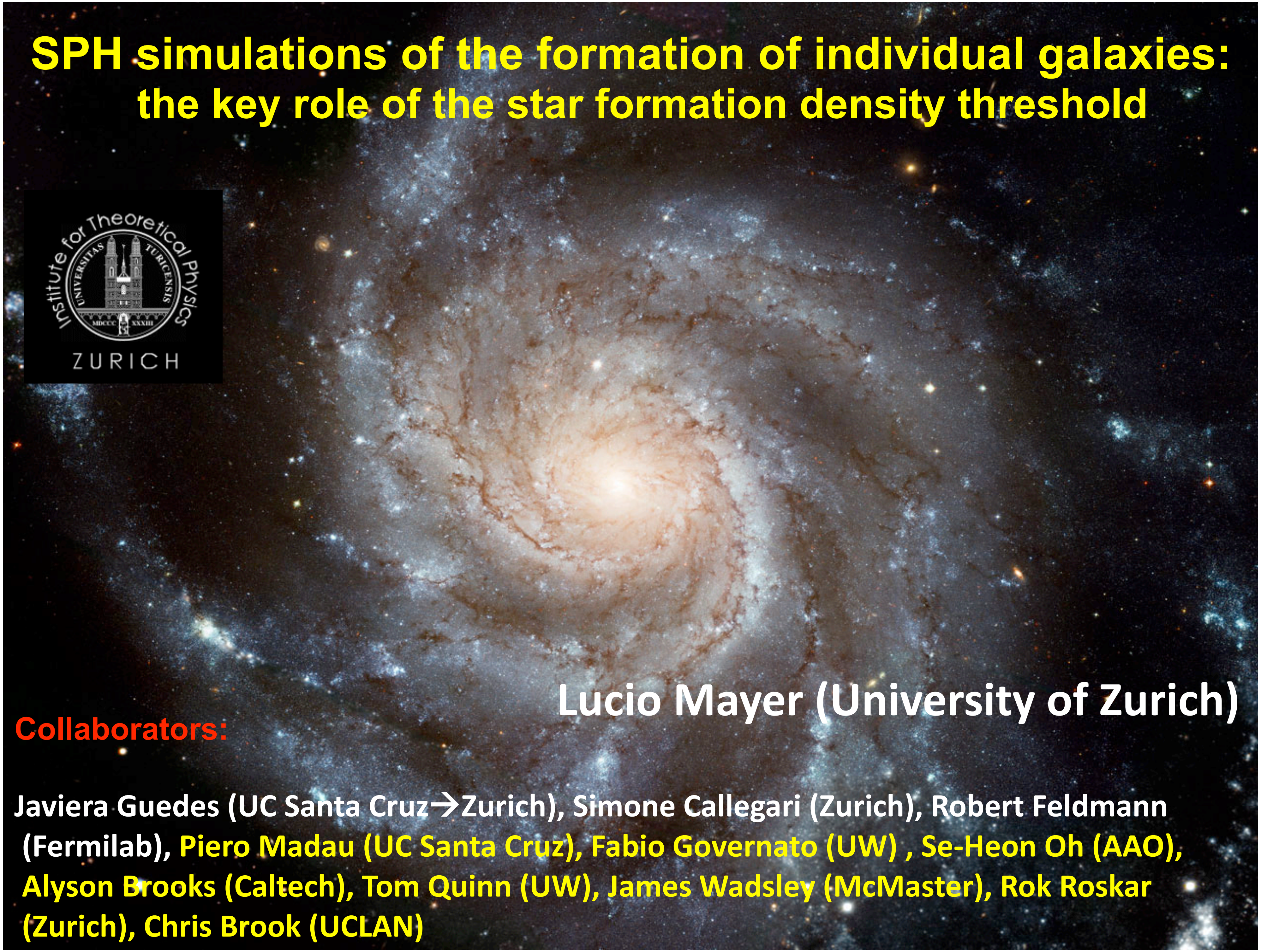

SPH simulations of the formation of individual galaxies: the key role of the star formation density threshold

Institute for Theoretical Physics ZURICH

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MAJOR PROBLEMS IN ΛCDM SIMULATIONS:

(1)OVERSIZED BULGES

(2) STEEP ROTATION CURVES (Vpeak >~ 300 km/s for MW-sized galaxies)

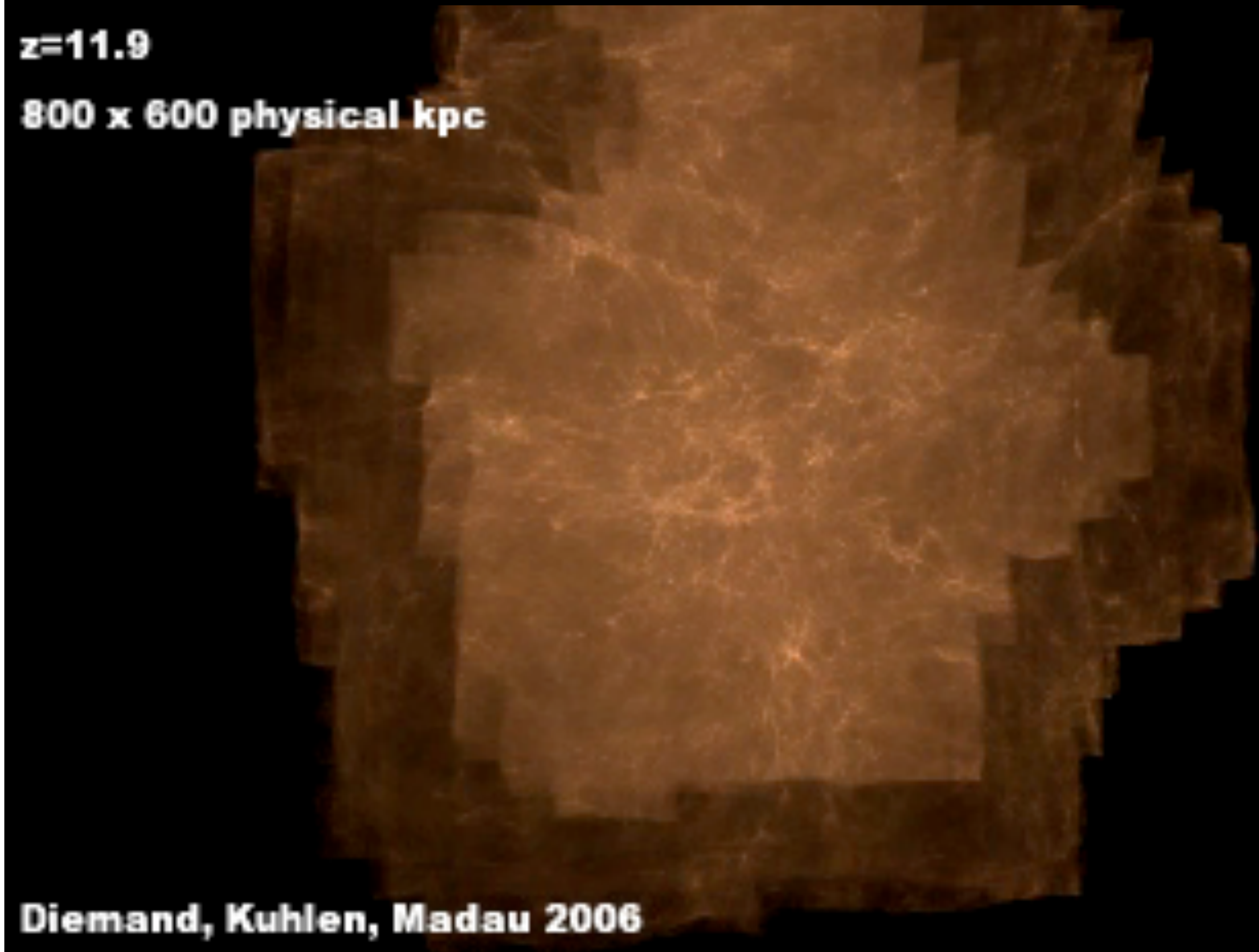
(3) EXCESSE STELLAR MASS

UNDERLYING PHYSICAL ISSUES:

ANGULAR MOMENTUM, ENERGY BUDGET OF THE GAS PHASE, CONVERSION OF GAS INTO STARS

ΛCDM cosmology: structure formation driven by gravity

Primordial small matter density fluctuations amplified by gravitational instability in an expanding Universe
→ hierarchical build-up of dark matter halos

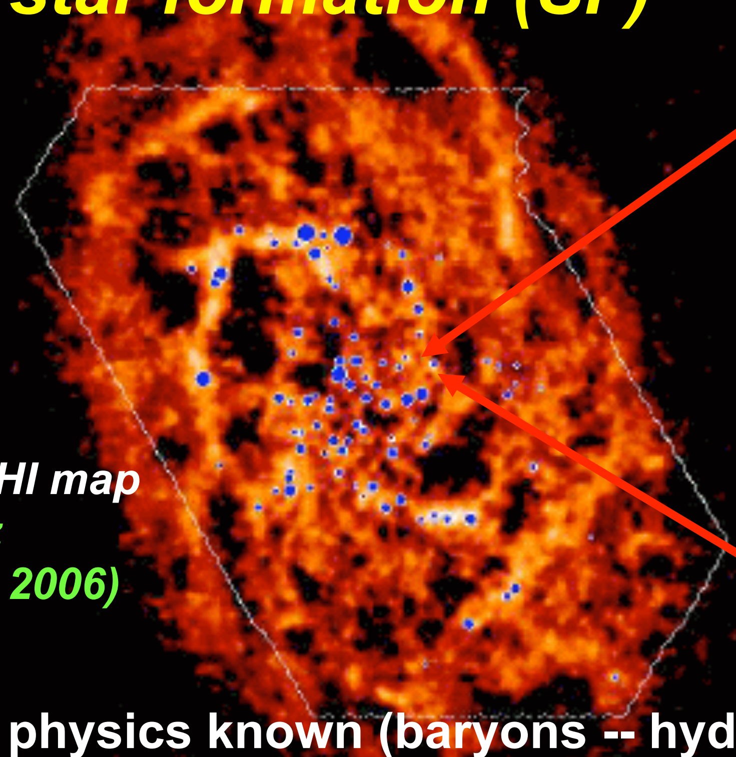


Formation of MW-sized dark matter halo

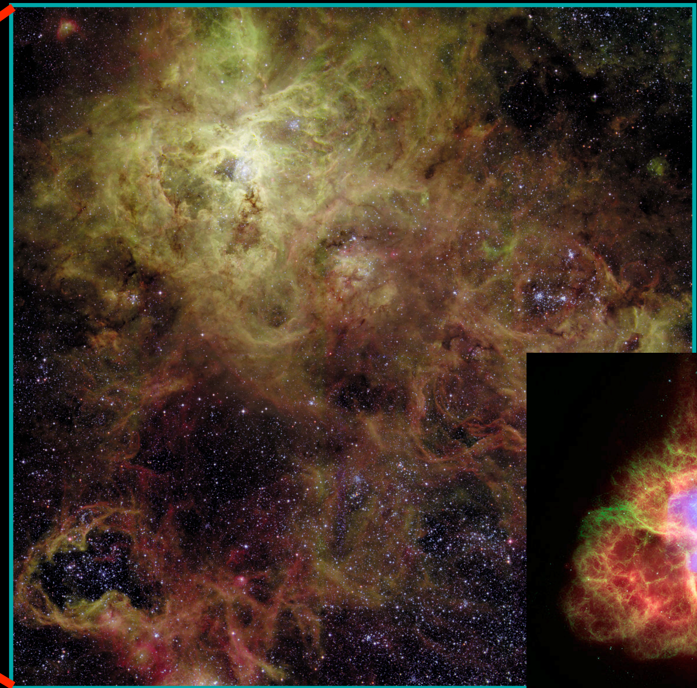
N-Body code PKDGRAV2

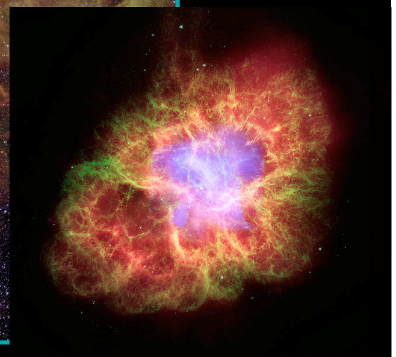
VIA LACTEA simulation (Diemand et al. 2007; 2008)

Complexity: *Physics of the interstellar medium (ISM) and star formation (SF)*



M33 HI map
(Blitz et al. 2006)





Basic physics known (baryons -- hydrodynamics, gravity, radiative mechanisms, magnetic fields) but major issues in modeling

- **Multi-scale (< 1 pc to 1 kpc) – resolution of numerical models of cosmic structure formation was only ~ 1 kpc till 2004, <100 pc today -→ *need sub-grid models***

- **Multi-process: cooling, heating, phase transitions (e.g. from atomic H to H_2), hydro/MHD turbulence, star formation, stellar explosions, self-gravity, MHD phenomena, viscous phenomena (what source of viscosity?).** *Some of these processes not completely understood plus require interplay between many scales*

Hydro Simulations of Galaxy Formation have improved significantly over the last decade.

- **Numerics/Mass and spatial resolution (N: 10k to ~ 20M; spatial resolution from ~ > 1 kpc to <100 pc), e.g.**

  Okamoto et al. 2003; 2008; Sommer-Larsen et al. 2003; Governato, Mayer et al. 2004; Kaufmann, Mayer et al. 2007; Naab et al. 2008; Piontek et al. 2009; Mayer, Governato & Kaufmann 2008; Keres et al. 2009; Scannapieco et al. 2008;2009; 2010; Brooks et al. 2010; **Guedes, Callegari, Madau & Mayer 2011**; Brook et al. 2011)

- **Also first AMR simulations of disk formation**

  (Ceverino & Klypin 2009; Agertz et al. 2009,2010 – see Romain Teyssier's talk; Gnedin et al., in prep.)

- **Improved sub-grid models of ISM/Star formation/feedback**

---→ sustain warm/hot gas phase, prevent overcooling and SF

Thacker & Couchman 2001; Governato, Mayer et al. 2004; Abadi et al. 2003; Sommer-Larsen et al. 2004; Brook et al. 2005; Robertson et al. 2005; Governato, Willman, Mayer et al. 2007,2008; Robertson & Kravtsov 2008; Schaye & Della Vecchia 2008; Ceverino & Klypin 2009; Joung, Chen & Bryan 2008; Tissera et al. 2009; Shen et al. 2010; Nickerson et al. 2011; Piontek & Steinmetz 2011

A CRUCIAL INGREDIENT TO GET REALISTIC DISK GALAXIES : A HIGH STAR FORMATION DENSITY THRESHOLD

STARS FORM IN GIANT MOLECULAR CLOUDS, i.e. in gas at densities in range 10-100 cm^{-2} (depends on metallicity, ambient UV flux)

BUT IN COSMOLOGICAL SIMULATIONS OF GALAXY FORMATION STARS FORM AT DENSITIES > 0.1 cm^{-3} (typical density of Warm Neutral Medium in Milky Way!)

(eg Abadi et al. 2003; Governato, Mayer+, 2004; Governato et al. 2007, Mayer+ 2008; Piontek & Steinmetz 2010; Scannapieco et al. 2009; 2010; Agertz et al. 2011; Naab et al. 2007)

TO CAPTURE COLD DENSE MOLECULAR PHASE:

FIRST STEP IS TO RESOLVE REGIONS OF CORRESPONDING DENSITY

IN SPH >~ 2 SPH kernels per Jeans mass ~ 10^{5-6} Mo, eg Bate & Burkert 1997 → mass resolution 10^3-10^4 Mo → *hi-res zoom-in cosmo sim*

-EXAMPLE 1: FORMATION OF BULGELESS GAS-RICH DWARFS (Governato, Brook, Mayer +, Nature, 2010)

- EXAMPLE 2: FORMATION OF MASSIVE LATE-TYPE SPIRALS (Guedes, Callegari, Madau & Mayer 2011, ApJ submitted)

w/GASOLINE SPH code

Hi-res dwarf galaxy formation

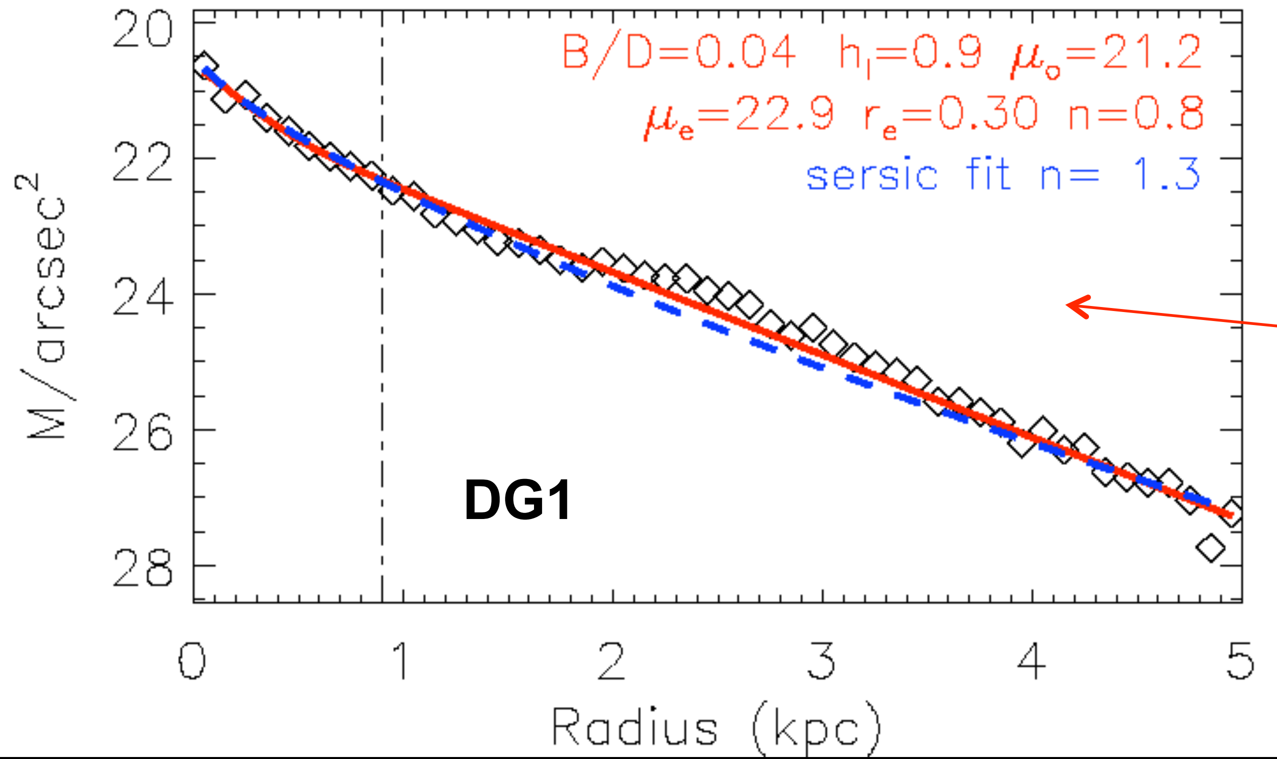
TWO Ics (DG1 and DG2, different mass assembly history)
Vvir ~ 50 km/s
NSPH ~ 2 x 10^6 particles
Ndm ~2 x 10^6 particles
Msph ~ 10^3 Mo
gravitational softening = 86 pc
WMAP5 cosmology

-Schmidt-law SF w/high density threshold of 100 atoms/cm^3
-Supernovae blastwave feedback model (Stinson et al. 2006)
-Cooling to 300 K owing to metal lines
-Heating/ionization by cosmic UV bg (Haardt & Madau 2006)

Frame = 15 kpc on a side
color-coded gas density
Evolution of DG1 from z=100 to z=0

Governato, Brook, Mayer et al., Nature, 463, 203, 2010

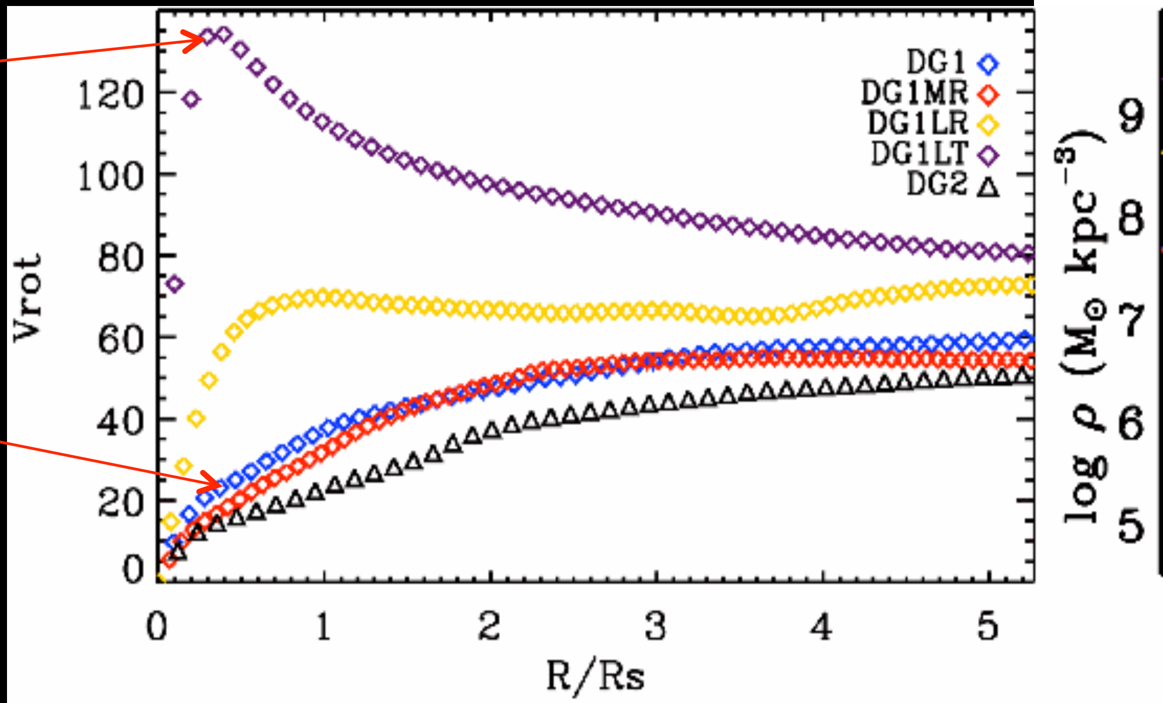
-- Final baryonic mass fraction within Mvir = 0.3 x f_b (cosmic)
-- Final stellar mass ~ 0.05 f_b (cosmic) <~ 0.01 Mvir
(see Oh et al. 2011 for comparison with dwarf galaxies in THINGS survey and other datasets)
-- Final gas/stars ratio in disk ~ 2.5



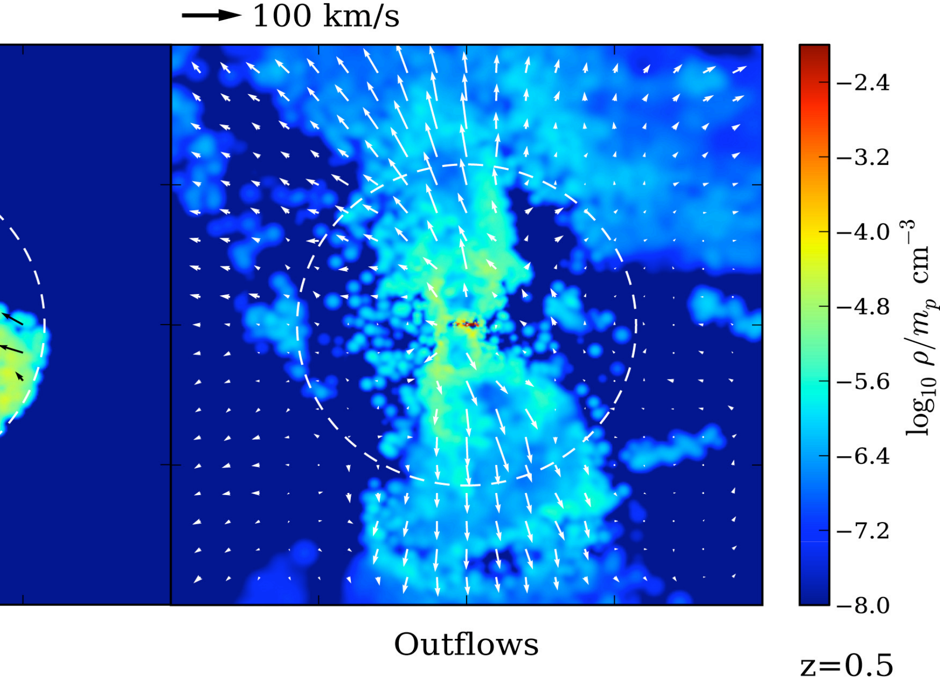
Bulgeless exponential disk (instead B/D ~ 0.3 in run with low SF threshold)

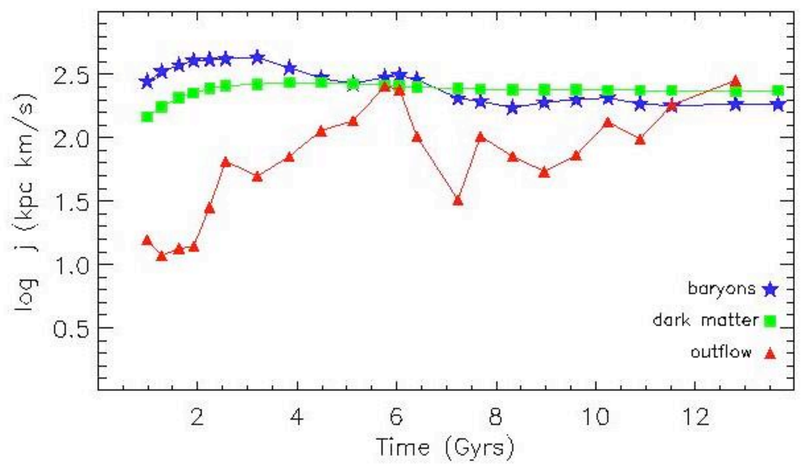
From unrealistic steep rotation curves at low SF threshold to realistic slowly rising rotation curves at high SF threshold

Inner dark matter profile flattened by expansion following impulsive supernovae outflows producing potential fluctuations – see Andrew Pontzen's talk and Pontzen+Governato 2011 (also Navarro, Frenk & Eke 1996; Read & Gilmore 2005; Maschenko et al. 2008)



The benefits of a high SF density threshold:
star formation and feedback in an *inhomogeneous* ISM





than DISTRIBUTED, only in high density peaks

Stronger outflows compared to control run with "standard" low SF threshold **because more supernovae energy deposited in smaller volume via blastwaves (more gas heated at T > Tvir at z ~ 1-3, outflows at ~ 100km/s --→ final baryonic fraction ~ 1/3 of cosmic)**

•Outflows correlated with peaks in SFR, in turn correlated with mergers (hence occur preferentially at z > 1) – see Brook et al. (2010) for details

▪Outflows mostly in the center of galaxy where star forming density peaks higher
-→ *selectively removes lowest angular momentum material*
-→ *suppress bulge formation and produce exponential profile*

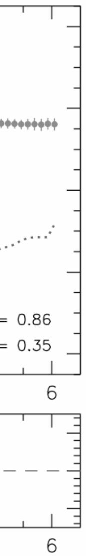
Independent analysis by the THINGS team + comparison with dwarf galaxies in THINGS shows excellent agreement

(Oh et al. 2011)

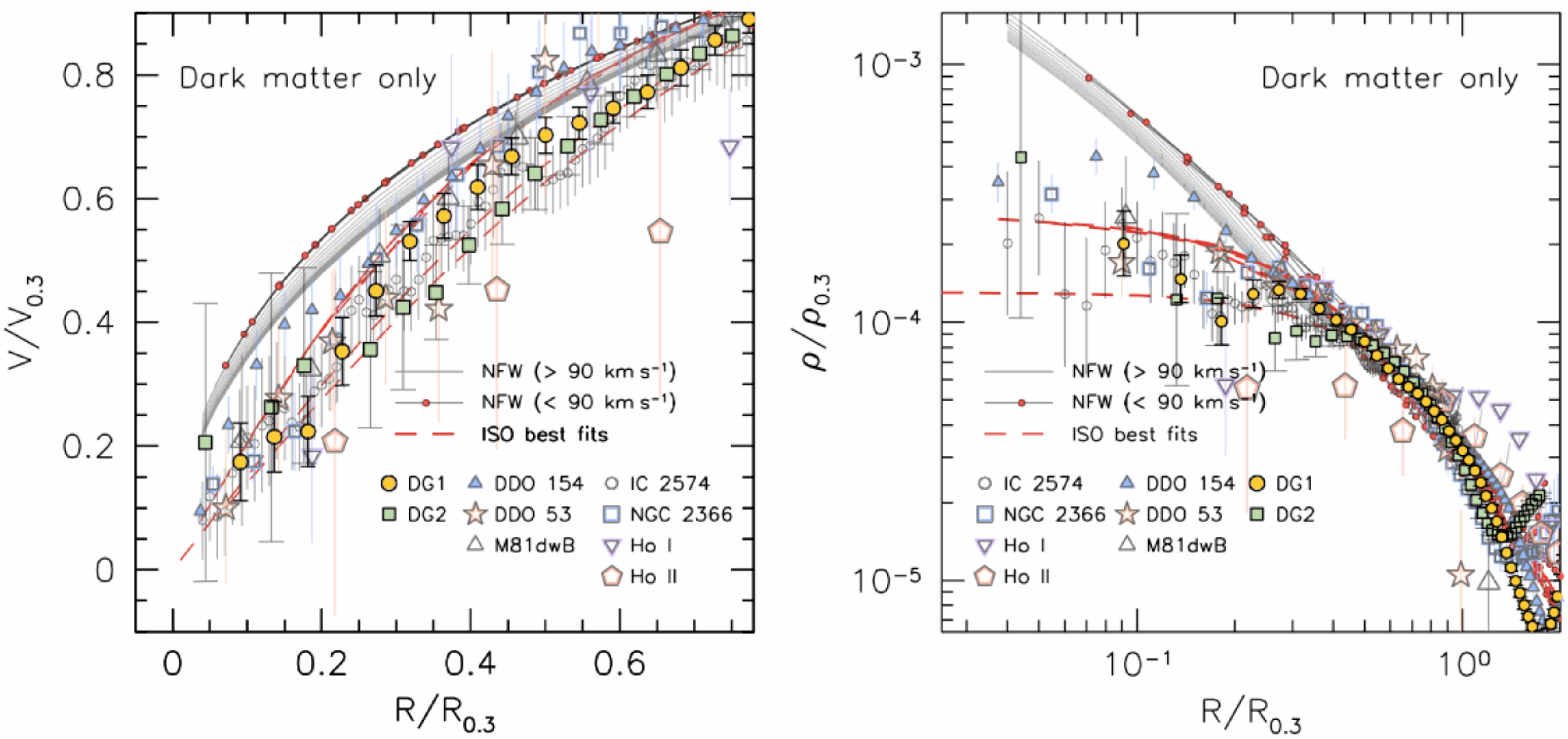
Inner DM slope - 0.29 from rotation curve modeling, mean for THINGS is - 0.31

(we obtain ~ - 0.5 from direct measure of the dm profile in sim)

Note: no explicit correction for non-circular motions



Mock HI observations of DG1 and DG2 compared with THINGS galaxies



MW-sized galaxies with a high SF threshold

The ERIS simulations *(not an acronym!)*

A "light MW": Mvir ~ 7.9 x 10^{11} Mo, *no merger > 1:10 after z ~ 3*, **λ = 0.019**

3 hi-res runs with:

11.6 million baryonic particles (gas + stars) + 7 million DM particles within Rvir at z=0 (M_{SPH} ~ 2 x 10^4 Mo, M_{dm} ~ 10^5 Mo, grav. softening =120 pc)

- ***Same blastwave feedback model used for dwarf simulations*** ***(Stinson et al. 2006)***
- ***High SF threshold ρ_{th} = 5 atoms/cm^3*** ***(highest allowed by requiring to resolve local thermal Jeans mass with > 2 SPH kernels for gas that can cool to ~ 300 K)***

(1) ErisLT	ρ_{th} = 0.1 cm^{-3}	c_{sf}*=0.05	z_f=0.7
(2) Eris	ρ_{th}=5 cm^{-3}	c_{sf}*=0.1	z_f = 0
(3) ErisLE	ρ_{th} 5 cm^{-3}	c_{sf}*=0.05	z_f = 0
(4) ErisLowRes (res/8)	ρ_{th} = 0.1 cm^{-3}	c_{sf}*=0.05	z_f=0

~ 5 million CPU hours on CRAY XT5 at Swiss Supercomputing Center + NASA Ames PLEIADES Cluster -- hi-res runs worth 9-10 months of computation each.

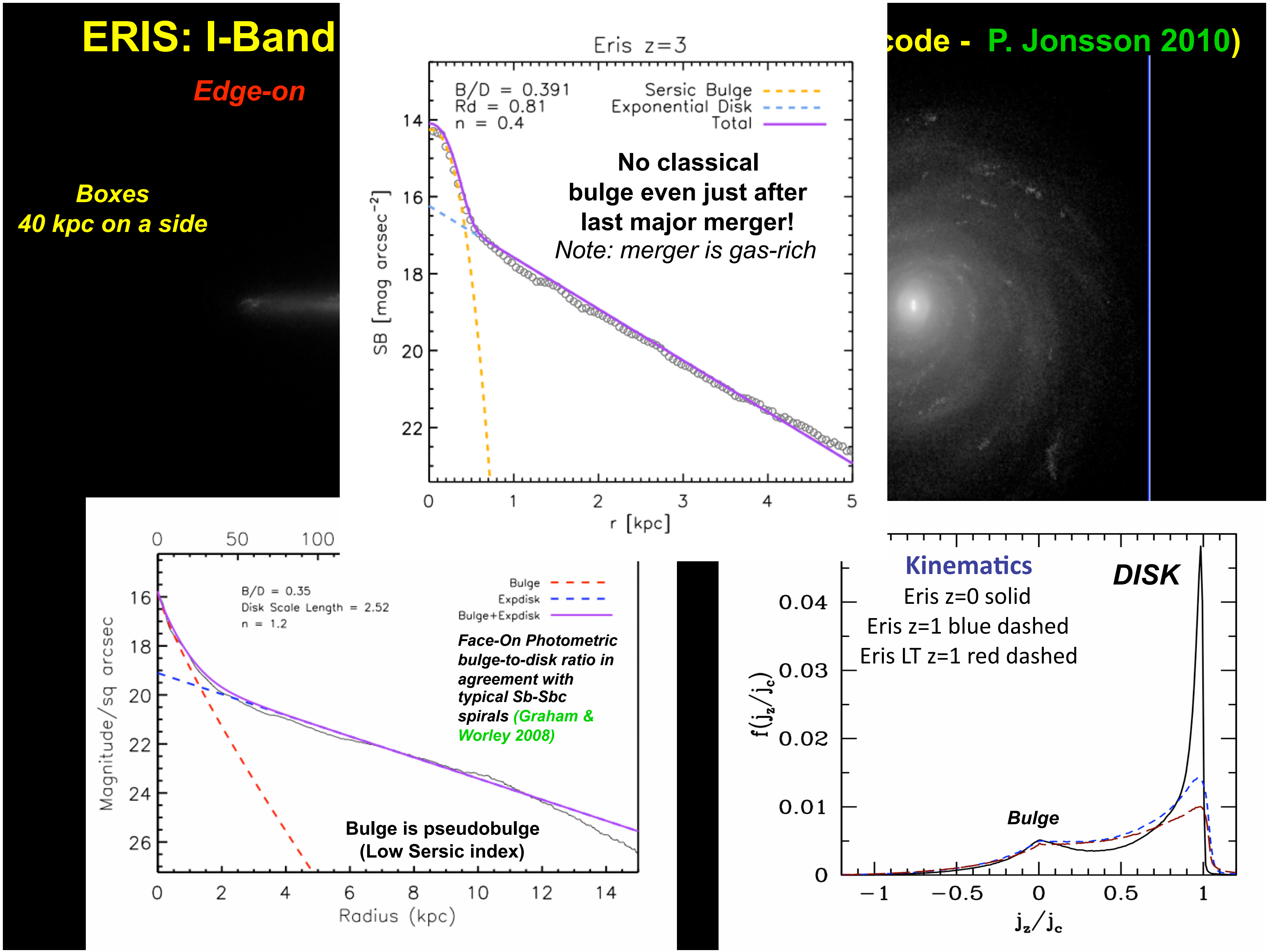
(Guedes, Callegari, Madau & Mayer 2011; Shen et al. 2011; Guedes et al. in preparation; Oh et al., In prep.)

Please see poster by Javiera Guedes !

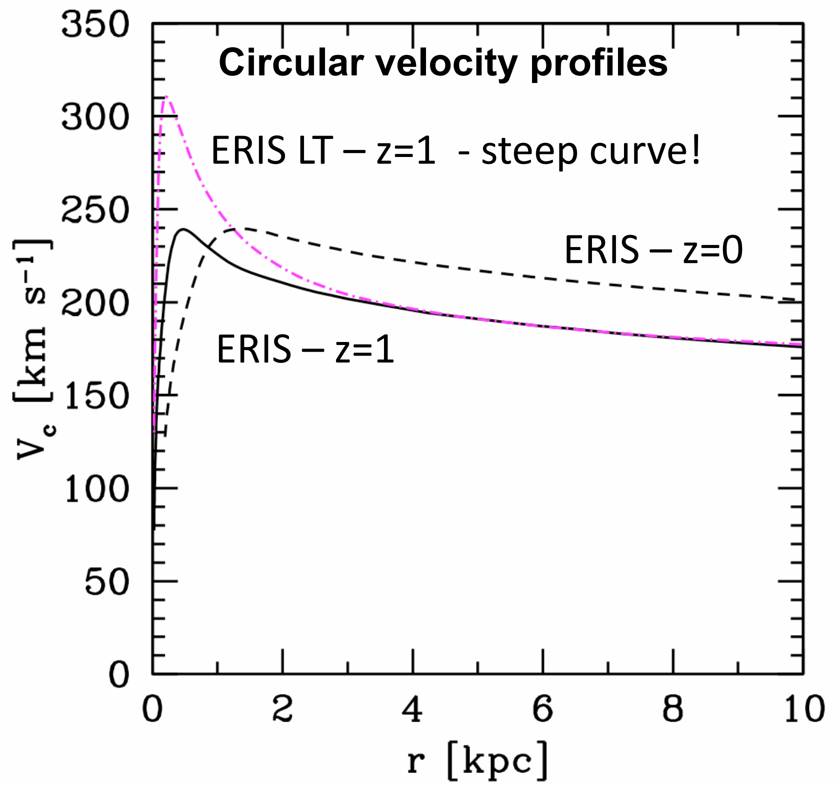
Green=gas
Blue=young stars
Red=old stars

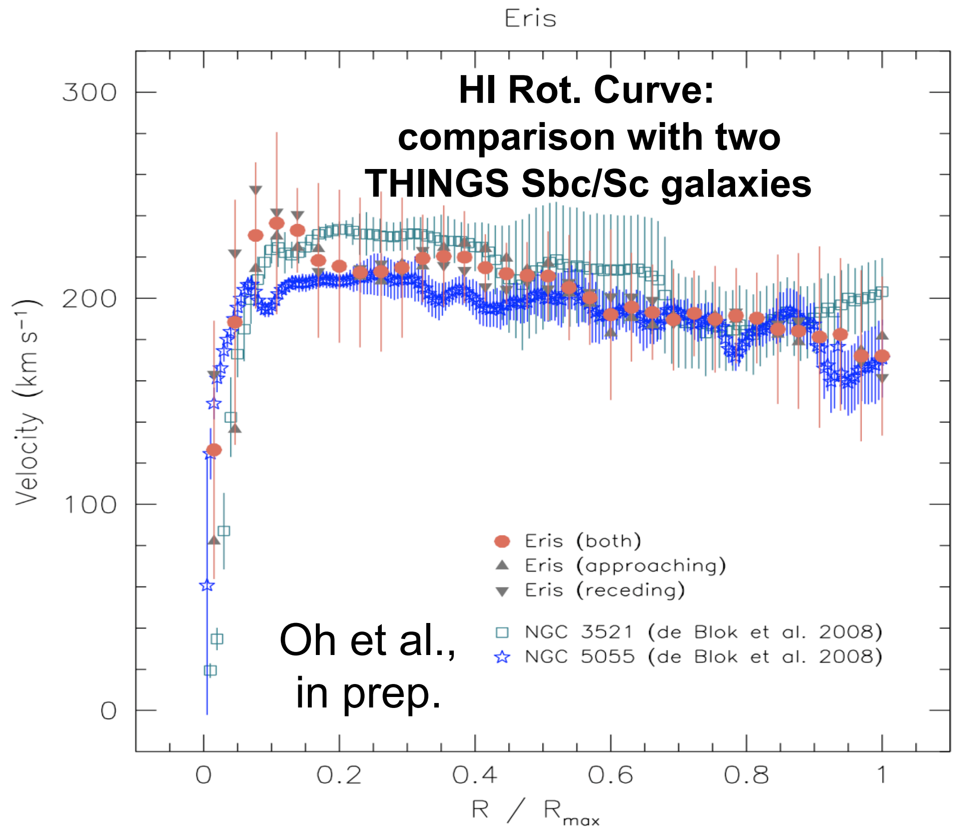
Box is 30 physical kpc
(total computational box is 60 Mpc)

At z=0 baryon fraction ~ 70% below cosmic as a result of outflows (stays at cosmic value in run with low SF threshold run
Low J material preferentially removed

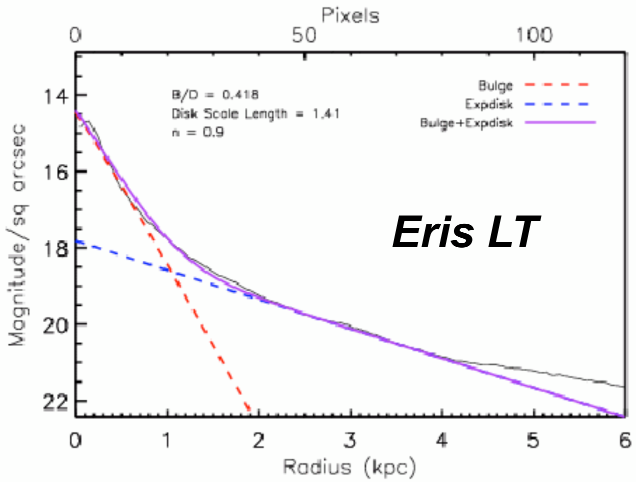


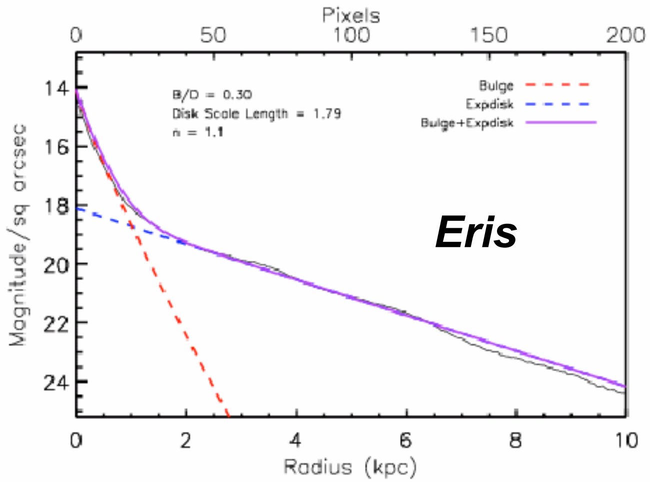
ERIS: I-Band
code - P. Jonsson 2010)
Edge-on
Boxes
40 kpc on a side
Eris z=3
B/D = 0.391
Rd = 0.81
n = 0.4
Sersic Bulge
Exponential Disk
Total
No classical bulge even just after last major merger!
Note: merger is gas-rich
SB [mag arcsec^{-2}]
r [kpc]
B/D = 0.35
Disk Scale Length = 2.52
n = 1.2
Bulge
Expdisk
Bulge+Expdisk
Face-On Photometric bulge-to-disk ratio in agreement with typical Sb-Sbc spirals (Graham & Worley 2008)
Bulge is pseudobulge
(Low Sersic index)
Magnitude/sq arcsec
Radius (kpc)
Kinematics
Eris z=0 solid
Eris z=1 blue dashed
Eris LT z=1 red dashed
DISK
Bulge
$f(j_z/j_c)$
j_z/j_c





Steeper rotation curves in LT run reflected by its higher B/D and smaller disk scale length *(runs compared at z=1)*

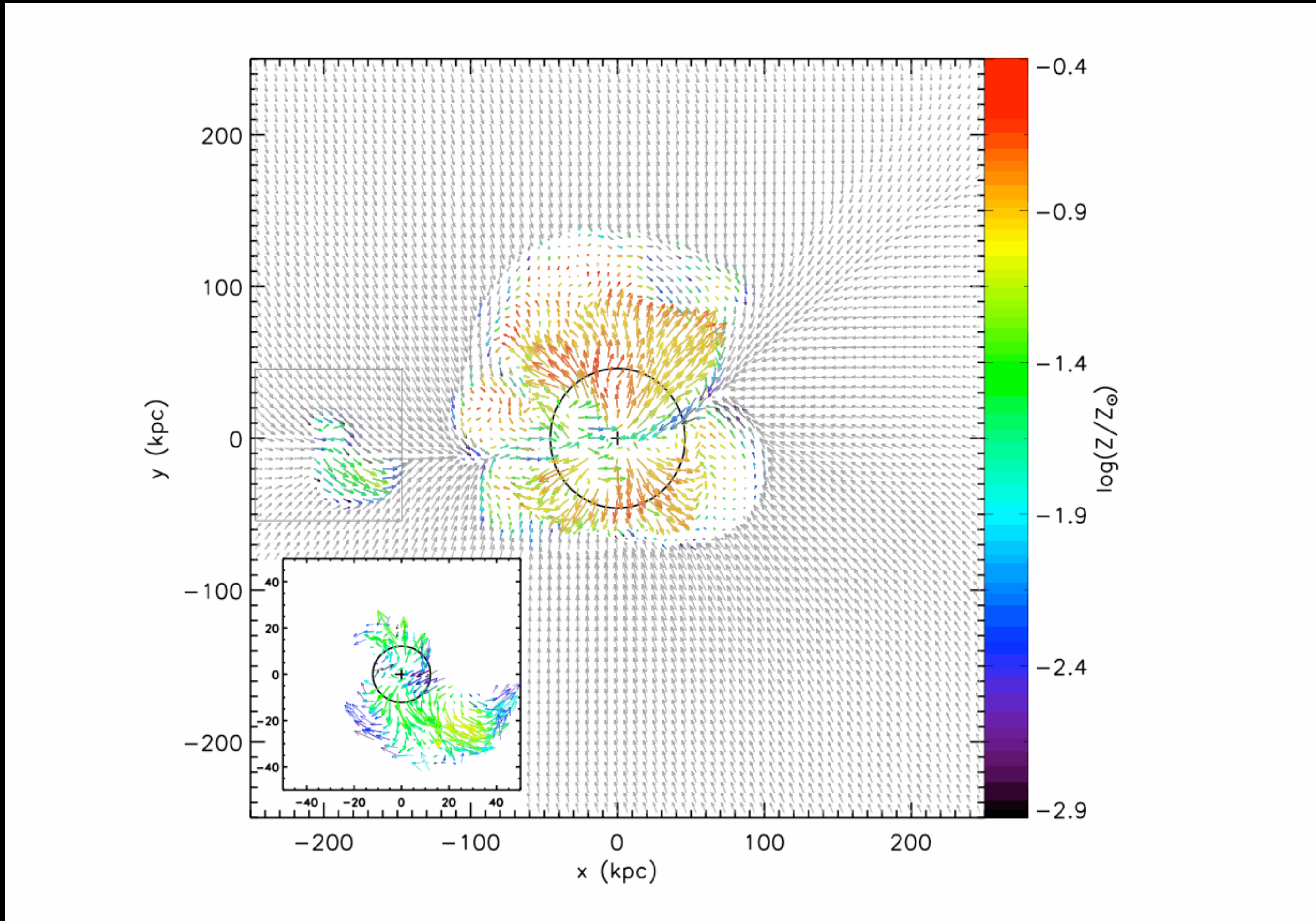




AS FOR DWARF GALAXY SIMULATIONS OUTFLOWS ARE NATURALLY PRODUCED BY THERMAL (BLASTWAVE) FEEDBACK IN AN INHOMOGENEOUS MEDIUM *(NO MOMENTUM FEEDBACK!)*

OUTFLOWS WELL TRACED BY METALS: IN FIGURE BELOW METALLICITY BUBBLES SHOWN FOR PRIMARY AND A SATELLITE AT z=4 (Shen et al., in prep., circle marks virial radius)

Maximum length of Velocity vectors ~ 200 km/s



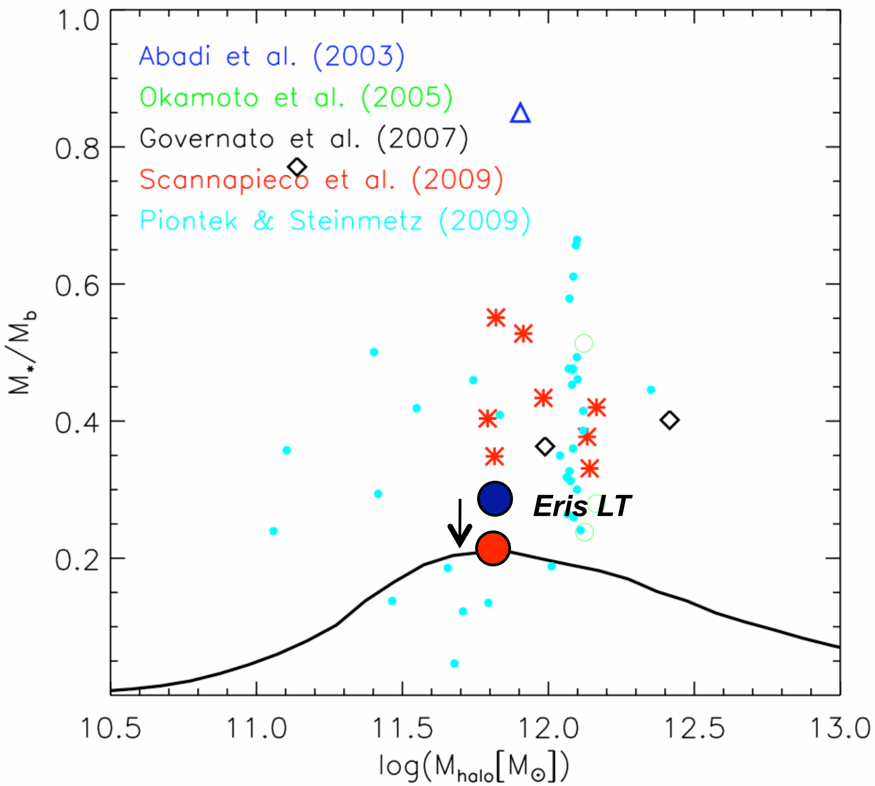
Reductio
mas

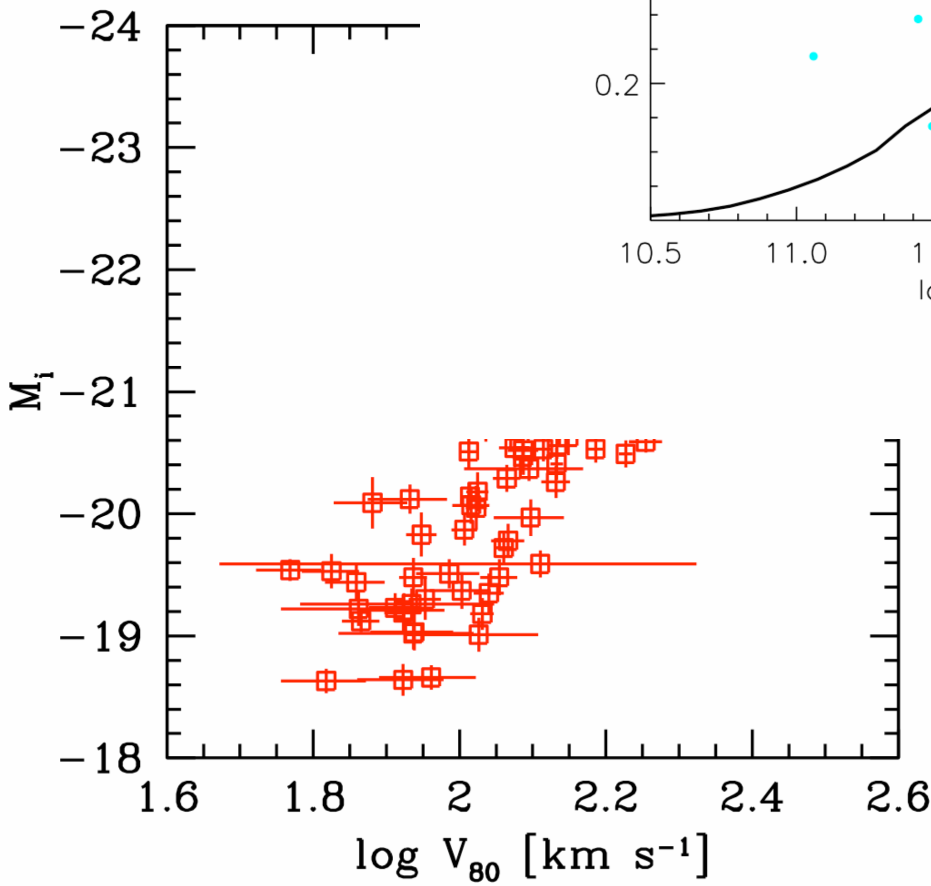
i-Band Tully-Fishe
Pizagno et
ERIS = Bl

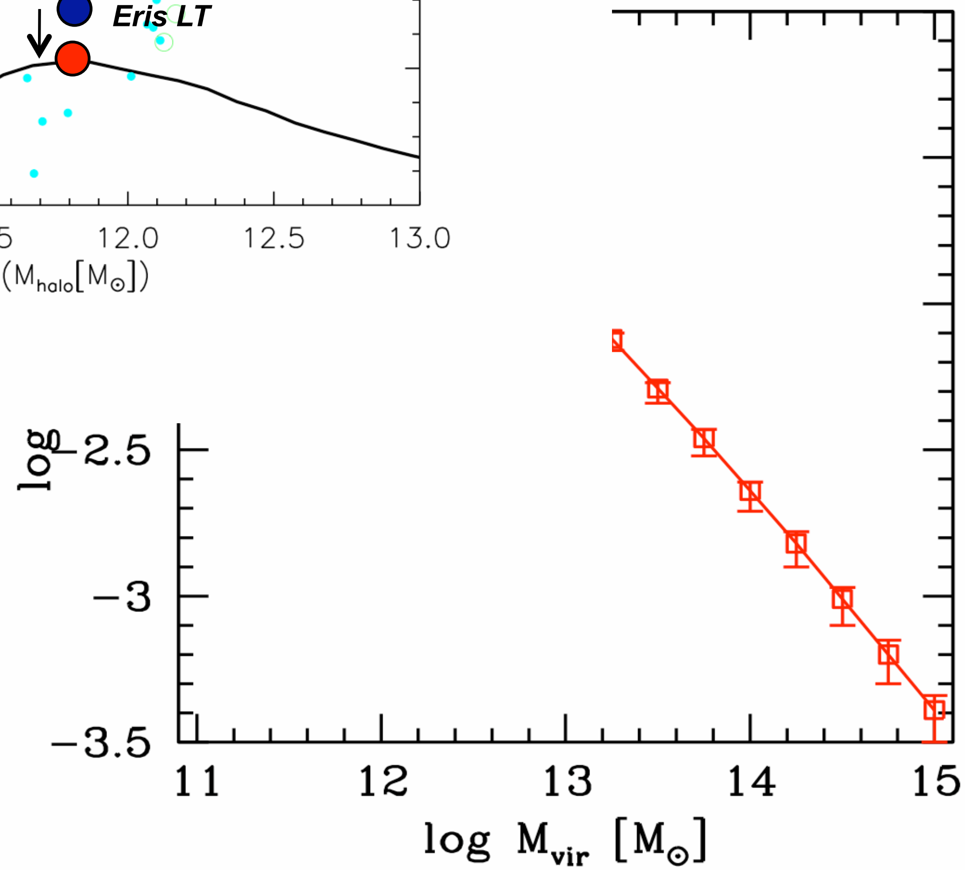
stellar
→

Behroozi et al. 2010
ic mass of 3.2×10^{10}

Guo et al. 2010



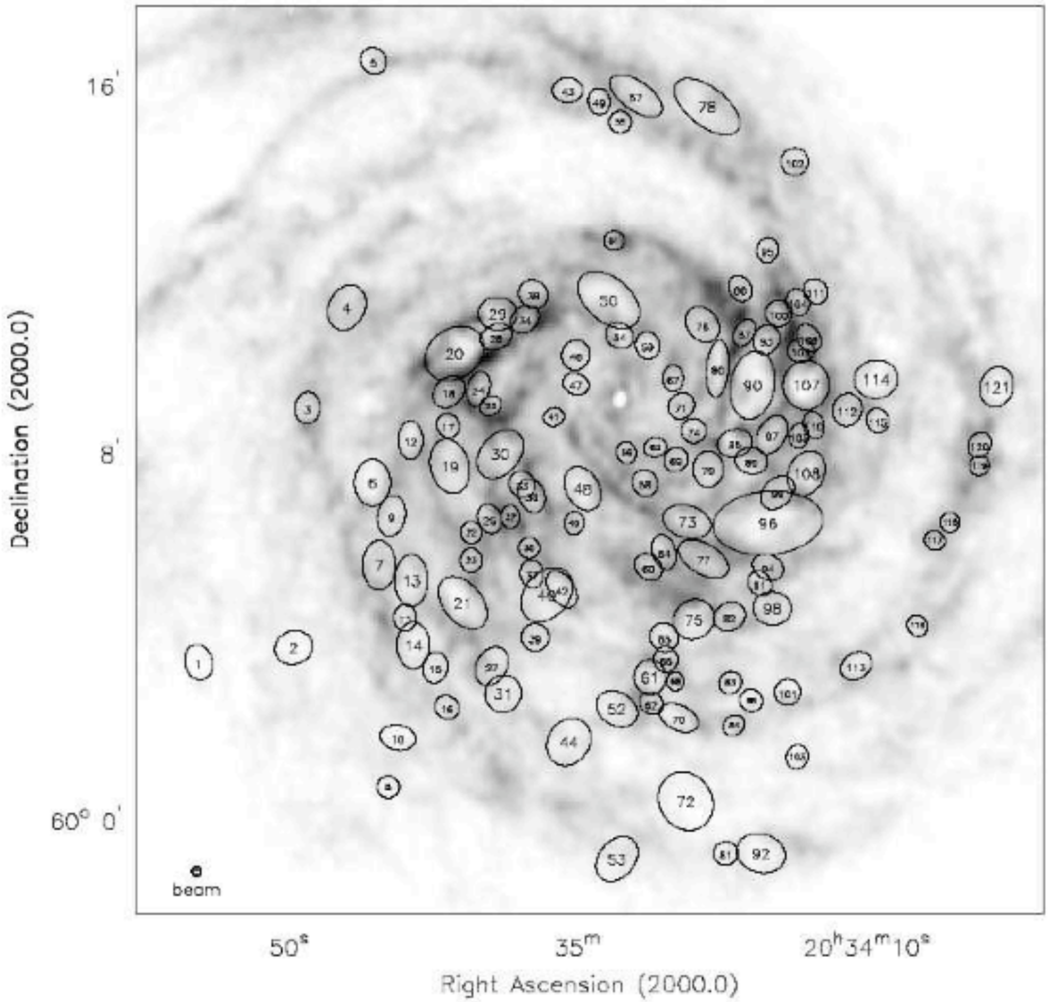




Gas Content and Distribution

HI disks observed in nearby face-on spirals extend further than the stellar disk have a distribution of holes with mean diameter ~1 kpc. ***Boomsma et al. 2008***

HI map of NGC 6946



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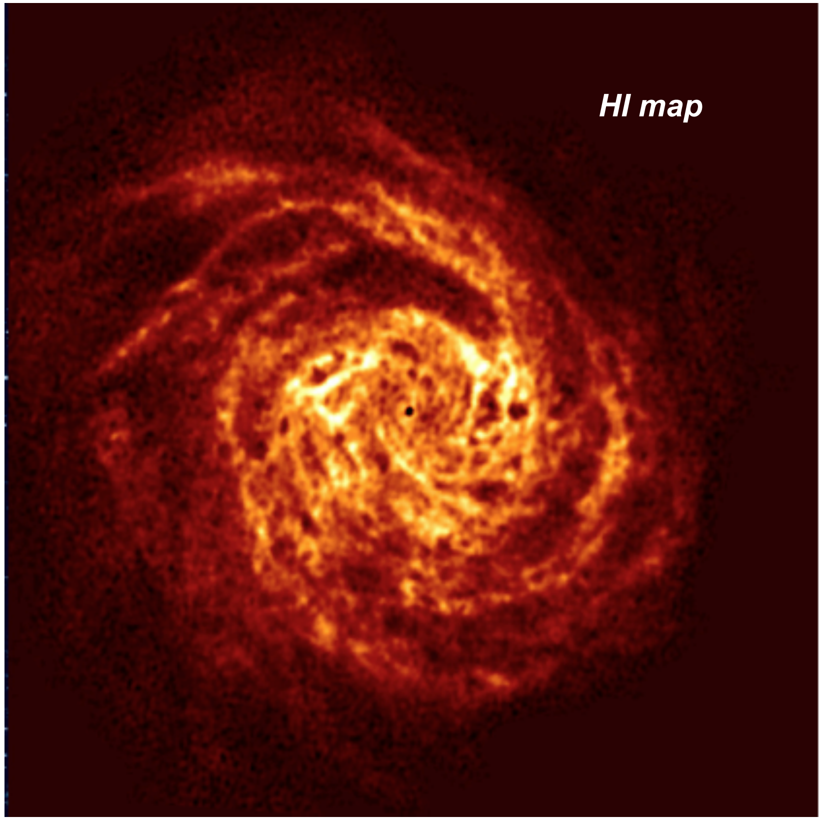
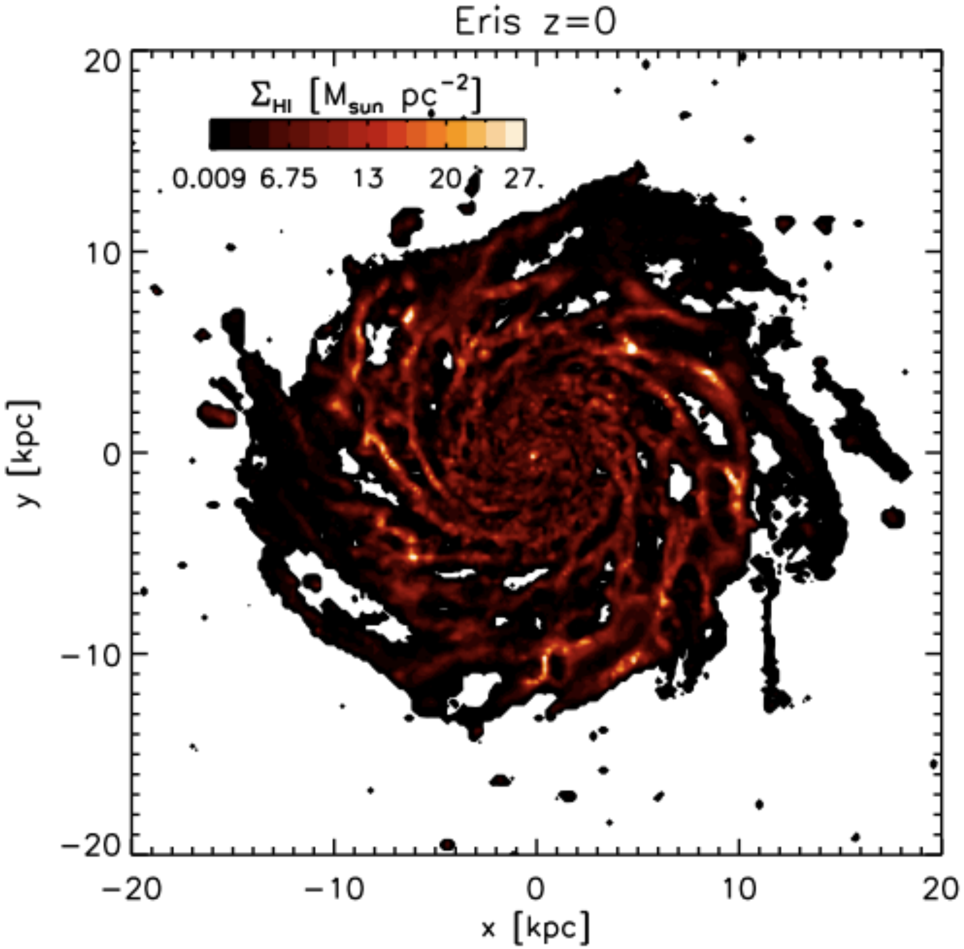
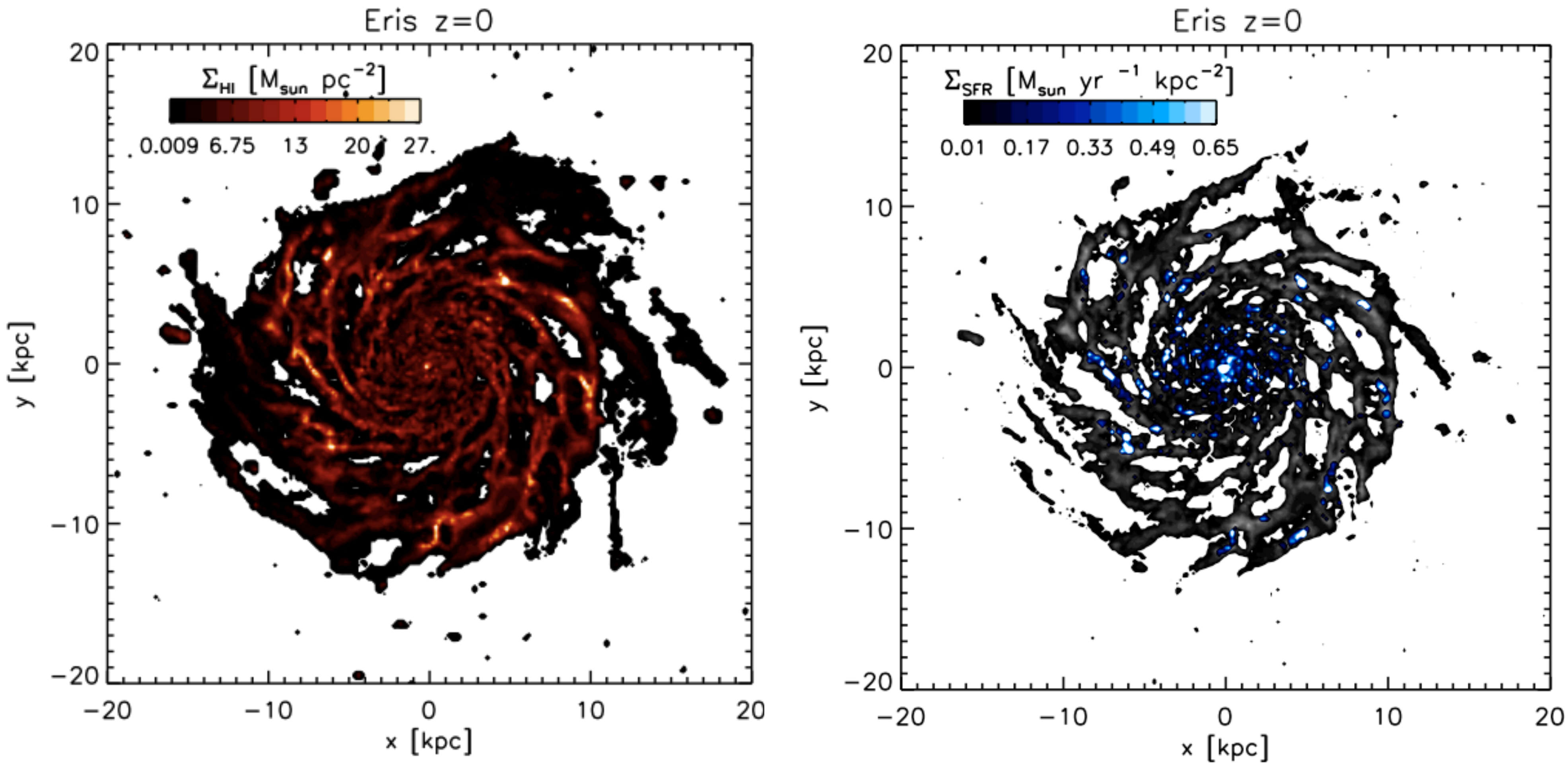
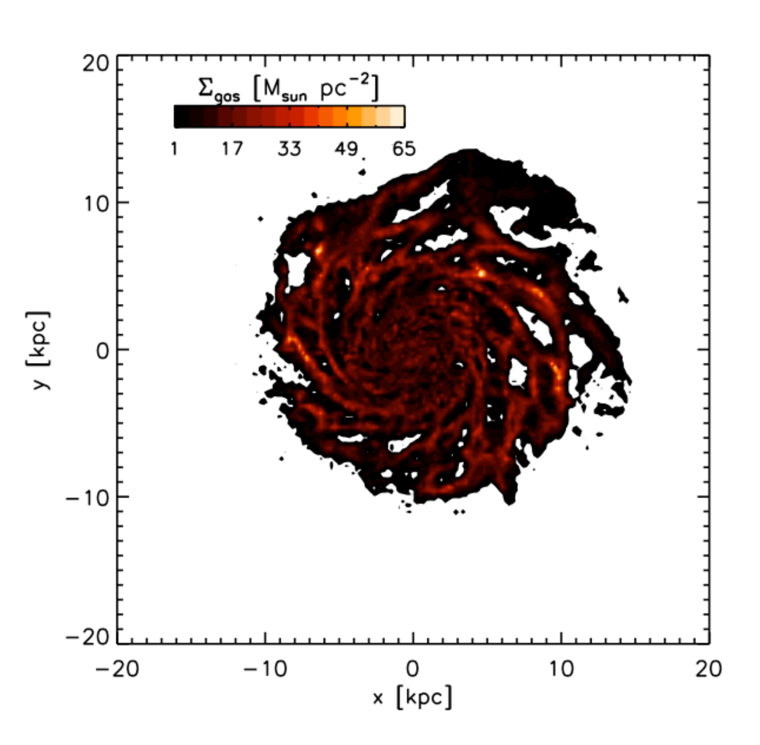


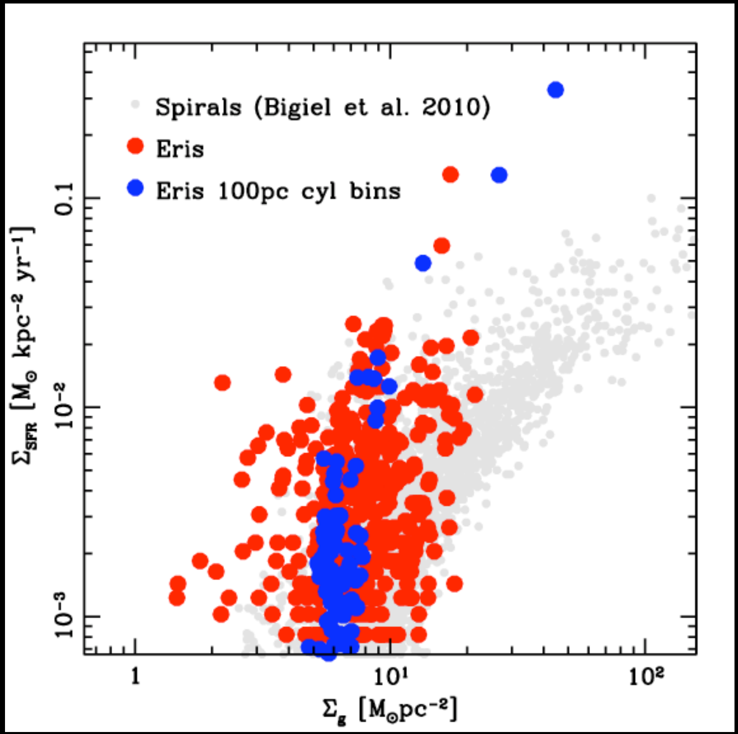


Star formation occurs at the peaks of the HI distribution.



Gas Content and SFR: success with caveats





(1) HI gas/stars fraction = 0.049 in agreement with median in GASS survey for galaxies of comparable stellar mass (Catinella et al. 2010)

(2) Mean SFR ~ 1.1 Mo/yr as in MW (SFR=0.68-1.45 Mo/yr – Robitaille & Whitney 2010)

SFR-total gas density diagram shows lack of high density gas, but:

(a) SF density threshold still not as high as in GMCs (H_2 formation model not necessarily required)?

(b) lack of self-shielding in cold atomic phase?

(c) Cloud condensation scale still limited by gravitational softening (120 pc)?

Conclusions and Outlook

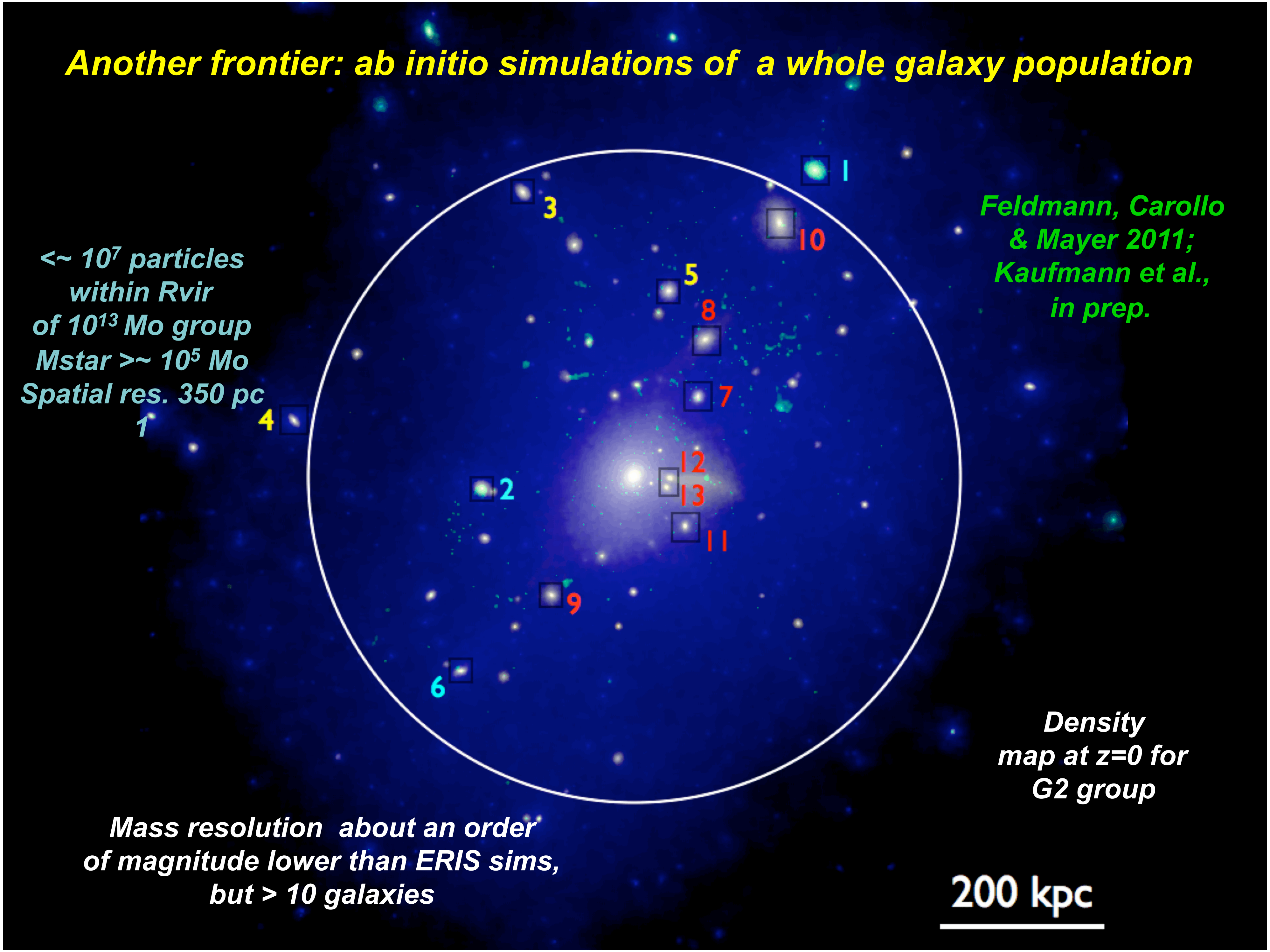
- Adopting a high SF density threshold approaching that of GMCs coupled with blastwave feedback appears to simultaneously solve all the major problems of disk galaxy formation at both large and small scales **and without fine tuning of parameters when moving across almost two decades in mass**

- **Key is stronger effect of outflows due to more clustered star formation in inhomegeneous ISM** -→ decreases baryon fraction, preferentially remove low angular momentum gas, reduce rate of conversion of gas into stars (gas/stars ratio increases), even make cores in low mass galaxies

- ***Is our success a fluke, perhaps because Eris selected with exceptionally quite merging history?*** New IC with typical merging history for ~10^{12} Mo in preparation (last major merger at z ~ 1.5, see Stewart et al. 2008)

- In the local volume (8 Mpc) many massive spirals are Sc or Sd (B/D < 0.1 – see eg Kormendy et al. 2011) how do we get those? *Perhaps more mergers lead to decrease of B/D as a result of more efficient outflows from repeated starbursts* (*suggested by evoluton of photometric B/D in Eris*) *-→ also need to explore range of ICs*

More puzzling: LSBs – difficult to fit in a "merger-triggered outflows" picture (see R. Kuzio del Naray's talk yesterday)


Another frontier: ab initio simulations of a whole galaxy population
<~ 10^7 particles
within Rvir
of 10^{13} Mo group
Mstar >~ 10^5 Mo
Spatial res. 350 pc
1
Feldmann, Carollo
& Mayer 2011;
Kaufmann et al.,
in prep.
1
3
10
5
8
7
4
12
2
13
11
9
6
Density
map at z=0 for
G2 group
Mass resolution about an order
of magnitude lower than ERIS sims,
but > 10 galaxies
200 kpc

A ZOO OF MORPHOLOGIES....See poster by Robert Feldmann!