Do baryons dominate the centres of high-redshift galaxies?

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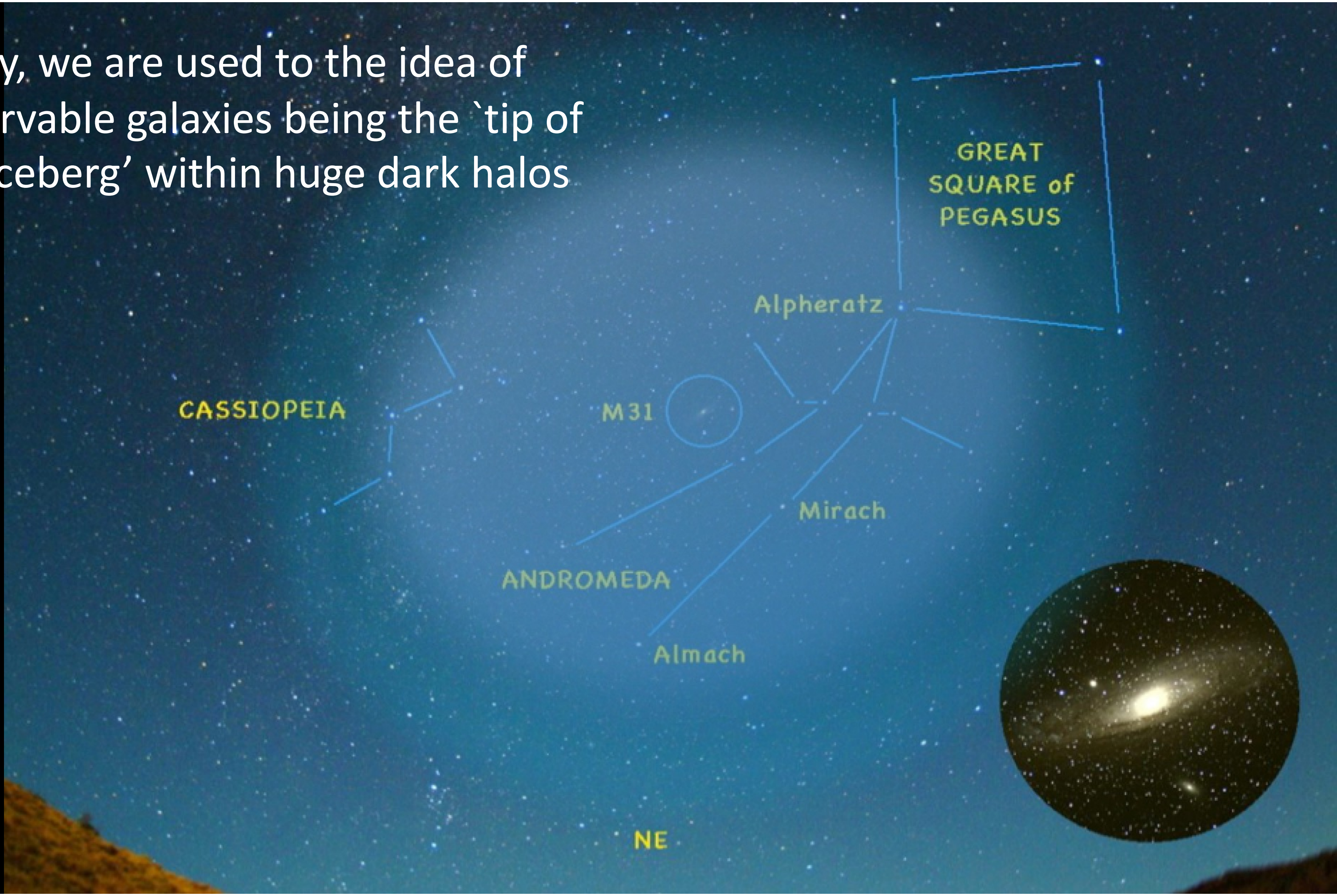
With **Thor Tepper-Garcia**, Oscar Agertz, Ken Freeman

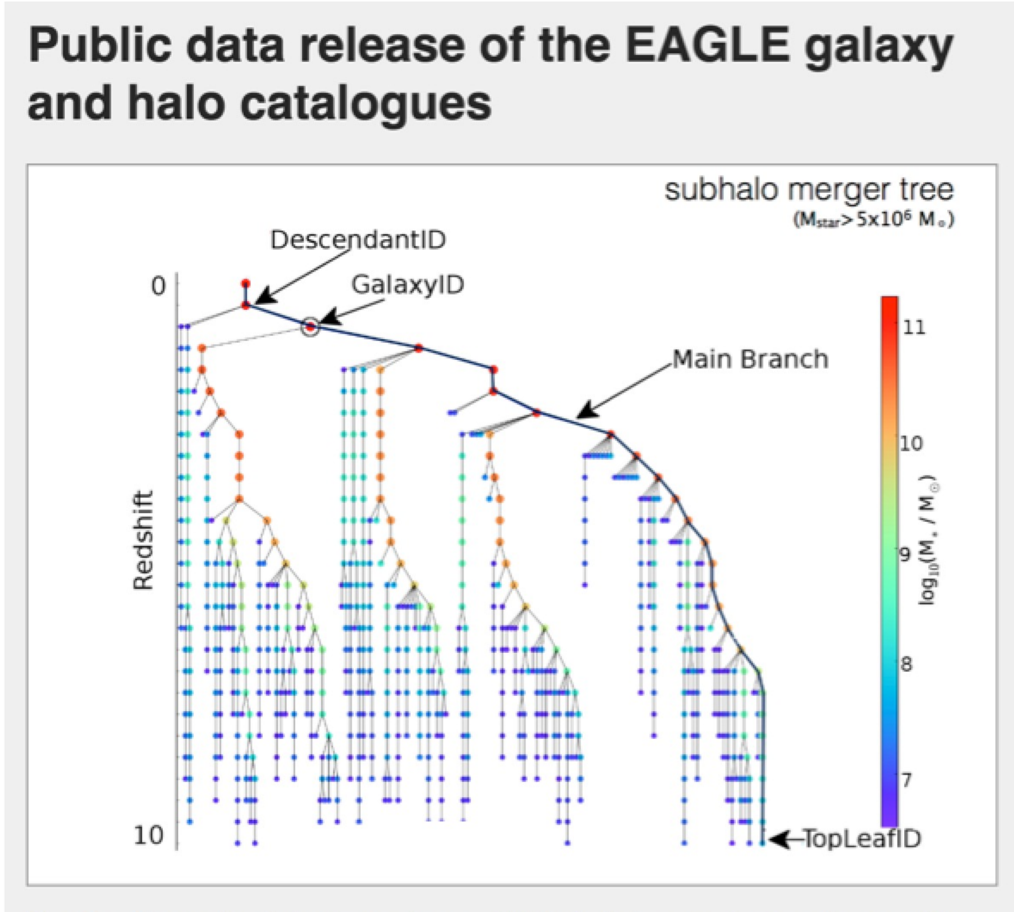
Presented for the first time as a seminar; my thanks to hosts Alejandra & Patrick for the invitation to speak.

Today, we are used to the idea of observable galaxies being the `tip of the iceberg' within huge dark halos



We also know about the merging CDM hierarchy. Semi-analytic models work with merger trees, either from expensive N-body simulations, or inexpensive Press-Schechter codes.

Benedikt Diemer (U. Maryland)



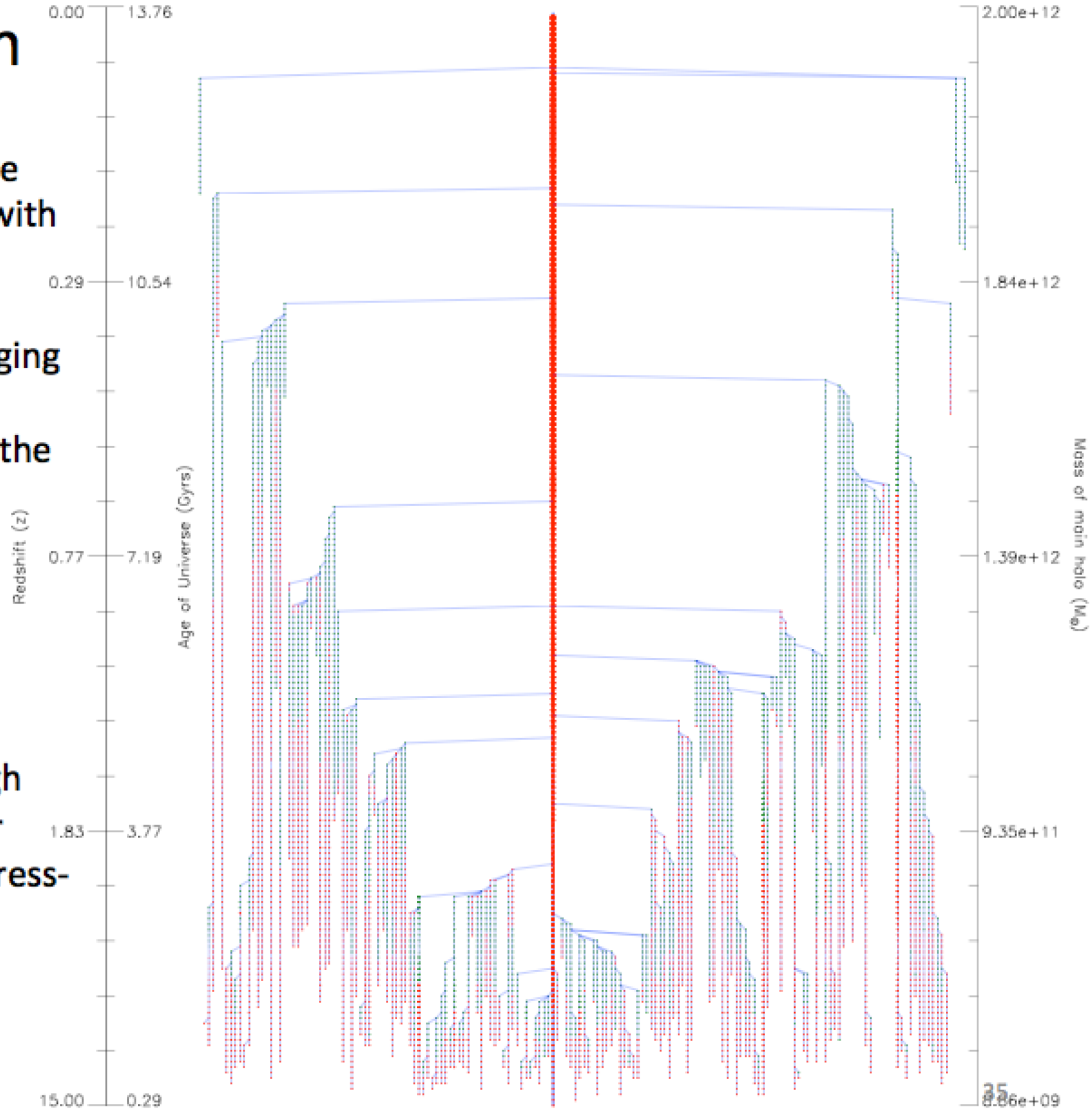
CDM simulation

In the Millenium movie, we see how dark halos grow with cosmic time.

This schematic tracks merging DM blobs with time. The galaxy (red) is growing up the middle.

In fact, this plot was not made from an N-body simulation.

It was made purely through running a random number generator and using the Press-Schechter theory.



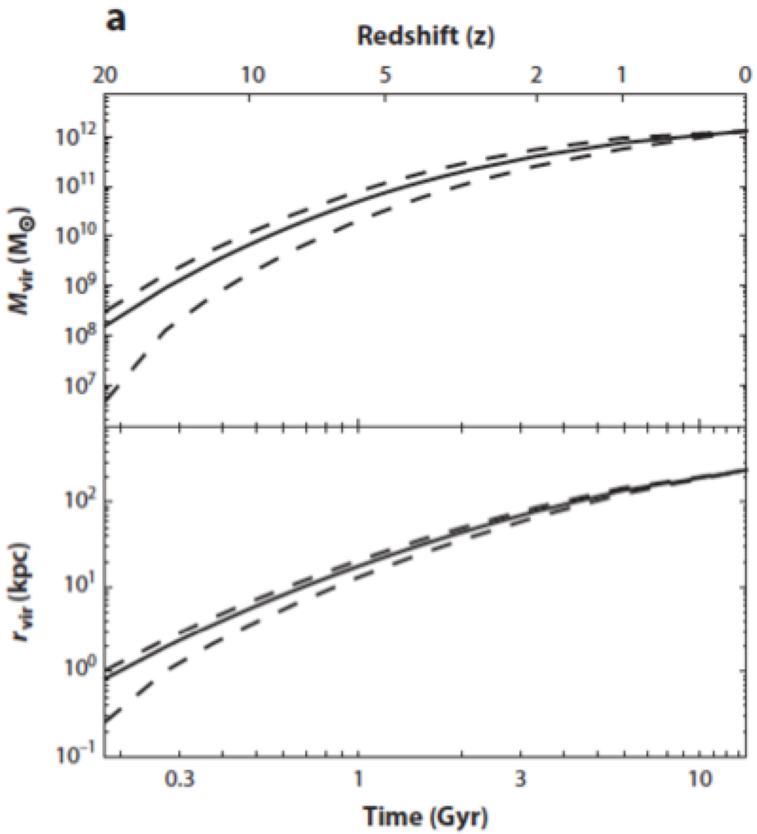


Figure 1

The Galaxy in Context: Structural, Kinematic, and Integrated Properties

Joss Bland-Hawthorn[1] and Ortwin Gerhard[2]

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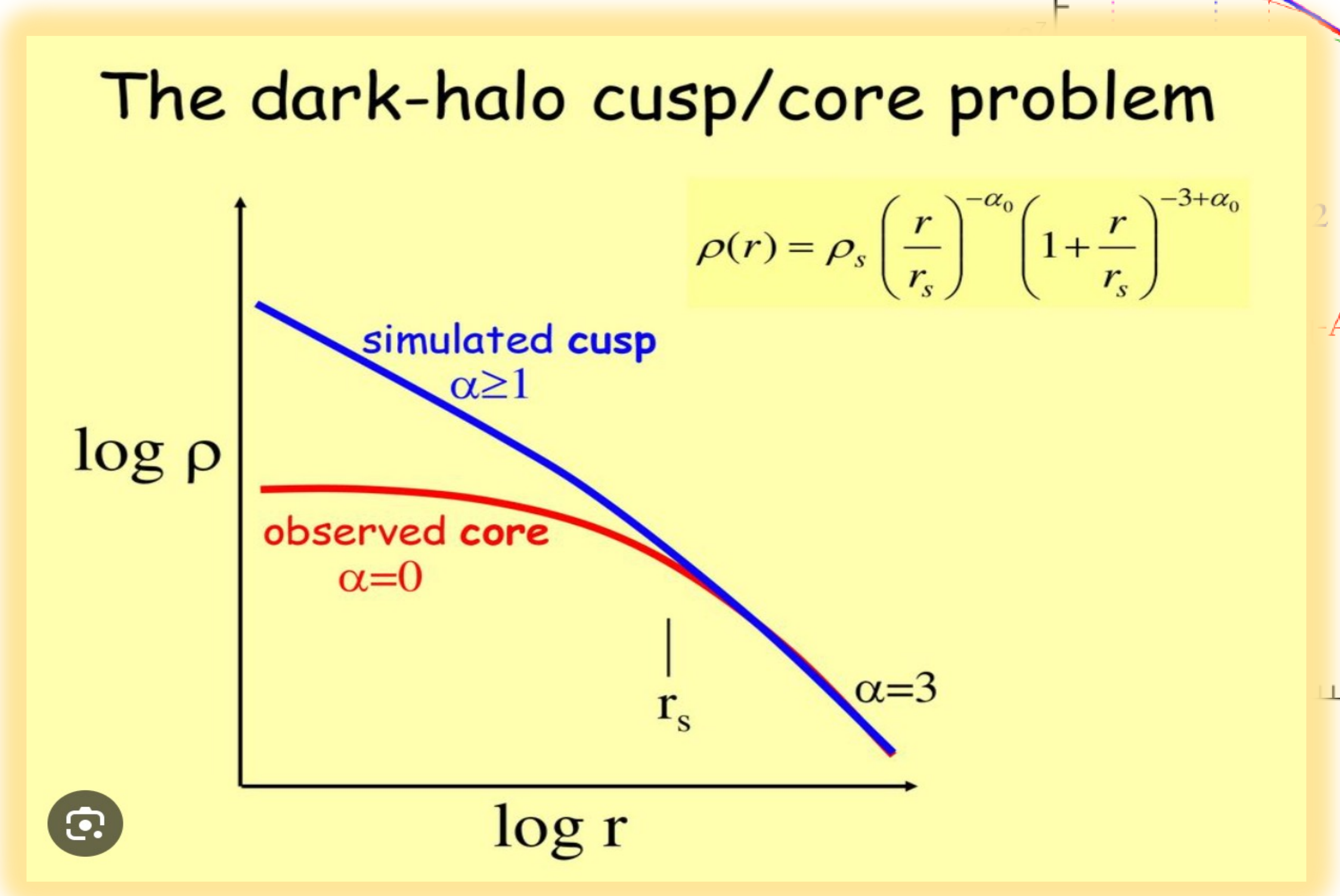
We ran the Press-Schechter code from Parkinson et al (2008) roughly 2000 times at each of z = 20, 15, 12, 10, ... 1

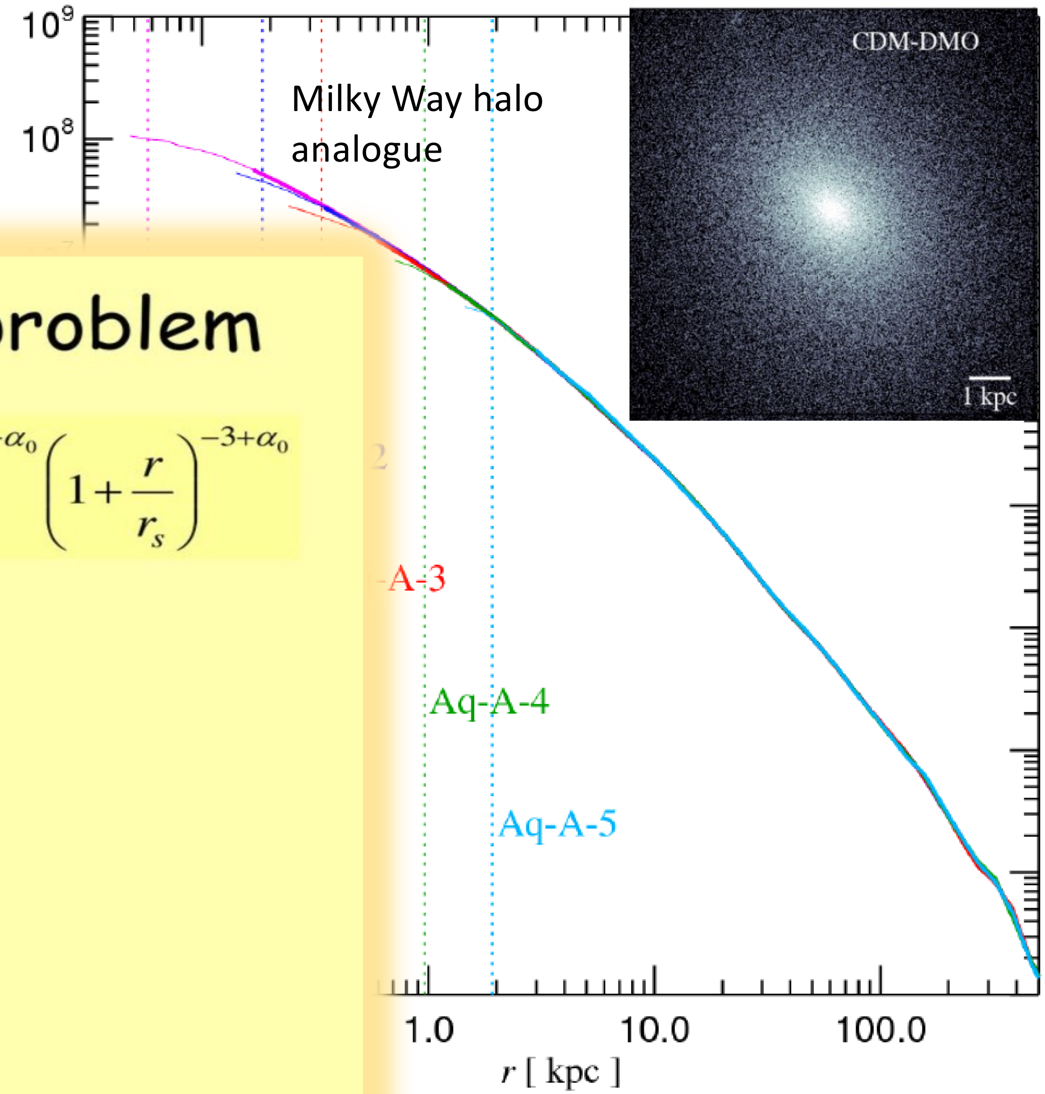
Here we show the mean trend and 1σ spread about the mean.

Virial mass within a virial radius is just the domain over which collapsing stuff has virialized = stabilized.

2016 Annual Reviews of Astronomy & Astrophysics

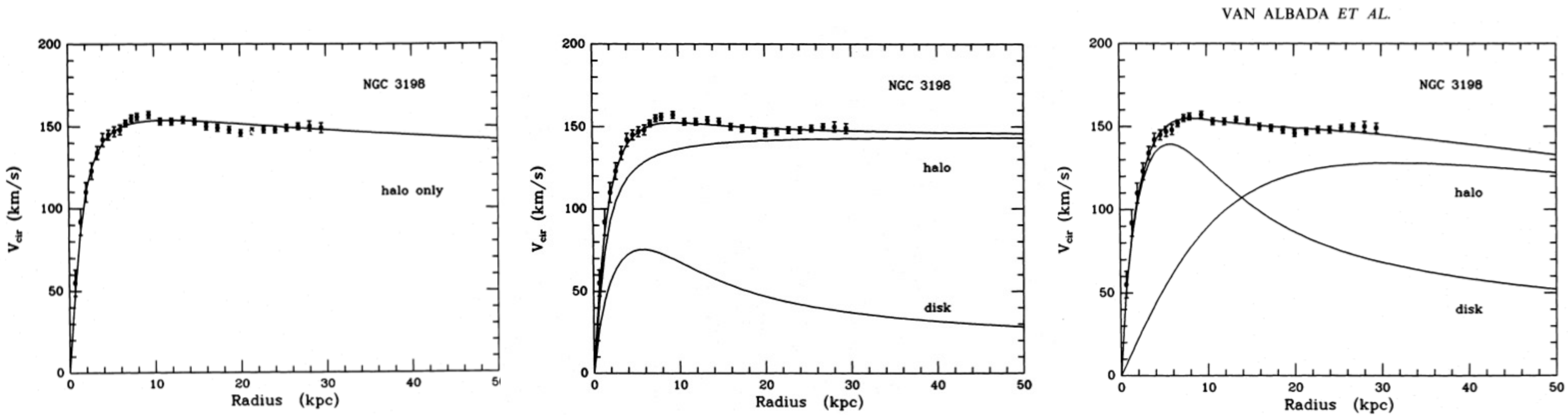
NFW 1990s





Aquarius project:
different resolutions

NFW is an important step. The expectation was that halos were self-similiar on all scales. This created an industry of `rotation curve' fitting in galaxies, e.g. **minimum vs. maximum discs.**



Kalnajs 1983: the substantial wiggles argue for baryons being important

So we know a great deal about **CDM evolution** across the full self-similar hierarchy, assuming it's not fuzzy or decaying.

That does ***not*** mean we know much about **galaxy formation & evolution.**

DM drives structure formation, but baryons introduce orders of magnitude more complexity, which we must truly understand to get to galaxies (and stars!).

In the near field, we have long known that baryons dominate at the centre – *not* DM. How far back does this go ?

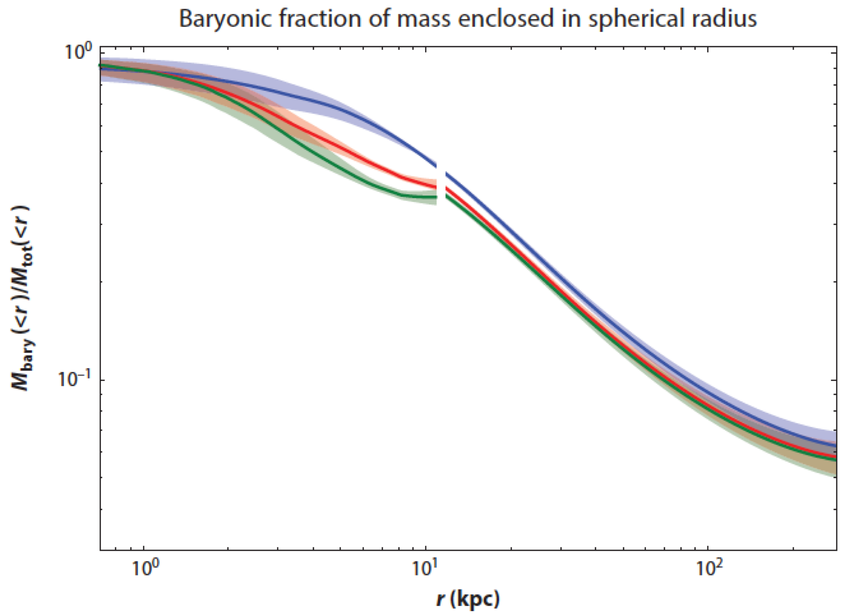


Figure 17

Fraction of baryonic mass within radius r including the stellar and cold gas mass from the dynamical models shown in **Figure 16** and the additional mass in hot gas predicted by Tepper-Garcia et al. (2015) with an assumed uncertainty of 35% (Section 6.2).

How dynamically dominant are the baryons?

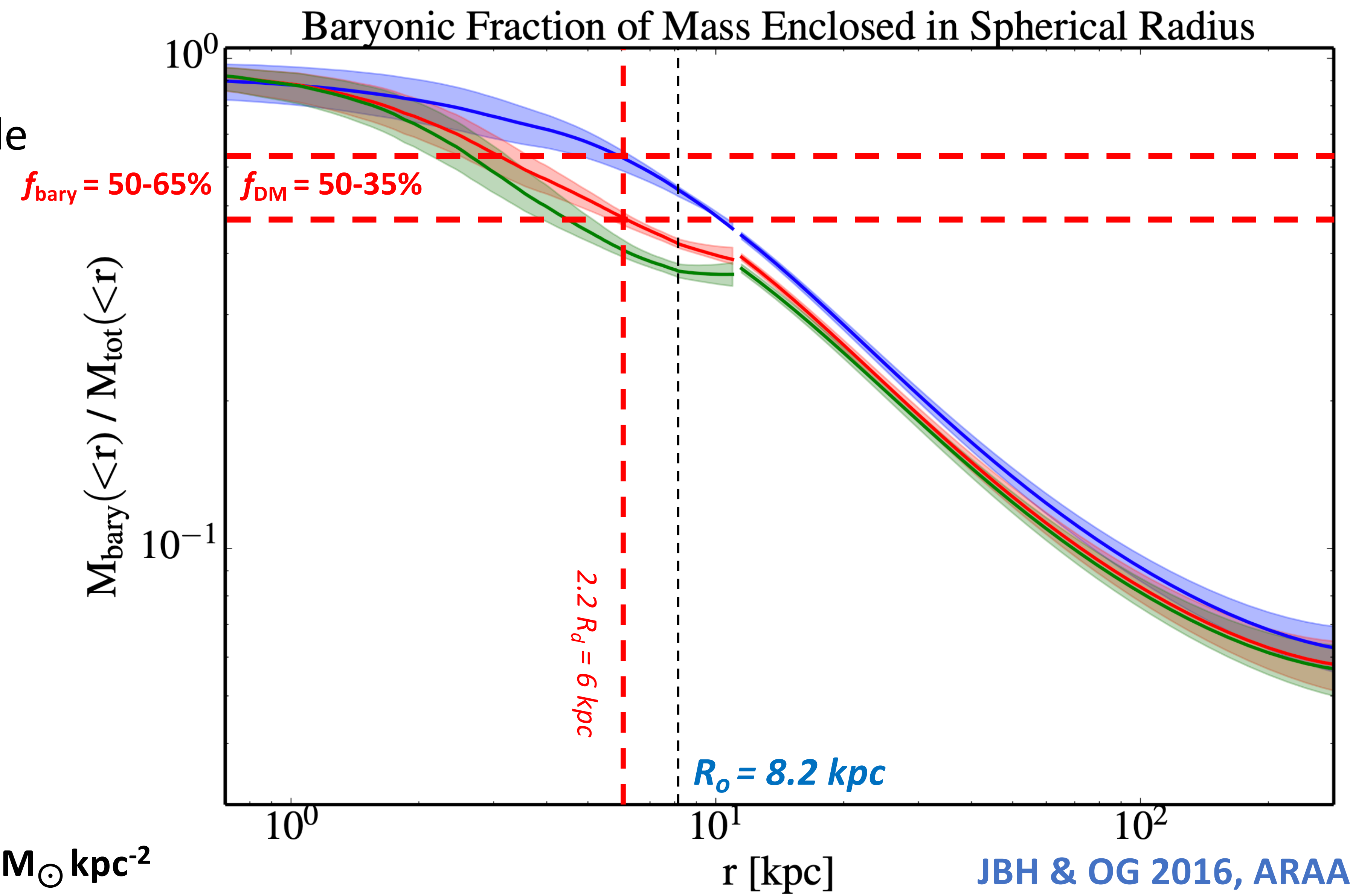
This is an important factor for how discs evolve in cosmic time.

$$f_{\rm disk} = \left(\frac{V_{\rm c,disk}(R_s)}{V_{\rm c,tot}(R_s)} \right)^2_{R_s=2.2R_{\rm disk}}$$

Another crucial factor is the gas fraction.

$$f_{\rm gas} = \left(\frac{M_{\rm disk,gas}}{M_{\rm disk}} \right)$$

Milky Way
baryon/dark matter profile



R_d = 2.6 kpc
f_{disk} = 50%
f_{gas} = 10-20%

Σ_{bary} = 3 x 10^8 $M_\odot$ kpc^{-2}

JBH & OG 2016, ARAA

So when did galaxy discs first emerge ?

When did **baryon discs** first dominate over **dark matter** ?
How ancient is this signature ?

Annu. Rev. Astron. Astrophy. 2014 1056-8700/97/0610-00

The Evolution of Galaxy Structure over Cosmic Time

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Centre for Astronomy and Particle Theo
School of Physics and Astronomy
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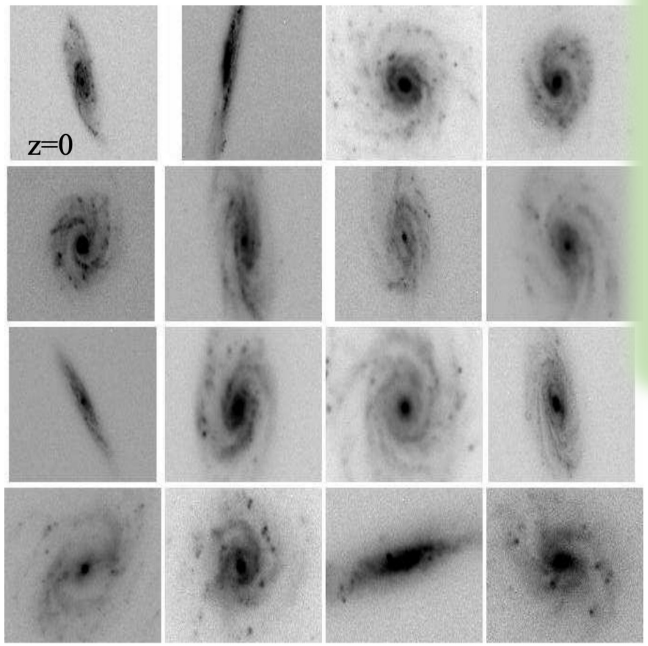
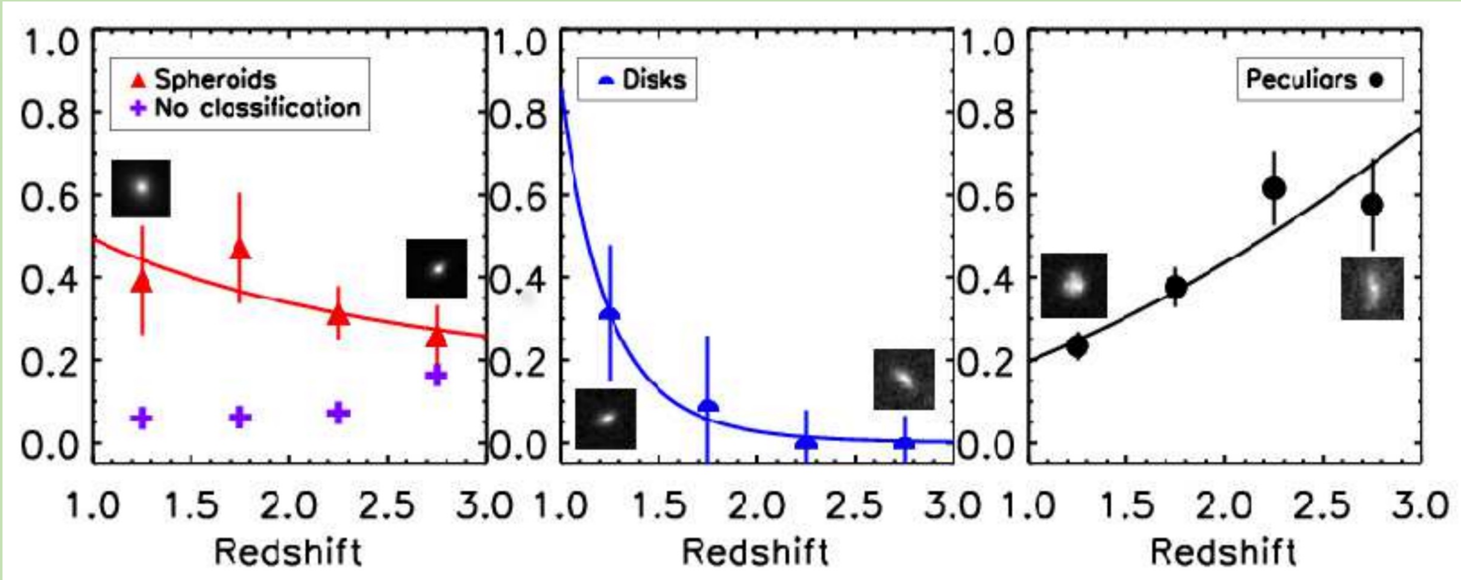
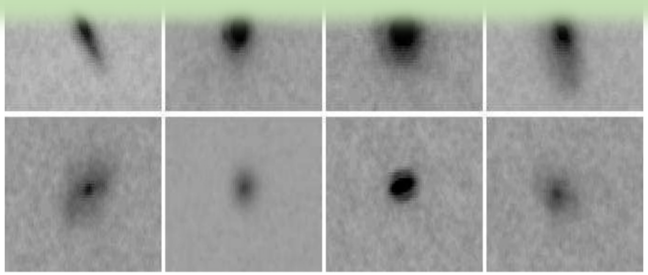
Just nine years ago, we thought that most discs appeared after z ~ 1, and simulators made sure that this was the case!







Near-field galaxies degraded to expected HUDF in rest frame B.

But there is a case for earlier discs, both from observations and a select few simulations.

ALMA Reveals Potential Evidence for Spiral Arms, Bars, and Rings in High-redshift Submillimeter Galaxies

J. A. Hodge[1], I. Smail[2,3], F. Walter[4], E. da Cunha[5], A. M. Swinbank[2,3], M. Rybak[1], B. Venemans[4], W. N. Brandt[6,7,8], G. Calistro Rivera[1], S. C. Chapman[9], Chian-Chou Chen[10], P. Cox[11], H. Dannerbauer[12,13], R. Decarli[14], T. R. Greve[15,16,17], K. K. Knudsen[18], K. M. Menten[19], E. Schinnerer[5], J. M. Simpson[20], P. van der Werf[1], J. L. Wardlow[21], and A. Weiss[19]

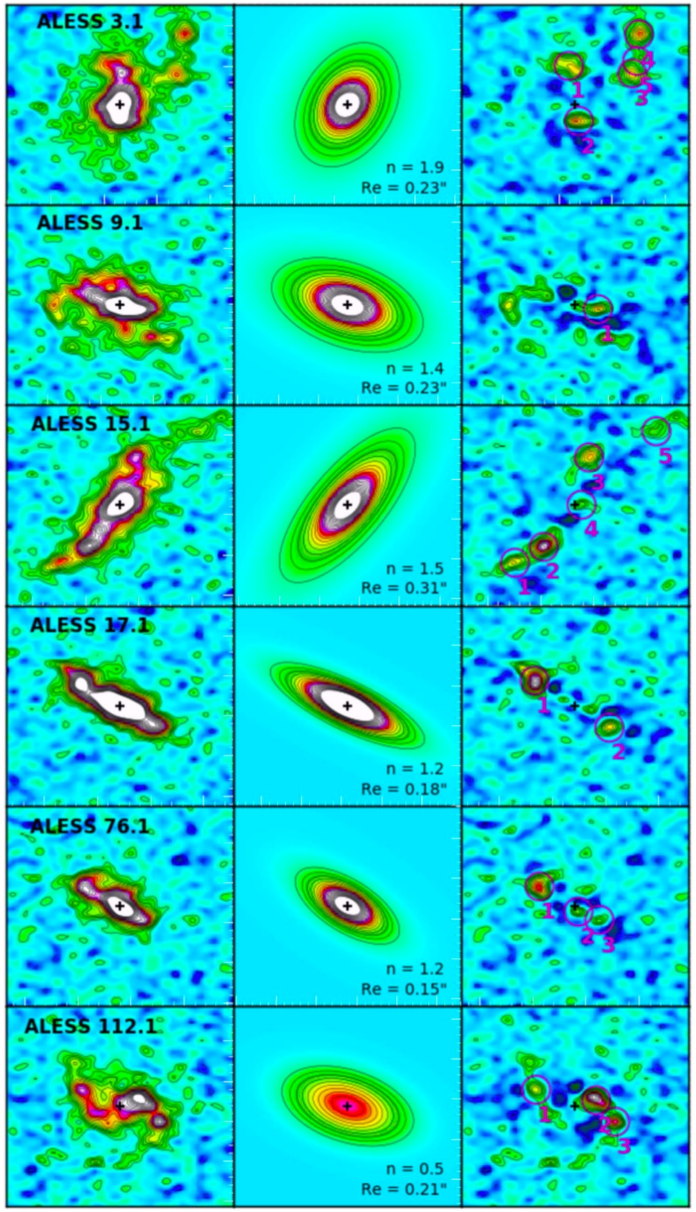
2016, 2019

These authors targetted **z=1-5** sub-mm sources, i.e. massive galaxies with high star formation rates. These were found to be disc-like, and subsequently well-ordered rotators, even with the blobby appearance.

Table 1
Galaxy Properties

Source ID[a]	z[b]	z_{source}[b]	$\log(M_*/M_\odot)$[c]	$\log(\mathrm{SFR}/M_\odot\ \mathrm{yr}^{-1})$[c]	T_{dust}/K[c]
ALESS 3.1	3.374	CO (4–3)	$11.30^{+0.19}_{-0.24}$	$2.81^{+0.07}_{-0.08}$	36^{+5}_{-2}
ALESS 9.1	4.867	CO (5–4)	$11.89^{+0.12}_{-0.12}$	$3.16^{+0.07}_{-0.08}$	51^{+5}_{-4}
ALESS 15.1	2.67	z_{phot}	$11.76^{+0.21}_{-0.26}$	$2.44^{+0.15}_{-0.26}$	33^{+7}_{-4}
ALESS 17.1	1.539	Hα, CO (2–1)	$11.01^{+0.08}_{-0.07}$	$2.29^{+0.02}_{-0.03}$	28^{+6}_{-0}
ALESS 76.1	3.389	[O III]	$11.08^{+0.29}_{-0.34}$	$2.56^{+0.11}_{-0.12}$	37^{+10}_{-4}
ALESS 112.1	2.315	Lyα	$11.36^{+0.09}_{-0.12}$	$2.40^{+0.07}_{-0.08}$	31^{+5}_{-2}

Some ALMA `discs' are now claimed up to z ~ 9 (Inoue et al 2023).



Disc formation and the origin of clumpy galaxies at high redshift

Oscar Agertz,[1★] Romain Teyssier[1,2] and Ben Moore[1]
[1]*Institute for Theoretical Physics, University of Zürich, CH-8057 Zürich, Switzerland*
[2]*CEA Saclay, DSM/IRFU/SAp, Batiment 709, 91191 Gif-sur-Yvette Cedex, France*

2009, 2011

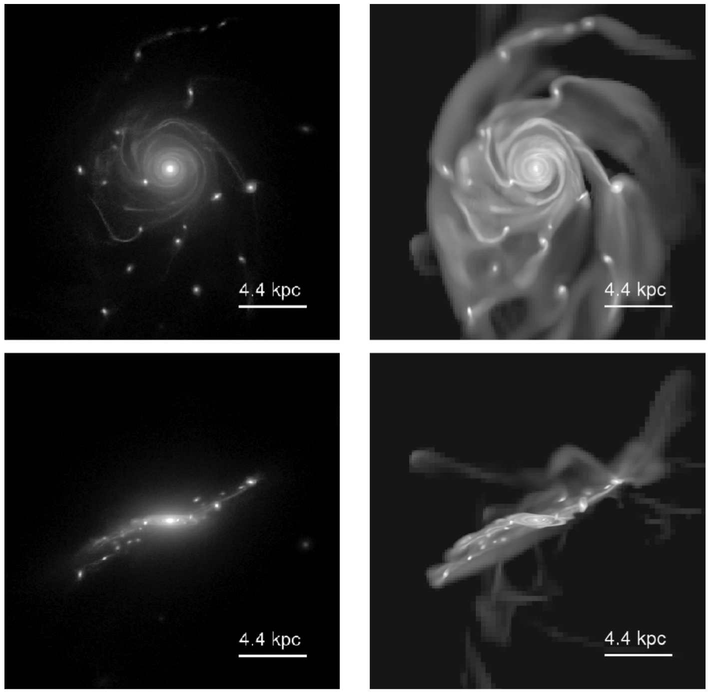
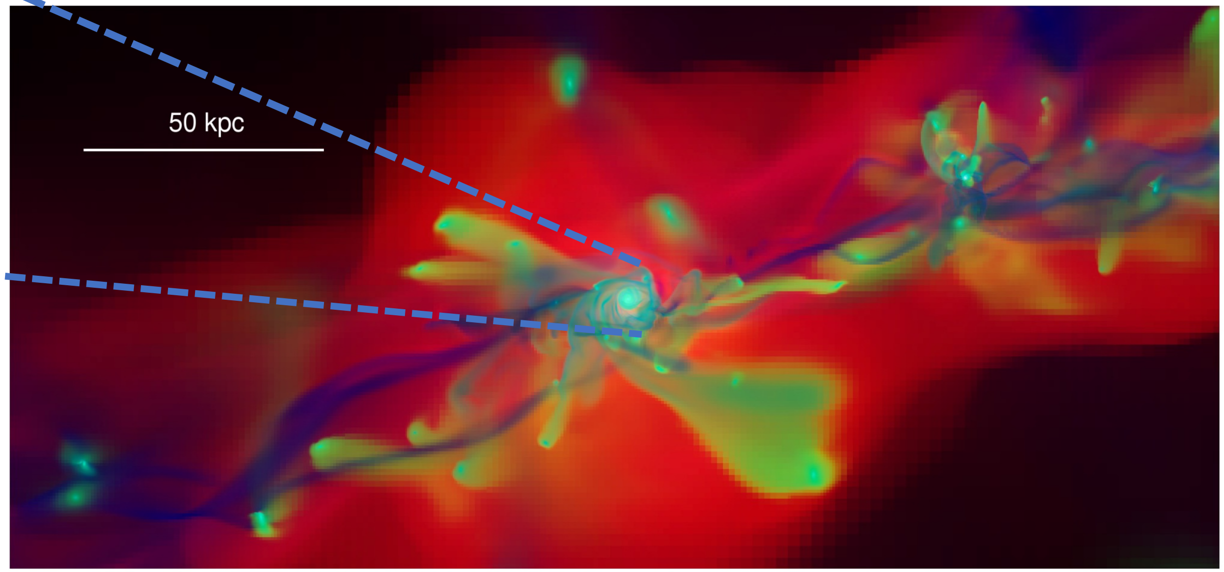


Figure 3. Density projection of the stars (left-hand panels) and gas (right-hand panels) at $z \sim 2.7$ illustrating the fragmentation process and the formation of large clumps of mass $\sim 10^7$–10^9 $M_\odot$.



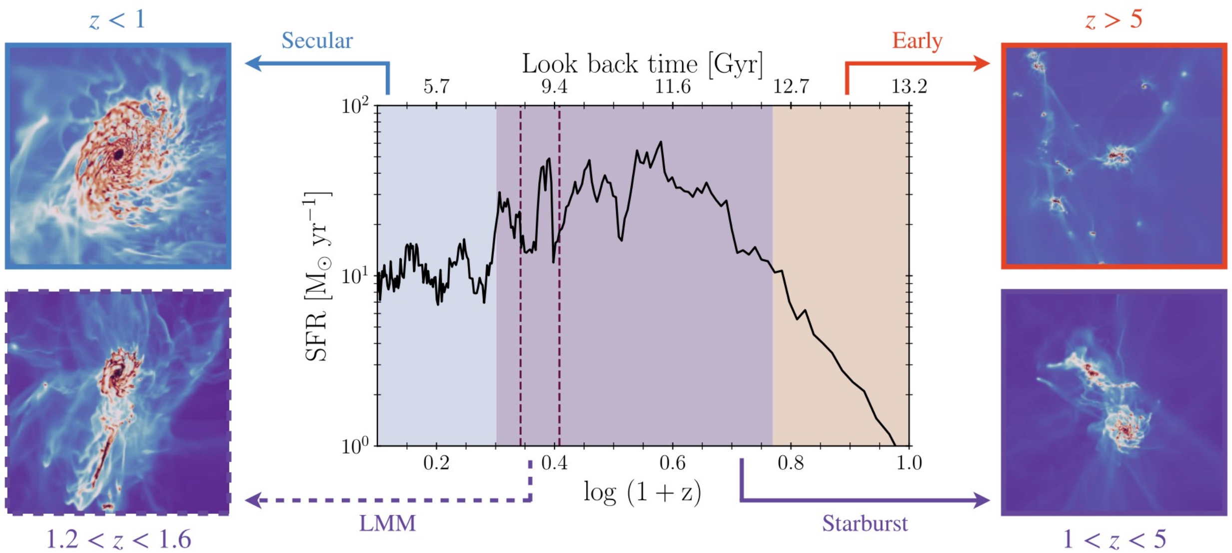
This beautiful work showing **cool flows** (in blue) was the first to run AMR hydrodynamics to z ~ 0. They predicted z ~ 3 discs.

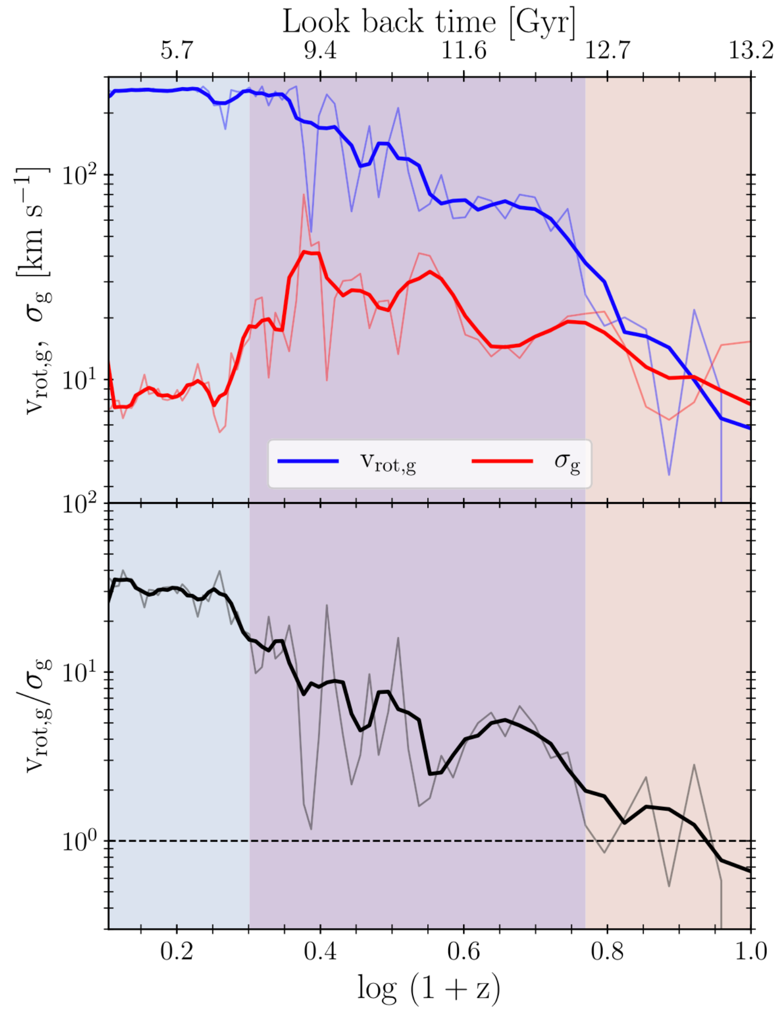
VINTERGATAN IV: Cosmic phases of star formation in Milky Way-like galaxies

Álvaro Segovia Otero ,★ Florent Renaud and Oscar Agertz
Department of Astronomy and Theoretical Physics, Lund Observatory, Box 43, SE-221 00 Lund, Sweden

2022

In view of ALMA discs, their follow-up papers argue for gas discs with ordered rotation, moderate gas dispersion, by z~6. **See also the latest FIRE paper by Gurvich et al (2022).**





So what are we learning ?

Early discs exist and may even be widespread.

Baryons got in early and maybe even dominated the centres of massive forming galaxies from the start.

What does JWST have to say ?

The Astrophysical Journal Letters, 946:L15 (17pp), 2023 March 20

see also: Ferreira et al 2022, next slide.

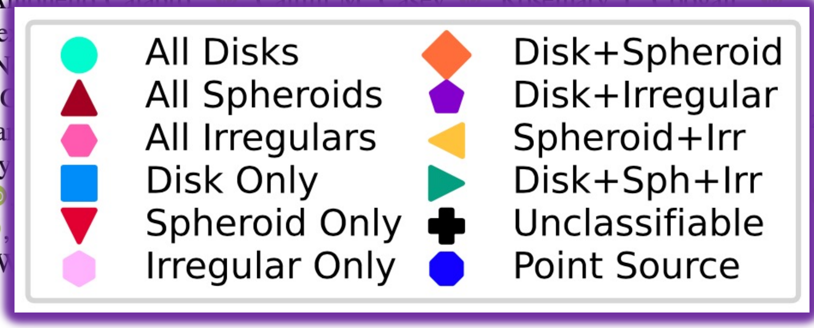
Disc-like galaxies

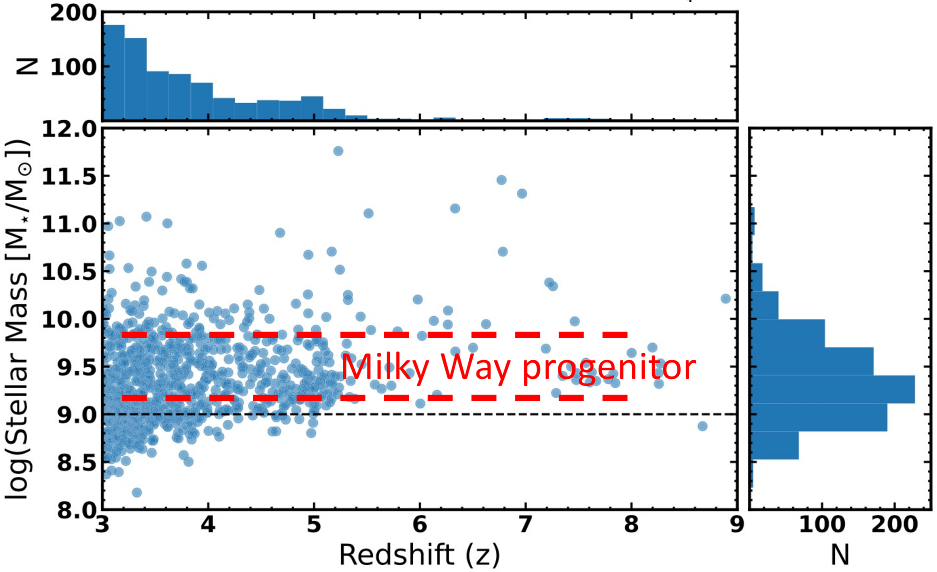
60% @ z ~ 3-6
30% @ z ~ 6-9

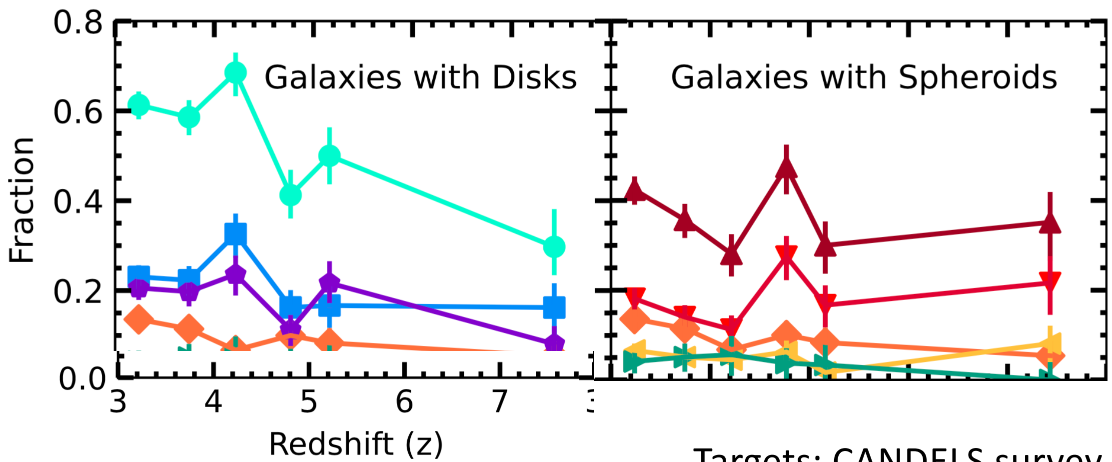
(also ALMA results)

CEERS Key Paper. III. The Diversity of Galaxy Structure and Morphology at $z = 3–9$ with JWST

Jeyhan S. Kartaltepe[1], Caitlin Rose[1], Brittany N. Vanderhoof[1], Elizabeth J. McGrath[2], Luca Costantin[3], Isabella G. Cox[1], L. Y. Aaron Yung[4,46], Dale D. Kocevski[2], Stijn Wuyts[5], Henry C. Ferguson[6], Micaela B. Bagley[7], Steven L. Finkelstein[7], Ricardo O. Amorín[8,9], Brett H. Andrews[10,11], Pablo Arrabal Haro[12], Bren E. Backhaus[13], Peter Behroozi[14,15], Laura Bisigello[16,17], M. C. Cooper[20], Darren Croton[21,22], Ale
Maximilien Franco[7], Andrea Grazian[17], N
Marc Huertas-Company[25,26,27], Kartheik
Allison Kirkpatrick[30], Anton M. Koekemoer[6], Ja
Camilla Pacifici[6], Viraj Pandya[33,47], Casey
Jayse Petersen[1], Nor Pirzkal[6], Marc Rafelski[6,36]
Rachel S. Somerville[37], Elizabeth R. Stanway[38]
Jesús Vega-Ferrero[25], Stephen M. V

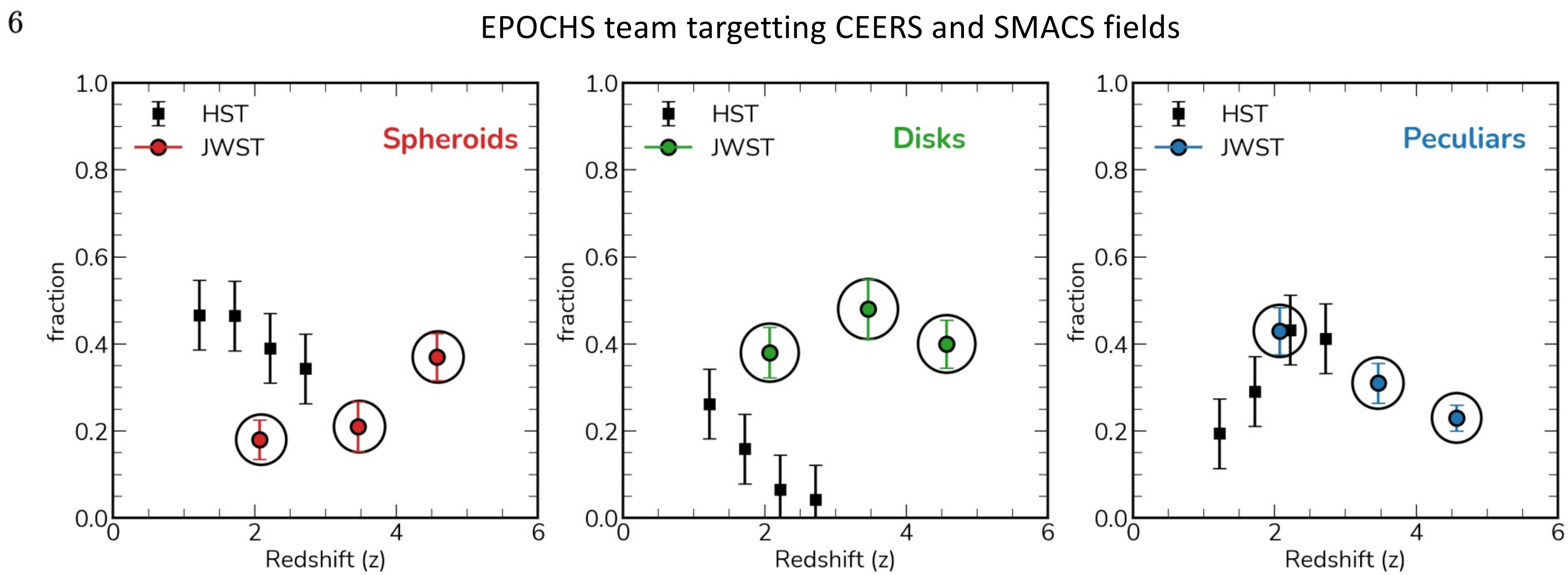






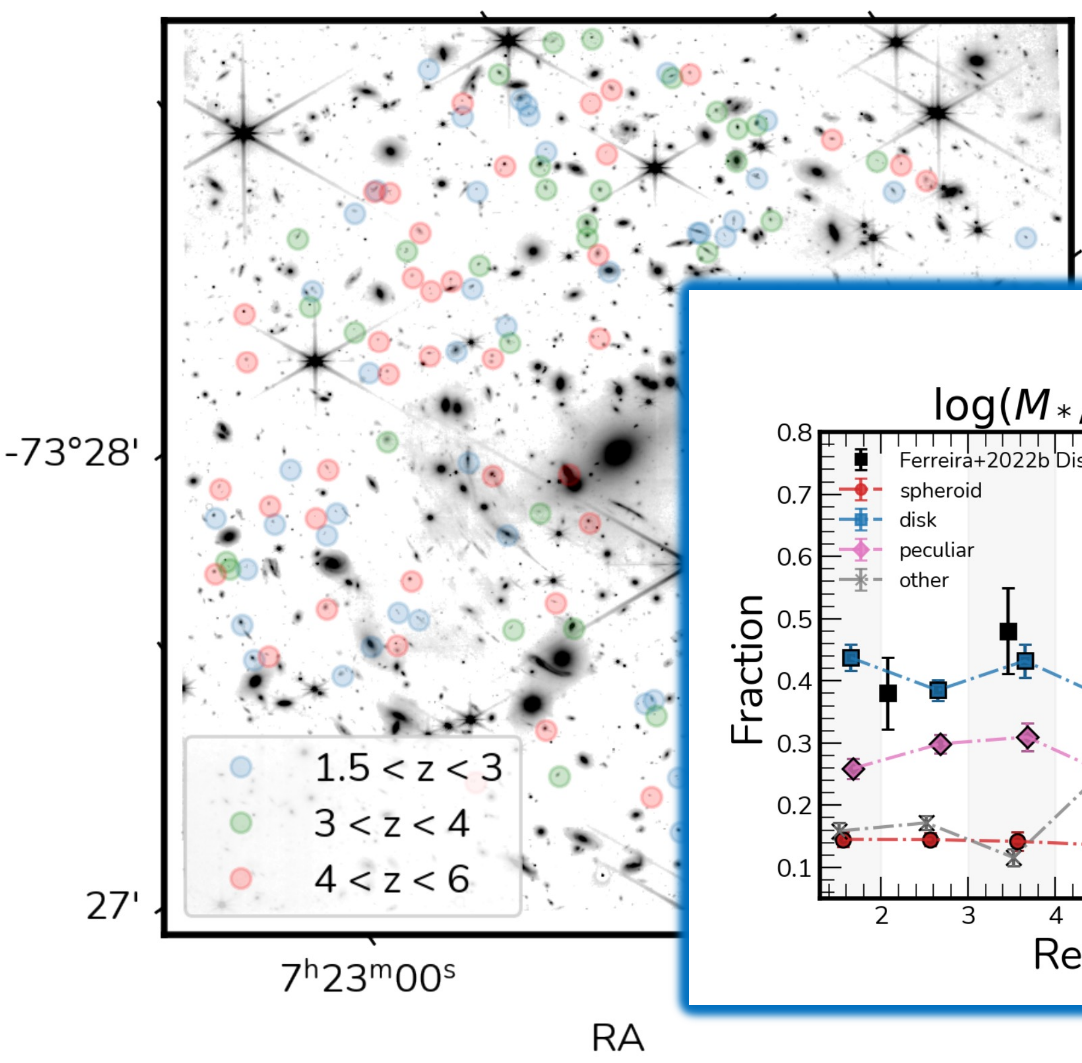
Targets: CANDELS survey

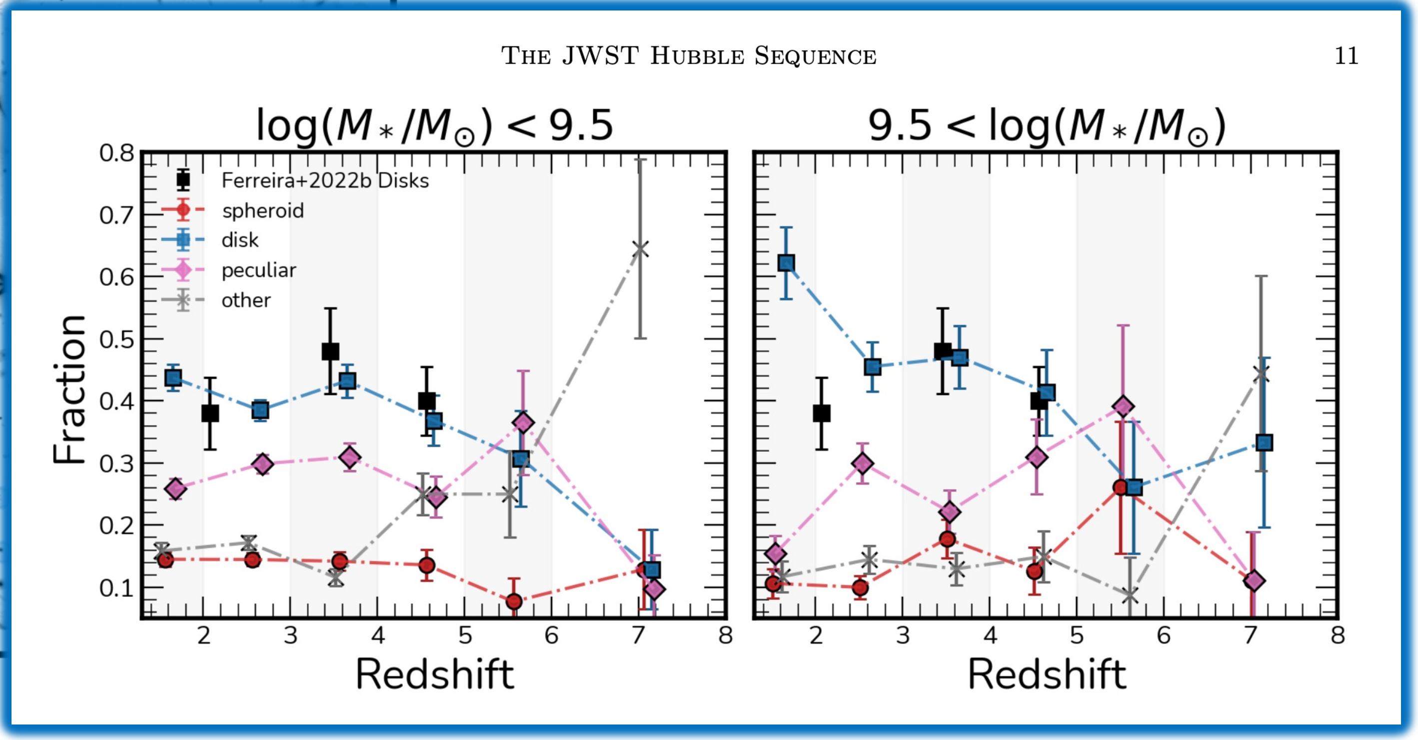
HST imaging surveys got this wrong! – the Universe likes to make discs, and got started at early times.



Ferreira et al 2022: what I like about this paper is one of the key authors is Chris Conselice who was responsible for the HST measurements. Bravo - this is good science !

Results same for low/high mass





Ferreira et al 2022

EPOCHS team targetting CEERS and SMACS fields

Dominant discs are *very* responsive to internal or external perturbations.

This is an important factor in how discs evolve in cosmic time. Bars, spiral arms, etc. are a direct consequence.

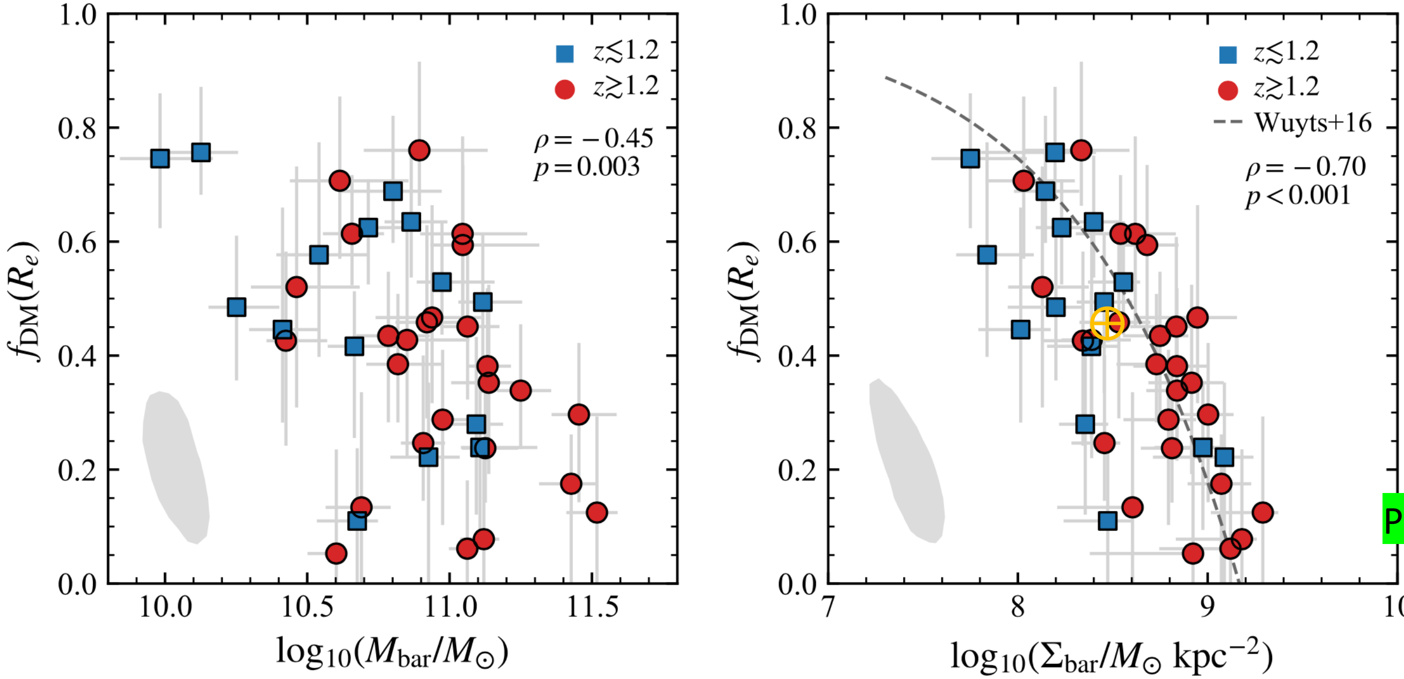
ALMA & IFS kinematics are challenging. We can look for stellar or gas bars to argue for baryon domination *independent of kinematics.*

Here we focus on internally triggered bars (smaller parameter space) but we believe the same result holds true for merger-triggered bars.

THE ASTROPHYSICAL JOURNAL, 902:98 (29pp), 2020 October 20
https://doi.org/10.3847/1538-4357/abb0ea

Rotation Curves in $z \sim 1$–2 Star-forming Disks: Evidence for Cored Dark Matter Distributions

R. Genzel[1,2], S. H. Price[1], H. Übler[1], N. M. Förster Schreiber[1], T. T. Shimizu[1], L. J. Tacconi[1], R. Bender[1,3], A. Burkert[1,3], A. Contursi[1,4], R. Coogan[1], R. L. Davies[1], R. I. Davies[1], A. Dekel[5], R. Herrera-Camus[6], M.-J. Lee[1], D. Lutz[1], T. Naab[7], R. Neri[4], A. Nestor[8], A. Renzini[9], R. Saglia[1,3], K. Schuster[4], A. Sternberg[1,8,10], E. Wisnioski[11,12], and S. Wuyts[13]



Massive disc galaxies.

This is a correlation with baryon surface density, *not* with total baryon mass.

Note MW sits on relation.

Price et al 2021

This was the motivation for our recent paper. We make strong predictions based on Price et al (2021) about **bars being common out to z ~ 5**, depending on the disc formation epoch. It could be earlier still.

THE ASTROPHYSICAL JOURNAL, 947:80 (15pp), 2023 April 20 https://doi.org/10.3847/1538-4357/acc469

The Rapid Onset of Stellar Bars in the Baryon-dominated Centers of Disk Galaxies

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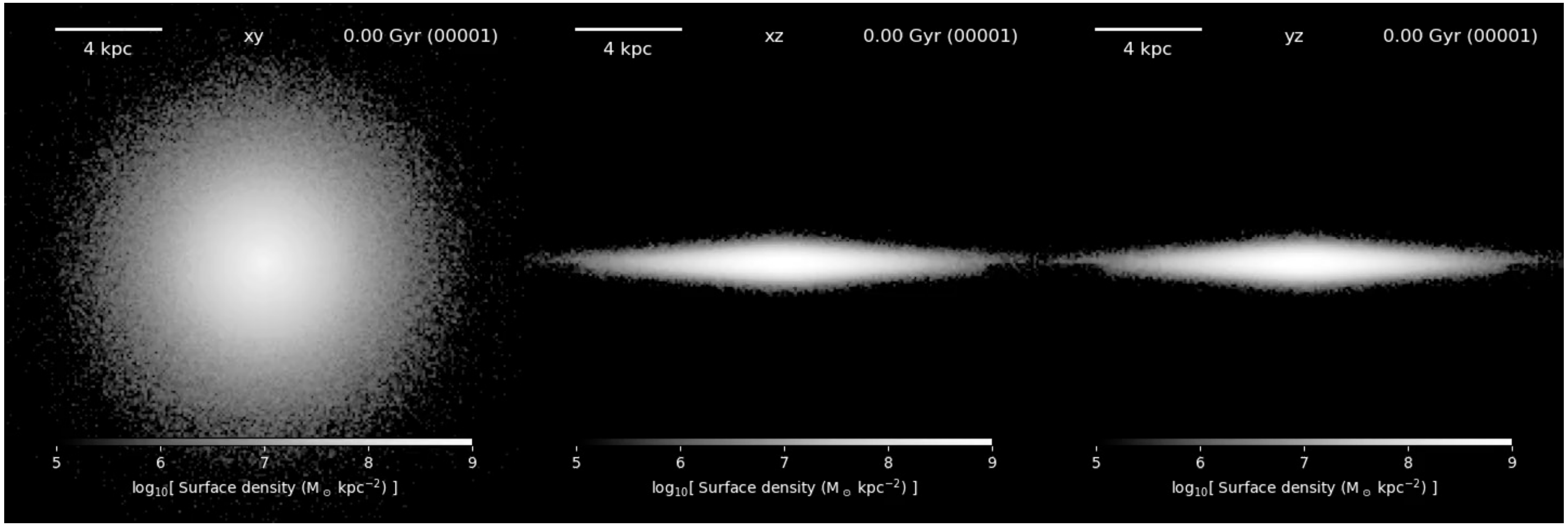
Received 2022 December 15; revised 2023 March 3; accepted 2023 March 8; published 2023 April 25

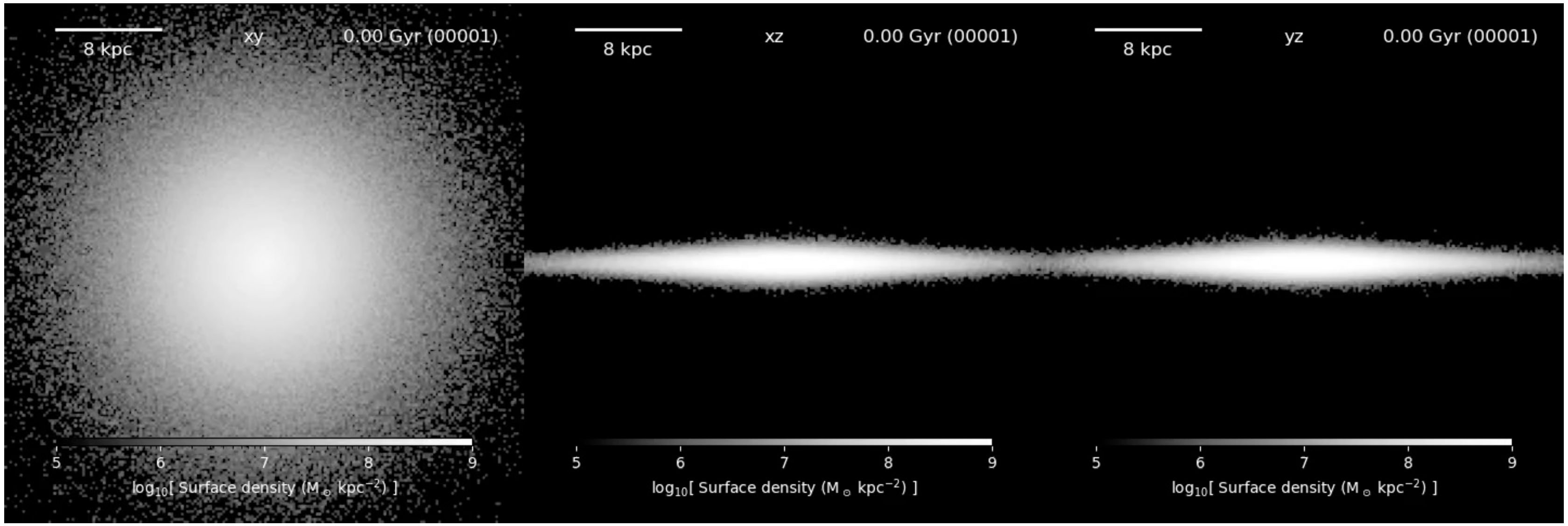
Abstract

Recent observations of high-redshift galactic disks ($z \approx 1$–3) show a strong negative trend in the dark-matter (DM) fraction $f_{\rm DM}$ with increasing baryon surface density. For this to be true, the inner baryons must dominate over DM in early massive galaxies, as observed in the Milky Way today. If disks are dominant at early times, we show that stellar bars form promptly within these disks, leading to a high bar fraction. New James Webb Space Telescope observations provide the best evidence for mature stellar bars in this redshift range. The disk mass fraction $f_{\rm disk}$ within $R_s = 2.2\ R_{\rm disk}$ is the dominant factor determining how rapidly a bar forms. Using 3D hydro simulations of halo-bulge-disk galaxies, we confirm the "Fujii relation" for the exponential dependence of the bar formation time $\tau_{\rm bar}$ as a function of $f_{\rm disk}$. For $f_{\rm disk} > 0.3$, the bar formation time declines exponentially fast with increasing $f_{\rm disk}$. Instead of Fujii's arbitrary threshold for when a bar appears, for the first time, we exploit the exponential growth timescale associated with the positive feedback cycle as the bar emerges from the underlying disk. A modified, mass-dependent trend is observed for halos relevant to systems at cosmic noon ($10.5 < \log M_{\rm halo} < 12$), where the bar onset is slower for higher-mass halos at a fixed $f_{\rm disk}$. If baryons dominate over DM within $R \approx R_s$, we predict that a high fraction of bars will be found in high-redshift disks long before $z = 1$.

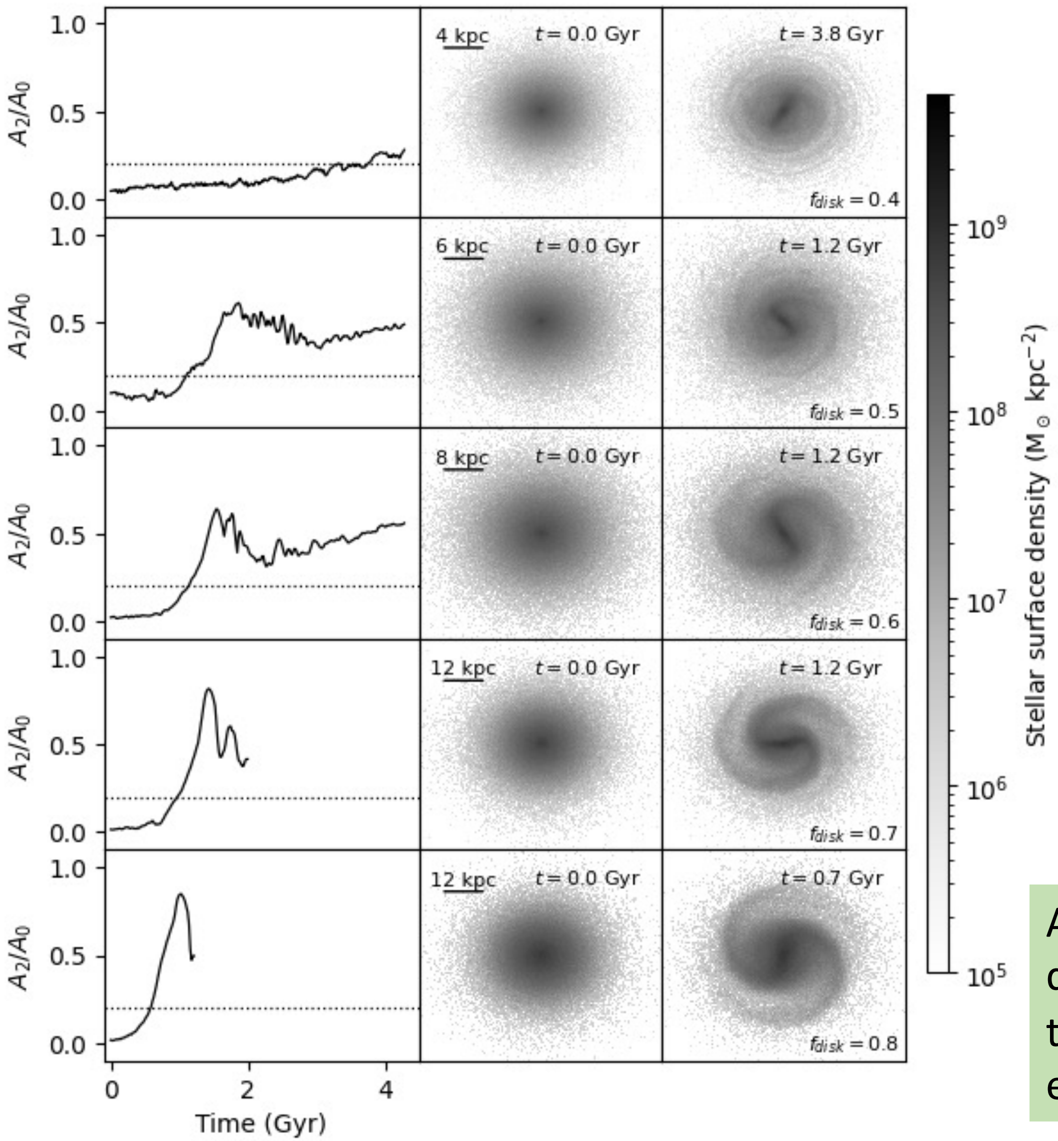


f_D = 0.4

AGAMA/RAMSES N-body

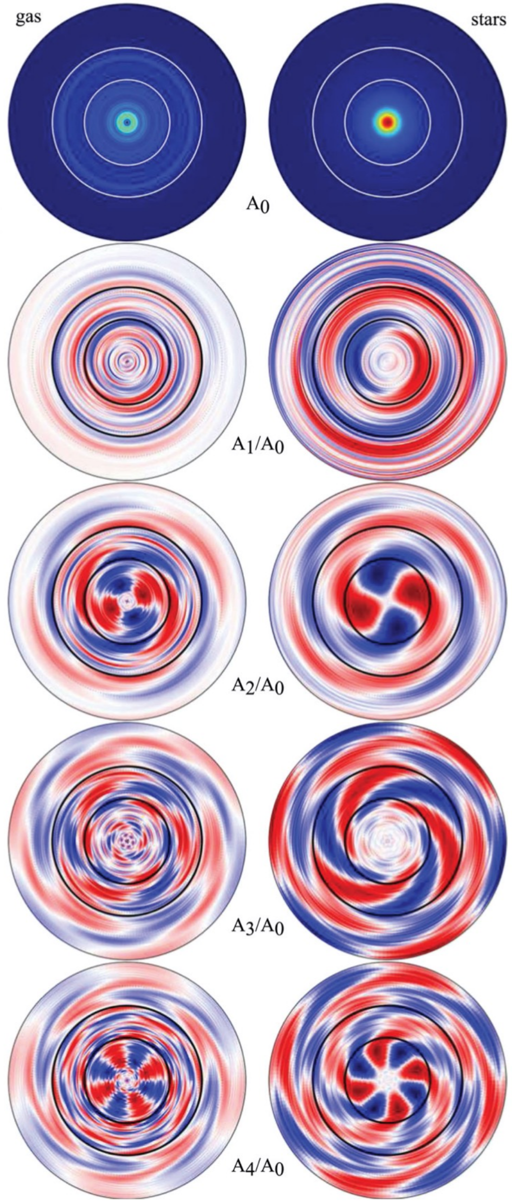


f_D = 0.6

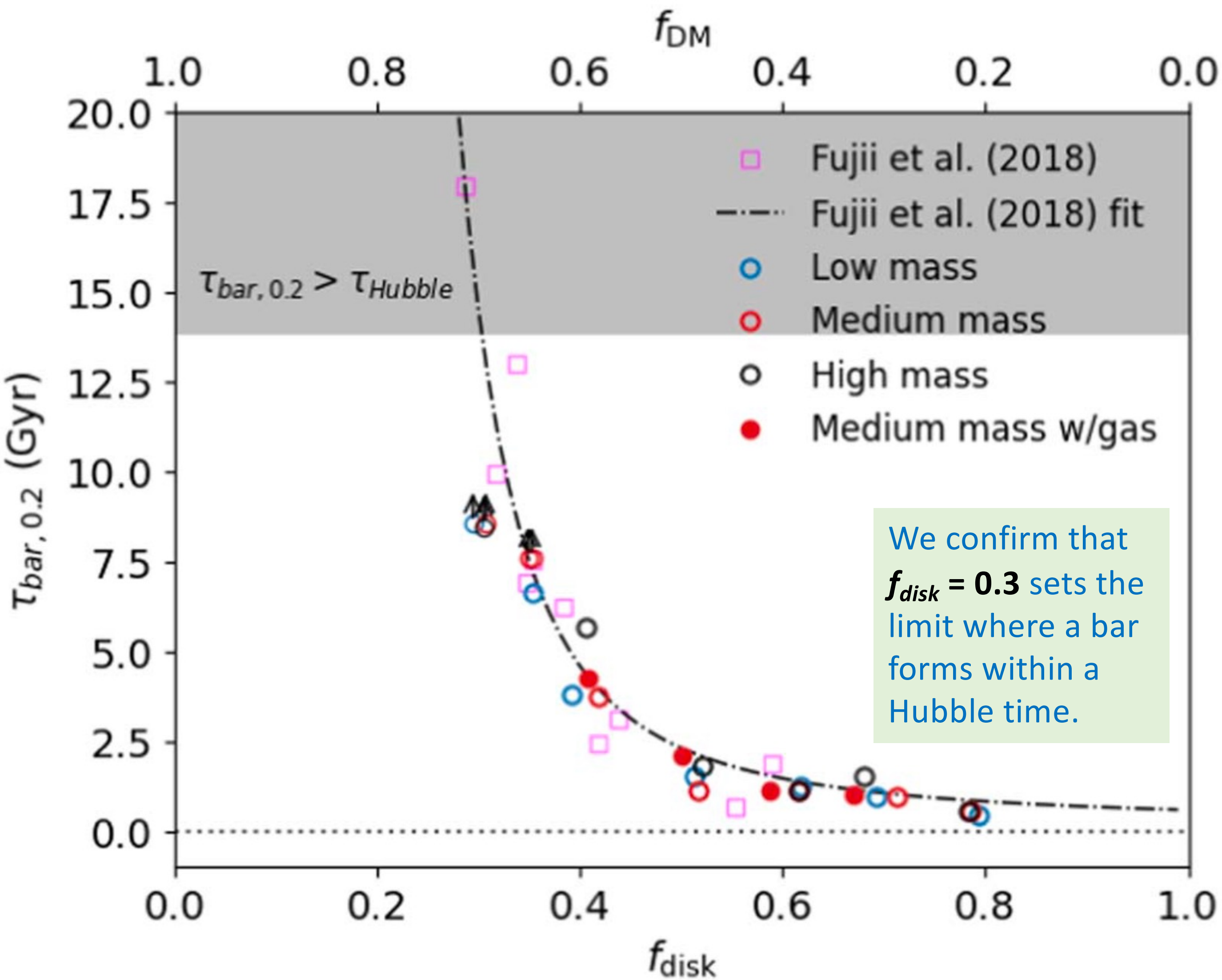


Fourier modes taken from Renaud+ 2013

$$\frac{\Sigma(R,\phi)}{\Sigma_o} = \sum_{m=0}^{\infty} A_m(R) e^{im[\phi_o - \phi_m(R)]}$$



A widespread N-body definition is $A_2 = 0.2$ for the **bar formation time**, e.g. Fujii et al 2018.

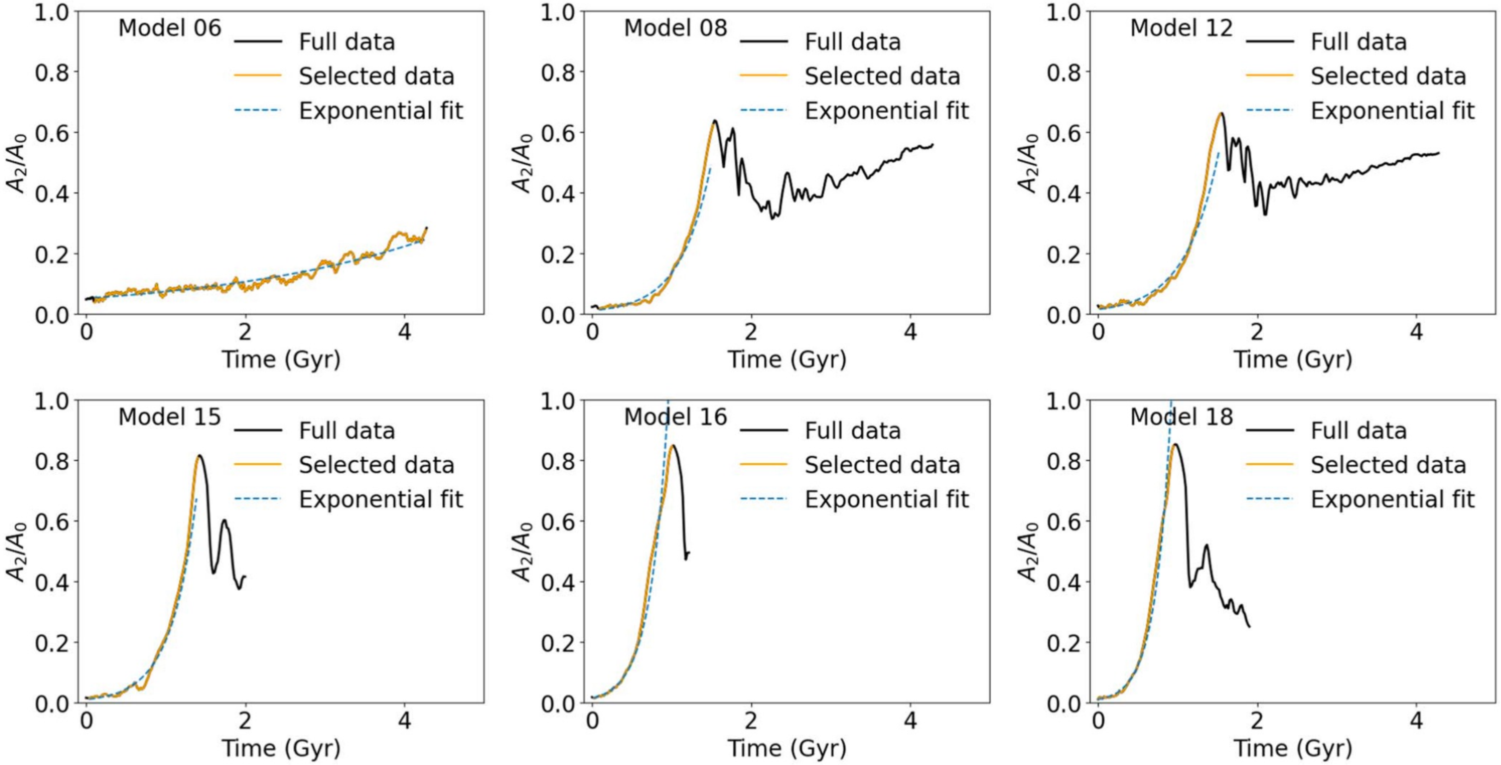


Our models all give same trend for a wide range of resolutions (**N ~ $10^{6.5-8.5}$**), different halo mass, with & without gas (0-20%).

The “Fujii plot” has never been done for **high gas mass fraction** – results on the way.

We challenge cosmological N-body simulators to reproduce this plot to test “credibility” of their bars.

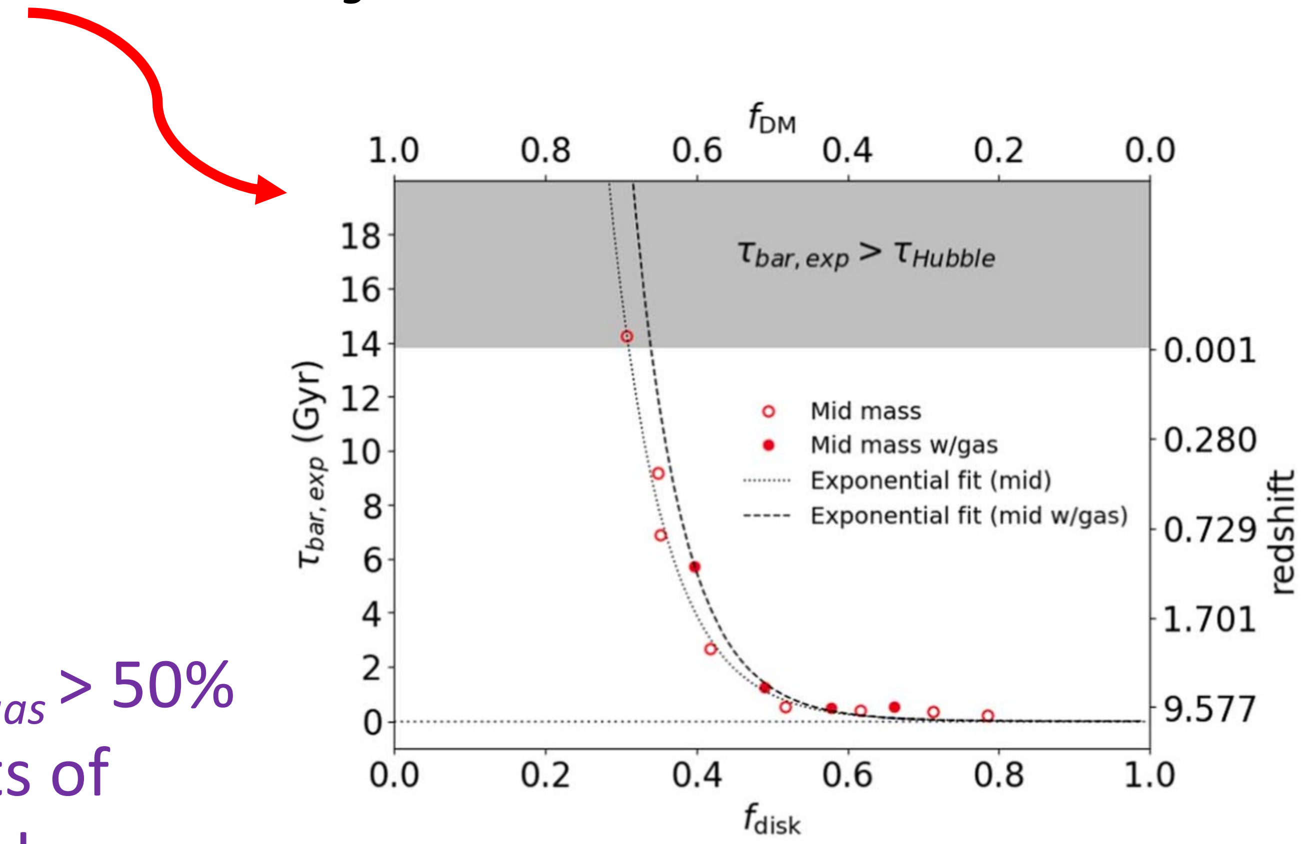
Swing amplification is an exponentially positive feedback loop (Goldreich & DLB 1965; Julian & Toomre 1966)



We fit an exponential to $A_m(t)$ for the first time. This is more physical than an arbitrary value.

When we plot **exponential bar formation time** vs. **disc mass fraction**, we recover the Fujii relation, but with a secondary dependence on halo mass and gas fraction.

To date, we find turbulent gas with $\boldsymbol{f_{gas}}$ =10-20% has low impact.



We need to investigate $f_{gas} > 50\%$ in detail where the effects of massive clouds and turbulence may be stronger, but just how ?

So are there bars beyond z~1 ?

Absolutely, and they are spectacular in rest-frame K band.

First Look at $z > 1$ Bars in the Rest-Frame Near-Infrared with *JWST* Early CEERS Imaging

Yuchen Guo,[1] Shardha Jogee,[1] Steven L. Finkelstein,[1] Zilei Chen,[1] Eden Wise,[1] Micaela B. Bagley,[1]
Guillermo Barro,[2] Stijn Wuyts,[3] Dale D. Kocevski,[4] Jeyhan S. Kartaltepe,[5] Elizabeth J. McGrath,[4]
Henry C. Ferguson,[6] Bahram Mobasher,[7] Mauro Giavalisco,[8] Ray A. Lucas,[6] Jorge A. Zavala,[9]
Jennifer M. Lotz,[10] Norman A. Grogin,[6] Marc Huertas-Company,[11,12,13] Jesús Vega-Ferrero,[11]
Nimish P. Hathi,[6] Pablo Arrabal Haro,[14] Mark Dickinson,[14] Anton M. Koekemoer,[6] Casey Papovich,[15,16]
Nor Pirzkal,[17] L. Y. Aaron Yung,[18,*] Bren E. Backhaus ,[19] Eric F. Bell,[20] Antonello Calabrò,[21]
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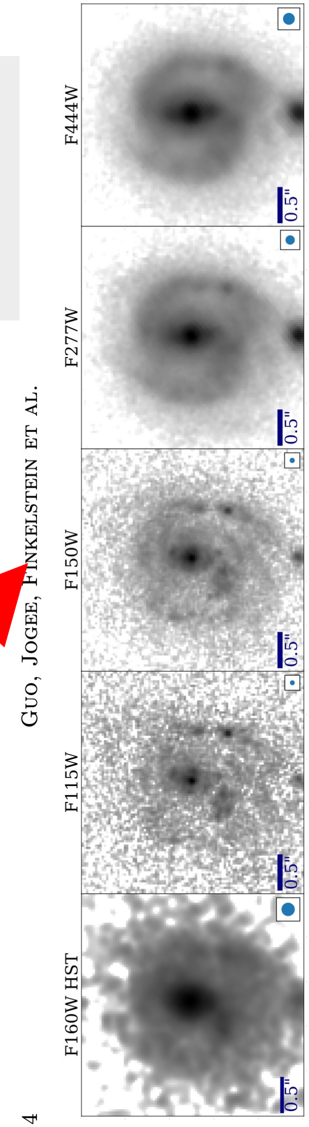
Kelcey Davis,[27] Alexander de la Vega,[28] Maximilien Franco,[1] Jonathan P. Gardner,[18] Benne W. Holwerda,[29]
Taylor A. Hutchison,[18,*] Viraj Pandya,[30,†] Pablo G. Pérez-González,[31] Swara Ravindranath,[6] Caitlin Rose,[5]
Jonathan R. Trump,[19] and Weichen Wang[32]

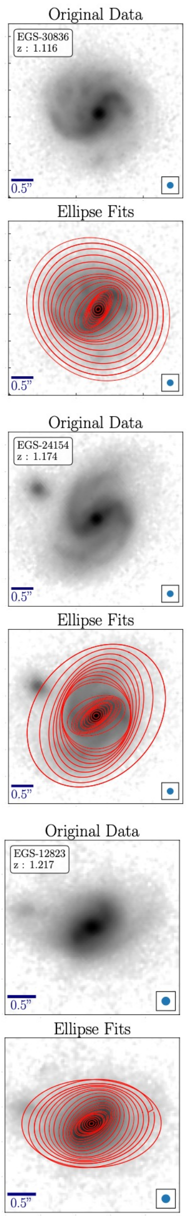
6 barred discs found across 4 x 2.2’ CEERS fields. More to come, mostly at lower SFR. Rest frame IR crucial.

Table 1. Barred Galaxies at $z > 1$ in the Rest-Frame NIR from *JWST*

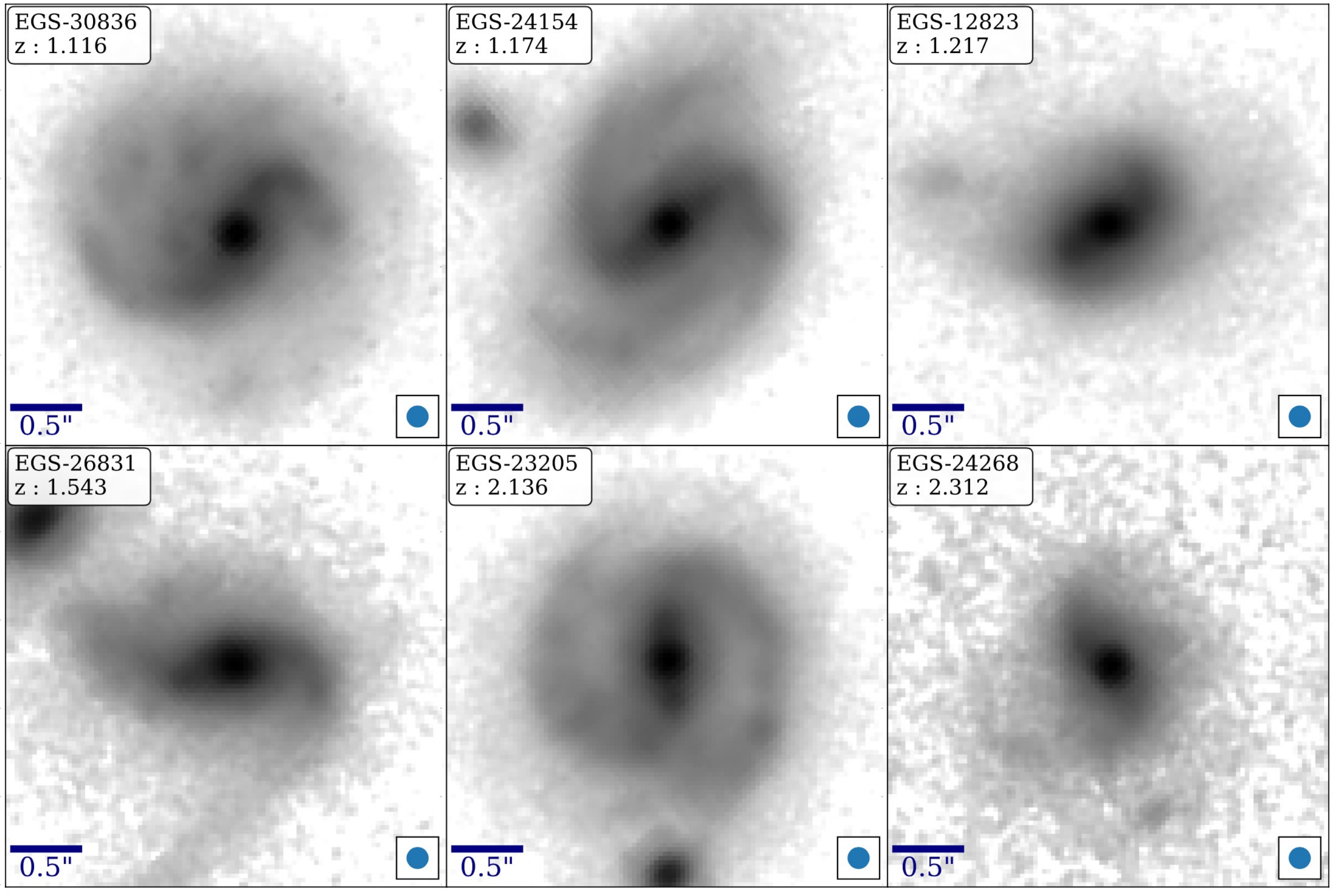
Galaxy Name	$z_{\rm spec}$	$e_{\rm bar}$	$a_{\rm bar}$ (”)	$a_{\rm bar}$ (kpc)	$\log(M_\star/M_\odot)$	SFR $M_\odot$ yr^{-1}
(1)	(2)	(3)	(4)	(5)	(6)	(7)
EGS-30836	1.116 (DEEP2 DR4)	0.53	0.51	4.28	10.80	48.430
EGS-24154	1.174 (DEEP2 DR4)	0.52	0.42	3.57	11.05	45.395
EGS-12823	1.217 (3D-HST)	0.48	0.38	3.26	10.63	21.230
EGS-26831	1.543 (MOSDEF)	0.49	0.42	3.65	10.40	74.290
EGS-23205	2.136 (3D-HST)	0.50	0.35	2.95	11.29	295.023
EGS-24268	2.312 (MOSDEF)	0.41	0.35	2.91	10.16	112.808

Except for elevated SFR, much like MW’s baryon mass and bar size today.

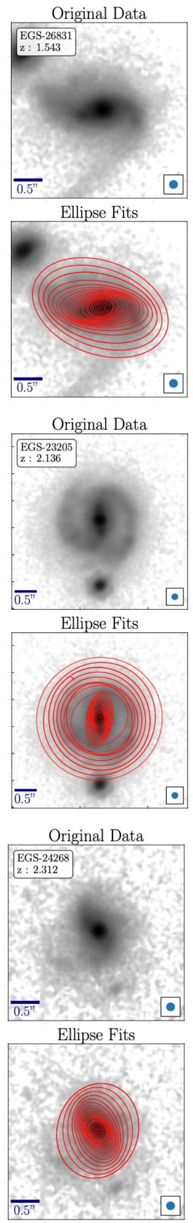




GUO, JOGEE, FINKELSTEIN ET AL.



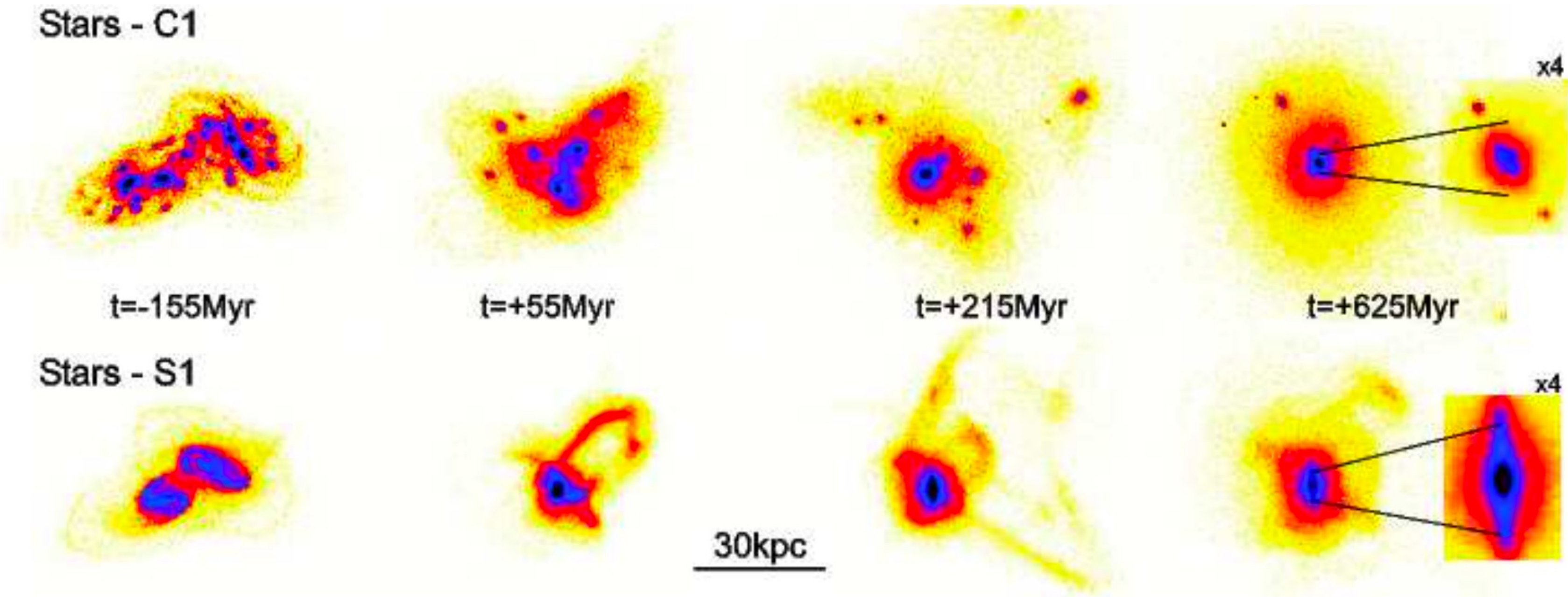
Rest frame near-infrared light (*JWST* F444W filter, CEERS survey)



So what about those high SF rates, indicating high gas fractions, high levels of turbulence?

Historically, it’s not at all clear if these help or hinder bar formation, spiral arms, etc.

The physics may be different in high accretion, high dispersion early discs?



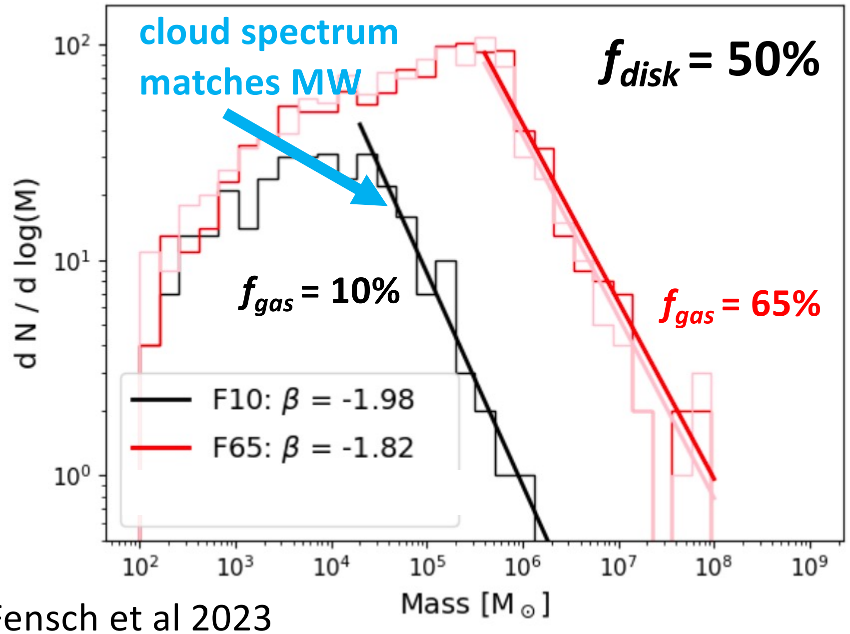
At high gas fraction, disc evolution unfolds differently with **cooling ISM** (**C1**) vs. **stabilized ISM** (**S1**) – Bournaud+ 2018.

We suspect that high disc mass fraction is important, but high gas mass fraction is equally or more important ?

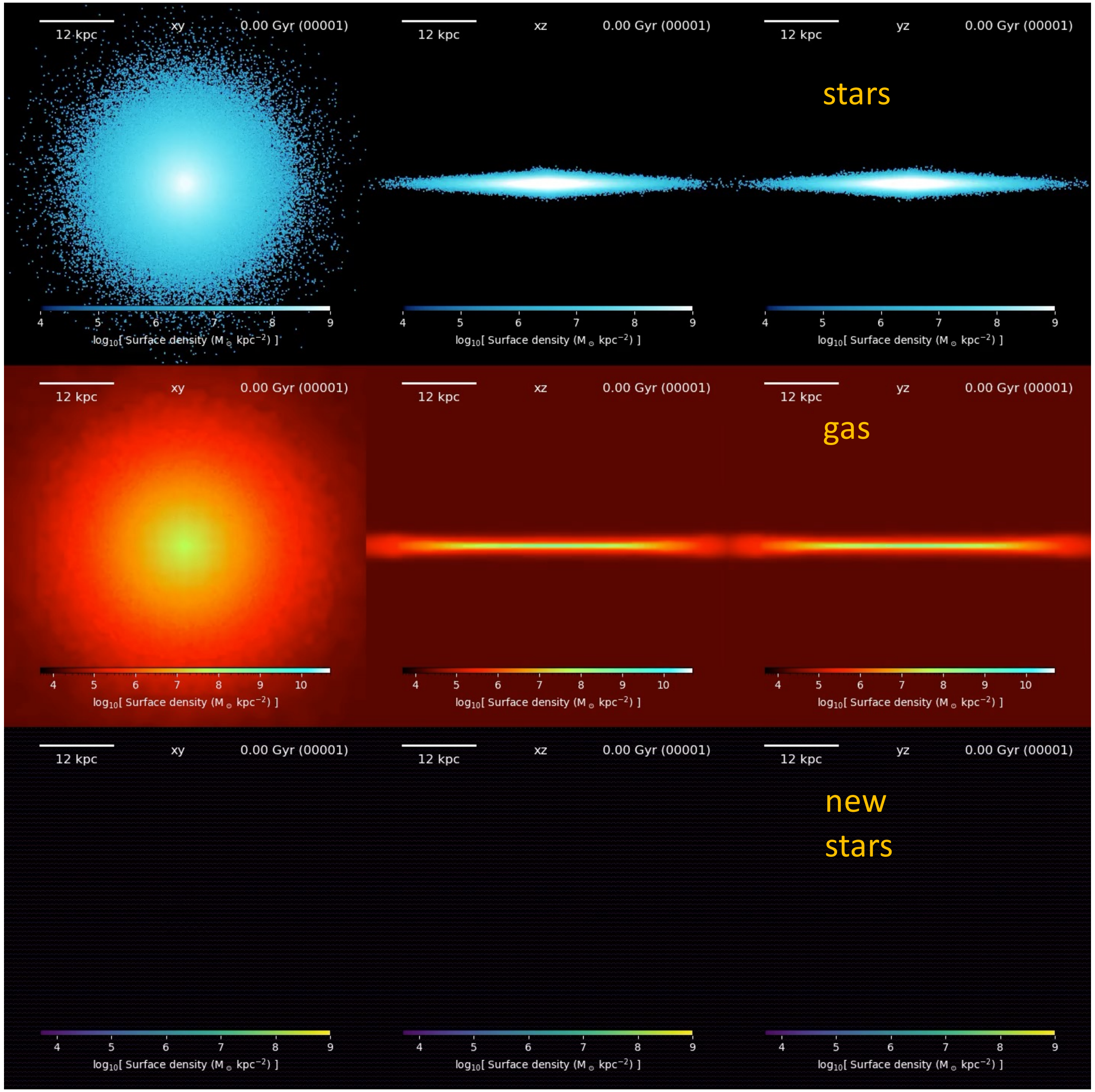
Milky Way surrogate

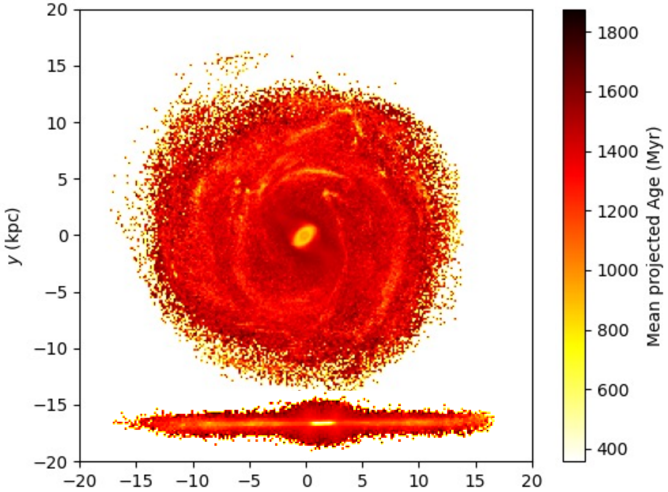
AGAMA/N-body, RAMSES/AMR, star formation, turbulence.

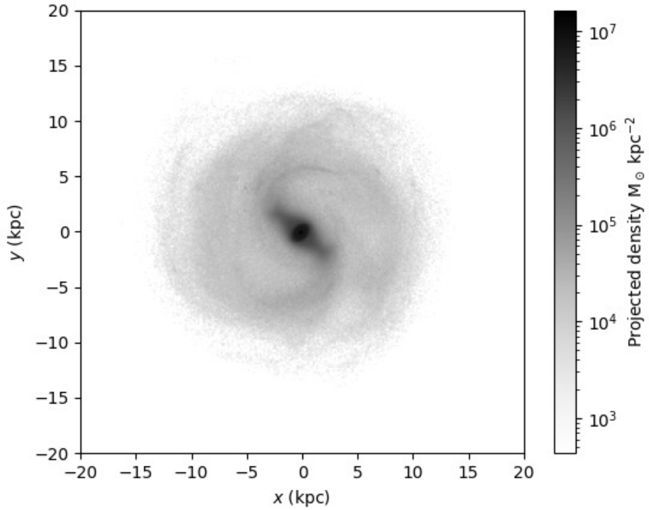
10-20% gas fraction, SFR = 1.5-3 $M_\odot$/yr energy injection reaches dynamical equilm. with turbulent pressure support.

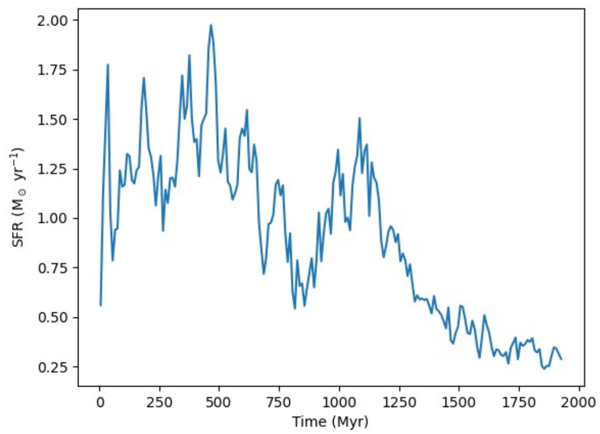


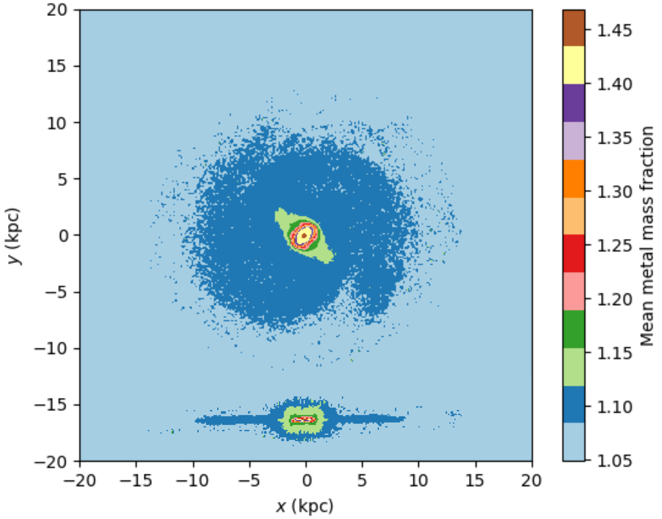
Fensch et al 2023



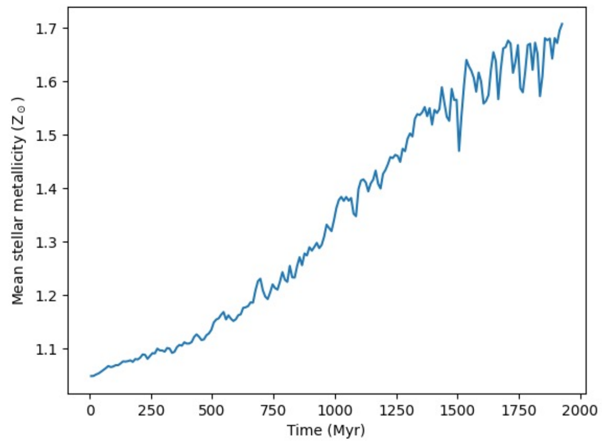








We fully anticipate metal-enriched young blue bars, and gas bars at the highest redshifts.



PUNCHLINE

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CrossMark

The Rapid Onset of Stellar Bars in the Baryon-dominated Centers of Disk Galaxies

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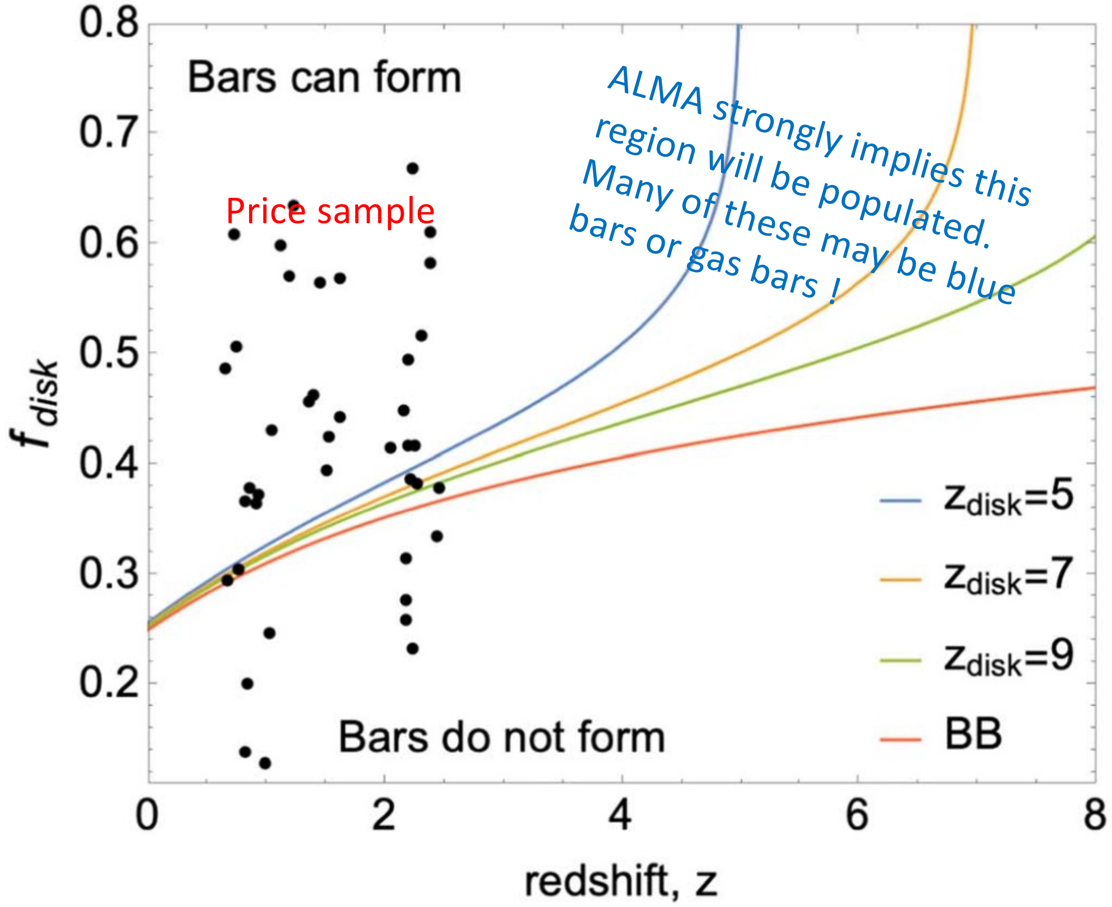


Abstract

ı-redshift galactic disks ($z \approx 1$–3) show a strong negative trend in the dark-matter (DM)
ʒ baryon surface density. For this to be true, the inner baryons must dominate over DM
ıs observed in the Milky Way today. If disks are dominant at early times, we show that
within these disks, leading to a high bar fraction. New James Webb Space Telescope
est evidence for mature stellar bars in this redshift range. The disk mass fraction f_{disk}
dominant factor determining how rapidly a bar forms. Using 3D hydro simulations of
e confirm the "Fujii relation" for the exponential dependence of the bar formation time
For $f_{disk} > 0.3$, the bar formation time declines exponentially fast with increasing f_{disk}.
threshold for when a bar appears, for the first time, we exploit the exponential growth
he positive feedback cycle as the bar emerges from the underlying disk. A modified,
served for halos relevant to systems at cosmic noon ($10.5 < \log M_{halo} < 12$), where the
ıer-mass halos at a fixed f_{disk}. If baryons dominate over DM within $R \approx R_s$, we predict
will be found in high-redshift disks long before $z = 1$.

We expect that **50% of disc galaxies** will have bars ***before* z = 1**, if the Price sample is representative. A significant fraction of these will have young, blue bars. Some may even have ALMA gas bars!

A. EFSTATHIOU, LAKE & NEGROPONTE CRITERION

Efstathiou et al. (1982) derived a simple criterion for bar instability based on a disc's mass M_d, scale length R_d and maximum rotation velocity $V_{\max}$, such that for

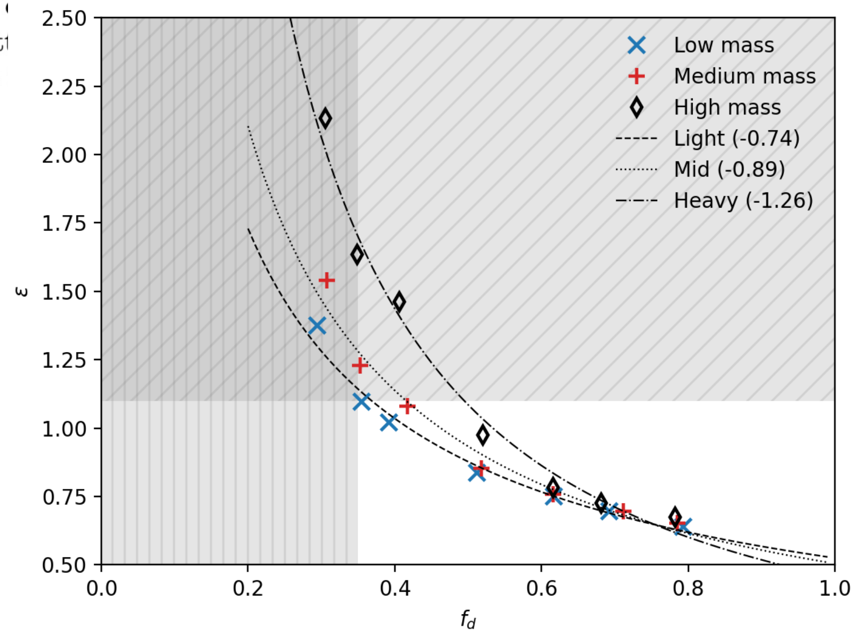
$$\varepsilon = V_{\max}/(GM_d/R_d)^{0.5} \tag{A1}$$

then the disc is bar unstable when $\varepsilon \lesssim 1.1$ and stable otherwise. They arrived at the formula from 2D stellar disc simulations held within a rigid halo. Subsequently, Christodoulou et al. (1995) derived a similar relation for purely gas discs. Athanassoula (2008) has exposed shortcomings in the use of the ELN relation. We note, however, that the ELN criterion is still popular among cosmological N-body simulators, regardless of these shortcomings (e.g. Izquierdo-Villalba et al. 2022).

In Fig. 5, the ELN parameter is presented for all of our models. A comparison with Fig. 4 shows that there are a number of models that do form a bar in our numerical experiments that would be considered stable based on the ELN criterion (diagonally shaded region). Thus we concur with Athanassoula (2008) in that the latter is not a reliable estimator of a disc's stability against bar formation.

In view of the definitions of f_d and ε, we expect an inversely proportional relation between these simplest and at the same time most general relation is a power law $\varepsilon \propto (f_d)^\alpha$, with $\alpha < 0$. We have fit function to each of the results for a given halo mass model, and find that it provides a reasonable between ε and f_d, although α has a secondary dependence on halo mass (cf. Fig 5).

JBH et al (2023)



For the specialist, a note in passing.

PUNCHLINE

You don't need to believe in disc kinematics to infer baryon domination at high redshift – **look for the bars.**

The full 10-field galaxy survey from the JWST teams will be announced in July, but nobody is talking !