Intermediate-mass Black holes, and nature of dark matter, and ...

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Unión Europea
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"Una manera de hacer Europa"

(Fornax Dwarf - ESO)

Outline

1.- Estallidos 7:

- Searching for the cosmic web in emission
- Cores in tiny galaxies and the nature of DM

2.- Estallidos 8: Plans

- Searching for wandering IMBHs
- Cores in tiny galaxies and the nature of DM

3.- Starless dark matter halos – is Cloud 9 one of them?

4.- Conclusions

Estallidos 7: Searching for the cosmic web in emission

JSA, J. Calhau, C. Muñoz-Tuñón, A.L. Gonzalez-Morán, & J.M. Rodríguez-Espinosa (2022, ApJ, 934, 100)



Grupo ESTALLIDOS7 @ IAC:



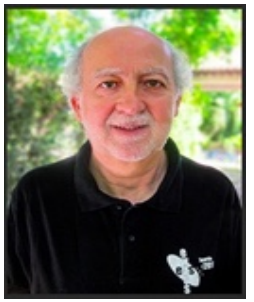
- Joao Calhau (post Doc)



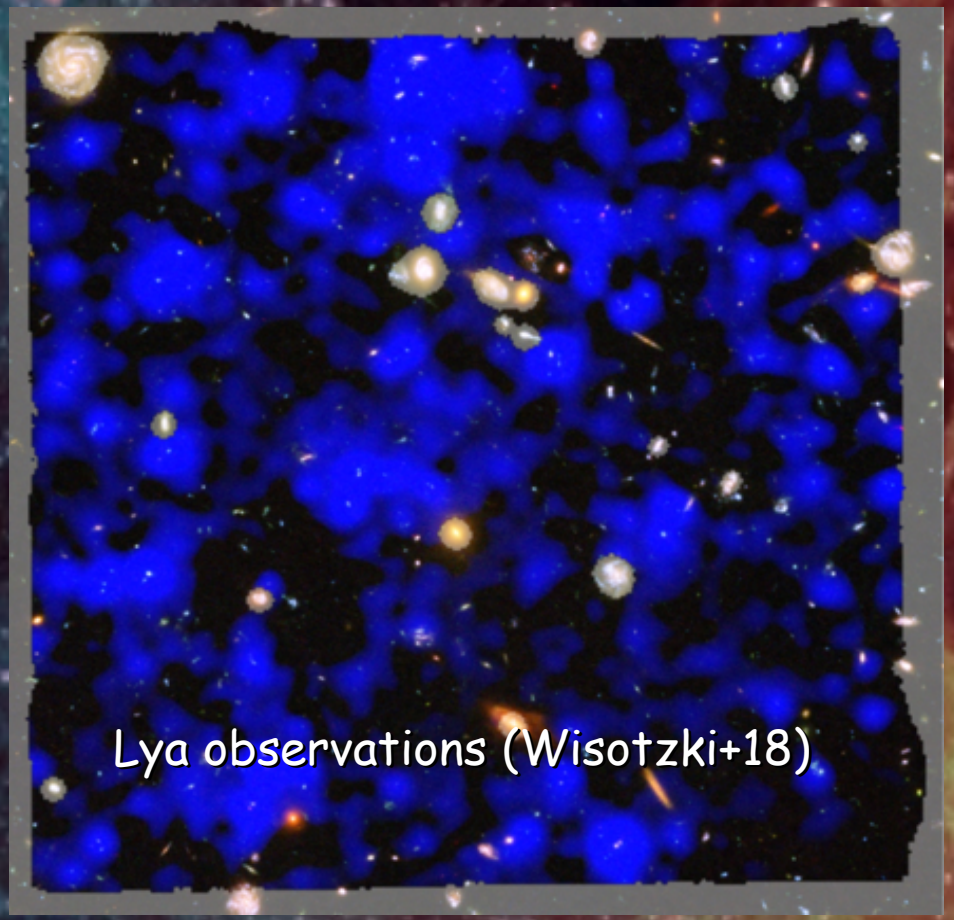
- Ana Luisa Gonzalez (post Doc)



- Casiana Muñoz Tuñon.

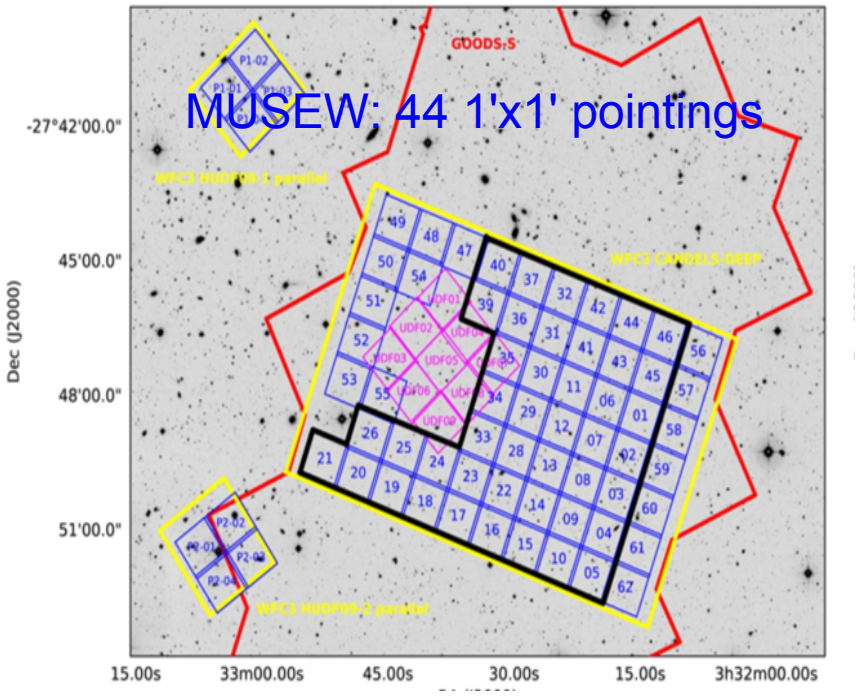


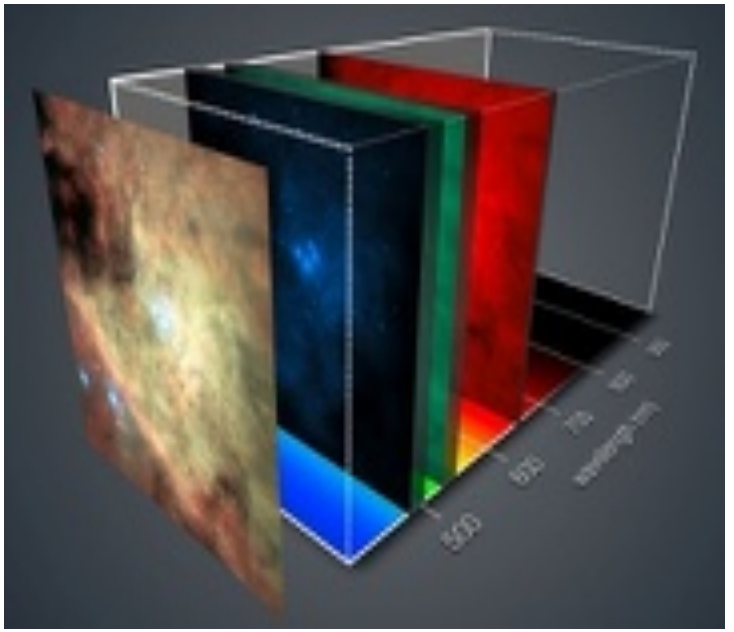
- Jose Miguel Rodriguez Espinosa



Illustris TNG simulation (Springel+18)

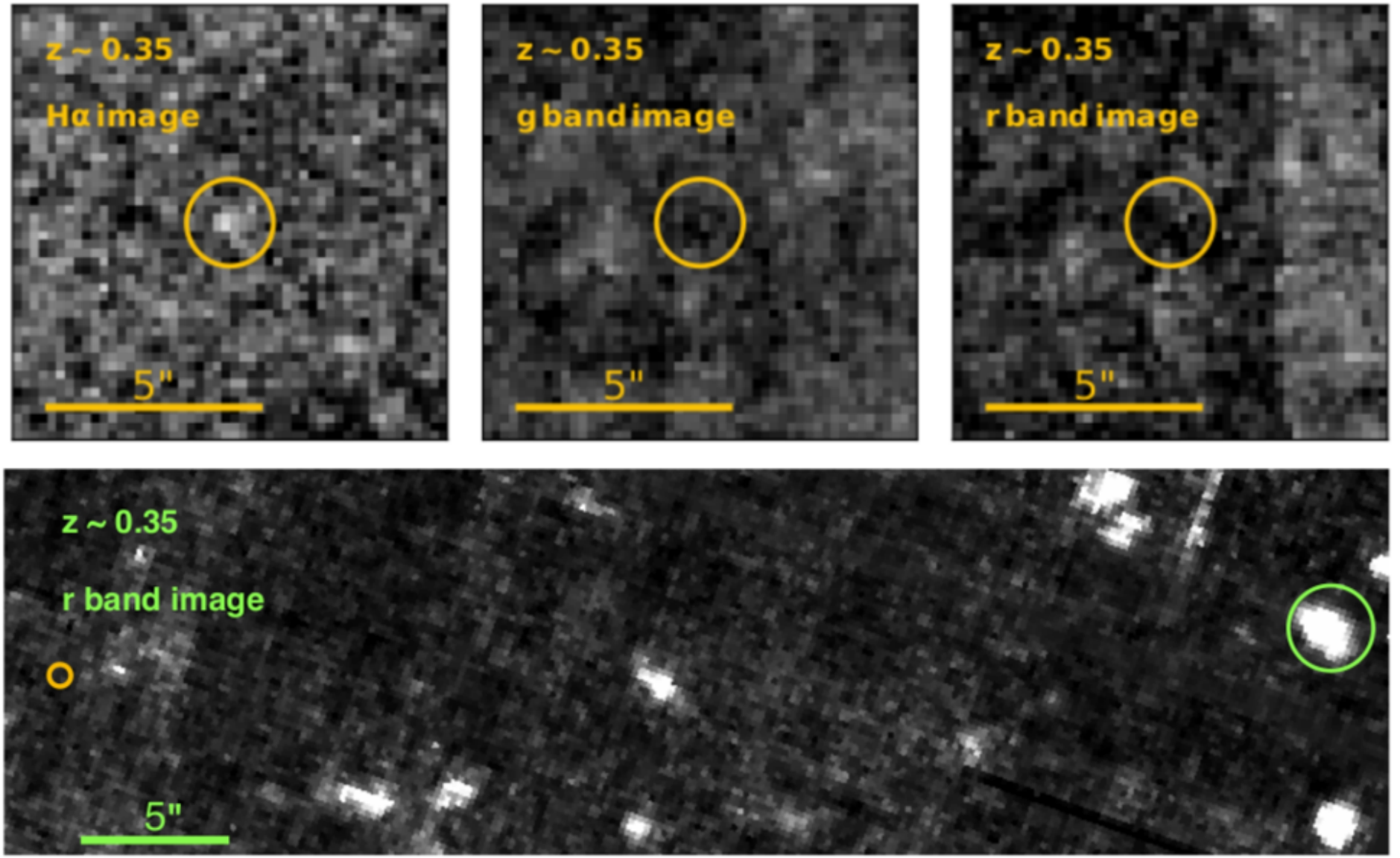
We tried to detect the gas in the circum-galactic medium (CGM) and inter galactic medium (IGM) in the nearby Universe in Ha using MUSE Wide public datacubes (Urrutia+19)





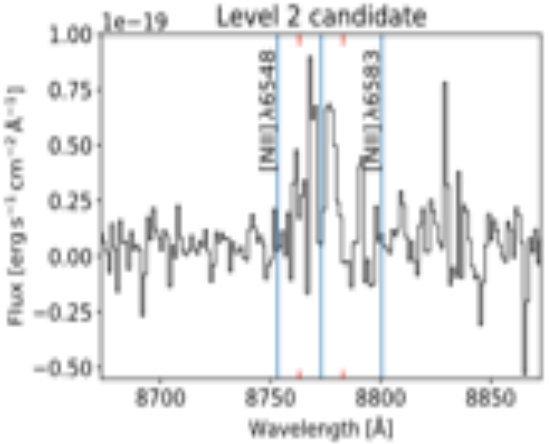
MUSE@VLT: Bacon+14,15

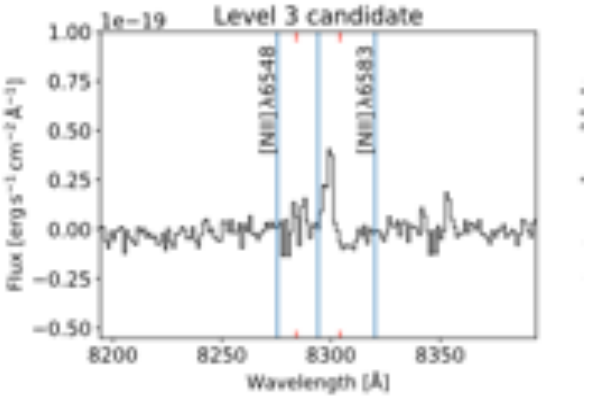
Spectral range (simultaneous)	0.465-0.93 μm
Resolving power	2000@0.46 μm
	4000@0.93 μm
Wide Field Mode (WFM)	
Field of view	1x1 arcmin^2
Spatial sampling	0.2x0.2 arcsec^2
Spatial resolution (FWHM)	0.3-0.4 arcsec



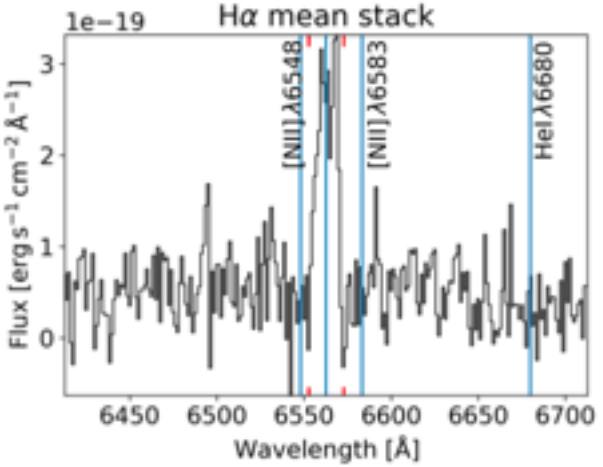
Ha image tuned to each nearby galaxy in the FOV (164 galaxies)

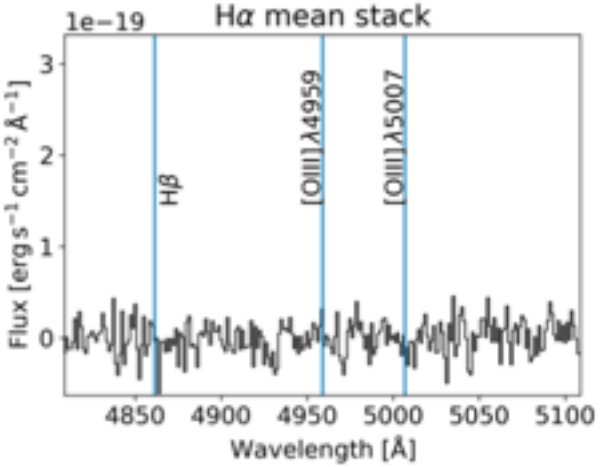
Ha often show two peaks + weak continuum





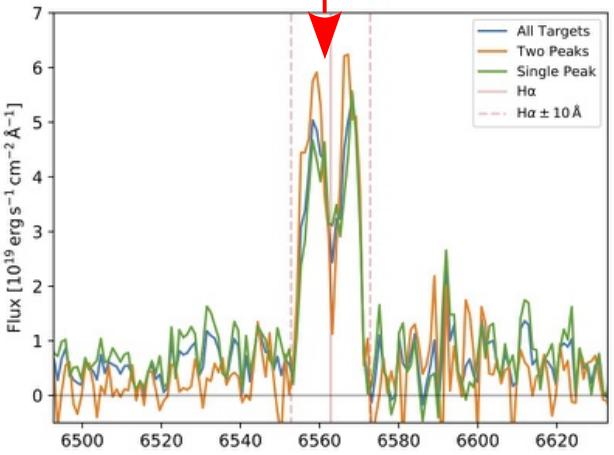
Individual spectra





Stacked spectra:
Ha has two peaks
No Hb or [OIII] emission

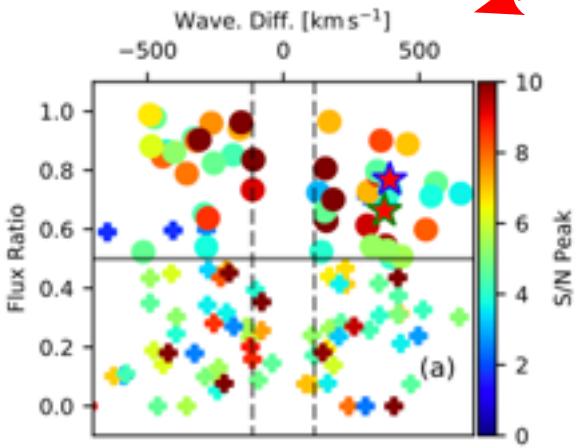
Ha of the central galaxy

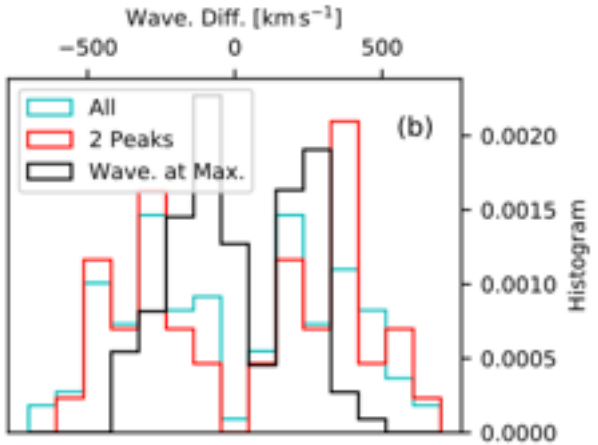


Also single peak stacking shows two peaks

Stacked spectra

38% two peaks

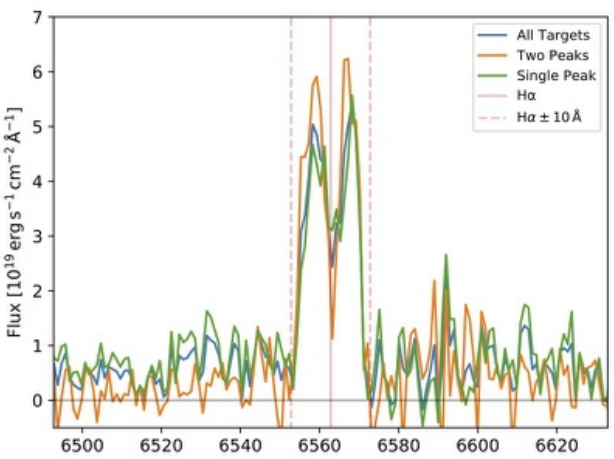




± 175 km/s

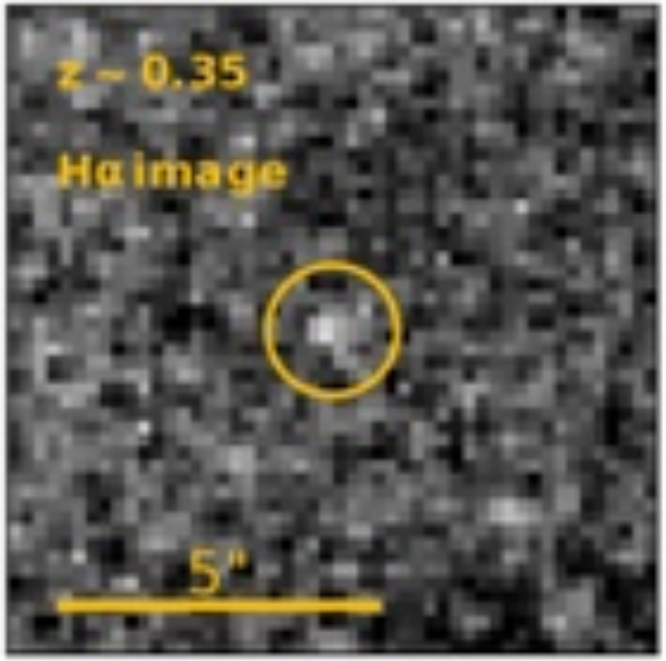
Possible Physical Origin of the Ha emission

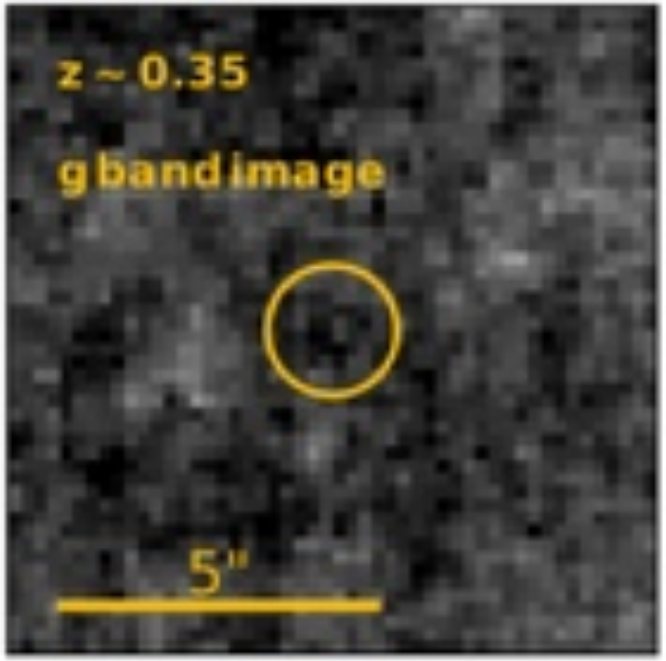
Mechanism	Surface Brightness	Number Density	Double Peak	Central Drop	Hβ/Hα	No Continuum	Size	Spatial Distribution
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Accretion disks (IMBH)	✓	✓	✓	✓	?	✓	✓	✓
Expanding bubbles (SN)	✓	✓	✓	✓	?	✓	✓	✗
Cosmological gas	✓	✓	?	?	✗	✓	✓	✓
Planetary nebulae	✗	✓	✓	✓	?	✓	✓	?
X-ray binaries	✗	✓	✓	✓	?	✓	✓	?
Shocks	?	✓	✓	✗	?	✓	?	✓
Galaxy outflows	✓	✓	✓	✗	✓	✓	?	✗
Tidal disruption events	?	✗	✓	✓	?	✓	✓	✗
Interlopers	✓	✗	?	✗	✓	✓	?	✗
Jets	?	?	✓	✓	?	?	?	✗

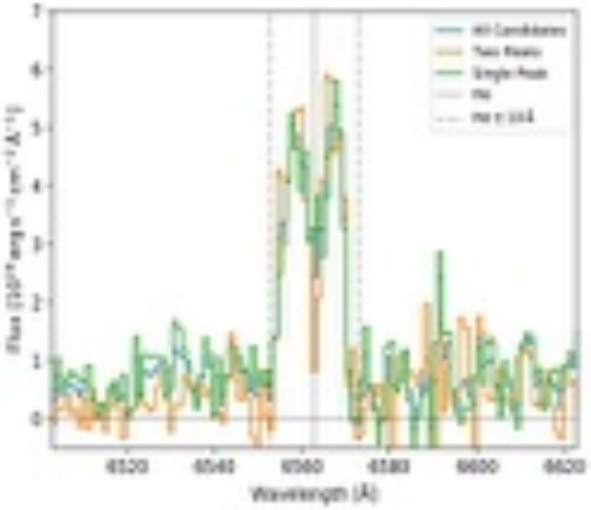


The spatial distribution discards telluric line contamination

IMBHs with masses between 10^3 and 10^6 $M_\odot$







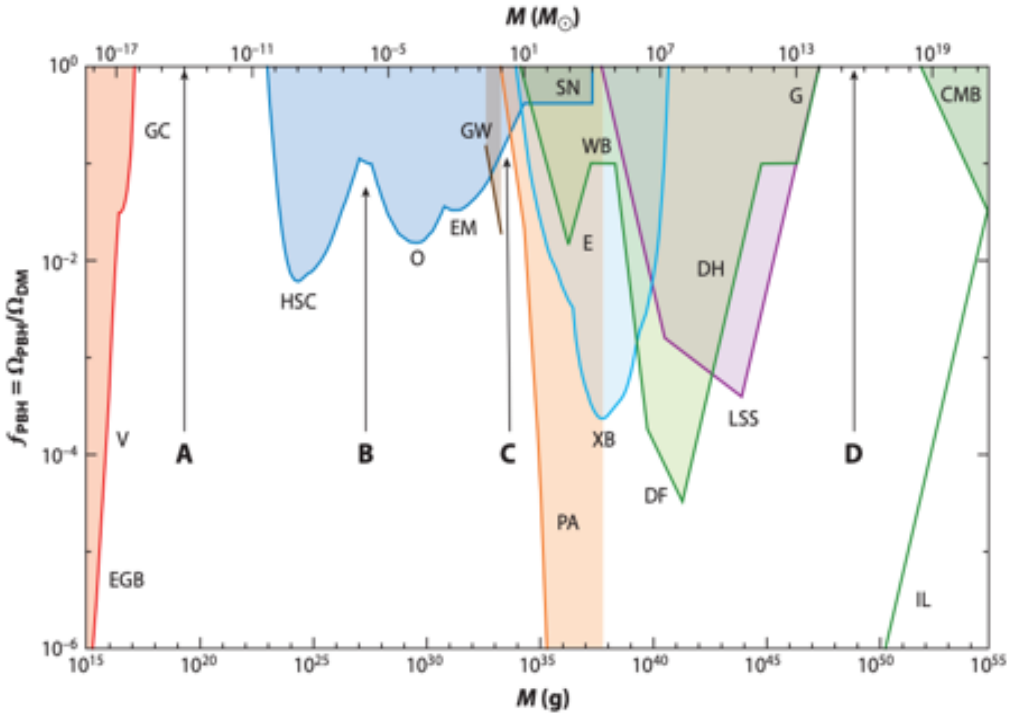


Are IMBHs to be expected?

(Reviews; e.g., Mezcua 17, Greene+21)

- Primordial BHs (created during the BB, there are claims that the may account for all the Dark Matter of the Universe; e.g., García-Bellido+)





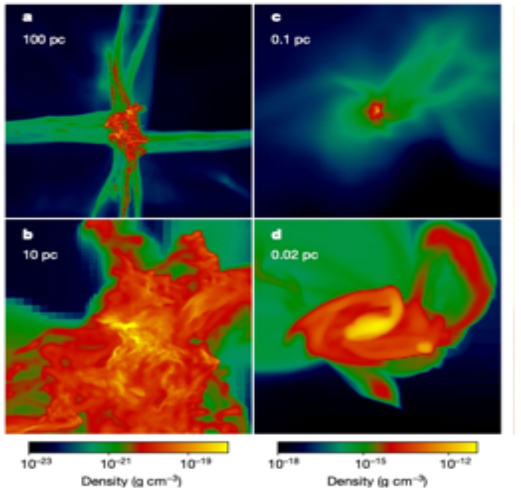
Carr & Kuhnel 20, ARNPC

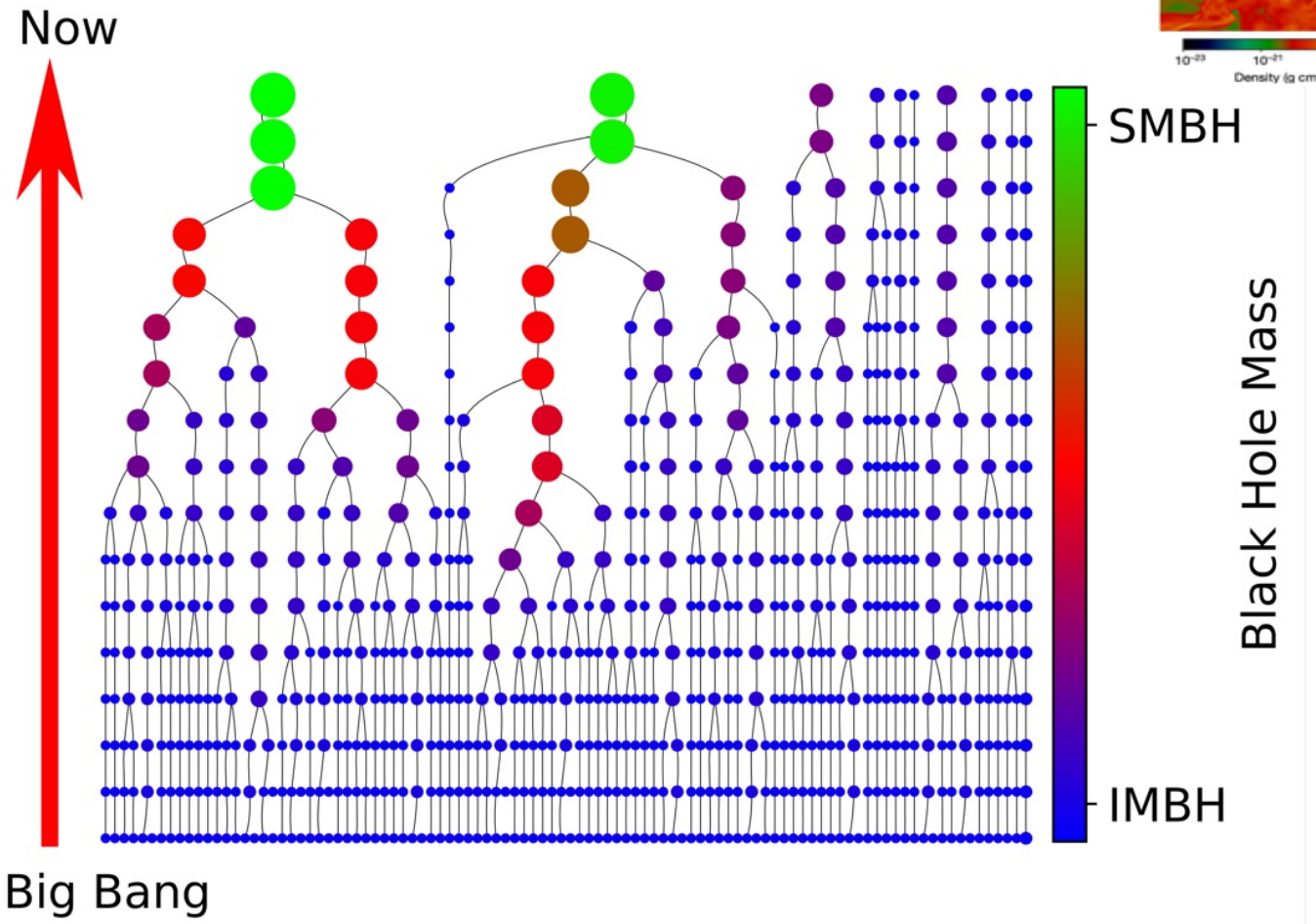
f_{BH}=1 ~100 BH/Star

Figure 1

Constraints on $f(M)$ for a monochromatic mass function from evaporations (*red*), lensing (*dark blue*), gravitational waves (GW) (*brown*), dynamical effects (*green*), accretion (*light blue*), cosmic microwave background distortions (*orange*), and large-scale structure (*purple*). Evaporation limits come from the extragalactic γ-ray background (EGB), the *Voyager* positron flux (V), and annihilation line radiation from

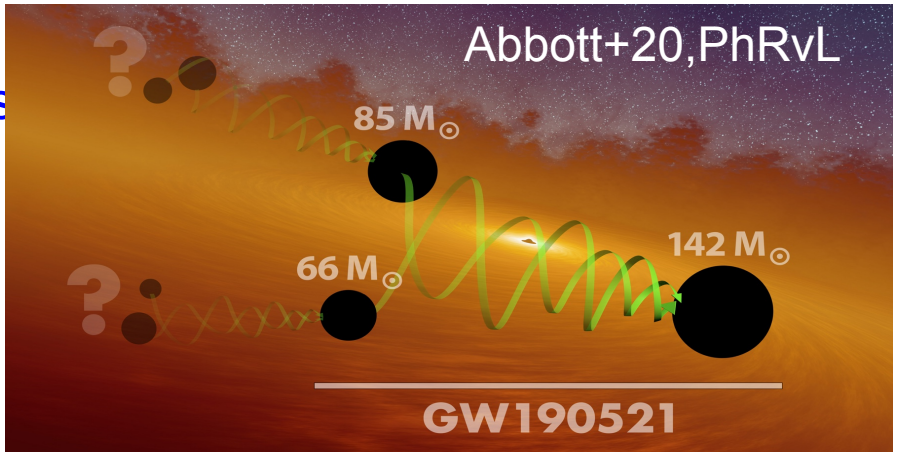
- Seeds for SMBHs (direct collapse in the early Universe; e.g., Jhonson+13, MNRAS; Latif+22, Nat)

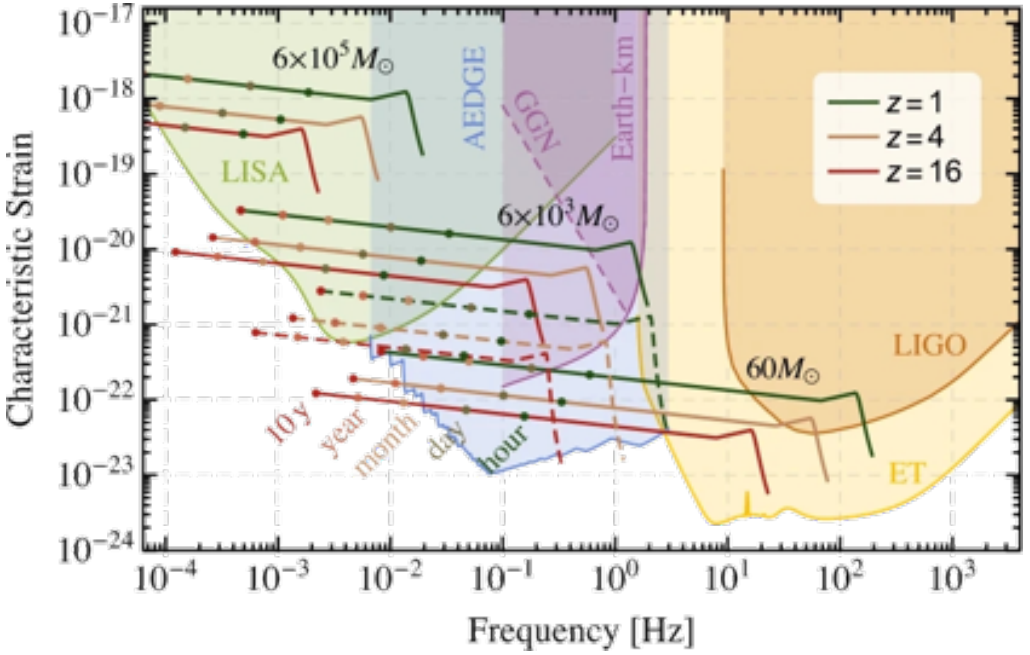




BH-BH mergers are very inefficient; left overs expected

- progenitors of the BH-BH mergers producing the GW





El-Neaj+20, EPJ Quan.

- however, very few confirmed so-far: <30 (Greene+21, ARA&A)

Estallidos 7
Cores in tiny galaxies and the nature of dark matter (DM)

J. Sánchez Almeida,
A. R. Plastino, &
I. Trujillo





SA+23, ApJ, 954, 153

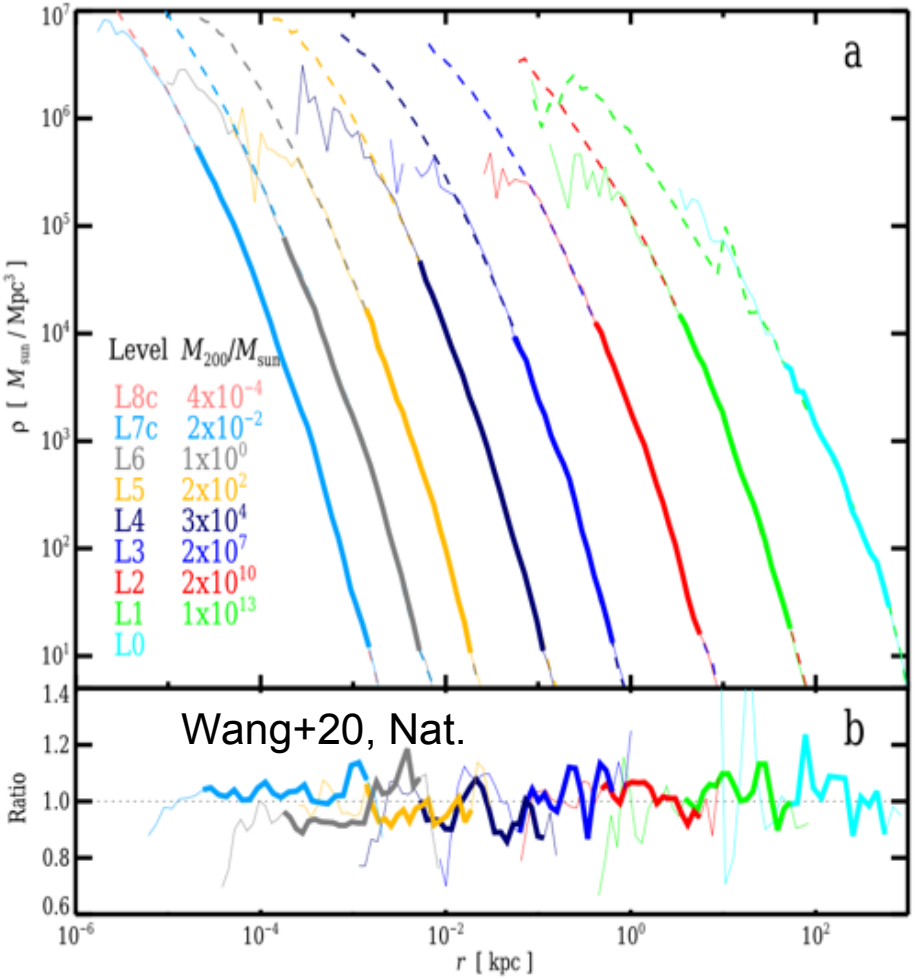
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(Fornax Dwarf - ESO)

Navarro, Frenk, and White profile:

Collision-less CDM haloes must have a particular shape (NFW profile)



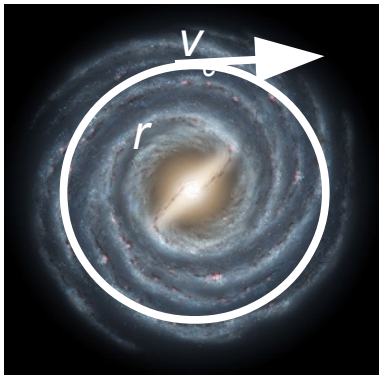


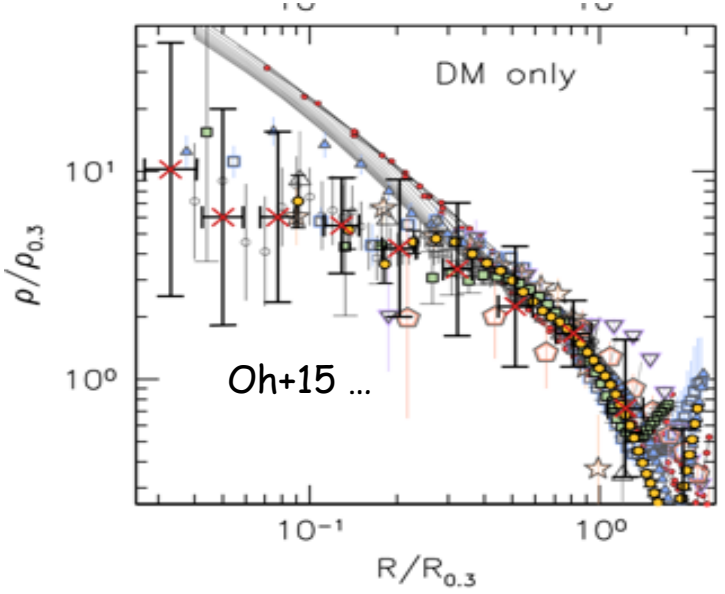
$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

$\rho(r)$ diverges as $1/r$ when $r \rightarrow 0$

Small-scale tensions: core – cusp problem

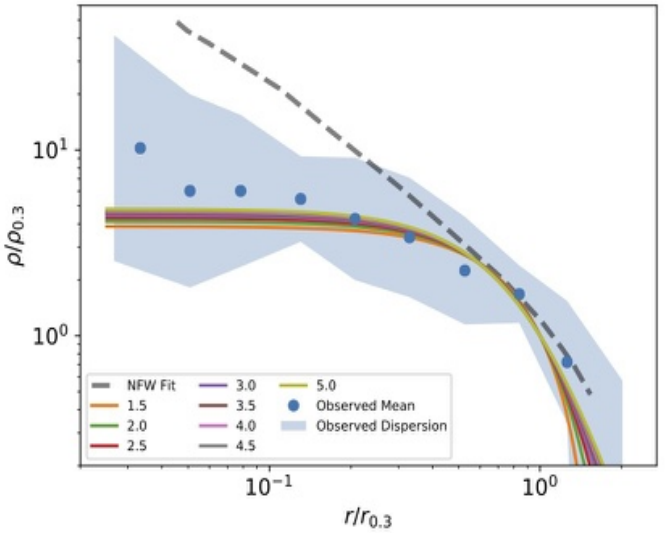
One can measure the DM distribution using kinematic information (e.g. HI rotation curves).



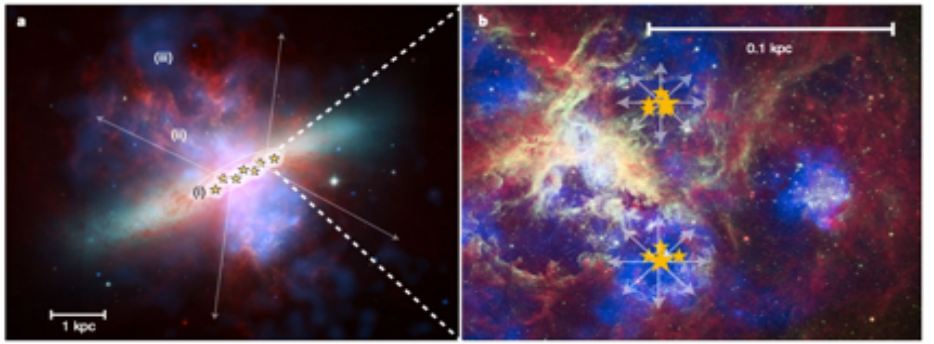


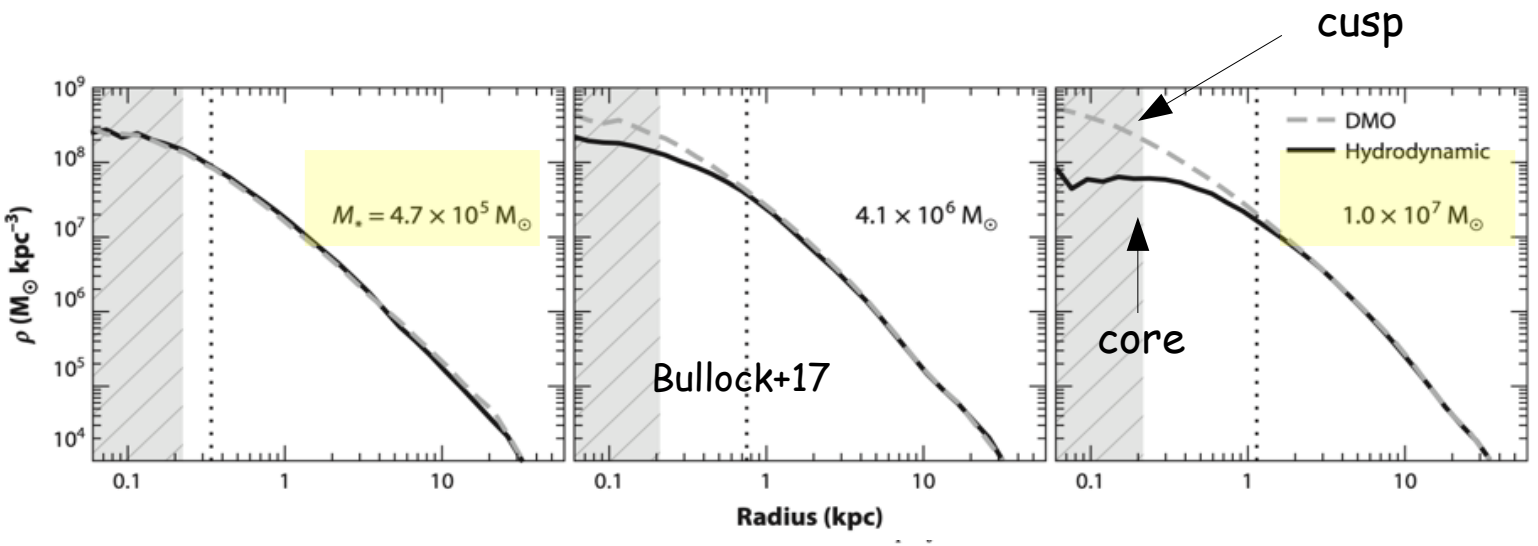
The smallest observed galaxies, M_* $\gtrsim 10^6$ $M_\odot$, show cores rather than cusps (NFW profile)

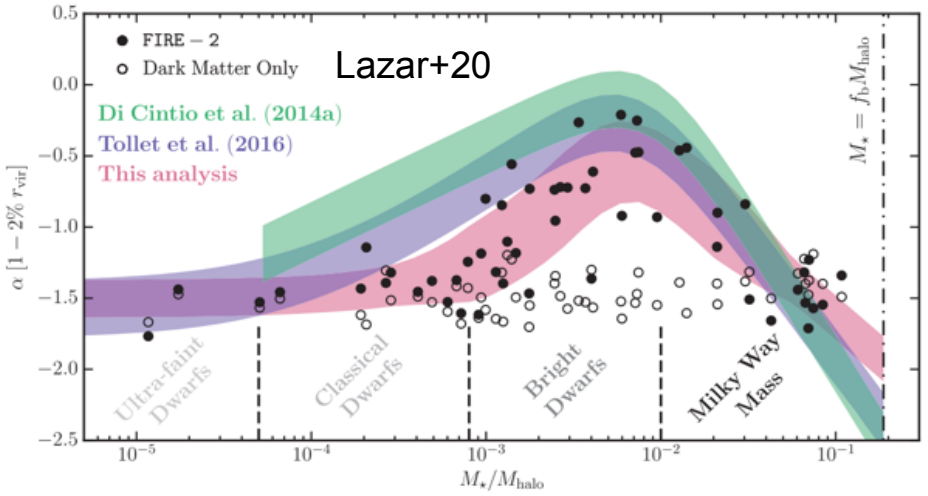
SA+20, cores imply is DM is in thermodynamic equilibrium



Solution within the CDM paradigm: stellar feedback on the DM distribution Governato+10)







Baryon feedback is unable to modify the CDM profile (NFW profile) for stellar masses smaller than some 10^6 $M_\odot$. (There is not enough energy, e.g., Peñarubia+12)

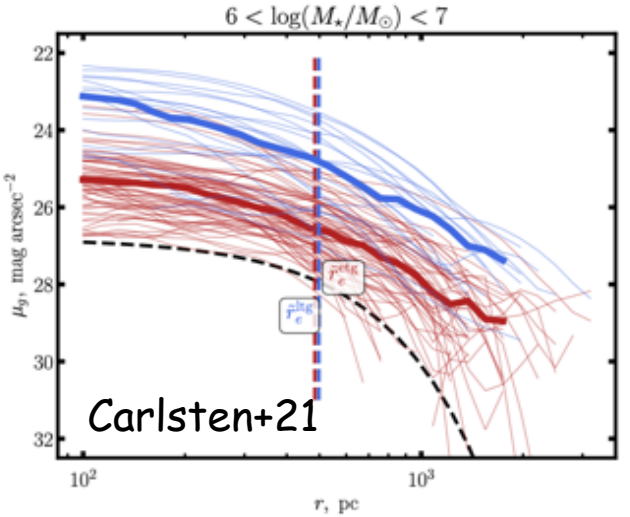

SUPER SIMPLE
Loading...

- In cores exist for $M_* < \sim 10^6\ M_\odot$ then it cannof

be due to baryon feedback but has to reflect the nature of DM whether is is fuzzy, self interecting, warm, or else.

- Kinematic measurements at these masses is technically very challenging (if not impossible), however, photometry is doable. We can measure the mass profile from photometry.

- … and the observed mass profiles tend to show cores …



The question arises as to whether stars trace the DM distribution in these low-mass systems

There is no trivial answer since in general they do not :the distribution of DM and stars do not necessarily have to be the same.

The Eddington inversion method comes to help:

For spherically symmetric systems of particles with isotropic velocity distribution, the phase-space DF f(ε) depends only on the particle energy ε.

$$\rho(r) = 4\pi\sqrt{2}\int_0^{\Psi(r)} f(\epsilon)\sqrt{\Psi(r)-\epsilon}\,d\epsilon.$$

$\epsilon = \Psi - \frac{1}{2}v^2$ is the relative energy

$\Psi(r) = \Phi_0 - \Phi(r)$ is the relative potential

$$f(\epsilon) = \frac{1}{\sqrt{2}\pi^2}\int_0^{\epsilon}\frac{d^3\rho}{d\Psi^3}\sqrt{\epsilon-\Psi}\,d\Psi.$$

Give a stellar mass density profile, ρ(r), and a potential, Ψ(r), the Eddington Inversion Method provides the distribution function consistent with both, f(ε).

- There is no guarantee that two arbitrary ρ(r) and Ψ(r) are physically consistent with each other.

- The absolutely minimum requirement for consistency is $f(\varepsilon) \geq 0$

- Pairs ρ(r) - Ψ(r) leading to $f(\varepsilon) < 0$ can be discarded, thus, given an observed stellar ρ(r) we can constraint the DM Ψ(r).

- Is a cored estellar ρ(r) consistent with a cuspy CDM Ψ(r)?

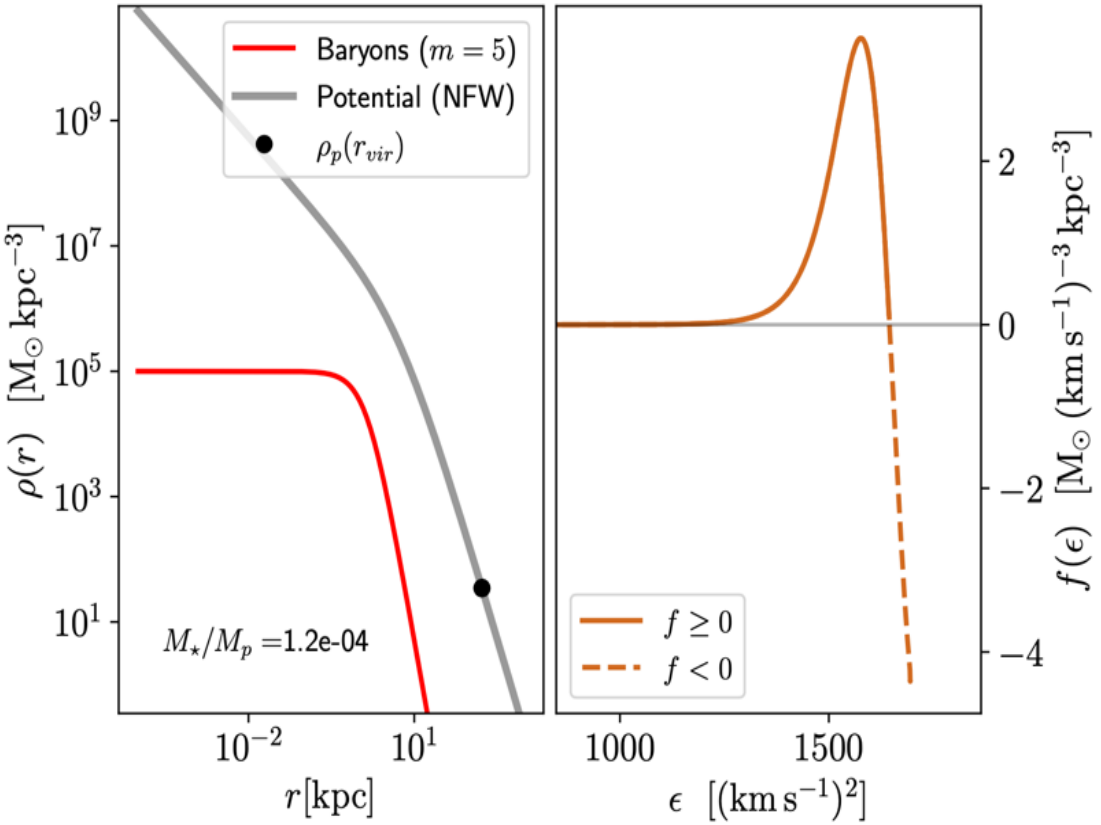
- Is a cored estellar ρ(r) consistent with a cuspy CDM Ψ(r)?

$$\frac{d\rho}{d\Psi} = 2\pi\sqrt{2}\int_0^{\Psi}\frac{f(\epsilon)}{\sqrt{\Psi-\epsilon}}d\epsilon.$$ =0 implies f(ε) <0

$$\frac{d\rho}{d\Psi} = \frac{d\rho/dr}{d\Psi/dr},$$

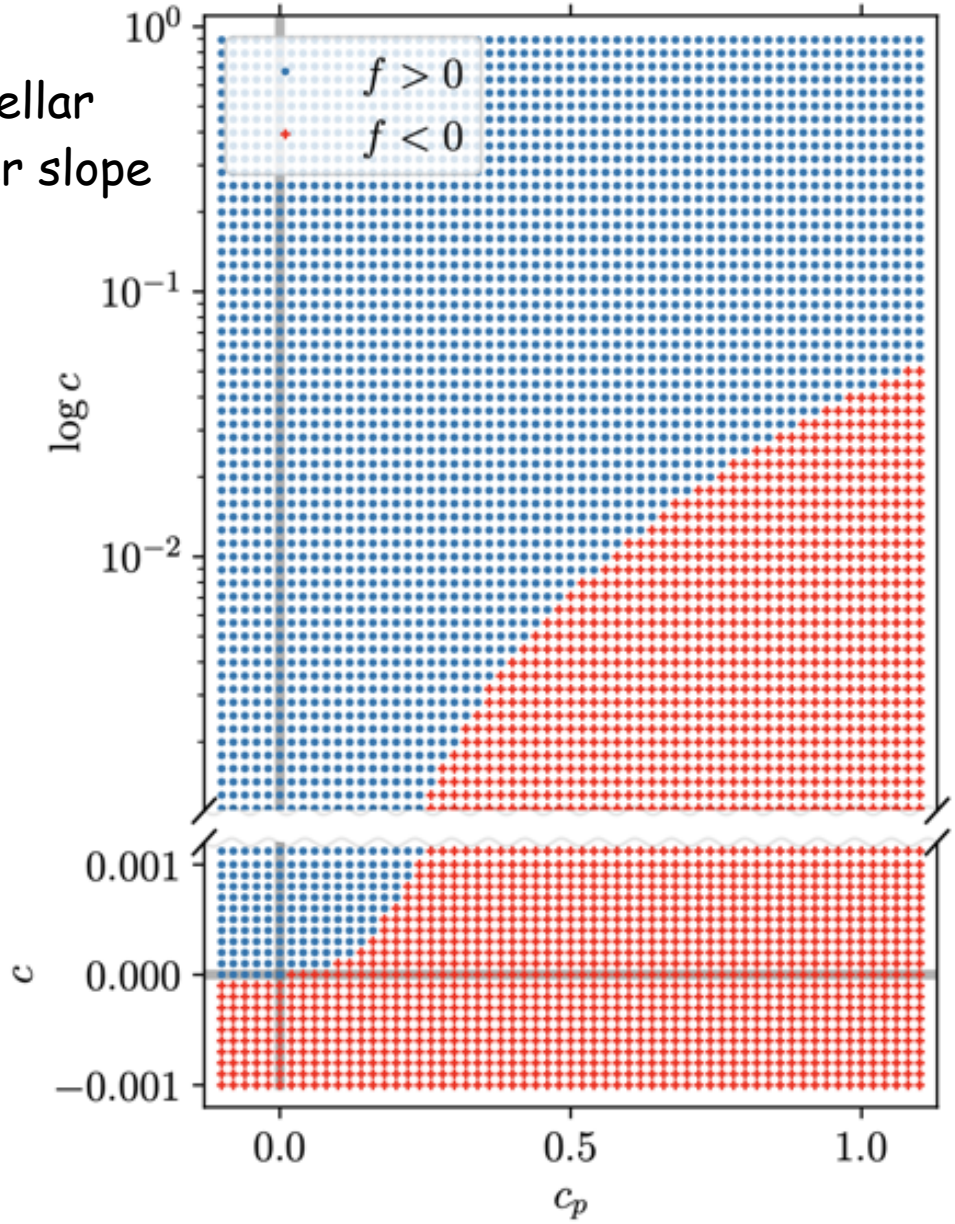
$$\lim_{r\to 0}\frac{d\Psi}{dr} = -\frac{V_c}{2\,r_s^2} \neq 0;$$

$$\lim_{r\to 0}\frac{d\rho}{dr} = 0,$$

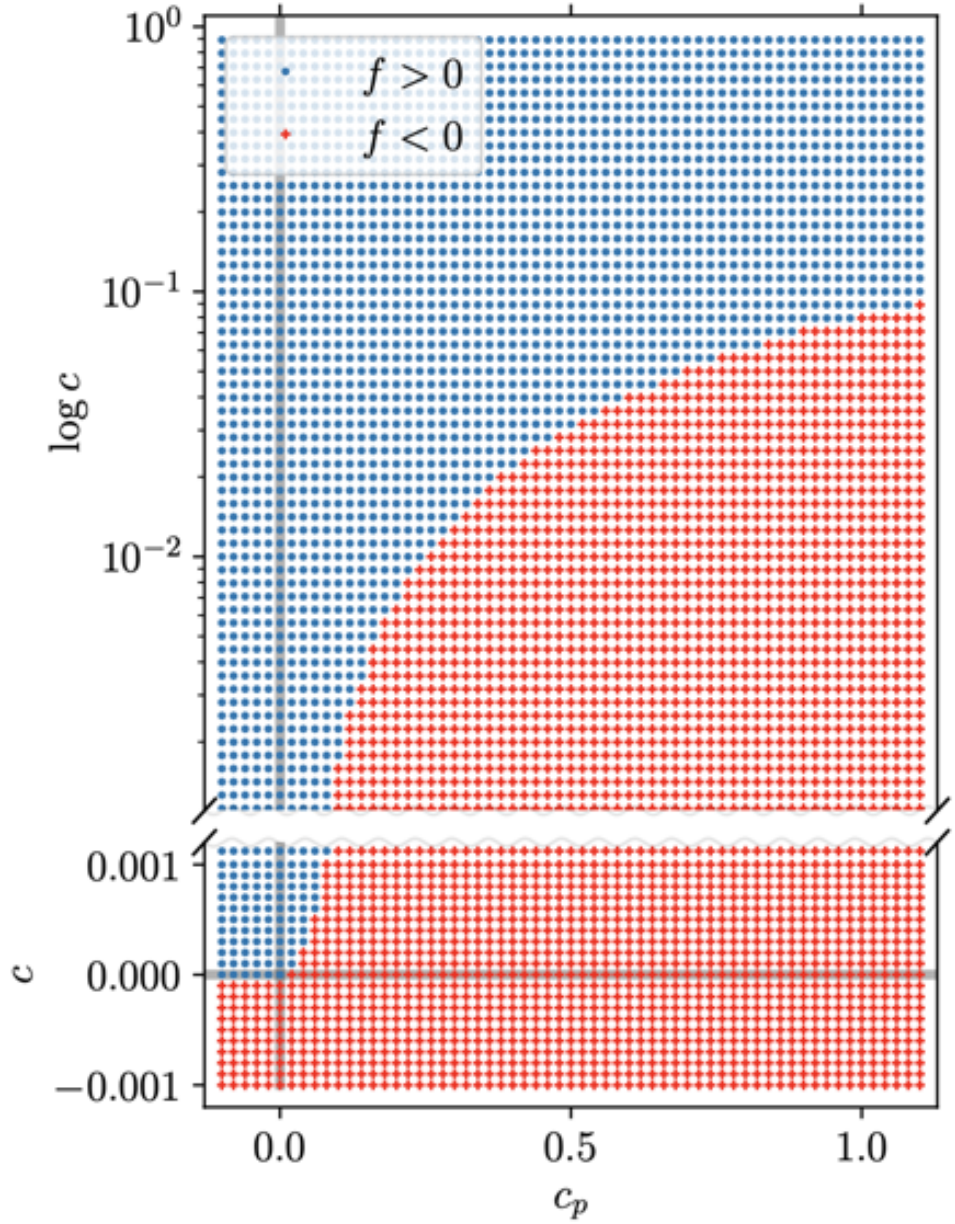


NO for spherical systems with isotropic velocities

Stellar inner slope



Potential inner slope



SA+23a, ApJ, 954, 153

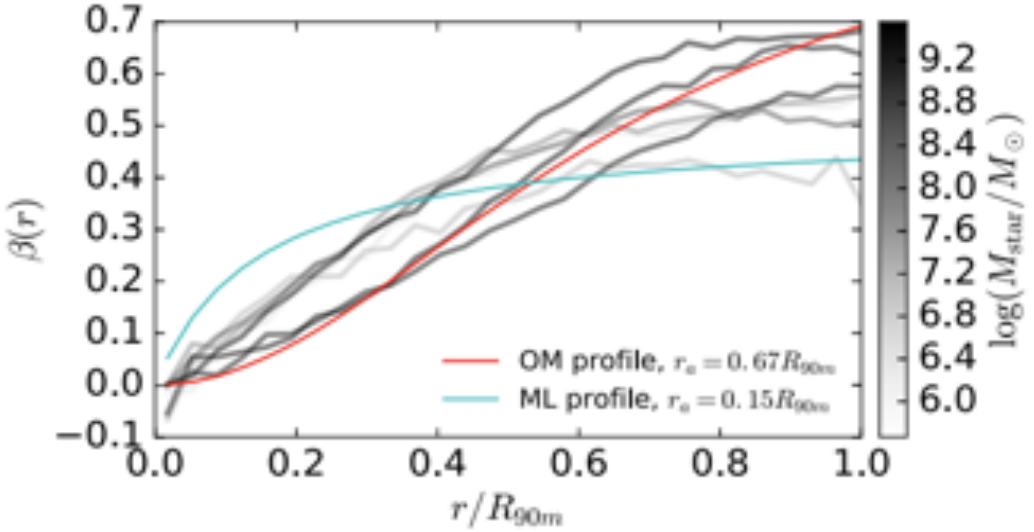
Table 1. Summary of the compatibility between baryon density profile (ρ) and potential

Baryons & Potential, Velocity	Consistency	Comments	Section
(1)	(2)	(3)	(4)
Core [†] & NFW [‡], isotropic	✗	Eqs. (23) and (24). $\beta = 0$ [*]. Fig. 1	Sect. 3
Power law [§] & Power law, isotropic	✍	$\alpha > 0$ [§] ✓ $\alpha < 0$ ✗. Eq. (25). $\beta = 0$	Sects. 3, 4.2
Core & Soft-core [#], isotropic	✗	$\beta = 0$. Fig. 4. Fig. 5	Sect. 4.2, App. E
Core & Core, isotropic	✍	$\beta = 0$. $a \leq 2$ ✓ $a > 2$ ✗. Fig. 2. Fig. 7	Sects. 4.1, 4.2, App. E
Soft-core & NFW, isotropic	✍	$\beta = 0$. Figs. 5, 6. $c \gtrsim 0.1$ ✓ $c \lesssim 0.1$ ✗.	Sects. 3, 4.2
Soft-core & Soft-core, isotropic	✍	$\beta = 0$. Figs. 5, 6	Sects. 3, 4.2
		$r_s \gtrsim 2\, r_{sp}$ ✗, $c > c_p$ ✓	Sect. 4.2
Core & NFW, O-M model	✗	$\beta(\neq 0)$ in Eq. (12)	Sect. 3
Core & NFW, radially biased	✗	Constant β. $\beta > 0$	Sect. 3, App. D
Core & Any, radially biased	✗	Constant β. $\beta > 0$	Sect. 3, App. D
Power-law & Any, anisotropic	✍	Constant β. $\alpha > 2\beta$	Sect. 3, App. D
Core & NFW, circular	✓	$\beta = -\infty$	App. C
Any & Any, circular	✓	$\beta = -\infty$	App. C
Any & Any, tangentially biased	✍	$\beta < 0$. Eq. (18). ✗ $f_i < 0$	Sects. 2.3, 3

NOTE—
[†] Core $\equiv d\log\rho/d\log r \to 0$ when $r \to 0$.
[‡] Navarro, Frenk, and White potential (Eq. [A6]) produced by a NFW profile (Eq. [A5]).
[*] Velocity anisotropy parameter β defined in Eq. (11).
[§] $\rho \propto r^{-\alpha}$.
[#] Soft-cores defined in Eqs. (30) and (32), and illustrated in Fig. 3. Power laws [§] are a particular type of those.
(1) Description of the baryon density, the gravitational potential, and the velocity distribution.
(2) The symbols ✓, ✗, and ✍ stand for *compatible*, *incompatible*, and *may or may not*, respectively.
(3) Additional comments and keywords.
(4) Section of the text where the combination described in (1) is discussed.

SA+23b, ApJ

How good or bad are these assumptions? Isotropic velocities and the like

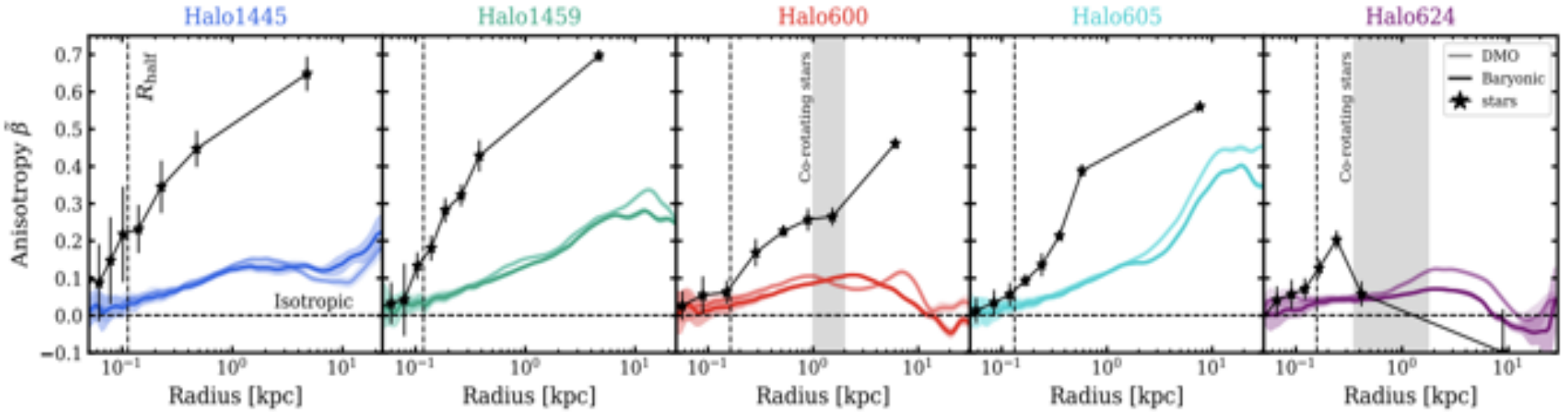


$$\beta(r) = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2},$$

β = 0 Isotropic orbits

β > 0 Radially biased orbits

FIRE numerical simulation (El-Badry+17, ApJ)

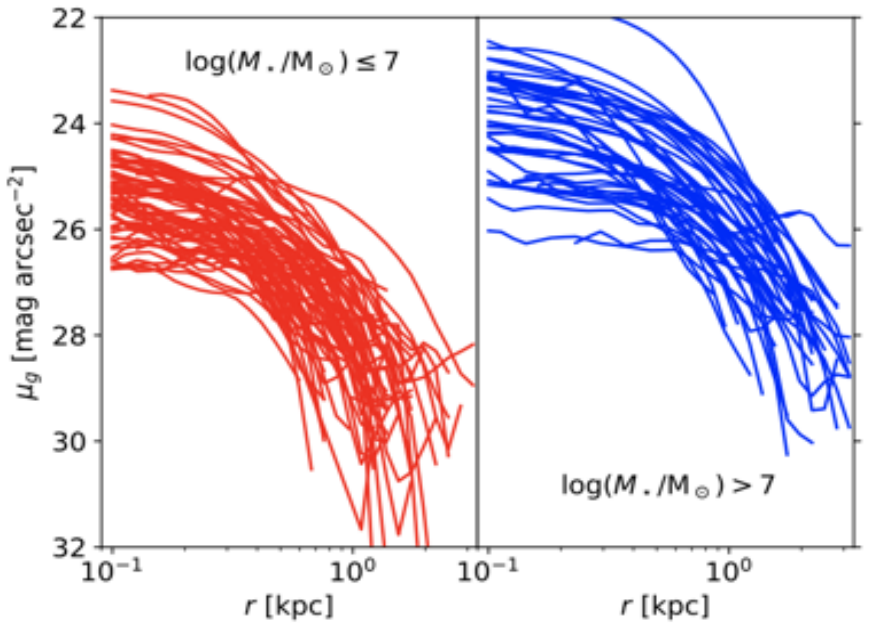


EDGE numerical simulations (Orkey+23, MNRAS)

Application to real galaxies:

(SA+24, A&A, submitted)

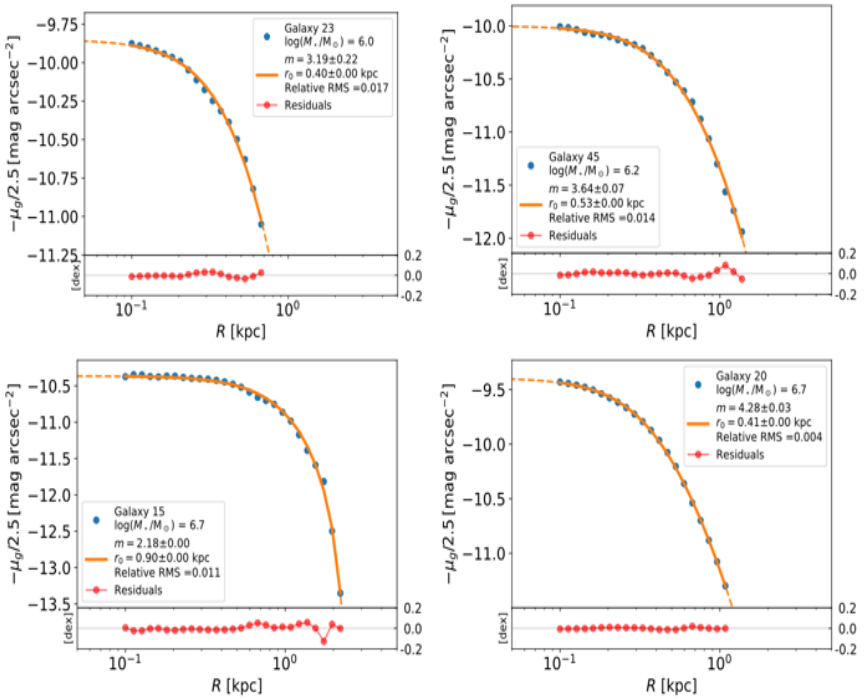
For the galaxies in Carlsten+21,22 (massive satellites of MW-like galaxies) and under the assumption of spherical symmetry and isotropic velocities (SA+23b, in prep.)

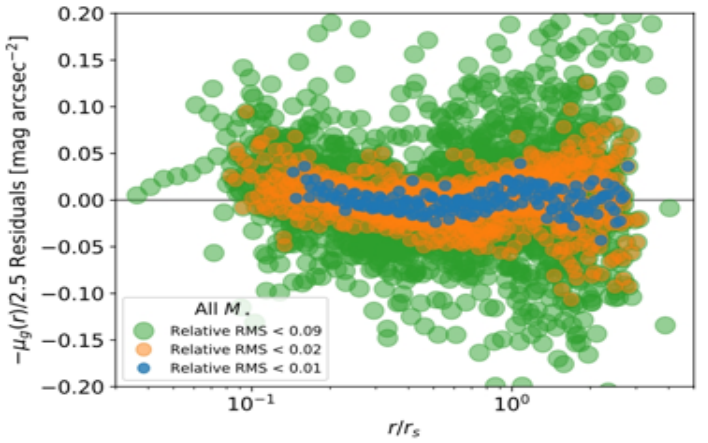


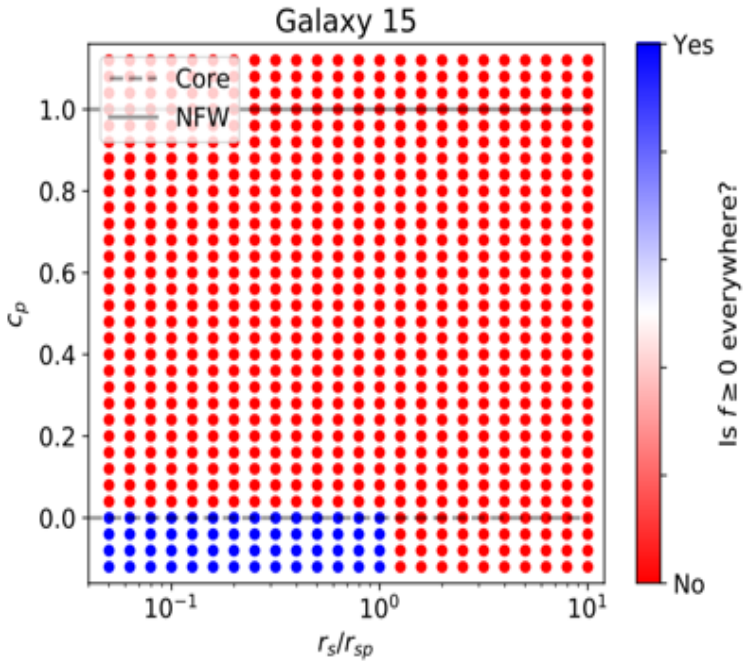
- Good for testing purposes (S/N and number of targets)

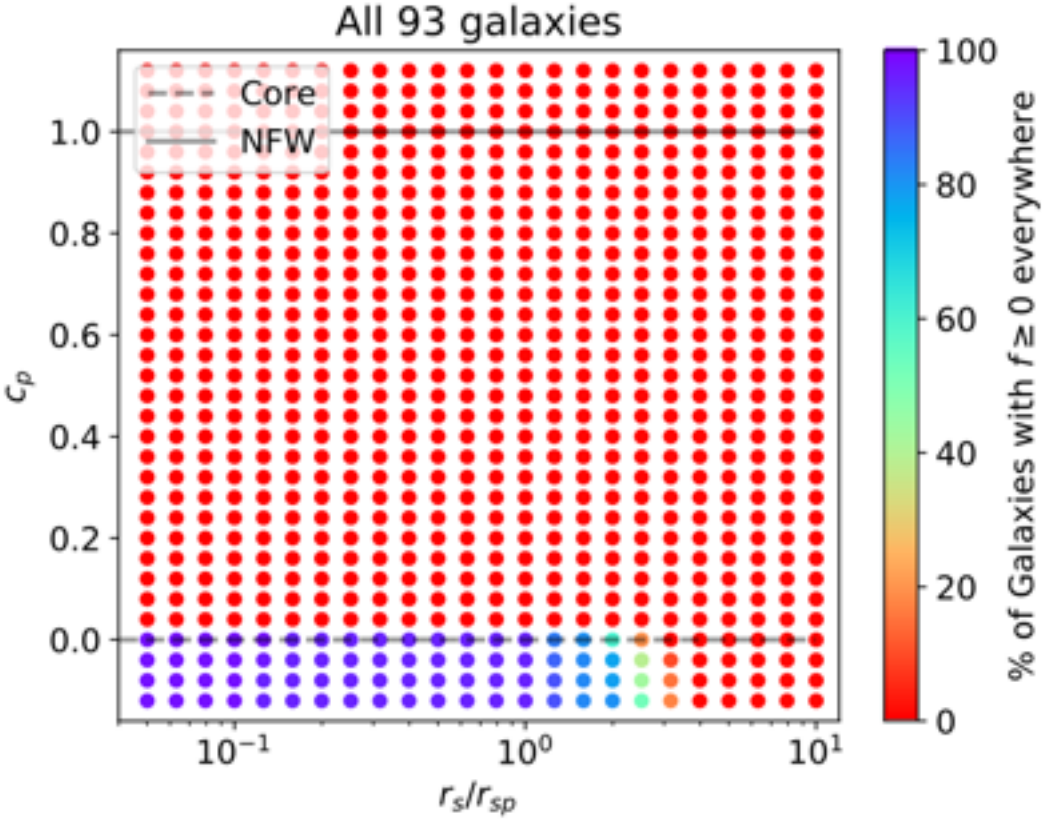
- No good for constraining the nature of DM ($6 < \log(M_*/M_\odot) < 7$)

Polytropic fit (with a forced core)

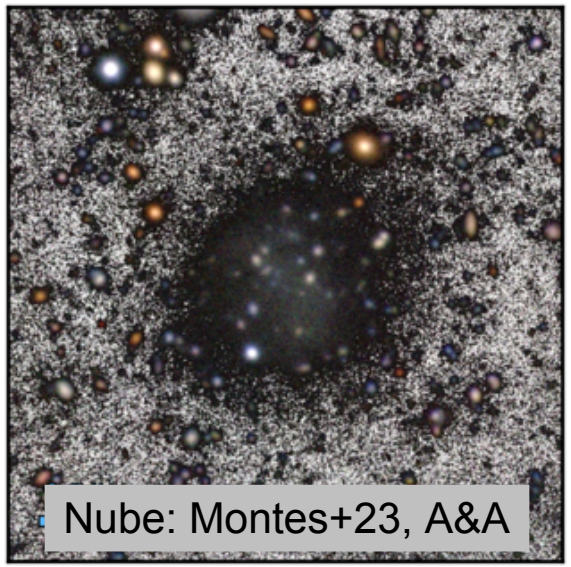


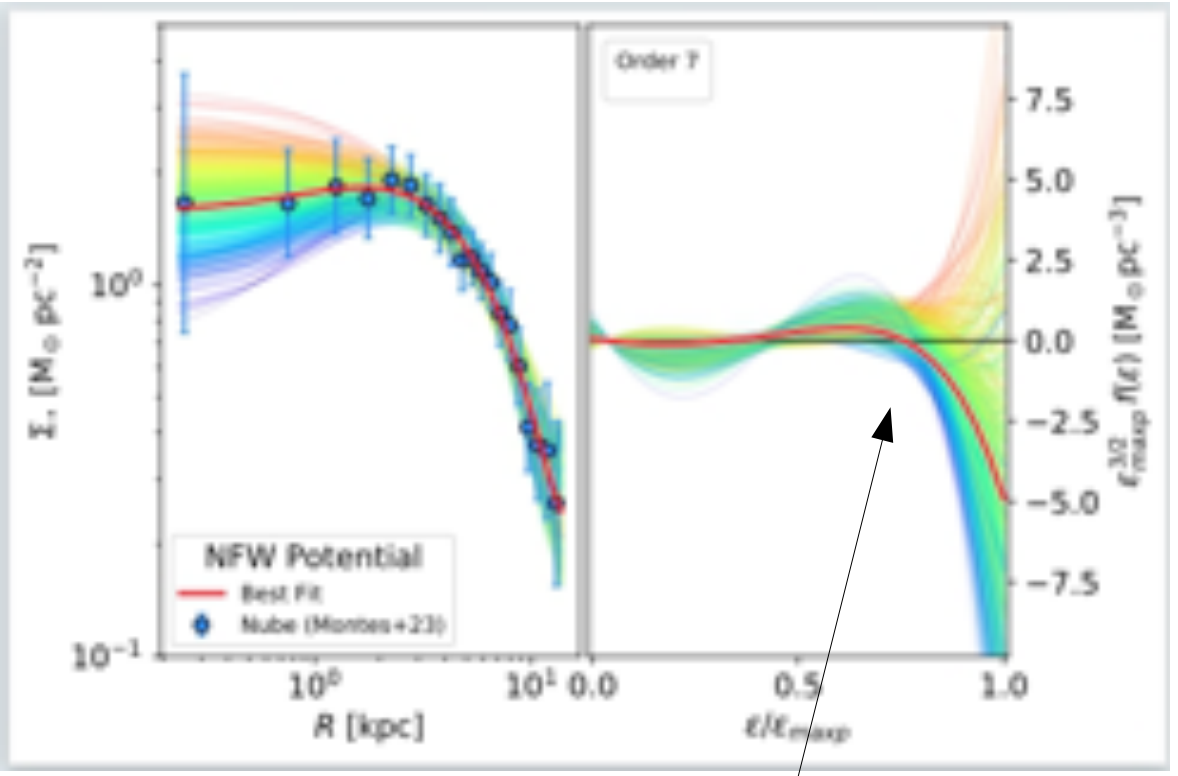






Using the Eddington inversion technique, we are starting to develop techniques that allow us to infer the distribution function needed for an observed profile to live in a particular DM halo.

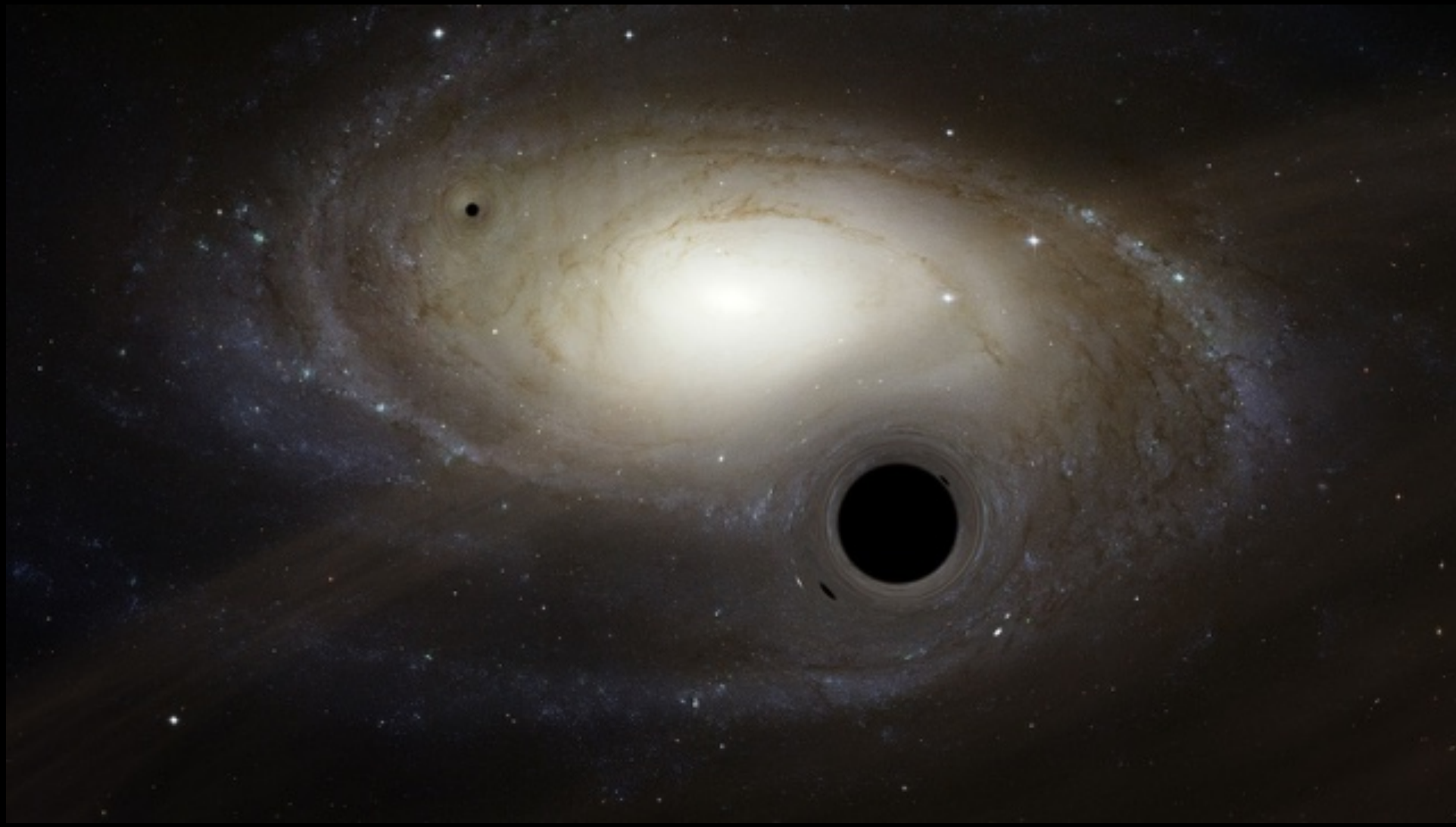




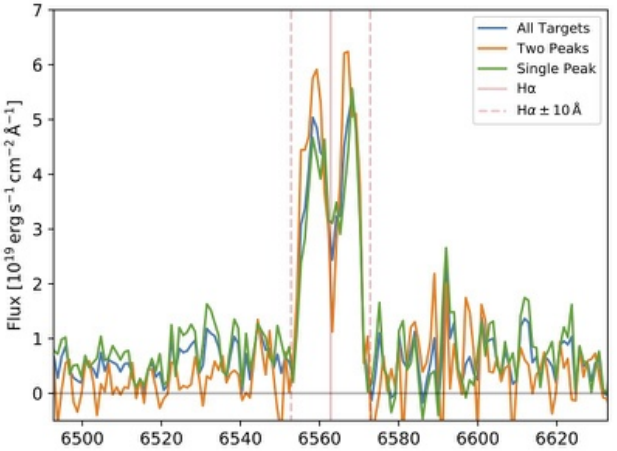
Nube does not live in a NFW potential because f < 0!

SA+24, in preparation

Estallidos 8:
Searching for IMBHs

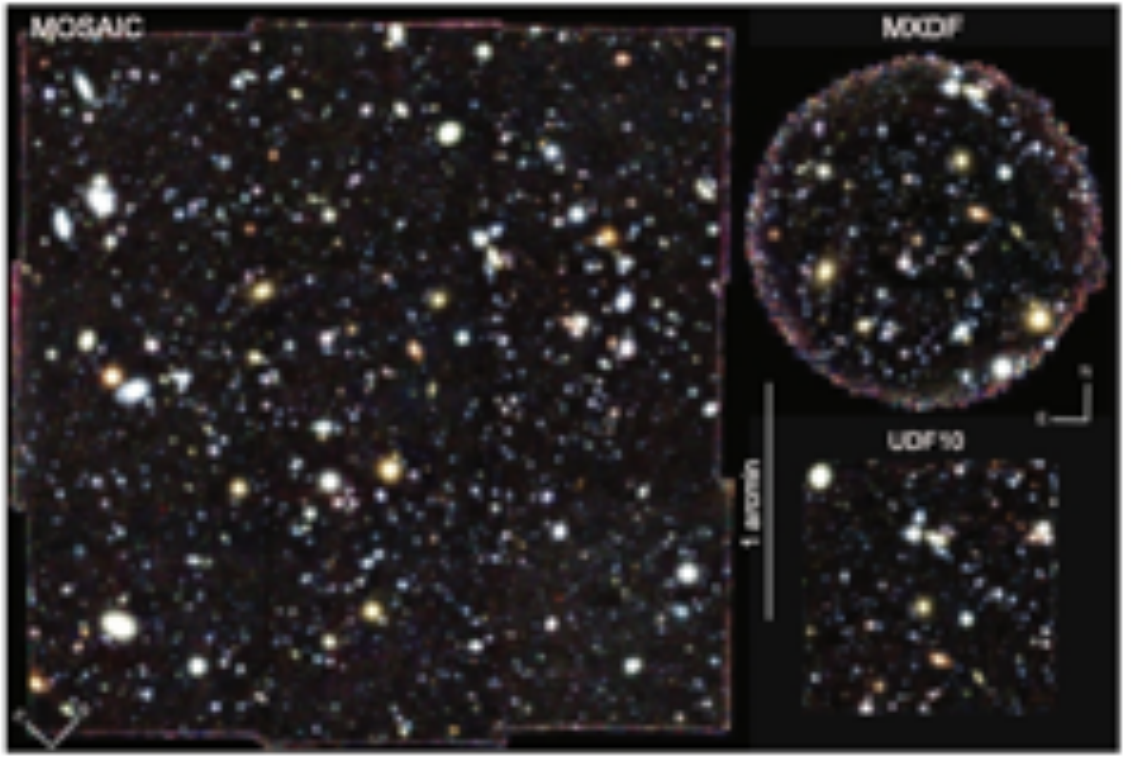


- Assuming the double peak Ha emission to be a fingerprint for IMBHs



- Look for these characteristic signals in the MUSE-UDF (Bacon+23, A&A). It corresponds to 150 hours of integration! (The MUSE Wide survey SA+22 used is just 1 hour integration.)

- **AI aided search** …. as it corresponds to these days. In principle, a simple task. J. Calhau already started the task before leaving.



Estal

Estallidos 8:
Costraining the nature of DM



Nube (Montes+23)

- Polish the tools to infer the distribution functions give a mass surface density profile

$$f(\epsilon) \simeq \sum_{i=3}^{n} \frac{a_i}{\epsilon_{max}^{3/2}} (\epsilon/\epsilon_{max})^i,$$

$$\Sigma(R) \simeq \sum_{i=3}^{n} a_i S_i(R),$$

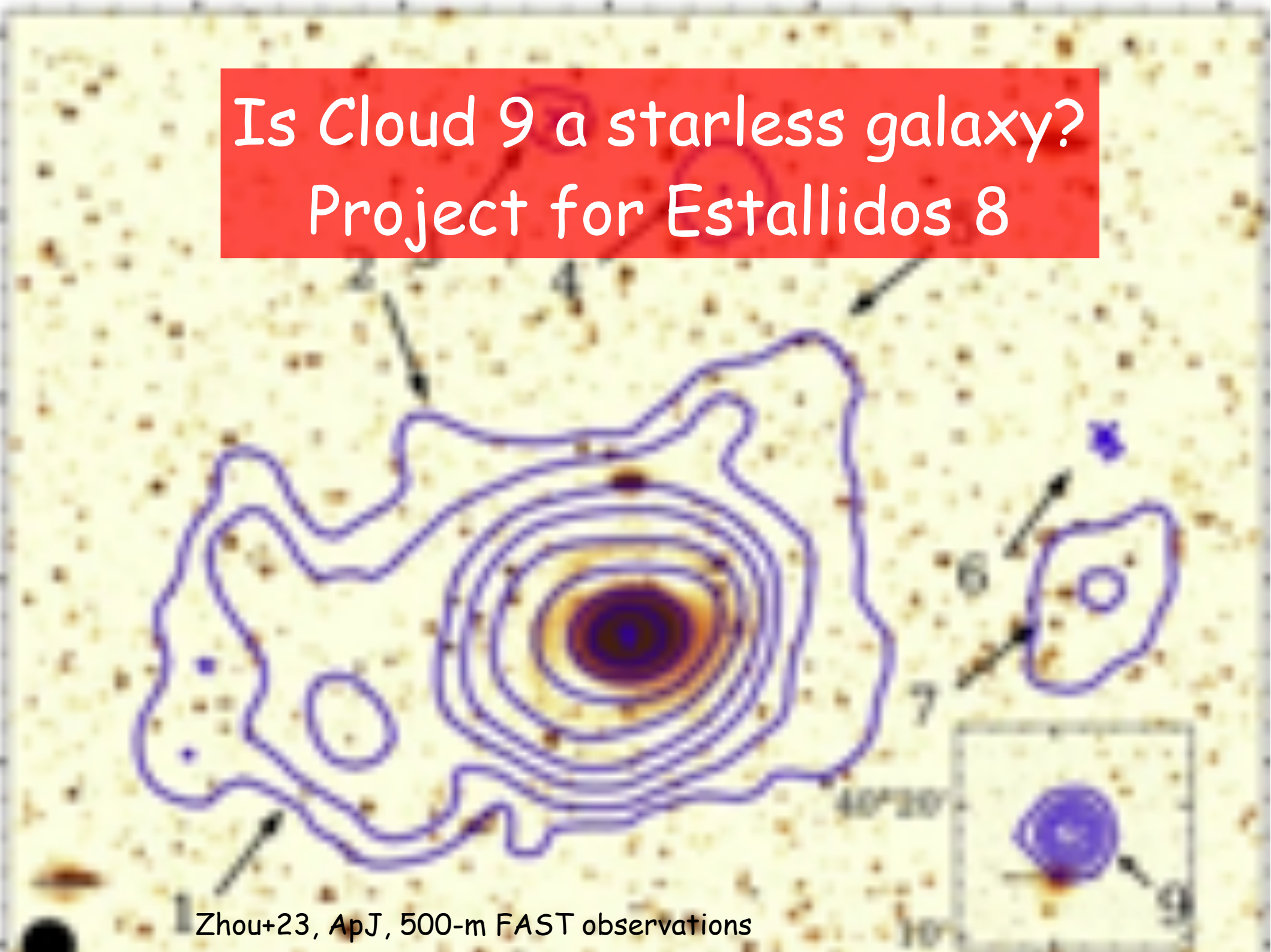
$$S_i(R) = \int_0^1 \alpha^i \frac{\xi_\Sigma(\alpha\epsilon_{max}, R)}{\sqrt{\epsilon_{max}}} d\alpha,$$

- Find large datasets of faint galaxies (thousands!, to be able to trim the sample and renove bias!) Short term: DES, DESI, LIGHTS ... Long term: LSST, Euclid, ...

- Find ways to estimate distances (i.e masses) to these tinies (e.g., if satellites, surface brightness fluctuations, detallied spectroscopic follow up of selected candidates)

- Do galaxies with $M^* < 10^5 M_\odot$ have cores? If they do then DM MUST collide proving that we have to go beyond the ΛCDM paradigm!

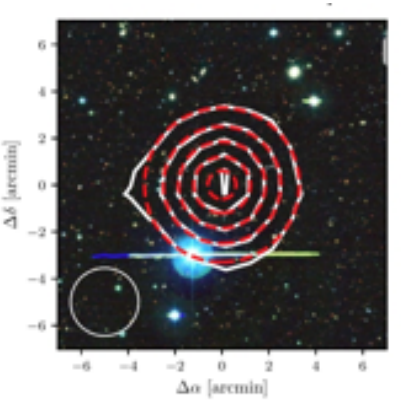
Is Cloud 9 a starless galaxy?
Project for Estallidos 8



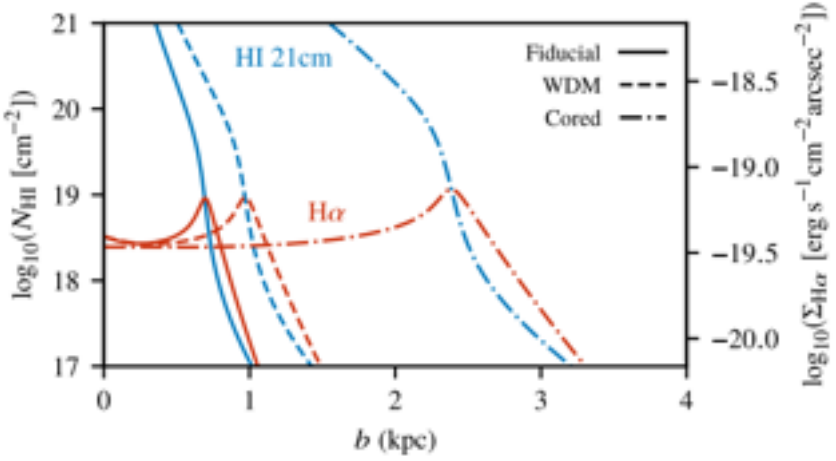
Zhou+23, ApJ, 500-m FAST observations

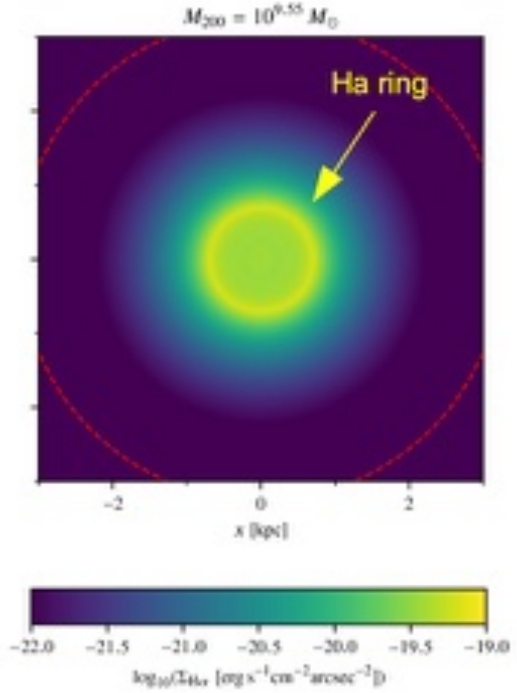
- Starless haloes are the Holly Grail of the halos where observing a core implies deviations from CDM

- According to Benitez-Llambay & Navarro 23, cloud 9 could be one of the many expected starless dark matter haloes: it has the right gas mass and an HI line width consistent with a massive DM halo.

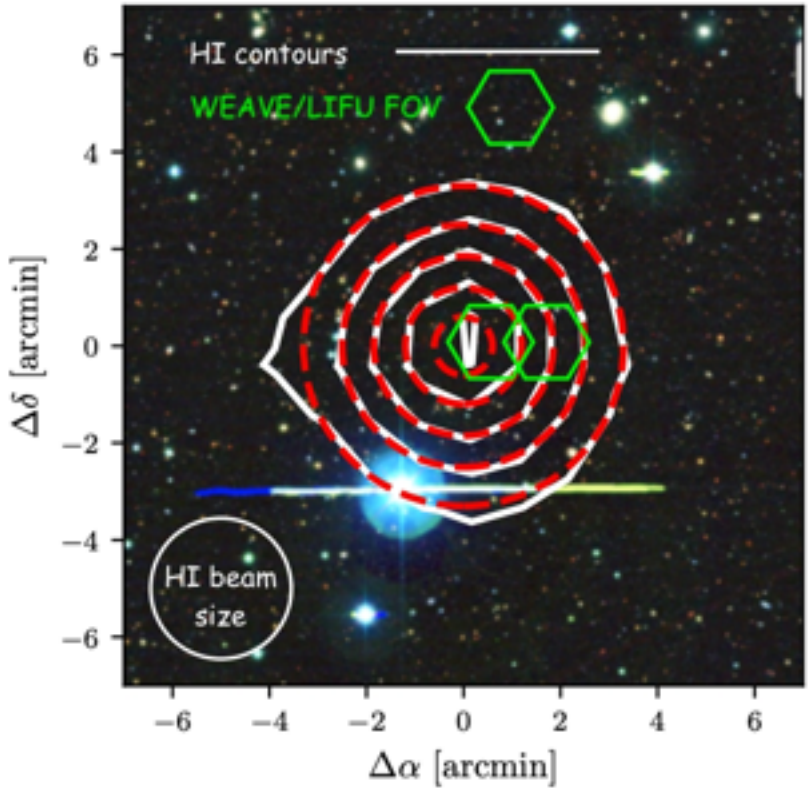


- Where does the Estallidos expertise come into play? The starless DM halos are expected to emit in Ha in a ring-like structure excited by the cosmic UV background (e.g., Sykes+19).





We apply to observe the Ha of Clound 9 with large IFU of WEAVE @ WHT



- got 35.7 hours in Band A for Semester 24A

- to be carried out April/2024

- Tasks: (a) reduce the data (first trial by the WEAVE team)

(b) Interpret the Ha emission (even a negative detection is a result)

(c) Publish the result. Luckily, the first starless DM ever confirmed.

Project for Estallidos 8?

Recommended time allocation by the CAT

Semester 2024A

William Herschel Telescope

Ref. CAT	Band	PI	Awarded hours	Instrument	Large program	Title
SW2024a11	A	Jorge Sánchez Almeida	35.7	WEAVE/LIFU	-	First Halpha detection of a fossil starless dark-mater halo
SW2024a07	B	Jesús Maíz Apellániz	48.6	WEAVE/LIFU	-	A multiplicity survey of stellar clusters with O stars
SW2024a13	B	Ignacio Negueruela	9.0	WEAVE/LIFU	-	A massive young cluster in the Outer Milky Way
SW2024a12	B	Martín Guerrero	9.0	WEAVE/LIFU	-	Unveiling the Ejecta 3D structure of Nova Remnants
SW2024a09	B	Ignacio Trujillo	9.0	WEAVE/LIFU	-	A precise distance estimation to Nube
SW2024a14	B	Anelise Audibert	10.8	WEAVE/LIFU	-	WEAVEing insights into jet-ISM interaction: a pilot study of radio-loug galaxies
SW2024a15	BC	MariCruz Gálvez-Ortiz	36.0 (B:19, C:17)	WEAVE/LIFU	-	Characterization of low-mass eclipsing binaries with WEAVE
SW2024a10	C	Francesca Pinna	24.3	WEAVE/LIFU	-	WEAVE-GECKOS: unveiling the assembly of young cold disks in spiral galaxies

Summary:

1.- Estallidos 7:

- Searching for the cosmic web in emission
- Cores in tiny galaxies and the nature of DM

2.- Estallidos 8: Plans

- Searching for wandering IMBHs
- Cores in tiny galaxies and the nature of DM

3.- Is Cloud 9 a starless dark-matter halo? Estallidos 8

4.- Conclusions

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