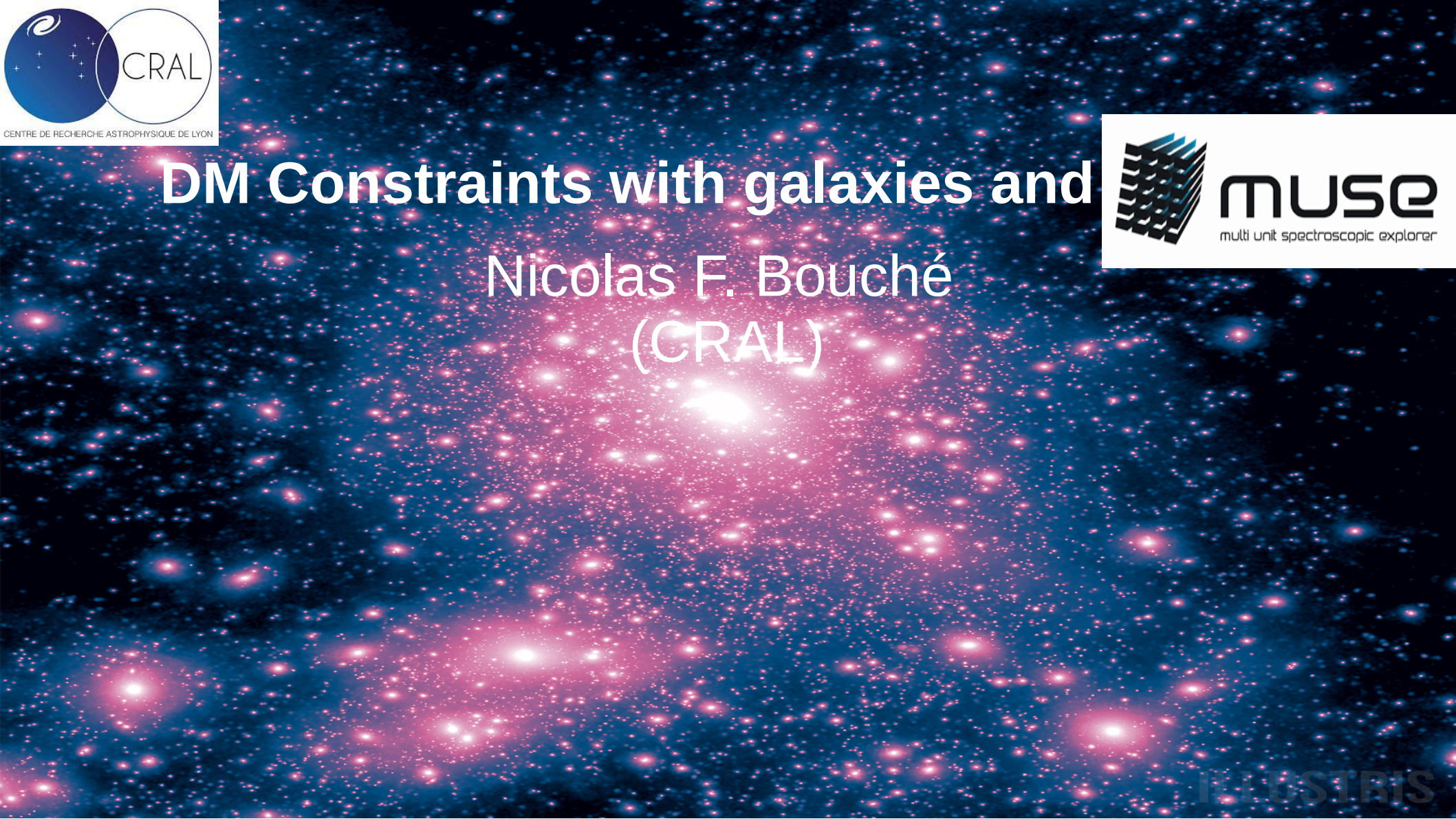
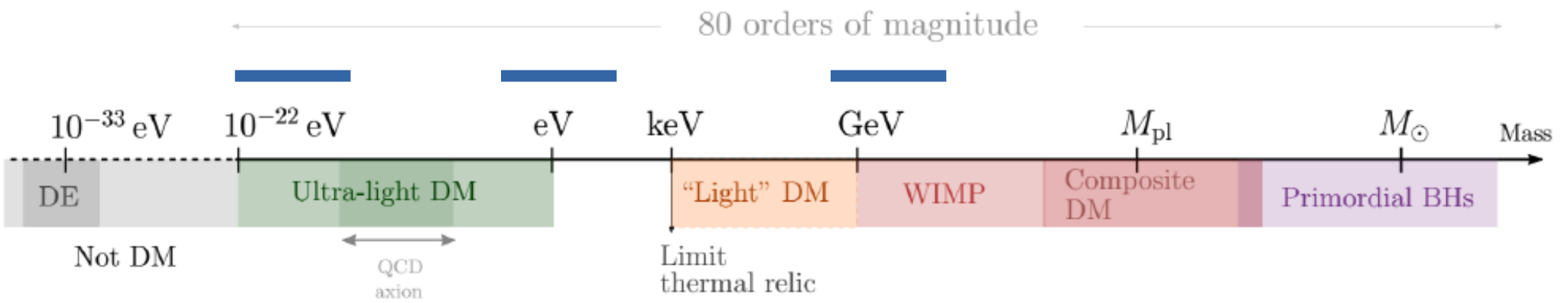

CRAL
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON
muse
multi unit spectroscopic explorer
DM Constraints with galaxies and
Nicolas F. Bouché
(CRAL)
ILLUSTRIS

DM Constraints with galaxies and

Nicolas F. Bouché
(CRAL)



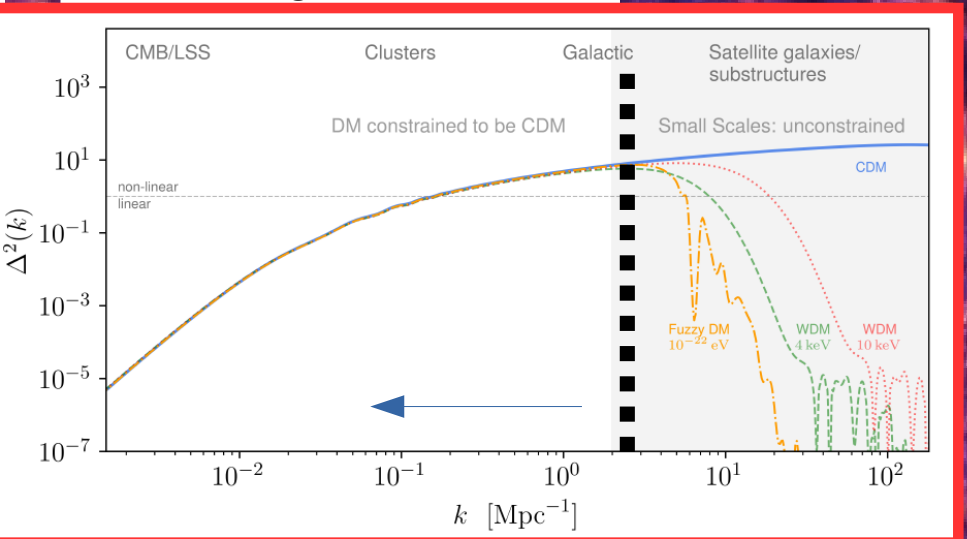
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

DM Constraints with galaxies and

Nicolas F. Bouché
(CRAL)

multi unit spectroscopic explorer

A big sucess

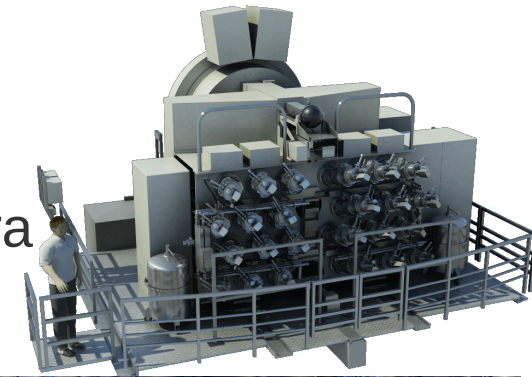


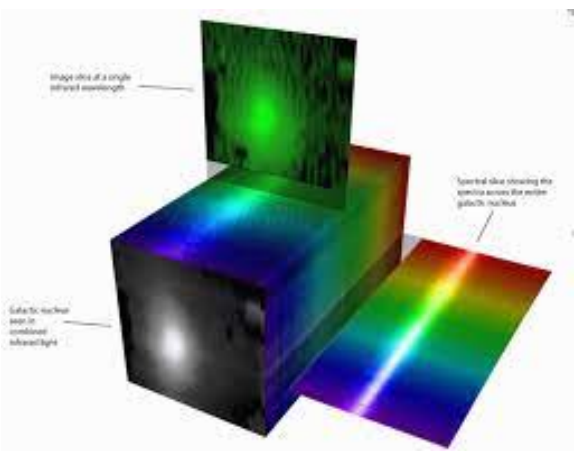
CDM failures on small scales :

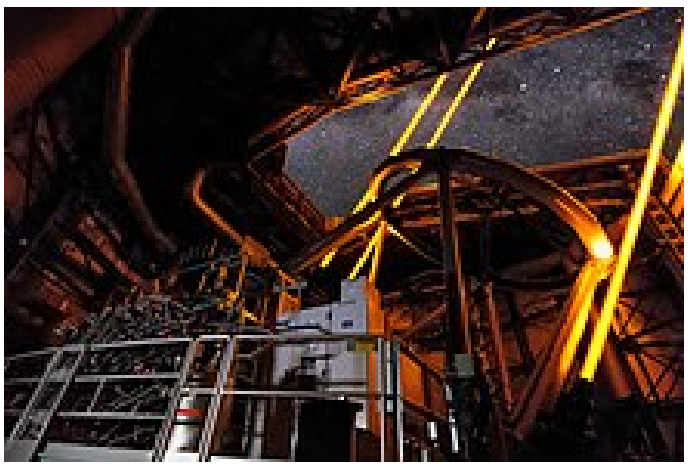
- Many small halos / satellite problems
- Dense DM profiles (Cuspy)

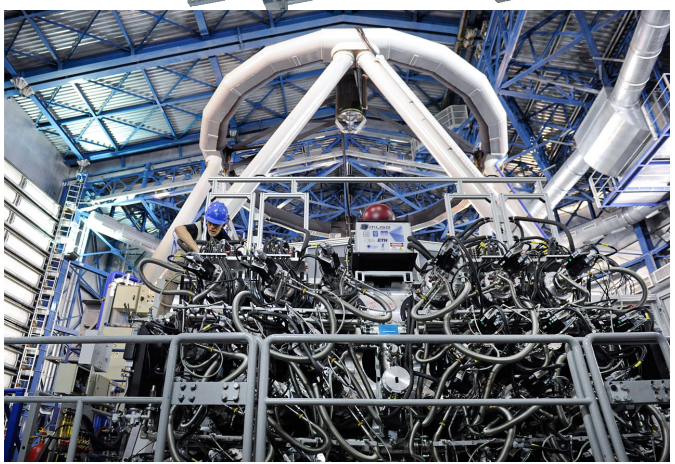
What is MUSE ?

- **Optical IFU @VLT**
  - Built @CRAL (PI : R. Bacon)
  - ~24 instruments (slicers, spectrographs)
  - **Largest** FOV : 1'x1' @0.2"/spaxel → 90,000spectra
  - 5000-9300 Ang. @ R~3000







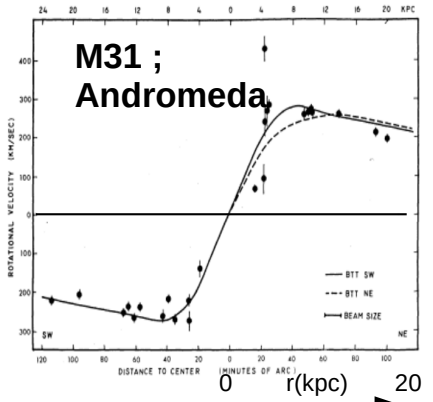


Outline

- **Rotation curves as DM laboratory**
- Small scale problem (Core-Cusp)
- 3 things you might not know
  - A) MUSE rules out ALP 1e-22eV in (ultra-) faint dwarfs
  - B) MUSE gives strongest constraints on Axions at ~eV
  - C) MUSE reveals Core/Cusp problem at high-redshifts
- What’s next ?

Rubin& Ford 1970

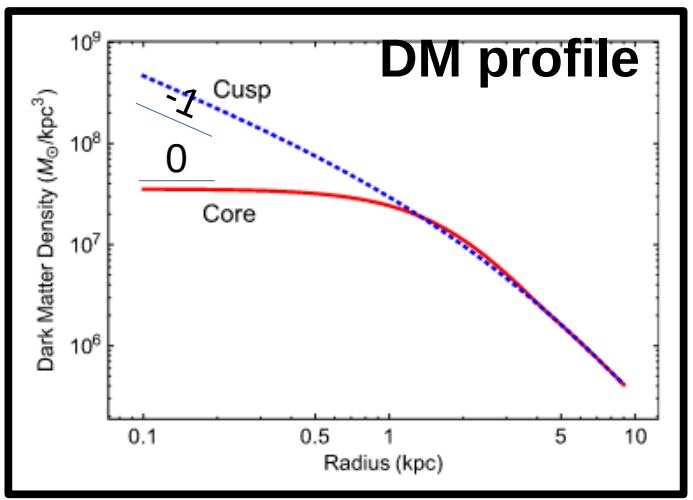
v(r) as DM laboratory

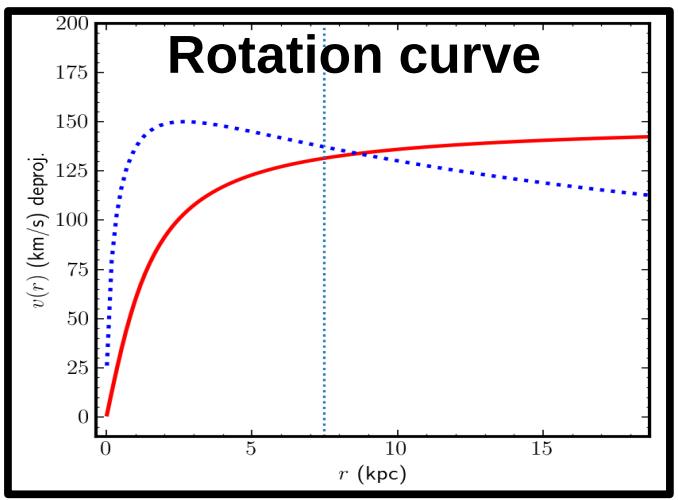


- Historical DM `discovery' at z=0 in M31

Flat v(r) → DM

- RC are *sensitive probes* of DM density profiles





In other words, the curvature of v(r) relates to DM models (CDM, SIDM, fuzzy, etc)

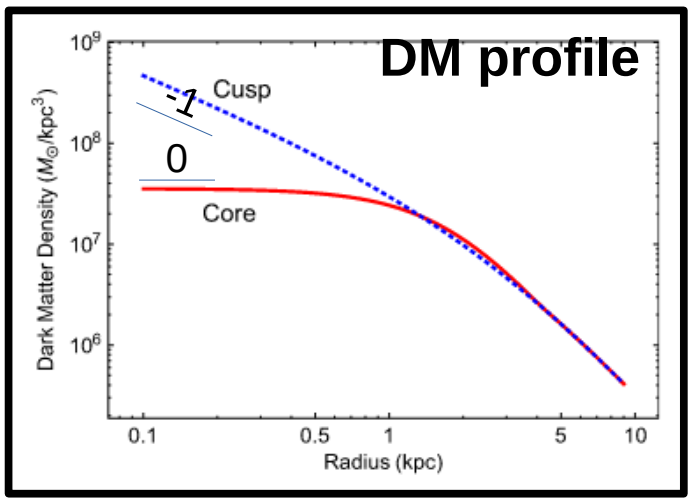
→ **Need DM-dominated galaxies !!**

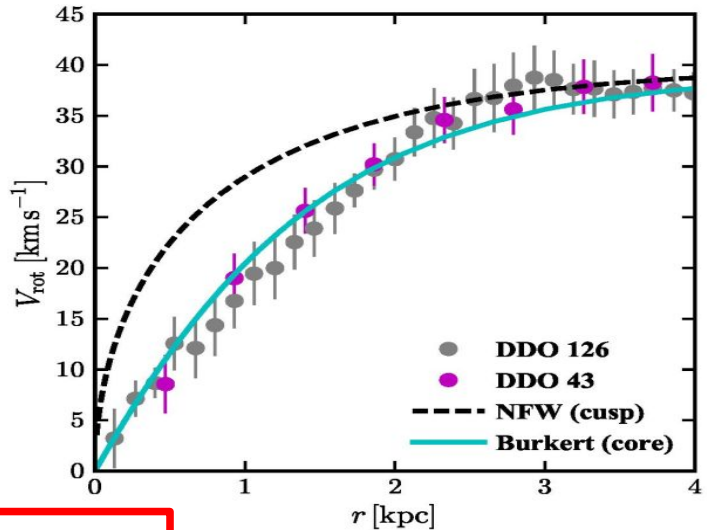
v(r) as DM laboratory

A problem in **dwarfs** since 1994 (before NFW96) !

- RC are *sensitive probes* of DM density profiles

De Blok et al. 2001
Oh et al. 2011, 2015





The cusp-core problem
The small-scale problem (<2kpc)

Possible ways out

A CDM is wrong (wimp ~ GeV)

B

Possible ways out

A CDM is wrong (wimp ~ GeV)

B Warm DM (non-thermal keV)

C Self Interacting DM (SIDM)

D Axion-like Fuzzy DM

E Extend/modify GR

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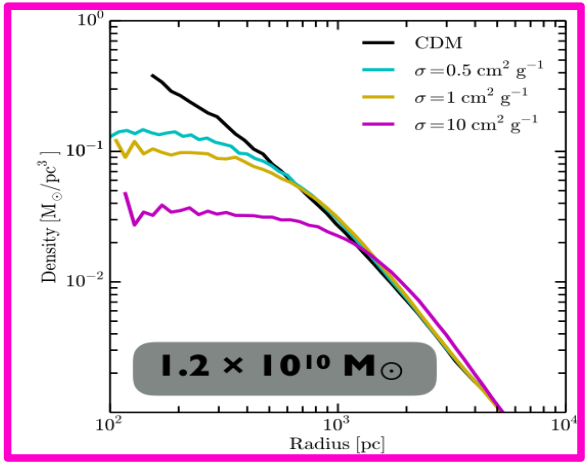


Boldrini 2022

Possible ways out

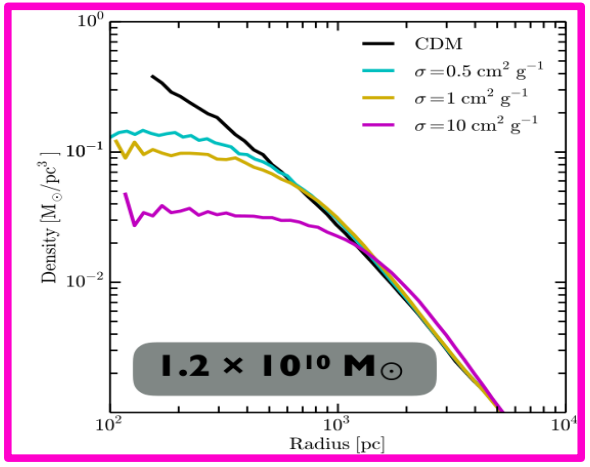
A CDM is wrong (wimp ~ GeV)

B Warm DM (non-thermal keV)

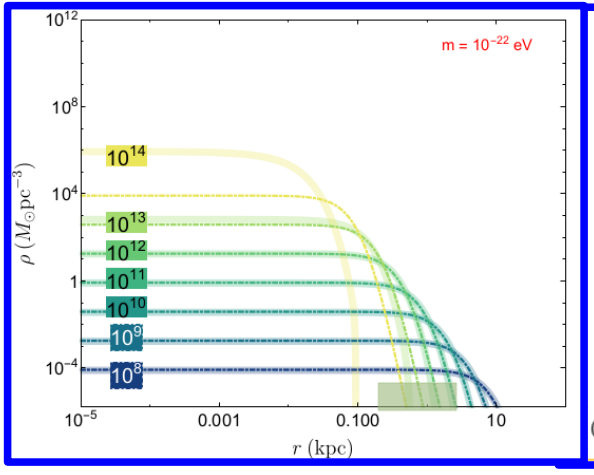
C Self Interacting DM (SIDM)

D Axion-like Fuzzy DM

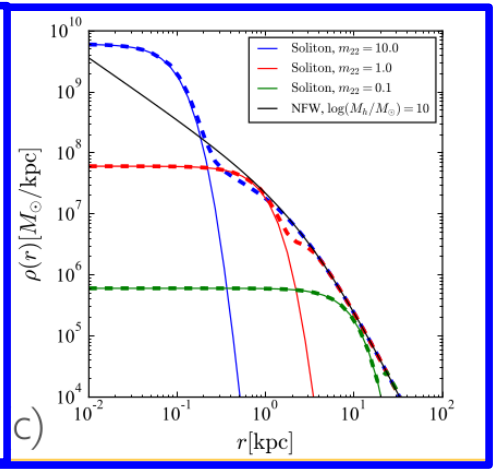
$$\lambda = 1.19\left(\frac{10^{-22}\mathrm{eV}}{m}\right)\left(\frac{100\mathrm{km.s}^{-1}}{v}\right)\mathrm{kpc},$$



Boldrini 2022



Davies&Mocz 2019



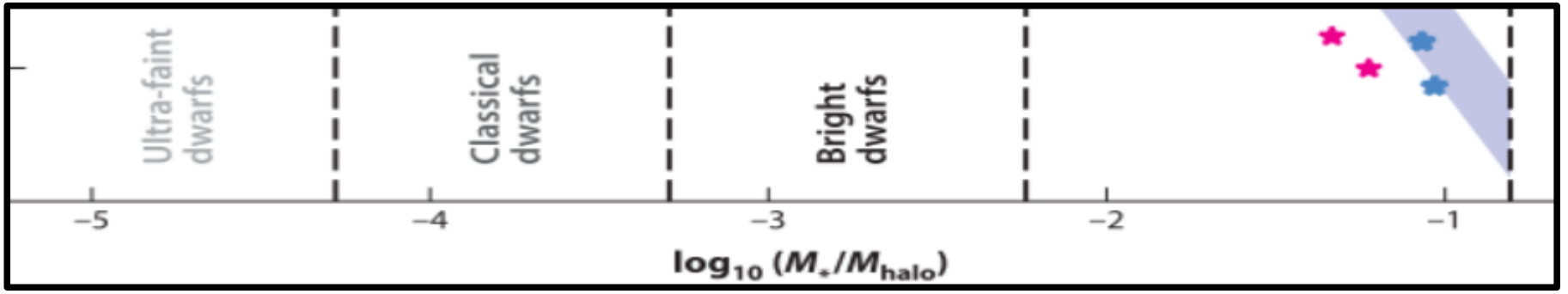
Boldrini 2022

A) MUSE-faint

- A survey of ultra-faint dwarfs with MUSE
  - PI : J. Brinchmann (U. Porto)
  - 100hr of MUSE (GTO) down to r~25 mag
  - Sample : 10 ultra-faint dwarfs (Mdyn/M* > 100-1000)

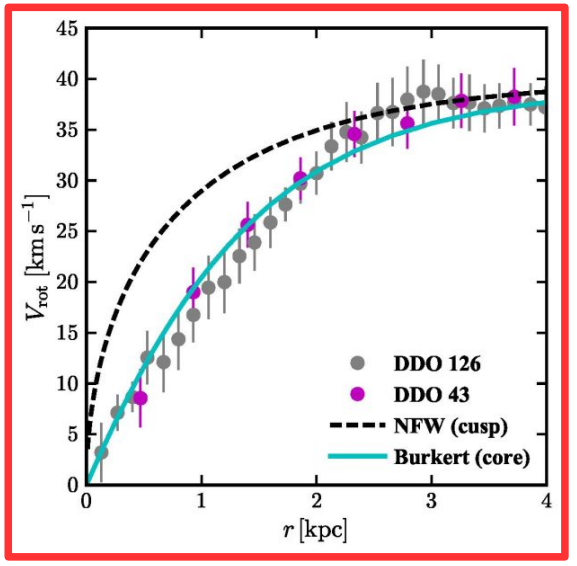
Zoutendijk 22 (4dw)
Zoutendijk 21 (Erid2)

MUSE-faint



Are the inner DM profiles cored ?

DM problem in dwarfs

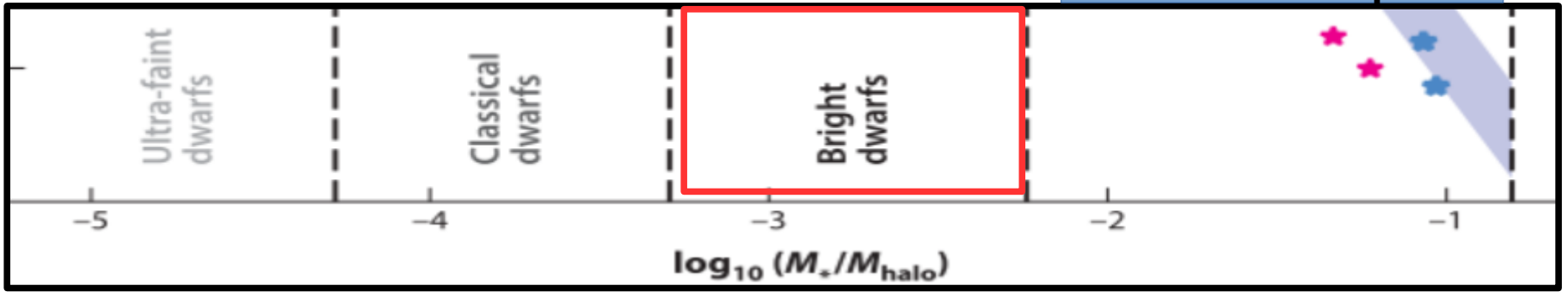


Classical dwarfs

cores

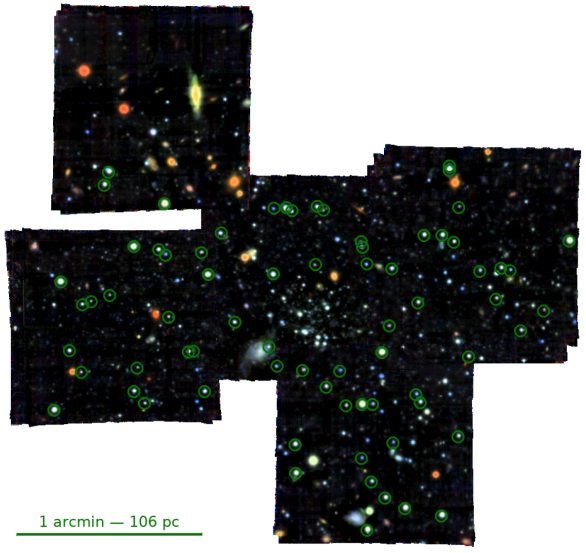
This talk
MUSE-faint

This talk
MUSE-deep



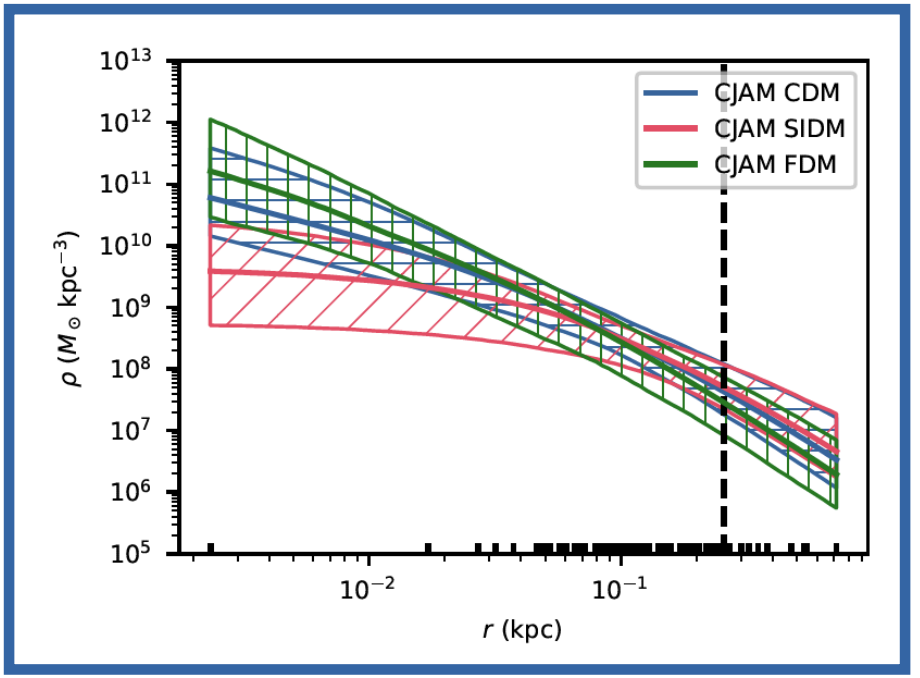
A) MUSE-faint : Erid II

- Approach :
  - From 5 MUSE fields find 92 stars (CMD)
  - Dynamical modelling to predict vdisp
    CJAM ; pyGravsphere
  - Estimate likelyhood parameters (MCMC)



A) MUSE-faint : Results

Zoutendijk, Brinchmann, NB 2021



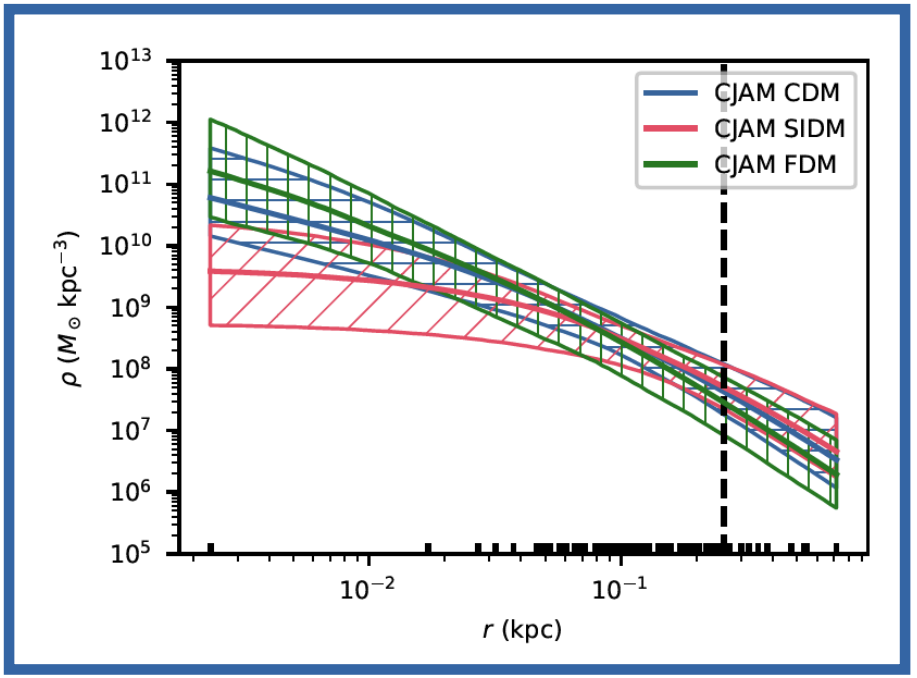
- Data against
  1) Fuzzy DM
  2) CDM
  3) SIDM

In that order, small significances

No core (rc<35pc or rsol<3pc)

A) MUSE-faint : Results

Zoutendijk, Brinchmann, NB 2021



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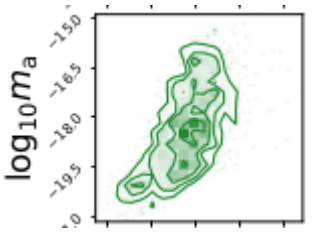


In that order, small significances

No core (rc<35pc or rsol<3pc)

→ $m_a \gtrsim 8.5 \times 10^{-20}\ \mathrm{eV}\ c^{-2}$

<> for FDM in classical dwarfs (ma~1e-22 eV)

Confirmed by a joint analysis on 5 faint dwarfs

B) MUSE-faint: Results on Axions

$$\tau_a = \frac{64\pi}{m_a^3 g^2},$$

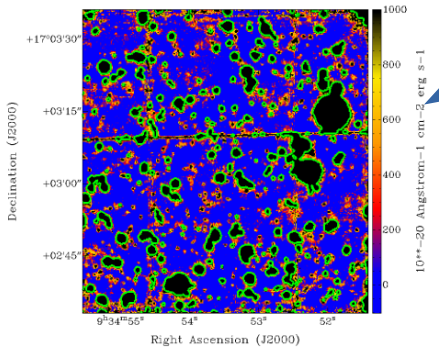
Regis, Taosco, et al. 2021

$$S_{\rm sd} = \frac{m_a^2 g^2}{64\pi} \frac{D(\alpha_{\rm int})}{\sigma_{\rm disp}},$$

$$\lambda = 24600\, AA / ma\,(eV)$$

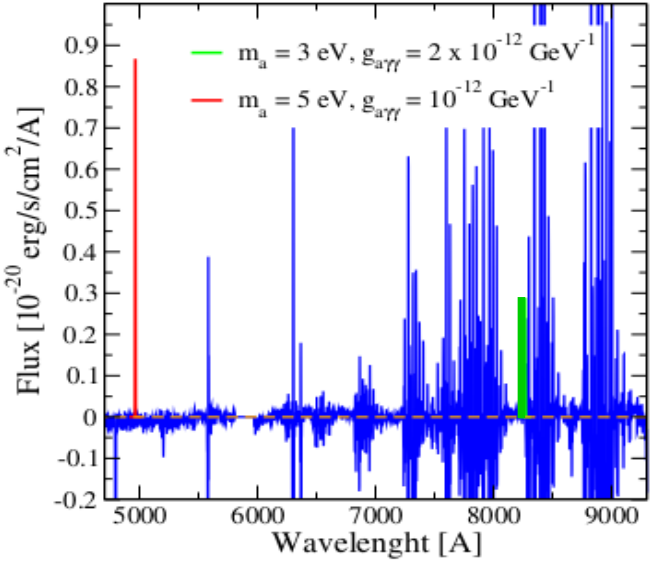
- For Axions, coupling with EMF → <u>spontaneous</u> decay in 2 photons

  If @2-5eV → can look into empty MUSE cubes (LeoT 3.7hr)



1) Mask all objects

2) `stack` noise



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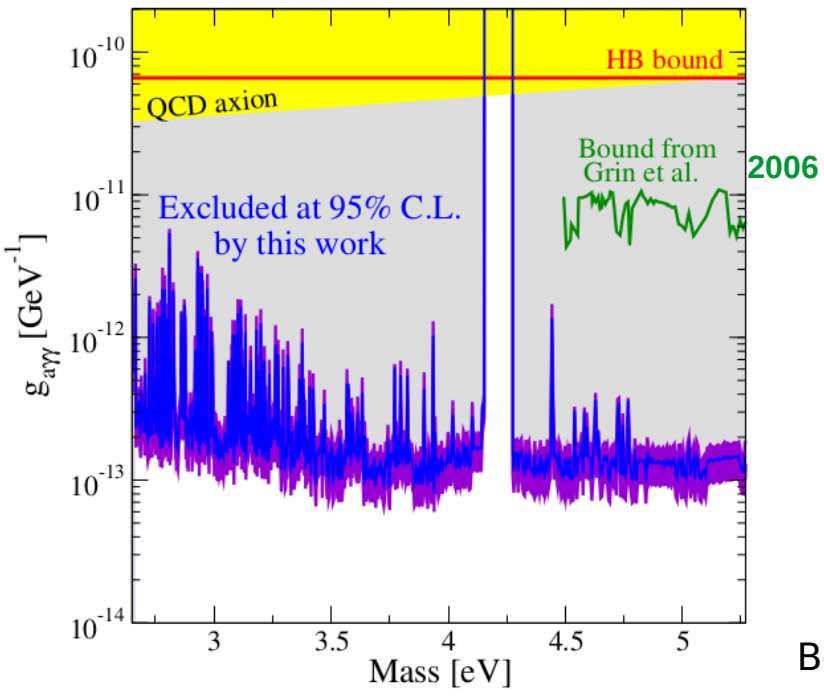

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Regis, Taosco, et al. 2021

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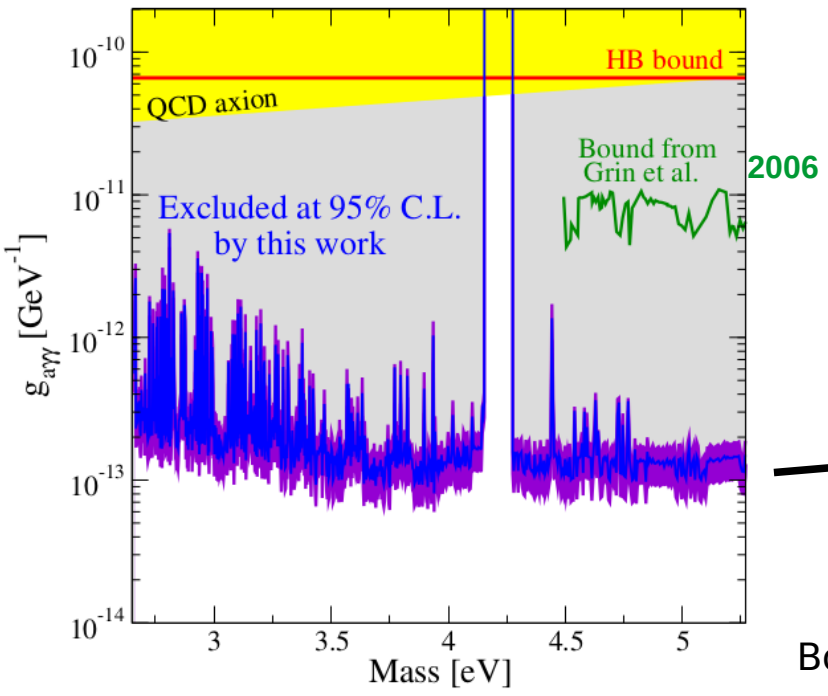
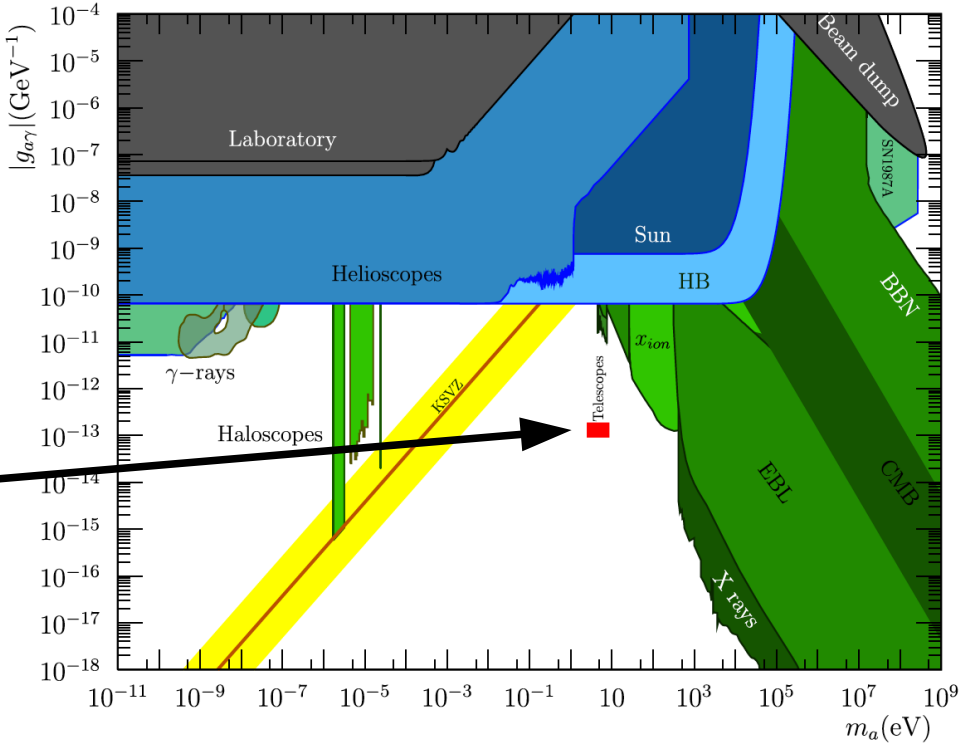


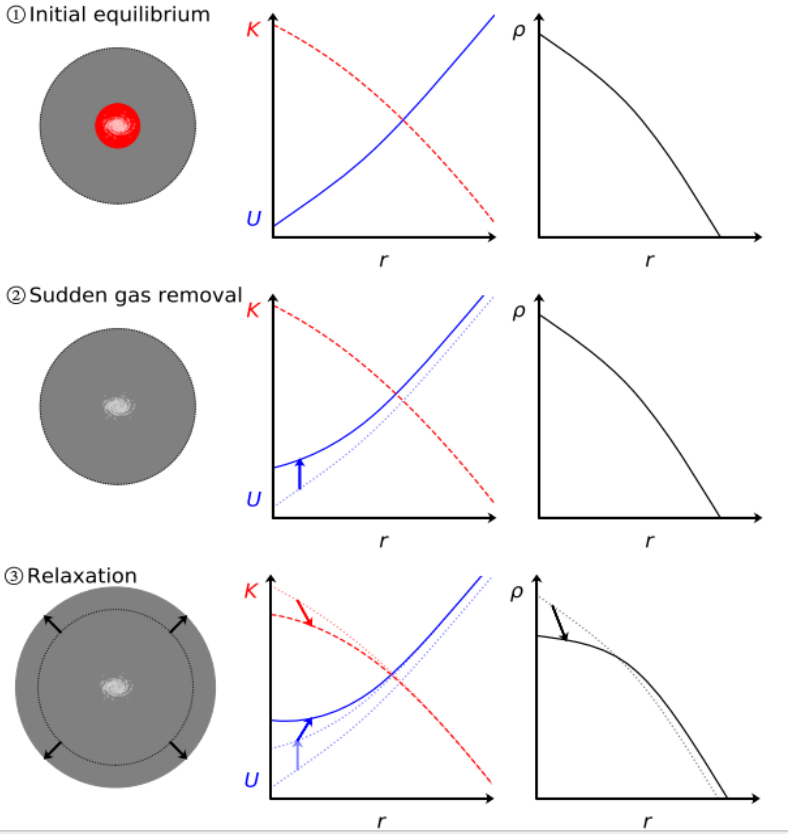


Bouc

C) Baryons to the rescue
→ core formation (in CDM)

Freundlich et al. 2020a,b

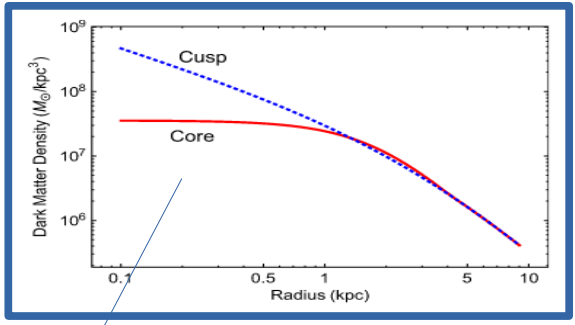
- Enduced by SFR/feedback with :
  - Sudden outflows (episodic)
  - Changes in U
  - Relaxation DM → Cores



Baryons to the rescue

→ core formation (in CDM)

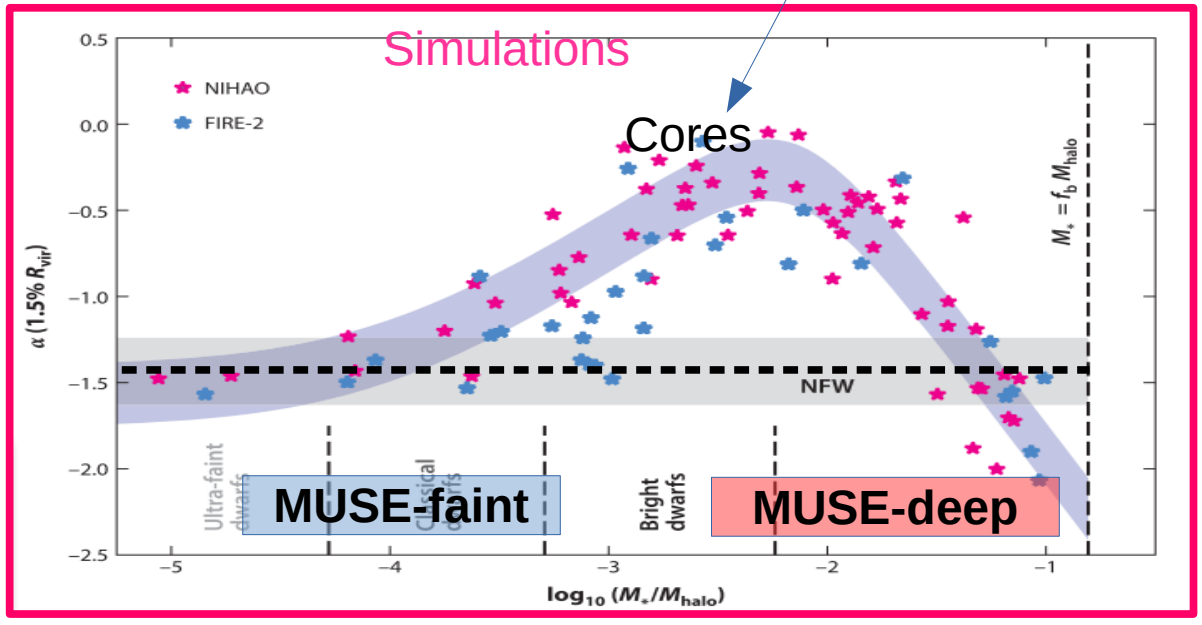
- Enduced by SFR/feedback (also AGN)



Navarro et al. 1996
Governato et al. 2010
Pontzen et al. 2012,2014
Teyssier et al. 2013
DiCintio et al. 2014

Freundlich et al. 2020a,b

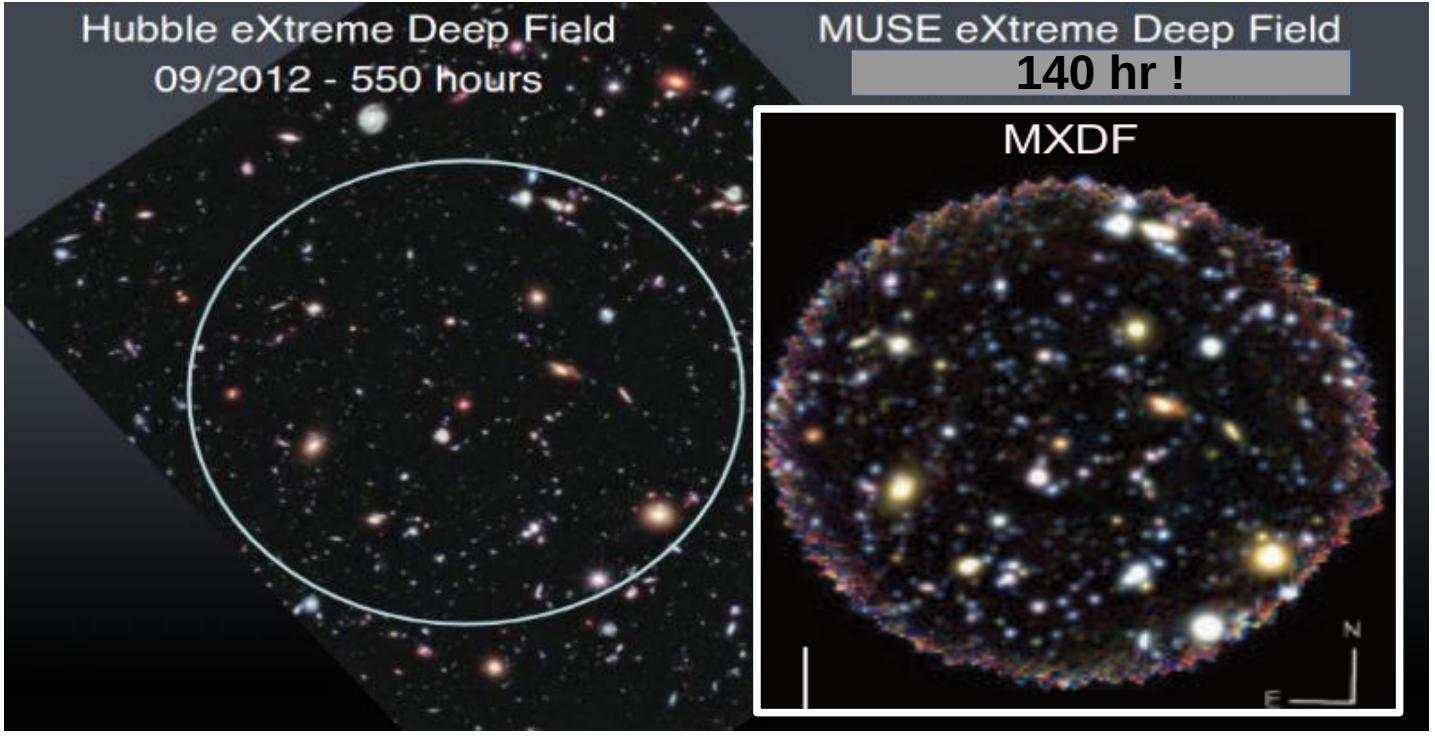
$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}},$$



Bullock et al. (2017) ARAA

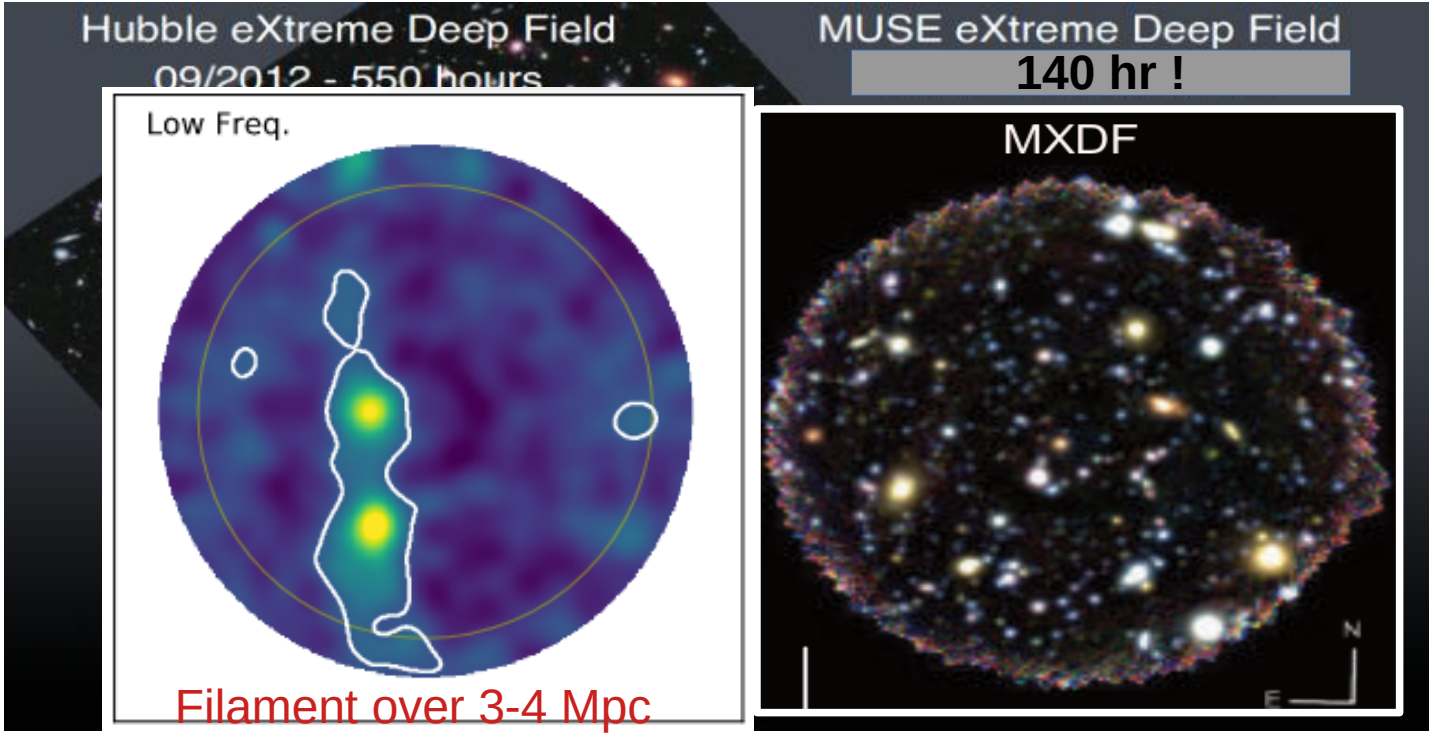
Going Extremely deep w/ MUSE-Deep

HST : MUSE : Bacon et al. 2021



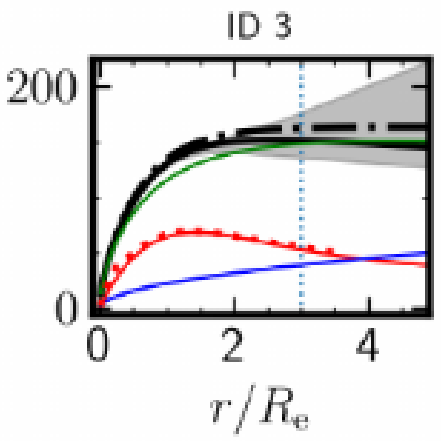
Going Extremely deep w/ MUSE-Deep

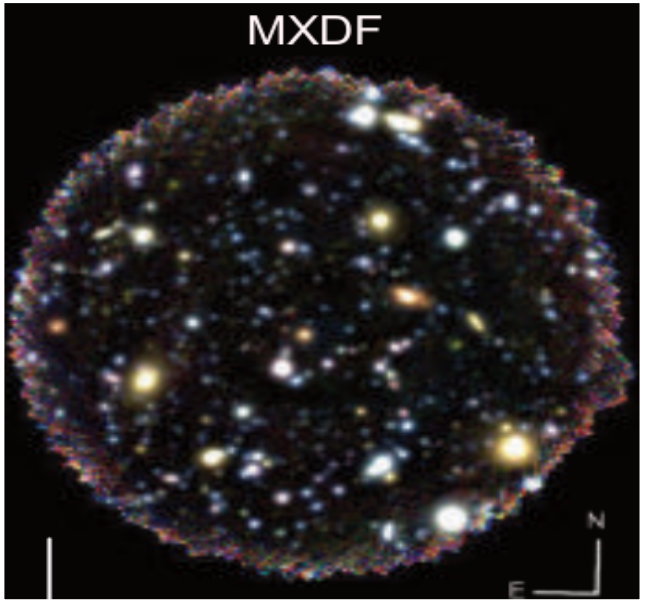
HST : MUSE : Bacon et al. 2021

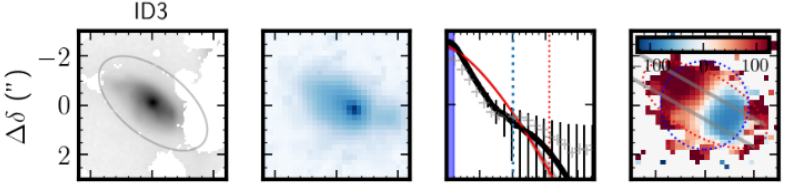


Going Extremely deep w/ MUSE-Deep

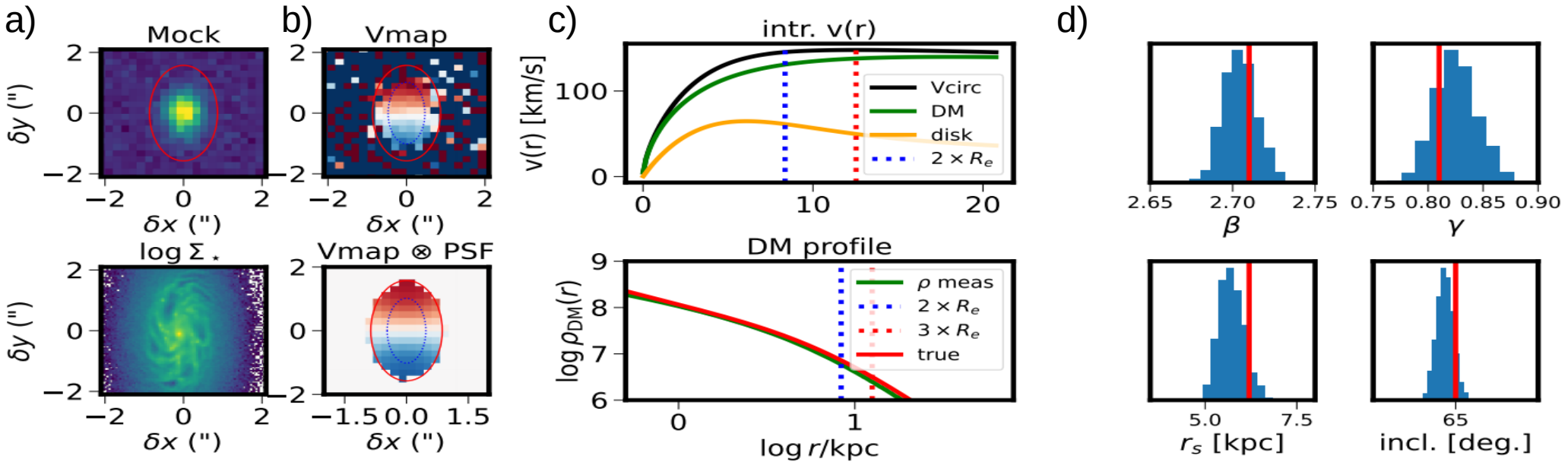
- Pilot study:
  1) Select **Bright** [OII] emitters 0.3<z<1.4
     → very high S/N
  2) Compare disk-DM **halo** 3Dmodel (14 parameters) to 3D data
     1) CDM (NFW)
     2) CDM + Baryons
     3) next : SIDM, FDM







3DMethod : Validation on Sims



Mock from M*=1e10 Mh=1e11.7

Next: study systematics with range of M*/Mh ; SFR (burstines) ; etc

MUSEdeep : Results

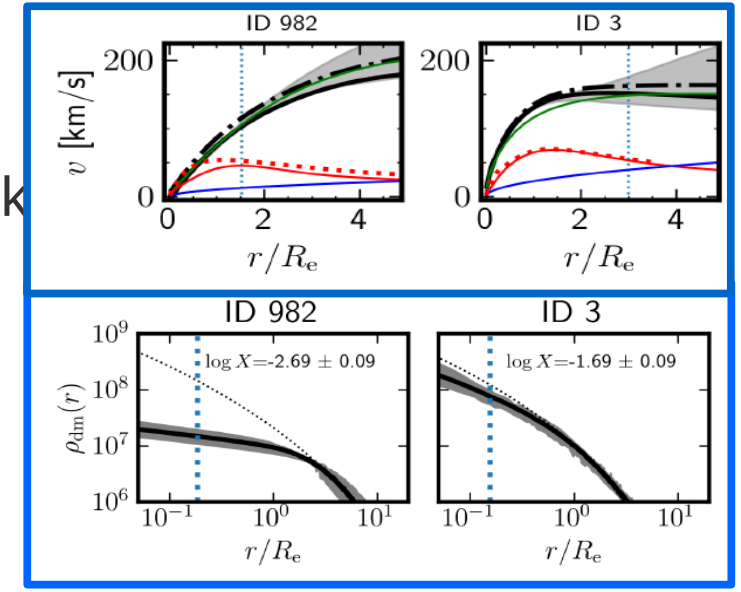
Core / Cusp @z=1 Examples

Pilot program on 9 galaxies:

1) 50 % cores
2) `CDM-only' not ok / CDM+baryons ok

Compare to state-of-the-art :

- 3D method (vs. 1D)
- No priors (M*, incl., c)
- morpho-kine simulatenously (14)
- New field at z>1 since 2020
-



Bouché et al. 2022

Next : apply on all deep MUSE data-sets >300-600 galaxies at 0.4<z<1.4

anr

DARK ANR
Use RCs as DM laboratory

- Scientific Objectives :

Difficulty

1) What is DM content of distant galaxies ? (r>Re)

   Does it depend on galaxy properties ?

2) What is the shape of DM profiles ? (1-5kpc)

   Cusp (NFW) vs core ; M-concentration

3) How do the DM properties evolve with redshift ?

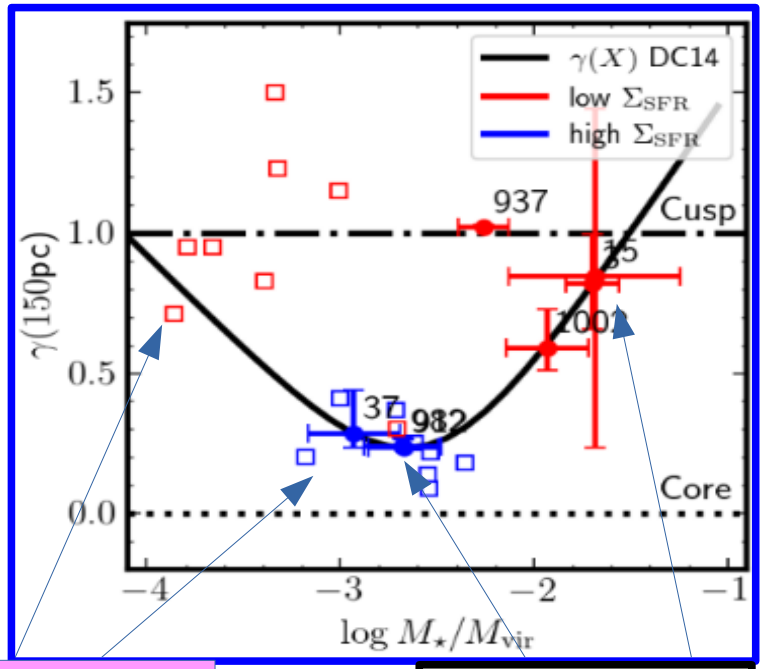
4) What is nature of DM ?

   - CDM, Fuzzy (Axion-like), SIDM, WDM, etc..
   - Cotton, Mond ...

Putting it all together

Putting it all together

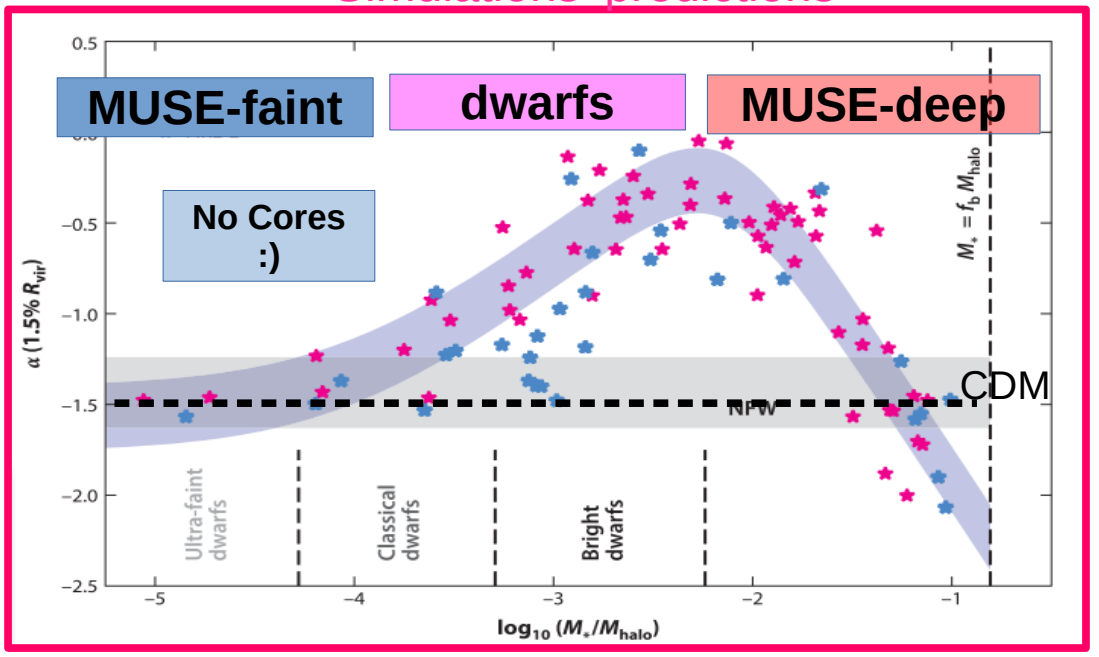
Observations



dwarfs

MUSE-deep

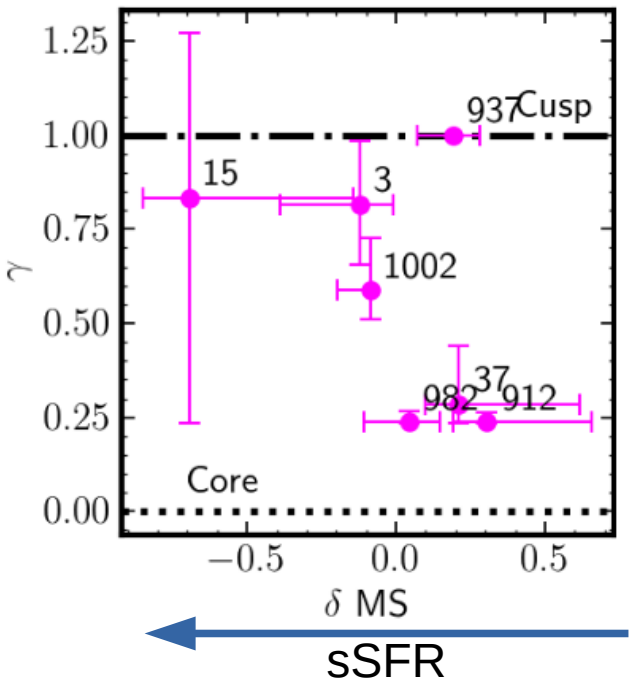
Simulations ‘predictions’



Bouché et al. 2022
Read et al. 2019

Cusp(CDM)→ Cores // Cores→ Cusp ?

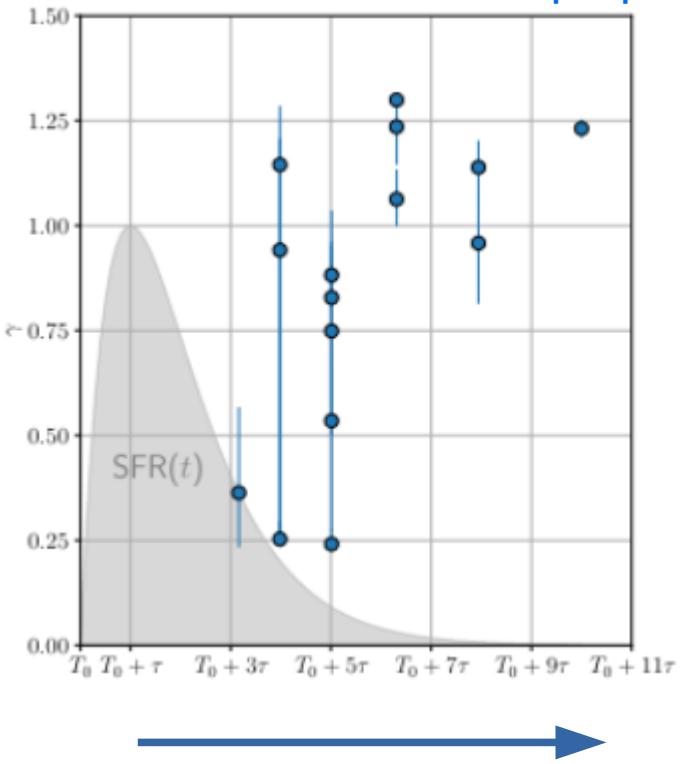
Bouché et al. 2022



When SFR declines,

Cusp reforms !

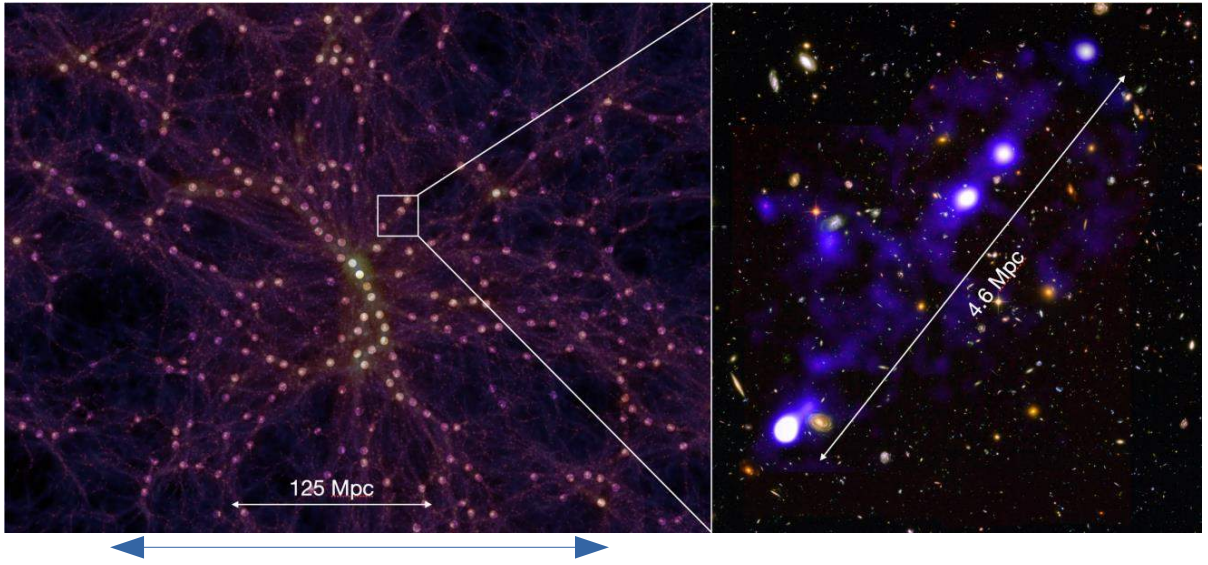
Jeanneau et al. In prep



What’s next ? In 2035+

https://wstelescope.com

- WST : A new facility for 2035+ (R. Bacon)
  - 10 x MUSE [200 spectrographs]
  - & 20,000 fibers over 5sq.deg
  - All on a (new) 10m tel.
  - Survey facility



- **Will need advanced ML tool adapted to 3D datacubes.**

Conclusions

- 3 things you should *now* know
  - MUSE-deep reveals Cores at high-redshifts

    Pilot study of 9 galaxies Bouché et al. 2022

    NEXT → >300-600 SFGs 0.4<z<1.4 (**ANR DARK**)
  - MUSE-faint gives strongest constraints on Axions at ~eV

    Pilot study of 1 UF dwarfs Regis et al. 2021
  - MUSE rules out 1e-22eV ALP in (ultra-) faint dwarfs

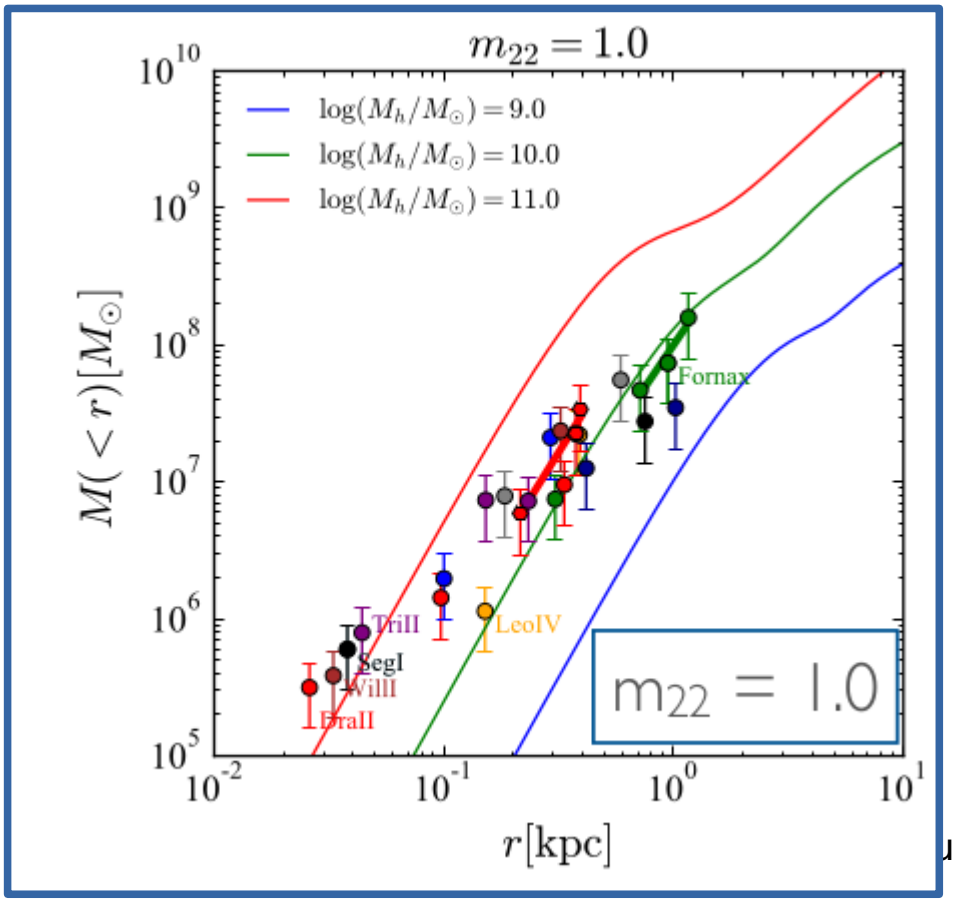
    Pilot study of 4 UF dwarfs Zoutendijk et al. 21/22

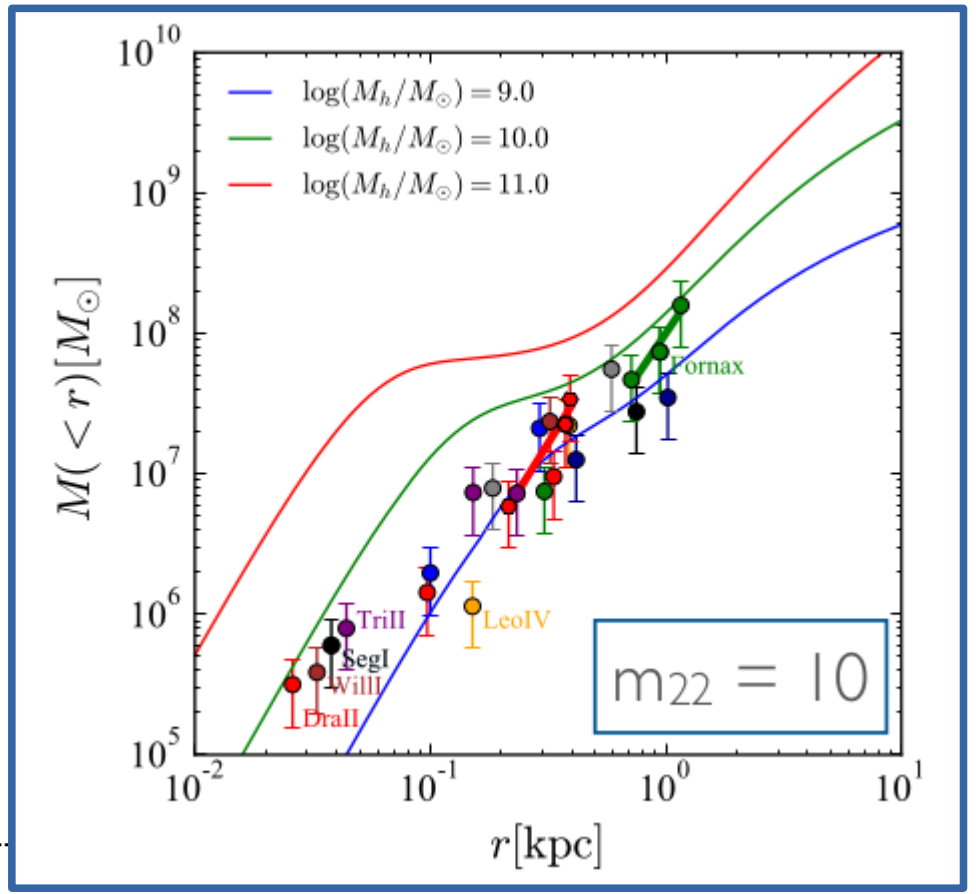
    NEXT → joint analysis of full sample (10)

Thank you !

Other way to look at Fuzzy DM

Bar, Blum et al. 2019

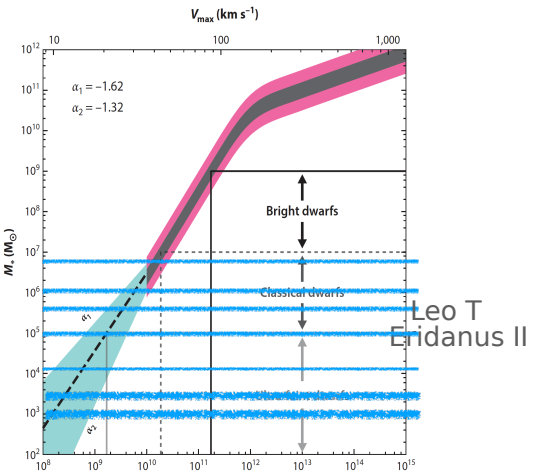




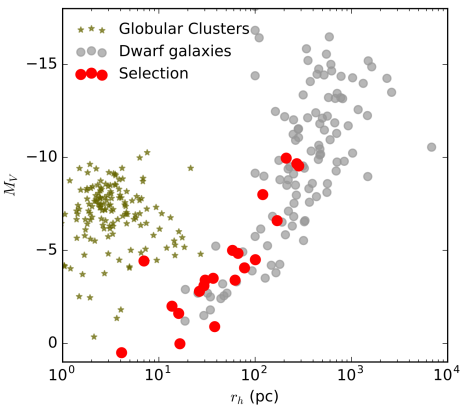
DM dominated dwarfs

- **MUSE-faint** : A survey of ultra-faint dwarfs with MUSE
  - PI : J. Brinchmann (U. Porto)
  - 100hr of MUSE (GTO) down to r~25 mag
  - Sample : 10 ultra-faint dwarfs (Mdyn/M* > 100-1000)

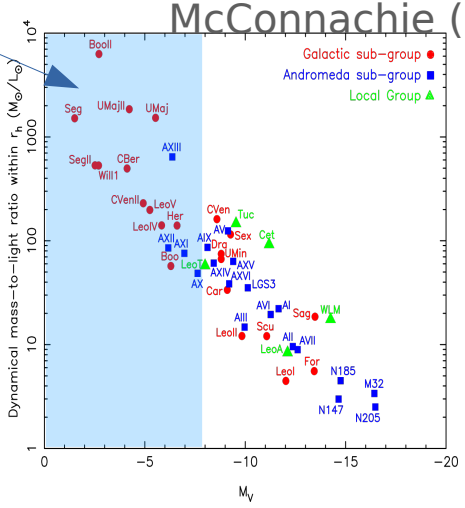
Zoutendijk 22 (4dw)
Zoutendijk 21 (Erid2)
Zoutendijk 20 (Machos)



Bullock & Boylan-Kolchin (2017, ARA&A)

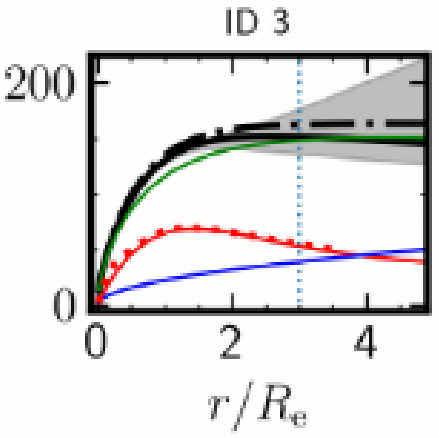


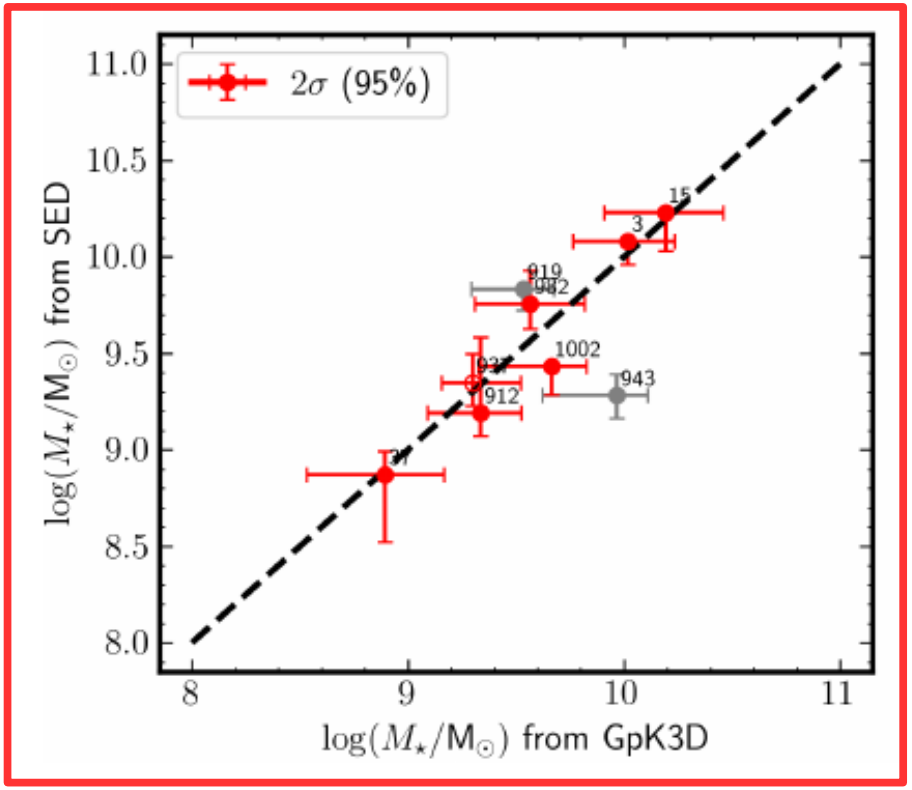
McConnachie (2012)



Are the inner DM profiles cored ?

3DMethod : Validation on data



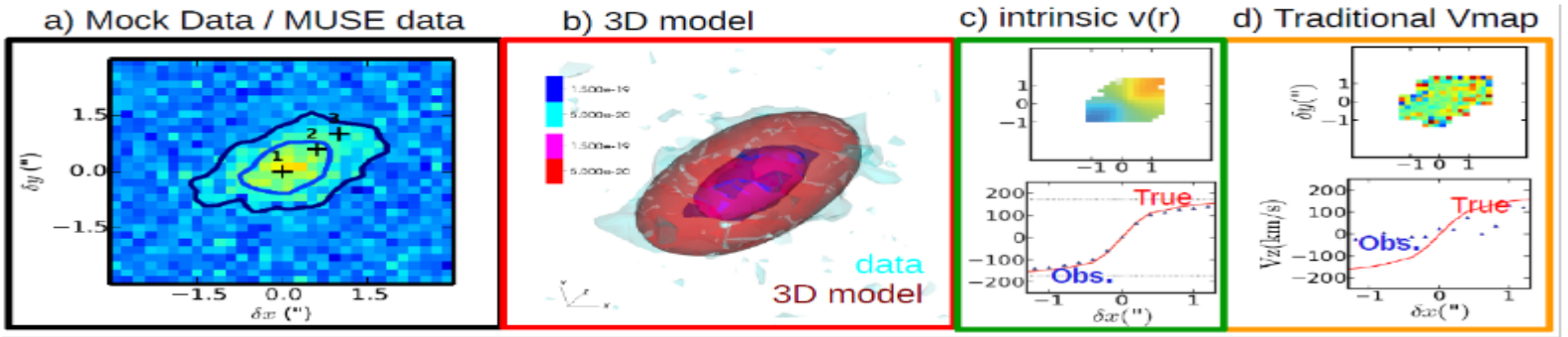


State-of-the-art at z>1

	Sample size	Method	Assumptions Priors	Mass
Genzel+17,20 Genzel 22	41 (z=2) 100	1D RC	NFW ; c-M Incl ; M*	**10.5**-11
Sharma 22	250 stack	1D RC	NFW ; Incl. ;	9.0 – 11.3
Rizzo 20,21	5 z=4-5	1D RC +lensing	NFW ; c-M Incl. ;	10-10.5
Bouché 2022 (pilot study)	9 z=1	3D RC likelihood	– CDM	9 – 10
This project	**>300** (0.3<z<1.5)	3D RC likelihood & lensing	– –	**9 –** 10

Method : 3D Modelling

- Use all information available

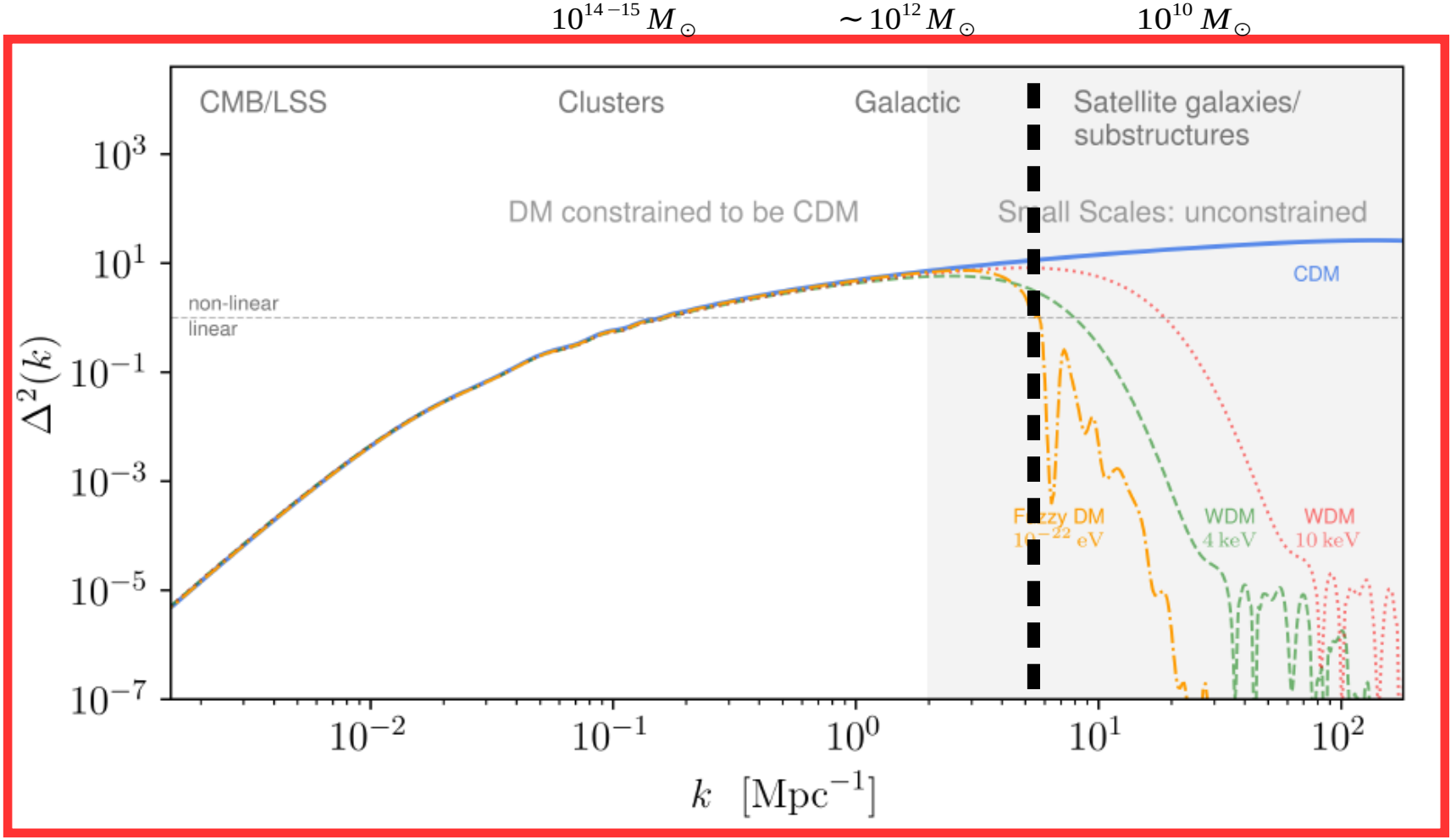


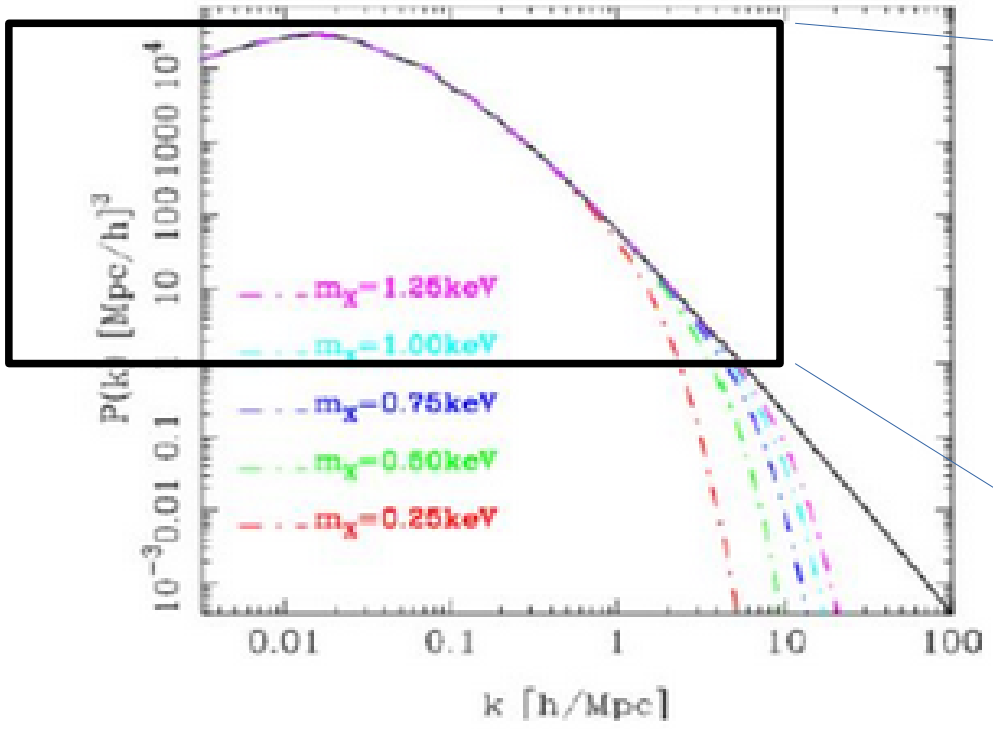
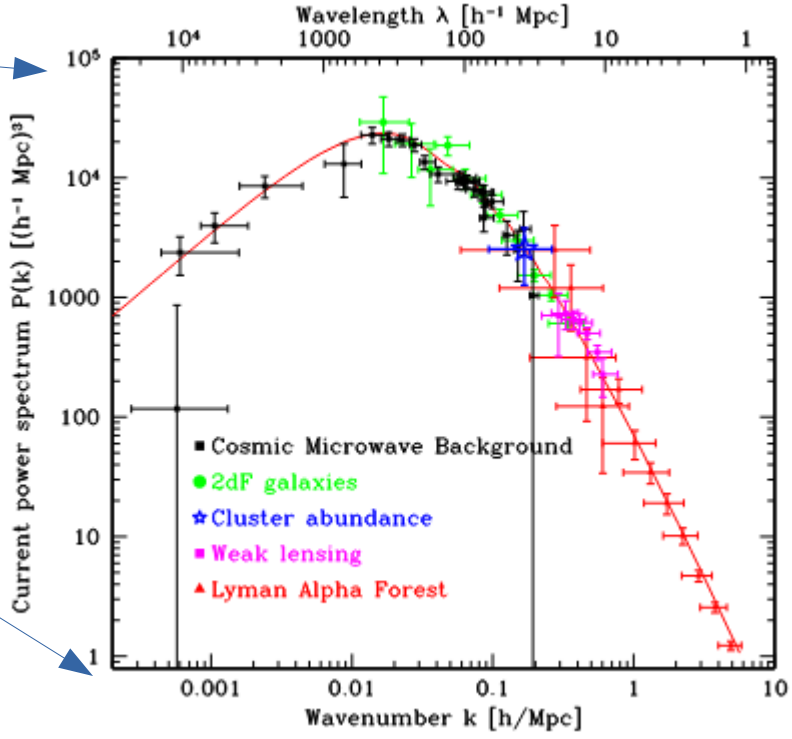
GalPaK
galaxy parameters and kinematics

http://galpak3d.univ-lyon1.fr

- Advantages :
  - Works in low S/N regime [good for R>Re]
  - Flexible parametric models
  - morpho&kinematics simultaneously

Ferreira (2020)



WDM

Tegmark 2002