Testing dark matter in galaxies with the Normalized Additional Velocity Distribution

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Based on:
Alejandro Hernandez-Arboleda, Davi C. Rodrigues, Aneta Wojnar [2204.03762]
Code available at: https://github.com/davi-rodrigues/NAVanalysis

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image credit: joelmiranda.com

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Galaxy rotation curves: basics

Gas contribution:

Derived from the 21 cm radiation surface brightness.
Hydrogen density found from hyperfine transition.
Gas density $\rho_{\text{gas}} = 1.33\,\rho_{\text{H}}$, from BBN.

$$V^2_{\text{gas}} = r\partial_r\Phi_{\text{gas}}\,,\ \text{with}\ \nabla^2\Phi_{\text{gas}} = 4\pi G\rho_{\text{gas}}\,.$$

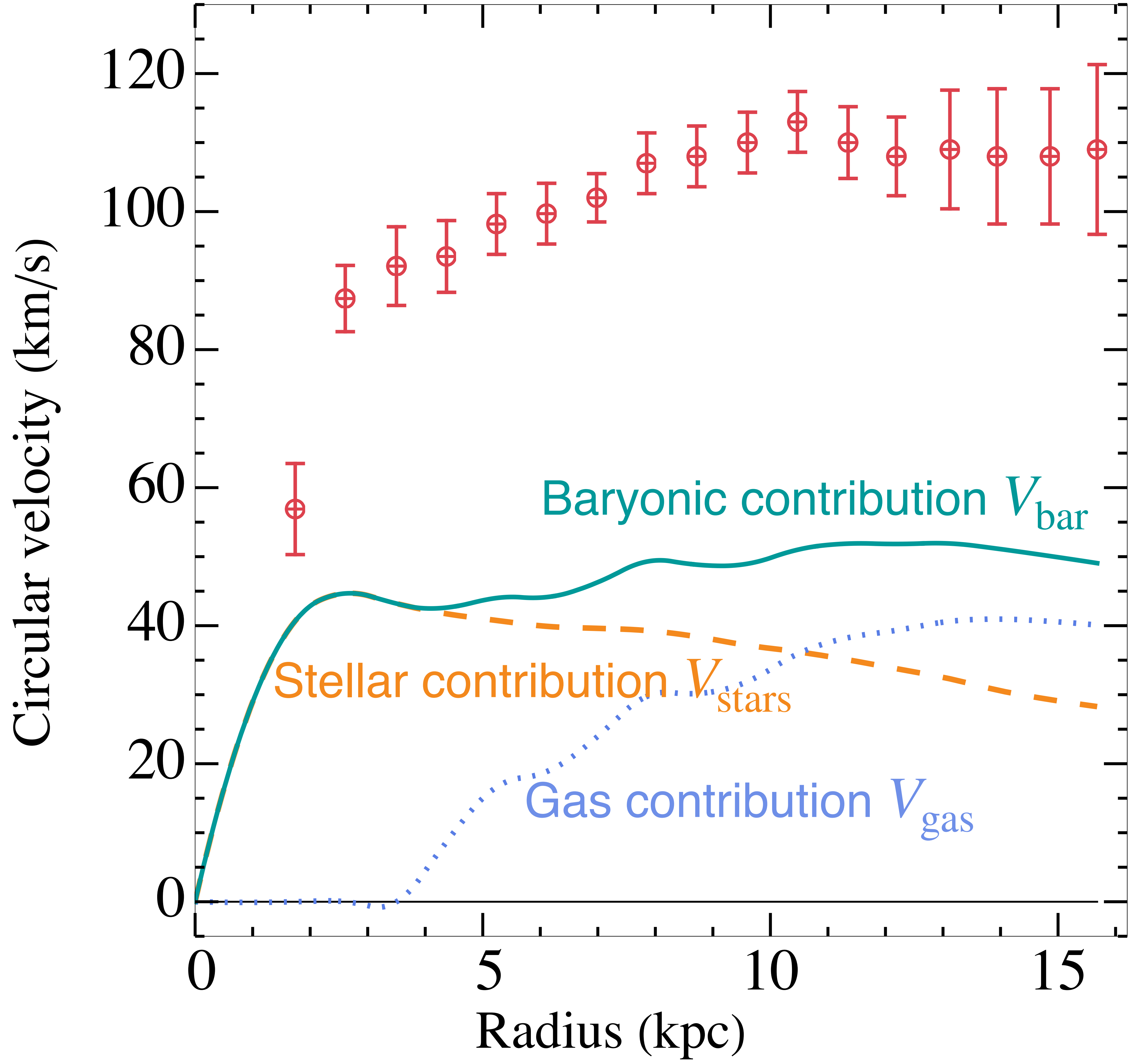
Stellar contribution:

Derived from the stellar surface brightness (near infrared).
Stellar density depends on stellar population models.
For the Spitzer 3.6 μm band (e.g., Meidt et al ApJ 2014):

$\Upsilon_* = 0.50^{+0.13}_{-0.10}$ (dimensionless mass-to-light ratio, stellar disk)

$$V^2_* = r\partial_r\Phi_*\,,\ \text{with}\ \nabla^2\Phi_* = \Upsilon_*\,4\pi G\rho_{*|\Upsilon_*=1}\,.$$

Data from SPARC, plot from MAGMA
[https://github.com/davi-rodrigues/MAGMA]

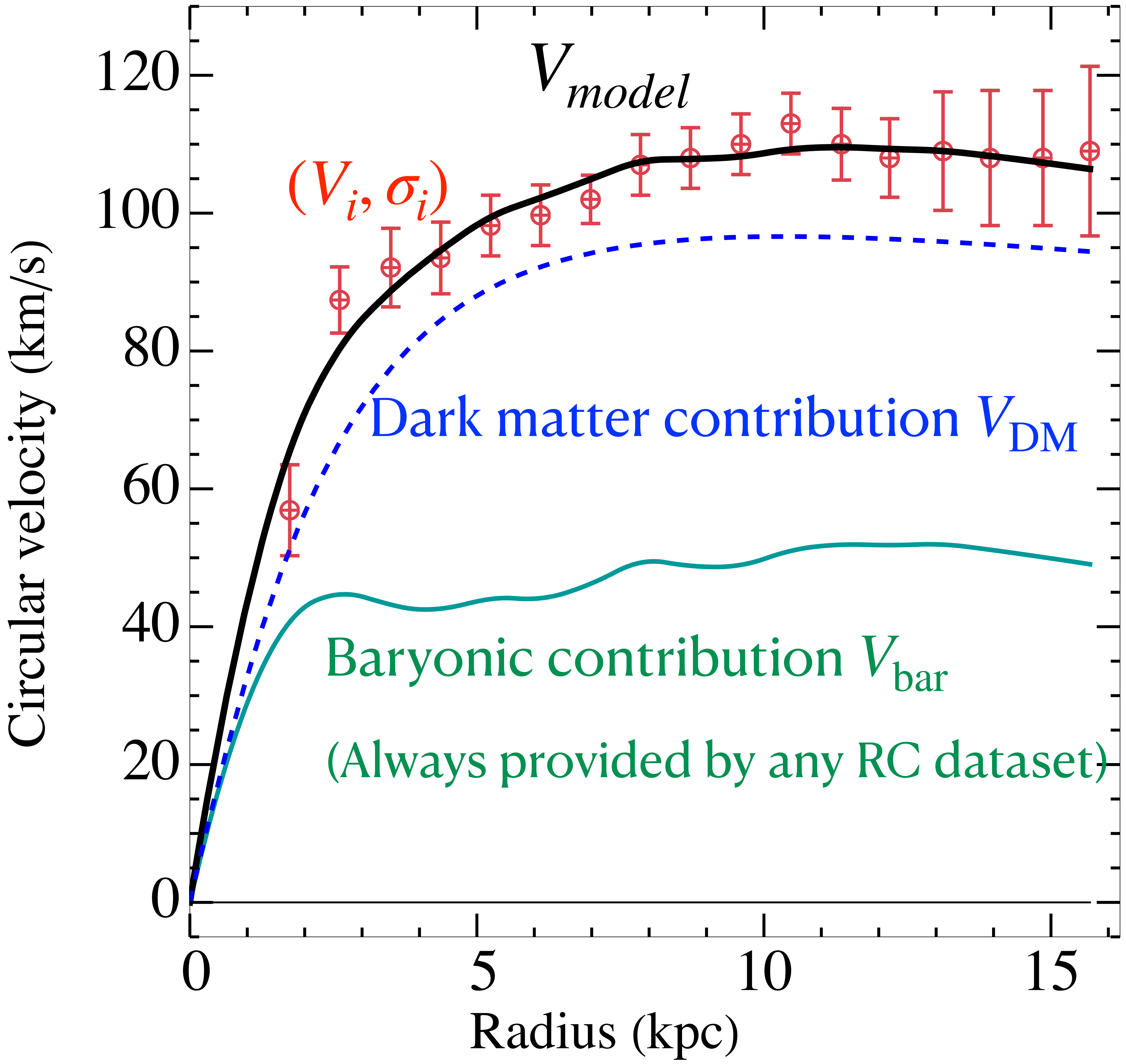


$$\boxed{V^2_{\text{bar}} = V^2_{\text{stars}} + V^2_{\text{gas}}}$$

Testing a DM profile for a given galaxy

Typical procedure:

- One assumes a DM profile with free parameters (e.g., NFW, Einasto, Burkert, DC14…)
- For each galaxy RC data, the halo is fitted together with relevant baryonic uncertainties, if any (e.g., Υ_*, δD, δi).



The maximization of the likelihood yields the best fit model parameters (p_a)

$$-\ln \mathscr{L}(p_a) \propto \chi^2(p_a) = \sum_i \left(\frac{V_{model}(p_a, R_i) - V_i}{\sigma_i} \right)^2$$

$$V^2_{model} = V^2_{\rm bar} + V^2_{\rm DM}$$

Which model is better?

A simple and common approach: compute $\chi^2_{\rm red}$ for **each** galaxy.

- Models that yield the minimum average $\langle \, | \chi^2_{\rm red} - 1 \, | \, \rangle$ for a sample are the best.
- Variation: instead of the average, use the CDF distribution of $\chi^2_{\rm red}$ [Katz et al, MNRAS 2016]

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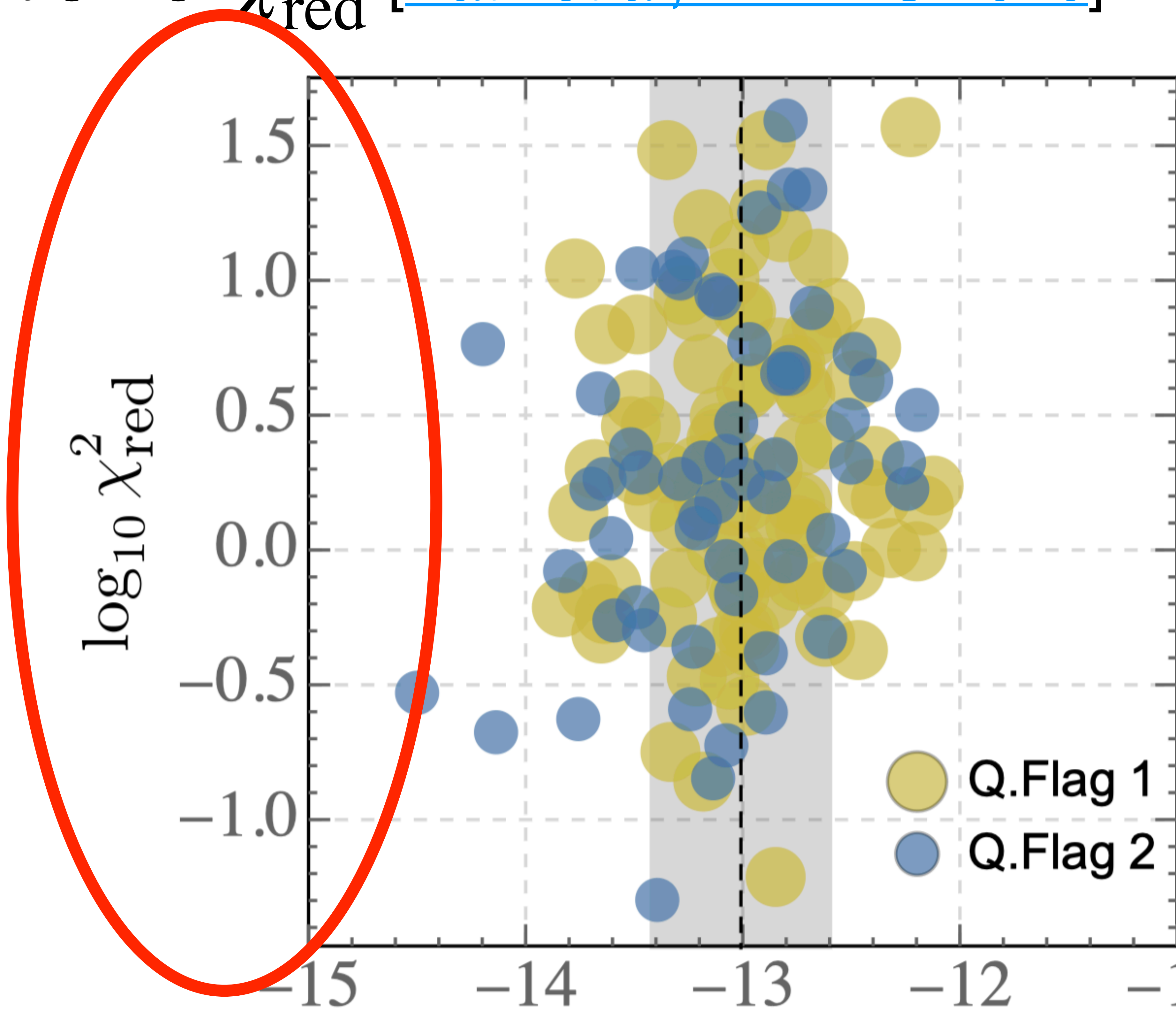
Problem: DM halo profiles are nonlinear models, the rule $\chi^2_{\rm red} \sim 1$ is not correct. [Andrae et al 1012.3754].

Issue: Computational time. Each galaxy needs to be carefully *individually* studied, even though the purpose is the overall sample result.



[Rodrigues et al Nat.Ast. 2018]

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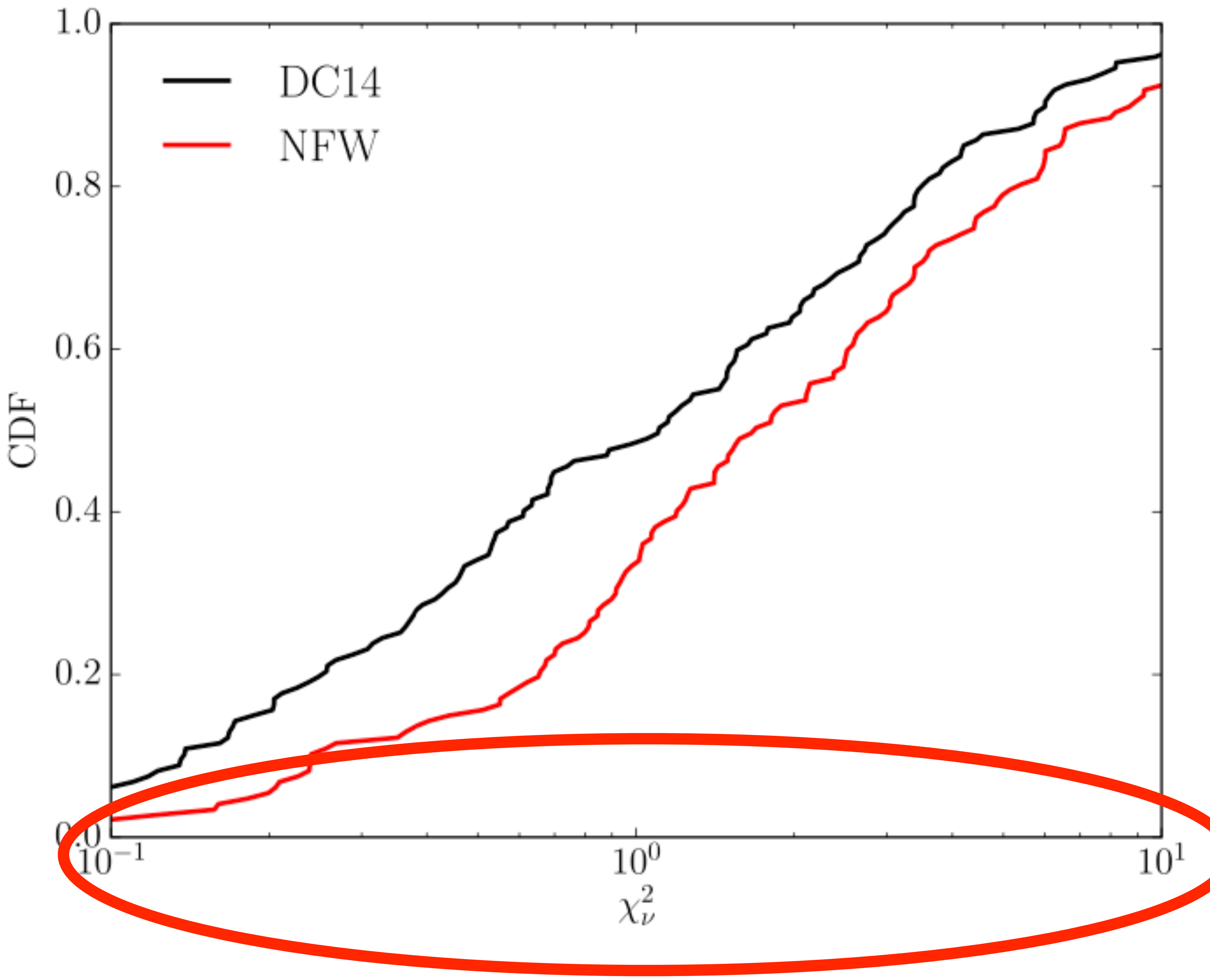

- [Katz et al, MNRAS 2016]

SPARC and modified gravity

- The SPARC galaxy sample [Lelli et al AJ 2016] is a well organized and well known galaxy RC sample. It includes 175 late-type galaxies with high quality data, with emphasis to the stellar component.
- From these, 153 are considered to be specially suitable for galaxy modeling (highly symmetric and with $i \geq 30°$).
- However, there is no public data on the complete $3D$ baryonic distribution.
- [Green, Moffat PDU 2019] develop their own $3D$ baryonic models in part based on the available SPARC data plus analytical approximations that can be found in the literature. This lead to systematical changes in the RC's.
- [Naik et al MNRAS 2019] use exponential profiles to mimic the stellar and the gaseous parts of each galaxy. The latter approximation is less suitable.

Method principles

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- We focus on one relevant rotation curve feature: its shape

Normalized Additional Velocity

- One can define the observational (model independent) additional velocity as

$$\Delta V^2_{\rm obs}(r) \equiv V^2_{\rm obs}(r) - V^2_{\rm bar}(r)\ .$$

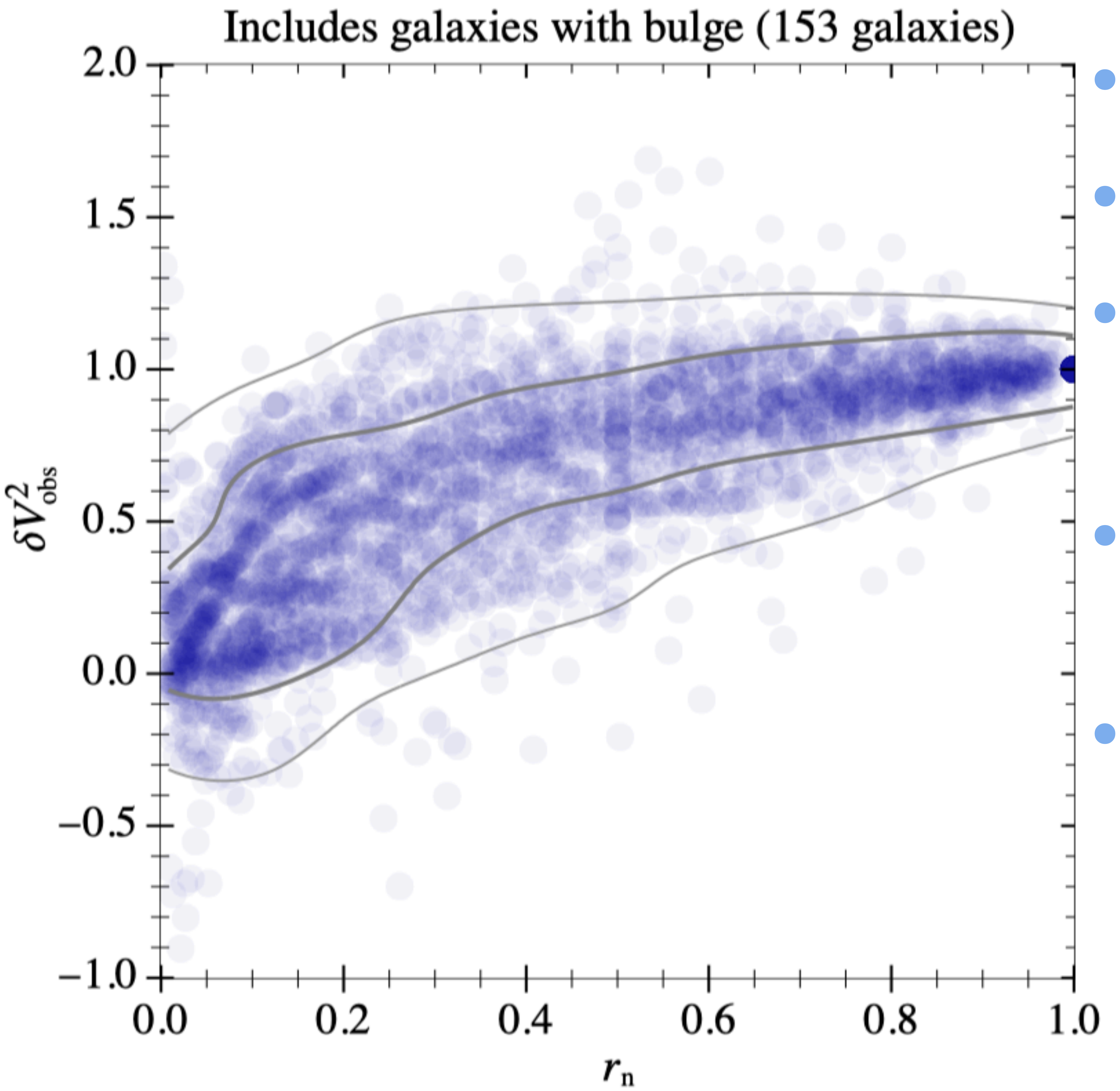
(Newtonian gravity without DM $\Longrightarrow \Delta V^2_{\rm obs} \sim 0$, i.e., small oscillations about zero)

- And the *normalized additional velocity,* as function of $r_n \equiv r/r_{\rm max}$, reads

$$\delta V^2_{\rm obs}(r_n) \equiv \frac{\Delta V^2_{\rm obs}(r_n\, r_{\rm max})}{\Delta V^2_{\rm obs}(r_{\rm max})}\ .$$

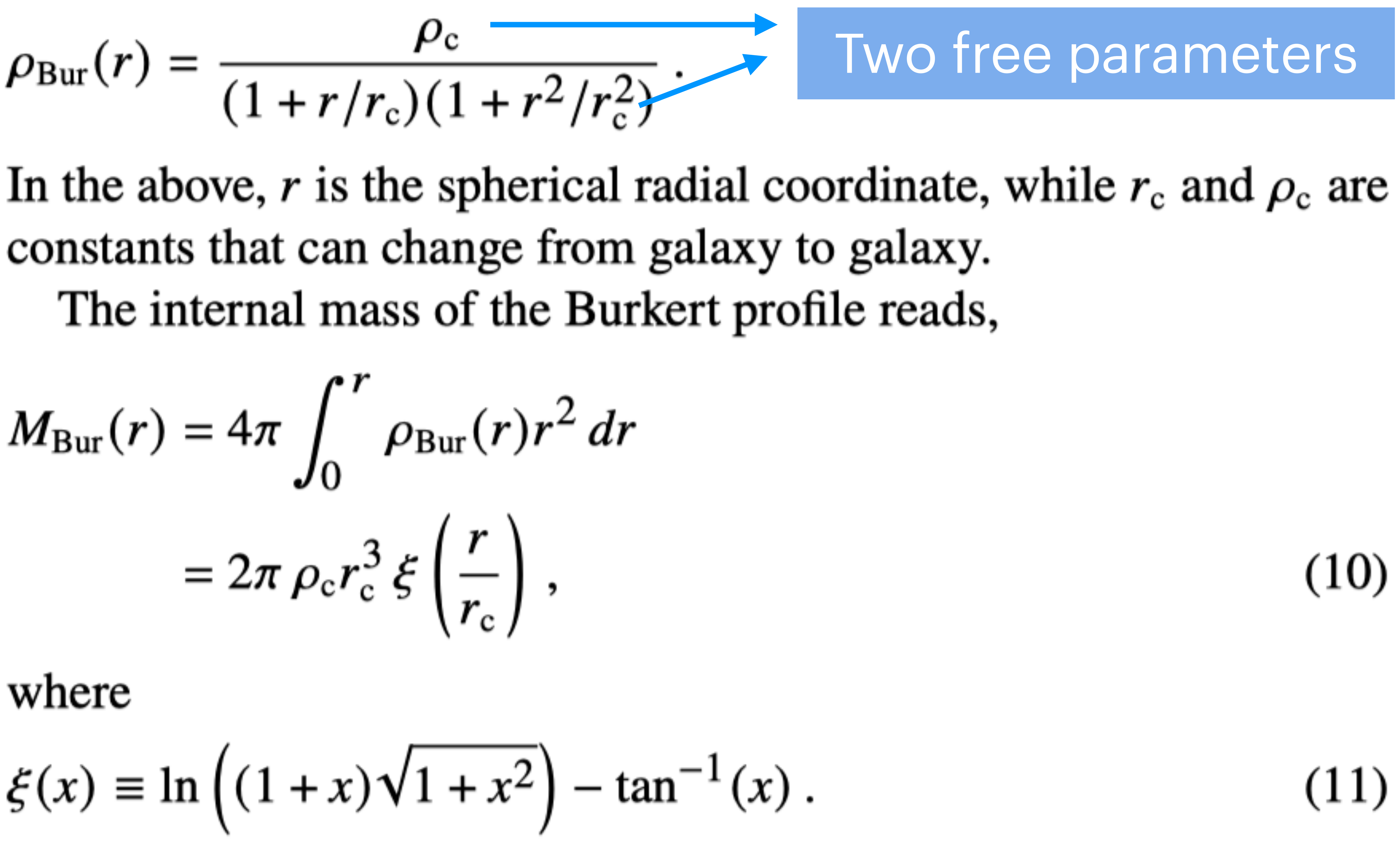
(Newtonian gravity without DM $\Longrightarrow \delta V^2_{\rm obs}(r_n)$ oscillate with arbitrary magnitude)

The NAV distribution form the SPARC data



- This plot is model independent.
- Each blue circle is a data point from a galaxy.
- All the 153 galaxies have a point at $(r_n, \delta V^2_{\rm obs}) = (1{,}1)$.
- The gray curves delimit the 1σ and 2σ *highest density regions*.
- If there was no dark matter, this plane should be randomly populated, without preference for $\delta V^2_{\rm obs} > 0$.

First application: Burkert profile



$$\rho_{\rm Bur}(r) = \frac{\rho_c}{(1+r/r_c)(1+r^2/r_c^2)} .$$

Two free parameters

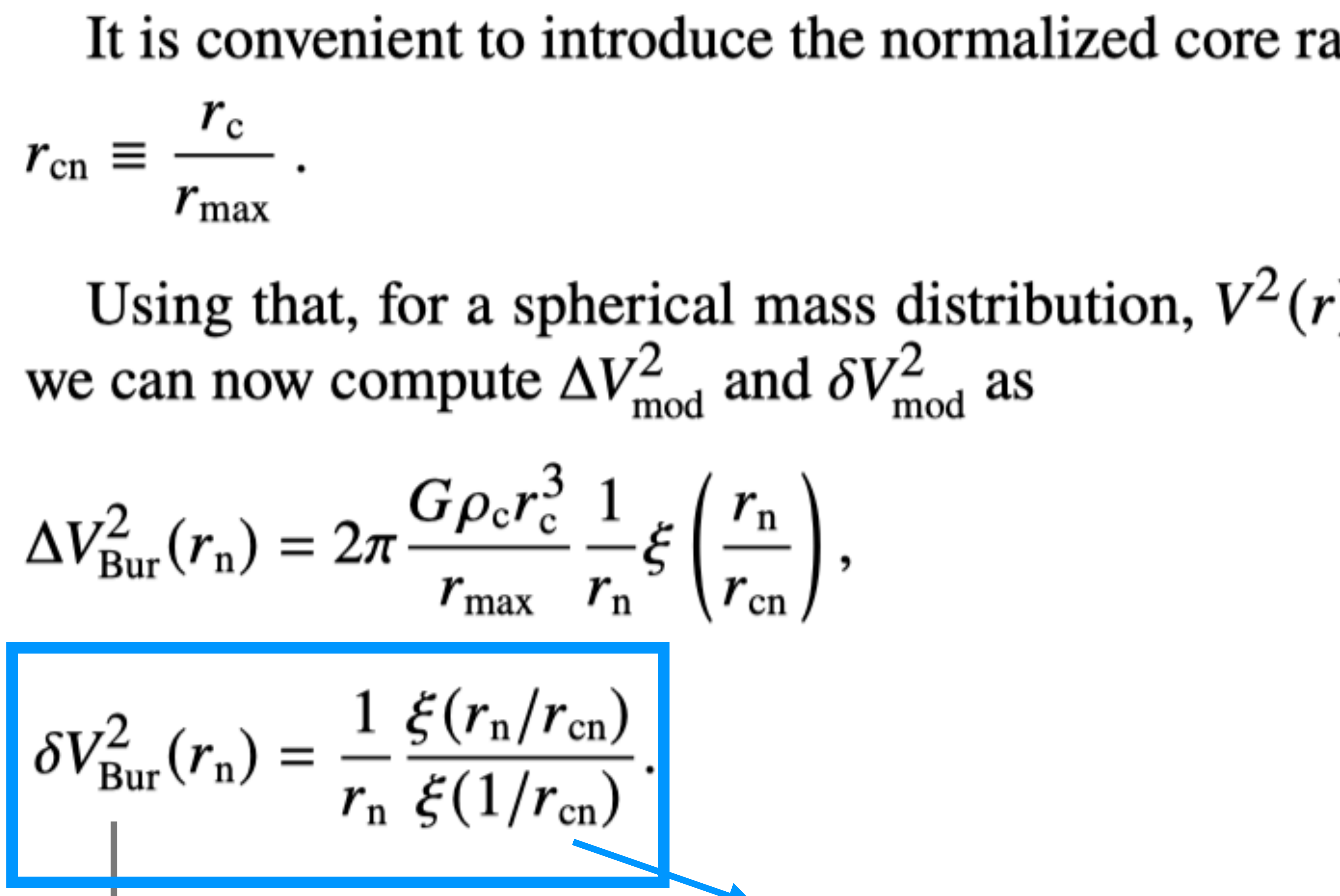
In the above, r is the spherical radial coordinate, while r_c and ρ_c are constants that can change from galaxy to galaxy.

The internal mass of the Burkert profile reads,

$$M_{\rm Bur}(r) = 4\pi \int_0^r \rho_{\rm Bur}(r) r^2\, dr$$
$$= 2\pi\, \rho_c r_c^3\, \xi\left(\frac{r}{r_c}\right) , \qquad (10)$$

where

$$\xi(x) \equiv \ln\left((1+x)\sqrt{1+x^2}\right) - \tan^{-1}(x) . \qquad (11)$$



It is convenient to introduce the normalized core ra

$$r_{\rm cn} \equiv \frac{r_c}{r_{\rm max}} .$$

Using that, for a spherical mass distribution, $V^2(r$ we can now compute $\Delta V^2_{\rm mod}$ and $\delta V^2_{\rm mod}$ as

$$\Delta V^2_{\rm Bur}(r_n) = 2\pi \frac{G\rho_c r_c^3}{r_{\rm max}} \frac{1}{r_n} \xi\left(\frac{r_n}{r_{\rm cn}}\right) ,$$

$$\boxed{\delta V^2_{\rm Bur}(r_n) = \frac{1}{r_n} \frac{\xi(r_n/r_{\rm cn})}{\xi(1/r_{\rm cn})} .}$$

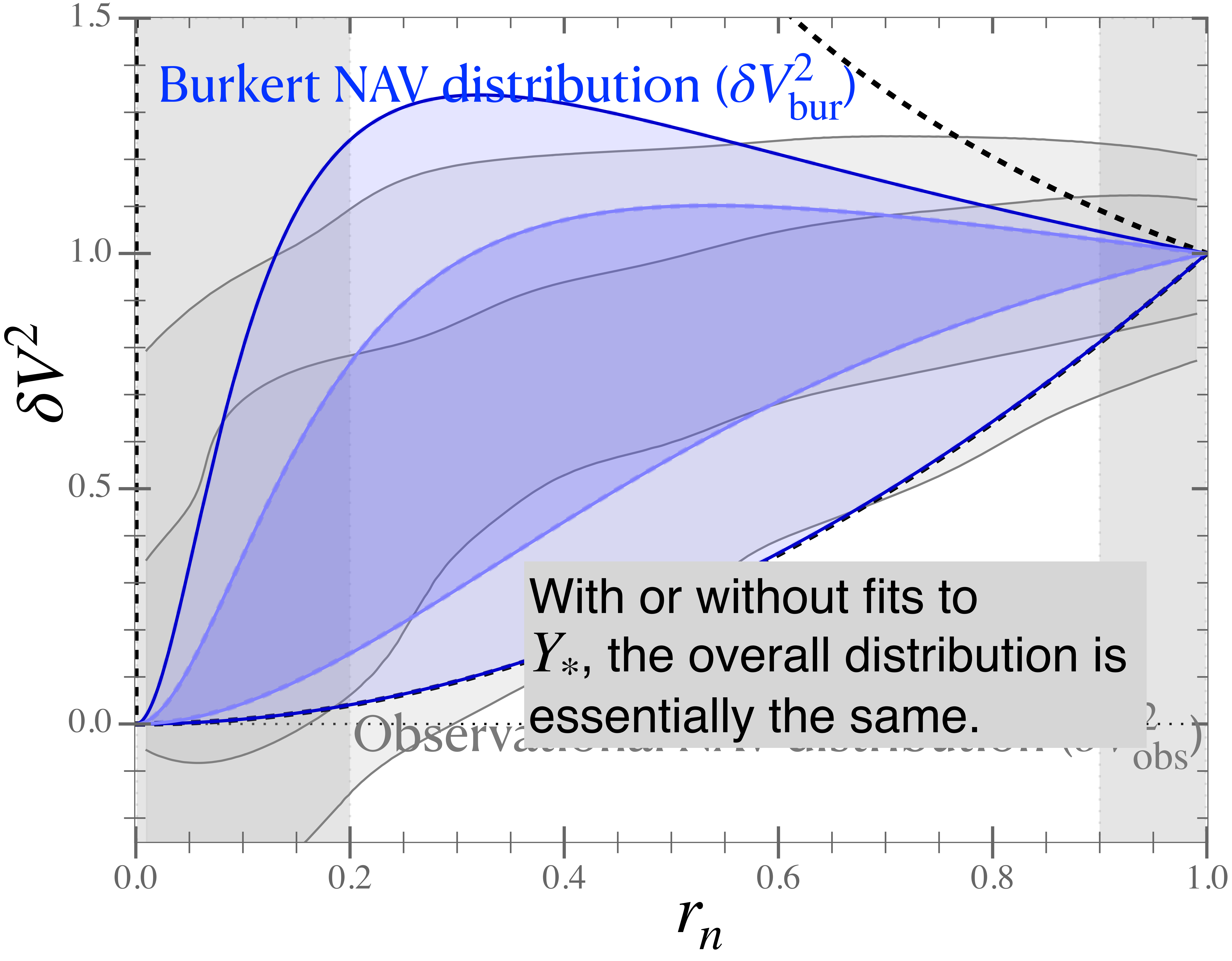
One free parameter

Model NAV: it will be compared with $\delta V^2_{\rm obs}$

Burkert profile's NAV

- Instead of fitting individual galaxies, one fits the distribution.
- $r_{\rm cn}$ is fitted to mimic the $\delta V^2_{\rm obs}$ distribution as close as possible.
- The most probable values of r_{cn} :
  $0.2 < r_{\rm cn} < 0.6$ (1σ region, NAV).
  $0.1 < r_{\rm cn} < 0.5$ (1σ region, individual)
- Efficiency coefficient: 0.74
  $\propto$ (Intersection region − Model region beyond observational region).

Results valid for any ρ_c



With or without fits to Y_*, the overall distribution is essentially the same.

Burkert profile's NAV

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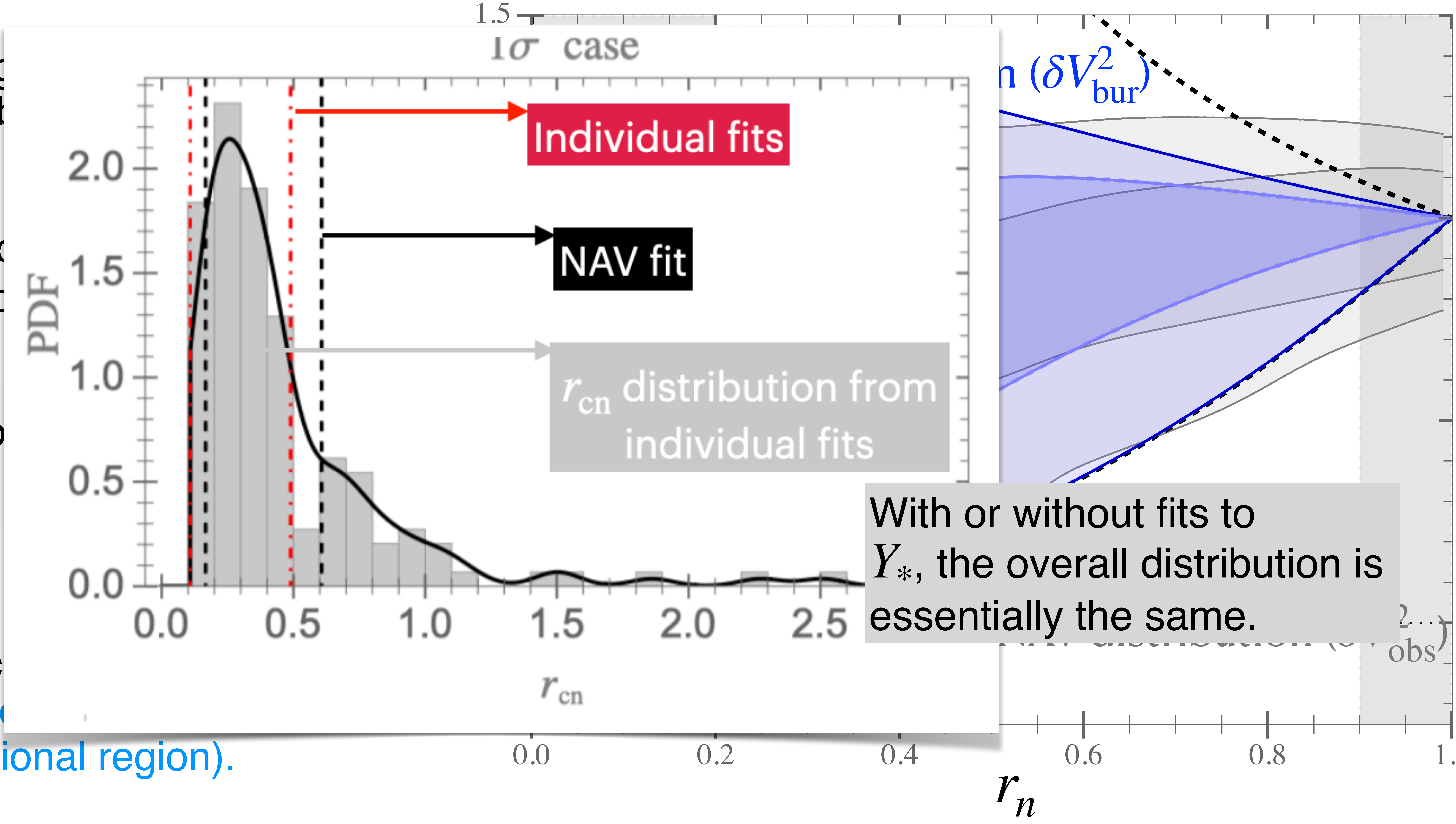
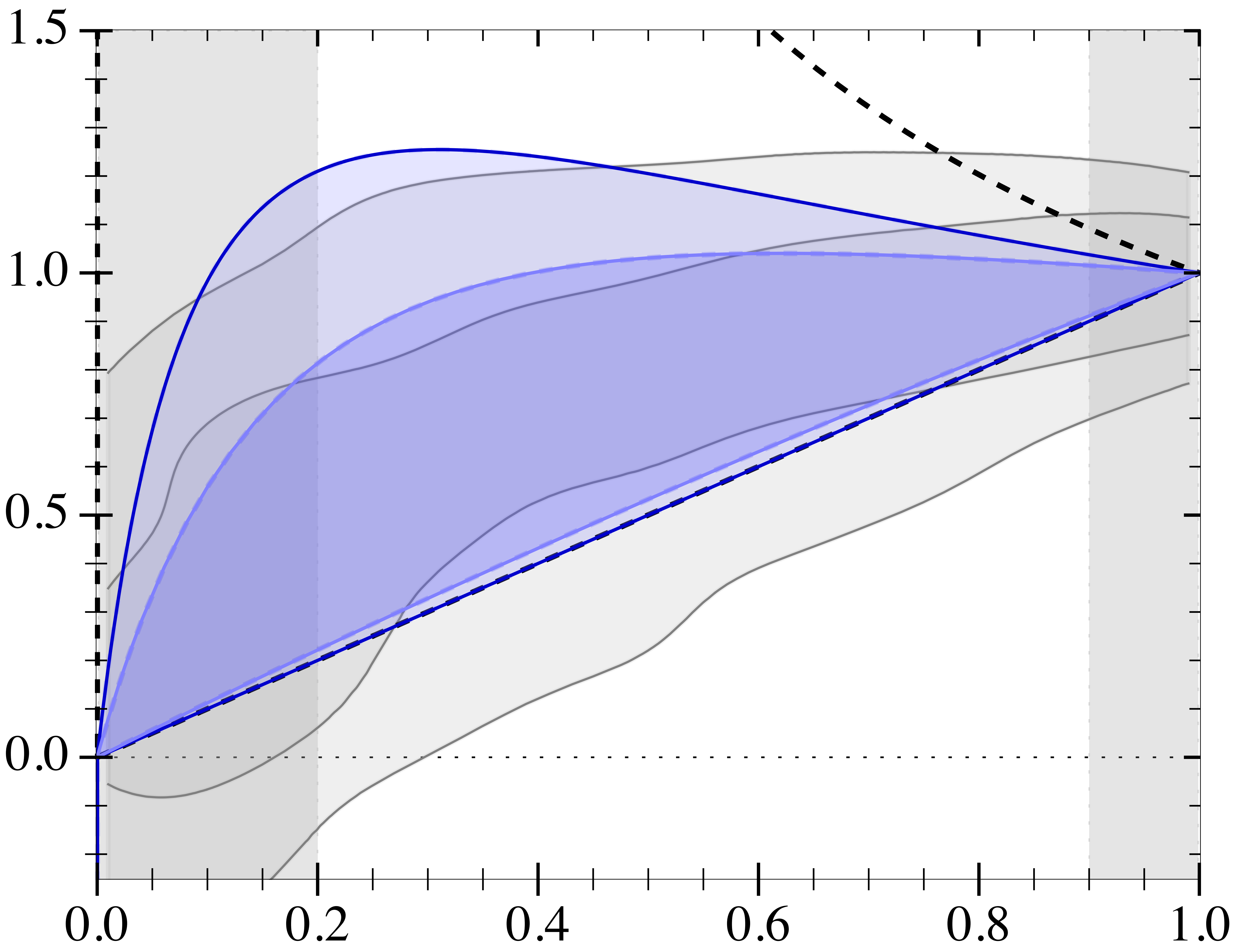


With or without fits to Y_*, the overall distribution is essentially the same.

NFW profile's NAV

$$\rho_{\mathrm{NFW}} = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

- Are there r_{sn} values that can cover a large part of the $\delta V^2_{\mathrm{obs}}$ region? ANS: Yes, but problems in the lower part of the plot.
- The most probable values of r_{cn}
  $0.29 < r_{\mathrm{sn}} < 9.9$
- Efficiency coefficient: 0.67



Results valid for any ρ_s

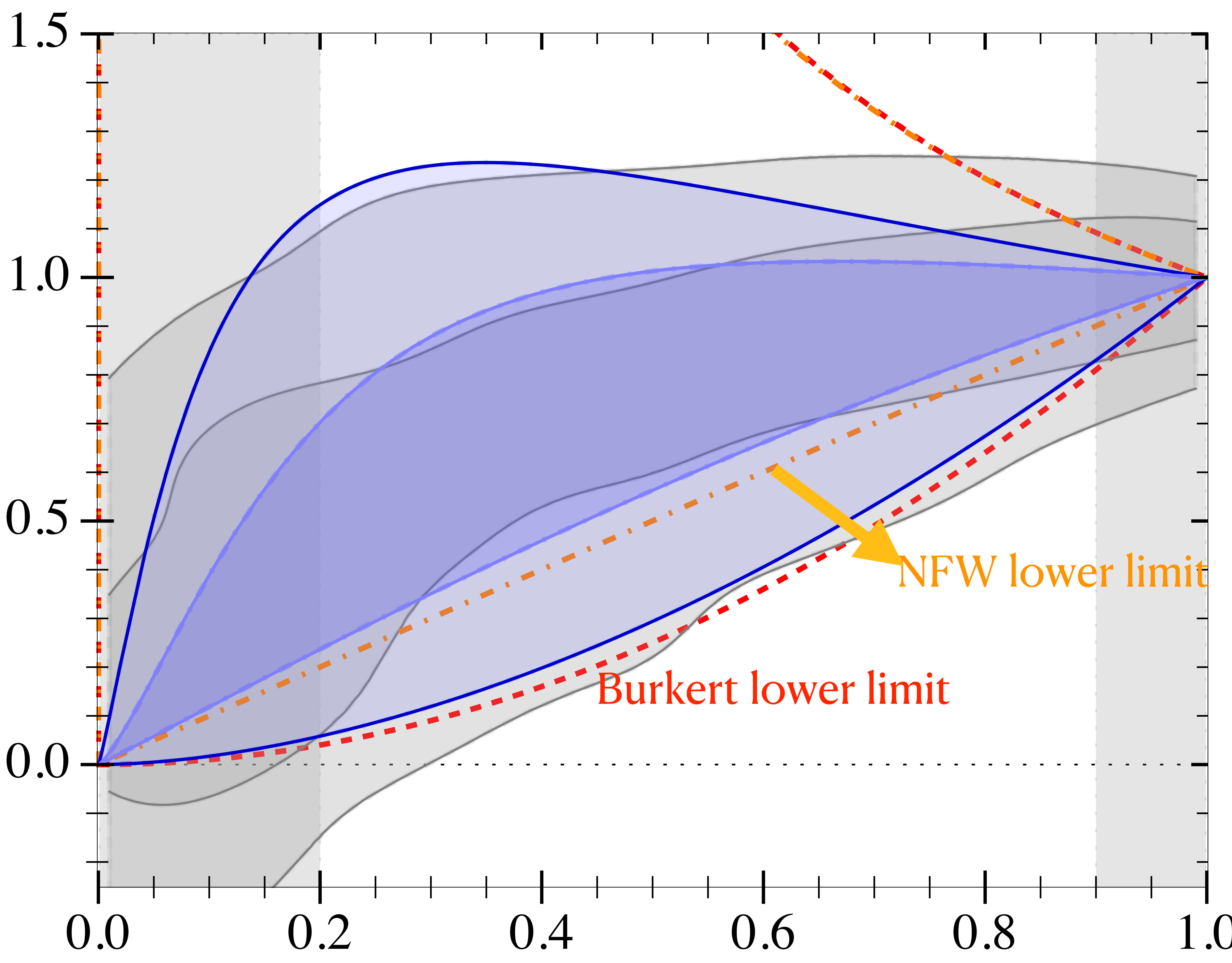
DC14 profile NAV

$$\rho_{\mathrm{DC14}} = \frac{\rho_s}{\frac{r^\gamma}{r_s^\gamma}\left(1+\frac{r^\alpha}{r_s^\alpha}\right)^{(\beta-\gamma)/\alpha}}$$

[Di Cintio et al MNRAS 2014]

Where α, β, γ depend on a quantity X, which depends on the stellar mass of the galaxy.

- Is there r_{sn} values that can cover a large part of the $\delta V^2_{\mathrm{obs}}$ region? ANS: Yes.
- Efficiency: 0.80



MOND's NAV

Without modified gravity approximations

With modified gravity approximations

MOND RC's

We provide approximations to generate these RC's easily

MOND 1σ and 2σ regions

- MOND's result is excessively concentrated: much less diversity. Efficiency: 0.53. (χ^2 values of MOND are much larger than those of DM).
- With or without approximations, the results are the same.

f(R) Palatini NAV (identical results for EiBI)

$$S[g,\Gamma,\Psi] = \frac{1}{2\kappa}\int f\left(R(\Gamma,g)\right)\sqrt{-g}\,d^4x + S_{\text{matter}}[g,\Psi]\,,$$

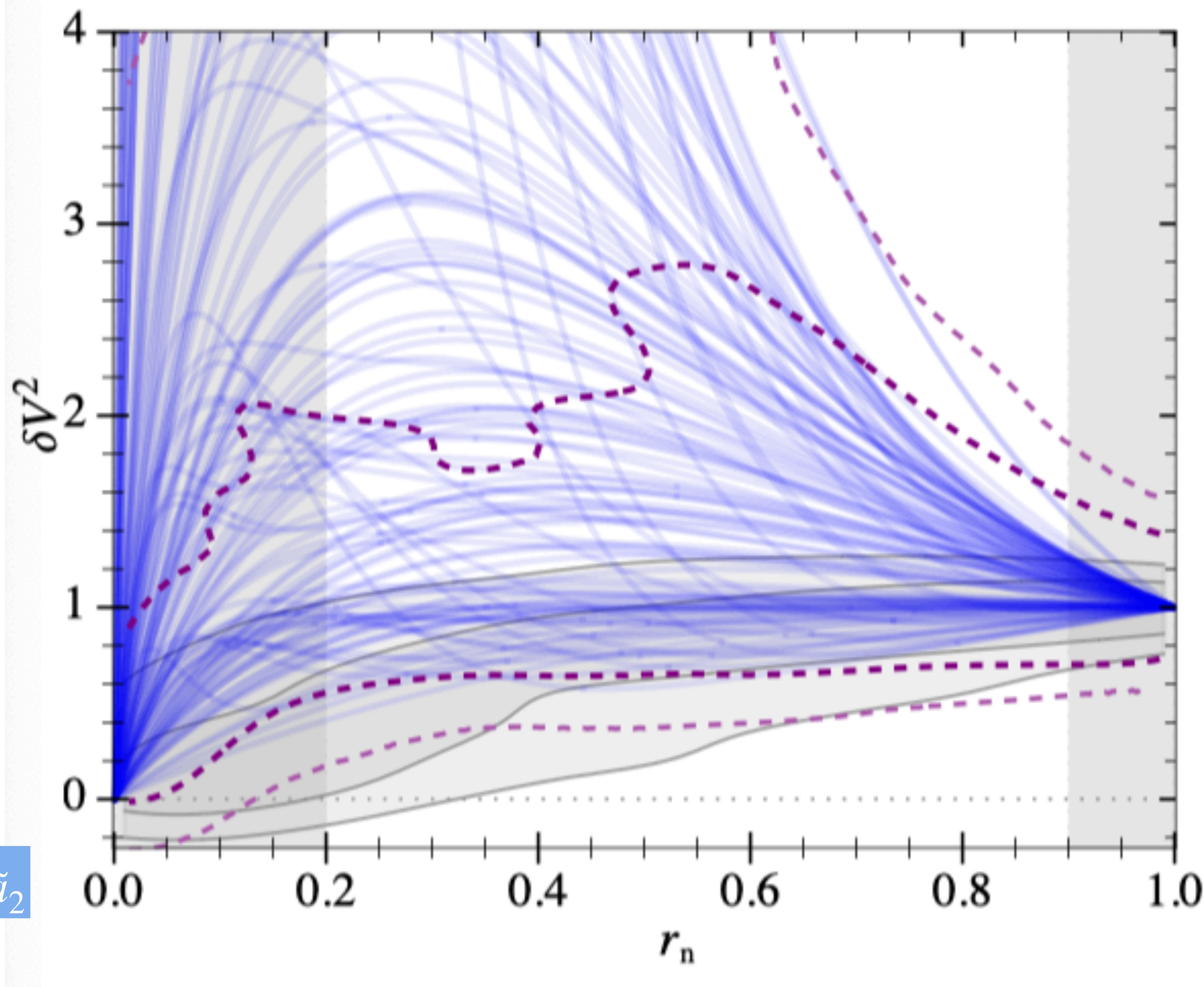
$$\frac{V_c^2}{r} = \partial_r U + \tilde{a}_2 \partial_r \rho$$

$$\Delta V_c^2 = r\,\tilde{a}_2 \partial_r \rho$$

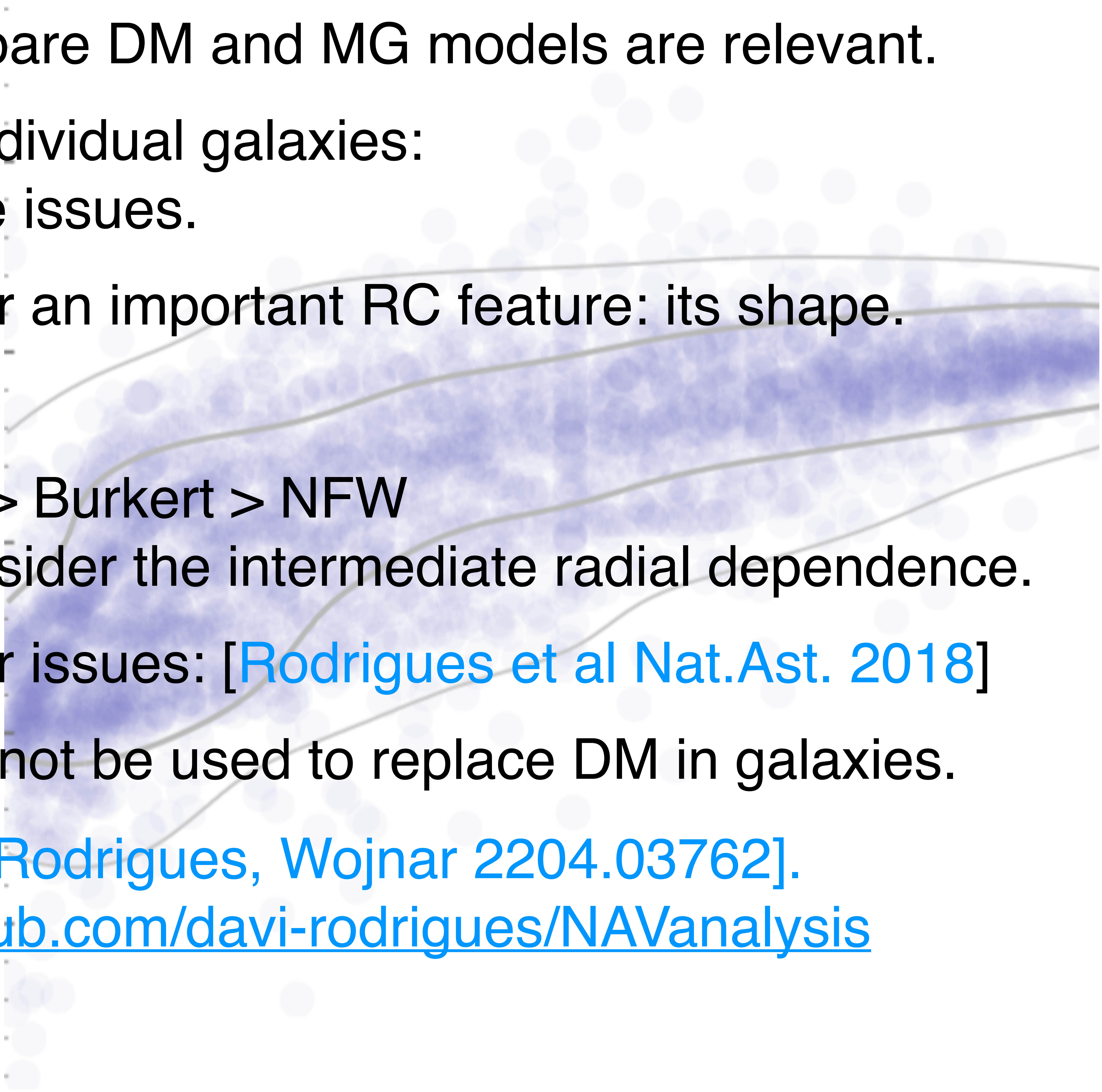
$$\delta V^2_{\text{Palatini}}(r_{\text{n}}) = r_{\text{n}}\frac{\rho'(r_{\text{n}})}{\rho'(1)}$$

Efficiency: < -2.0

Independent from $\tilde{a}_2$



Conclusions



- For large surveys, efficient ways to compare DM and MG models are relevant.
- It is particularly difficult to study MG in individual galaxies:
  Time consuming and data availability are issues.
- The NAV method provides fast results for an important RC feature: its shape.
- Some results:
  - Most NAV efficient DM models: DC14 > Burkert > NFW
    Besides cusp/core, it is relevant to consider the intermediate radial dependence.
  - MOND RC's lack diversity. For stronger issues: [Rodrigues et al Nat.Ast. 2018]
  - Palatini $f(R)$ and EiBI gravity: they cannot be used to replace DM in galaxies.
- Further details in [Hernandez-Arboleda, Rodrigues, Wojnar 2204.03762].
  The code can be found here: https://github.com/davi-rodrigues/NAVanalysis