Testing MOdified Gravity (MOG) Theory with the Milky Way

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Tensions in the LCDM paradigm

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Goal

- Test MOdified Gravity (MOG) theory of John Moffat using tracers of the total gravitational potential of the MW

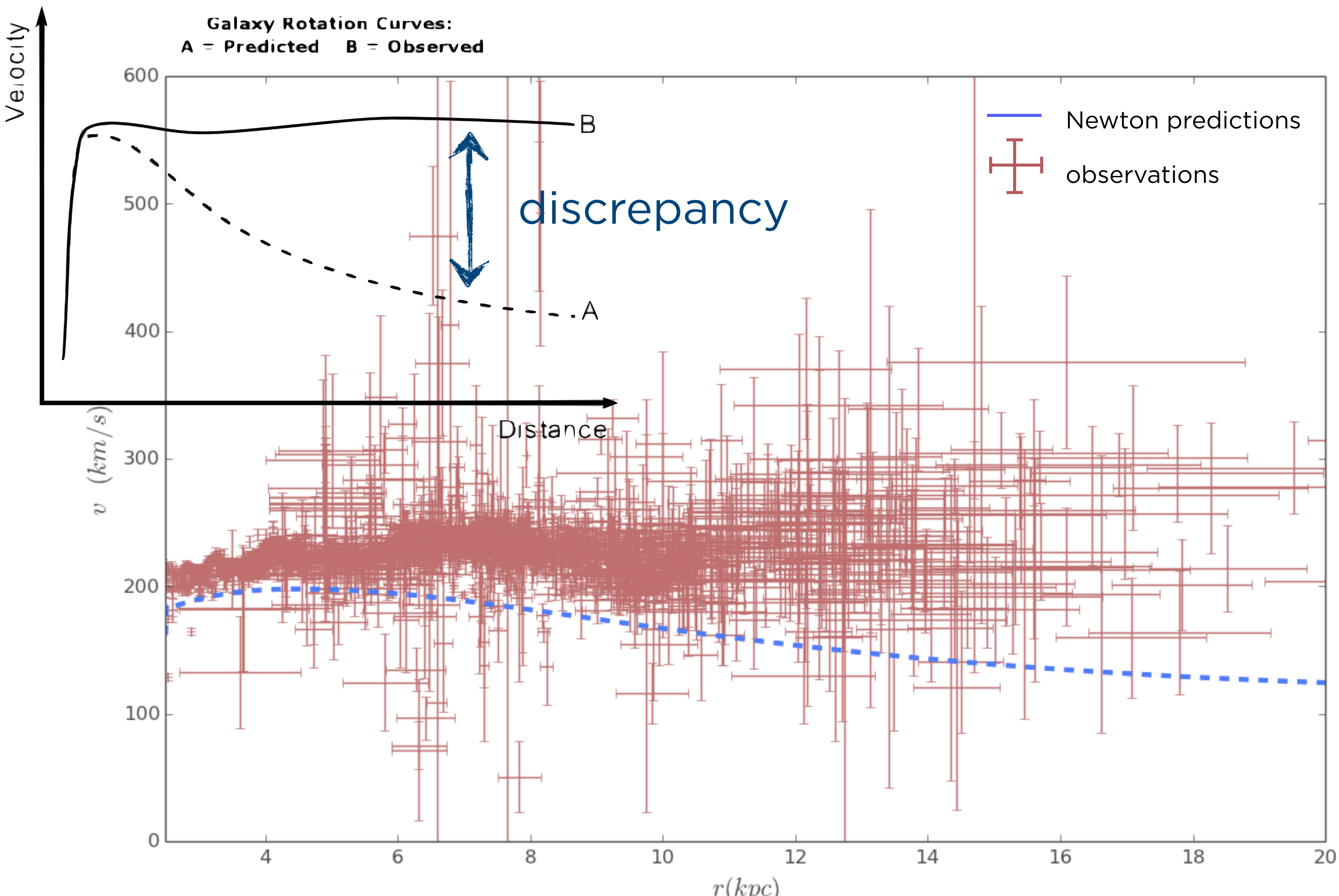
- Methodology already used for testing MOND phenomenology.

B. Famaey & J. Binney,
MNRS 363 (2005)
[astro-ph/0506723]

S. S. McGaugh, ApJ 683 (2008)
[0804.1314]

F. Iocco, M. Pato & G. Bertone,
Phys. Rev. D92 (2015)
[1505.05181]

Rotation Curve Milky Way



Motivation

- Observations of the dynamics of galaxies reveal a discrepancy between dynamical mass and the mass inferred from luminous matter.

V.C. Rubin +, ApJ 141 (1965)

V.C. Rubin & W.K. Ford Jr., ApJ 159 (1970)

- A proposal for explaining the mismatch is a modification of gravity.

M. Milgrom, ApJ 270 (1983)

J.D. Bekenstein, Phys. Rev. D70 (2004) [astro-ph/0403694

J.W. Moffat, JCAP 03 (2006) [gr-qc/0506021v7]

MOdified Gravity (MOG) Theory

J.W. Moffat, JCAP 03 (2006) [gr-qc/0506021v7]

- Scalar-Tensor-Vector Gravity (STVG) theory

Gravitational action:

$$S_G = -\frac{1}{16\pi}\int \frac{1}{G}\,(R+2\Lambda)\,\sqrt{-g}\;d^4x$$

Massive vector field action:

$$S_\phi = -\frac{1}{4\pi}\int \omega\left[\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\mu^2\phi_\mu\phi^\mu + V_\phi(\phi_\mu\phi^\mu)\right]\sqrt{-g}\;d^4x$$

$$B_{\mu\nu} = \partial_\mu\phi_\nu - \partial_\nu\phi_\mu$$

Scalar fields action:

$$S_S = -\int \frac{1}{G}\left[\frac{1}{2}g^{\alpha\beta}\left(\frac{\nabla_\alpha G\nabla_\beta G}{G^2} + \frac{\nabla_\alpha\mu\nabla_\beta\mu}{\mu^2}\right) + \frac{V_G(G)}{G^2} + \frac{V_\mu(\mu)}{\mu^2}\right]\sqrt{-g}\;d^4x$$

MOdified Gravity (MOG) Theory

J.W. Moffat, JCAP 03 (2006) [gr-qc/0506021v7]

- Able to explain data coming from:
  - ➡ motion of globular clusters (J.W. Moffat & V.T. Toth, ApJ 680 (2008) [0708.1935])
  - ➡ galaxy clusters (e.g. J.W. Moffat & S. Rahvar, MNRAS 441 (2014) [1309.5077])
  - ➡ rotation curves (RCs) of spiral and dwarf galaxies (e.g. M.H. Zhoolideh Haghighi & S. Rahvar, MNRAS 468 (2017) [1609.07851])
  - ➡ Bullet Cluster (J.R. Brownstein & J.W. Moffat, MNRAS 382 (2007) [astro-ph/0702146])

- Unable to explain:
  - ➡ Bullet Cluster (D. Clowe +, ApJ 648 (2006) [astro-ph/0608407])
  - ➡ galaxy clusters (e.g. T.M. Nieuwenhuizen +, MNRS 476 (2018) [1802.04891])

MOdified Gravity (MOG) Theory

J.W. Moffat & S. Rahvar, MNRAS 436 (2013) [1306.6383]

Weak field limit:

$$\Phi_{eff}(\vec{x}) = -\int \frac{G_0 \rho(\vec{x}')}{|\vec{x}-\vec{x}'|} d^3\vec{x}' + \kappa^2 \int \frac{e^{-\mu|\vec{x}-\vec{x}'|}}{|\vec{x}-\vec{x}'|} \rho(\vec{x}') d^3\vec{x}'$$

$$G_0 - \kappa^2 = G_N$$

$$\alpha = (G_\infty - G_N)/G_N$$

$$\vec{a} = -\vec{\nabla}\Phi_{\rm eff}$$

$$\vec{a}(\vec{x}) = -G_N \int \frac{\rho(\vec{x}')(\vec{x}-\vec{x}')}{|\vec{x}-\vec{x}'|^3} \times \left[1 + \alpha - \alpha e^{-\mu|\vec{x}-\vec{x}'|}(1 + \mu|\vec{x}-\vec{x}'|)\right] d^3\vec{x}'$$

For $r < 1/\mu$: recover Newtonian gravity

MOdified Gravity (MOG) Theory

Weak field limit:

$$\vec{a}(\vec{x}) = -G_N \int \frac{\rho(\vec{x}')(\vec{x} - \vec{x}')}{|\vec{x} - \vec{x}'|^3} \times \left[1 + \alpha - \alpha e^{-\mu|\vec{x}-\vec{x}'|}(1 + \mu|\vec{x} - \vec{x}'|)\right] d^3\vec{x}'$$

Parameters (α, μ):

- control the strength and the range of the repulsive force and
- can be expressed in terms of the mass of the system

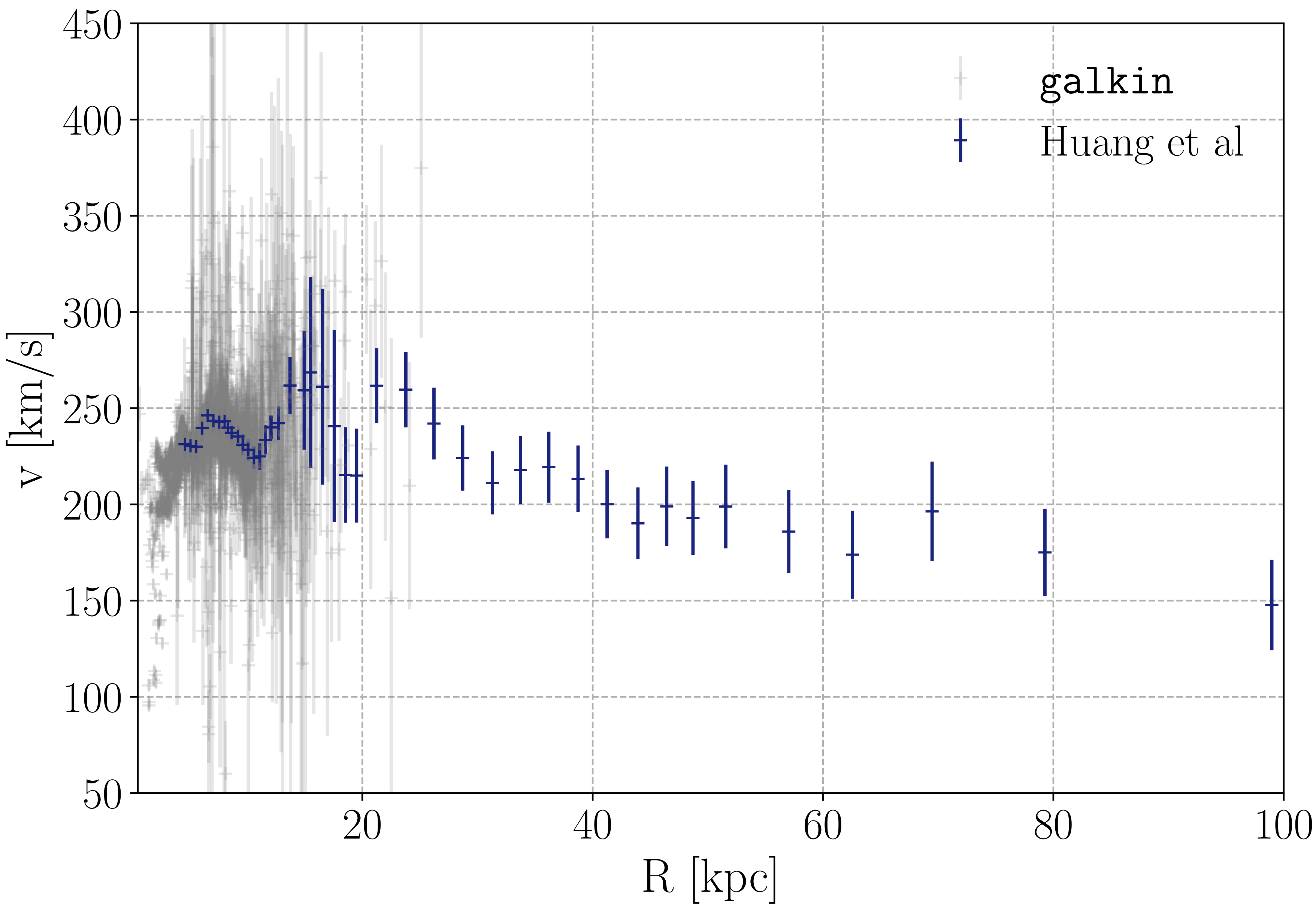
$$\mu = \frac{D}{\sqrt{M}} \qquad \alpha = \frac{M}{(\sqrt{M} + E)^2}\left(\frac{G_\infty}{G_N} - 1\right)$$

$(D,\, E,\, G_\infty)$ are constants that can be determined by observations

J.W. Moffat & V.T. Toth, Classical and Quantum Gravity 26 (2009) [0712.1796v5]

Methodology: Rotation Curve

- Observed RC: Two different compilations



galkin

M. Pato & F. Iocco, SoftwareX 6 (2017) [1703.00020]

$2.5 < \mathrm{R} < 22$ kpc

Huang et al

Y. Huang +, MNRS 463 (2016) [1604.01216]

$2.5 < \mathrm{R} < 100$ kpc

$$R_0 = 8.34 \text{ kpc}$$
$$V_0 = 239.89 \text{ km/s}$$

$$(U_\odot, V_\odot, W_\odot) = (7.01,\ 10.13,\ 4.95) \text{ km/s}$$

Methodology: Rotation Curve

- Observed RC: Two different compilations

M. Pato & F. Iocco,
SoftwareX 6 (2017)
[1703.00020]

Y. Huang +,
MNRS 463 (2016)
[1604.01216]

- Visible component (star + gas): Large array of observationally inferred 3D density profiles

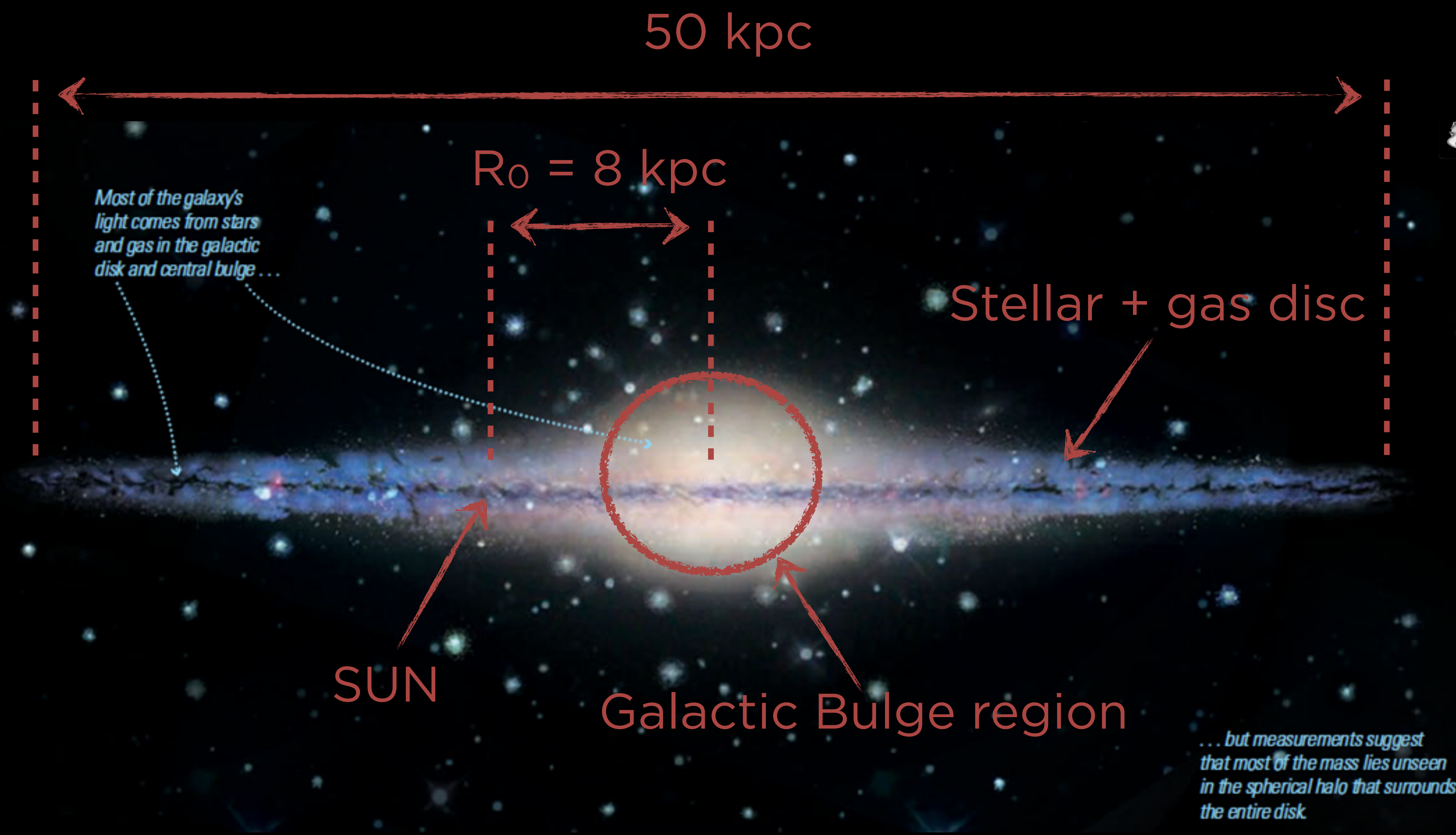
$$\rho_{\text{bulge}}(x, y, z) \quad \rho_{\text{disc}}(r, z) \quad \rho_{\text{gas}}(x, y, z)$$

$$\Phi_{\text{bulge}}(x, y, z) \quad \Phi_{\text{disc}}(r, z) \quad \Phi_{\text{gas}}(x, y, z)$$

$$v^2(r) = \sum_i v_i^2(r)$$

$$v_i^2(r) = r\frac{\mathrm{d}\Phi_i}{\mathrm{d}r}$$

Data-based density profiles → Gravitational potential → Expected RC



The visible Milky Way

Bulge distribution: $\rho_b(x,y,z) = \bar{\rho}_b f(x,y,z)$

$f(x,y,z)$	Bar angle [º]	x0:y0:z0	Reference
e^{-r}	25	2.8 : 1.4 : 1	K.Z. Stanek + (1996) [G2]
$e^{-r_s^2/2}$	24	3.6 : 1.5 : 1	K.Z. Stanek + (1996) [E2]
$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	20	3.7 : 1.5 : 1	H. Zhao (1996)
$e^{-r_s^2}/(1+r_s)^{1.8}$	20	2.6 : 0.8 : 1	N. Bissantz & O. Gerhard (2002)
$\mathrm{sech}^2(-r_s) + e^{-r_s}$	13	3.7 : 1.3 : 1	A.C. Robin + (2012)
$e^{-r_s^2}/(1+r_s)^{1.8}$	15	3.2 : 2.2 : 1	E. Vanhollebeke + (2013)

Normalisation $\bar{\rho}_b$

$$\langle \tau \rangle = 2.17^{+0.47}_{-0.38} \times 10^{-6} \quad (\ell, b) = (1.50^{\circ}, -2.68^{\circ})$$

P. Popowski +, ApJ 631 (2005) [astrop-ph/0410319]

Stellar disc distribution: $\rho_d(r,z) = \bar{\rho}_d f(r,z)$

$f(r,z)$		Scale-length [kpc]	Scale-height [kpc]	Reference
$e^{-r}\,\mathrm{sech}^2(z)$	thin	2.75	0.27 η(r)	C. Han & A. Gould (2003)
$e^{-r}\,e^{-(z+z_0)}$	thick	2.75	0.44 η(r)	
$e^{-r}\,e^{-\|z\|}$	thin	2.6	0.30	M. Juric + (2008)
$e^{-r}\,e^{-\|z\|}$	thick	3.6	0.90	
$(r^2+z^2)^{-2.77/2}$	halo			
$e^{-r}\,e^{-\|z\|}$	thin	2.75	0.25	J. T. A. De Jong + (2010)
$e^{-r}\,e^{-\|z\|}$	thick	4.1	0.75	
$(r^2+z^2)^{-2.75/2}$	halo			
$e^{-r}\,e^{-\|z\|}$	thin	2.75	0.25	S. Calchi Novati & L. Mancini (2011)
$e^{-r}\,e^{-\|z\|}$	thick	4.1	0.75	
$e^{-r}\,e^{-\|z\|}$	single	2.15	0.4	J. Bovy & H.W. Rix (2013)

Normalisation $\bar{\rho}_d$

$$\Sigma_*(R_0) = 38 \pm 4\,\mathrm{M_\odot pc^{-2}}$$

J. Bovy & H.W. Rix, ApJ 779 (2013) [1309.0809]

Gas distribution:

$$\rho_g(x,y,z) = \rho_{H_2}(x,y,z) + \rho_{H_I}(x,y,z) + \rho_{H_{II}}(x,y,z)$$

Components		Range	Reference
molecular ring	H_2	$r = 3 - 20$ kpc	K. Ferrière (1998)
cold, warm	HI		
warm, hot	HII		
CMZ, disc	H_2	$r = 0.01 - 3$ kpc	K. Ferrière + (2007)
CMZ, disc	HI		
warm, hot, very hot	HII		

Uncertainties

CO-to-H_2 factor: $X_{CO}(r > 3\,\mathrm{kpc}) = (5.0 \pm 2.5) \times 10^{19}\,\mathrm{cm^{-2}K^{-1}km^{-1}s}$

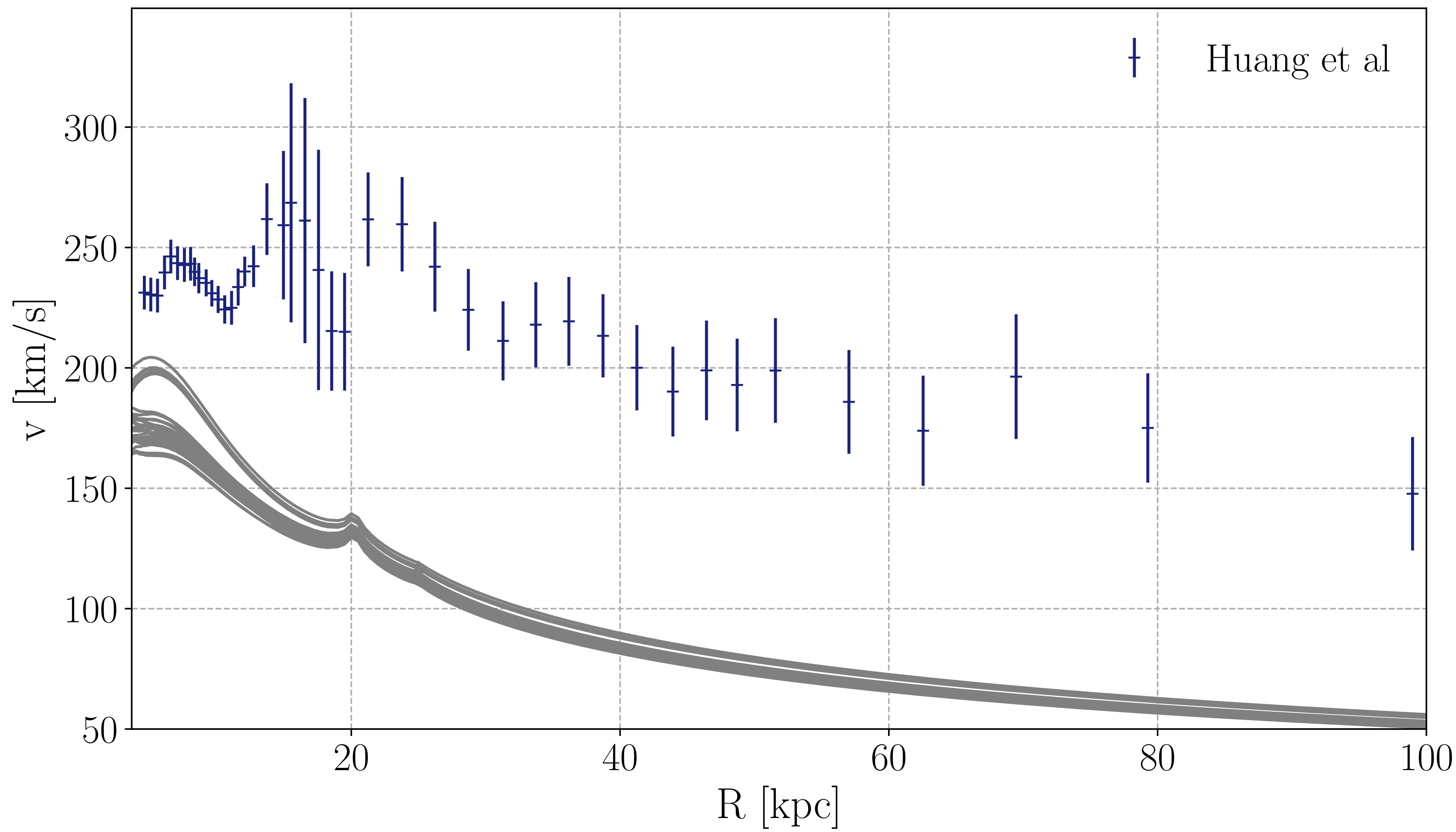
$X_{CO}(r < 3\,\mathrm{kpc}) = (1.9 \pm 1.4) \times 10^{20}\,\mathrm{cm^{-2}K^{-1}km^{-1}s}$

K. Ferriere +, ApJ 467 (2007) [astro-ph/0702532]

Baryonic morphologies

$$\rho_{\rm bulge}(x,y,z) \quad \rho_{\rm disc}(r,z) \quad \rho_{\rm gas}(x,y,z) \longrightarrow \Phi_{\rm bulge}(x,y,z) \quad \Phi_{\rm disc}(r,z) \quad \Phi_{\rm gas}(x,y,z) \longrightarrow v^2(r) = \sum_i v_i^2(r)$$

$$v_i^2(r) = r\frac{\mathrm{d}\Phi_i}{\mathrm{d}r}$$



MOG (α, μ) parameters

- Rotation curve of the MW

$$(\alpha,\mu)^{\rm MW} = (15.01,\, 0.0313\,{\rm kpc}^{-1})$$

J.W. Moffat & V.T. Toth, Phys. Revm D91 (2015) [1411.6701]

- We use equations

$$\mu = \frac{D}{\sqrt{M}} \qquad \alpha = \frac{M}{(\sqrt{M}+E)^2}\left(\frac{G_\infty}{G_N} - 1\right)$$

to obtain $(\alpha, \mu)^c$ self-consistently with our MW mass determination

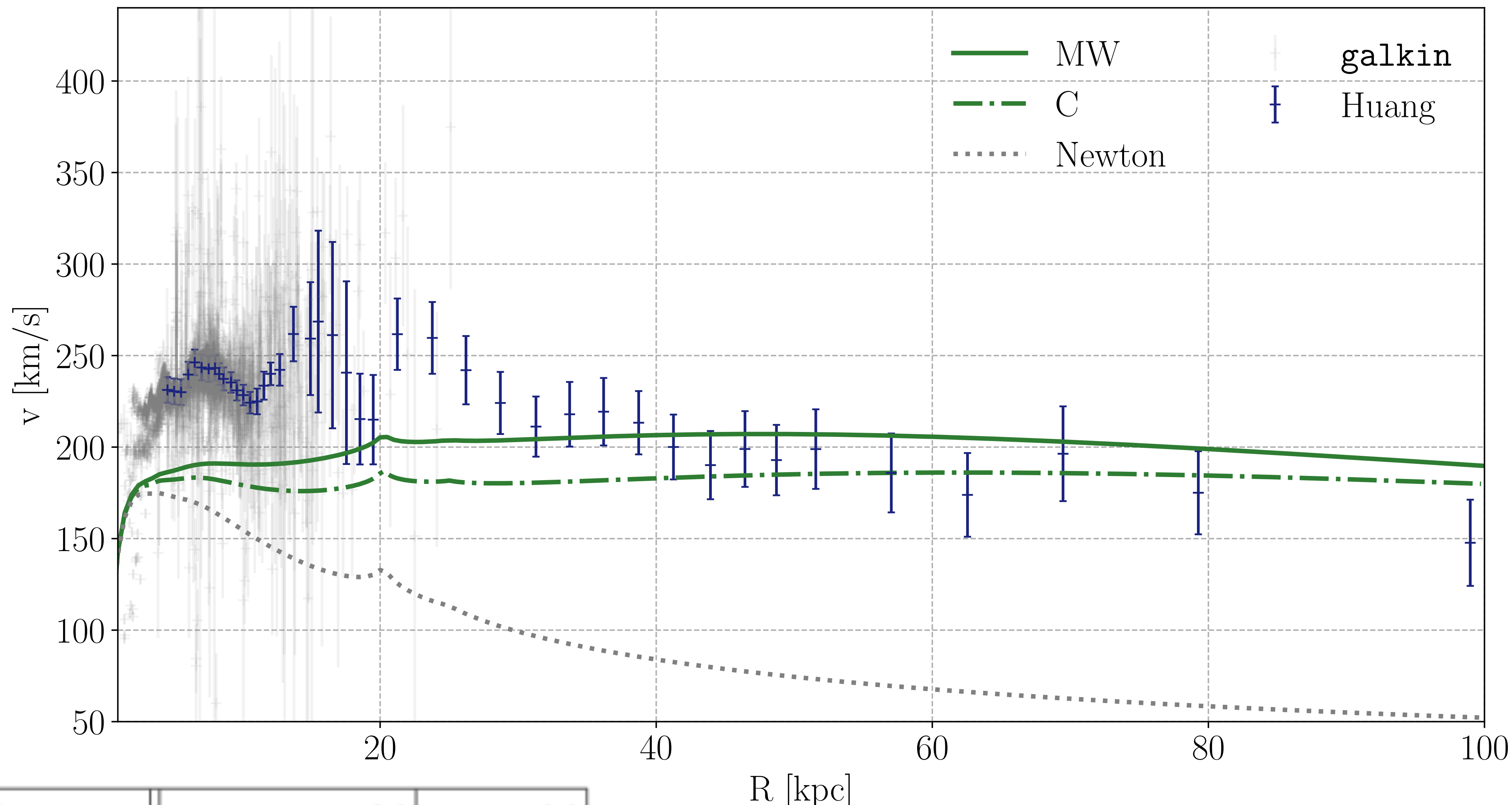
$$D = 6.25\ {\rm M_\odot pc^{-1}}$$
$$E = 25\times 10^3\ {\rm M_\odot^{1/2}}$$
$$G_\infty = 20\, G_N$$

J.W. Moffat & V.T. Toth, Classical & Quantum Gravity 26 (2009) [0712.1796]

Representative Morphology

K.Z. Stanek + (1996) [E2]
S. Calchi Novati & L. Mancini (2011)

$$M_{MW} = 6.7^{+0.7}_{-0.6} \times 10^{10}\ M_\odot$$

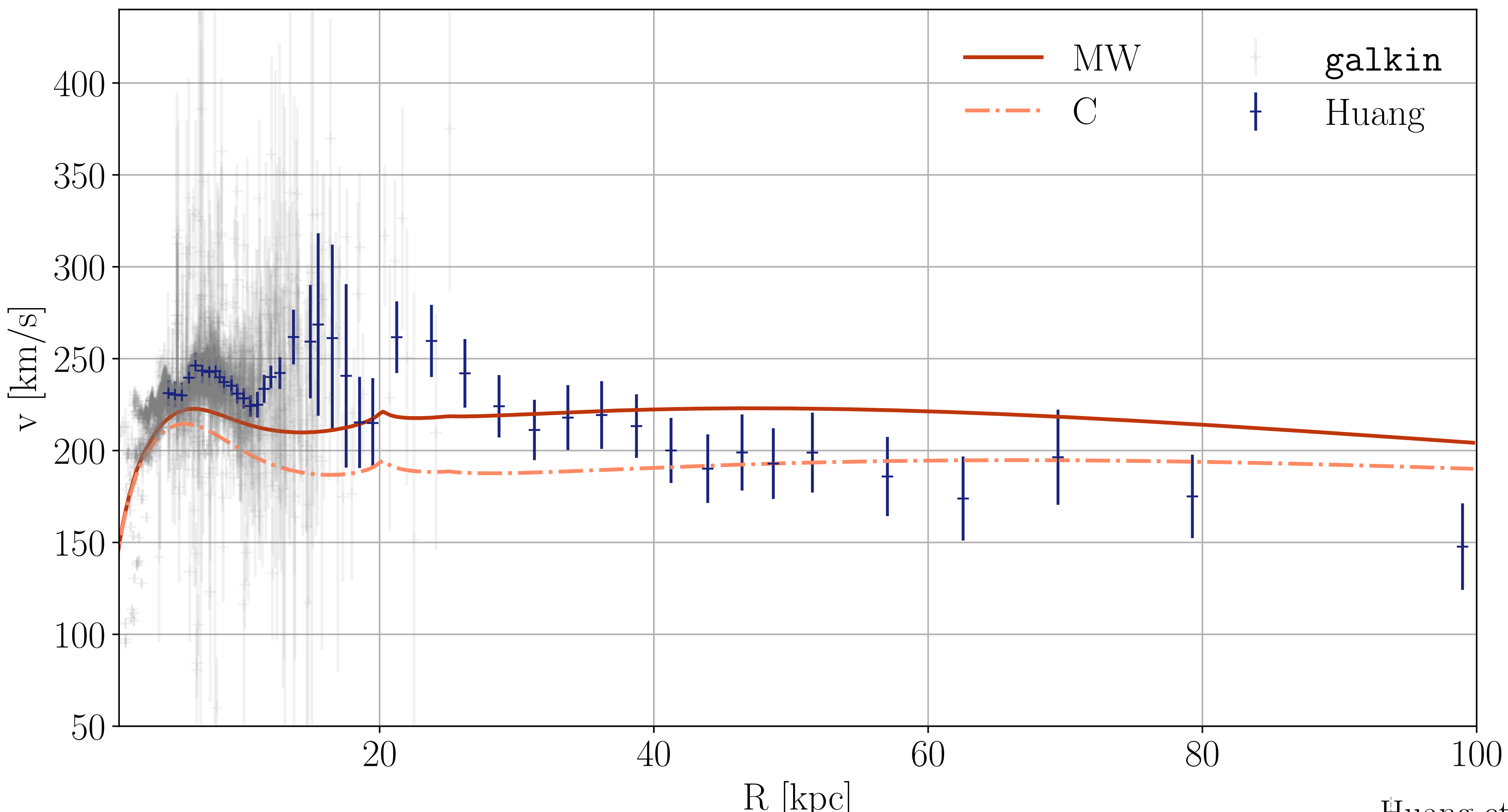


$(\alpha, \mu\ [\mathrm{kpc}^{-1}])$	Huang et al. [1]	**galkin** [2]
$(15.01, 3.13 \cdot 10^{-2})^{MW}$	5.02	8.54
$(15.80, 2.41 \cdot 10^{-2})^{C}$	9.14	10.61
Newton	32.65	21.84
5 σ equivalent $\tilde{\chi}^2_{5\sigma}$	2.41	1.14

Best Performing Morphology

N. Bissantz & O. Gerhard (2002)
J. Bovy & H.W. Rix (2013)

$$M_{MW} = 7.7^{+0.8}_{-0.7} \times 10^{10}\ M_\odot$$



$(\alpha, \mu\ [\mathrm{kpc}^{-1}])$	Huang et al. [1]	galkin [2]
$(15.01, 3.13 \cdot 10^{-2})^{MW}$	1.58	1.98
$(15.98, 2.26 \cdot 10^{-2})^{C}$	3.82	2.82

2.6σ discrepancy

	Huang et al	galkin
5 σ equivalent $\tilde{\chi}^2_{5\sigma}$	2.41	1.14

Dynamical parameters (α, μ)

$$\vec{a}(\vec{x}) = -G_N \int \frac{\rho(\vec{x}')(\vec{x}-\vec{x}')}{|\vec{x}-\vec{x}'|^3} \times \left[1+\alpha-\alpha e^{-\mu|\vec{x}-\vec{x}'|}(1+\mu|\vec{x}-\vec{x}'|)\right] d^3\vec{x}'$$

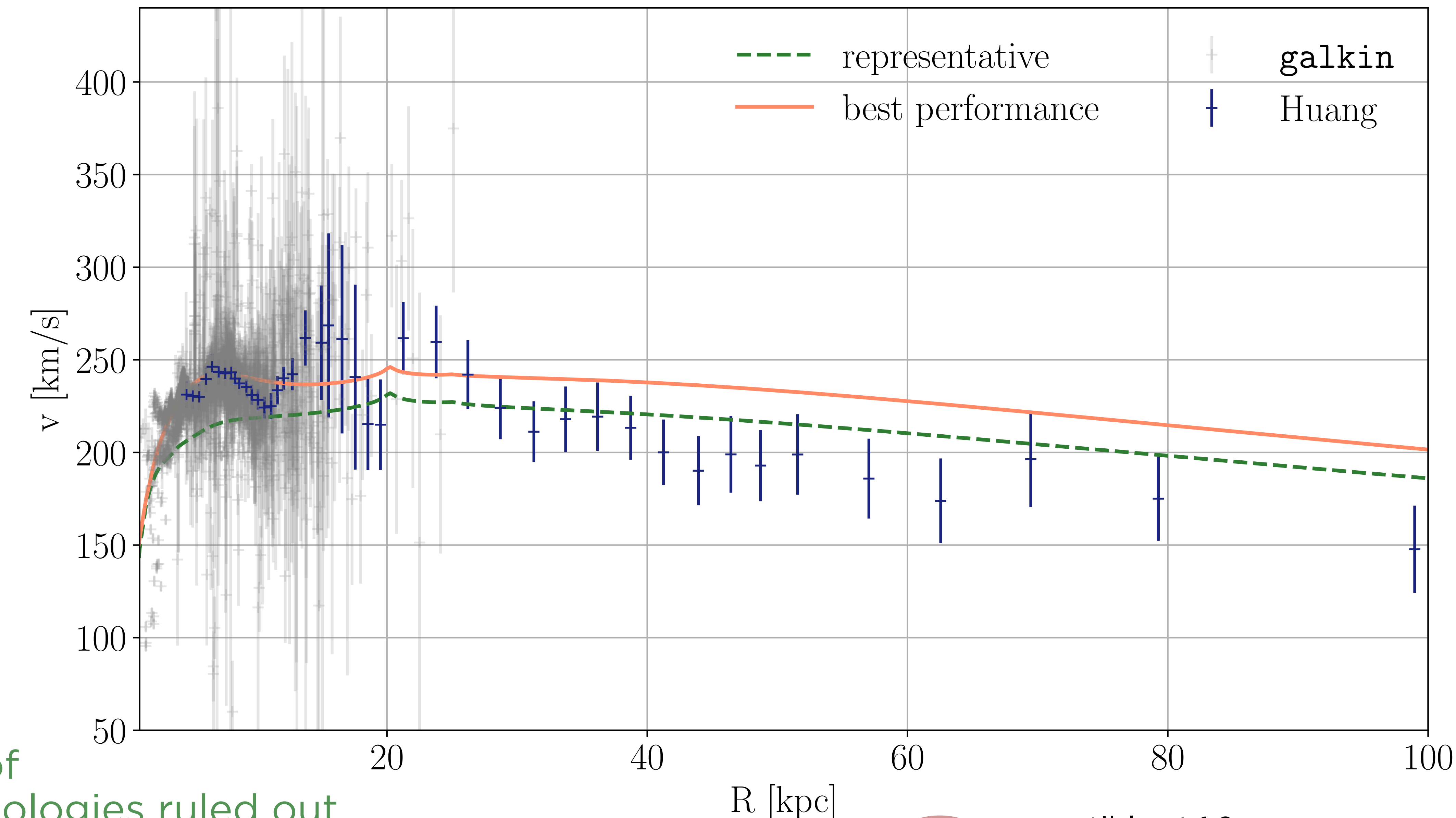
$$\mu = \frac{D}{\sqrt{M}} \qquad \alpha = \frac{M}{(\sqrt{M}+E)^2}\left(\frac{G_\infty}{G_N}-1\right)$$

(α, μ) calibrated with spiral galaxies

(α, μ) is a function of the enclosed mass:

$$\mu = \mu(R) \propto \int \rho(R)\mathrm{d}V \qquad \alpha = \alpha(R) \propto \int \rho(R)\mathrm{d}V$$

Dynamical parameters (α, μ)



Most of morphologies ruled out

Representative:

$$\bar{\chi}^2_{\rm H} = 1.15$$

$$\bar{\chi}^2_{\rm G} = 1.94$$

Best performance:

$$\bar{\chi}^2_{\rm H} = 0.67$$

$$\bar{\chi}^2_{\rm G} = 0.37$$

compatible at 1.2σ

	Huang et al	galkin
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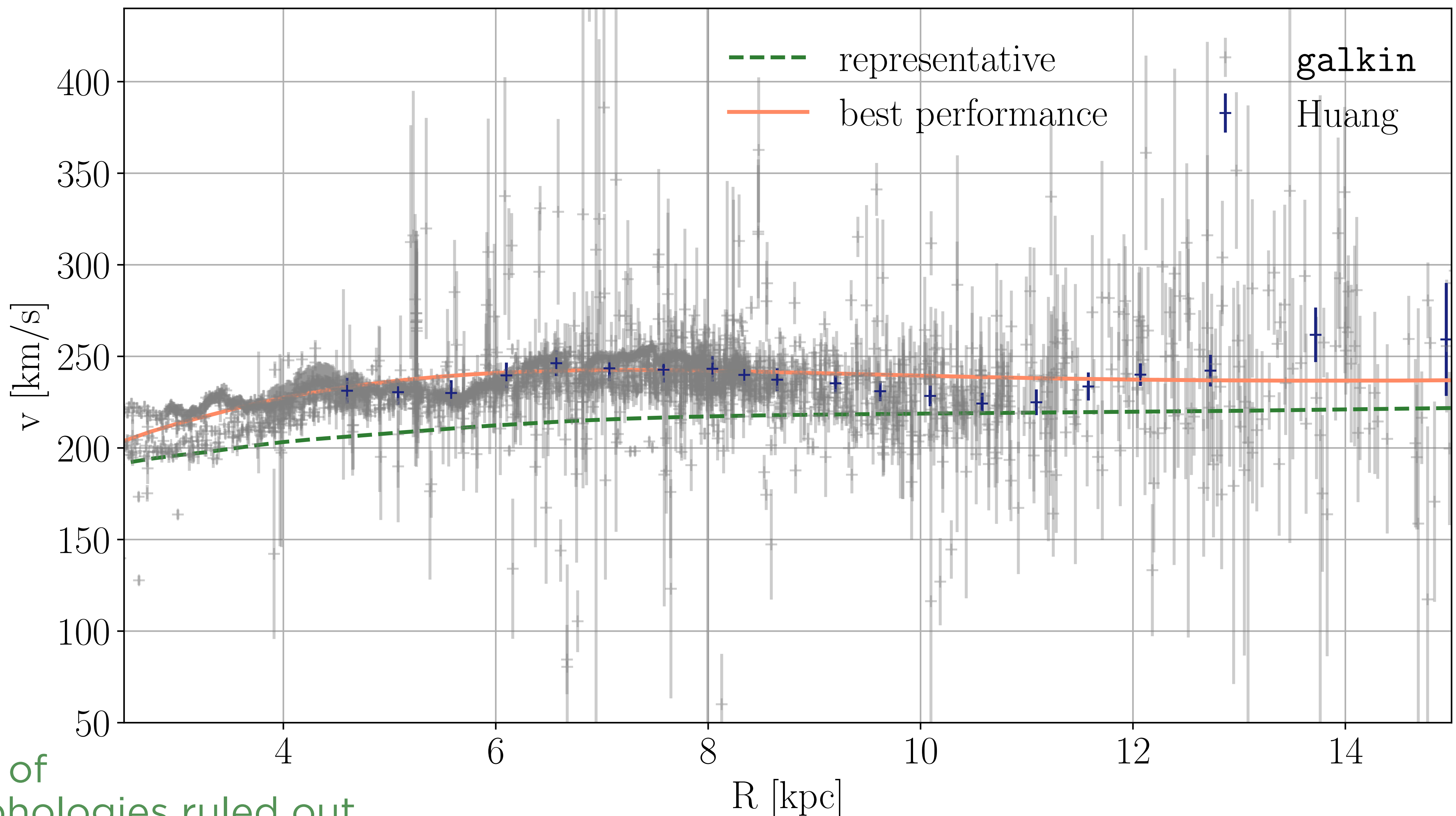

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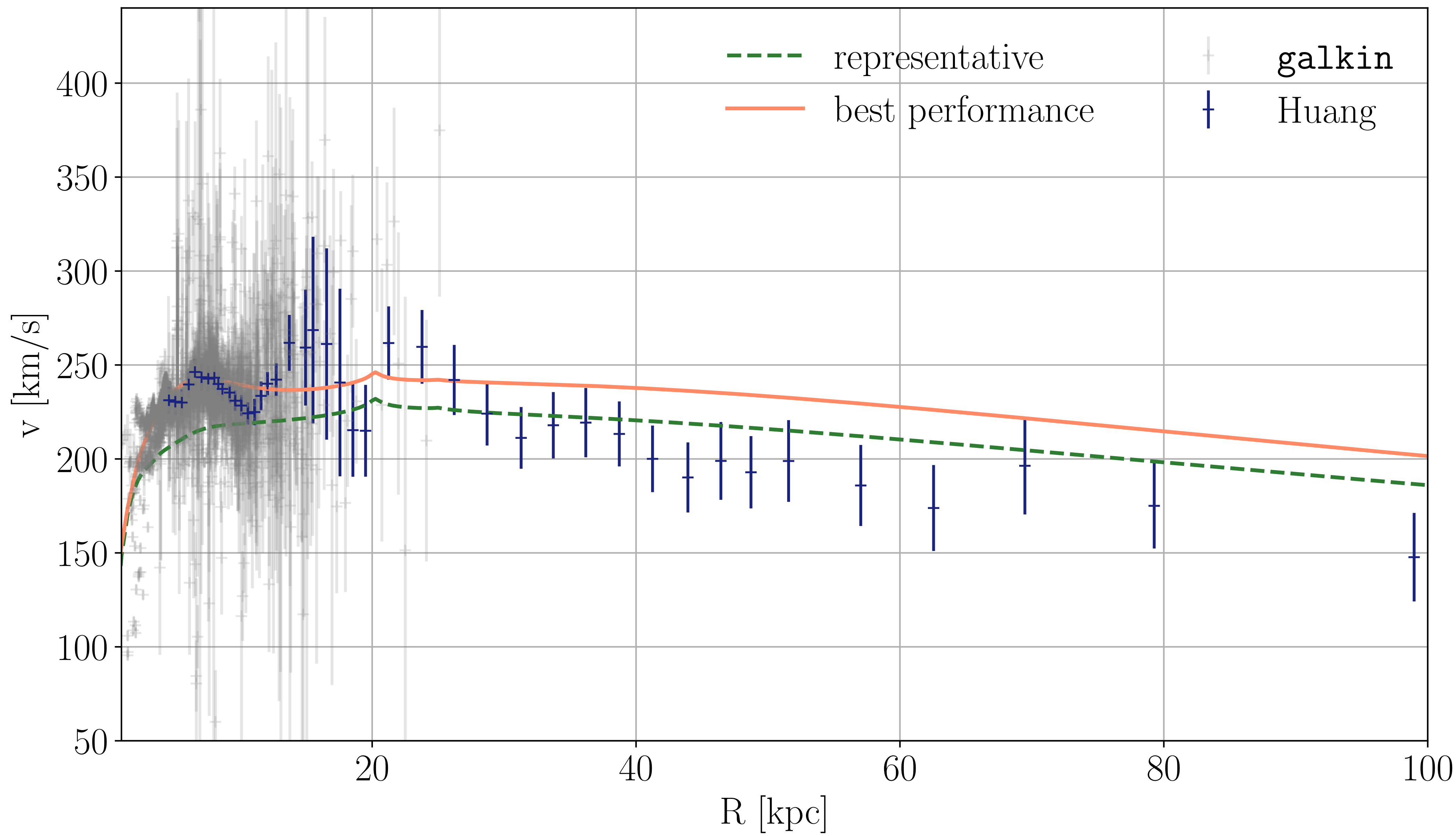

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	Huang et al	galkin
5 σ equivalent $\tilde{\chi}^2_{5\sigma}$	**2.41**	**1.14**

Conclusions

- Simplified version of MOG ruled out.

- Dynamical (calibrated self-consistently) MOG:
  depends on the morphology (ignorance on shape crucial).