Testing Gravity models
(Emergent Gravity, MOND and ΛCDM) with the RAR

Edwin A. Valentijn
Kapteyn Astronomical Institute
University of Groningen

MOND40

St Andrews 6 June 2023

Testing

- Leiden – 70's Oort school
  - Phenomenology/observing- theory
  - Mekka of Radio astronomy
  - WSRT continuum – galaxy clusters
  - Groningen HI rotation curves
    - Bosma, Sanders, Milgrom

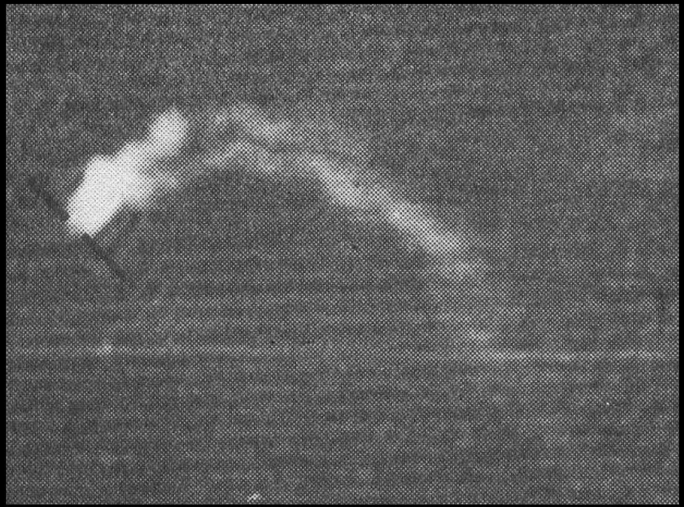
Figure 2: Leiden, August 22, 1974. Jan Oort introduces the last ever astronomical colloquium in the

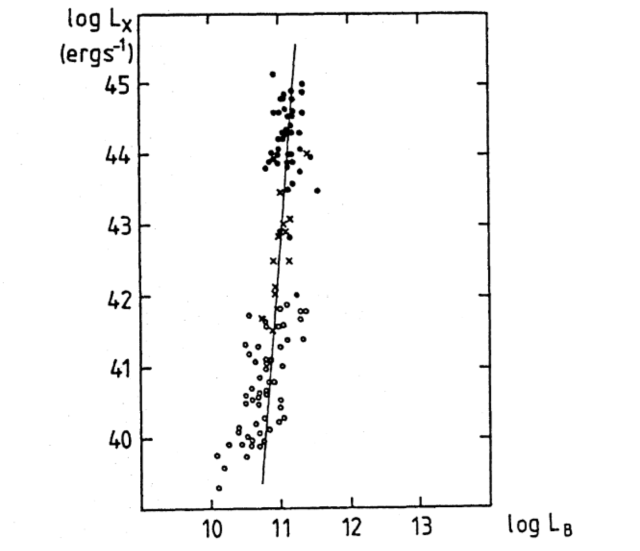
Front row: Luc Braes, Ernst Raimond, Harm Habing, Walter Jaffe, Edwin Valentijn.
Second row: Jean Casse, Richard Strom, Ger de Bruijn, Hans van Someren Greve, Xander Tielens.
Third row: Roelf Marten Duin, Frank Israel, Johan Degeweij, Steve Bajaja.
Fourth row: Gerard Uiterwaal, Wil van Breugel, unidentified, George Rossano. The person way in the back behind Uiterwaal might be Ron Harten.

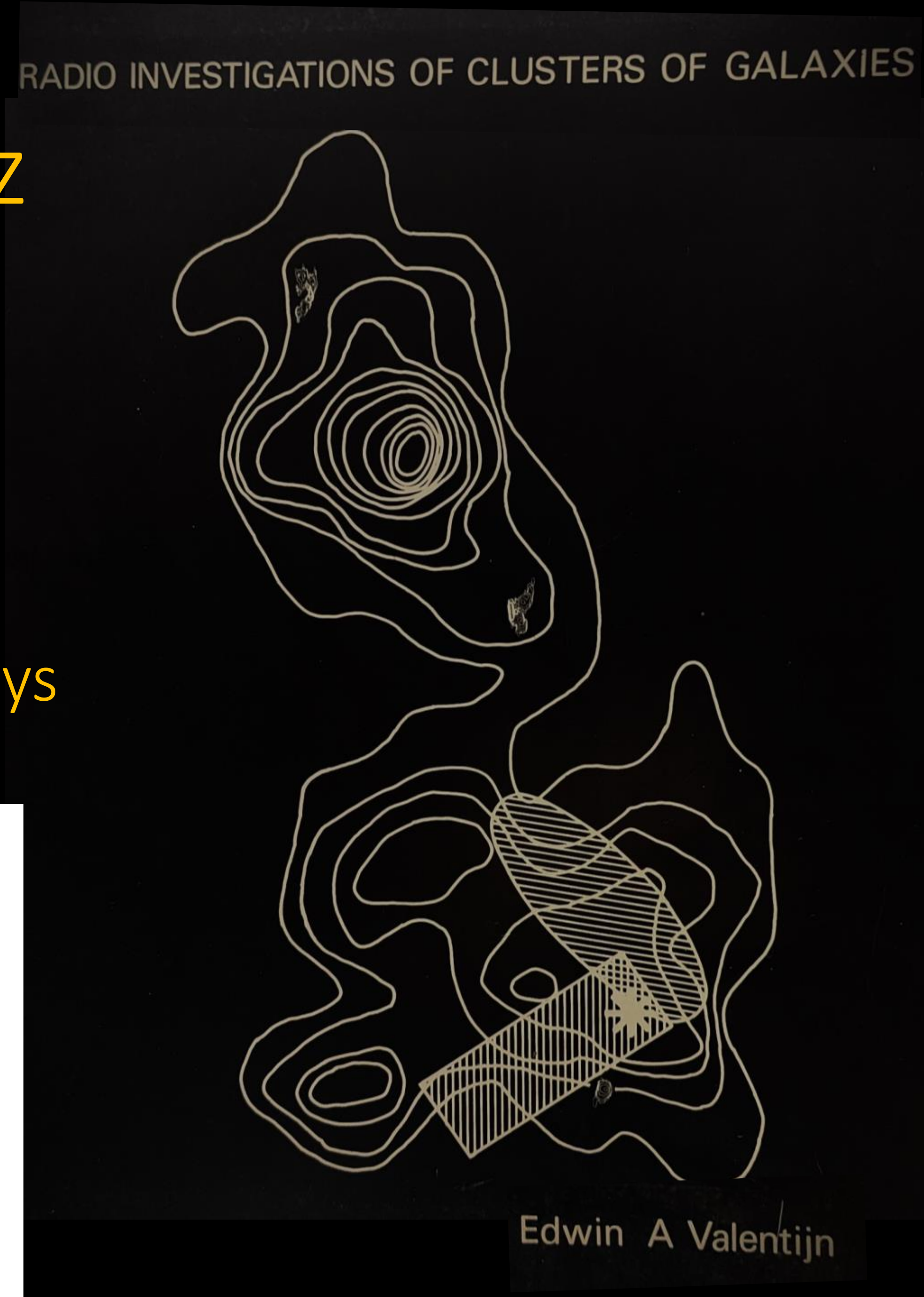
Photo credit: Sterrewacht Leiden/L.A. Zuiderduin

1978
Hercules supercluster at 610 MHz

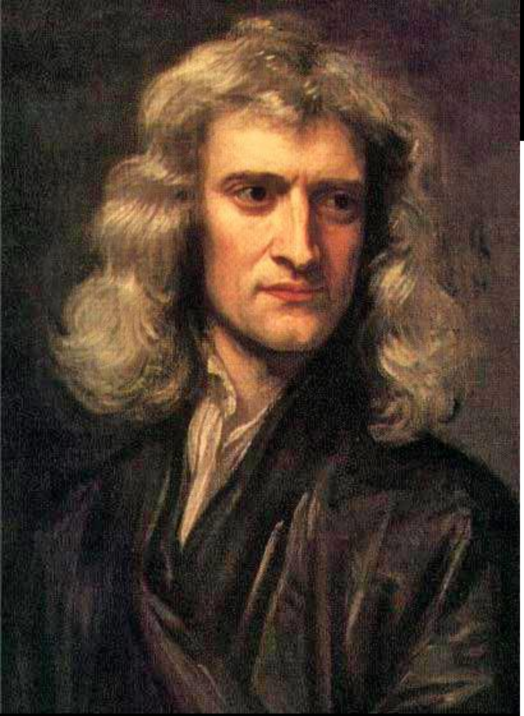
- large scale structure
- head tail radio galaxies: ICM 10^{-3}-10^{-4} cm^{-3}
- predicted X-Ray haloes cDs
    - Einstein satellite ~80
- wide angle head tails: ICM 10^{-5} cm^{-3}
- supercluster pervading gas - never detected in X-rays
- gEs trivariate X-opt-radio luminosty function

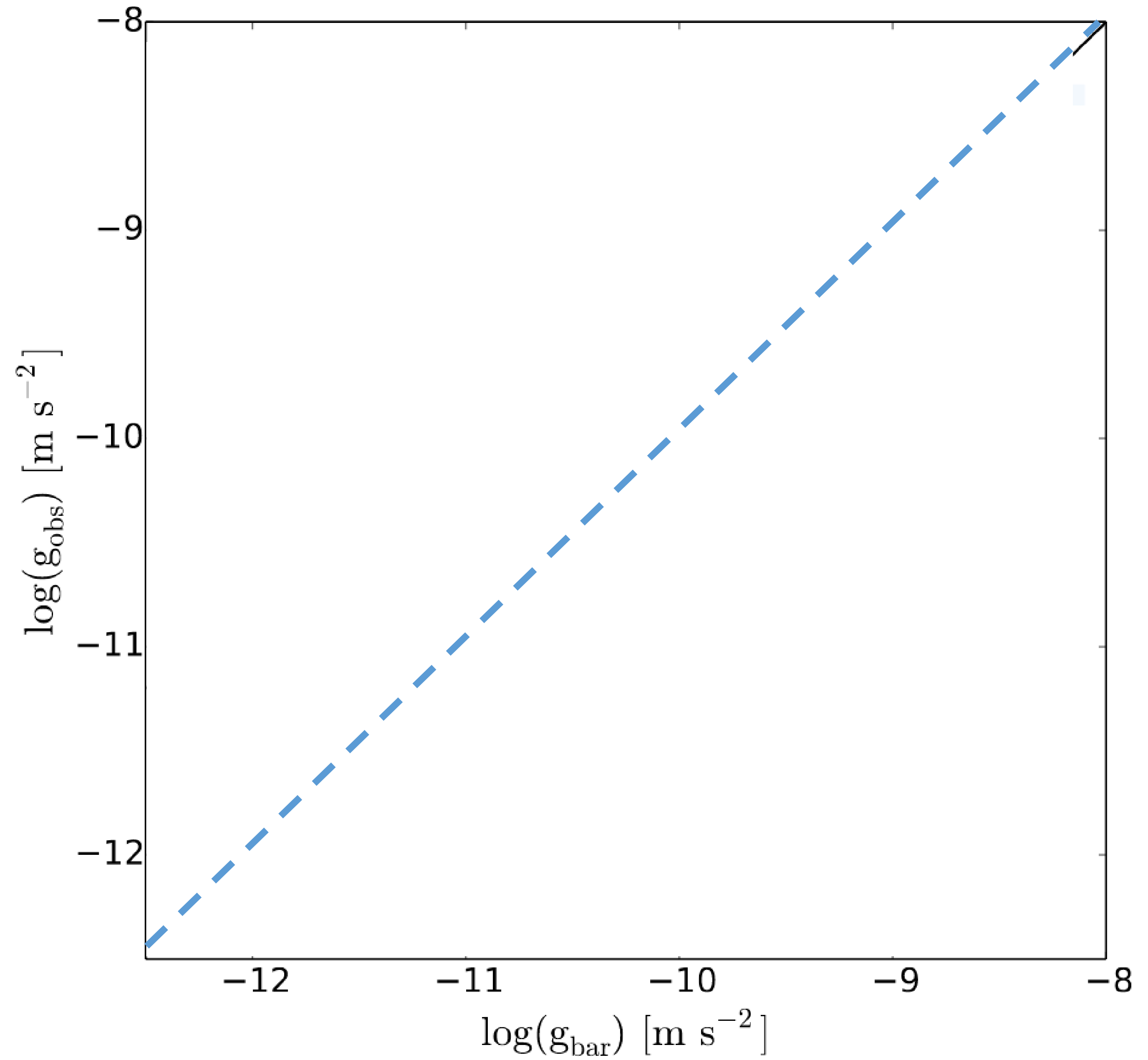


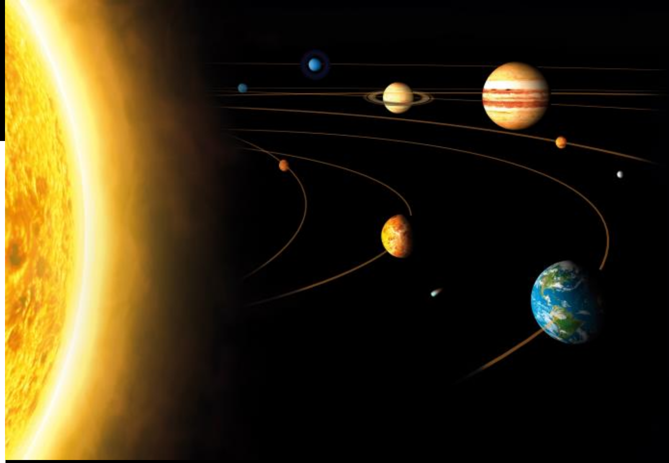




RAR





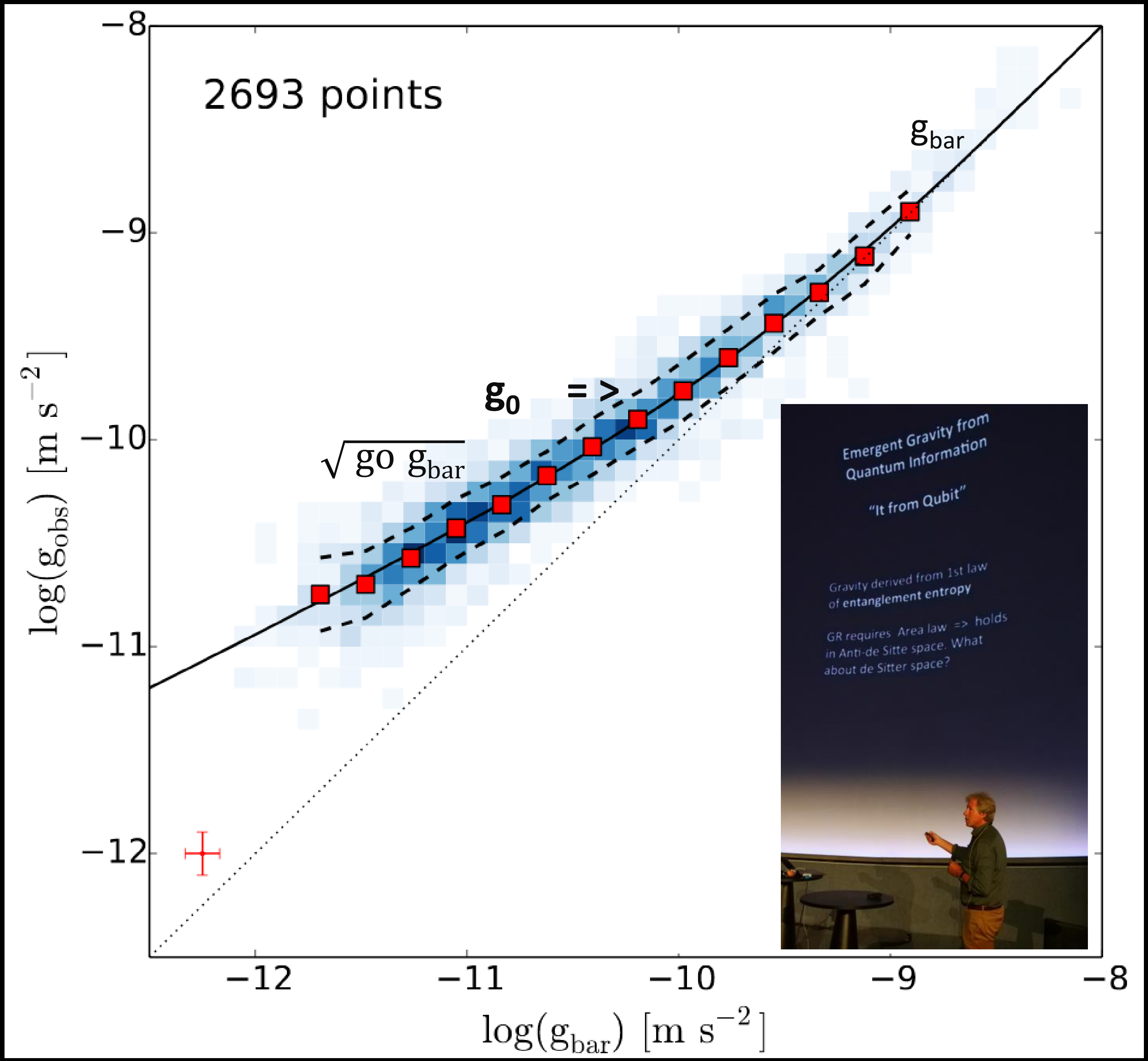


$\log(g_{obs})$

- ✓ g <–> physics
- ✓ Various sources
- ➢ Selection effects

$\log(g_{bar})$

log(g_{obs})



log(g_{bar})

g_{obs} fully specified by g_{bar}

MOND emperically

g_{char}= 1.20 10^{-10} m s^{-2}

EG : g_0 = c H_0 / 6 info

H_0 = 70 km/s /Mpc

g_o = 1.135 10^{-10} m s^{-2}

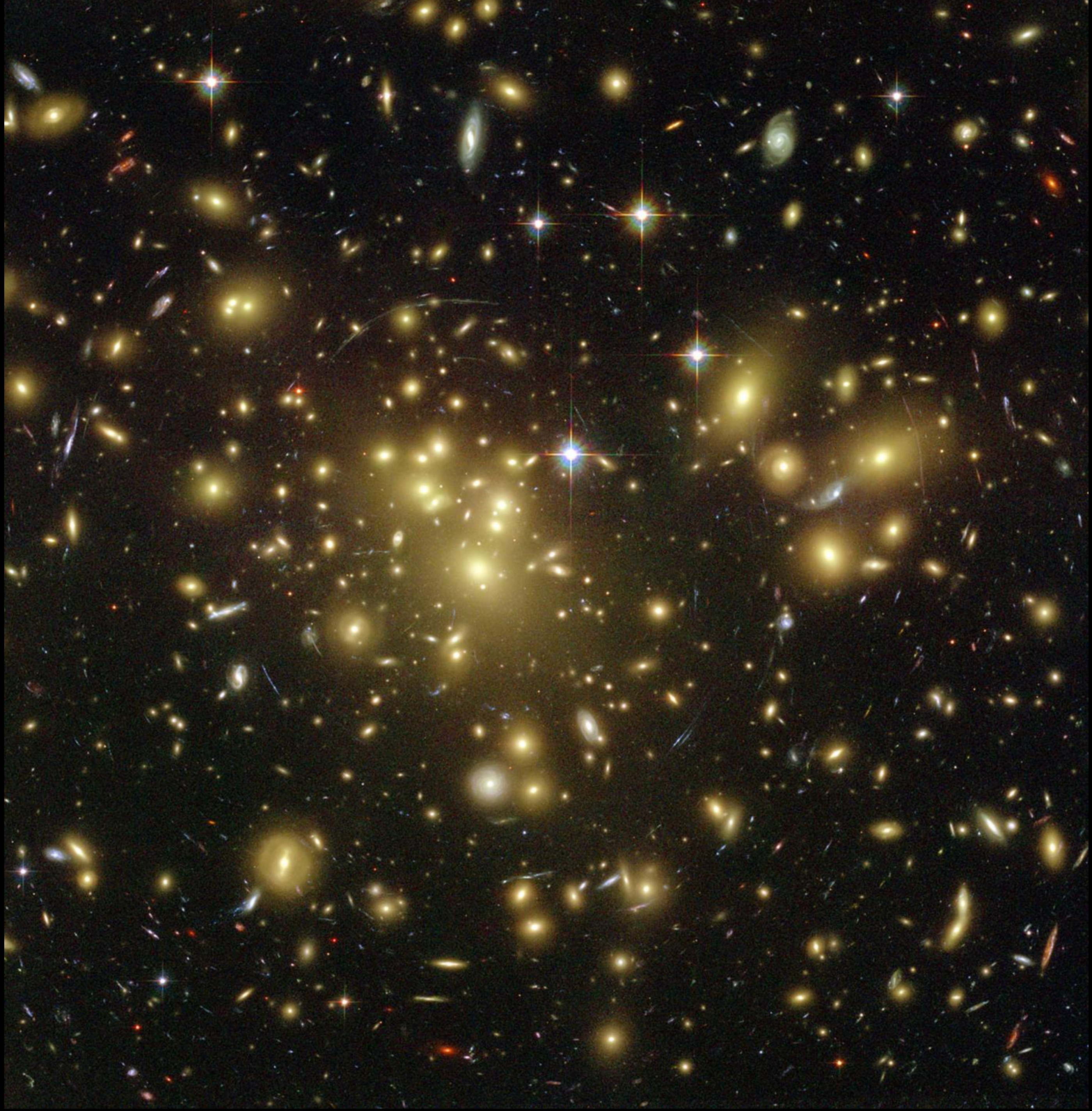
$g_D = \sqrt{go\ g_{bar}}$

$g_{obs} = g_{bar} + g_d =$

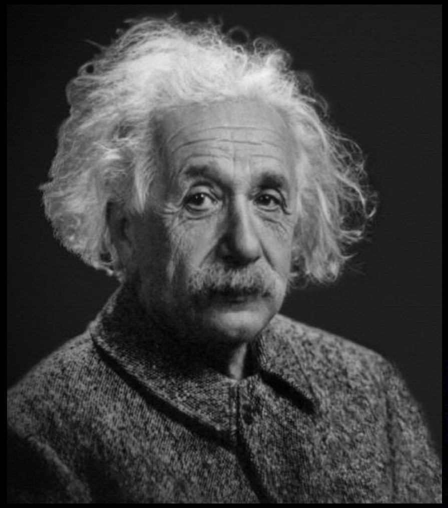
$g_{bar} + \sqrt{go\ gbar}$

ΛCDM - circumstantial

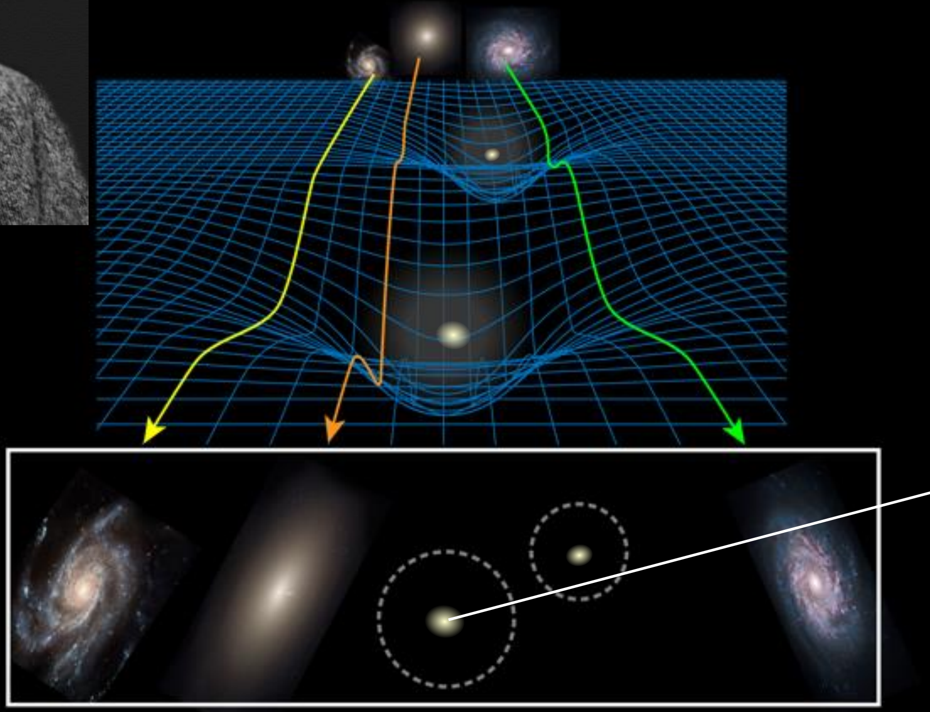
Strong lensing



galaxy-galaxy weak lensing

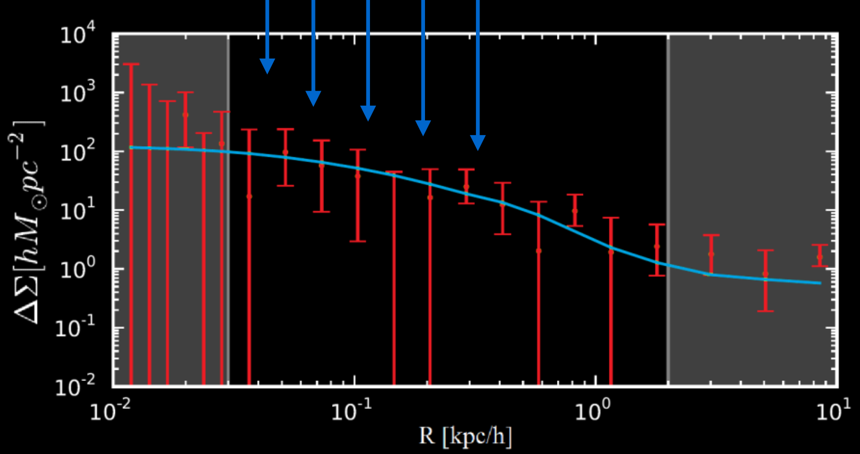


in vivo



Space – time bents- distorts – tangential shear ~1%

Stacking the signals in concentric circles



in vitro

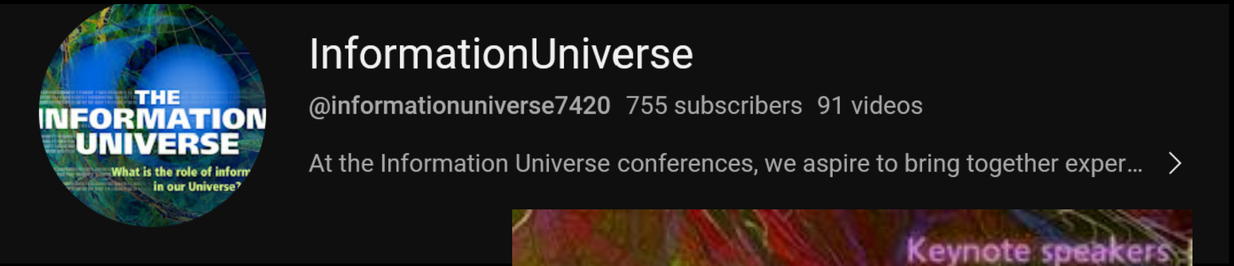
Catherine Heymans Credits: APS/Alan Stonebraker; galaxy images from STScI/AURA, NASA, ESA, and the Hubble Heritage Team.

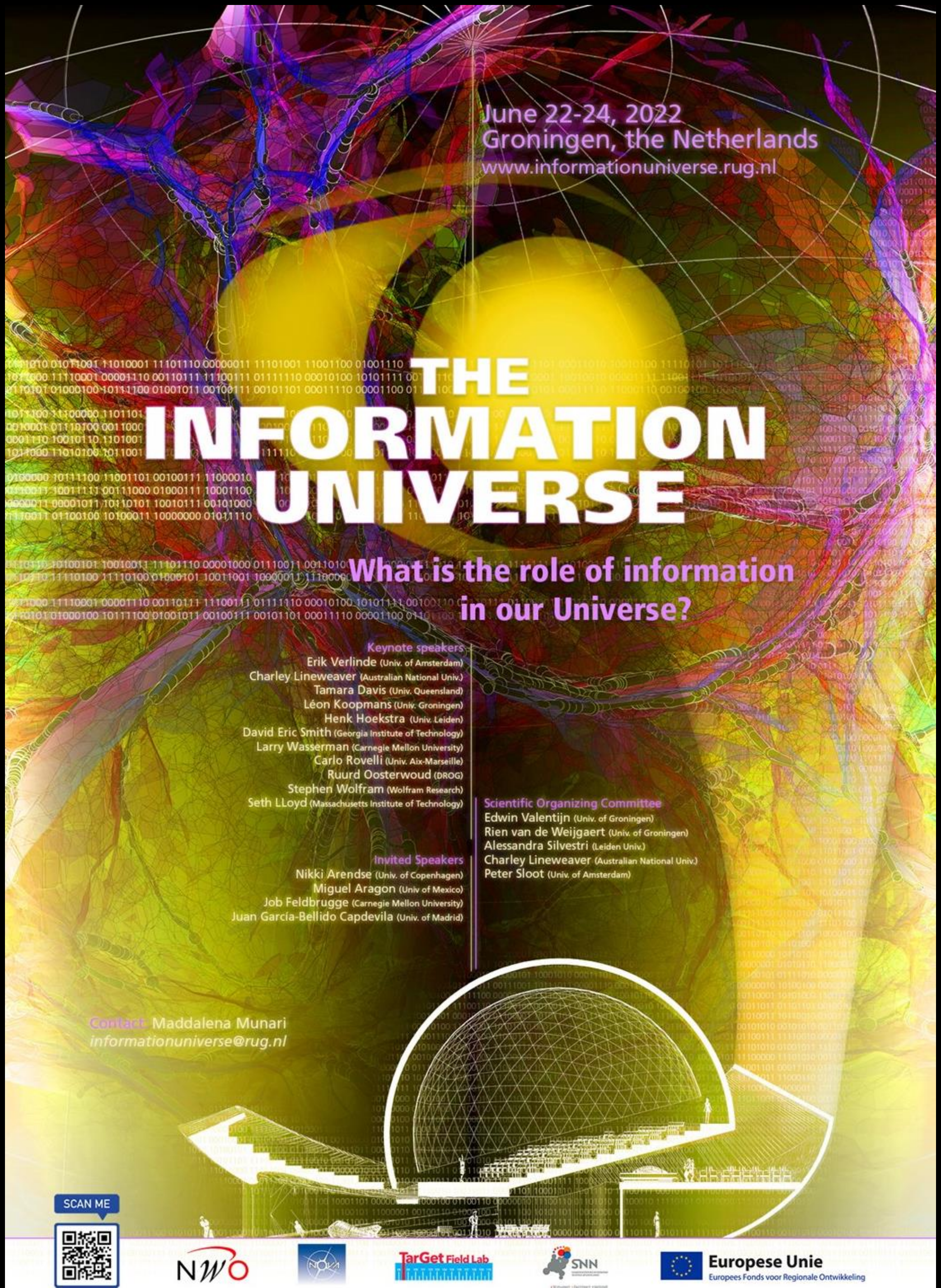
Weak lensing =

AstroWISE

- Statistics: as much data as you can
  = deep large area surveys
- (photometric) redshifts
- high image quality KiDS R band < 0.67'', Euclid 0.2"
  - PSF
    - Atmosphere
    - Focal plane geometry
    - Colour term (colour of galaxy)
    - Fabry Perot effects in filters – dichroic mirrors
    - Jitter of telescope
    - Detector electronics- CTE

in vivo in vitro



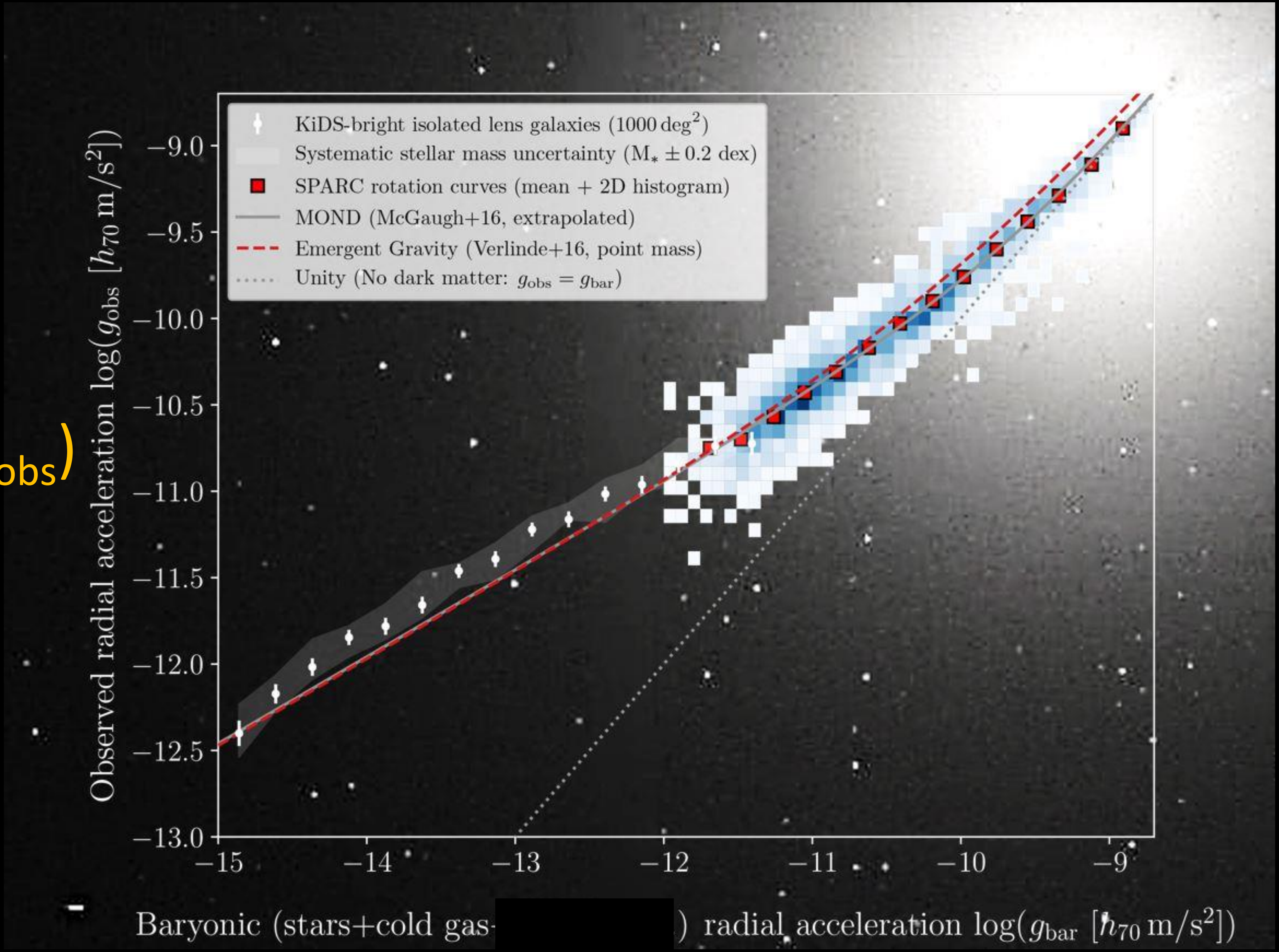


KiDS OmegaCAM at VST Paranal 2000-2020 Kuijken - EV

- 1 Million galaxies in 1,000 Sq degree (now completed DR5 1350 Sq degree)
- Brouwer, Oman, Valentijn et. al 2021
- Select isolated galaxies:
  - No satellites > 10% mass of lens galaxy within 3 Mpc
  - Stellar mass lens < 10^{11} $M_\odot$ (to avoid brighter galaxies with many satellites)

- Excess surface density: $\Delta M(<R)$ $M_\odot$ kpc^{-2} at R = 30 kpc – 3 Mpc
- M_*/L_*stars
  - KiDS: Taylor et. al (2011) M_* ugrizZY sprectral energy distrib. SDSS, Viking fitted to
  - Bruzual Charlot (2003) population synthesis, IMF Chabrier (2003)
  - GAMA -> 1,000 Sq Degree

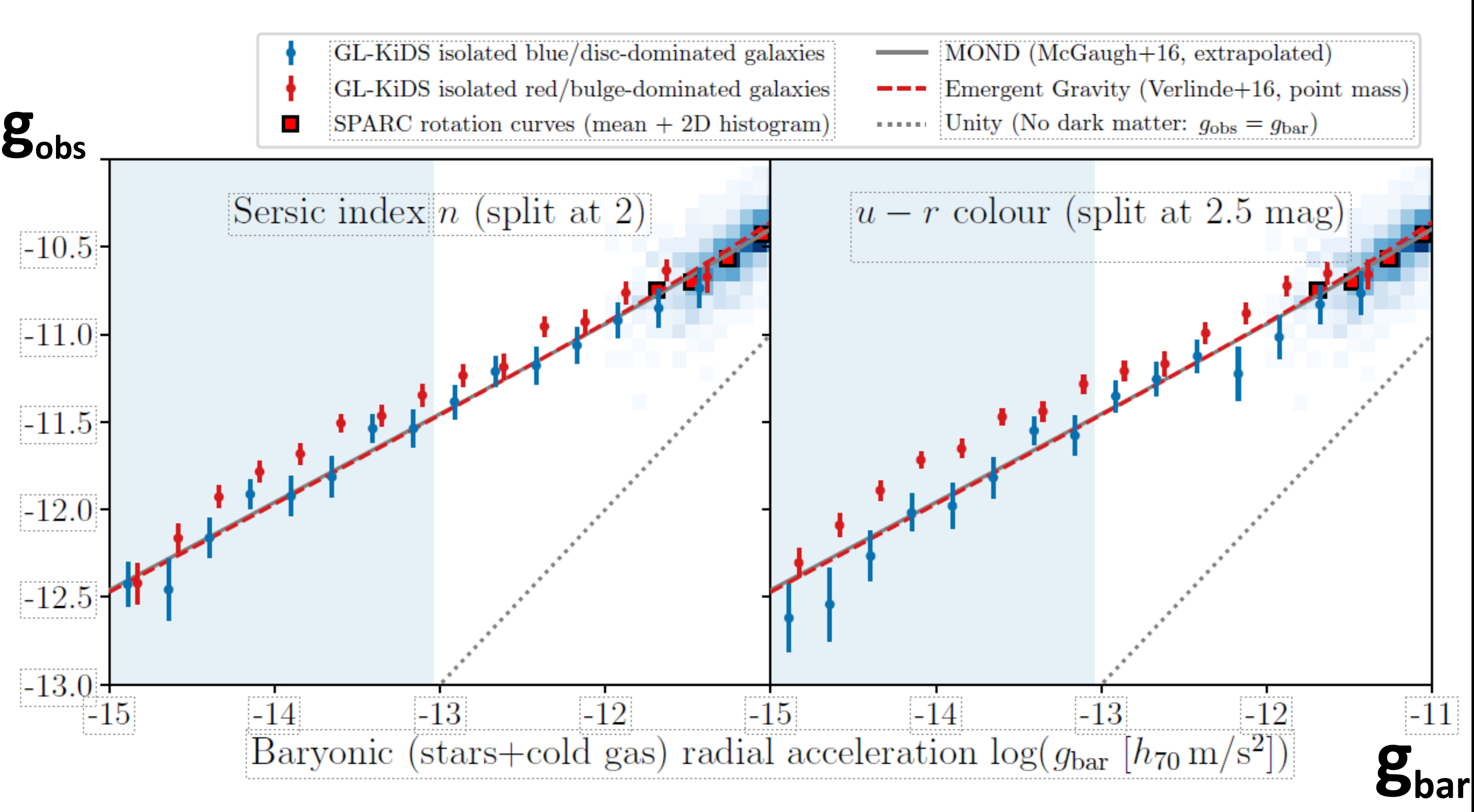
-> the RAR around 259,383 isolated galaxies log(g_{obs})



log(g_{bar})

- the RAR is extended by 2 decades in g_{obs} beyond the outskirts of galaxies
- at the low accelerations the RAR follows a $g_{obs} \propto$ √g_{obs} g_{bar} relation
- two completely different observing techniques: agreement with the expectations from both EG and MOND
- by now, we know the DM better than the baryonic matter
- M/L 0.2 dex

ETG - LTG split in Sérsic index or u – r colour



- At least a factor 1.5 (~0.2 dex) difference significance of at least 5.7σ.
- It is already notable in the regime where isolation criterion is sound
- This observed difference could be resolved by a ~0.4 dex systematic bias between the stellar masses of the two types.
- This variation in the RAR based on galaxy type could be difficult to explain for MG models

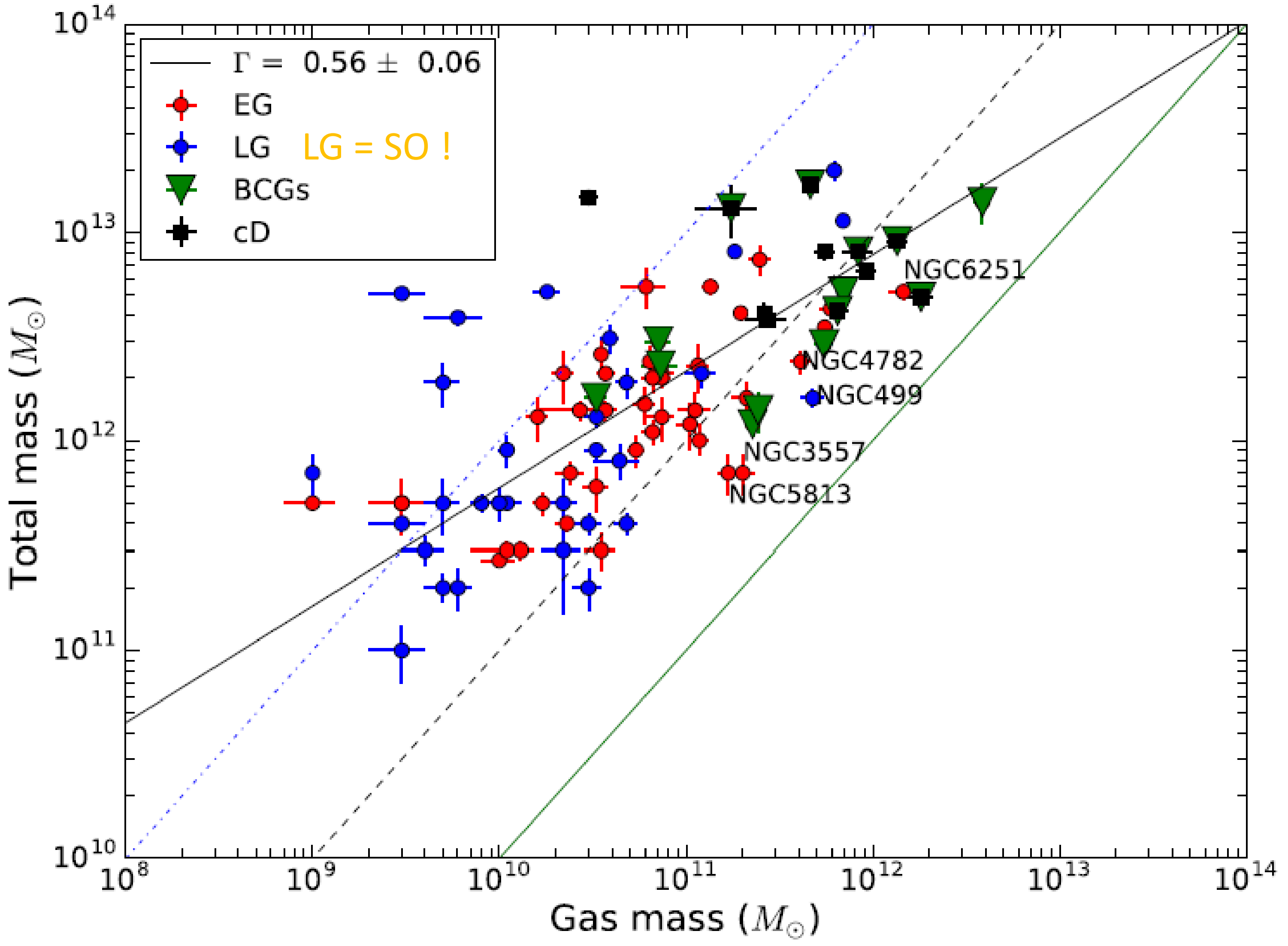


Figure 7. Relation between total mass and gas mass, both derived within $5r_e$. The solid, dashed, and dashed–dotted lines correspond to gas fractions of 1, 0.1, and 0.01, respectively.

Chandra
Babyk et. al 2018

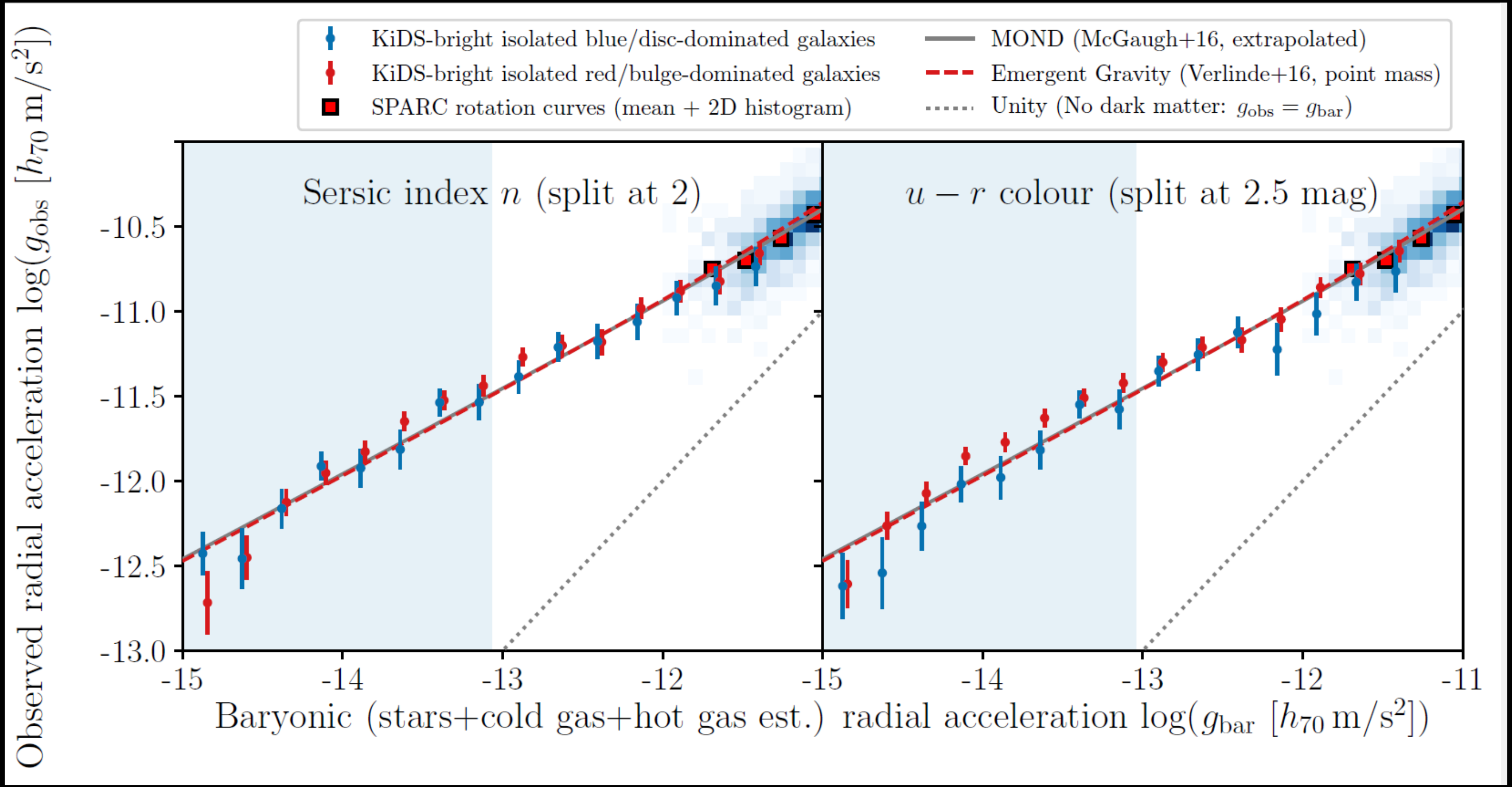
94 ETGs

at 10^{12} $M_\odot$

< $5r_e$ 0.1 -1

>> $5r_e$ 3x 1-3

RAR with M_{gas} =M_* for ETG and M_{gas} = 0 for LTG

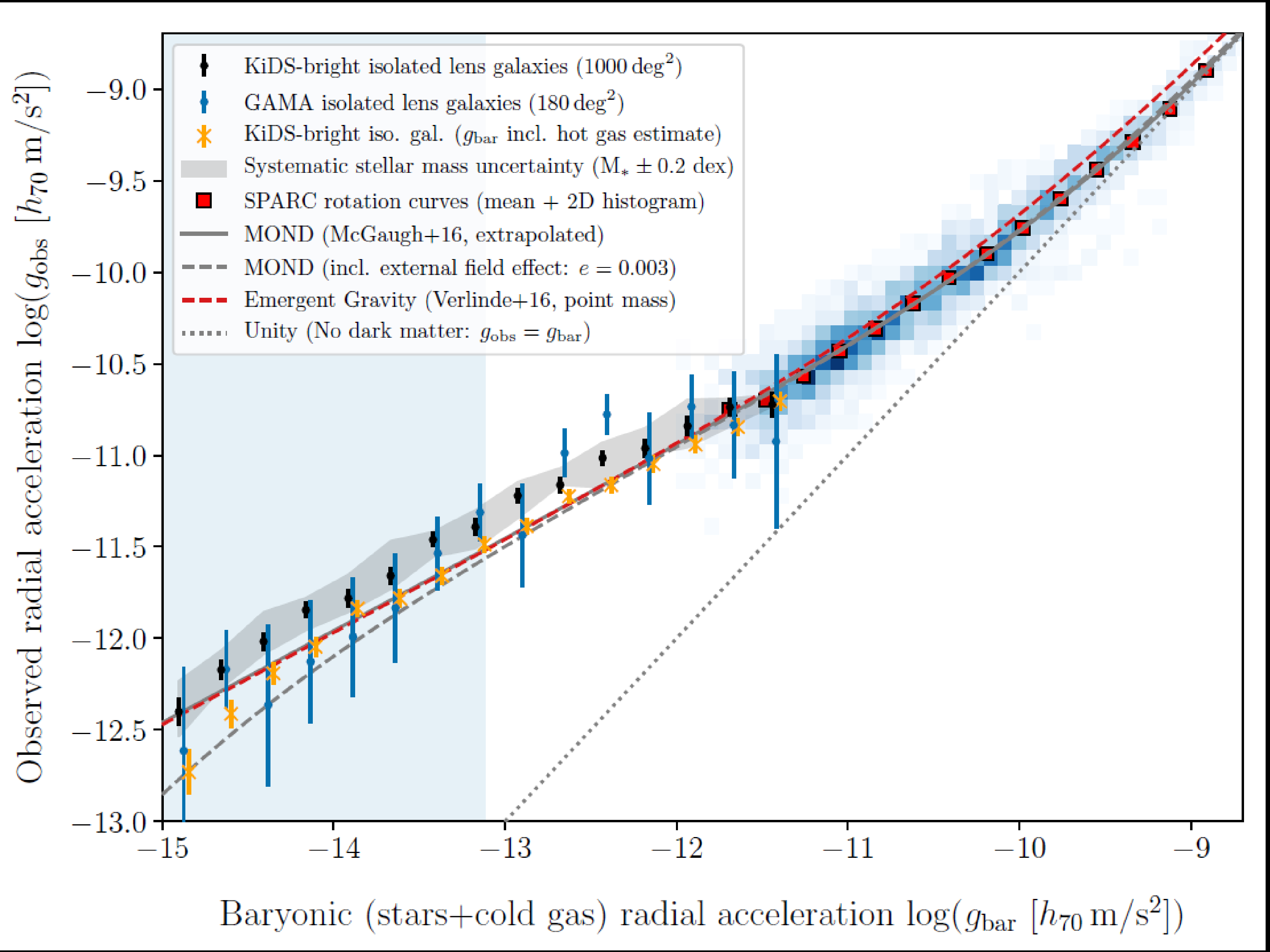


The found difference can only be explained in MOND or EG if ETGs host *massive hot gas haloes* (M_{gas}=M_*), while LTGs have negligible gas haloes

Unknown properties of CGM is potential trap for the interpretation of Euclid data

Though M_{gas}= M_* matches well to the missing baryonic matter problem

KiDS-1000: hot circumgalactic gas $M_{star} = M_{gas}$



GAMA sample

180 Sq degree vs KiDS 1000 Sq d

Spectroscopic redshift

Sampling error bars

- ➢ co-variance matrix diagonal
- ➢ standard deviation linear fit:
  - KiDS1000 = 0.07 dex
  - GAMA = 0.16 dex
- ✓ match to co-var error bars
- ✓ sd GAMA scales to 1000 Sq d !

Systematic errors:

- ➢ (M/L) 0.2 dex
- ➢ ΔM(<R) -> g_obs
  0.05 dex (g_{bar} -2 10^{-12} -10^{-15})

✓ Isolation criterion

The eROSITA Final Equatorial Depth Survey (eFEDS):

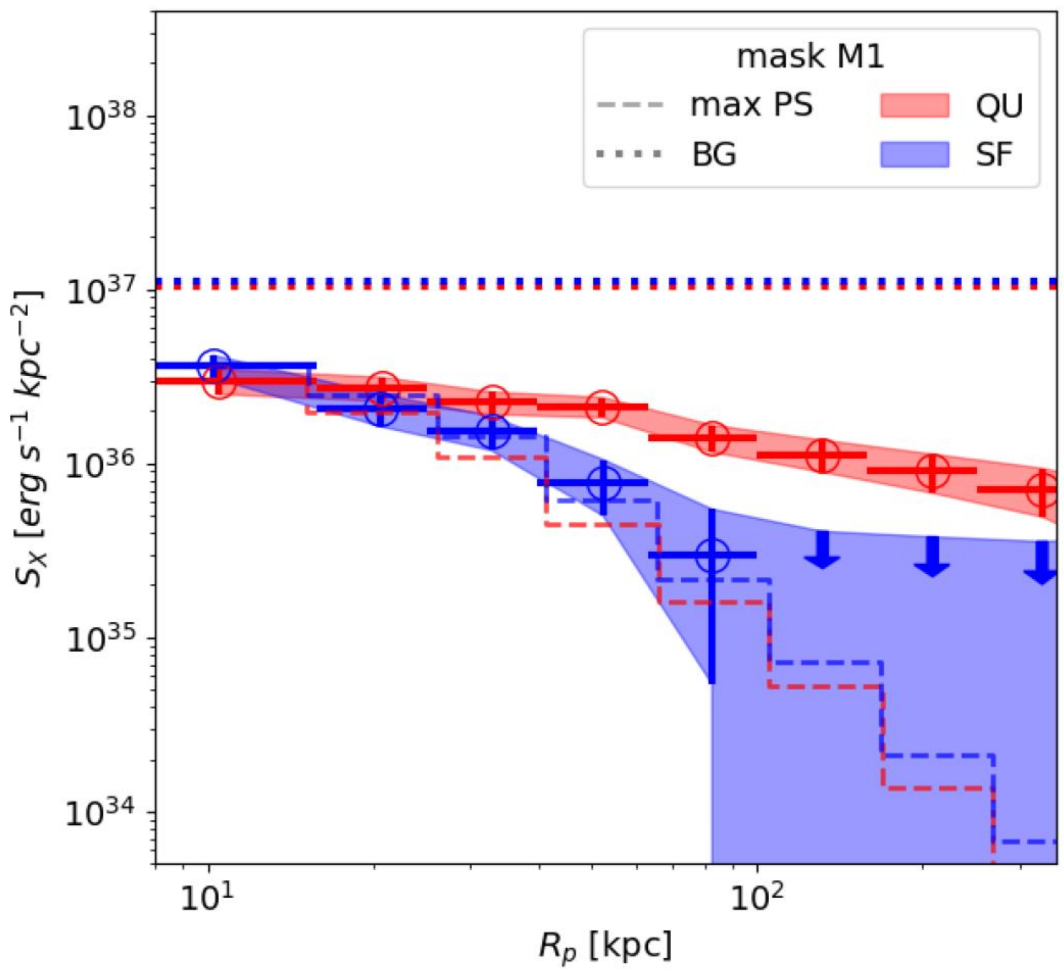
X-ray emission around star-forming and quiescent galaxies at $0.05 < z < 0.3$

Johan Comparat[1★], Nhut Truong[2], Andrea Merloni[1], Annalisa Pillepich[2], Gabriele Ponti[3,1], Simon Driver[4,5], Sabine Bellstedt[4], Joe Liske[6], James Aird[7,8], Marcus Brüggen[6], Esra Bulbul[1], Luke Davies[4], Justo Antonio González Villalba[1], Antonis Georgakakis[9], Frank Haberl[1], Teng Liu[1], Chandreyee Maitra[1], Kirpal Nandra[1], Paola Popesso[10], Peter Predehl[1], Aaron Robotham[4], Mara Salvato[1], Jessica E. Thorne[4], Yi Zhang[1]

At scales larger than 100 kpc, the quiescent galaxy profile is at least two times brighter than that of the star-forming galaxies.

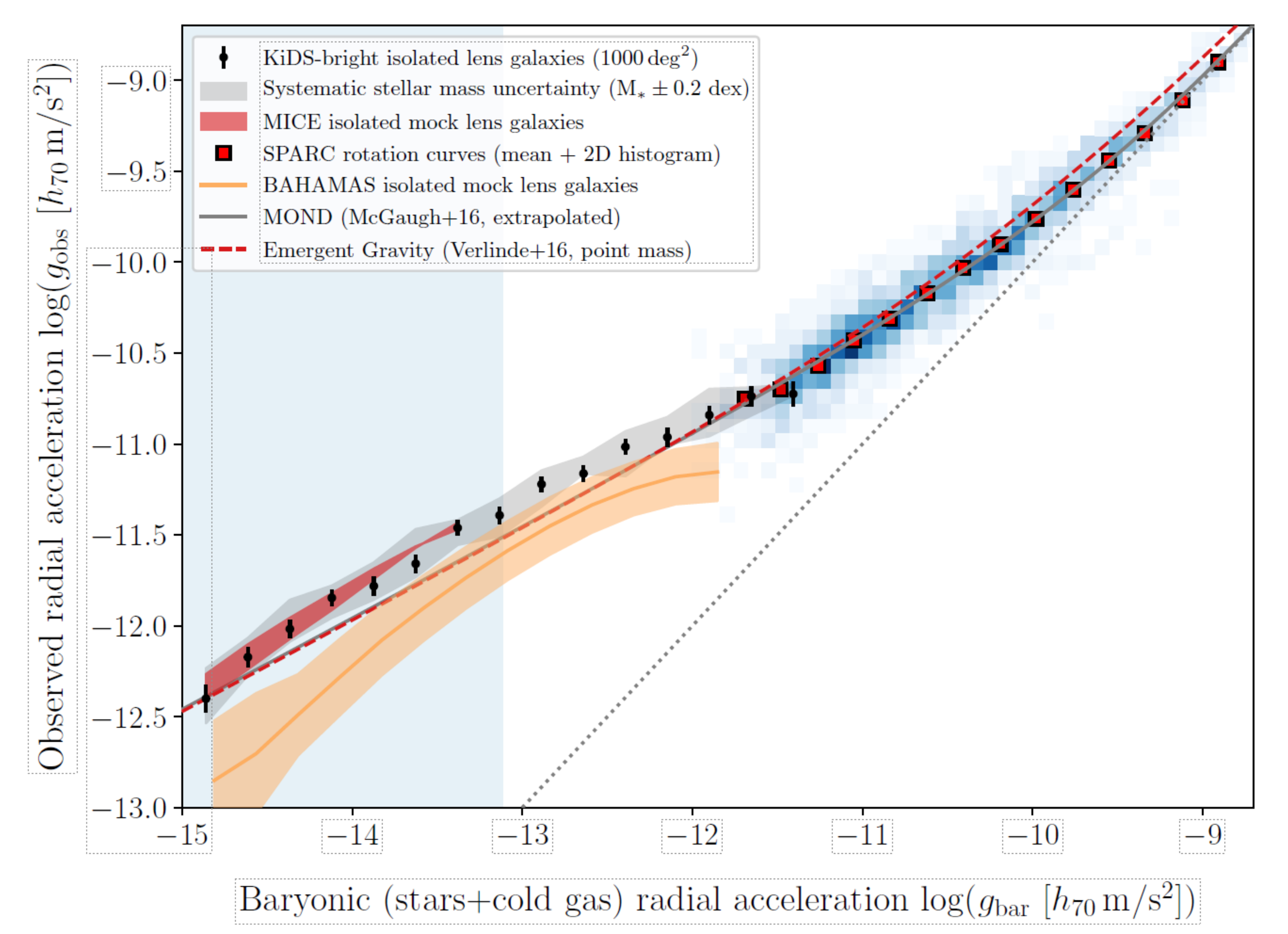
Our measurement, using a nearly complete galaxy catalog, provides firm observational evidence: at the same mean stellar mass of $\sim 5 \times 10^{10} M_{\odot}$, star-forming galaxies show significantly

less projected X-ray emission on large scales in the 0.5–2 keV rest-frame energy range.



Comparat et. al 2022
GAMA sample 35.000 stack
M1: All detected sources masked
apart from clusters- groups
at >100 kpc Quiescent >2x brighter Starforming

Jan 2023



Kyle Oman

BAHAMAS

- ➢ underestimates the KiDS RAR

  Bias in stellar-to-halo-mass-relation of isolated galaxies vs non isolated

  BAHAMAS galaxies have stellar masses typically 3x higher at fixed halo mass than their non-isolated counterparts.

- ✓ the RAR still has approximately the correct low g_{bar} slope

MICE

- ✓ matches RAR very well
- ✓ red band mimic phot-z errors

SIMULATIONS

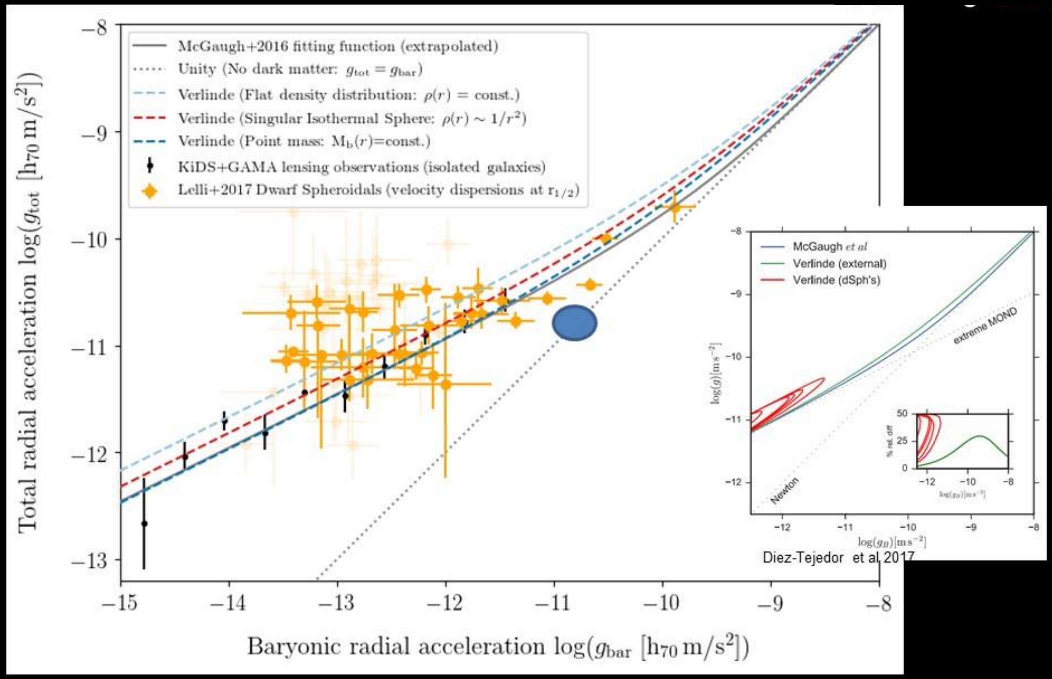
- ➢ but they are tuned to observations

  2 highly non-linear processes in hydro simulations:

  feed-back - ionization

- ✓ Eagle simulation - Schaye

Dwarf spheroidals - Fornax cluster - SAMI
Eftekhari et al. 2022 OmegaCAM



MNRAS 000, 1–23 (2021) Preprint 26 February 2022 Compiled using MNRAS LaTeX style file v3.0

The SAMI – Fornax Dwarfs Survey II: The Stellar Mass Fundamental Plane and the Dark Matter fraction of Dwarf Galaxies

F. Sara Eftekhari[1], Reynier F. Peletier[1★], Nicholas Scott[2,3], Steffen Mieske[4], Joss Bland-Hawthorn[2,3], Julia J. Bryant[2,3], Michele Cantiello[5], Scott M. Croom[2,3], Michael Drinkwater[6], Jésus Falcón-Barroso[7,8], Michael Hilker[9], Enrichetta Iodice[10], Nicola R. Napolitano[10], Marilena Spavone[10], Edwin A. Valentijn[1], Glenn van de Ven[11] and Aku Venhola[12,1]

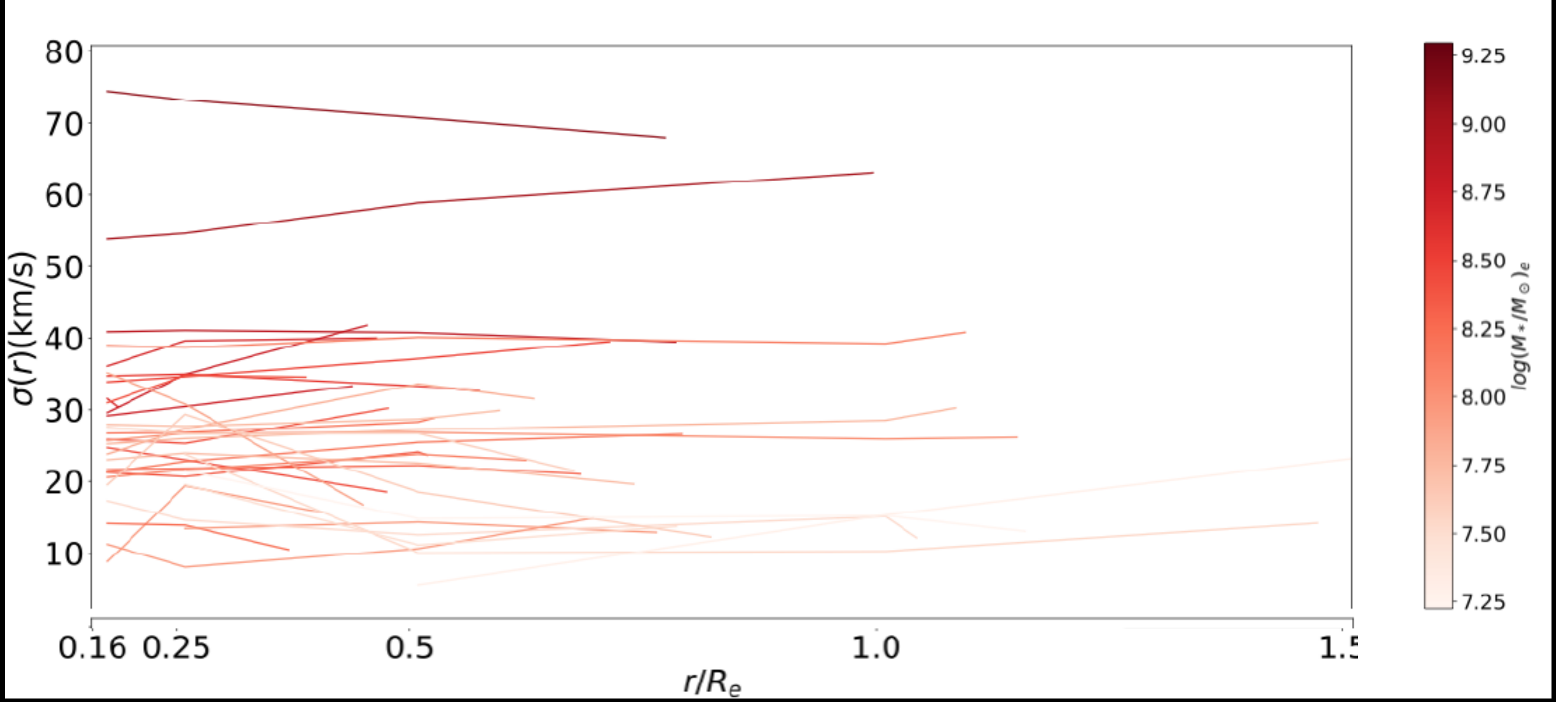
Single dwarfs:
- Inclination correction
- dyn. stable?
- cool H_2

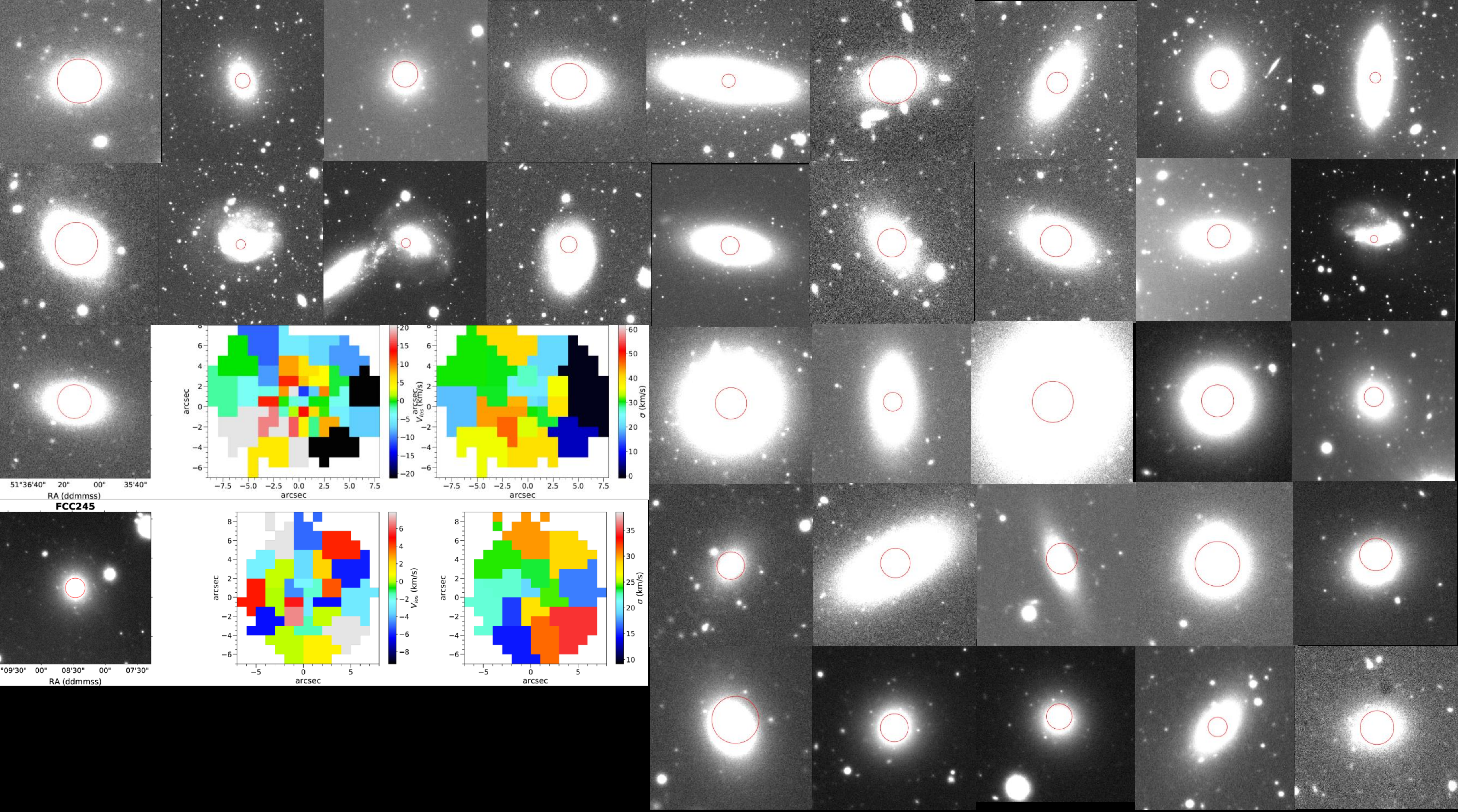
EG :

$$M_D(<r) = \sqrt{\frac{cH_0}{6G}}\; r \sqrt{M_B(<r) + r\,\frac{dMB(<r)}{dr}}$$

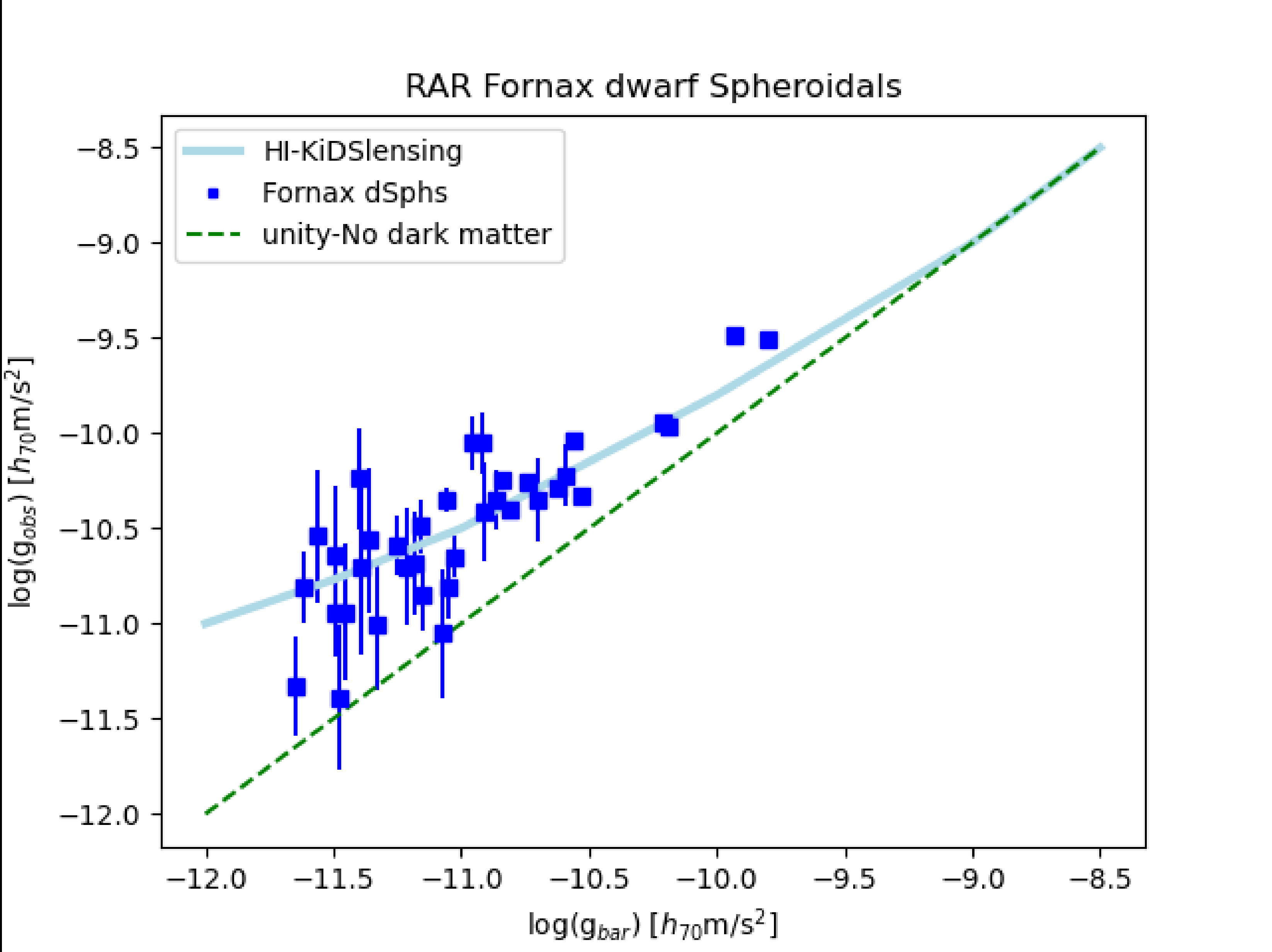
SAMI @ AAT Fornax Dwarf galaxies

- 36 Dwarf Spheroidals - 7 h/field
- Integral field spectrograph - 1.6 arcsec fibers
- fov 15 arcsec - 1.6 arcsec fibers
- Instrumental resolution 27 km/sec -> 10 km/sec





51°36'40"
20"
00"
35'40"
RA (ddmmss)
arcsec
V_{los} (km/s)
σ (km/s)
FCC245
°09'30"
00"
08'30"
00"
07'30"
RA (ddmmss)

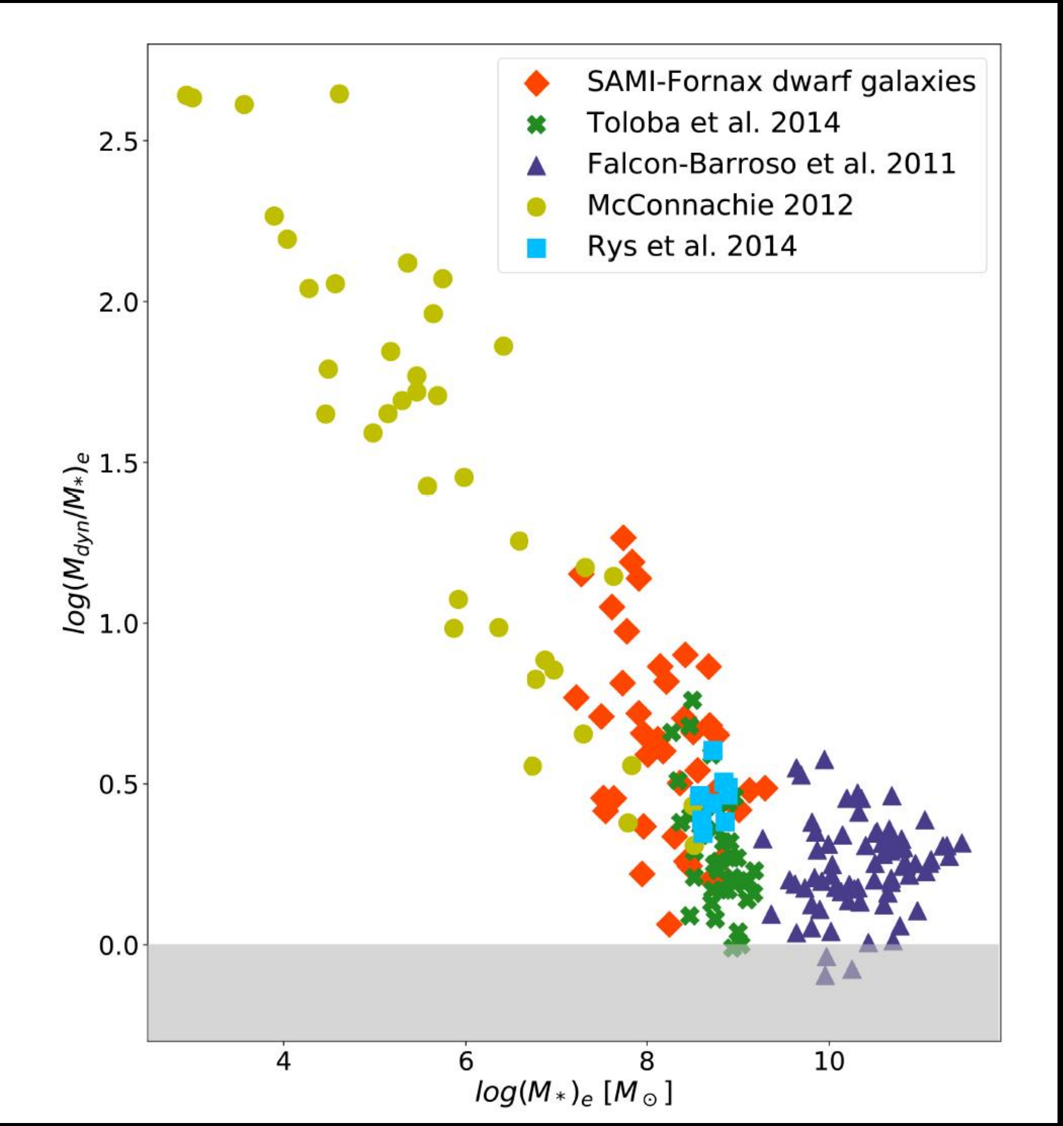


Reff
= 4/3

$\log(g_{obs})$

$\log(g_{bar})$

$\log(M_{dyn}/M_*)$

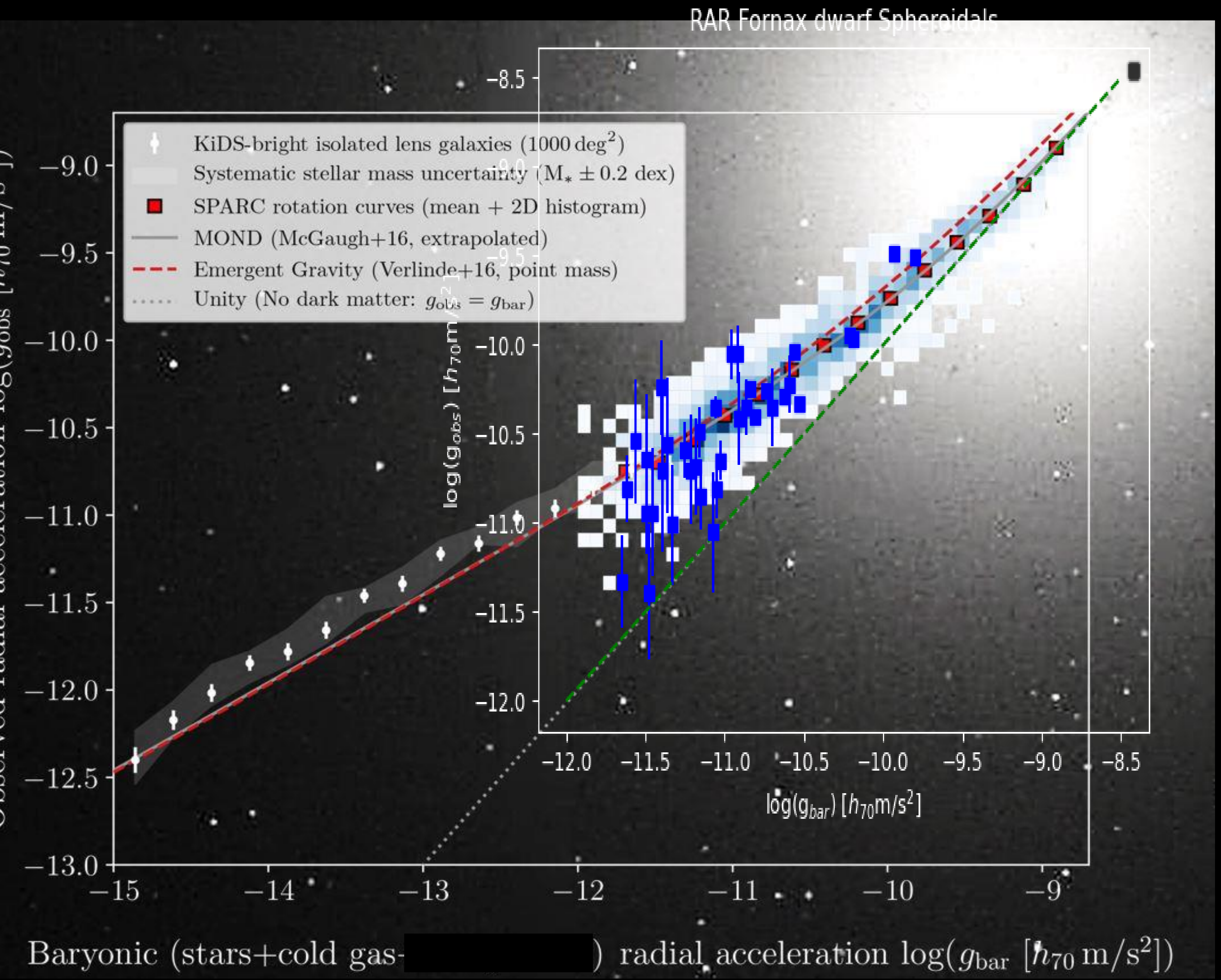


$\log(M_*)$

Fundamental plane:

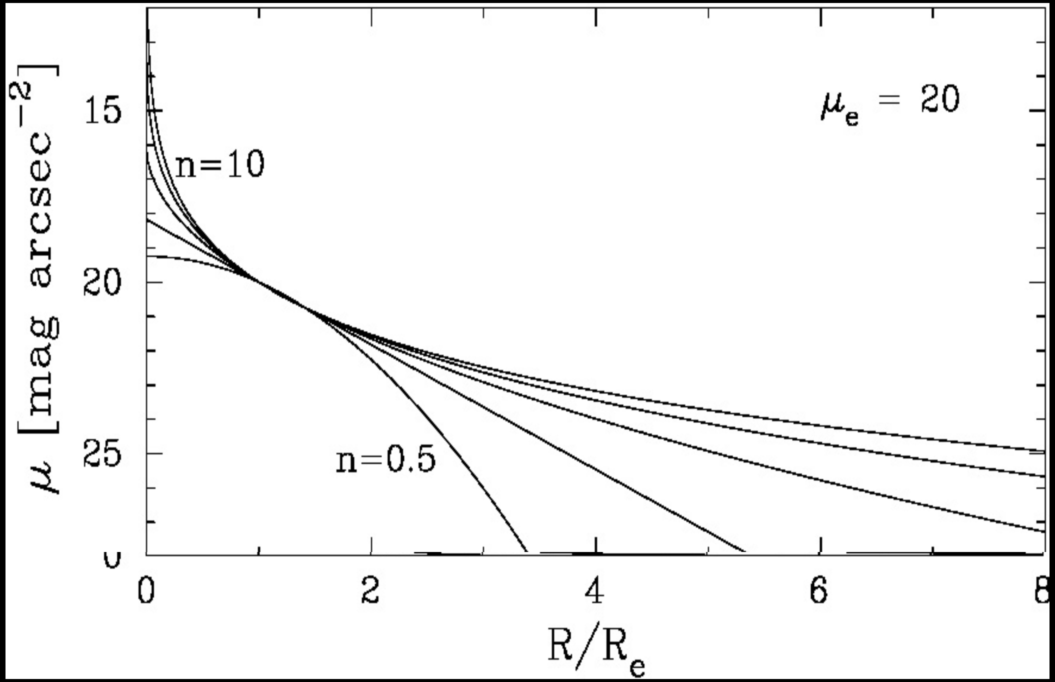
M_{dyn} / M_{bar} higher indeed
but conform the RAR

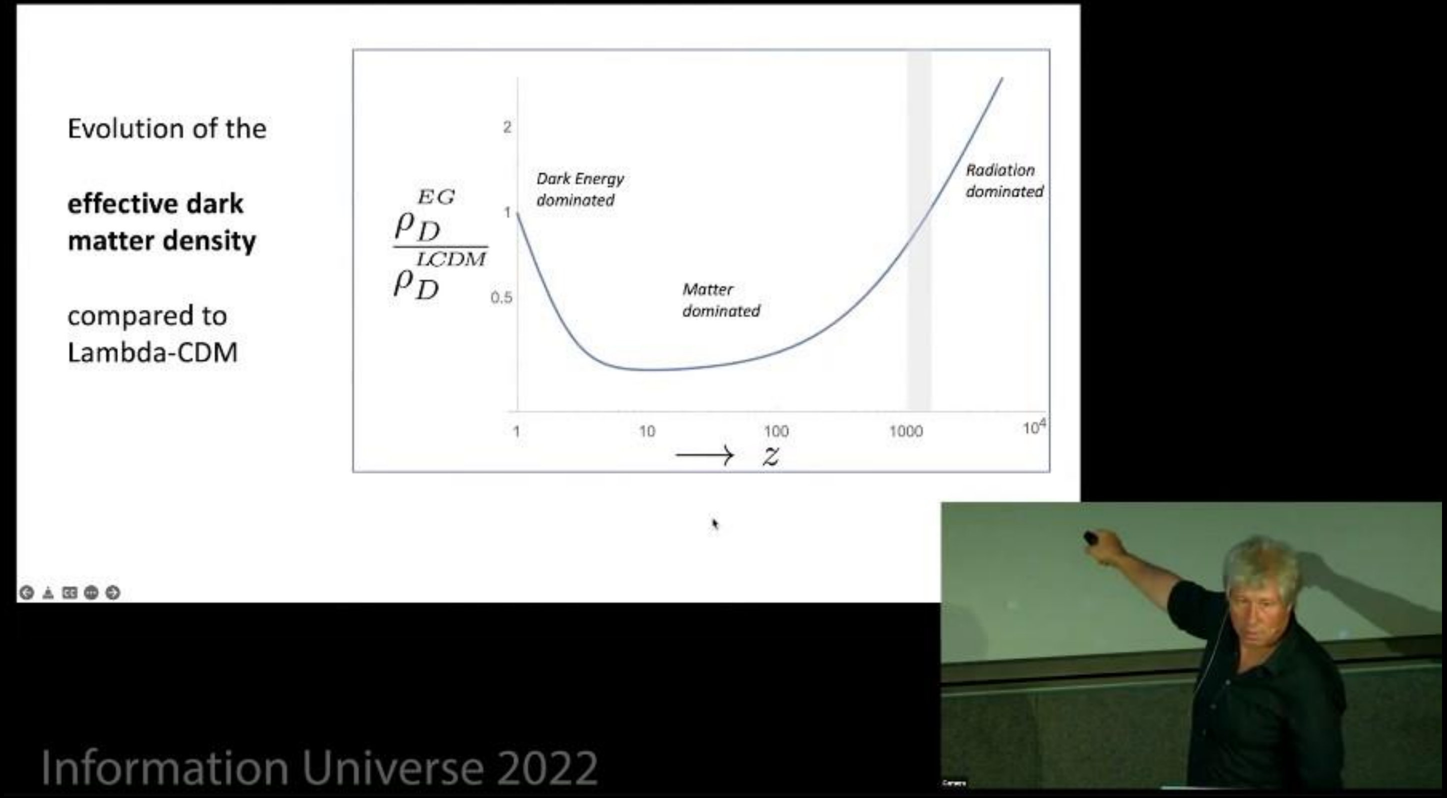
solves the riddle
further supports a universal RAR



- ➢ Fornax dwarfs **0. 6 -1 kpc** while M87 and HI Spirals out to **50-100 kpc** and beyond
- ✓ 100! the underlining property of DM appears scale invariant adds another dimension to RAR . as scale invariant
- ➢ difficult to assemble circumstantially by **ΛCDM**
- ➢ though Eagle simulations predict high M_{dyn} / M_{bar} as a result of highly non-linear effects : feedback and ionization
- ➢ but there is no physical reason this slope leads to the RAR both a 1kpc and of 100 kpc scale – challenge for **ΛCDM**

Next tests





- $dM_B(<r) / dr$ term in EG

z -evolution – Euclid z = 0 - ~2

Euclid

A space mission to map the dark universe

$z = 0 - {\sim}2$

$2\ 10^9$ galaxies

- NIR spectra for $\sim 3.5\times10^7$ galaxies (0.7<z<1.8) R~250

launch expected 1 July 2023 SpaceX Falcon-9

>250 days
20k x 20k
265.000 galaxies

Hubble Legacy Field

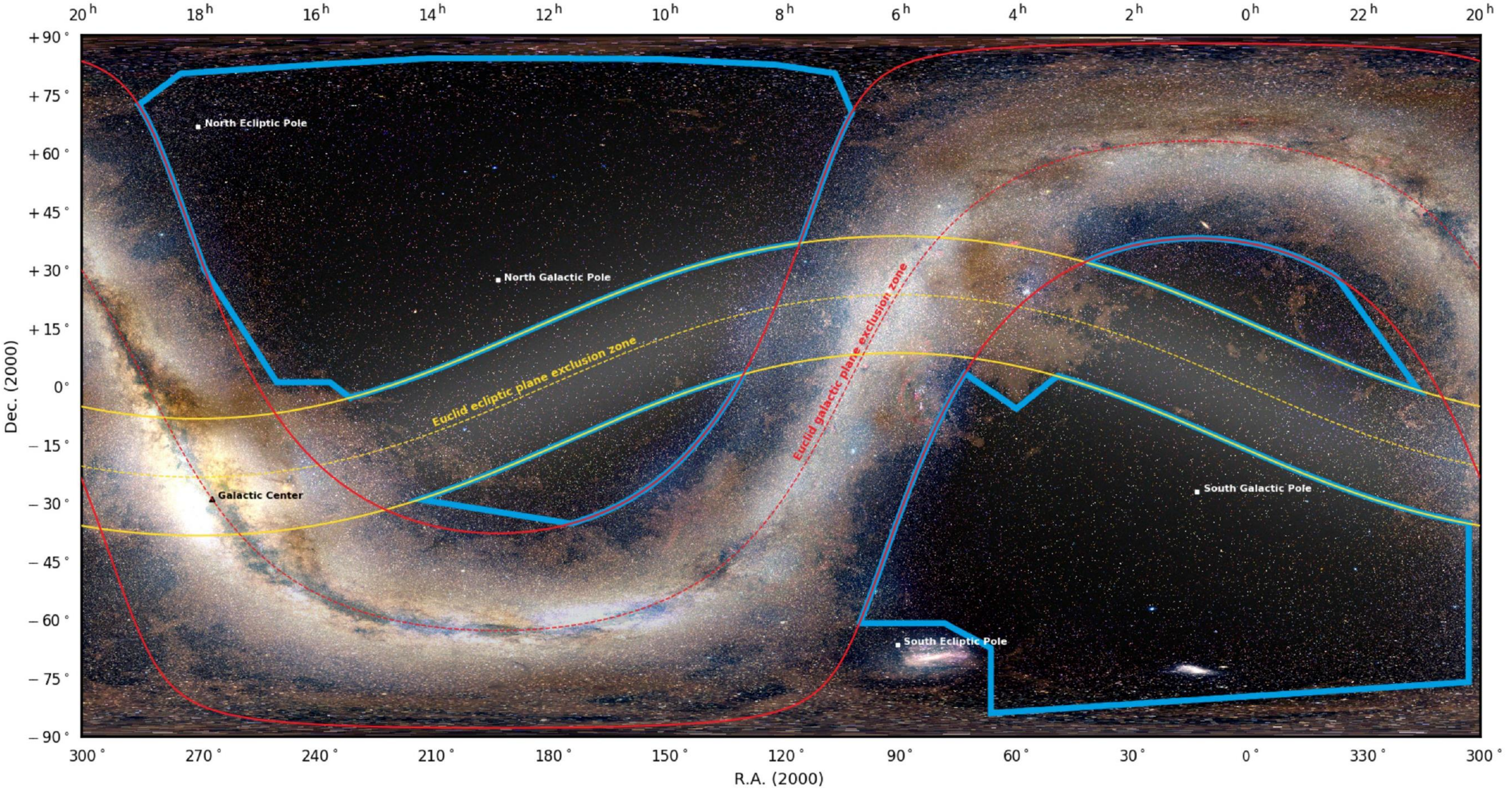
4400 sec nominal = 15.000 Sq deg in 5,5 year
24k x 24 k 1/60,000 of the survey
300.000 galaxies
50.000 distances

Euclid

30’

30’

Credit: [Hubble Legacy Field Image: NASA, ESA, and G. Illingworth and D. Magee (University of California, Santa Cruz); Moon Image: NASA, Goddard Space Flight Center and Arizona State University]



The Euclid Wide Survey based on ecliptic&galactic latitude thresholds (2014) + Stellar density & Reddening (Gaia/Planck, 2019)

Euclid Wide Survey : total area of 15,000 deg.^{2} evenly split across the two hemispheres

Ecliptic plane [zodical light background] : +/- 15 deg. ecliptic latitude exclusion zone

Galactic plane [stellar contamination] : +/- 25 deg. galactic latitude exclusion zone

euclid esa

Background image: Euclid Consortium / A. Mellinger / Planck Collaboration

Feynman   BBC interview

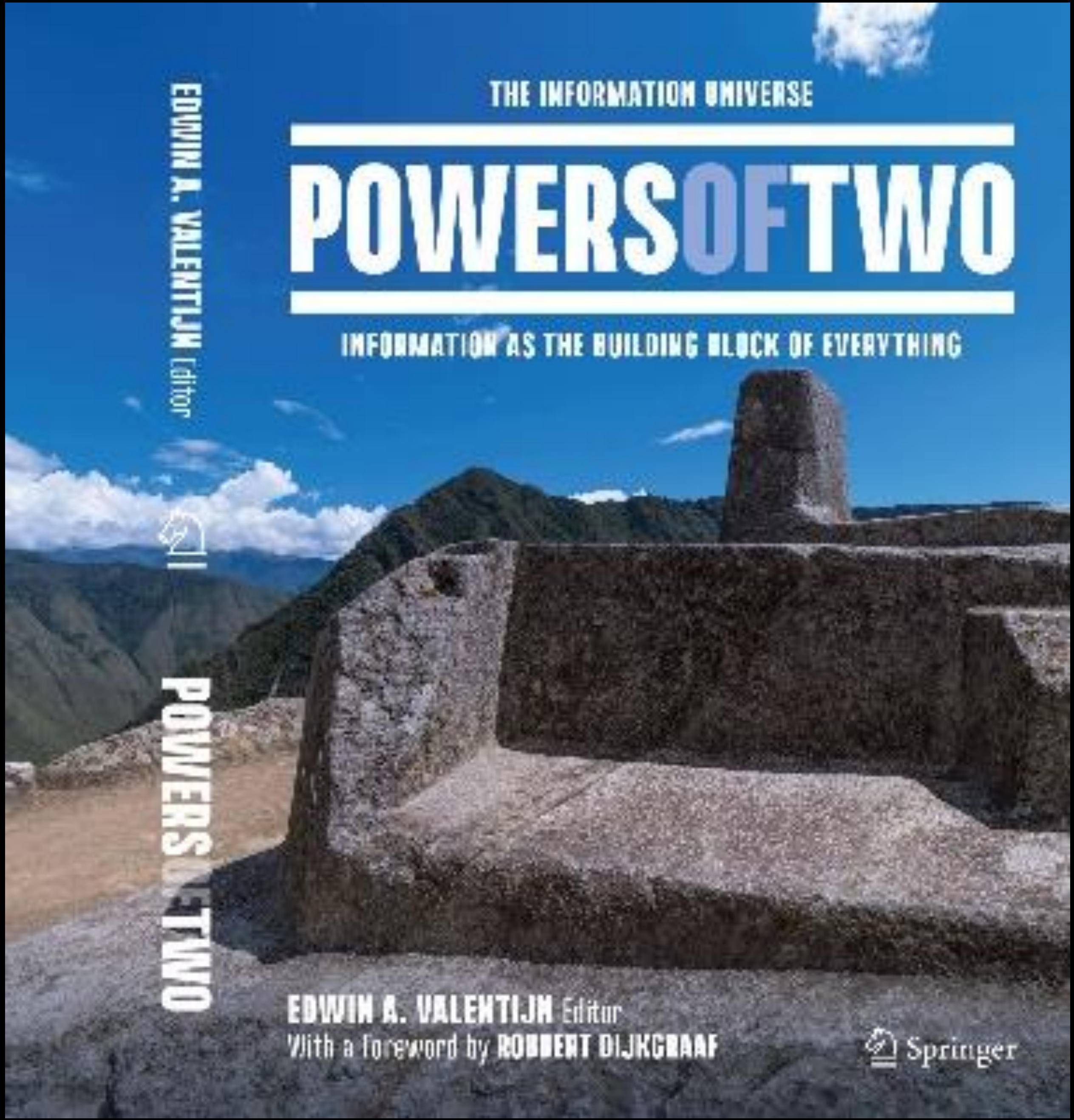
What are the criteria the accept a hypothesis?

1. Good physics – mathematics
2. Predictions
3. Avalanche of small things becoming understandable

} observations (items 2–3)

testing the hypothesis vs the RAR

		MOND	EG	L-CDM
1) physics		$F_{\mathrm{N}} = m\,\mu\left(\frac{a}{a_0}\right)\,a$	g ~ T	no fundamental
		interpolating function	Area in Planck length **2	circumstantial
			entanglement Dark energy	
			BIG3: DM DE QM<->GR	
2) predictions	free parameters	1-2 gal. clusters	0* -> 1	2+ non-linear: feed back -ionization
	scale invariant < 100 kpc dwarfs 0.6-1 kpc - 100kpc	yes	yes	no
	scale invariant small scatter in LTG rotation curves	yes	yes	no
	z- evolution		~	yes
3) avalanche	dwarfs > M_dyn/M_bar- fundamental plane	yes	yes	no
	Missing baryonic matter ~ hot CGM	yes	yes	
	We know DM now better than baryonic matter			
	find workable prior for dM_bar/dr in EG			
	we need to predict z=0-2 -evolution rather than wait for Euclid			
	hot CGM will stay a challenge for Euclid			


EDWIN A. VALENTIJN Editor
POWERSOFTWO
THE INFORMATION UNIVERSE
POWERSOFTWO
INFORMATION AS THE BUILDING BLOCK OF EVERYTHING
EDWIN A. VALENTIJN Editor
With a foreword by ROBBERT DIJKGRAAF
Springer