Astrophysical Tests of Gravity: Constraints from Nearby Universe

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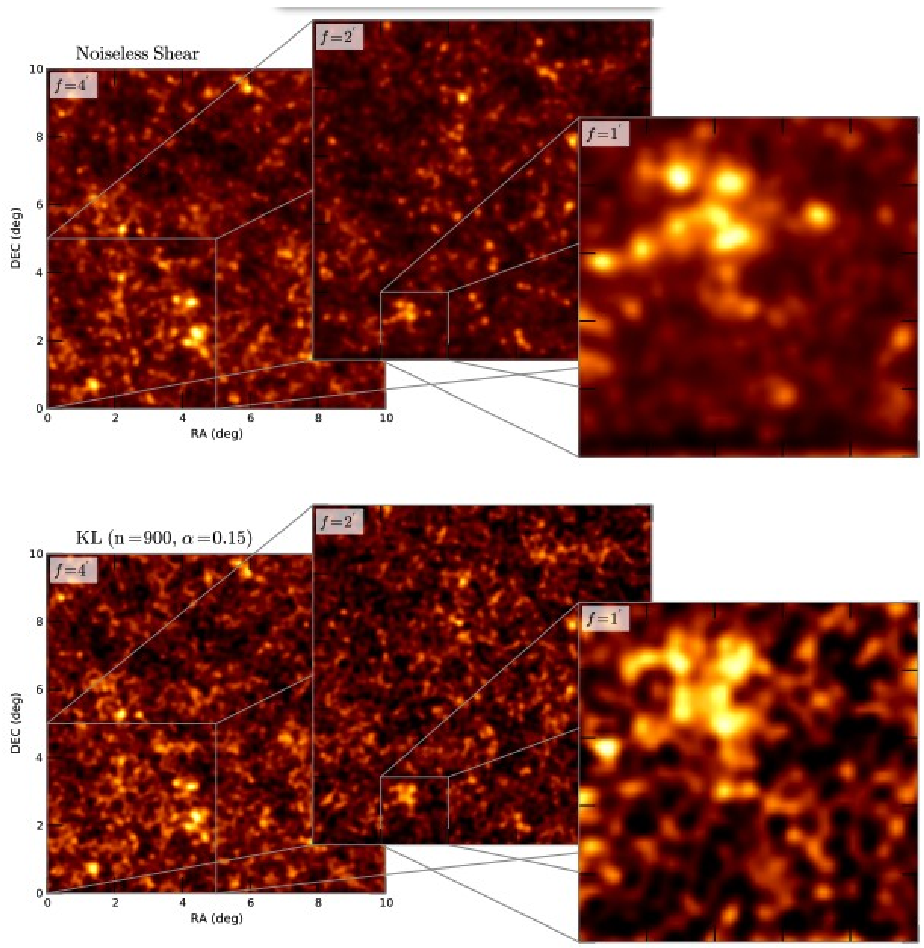
Vikram, Cabre, Jain, VanderPlas JCAP 2013
Jain, Vikram & Sakstein, ApJ 2013
Cabre, Vikram et al JCAP 2012

UC Berkeley November 2013

Before I start,

- Dark Energy Survey
  - Mass mapping – KS & Karhunen-Loeve (KL)basis
  - Cross correlating SZ and galaxies using SPT data
  - Bias Estimation & Large scale M/L
  - Flux dependence of PSF
- Galaxy evolution
  - Structural parameters of ~700,000 SDSS (DR7) galaxies in three bands, Sersic, Sersic + Disk, Dev + Disk
  - Luminosity – Size relation, luminosity function, evolution of concentration etc.

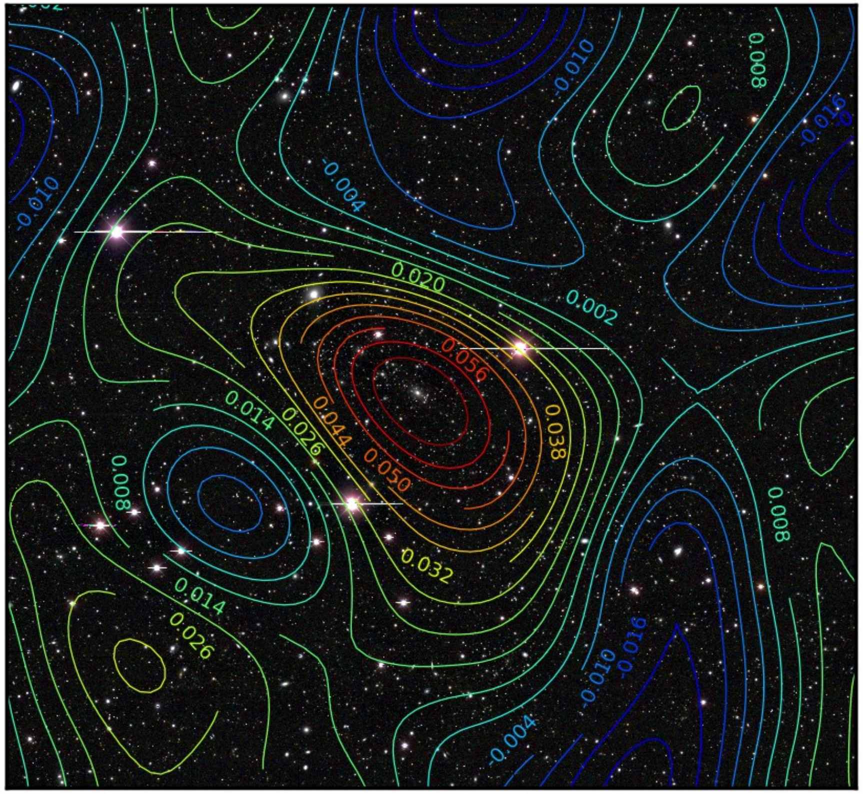
Mass mapping



- Mapping using DES simulation based on KL method
- Include 10% real mask due to bright stars and bad columns
- Use the first 900 modes of the KL

DES SV data

RXJ 2248 cluster



OSU, UPenn, BNL, Manchester, FermiLab, LMU etc.

People involved

Anna Cabre
Joseph Clampitt
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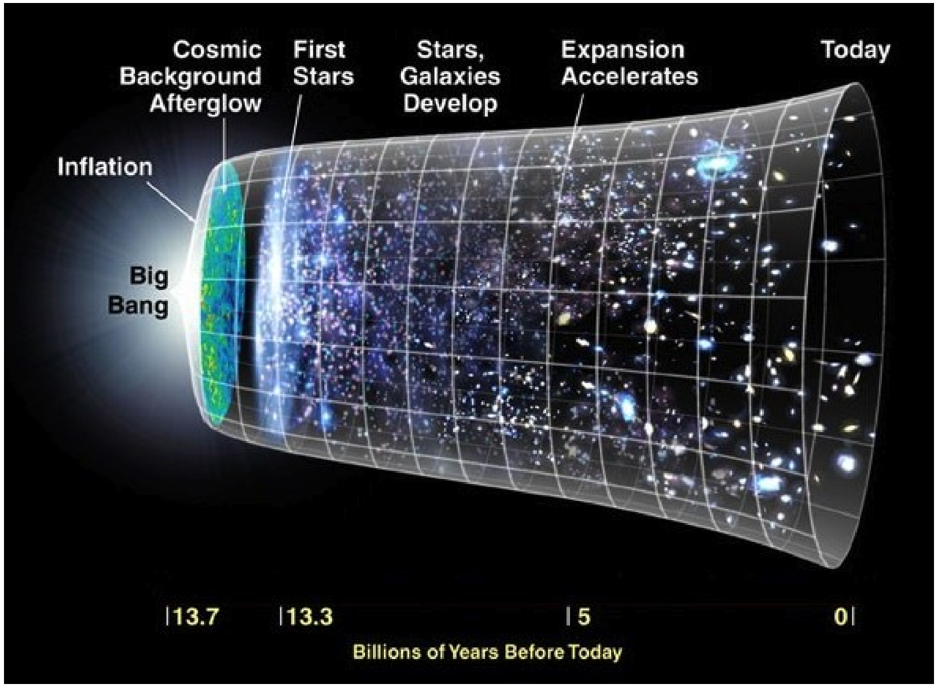
Mike Jarvis
Jeremy Sakstein
Jake Vanderplas
Vinu Vikraman
Gongbo Zhao

Plan

- Concept: MG, screening mechanism
- Part I
  - Predictions for dwarf galaxies and finding unscreened galaxies
  - Observational constraints from dwarf galaxies
- Part II
  - Observational constraints from distance indicators
- Conclusion

Accelerated expansion and MG



- To explain the accelerated expansion of the Universe standard LCDM requires dark energy
- Cosmological constant serves that purpose
- Do we have alternate ideas?

Accelerated expansion and MG

•Modify GR (eg. f(R) theories Hu & Sawicki 2007)

•Such modification lead to a scalar field coupled with matter and can explain the accelerated expansion

•Fundamental 'fifth force' due to the scalar field

•Problem: Why we don't see such a force in the solar system?
Answer: Screening mechanism

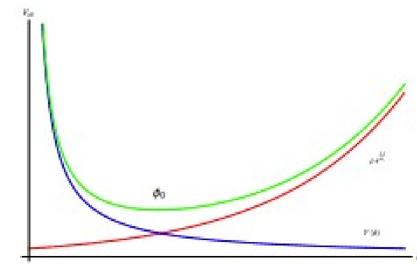
Screening Mechanism : Chameleon

- Range of the fifth force is limited by the mass of the scalar field (Yukawa potential). Low (high) mass → long (short) range!
- One solution: environmental dependence of scalar potential

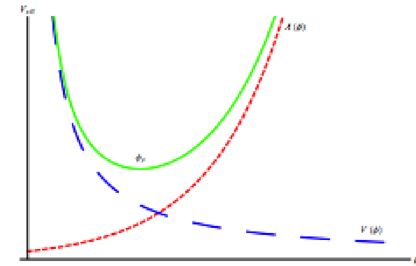
$$V_{\text{eff}}(\phi) = V(\phi) + \rho A(\phi)$$

$$V(\phi) = \frac{M^{4+n}}{\phi^n} \quad A(\phi) = e^{\beta \frac{\phi}{M_{\text{pl}}}}$$

- Mass of the scalar field will be larger at high density region and therefore the range of fifth force will be shorter



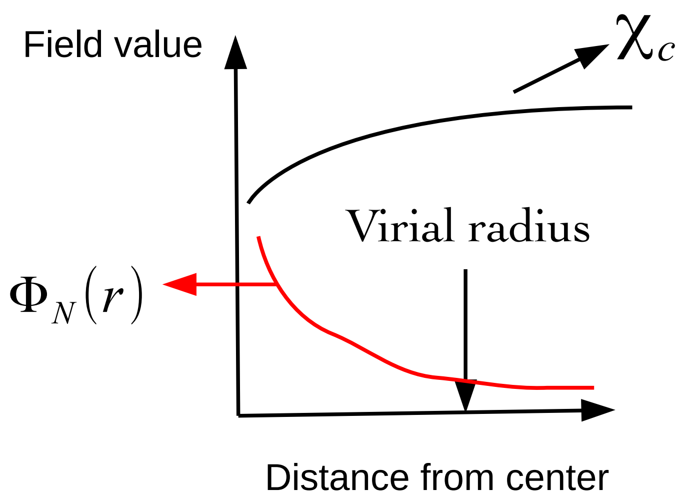
Low ρ

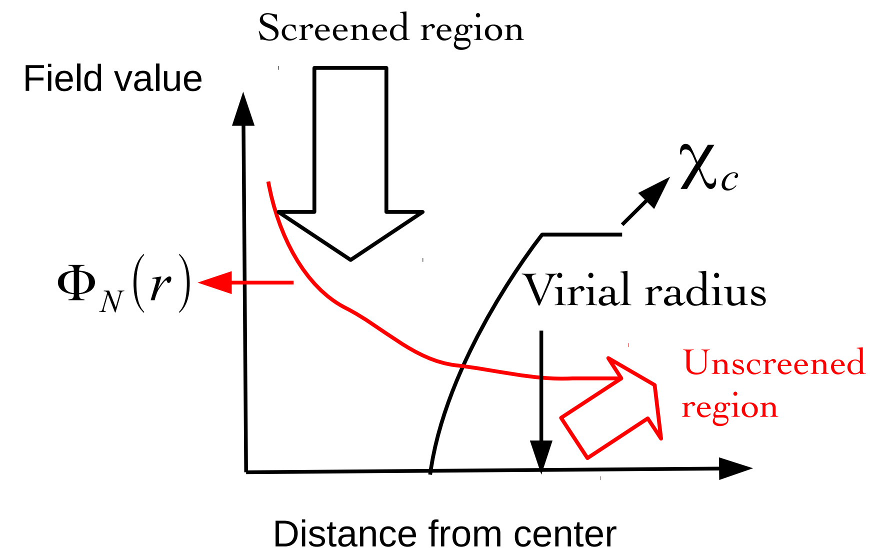


High ρ

Khoury & Weltman 2004

Screening mechanism





Low mass objects with Newtonian potential less than the background field value

High mass objects with Newtonian potential greater than the background field value

Screened if $\Phi_N > |\chi_c|$

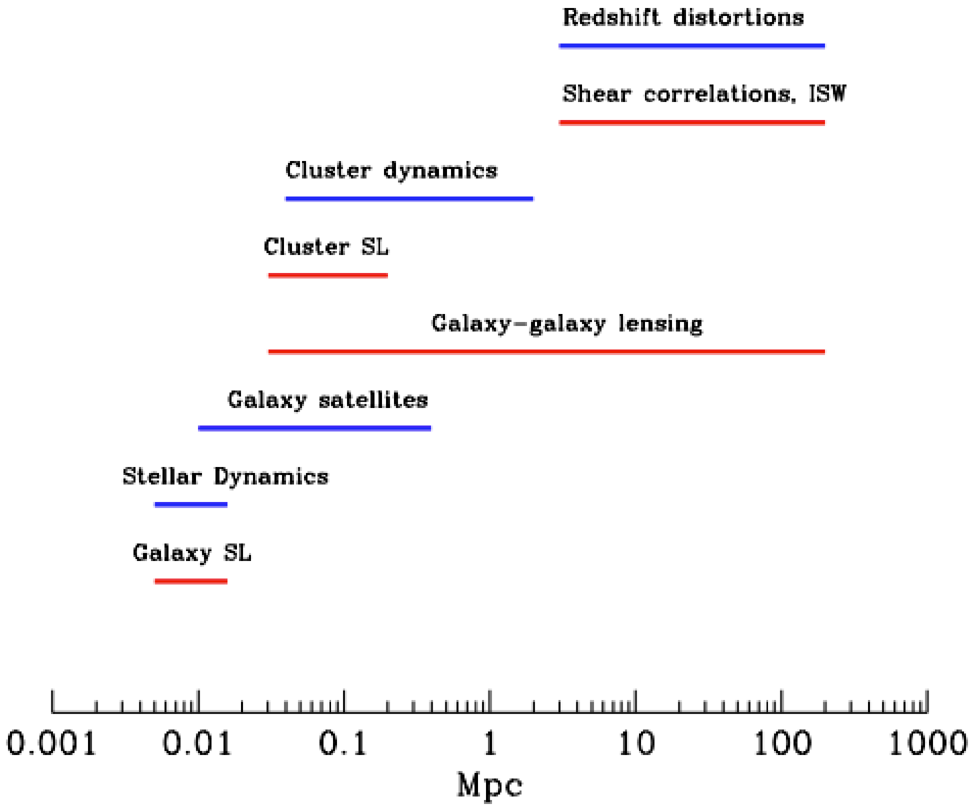
the parameters to constrain?

- The background field value. This tells at which mass scale the screening mechanism starts?
- The coupling coefficient. This implies how strongly the field and matter coupled.
- For f(R) gravity, field value will be the first derivative of f(R)
- Coupling will be 1/3
- For general chameleon theory coupling can vary

$$f_{R0} \equiv \chi_c = \frac{df(R)}{dR}(\ln a = 0)$$

$$\alpha = \frac{1}{3}$$

Tests of gravity



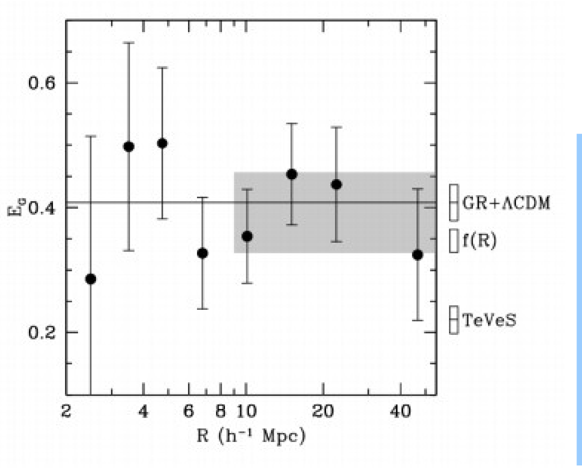
Jain & Khoury 2010

Red lines shows observations that probe the true mass of the objects typically via gravitational lensing, while blue lines show dynamical measurements that rely on the non-relativistic motions of stars or galaxies and are sensitive to dynamical potential alone

Upper limits

- Comparing lensing and dynamical mass estimates $\chi_c < 1$

  Reyes, Mandelbaum et al. 2010



- Cluster abundance $\chi_c < 10^{-4}$

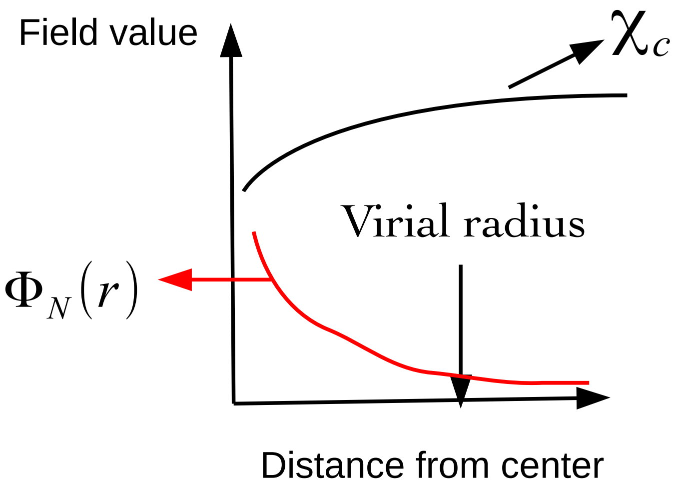
  Schmidt, Vikhlinin & Hu 2009

$\alpha_c = 1/3$

- Solar system $\chi_c < 10^{-6}$

How to improve these constraints? Dwarf galaxies

$$M < 10^{10} M_{\Theta} \quad \Phi_N < 10^{-7}$$



- Low Newtonian potential of these objects implies that they are unscreened objects
- Stellar component is screened
- Gaseous component has low density and remain unscreened. This will experience fifth force
- Differential force on gaseous and stellar component leads morphological and kinematical signature on the galaxies

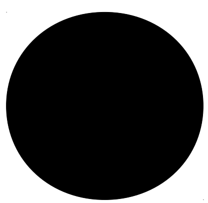
Predictions for dwarf galaxies - 1
Offset between stellar and gaseous components

Stars feel

$$F = \frac{GM}{r^2}$$

Gas feel

$$F = (4/3)\frac{GM}{r^2}$$

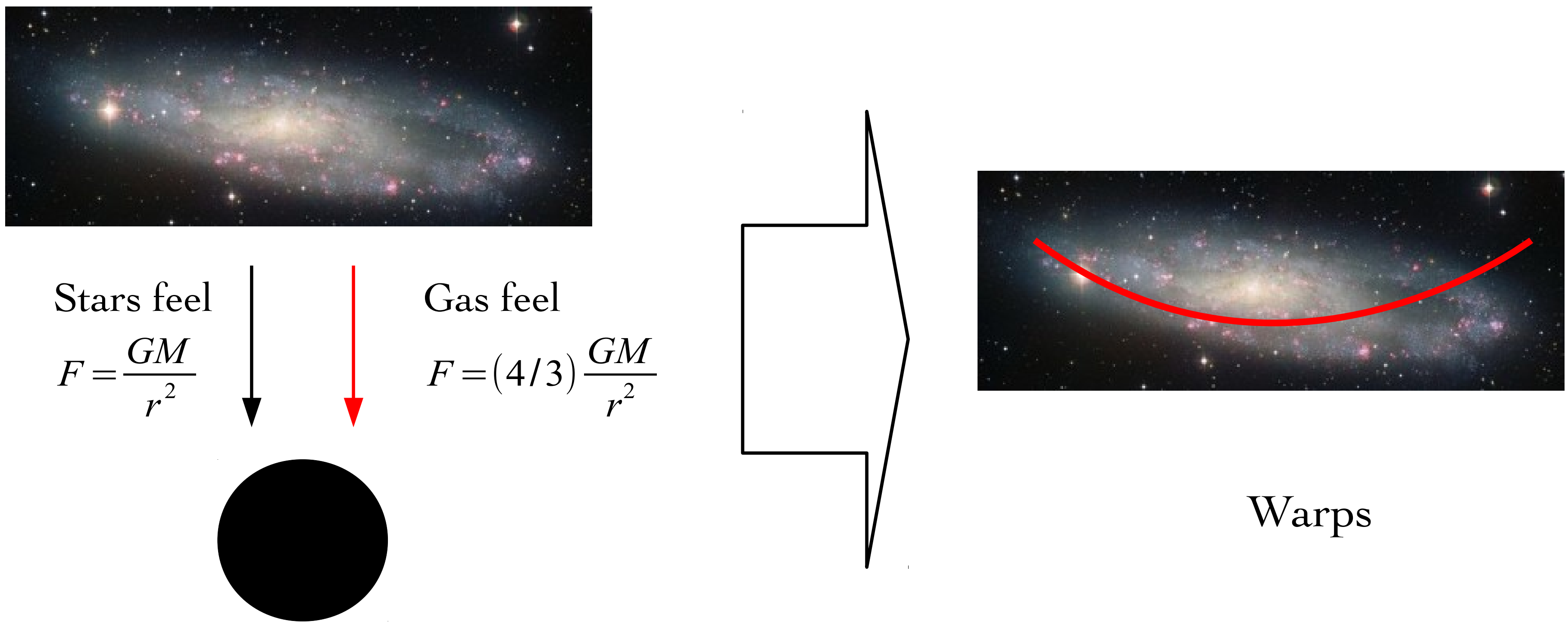


Offset between stellar and gaseous components

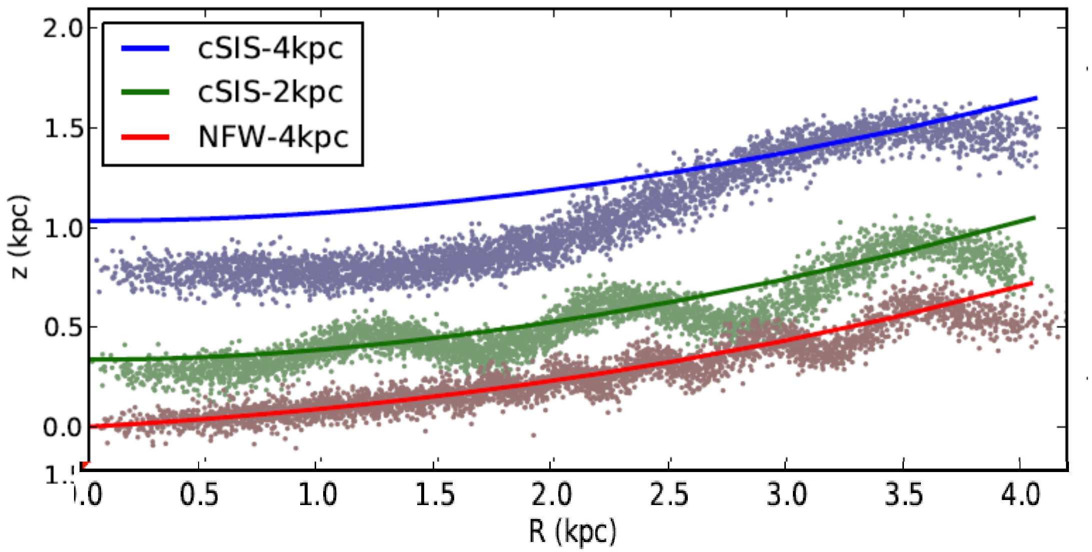
Hui et al 2009
Jain & VanderPlas 2011

Predictions for dwarf galaxies – 2

Warp



Magnitude of offset & warp



- O(1 kpc) offset between stars and gas
- Depends on the dark matter profile of the galaxy
- Low for NFW and large for cored SIS
- ~0.5 kpc warp for all kind of profiles

Predictions for dwarf galaxies - 3

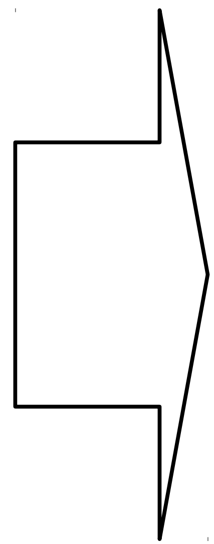
Asymmetry in stellar rotation curves

Stars

$$F = \frac{GM}{r^2}$$

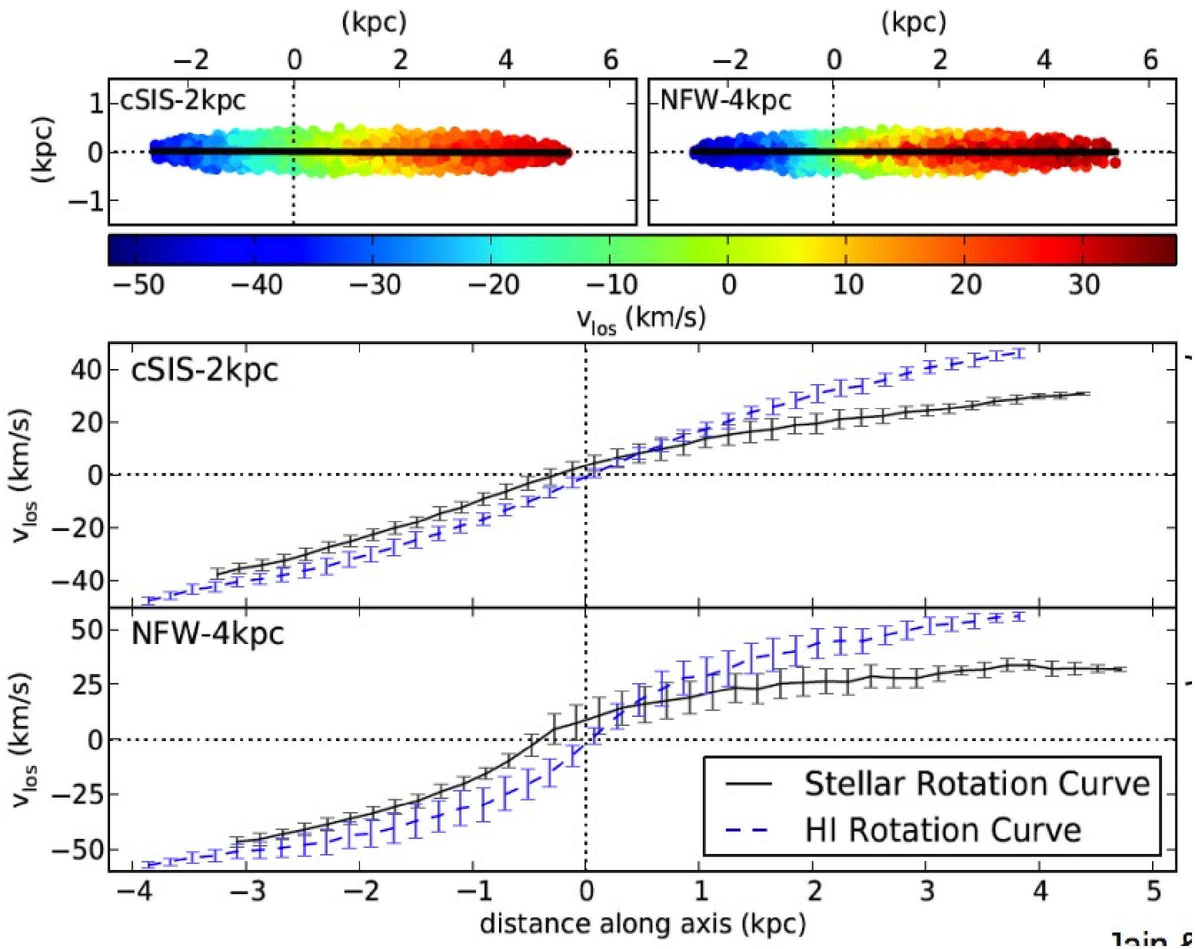
Gas

$$F = (4/3)\frac{GM}{r^2}$$



Asymmetry in the rotation curves

Asymmetry in the rotation curve



•O(10 km/s) asymmetry in the stellar rotation curve
•Gaseous rotation curve stays almost the same due to the large M

Jain & VanderPlas 2011

Predictions for dwarf galaxies - 4

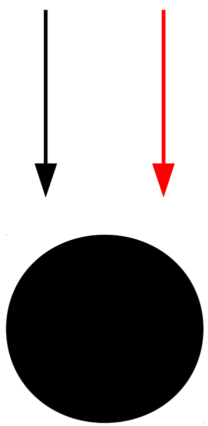
Gas rotate faster than stars

Stars feel

$$F = \frac{GM}{r^2}$$

Gas feel

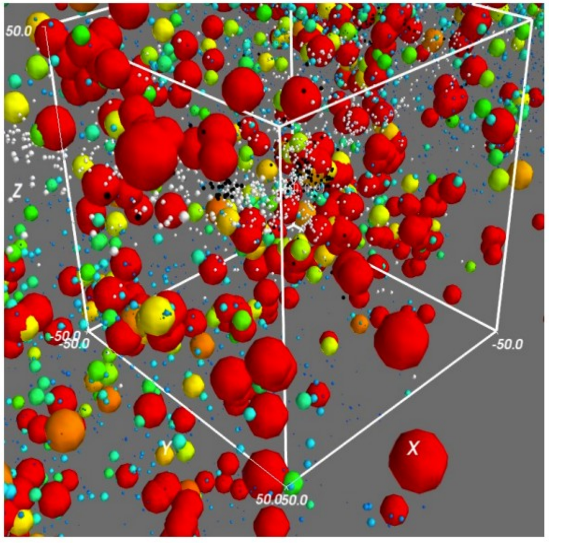
$$F = (4/3)\frac{GM}{r^2}$$



Gas rotate faster than stars by (4/3)^0.5, ~15%

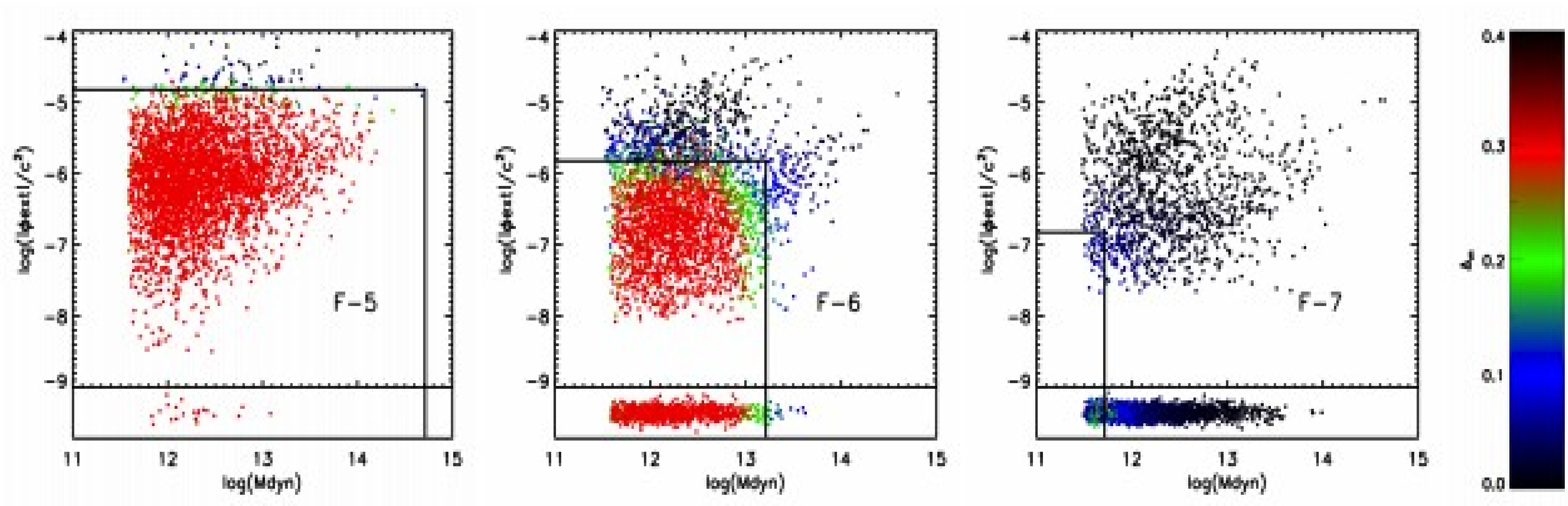
How to find unscreened galaxies?

- Need to solve scalar field equation
- We decided to make use of simulations (Zhao et al 2011a,b)
- f(R) simulations for different field value
- Our goal is to find a classification scheme based on observable parameters like the Newtonian potential due to environment, the dynamical mass of the object, the distance to the neighbours etc.



Cabre, Vikram et al. (2012)

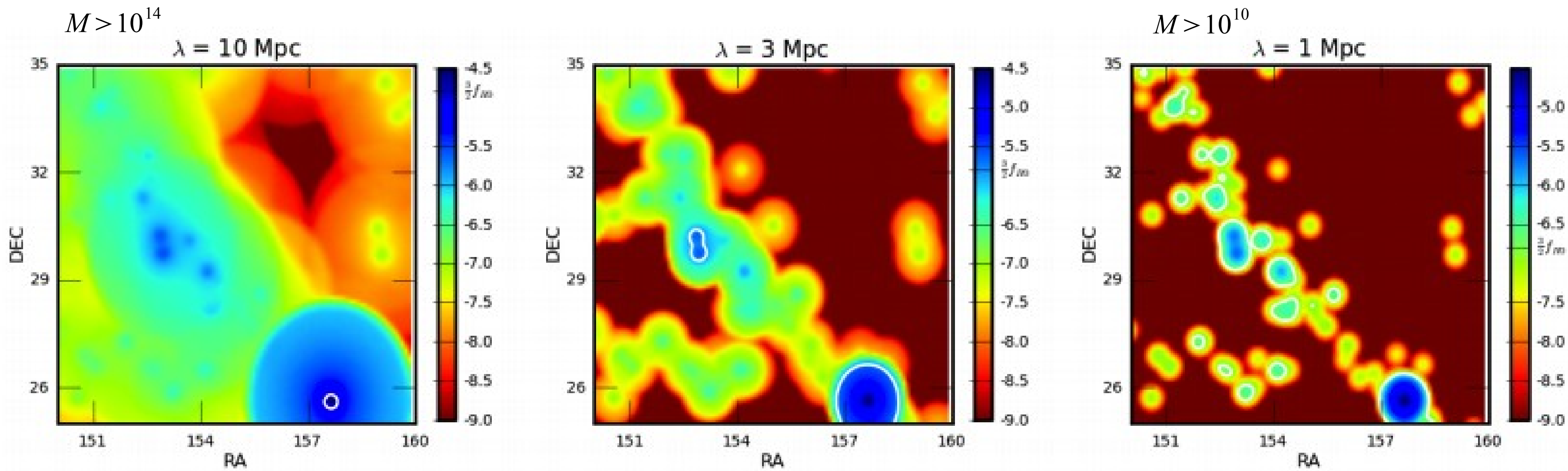
Simulation: unscreened galaxies



- Classification based on the Newtonian potential due to environment and the dynamical mass of the object

Cabre, Vikram et al. (2012)

Screening map of SDSS region



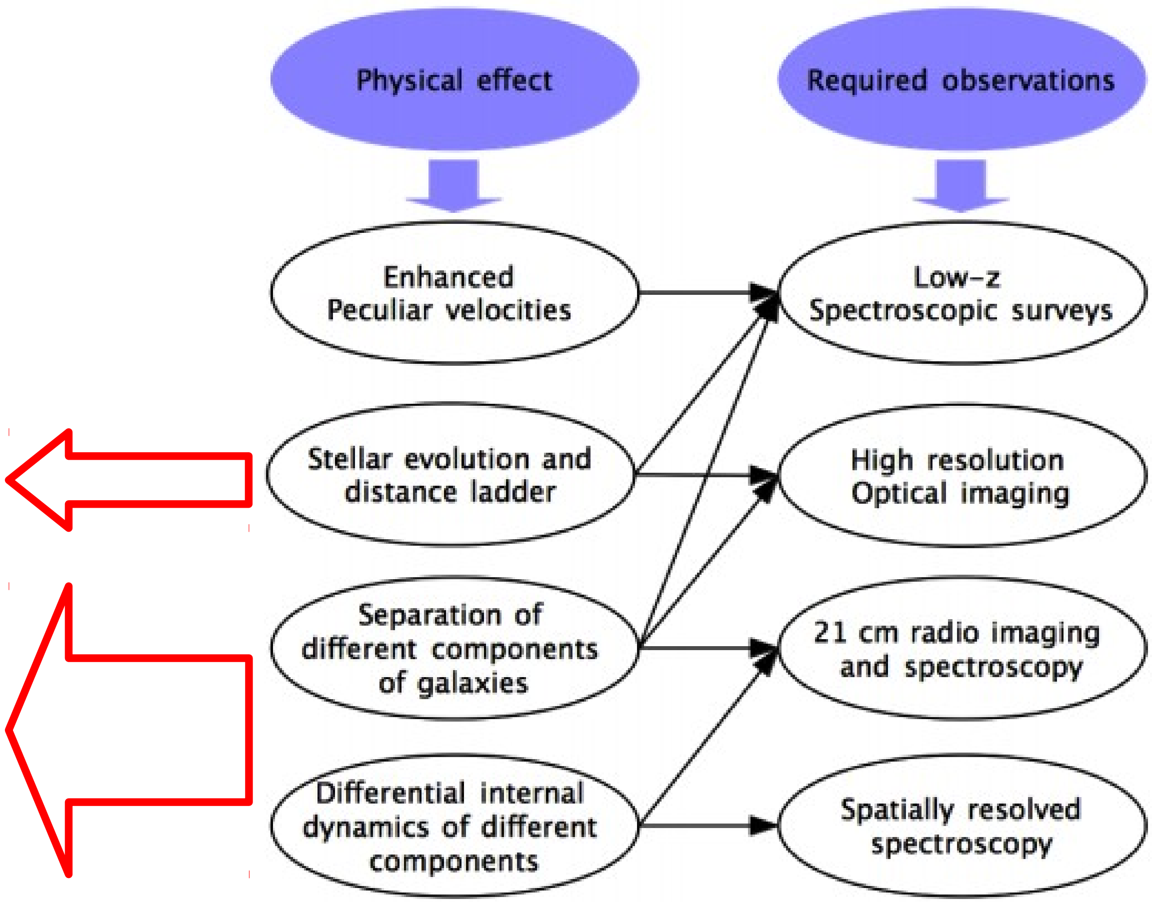
- Use cluster, groups and galaxy catalogs
- X-ray (ROSAT), optical, (SDSS, 2MASS), radio (ALFALFA) observations
- Scaling relations used are M-Lx, M-σ, stellar mass-halo mass, which introduces ~30% mass uncertainty
- Karachentsev (2004) local catalog

MG Predictions and required data

Jain et al. (2013), Snowmass report

Jain, Vikram & Sakstein (2012)

Vikram et al (2013)



General analysis strategy

•Several astrophysical effects can mimic predictions of modified gravity

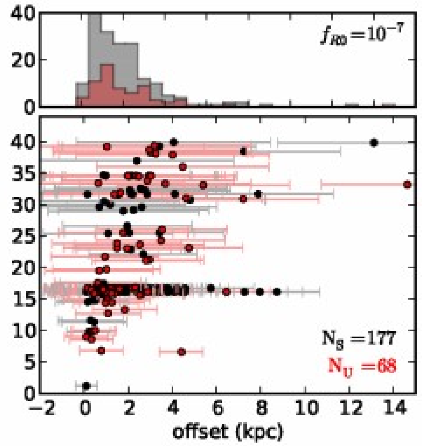
•Study the signatures statistically

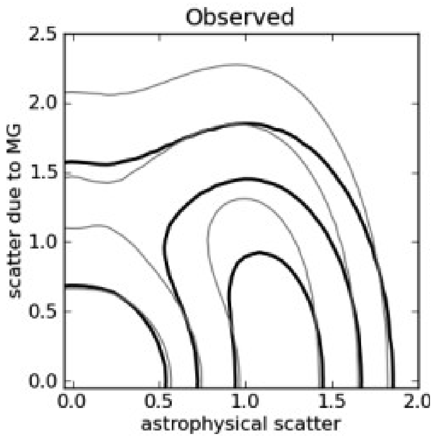
•Assume the astrophysical effects act on screened and unscreened sample in the same way and the astrophysical and modified gravity effects add linearly

•Measure the astrophysical effects from the screened sample and correct it in the unscreened sample

•Caveat: There could be environmental dependence of these properties even in the absence of MG.

Offset between gaseous and stellar components

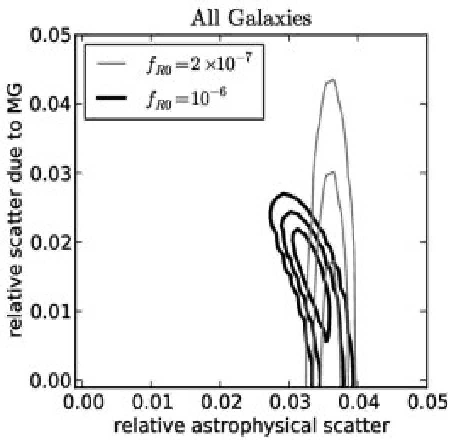




- Optical images traces the stellar center (SDSS)
- HI images traces the gaseous center (ALFALFA)
- Optical centers are < 1 arcsec precision and radio has > 24 arcsec which leads to large error in the measurement
- Poor constraints

Vikram et al (2013)

Improved offset measurement using Hα

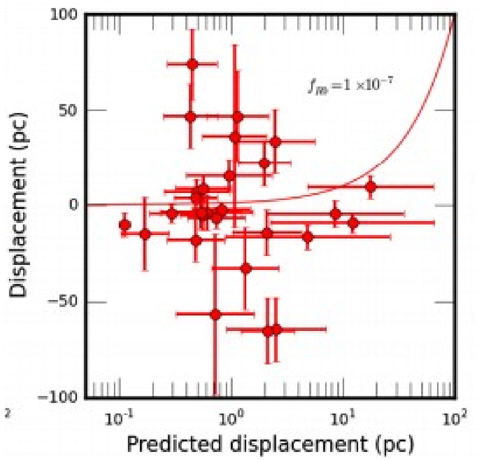


Upper limit of <3% offset compared to 10% expected offset for field value 10^{-6} and <5% offset for field value $2X10^{-7}$

Vikram et al (2013)

- Use kinematic center of Hα rotation curves instead of HI images Persic & Salucci 1996
- Does Hα trace gas? Yes!
- Hα comes from HII regions around massive O & B stars. The radius of HII region is ~10pc and the surface potential due to the center star is much below the background field values tested

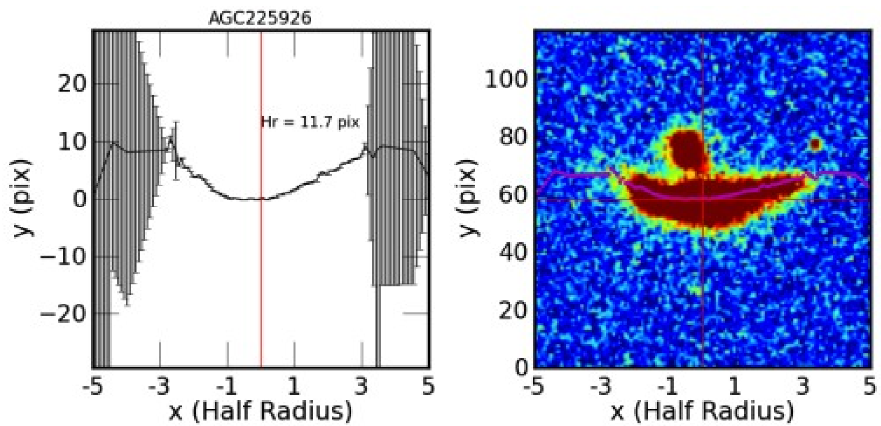
Offset between stars and partially screened stars



Vikram et al (2013)

- Red giant stars are very luminous last phase of star with mass between 0.5 and 8 solar
- Radius can be 20-100 solar
- Red giant stars are partially screened objects
- Possible to observe individual RG with HST
- 69 nearby dwarf galaxies: d<4Mpc , -20<M_B<-8 Dalcanton et al. (2009))
- Offset is consistent with zero! -10.2 \pm 5.5 pc and -4.7 \pm 6.4 pc for 1e-6 and 1e-7!

Warping of edge-on galaxies



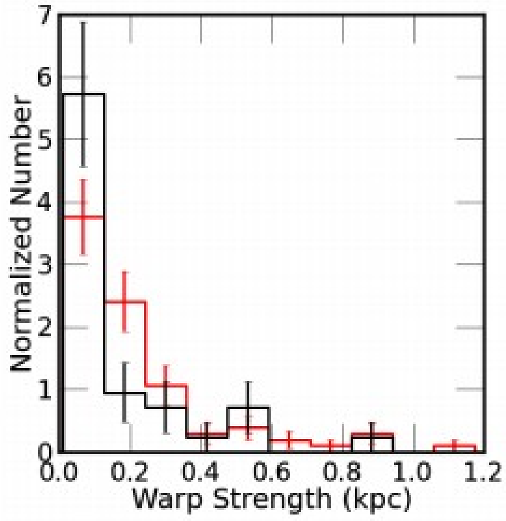
$$w_1 = \frac{\int_0^L \frac{x}{L}\frac{y}{L}\frac{dx}{L}}{\int_0^L \frac{x}{L}\frac{dx}{L}} = \frac{2}{L^3}\int_0^L xy\,dx$$

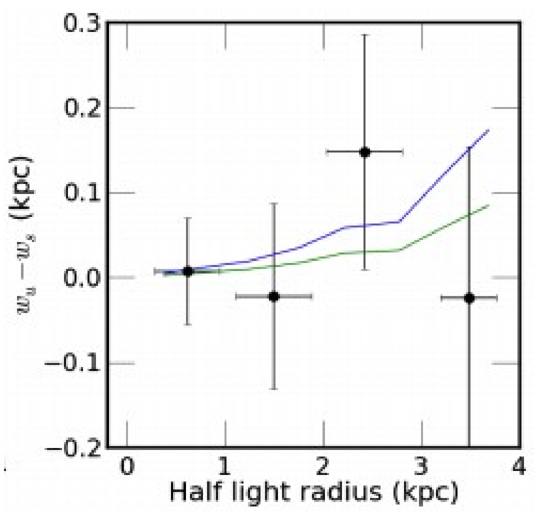
$$w_2 = \frac{\int_0^L xy\,dx}{\int_0^L x\,dx} = \frac{2}{L^2}\int_0^L xy\,dx$$

Vikram et al (2013)

- SDSS galaxies along with ALFALFA rotation velocity
- b/a < 0.6
- 128 (58) screened and 367 (158) unscreened galaxies for field value 10^{-6} ($2X10^{-7}$)
- Fitting gaussian in each column
- Cleaning the warp curve

Warping of edge-on galaxies

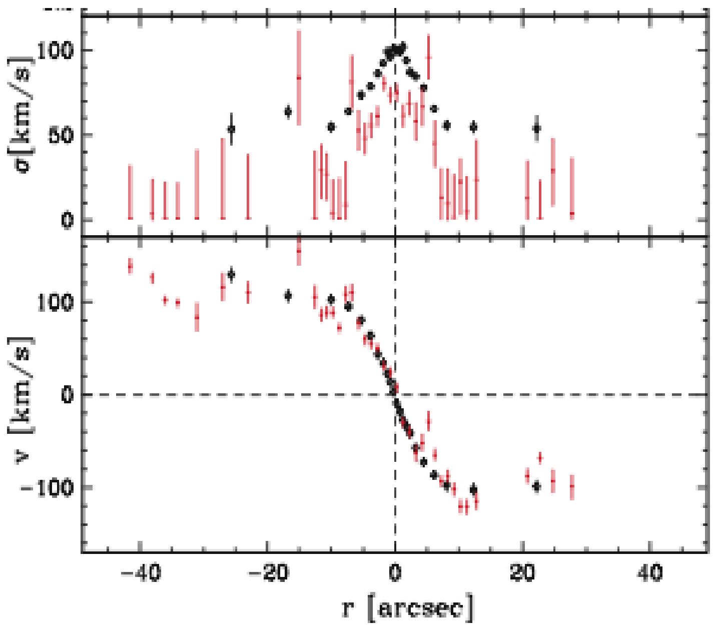




Vikram et al (2013)

- No difference between the distributions of warp of screened and unscreened sample
- The measured value of warp is consistent with zero
- Cannot rule out any of the model with the current data

Stellar and gaseous rotation curves



Pizzella et al (2008)

- Use stellar absorption line (e.g. *Mg* triplet) to estimate the rotation curve
- They originate from the stellar atmosphere
- Absorption lines are really faint and difficult to measure the rotation based on that
- Model the stellar and gaseous rotation curve based on modified gravity theory

Ongoing work Andrew Neil, Charles Davis (undergrads) , Joseph Clampitt, Bhuvnesh Jain (UPenn), Matthew Walker (Carnegie)

Constraints from Distance indicators

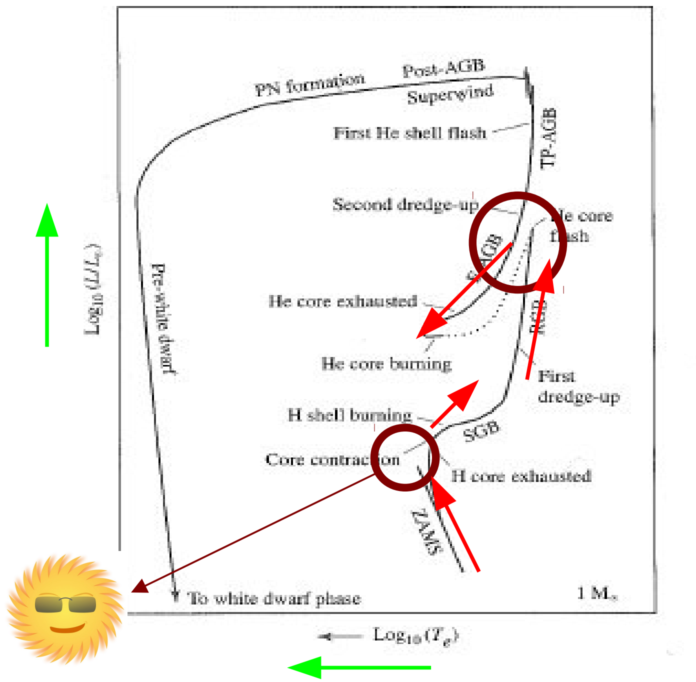
Jain, Vikram & Sakstein (2012)

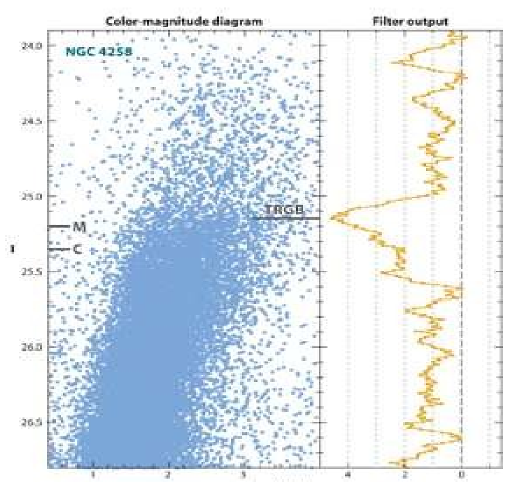
- Tip of Red Giant Branch (TRGB) (up to 20 Mpc)
- Cepheid period – luminosity relation (up to 50 Mpc)

- For any standard candle method:
  1. Find a method to estimate the intrinsic luminosity of the object (calibration)
  2. Compare with observed luminosity to derive distance

Tip of the Red Giant Branch

Isochrone: evolutionary tracks of stars in the T-L plance

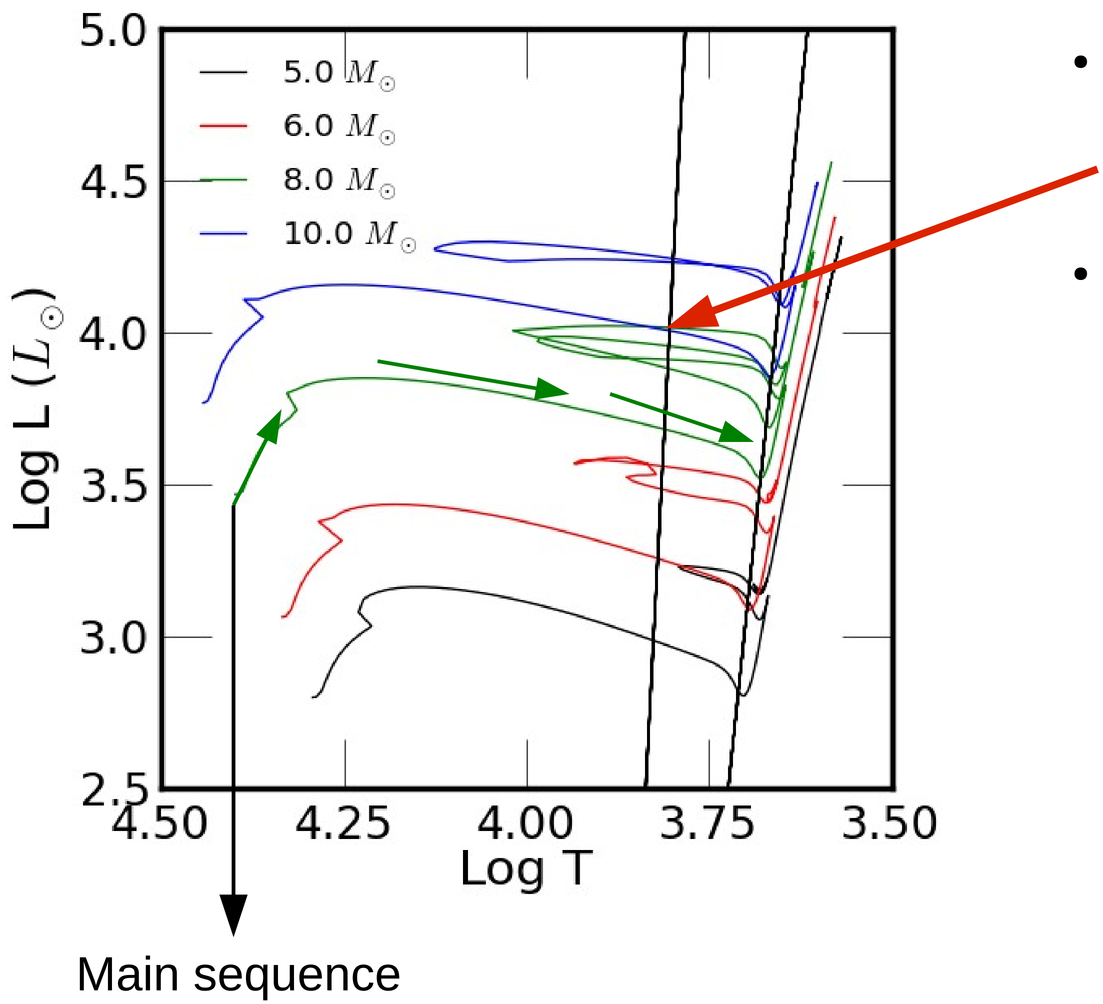




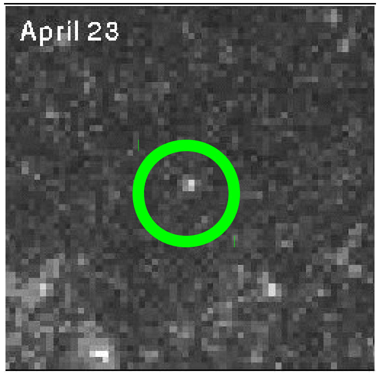
- Post main sequence phase low mass stars $M < 1.8\ M_\odot$
- Luminosity is set by mass and radius of He core
- $L \sim M_C^7/R_C^5$
- Luminosity is constant for wide range of metallicities and ages

$$M_I = -4.0 \pm 0.1$$

Cepheid variables

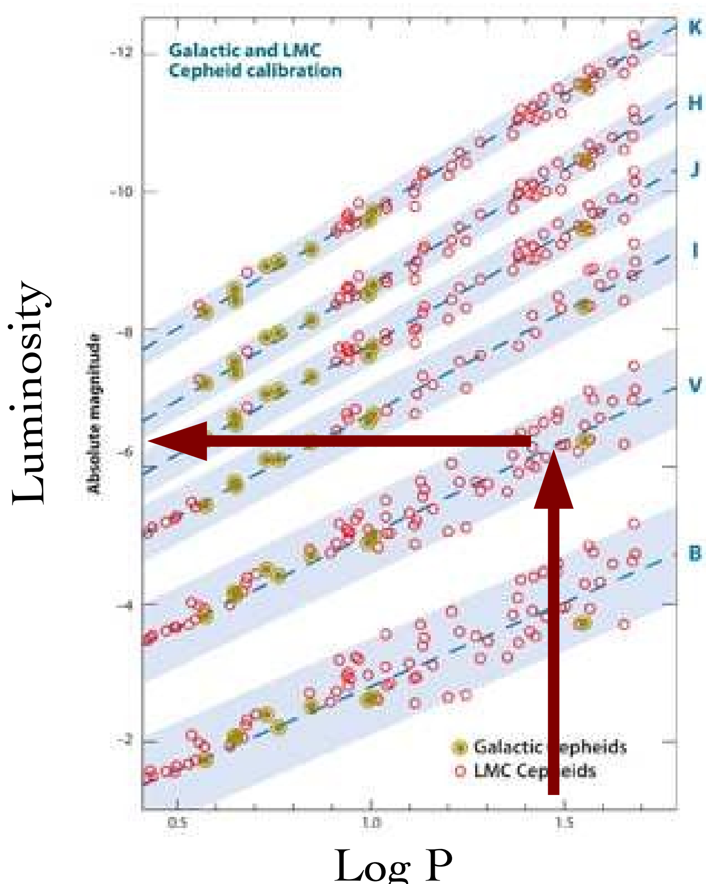


- Stars with $M > 4\ M_\odot$ solar pass through instability strip and oscillate
- Oscillation are triggered by kappa mechanism where a layer of ionized He at 10^4K plays key role



Cepheid based distance

- Henrietta Swan Leavitt (1900)



•Brighter cepheids oscillate slower

•Calibrate the relation with sources of known distances

$$M_V = -2.81 \log P - 1.43$$

•Measure period of oscillation which gives true brightness of the star

•Compare with apparent brightness (m_V) to get distance

$$m_V - M_V = 5 \log d - 5$$

Uncertainty in the distance is ~ 5%

Cepheid distances & MG

Period of pulsation : linear adiabatic analysis

$$\Pi \propto \frac{1}{\sqrt{G\rho}}$$

$$\frac{\Delta G}{G_N} = 1 \Rightarrow \Pi = \frac{\Pi_N}{\sqrt{2}}$$

$$\frac{\Delta G}{G_N} = 1/3 \Rightarrow \Pi = \frac{\Pi_N}{\sqrt{4/3}}$$

$$M_V = -2.81 \log \Pi - 1.43$$

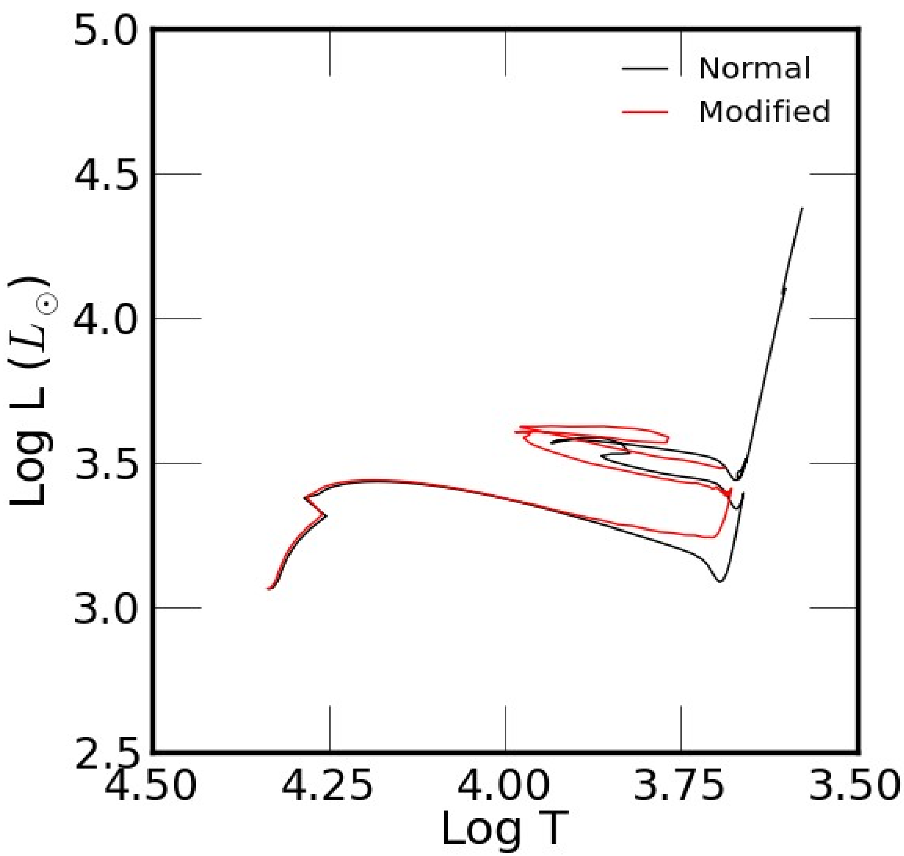
$$\Pi \downarrow \Rightarrow M_V \downarrow \Rightarrow m - M_V \downarrow \Rightarrow d \downarrow (10-20)\%$$

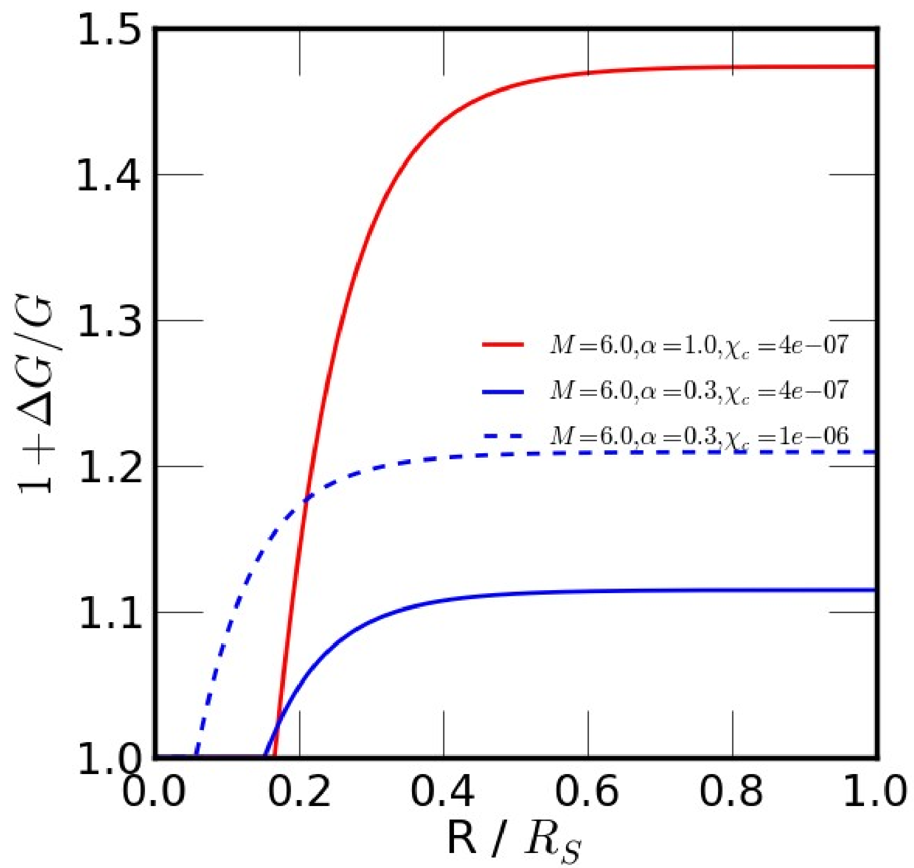
Distance to the object will be underestimated under MG

Sakstein (2013) shows that the oscillations are faster than the simple descriptions

Cepheid & MG

MESA – stellar evolution code





$$\Delta G/G \approx 10-45\%$$

$$\Delta d/d \approx 3-12\%$$

Underestimation!!!

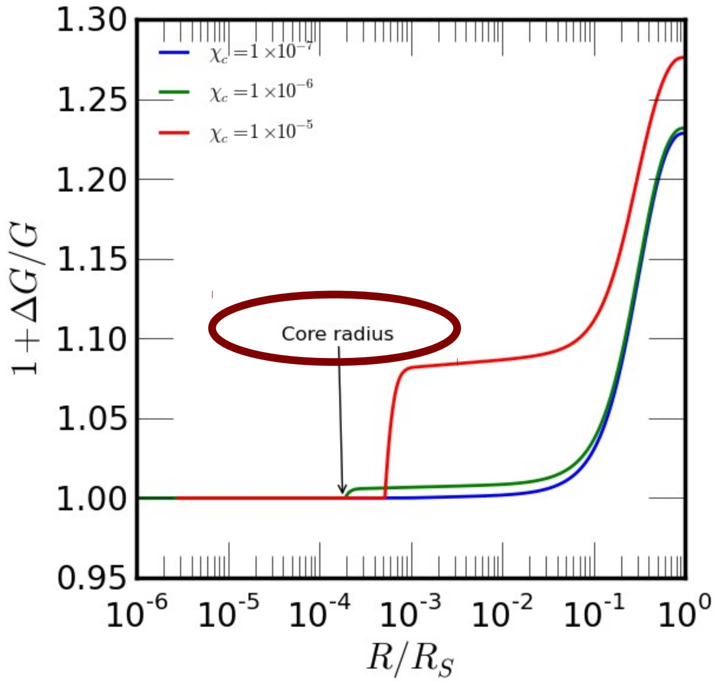
Cepheid distance & MG

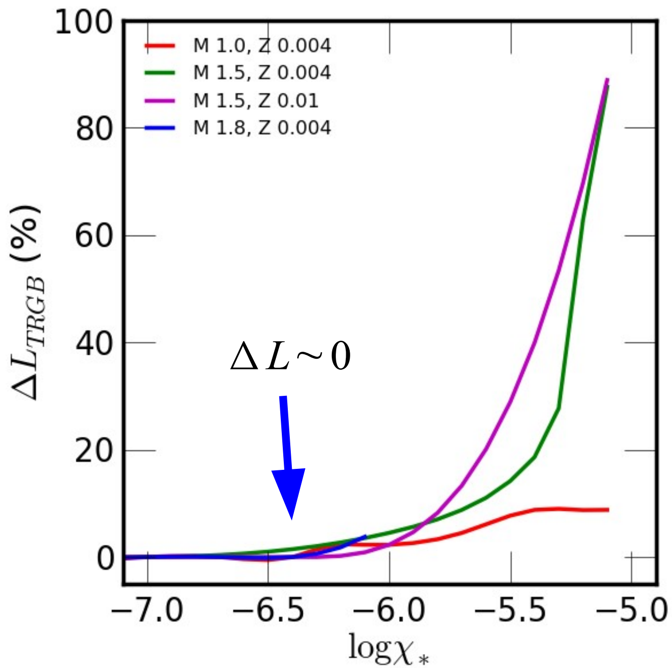
α_c	χ_c	$\Delta G/G$	$\Delta d/d$
$1/3$	4×10^{-7}	0.11	-0.03
$1/3$	1×10^{-6}	0.21	-0.06
$1/2$	4×10^{-7}	0.17	-0.05
$1/2$	1×10^{-6}	0.34	-0.09
1	2×10^{-7}	0.21	-0.06
1	4×10^{-7}	0.45	-0.12

$$\Pi\downarrow\Rightarrow d\downarrow(3-12)\%$$

Sakstein (2013) shows that this can larger than 12%

TRGB & MG





- No enhanced force within the core
- No change in distance estimation for $\chi_c < 10^{-6}$
- Distance will be over estimated for larger χ_c which leads to larger discrepancy between cepheid based distance

So far

- TRGB distance will be unaffected by MG for $\chi_c < 10^{-6}$
- Cepheid distance will be 3-12% underestimated

Expectations

- Systematic difference between distances for unscreened galaxies
- Zero difference for screened galaxies

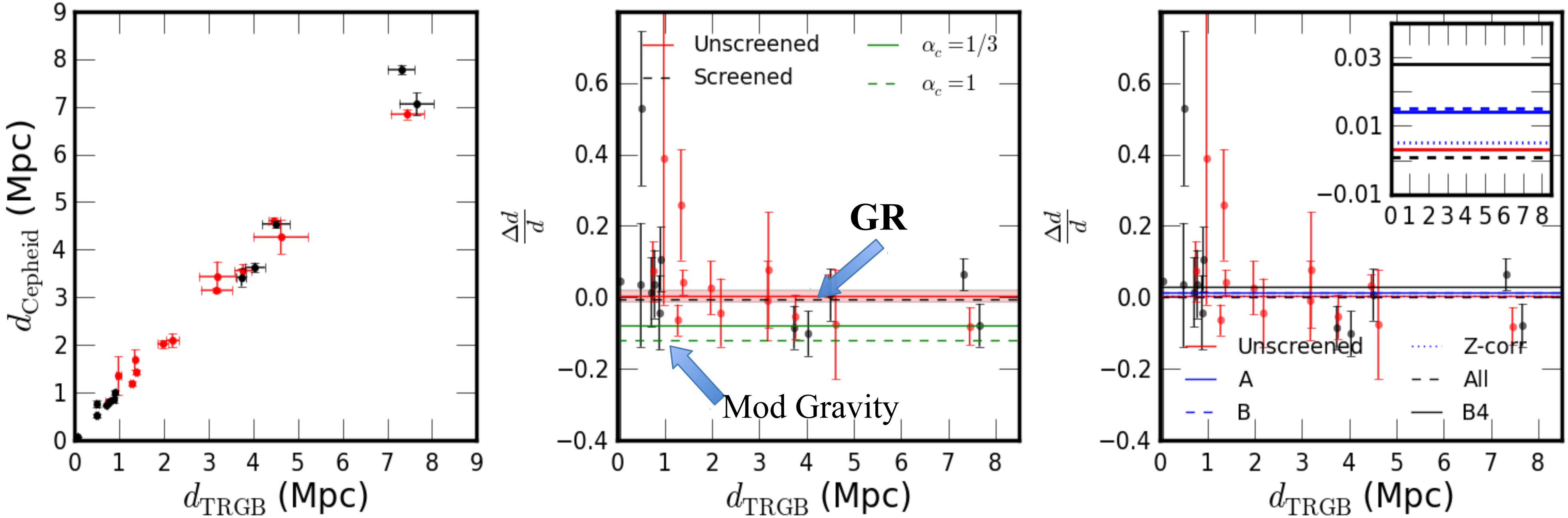
Data

25 galaxies within 10 Mpc

V_{rot} = 40 – 240 km/s

13 unscreened 12 screened (Cabre at al.)

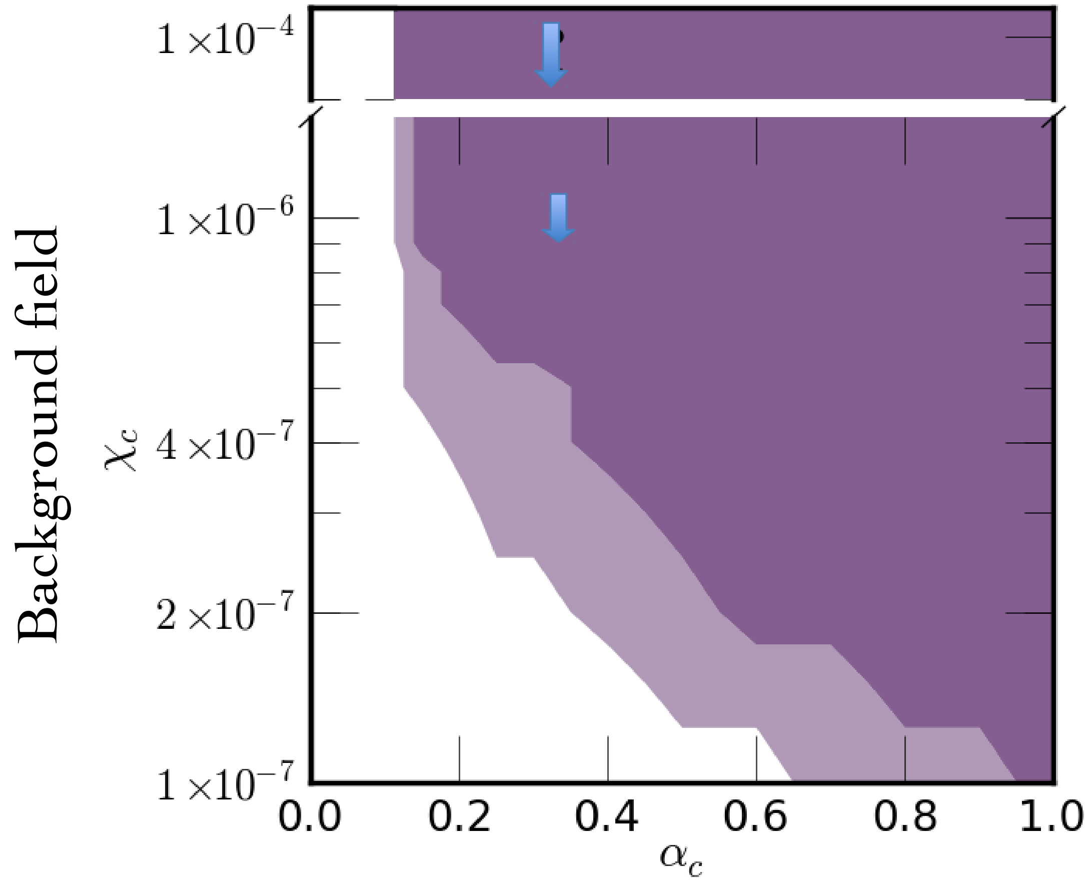
Cepheids vs TRGB distances



Gravity test with 25 galaxies: no sign of deviation from GR

Sample	N	$\Delta d/d$	σ
Unscreened	13	0.003	0.017
Screened	12	-0.005	0.022

Chameleon constraints

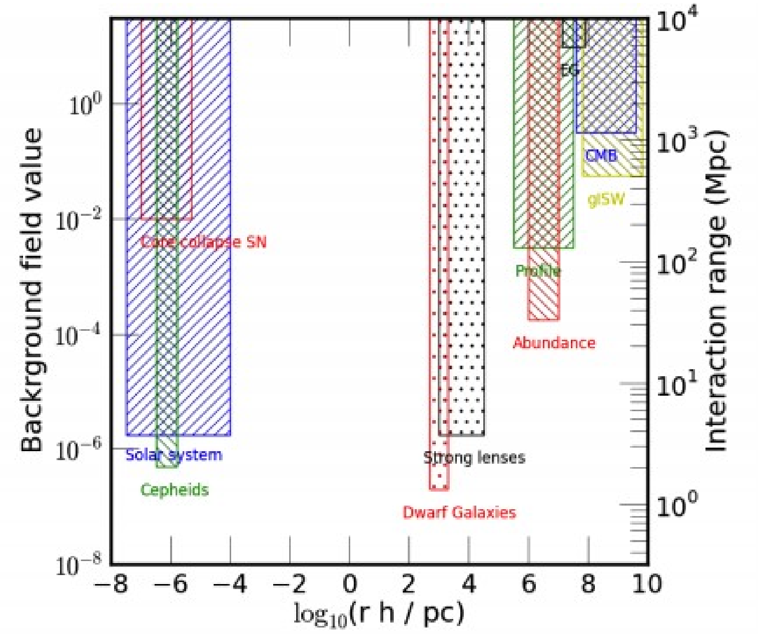


Coupling parameter of scalar to matter

$$\chi_c = 1 \times 10^{-6} \downarrow 2\sigma$$

$$\chi_c = 4 \times 10^{-7} \downarrow \sigma$$

New constraints



Lombriser et al 2012
Jain et al 2013

Pushed the upper limit to an order of magnitude lower

Summary

- Astrophysical tests of modified gravity theories are demonstrated
- Came up with classification scheme for screened and unscreened galaxies
- New upper limits are deduced from the observed values

What we learnt from this exercise?

- Need homogenous data
- Need better measurements (e.g. HI centroid)
- Need more data (e.g. surveys like ALFALFA)

- Rotation curve measurements by absorption lines (Ongoing work)

Thanks!

Metallicity & Distance