Astrophysical tests of gravity

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References

BJ & Khoury (2010) arXiv: 1004.3294

BJ & VanderPlas (2011) arXiv: 1106.0065

BJ, Vikram & Sakstein (2012) arXiv: 1204.6044

Vikram, Cabre, BJ & VanderPlas (2013) arXiv: 1303.0295

Outline

- A new opportunity for gravity tests within few-100 Mpc
- Results on tests of gravity using distance indicators: Cepheids, TRGB stars and SMBH masers
- Disks of dwarf galaxies: signatures in warps, rotational and infall motions
- Stepping back: fashioning tests of gravity in the era of dark energy

Note: Simplified and approximate treatment; see papers for caveats!

Modified Gravity I

how cosmological effects show up in local galaxies

Why should we do weak field tests outside the solar system?

- Glib answer: because the universe is accelerating!
- **Generically** get scalar-tensor theories: scalar field provides an attractive, fifth-force (Theories:Vainshtein/DGP, Chameleon/f(R), Symmetron…)
  - $a = -\nabla(\Psi_S + \Psi_N)$, *and* $\Psi_S \sim \Psi_N$

⇨ This can enhance effective G & forces on galaxies by 10s of %

- GR restored in the Milky Way via **screening mechanisms** that work for massive/dense objects. *Vainshtein 72; Khoury & Weltman 2004*

⇨ Unscreened galaxies in the local universe are ideal places to look for signatures of modified gravity

Modified Gravity II

stars, gas and dark matter

• Enhanced forces can alter the luminosities, colors and ages of stars in unscreened galaxies.

- Newtonian potential of Milky Way **and** of main sequence stars: $\psi \sim 10^{-6}$
- Giant stars may feel higher G_{eff}.

Chang & Hui 2010; Davis et al 2011; BJ, Vikram, Sakstein 2012

• Dark matter and gas clouds are diffuse -> should feel the fifth/scalar force if their host galaxy is unscreened.

- Stars rotate slower and separate from gas due to external forces
- Black holes and stars may also separate in some scenarios

Hui, Nicolis & Stubbs 2009; BJ & VanderPlas 2011; Hui &Nicolis 2012

Modified Gravity III

deviations from GR on different scales

- Galaxy infall
  - Redshift space infall motions enhanced
  - Dynamical masses > Lensing masses
- Galaxy kinematics
  - Gas rotates faster than stars
  - Asymmetric rotation curves
- Galaxy morphology
  - Warped disks, aligned with fifth force
  - Stellar disk offset from gas disk (and red giants)
  - SMBH black holes offset from central starlight
- Stars
  - Giant stars are hotter and evolve faster
  - Cepheids pulsate faster

Length scale:
100 Mpc

10^{-12} Mpc

Tests with distance indicators

Giant stars and SMBH masers as distance indicators

• Cepheids are 3-10 $M_\odot$ giant stars that pulsate over days to weeks. The period P and luminosity L are tightly related -> distance indicator

-Newtonian potential in oscillating envelope of star ~ 10^{-7}

- $P \sim 1/\sqrt{G\rho}$

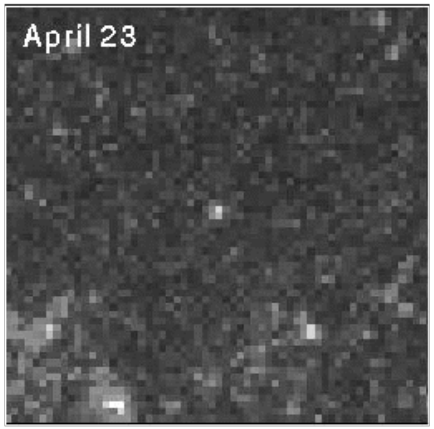
-Scalar force enhances G -> lowers P -> underestimate distance.

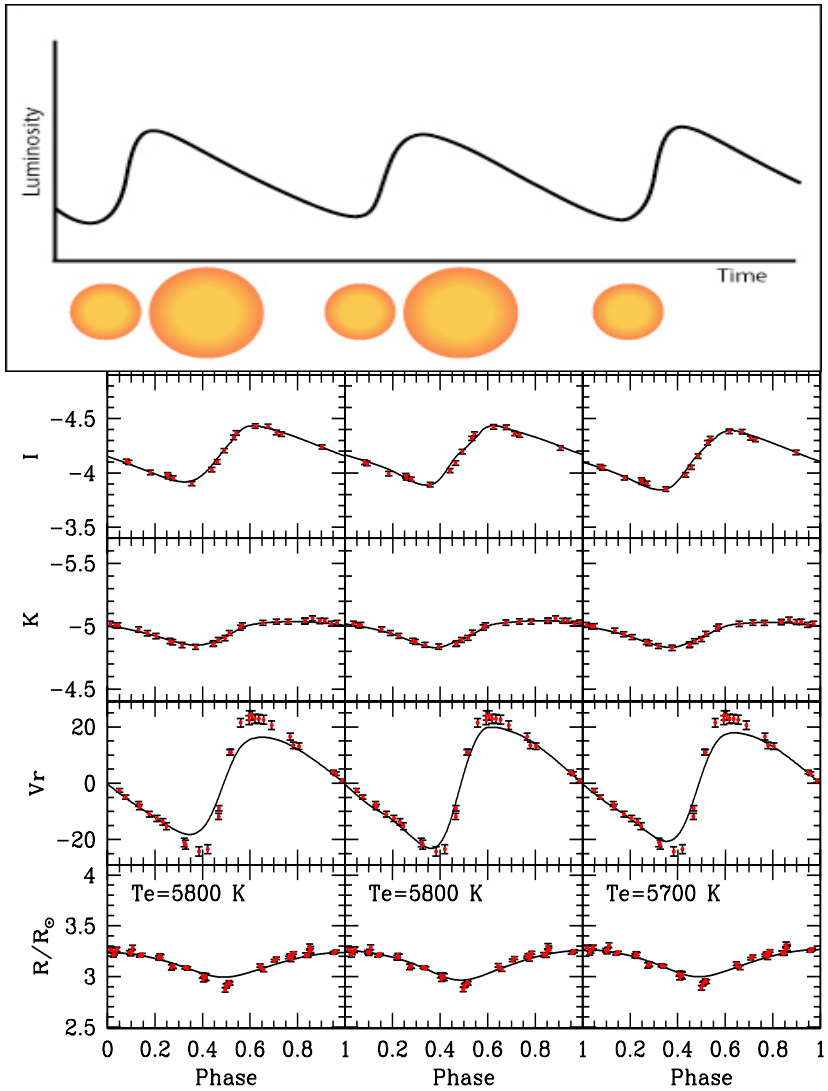
• The peak luminosity at the TRGB (tip of the red giant branch) is nearly universal for 1-2 $M_\odot$ stars -> distance indicator

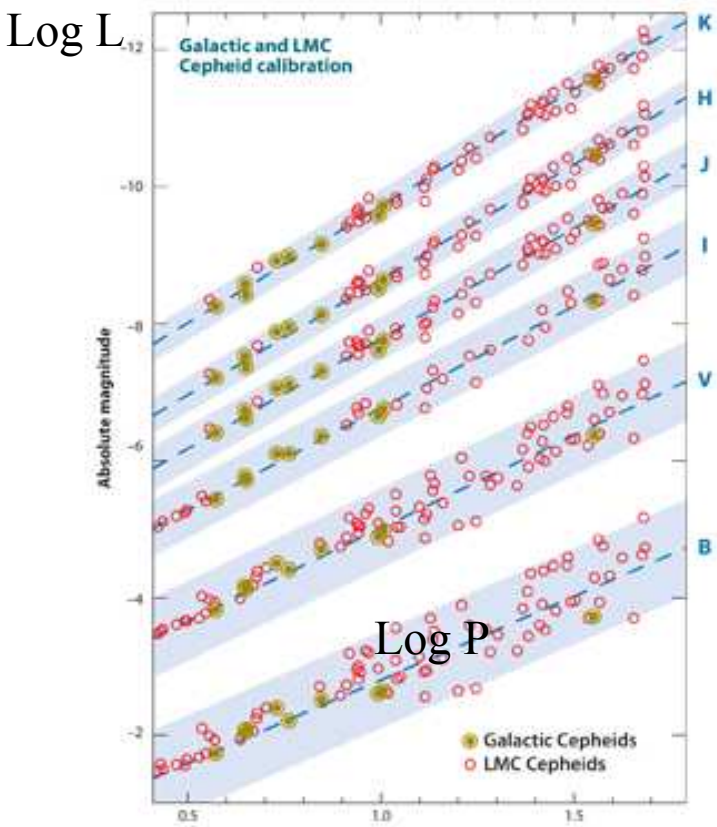
- *Newtonian potential at surface of He core ~ 10^{-5}*
- *Distance is affected only for large field values, and has the opposite change from cepheid distance*

• Water masers around SMBHs provide a geometric method: independent of G!

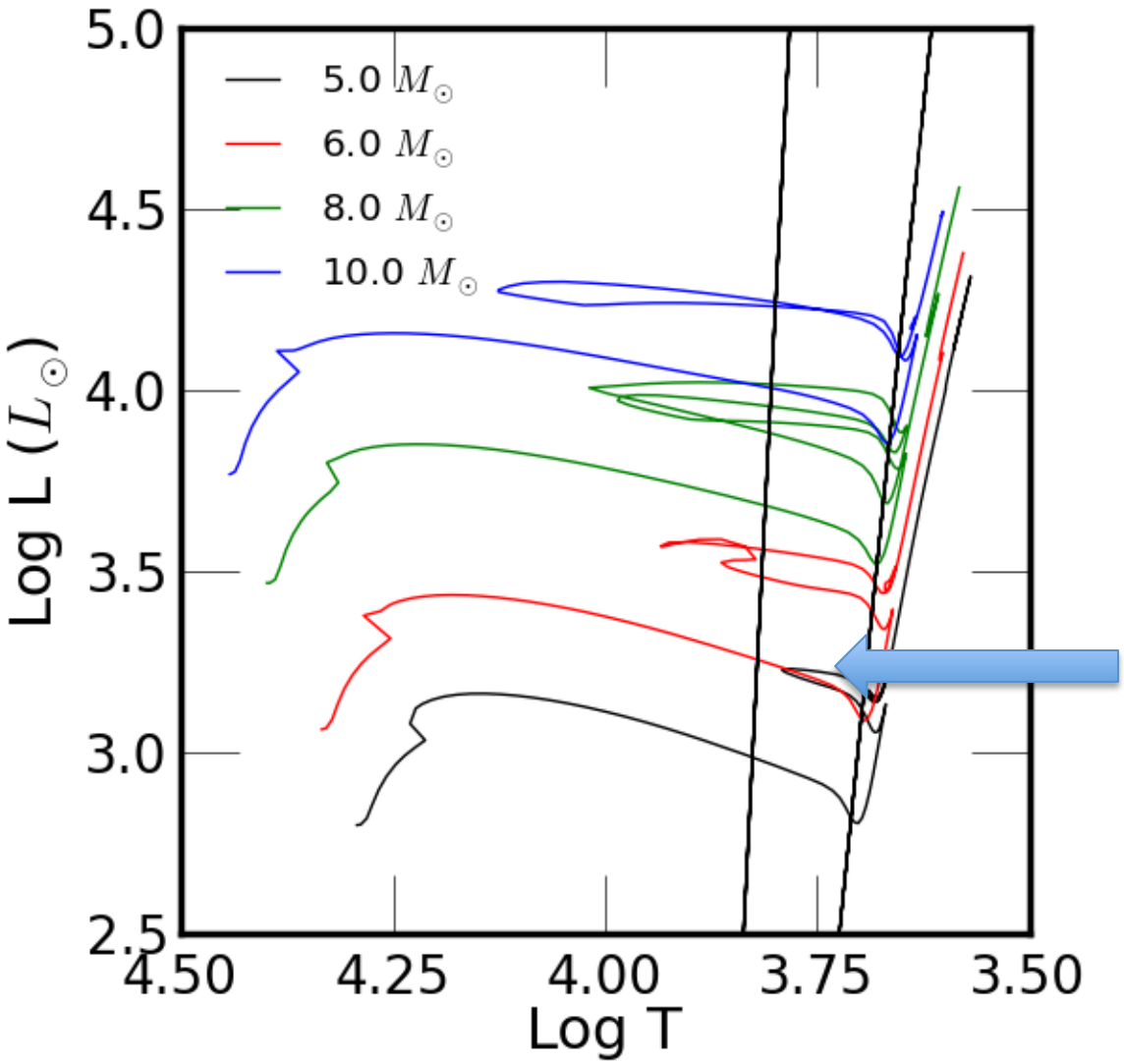
Cepheid Variables

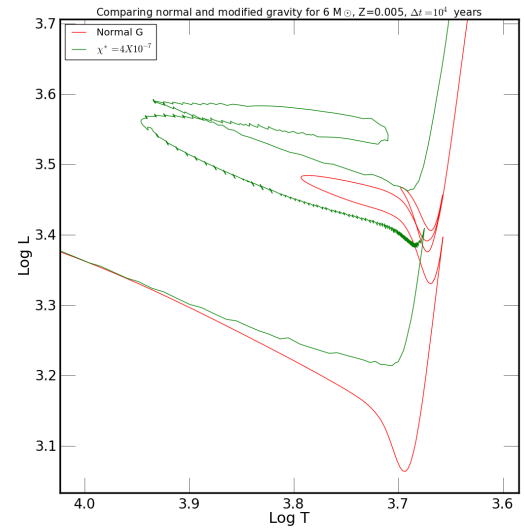






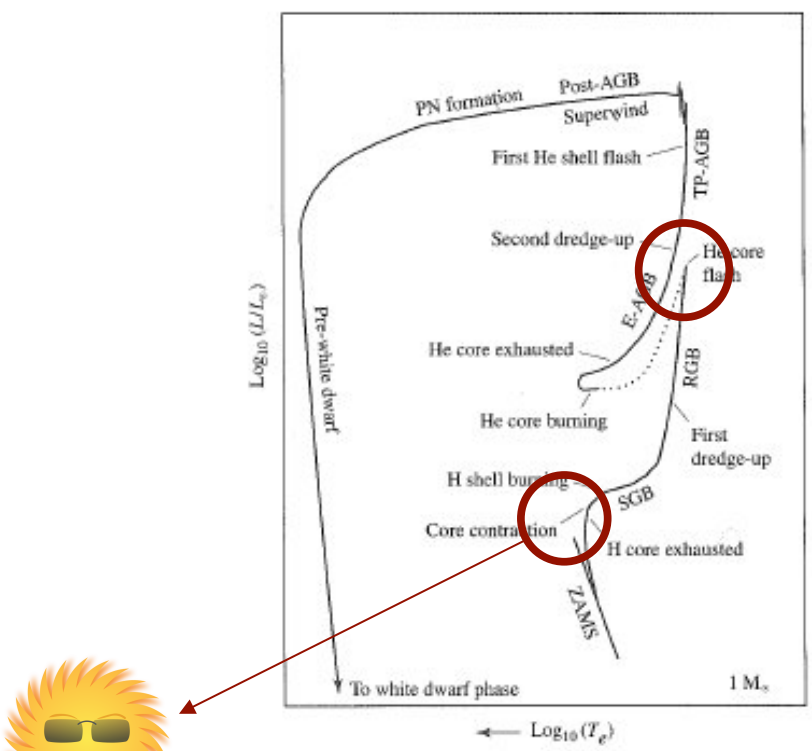
Stellar evolution beyond the main-sequence



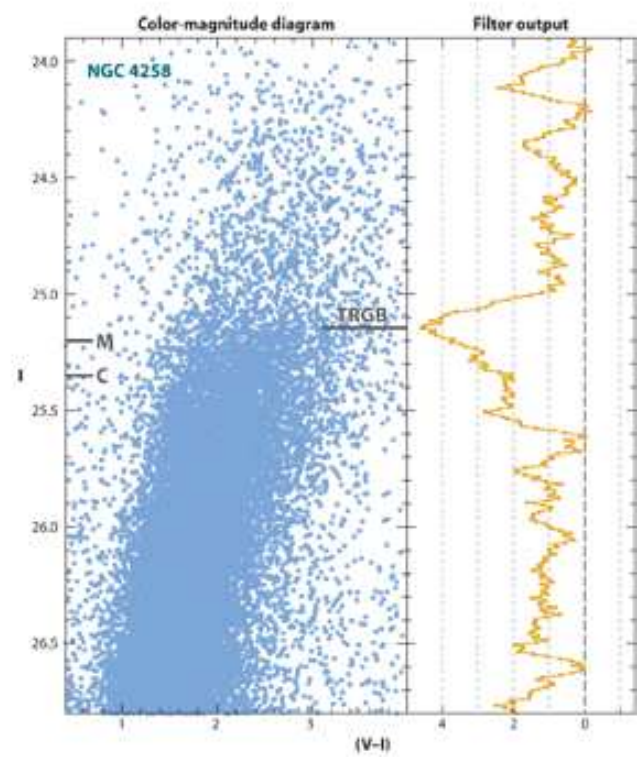


Cepheids live in the instability strip

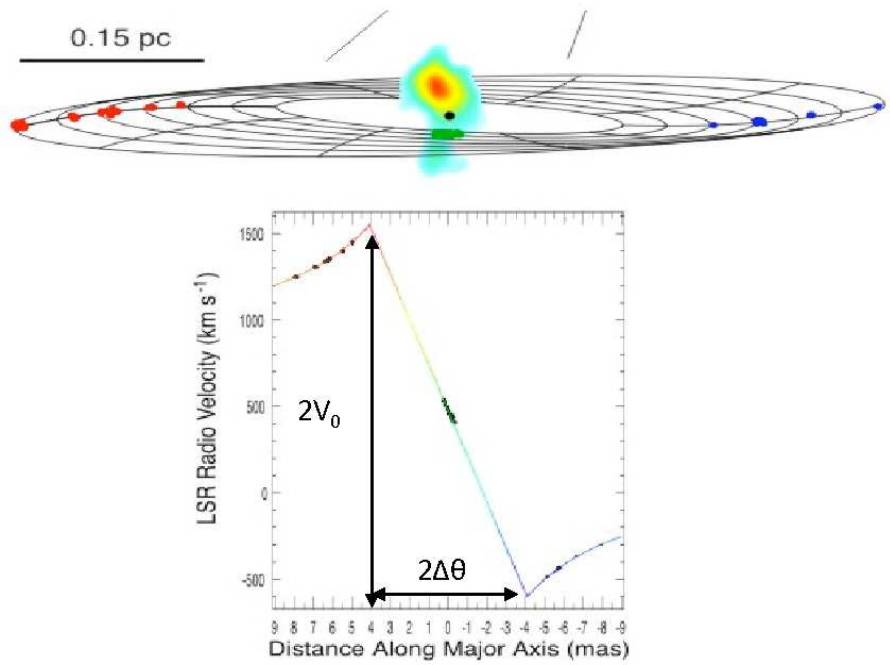
Tip of the Red Giant Branch



- $M < 1.8\ M_\odot$, He core
- $L \sim M_C^7/R_C^5$

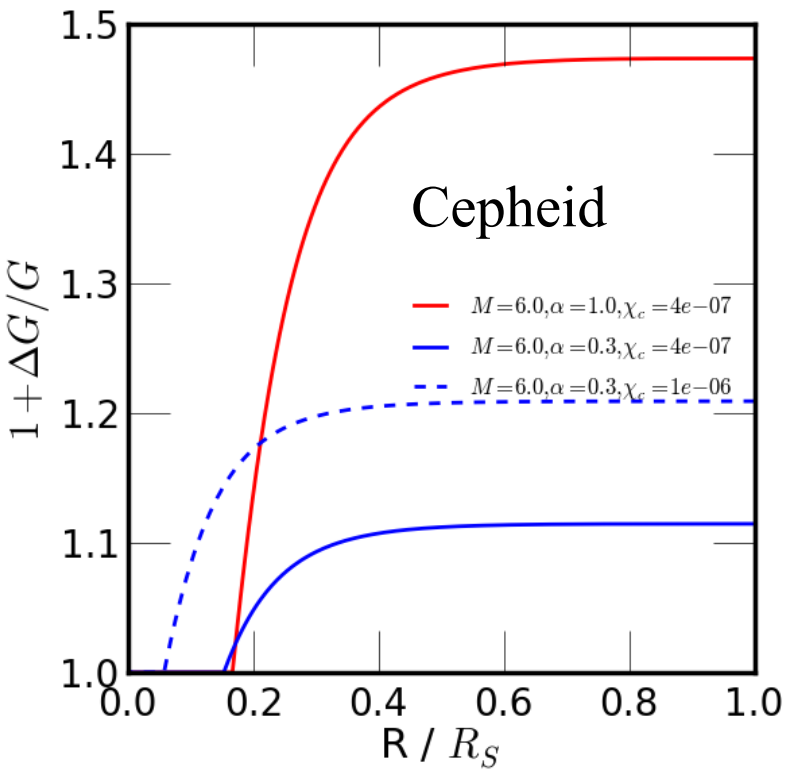


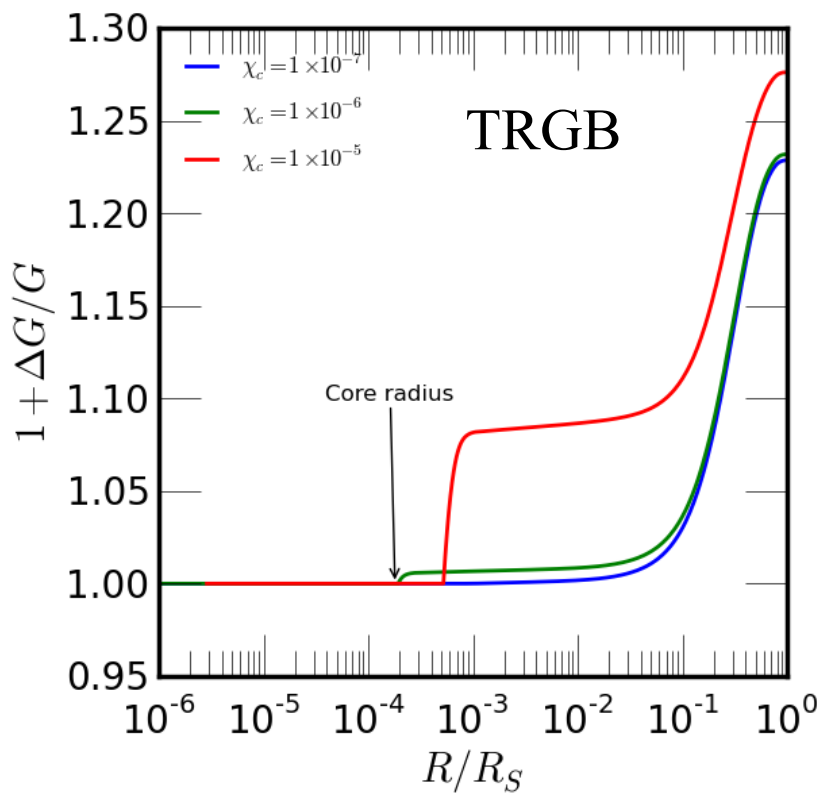
Masers



Two ways of getting purely geometric distance

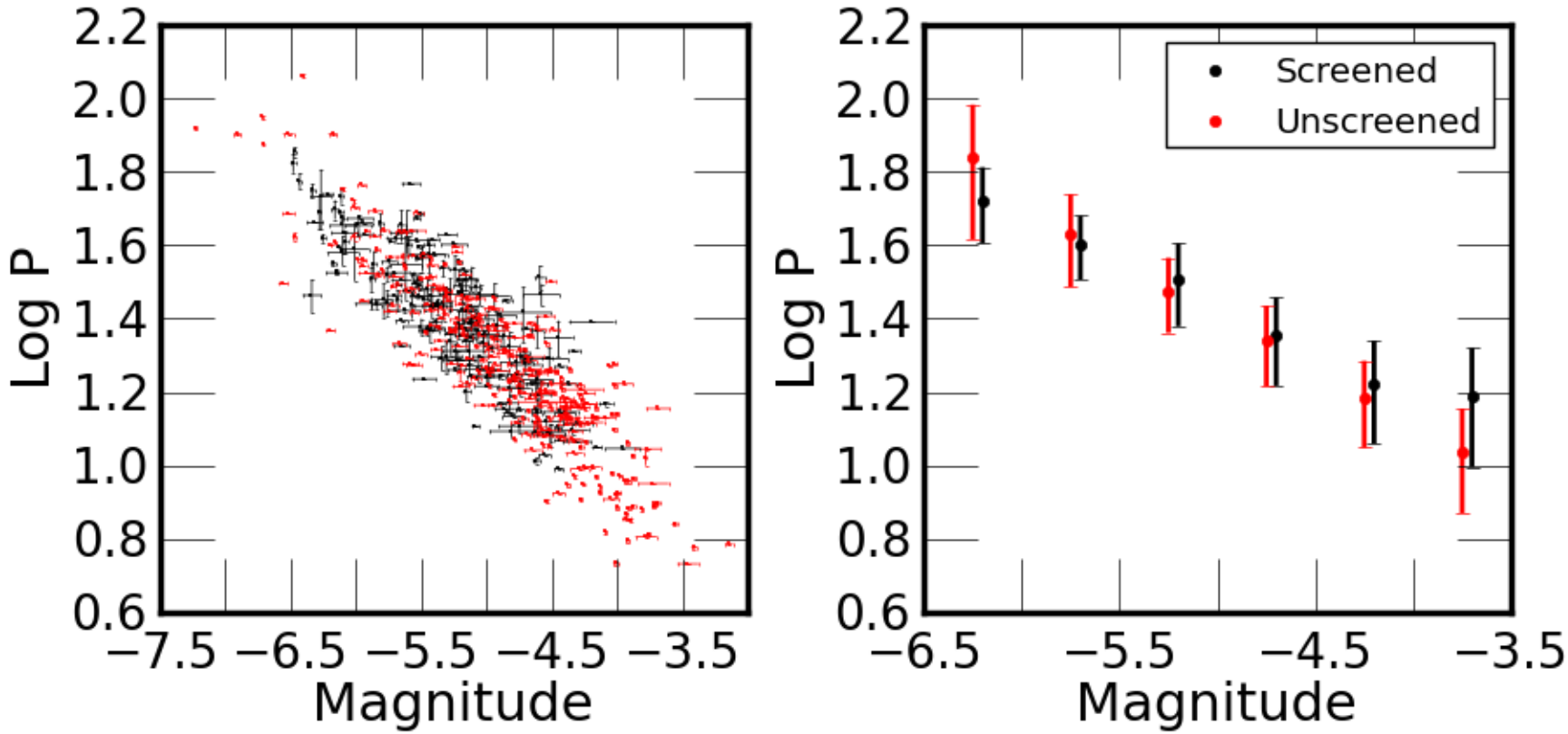
Enhanced G inside giant stars





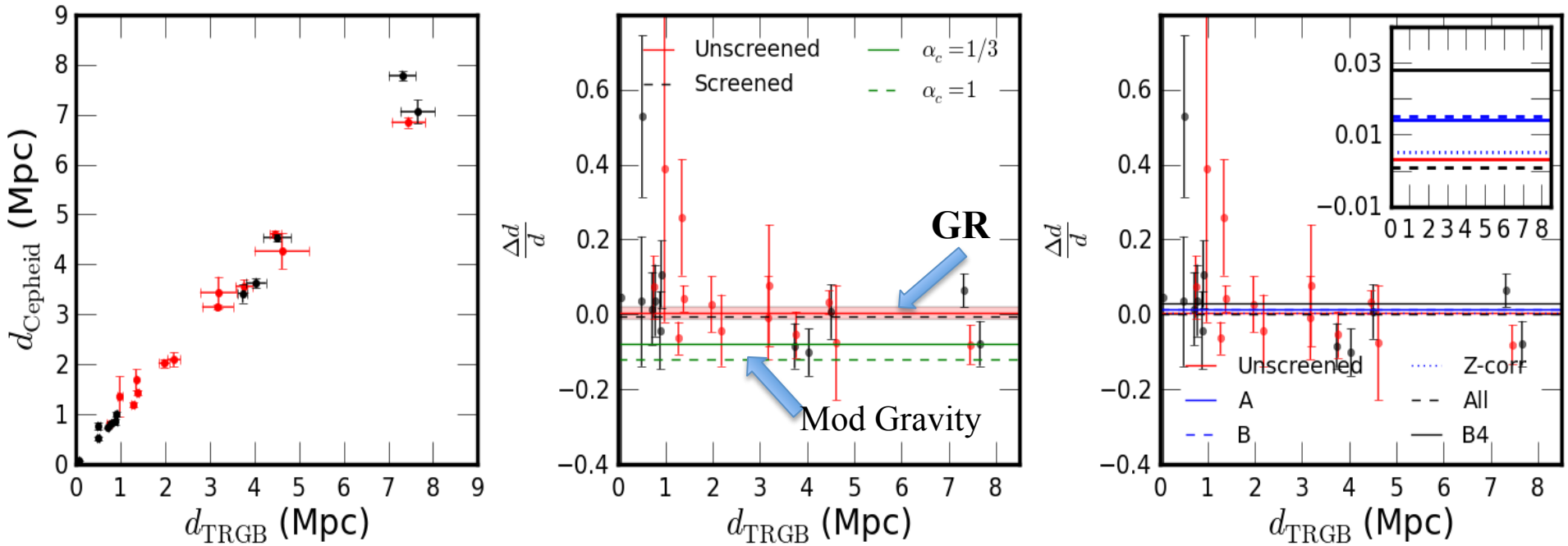
Modified gravity -> enhanced forces in stellar envelopes

Cepheid Period-Luminosity Relation



Screened and unscreened samples have consistent P-L relations.

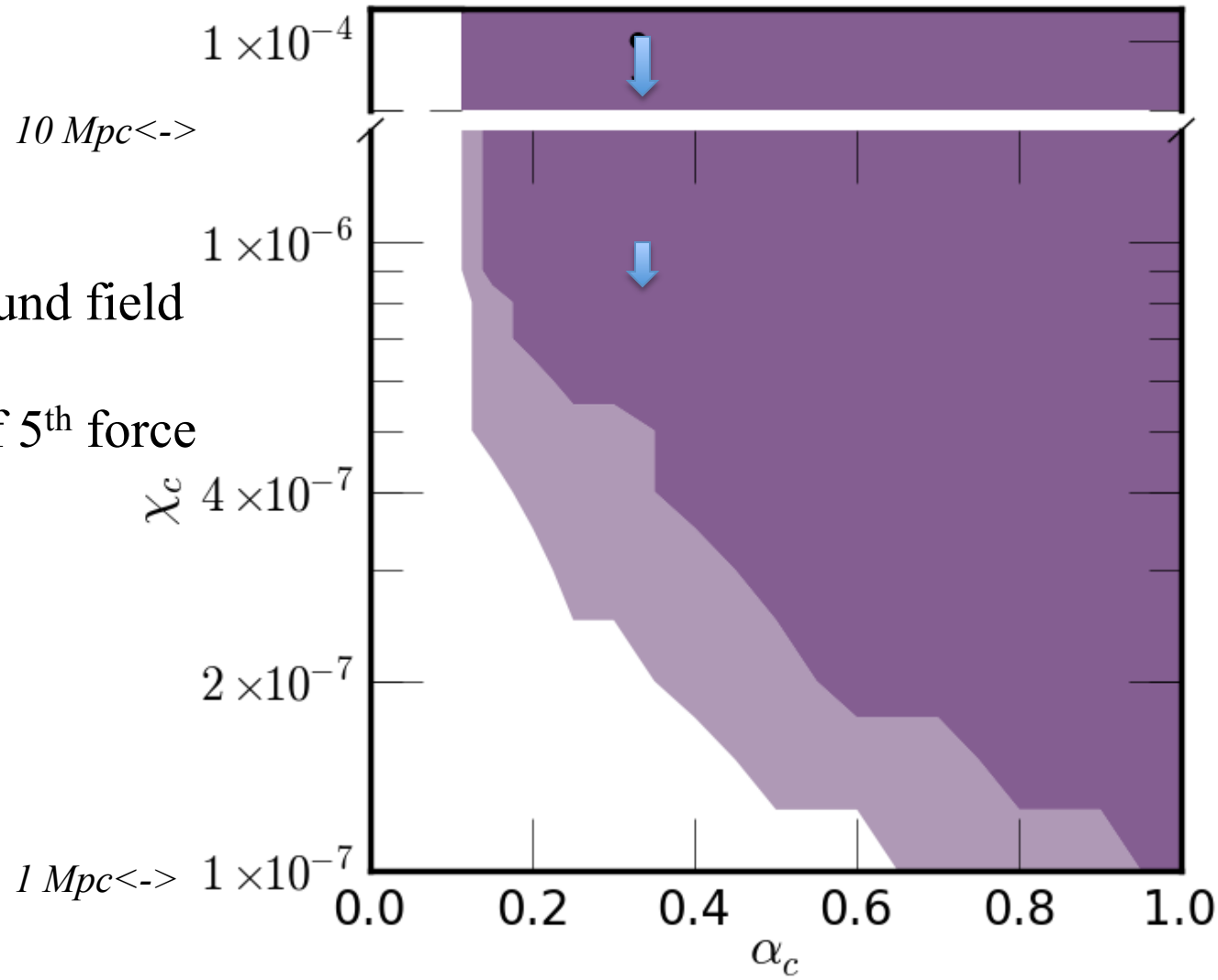
Cepheids vs TRGB distances



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

Chameleon constraints

Background field
or
Range of 5th force



Coupling parameter of scalar to matter

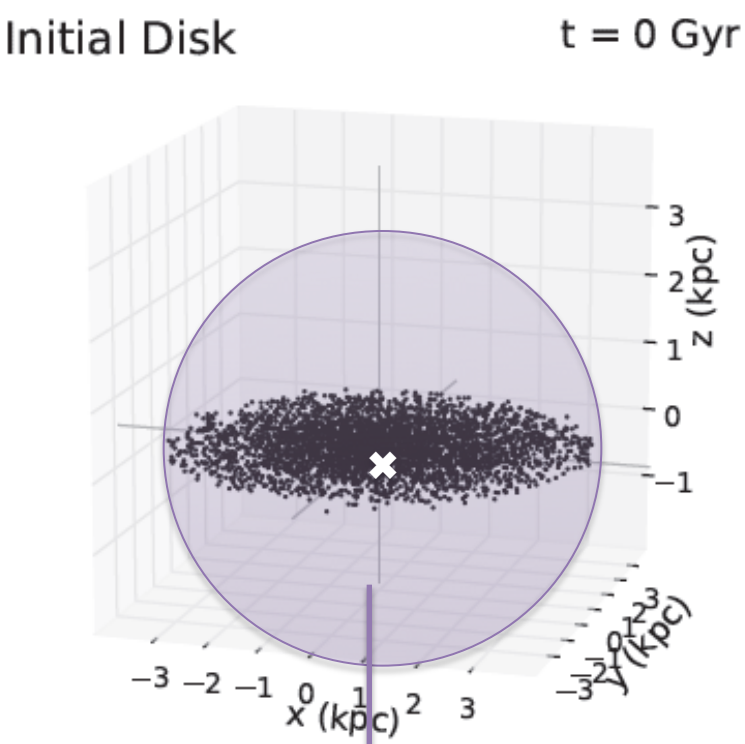
Summary: Constraints on Gravity

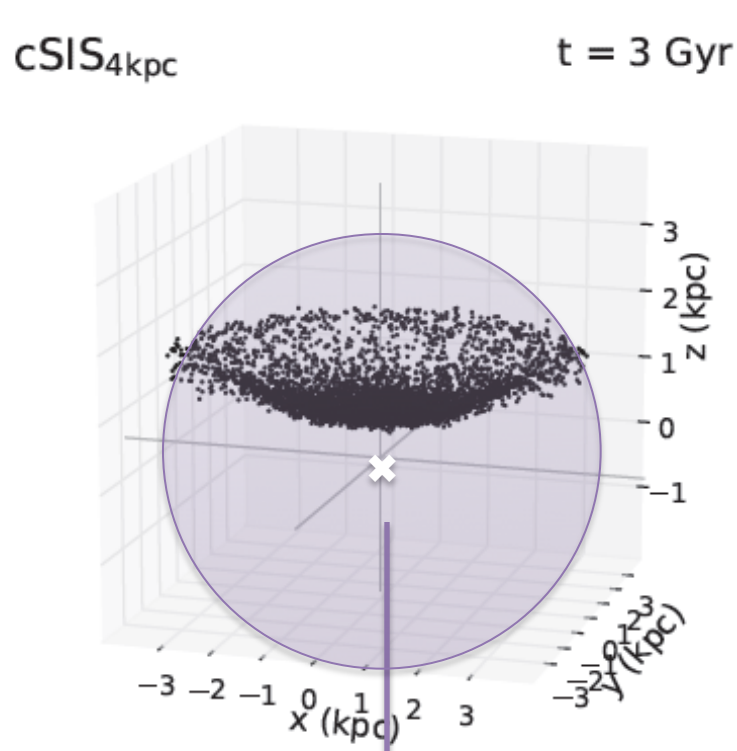
- Coupling Strength α -> $\Delta G/G$
  - α=1/3 for all f(R) gravity models)
- Background field value (aka f_{R0}, or, Range of 5th force) -> Threshold Newtonian Potential which determines screened vs. unscreened halos
- Astrophysical tests with dwarf galaxies and cepheids probe:
  - $f_{R0} > 10^{-7}$ (Fifth force range of >1 Mpc)
  - $\alpha \sim 1/5 - 1$
- No deviations from GR are detected
- Our tests are designed for chameleon theories; also apply to symmetron and possibly to dilaton theories.
- Several caveats apply…

BJ, Vikram & Sakstein 2012

Tests with disk galaxies

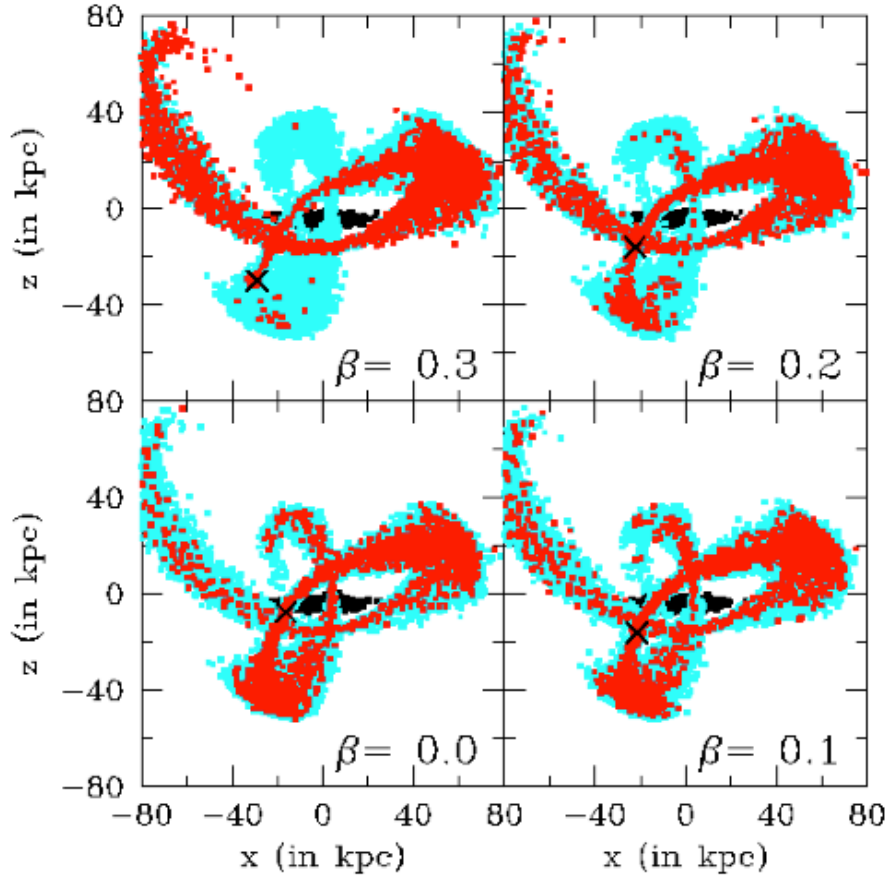
Small scale tests: warps and offsets





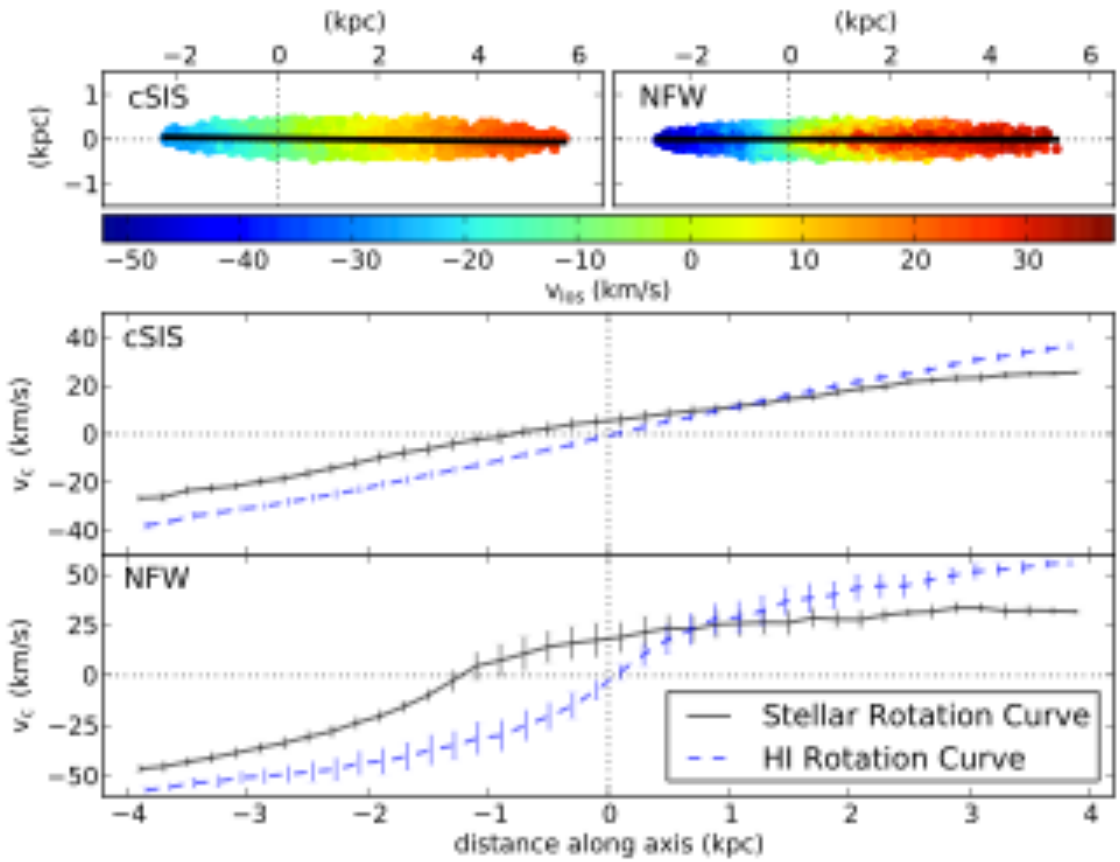
- Enhanced forces between dwarf galaxies can displace stellar disk from halo center
- The gas disk tracks the dark matter halo -> observable offsets

BJ & VanderPlas 2011



- Tidal streams study of Kesden & Kamionkowski (2006) constrained dark matter-only fifth force within the Milky Way. Modified gravity effects are universal and suppressed in Milky way.
- Dwarf galaxies are fascinating for many reasons!

Small Scale Tests: Rotating Disks

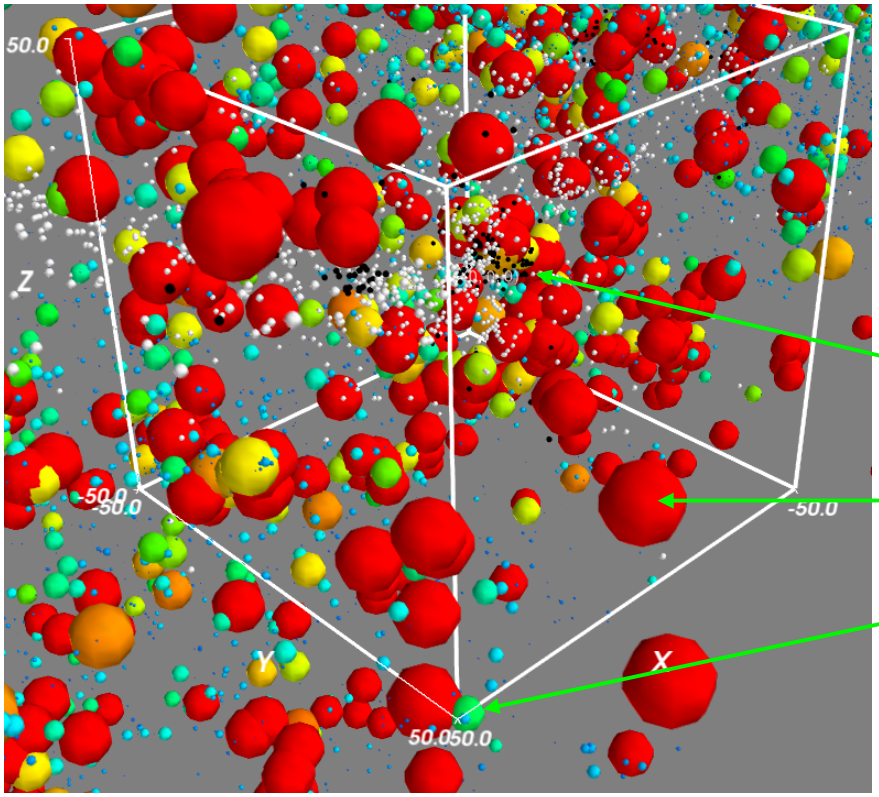


- Rotation curves of stars are displaced from HI gas, and are asymmetric

BJ & VanderPlas 2011; Hui, Nicolis & Stubbs 2009

- Analysis of radio and optical data ongoing: *Vikram et al, in preparation*

How to find (un)screened regions?



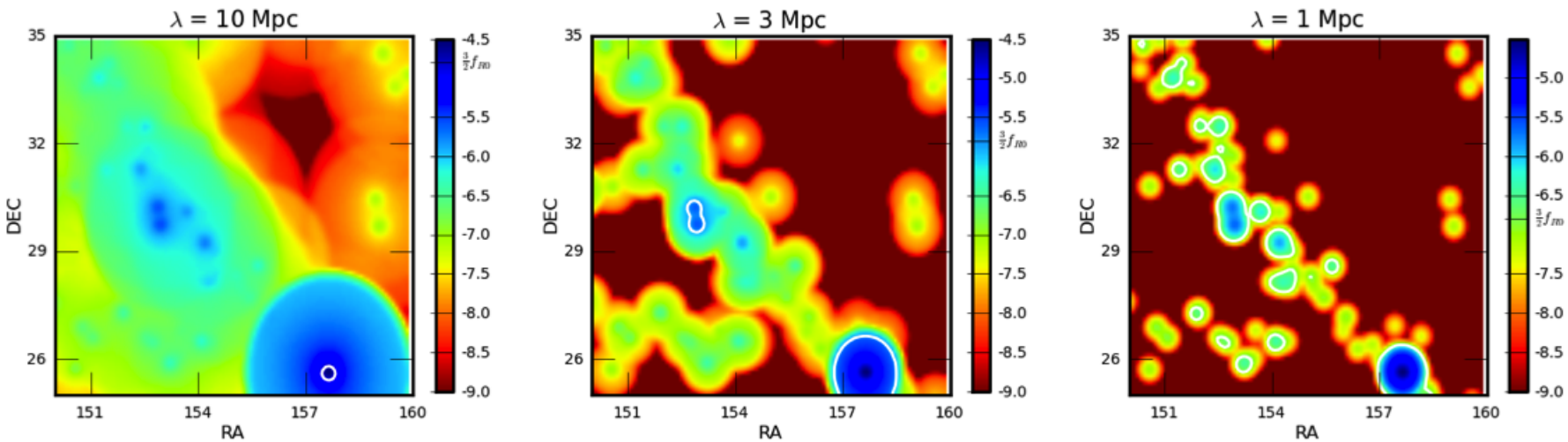
Nearby clusters
SDSS groups
2MASS groups
Nearby galaxies

Dwarf galaxies

Clusters

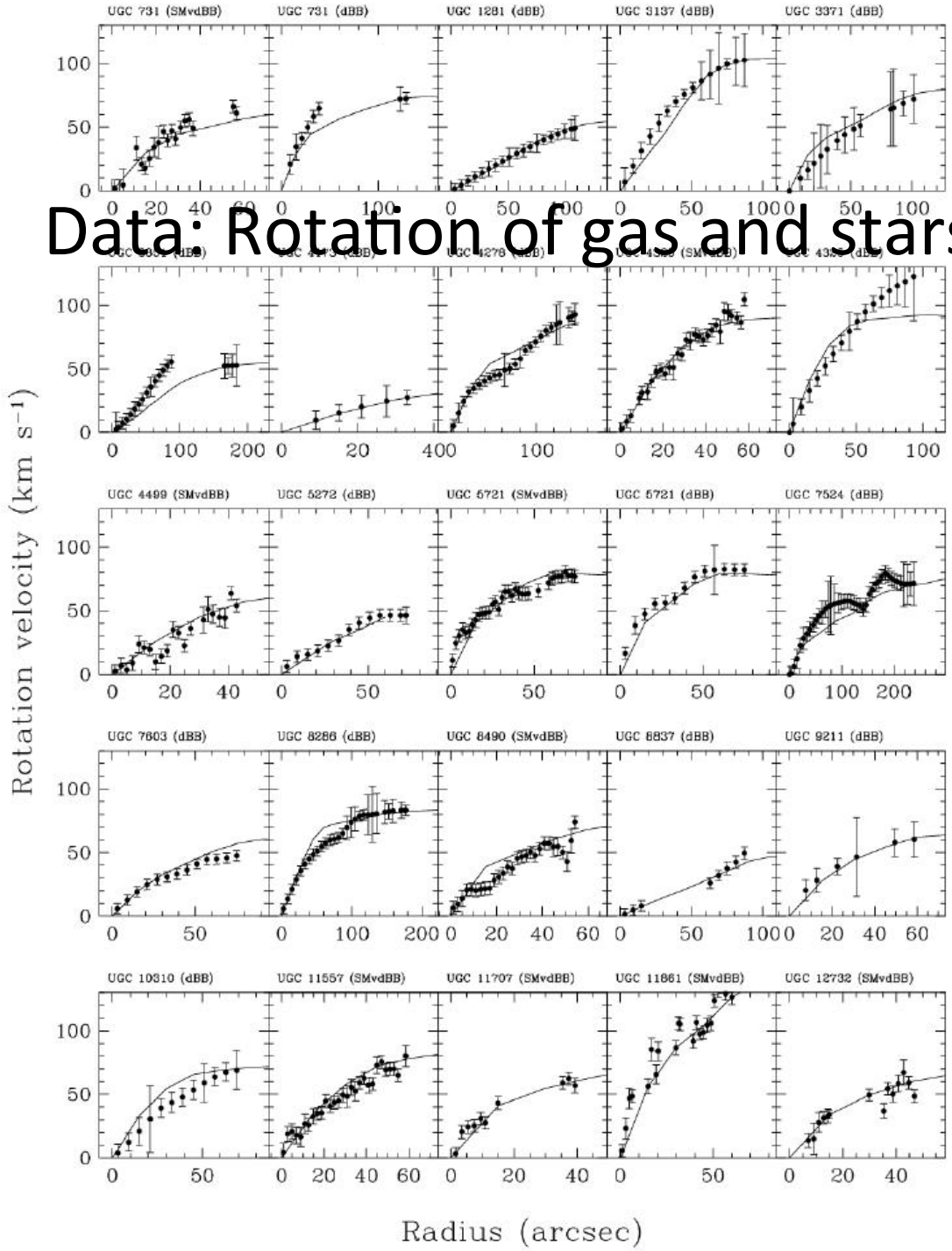
Groups

SDSS screening map

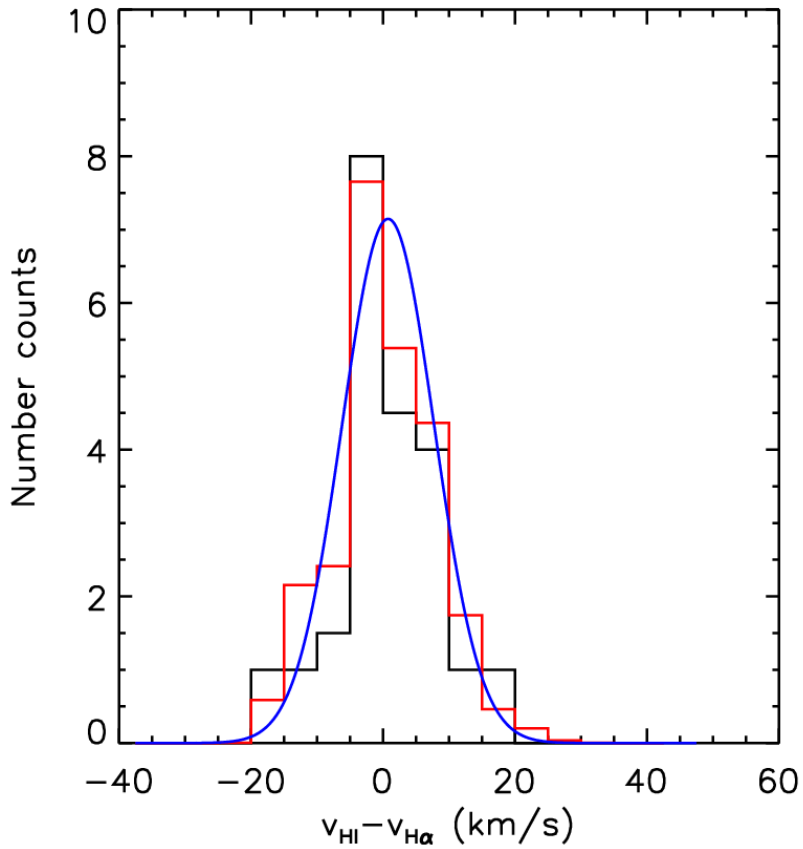


Cabre et al. 2012: publicly available catalog

Data: Rotation of gas and stars

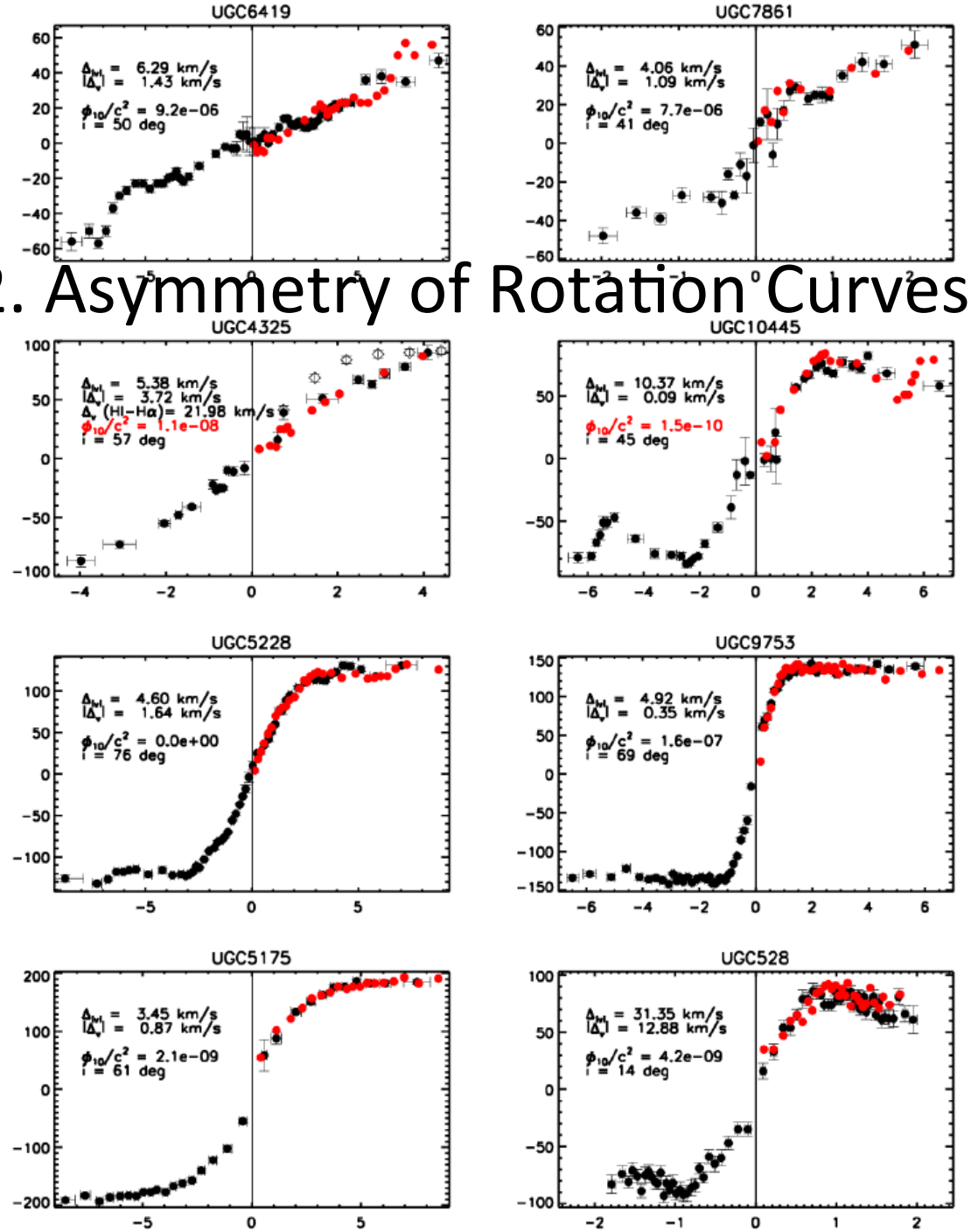


1. Offset in HI vs. Hα rotation curves

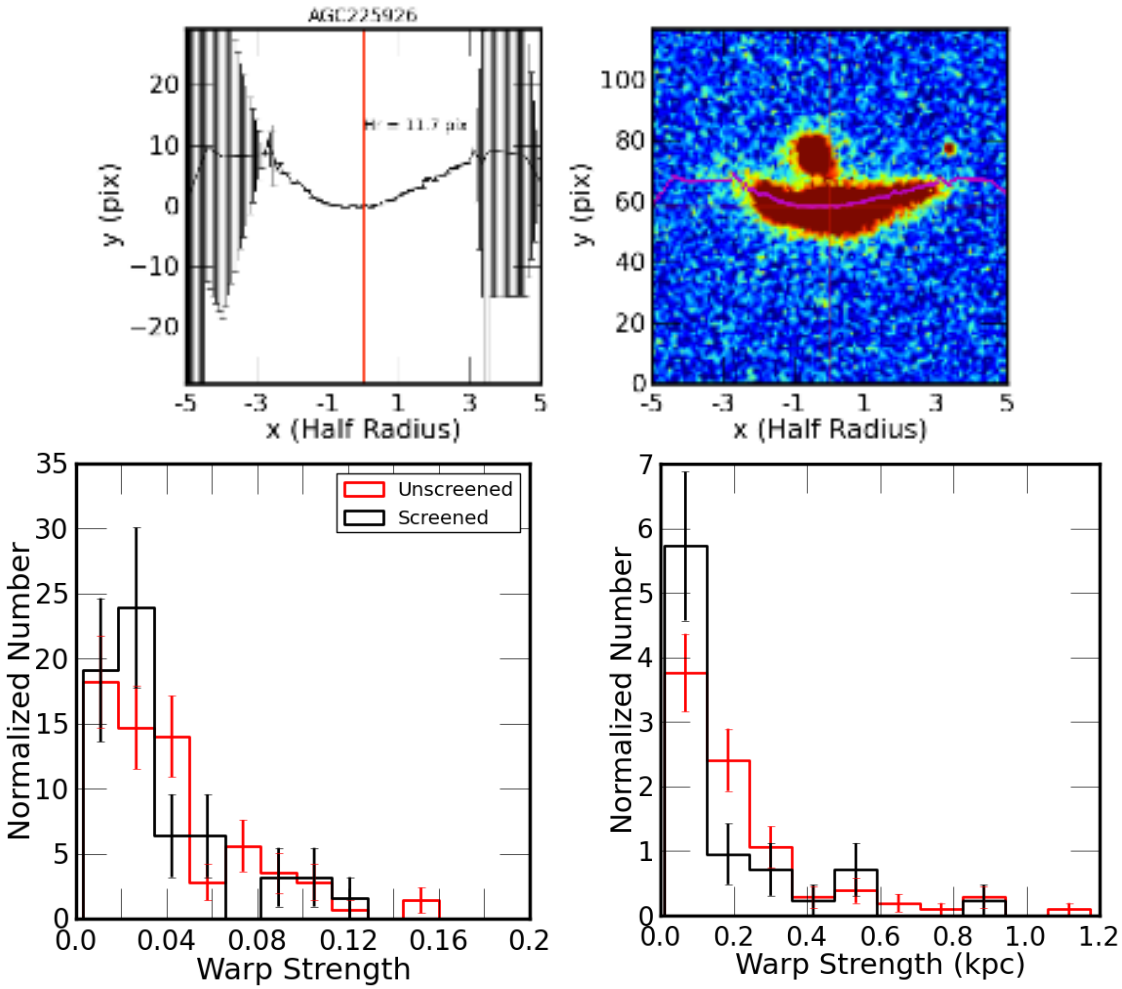


Mean velocity offset is 0.76 +/- 1.49 km/s for a sample of over 20 late-type dwarf galaxies. Expected signal: >5 km/s

2. Asymmetry of Rotation Curves



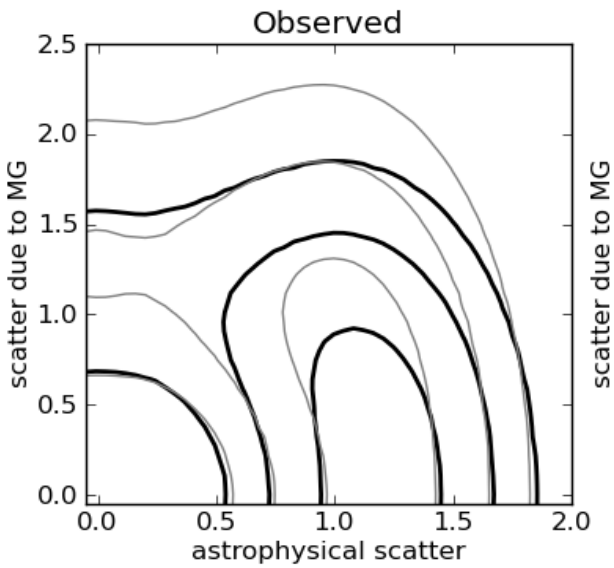
3. Warping of stellar disks

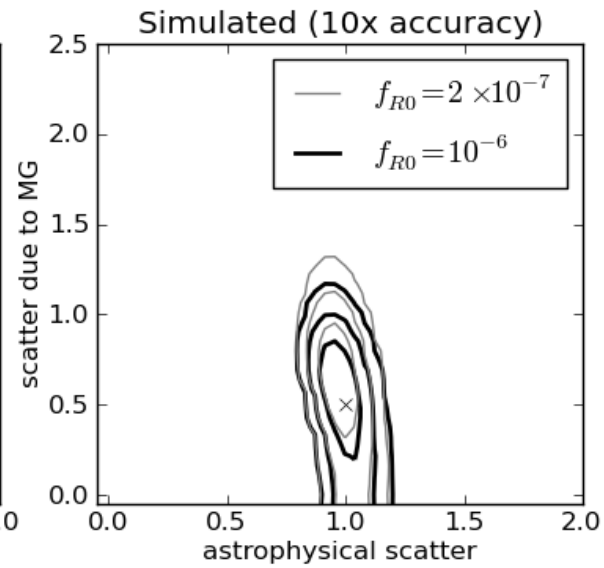


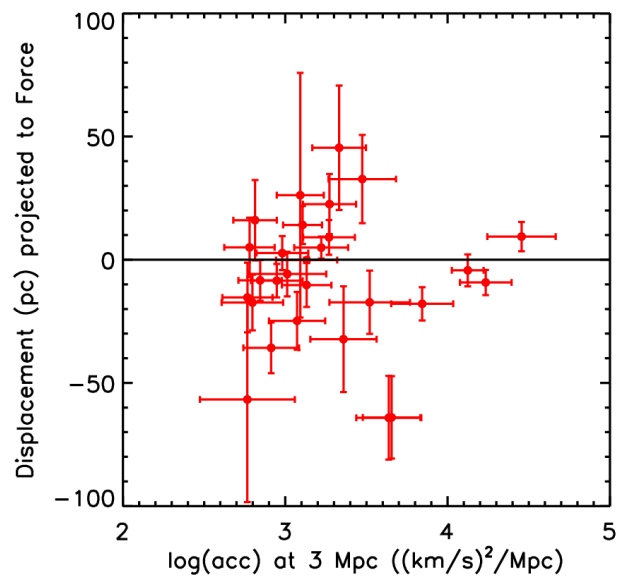
Warps for ~400 galaxies with ALFALFA and SDSS images.

Vikram, Cabre et al, in prep.

4. Small Scale Tests: Offset of Gas and Stars







- Offset between HI gas and stars: requires improved resolution/100x bigger sample
- Offset between centroid of red giants in dwarf galaxies

within 10 Mpc with HST imaging. No trend..

Vikram, Cabre, BJ, Vanderplas 2013

Summary of dwarf galaxy tests

Using 4 different tests of gravity effects on disk galaxies, we obtain complementary constraints on modified gravity theories.

Stepping back: tests at higher redshift and cosmological scales

Halos: 101.1

$$ds^2 = -(1+2\psi)d\mathrm{t}^2 + (1-2\phi)a^2(\mathrm{t})d\mathbf{x}^2$$

•***Lensing***: Einstein Rings, Shear, Magnification:
Measures ($\phi+\psi$). Relation to mass involves Poisson eqn.

•***Dynamics***: Velocity dispersion, Rotation, Infall:
Measures Newtonian potential ψ

$M_{lensing} = (1+\gamma)/(2\gamma)\ M_{dynamics}$, $\gamma = \psi/\phi$

•If we use the same set of galaxies, can compare halo dynamics and lensing without needing the relation of galaxies to host halos.

Small Scale Tests at z>0.1: Einstein rings

$\gamma = \psi/\phi = 1.01+/-0.05$ from Einstein Rings + velocity dispersion

Error bars are statistical.

Bolton et al 2006; Schwab, Bolton, Rappaport 2010

Linear Regime Growth Factors

$$ds^2 = -(1+2\psi)d\mathrm{t}^2 + (1-2\phi)a^2(\mathrm{t})d\mathbf{x}^2$$ **Metric**

$$\nabla^2(\psi+\phi) = 8\pi G_{eff} a^2 \bar{\rho}\delta$$ **Poisson**

$$\eta = \phi/\psi$$

η and G_{eff} can be scale and time dependent in modified gravity

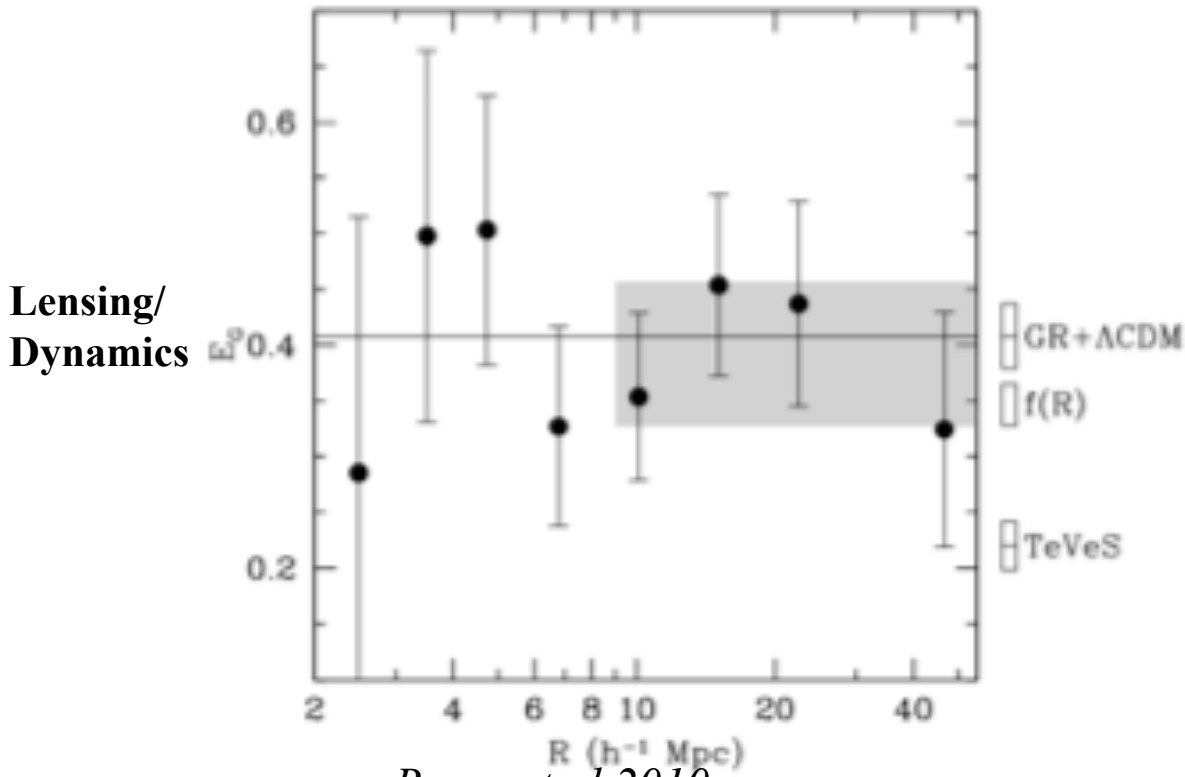
$$\delta'' + 2H\delta' - \frac{8\pi G_{eff}}{1+\eta}\bar{\rho}a^2\delta = 0$$

Different growth factors for density and metric potentials:

- Density growth factor: $D_\delta(z,k)$
- Lensing growth factor: $D_{\psi+\phi} \propto G_{eff}\, D_\delta$,
- Dynamical growth factor $D_\psi = \eta/(1+\eta)\, D_{\psi+\phi}$

This description is valid on scales of 10s-100s Mpc.

Tests on Large Scales: Lensing+Dynamics

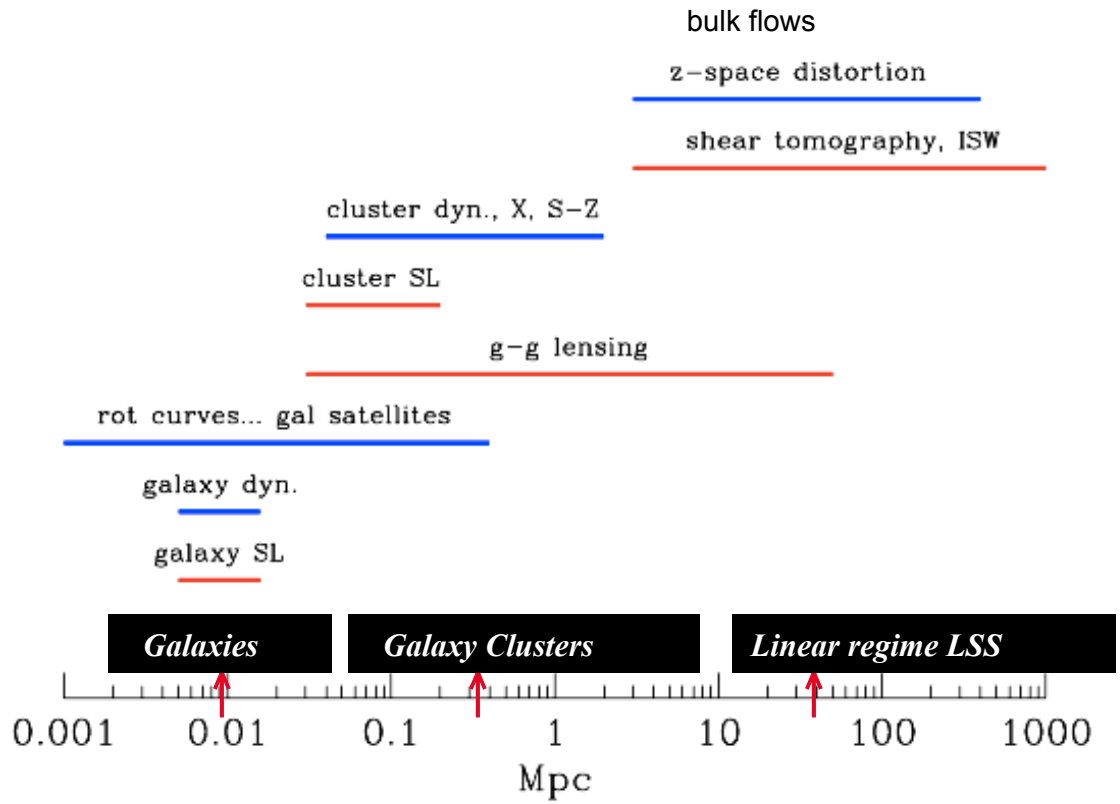


Reyes et al 2010

- SDSS data: 20% test of gravity at 10-30 Mpc scale
- Other large-scale tests: CMB, ISW, galaxy clustering, lensing, cluster counts
- Caveat: signal appears to be weak if current models are any indication

Zhang et al 2007; BJ & Zhang 2007; Schmidt, Vikhlinin, Hu 2010; Lombriser et al 2010; Appleby & Linder 2012

Astrophysical and cosmological probes of gravity



BBN+CMB

Dynamical probes (blue) measure Newtonian potential ψ

Lensing and ISW (red) measures $\phi + \psi$ *Jain & Khoury 2010*

Research program for dark energy (BOSS, DES, LSST, MS-DESI) can be augmented to test gravity.

What next for gravity tests?

- What kind of gravity test will be most powerful?
  - Depends on the theory, and we don't have a working model at the moment, so need to keep an open mind. But screening mechanisms are generic and some signatures of different mechanisms are already known
  - Lab, solar system, stellar, intra- and inter-galactic scales all have potential: see talks by Amol Upadhye, Fabian Schmidt and Andrew Tolley

- What can we do now for astrophysical tests?
  - Study the instrumental capabilities for studying individual galaxies via:
    (a) high resolution imaging, (b) spectroscopy and (c) radio observations of HI disks
  - Scope out other tests, such as via pulsars and supermassive black holes, and figure out the instrumental needs
  - Map out the nearby universe to determine screening level in different scenarios
  - Develop detailed predictions for screening mechanisms: how well can this be done without full models?

- Cosmological scale tests will be carried out by surveys already planned. There is ongoing work on fashioning the tests.