Significance of relativistic dynamics to the Dark Matter problem.

A. Deur

Uppsala, Sept. 24th 2020

A.D., C. Sargent, B. Terzić, ApJ 896 2, 94 (2020)
A.D., EPJC 79 10, 883 (2019)
A.D., EPJC 77 6, 412 (2017)
A.D., MNRAS, 438, 1535 (2014)
A.D., PLB, 676, 21 (2009)

Dark Matter

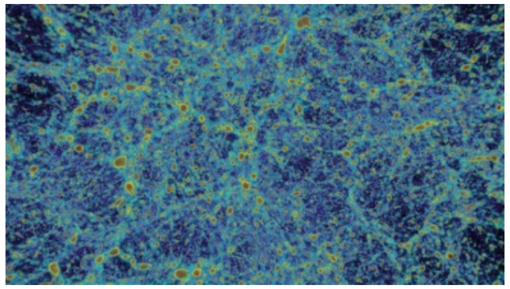
Dark Matter is ubiquitous in the universe.
It is estimated to represent 85% of the matter in the universe and 27% of its mass.

What it is needed for:

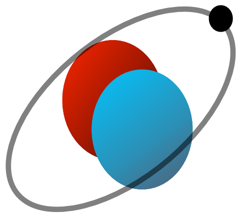
- Explains the fast rotation of disks galaxies.

- Keeps galaxies confined in clusters.

- Speed-up large structure formations.



- Needed for Cosmic Microwave Background anisotropy distributions
- Add necessary non-baryonic density explaining amount of deuteron created in primordial nucleosynthesis.

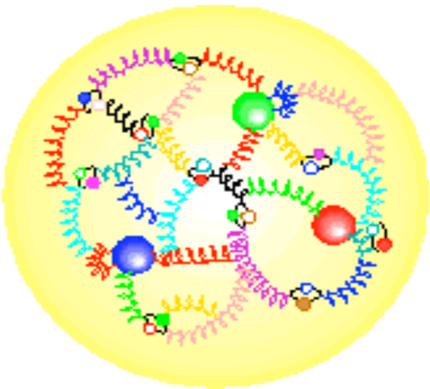


- Etc…

What it is remains a mystery.

Our Ariadne thread: Quantum Chromodynamics (QCD)

QCD: Theory of the strong force binding quarks into hadrons.



The vectors of the strong force (the gluons) carry color charges.

⇒ They interact with each other. Origin of quark and gluon confinement.

We will follow here our QCD/Ariadne thread.
⇒ Not an exhaustive survey of the possible solutions to the dark matter mystery.

What can QCD teach us about dark matter?

- Electric force
  Magnetic force } QED
  Weak force } Electroweak force
  QCD
  ? } Supersymmetric grand unified theory?

  ⇒WIMPs

- QCD is free to violate Charge-Parity (CP) symmetry. Yet, there is no evidence of violation. To force QCD to not be CP-violating, add new symmetry which is spontaneously broken.

  ⇒Axions

What can QCD teach us about dark matter?

- Electric force
  Magnetic force } Q

  Most natural SUSY has not been found at LHC.

  Weak force } force ? } Supersymmetric grand unified

  ⇒WIMPs

  Direct searches (LUX, CDMS...) or production (LHC,...) are so far negative and most favored models are ruled out.

- QCD is free to violate Charge-Parity (CP) symmetry. Yet, there is no evidence of violati... new symmetry which is spontaneously broken.

  The WIMP miracle did not come to pass.

  ⇒Axions

  Axions searches (ADMX, XENON) have also excluded favored phase space.

What can QCD teach us about dark matter?

- Electric force, Magnetic force } QED; QED, Weak force } Electroweak force; Electroweak force, QCD } ? Supersymmetric grand unified theory?

  ⇒WIMPs

- QCD is free to violate Charge-Parity (CP) symmetry. Yet, there is no evidence of violation. To force QCD to not be CP-violating, add new symmetry which is spontaneously broken.

  ⇒Axions

- QCD and gravity have a similar underlying structure (similar field Lagrangians). Complex QCD effects (e.g. confinement) could not have been predicted.
  ⇒Hard to guess the consequences of the similar Lagrangian of gravity.

⇒Look for parallels between hadron phenomenology and dark matter observations.

Key facts of Strong Force

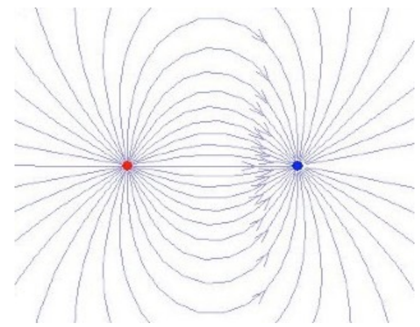
Facts

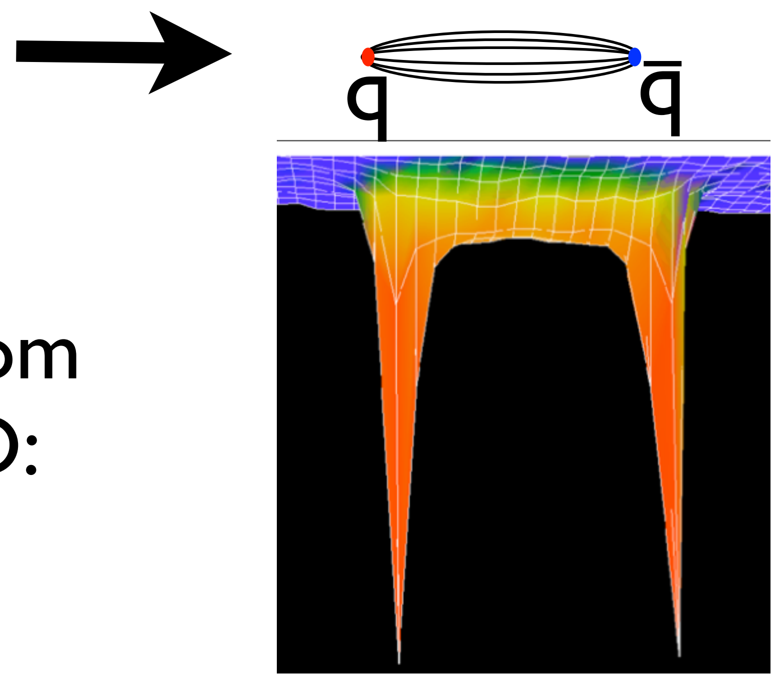
- Quarks and gluons are confined inside hadrons

Explanations

Strong force coupling is large & gluons are color-charged

$\Rightarrow$ field-lines collapse into string-like flux-tubes.





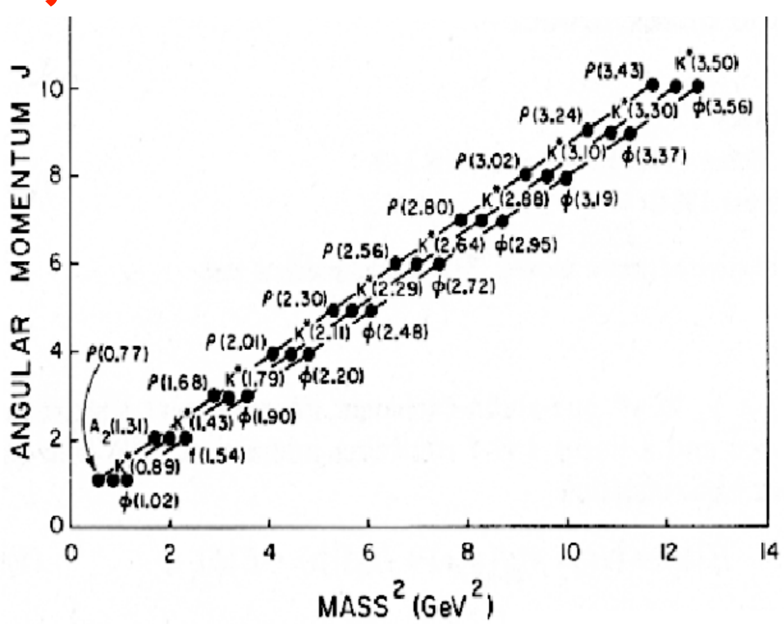
Evidences from lattice QCD:

Key facts of Strong Force

Facts

- Quarks and gluons are confined inside hadrons

- Hadrons lie on Regge trajectories

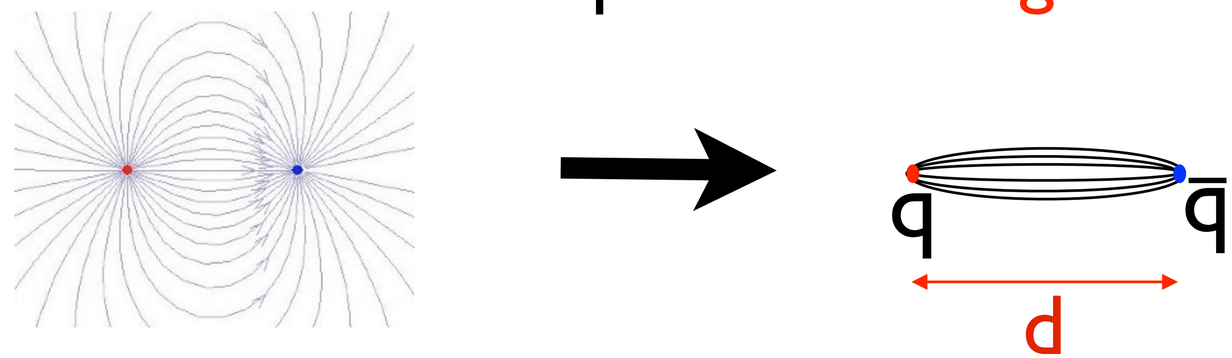


- Strong force not felt at large distances (but for residual effects: Yukawa potential, etc...)

Explanations

Strong force coupling is large & gluons are color-charged

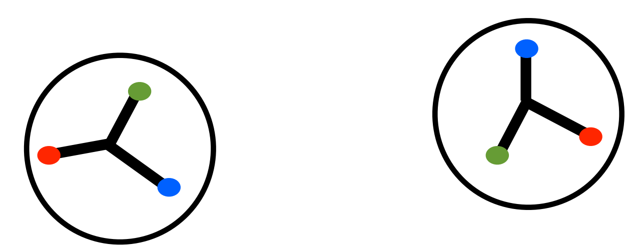
$\Rightarrow$ field-lines collapse into string-like flux-tubes.



The more a hadron spins, the larger the binding energy (i.e. the mass) to compensate for the centrifugal force.

String Potential $\propto$ d $\Rightarrow$ Ang. Mom. $\propto M^2$+constant

Field lines (i.e. gluons) are inside the hadron.



Empirical parallels between cosmology and hadronic physics

Cosmology

Galaxies (or clusters of galaxies) have a larger mass than the sum of their known constituents.

Tully-Fisher relation:

$\log(M)=\gamma\log(v)+\varepsilon$ (γ=3.9±0.2, ε ~1.5)

(M galaxy visible mass, v rotation speed)

Hadronic physics

2 quarks ~7 MeV, Pion mass 140 MeV

3 quarks ~9 MeV, Proton: 938 MeV

Regge trajectories:

$\log(M)=c\,\log(J)+b$ (c=0.5)

(M, hadron mass, J angular momentum)

Empirical parallels between cosmology and hadronic physics

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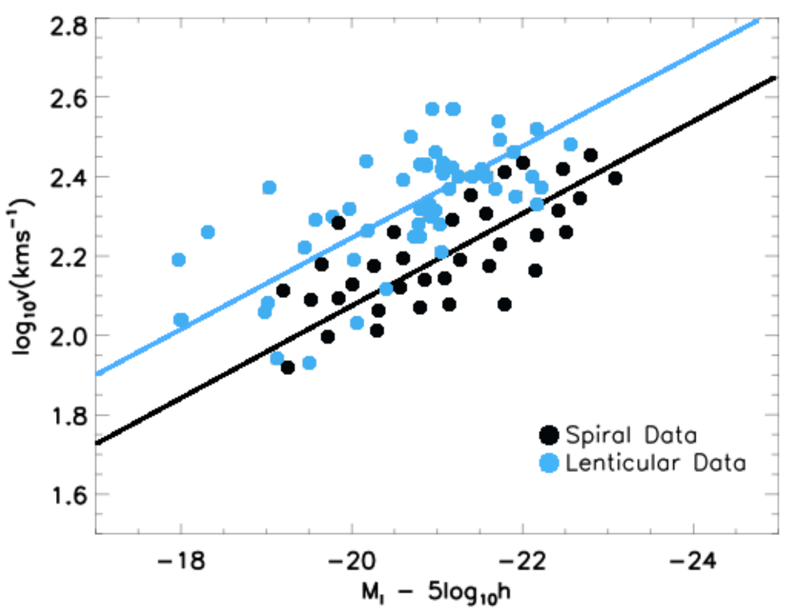
Galaxies (or clusters of galaxies) have a larger mass than the sum of their known constituents.

Tully-
log(~1.5)
(M gal speed)



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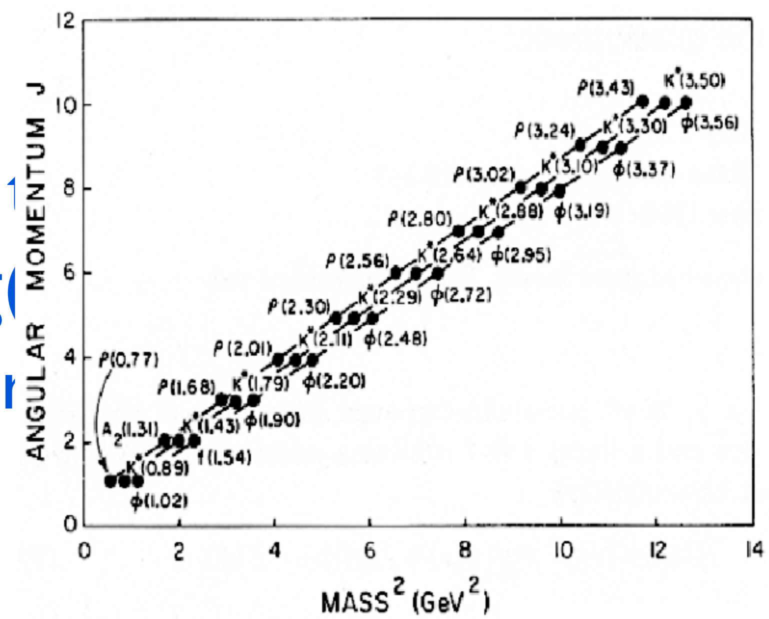

Empirical parallels between cosmology and hadronic physics

Cosmology	Hadronic physics
Galaxies (or clusters of galaxies) have a larger mass than the sum of their known constituents.	2 quarks ~7 MeV, Pion mass 140 MeV 3 quarks ~9 MeV, Proton: 938 MeV
Tully-Fisher relation: $\log(M)=\gamma\log(v)+\varepsilon$ ($\gamma=3.9\pm0.2$, $\varepsilon\sim1.5$) (M galaxy visible mass, v rotation speed)	Regge trajectories: $\log(M)=c\log(J)+b$ ($c=0.5$) (M, hadron mass, J angular momentum)
Negative pressure pervades the Universe and repels galaxies from each other.	Strong force ~0 outside hadrons (only residual Yukawa force).
Presently, gravity + dark energy ~ 0 at large distance (cancel in Universe's evolution). "Cosmic coincidence".	

Intriguing correspondence between key phenomena of hadronic physics and observations involving dark matter and dark energy.

It might be due to the similarities between gravity's underlying theory (General Relativity) and that of the strong force (QCD).

Theoretical parallels between gravity and the strong force

General Relativity

$$\mathcal{L}_{GR} = \frac{1}{16\pi G}\sqrt{-g}\; g^{\mu\nu} R_{\mu\nu}$$

Curvature tensor

det $g_{\mu\nu}$

Metric tensor

Expand $\mathcal{L}_{GR}$ in term of gravity field $\psi_{\mu\nu}$ by developing $g_{\mu\nu}$ around the flat metric:
$g_{\mu\nu} \sim \eta_{\mu\nu} + G^{1/2}\psi_{\mu\nu} + \ldots$

$$\mathcal{L}_{GR} = [\partial\psi\partial\psi] + \sqrt{16\pi G}[\psi\partial\psi\partial\psi] + 16\pi G[\psi^2\partial\psi\partial\psi] + \ldots$$

(pure field Lagrangian)

Newton's gravity (static case): 1/r potential

QCD

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^{\mu\nu}F_{\mu\nu}$$

(pure field Lagrangian)

Expand $\mathcal{L}_{QCD}$ in term of gluon field ψ^a_μ:

$$\mathcal{L}_{QCD} = \frac{1}{4}[\partial\psi\partial\psi] + \sqrt{\pi\alpha_s}\,[\psi^2\partial\psi] - \pi\alpha_s[\psi^4]$$

(pure field Lagrangian)

Perturbative QCD (static case): 1/r potential

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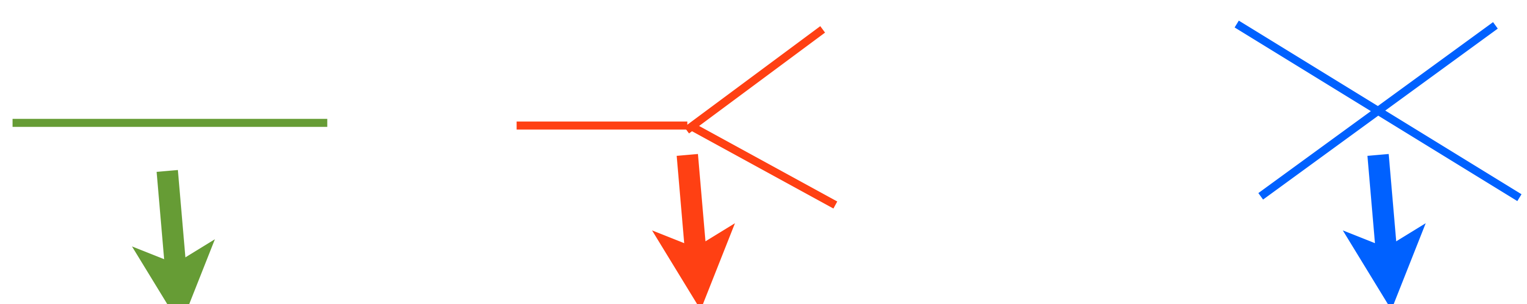
Field self-interaction terms



$$\partial\psi\partial\psi \quad + \quad G^{1/2}\psi\partial\psi\partial\psi \quad + \quad G\psi^2\partial\psi\partial\psi$$

Theoretical parallels between gravity and the strong force

General Relativity

$$\mathscr{L}_{GR}= \frac{1}{16\pi G}\sqrt{-g}\, g^{\mu\nu}R_{\mu\nu}$$

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$$\boxed{\mathscr{L}_{QCD}=\frac{1}{4}[\partial\psi\partial\psi]+ \sqrt{\pi\alpha_s}\,[\psi^2\partial\psi]- \pi\alpha_s\,[\psi^4]}$$

(pure field Lagrangian)

Differences between GR and QCD

- G is very small ($GM_p^2=5.9\times10^{-39}$)
- Tensor field, spin: 2 (gravity always attracts ⇒ gravity effects add up)

- α_s is large: ~0.1
- Gluon spin: 1 (QCD attracts or repulses, as for QED)

That $\sqrt{16\pi G}$ is small can be compensated by large ψ for massive enough systems (see QED and non-linear optics).

⇒ $\sqrt{16\pi G}\,[\psi\partial\psi\partial\psi]$ can be significant.

⇒ Open possibility for gravity self-interaction to generate similar effects to those seen in QCD

Near a proton $\sqrt{16\pi G M_p/r_p} = 1\times10^{-17}$ with M_p the proton mass and r_p its radius.

⇒Self-interaction effects are negligible:

$$\mathscr{L}_{GR}=[\partial\psi\partial\psi]+\sqrt{G}\,[\psi\partial\psi\partial\psi]+G[\psi^2\partial\psi\partial\psi]+\ldots$$

~0

For a typical galaxy: $\sqrt{16\pi G M/size_{system}} \sim 0.05$.

If GR's self-interaction is not negligible: causes an increase in gravitational force.

If galaxy dynamics analyzed using Newton's law, this increase would appear as a missing mass (Dark Matter).

Quantitative estimate of gravity's self-interaction

$$\boxed{\mathscr{L}_{GR}=[\partial\psi\partial\psi]+\sum_{n=1}(16\pi G)^{n/2}[\psi^n\partial\psi\partial\psi]-\sum_{n=1}(16\pi G)^{n/2}\psi^{n-1}\psi_{\mu\nu}T^{\mu\nu}}$$

Short hand for sum of possible Lorentz-invariant terms of form $[\partial\psi\partial\psi]$.

Explicitly given by the Fierz-Pauli Lagrangian:

$$[\partial\psi\partial\psi]\equiv\tfrac{1}{2}\partial^\lambda\psi_{\mu\nu}\partial_\lambda\psi^{\mu\nu} - \tfrac{1}{2}\partial_\lambda\psi^\mu_\mu\partial^\lambda\psi^\nu_\nu - \partial^\lambda\psi_{\lambda\nu}\partial_\mu\psi^{\mu\nu} -\partial^\nu\psi^\lambda_\lambda\partial^\mu\psi_{\mu\nu}$$

Quantitative estimate of gravity's self-interaction

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For a stationary system, we approximate ψ as scalar (ψ_{00} component)

$$\mathscr{L}_{GR}=\partial\psi\partial\psi+\sqrt{16\pi G}\psi\partial\psi\partial\psi+16\pi G\,\psi^2\partial\psi\partial\psi+\ldots+\sqrt{16\pi G}\,\psi_{00}T^{00}$$

Use Feynman path-integral formalism on a lattice to obtain gravity's potential.

Stationary system:

- 3D problem (ignore time dimension);
- Instantaneous potential given by 2-point Green's function;
- Results are classical: Path-integral weight: $e^{-iS/\hbar}$

$S \overset{\text{def}}{=} \int \mathscr{L}\, d^4x=\tau\int\mathscr{L}\, d^3x=\tau S'$ with $\tau\rightarrow\infty$.

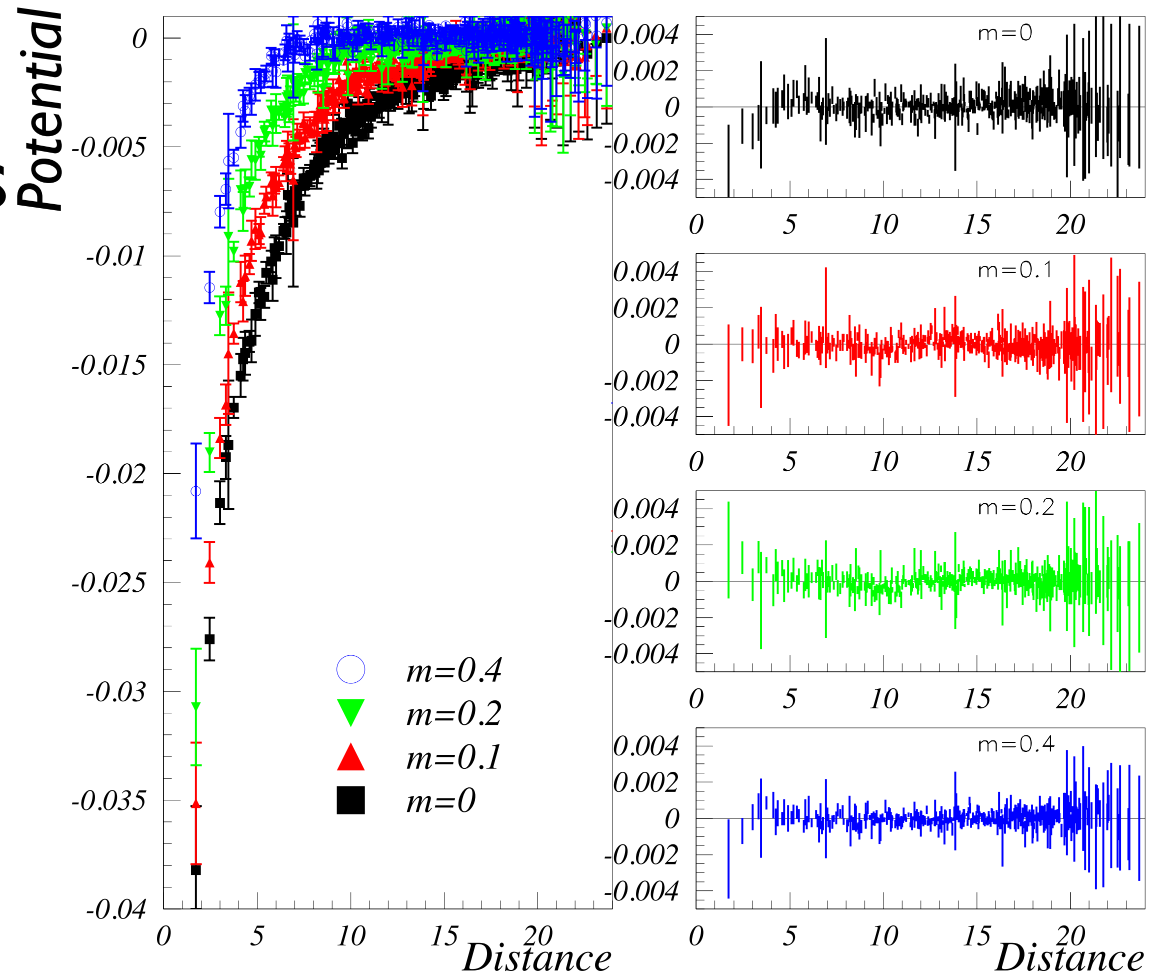
$e^{-iS'\tau/\hbar}$ with $\tau/\hbar\rightarrow\infty \equiv \hbar\rightarrow 0$: classical case.

($\tau\rightarrow\infty$ equivalent to hight temperature limit in condensed matter. Hight temperature limit $\equiv$ classical limit)

Verifications

Calculation:

Recover Newton and Yukawa potentials



Verifications

Calculation:

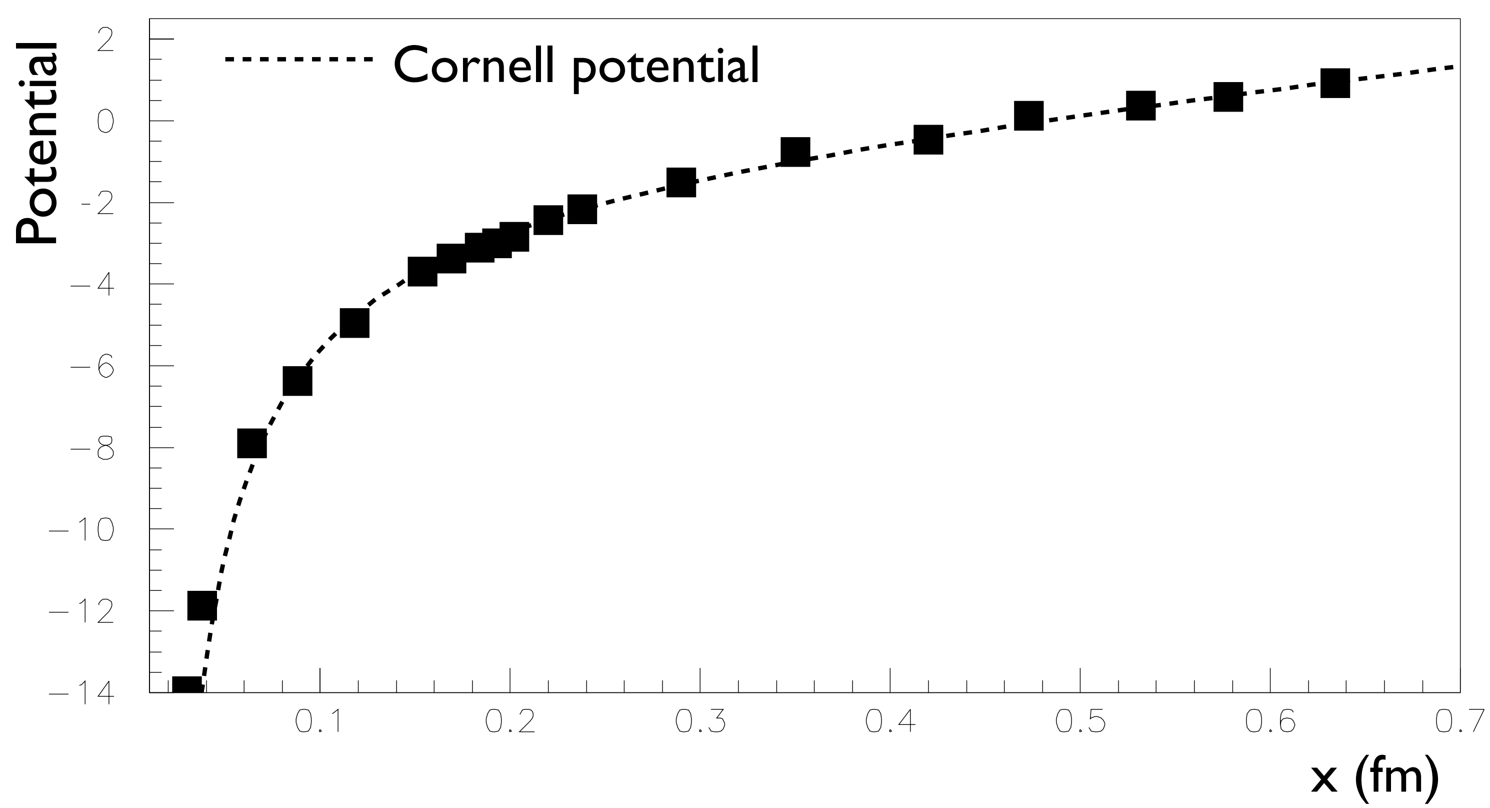
Recover Newton and Yukawa potentials (no self-coupling)

Apply the same approximation to $\mathscr{L}_{QCD}$ (toy model):

Mass gap;

Running effective field mass similar to QCD's gluon effective mass from Schwinger-Dyson Equations.

Running coupling ⇒ Recover Cornell potential (potential for static quarks).



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Mass gap;

Running effective field mass similar to QCD's gluon effective mass from Schwinger-Dyson Equations.

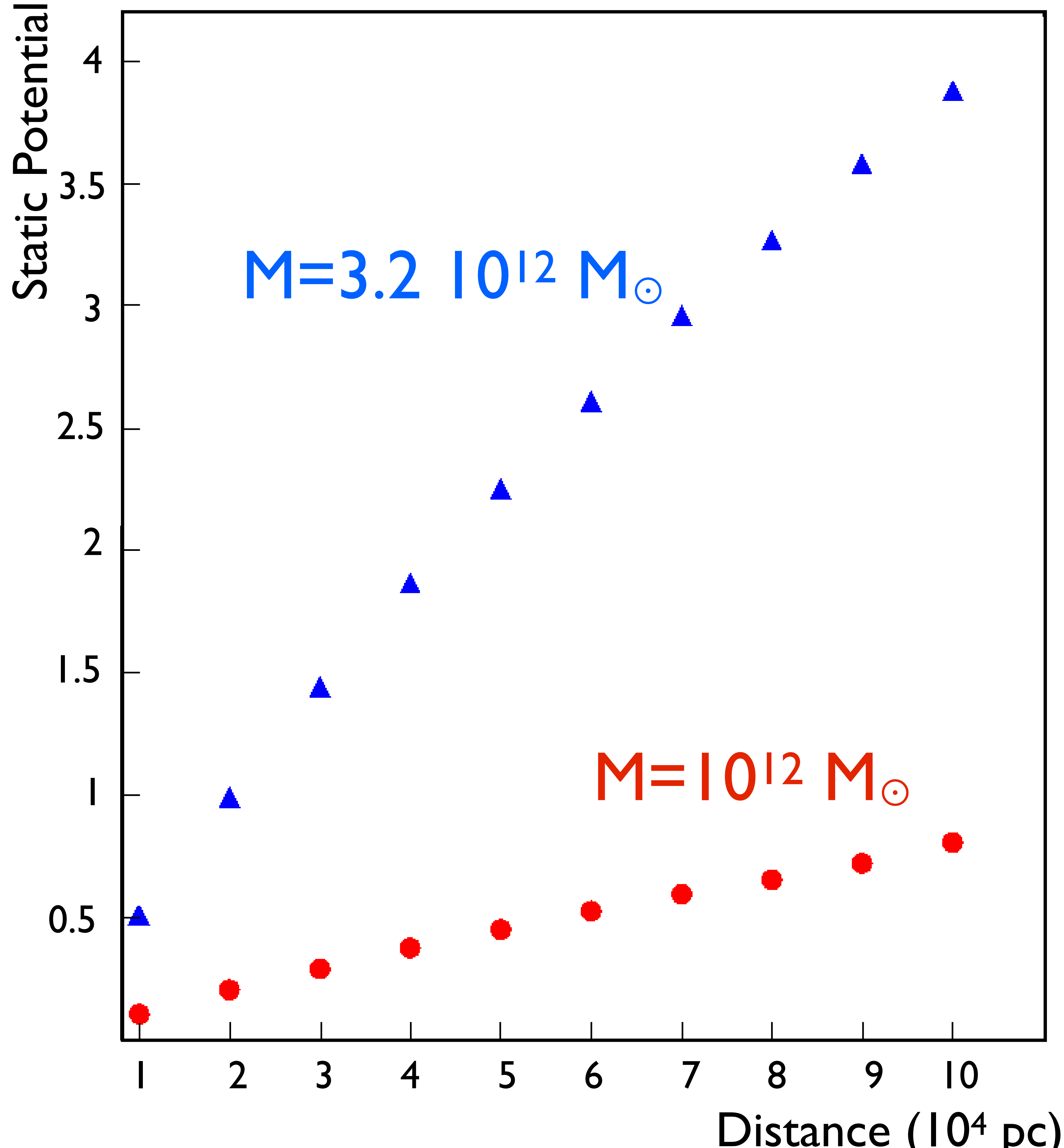
Running coupling ⇒ Recover Cornell potential (potential for static quarks).

Method generates a model that recovers principal characteristics of static QCD.

⇒ Confidence that method works for GR with self-coupling included

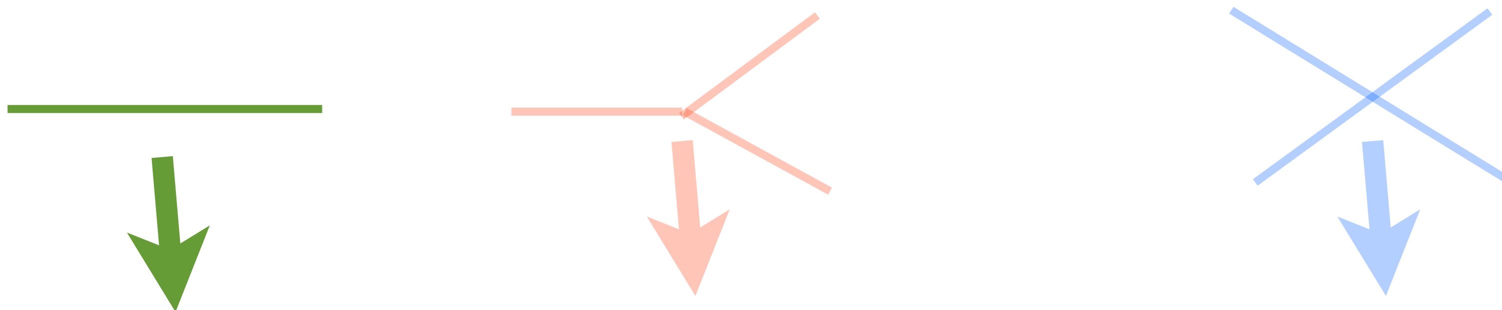
GR with self-coupling:

Full $\mathscr{L}_{GR}$ for two point masses M:

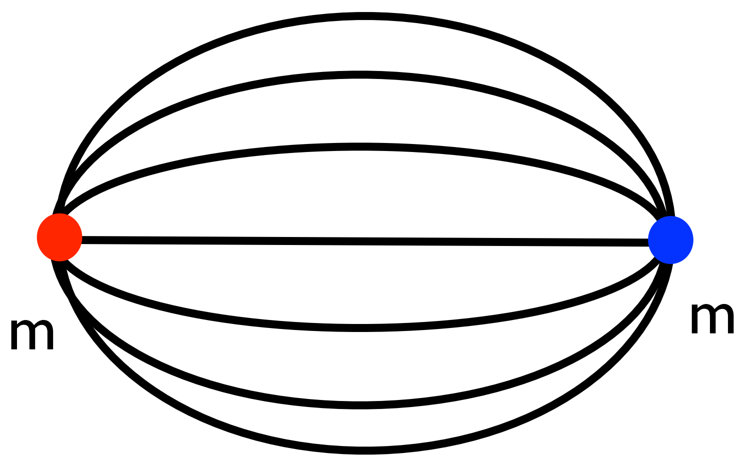


Linear potential, similar to QCD's Cornell potential

Interpretation



$$\partial\psi\partial\psi + G^{1/2}\psi\partial\psi\partial\psi + G\psi^2\partial\psi\partial\psi \quad \bullet\bullet\bullet$$



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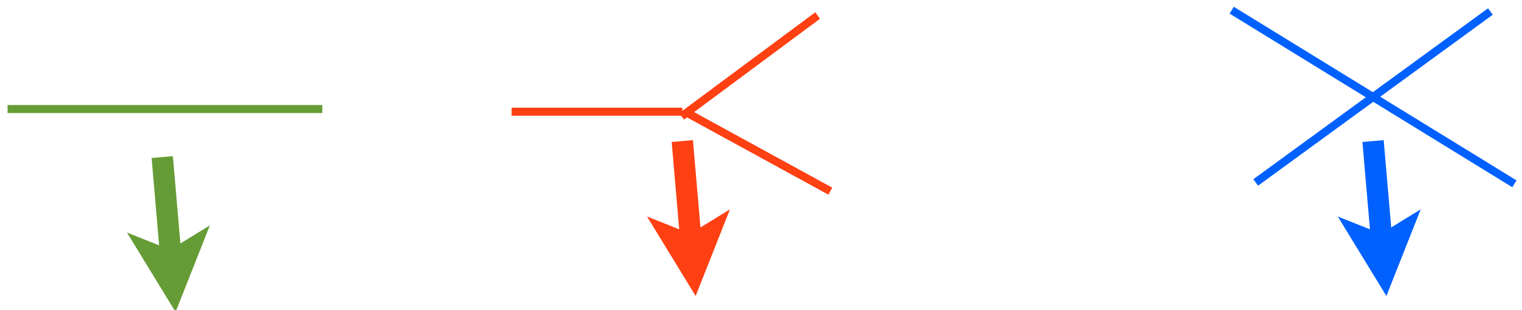
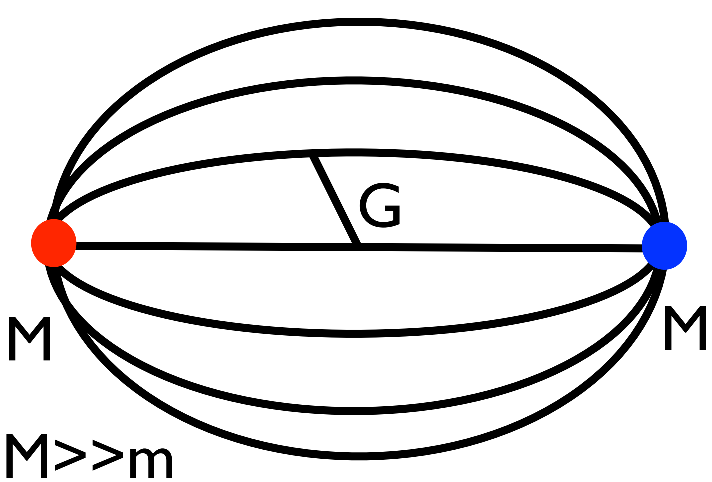
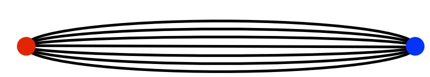


$$\partial\psi\partial\psi \;+\; G^{1/2}\psi\partial\psi\partial\psi \;+\; G\psi^2\partial\psi\partial\psi \quad \ldots$$

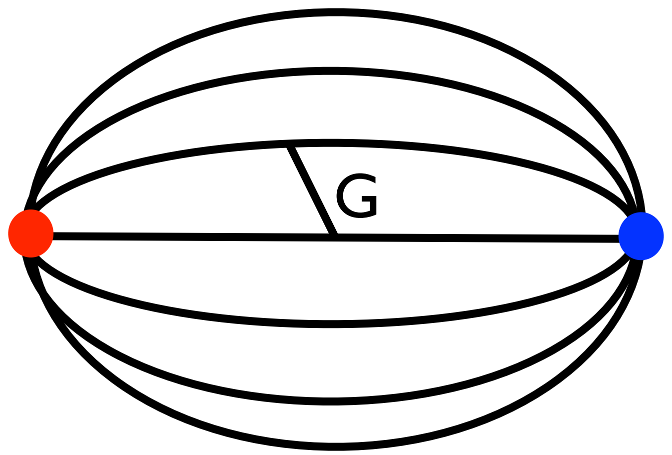


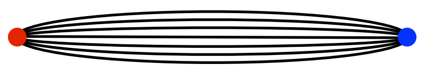
$\Rightarrow$



String-like flux tube

Interpretation

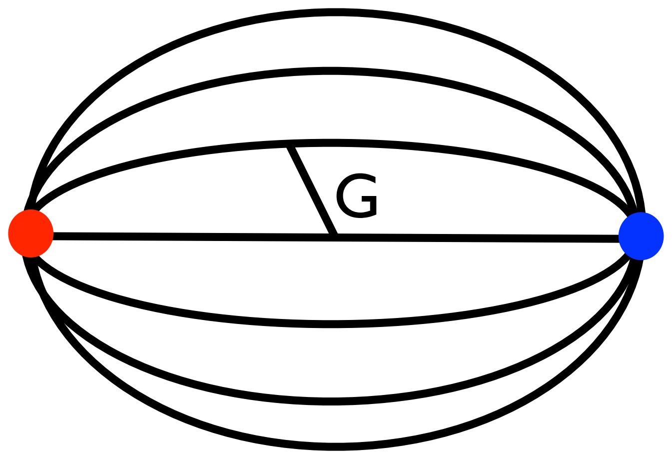


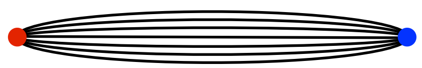


3D system becomes 1D
⇒Force~constant

The system is more strongly bound than with $1/r^2$ force. Not accounting for this (i.e. using Newton's gravity) creates a missing mass discrepancy (i.e. a dark mass).

Consequences

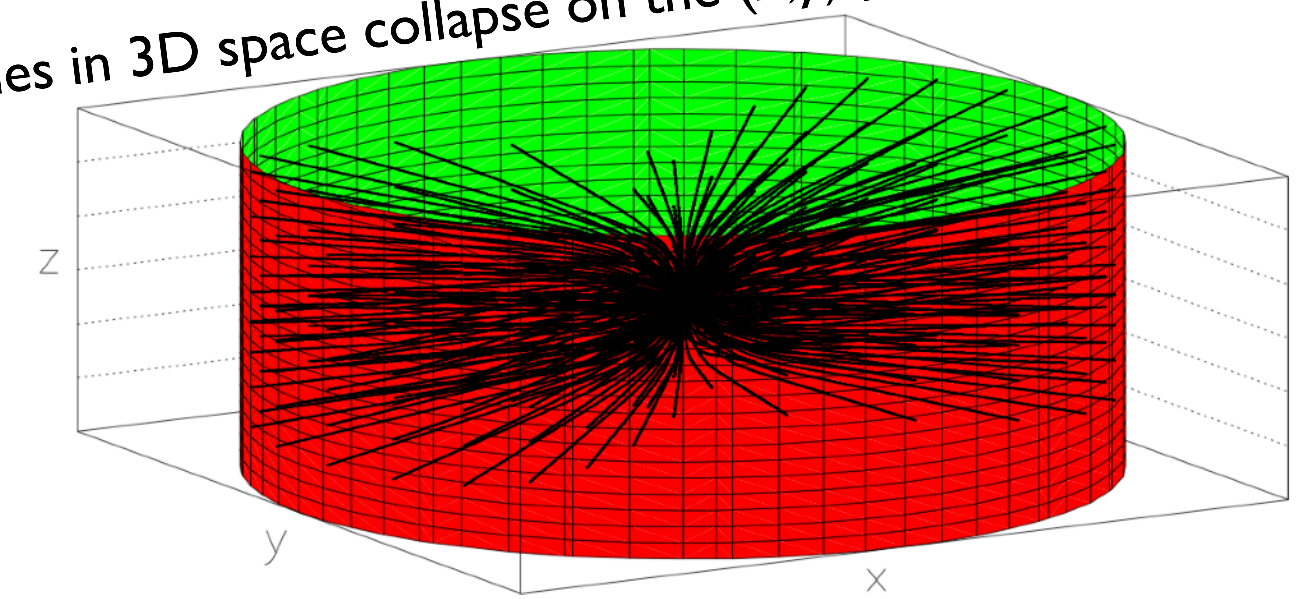




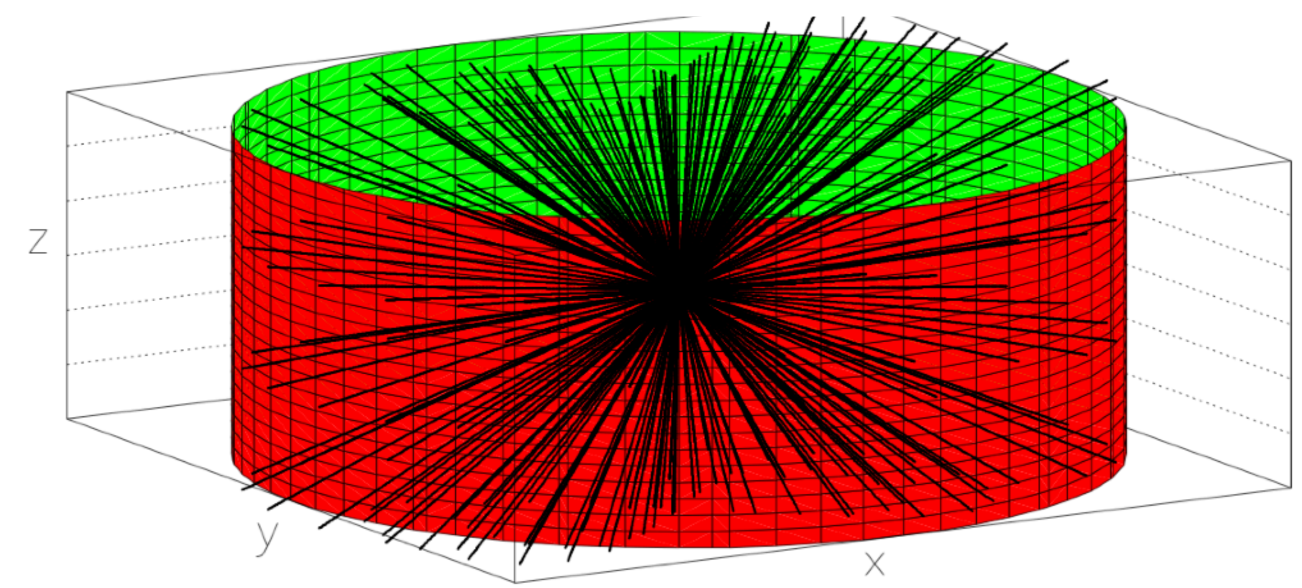
3D system becomes 1D
⇒Force~constant

- Likewise, for an homogeneous distribution of mass into a (x,y) plan, field lines are confined into the plan.
 3D system becomes 2D ⇒Force~1/r

Field lines in 3D space collapse on the (x,y) plan.



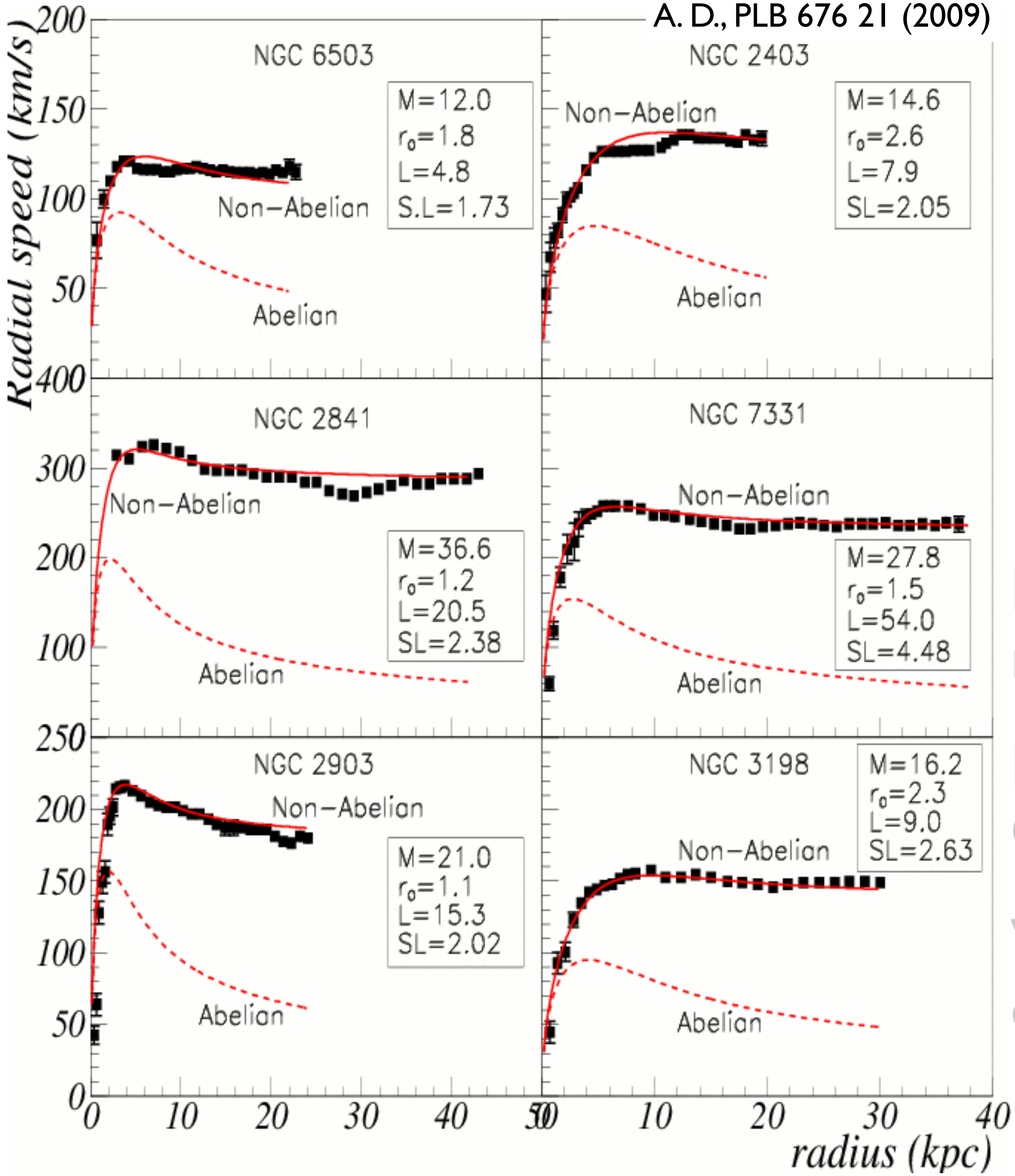
- For an homogeneous spherical mass distribution, there is no effect (no preferred directions).
Force~1/r^2



Consequences

*Very massive disk: 1/r force. For $\rho=\frac{M}{2\pi r_0{}^2}e^{-r/r0}$ density profile ⇒rotation speed of a disk becomes constant at large radius.

A. D., PLB 676 21 (2009)



Full calculation.

No field self-interaction (Newton).

■ data.

M: galaxy mass (10^9 solar mass)
r0: Scale length.
Free parameters

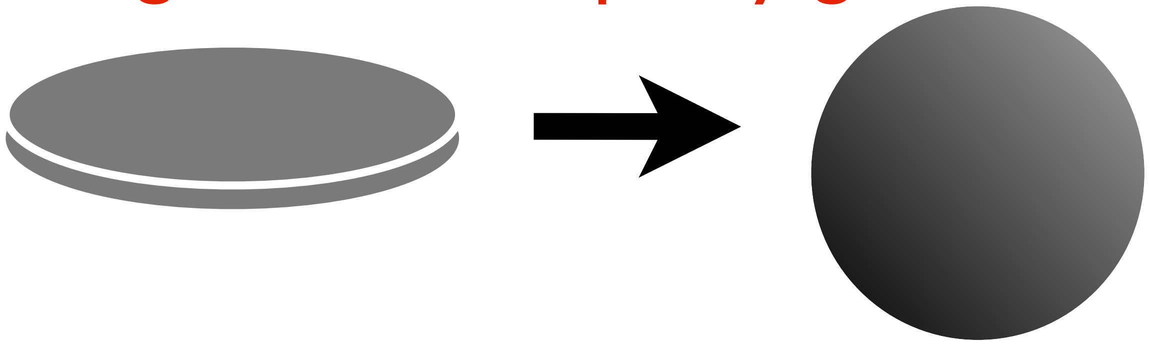
L: galaxy luminosity (B-band) (10^9 solar luminosity)

With only baryonic matter, expect M~2-3L and r0=SL

Consequences

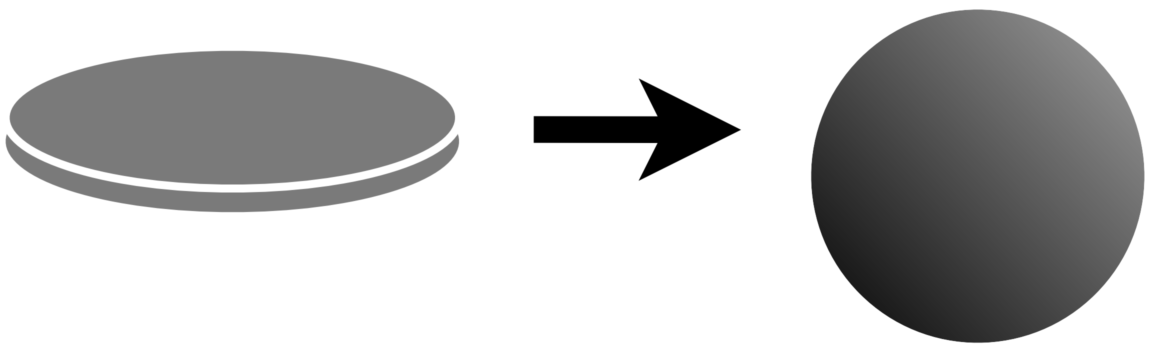
* For a disk, 1/r force + $\rho=\frac{M}{2\pi r_0^2}e^{-r/r0}$ density profile ⇒rotation speed of a disk becomes constant at large radius. (postdiction)

* Prediction (2009) for elliptical galaxies: missing mass discrepancy grows with ellipticity.



Dark Mass $\propto$ ellipticty

Consequences



Dark Mass = **a** × ellipticty ?

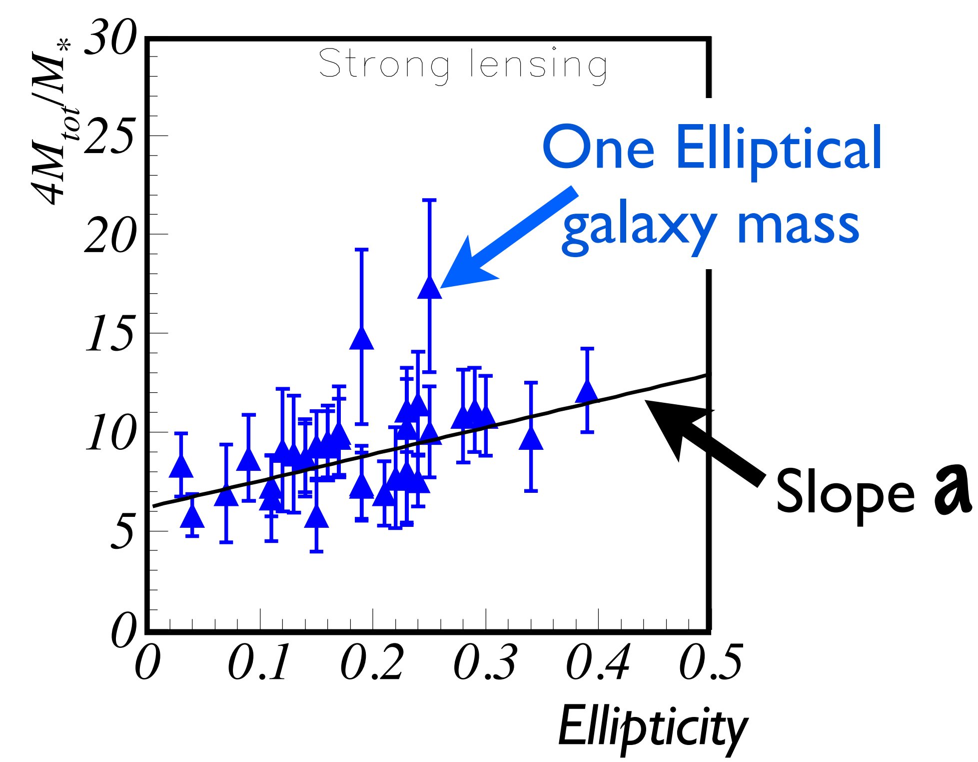
Method:

- Use 41publications reporting dark masses for sets of elliptical galaxies (totaling 685 galaxies).

- Publications often use different methods to obtain dark mass.

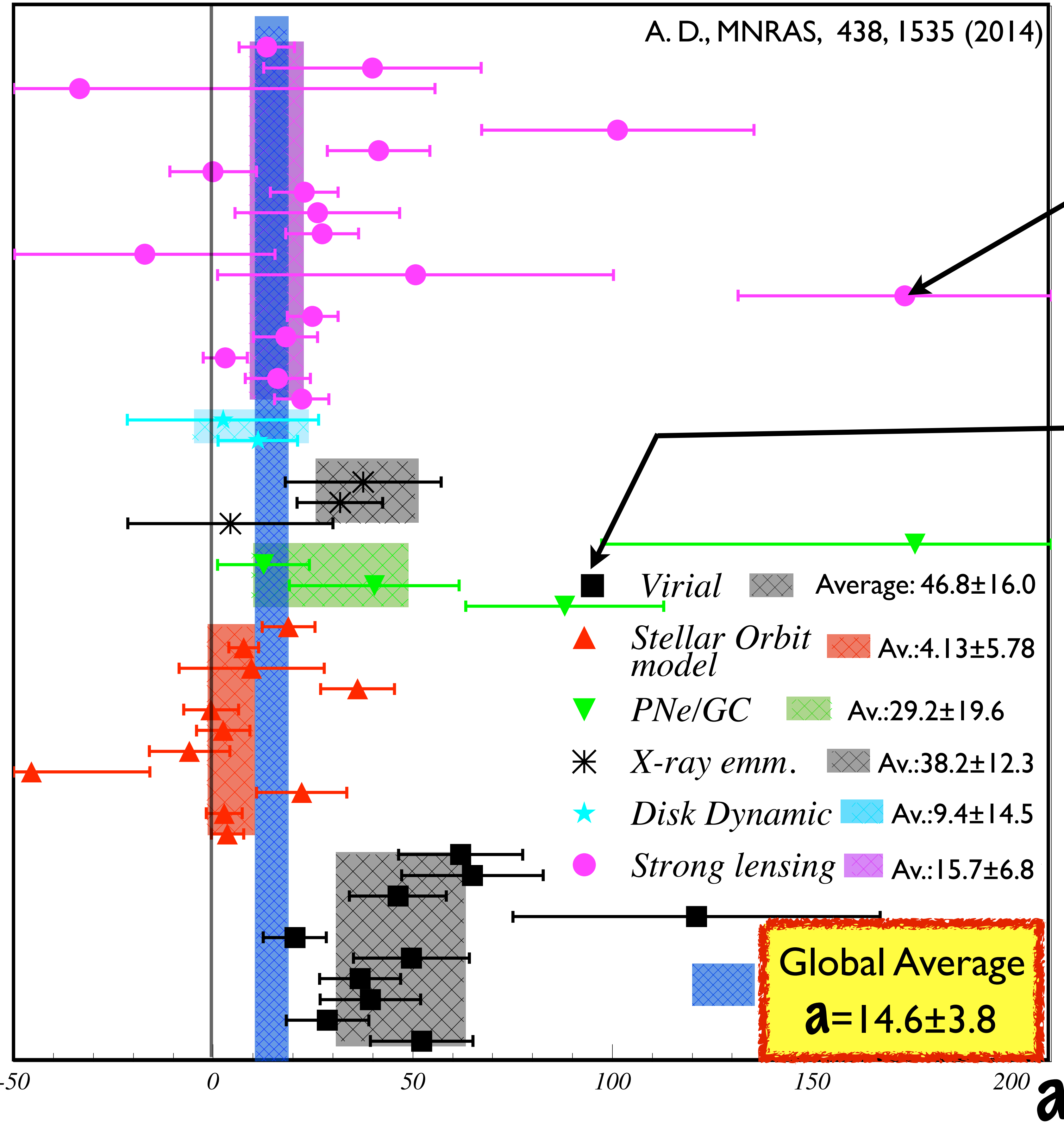
- For each publication, extract **a**.

One publication



- Average results of all publications.

Consequences



One symbol: one publication (many galaxies).

Different symbol type: different method of extracting the dark mass

a ≠0 ⇒ Dark Mass ∝ ellipticty

Consequences

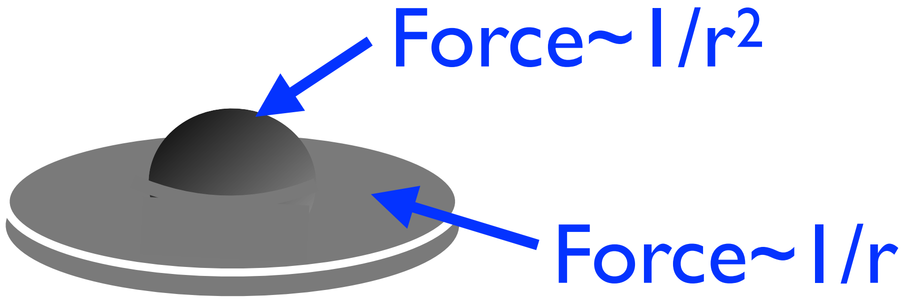
* 1/r force + $\rho=\frac{M}{2\pi r_0{}^2}e^{-r/r0}$ stellar density profile ⇒ rotation speed of a disk galaxy becomes constant at large galactic radius.

* Elliptical galaxies: Dark Mass, varies with ellipticity.

* Galactic missing mass discrepancy suppressed in (nearly spherical) galaxy bulges and grows with radius.

Consequences

*Galactic missing mass discrepancy suppressed in (nearly spherical) galaxy bulges and grows with radius.



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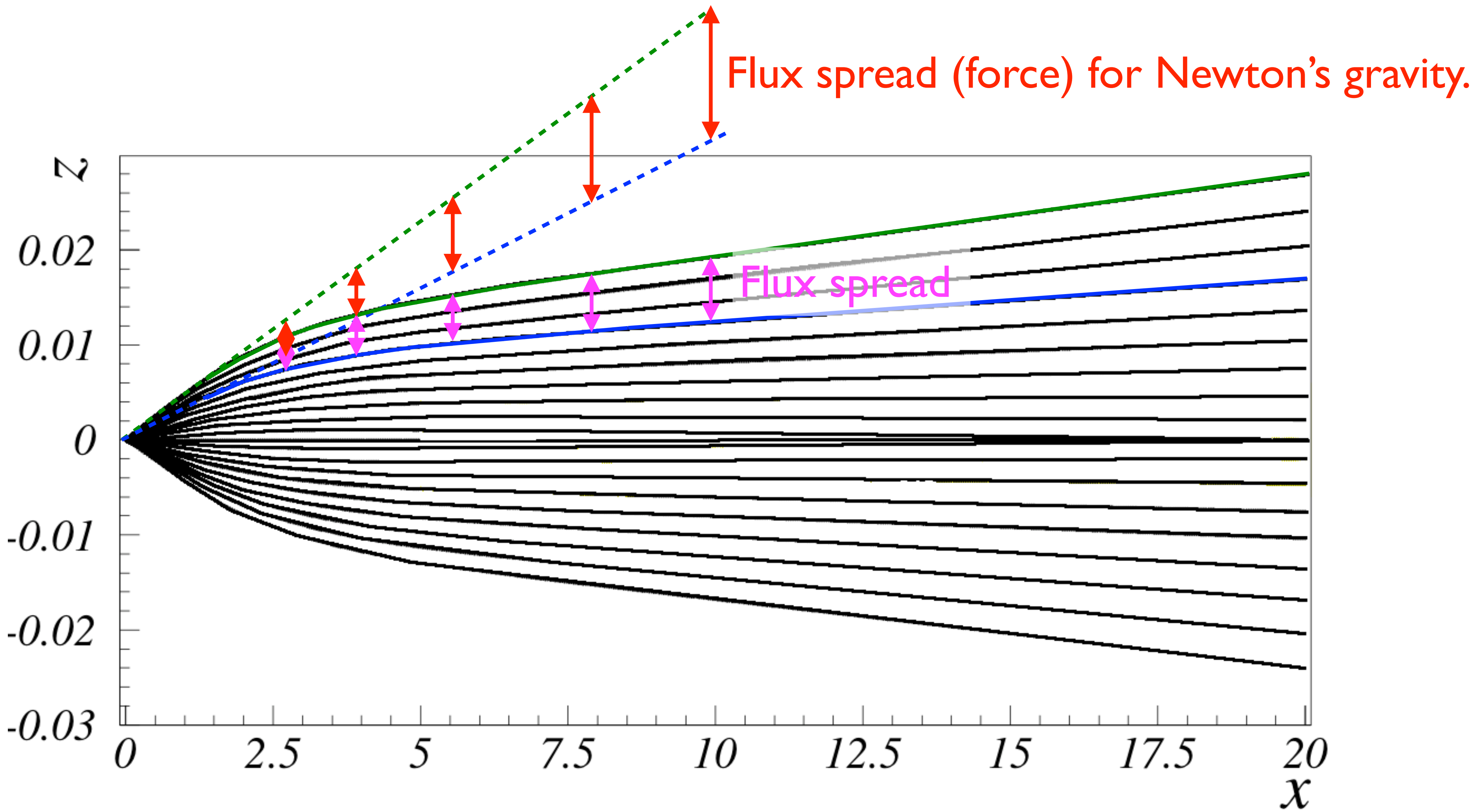

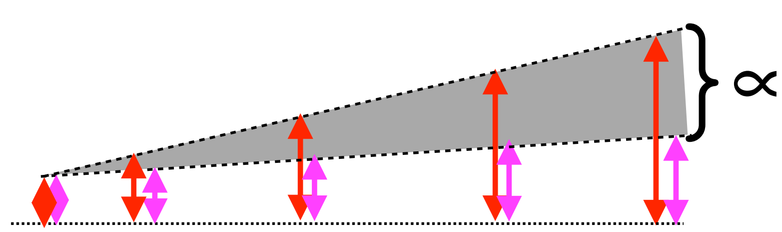

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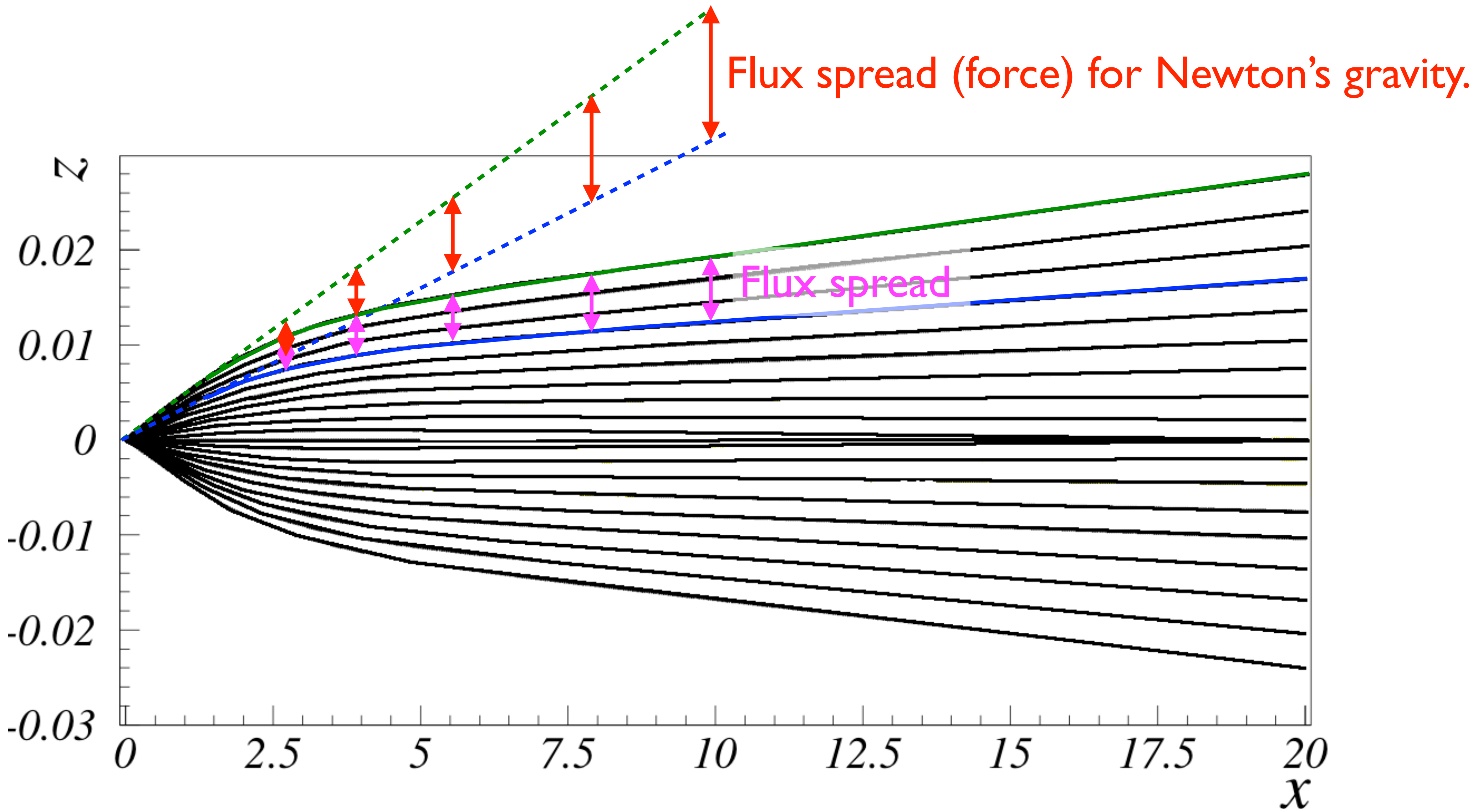
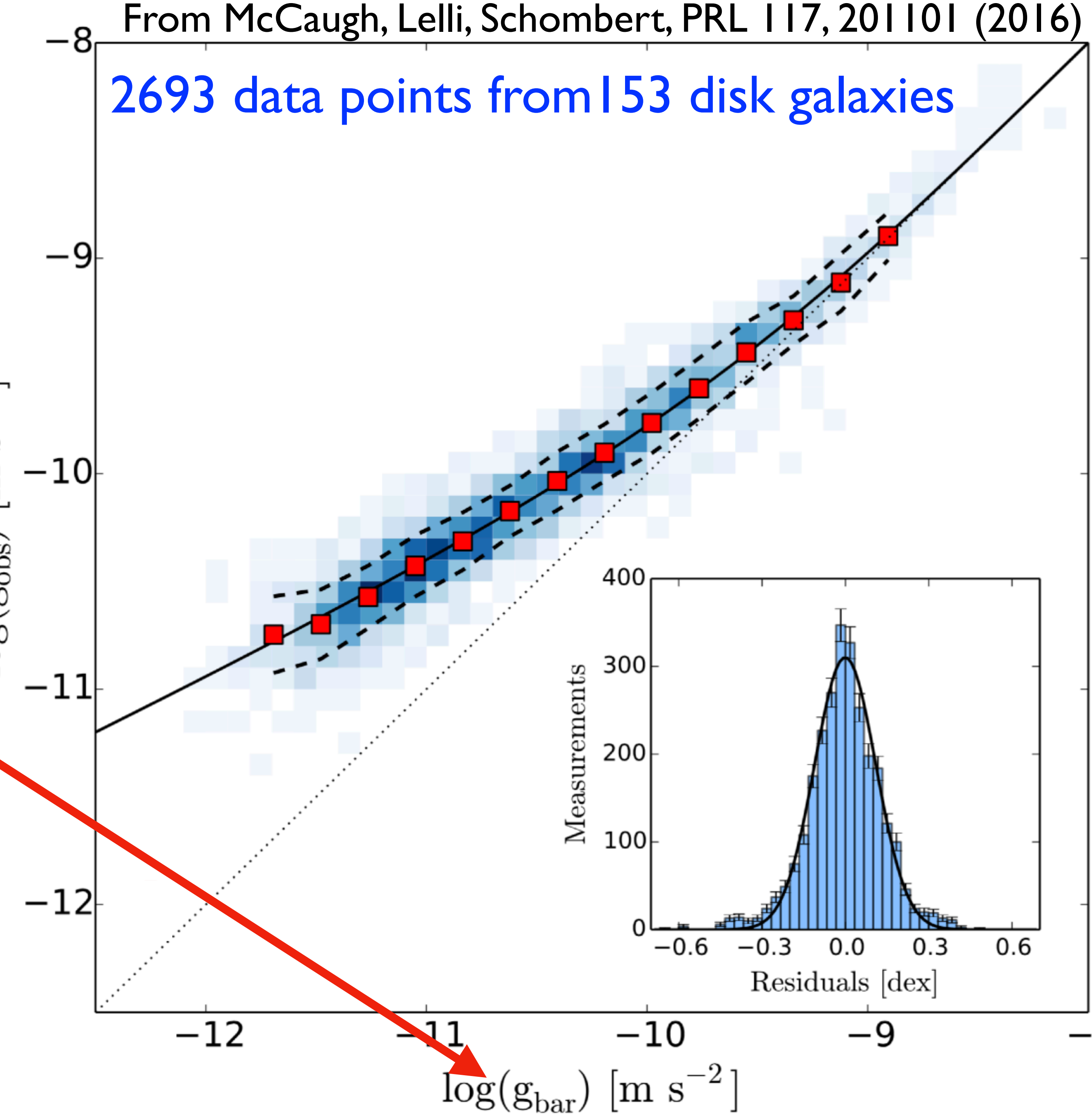


Bending of field lines happens where the field is large (near the galactic center), but the effect remains small. Consequences start to appear at large distances due to lever-arm magnification.

Consequences

*Galactic missing mass discrepancy suppressed in (nearly spherical) galaxy bulges and grows with radius.

From McCaugh, Lelli, Schombert, PRL 117, 201101 (2016)



Empirical tight relation between observed accelerations and computed accelerations from galactic baryonic mass.
Surprising: total mass (mostly dark) should determine the dynamics.

Problem for Dark Matter models: no strict correlation between dark and baryonic distributions expected.

Consequences

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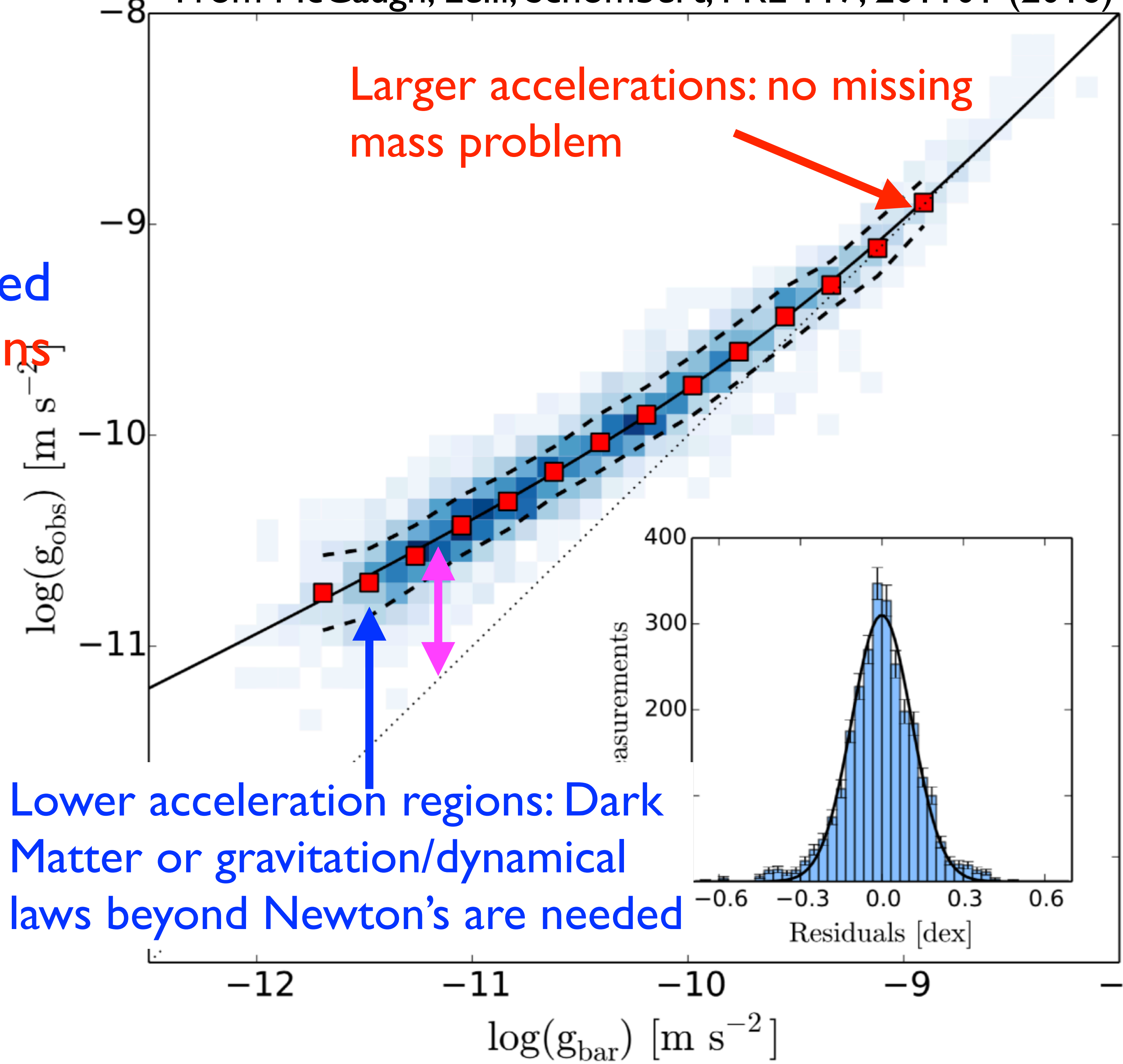

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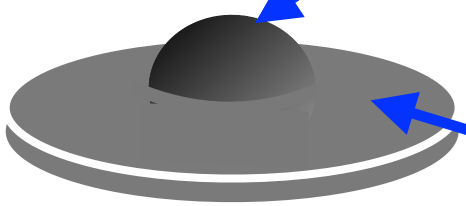
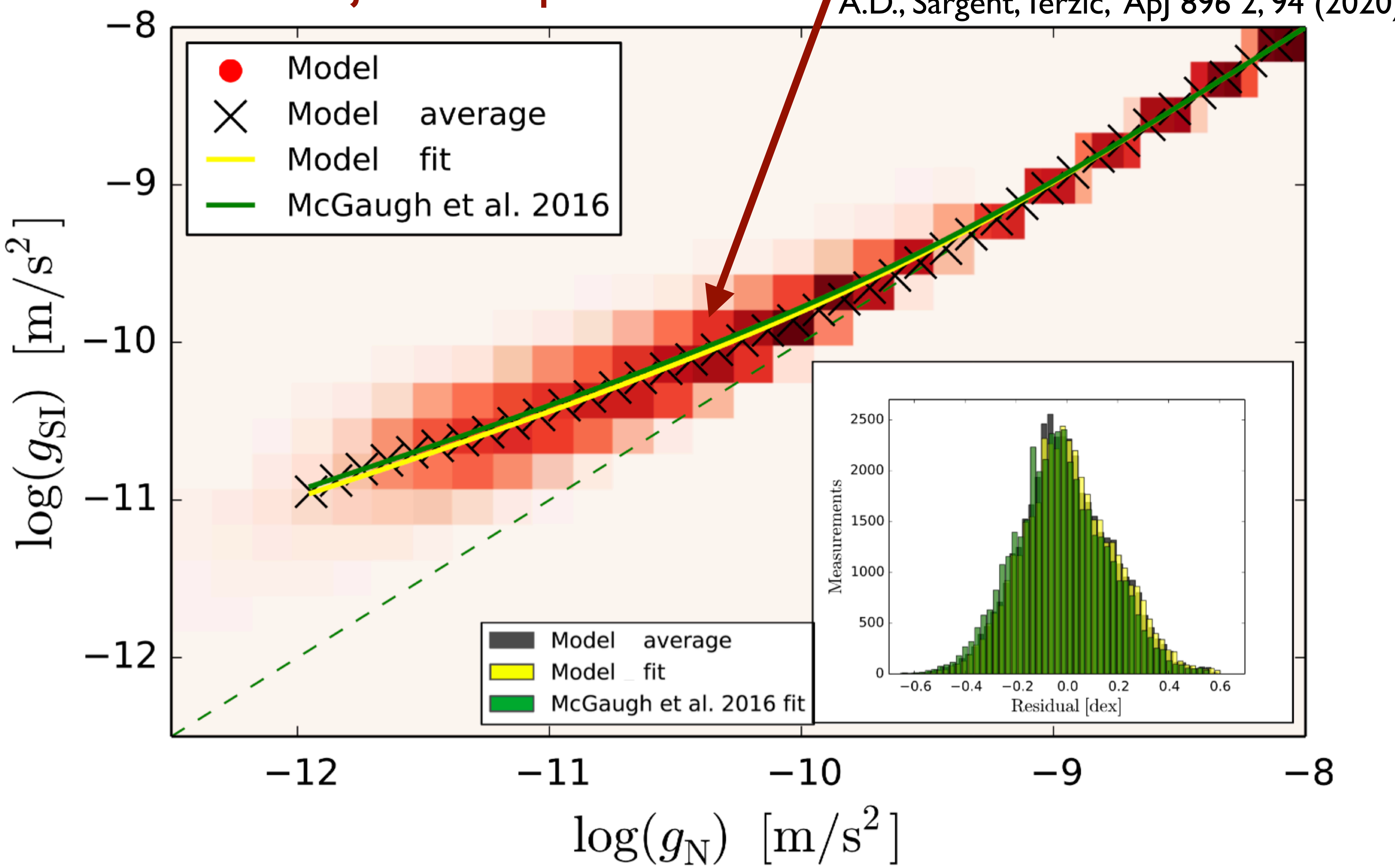


Simple model with $1/r^2$ force in bulge and $1/r$ force in disk explains the data. Model spans galactic parameter space (many different disk galaxies). No adjustable parameters!

A.D., Sargent, Terzić, ApJ 896 2, 94 (2020)



Consequences

* 1/r force + $\rho = \frac{M}{2\pi r_0^2} e^{-r/r0}$ stellar density profile ⇒ rotation speed of a disk galaxy becomes constant at large galactic radius.

* Elliptical galaxies: Dark Mass, varies with ellipticity.

* Galactic missing mass discrepancy suppressed in (nearly spherical) galaxy bulges and grows with radius.

* Dark Energy.

Possible link to dark energy

Negative pressure pervades the Universe and repels galaxies from each other.

Presently, gravity + dark energy ~ 0 at large distance (cancel in Universe's evolution). "Cosmic coincidence".

Strong force ~ 0 outside hadrons. (Only residual Yukawa force).

Energy conservation:

Increase in galaxy binding $\underset{\text{equivalently}}{\Rightarrow}$ decrease of outside potential energy.

Field lines are partially trapped in systems (galaxies or clusters).

Two clusters or two spiral galaxies should interact less than naively expected:

$F_{true} = D.F_{expect}$, where $D<1$ expresses the depletion of outside field lines

$F_{true} = F_{expect} - F_{DM\ pressure}$ where $F_{DM\ pressure} = (1-D)F_{expect}$

Effect of D would look like a (time and space -dependent) negative force.

⇒ May account for dark energy.

Modification of Universe's evolution

General relativity+assuming isotropic and homogeneous universe:

$$\frac{2K}{a^2} + \frac{2\dot{a}^2}{a^2} + \frac{\ddot{a}}{a} = 4\pi G(\rho - p)$$

Universe standard evolution equation

with

K: space curvature sign,
a: scale factor,
ρ: density,
p: pressure.

Lifting isotropy and homogeneity assumption, a factor appear in front of ρ.
Can be interpreted as field trapping effect.
⇒ Depletion factor D(z) in front of ρ of matter.

(redshift z ~distance or Universe age^{-1})

Construction of D(z)

Use known timeline of large structure formation and the known amounts of baryonic matter in these structures (galaxies, clusters, superclusters).

Construction of D(z)

Timeline:

Galaxies

•z=15→z=0: galaxies formation and evolution.

•z=10→z=2: galaxies are highly asymmetric (e.g. filements-like). Field trapping

•z=2→z=0: galaxies evolve to more symmetric shapes; Elliptical/Spiral galaxy ratio increases. Field release

Groups, clusters and superclusters

•z=10→z=2: galaxies form groups and proto-clusters Field trapping

•z=2→z=1.2: proto-clusters evolve to clusters. Field trapping

•z=1.2→z=0: clusters arrange into more symmetric formation (sheets, filements) Field release

Structure depletion functions:

Field trapping | Field release

$$D_g(z) \simeq \left[1 - \left(1 + e^{(z-z_{g0})/\tau_g}\right)^{-1}\right] + \left[A_g e^{-B_g z}\right]$$

Galaxies

$$D_c(z) \simeq \left[1 - \left(1 + e^{(z-z_{c0})/\tau_c}\right)^{-1}\right] + \left[A_c e^{-B_c z}\right]$$

Groups, clusters and superclusters

•z_0 is the redshift at the middle of the formation process of the specific structure type: $z_{g0}=9\pm1$, $z_{c0}= 5.6\pm1$

•τ is the typical duration for the specific formation process: $\tau_g=3\pm0.5$, $\tau_c=2.2\pm0.5$

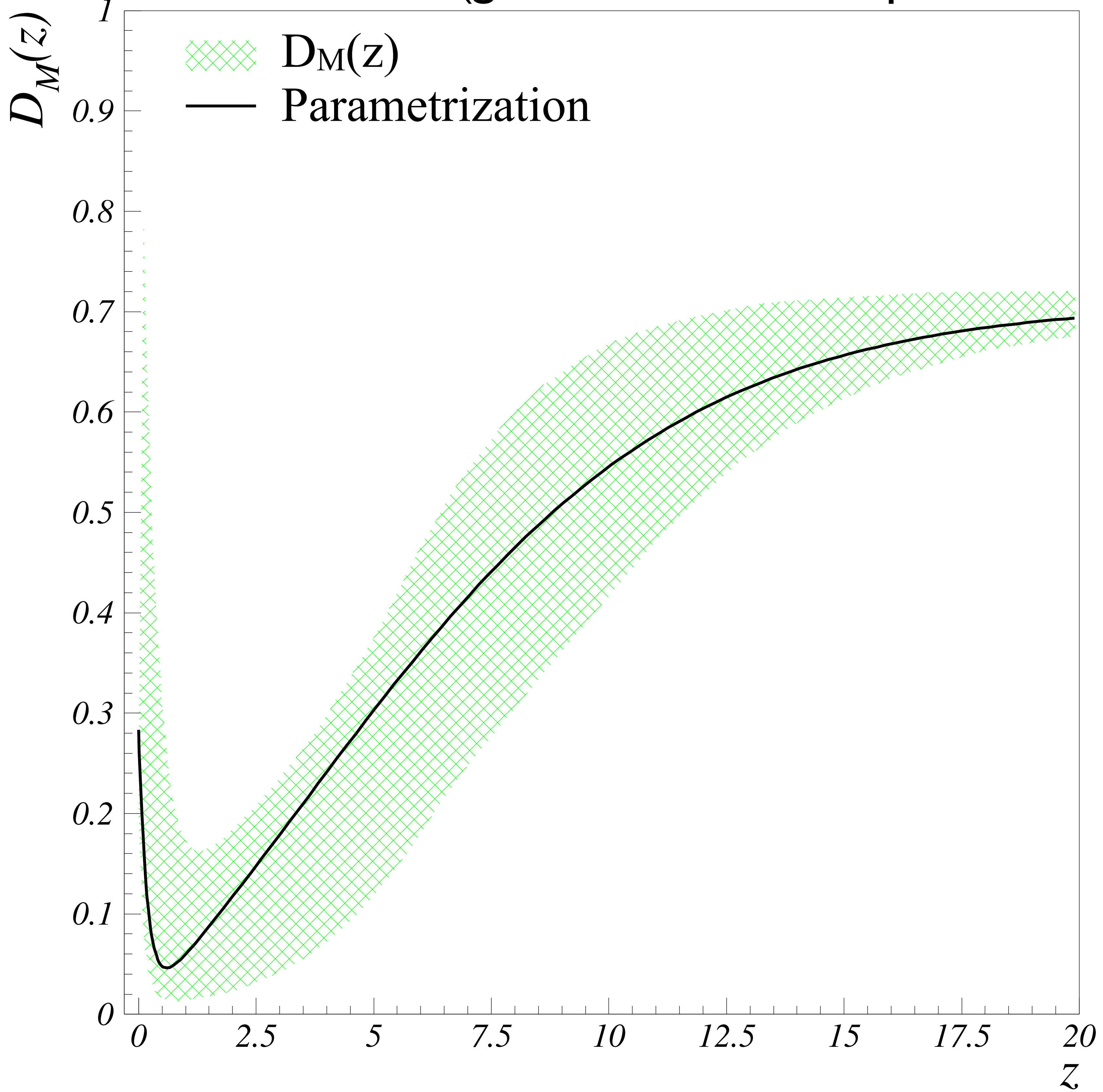
•A: matter in specific structure concerned by evolution to more symmetric shapes: $A_g=10\%\pm10\%$, $A_c= 87\%\pm87\%$

•B^{-1}: Typical duration of evolution to more symmetric shapes: $B_g^{-1}=0.08\pm0.03$, $B_c^{-1}=0.21\pm0.10$

Chosen so $0<D(0)<1$

Construction of D(z)

Use known timeline of large structure formation and the known amounts of baryonic matter in these structures (galaxies, clusters, superclusters).



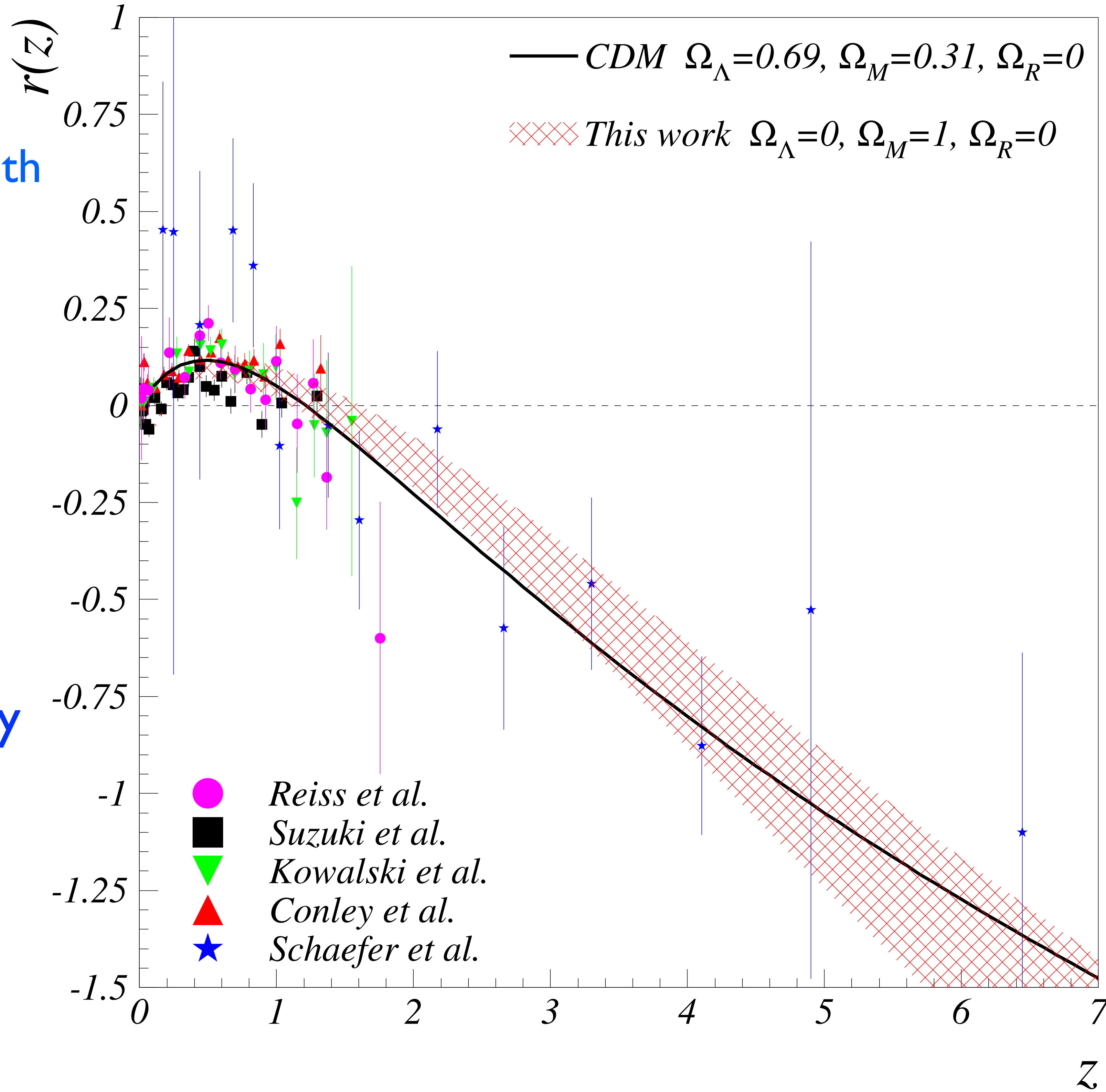
Comparison with supernova and γ-ray burst observations

Compute residual r(z) between Luminosity distance computed with self-interaction and empty flat universe baseline.

⇒Good agreement with the observational evidence for dark energy.

Suggest that dark energy may be the consequence of the trapping of gravitational field lines in large structures.

Cosmological constant Λ=0



Relevance to dark energy phenomenology

•Supernova data

•Age of the Universe
13.5±0.3 Gyears.

•Agrees (by construction of D(z)) with large structure formation (galaxies, clusters, superclusters...)

•Main feature of cosmic microwave background and baryon acoustic peak observations (main feature explained. Detailed work not done)

Yields naturally the Cosmic Coincidence i.e. that presently, dark energy repulsive effect ≈ gravity's attraction, while in the past, attraction≫repulsion and in the future repulsion≫attraction is expected.

Consequences

* 1/r force + $\rho = \frac{M}{2\pi r_0^2} e^{-r/r0}$ stellar density profile $\Rightarrow$ rotation speed of a disk galaxy becomes constant at large galactic radius.

* Elliptical galaxies: Dark Mass, varies with ellipticity.

* Galactic missing mass discrepancy suppressed in (nearly spherical) galaxy bulges and grows with radius.

* Dark Energy.

* Galaxy clusters contain ~90% of Dark Mass.

* Straightforward explanation for the Bullet Cluster observation.

Summary

- Complex and important non-perturbative QCD effects have been observed. Not intuitive: would have been hard to predict, just looking at QCD's Lagrangian.

- Since QCD and GR have a similar structure, maybe similar effects also arise when large masses are involved (e.g. galaxies).

- Hadronic and galactic dynamics have intriguing phenomenological parallels.

- The WIMP and axion search negative results, the trouble with SUSY, make this natural explanation attractive.

- Numerical calculations show that field self-interactions can explain quantitatively several key phenomena of the Dark Universe:
  - Flat rotation curves of disk galaxies.
  - Correlation between the ellipticity of elliptical galaxies and their dark mass.
  - Galactic missing mass correlation with baryonic mass.
  - Dark Energy.
  - Cluster dynamics.
  - Bullet Cluster observation.

Thank you