What can QCD teach us about Dark Matter?

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A. D., MNRAS, 438, 1535 (2014)
A. D., Phys. Lett. B676 21 (2009)

Dark Matter

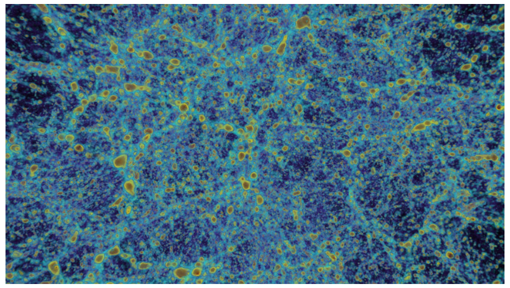
Dark Matter is ubiquitous in the universe.

It is estimated to represent 85% of the total mass of the universe.

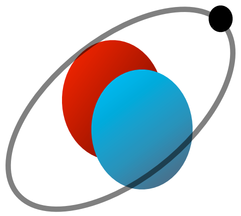
What it does:

- Allows disks galaxies to spin faster.

- Keeps galaxies confined in clusters.



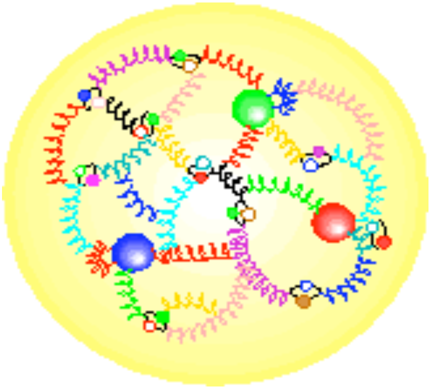
- Shapes structure formations.



- Solves problem of deuteron Primordial Nucleosynthesis.
- Etc...

What it is remains a mystery.

Quantum Chromodynamics (QCD)



Theory of the strong force binding quarks into hadrons.

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

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

What can QCD teach us about dark matter?

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

⇒WIMPs

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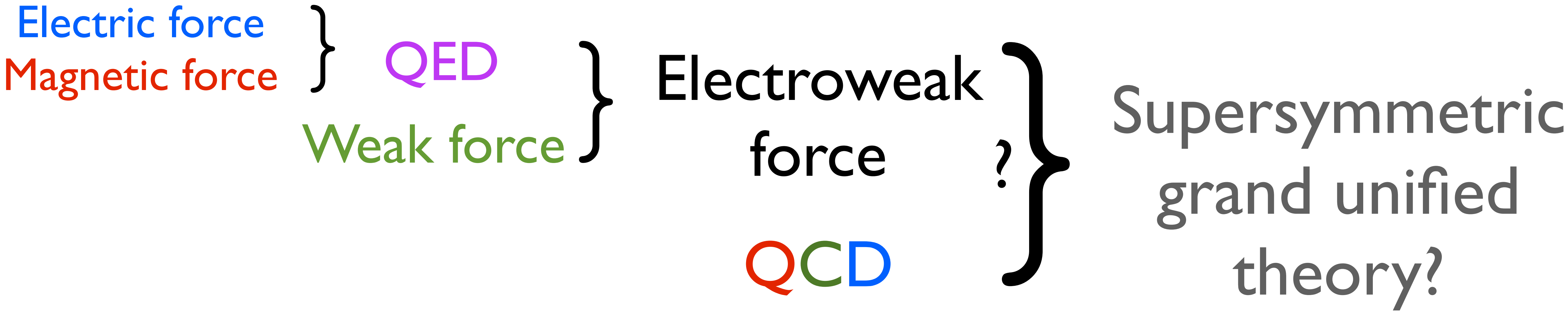

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  QCD
  ?
  Supersymmetric grand unified theory?

  ⇒WIMPs

- QCD is free to violate Charge-Parity (CP) symmetry. But it does not (or very slighly). To force QCD to not be CP-violating, add new symmetry which is spontaneously broken.

  ⇒Axions

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WIMPs are the most promising Dark Matter candidates. But direct searches (LUX, CDMS...) or production (LHC,...) are so far negative.

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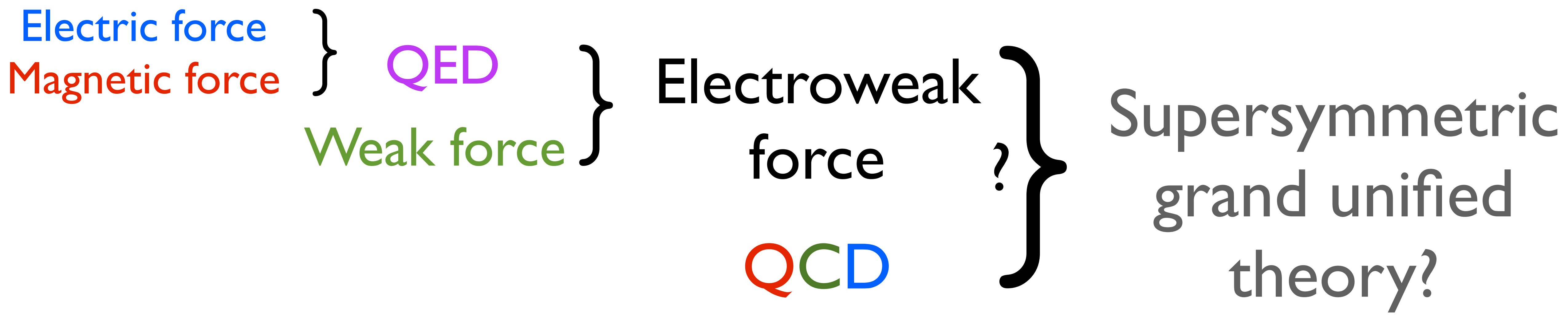
Axions searches are also negative.

What can QCD teach us about dark matter?



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⇒Axions

- QCD and gravity have a similar underlying structure (similar field Lagrangians). Complex QCD effects could not be predicted.

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

Key facts of Strong Force

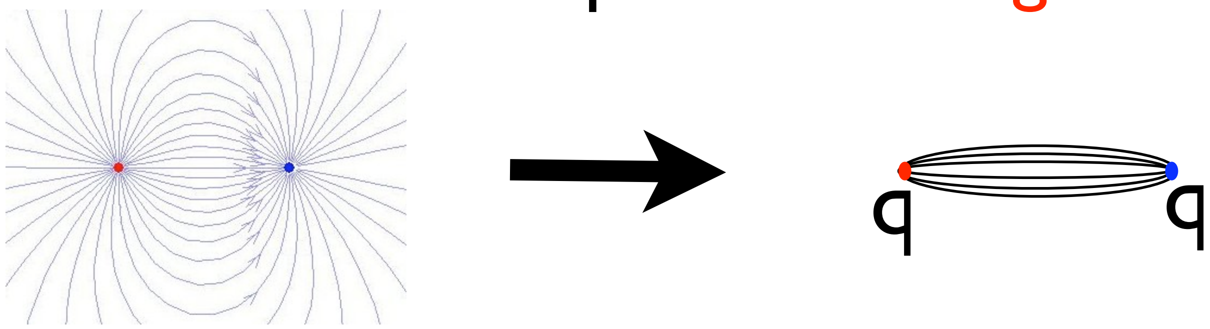
Facts

- Quarks and gluons are confined inside hadrons

Explanations

Strong force coupling is Large & gluons are color-charged

⇒ field-lines collapse into string-like flux-tubes.



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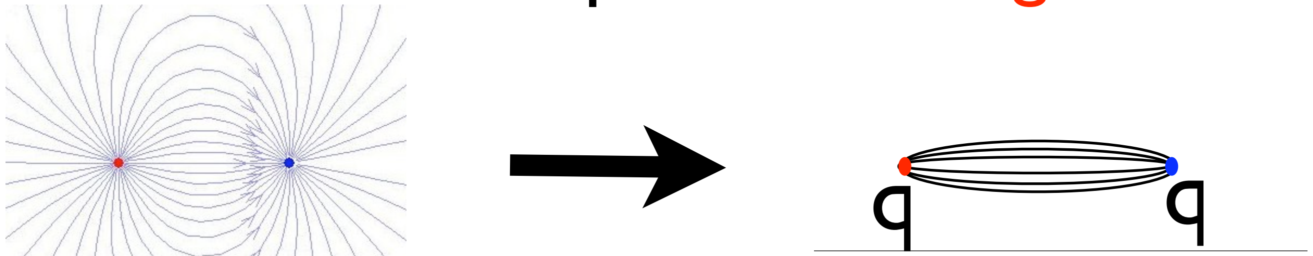
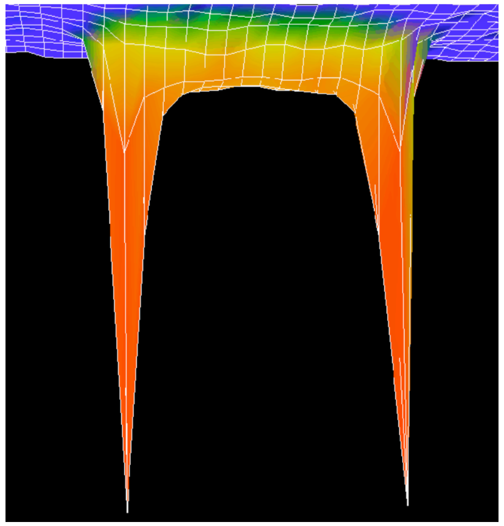


Evidences from lattice QCD (action density, G. Bali et al):



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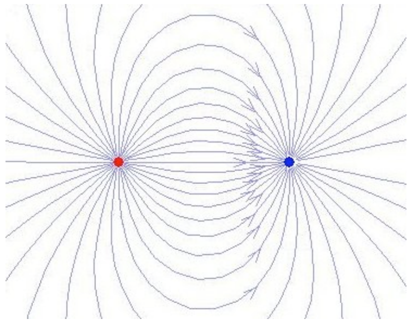

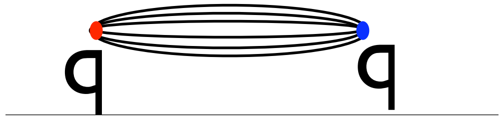

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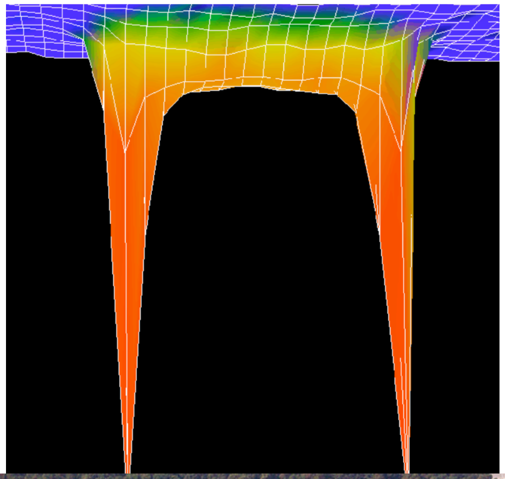

GlueX experiment in JLab's Hall D

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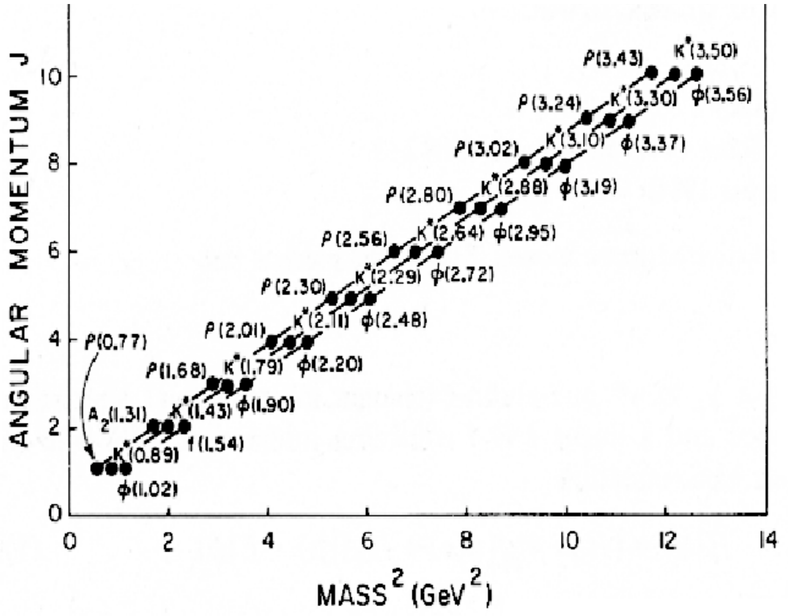
- Quarks and gluons are confined inside hadrons

- Hadrons lie on Regge trajectories



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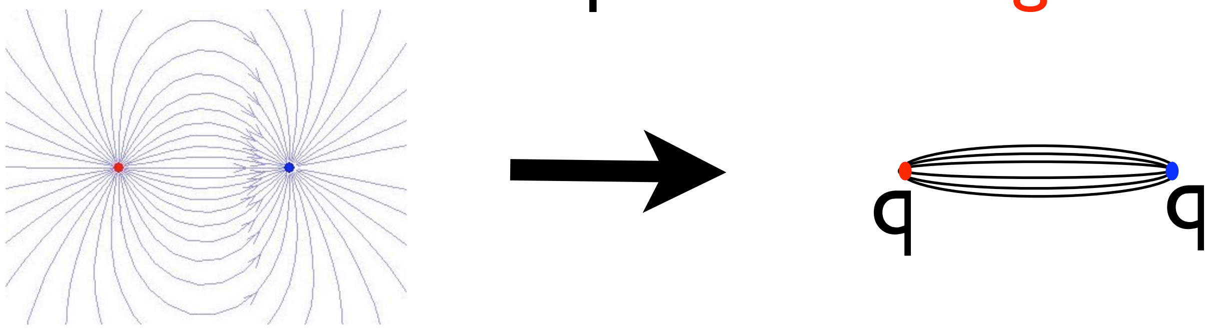

The more a hadron spins, the larger the binding energy (i.e. the mass) to compensate for the centrifugal force.

Linear potential ⇒ Ang. Mom. $\propto M^2$+constant

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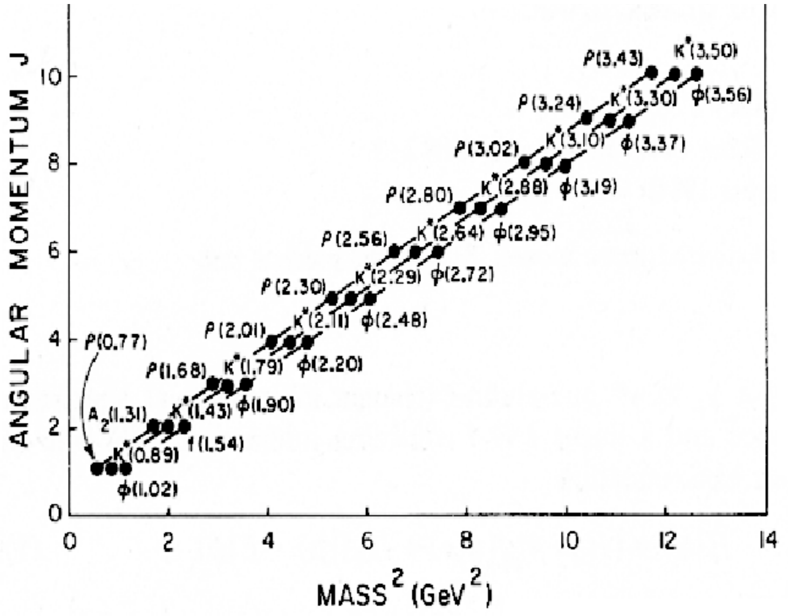

- Strong force not felt at large distances (but for residual effects: Yukawa potential, etc...)

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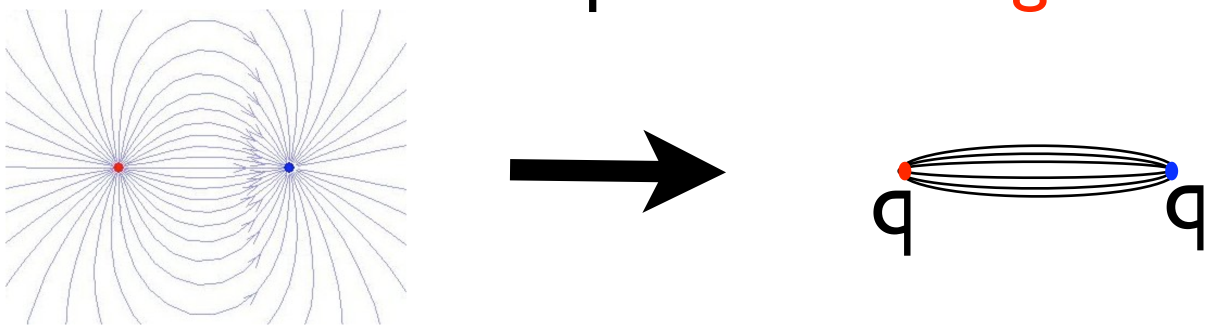

The more a hadron spins, the larger the binding energy (i.e. the mass) to compensate for the centrifugal force.

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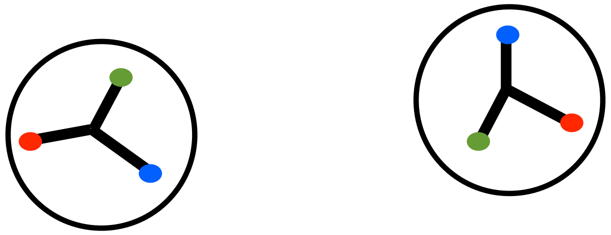
Field lines are inside the hadron. Gluons are confined as well:



Empirical parallels between cosmology and Hadronic physics

Cosmology

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

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 ~10 MeV, Pion mass 140 MeV 3 quarks ~15 MeV, Nucleon: 938 MeV

Empirical parallels between cosmology and Hadronic physics

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Tully-Fisher relation:

$\log(M)=\gamma\log(v)+\varepsilon$ ($\gamma=3.9\pm0.2$, $\varepsilon \sim 1.5$)

(M galaxy visible mass, v rotation speed)

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Regge trajectories:

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

(M, hadron mass, J angular momentum)

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Negative pressure pervades the universe and repels galaxies from each other.	
The attraction of galaxies is smaller than we think at very large distances.	

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Negative pressure pervades the universe and repels galaxies from each other. The attraction of galaxies is smaller than we think at very large distances.	Relatively weak effective force between hadrons (Yukawa potential) compared to QCD's magnitude.

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

It might be due to the similarities between gravity theory and QCD.

Theoretical parallels between gravity and QCD

gravity

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

Curvature tensor

det $g_{\mu\nu}$

Metric tensor

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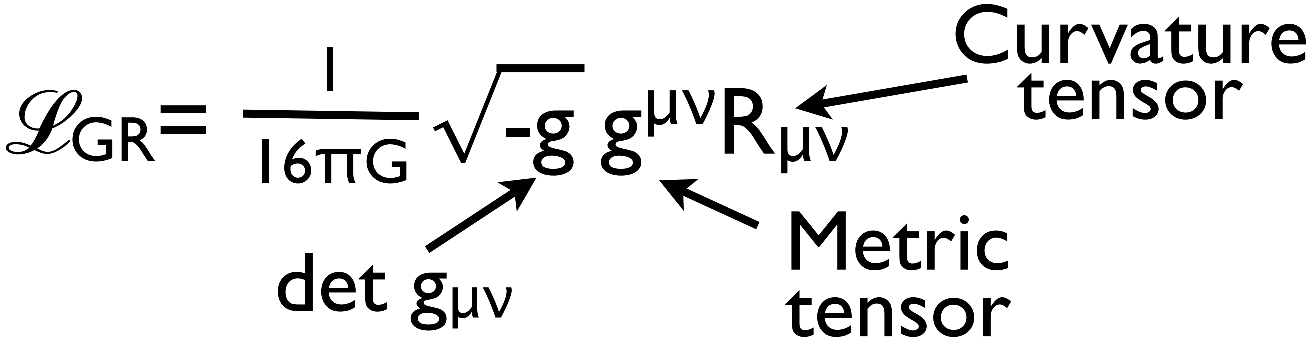

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$$\boxed{\begin{aligned}\mathscr{L}_{GR}=&[\partial\psi\partial\psi] + \sqrt{G}\, [\psi\partial\psi\partial\psi]+\\ &G[\psi^2\partial\psi\partial\psi] +\ldots\end{aligned}}$$

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

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Perturbative QCD (static case): 1/r potential

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Field self-interaction terms

Theoretical parallels between gravity and QCD

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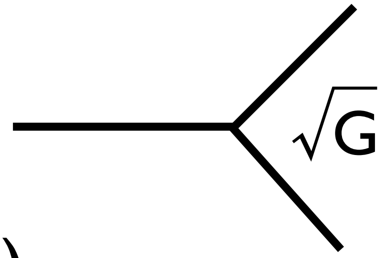
- Gravitons couple to each other:

(m$_{graviton}$=0 but they have energy & momentum≠0 and gravity couples to that)



Gravity field is self-interacting.

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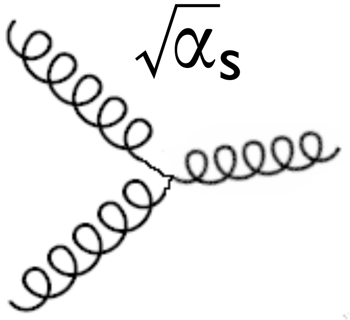

QCD is the archetype of a theory with self-interacting field.

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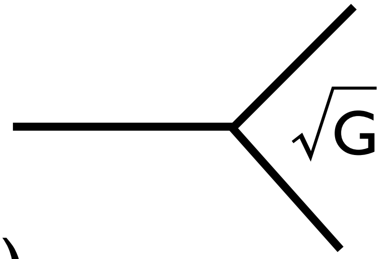

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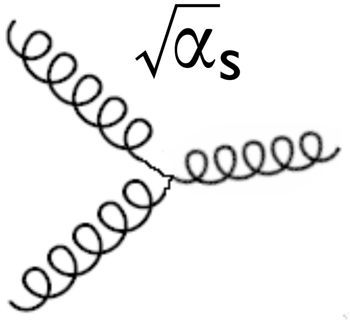

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Differences between gravity and QCD

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

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

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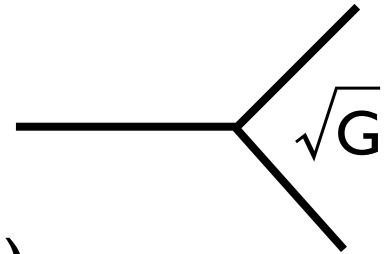

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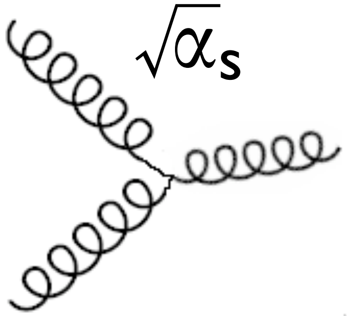

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That $\sqrt{G}$ is small is compensated for massive enough systems.

⇒Occurrence of gravity self-interaction effects similar to those seen in QCD?

Near a proton $GM_p/r_p=4\times10^{-38}$ with M_p the proton mass and r_p its radius.

⇒Self-interaction effects are negligible:

$$\mathscr{L}_{GR}=[\partial\psi\partial\psi]+\underbrace{\sqrt{G}\,[\psi\partial\psi\partial\psi]+G[\psi^2\partial\psi\partial\psi]+\ldots}_{\sim 0}$$

For a typical galaxy: Magnitude of the gravity field ∝ $GM/\text{size}_{\text{system}}$ $\sim10^{-3}$.

Quantitative estimate of graviton mutual interaction

$$\mathscr{L}_{GR}=[\partial\psi\partial\psi]+\sqrt{G}\ [\psi\partial\psi\partial\psi]+G[\psi^2\partial\psi\partial\psi]+\sum G^{n/2}[\psi^n\partial\psi\partial\psi]+\sqrt{G}\ \psi_{\mu\nu}T^{\mu\nu}$$

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

Explicitly given by the Fierz-Pauli Lagrangian:

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

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In the static case, leads to Newton’s theory.

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For static case, we can approximate ψ as scalar

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

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

Examples with no mutual coupling

$\mathscr{L}_{GR}=\partial\psi\partial\psi+\sum \xcancel{G^{n/2}\psi^n\partial}\psi\partial\psi+\sqrt{G}\,\psi T$

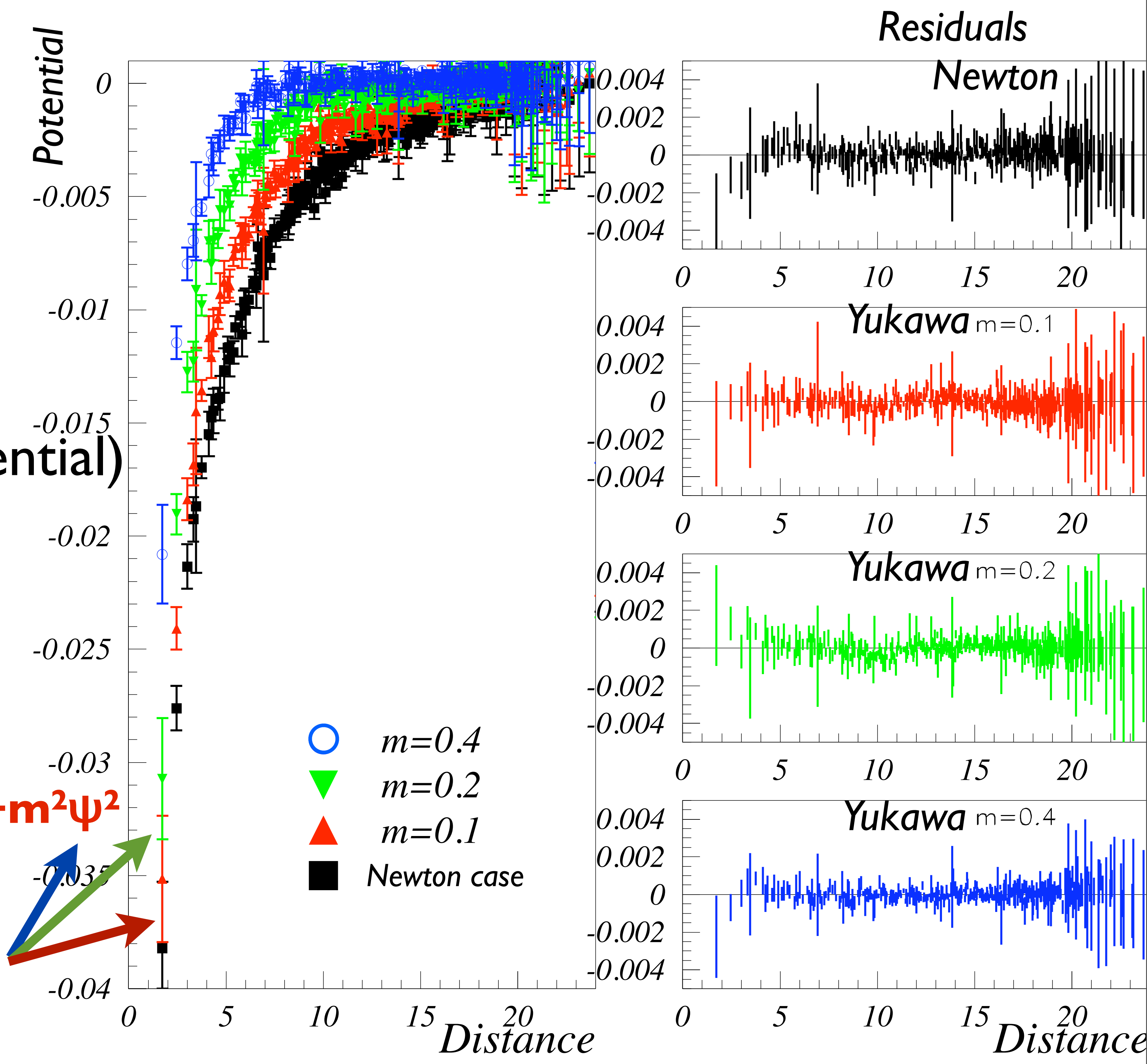
With this, on the lattice,
I obtain:

Expect: $V\propto 1/r$ (Newton potential)

With

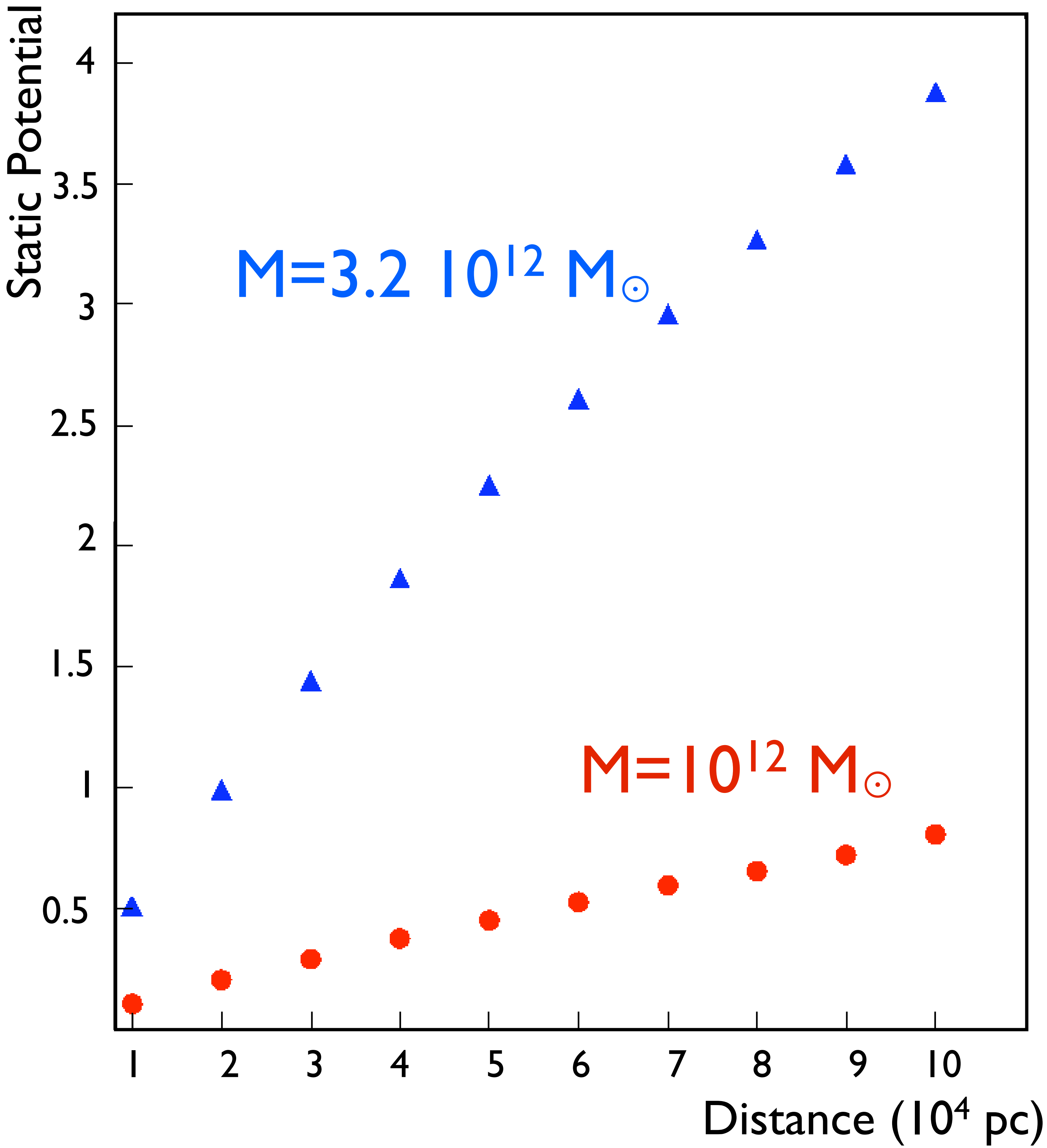
$\mathscr{L}_{GR}=\partial\psi\partial\psi+\sum \xcancel{G^{n/2}\psi^n\partial}\psi\partial\psi+\sqrt{G}\,\psi T\mathbf{+m^2\psi^2}$

$V\propto e^{-mr}/r$ (Yukawa potential)



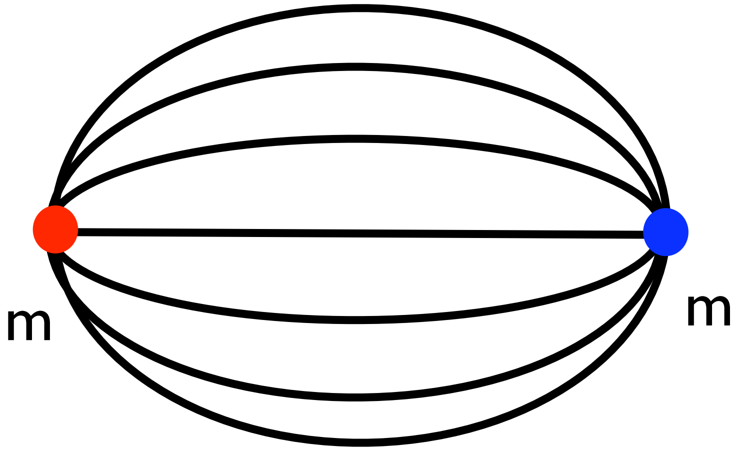
Full $\mathscr{L}$ for two masses M:

Typical galactic mass
$M \sim 10^{12}\ M_\odot$



Interpretation

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



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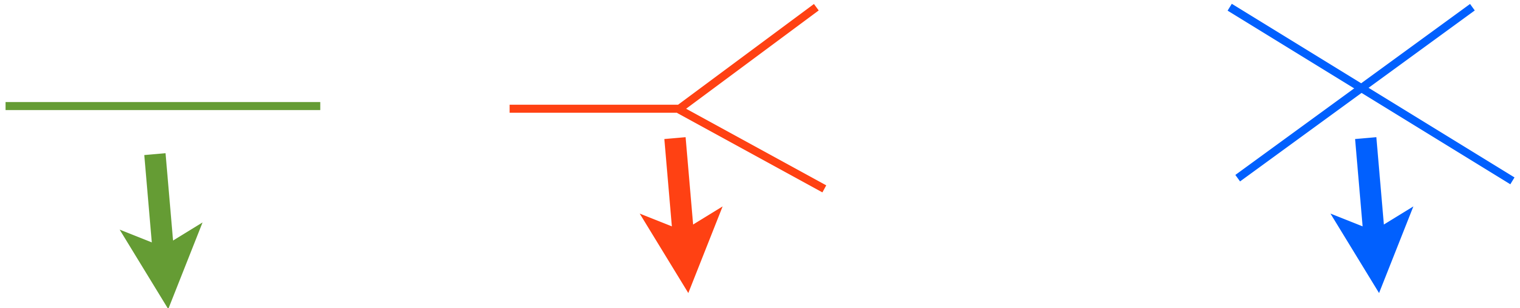

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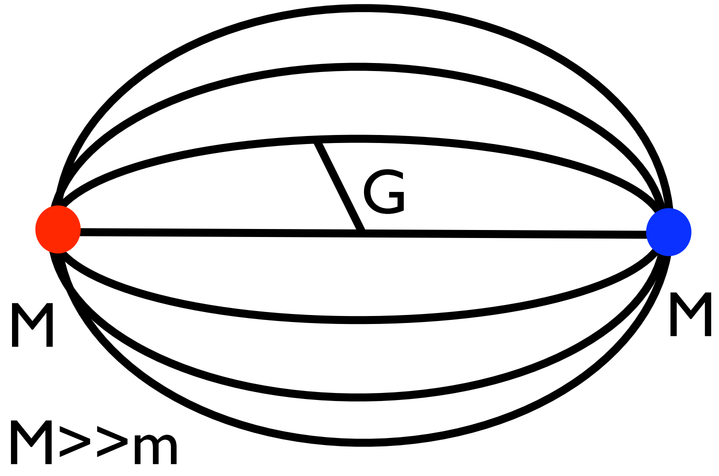

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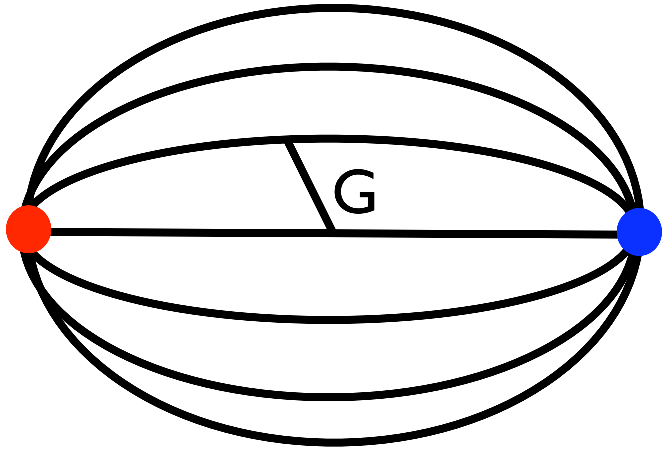
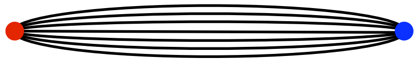
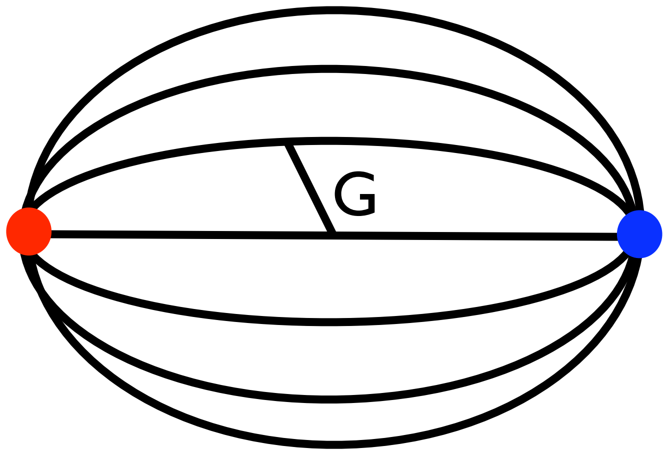
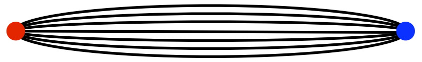




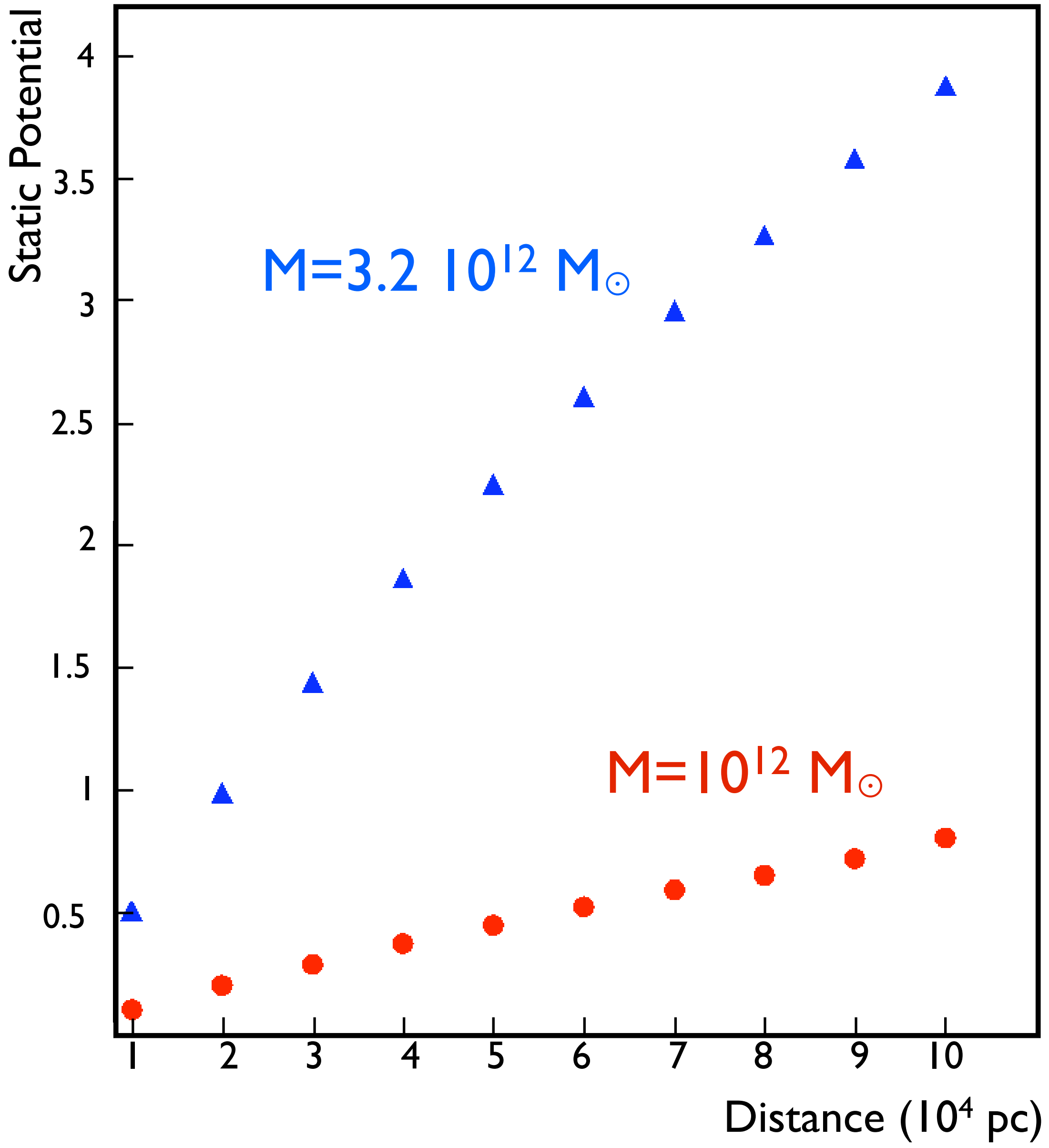
3D system becomes 1D
⇒Force~constant

Interpretation



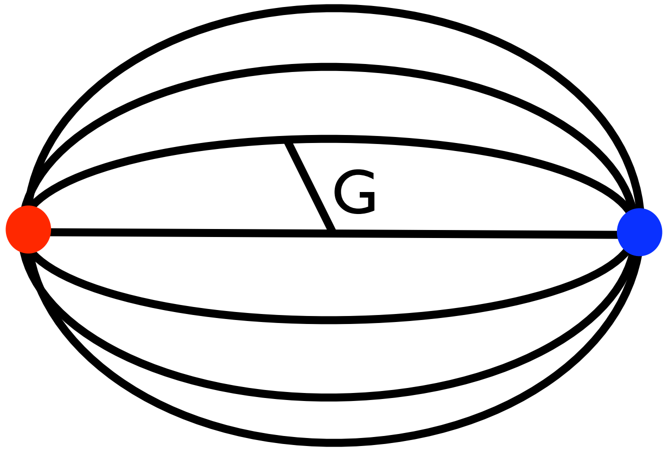


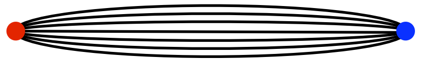
3D system becomes 1D
⇒Force~constant



System is more strongly bound than with $1/r^2$ force. Effectively, the system mass increases (dark mass).

Consequences



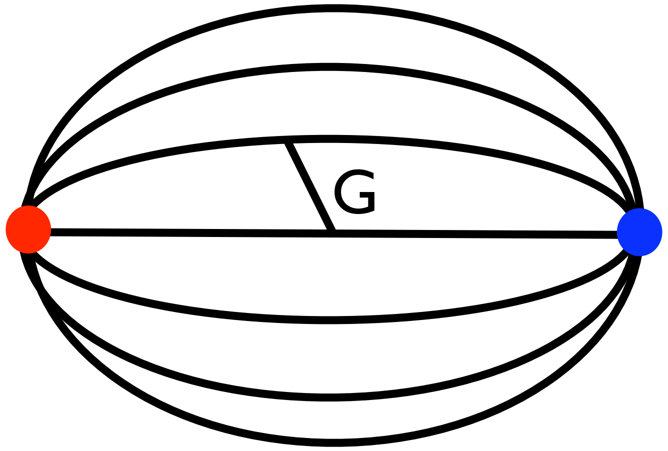


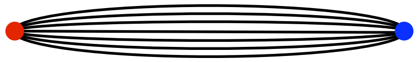
3D system becomes 1D
⇒Force~constant

- Likewise, for an homogeneous planar distribution, gravitons propagation is confined into the plan.

3D system becomes 2D ⇒Force~1/r

Consequences



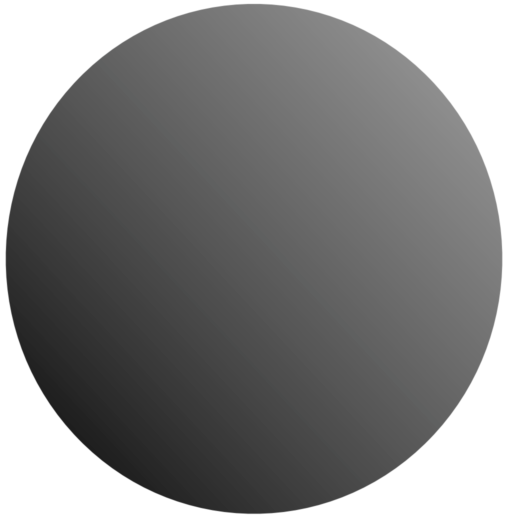


3D system becomes 1D
⇒Force~constant

- Likewise, for an homogeneous planar distribution, gravitons propagation is confined into the disk.

3D system becomes 2D ⇒Force~1/r

- For an homogeneous spherical mass distribution, there is no effect (no preferred directions).



Force~1/r^2

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.

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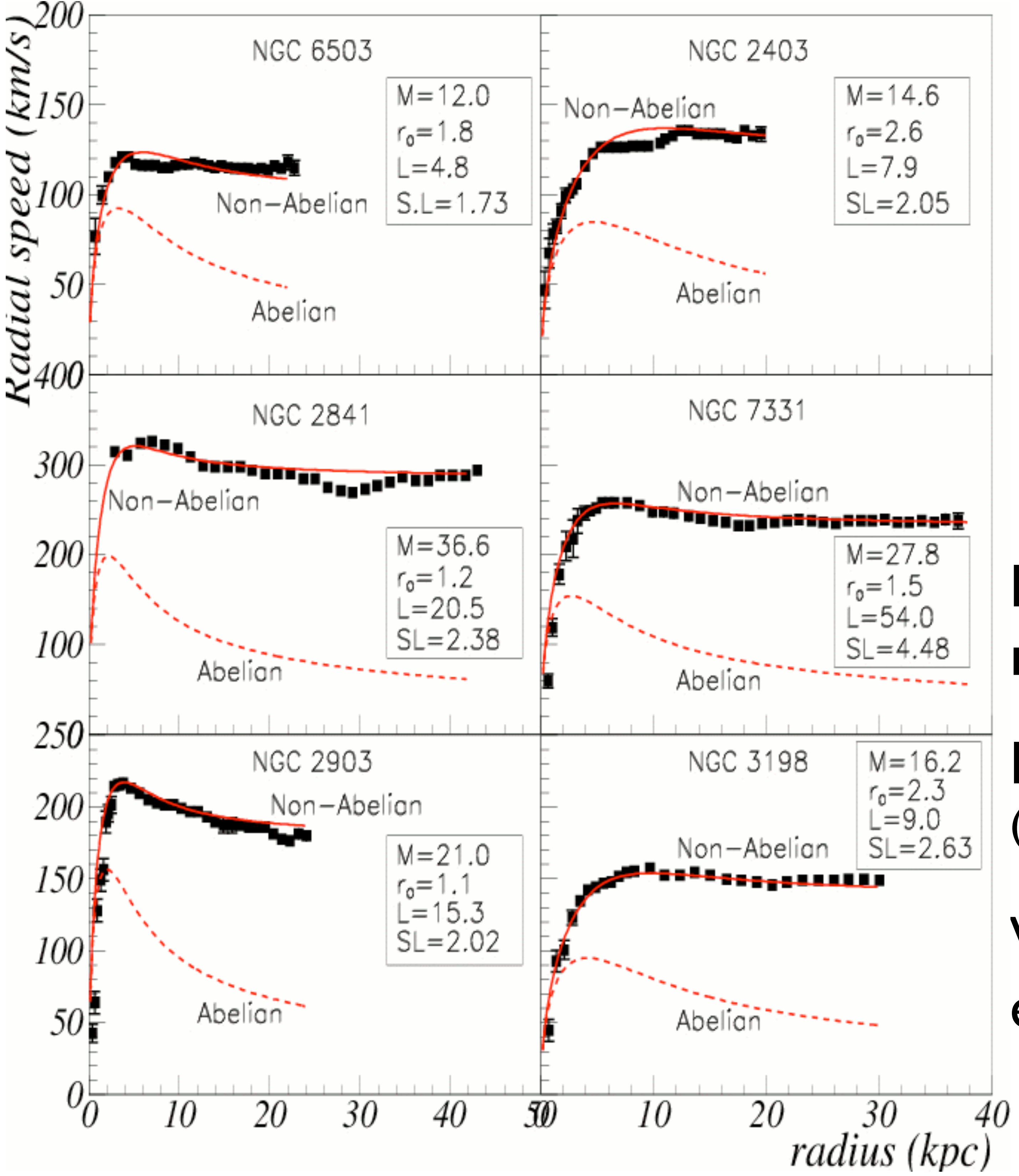


— Full calculation.

- - - 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)

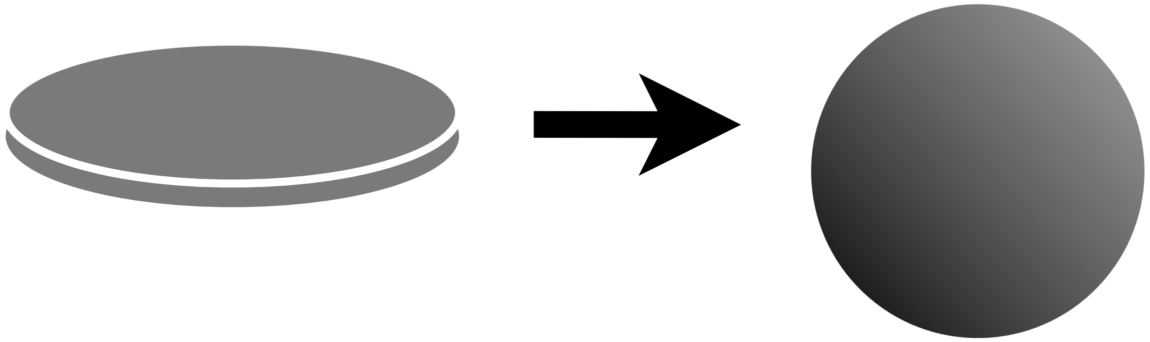
With only baryonic matter, expect M~2-3L and r0=SL

A. D., Phys. Lett. B676 21 (2009)

Consequences

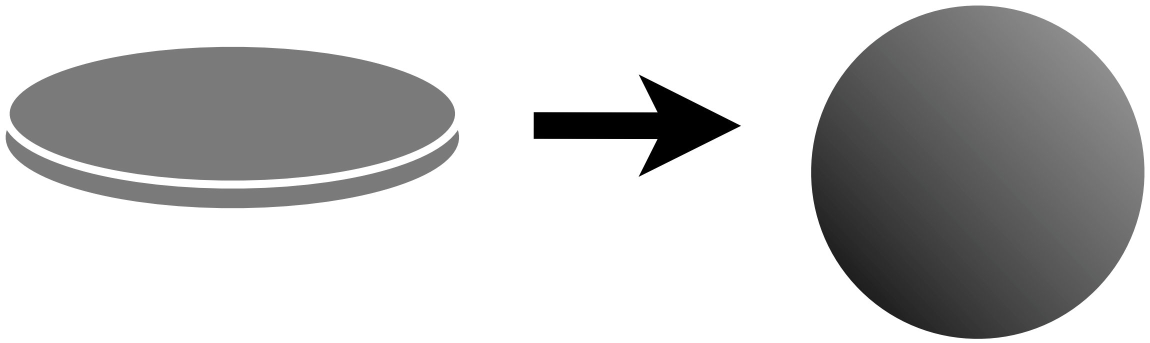
- For a disk, 1/r force + $\rho = \frac{M}{2\pi r_0^2} e^{-r/r0}$ density profile ⇒rotation speed of a disk becomes constant at large radius (postdiction)

- Prediction (2009) for elliptical galaxies: total effective mass, i.e. Dark Mass, varies with ellipticity.



Dark Mass ~ **a** × elliptcty, with **a** >0

Consequences

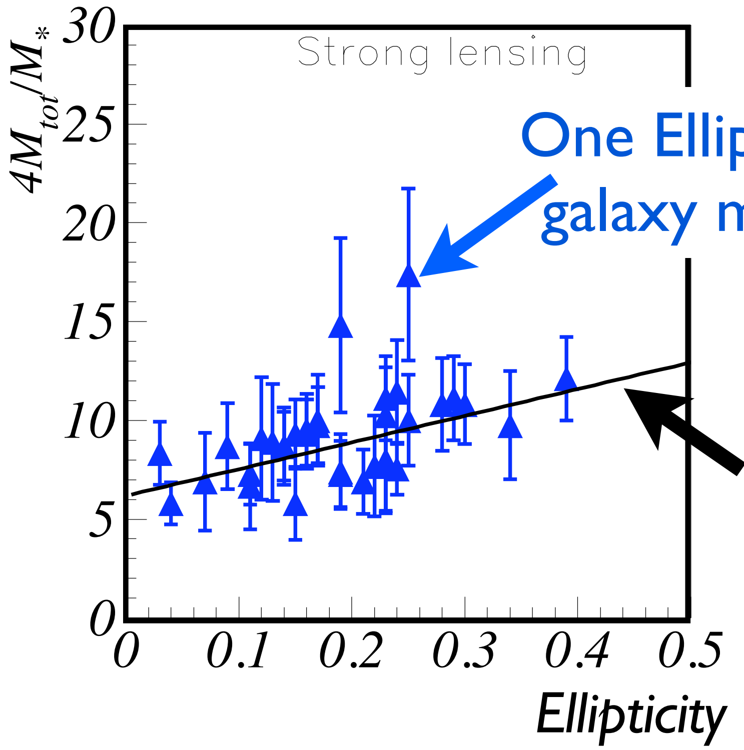


Dark Mass ~ **a** × ellipticty ?

Method:

- Use many publications reporting dark masses for sets of elliptical galaxies.
- Publications often use different methods to obtain dark mass.
- For each publication, extract **a**.

One publication

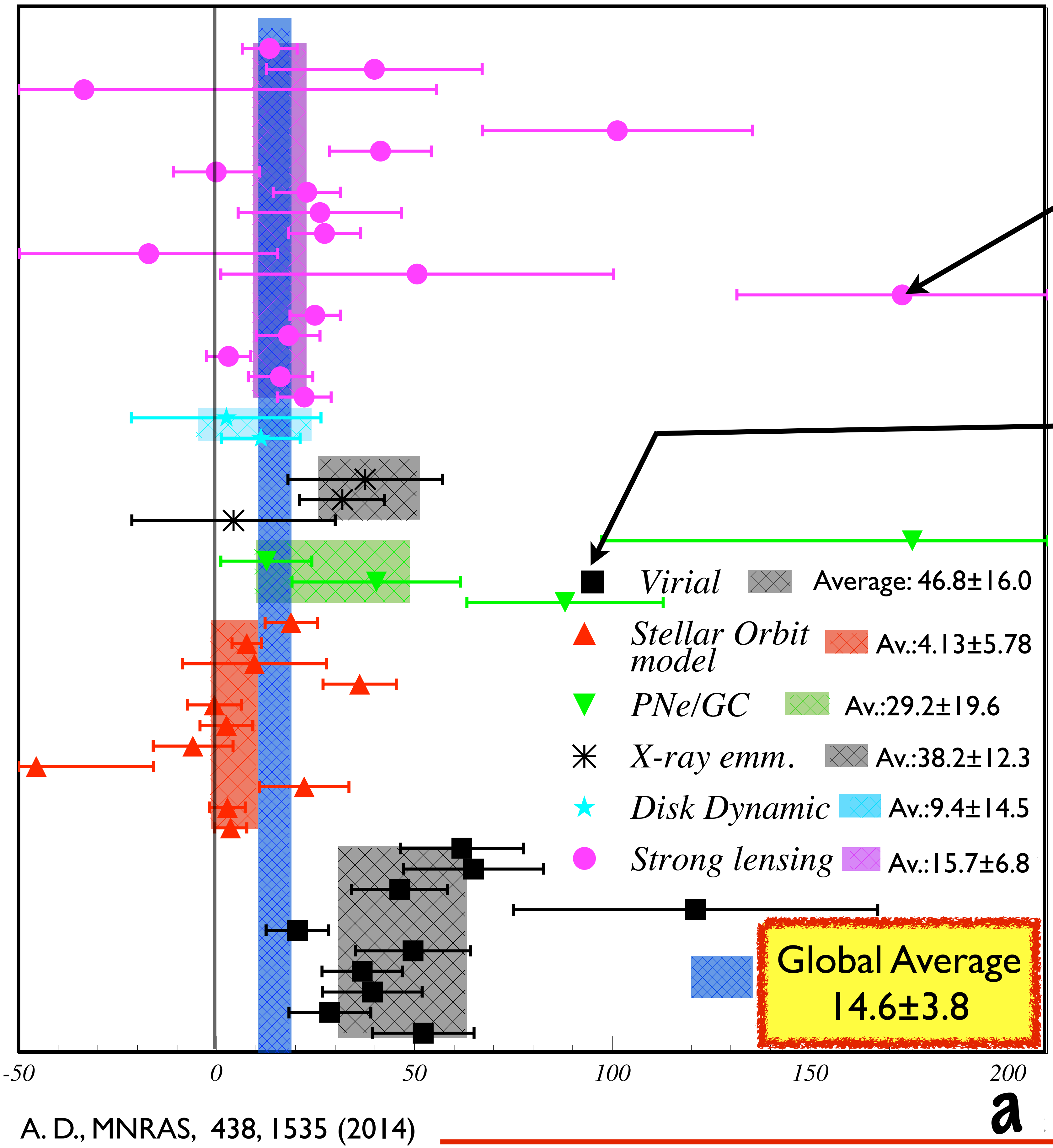


One Elliptical galaxy mass

Slope **a**

- Average results of all publications.

Consequences



One symbol: one publication (many galaxies).

Different symbol type: different method of extracting the dark mass

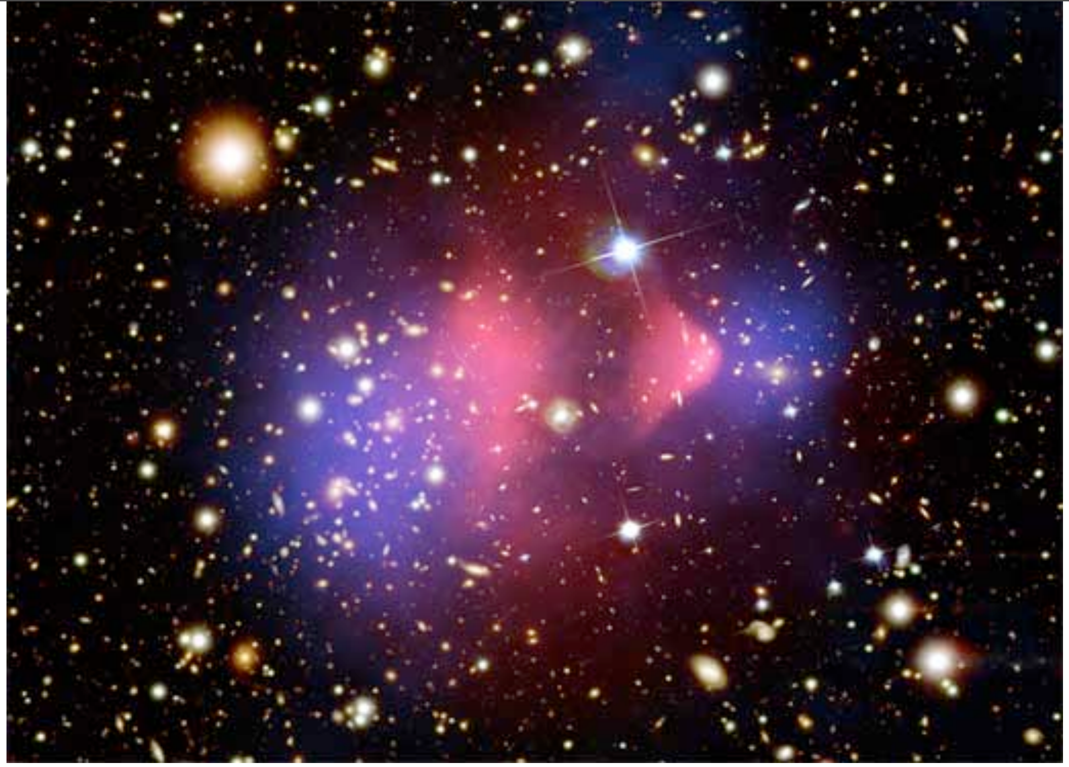
A. D., MNRAS, 438, 1535 (2014)

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.
- Galaxy clusters contain ~90% of Dark Mass.
- Bullet Cluster.

Bullet cluster

Direct evidence of dark matter was found in the Bullet Cluster:



The bullet cluster is formed of two colliding clusters.

Bullet cluster

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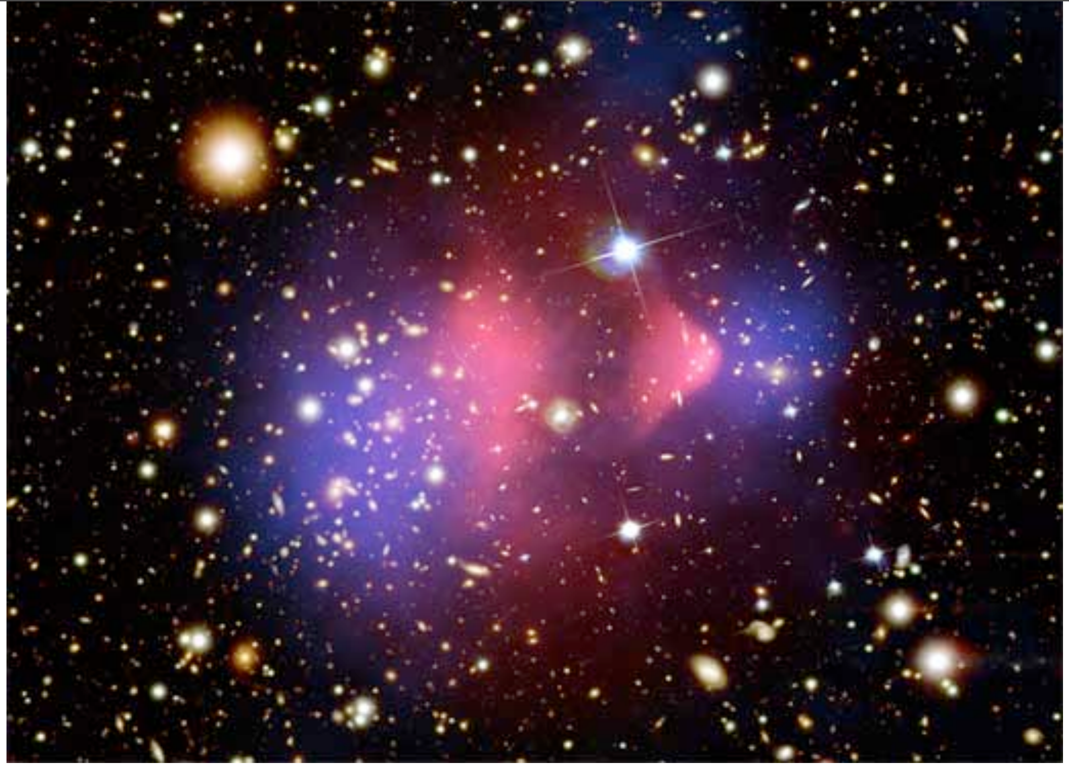
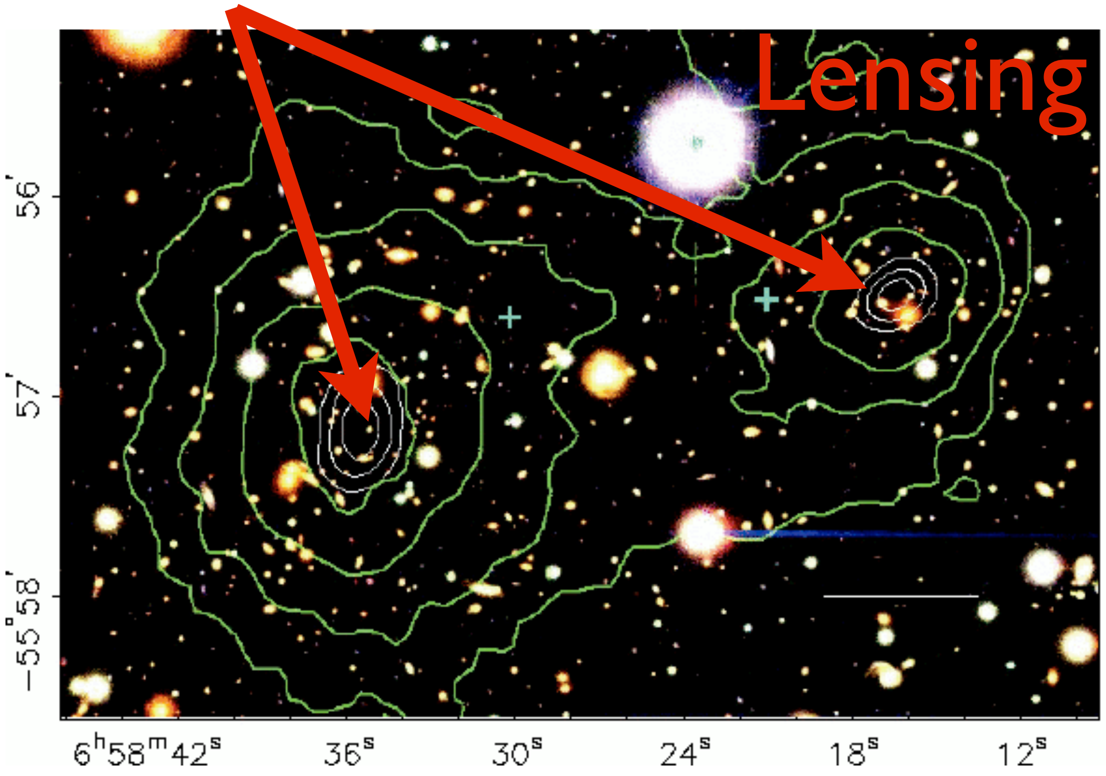
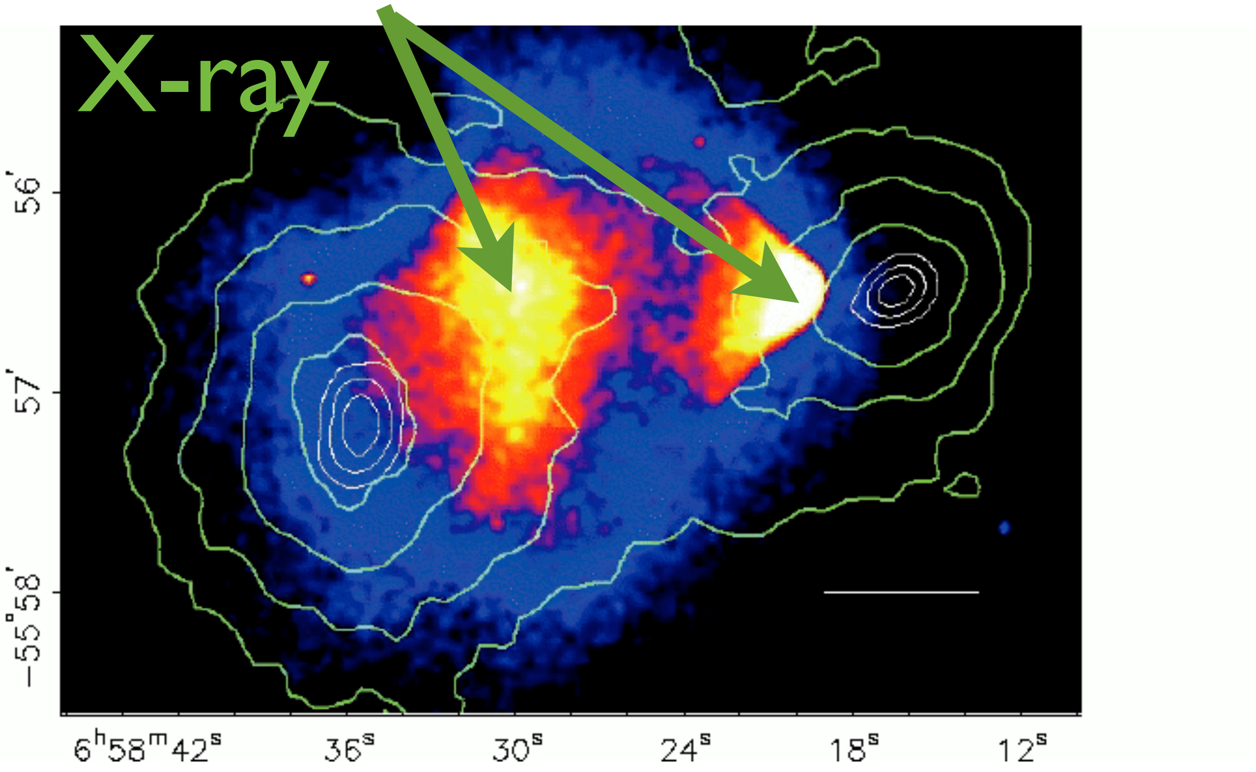


The bullet cluster is formed of two colliding clusters.

Gravitational lensing and x-ray imaging of the gas show that the locations of the two mass maximums are offset from the two maximums of the gas density.





Bullet cluster

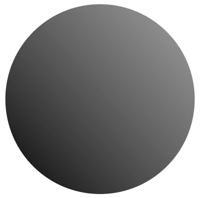
WIMP/Axion interpretation:

- Galaxies: small cross section: galaxy sizes ≪ cluster size.
- Dark matter: small cross section: weakly interacting particles.
- Gas: large cross section since interacts electromagnetically and size~cluster size.

⇒ Since gas dominates the visible mass of a cluster, the observation that most of the total (dark) mass did not stay with the gas appears to rules out modifications of gravity as an alternative to dark matter.

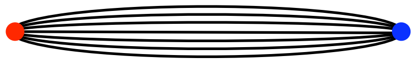
Bullet cluster

Field self-interaction effects also offers a straightforward explanation.
Effects are associated with geometrically asymmetric distributions:



No effects

Some effects



Large effects

These effects should be suppressed for the homogeneous gas, but not the galaxies.

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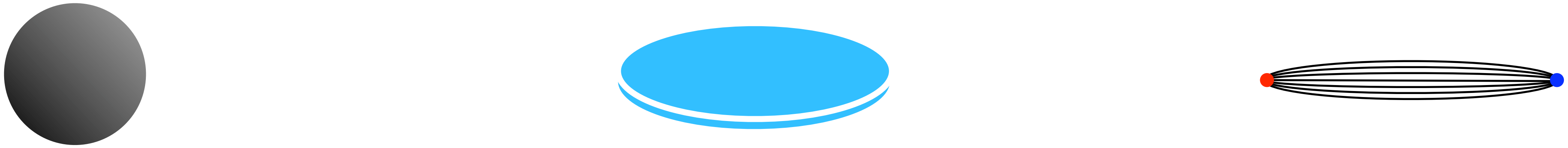

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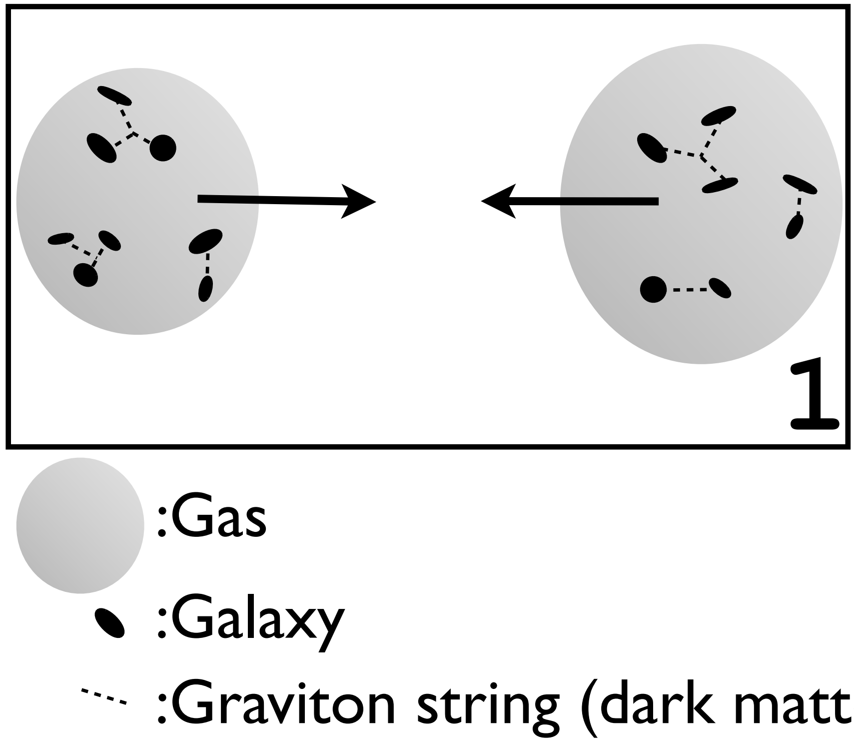

● :Gas

● :Galaxy

⋯ :Graviton string (dark matter)

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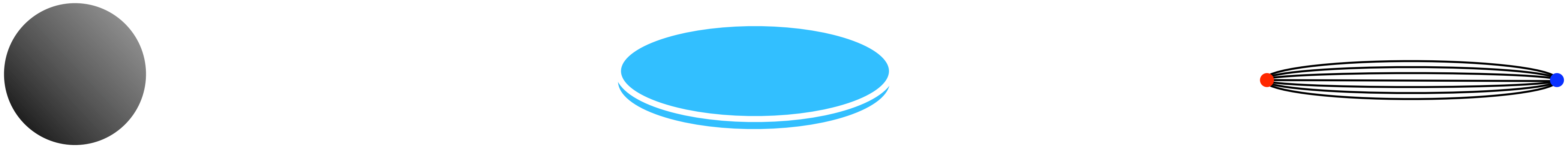

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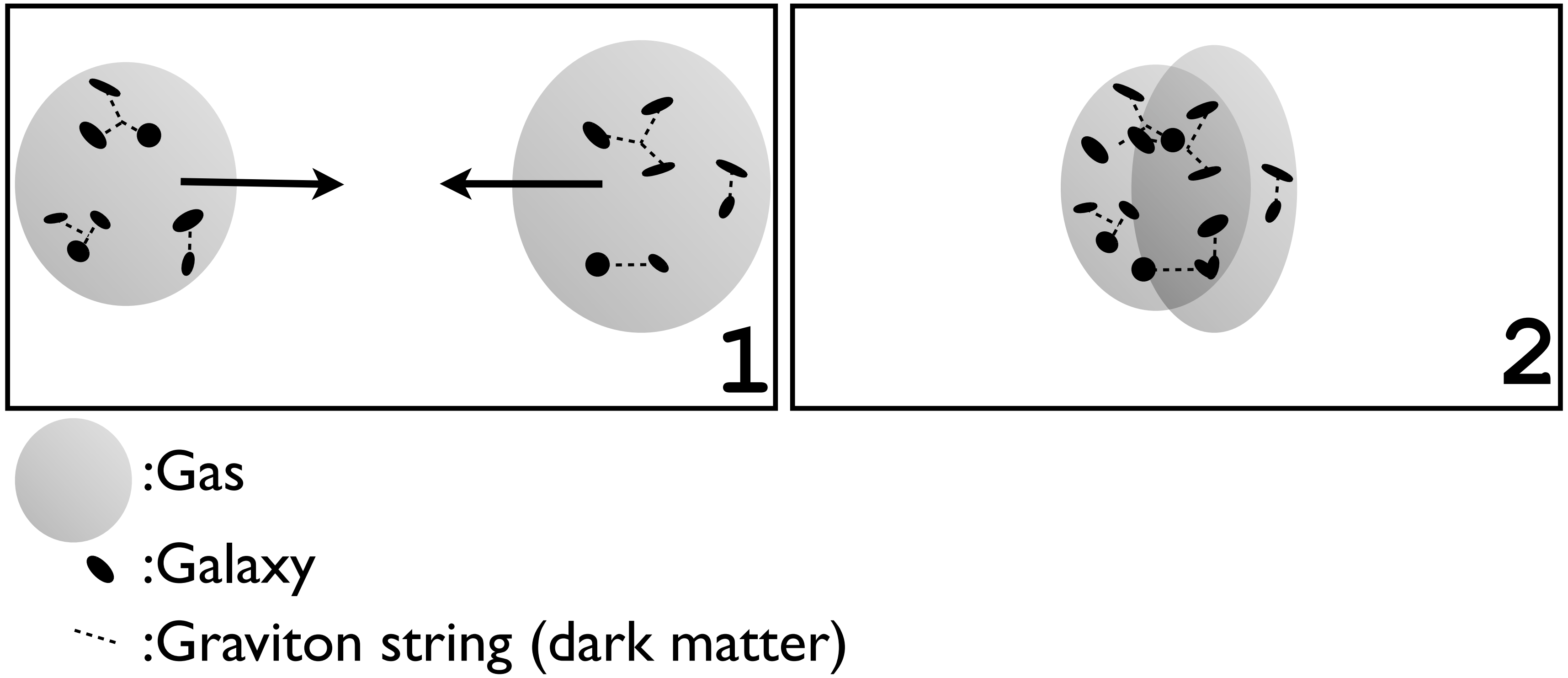

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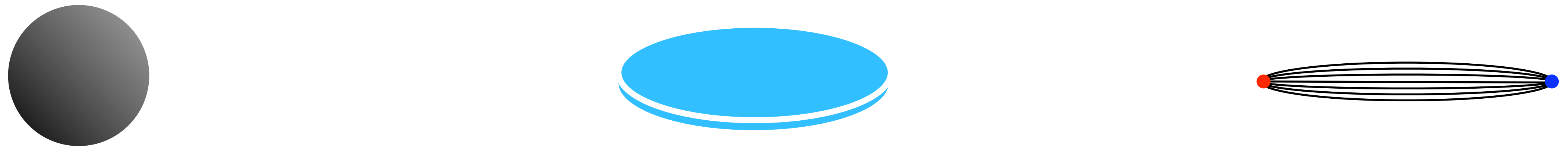

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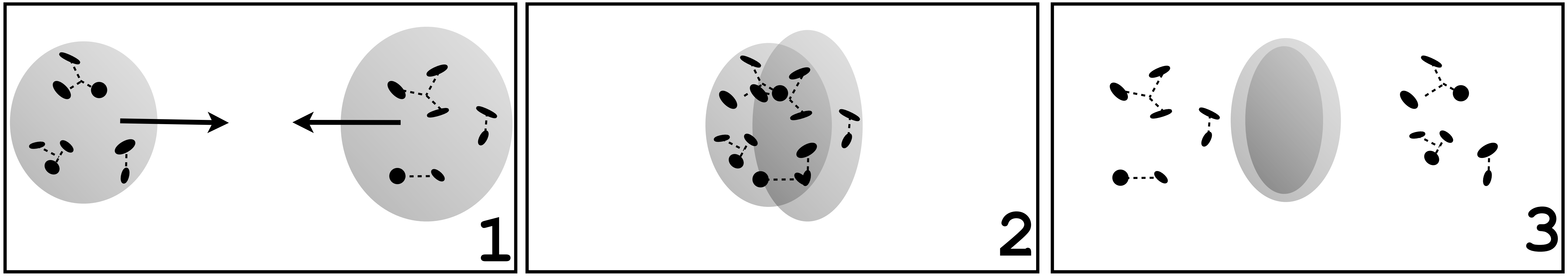

⬤ :Gas

● :Galaxy

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⇒Most of dark matter follows the galaxies.

Summary

- Complex and important QCD effects have been observed. They would have been hard to guess from just looking at the QCD Lagrangian. They are invisible in weak coupling perturbation QCD calculations (pQCD).

- Since QCD and GR have a similar structure, maybe such effects are present in gravity too when large masses are involved.

- Hadronic and galactic dynamics share common phenomena.

- The WIMPs and axion search negative results make this natural explanation attractive.

- Numerical calculations show that mutual interactions of gravitons can explain quantitatively several dark matter phenomena:
  - Large correlation between the ellipticity of elliptical galaxies and their dark mass.
  - Flat rotation curves of disk galaxies.
  - Cluster dynamics.
  - Bullet cluster observation.

Back-up slides

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.
- Galaxy clusters contain ~90% of Dark Mass.
- Bullet Cluster.
- "Graviton strings" between heavy masses.

Elliptical galaxies

One of the 3 morphological classes of galaxies. (Others: disk and irregular.)

Elliptical galaxies have smooth featureless ellipsoidal shapes:

Many correlations exist between different quantities characterizing a galaxy. Sometime understood, but often phenomenological.

Two most evident characteristics of E galaxy:

Its mass (mostly dark), its ellipticity.

Are those correlated? No expected reason but Dark Matter phenomenology is still puzzling at galactic level. So it's worth to have a look.

A. Deur, Monthly Notices Royal Astro. Soc., 438, 1535 (2014)

Challenges

- Many types of Ellipticals with many particularities.

- Projected ellipticity.
- Difficulty in assessing the Dark Matter content of Ellipticals.

Solutions

- Many types of Ellipticals with many particularities
  - Strict selection criteria:
    - No Dwarf or Giant.
    - No Peculiar/interacting/disturbed galaxy.
    - No Lenticular galaxy.
    - No unusual feature (HII regions, AGN, Seyfer or BLLac galaxies, LINER,...).
  - Large homogeneous samples (statistical reduction of peculiarities).
- Projected ellipticity
  - Large homogeneous samples ⇒ Statistical treatment.
- Difficulty in assessing the Dark Matter content of Ellipticals
  - Use published results based on 6 independent methods of assessing Dark Matter content ⇒ Data mining.

Each publication should have analyzed several acceptable galaxies.

⇒ 41 homogeneous samples totaling 685 galaxies (225 different galaxies).

Dark Matter content estimates

Virial theorem

Total galactic mass ∝ (velocity dispersion)^2 of stars. Galaxy must be in relaxed state (virial equilibrium).

8 data sets

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Model orbits of stars ⇒ light distribution. Matched to measurements ⇒ Gravitational potential.

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Measurement of the interstellar hot gas temperature and density yields total galactic mass (assuming hydrostatic equilibrium).

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Well Resolved bodies ⇒ Gravitational potential.

4 data sets

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Warm or cold gas disks sometimes found in ellipticals. ⇒

Dark Matter content obtained the same way as for disk galaxies.

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  4 data sets

- ## Gas disk dynamics

  Warm or cold gas disks sometimes found in ellipticals. ⇒ Dark Matter content obtained the same way as for disk galaxies.

  2 data sets

- ## Strong Lensing

  Gravitational lensing of luminous objects lying behind the galaxy provides its gravitational potential.

  16 data sets

Dark Matter content estimates

Multiple independent techniques protect us against a particular methodological bias.

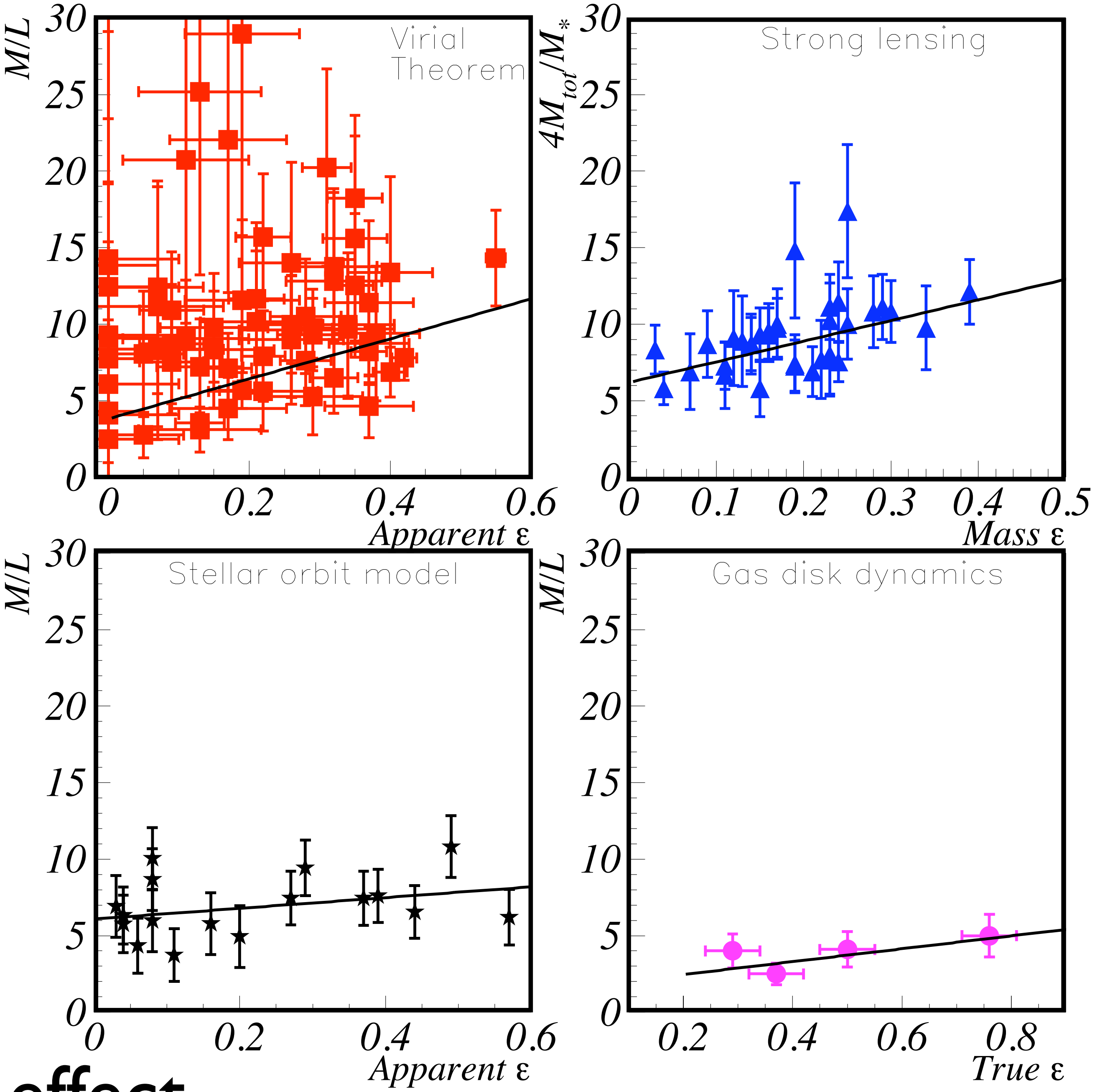
Usually, M/L (or M/M_*) are given.

Analysis

- Apply selection criteria.

- Linear fits of M/L vs ellipticity ε are performed for each of the 41 homogeneous samples.

Ex. for 4 samples:

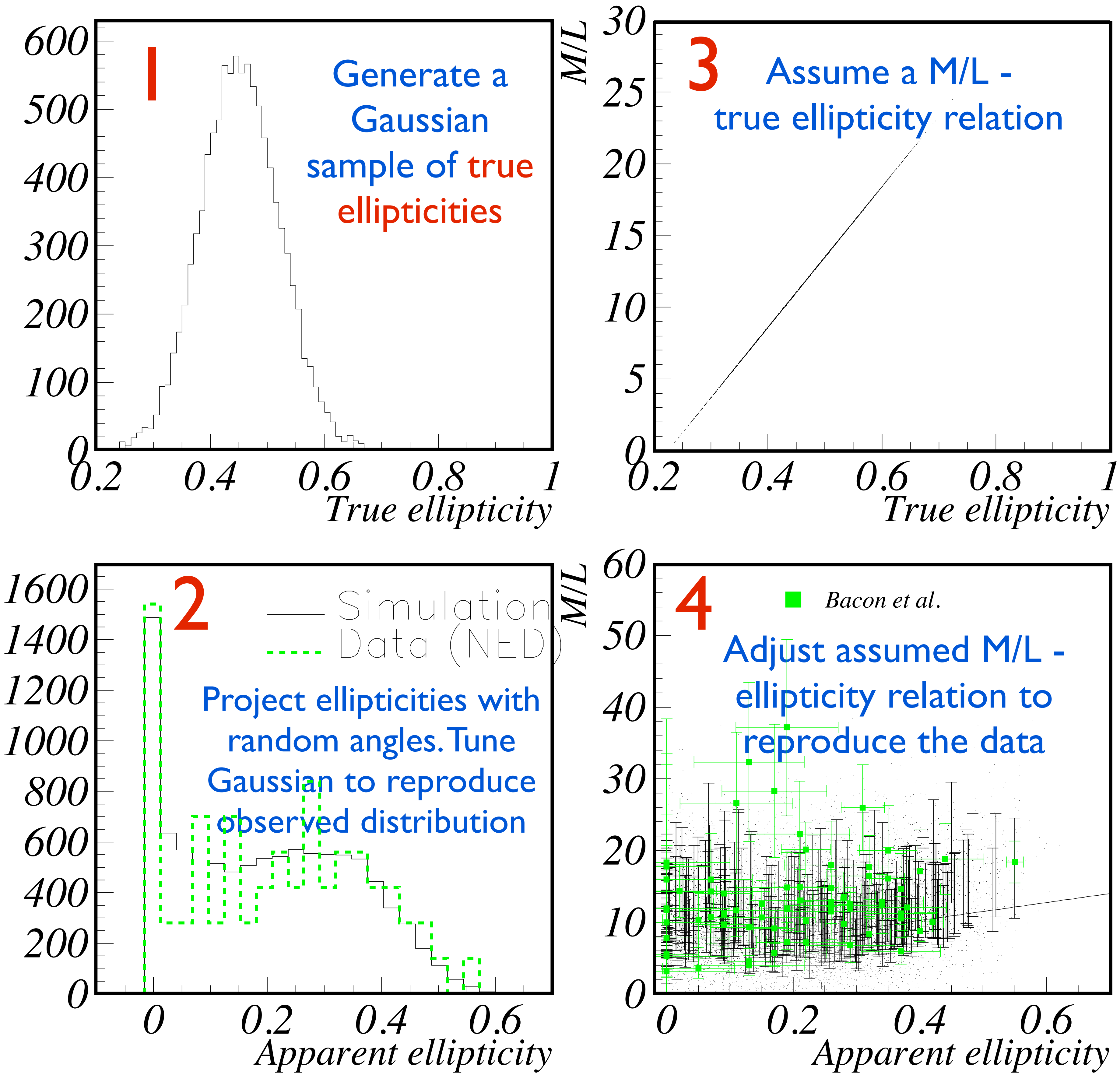


- Results corrected for projection effect.

- 41 results on $\frac{d(M/L)}{d\varepsilon}$ are combined to provide one overall result.

projection correction

Statistical method.
Use a large sample and assume the correction is the same for all samples.



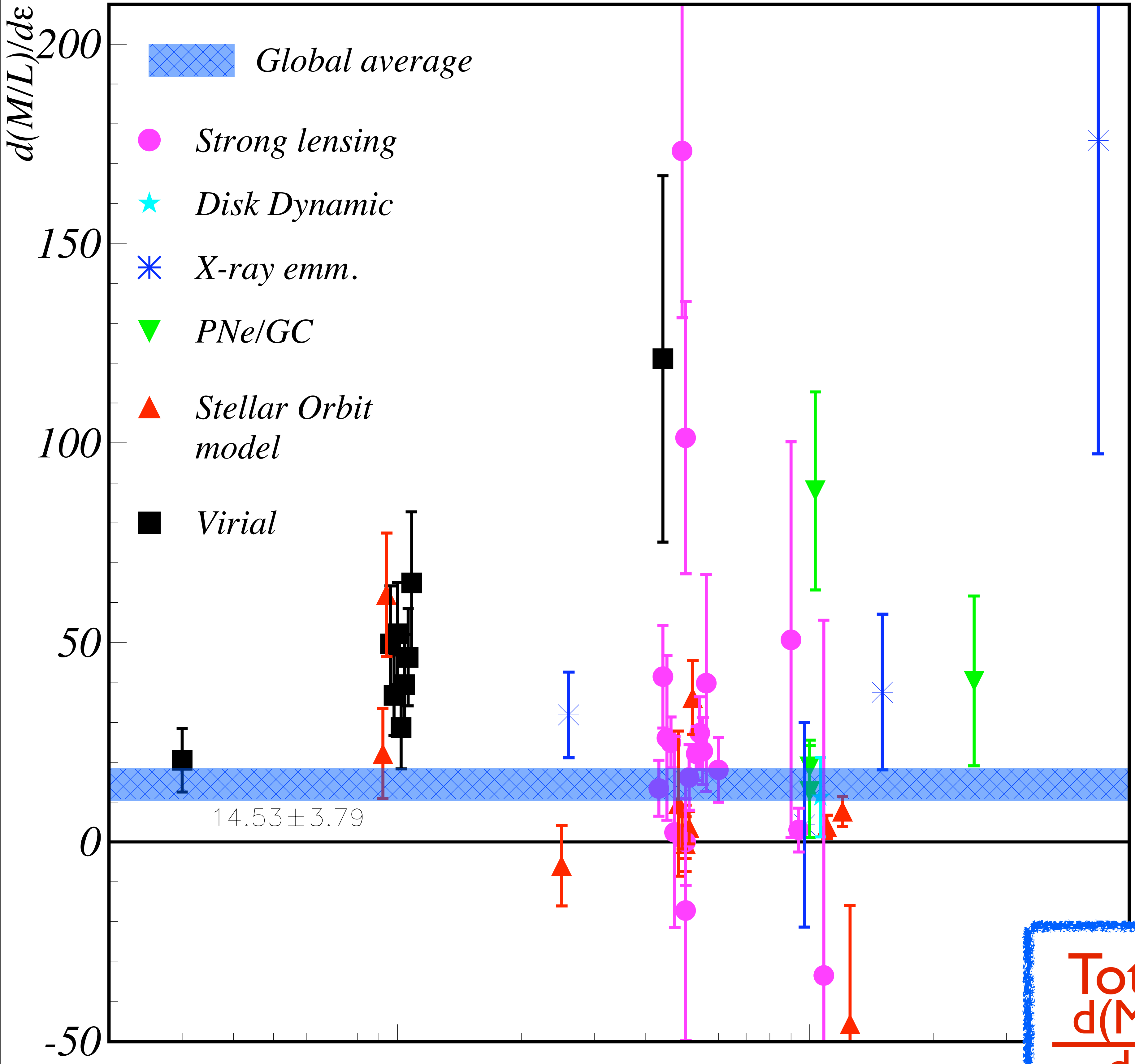
1 Generate a Gaussian sample of true ellipticities

2 Project ellipticities with random angles. Tune Gaussian to reproduce observed distribution

3 Assume a M/L - true ellipticity relation

4 Adjust assumed M/L - ellipticity relation to reproduce the data

Result



Data sets from different methods indicate positive averaged $\frac{d(M/L)}{d\varepsilon}$:

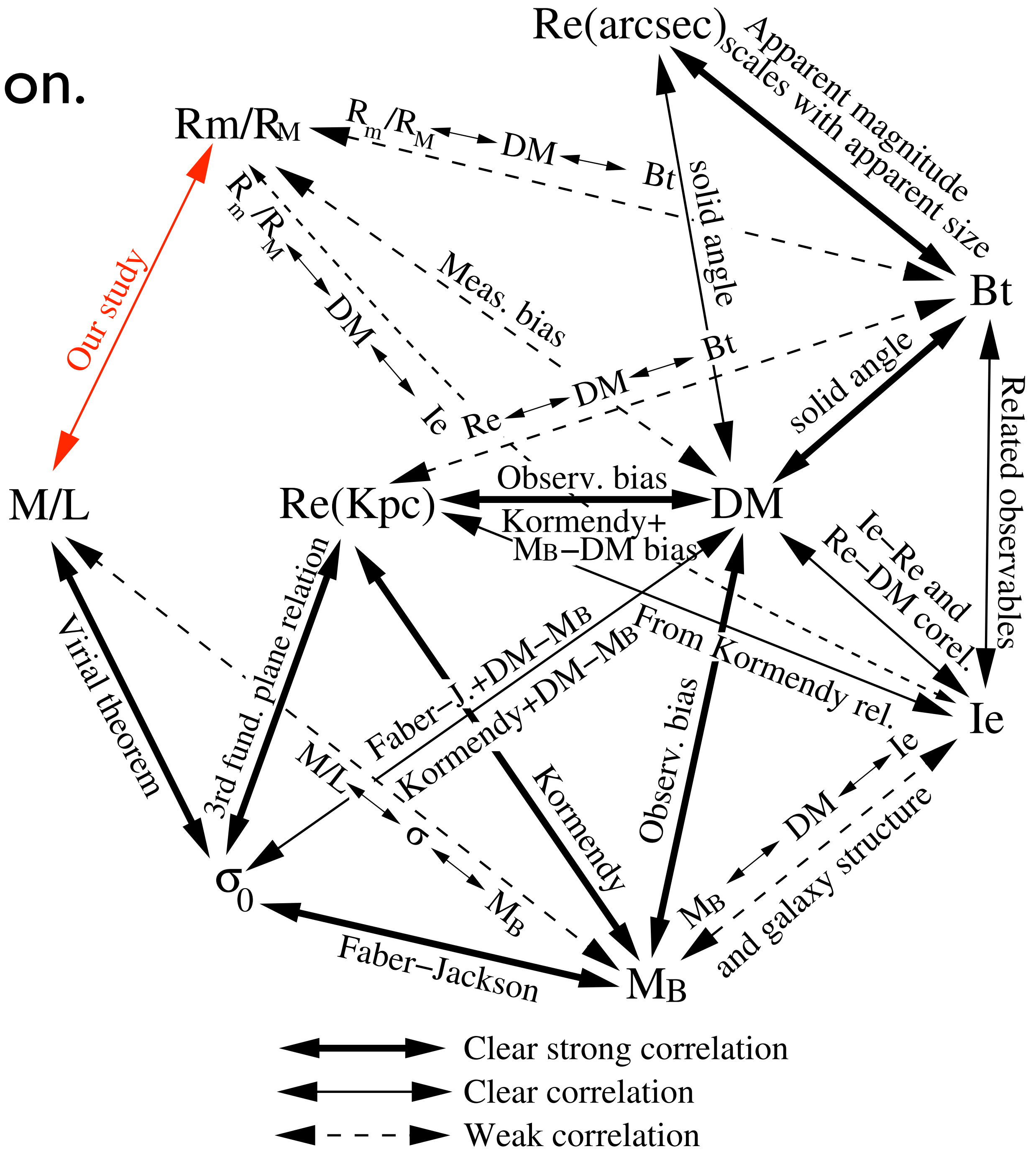
Method	$\frac{d(M/L)}{d\varepsilon}$
Virial	46.77 ± 16.00
Stellar orbit	3.92 ± 5.74
PNe/GC	29.22 ± 19.63
X-ray	38.21 ± 12.29
Disc Dyn.	9.38 ± 14.52
Strong lensing	15.72 ± 6.84

Total average:

$$\frac{d(M/L)}{d\varepsilon} = 14.53 \pm 3.79$$

Systematic studies

- Methodological bias: 6 independent methods, many different publications.
- Studied effect of relaxed selections, environment, correlation assessment.
- S0 (lenticular) galaxy contamination.
- Other correlations:



Consequences

$\frac{d(M/L)}{d\varepsilon} = 14.53 \pm 3.79$ Large compared to <M/L>~8

⇒ Roundest elliptical galaxies contain very little Dark Matter.

⇒ Puzzling:

- Hard to explain in the context of structure formation (need Dark Matter seed).
- No obvious reason for such relation in the Cold Dark Matter model context.

Combining homogeneous samples

To combine the 41 $\frac{d(M/L)}{d\varepsilon}$:

- Normalize all data sets to same M/L(ε=0.3).
- Correct for correlations between data sets using same method and sharing same galaxies.
- Correction for dependence of M/L with galactic radius.