THE DARK WORLD THROUGH THE LOOKING GLASS

How a hypothetical mirror-reflected world could solve the mystery of
dark matter

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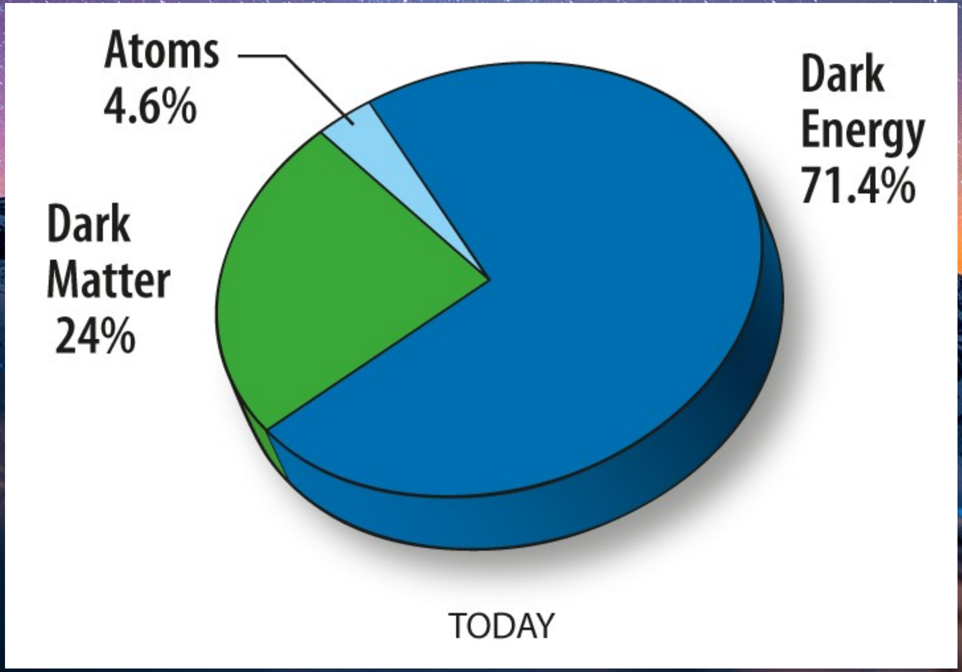
DARK MATTER

- We can only see up to 5% of what’s out there! (kinda creepy…)
- Dark matter is the dominant form of matter in the Universe (85%!)



WHAT WE (THINK WE) KNOW ABOUT DARK MATTER

- Massive
- Cold
- Collisionless
- Invisible
- Non-interacting or weakly-interacting

Q: HOW DO WE SEE THE INVISIBLE I?

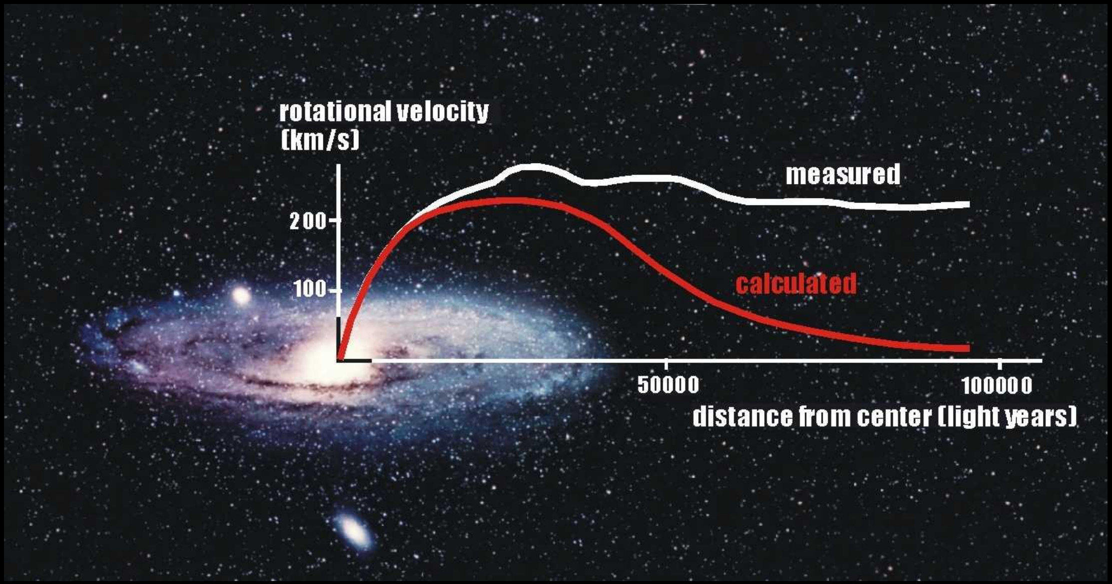
- A: Erm…sometimes we’d rather not

Q: HOW DO WE SEE THE INVISIBLE II?

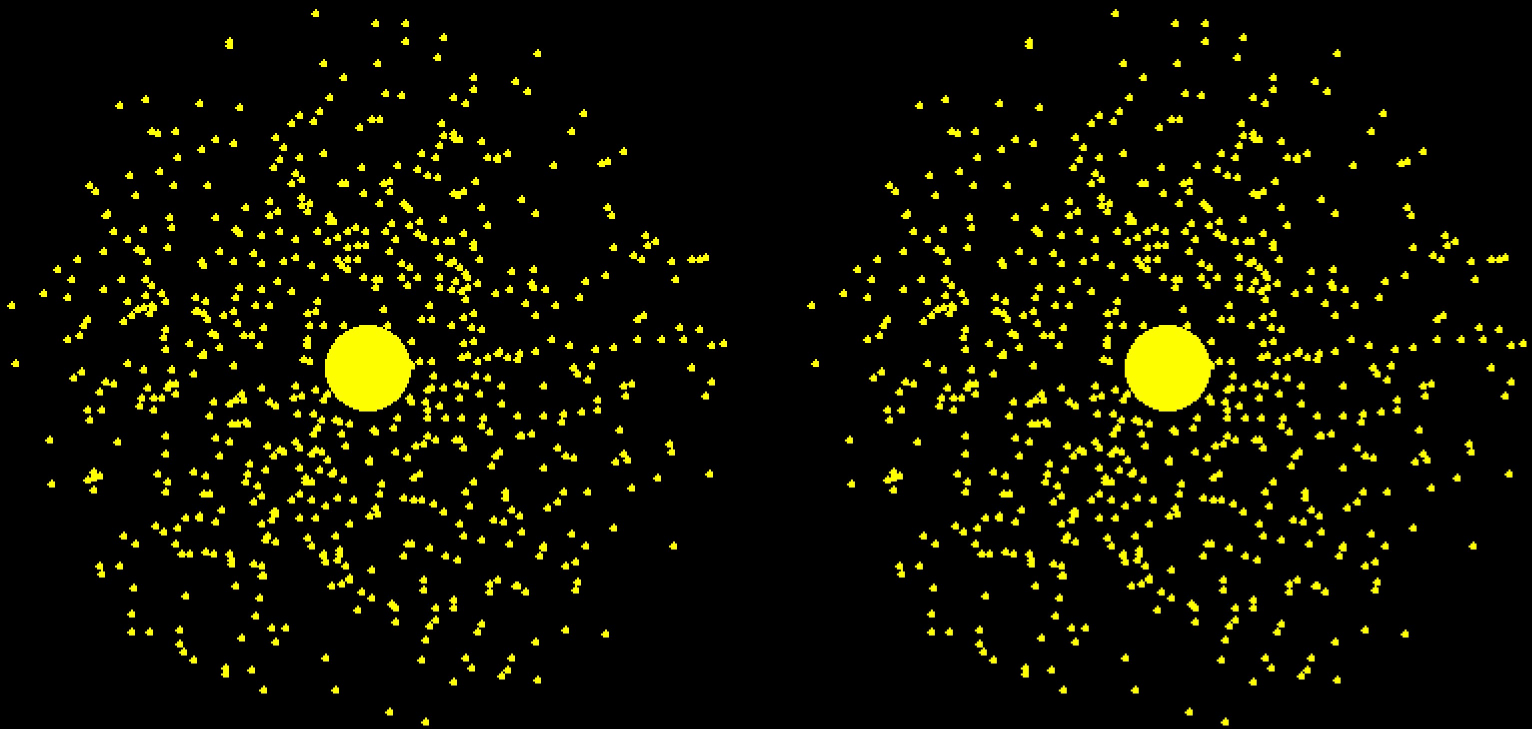
- A: Gravity!

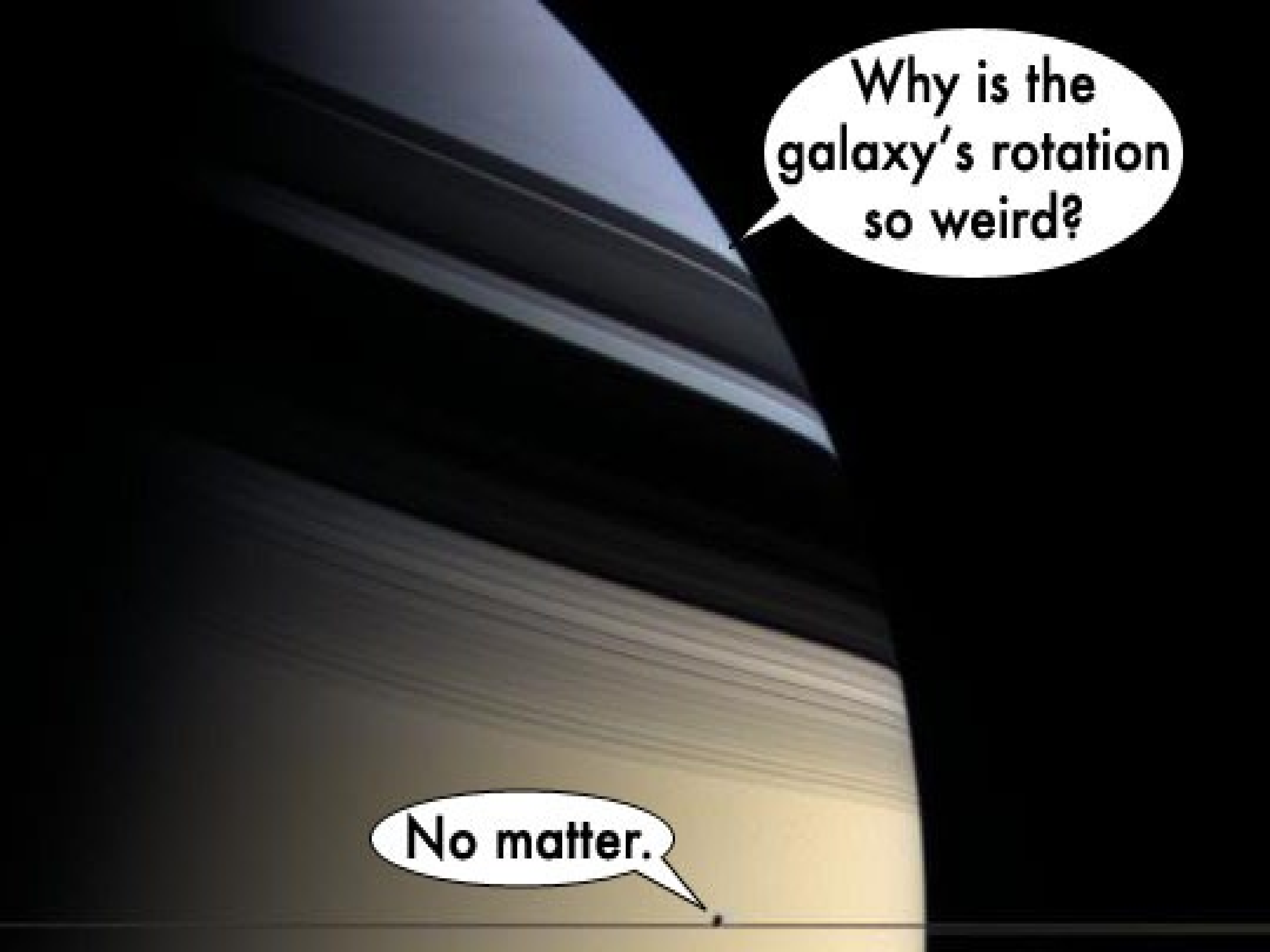
EVIDENCE FOR DARK MATTER I

- Galactic rotation curves: expect fall-off at edges (if use Newtonian Mechanics)
- Rotation curve is instead flat -> much more matter than what we actually see!



SOLAR SYSTEM vs GALAXY



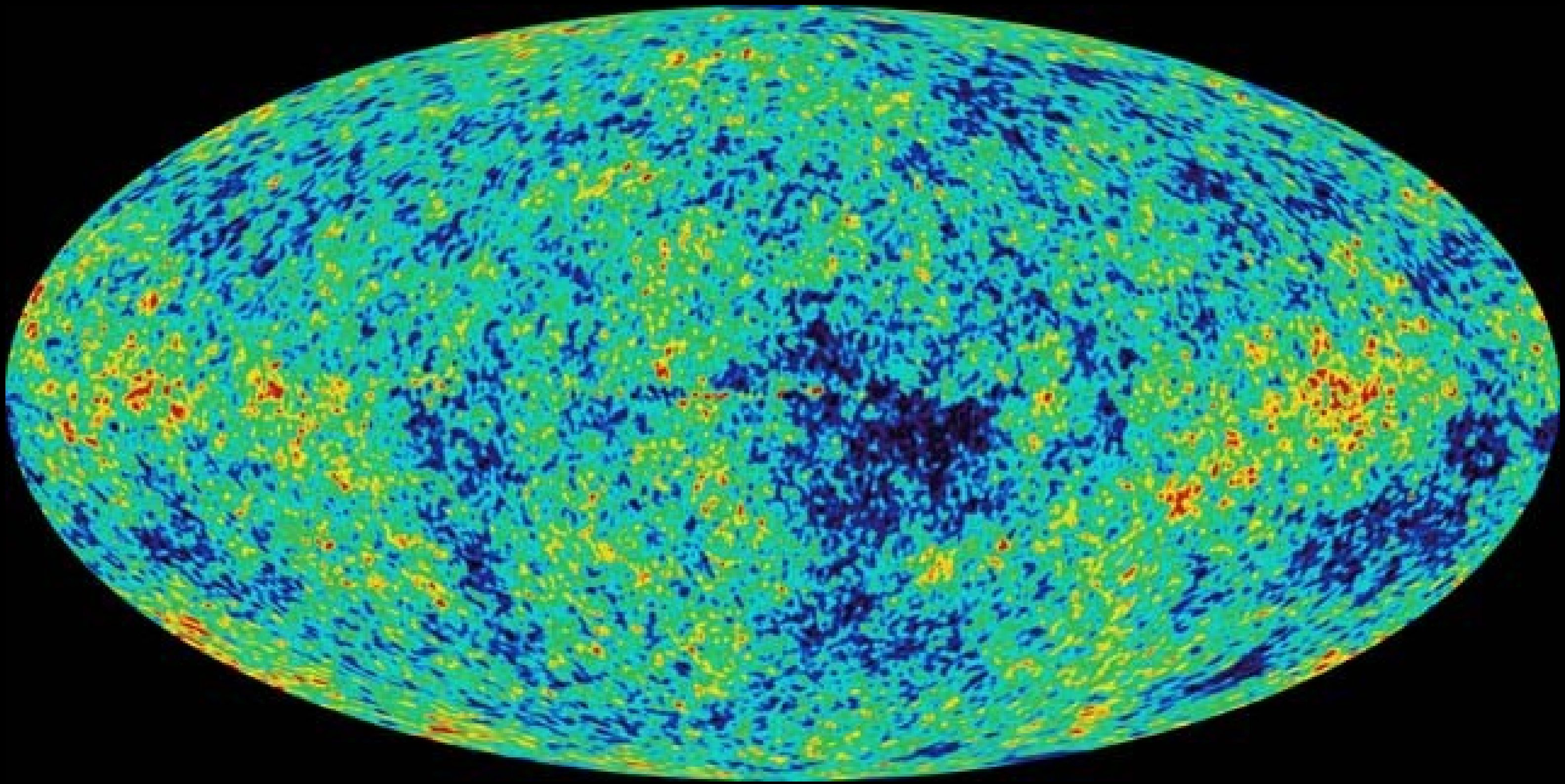

Why is the galaxy's rotation so weird?
No matter.

EVIDENCE FOR DARK MATTER II

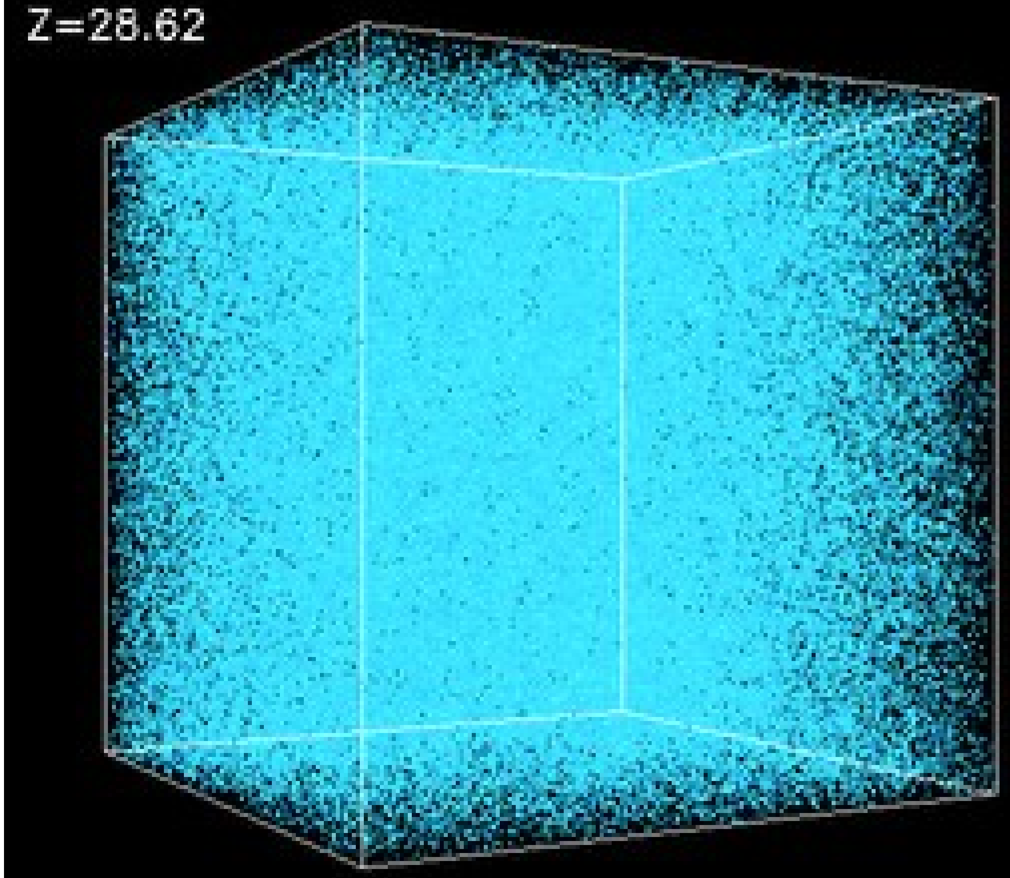
- Need dark matter to explain Large-Scale Structure (LSS)
- Structure (galaxies, clusters, etc.) arise from small perturbations on an otherwise smooth Universe but...
- Initial perturbations are too small (1/100000) to form structure in time

COSMIC MICROWAVE BACKGROUND

- Earliest snapshot of the Universe!

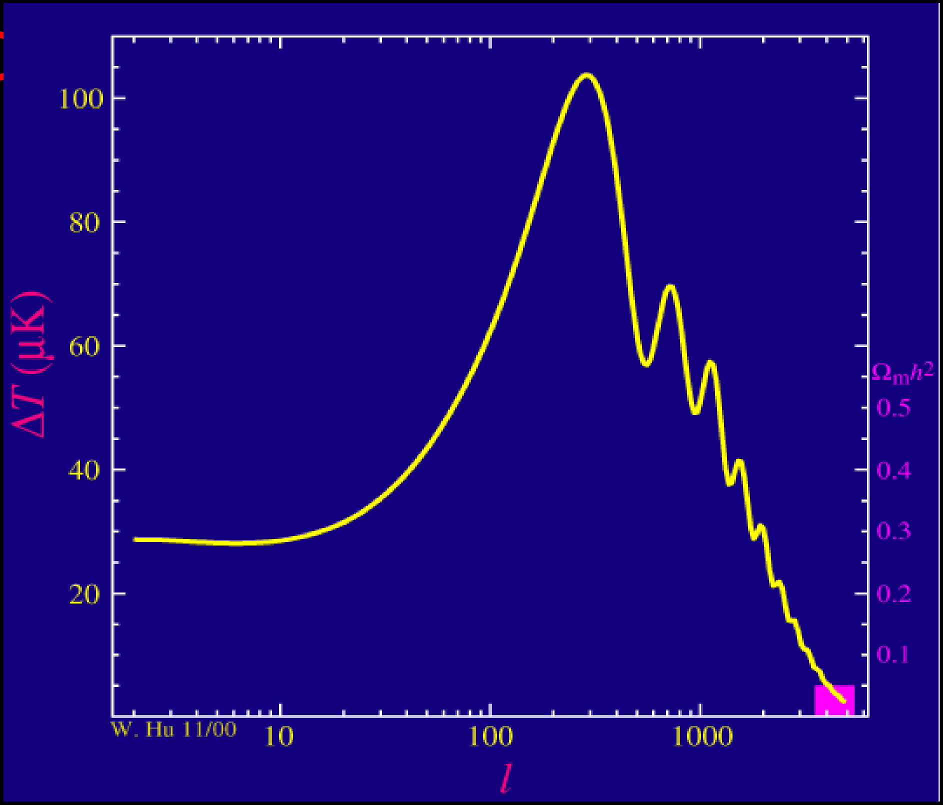


DARK MATTER SIMULATIONS



EVIDENCE FOR DARK MATTER III

- Necessary to explain peaks (particularly first three) of CMB anisotro



OTHER EVIDENCES

- Gravitational lensing/microlensing
- Matter power spectrum
- Cluster collisions
- Direct detection experiments?
  (very controversial)

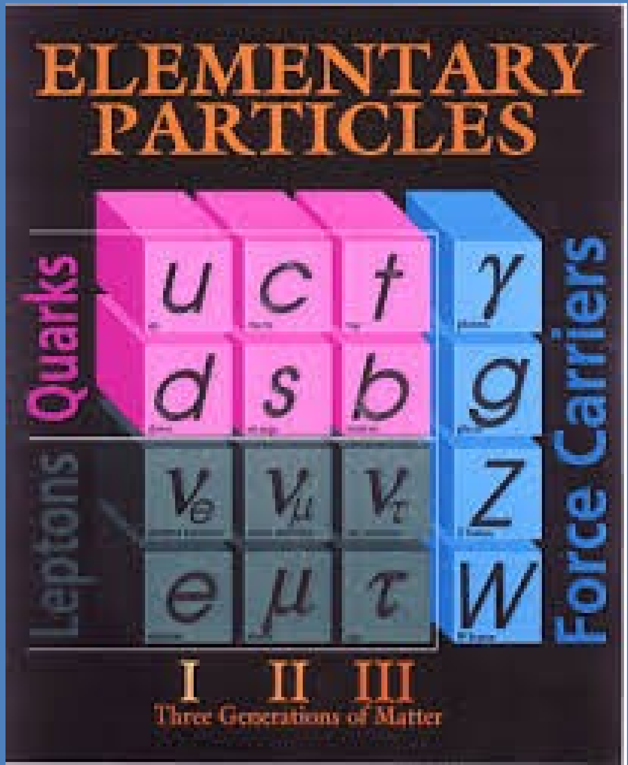
CANDIDATES FOR DARK MATTER

- Weakly interacting massive particles (WIMPs)
- Massive Astrophysical Compact Halo Objects (MACHOs): white dwarfs, brown dwarfs, unassociated planets…highly unlikely!
- Exotic particles (axions, LKP)
- A good candidate has to be stable, dark, weakly interacting and reproduce relic abundance


and now it's time for something
completely different

THE STANDARD MODEL I

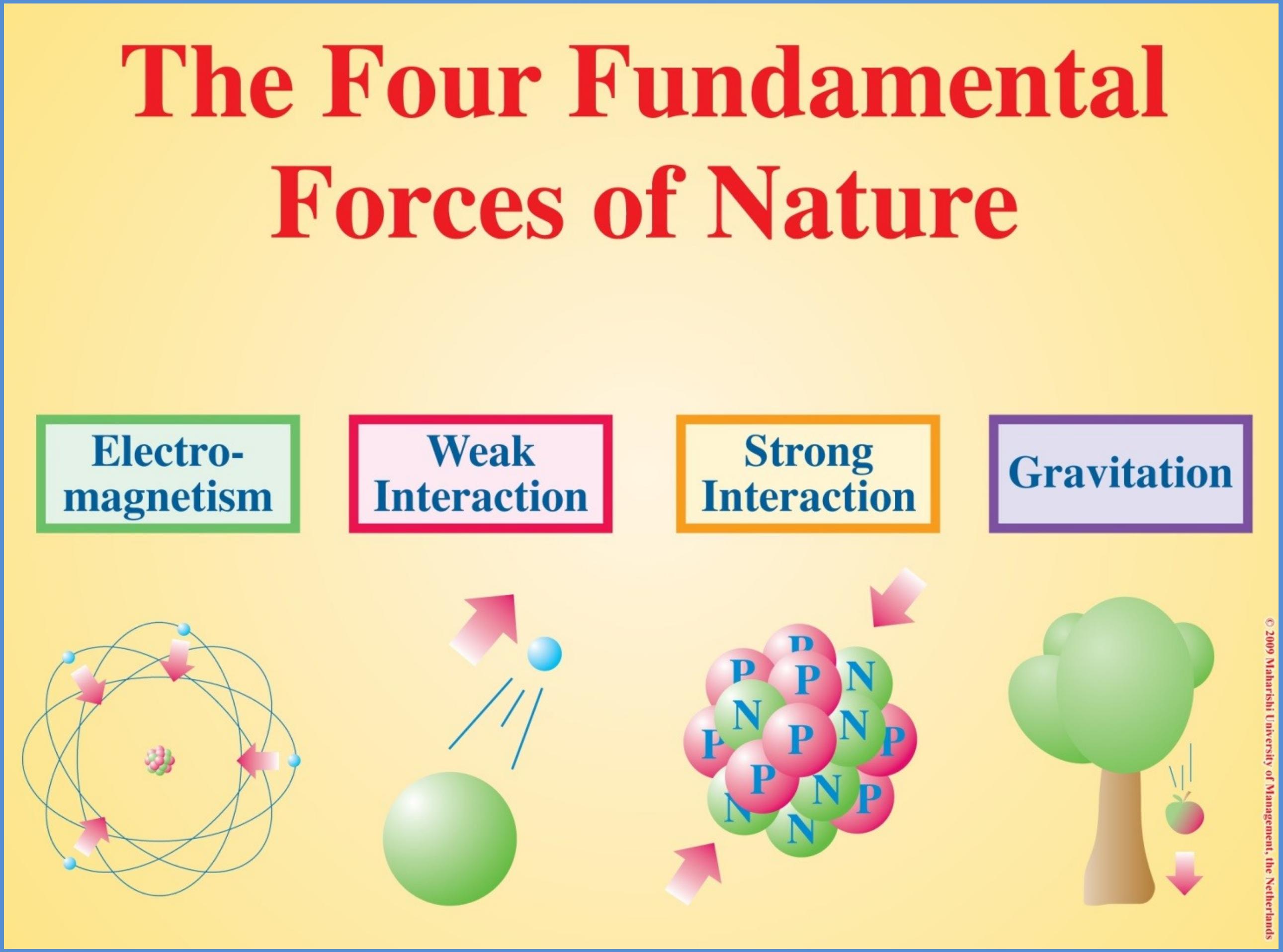
- Describes the known particles and interactions (except gravity) within the QFT framework
- 5 open problems: hierarchy problem, dark matter and dark energy candidates, neutrino masses, gravity



THE STANDARD MODEL II

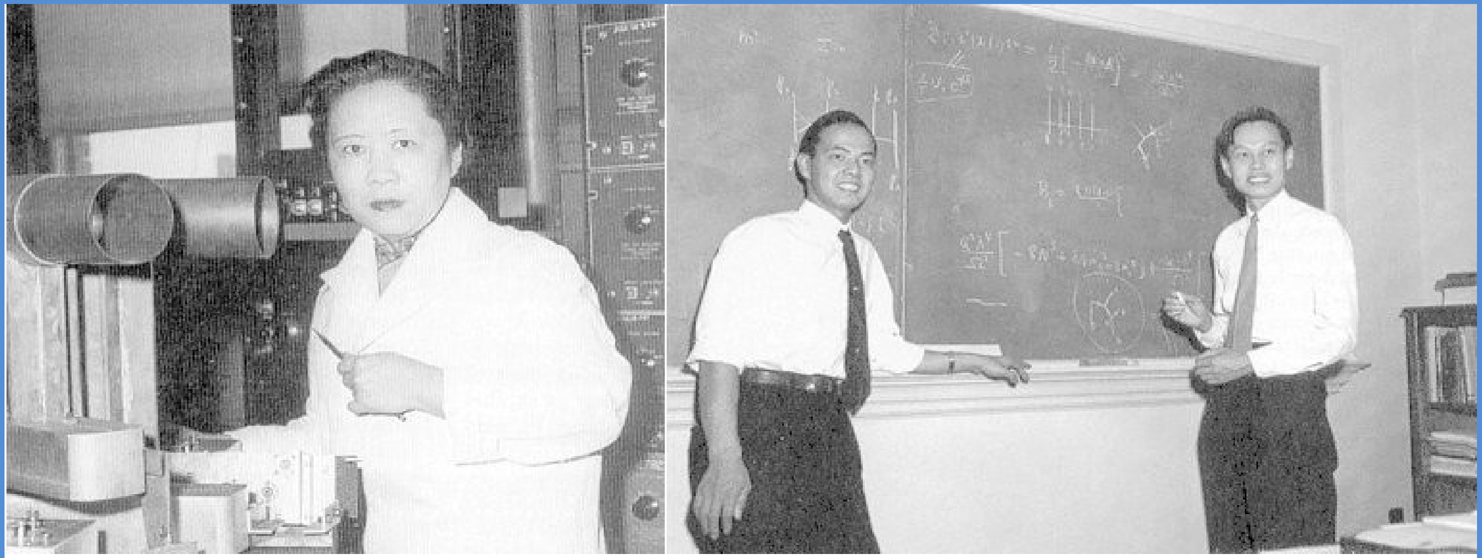
$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu +$$
$$\bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu -$$
$$\frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 -$$
$$\frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu -$$
$$A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 +$$
$$H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- +$$
$$2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 -$$
$$\phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- -$$
$$\phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) -$$
$$\frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda -$$
$$\bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) -$$
$$\frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1 +$$
$$\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 -$$
$$\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1 -$$
$$\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$
$$\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) +$$
$$igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ -$$
$$\bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$\frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

THE STANDARD MODEL III



PARITY VIOLATION I

- Particles have “handedness” (left or right)
- Weak force breaks parity (reflection) symmetry! Couples preferentially to left handed particles



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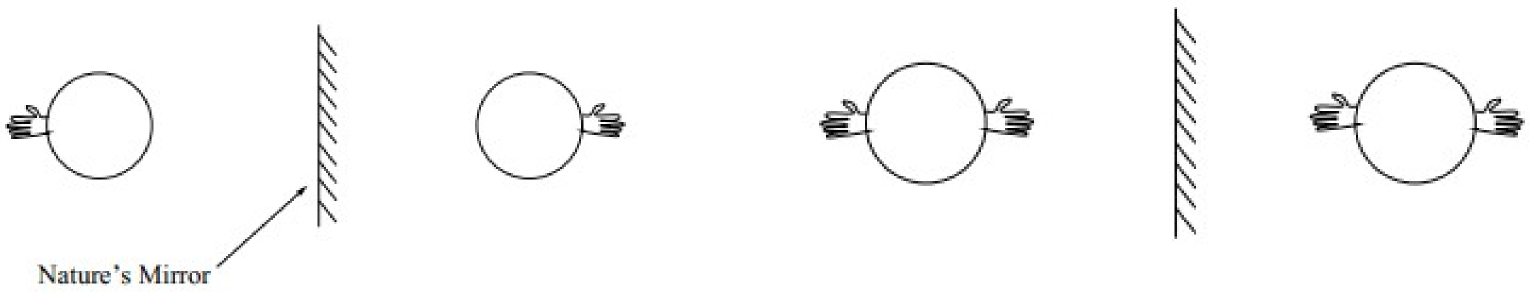
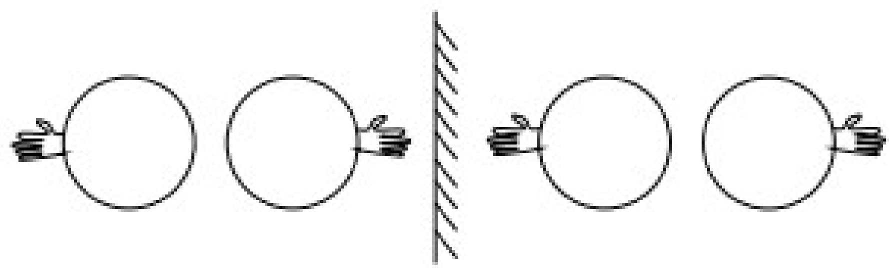
PARITY VIOLATION II

- Physics is different if we view it reflected in a mirror…
- …kinda weird

PARITY VIOLATION III

- Physics is different if we view it reflected in a mirror…
- …or is it really?





MIRROR MATTER I

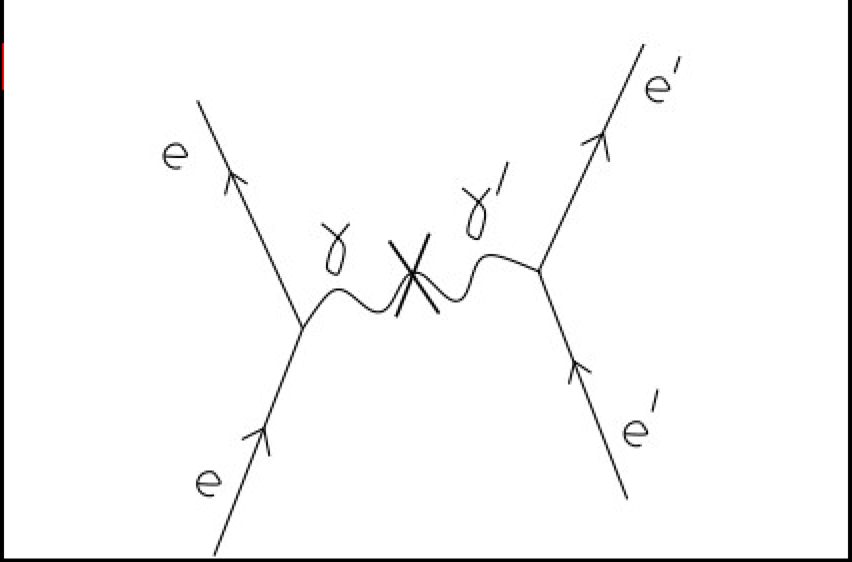
- Each known particle has now a mirror counterpart, with reversed chirality
- Parity (reflection symmetry) is now restored!
- Full Lagrangian is:

$$\mathcal{L} = \mathcal{L}_{SM}(e, u, d, \gamma, W, Z, ...) + \mathcal{L}_{SM}(e', u', d', \gamma', W', Z', ...) + \mathcal{L}_{mix}$$

MIRROR MATTER II

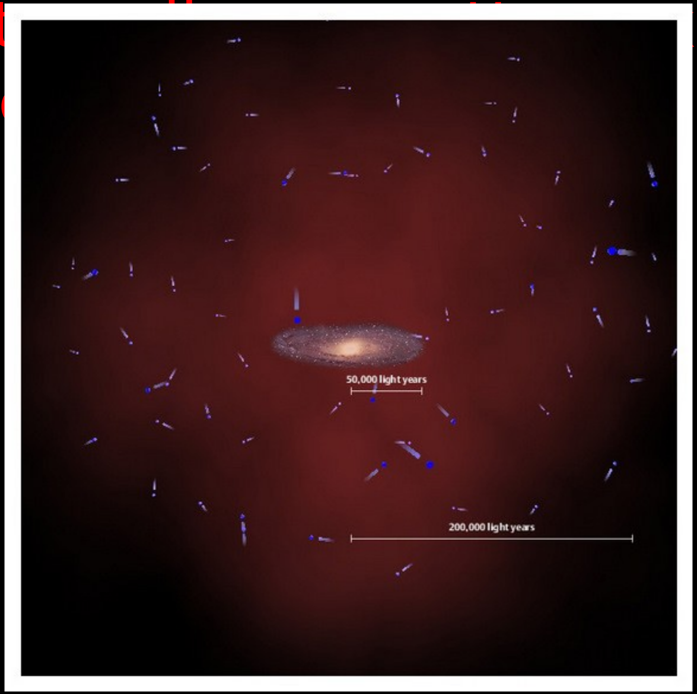
- Interacts very weakly with known particles, through mixing term in Lagrangian
- Is naturally dark and stable: good dark matter ca

$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$



DARK MATTER HALOS

- In most galaxies (particularly spiral), ordinary matter is distributed on a flat disk, dark matter in a halo
- How can mirror matter, which is microscopically symmetric t… …plain this macroscopi…



HEATING MECHANISM

- Mirror matter has dissipative self-interactions, would lose energy and collapse to a disk
- Energy from ordinary supernovae goes partly in neutrinos partly in light mirror particles
- Mirror particles heat the halo…halo remains spherical!
- Essentially halo is in hydrostatic equilibrium (so much energy comes in, so much comes out)
- Check out astro-ph/0407522!
- (Aside: mirror matter can also explain direct detection experiment results)

WHAT I DO

- Work on a model called two-component hidden sector dark matter
- Very simple model that can mimic explain dark matter direct detection experiments and mimic mirror matter
- Have Standard Model particles, dark photon and two dark fermions (one mimics mirror electron, other mimics heavy mirror nucleus)

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F^{'\mu\nu}F_{\mu\nu} + \overline{\psi}_j(iD_{\mu_j}\gamma^{\mu} - m_j)\psi_j - \frac{\epsilon^{'}}{2}F^{\mu\nu}F^{'}_{\mu\nu}$$

WHAT I DO (CONTINUED)

- Model (as of 2013) had not been examined in the context of very early Universe
- I look at the physics of the very early Universe (CMB and BBN) in the light of this model, set bounds on parameters
- Check whether correct halo – disk structure can be reproduced
- Extremely: interesting results: for this model to work parameters have to be very close to that of mirror matter. Mirror matter is almost singled out!

WHAT I DO (TECHNICAL)

- "A simple way of explaining dark matter without modifying known Standard Model physics is to require the existence of a hidden sector, which interacts with the ordinary sector predominantly via gravity. We consider a hidden sector containing two stable Dirac fermions charged under an unbroken U(1)' gauge symmetry. The gauge field associated with this U(1)' symmetry can interact via kinetic mixing with the ordinary photon, with coupling ϵ. Such a process is particularly relevant for early Universe cosmology. This model has been studied in the context of direct detection experiments, however little has been done for cosmology. We calculate the additional relativistic energy density at recombination and the effect on Big Bang Nucleosynthesis. Following this we examine the process of dark recombination, when neutral dark states are formed, and the manner in which affects large-scale structure formation. Finally, we combine our results with those from direct detection experiments and show that the combined analysis sets strict bounds on the parameters in our model. These bounds can serve as a guideline for future experimental searches."

CONCLUSIONS

- Universe is a very interesting place!
- There’s much more stuff out there “than are dreamt of in your philosophy” [Shakespeare]
- Dark matter does exist, but its fundamental nature is still very unclear
- Stay tuned for more!


THANK YOU FOR PAYING
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QUESTIONS
~~NAP~~ TIME!
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