# The Mystery of Dark Matter

CERN Greek National
Teacher Program 2023

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

# Black Box

## Building and Revising Scientific Models

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**Predict, Observe, Explain Demonstration:** Uniform Circular Motion
This demonstration utilizes a typical uniform circular motion apparatus to introduce students to the concept of dark matter.

**Hands-on Demonstrations:** Gravitational Lensing
These demonstrations use simple objects to model gravitational lensing.

**Activity 1:** Video Summary
A set of discussion questions that review the content of the video.

**Activity 2:** Key Concepts
A question sheet that allows students to dig deeper into the material both numerically and conceptually.

**Activity 3:** Gravity and Orbital Motion
An activity where students use stretchy spacetime fabric and a variety of balls to model orbital motion.

**Activity 4:** Dark Matter within a Galaxy
Students use real data to explore the conflict between what is expected and what is observed.

**Activity 5:** Advanced Mathematical Analysis
An enrichment/extension activity for stronger students.

**Activity 6:** Dark Matter Lab
Students use a typical uniform circular motion apparatus to explore the connection between orbital speed and central force.

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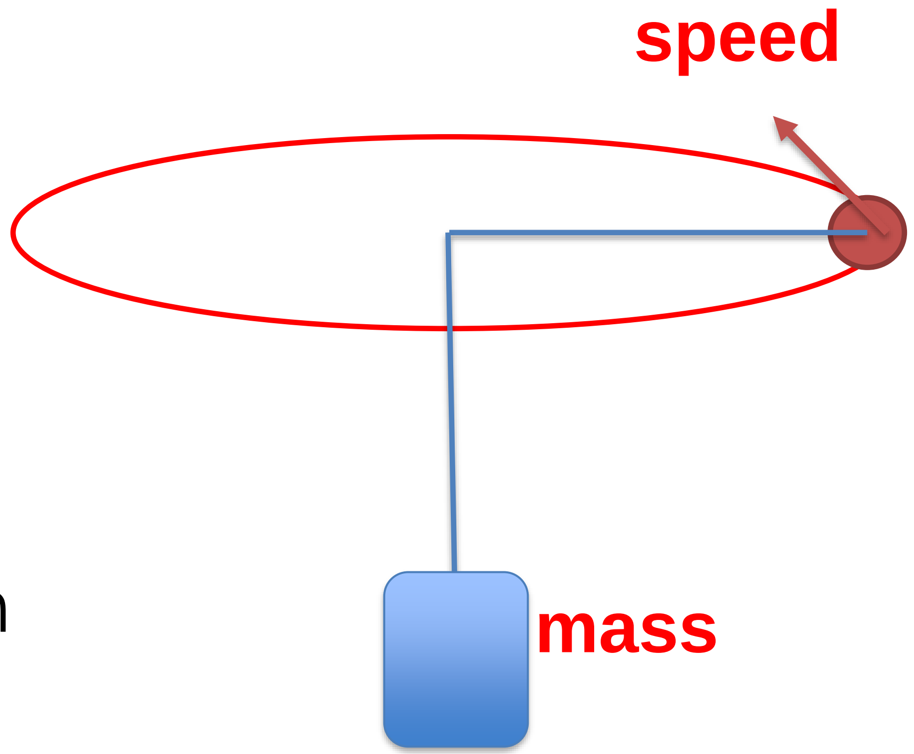
# Uniform Circular Motion Activity

**Predict**
**Observe**
**Explain**

How are mass and speed connected in circular motion?



# Uniform Circular Motion Activity

**Objective:**

**Determine the mass of an unknown item.**

1. Collect data for one mass per group.
2. Plot a graph of speed$^2$ vs mass on a collaborative spreadsheet.

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# Uniform Circular Motion Activity

**Collaborative version:**

1. Set radius = 60 cm
2. Use assigned masses
3. Record period for 10 orbits
4. Compare results
5. Report results

# Uniform Circular Motion Results

| # of washers | 10 Orbits (s) |
|---|---|
| 8 | |
| 10 | |
| 12 | |
| 14 | |
| 16 | |

How is the orbital speed related to the mass of the washers?

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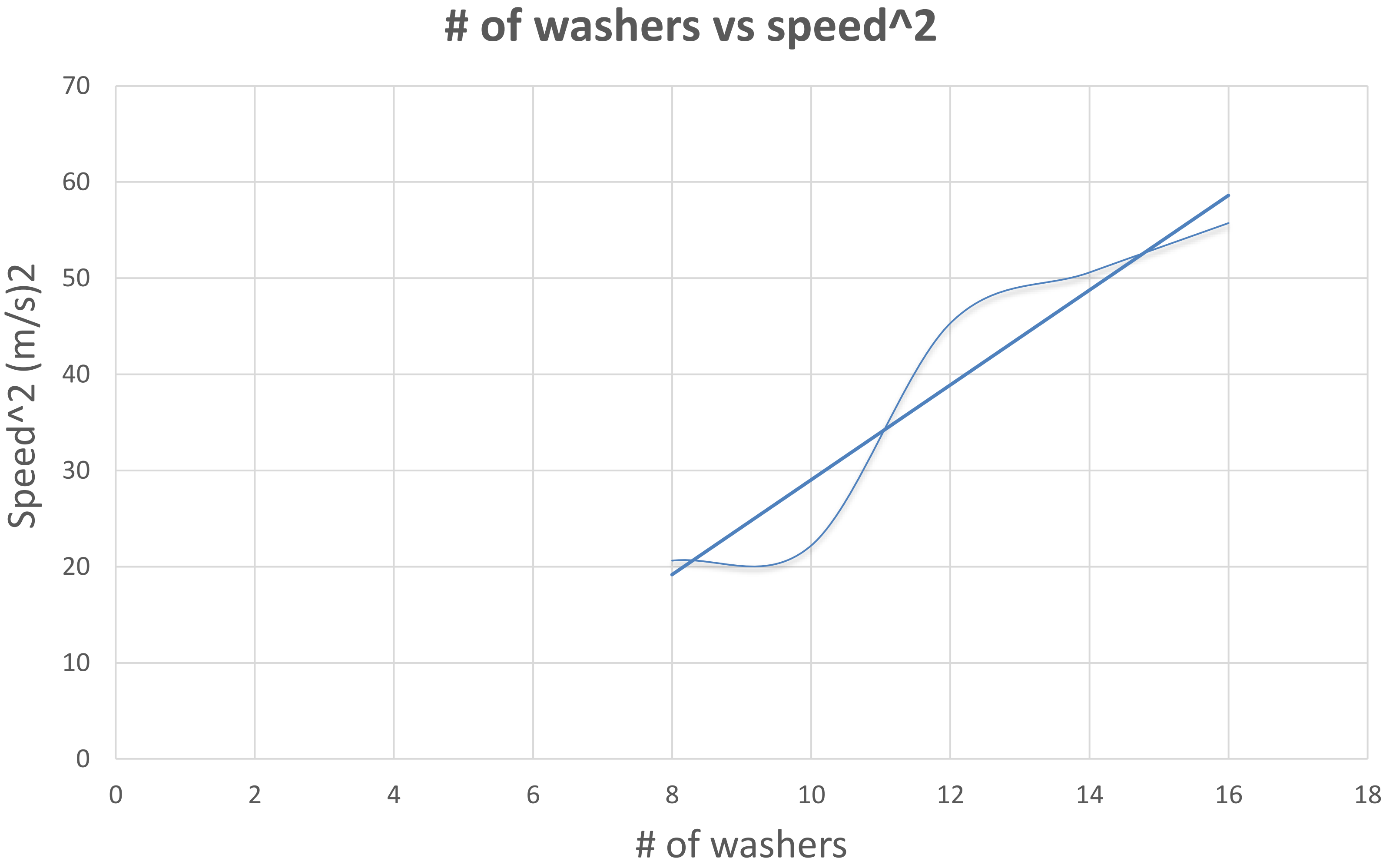
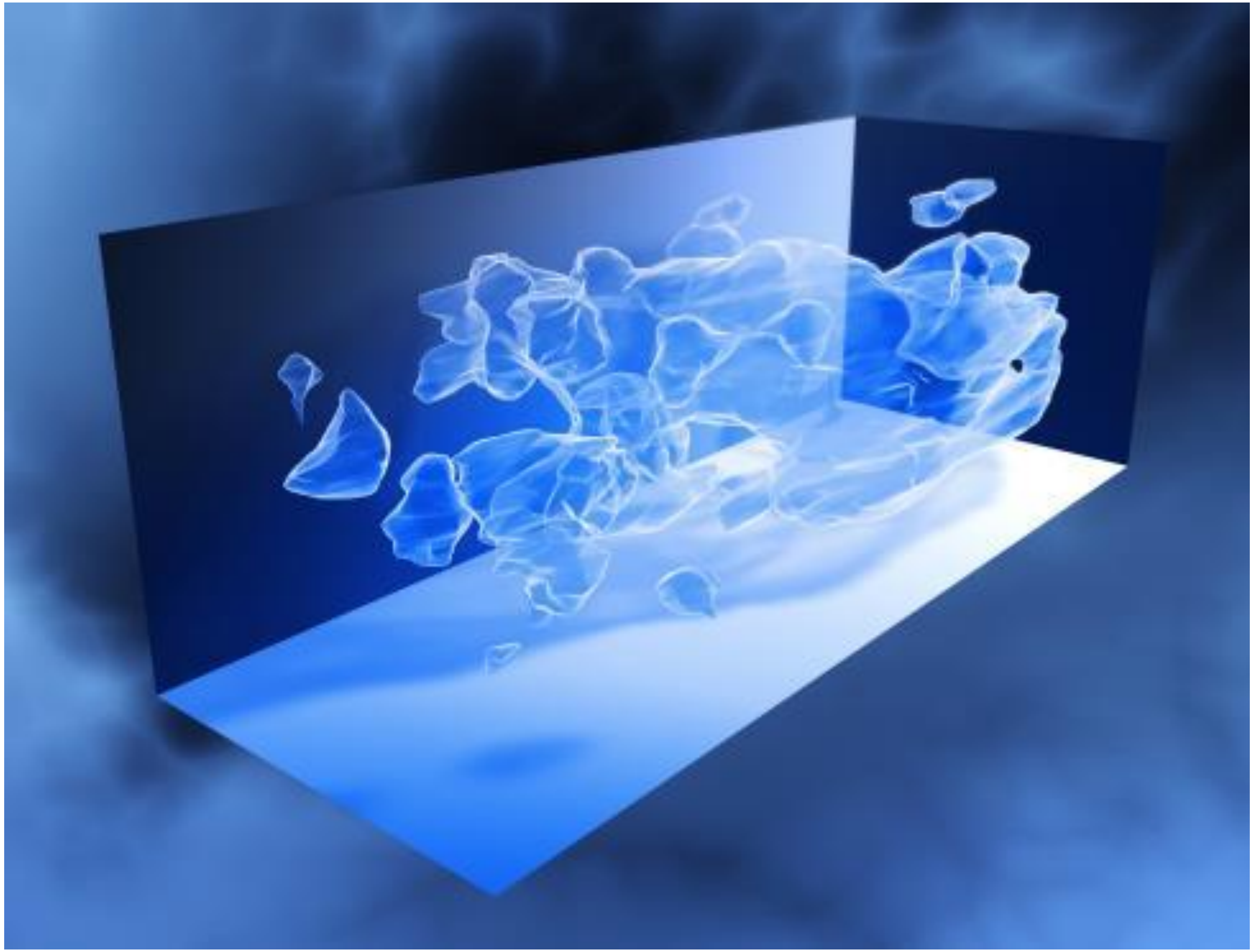
# Uniform Circular Motion Results



# Connecting standard classroom physics to Cutting-Edge Dark Matter



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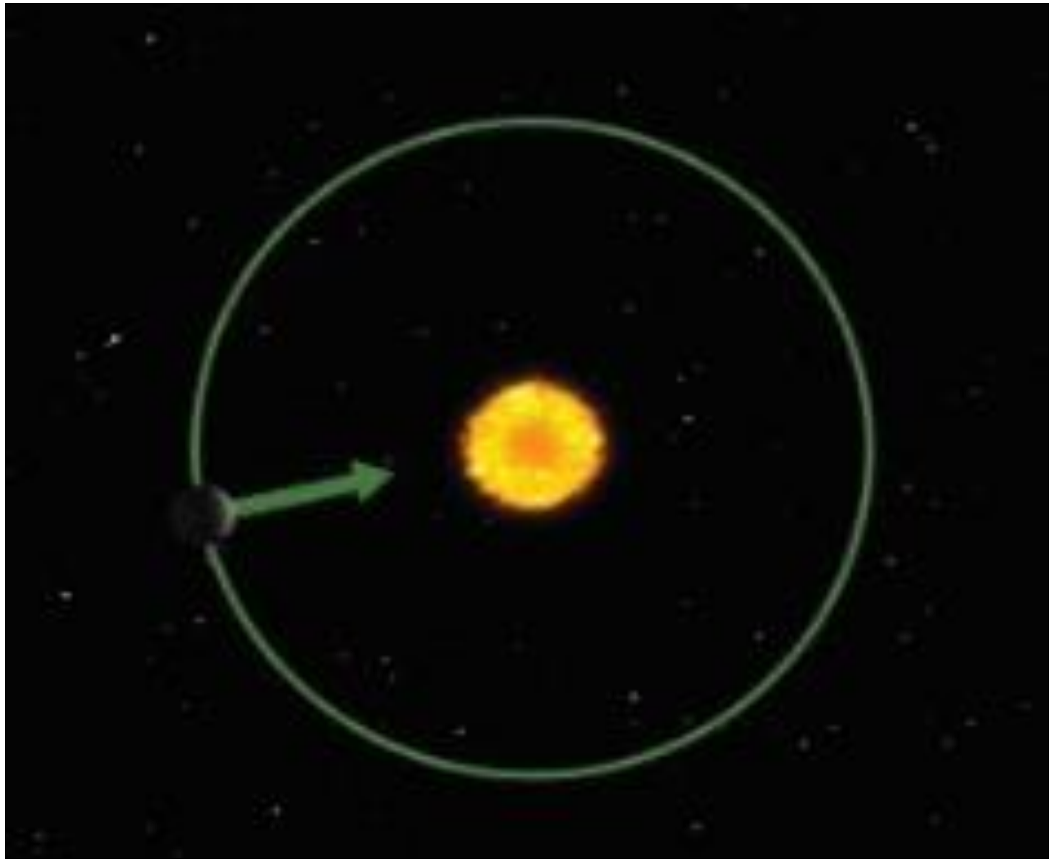
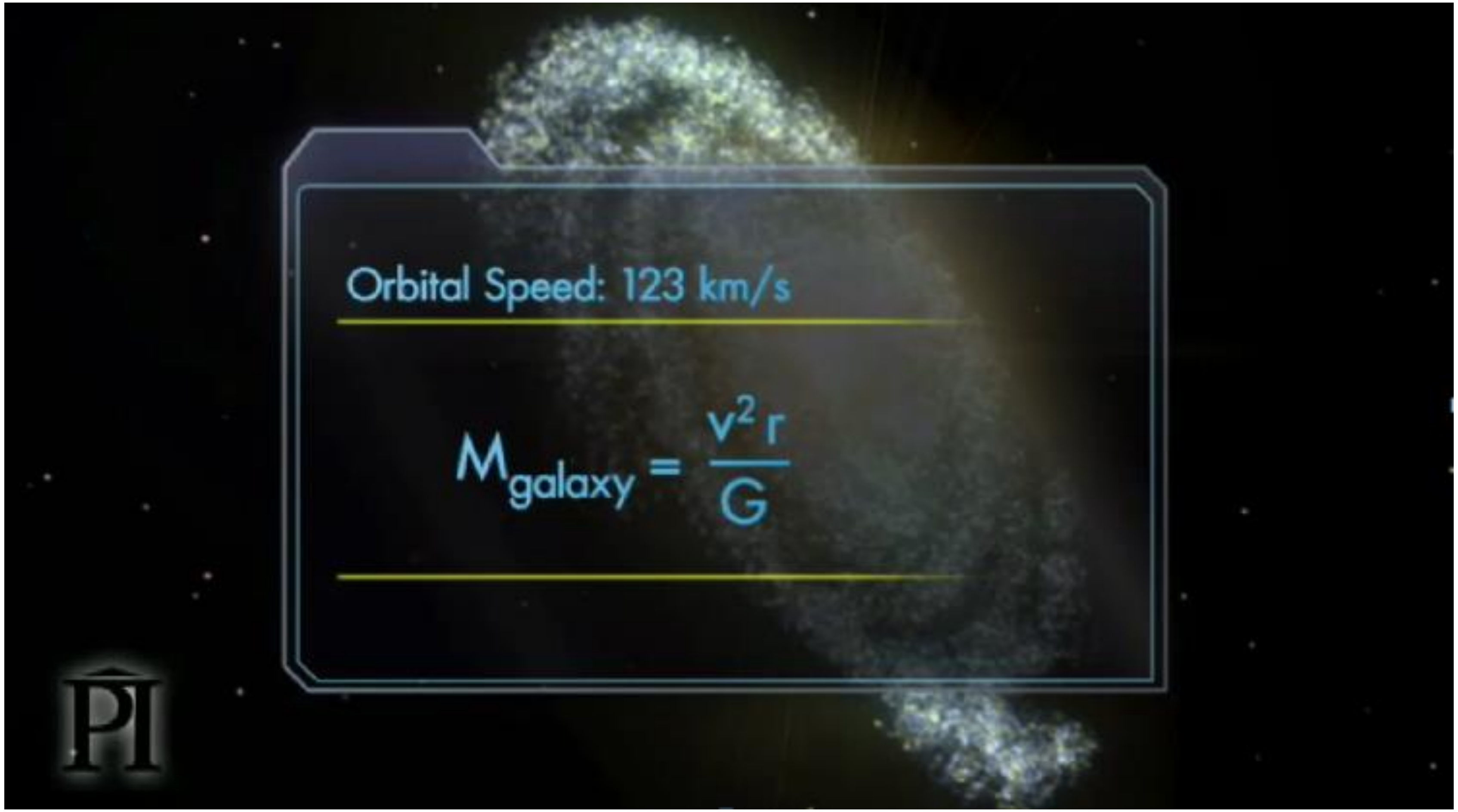
# Vera Rubin's Discovery

Orbital Speed Depends on the Mass of the Central Object

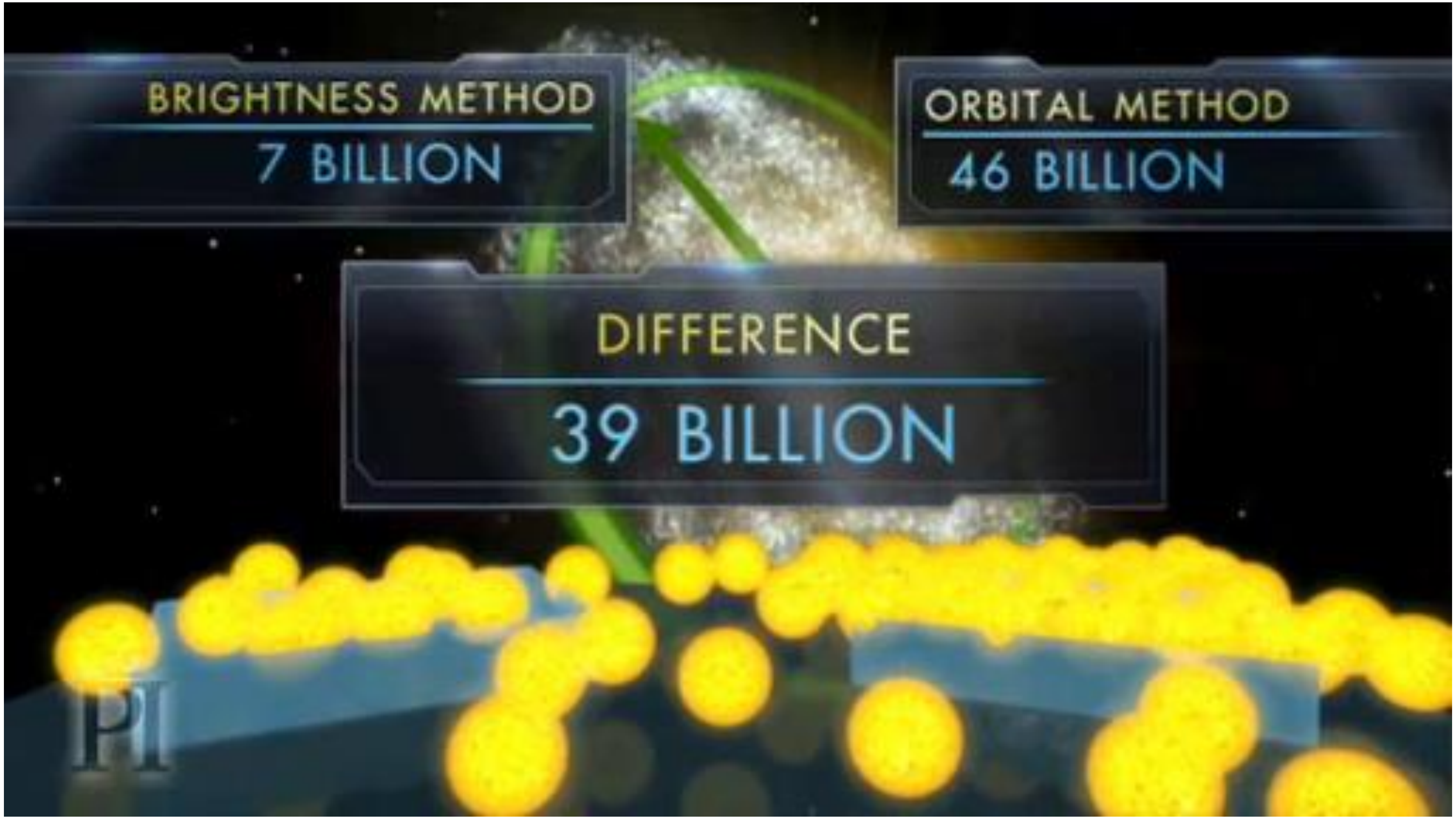
$$M = \frac{v^2 r}{G}$$



# Extend this to galaxies

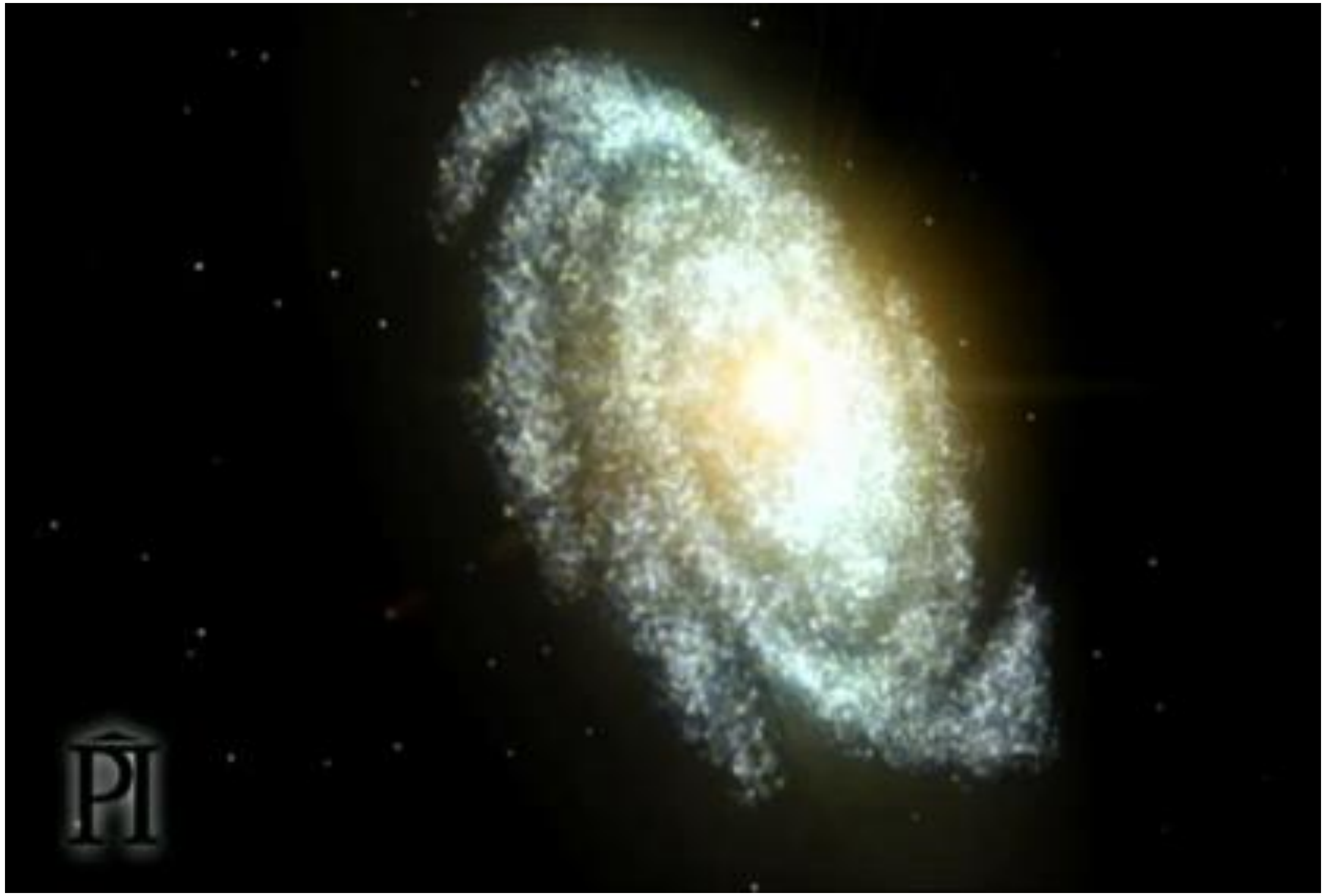


# Triangulum is More Massive Than it Looks

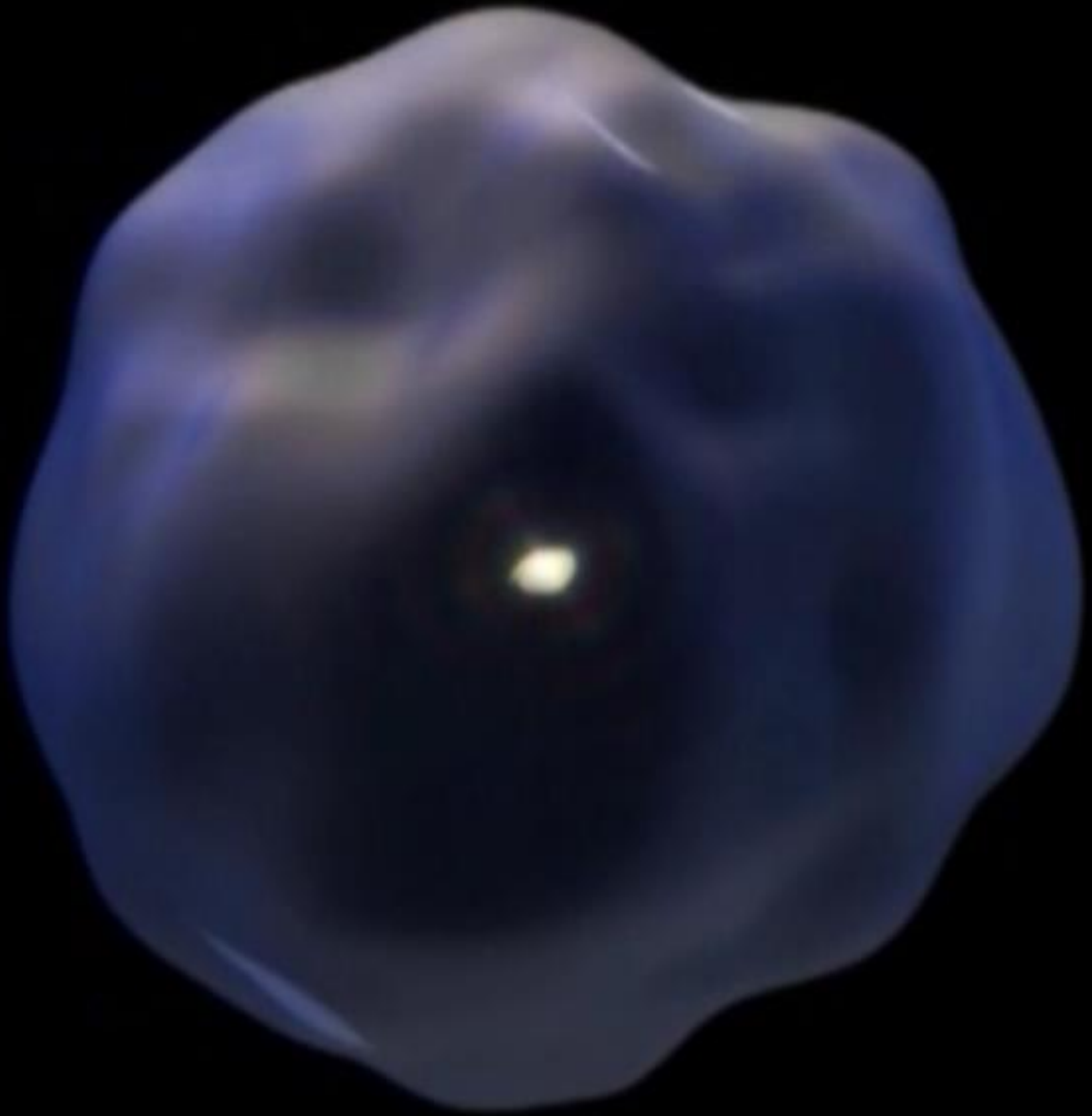


# The same discrepancy happens in all* galaxies

# Old View



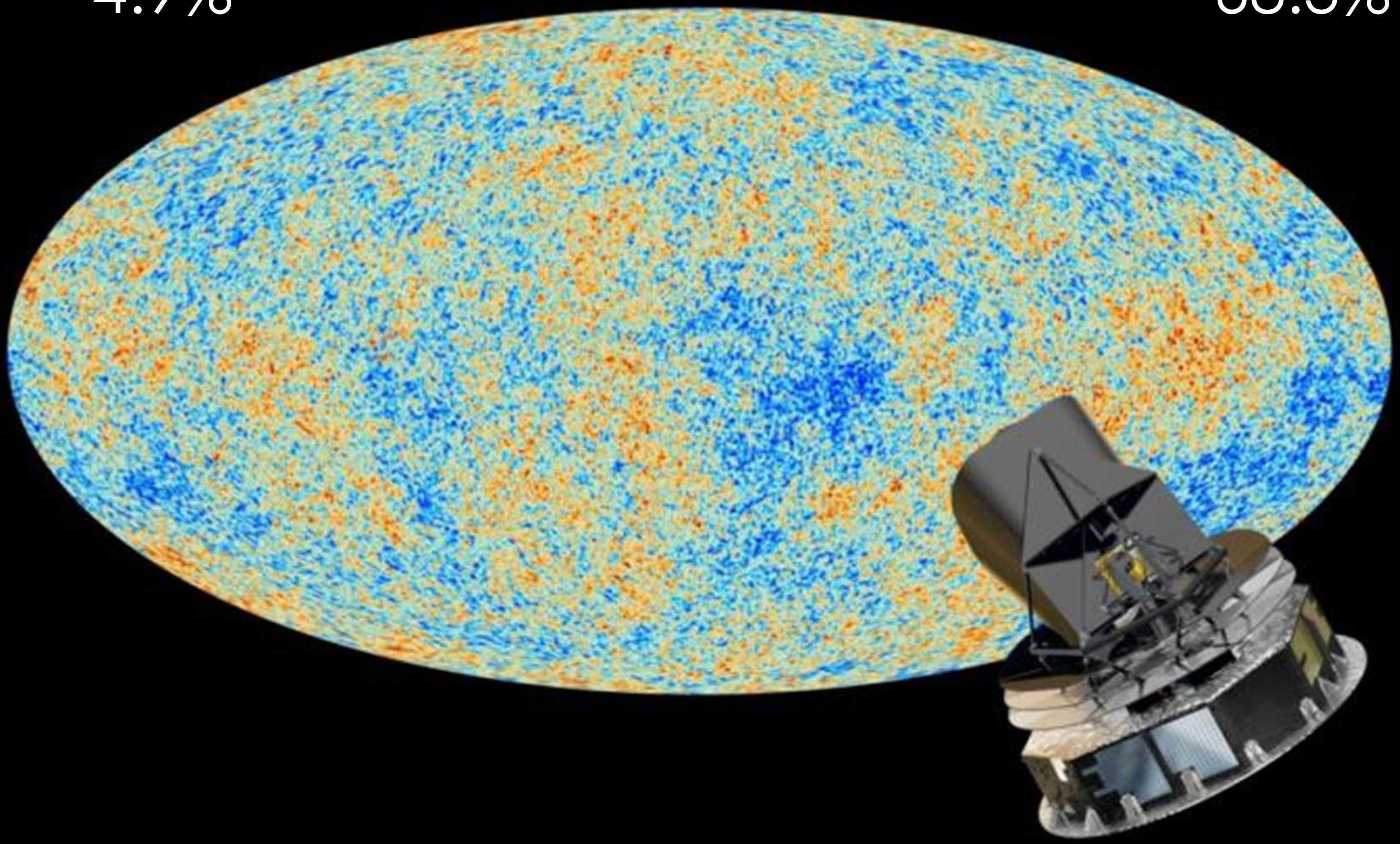
# New View



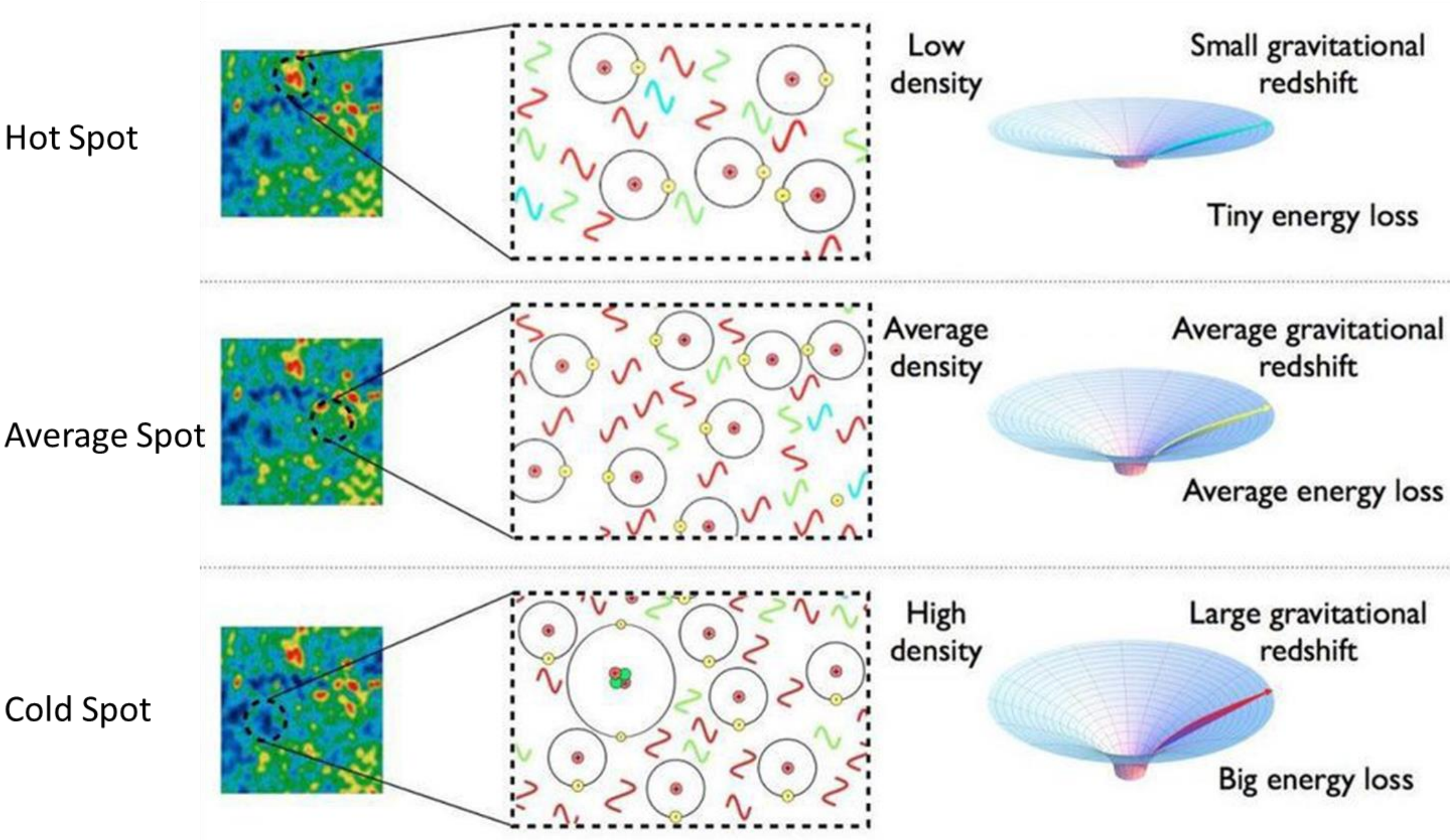
Dark Matter
26.8%

Normal Matter
4.9%

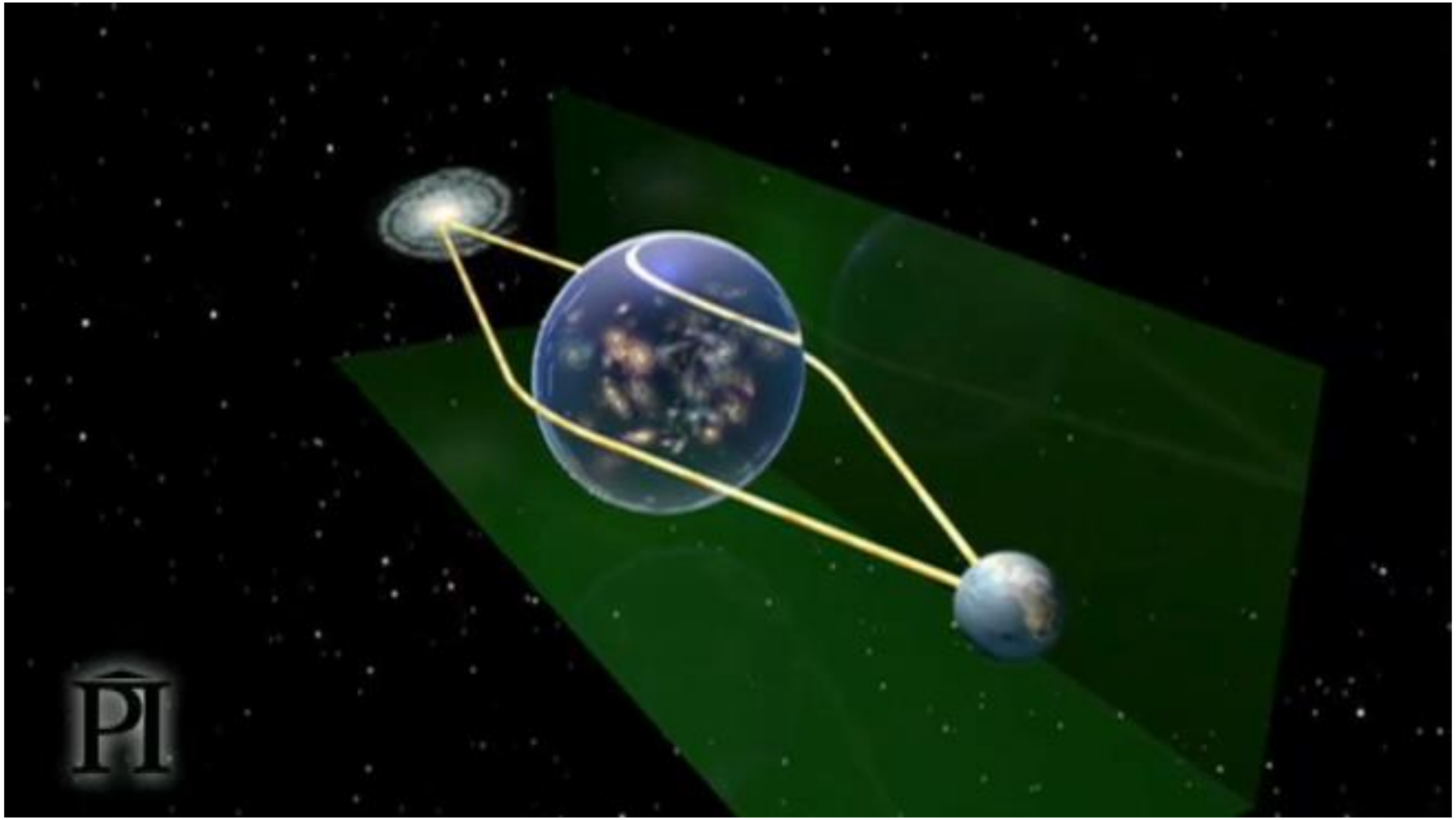
Dark Energy
68.3%



# 0.0001 K difference between hot and cold!

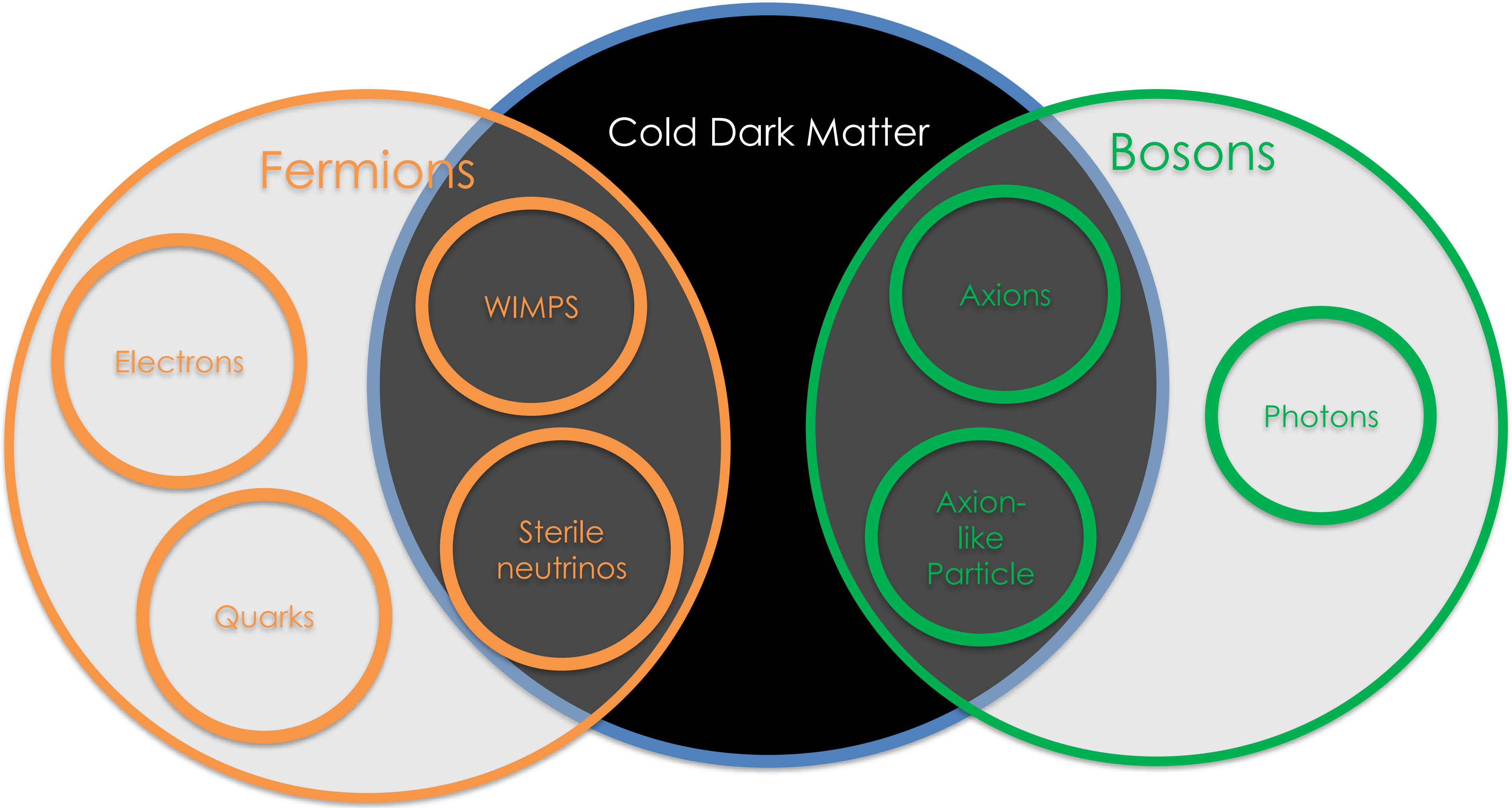


# Gravitational Lensing



# Competing Theories For Dark Matter

- Particle that hasn't been discovered yet

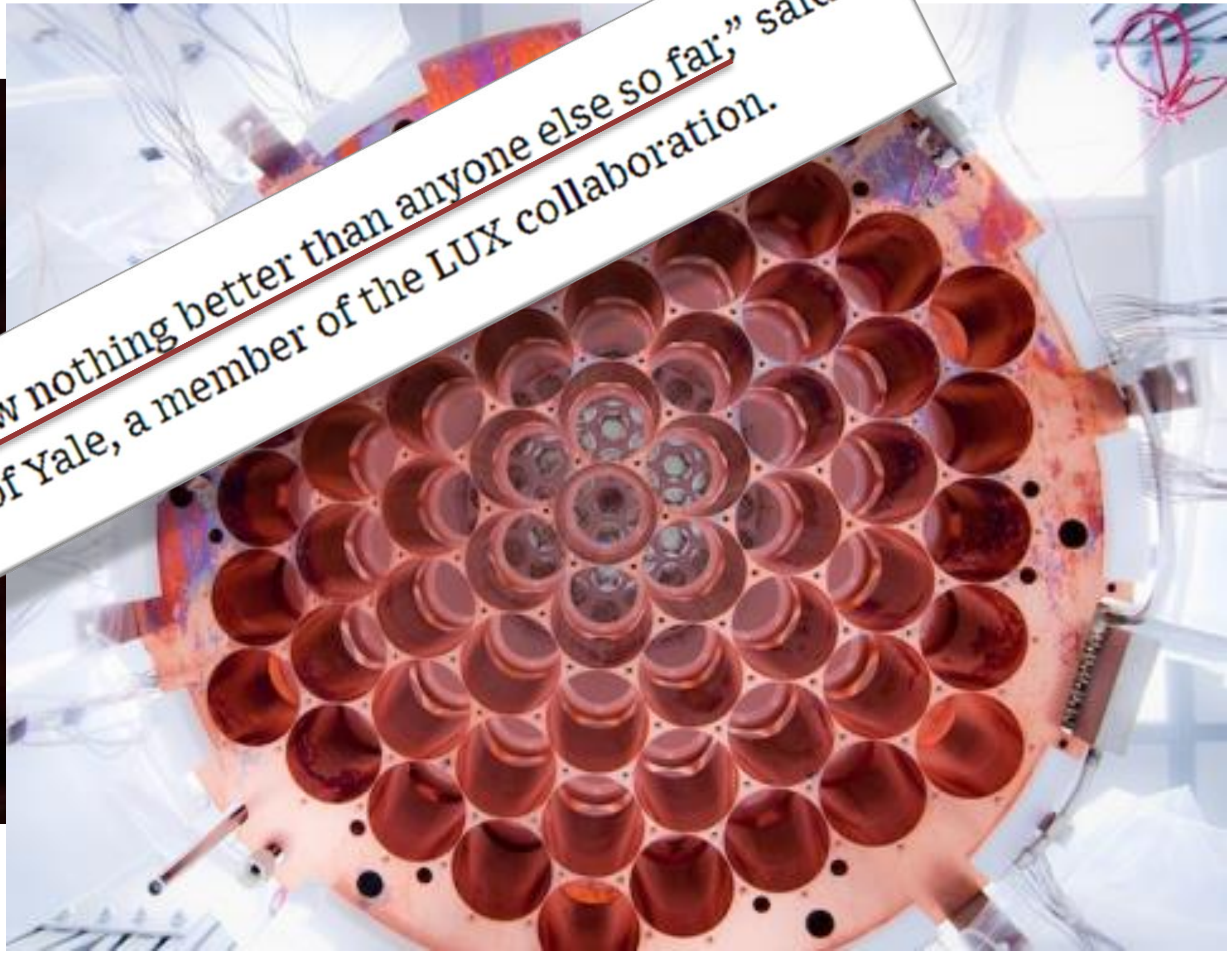


# How to Look for Dark Matter Particles

- Direct detection: wait for it to hit a detector
- Indirect detection: look for other signatures
- Particle colliders: make it

# **LUX**- **L**arge **U**nderground **X**enon Detector

*Homestake Mine, … Dakota*



"Basically, we saw nothing. But we saw nothing better than anyone else so far," said particle physicist Daniel McKinsey of Yale, a member of the LUX collaboration.

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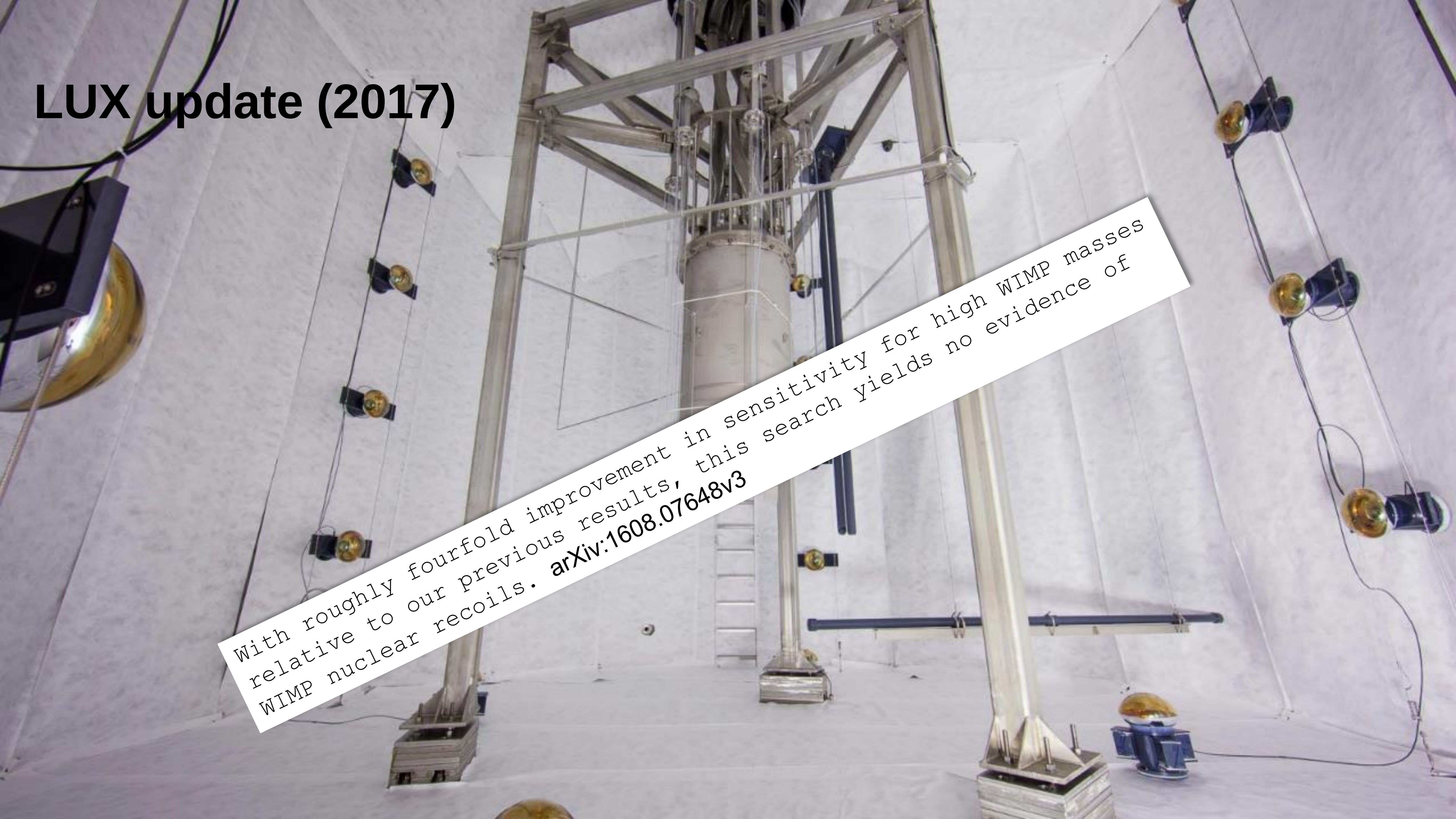
# LUX update (2017)



With roughly fourfold improvement in sensitivity for high WIMP masses relative to our previous results, this search yields no evidence of WIMP nuclear recoils. arXiv:1608.07648v3

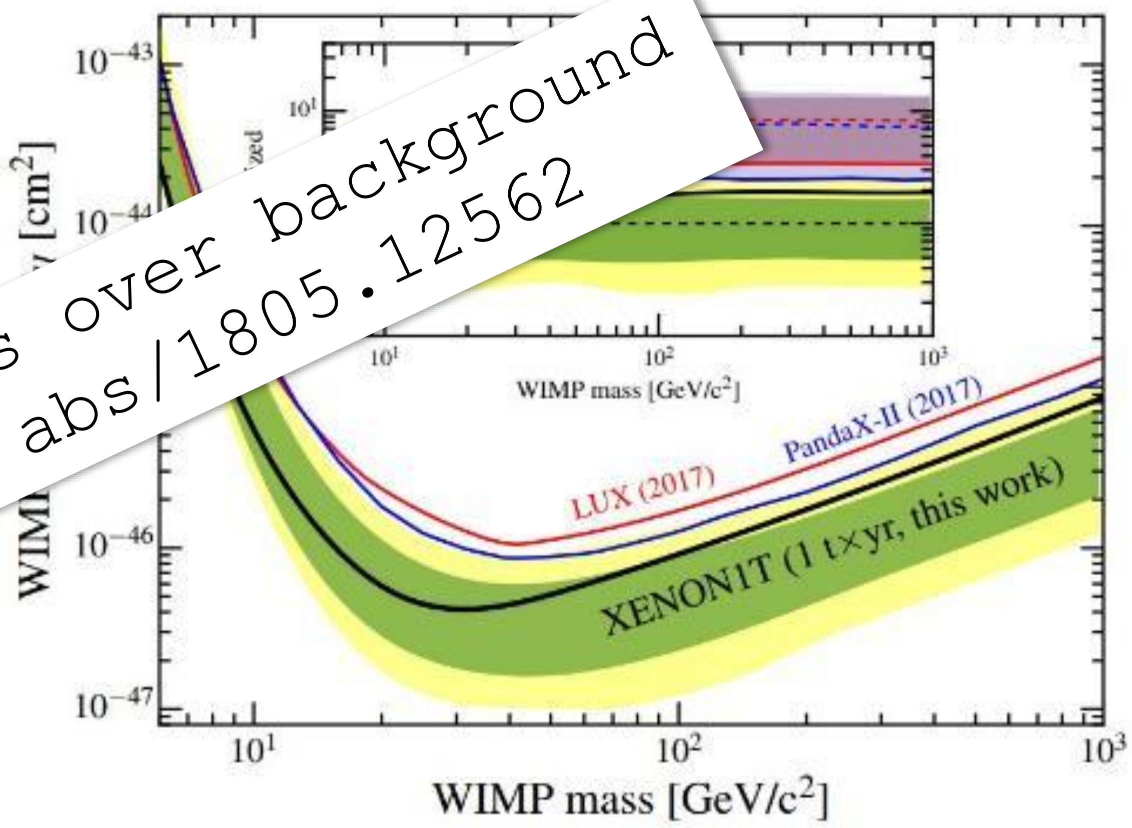
# LUX-ZEPLIN (LZ) update (2022)

A profile-likelihood ratio analysis shows the data to be consistent with a background-only

https://arxiv.org/abs/2207.03764

# **XENON1T** most sensitive measurement yet (2018)

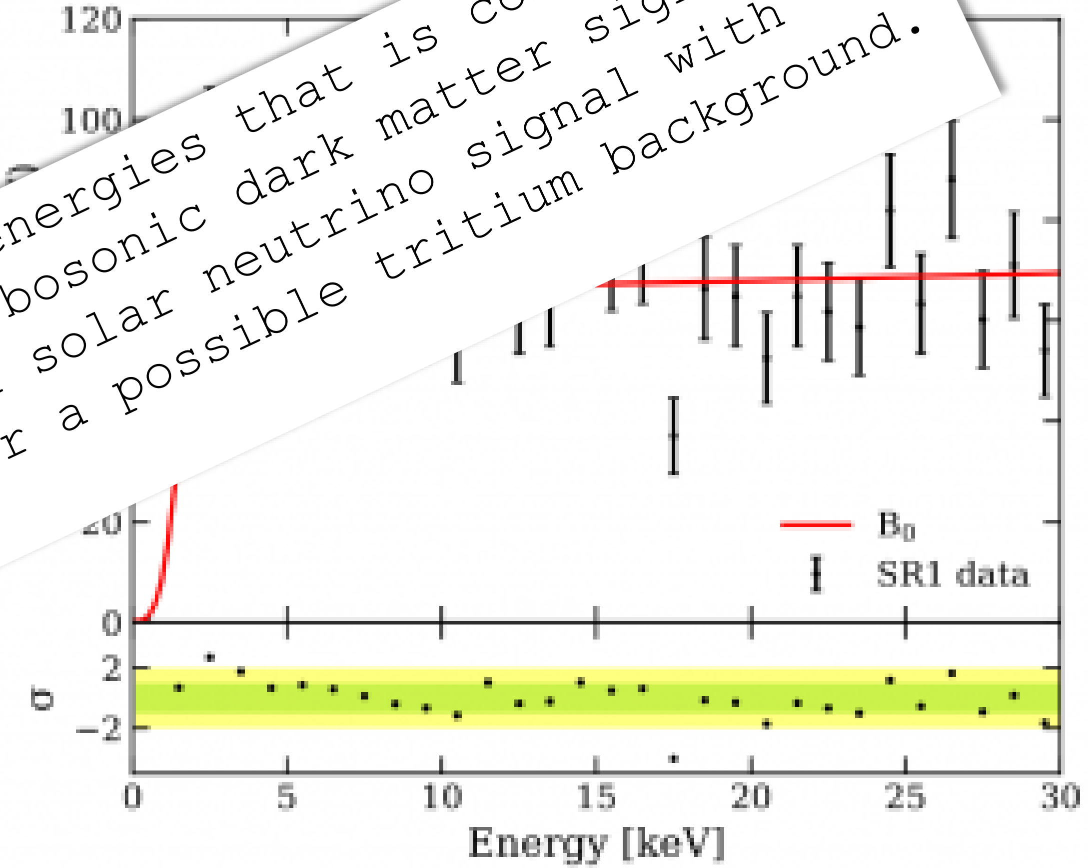
Image credit: Roberto Corrieri and Patrick De Perio



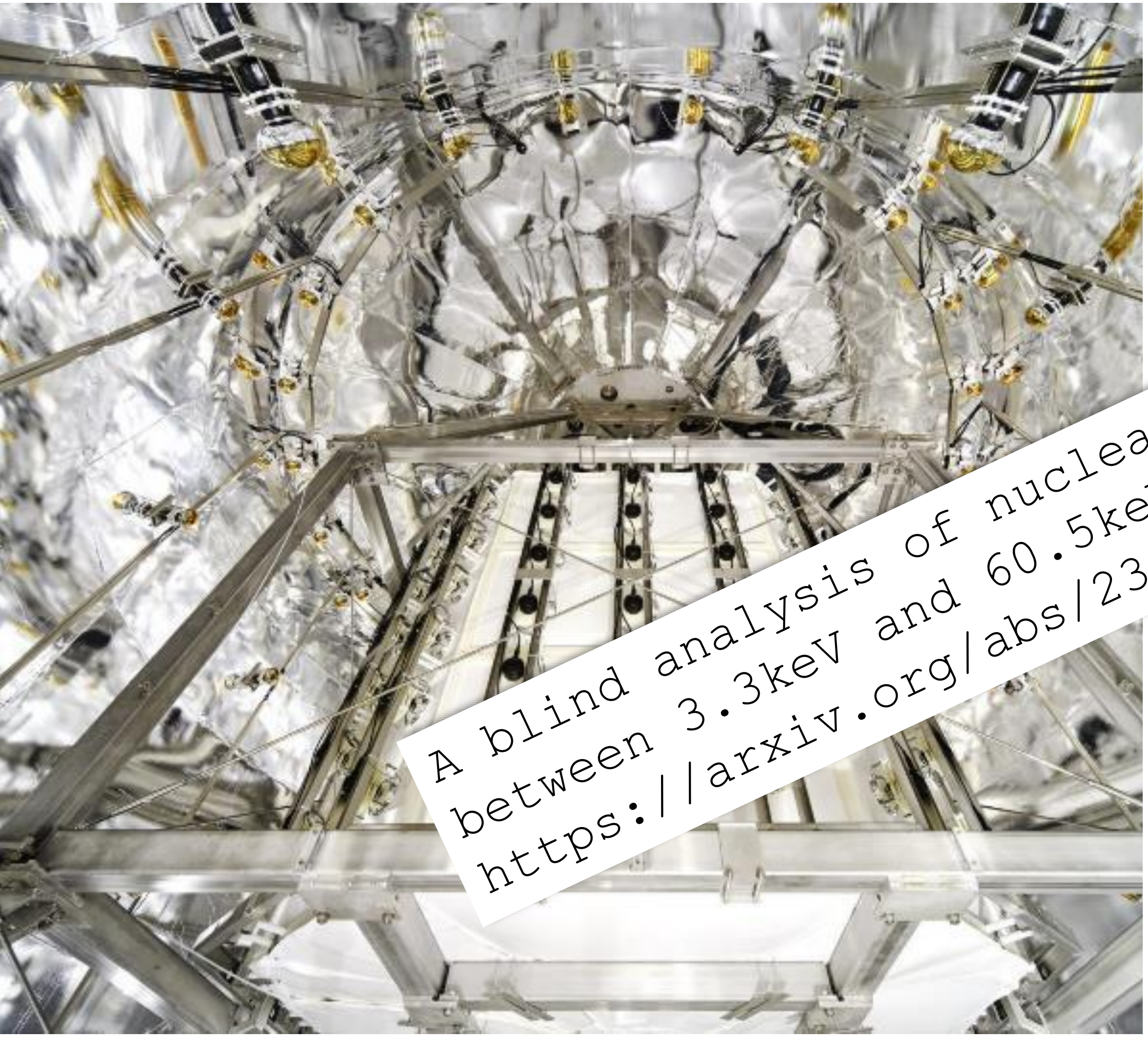

No significant excess over background is found. arxiv.org/abs/1805.12562

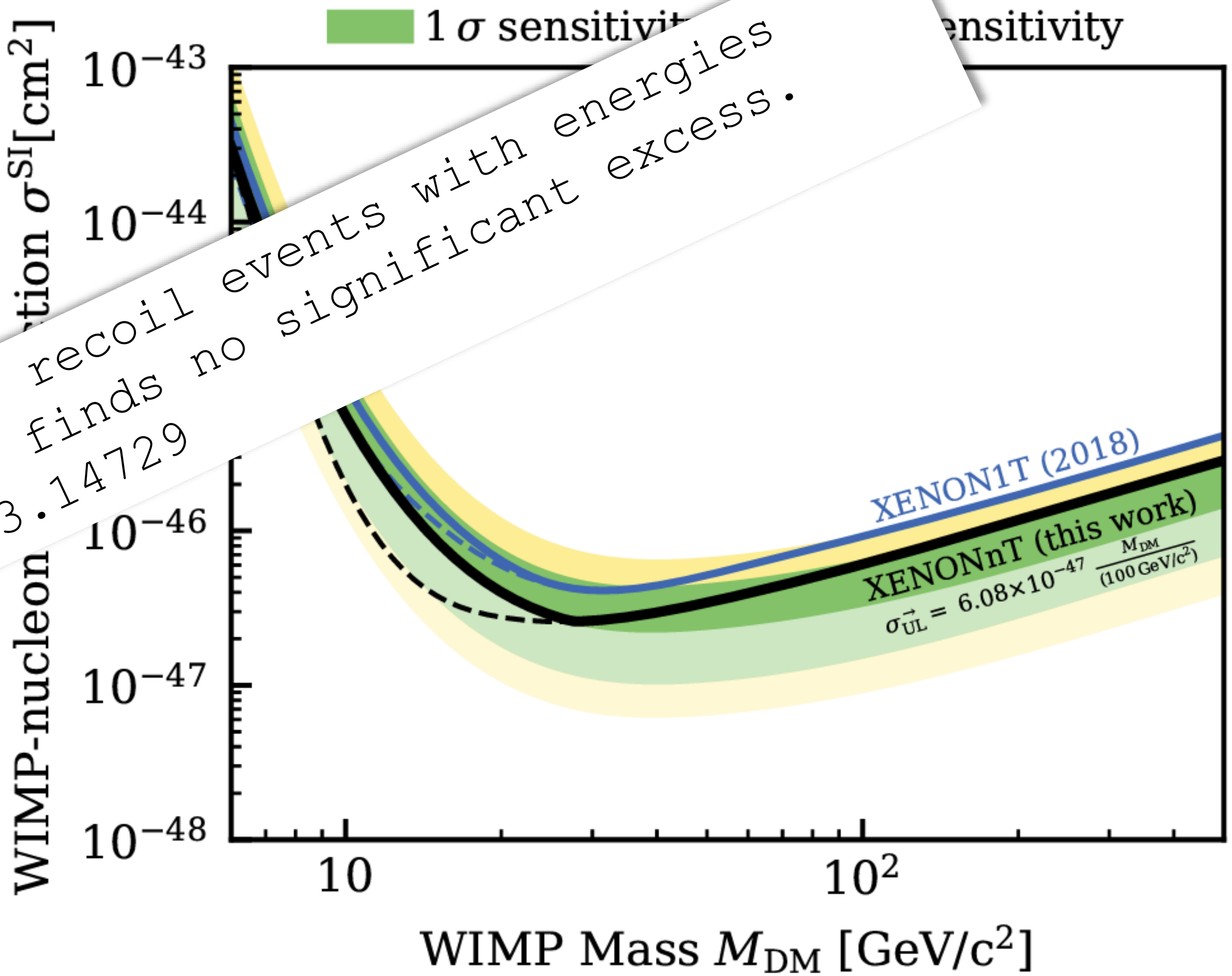
# **XENON1T** – electronic recoil excess (2020)

An excess is observed at low energies that is consistent with a solar axion signal, a bosonic dark matter signal with a mass of 2.3 keV/c2, a solar neutrino signal with enhanced magnetic moment, or a possible tritium background.
arxiv.org/abs/2006.09721



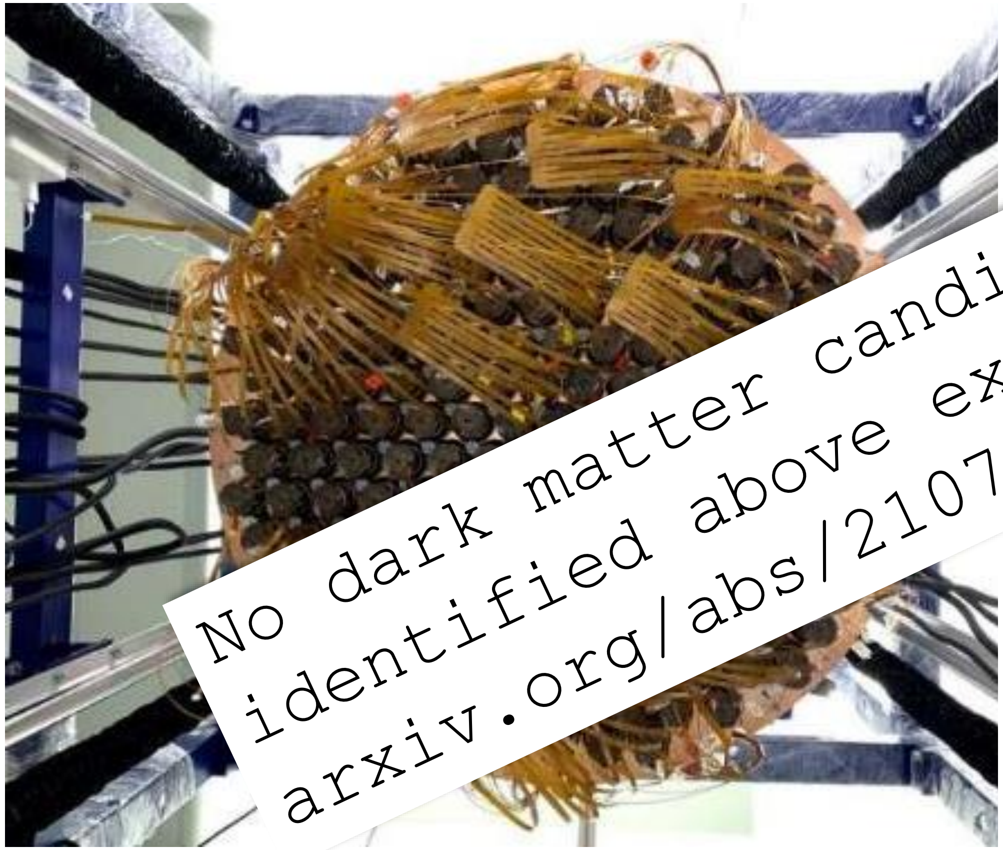
# XENONnT – (2023)

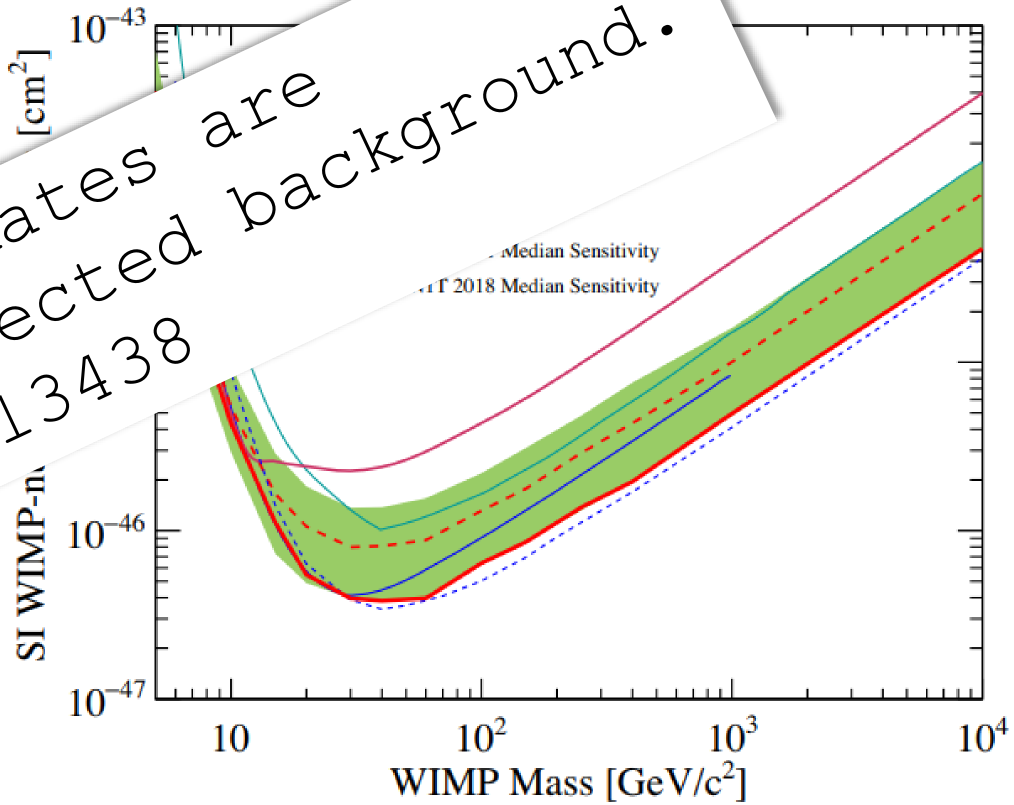





A blind analysis of nuclear recoil events with energies between 3.3keV and 60.5keV finds no significant excess.
https://arxiv.org/abs/2303.14729

# PANDAX- 4T (2021)



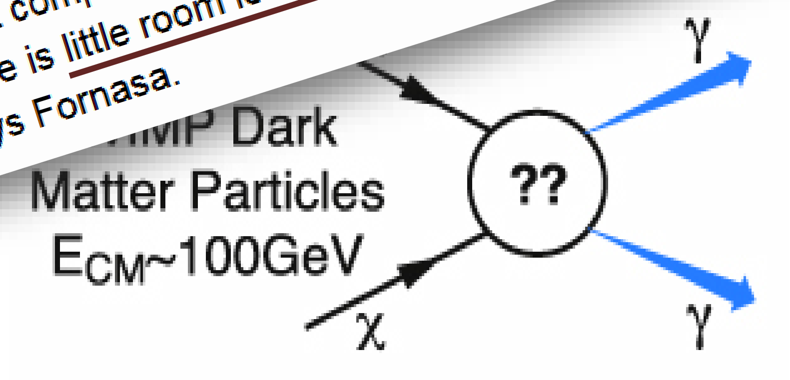



No dark matter candidates are identified above expected background.
arxiv.org/abs/2107.13438

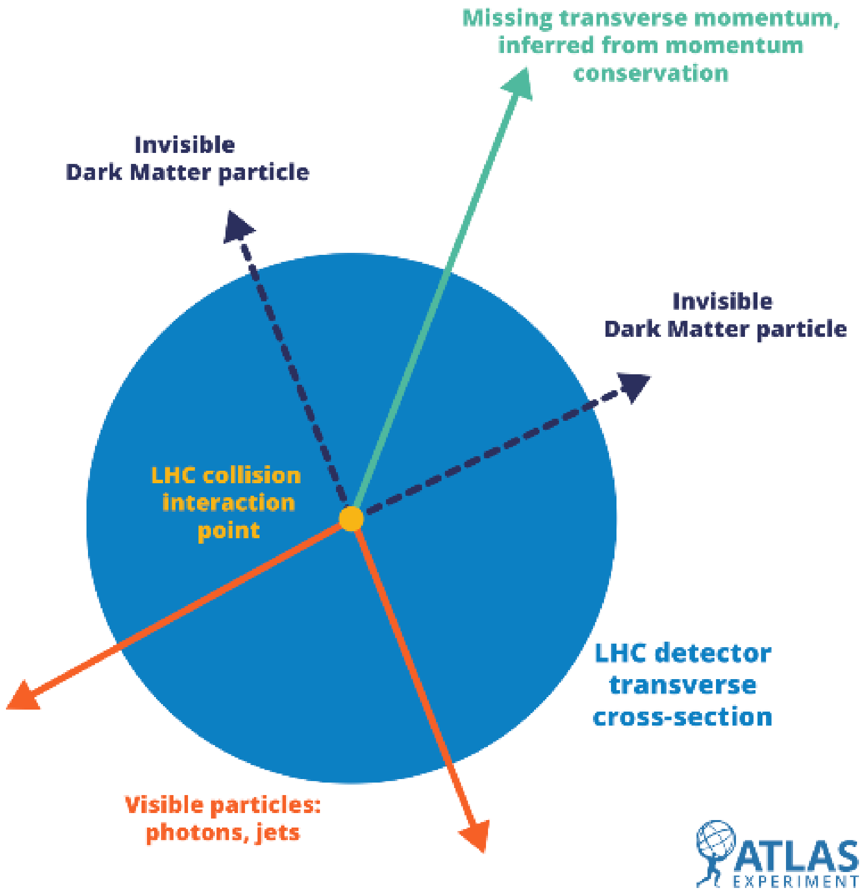
# FERMI

- Detects γ-rays
- DM particle annihilation

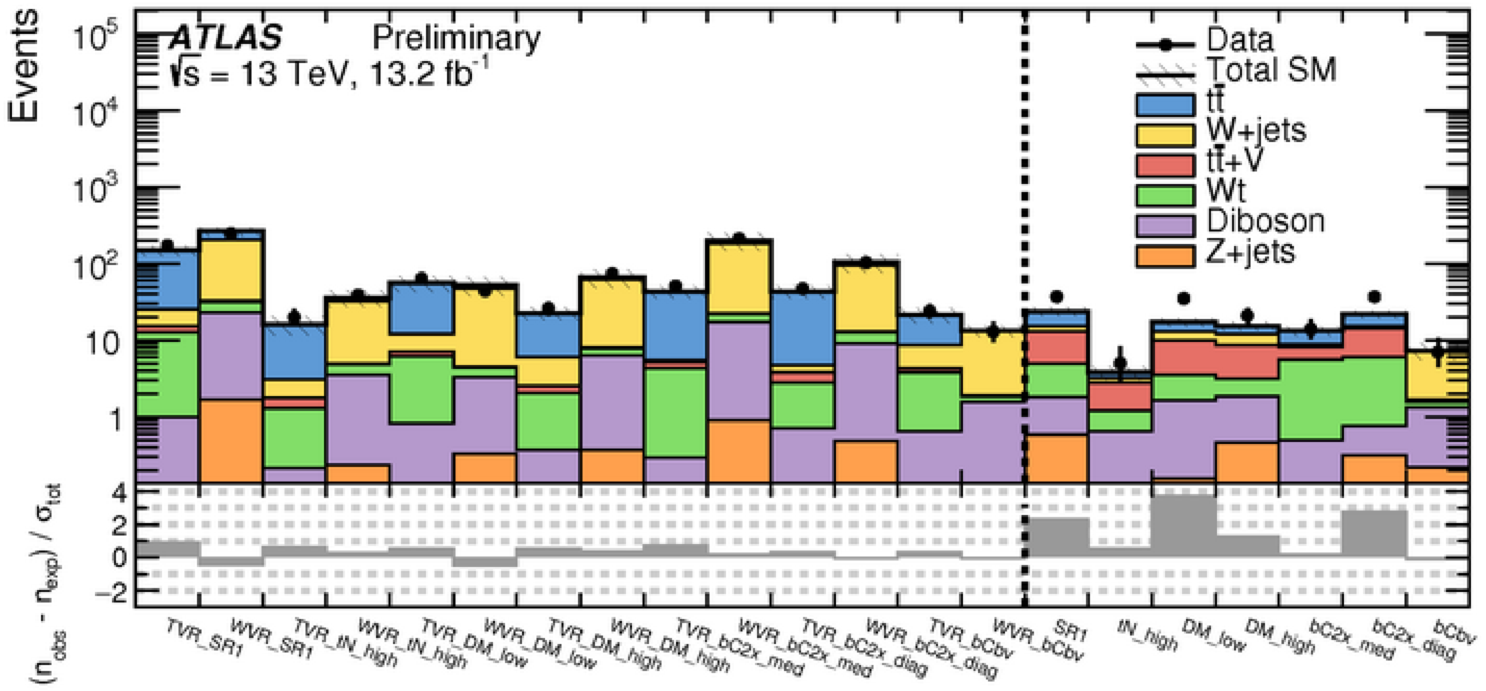
'Our measurement complements other search campaigns that used gamma rays to look for dark matter and it confirms that there is little room left for dark matter induced gamma-ray emission in the isotropic gamma-ray background,' says Fornasa.




# LHC



Missing transverse momentum, inferred from momentum conservation
Invisible Dark Matter particle
Invisible Dark Matter particle
LHC collision interaction point
LHC detector transverse cross-section
Visible particles: photons, jets
ATLAS EXPERIMENT

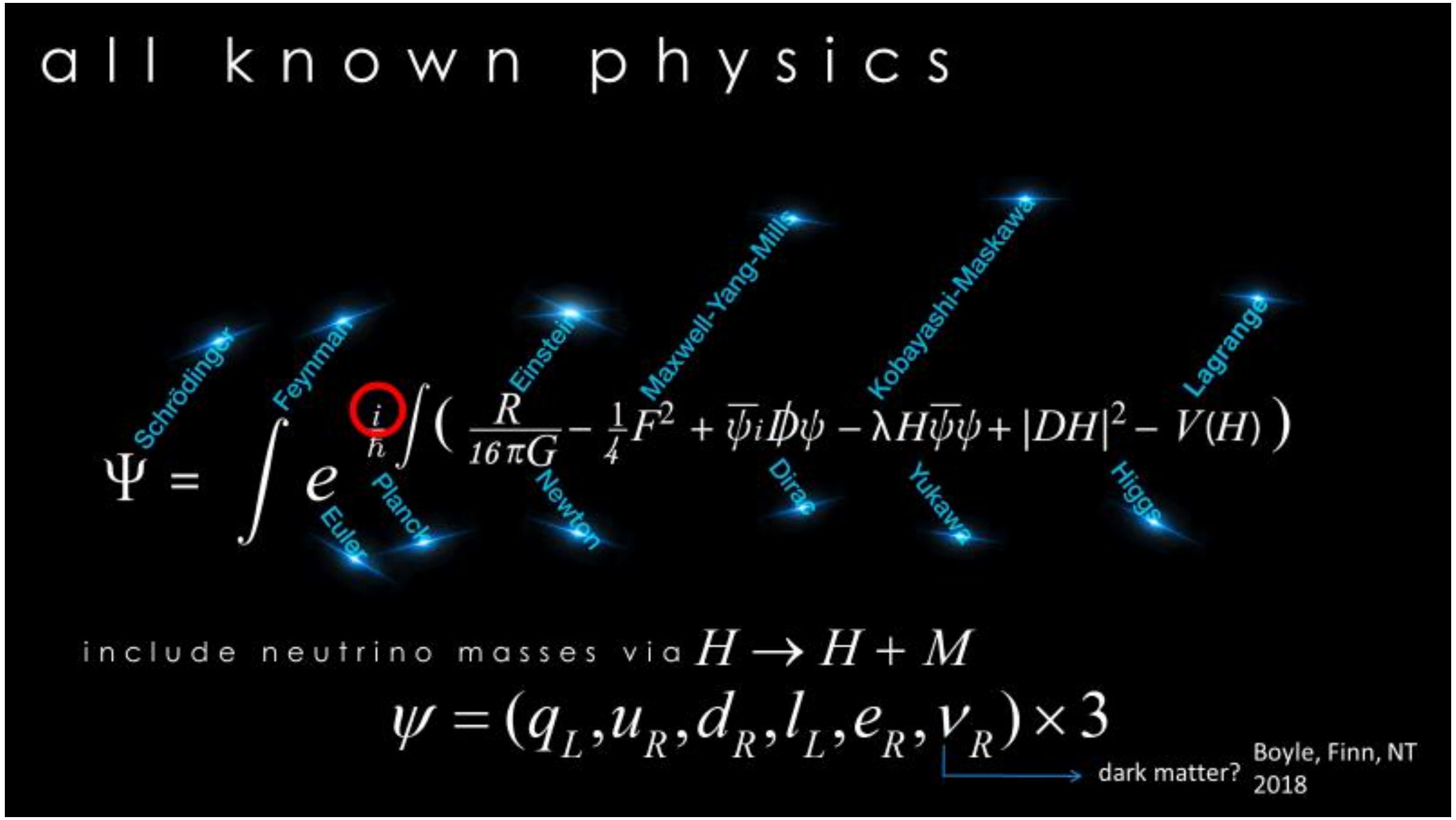



ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 13.2 fb$^{-1}$
Events
Data
Total SM
$t\bar{t}$
W+jets
$t\bar{t}$+V
Wt
Diboson
Z+jets
$(n_{obs} - n_{exp}) / \sigma_{tot}$
TVR_SR1
WVR_SR1
TVR_tN_high
WVR_tN_high
TVR_DM_low
WVR_DM_low
TVR_DM_high
WVR_DM_high
TVR_bC2x_med
WVR_bC2x_med
TVR_bC2x_diag
WVR_bC2x_diag
TVR_bCbv
WVR_bCbv
SR1
tN_high
DM_low
DM_high
bC2x_med
bC2x_diag
bCbv

# Empty-Handed?

# Modified Gravity Theories

# Sterile Neutrinos



# Dark Matter

- Works well on cosmological scales
- Does not work well in detail for galaxy rotation curves (small scale problems)
- We haven’t found it

# Modified Gravity

- Predicts galaxy rotation curves very well
- Does not predict well or ignores the data from CMB or gravitational wave data

# Stalemate

# Current Status of Dark Matter

# Thank You! - Ευχαριστώ!!

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