





STRONG  
GRAVITY

QUANTUM  
MATTER

COSMOLOGY

PARTICLE  
PHYSICS

MATHEMATICAL  
PHYSICS

QUANTUM FIELDS  
AND STRINGS

QUANTUM  
INFORMATION

QUANTUM  
GRAVITY

QUANTUM  
FOUNDATIONS



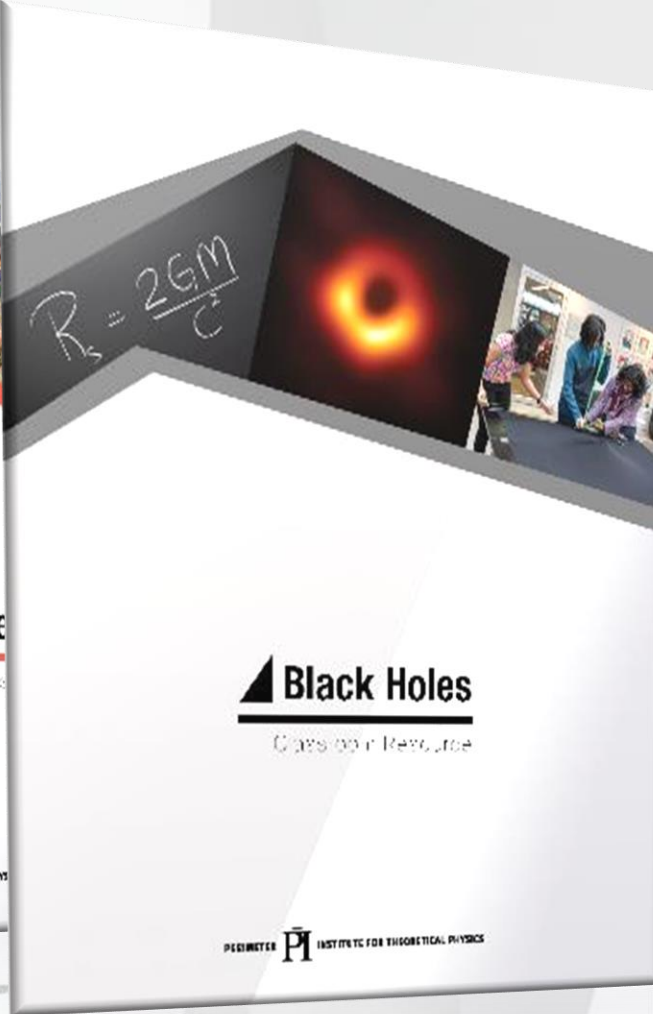
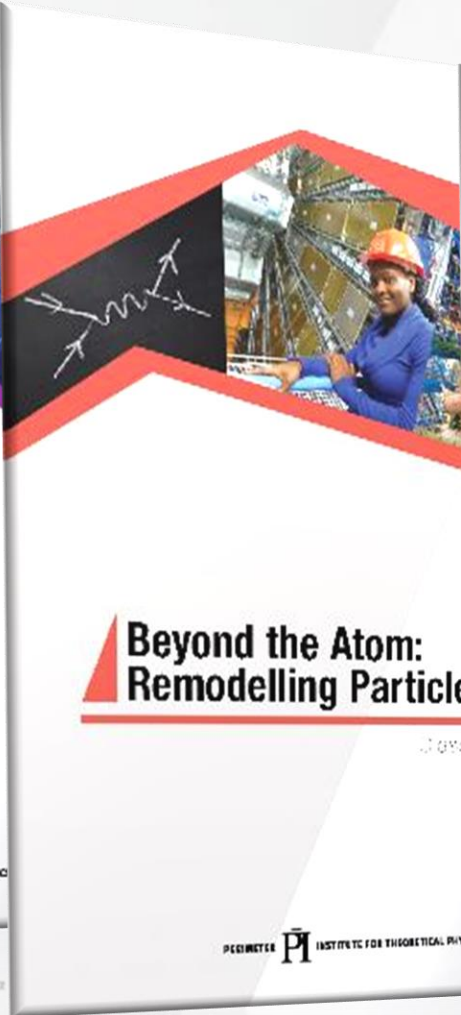
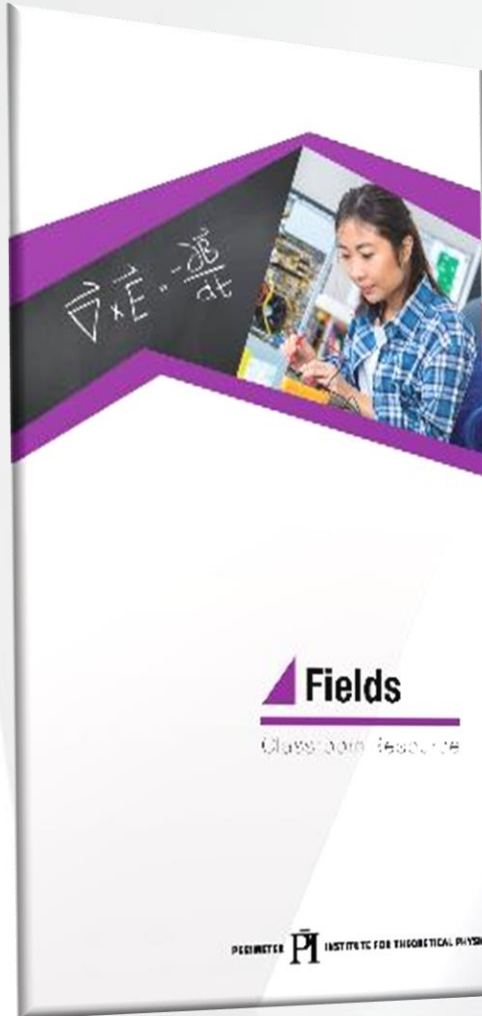
PI

# Teacher Programs

[www.perimeterinstitute.ca/outreach/teachers](http://www.perimeterinstitute.ca/outreach/teachers)



# IN-CLASS RESOURCES



Experienced teachers

Perimeter researchers

Pedagogy and teaching strategies



# High School Student Programs

[www.perimeterinstitute.ca/outreach/students](http://www.perimeterinstitute.ca/outreach/students)

Go Physics!

1-day workshops (online)



ISSYP

# INSPIRING THE NEXT GENERATION



STUDENTS

10 MILLION<sup>+</sup>/year



TEACHERS

40,000<sup>+</sup>  
teachers trained

In-class resources



130 countries



PUBLIC

100,000<sup>+</sup> on site

2 MILLION online views



PUBLIC LECTURE SERIES

EinsteinFest

Q2Cfestival





## Educational Resources

By Perimeter Institute

Free Educational Resources for Teachers

<https://resources.perimeterinstitute.ca/>



# The Mystery of Dark Matter

Perimeter Explorations 01



CERN  
Greek HST2022



# Building and Revising Scientific Models





- **Activity 6: Dark Matter Lab**
- Curriculum Links:
  - Circular Motion
  - Newtonian Gravity



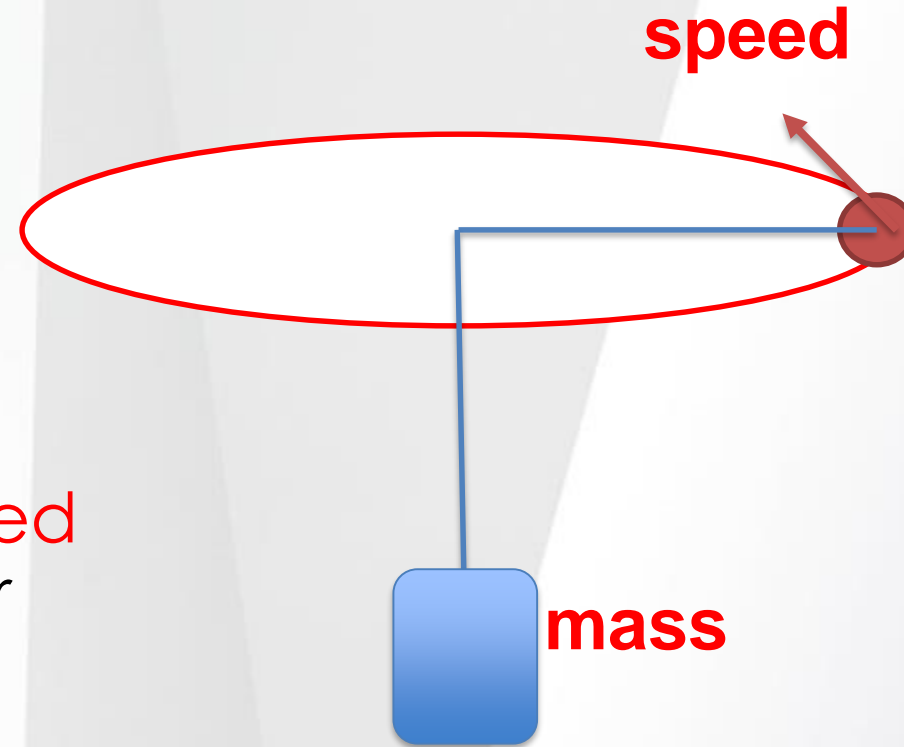
# Uniform Circular Motion lab



# Uniform Circular Motion

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

How are **mass** and **speed**  
connected in circular  
motion?





# Circular Motion Lab

1. Set radius = 60 cm
2. Record period for 10 orbits for various masses.
3. Plot results



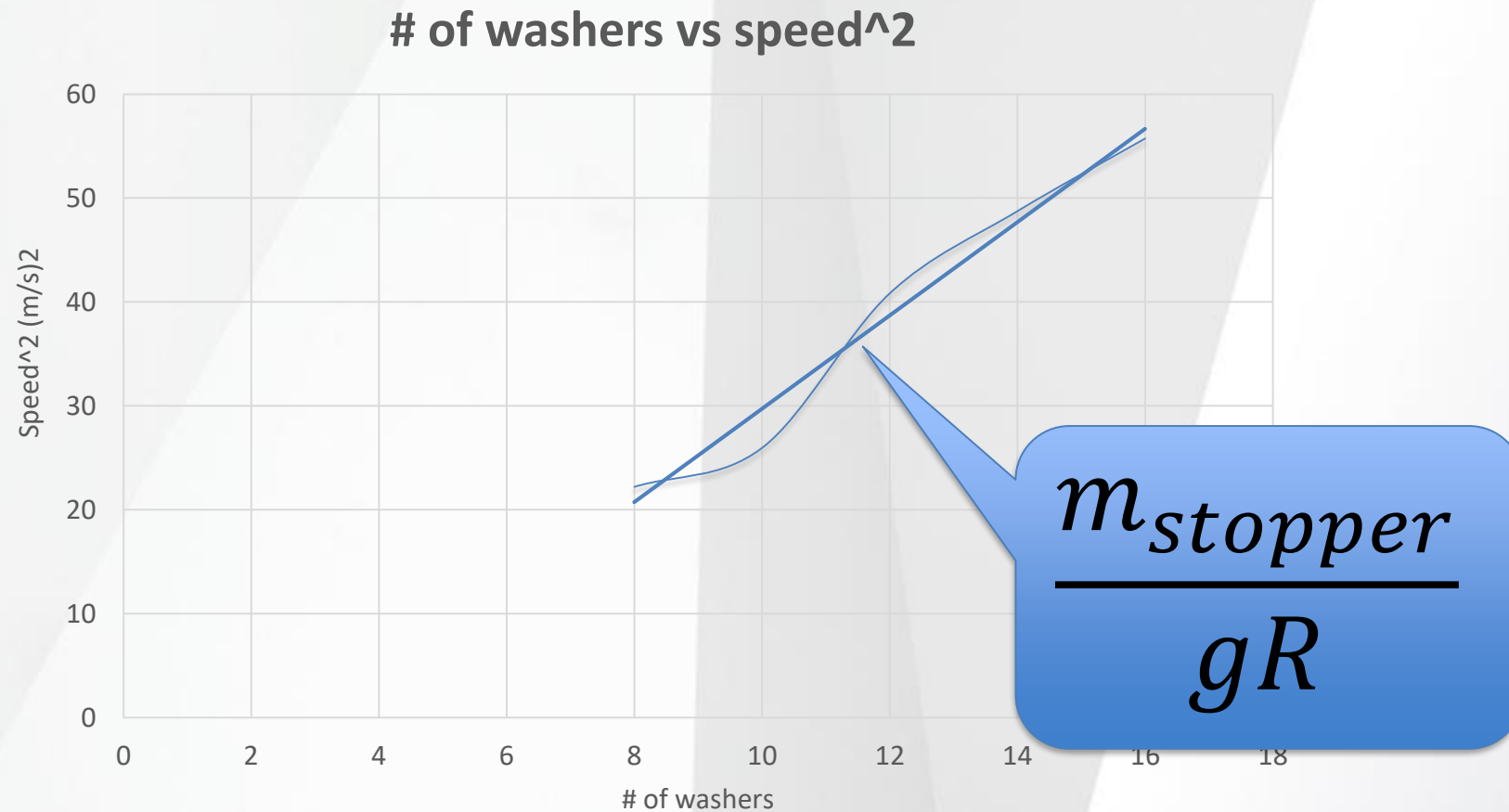
# Circular Motion Lab Results

# of washers	10 Orbits (s)
8	8.0
10	7.4
12	5.9
14	5.4
16	5.0

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



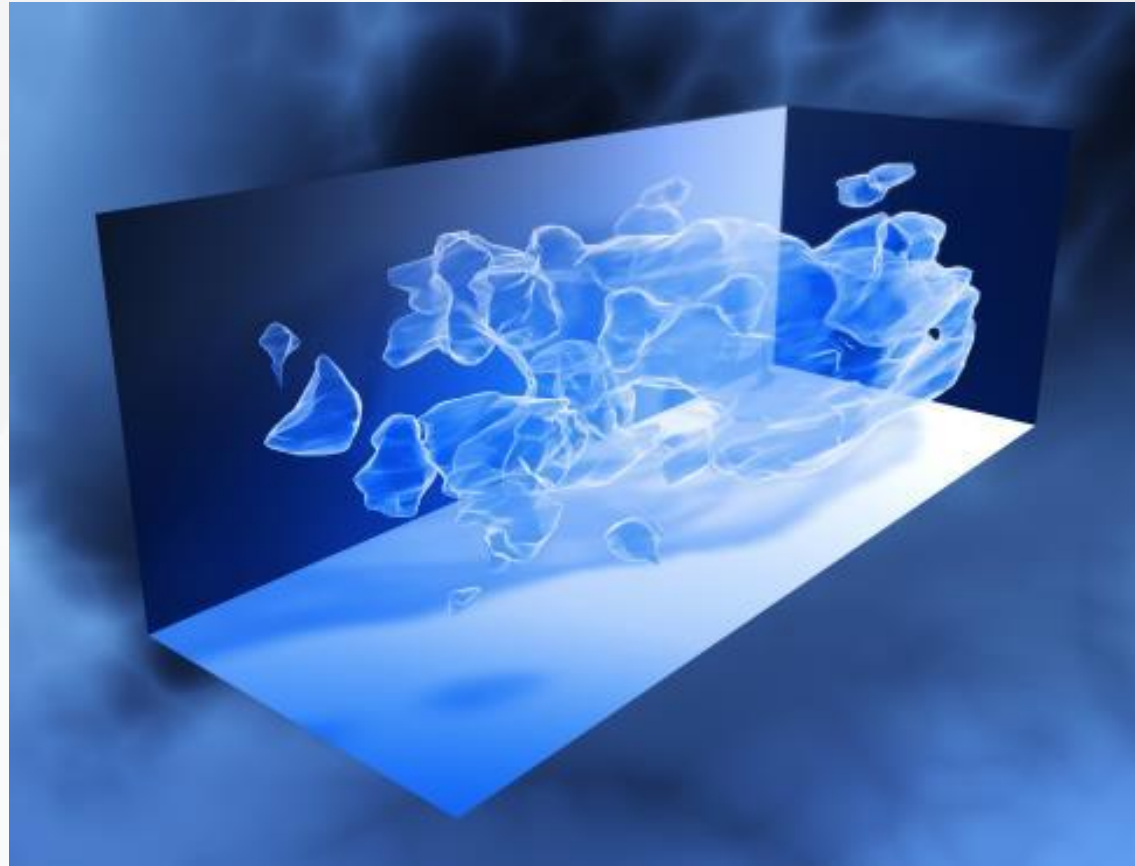
# Circular Motion Lab Results



**Which LED is connected to more mass?**



# Uniform Circular Motion $\rightarrow$ Dark Matter



# Vera Rubin's Discovery





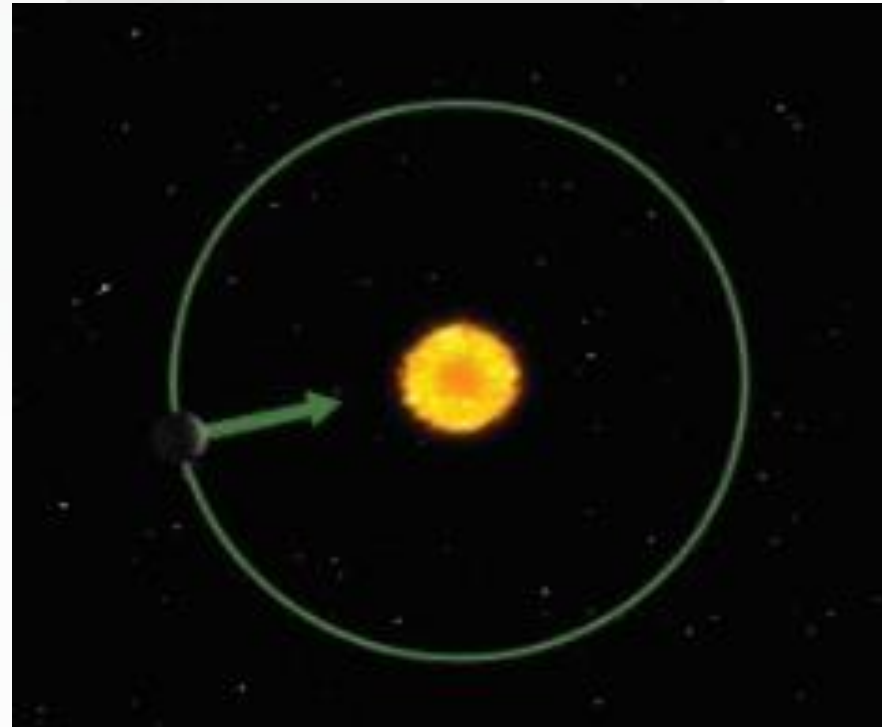
# Uniform Circular Motion



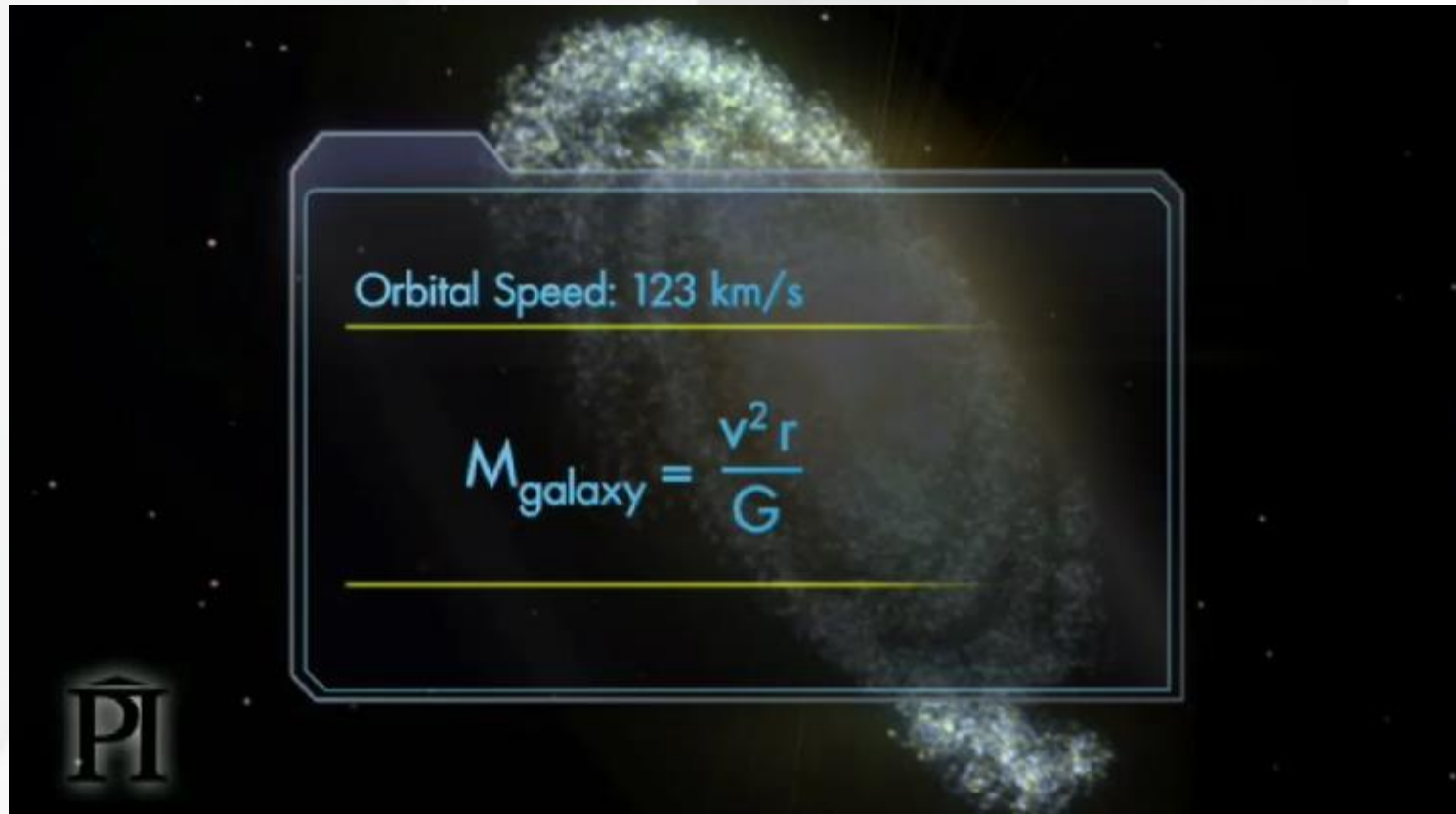
# Uniform Circular Motion

Orbital Speed  
Depends on the  
Mass of the Central  
Object

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



# Extend this to galaxies



Orbital Speed: 123 km/s

$$M_{\text{galaxy}} = \frac{v^2 r}{G}$$

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# Triangulum is More Massive Than it Looks





**What explanations might your students come up with?**



# Some Possibilities

## 1. BRIGHTNESS METHOD IS FLAWED

- Gas & dust between us & other galaxies make them appear dimmer
- Assumptions about relationship between brightness & mass are wrong
- There is a ***new kind of matter*** that we cannot see

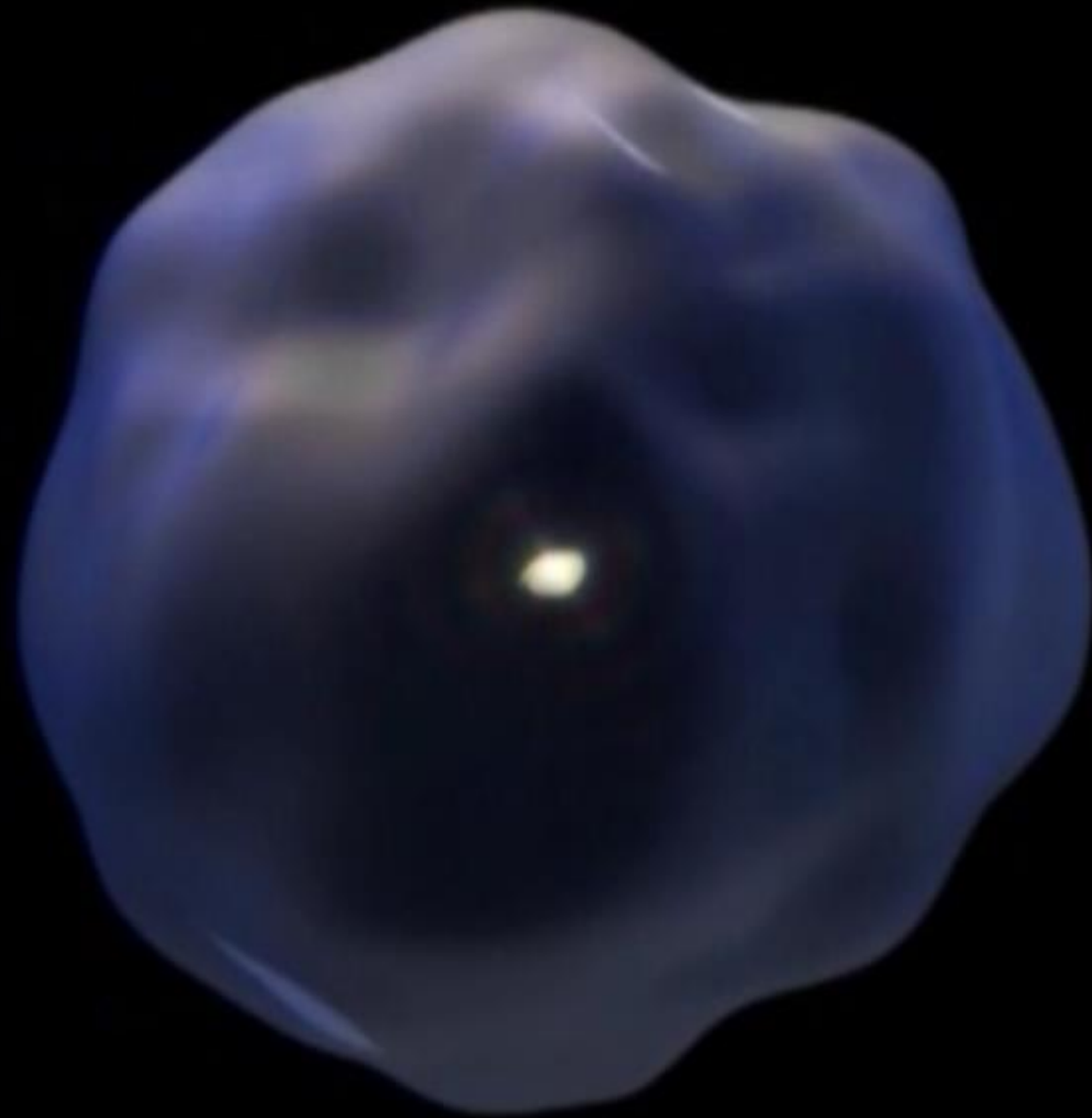
## 2. ORBITAL METHOD IS FLAWED

- Orbital radius measurements are inaccurate
- Speed measurements are inaccurate
- Newtonian gravity doesn't hold on the scale of galaxies
- There is some ***new physics*** that we don't understand

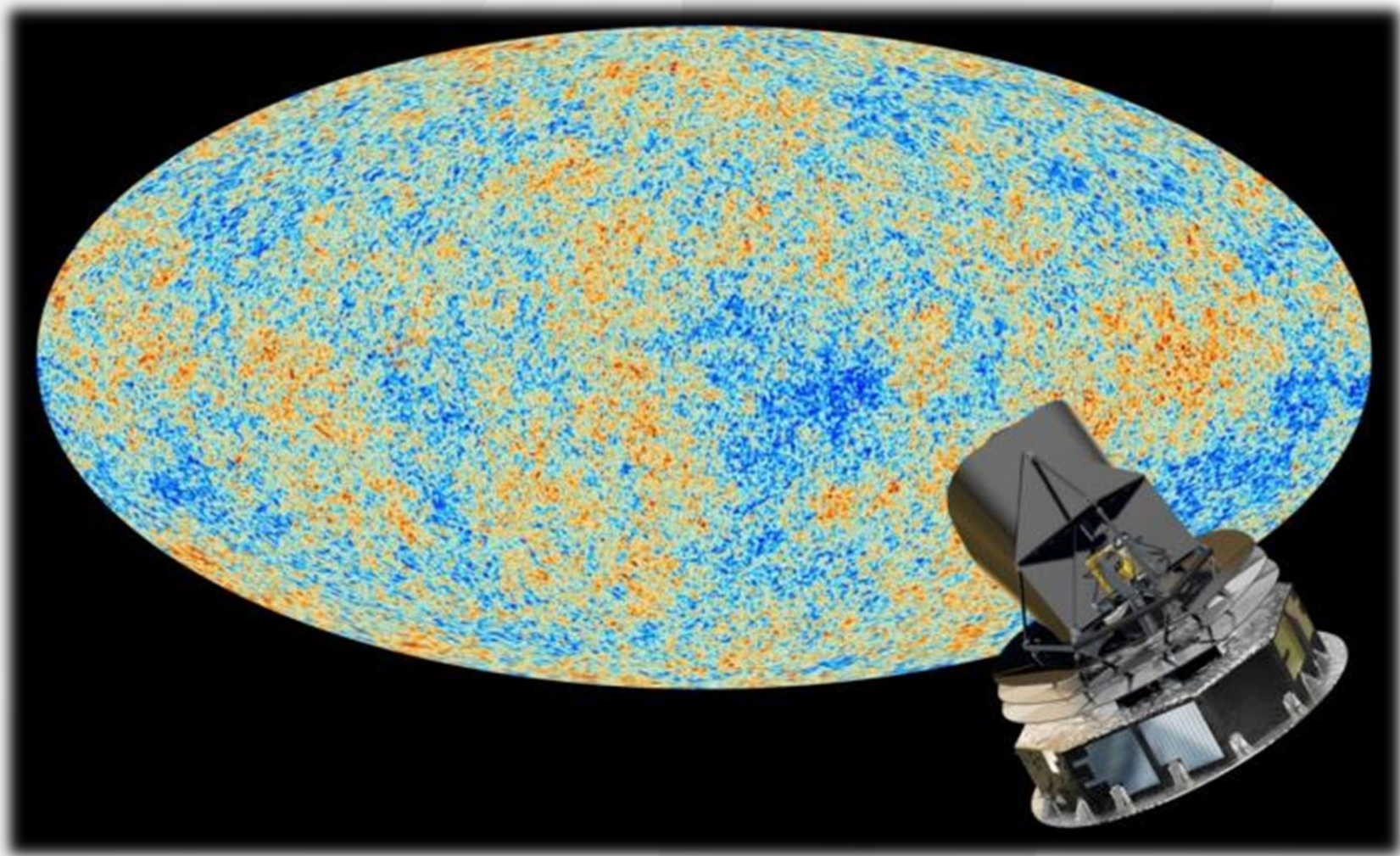
# Old View



New View





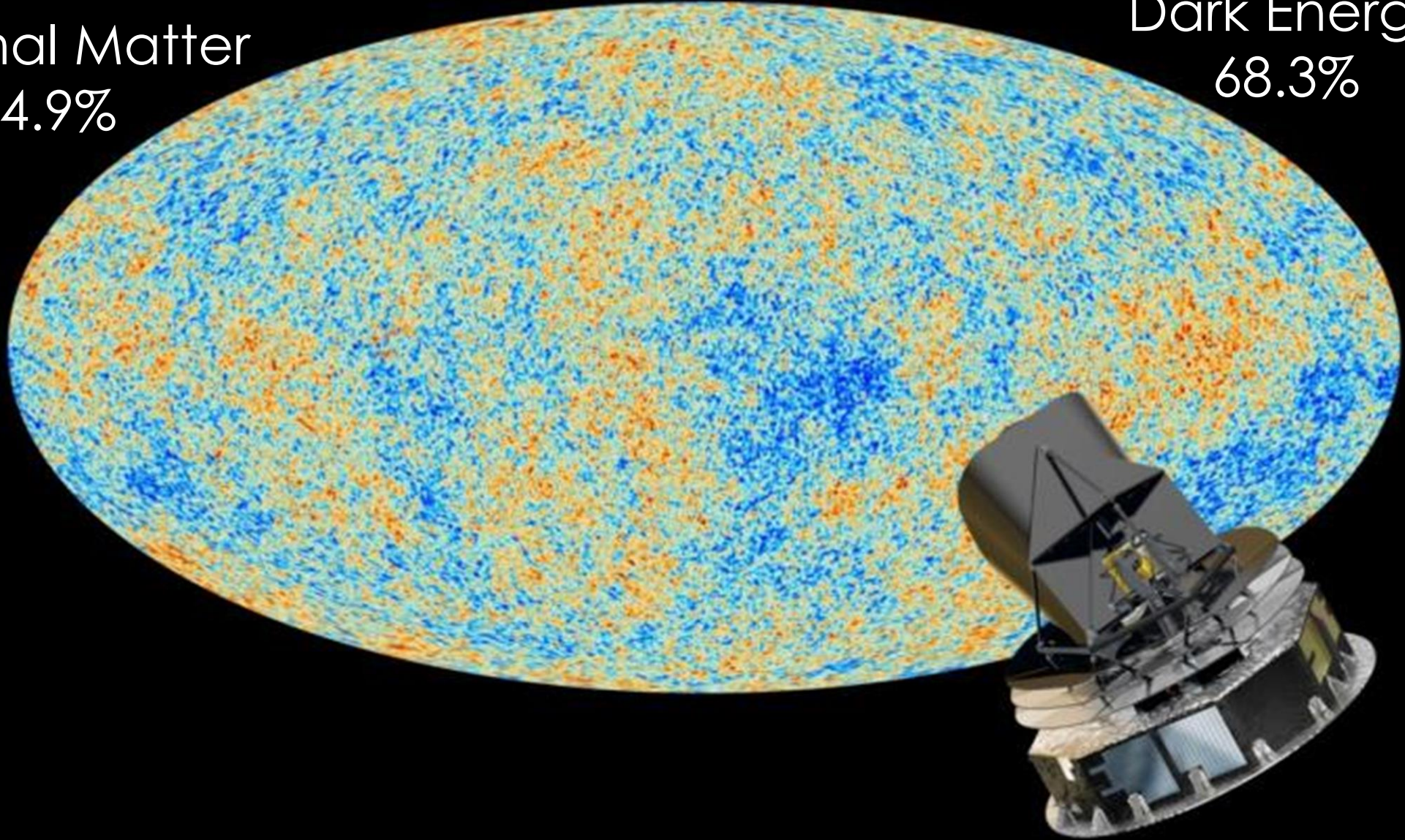




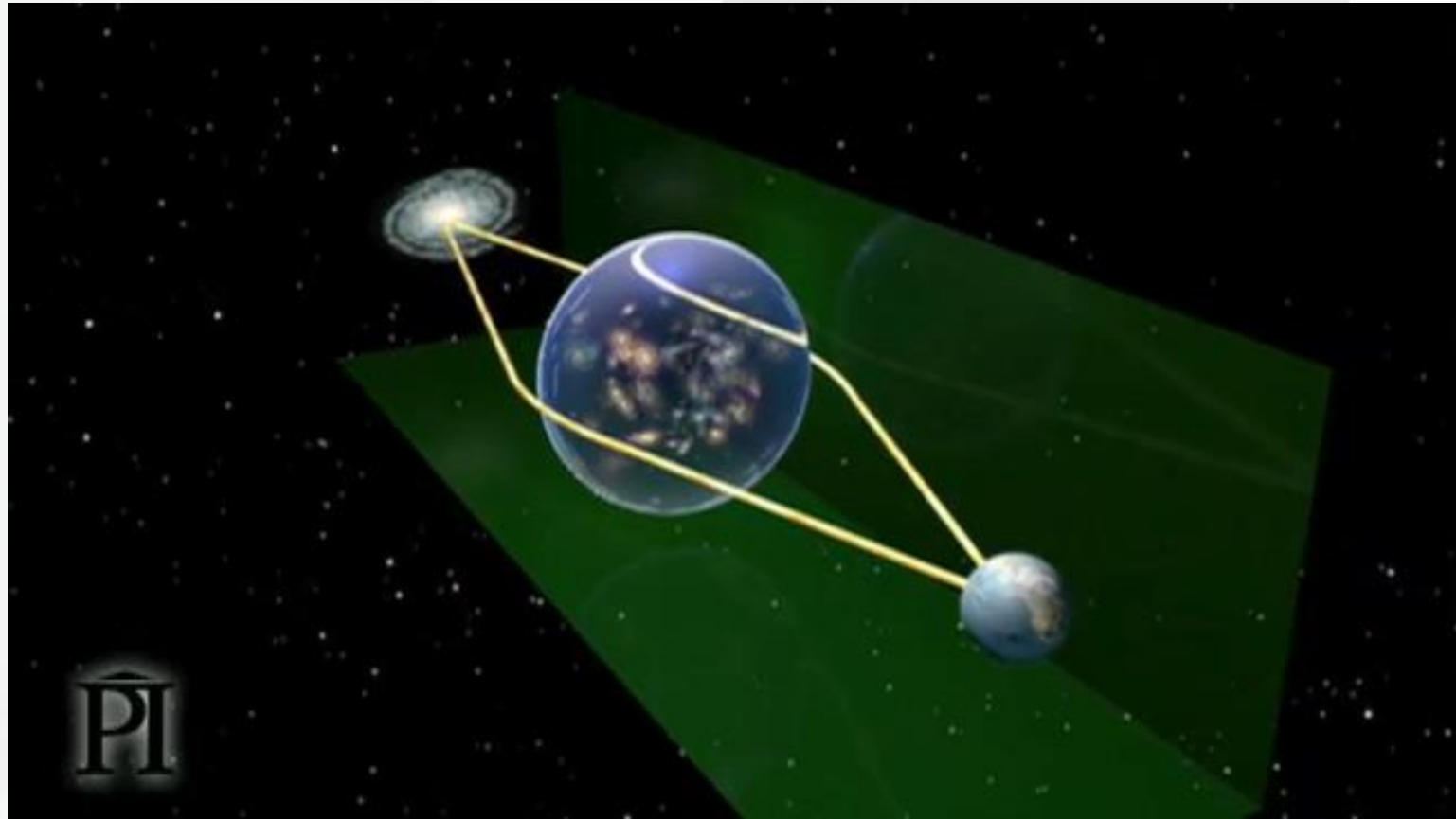
Dark Matter  
26.8%

Dark Energy  
68.3%

Normal Matter  
4.9%



# Gravitational Lensing



# Looking for Dark Matter particles

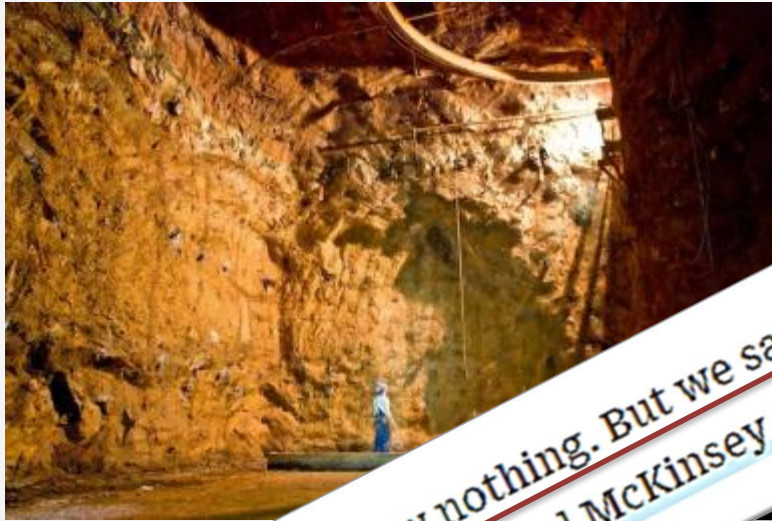


# How to Look for Dark Matter Particles

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



# LUX- Large Underground Xenon Detector



Homestake

“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.



# LUX update (2017)



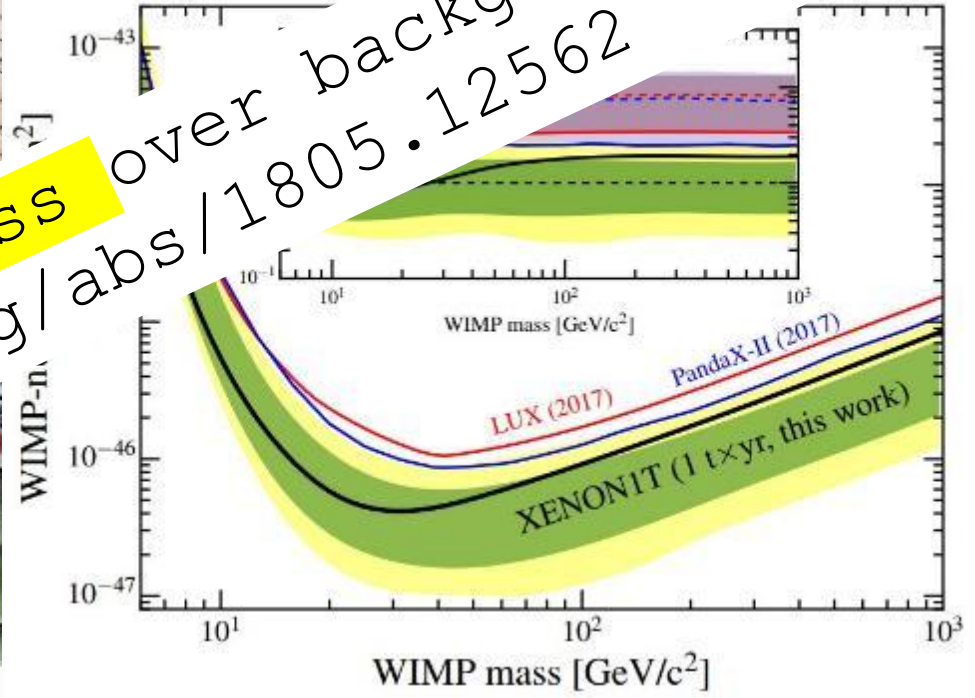
With roughly fourfold improvement in sensitivity for high WIMP masses relative to our previous results, this search yields **no evidence of WIMP nuclear recoils**. [arXiv:1608.07648v3](https://arxiv.org/abs/1608.07648v3)



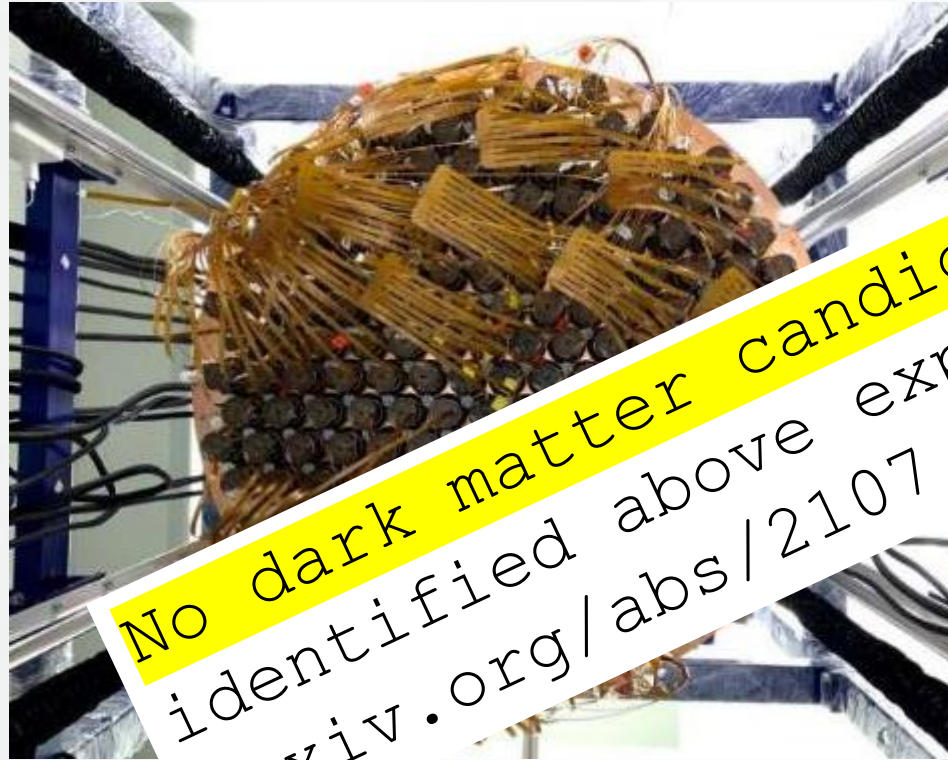
# XENON1T most sensitive measurement yet (2018)



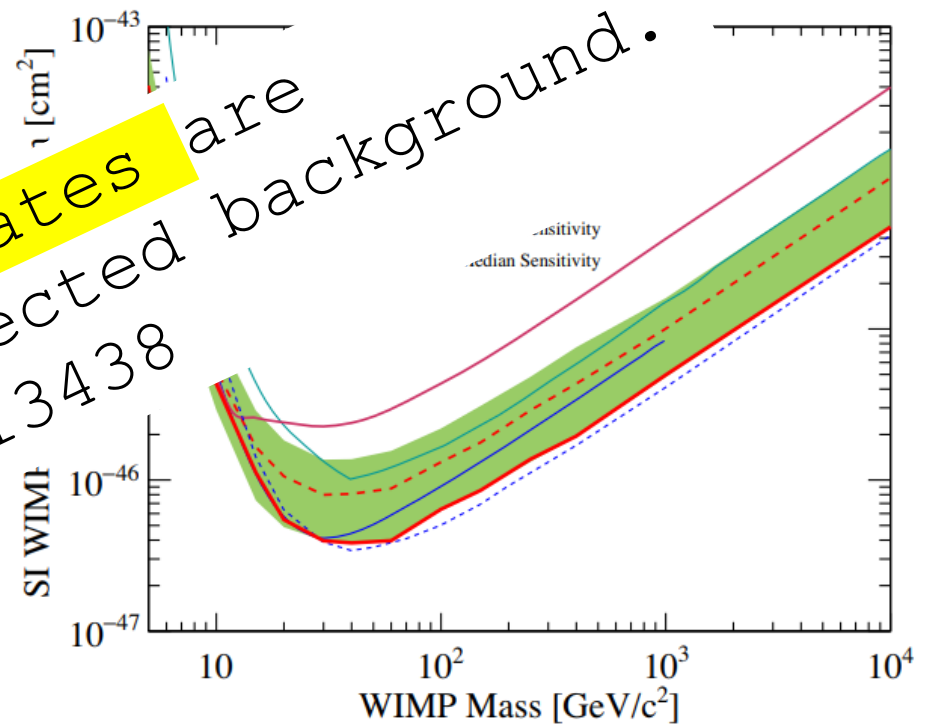
No significant excess over background is found. [arxiv.org/abs/1805.12562](https://arxiv.org/abs/1805.12562)



# PANDAX-4T (2021)



No dark matter candidates are identified above expected background. [arxiv.org/abs/2107.13438](https://arxiv.org/abs/2107.13438)

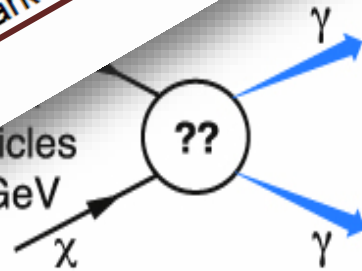


# FERMI

- Detects  $\gamma$ -rays

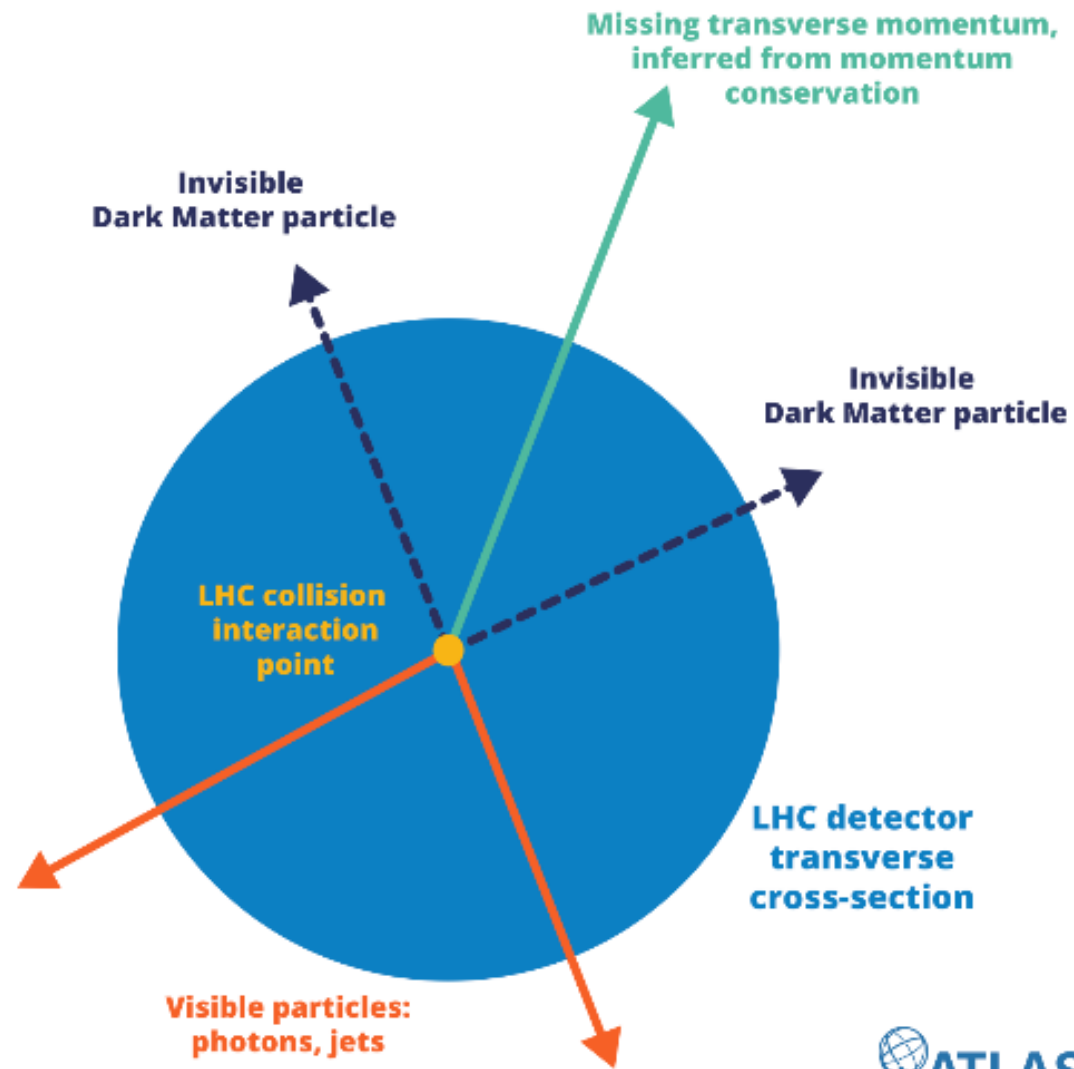
- DM particle annihilation

'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.





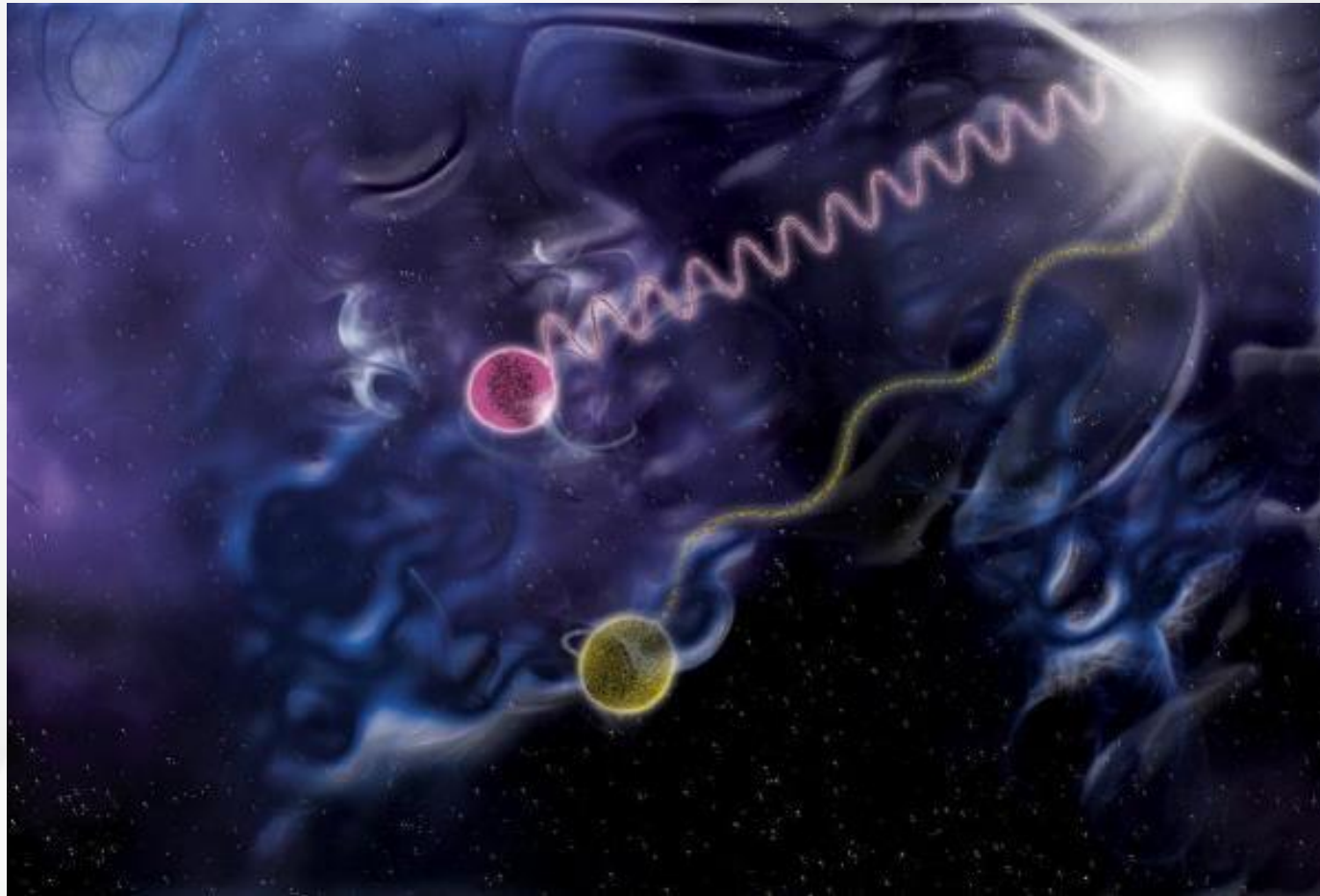
# LHC



# Empty-Handed?



## LIGO prefers a dark matter particle



# Modified Gravity Theories



Maybe the particle has been here  
all along...

all known physics

$$\Psi = \int e^{\frac{i}{\hbar} \int \left( \frac{R}{16\pi G} - \frac{1}{4} F^2 + \bar{\psi} i \not{D} \psi - \lambda H \bar{\psi} \psi + |DH|^2 - V(H) \right)}$$

include neutrino masses via  $H \rightarrow H + M$

$$\psi = (q_L, u_R, d_R, l_L, e_R, \nu_R) \times 3$$

dark matter? Boyle, Finn, NT 2018



# 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

# Competing Theories For Dark Matter



# Competing Theories For Dark Matter



# Free Resources for All Teachers



Middle School  
(Gr 5-8)



Junior High  
(Gr 9-10)



Senior High  
(Gr 11-12)

<https://resources.perimeterinstitute.ca/>



# Thank You!

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EDUCATIONAL  
RESOURCES

<https://resources.perimeterinstitute.ca/>