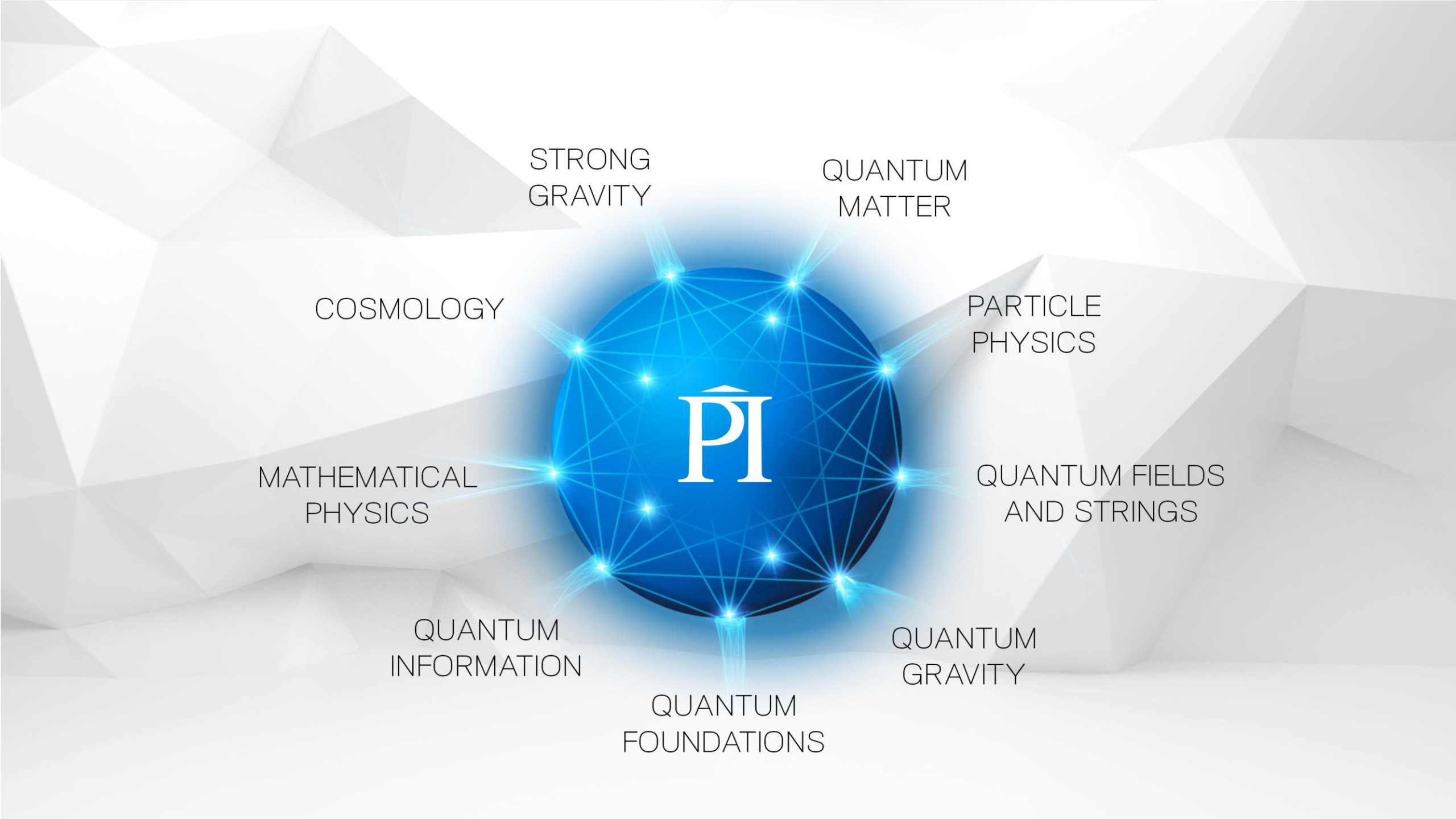
STRONG
GRAVITY
QUANTUM
MATTER
COSMOLOGY
PARTICLE
PHYSICS
PI
MATHEMATICAL
PHYSICS
QUANTUM FIELDS
AND STRINGS
QUANTUM
INFORMATION
QUANTUM
GRAVITY
QUANTUM
FOUNDATIONS

Teacher Programs

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IN-CLASS RESOURCES

- Experienced teachers
- Perimeter researchers
- Pedagogy and teaching strategies

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Go Physics!

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ISSYP

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INSPIRING THE NEXT GENERATION

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TEACHERS → 40,000+ teachers trained

In-class resources

130 countries

PUBLIC → 100,000+ on site

2 MILLION online views

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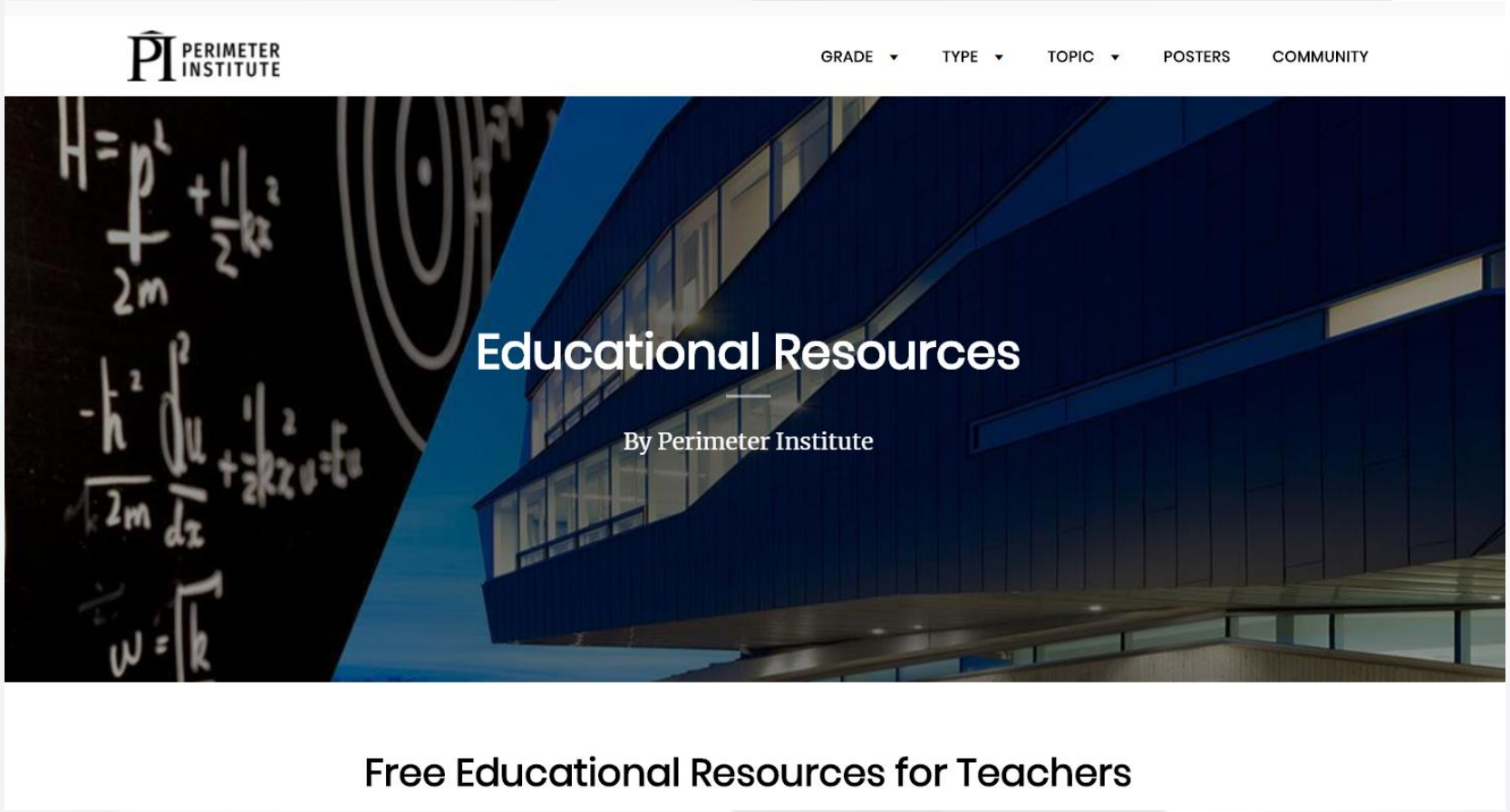

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The Mystery of Dark Matter

Perimeter Explorations 01

CERN
Greek HST2022

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Building and Revising Scientific Models

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

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Uniform Circular Motion lab

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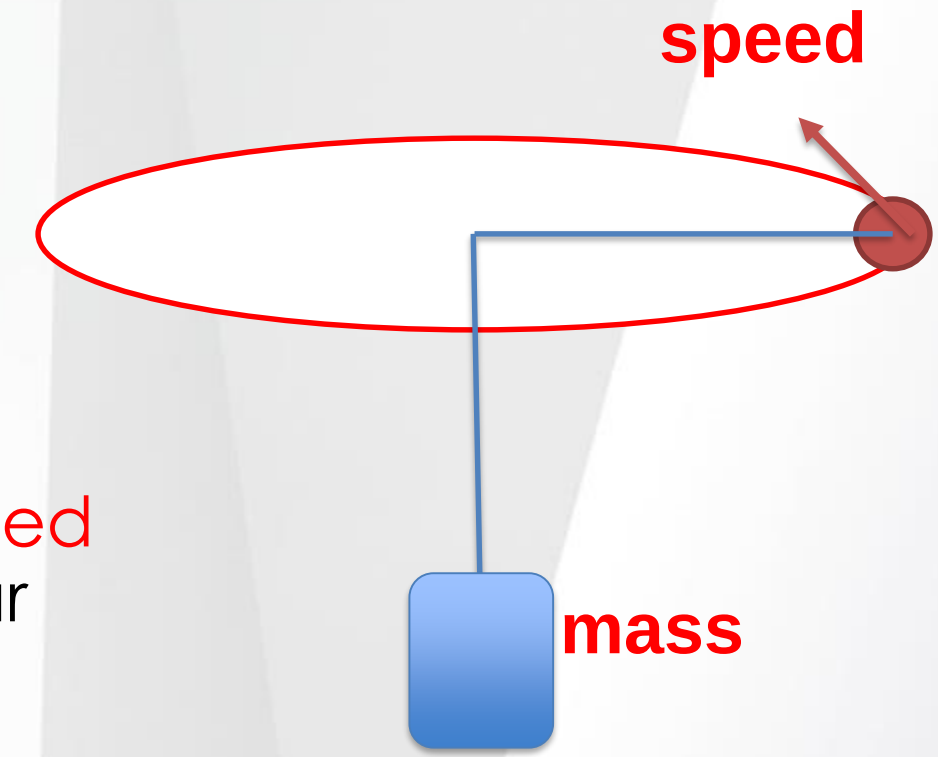
Uniform Circular Motion

Predict

Observe

Explain

How are mass and speed connected in circular motion?



Circular Motion Lab

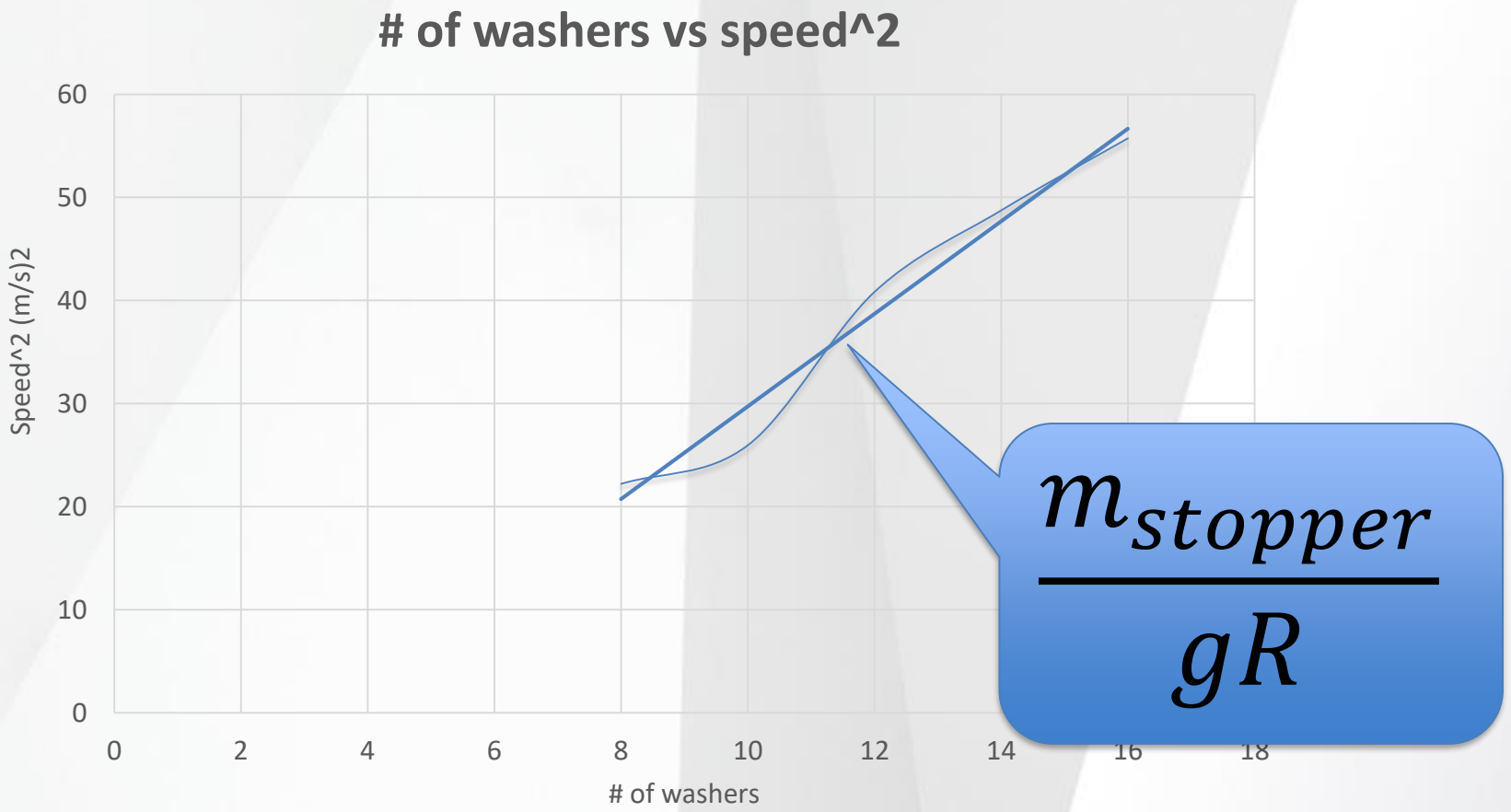
1. Set radius = 60 cm
2. Record period for 10 orbits for various masses.
3. Plot results

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



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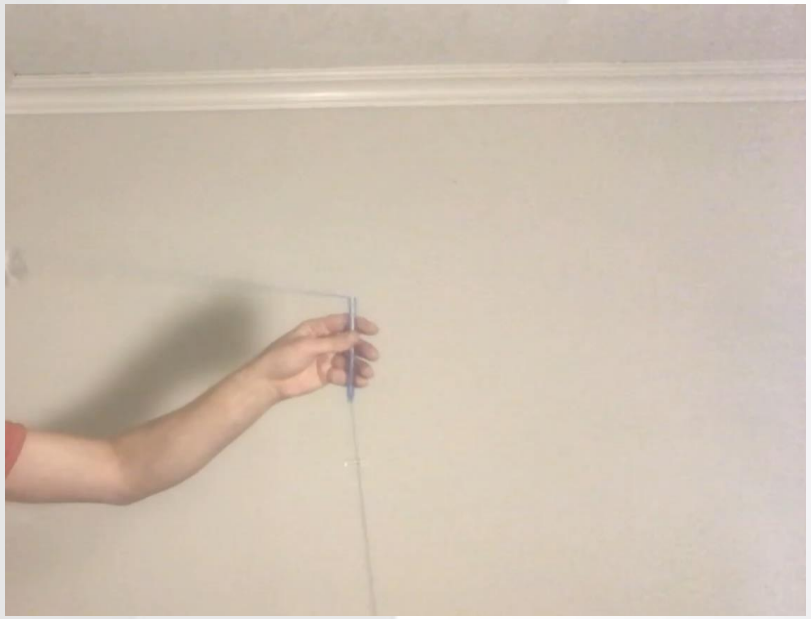
Which LED is connected to more mass?



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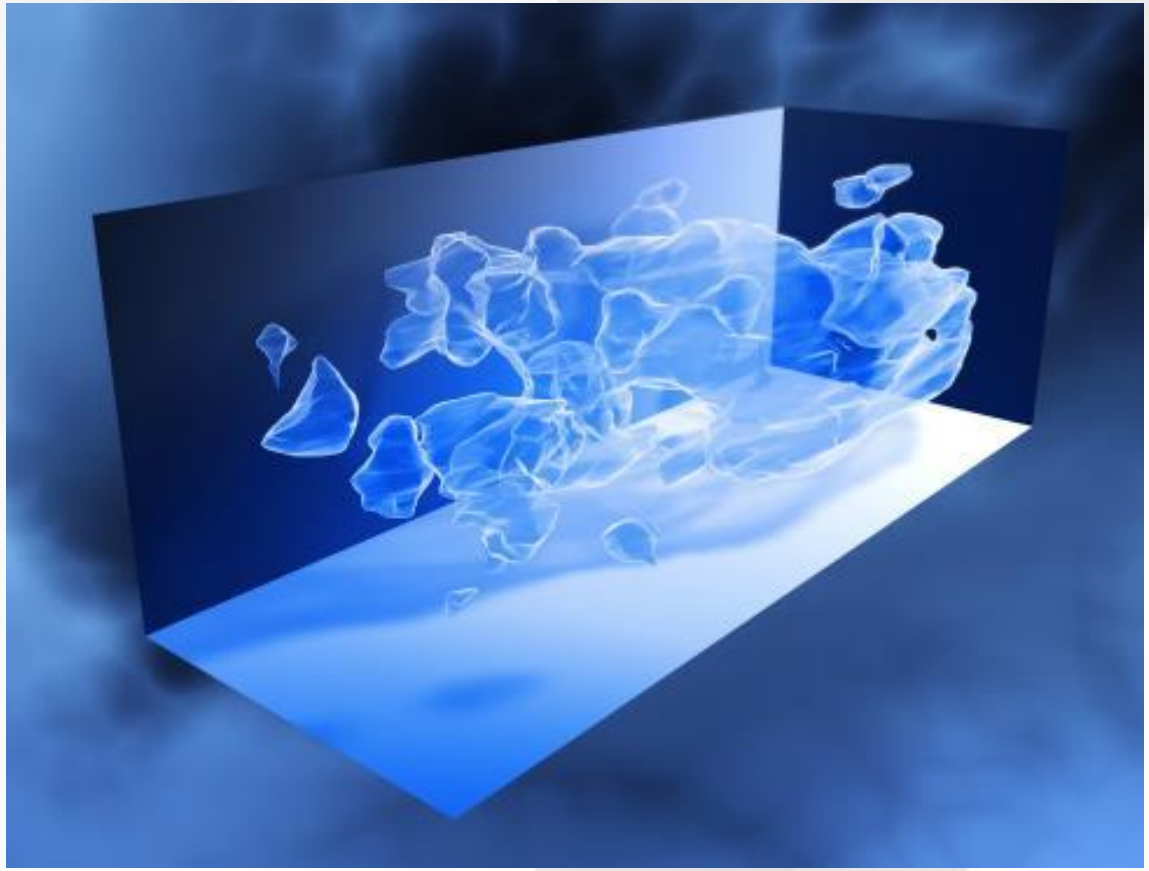
Uniform Circular Motion → Dark Matter



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Vera Rubin's Discovery

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Uniform Circular Motion

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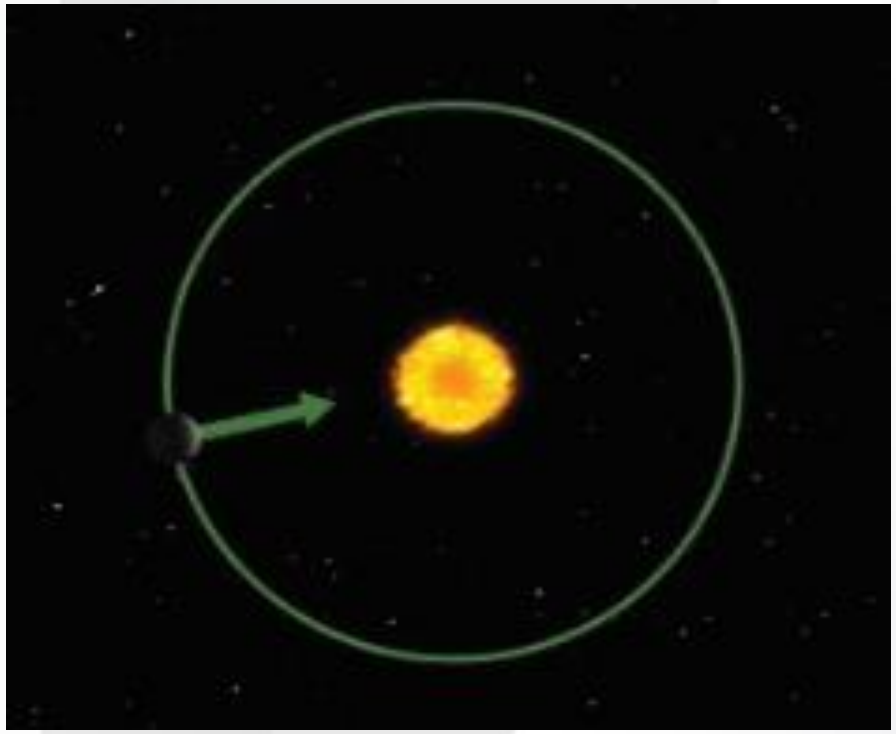
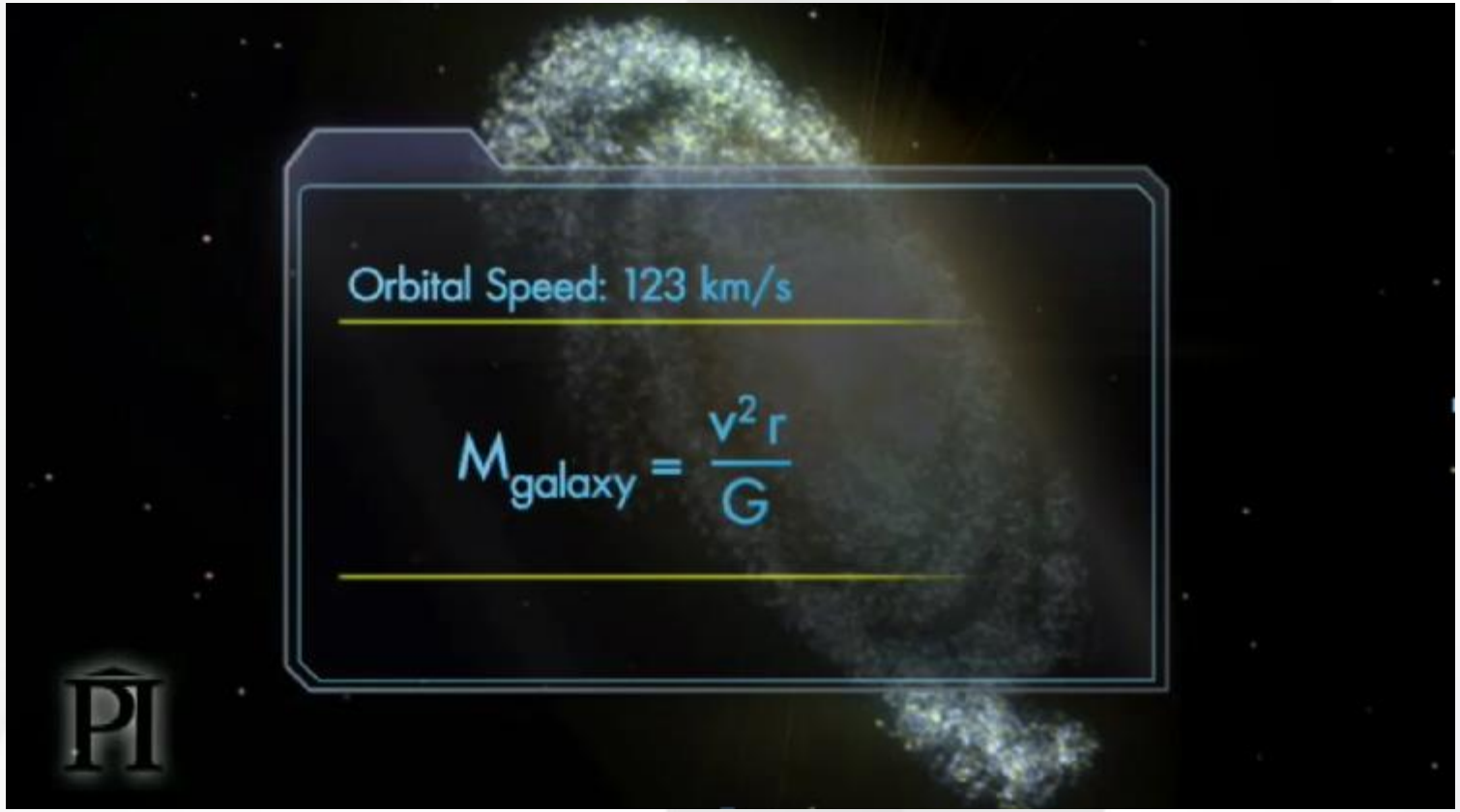
Uniform Circular Motion

Orbital Speed Depends on the Mass of the Central Object

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



Extend this to galaxies



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Triangulum is More Massive Than it Looks

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What explanations might your students come up with?

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Some Possibilities

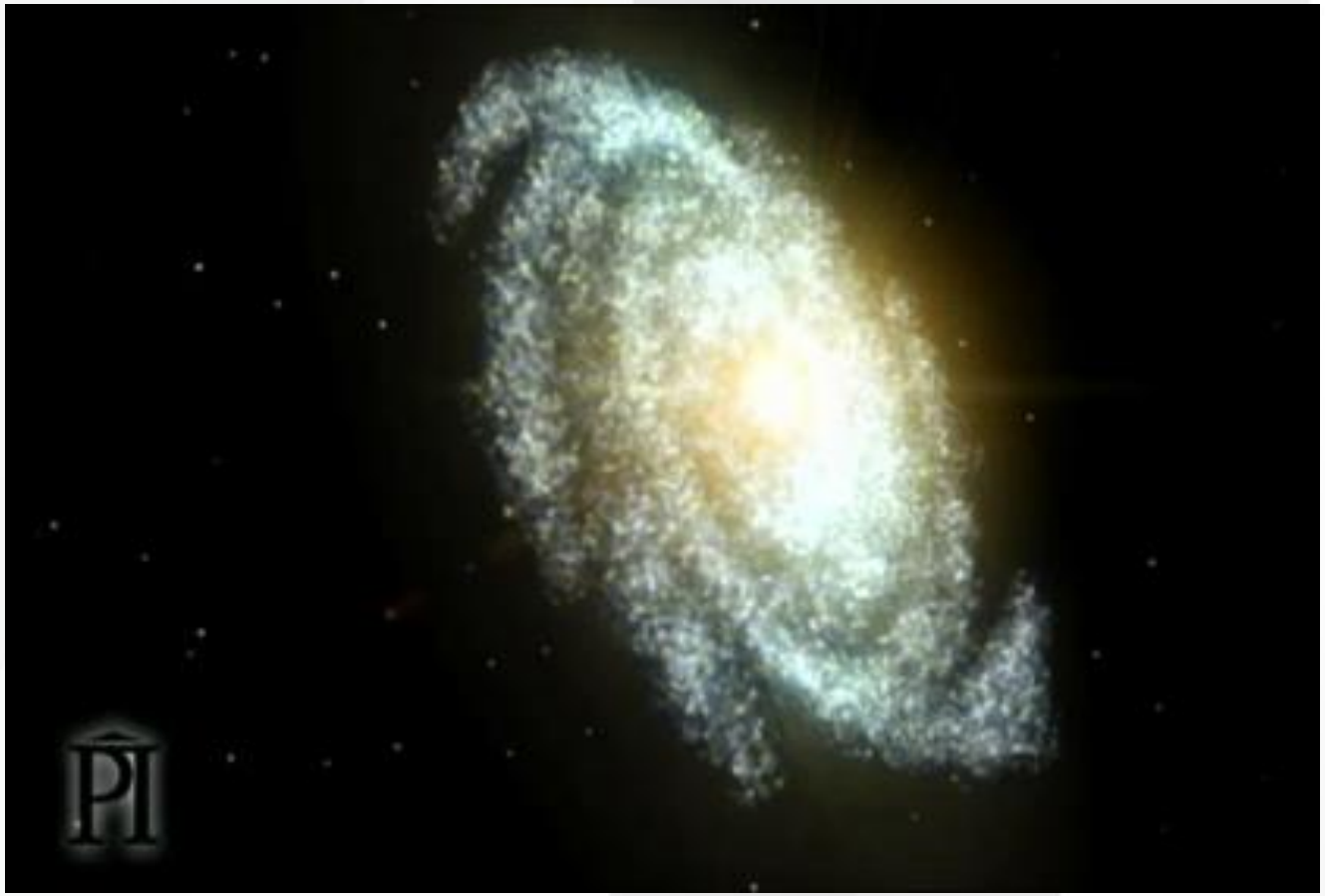
1. BRIGHTNESS METHOD IS FLAWED

- 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



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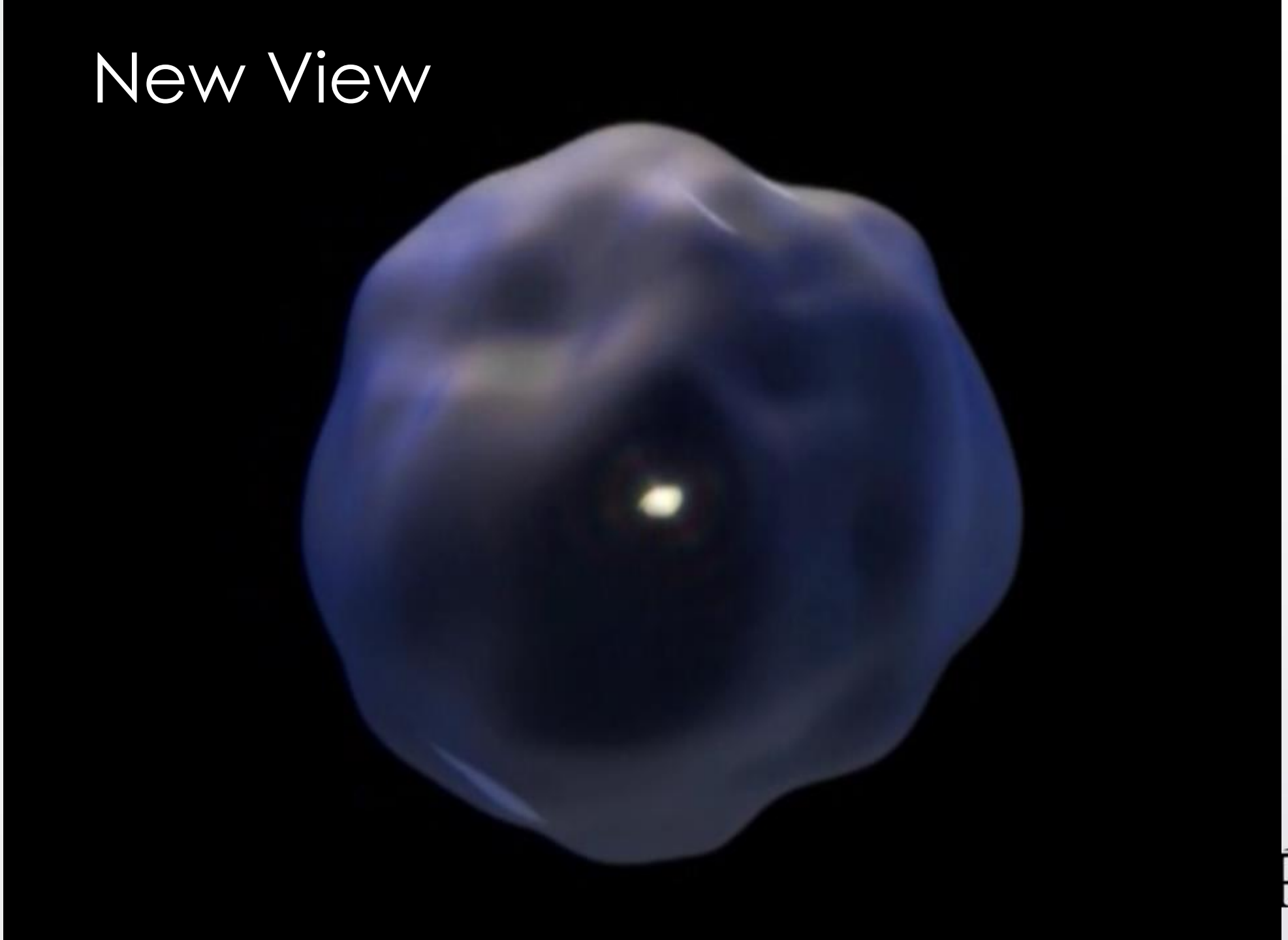
New View



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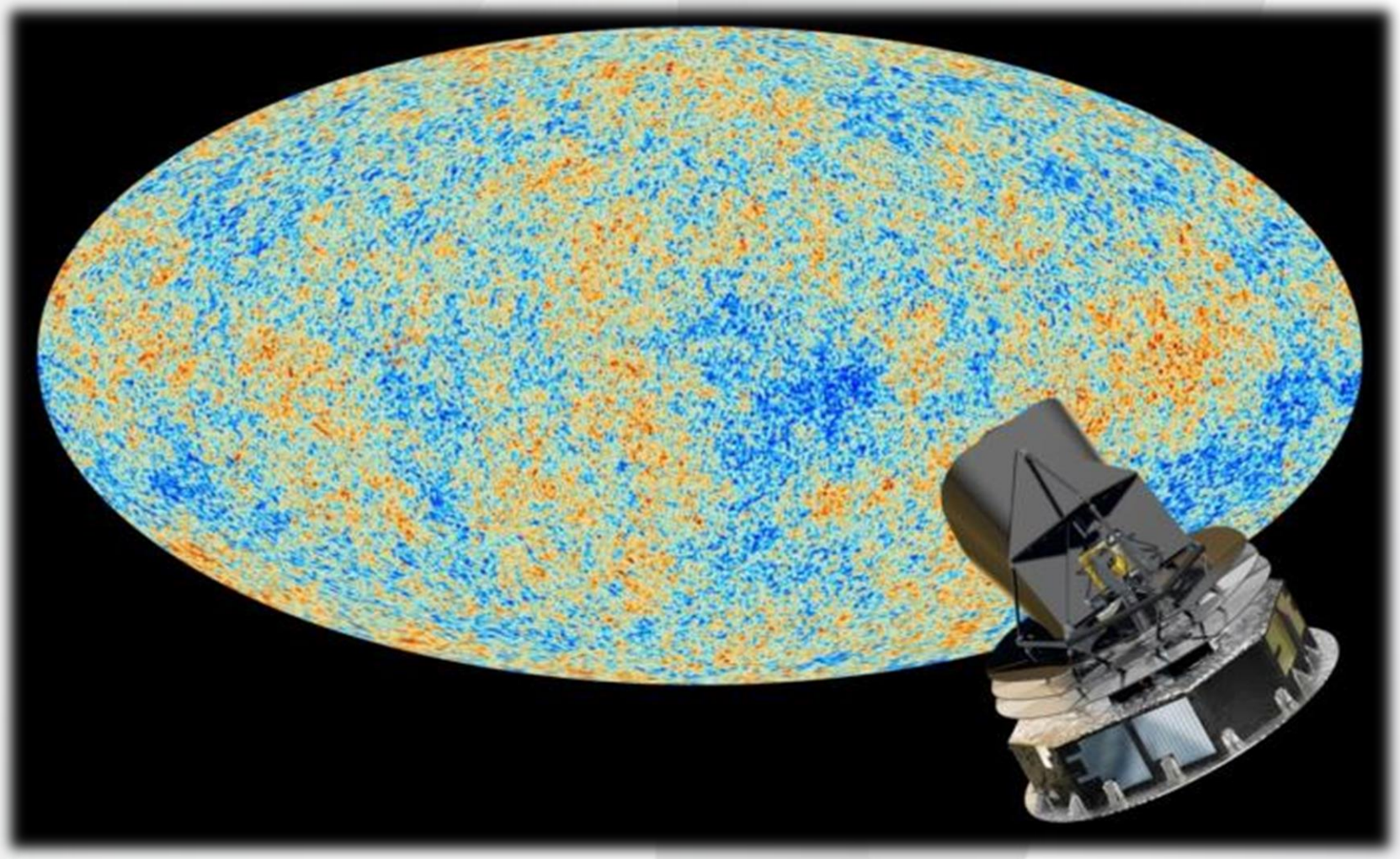

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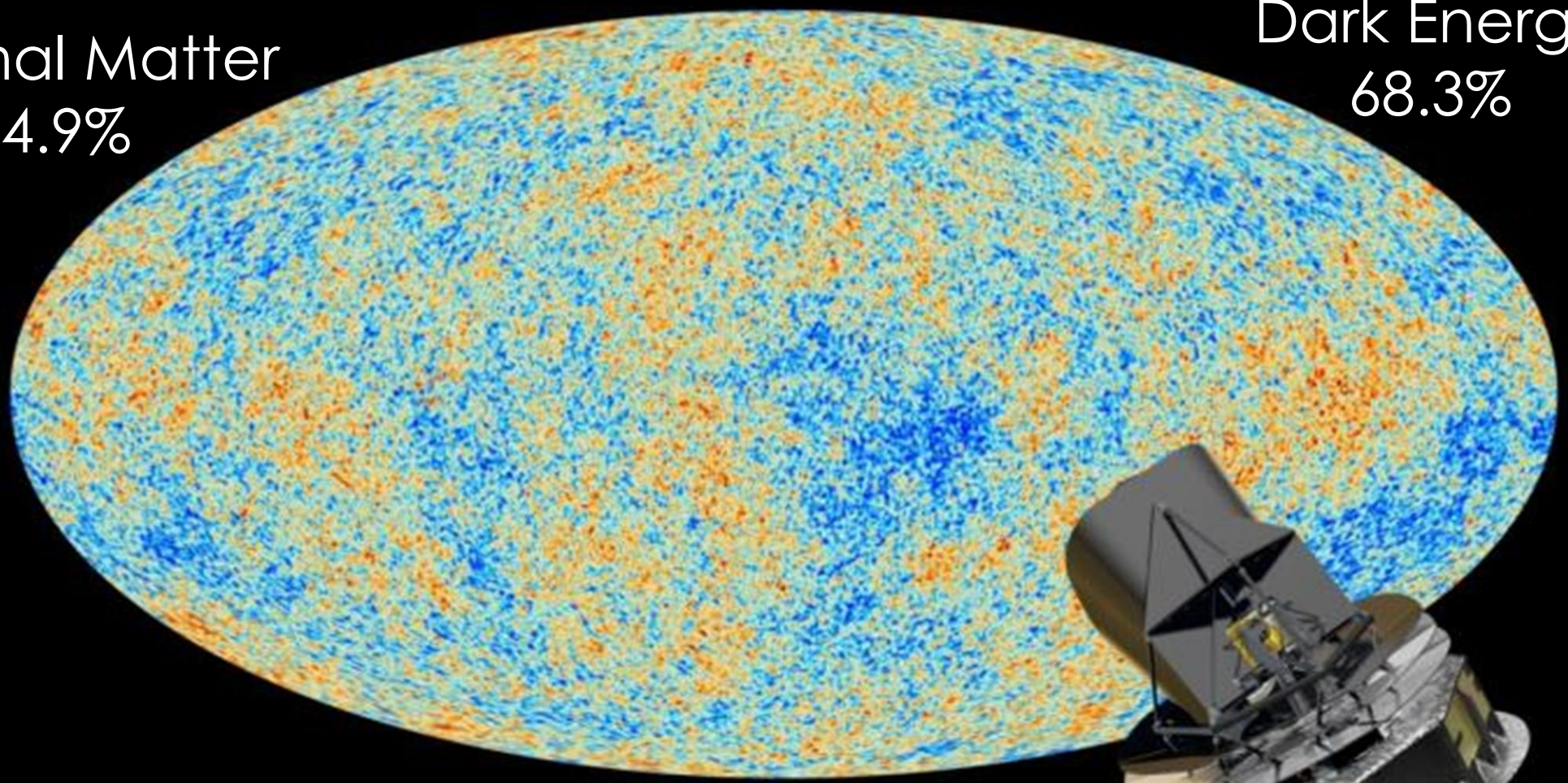
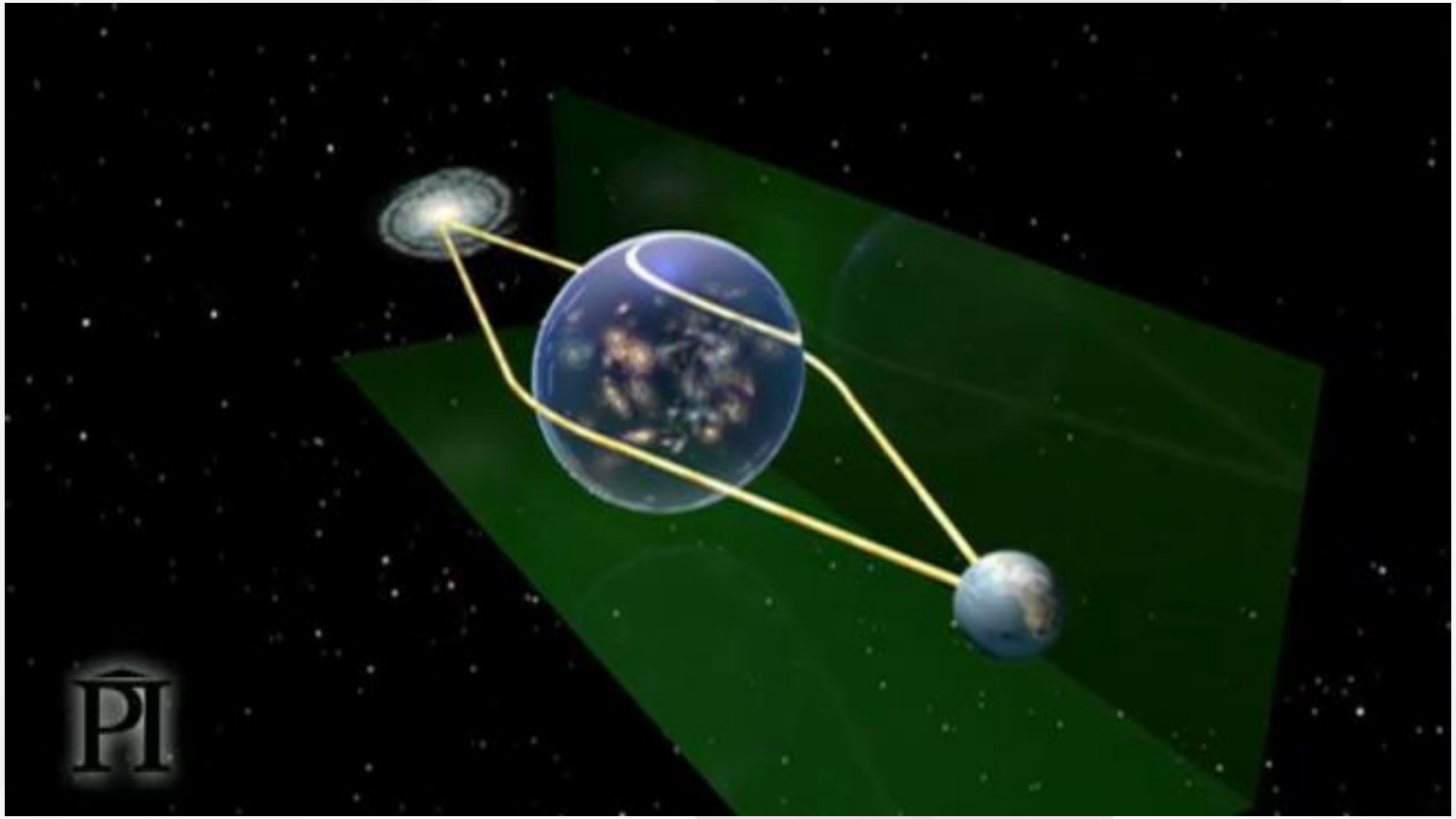
Dark Matter
26.8%

Normal Matter
4.9%

Dark Energy
68.3%



Gravitational Lensing



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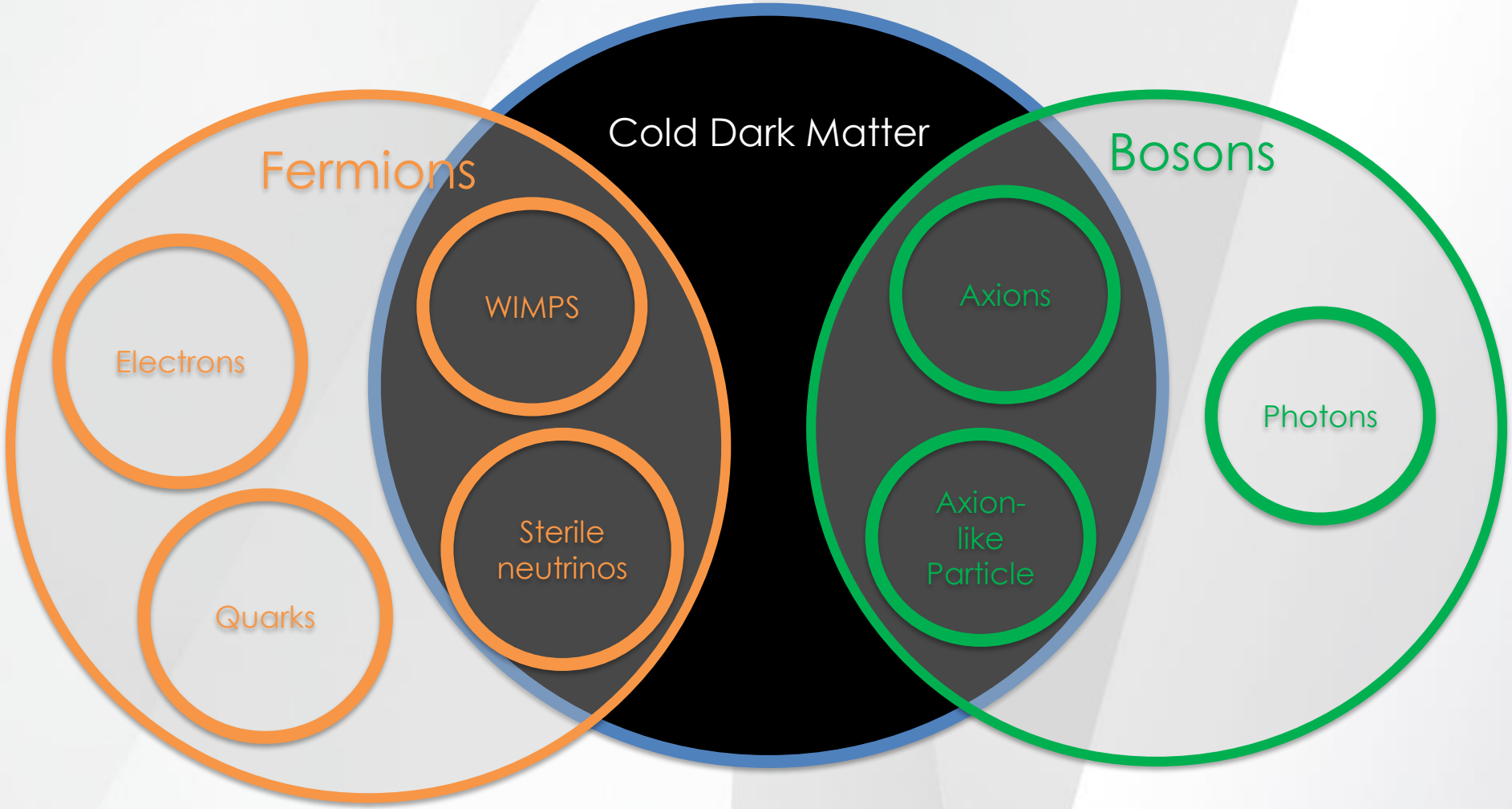
Looking for Dark Matter particles



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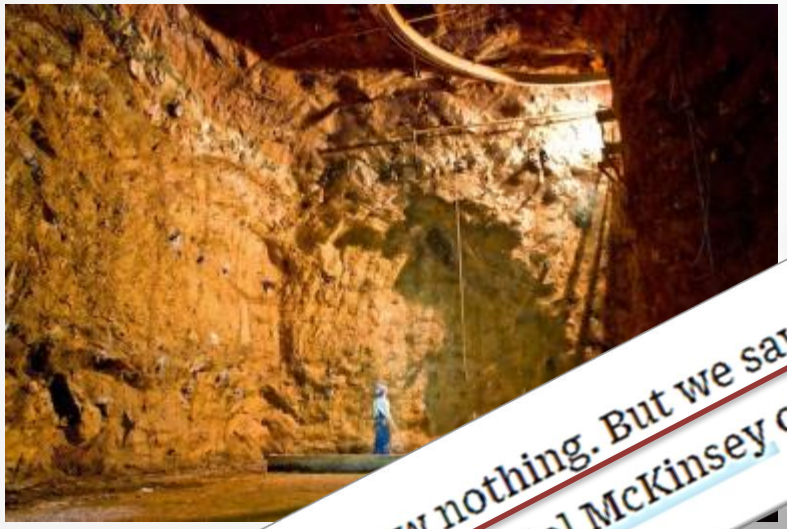
How to Look for Dark Matter Particles

- 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.

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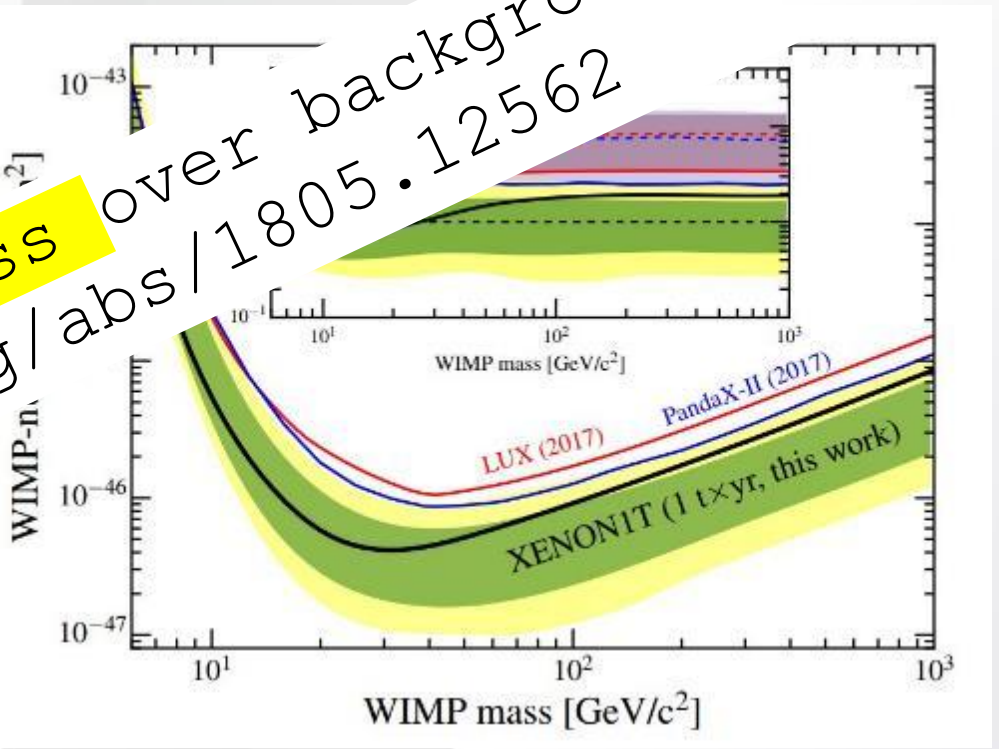
LUX update (2017)

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

XENON1T most sensitive measurement yet (2018)

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



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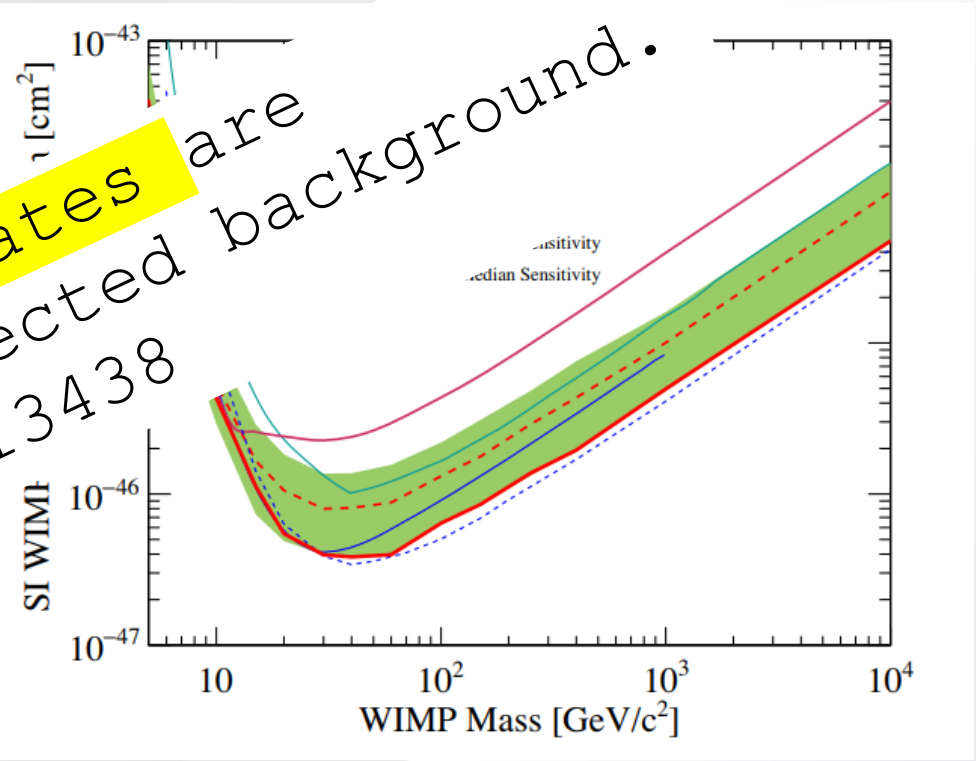
PANDAX-4T (2021)

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



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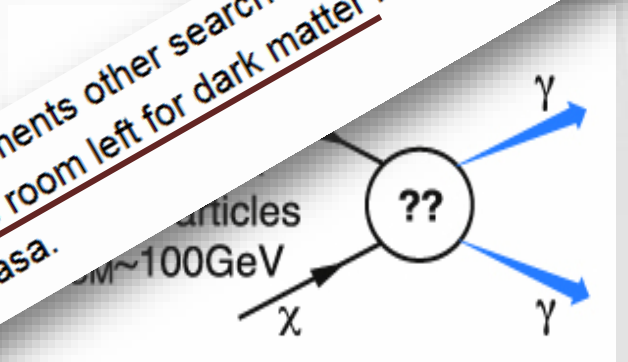
FERMI

- Detects ɣ-rays
- DM particle annih

'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.



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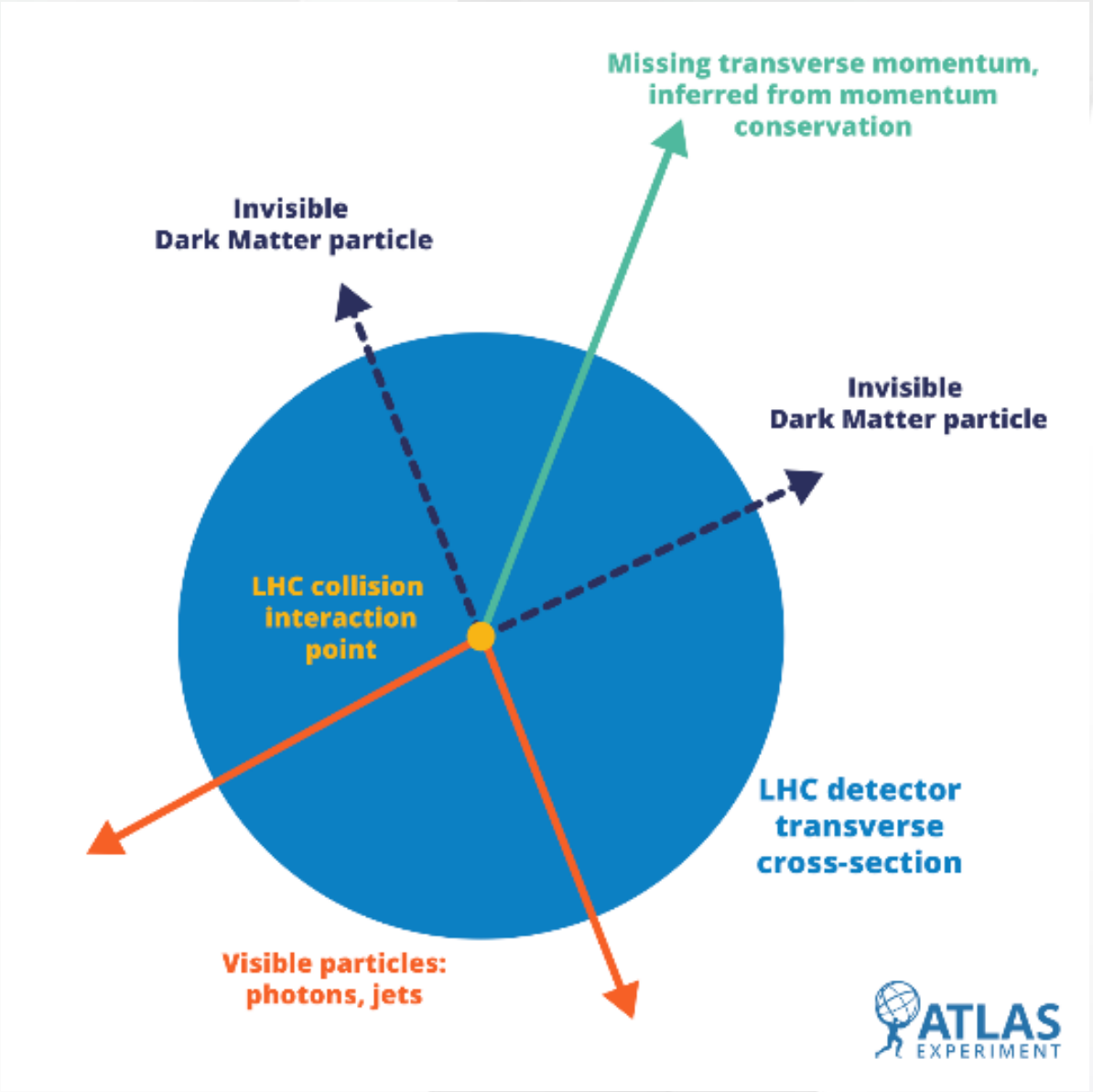
LHC



Empty-Handed?

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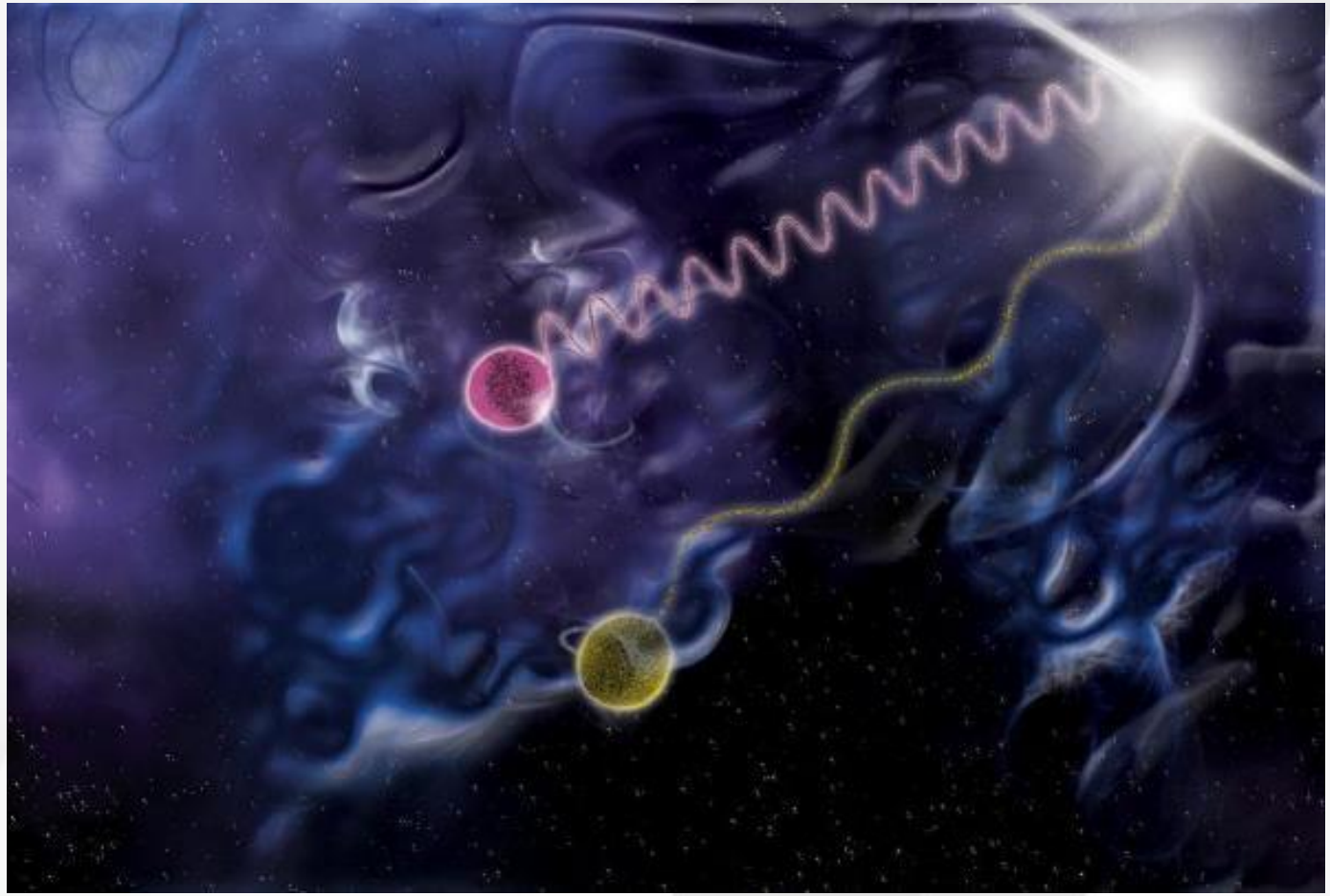
LIGO prefers a dark matter particle



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Modified Gravity Theories

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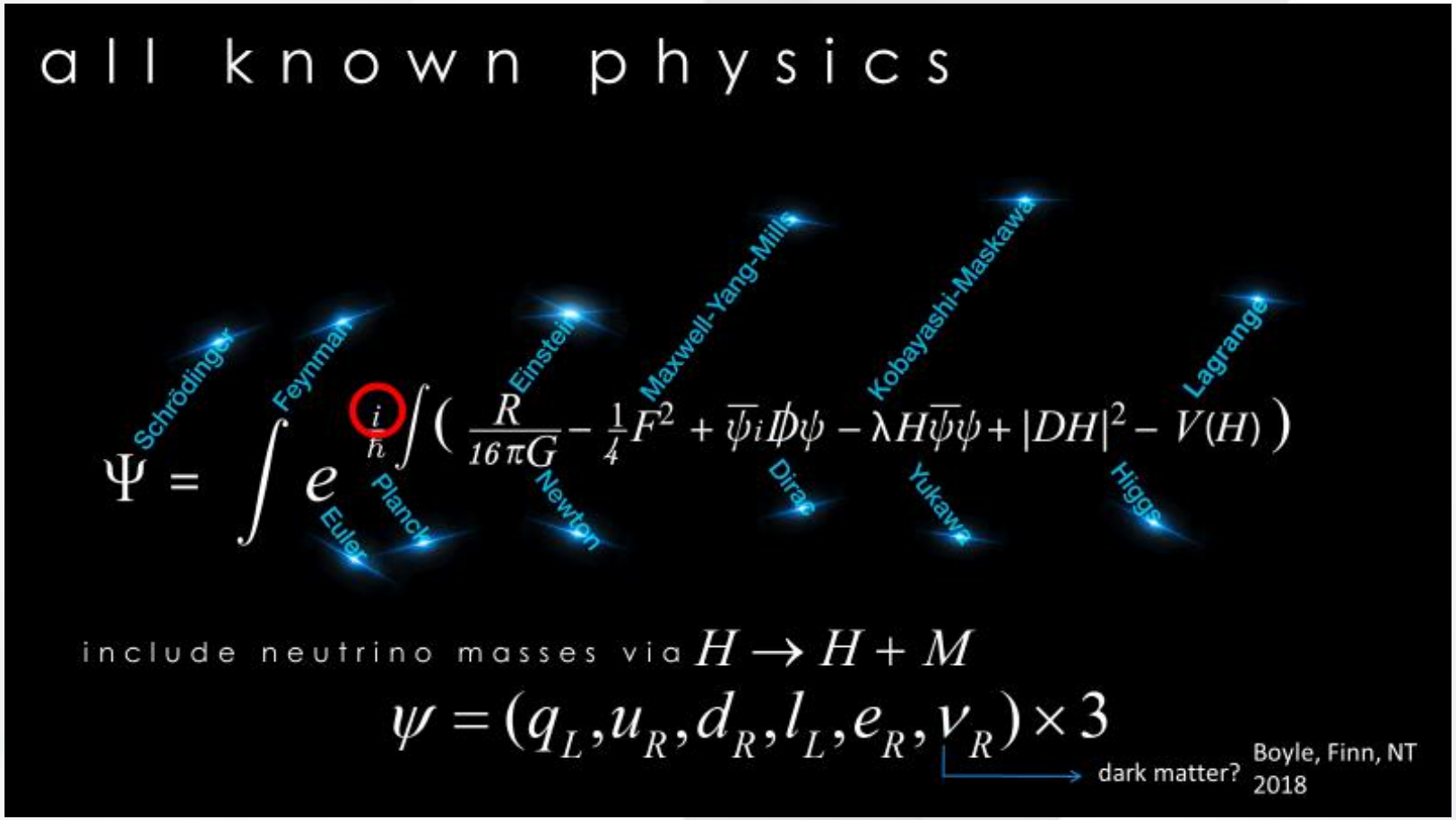
Maybe the particle has been here all along…



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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

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Competing Theories For Dark Matter

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(Gr 5-8)

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(Gr 9-10)

Senior High
(Gr 11-12)

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Thank You!

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dfish@perimeterinstitute.ca

Olga Michalopoulos
omichalopoulos@gmail.com

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