Introduction to the Standard Models of Particle Physics and Cosmology

Jason Kumar

University of Hawaii

Introduction

- What is the Standard Model of particle physics?

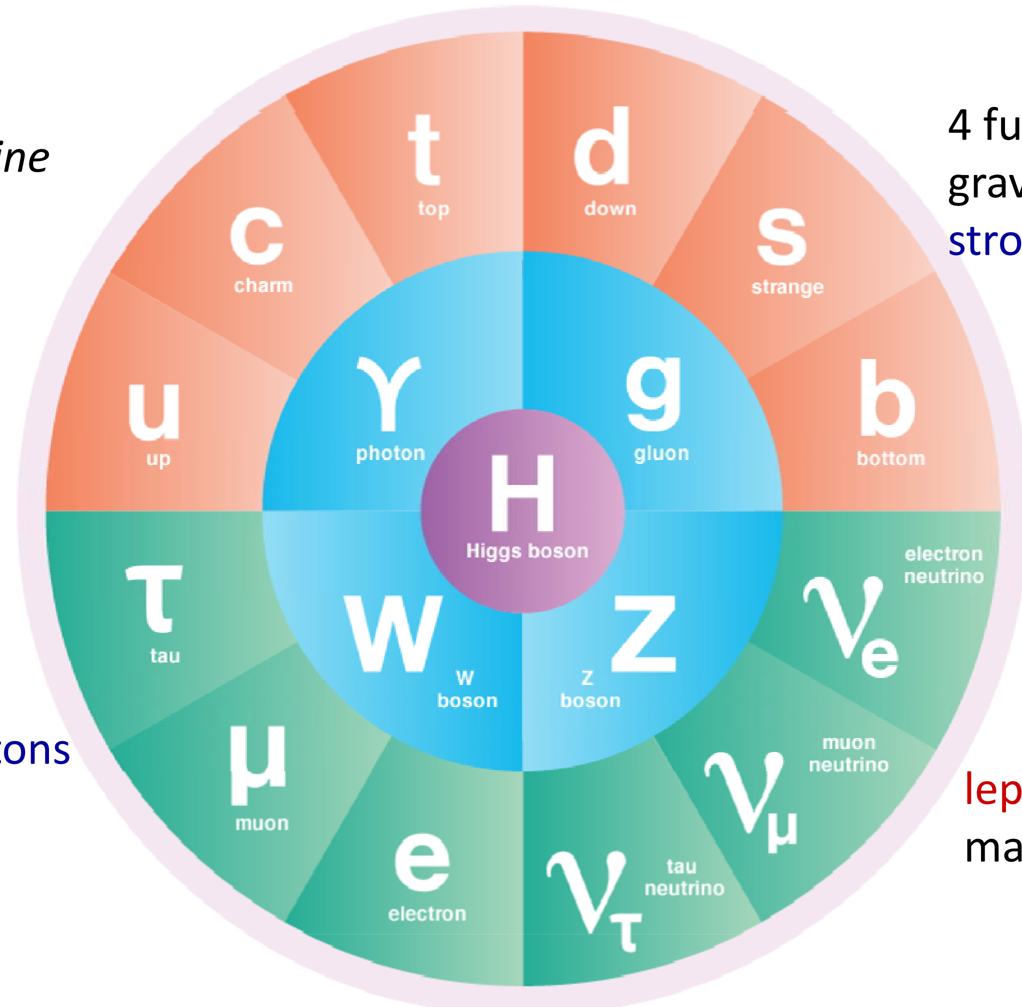
- What is the Standard Model of cosmology?

- How does dark matter fit into both of them?

- What can we learn from the LHC (CMS) and IceCube?

Standard Model of particle physics

Symmetry Magazine



4 fundamental forces
gravity, electromagnetism, strong, weak

quarks: make up protons and neutrons

leptons: electrons make up the rest of atoms

neutrinos are leptons, but hard to see, (almost) massless, produced by radioactive decay

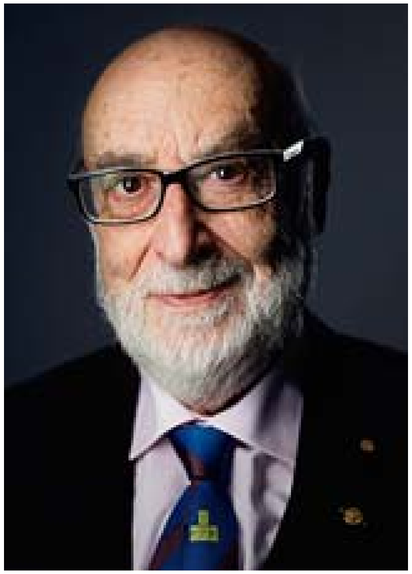
Higgs boson....?

Higgs boson

- discovered by ATLAS and CMS at LHC in 2012
- Nobel Prize in 2013
- from theory to experiment ... half a century!
  - lots of other people involved!
- theory idea: explains how the W and Z bosons become massive, unlike photon
- you'll identify the Z-boson mass using CMS data!

Peter Higgs

François Englert



(Photos by A. Mamoud, Noble website)

neutrinos

- neutrinos have mass!
  - <10,000,000th of an electron
- Nobel Prize in 2015
- don't know what it is, but we know it's not zero
- how do we know that?
  - neutrinos oscillate from one type to another
  - in quantum mechanics, only happens if masses are different (like a beat frequency)

Takaaki Kajita

Art McDonald

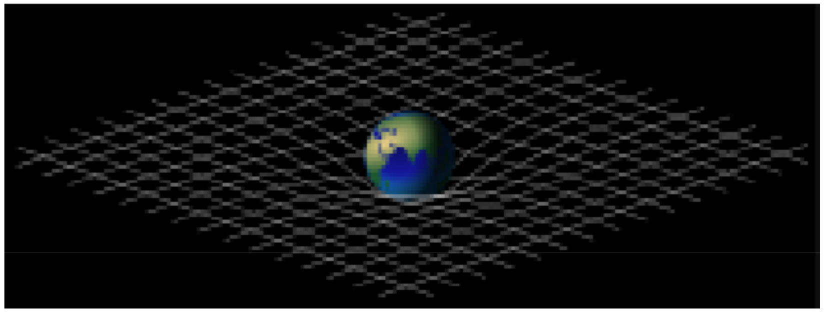
(Photos by A. Mamoud, Noble website)

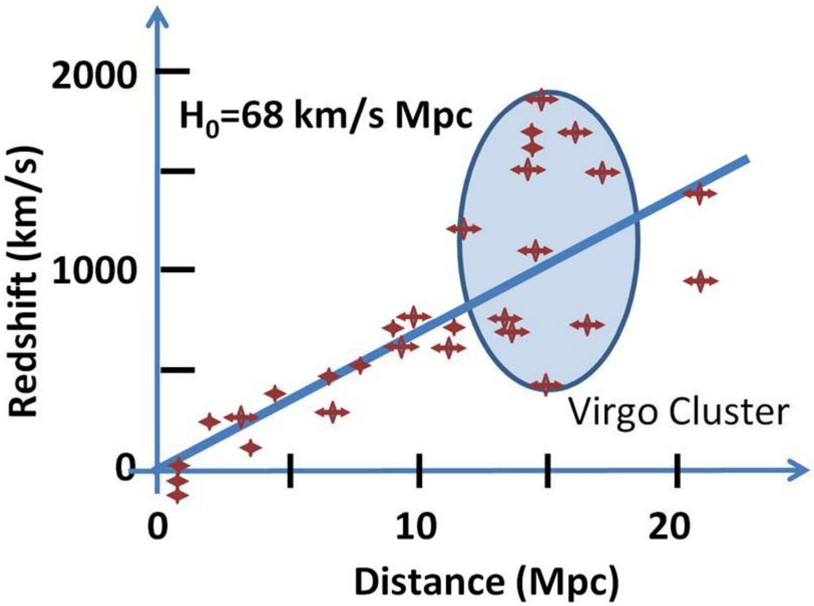
Art is now affiliate faculty at UH!

the expanding Universe....

- General Relativity
  - matter creates gravity by deforming space-time
- how can Universe be static if everything is pulled together by gravity?
  - add a cosmological constant
- Hubble → Universe is expanding from a Big Bang
- don't need CC anymore
  - Einstein called it his "biggest blunder" *...but was it?*

Wikipedia



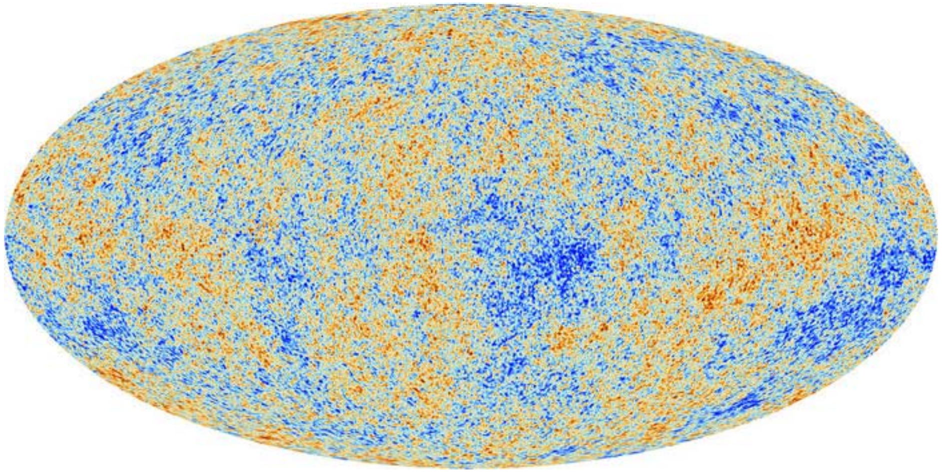


(W. Keel via Wikipedia)

accelerating expansion

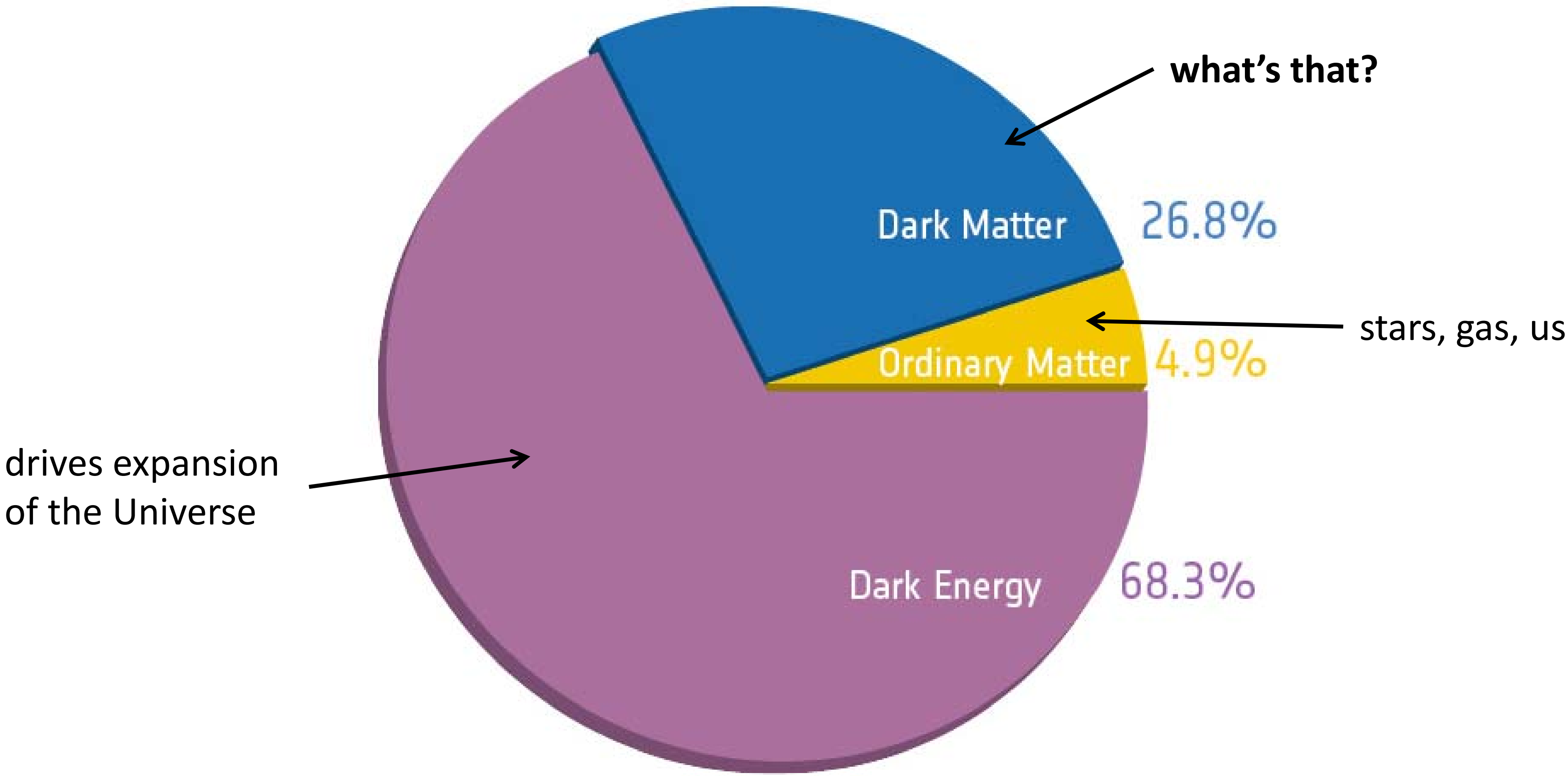
- expansion of Universe is accelerating!
- cosmological constant is back!... but not sure if it's really constant, so it's called dark energy
- think we understand cosmology from a t=10s onwards
  - it's all general relativity, therrmodynamics, and atomic/nuclear physics

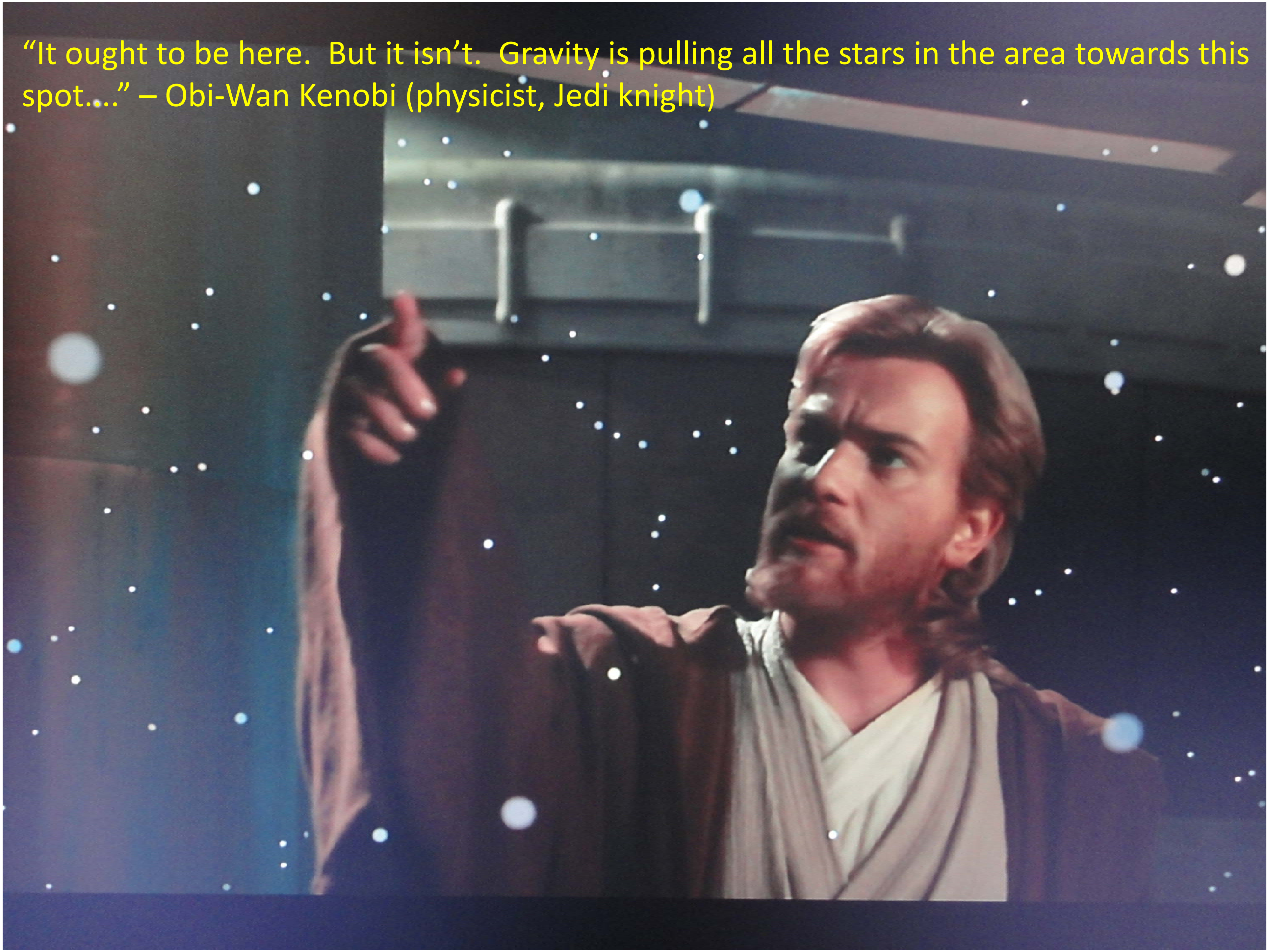
Planck



- let's us explain the Cosmic Microwave Background and light element abundances (Big Bang Nucleosynthesis)

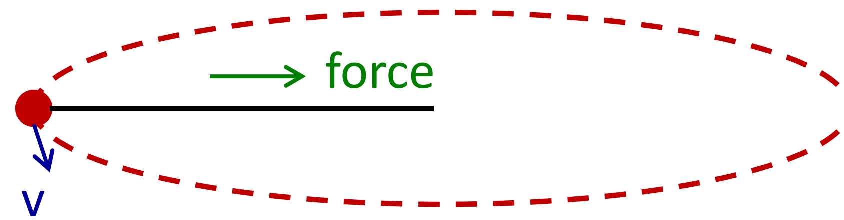
Standard Model of cosmology



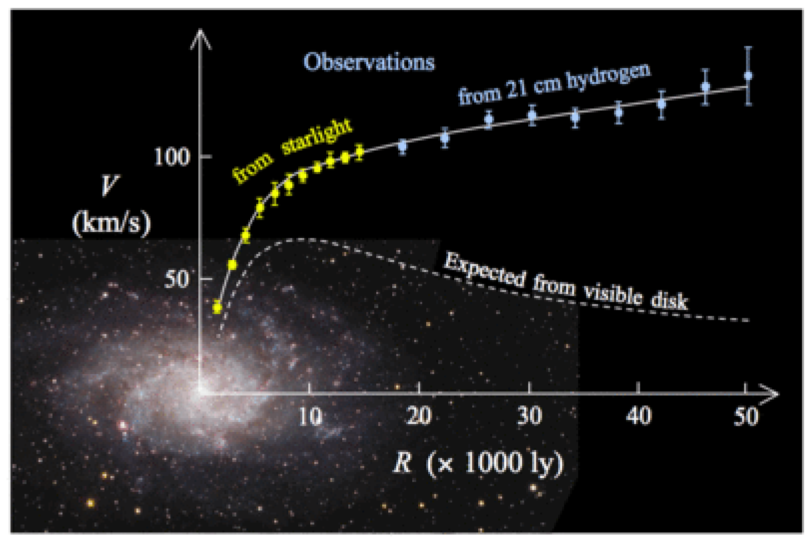

"It ought to be here. But it isn't. Gravity is pulling all the stars in the area towards this spot…." – Obi-Wan Kenobi (physicist, Jedi knight)

what’s the problem?

- like swinging a ball on a rope
  - if you know the speed of the ball, can compute how hard you pulled on rope
- celestial bodies move in orbits, where gravity is the “rope”
  - speed → force
  - force → mass
  - more mass than we can see



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

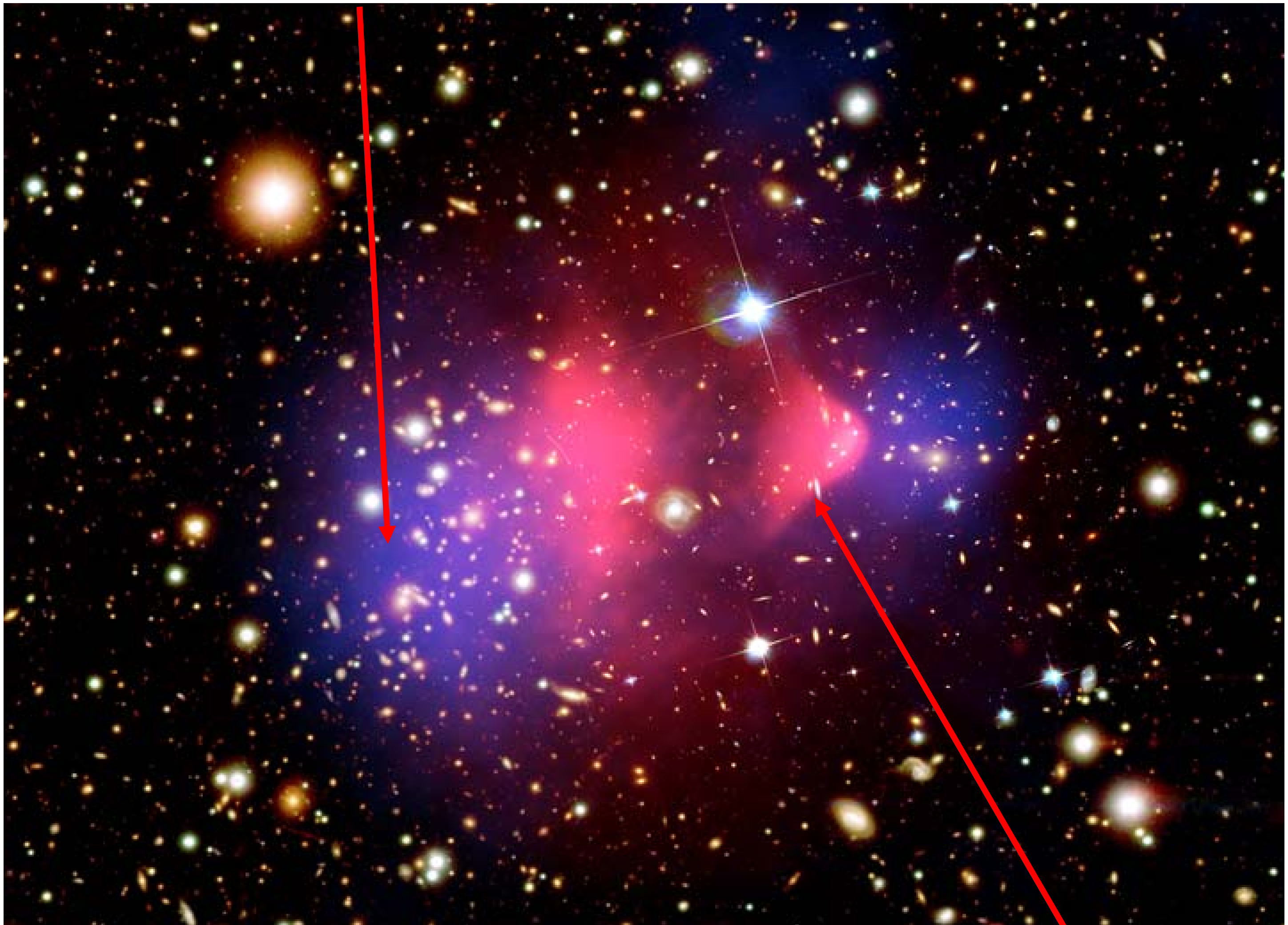


Wikipedia – M33 rotation curve

Bullet Cluster

NASA/CXC/Markevitch, et al.
STScl/Magellan/U. Ar1izona/
Clowe, et al./ESO/WFI

dark matter doesn't scatter (gravitational lensing)



visible gas scatters (x-ray)

what could it be?

- maybe there's a lot of ordinary stuff out there which we just don't see ...
  - big idea for a while, but has fallen out of favor in recent years
  - we can now compute how much ordinary matter we should have (hydrogen, helium, etc), and how much total matter
  - get a large discrepancy (factor of 5)
- maybe gravity works differently than Einstein thought ...
  - many people study this, but a distinct minority
  - evidence comes from galaxy-size to universe-size, and all in between
  - hard to explain it all with change to how gravity works
- maybe there's a new type of matter which we don't see
  - dark matter

a new particle

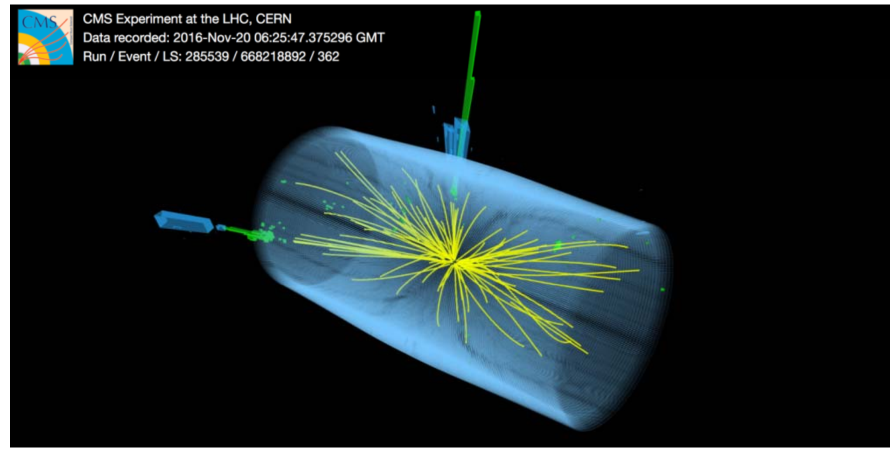
- if dark matter arises from a new stable particle, lots of things fit together
  - rotation of galaxies and galactic clusters, formation of larger structures, Cosmic Microwave Background
- what would the new particle have to be like?
- doesn't interact with light (electromagnetism) or strong force
- about 80% of all matter
- stable (or very long-lived)
- density and velocity near earth estimated from rotation curves and thermodynamics
  - v ~ 200-300 km / s
  - density ~ about 300,000 hydrogen atoms worth / m^3

WIMPs

- Weakly-Interacting Massive Particle
  - interacts through the **weak fundamental force**
  - mass of a WIMP is roughly determined by the range of the weak force ~ same mass as about 100 hydrogen atoms
- the amount of WIMPs can be computed from thermodynamics and general relativity
  - dark matter is created, dark matter annihilates (no decay), and the universe expands
- amount depends only on weak force strength and mass
- for WIMPs, get ~ 80%, which is what we need to match data
- could have been orders of magnitude off – “WIMP Miracle”

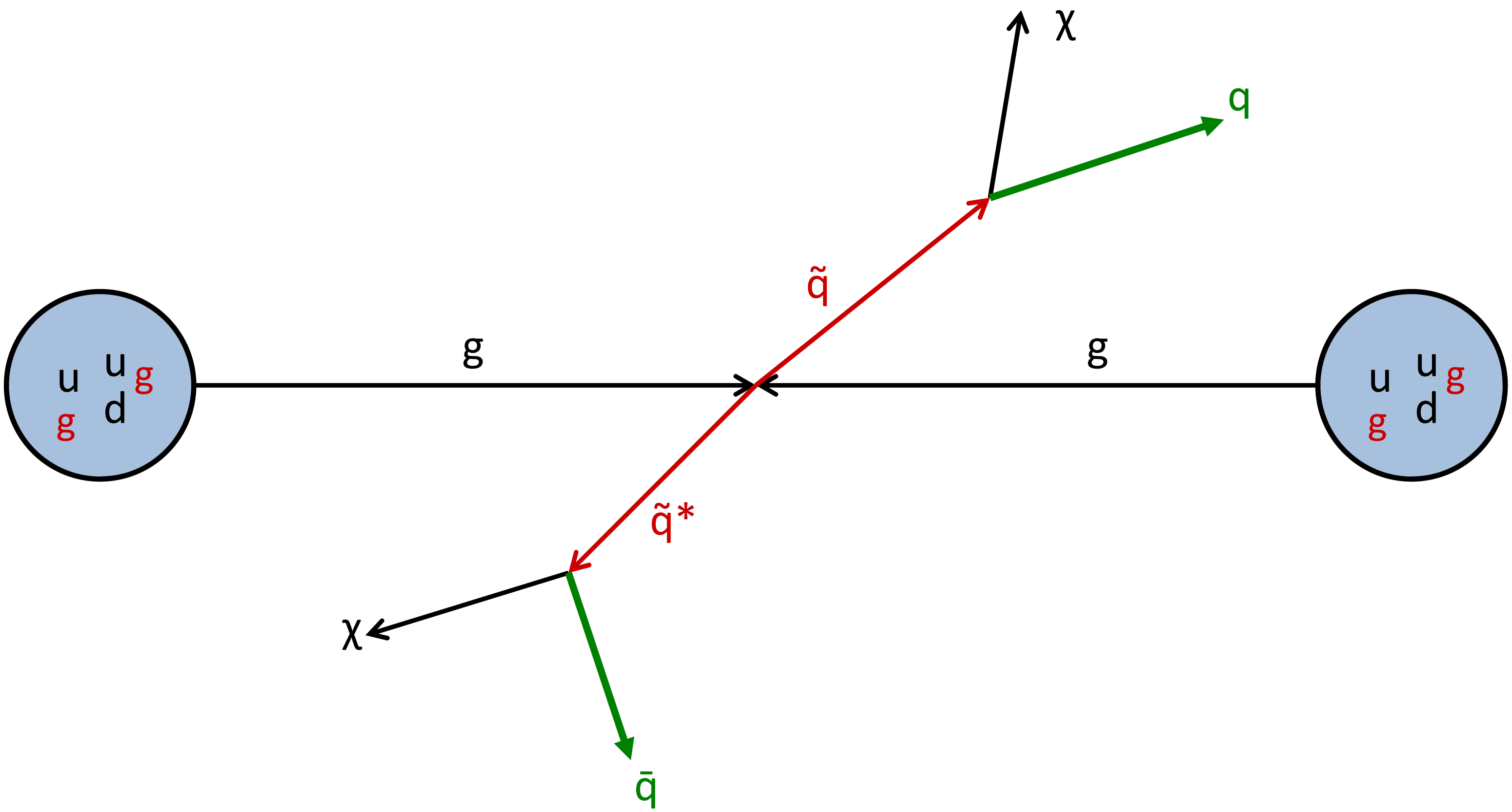
what can CMS do?

- LHC smashes protons together at very high energy
  - collisions can produce heavy particles
  - like the Higgs, or something completely new
- those short-lived particles decay into things we see at the detector...
- ... or into neutrinos, or dark matter, which will pass right through the detector



- missing momentum
  - looks like a violation of momentum conservation
  - the dog which does not bark
  - can study models like supersymmetry, in which dark matter is a part of the puzzle

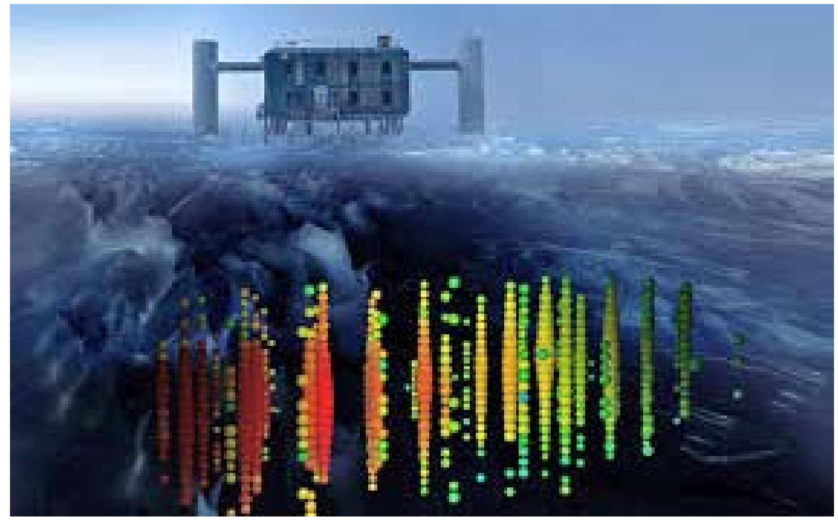
what would missing momentum look like?



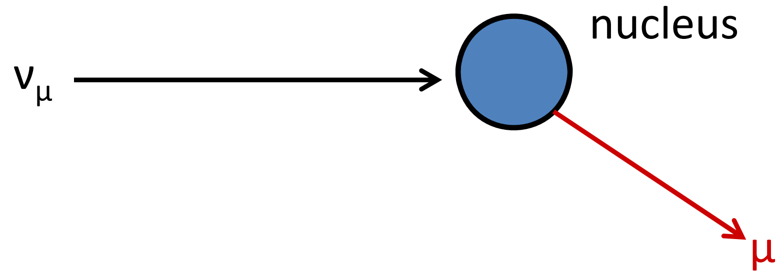
what can IceCube do?

- look for light produced when neutrinos interact with the ice at the South Pole
- neutrinos interact weakly, so need a lot of ice
- can tell us about the processes which produce neutrinos in astrophysical objects
  - dark matter?
  - cosmic rays?

SciTech Daily

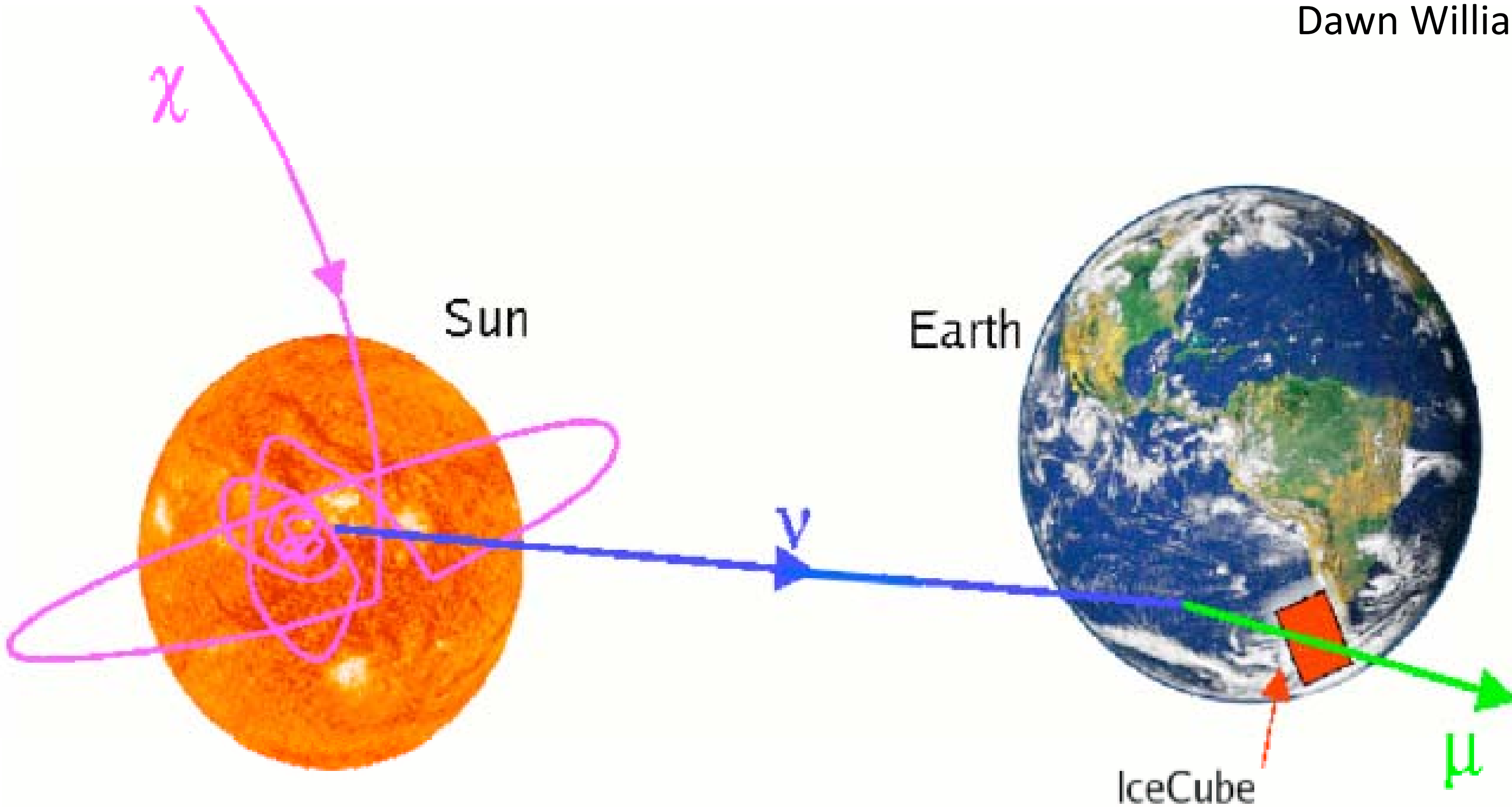


"charged current interaction"



dark matter annihilation in the Sun

Dawn Williams



Backup Slides

How do you see *dark* matter?

- the "size" of an object really tells you how close you can get to it before it "pushes" you away
- ordinary objects push with the electromagnetic force, i.e., light, or strong force
- dark matter **can't** push with electromagnetism or strong force
- WIMPs push with weak force... very short-range
- so WIMPs are "small" and can pass right through matter, only rarely bumping into things
- need a sensitive way to see those rare events when dark matter bumps into ordinary matter, or other dark matter