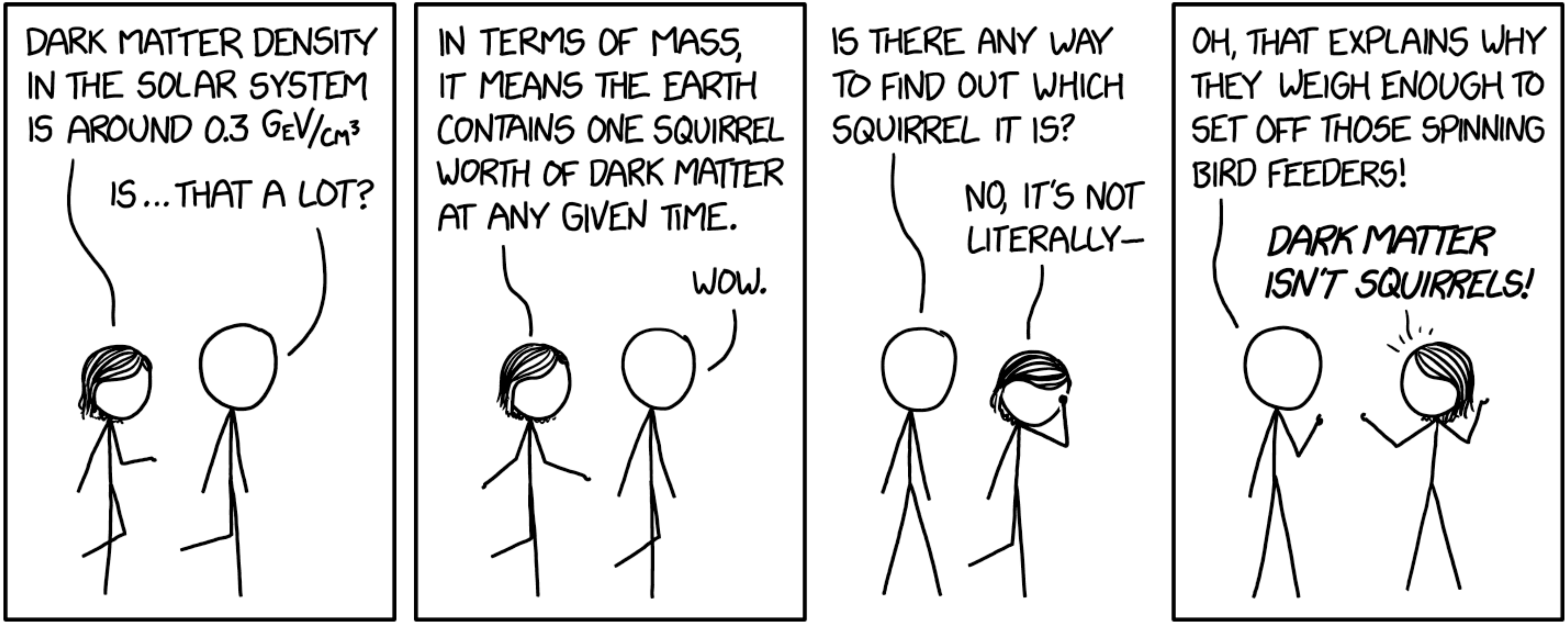
Dark Matter

https://xkcd.com/2186



QuarkNet Summer Session for Teachers: The Standard Model and Beyond

Allie Reinsvold Hall

https://quarknet.org/content/quarknet-summer-session-teachers-2020

Summer 2020

Course overview

What are the fundamental building blocks that make up our universe?

Mission: overview of the past, present, and future of particle physics

1. History of the Standard Model, Part 1: Ancient Greeks to Quantum Mechanics
2. History of the Standard Model, Part 2: Particle zoo and the Standard Model
3. Particle physics at the Large Hadron Collider (LHC)
4. Beyond the Standard Model at the LHC
5. Neutrino physics
6. **Dark matter and cosmology**

Credit to Dan Hooper for some of the material in these slides.

Loose ends

- More about the magnetic horns used to focus the pions to make a neutrino beam
  - Type of magnet: normal conducting electromagnet (not superconducting)
  - Strength: 1 Tesla, Length: 3 meters
  - Magnetic field can be tuned to only select pions (and therefore neutrinos) with specific energy ranges of interest
  - Not a huge difference in flux/intensity of neutrino vs. antineutrino beam in DUNE

- In the $\sin^2$ term, do the units actually cancel out?

$$\sin^2 \frac{\boldsymbol{\Delta m^2_{32}} L}{4E}$$

  - Yes – in natural units, L has units of 1/eV, m and E have units of eV, so we get eV^2 in numerator and denominator

- PMNS matrix
  - Introduced in 1962 by Ziro Maki, Masami Nakagawa and Shoichi Sakata, to explain the neutrino oscillations predicted by Bruno Pontecorvo in 1957
  - Theory fully developed in 1960s and 1970s

Loose ends

- So if neutrino oscillation patterns are mostly understood due to other experiments, why DUNE?
  - There are still unanswered questions about neutrinos, such as how much do neutrinos and antineutrinos differ (ie, what is δ_{CP}?)
  - DUNE is also looking for proton decay and hopes to see neutrinos from a supernova

- What happens to the Standard Model now, since we know neutrinos have mass?
  - Neutrinos masses are beyond-the-Standard-Model physics
  - But that doesn't mean we throw the SM away; instead, we add to it like we've done in the past
  - Same story if we observe new particles at the LHC

- How long will the links for this class be up?
  - Class website will remain up (although eventually the links will be out-of-date)
  - Hopefully it continues to be useful!
  - Also check out resources recommended by other teachers in the google doc

Dark Matter

One: There is no problem in science that can be solved by a man that cannot be solved by a woman.

Two: Worldwide, half of all brains are in women.

Three: We all need permission to do science, but, for reasons that are deeply ingrained in history, this permission is more often given to men than to women.

- Vera Rubin

Overview

Dark matter is our name for all the stuff that interacts gravitationally but not via the strong or electromagnetic forces

- Evidence for dark matter: there's a lot of it
  - Homework discussion
- Possible solutions to explain all this evidence
- Different ways to detect dark matter particles

- What's next for particle physics?
- Why is fundamental science worth doing?

- Course evaluation

Rotation speeds

- 1933: Fritz Zwicky coined the term “dark matter”
  - Discrepancy between mass of **galactic cluster** measured via rotational speeds and mass measured via luminosity
- 1967: Vera Rubin and Kent Ford studied rotational velocities of stars within the **Andromeda galaxy**
  - Speed of planets measured by looking at the Doppler shift of hydrogen
- Solution proposed by Rubin: dark matter halo surrounding each galaxy

Rubin operates the 2.1-meter telescope at Kitt Peak National Observatory. Kent Ford's spectrograph is attached so they can measure the speed of matter at different distances from galaxies' centers.

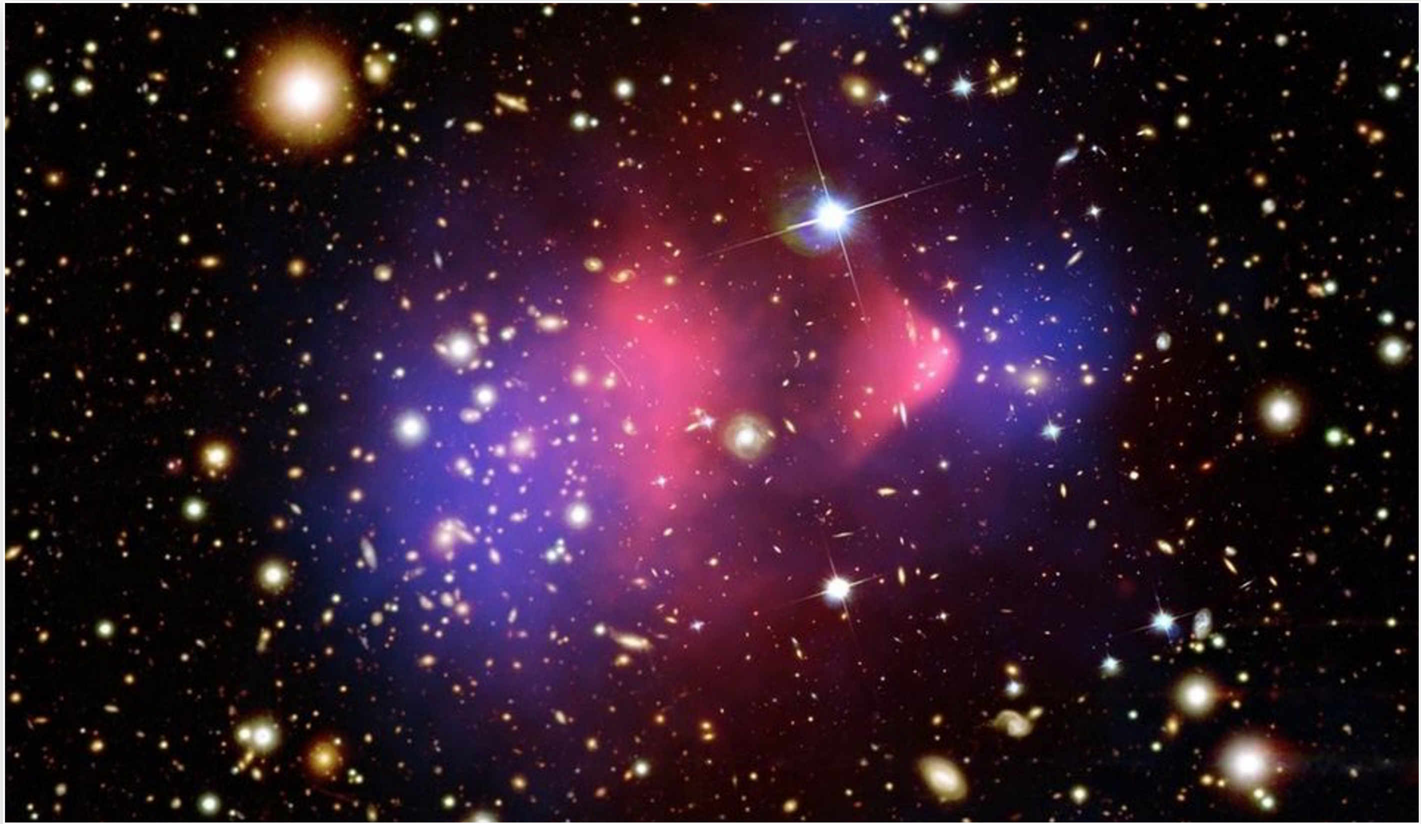
NOAO/AURA/NSF

Bullet cluster

- Looking at the debris after the collision of two galaxies

- Pink: Matter distribution measured using **visible light**
- Blue: Matter distribution measured using **gravitational lensing**

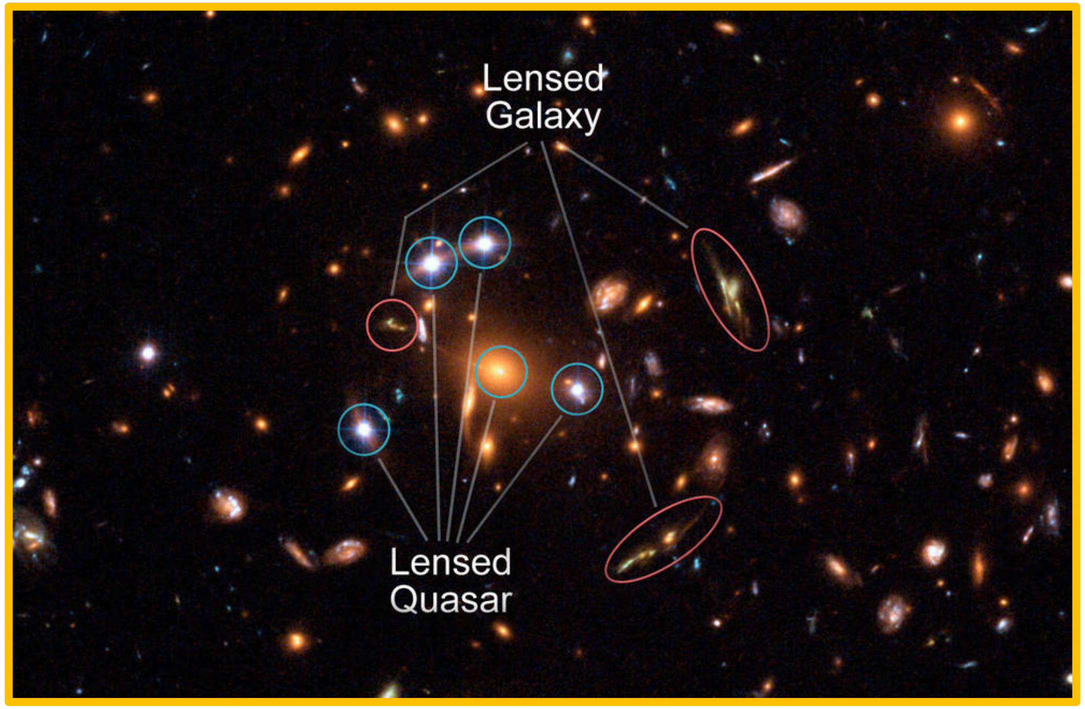
- Normal matter within the two galaxies gets slowed down in the collision
- Dark matter does not interact strongly with itself; passes through unaffected



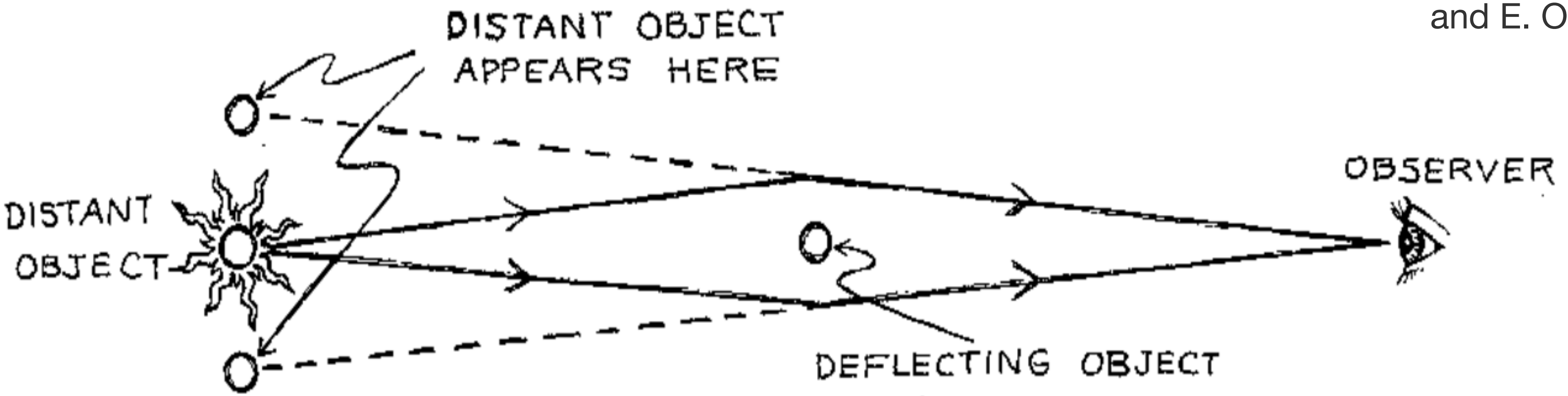
X-RAY: NASA/CXC/CFA/M.MARKEVITCH ET AL.; LENSING MAP: NASA/STSCI; ESO WFI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.; OPTICAL: NASA/STSCI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.

Gravitational lensing

- Massive objects distort space and act as a lens for stuff behind it
- Can be used to measure mass in the galaxy that acts as the lens
- Confirms that galaxies have about 5x as much total mass as measured from visible light



Credits: ESA, NASA, K. Sharon (Tel Aviv University) and E. Ofek (Caltech)



Structure of the universe

- Dark Energy Survey took data from 2013-2019 at an observatory in Chile
  - Dwarf galaxies form in regions of higher dark matter density
  - By counting dwarf galaxies, DES constrains how “warm” dark matter can be and how much it can interact with the standard model

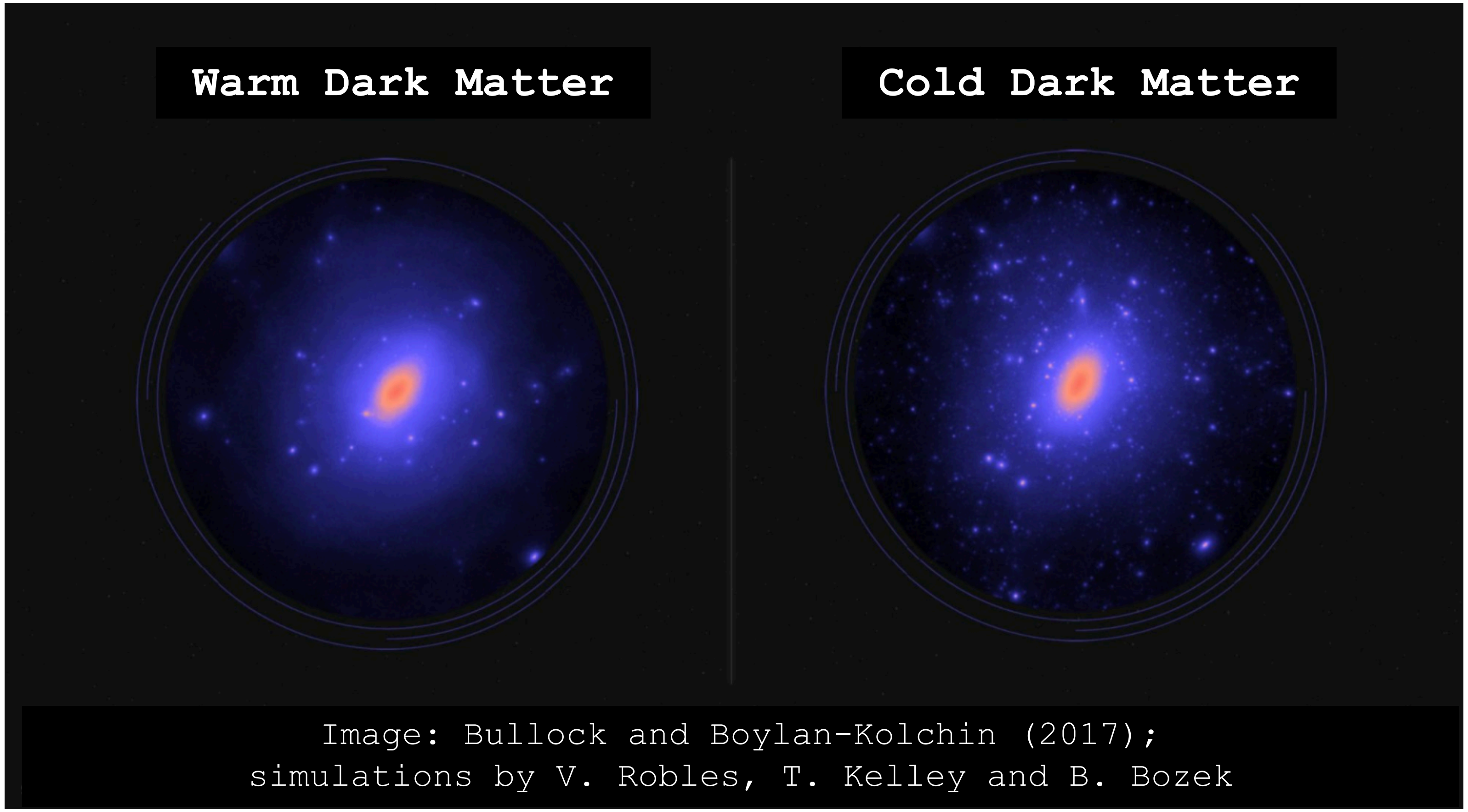
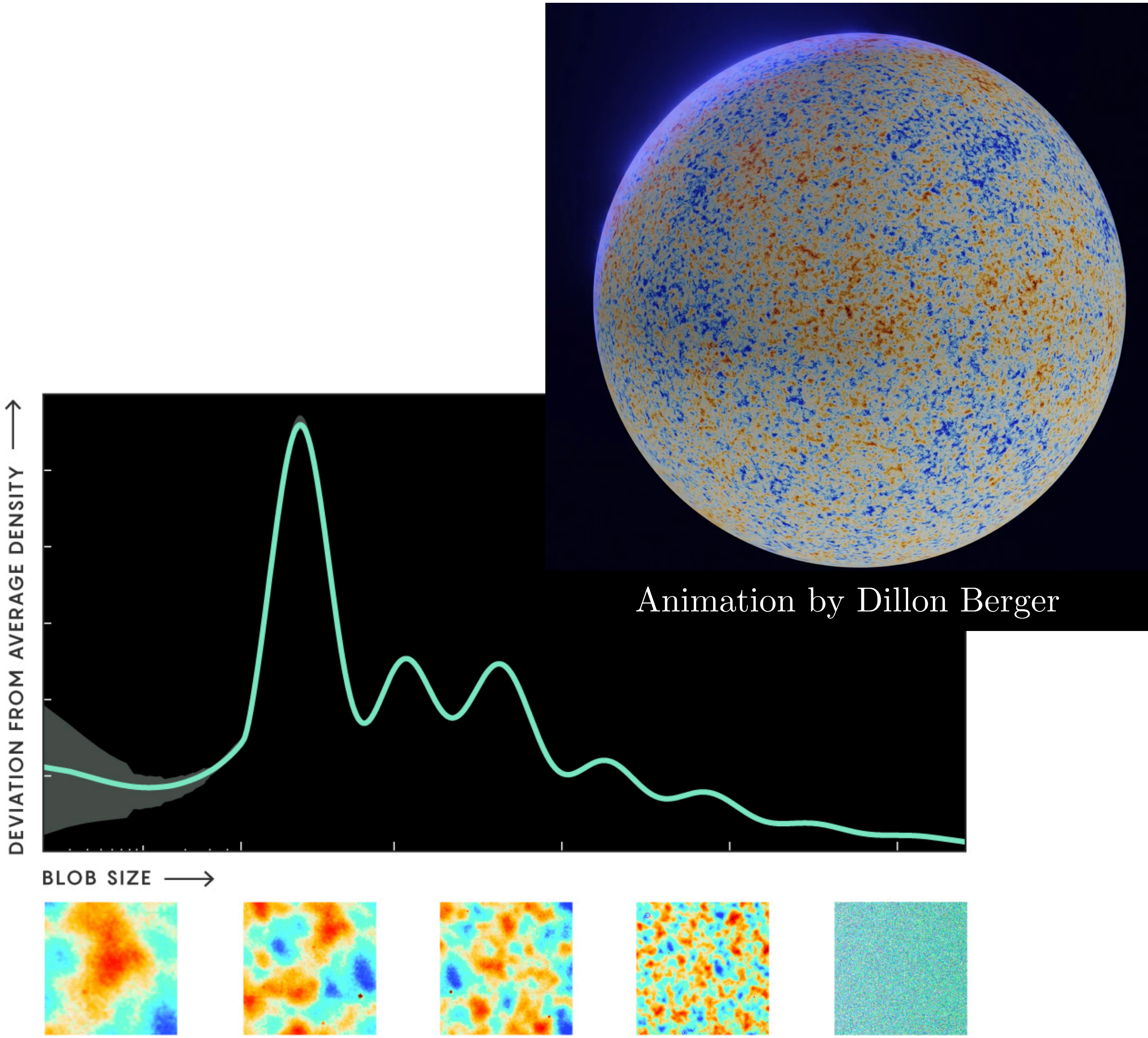


Image: Bullock and Boylan-Kolchin (2017); simulations by V. Robles, T. Kelley and B. Bozek

Cosmic Microwave Background (CMB)

- Early universe: light tried to push everything apart and gravity tried to hold everything together
    - Dark matter was affected by the inward pull of gravity but not the outward push of light
- CMB is the imprint of the light in the universe at 380,000 years post Big-Bang
    - Universe was finally cool enough for hydrogen atoms to form
    - Measured using WMAP, Planck space telescopes
- By studying CMB power spectrum, can precisely measure amount of dark matter versus normal matter
    - Dark matter = 5x normal matter

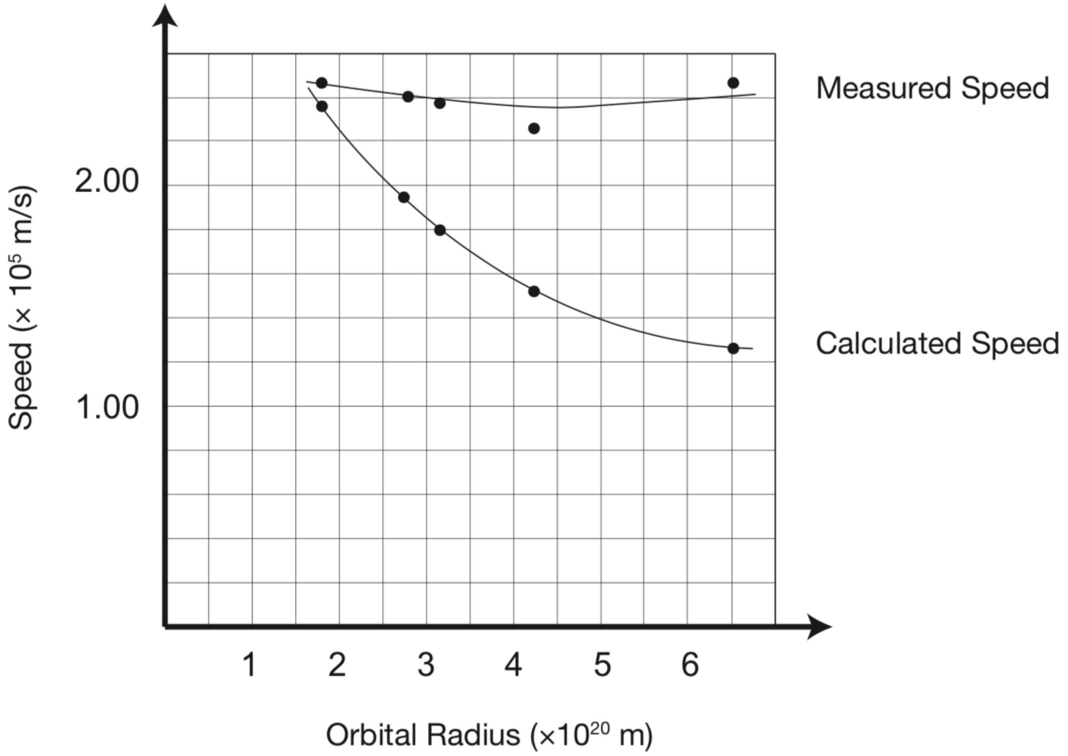


Animation by Dillon Berger

Lucy Reading-Ikkanda/Quanta Magazine; source: DOI: 1303.5076v3

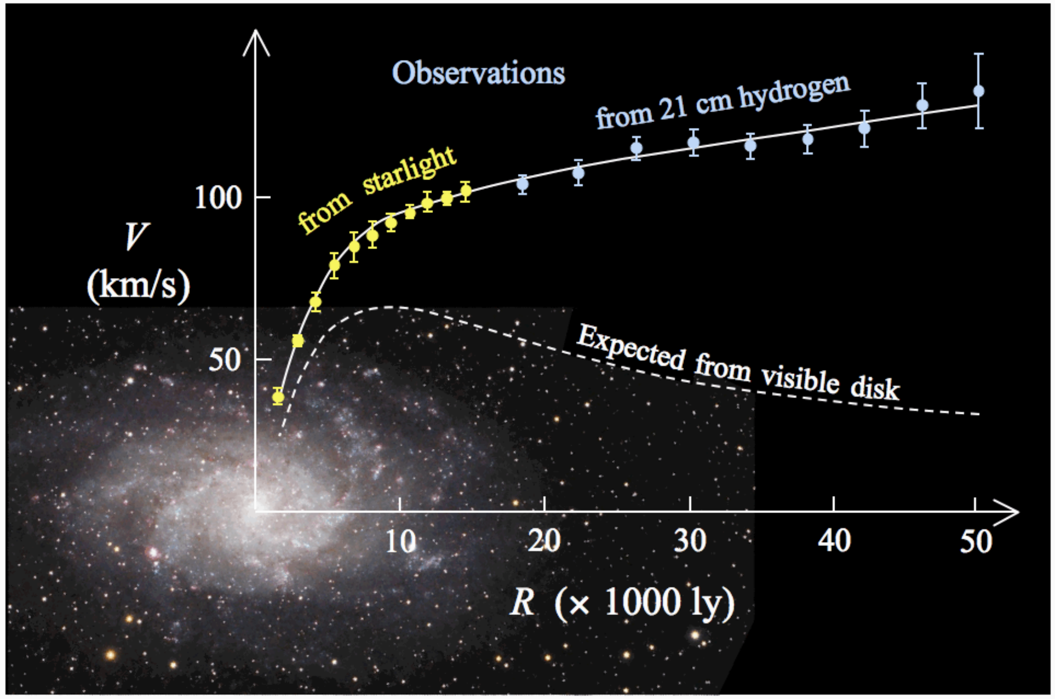
Homework discussion

- Compare your answers to the answer key (link sent in chat window) and discuss any questions
- Share your answers for question 5 in Activity 2: “How can you say that dark matter exists when no one can see it?"
- How did Vera Rubin’s measurements indicate that there was more mass than expected?
- What was challenging about this assignment?
- If anyone explored the full lesson from the Perimeter Institute, was there anything else in the less that you found useful/interesting?



Possible solutions: MOND

- Modified Newtonian Dynamics
- Maybe there is no such thing as dark matter, but instead $F = ma$ does not apply at such large scales
    - $F = ma$ in most cases, but $F = ma^2/a_0$ for small accelerations
    - Then $F = \frac{GMm}{r^2} = \frac{ma^2}{a_0} = \frac{mv^2}{a_0 r^2}$
    - So $v = (GMa_0)^{1/4}$ and is independent of r



ROTATION CURVE OF SPIRAL GALAXY MESSIER 33, IMAGE BY M. DE LEO

But probably not…

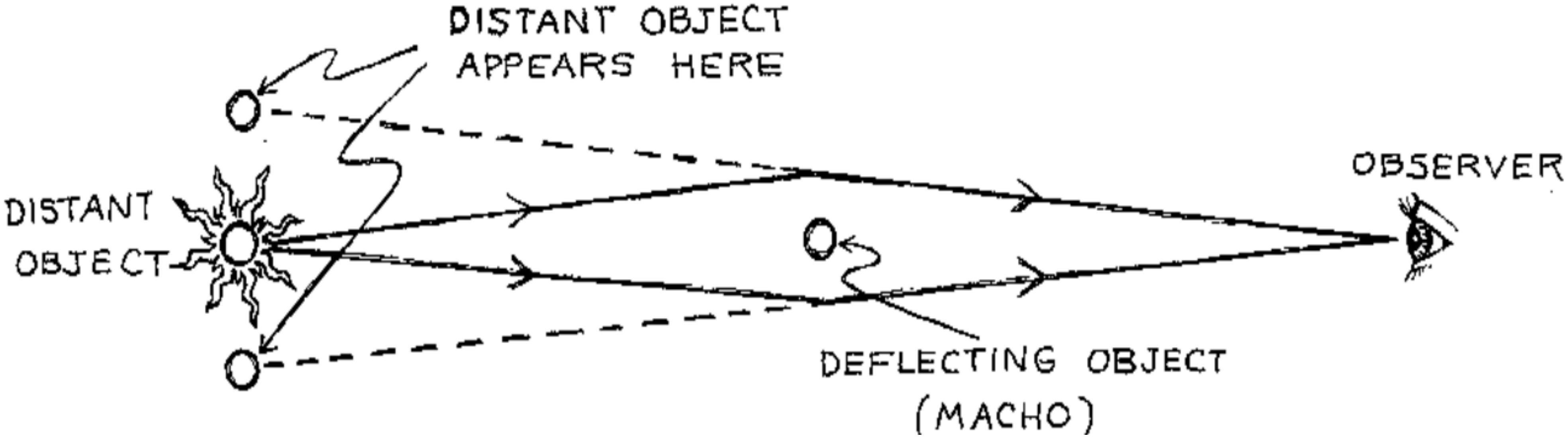
- Cannot explain the CMB or the structure of the universe or the bullet cluster
- Still an active area of research; maybe someone will be able to develop a theory that explains all the observations

Possible solution: MACHOs

- Massive Compact Halo Objects
- Maybe dark matter is made of **faint stars or black holes** that are hard to detect

But probably not..

- Can look for MACHOs using gravitational lensing, but we just don't see enough
- Conflicts with the successful predictions of Big Bang nucleosynthesis, the cosmic microwave background, and large-scale structure of the universe



Only remaining solution: new particles!

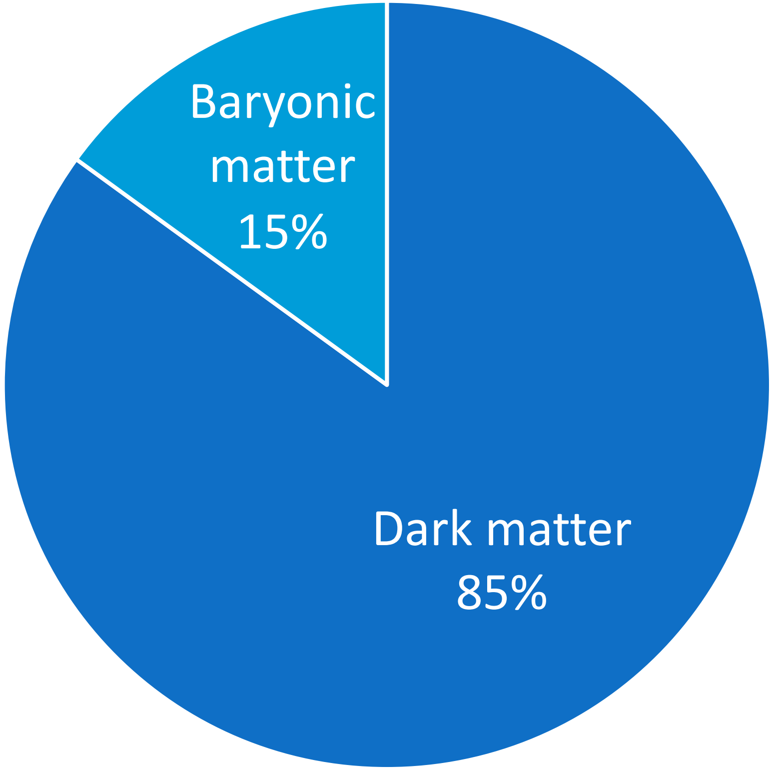
What we know:

1) Not made of baryons (protons, neutrons)
2) Comes in "small" pieces (relative to stars, planets, and black holes)
3) Does not significantly emit, reflect, or absorb light (electrically neutral)
4) Stable (or at least cosmologically long-lived)
5) Massive

Top candidate: **WIMPs** (weakly interacting massive particles)

- Mass ≈ 100 GeV, interaction strength $\leq$ strength of the SM weak force

Matter in the Universe

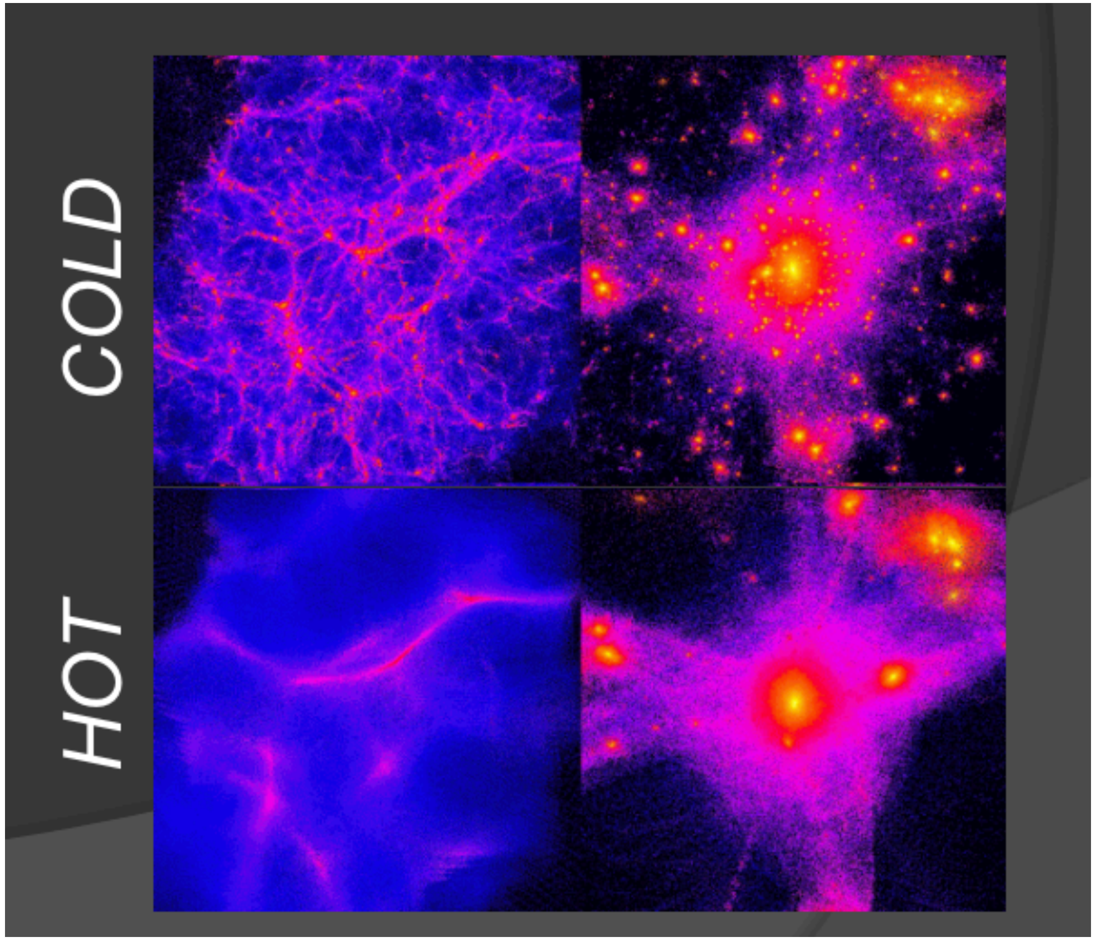


What about neutrinos?

- Neutrinos only interact via the weak force – maybe dark matter is made up of neutrinos?

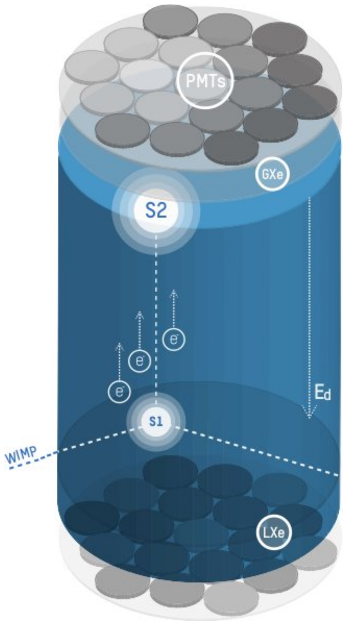
Probably not…

- Neutrinos were relativistic when gravity began to bind dark matter into large-scale structure
  - Example of "hot" dark matter
- The hotter the dark matter is, the less small-scale structure forms, and the "puffier" the halos are
- Observations clearly indicate that dark matter is **not** hot – dark matter is not neutrinos

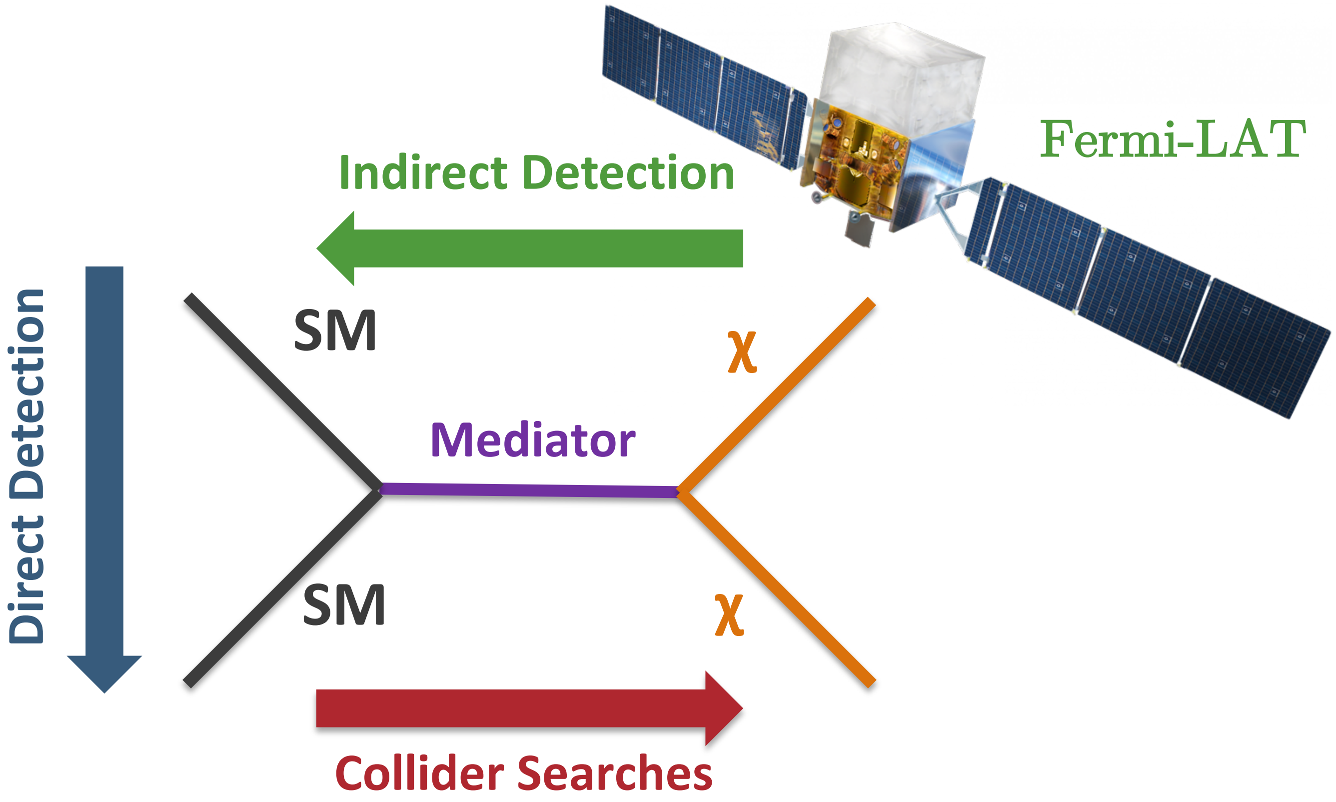


Detecting dark matter overview

- If dark matter (χ) shares interactions with standard model (**SM**) particles, we can try to detect dark matter
  - Requires a dark matter mediator that has interactions with both SM and dark matter
- Collider searches, indirect detection, and direct detection complement each other



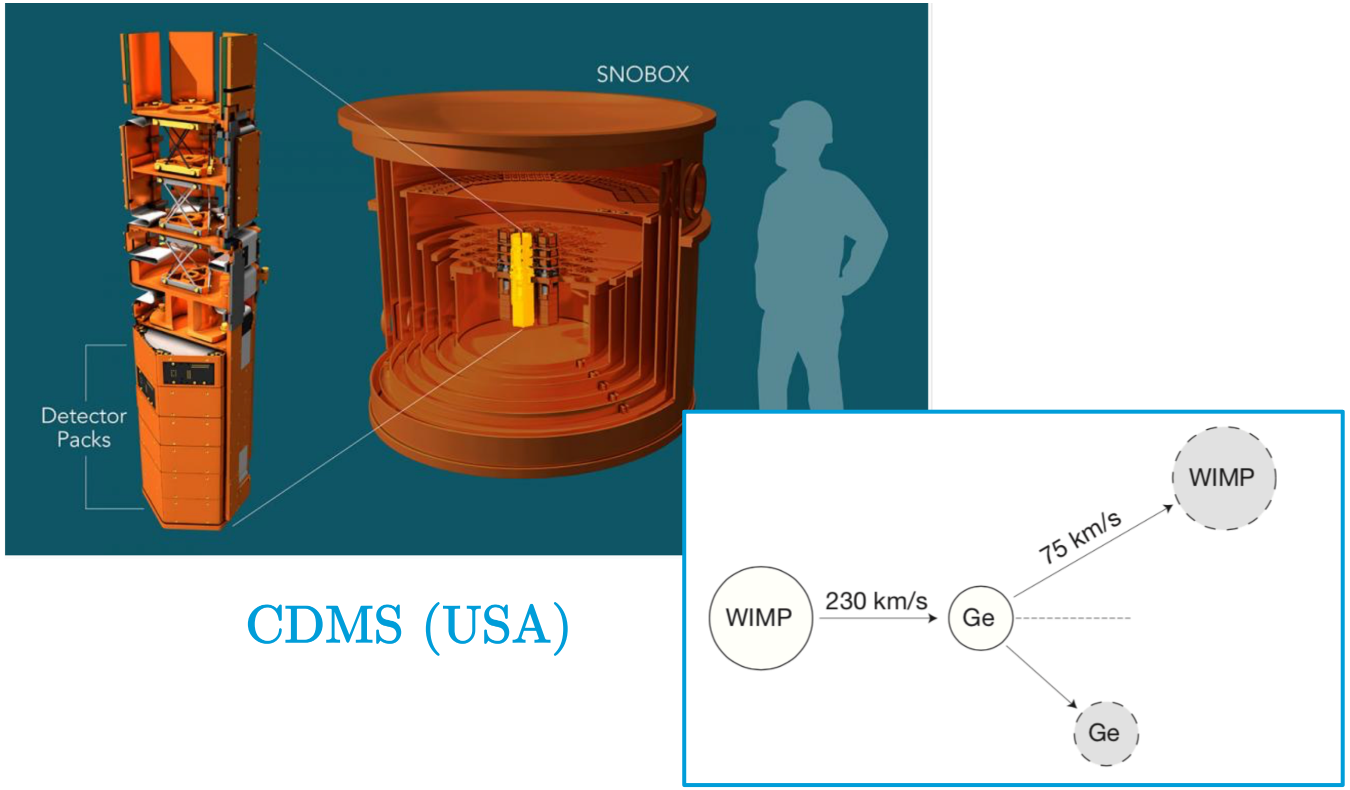
Xenon1T



Fermi-LAT

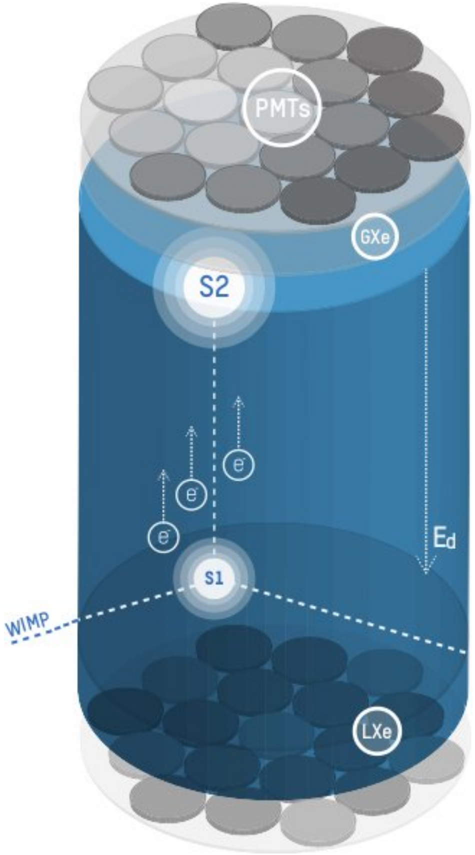
Direct detection experiments

- Direct detection experiments try to observe interactions between WIMPs and nuclei
- Like neutrino detectors: need ultra-pure, underground detectors
- **Cryogenic detectors:** observe heat from nuclear recoil in solid detector
- **Noble liquid detectors:** observe scintillation light in liquid Xe or Ar



CDMS (USA)

The XENON1T detector. Visible is the bottom array of photomultiplier tubes, and the copper structure that creates the electric drift field.

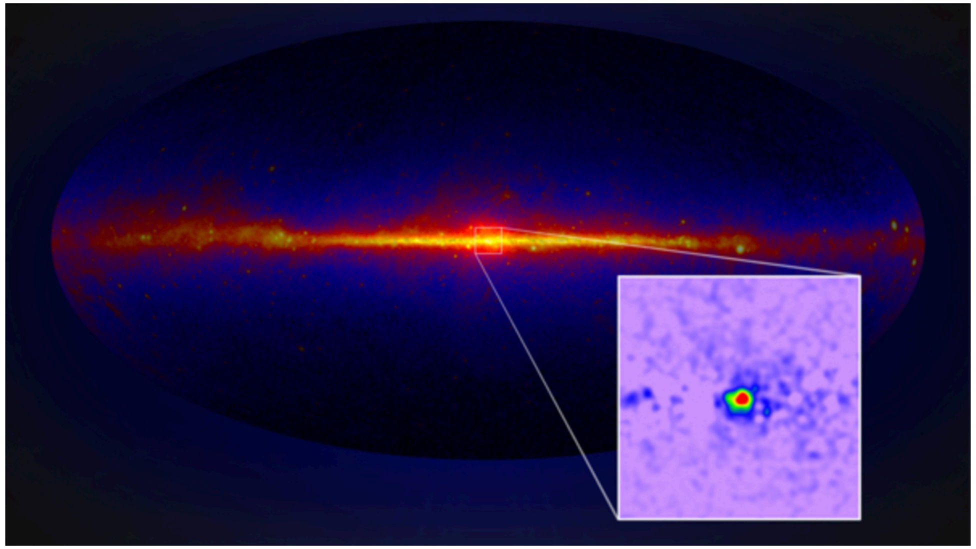


Xenon1T (Italy)

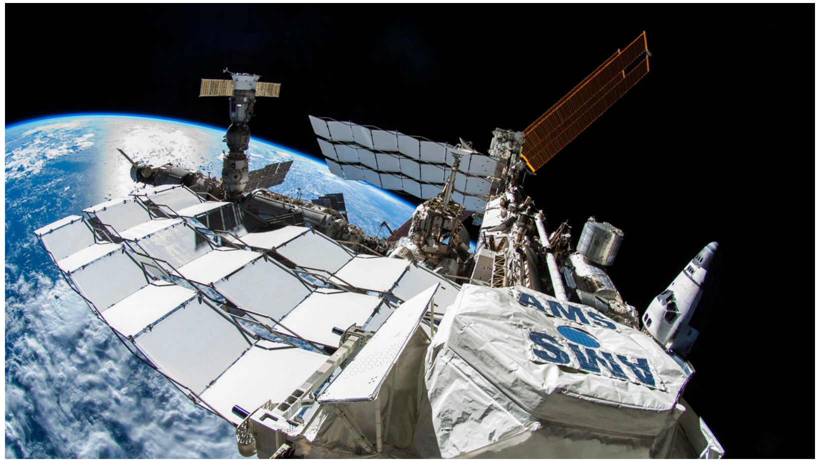
Indirect detection experiments

- Space-based observatories to detect photons or positrons produced when dark matter annihilates into SM particles
  - Look where dark matter is expected to be extra dense, like the center of the galaxy
- Excess of gamma ray photons observed in galactic center by Fermi-LAT
- Excess of positrons observed by AMS
- Maybe dark matter? But getting the background predictions right is really hard

Fermi-LAT
Launched 2008



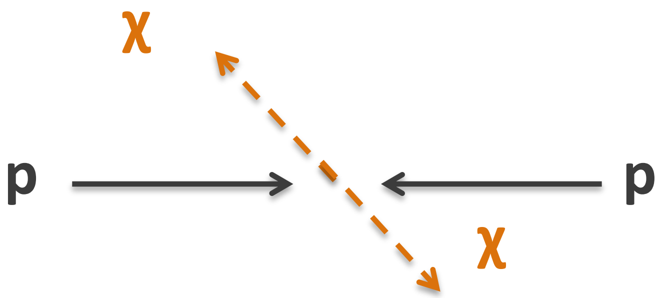
The total Fermi-LAT gamma-ray excess map with an inset showing the apparent GeV excess surrounding the Galactic Center. (Credit: NASA/T. Linden, U.Chicago) + Learn More



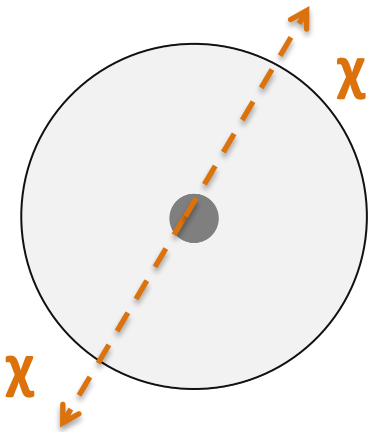
Alpha Magnetic Spectrometer
Launched 2011, mounted to ISS

Dark matter at the LHC

- Dark matter particles χ escape the detector without depositing energy (like neutrinos do)



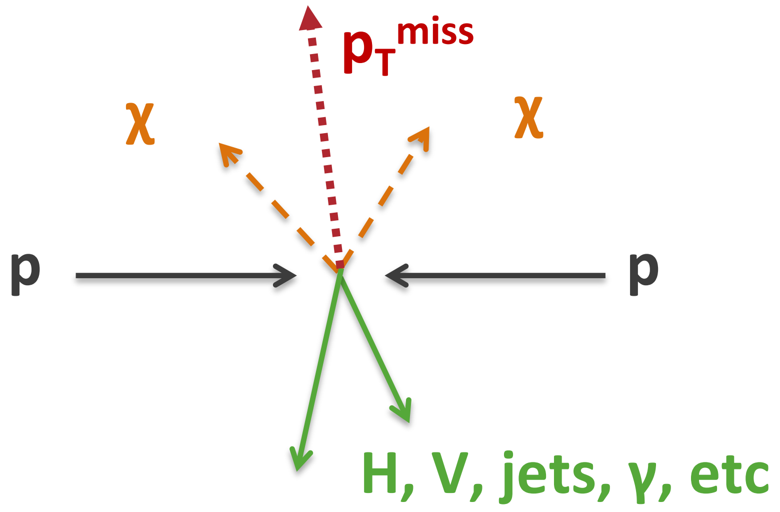
Side view



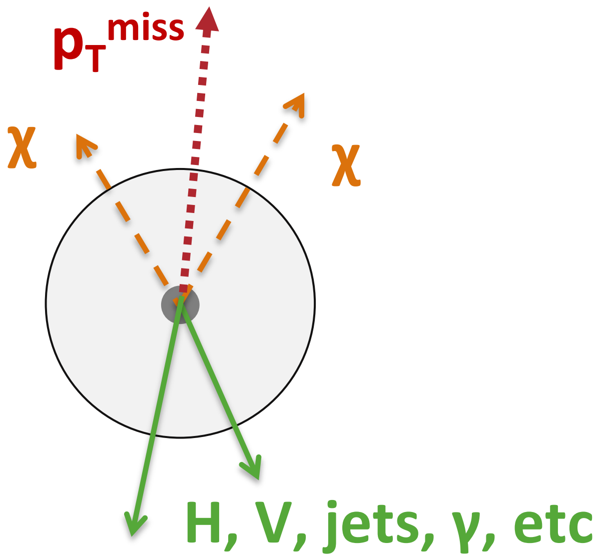
Transverse view

Dark matter at the LHC: mono-X

- Dark matter particles χ escape the detector without depositing energy (like neutrinos do)
- But if the dark matter is produced in association with SM particles (X)…
  → Detectable imbalance of momentum in the transverse plane (p_T^{miss})
  → Known as the mono-X technique



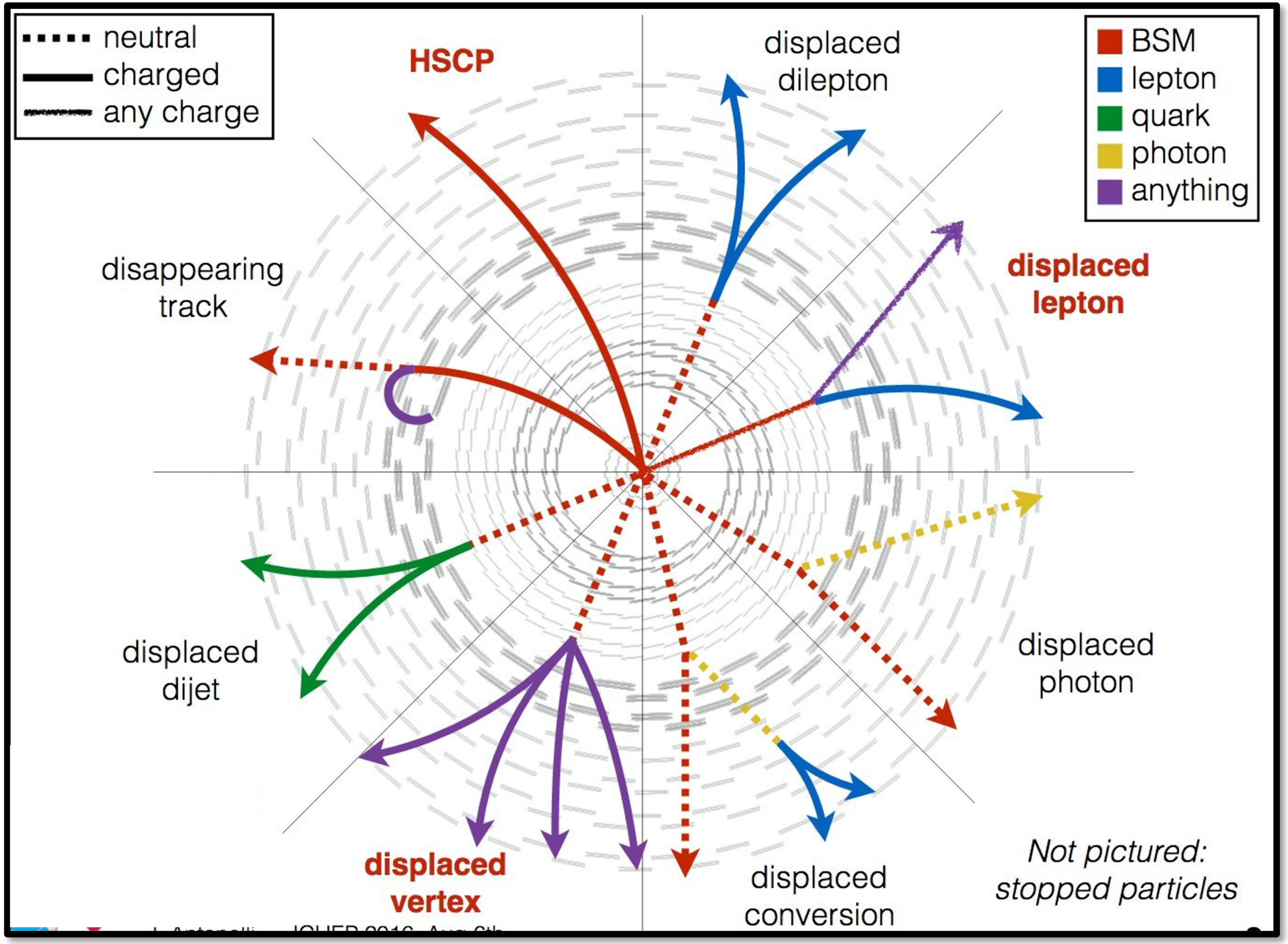
Side view



Transverse view

Dark matter at the LHC: “exotic” signatures

- No direct evidence for WIMPS has been observed
- What if the “dark sector” is not as simple as a single particle (WIMP)?
    - Dark matter particles could have long lifetimes (like many Standard Model particles do)
    - Dark matter could have complex self-interactions
- Leads to a wide range of interesting, challenging signatures to explore



Beyond WIMPs: axion dark matter

- “Strong CP problem”: QCD could violate CP symmetry but… doesn’t
    - Based on very precise experimental measurements of the neutron dipole moment
- Peccei-Quinn theory
    - Introduces a new particle: the axion
    - Axions would be extremely light (10 μeV), neutral, and abundant → excellent dark matter candidate
- Stringent limits set by the ADMX collaboration
- Completely different than other direct detection experiments:
    - 8 T magnetic field to convert axions into microwave photons
    - Photons get detected in microwave resonant cavity
    - Small and not underground

What's next for particle physics?

- Snowmass 2021: US effort to define the important questions and identify the most promising opportunities in particle physics
  - Culminating in a report clearly stating the main goals and high-priority projects
  - Similar report was just released by the European Strategy Group in May

Collider considerations:

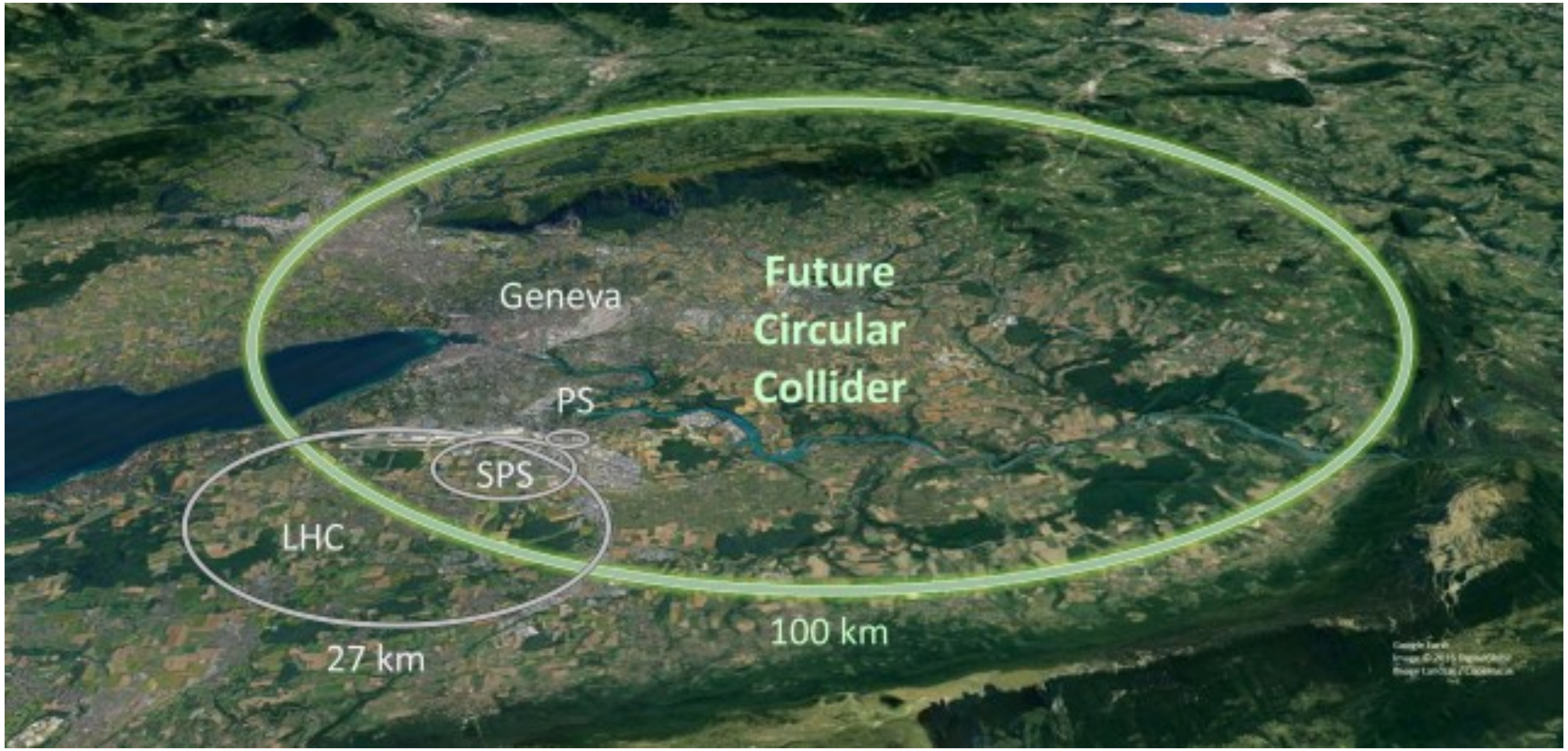
- What to collide?
  - Electron colliders are cleaner and more precise, but lower energy and luminosity
  - Proton colliders can reach very high energies, at the cost of messy collisions
  - Muon colliders combine the best of both worlds, but muons decay
  - Photon colliders could be useful when coupled with an electron collider
- What shape?
  - Linear colliders: don't have to deal with bremsstrahlung
  - Circular colliders: higher energies and luminosity because you can keep recycling particles

Future electron-positron colliders

- CLIC: Compact Linear Collider
  - 380 GeV – 3 TeV, 11 – 50 km, hosted at CERN
- ILC: International Linear Collider,
  - 500 GeV – 1 TeV, 30 – 50 km, hosted by Japan
- CEPC: Circular Electron Positron Collider
  - 240 GeV, 55 km, can be upgraded to 70 TeV pp collider, hosted by China

Even bigger: FCC

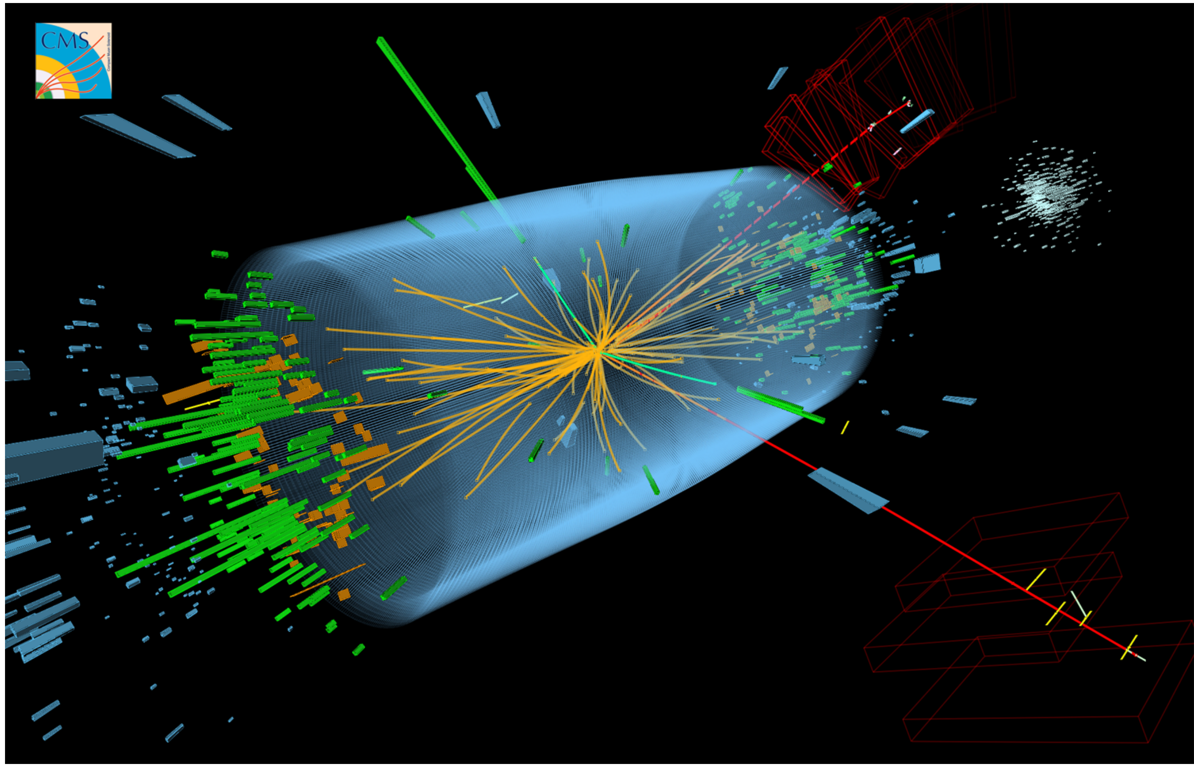
- Future Linear Collider at CERN
  - FCC-ee: 350 GeV, 100 km, could start operations in 2040
  - FCC-hh: 100 TeV, 100 km, could start operations in 2060
  - Compared to 13 TeV, 27 km for the LHC



Is all this worth it?

"Why should we do basic science? What's in it for me?"

- Because we are curious, and it is fun



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“Why should we do basic science? What’s in it for me?”

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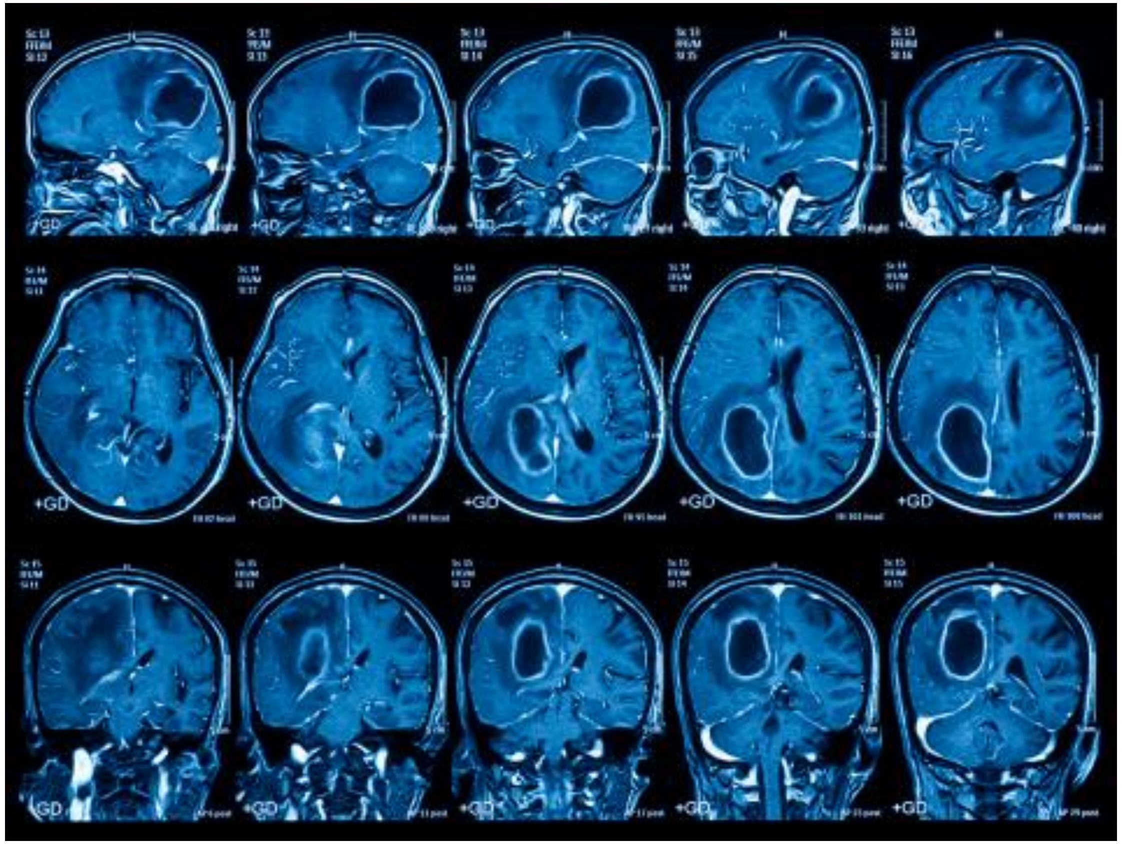
- Because the technology developed for science has immediate practical applications



https://kt.cern/success-stories/lhc-magnets-high-field-mri-and-efficient-power-grids

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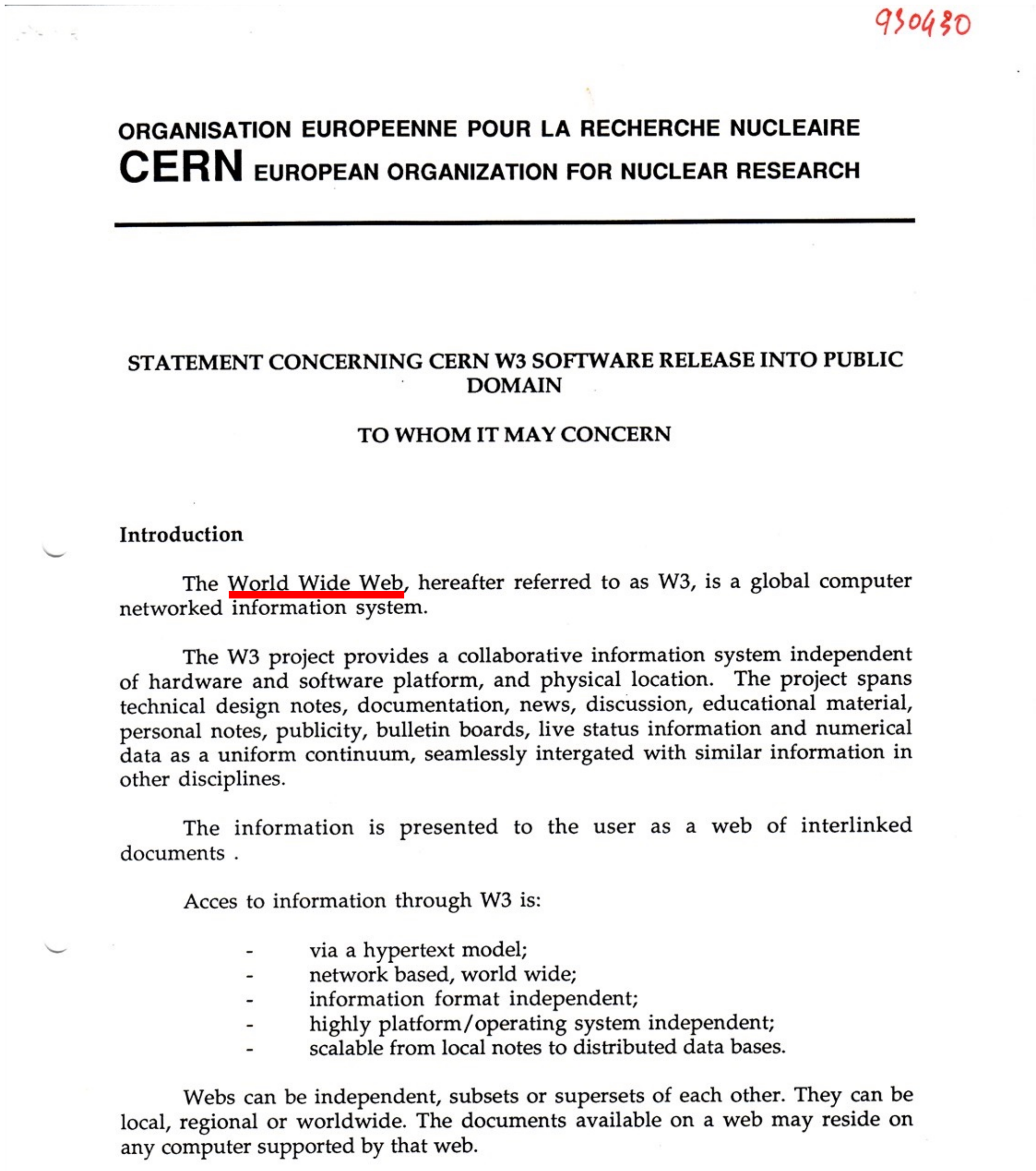

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ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

STATEMENT CONCERNING CERN W3 SOFTWARE RELEASE INTO PUBLIC DOMAIN

TO WHOM IT MAY CONCERN

Introduction

The World Wide Web, hereafter referred to as W3, is a global computer networked information system.

The W3 project provides a collaborative information system independent of hardware and software platform, and physical location. The project spans technical design notes, documentation, news, discussion, educational material, personal notes, publicity, bulletin boards, live status information and numerical data as a uniform continuum, seamlessly intergated with similar information in other disciplines.

The information is presented to the user as a web of interlinked documents .

Acces to information through W3 is:

- via a hypertext model;
- network based, world wide;
- information format independent;
- highly platform/operating system independent;
- scalable from local notes to distributed data bases.

Webs can be independent, subsets or supersets of each other. They can be local, regional or worldwide. The documents available on a web may reside on any computer supported by that web.

Is all this worth it?

“Why should we do basic science? What’s in it for me?”

- Because we are curious, and it is fun
- Because the technology developed for science has immediate practical applications
- Because the useless facts we learn today might be the essential technology of the future

John Bardeen, William Schockley, Walter Brattain; Bell Labs promotional photo, 1948

Course evaluation

- Part of my goal for teaching this class was to improve as a teacher
- I need your feedback to keep getting better!
- Fully anonymous – please be honest

Final thoughts

- Thank you for being so engaged and asking so many great questions! I hope you have enjoyed the class.

- You have my contact information – I'm happy to talk to any students who want to know more about life as a physicist!

One last homework assignment:

A. Fill out weekly survey to report professional development hours.

B. For those watching the recording: **please** fill out final course evaluation

End of 2020 QuarkNet SST :(

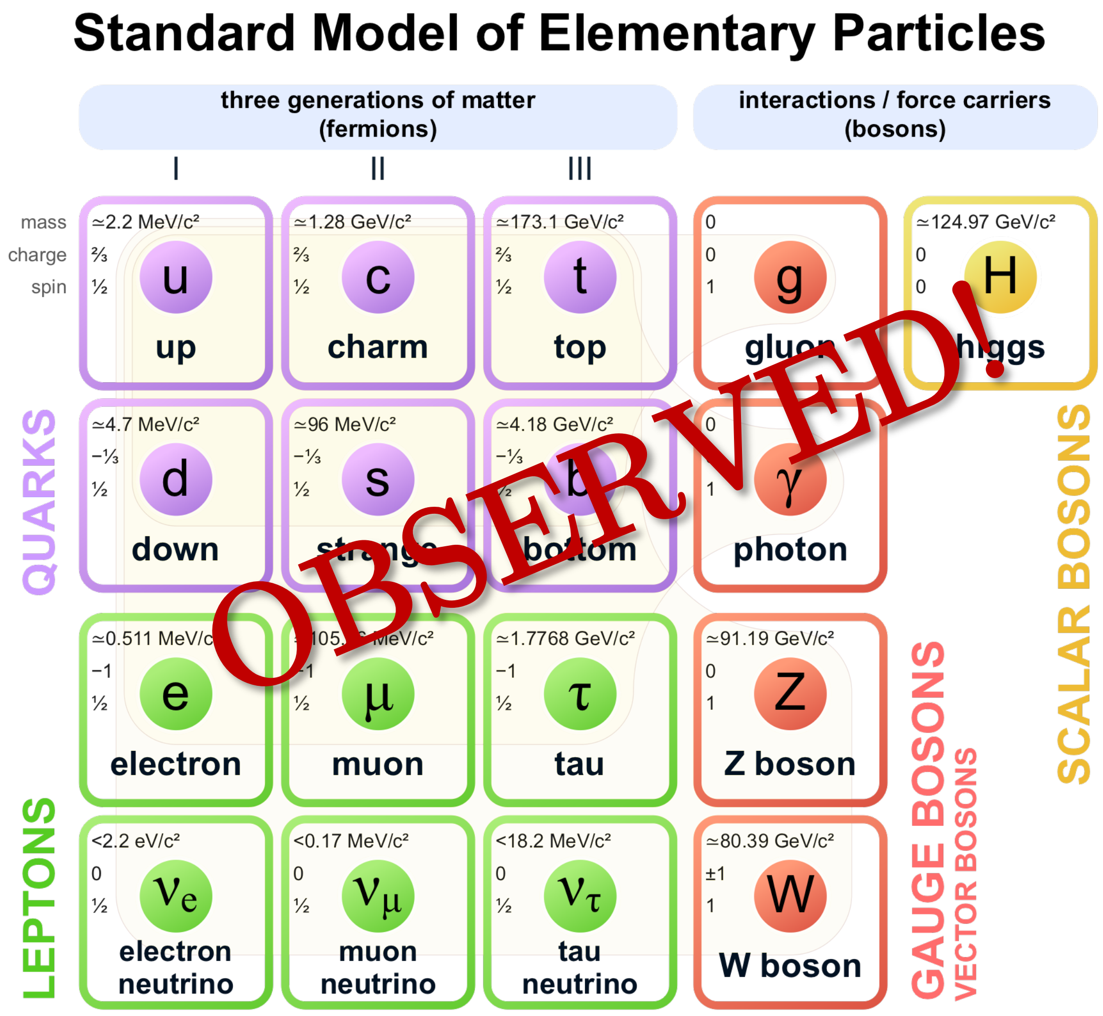
How do we do an analysis?

- Define which events are interesting for you (with help from theorists)
  - To look for a particular SUSY model, consider events with two photons plus missing transverse momentum (MET)
- Estimate how many of those events you would get from SM process
  - Use Monte Carlo simulation or similar-but-different events in data
- Use simulation to determine how many of those events you would get from SUSY
- Determine uncertainties, get other people in CMS to check your work
- Open the box! “Unblind” and see how many events CMS actually detected

Expected background events	15.6 ± 3
Expected signal events	50 ± 5
Observed events	19
Conclusion	SUSY’s not home: set limits!

Expected background events	15.6 ± 3
Expected signal events	50 ± 5
Observed events	63
Conclusion	We found SUSY!

Standard Model



Observations:

- electron: 1897 by JJ Thomson
- muon: 1937 by Anderson & Neddermeyer
- electron neutrino: 1956 by Cowan & Reines
- muon neutrino: 1962@BNL
- up, down, strange quark: 1968@SLAC
- charm quark: 1974@SLAC, BNL
- tau lepton: 1975@SLAC
- bottom quark: 1977@FNAL
- gluon: 1979@DESY
- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL
- Higgs boson: 2012@CERN

Colliders – a biased list

- Push to bigger accelerators at higher energies

Collider	Operation	Type	Energy	Major Discoveries
Super Proton Synchrotron (SPS)	1981-1991	proton-antiproton	540 GeV	W and Z bosons, 1983
Large Electron-Positron Collider	1989-2000	electron-positron	200 GeV	Precision studies of W and Z
Tevatron	1985-2011	proton-antiproton	2 TeV	Top quark, 1995
Large Hadron Collider	2009 - Present	proton-proton	14 TeV	Higgs boson, 2012
The next big collider	?	Probably electrons?	?	???