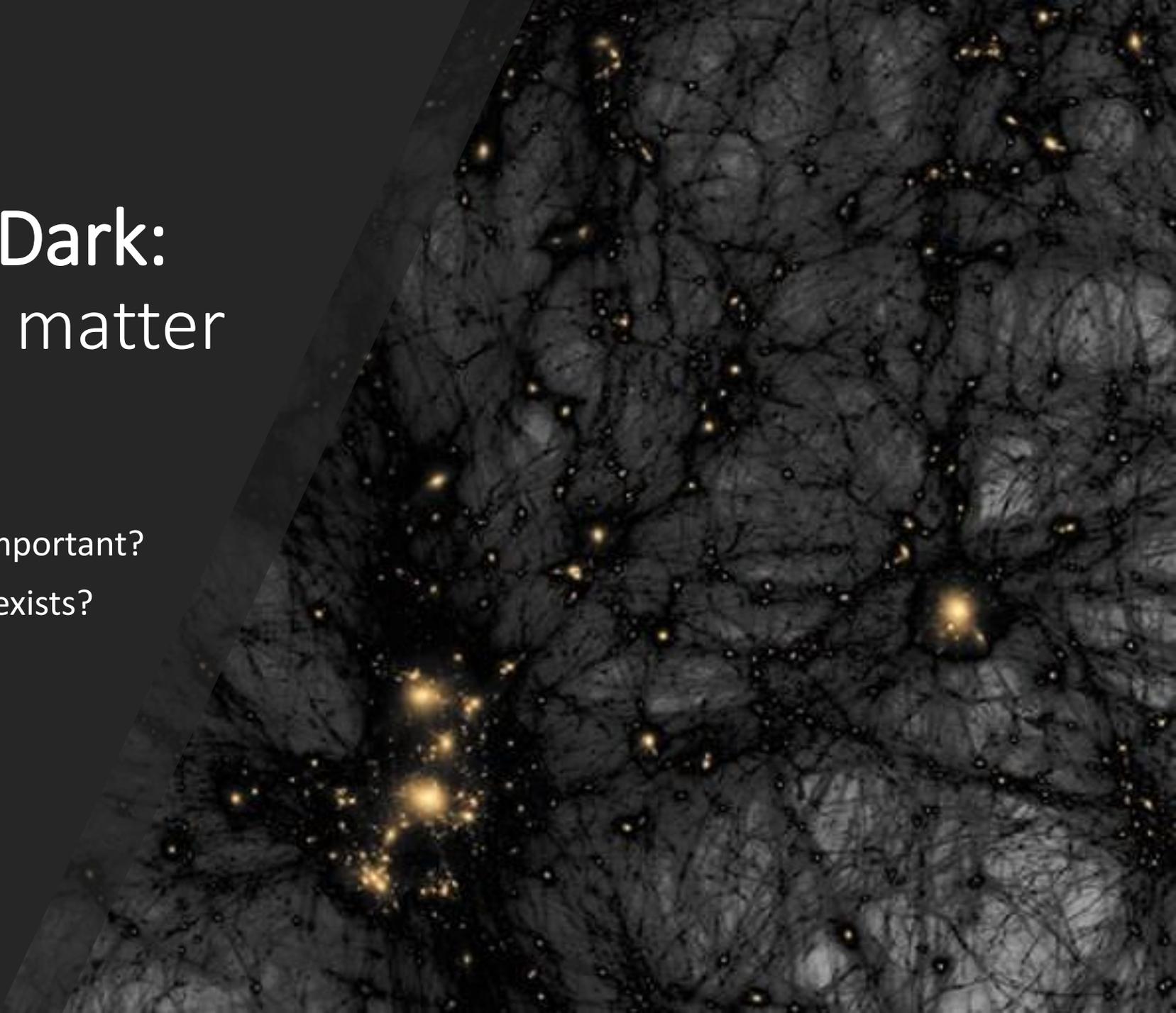
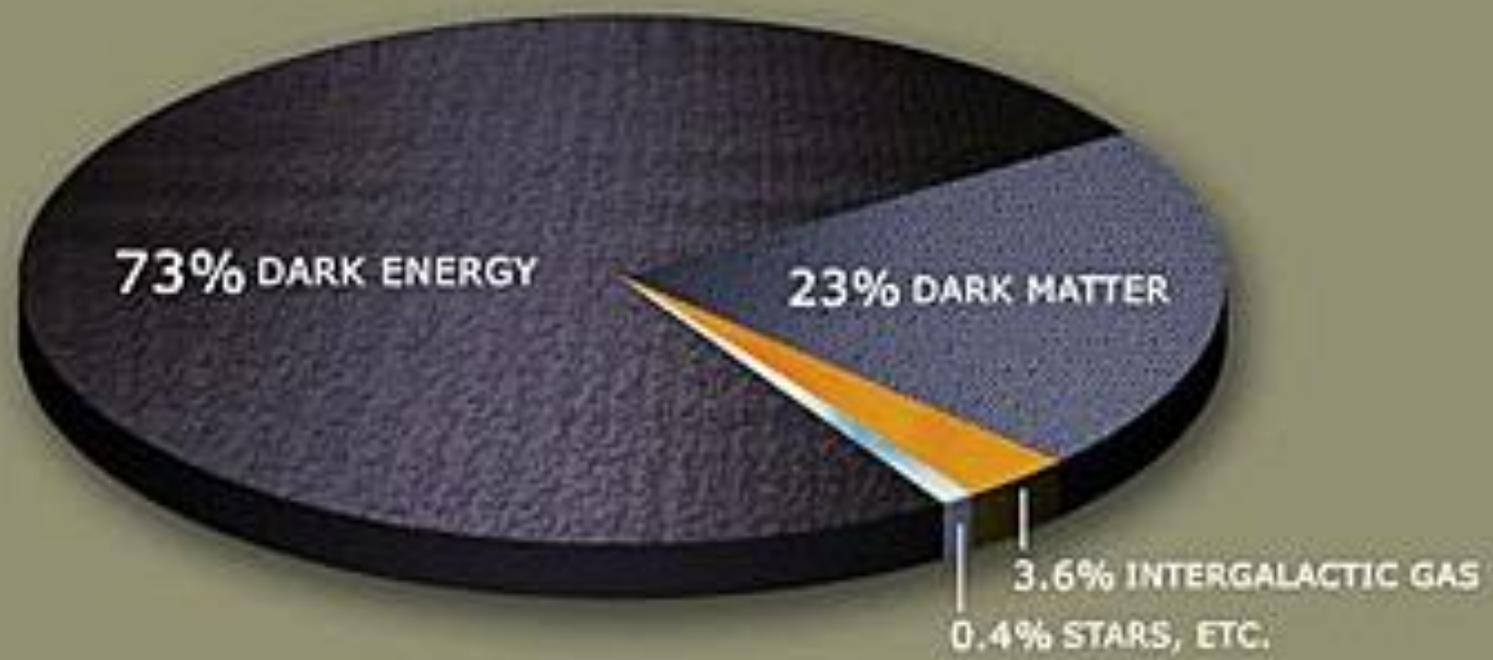


# Stumbling in the Dark: searching for dark matter

- What is dark matter and why it's important?
- What evidence do we have that it exists?
- Experiments for detecting it
- Astrophysical probes



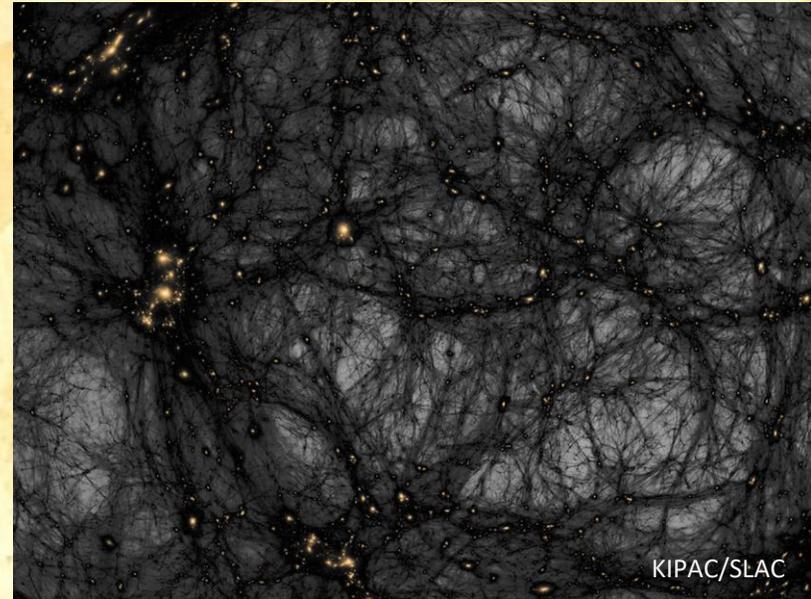


# WANTED

- **It is everywhere**
- **It does not absorb or emit light (doesn't feel the electromagnetic force)**
- **It interacts only through gravity (and maybe the weak force)**
- **Known to: bend light, form and destroy galaxies and many other mischiefs.**

# REWARD

# HAVE YOU SEEN THIS WIZARD?



KIPAC/SLAC

APPROACH WITH EXTREME CAUTION  
DO NOT ATTEMPT TO USE  
★ MAGIC AGAINST THIS WIZARD ★

Any information leading to the arrest of this Wizard shall be duly rewarded.  
Notify immediately by owl the Ministry of Magic-Witch Watchers department.

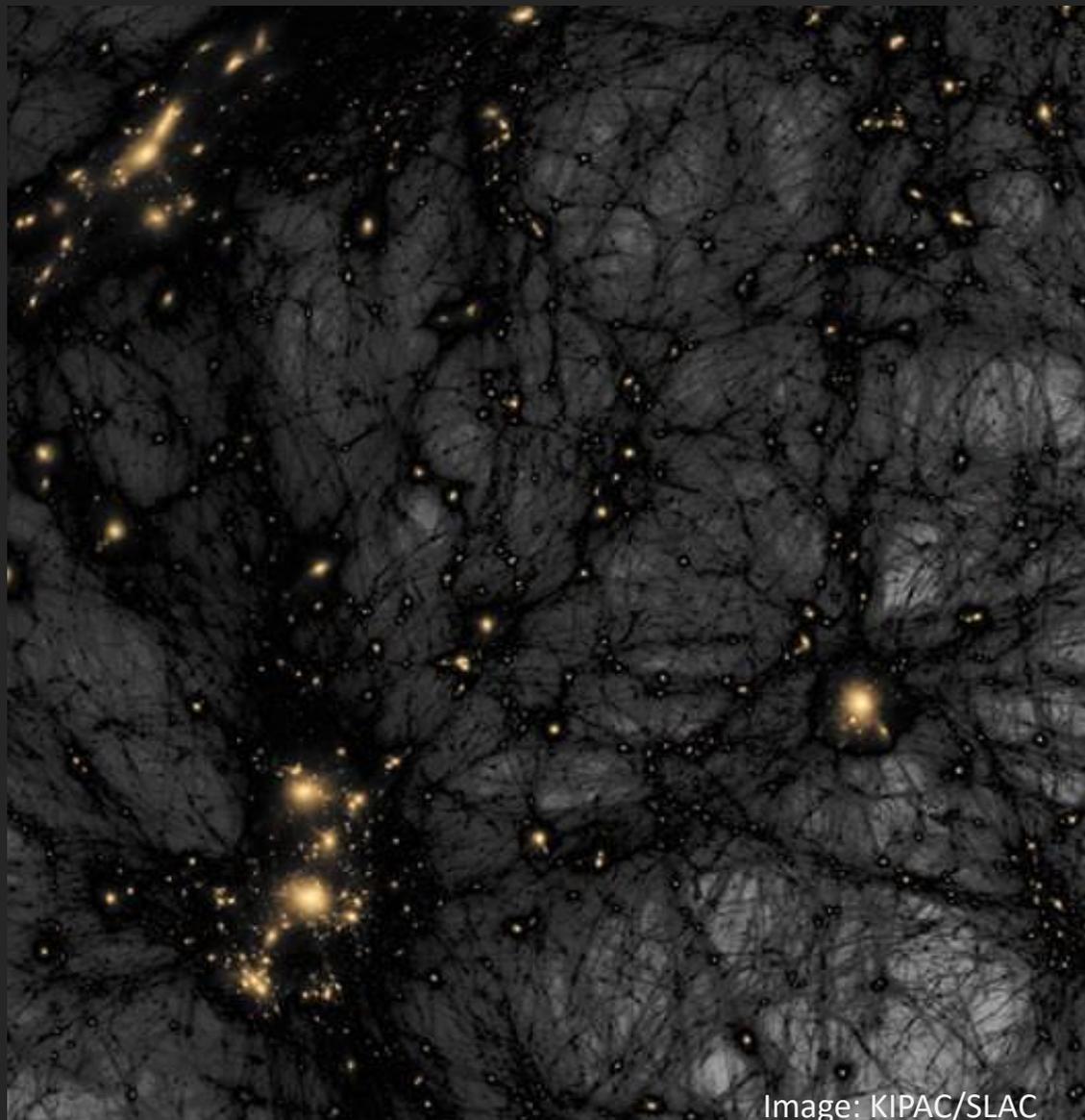
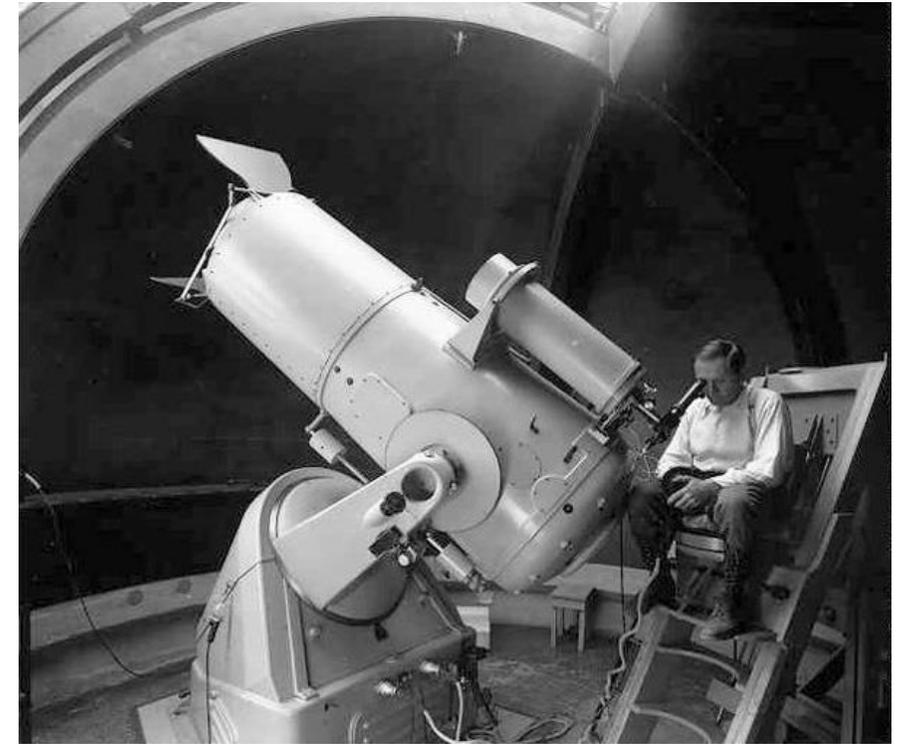


Image: KIPAC/SLAC

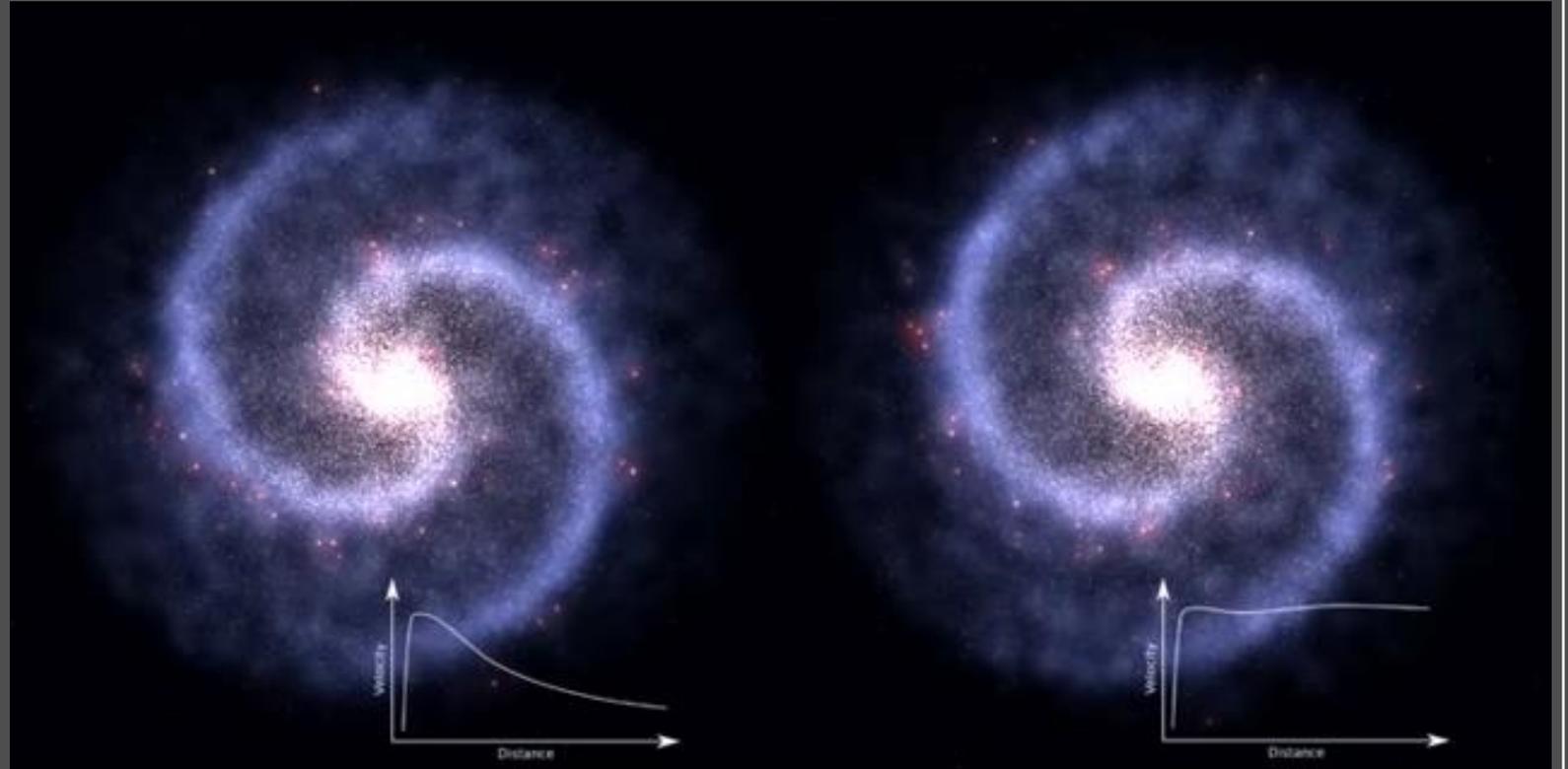




**Credit:** NASA, ESA, and the Hubble Heritage Team (STScI/AURA).



**Credit:** Palomar Observatory/Caltech



Source: ESO/L. Calçada



Source: ESO/L. Calçada

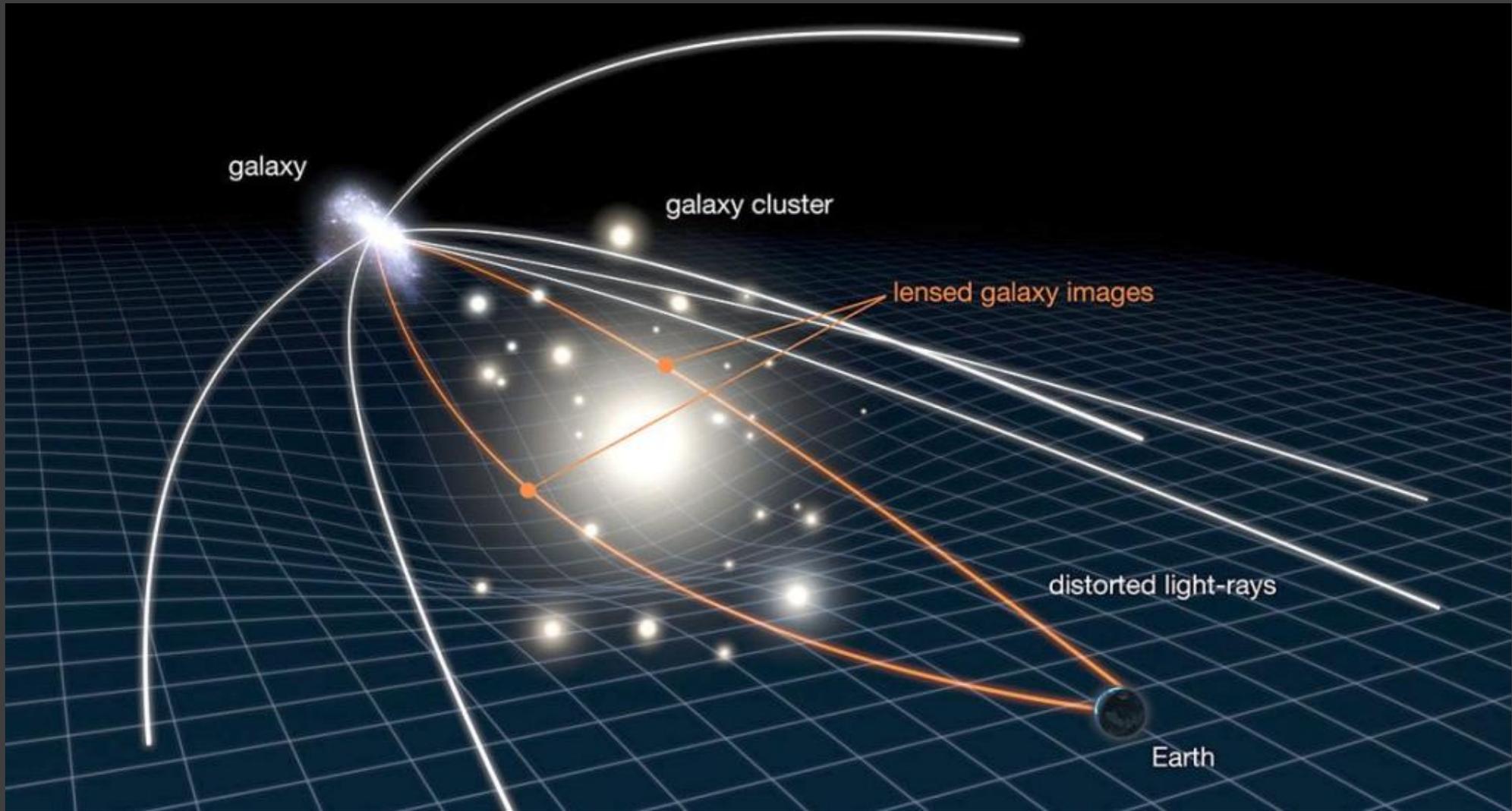
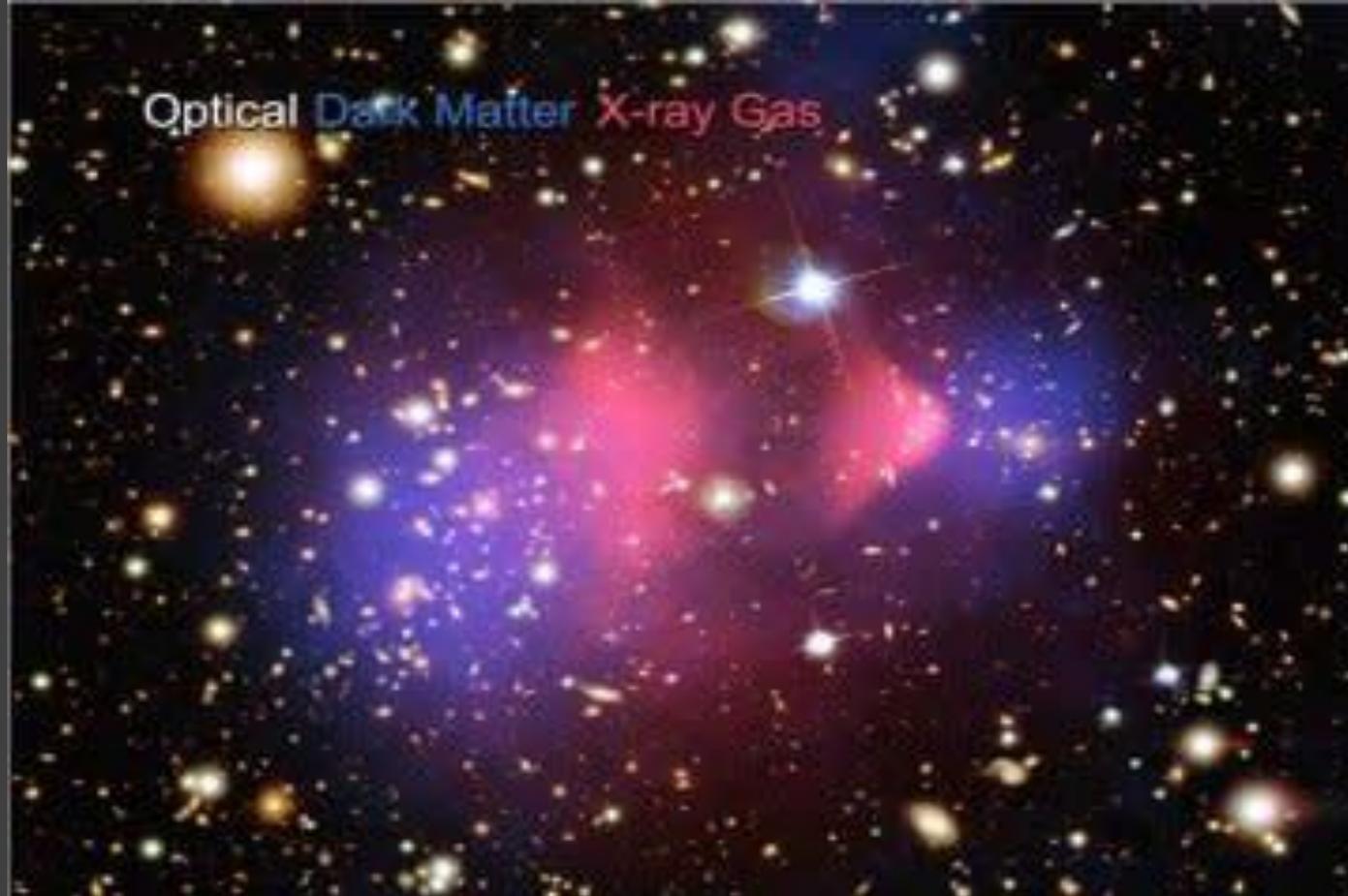
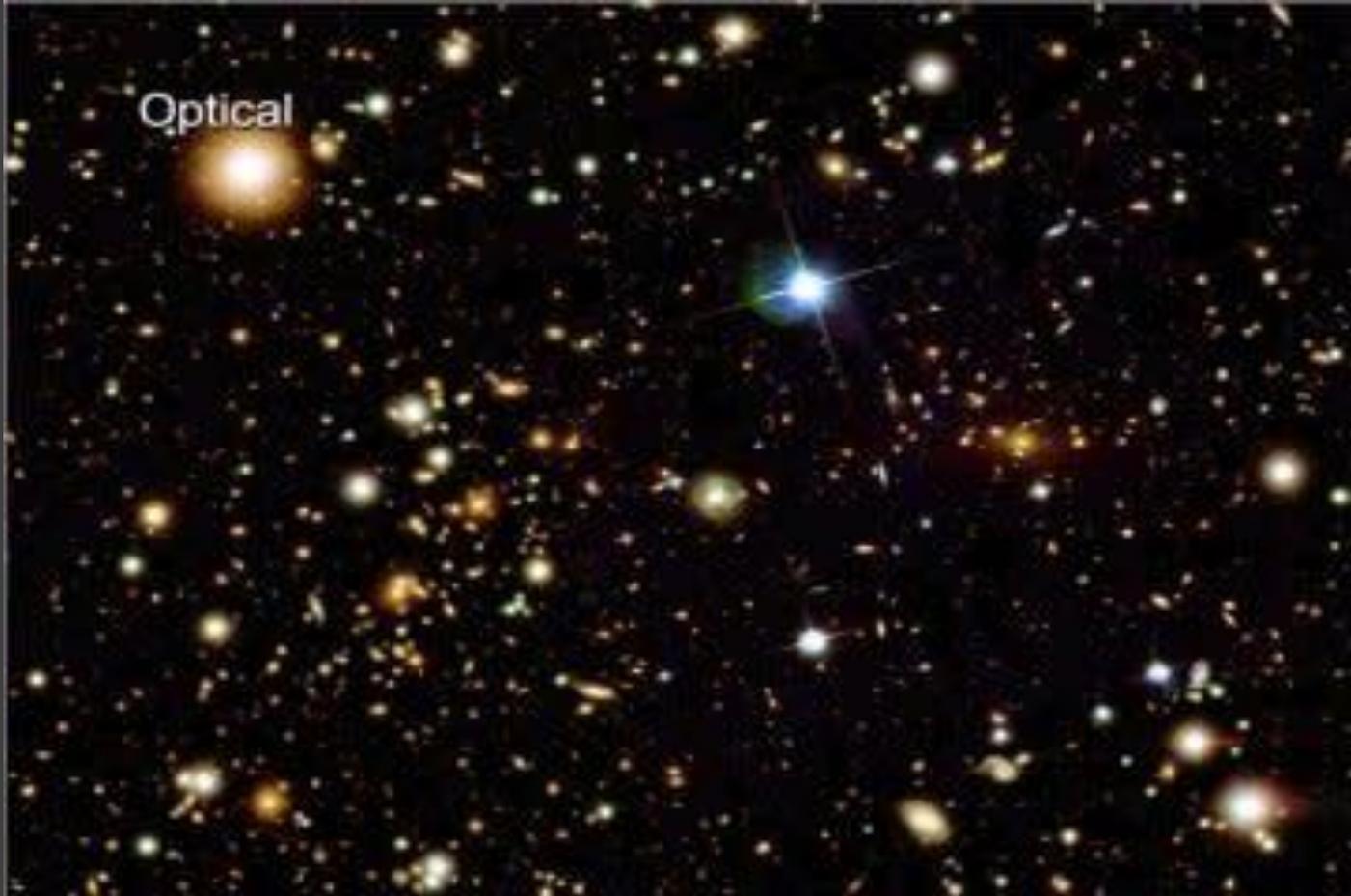


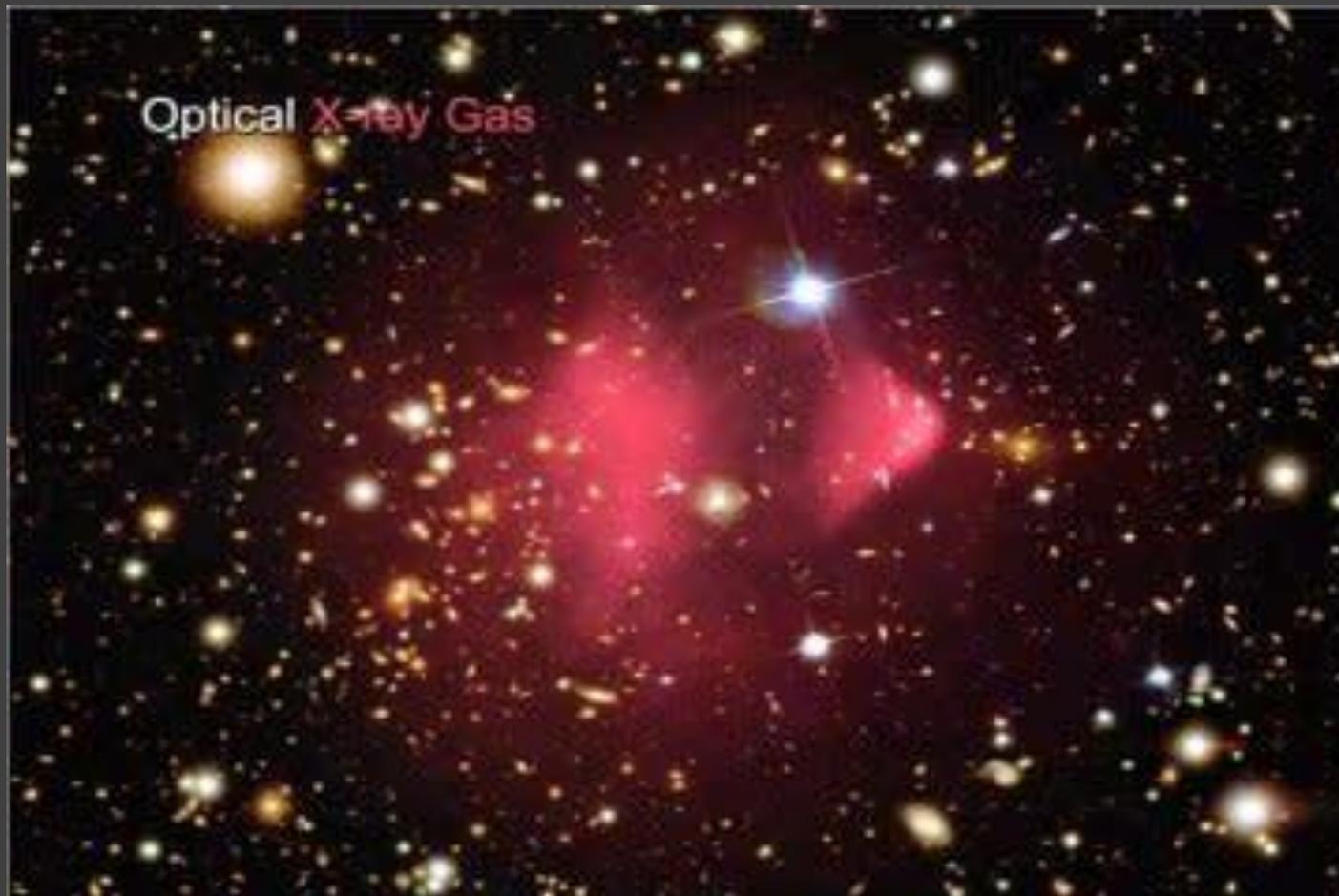
Image: NASA/ESA

# The Bullet Cluster

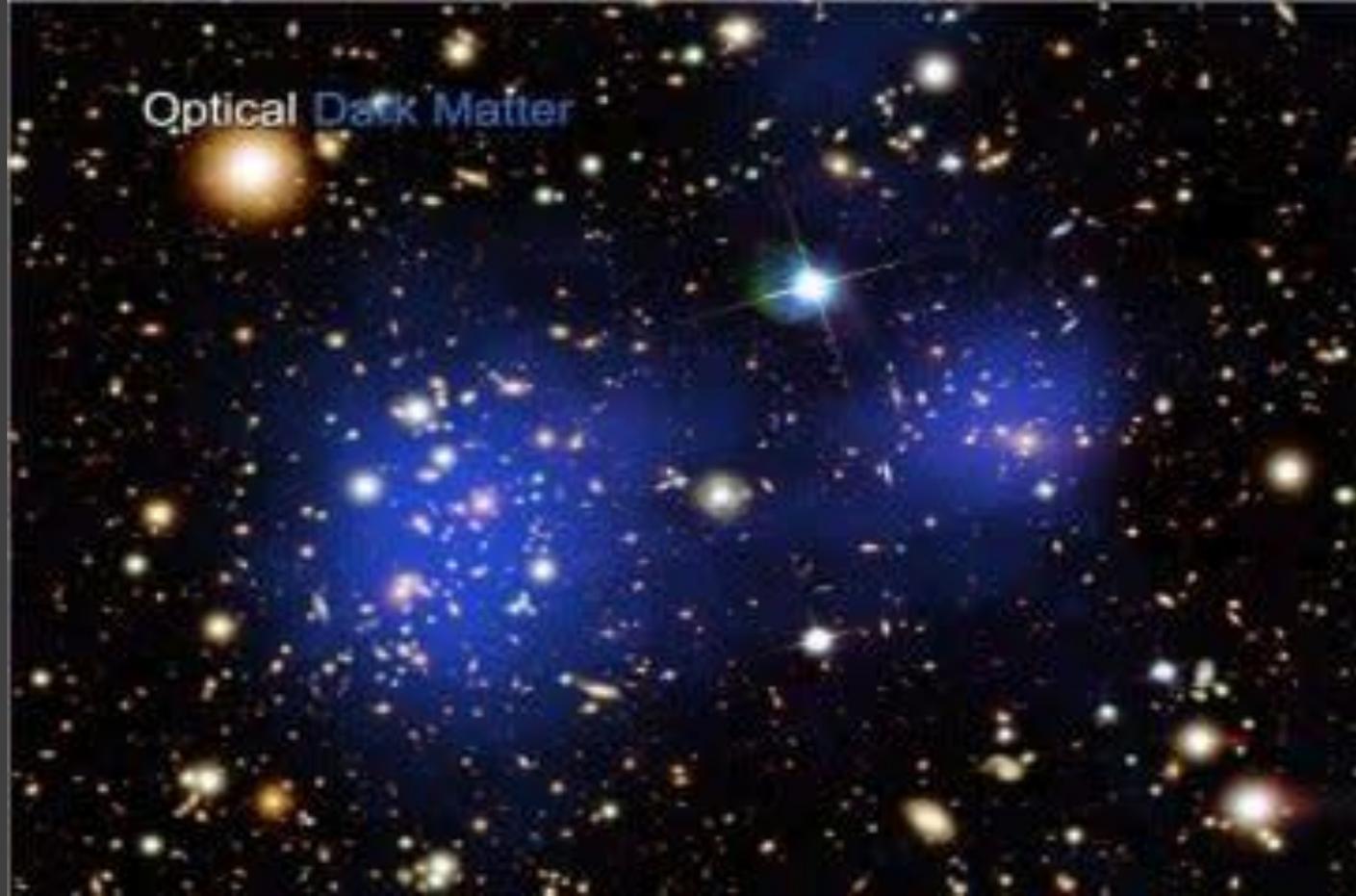




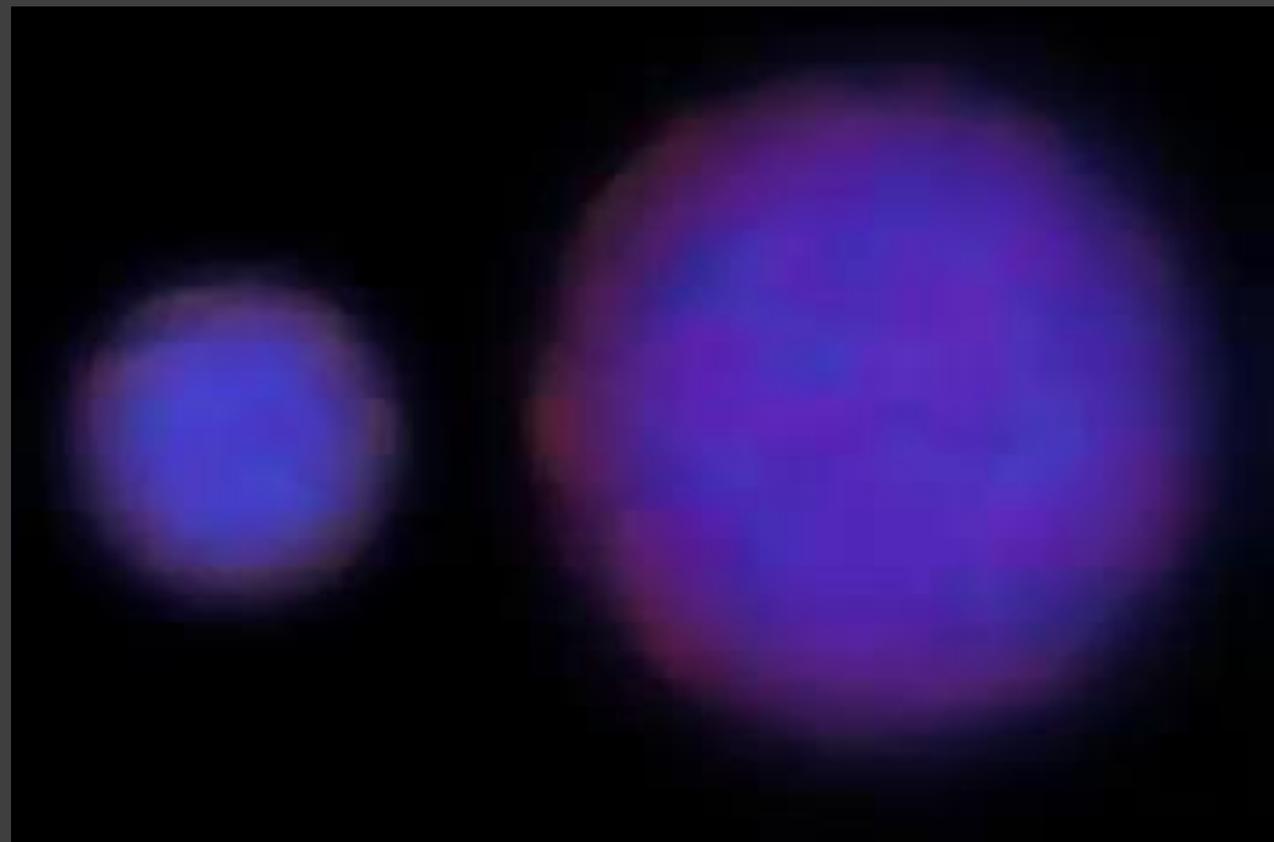
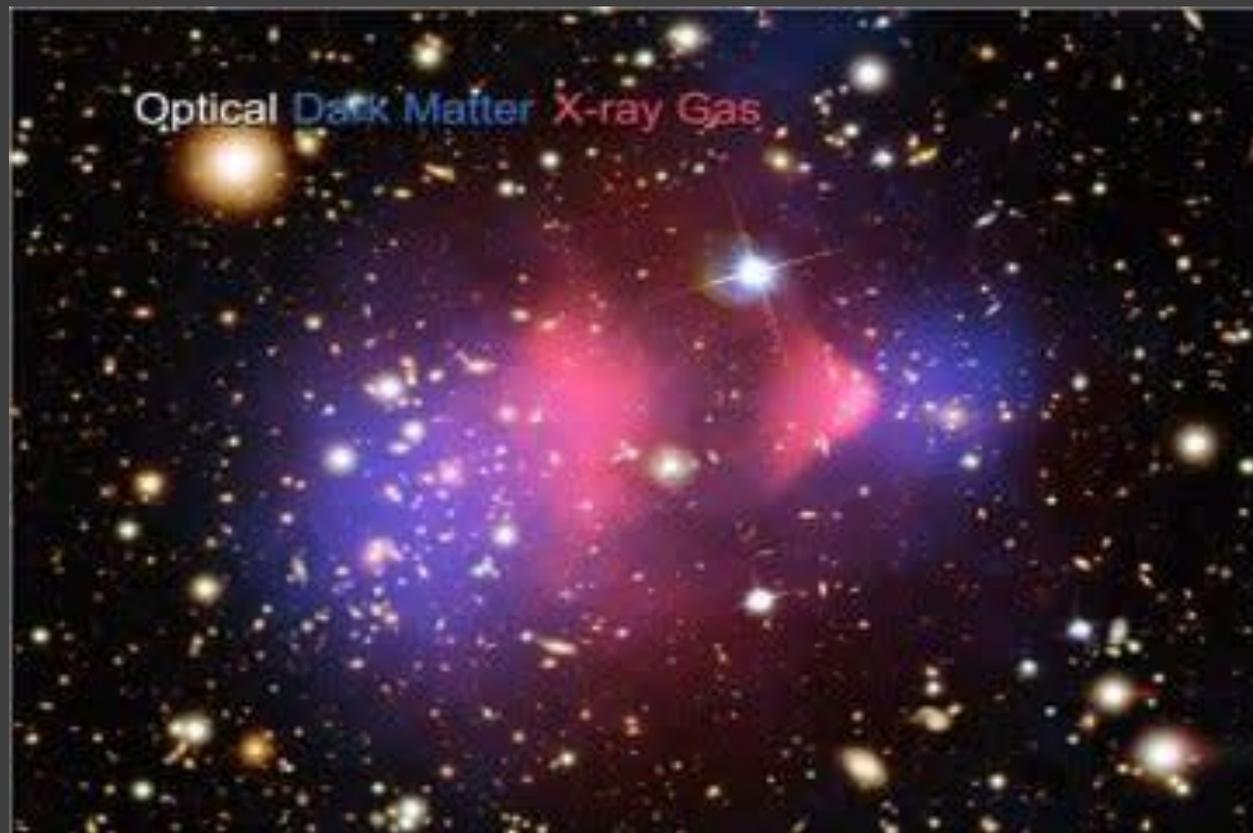
NASA/STScI; Magellan/U.Arizona/D.Clowe et al.



NASA/CXC/CfA/M.Markevitch et al



NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.



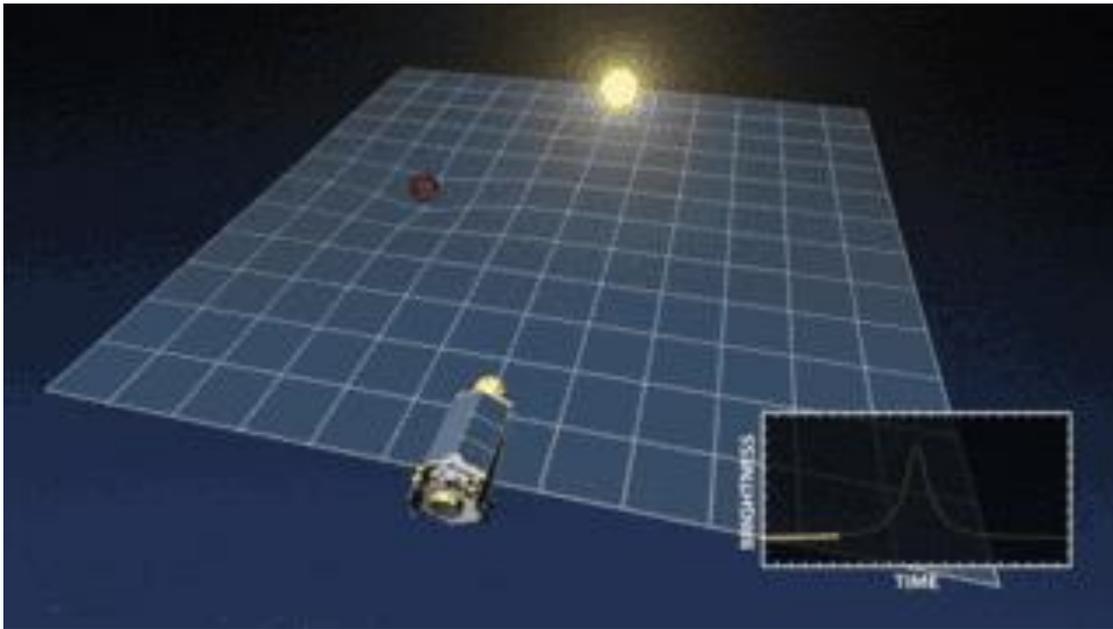
## Can dark matter be baryonic?

(e.g. of protons, neutrons, electrons, etc)



Artist's portrayal of a rogue planet. *NASA / Caltech*

- **Brown dwarfs**
- **Dead stars**
- **Rogue planets**
- **Cold gas, dust**
- **Primordial black holes**
- **...?**



*NASA Ames / JPL-Caltech / T. Pyle*

**Massive compact halo objects (MACHOs) cannot make most of dark matter.**

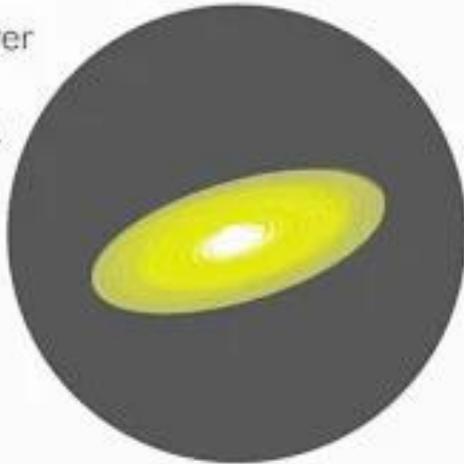
only a few percent of all dark matter ...

# What if we don't understand the force of gravity?

## Modified Newtonian Dynamics (MOND) theory

### Possible solutions

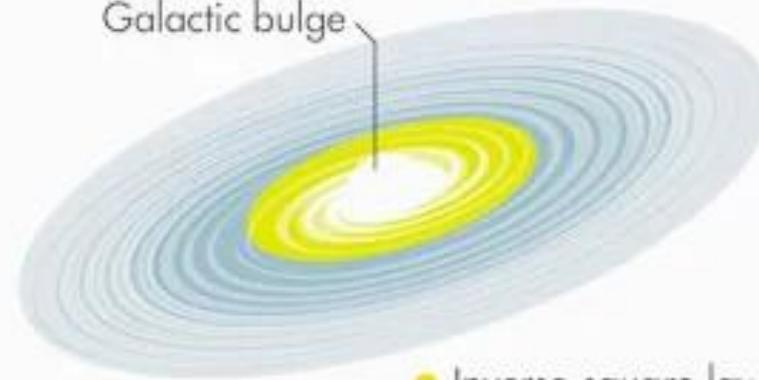
Dark matter  
"halo"  
surrounds  
rotating  
galaxy



#### Dark matter

Giant dark matter "halos" could give extra gravitational acceleration to outlying stars, flattening galaxy rotation curves.

Galactic bulge



● Inverse-square law  
● New law

#### MOND

Modified Newtonian dynamics posits that below a certain level, gravity switches from an inverse-square law to one that matches galaxy rotation curves.

# What if we don't understand the force of gravity?

## Modified Newtonian Dynamics (MOND) theory

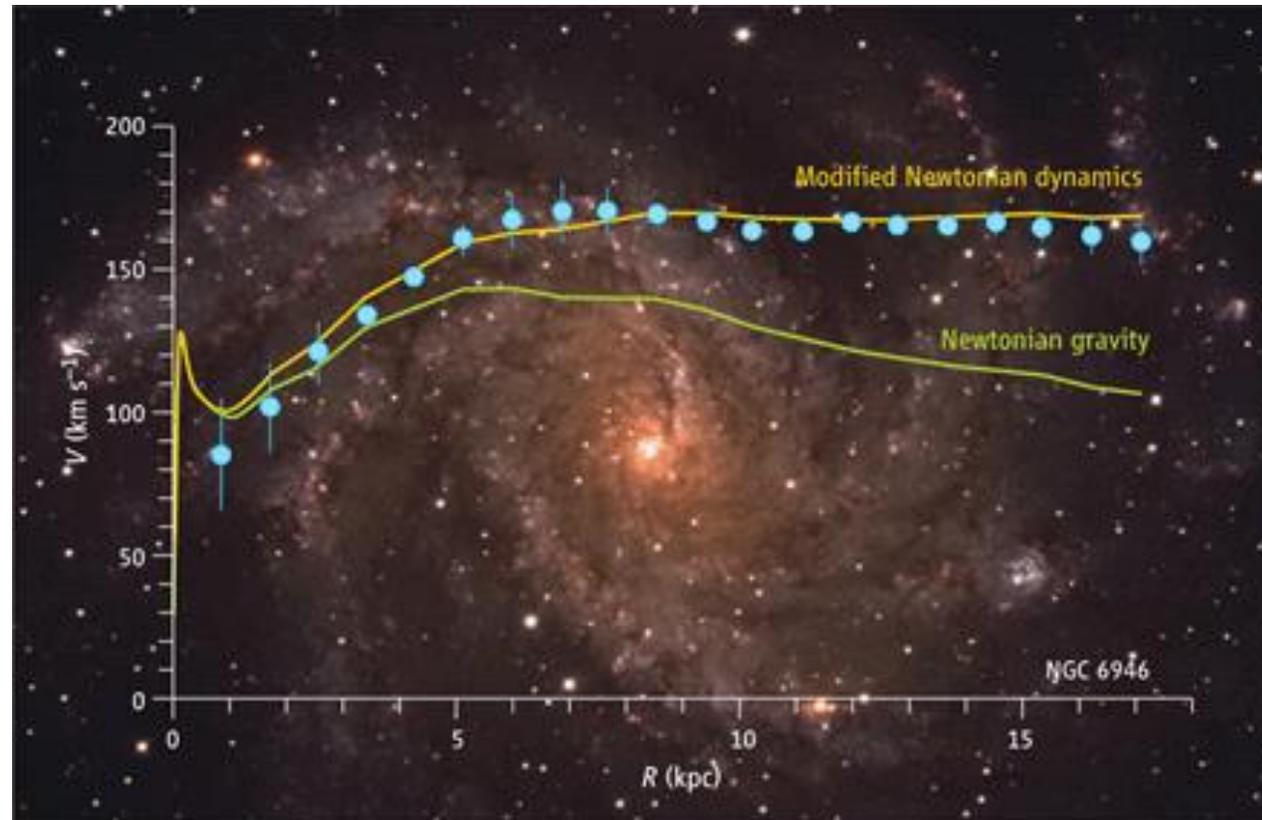


PHOTO CREDIT: STACY MCGAUGH

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs boson
<b>QUARKS</b>	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
<b>LEPTONS</b>	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	1/2	1/2	1/2	1	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	
					<b>GAUGE BOSONS</b>

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	up	charm	top	gluon	Higgs boson
	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$1/3$	$1/3$	$-1/3$	0	
	$1/2$	$1/2$	$1/2$	1	
	down	strange	bottom	photon	
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	$-1$	$-1$	$-1$	0	
	$1/2$	$1/2$	$1/2$	1	
	electron	muon	tau	Z boson	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	$1/2$	$1/2$	$1/2$	1	
	electron neutrino	muon neutrino	tau neutrino	W boson	

QUARKS

LEPTONS

GAUGE BOSONS

No electromagnetic force

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	up	charm	top	gluon	Higgs boson

QUARKS

mass →	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0
charge →	2/3	2/3	-1/3	0
spin →	1/2	1/2	1/2	1
	down	strange	bottom	photon

mass →	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$
charge →	-1	-1	-1	0
spin →	1/2	1/2	1/2	1
	electron	muon	tau	Z boson

LEPTONS

mass →	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$
charge →	0	0	0	±1
spin →	1/2	1/2	1/2	1
	electron neutrino	muon neutrino	tau neutrino	W boson

GAUGE BOSONS

No electromagnetic force  
No strong force

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0

QUARKS

mass →	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0
charge →	2/3	1/3	-1/3	0
spin →	1/2	1/2	1/2	1

mass →	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$
charge →	-1	-1	-1	0
spin →	1/2	1/2	1/2	1

LEPTONS

mass →	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$
charge →	0	0	0	±1
spin →	1/2	1/2	1/2	1

GAUGE BOSONS

No electromagnetic force  
 No strong force  
 Stable

	<p>mass → <math>\approx 2.3 \text{ MeV}/c^2</math></p> <p>charge → 2/3</p> <p>spin → 1/2</p> <p><b>up quark</b></p>	<p>mass → <math>\approx 1.275 \text{ GeV}/c^2</math></p> <p>charge → 2/3</p> <p>spin → 1/2</p> <p><b>charm quark</b></p>	<p>mass → <math>\approx 173.07 \text{ GeV}/c^2</math></p> <p>charge → 2/3</p> <p>spin → 1/2</p> <p><b>top quark</b></p>	<p>mass → 0</p> <p>charge → 0</p> <p>spin → 1</p> <p><b>gluon</b></p>	<p>mass → <math>\approx 126 \text{ GeV}/c^2</math></p> <p>charge → 0</p> <p>spin → 0</p> <p><b>Higgs boson</b></p>
QUARKS	<p>mass → <math>\approx 4.8 \text{ MeV}/c^2</math></p> <p>charge → 1/2</p> <p>spin → 1/2</p> <p><b>down quark</b></p>	<p>mass → <math>\approx 95 \text{ MeV}/c^2</math></p> <p>charge → 1/2</p> <p>spin → 1/2</p> <p><b>strange quark</b></p>	<p>mass → <math>\approx 4.18 \text{ GeV}/c^2</math></p> <p>charge → -1/2</p> <p>spin → 1/2</p> <p><b>bottom quark</b></p>	<p>mass → 0</p> <p>charge → 0</p> <p>spin → 1</p> <p><b>photon</b></p>	
LEPTONS	<p>mass → <math>0.511 \text{ MeV}/c^2</math></p> <p>charge → -1</p> <p>spin → 1/2</p> <p><b>electron</b></p>	<p>mass → <math>105.7 \text{ MeV}/c^2</math></p> <p>charge → -1</p> <p>spin → 1/2</p> <p><b>muon</b></p>	<p>mass → <math>1.777 \text{ GeV}/c^2</math></p> <p>charge → -1</p> <p>spin → 1/2</p> <p><b>tau lepton</b></p>	<p>mass → <math>91.2 \text{ GeV}/c^2</math></p> <p>charge → 0</p> <p>spin → 1</p> <p><b>Z boson</b></p>	
	<p>mass → <math>&lt; 2.2 \text{ eV}/c^2</math></p> <p>charge → 0</p> <p>spin → 1/2</p> <p><b>electron neutrino</b></p>	<p>mass → <math>&lt; 0.17 \text{ MeV}/c^2</math></p> <p>charge → 0</p> <p>spin → 1/2</p> <p><b>muon neutrino</b></p>	<p>mass → <math>&lt; 15.5 \text{ MeV}/c^2</math></p> <p>charge → 0</p> <p>spin → 1/2</p> <p><b>tau neutrino</b></p>	<p>mass → <math>80.4 \text{ GeV}/c^2</math></p> <p>charge → 0</p> <p>spin → 1</p> <p><b>W boson</b></p>	

**No electromagnetic force**  
**No strong force**  
**Stable**

**Neutrinos can't be all of dark matter: they move too fast (are "hot") and they do not contribute much by mass.**

### Standard particles

<b>u</b> Up	<b>c</b> Charm	<b>t</b> Tau	<b>g</b> Gluon
<b>d</b> Down	<b>s</b> Strange	<b>b</b> Bottom	<b>g</b> Photon
<b><math>\nu_e</math></b> Electron neutrino	<b><math>\nu_\mu</math></b> Muon neutrino	<b><math>\nu_\tau</math></b> Tau neutrino	<b>Z</b> Z boson
<b>e</b> Electron	<b><math>\mu</math></b> Muon	<b><math>\tau</math></b> Tau	<b>W</b> W boson

**H**  
Higgs

- Quarks
- Leptons
- Force particles

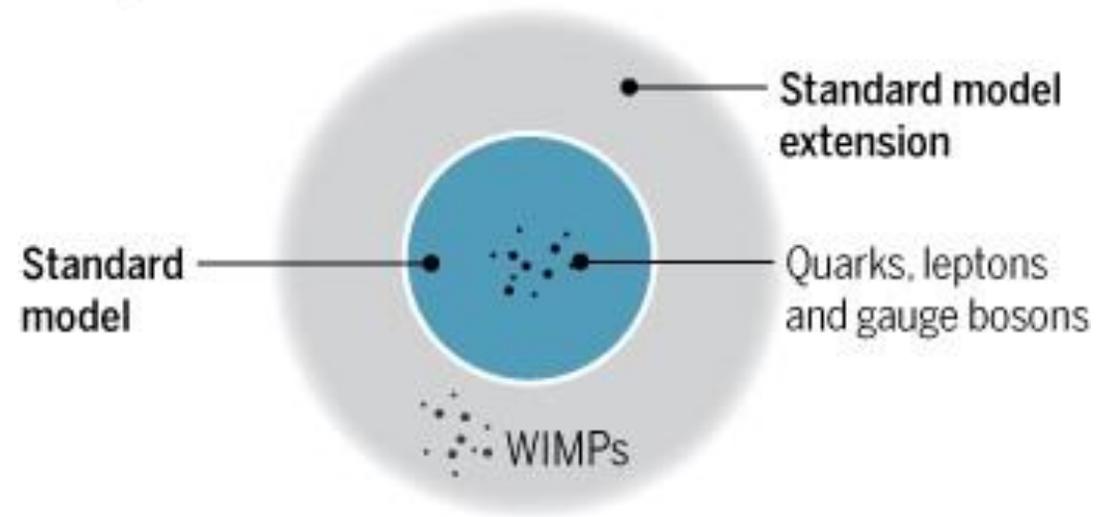
### Supersymmetry particles

<b><math>\tilde{u}</math></b>	<b><math>\tilde{c}</math></b>	<b><math>\tilde{t}</math></b>	<b><math>\tilde{g}</math></b> Gluino
<b><math>\tilde{d}</math></b>	<b><math>\tilde{s}</math></b>	<b><math>\tilde{b}</math></b>	<b><math>\tilde{g}</math></b> Photino
<b><math>\tilde{\nu}_e</math></b>	<b><math>\tilde{\nu}_\mu</math></b>	<b><math>\tilde{\nu}_\tau</math></b>	<b><math>\tilde{Z}</math></b> Zino
<b><math>\tilde{e}</math></b>	<b><math>\tilde{\mu}</math></b>	<b><math>\tilde{\tau}</math></b>	<b><math>\tilde{W}</math></b> Wino

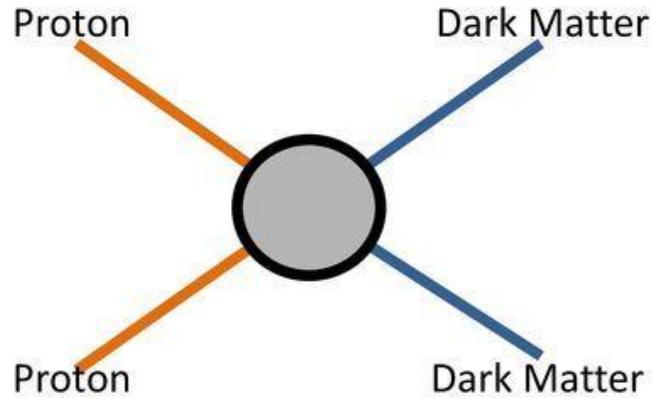
**$\tilde{H}$**   
Higgsino

- Squarks
- Sleptons
- Neutralinos & Charginos

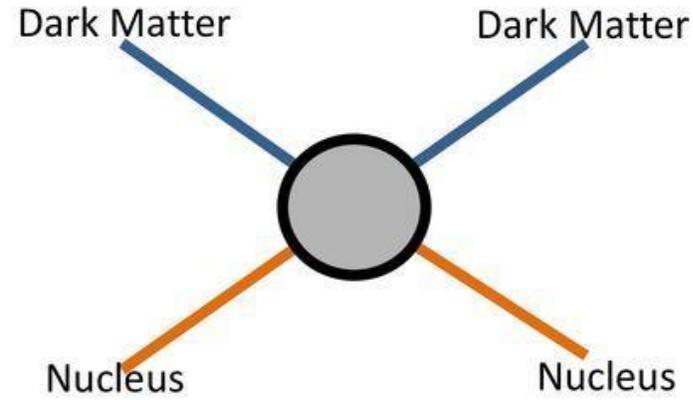
## SUPERSYMMETRY



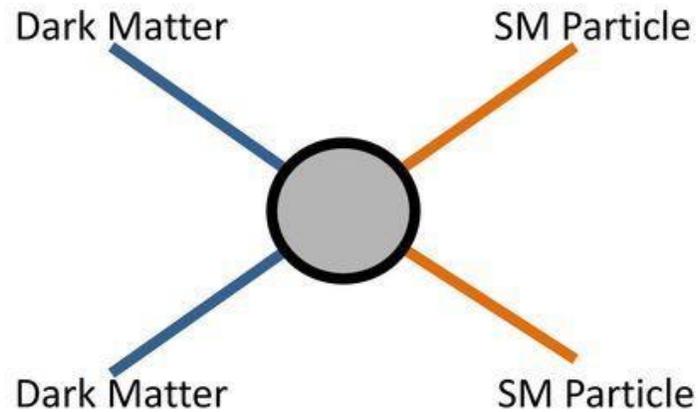
# Ways to Detect Dark Matter – *Make, Shake and Break*



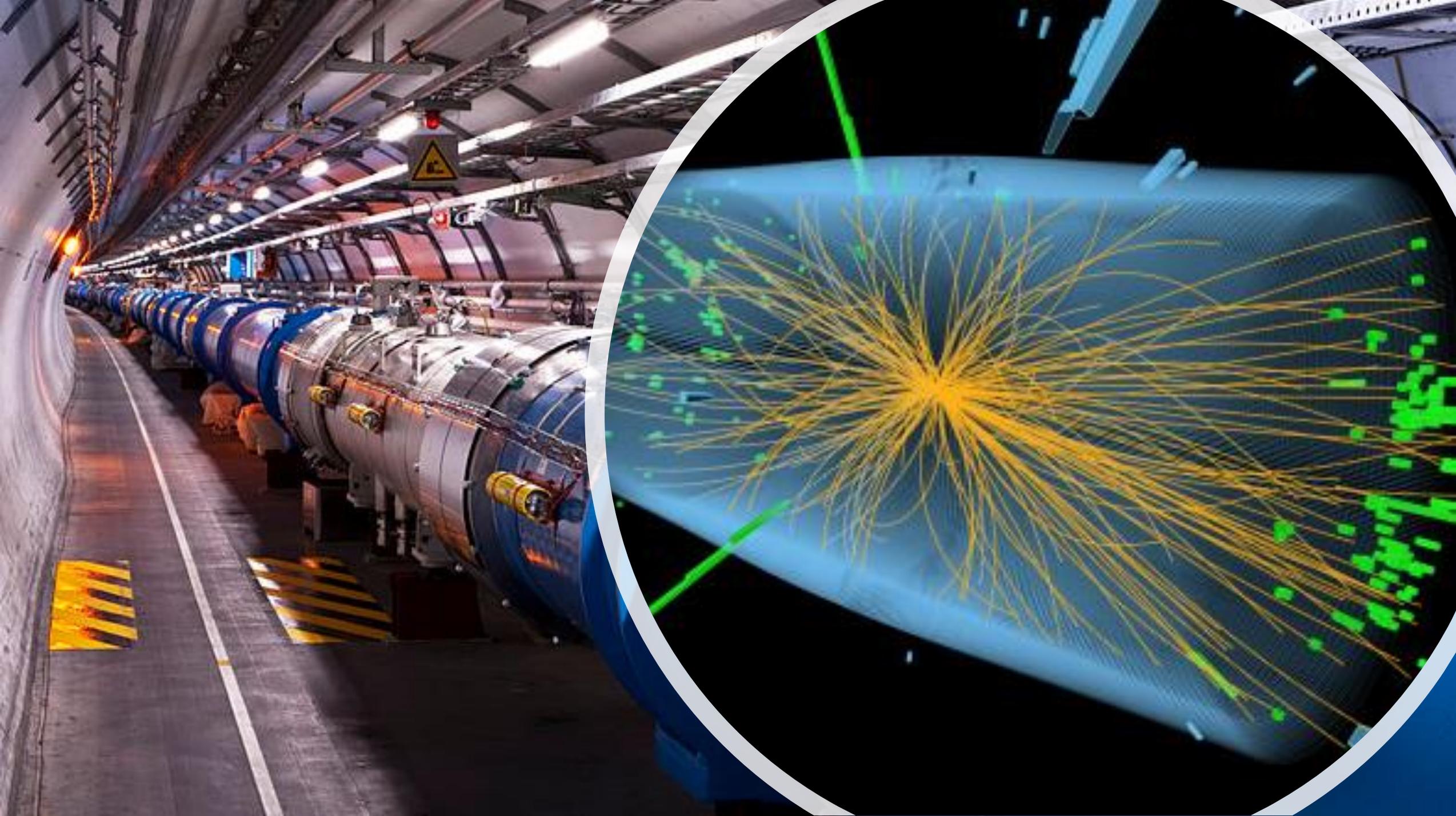
***Make*** – collider production



***Shake*** – direct detection scattering

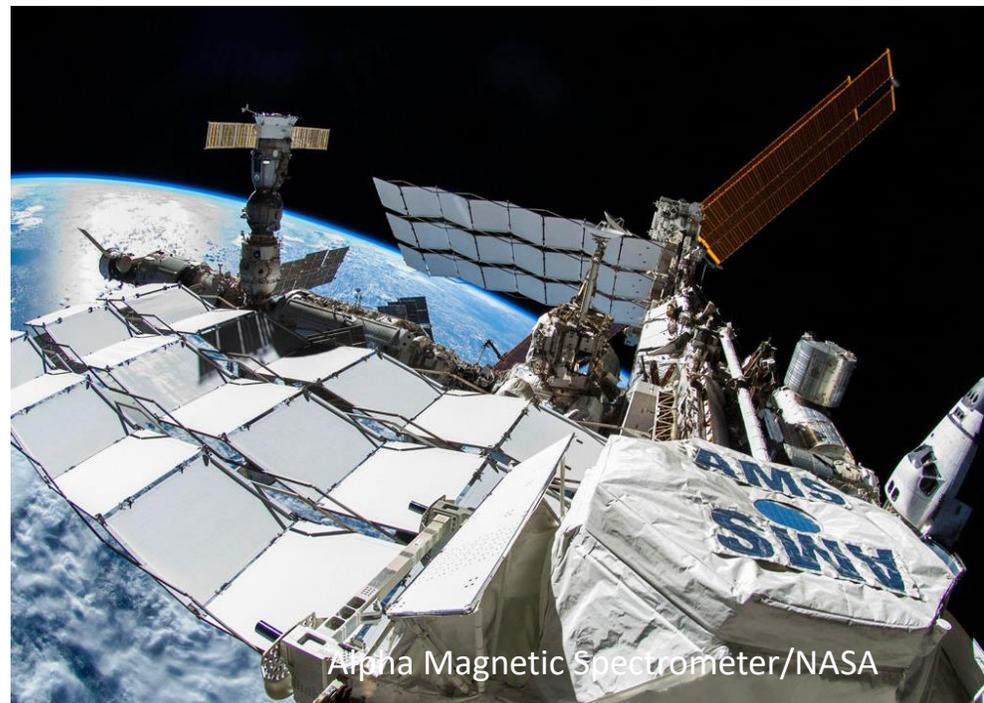


***Break*** – indirect detection of annihilation



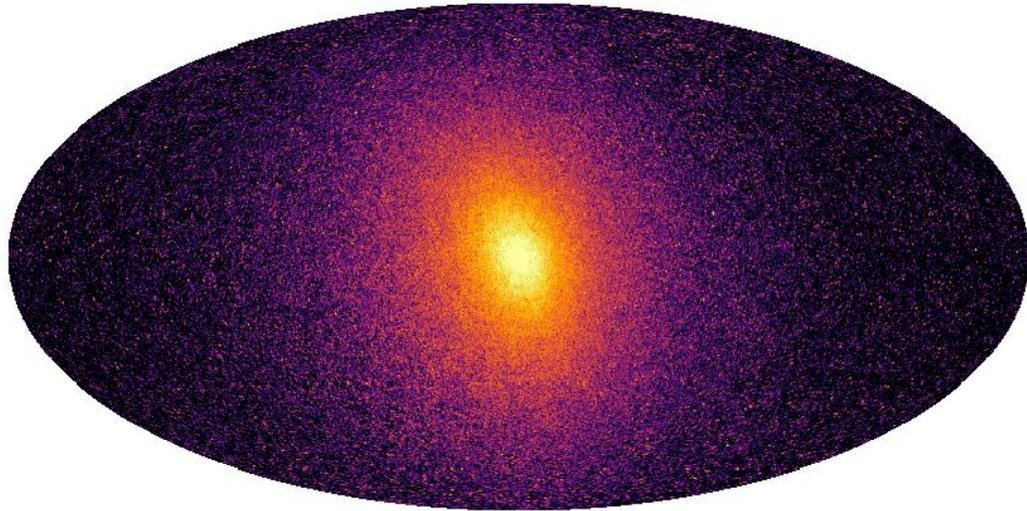


Fermi Space Satellite/ NASA. Photo: Sandbox Studio



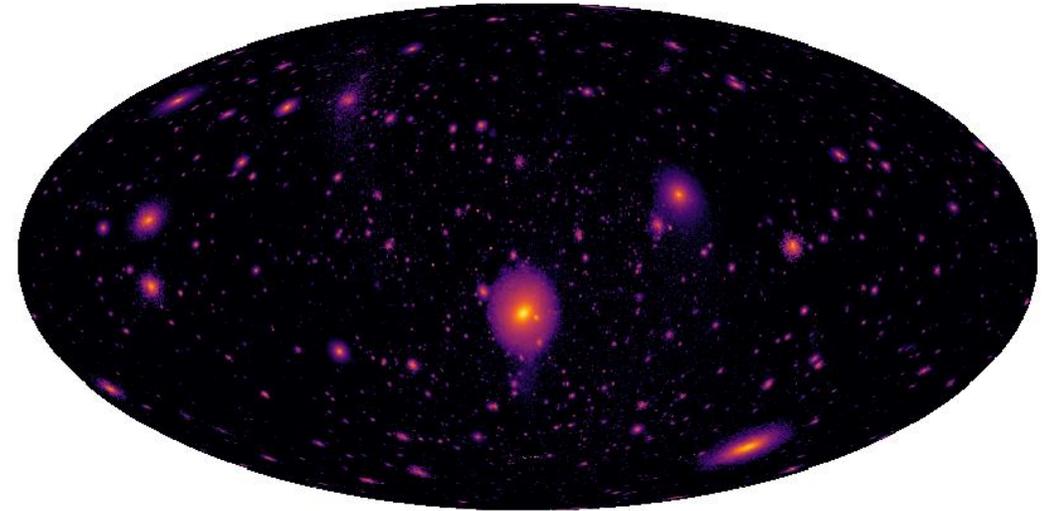
Alpha Magnetic Spectrometer/NASA

G15 HYDRO - Host flux



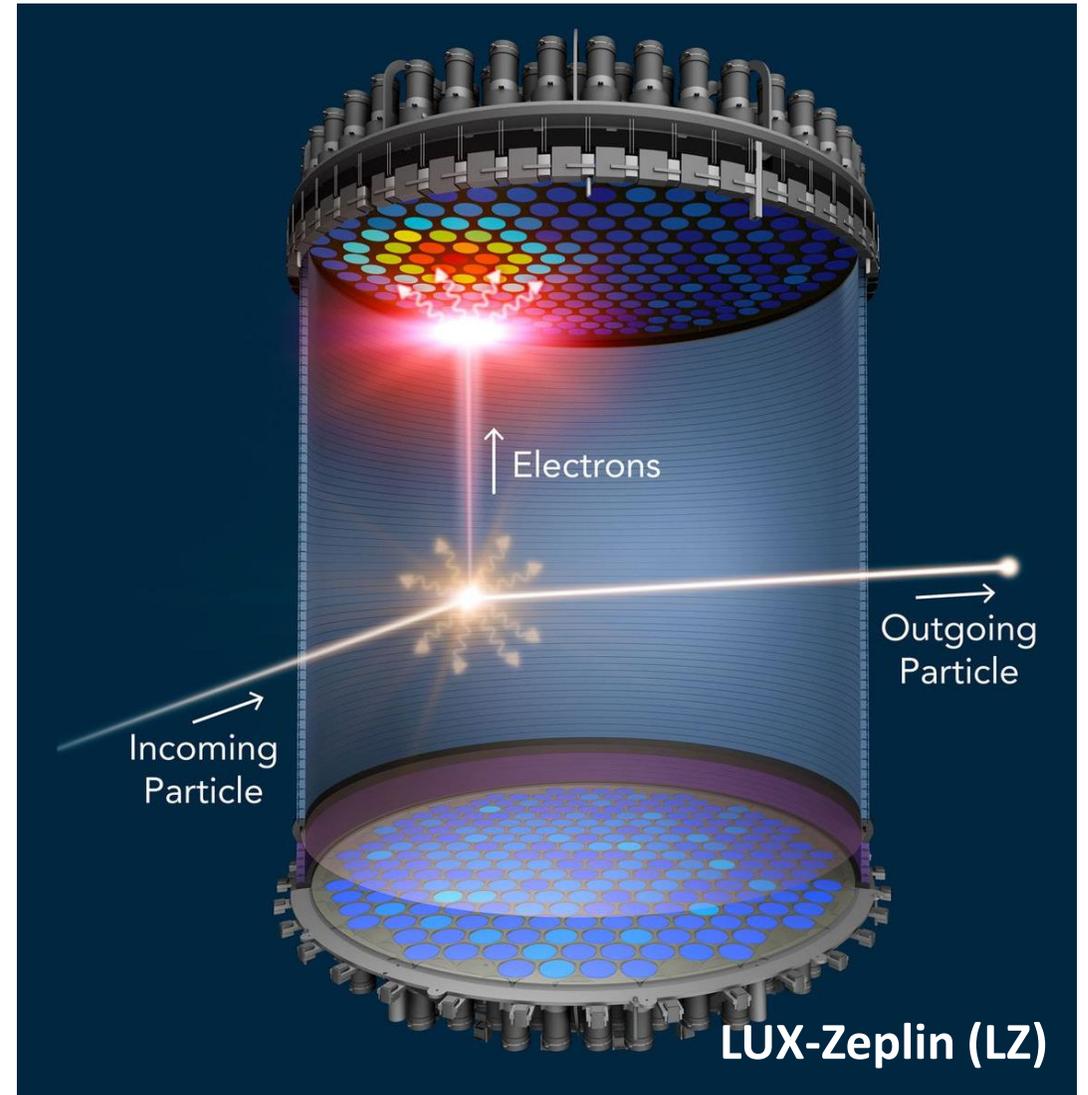
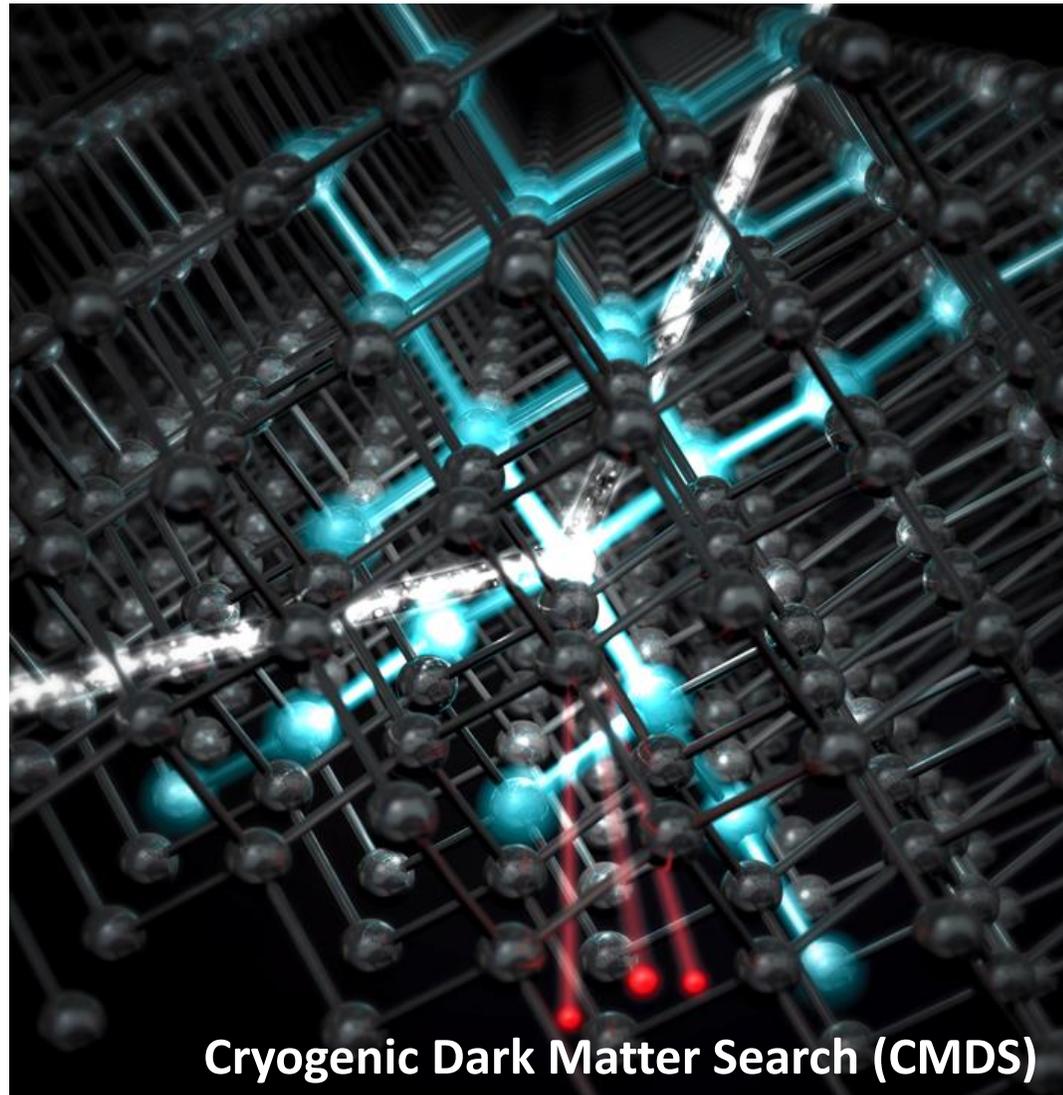
**ARTEMIS** simulations (Font et al 2020):  
Gamma-rays from the galaxy

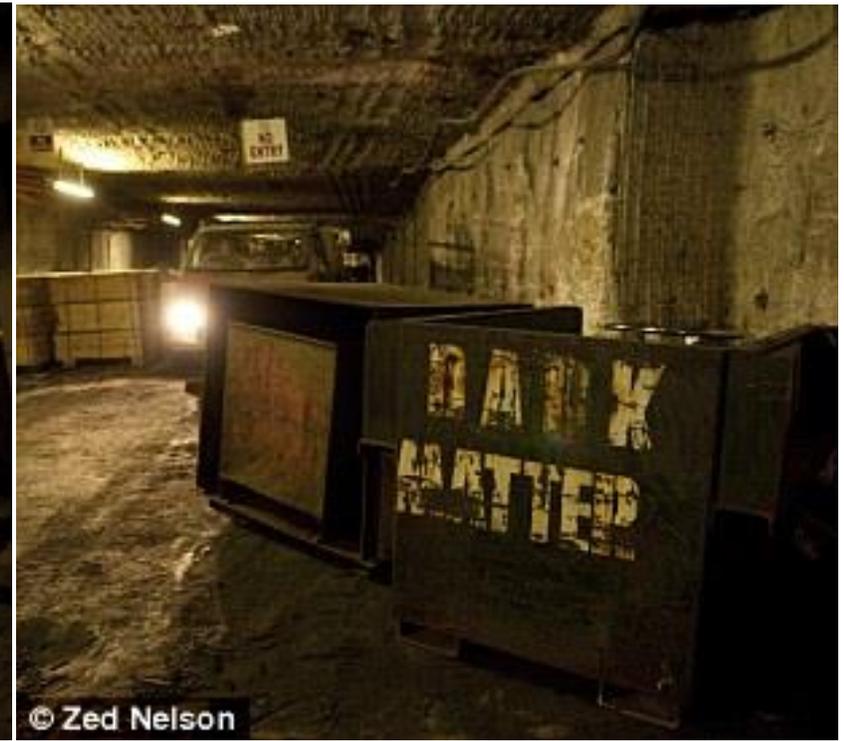
G15 HYDRO - Subhalo flux



**ARTEMIS** simulations:  
Gamma-rays from satellite galaxies

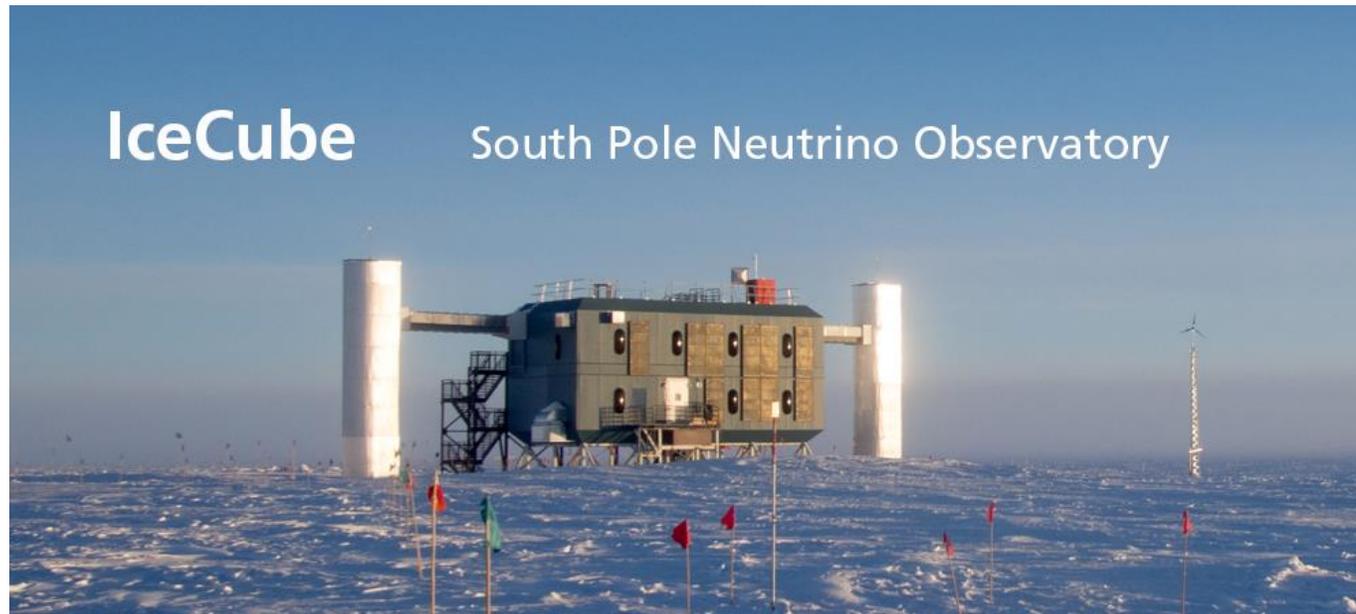
(Images: Rob Poole-Mckenzie)

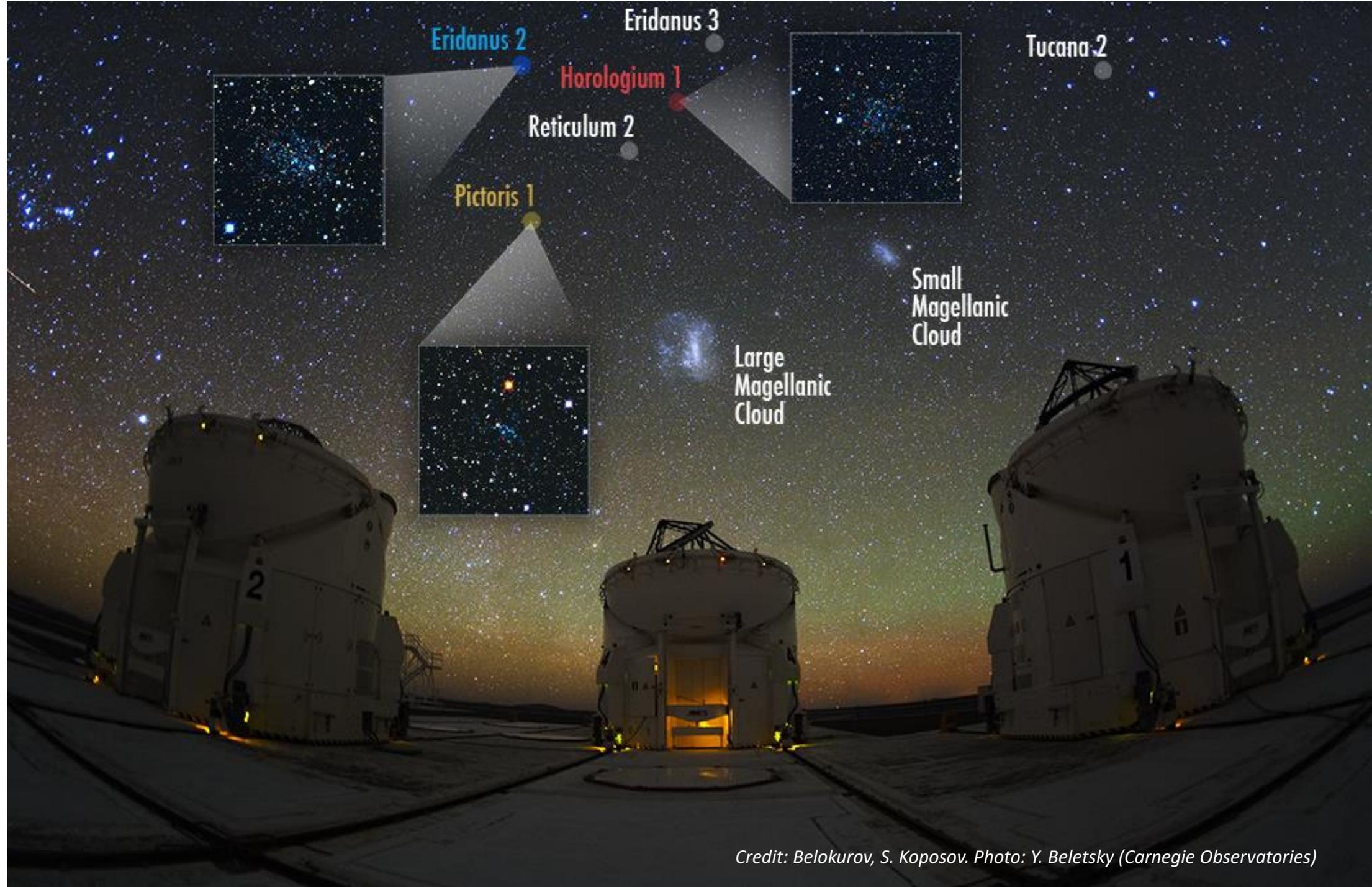




IceCube

South Pole Neutrino Observatory

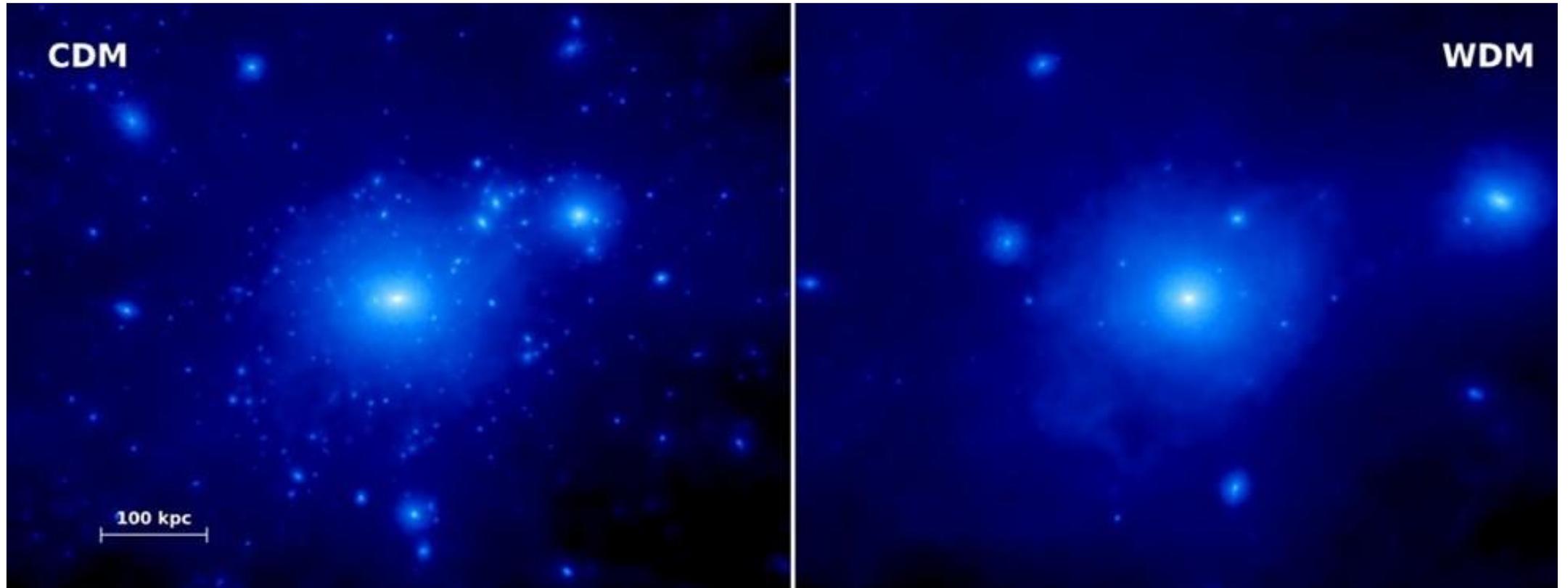




Credit: Belokurov, S. Koposov. Photo: Y. Beletsky (Carnegie Observatories)

**COLD**

**WARM**



C. Boehm et al. 2014

# Conclusions

- The search for dark matter continues. There are many ongoing and planned experiments that may detect it.
- If WIMPs are not the answer, there are lots of theories for what dark matter might be. [Yours here?]
- Theory and experiment need to go hand in hand for final confirmation.
- Dark matter may end up to be something very simple. It will be great when we'll find it, but searching for it is also exciting!