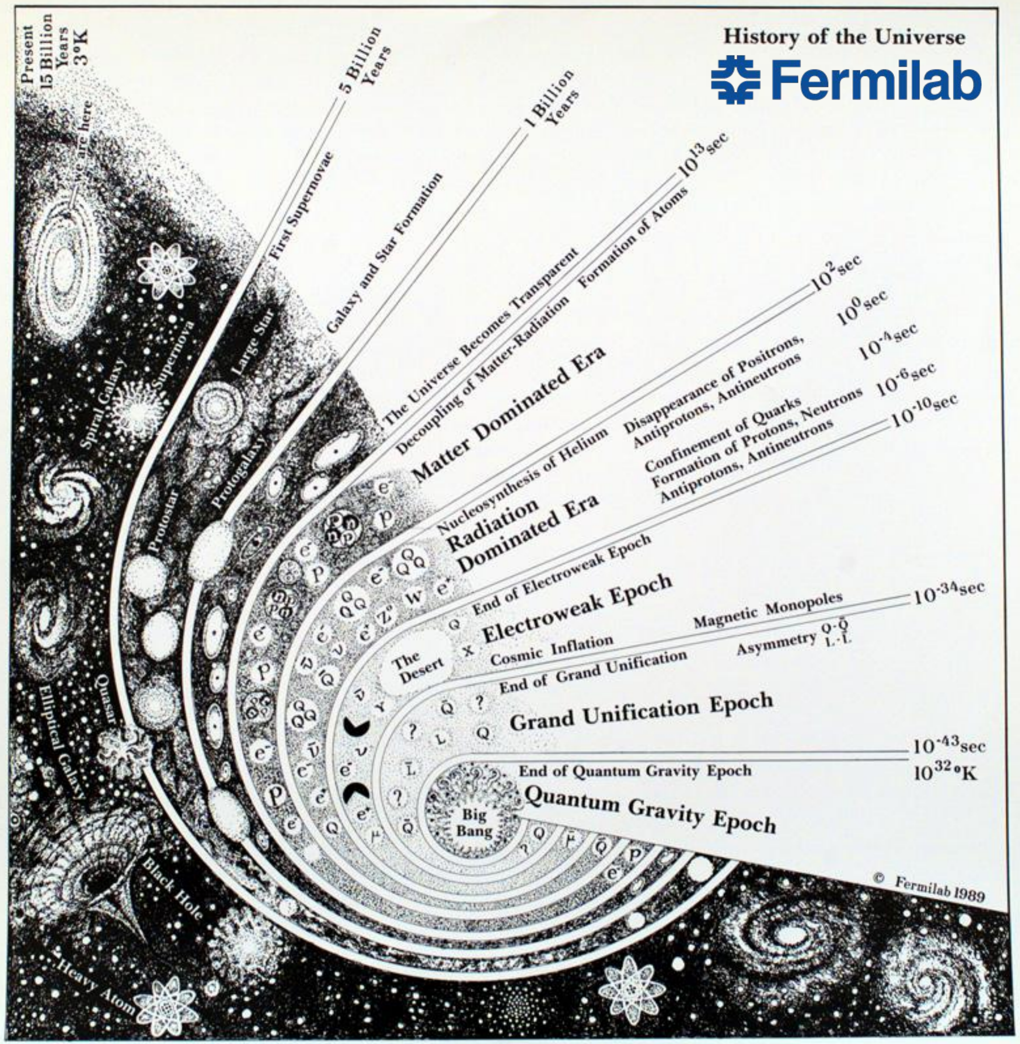
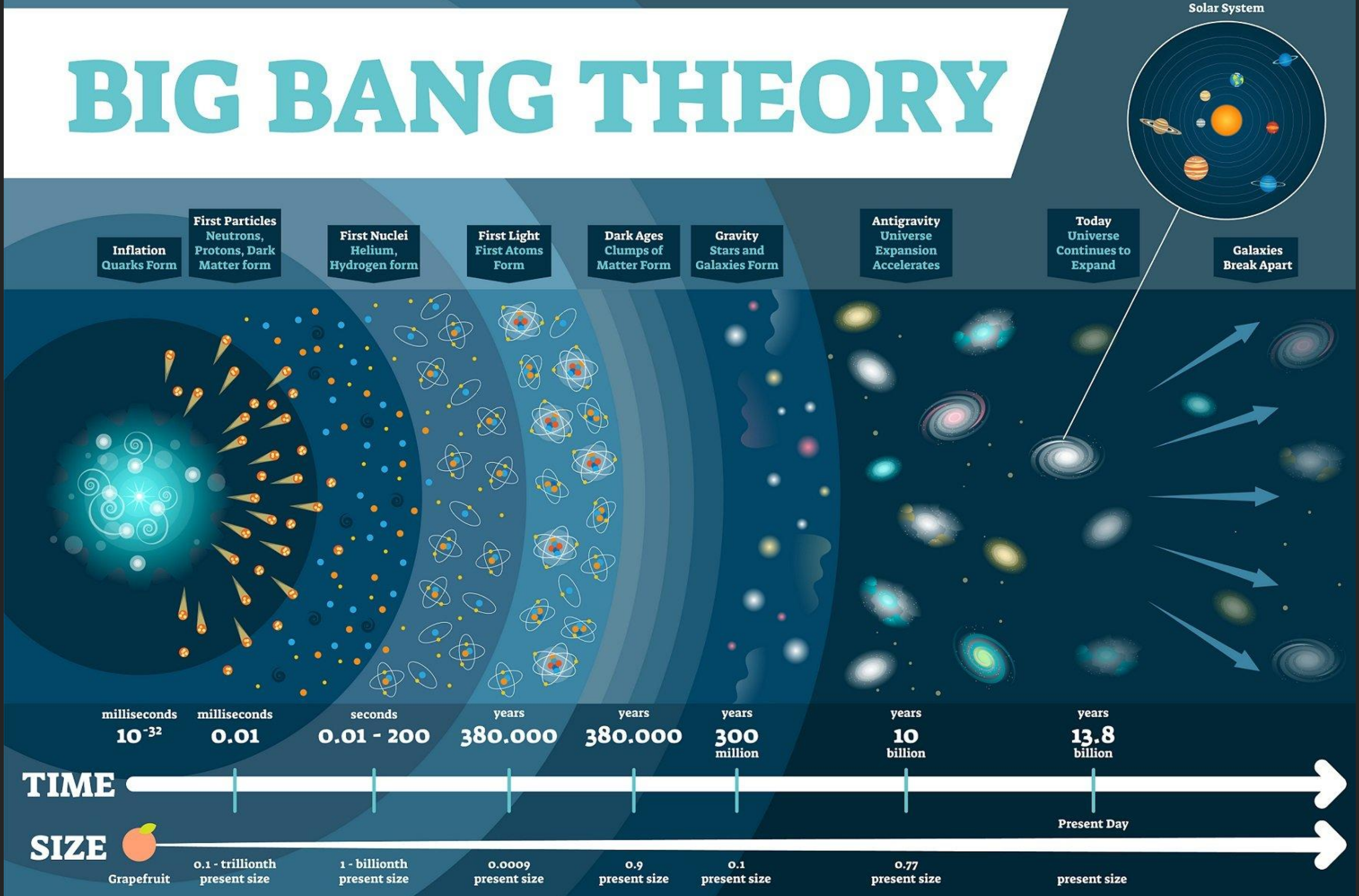


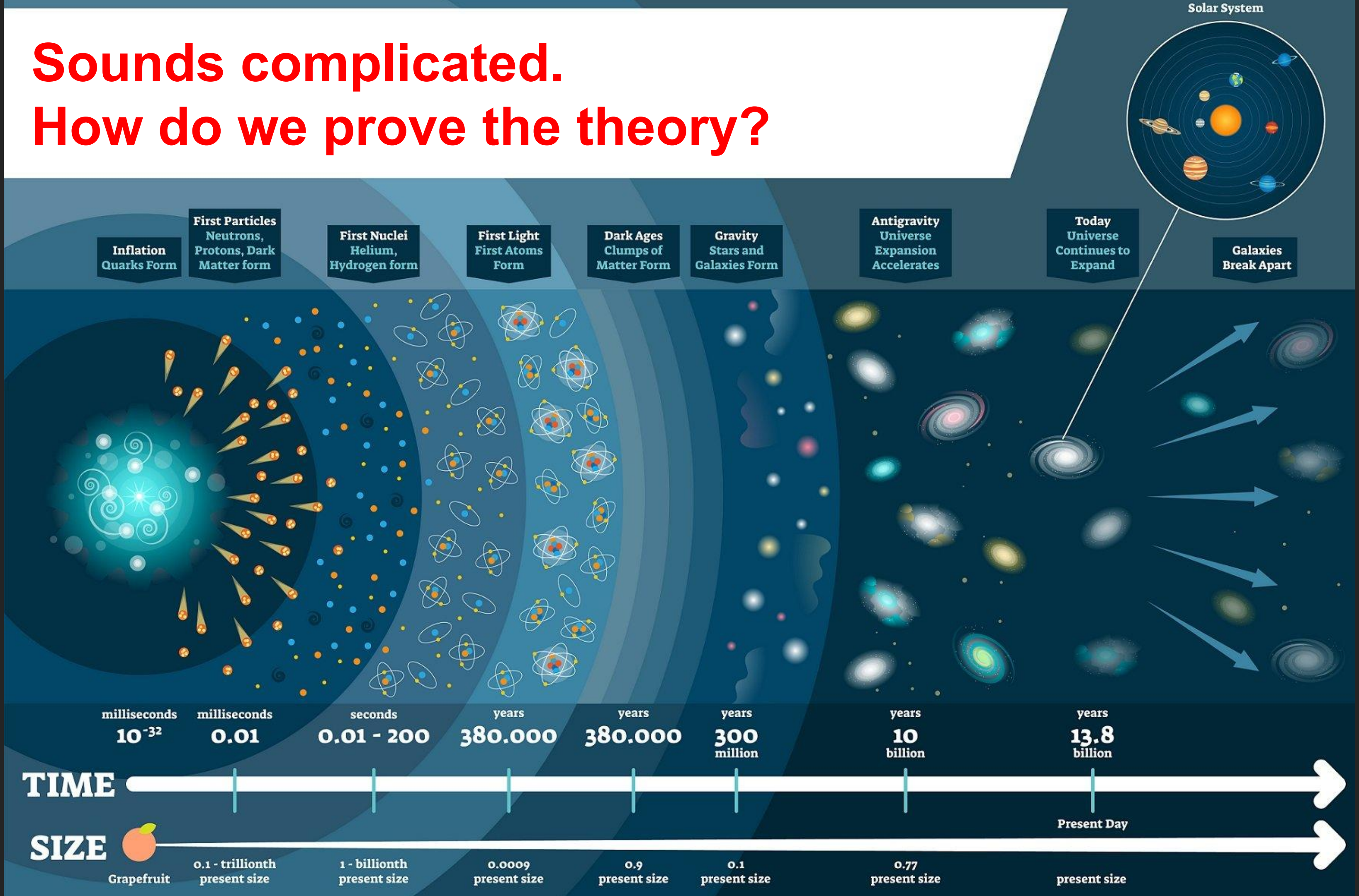
Particle Physics and Cosmology

HCPSS
July 2024

Aleksandra Ćiprijanović
Wilson Fellow Associate Scientist
Data Science, Simulation, and Learning Division
aleksand@fnal.gov


BIG BANG THEORY
Solar System
Inflation
Quarks Form
First Particles
Neutrons, Protons, Dark Matter form
First Nuclei
Helium, Hydrogen form
First Light
First Atoms Form
Dark Ages
Clumps of Matter Form
Gravity
Stars and Galaxies Form
Antigravity
Universe Expansion Accelerates
Today
Universe Continues to Expand
Galaxies Break Apart
milliseconds
10^-32
milliseconds
0.01
seconds
0.01 - 200
years
380.000
years
380.000
years
300 million
years
10 billion
years
13.8 billion
TIME
Present Day
SIZE
Grapefruit
0.1 - trillionth present size
1 - billionth present size
0.0009 present size
0.9 present size
0.1 present size
0.77 present size
present size

Sounds complicated.
How do we prove the theory?



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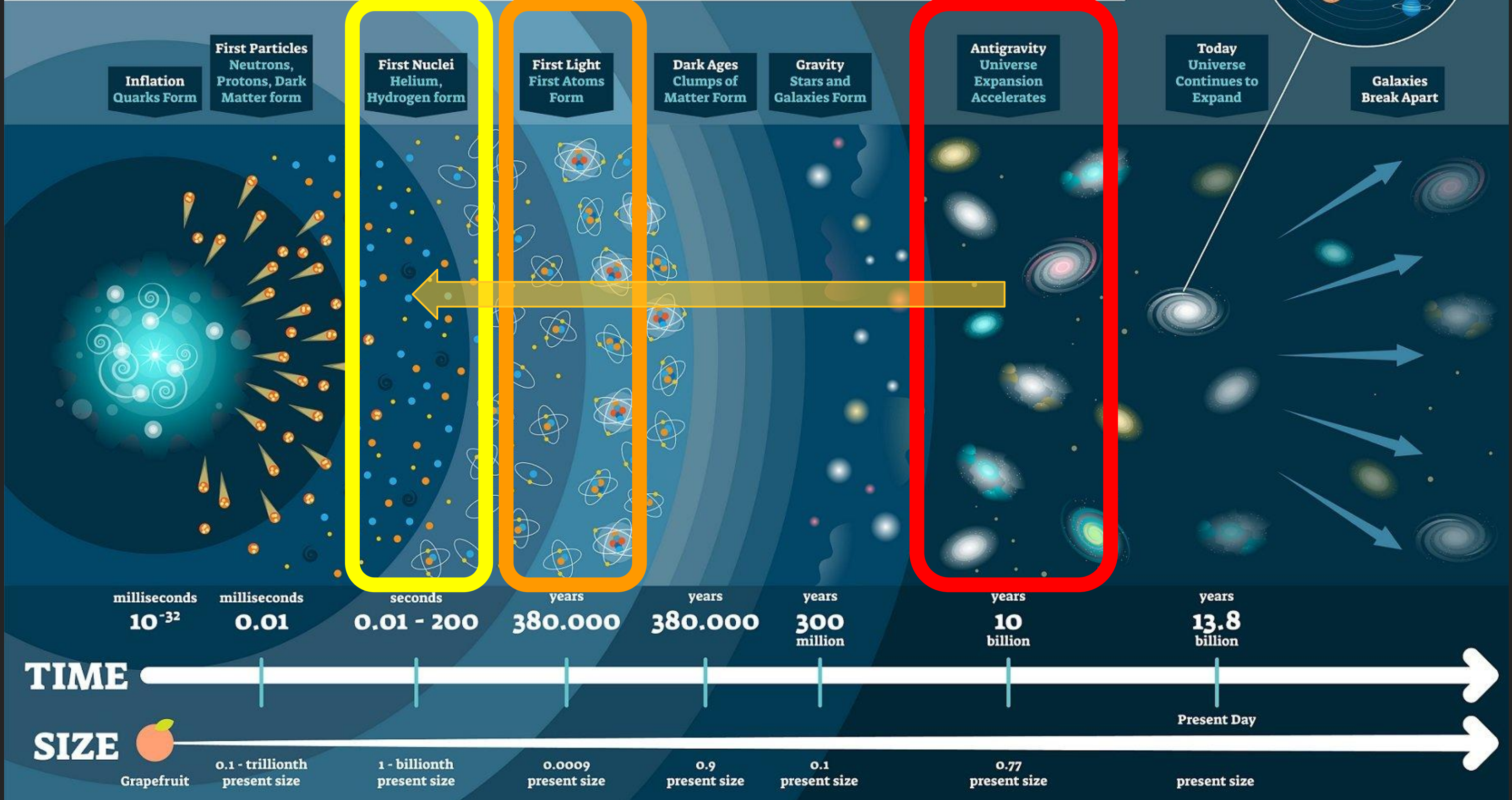

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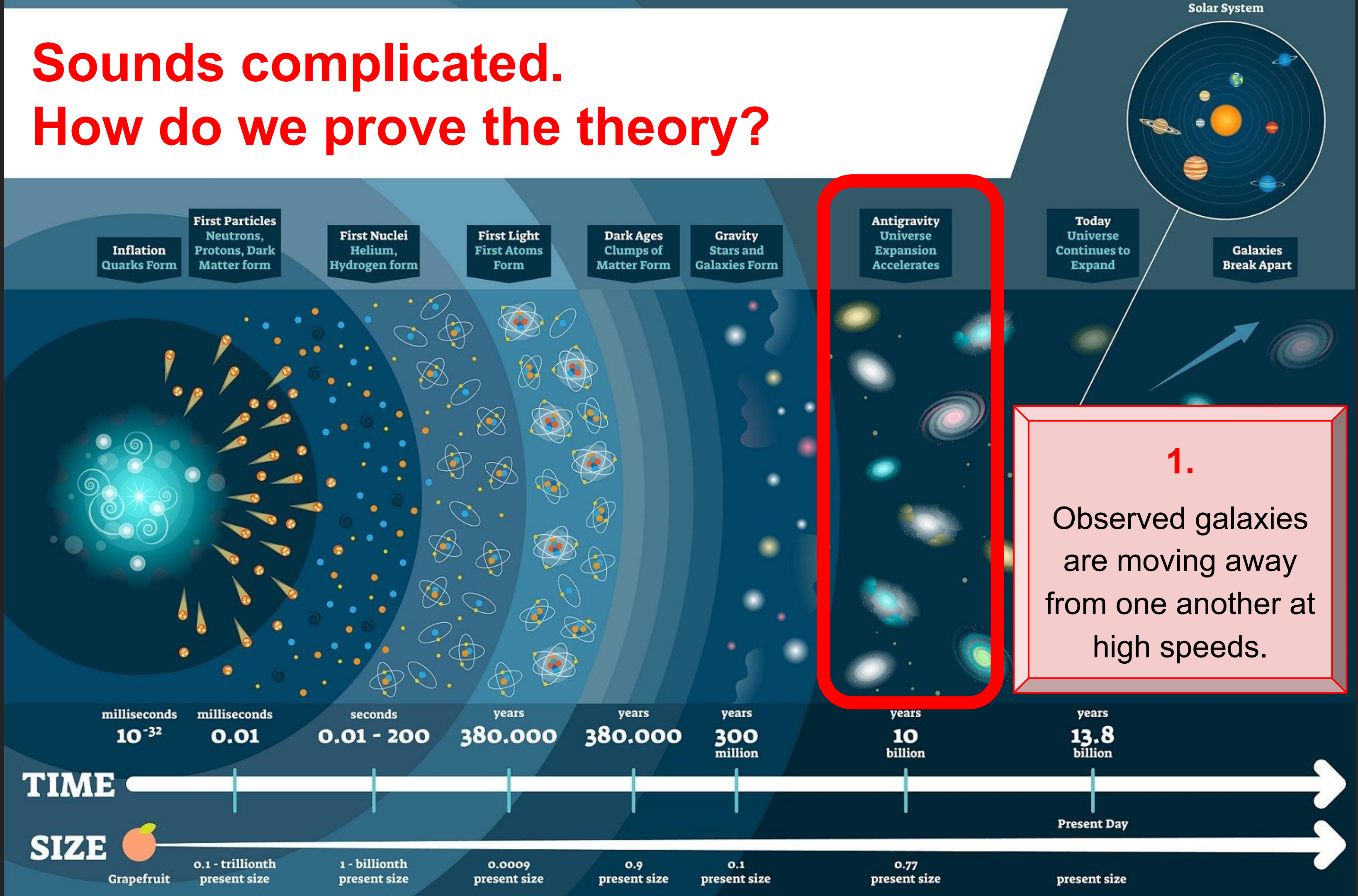

1.

Observed galaxies are moving away from one another at high speeds.

19th century

"Static cosmology" - Universe has no beginning and no end, stars move because of gravity, but structures in the universe are generally static.

19th century

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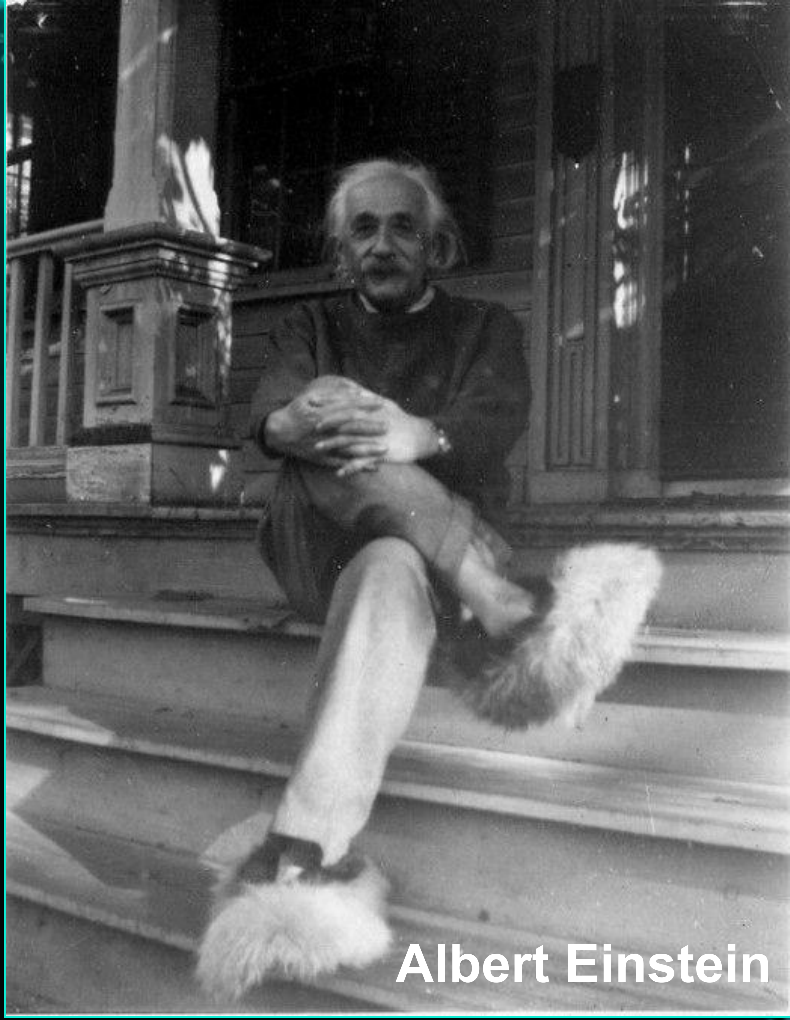
20th century

- **1905 – Special Theory of Relativity**, space and time are not separate continua.
- **1915 - General Theory of Relativity**, space can contract or expand.



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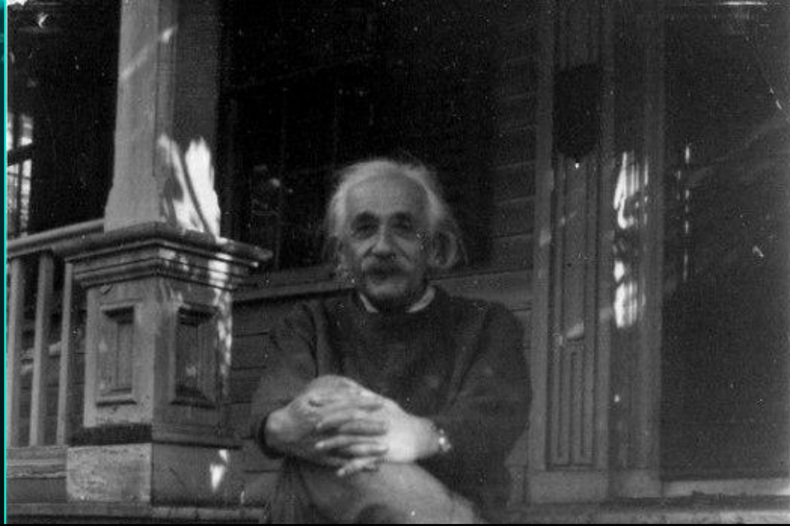

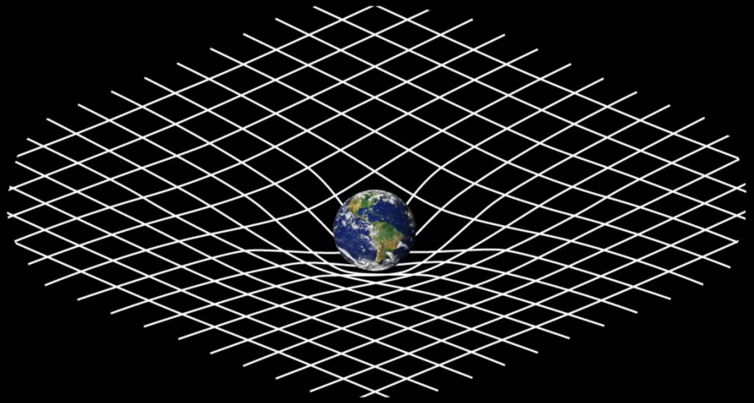

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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"Static cosmology" - Universe has no beginning and no end, stars move because of gravity, but structures in the universe are generally static.

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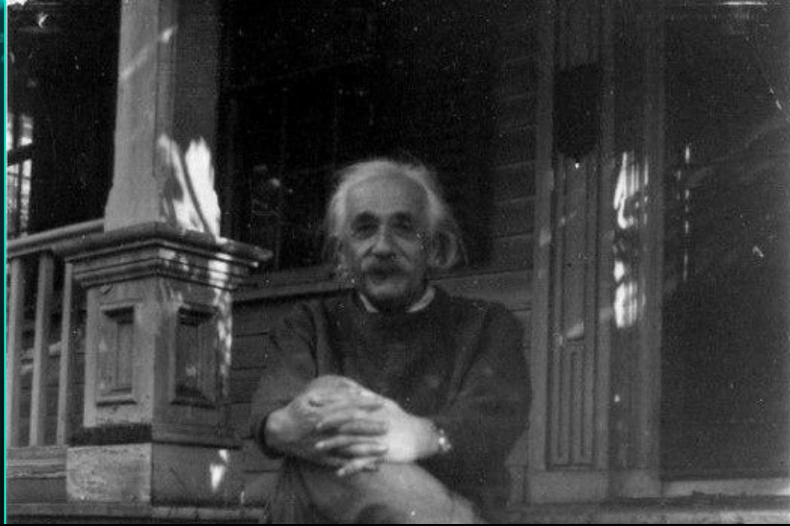
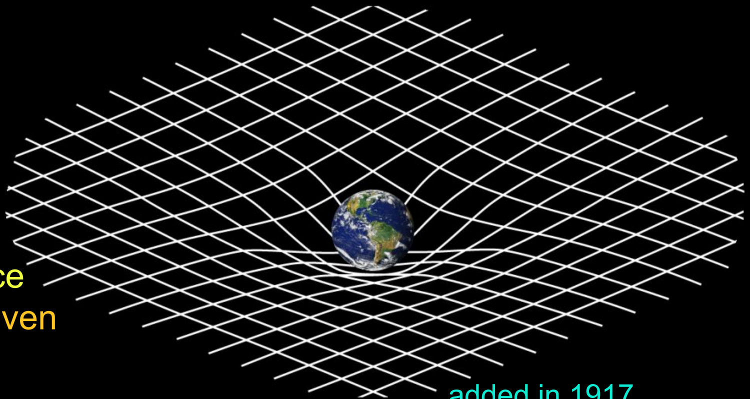




He accepts the idea of expanding universe in 1931.

1. Curvature change from place to place
2. How are distances calculated at a given point given the curvature
3. Mass-energy content (source of the curvature)
4. Cosmological constant opposing gravity

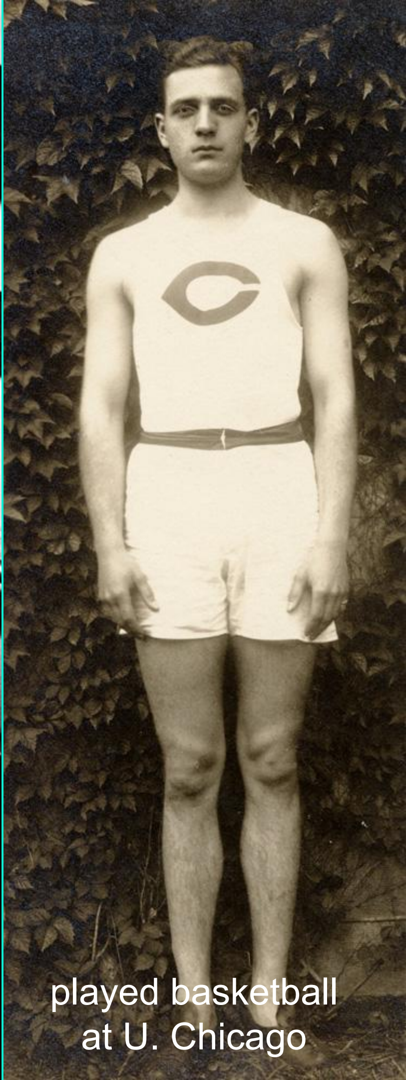
added in 1917.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Edwin Hubble
1889 – 1953

- Born in Missouri and moved to Wheaton, IL in 1900!

100 inch telescope at Mt. Wilson (near L.A.)



played basketball at U. Chicago

Edwin Hubble

1889 – 1953

- Born in Missouri and moved to Wheaton, IL in 1900!
- Discovered that nebulae we observe are in fact other Galaxies like our Milky Way!
- Measured **distances** and **velocities** to galaxies.

100 inch telescope at Mt. Wilson (near L.A.)

FINDS SPIRAL NEBULAE ARE STELLAR SYSTEMS

Dr. Hubbell Confirms View That They Are 'Island Universes' Similar to Our Own.

WASHINGTON, Nov. 22.—Confirmation of the view that the spiral nebulae, which appear in the heavens as whirling clouds, are in reality distant stellar systems, or "island universes," has been obtained by Dr. Edwin Hubbell of the Carnegie Institution's Mount Wilson observatory, through investigations carried out with the observatory's powerful telescopes.

The number of spiral nebulae, the observatory officials have reported to the Institution, is very great, amounting to hundreds of thousands, and their apparent sizes range from small objects, almost star-like in character, to the great nebulae in Andromeda, which extends across an angle some 3 degrees in the heavens, about six times the diameter of the full moon.

"The investigations of Dr. Hubbell were made photographically with the 60-inch and 100-inch reflectors of the Mount Wilson observatory," the report said, "the extreme faintness of the stars under examination making necessary the use of these great telescopes. The revolving power of these instruments breaks up the outer portions of the nebulae into swarms of stars, which may be studied individually and compared with those in our own system.

"From an investigation of the photographs thirty-six variable stars of the type referred to, known as Cepheid variables, were discovered in the two spirals, Andromeda and No. 33, of Messier's great catalogue of nebulae. The study of the periods of these stars and the application of the relationship between length of period and intrinsic brightness at once provided the means of determining the distances of these objects.

"The results are striking in their confirmation of the view that these spiral nebulae are distant stellar systems. They are found to be about ten times as far away as the small Magellanic cloud, or at a distance of the order of 1,000,000 light years. This means that light traveling at the rate of 186,000 miles a second has required a million years to reach us from these nebulae and that we are observing them by light which left them in the Pliocene age upon the earth.

"With a knowledge of the distances of these nebulae we find for their diameters 45,000 light years for the Andromeda nebulae and 15,000 light years for Messier 33. These quantities, as well as the masses and densities of the systems, are quite comparable with the corresponding values for our local system of stars."

FUNDS FOR SCHENCK HOUSE

William C. Redfield Says It Was Built of Timbers of Old Ship.

William C. Redfield, formerly Secretary of Commerce and now the President of the Netherland-America Foundation, 17 East Forty-second Street, was one of the many who were interested in the news printed in yesterday's TIMES that an offer had been submitted to Murray Hulbert, President of the Board of Aldermen, to sell to the city for $10,000 the old Schenck homestead at Mill Basin, Brooklyn, which is believed to be the oldest house in New York City.

Mr. Redfield, in a letter to Mr. Hulbert yesterday, said that the Schenck house was built out of the timbers of an ancient ship. The old beams are visible and the knees of the old vessel still support the upper floors.

"I earnestly hope that funds may be made available, in order that this exceptional landmark of our city's history may be preserved," wrote Mr. Redfield. Mrs. Redfield is connected by marriage with the Schenck family.

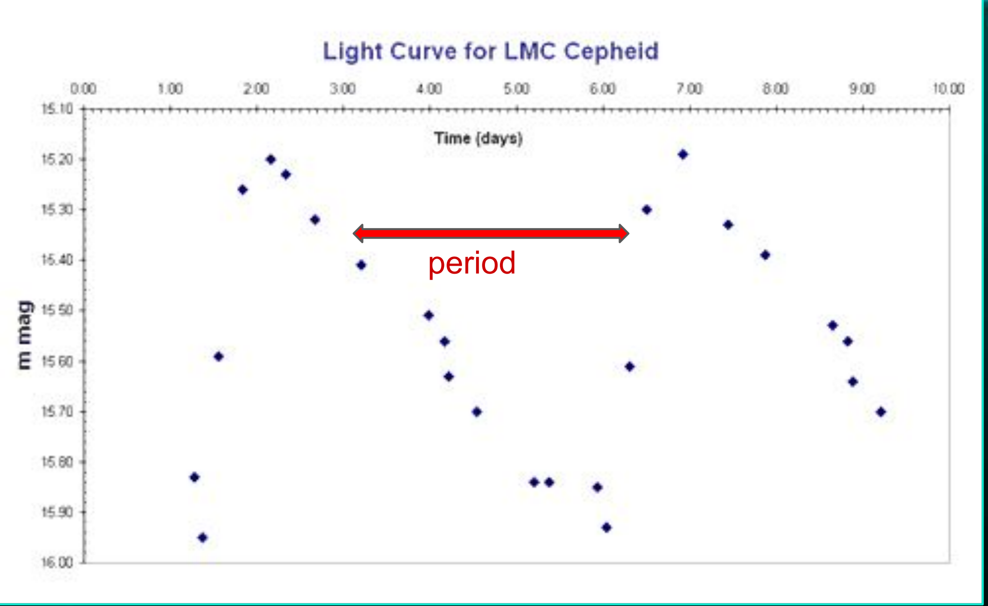
Published 1924.

The New York Times

Distances are measured using Cepheid stars

Henrietta Swan Leavitt
1868 - 1921

Harvard College Observatory
Observing stars in Small and Large Magellanic Clouds



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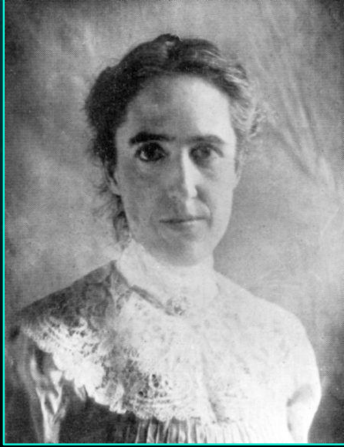
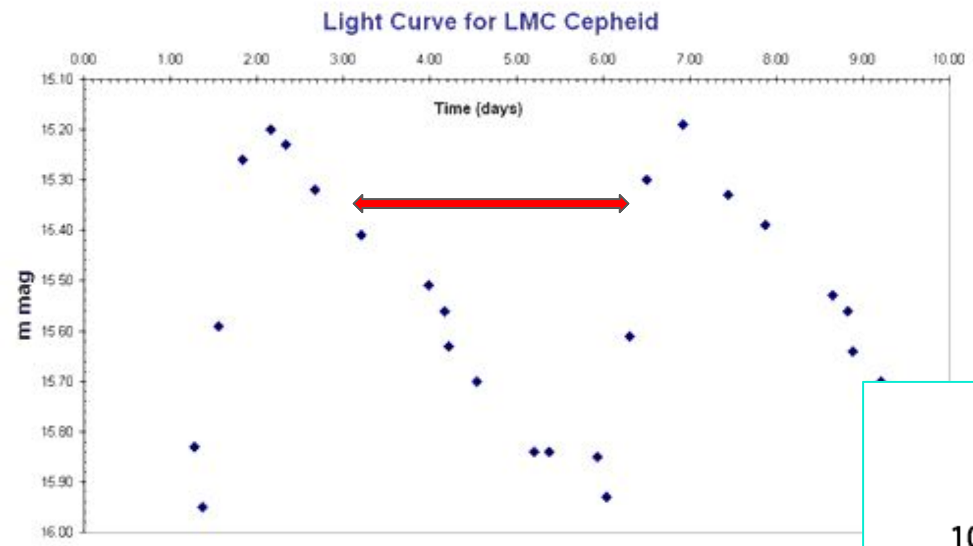


Some stars in these two nebulae have variable brightnesses!



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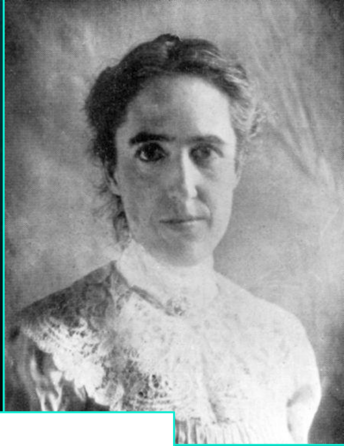
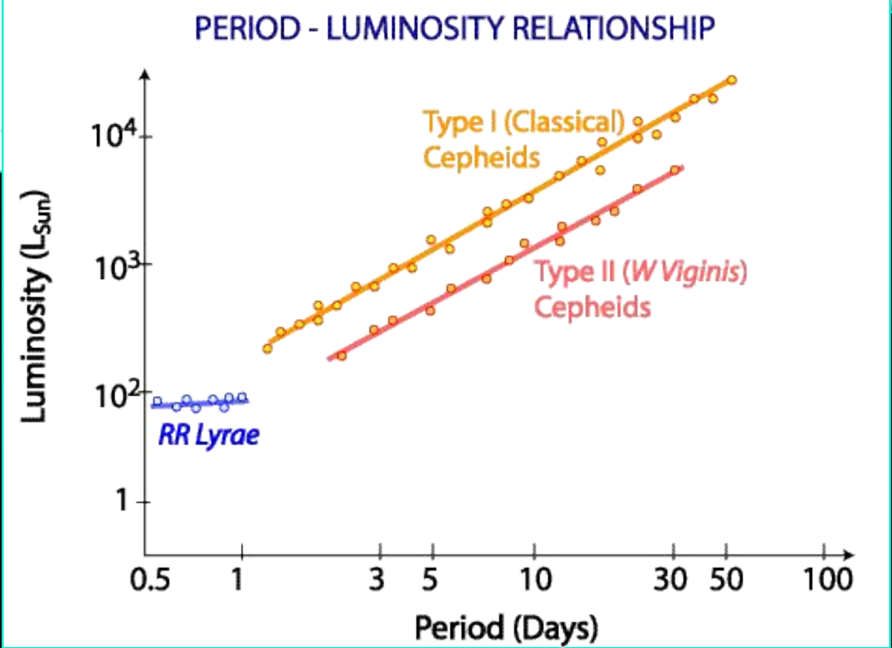
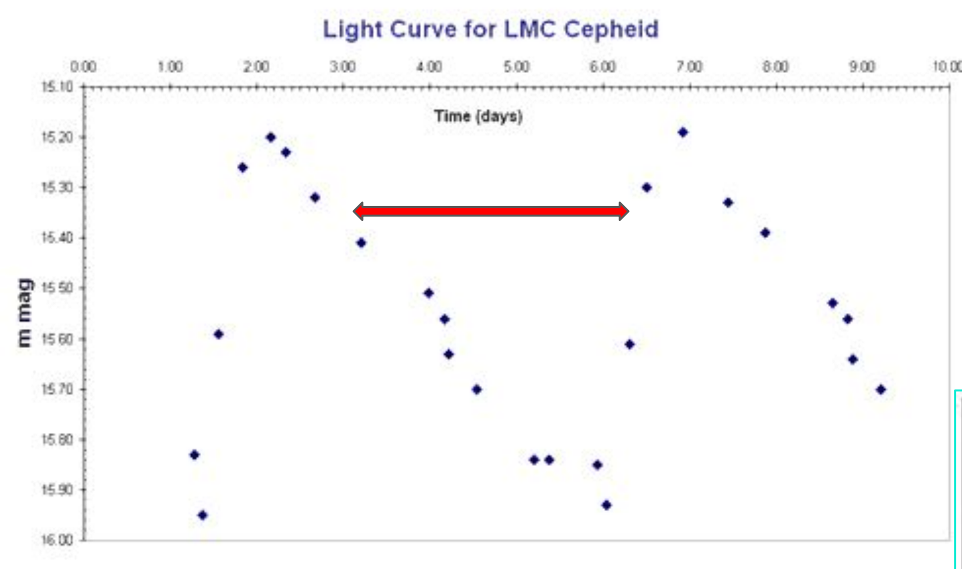


Some stars in these two nebulae have variable brightnesses!

Brighter stars have longer periods!





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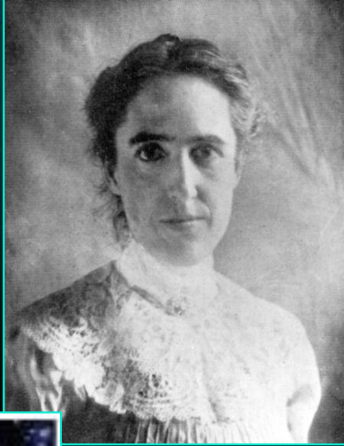

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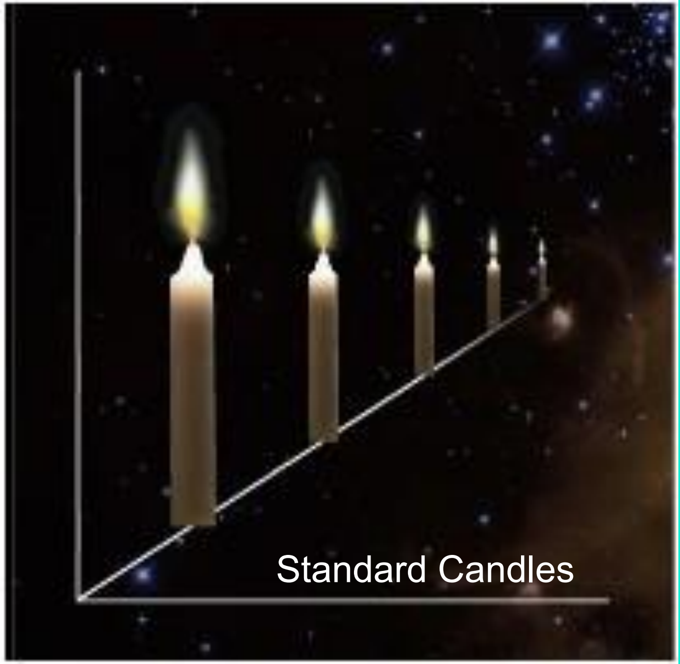
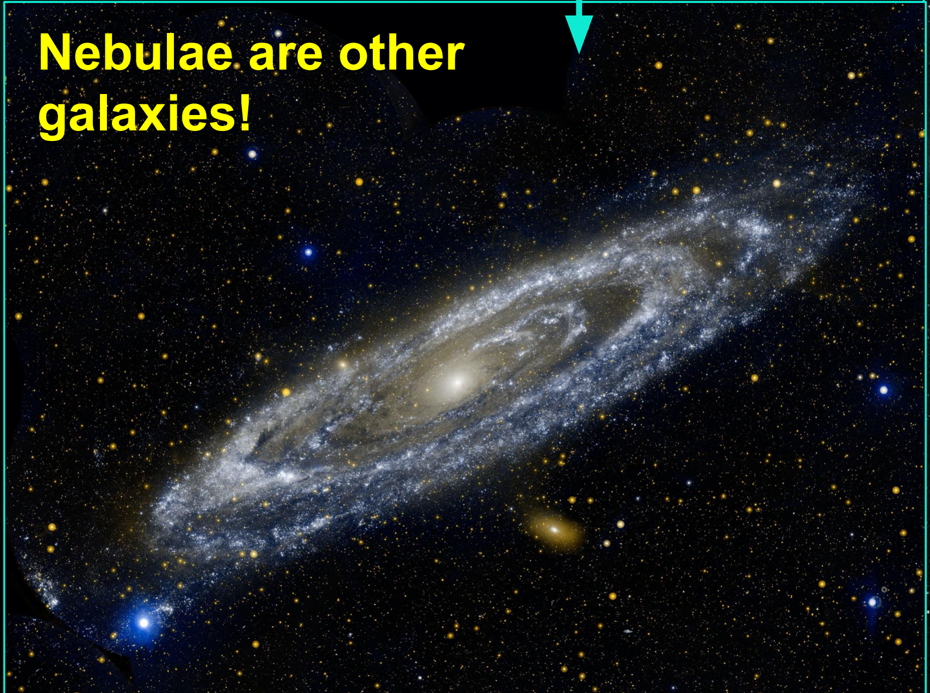
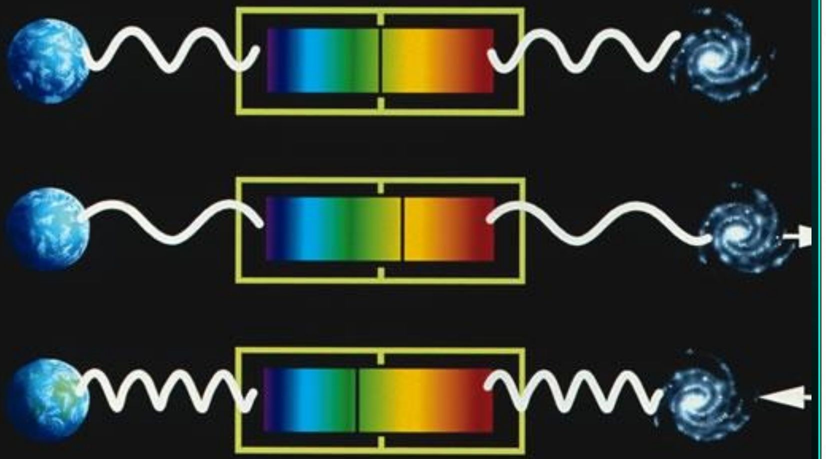


Hubble - finds Cepheids in Andromeda and M33 (Triangulum)

Andromeda is 930,000 light years away.

But Milky Way has a diameter of only 100,000 light years!





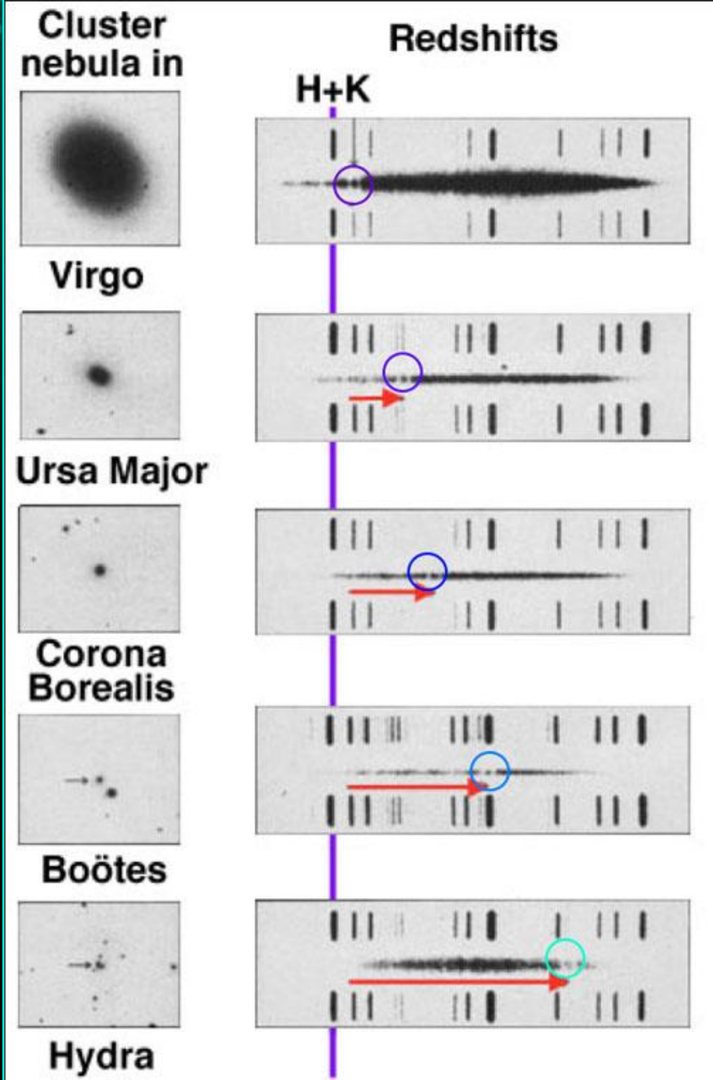
Vesto Slipher

1875 - 1969

Lowell Observatory, Arizona

1912. - **Velocities can be measured using the Doppler Effect!**

Slipher was first to observe the **shift of spectral lines of galaxies**, making him the discoverer of **galactic redshifts**.



More distant galaxies seem to be moving away faster!

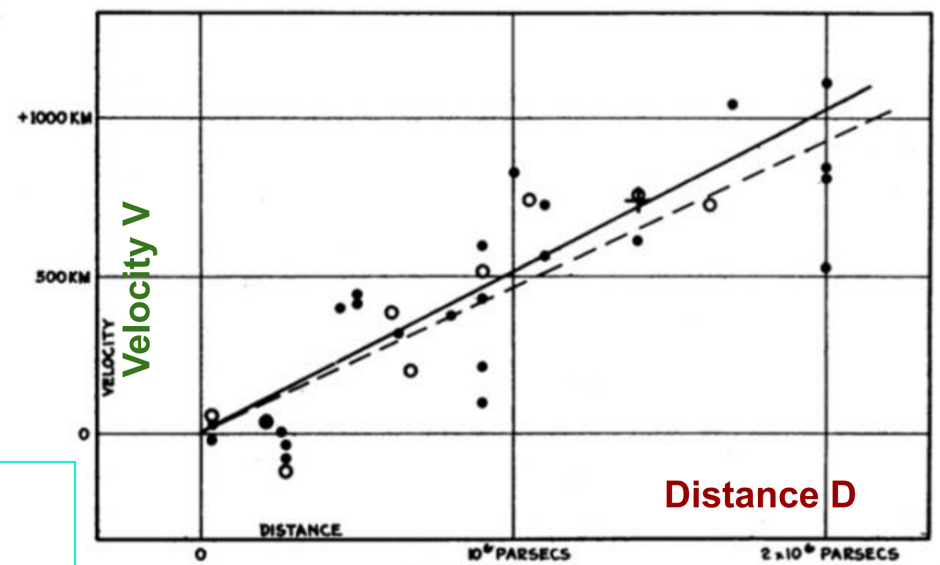
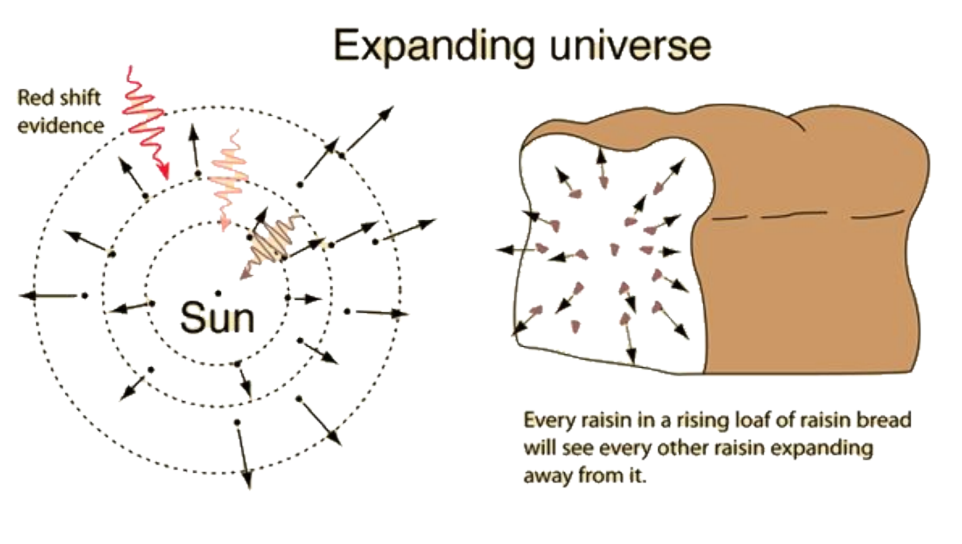
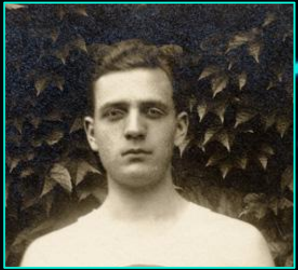


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

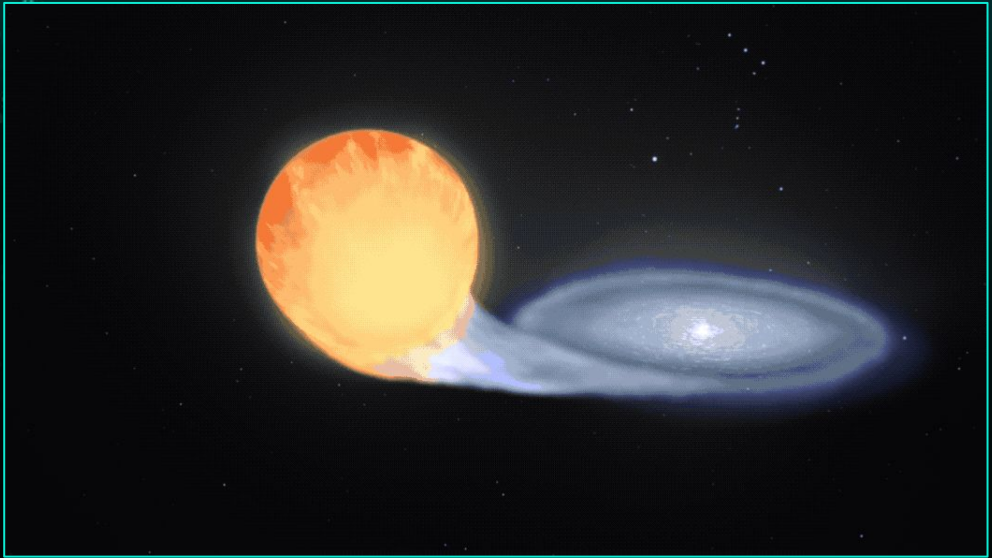


$$V = H\,D$$



Back to Hubble…

The expansion is accelerating!



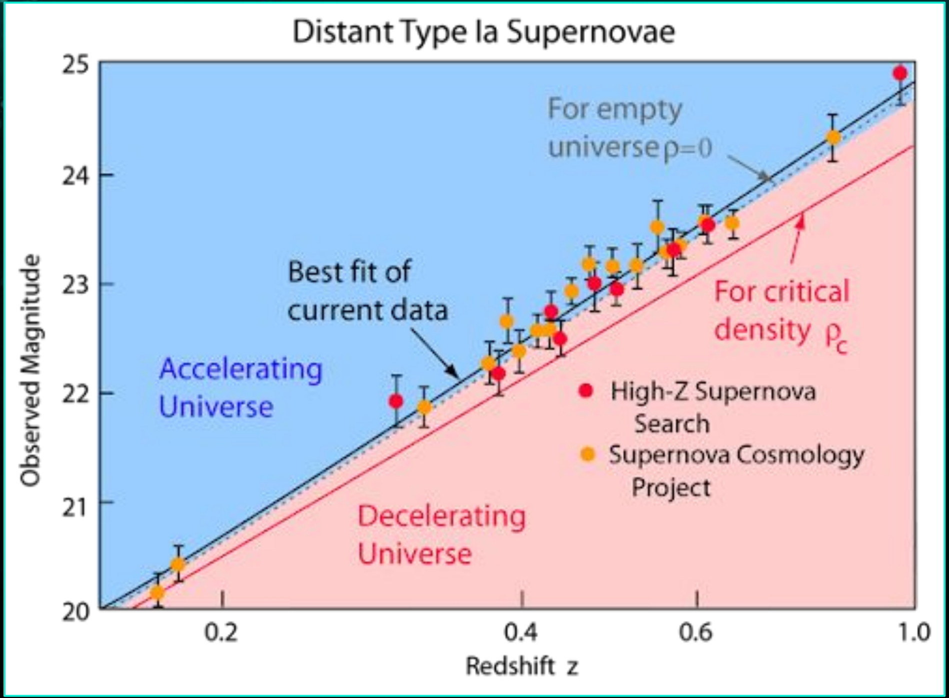
S. Perlmutter A. Riess B. Schmidt

Type Ia supernova

They can be used as standard candles but to much larger distances - they are super bright!

5 billion times brighter than the Sun

The expansion is accelerating!

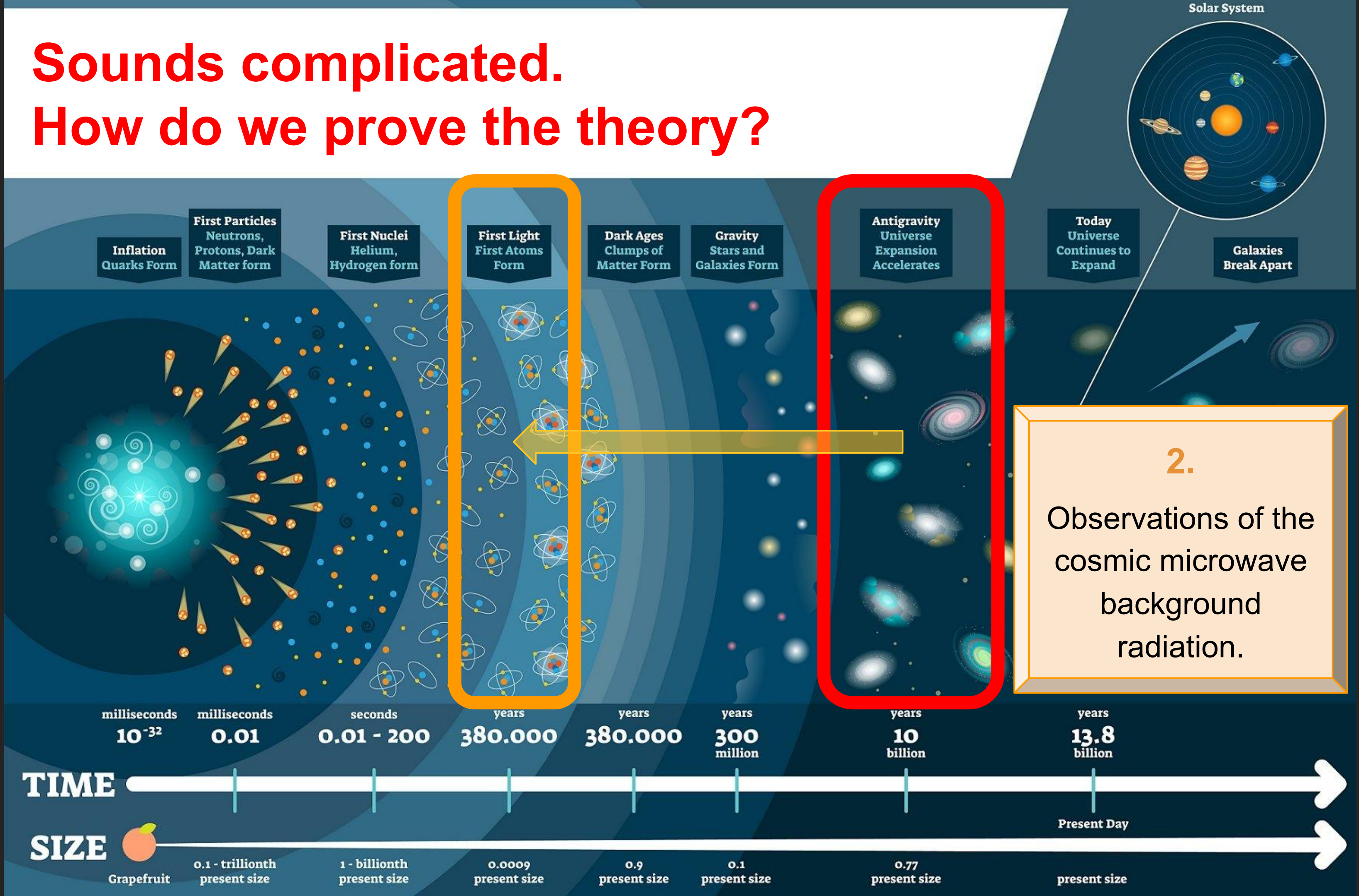


S. Perlmutter A. Riess B. Schmidt

Nobel Prize 2011.

Distant supernovae show that the speed of galaxies receding in relation to the Milky Way increases over time!

Sounds complicated.
How do we prove the theory?



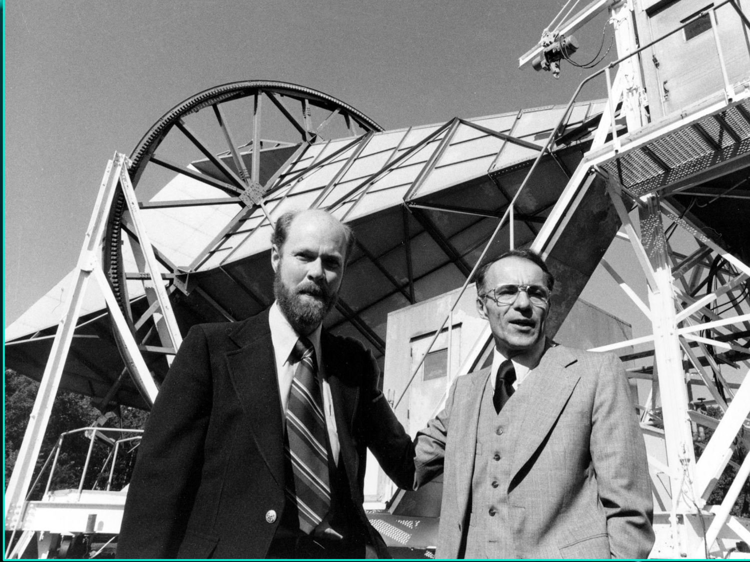
2.

Observations of the cosmic microwave background radiation.

We measure a 2.7 K signal.

380,000 yrs ago this signal was 3000K

Bell Labs, New Jersey, 1960.



Robert Wilson Anro Penzias

1965. - they publish the finding of a background "noise" coming from every direction.

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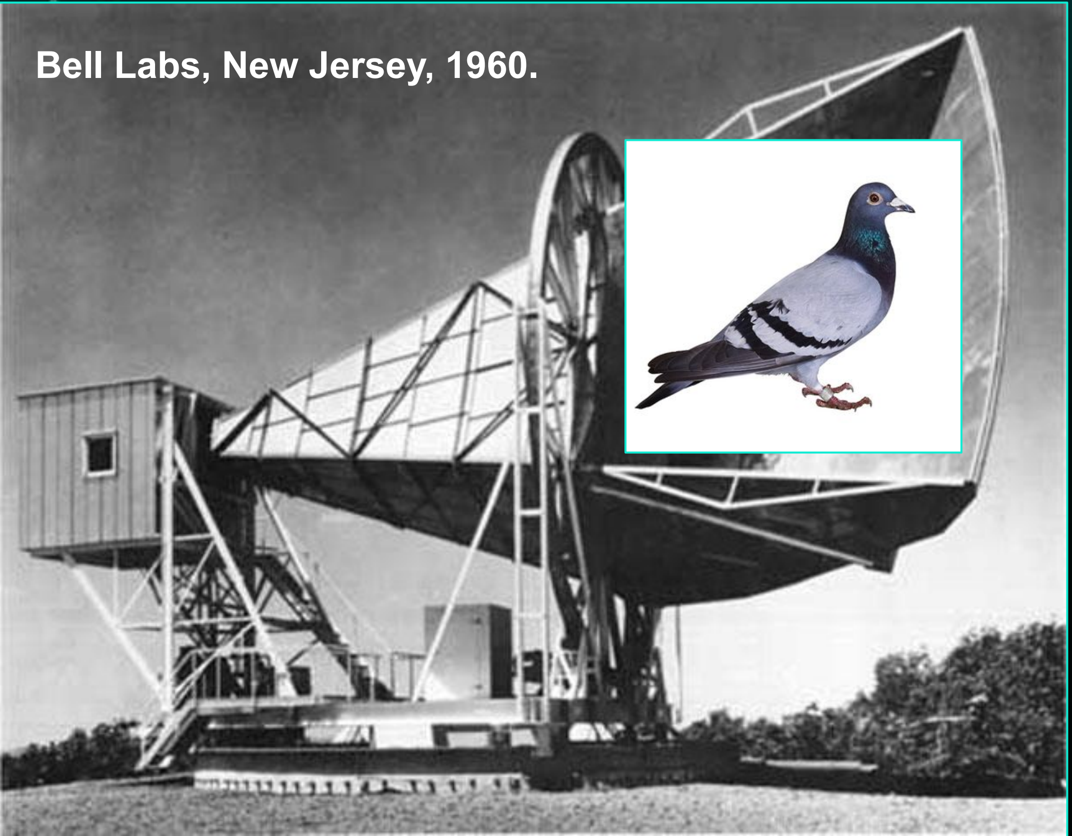

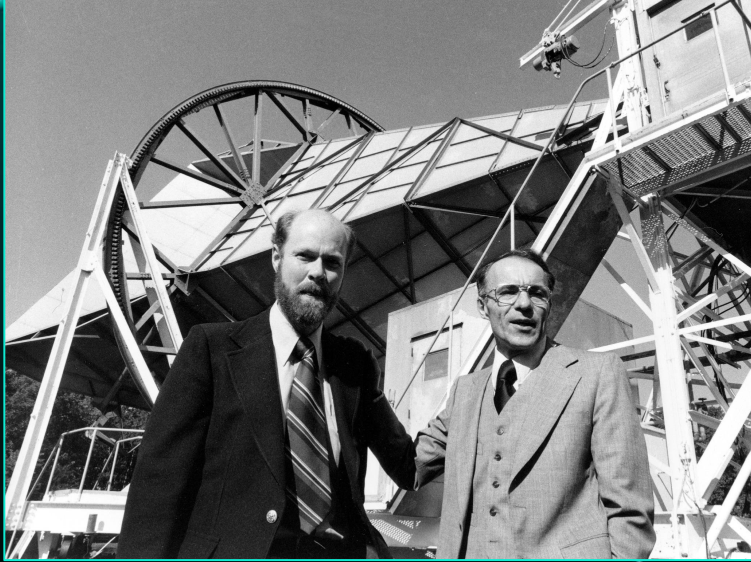

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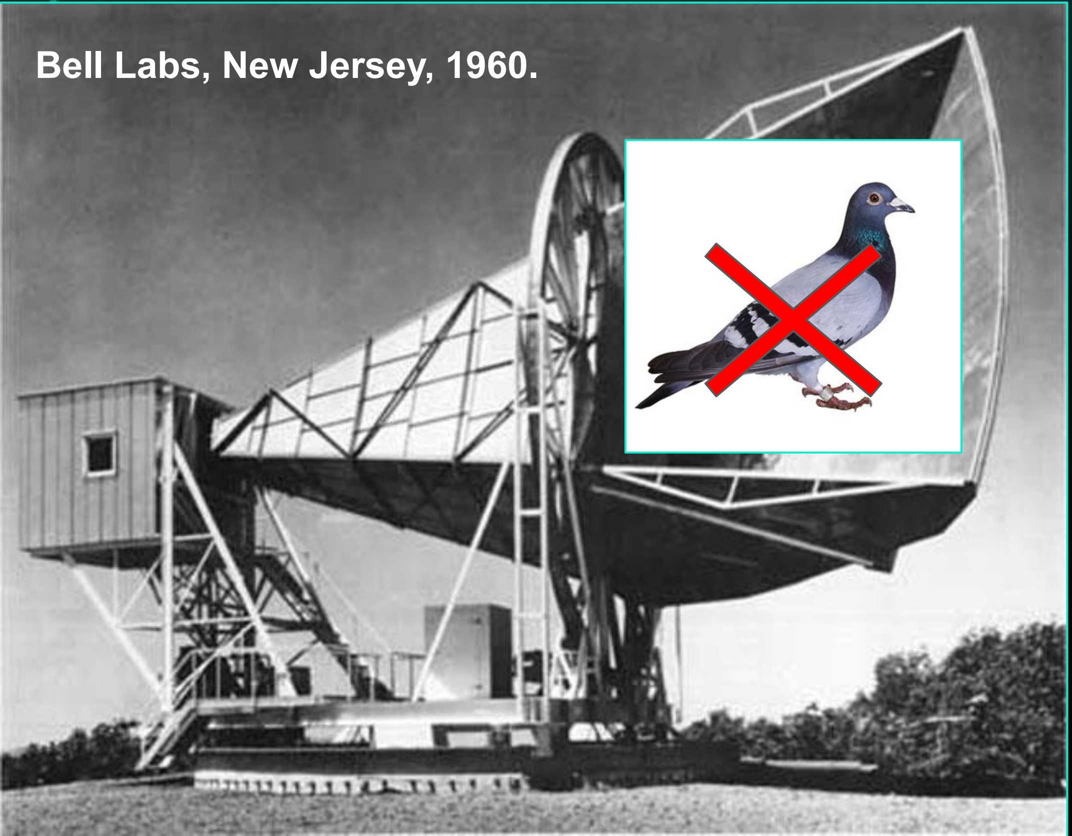

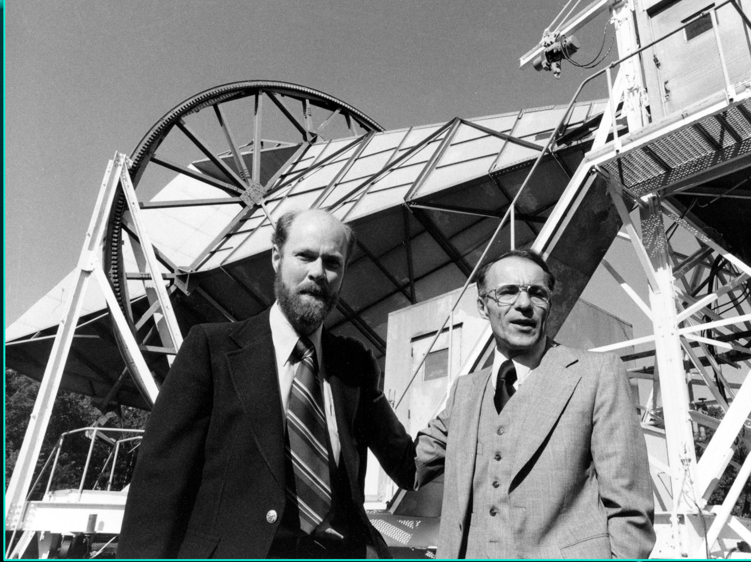

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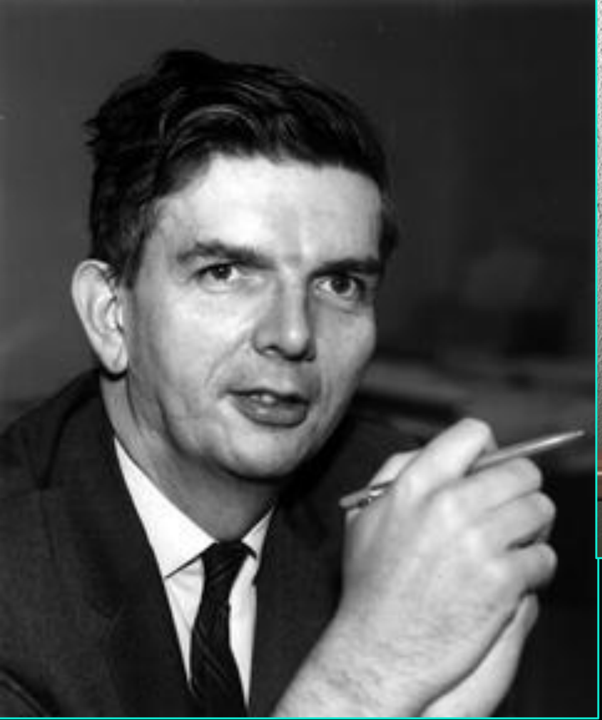


Robert Dicke

1916 - 1997

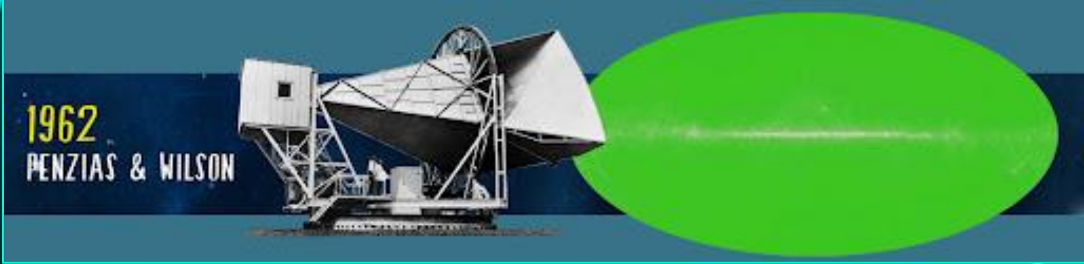
Princeton University

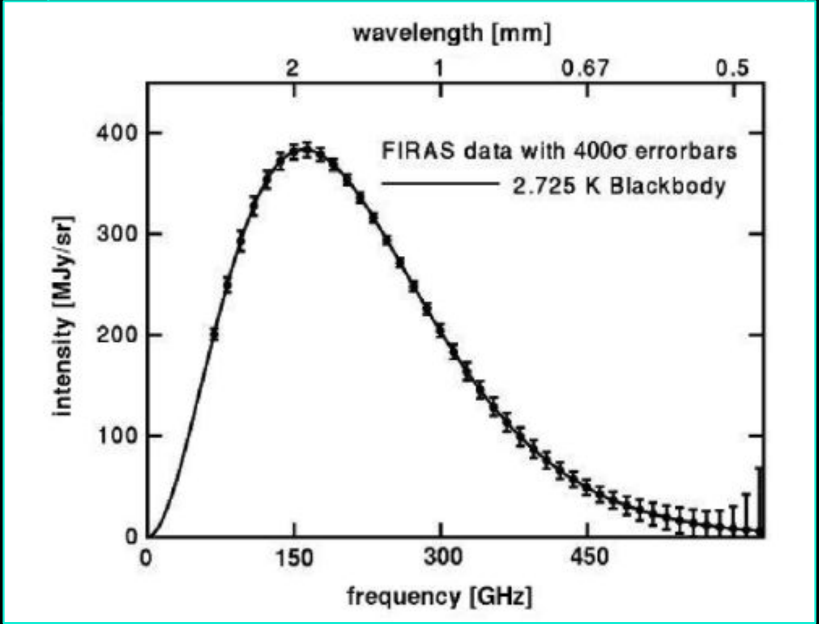
Nobel Prize 1987.

Penzias & Wilson

If there had been a big bang, the residue of the explosion should by now take the form of a low-level background radiation throughout the Universe.

With better telescopes we were able to see smaller and smaller fluctuations in the **2.7K signal**!





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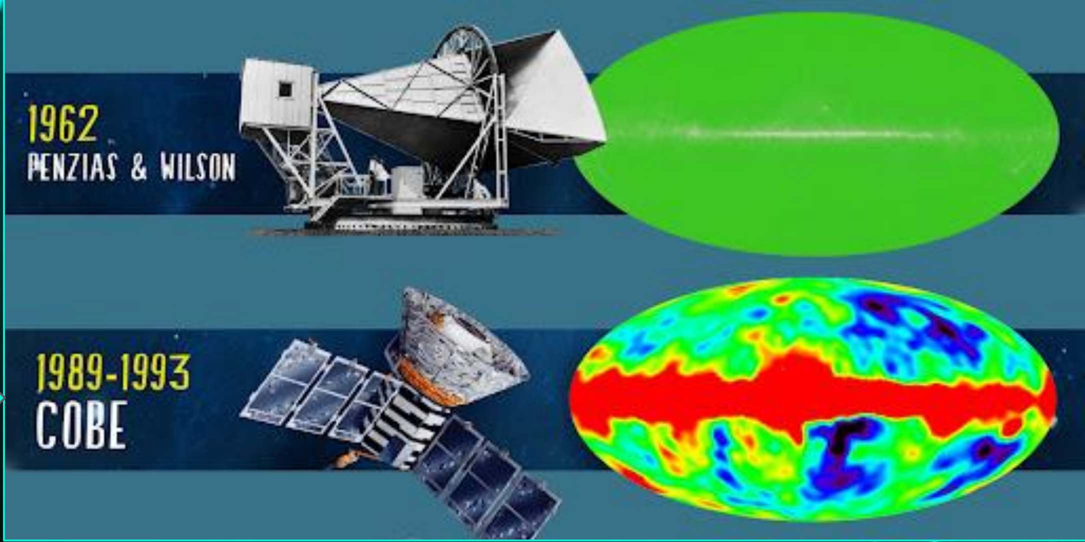
COBE: Resolution 7°

fluctuations of 0.0002 K



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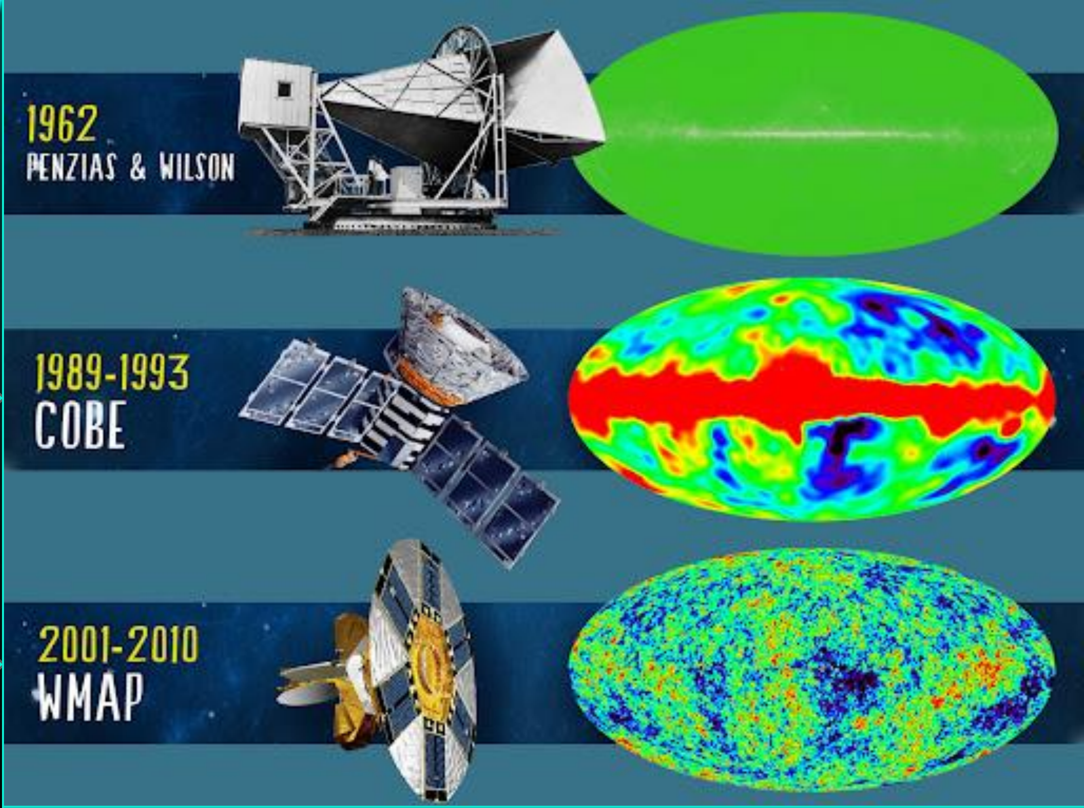
COBE: Resolution 7°

fluctuations of 0.0002 K

WMAP: 5 times better resolution 0.5°
0.00001 K



With better telescopes we were able to see smaller and smaller fluctuations in the **2.7K signal**!

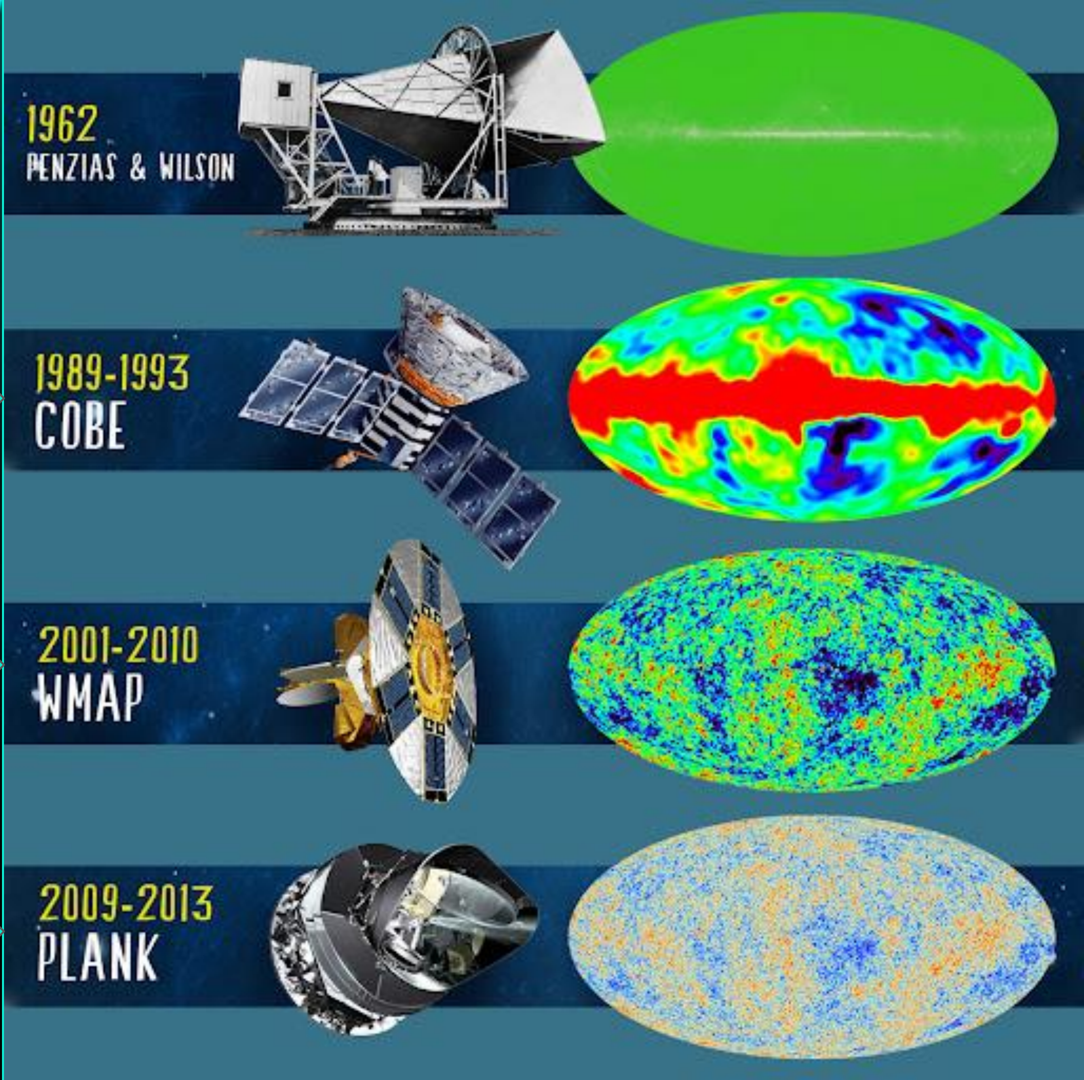
COBE: Resolution 7°

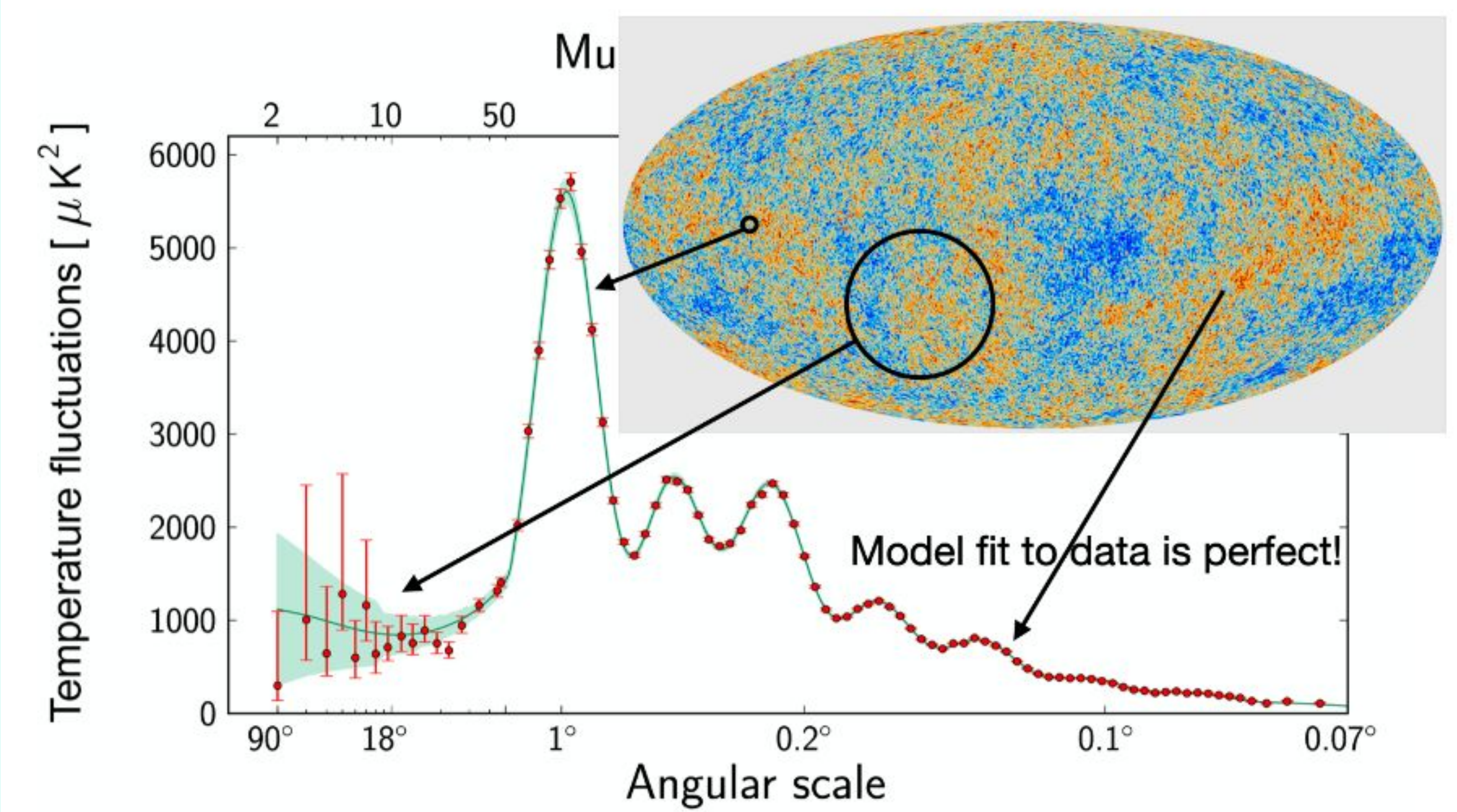
fluctuations of 0.0002 K

WMAP: 5 times better resolution 0.5°
0.00001 K

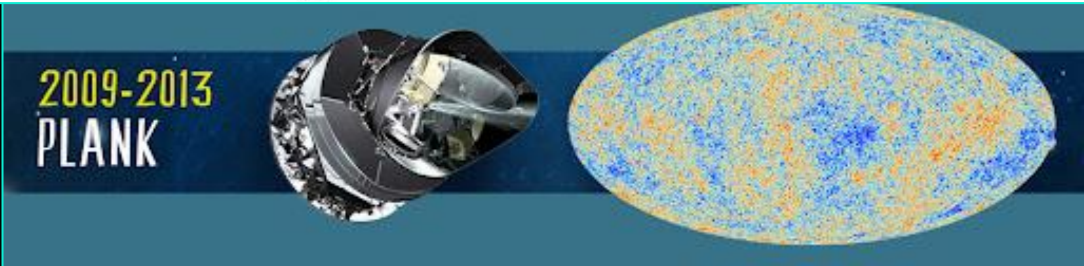
PLANK: 15 times better 0.16°

0.000001 K

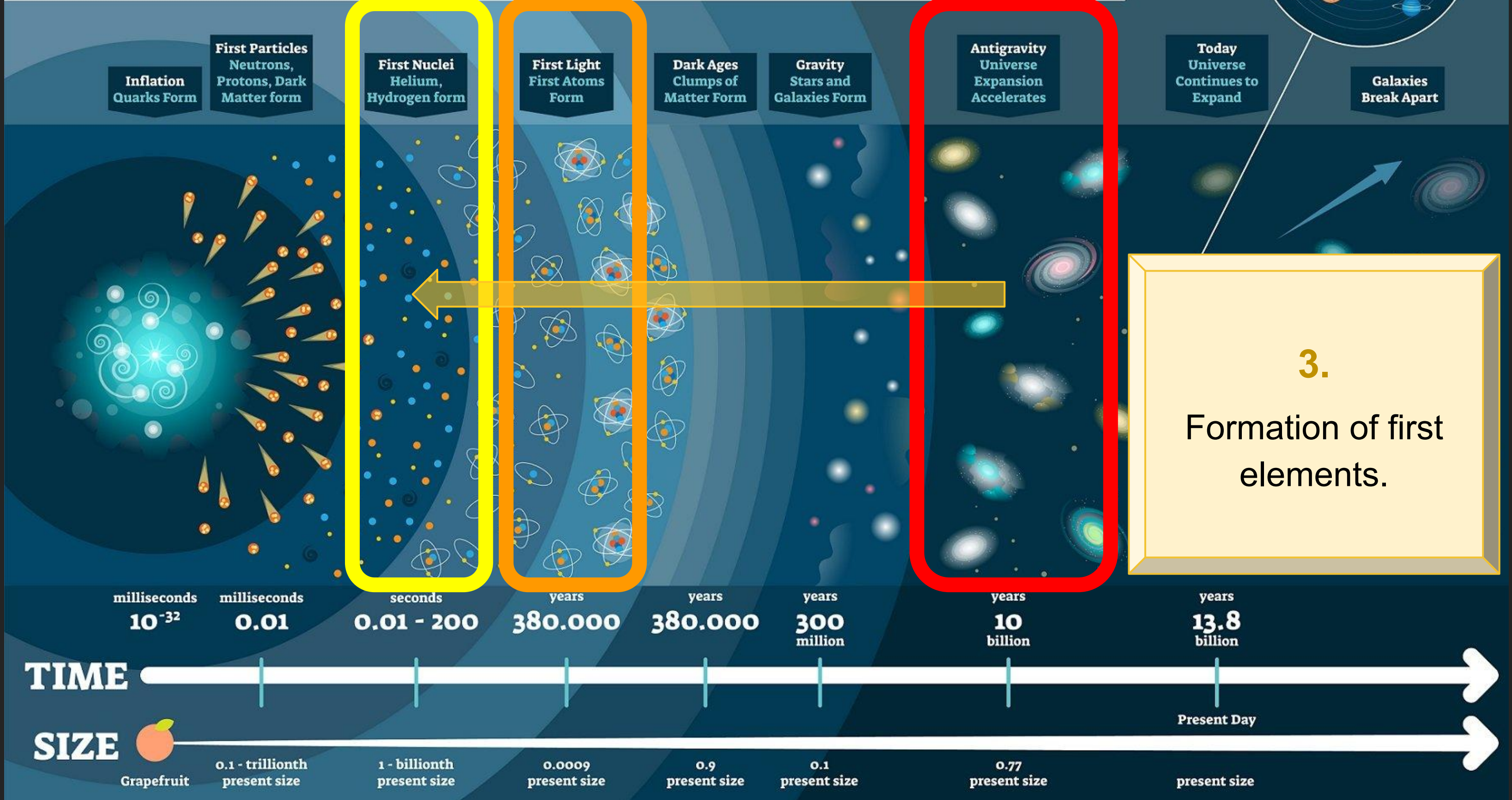




These fluctuations lead to the formation of galaxies and other structures!



Sounds complicated.
How do we prove the theory?



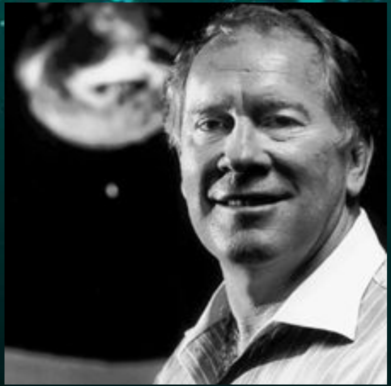
3.

Formation of first elements.

David N. Schramm

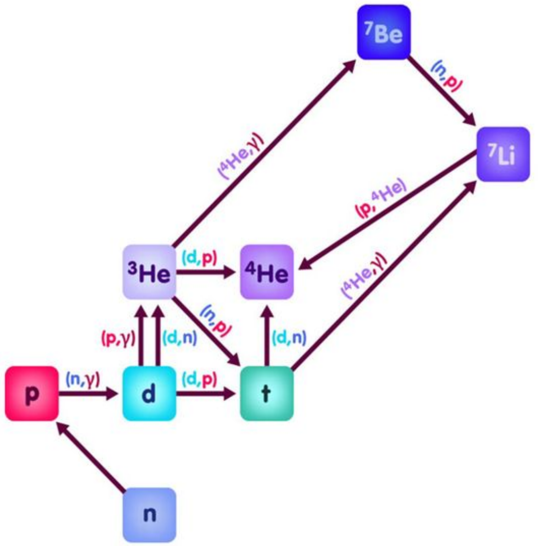
1945 - 1997

U. Chicago



10s - 20 min after the Big Bang

We know exactly the temperature (i.e. baryon-to-photon ratio) that the Universe had when it was forming first nuclei - H, D, He, Li.

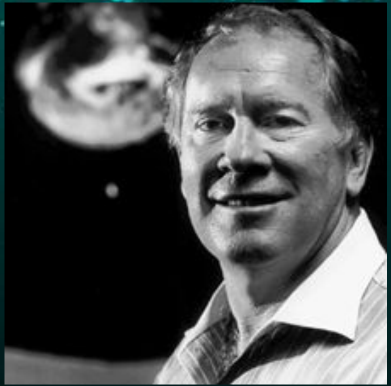


1) $n \rightarrow {}^1H + e^- + \bar{\nu}$
2) ${}^1H + n \rightarrow {}^2H + \gamma$
3) ${}^2H + {}^1H \rightarrow {}^3He + \gamma$
4) ${}^2H + {}^2H \rightarrow {}^3He + n$
5) ${}^2H + {}^2H \rightarrow {}^3H + {}^1H$
6) ${}^2H + {}^3H \rightarrow {}^4He + n$
7) ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8) ${}^3He + n \rightarrow {}^3H + {}^1H$
9) ${}^3He + {}^2H \rightarrow {}^4He + {}^1H$
10) ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11) ${}^7Li + {}^1H \rightarrow {}^4He + {}^4He$
12) ${}^7Be + n \rightarrow {}^7Li + {}^1H$
13) ${}^4He + {}^2H \rightarrow {}^6Li + \gamma$
14) ${}^6Li + {}^1H \rightarrow {}^3He + {}^3He$

David N. Schramm

1945 - 1997

U. Chicago



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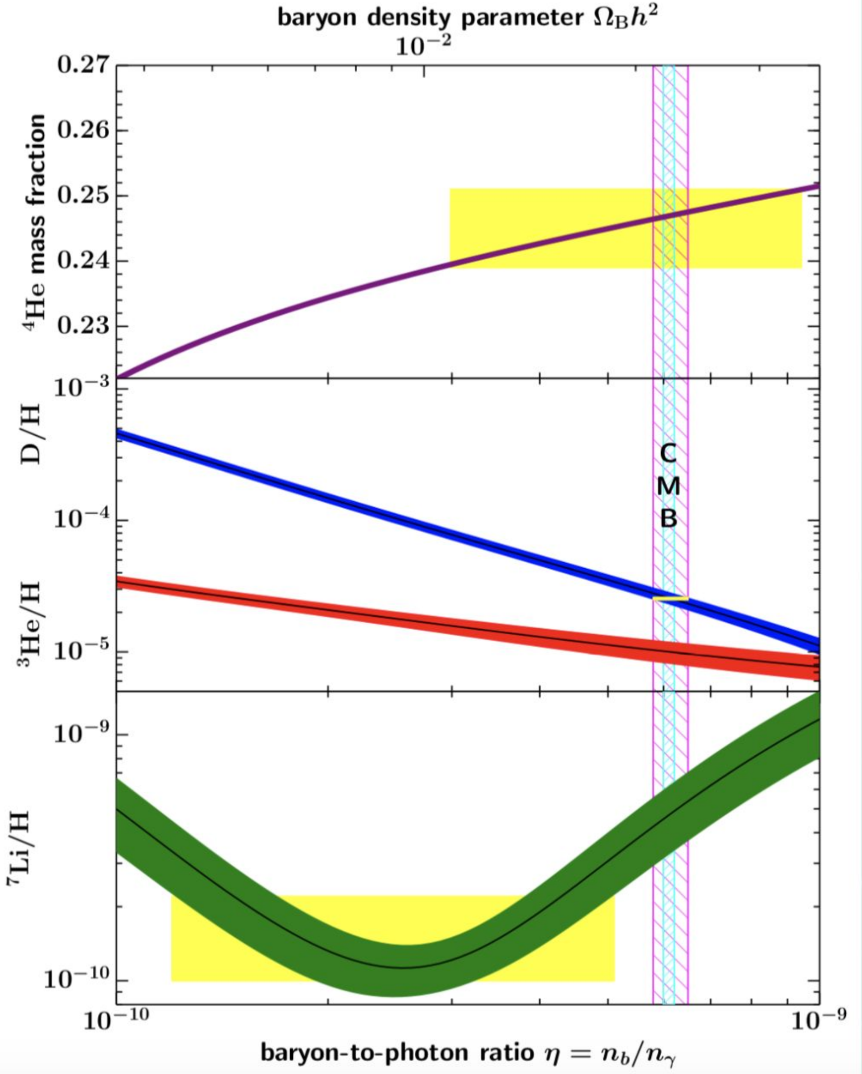

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1945 - 1997

U. Chicago

10s - 20 min after the Big Bang

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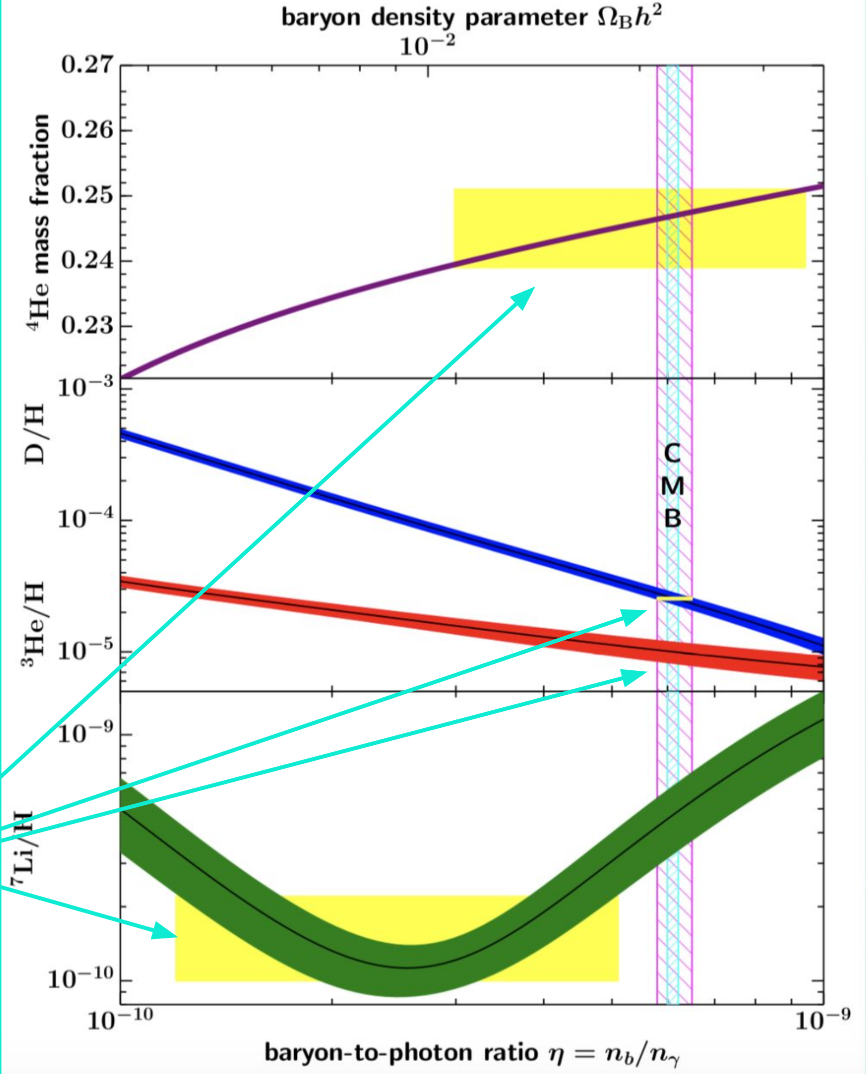
Let's observe some **very old stars** to see if abundances of these elements match our expectations.



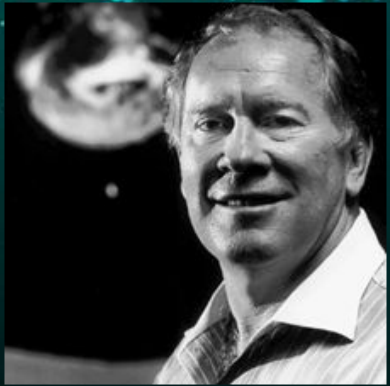
Observations and theory match very well!

….well almost all of them (Li problem)

David N. Schramm

1945 - 1997

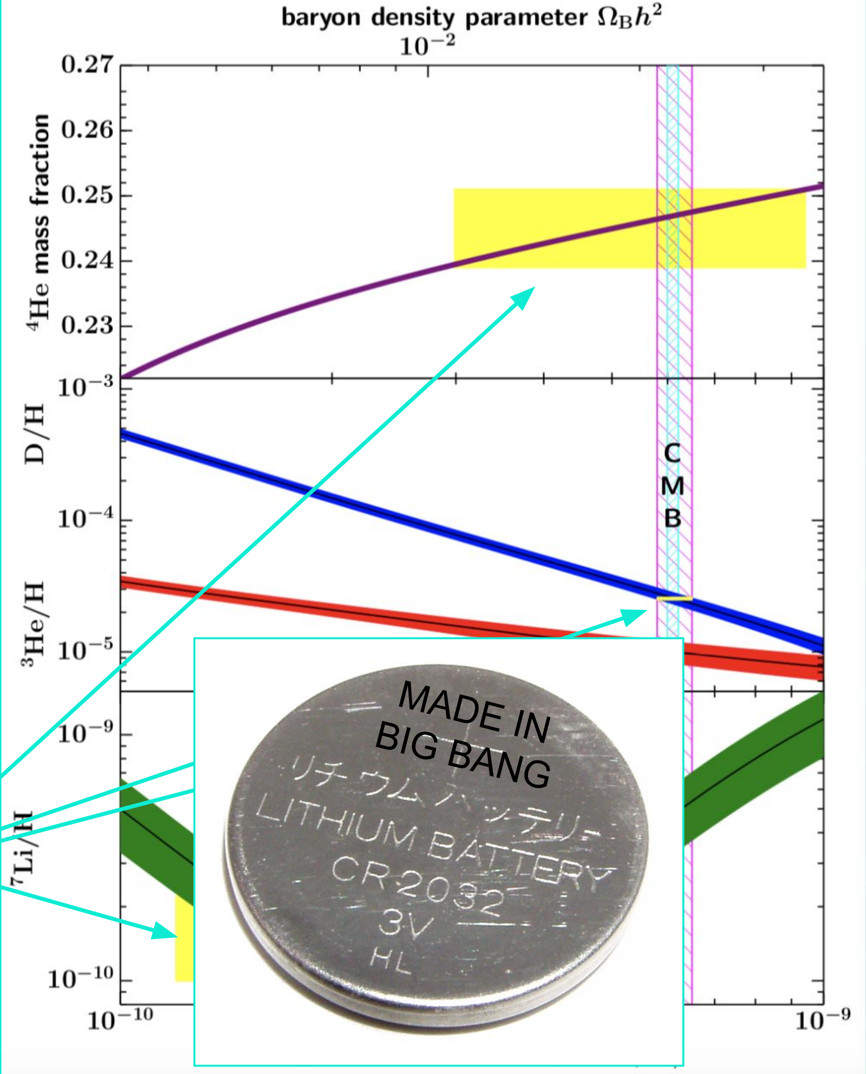
U. Chicago



10s - 20 min after the Big Bang

We know exactly the temperature (i.e. baryon-to-photon ratio) that the Universe had when it was forming first nuclei - H, D, He, Li.

Let's observe some **very old stars** to see if abundances of these elements match our expectations.



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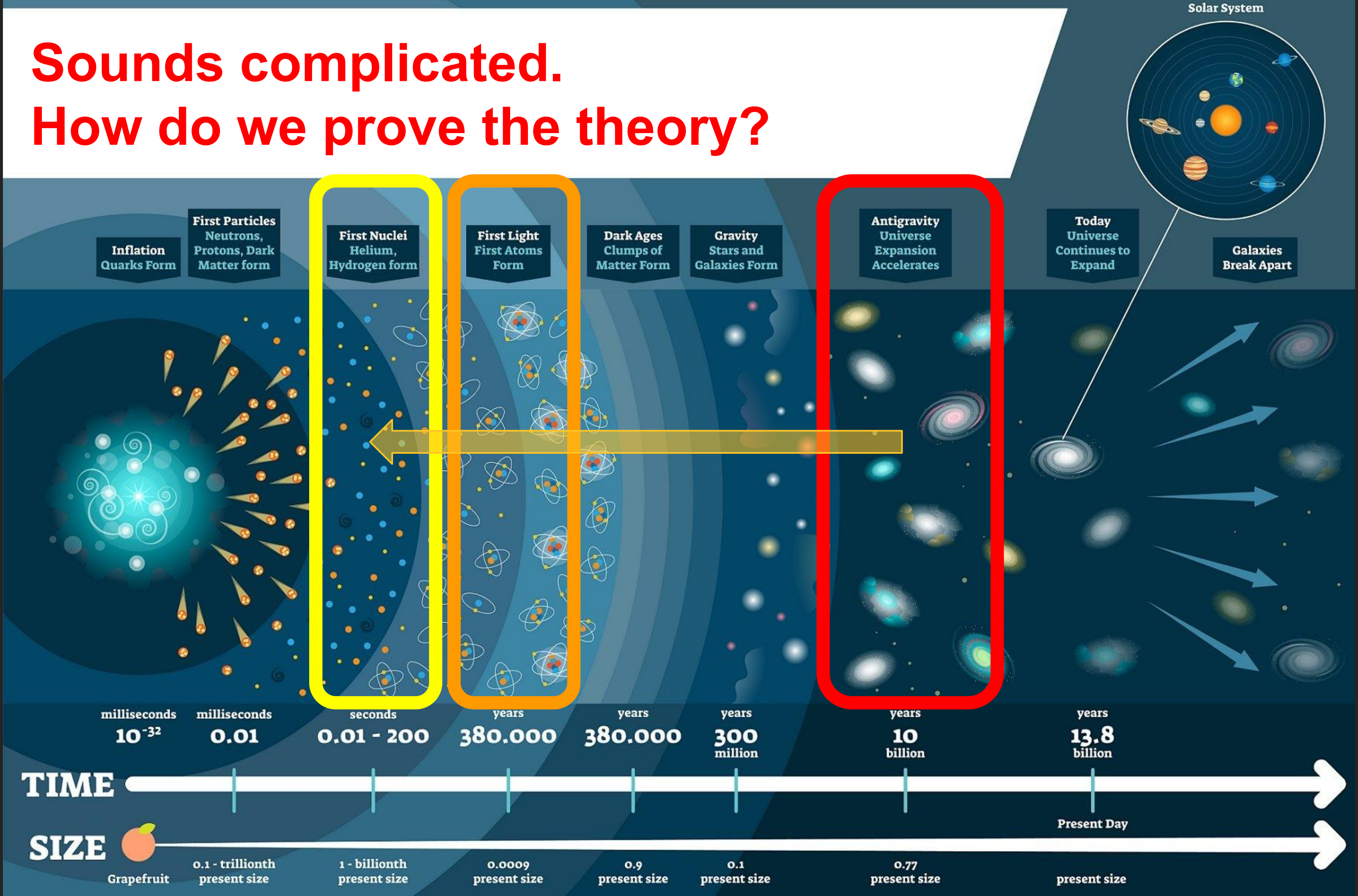
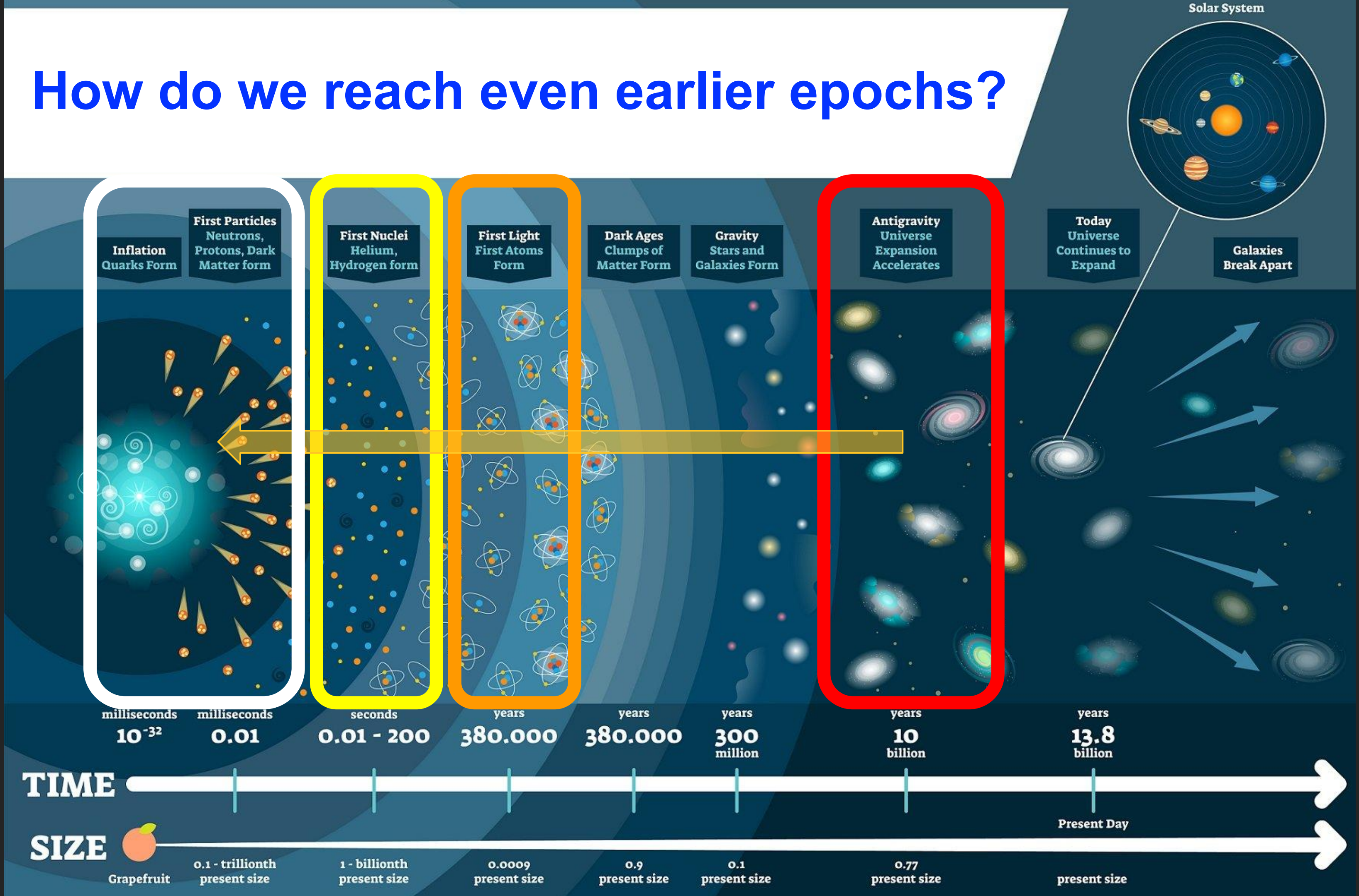
Sounds complicated.
How do we prove the theory?



How do we reach even earlier epochs?



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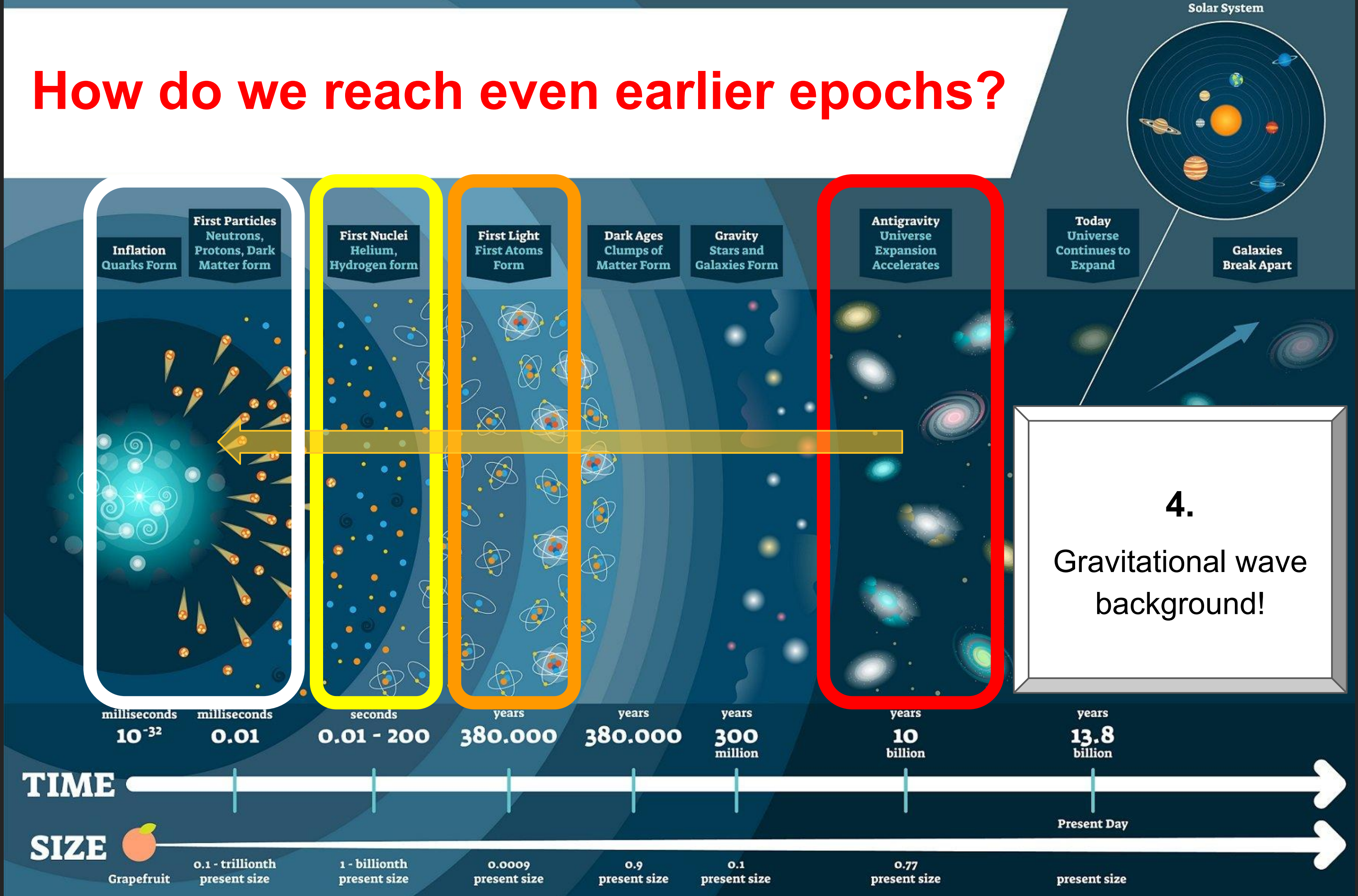
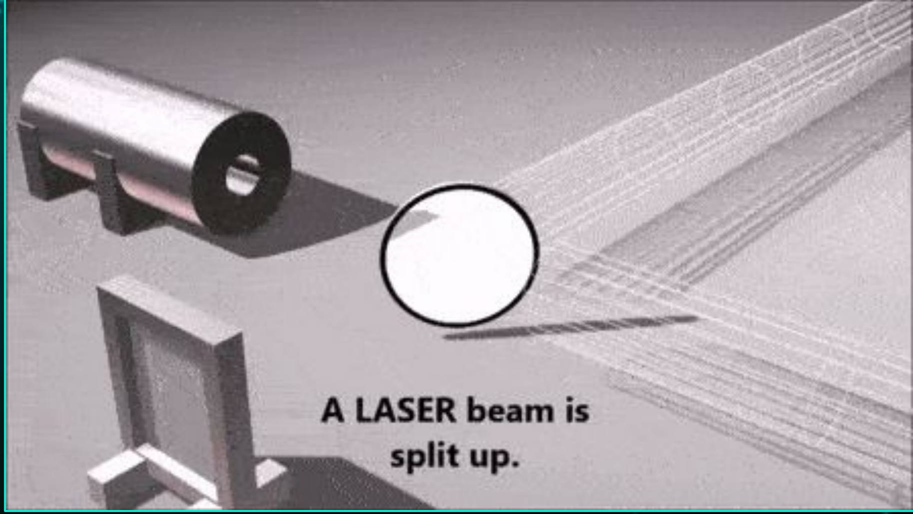


4.

Gravitational wave background!

Gravitational Waves

- **Stochastic gravitational wave backgrounds (SGWBs)** - superposition of gravitational waves with different frequencies coming from all directions.
- Evidence of the earliest moments before photons could propagate.
- Phenomena like **inflation, primordial black holes, cosmic strings, and phase transitions** as possible sources.
- In 2023 news from NANOGrav, CPTA, EPTA, and PPTA (first evidence, but still below 5σ).
- For higher frequencies we need longer detector arms.



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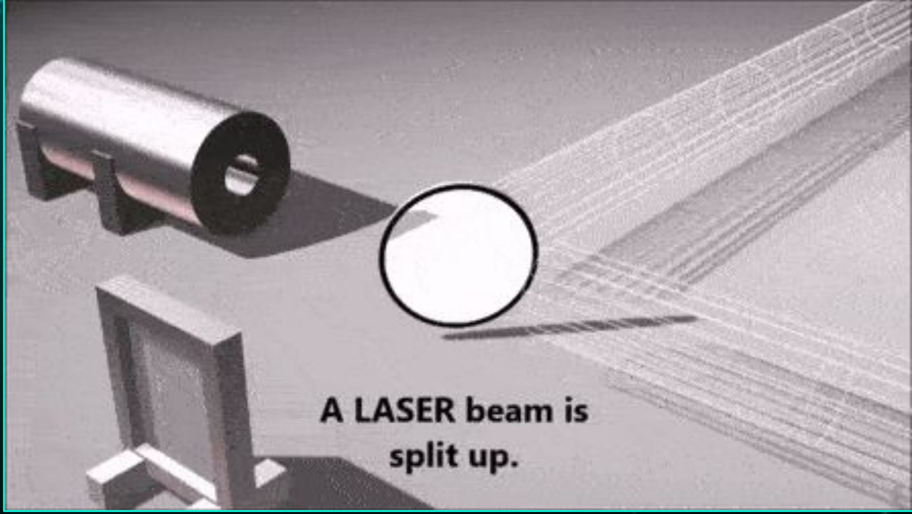
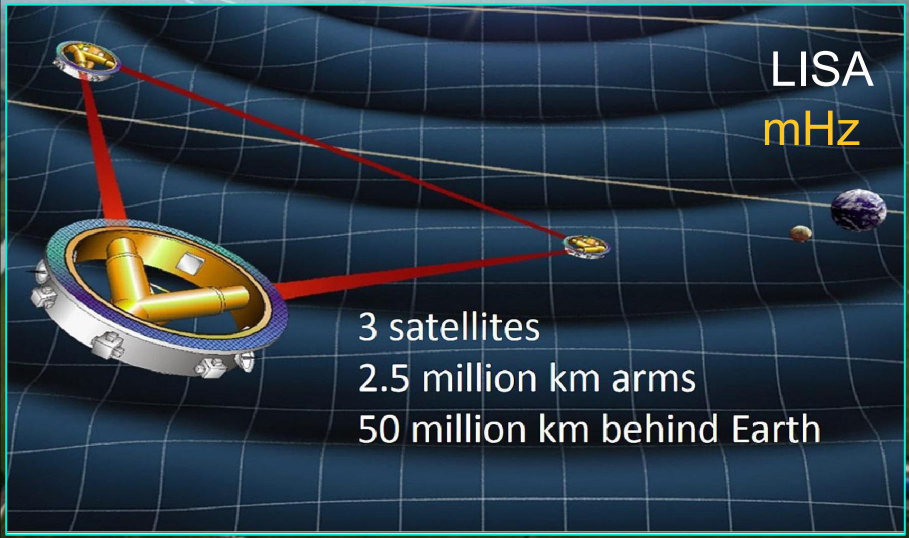
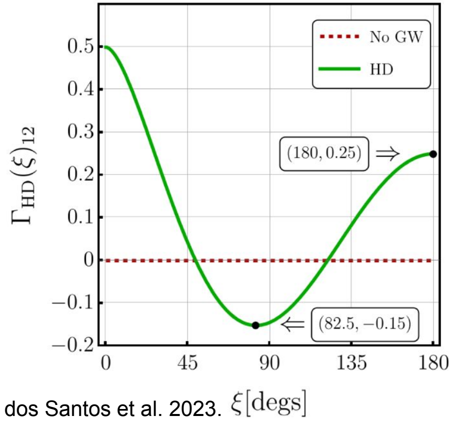




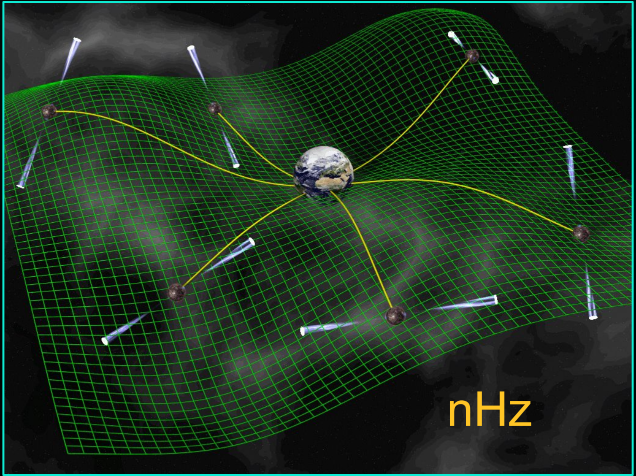
Gravitational Waves

- **Pulsar Timing Arrays** - detecting gravitational waves by measuring the time of arrival of radio pulses from millisecond pulsars. Pulses are disturbed by gravitational waves between the pulsar and Earth.



dos Santos et al. 2023.

Helling-Downs Curve for 2 pulsars as a function of their separation angle.



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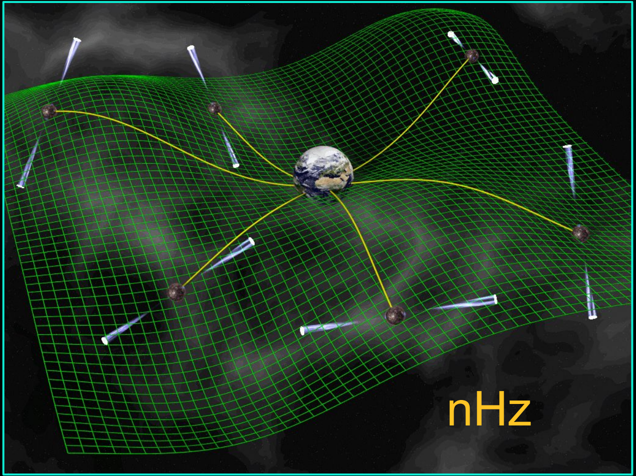

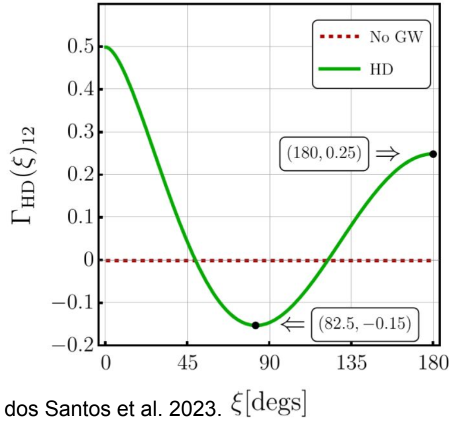

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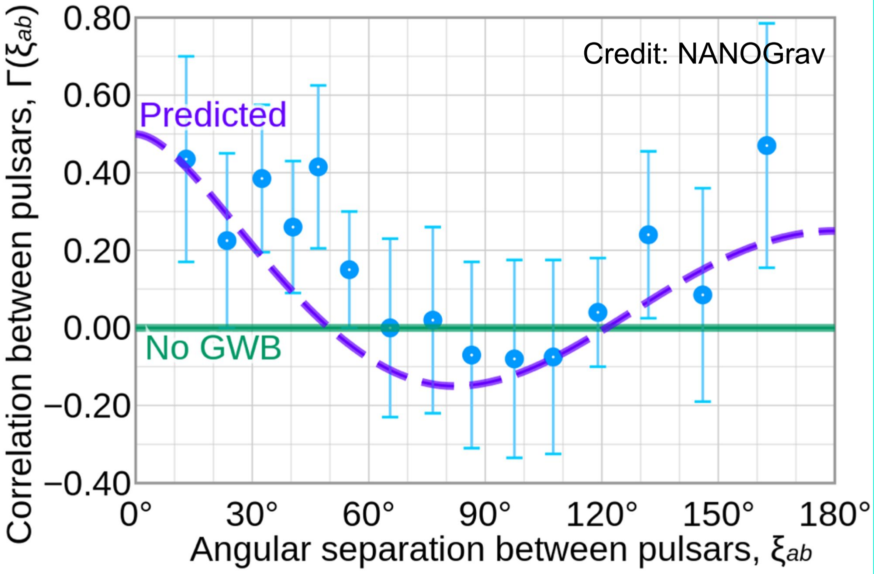
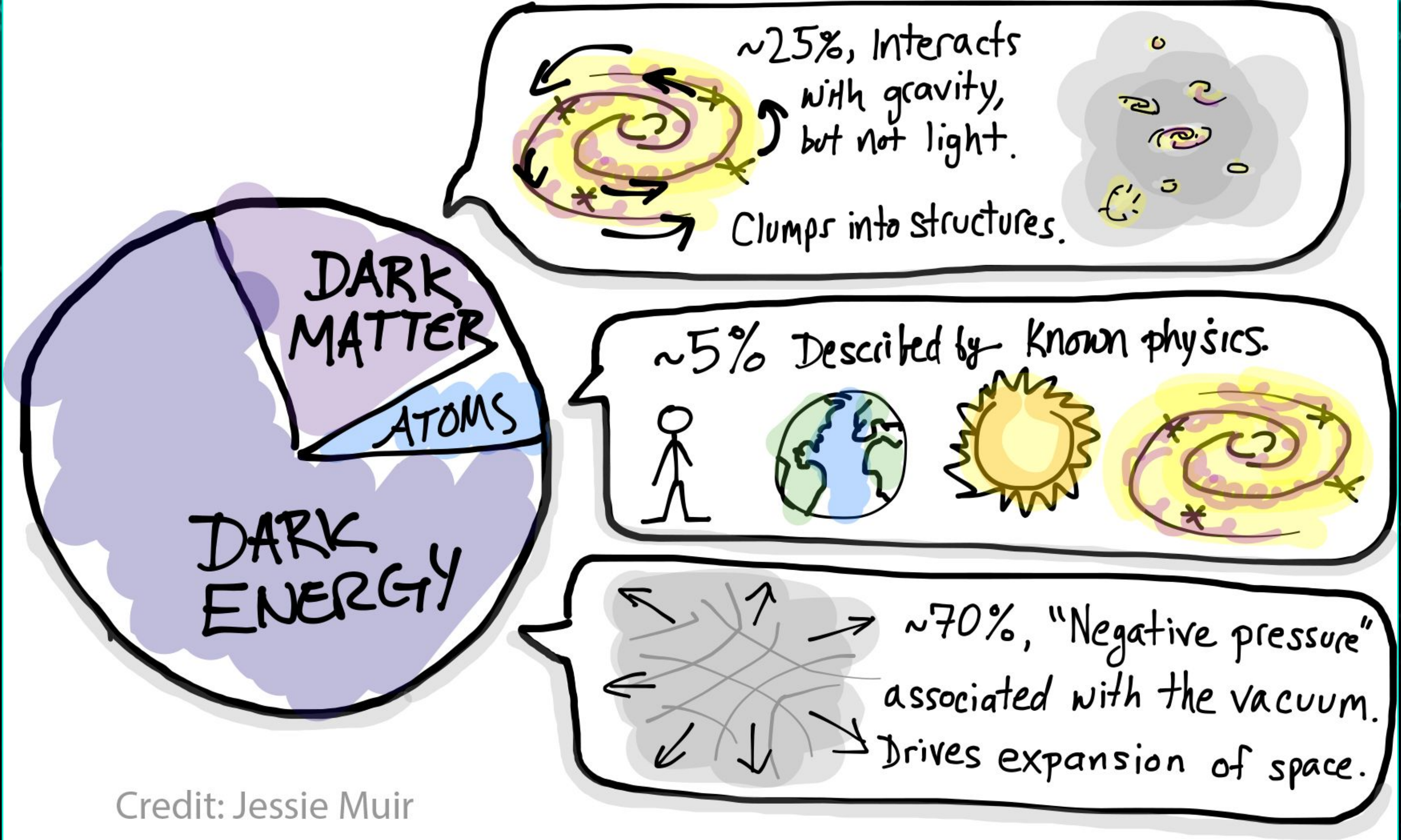
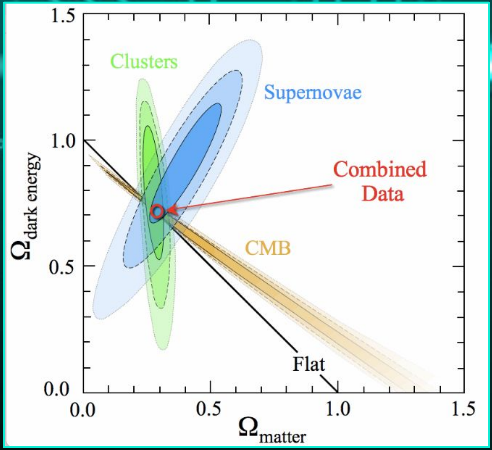
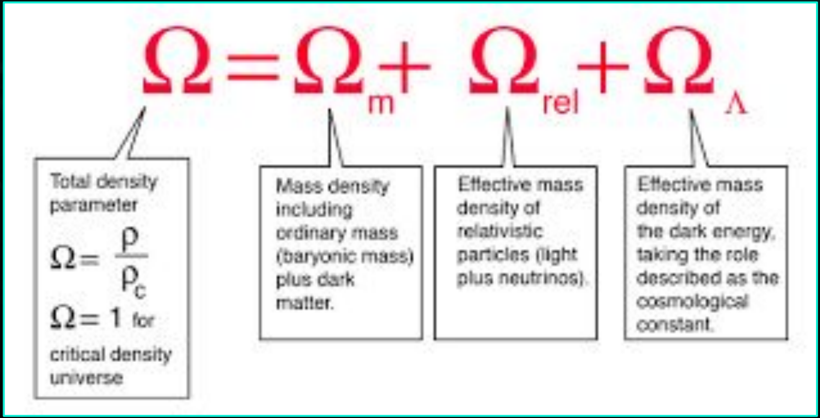
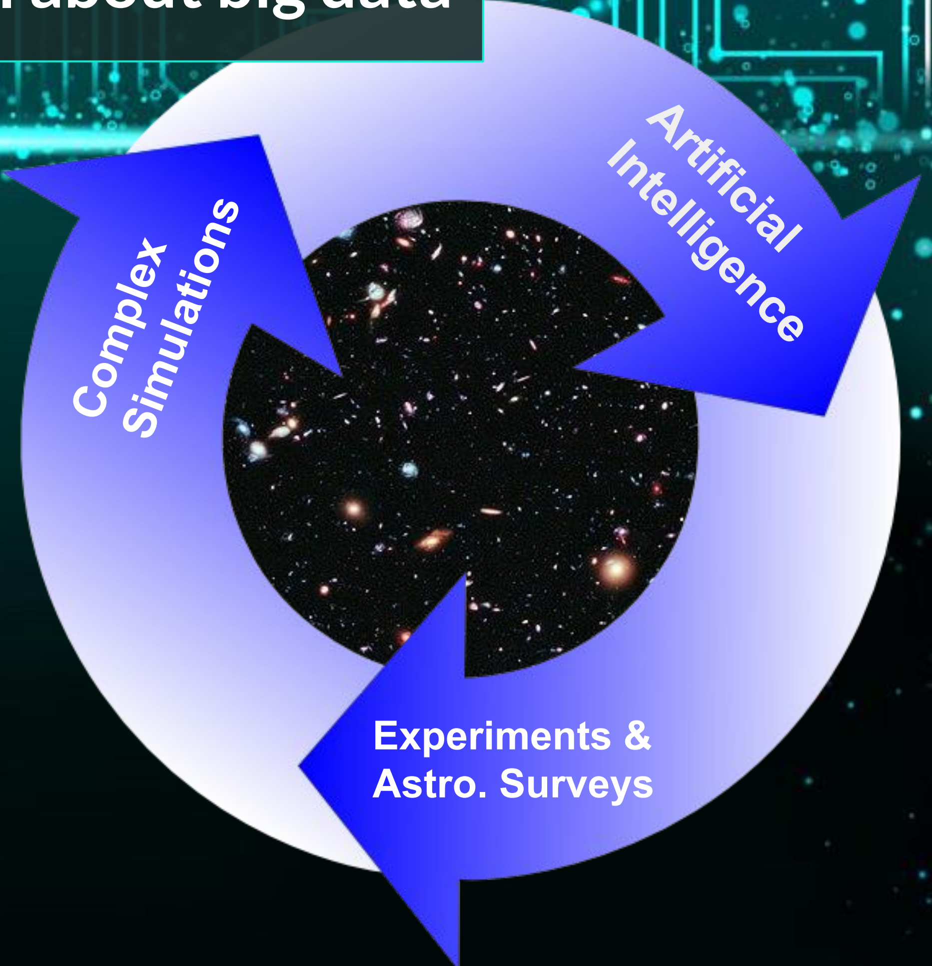


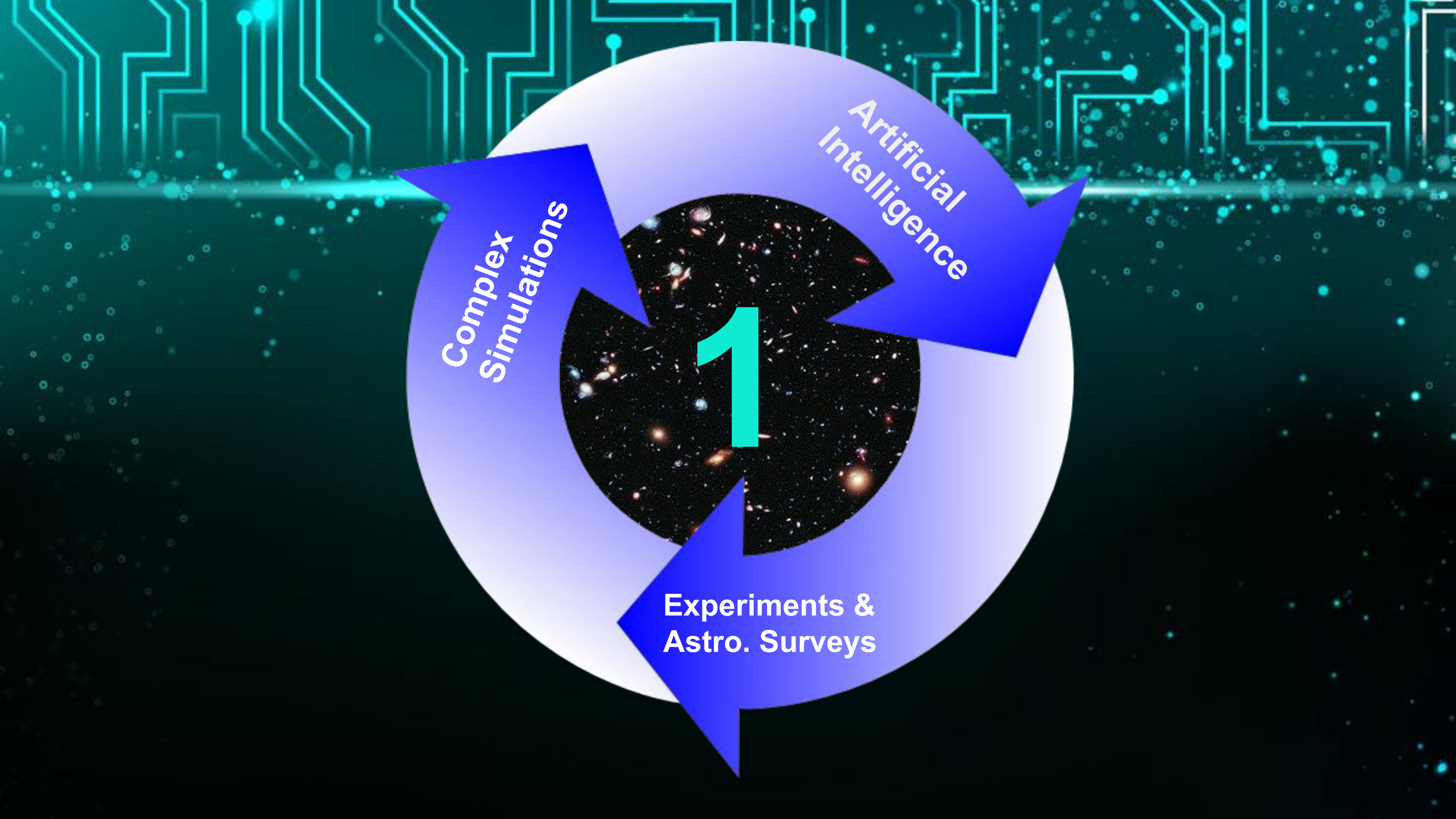

~25%, Interacts with gravity, but not light.
Clumps into structures.
DARK MATTER
ATOMS
~5% Described by known physics.
DARK ENERGY
~70%, "Negative pressure" associated with the vacuum. Drives expansion of space.
Credit: Jessie Muir

Being a cosmologist today is all about big data








Artificial Intelligence
Complex Simulations
1
Experiments & Astro. Surveys

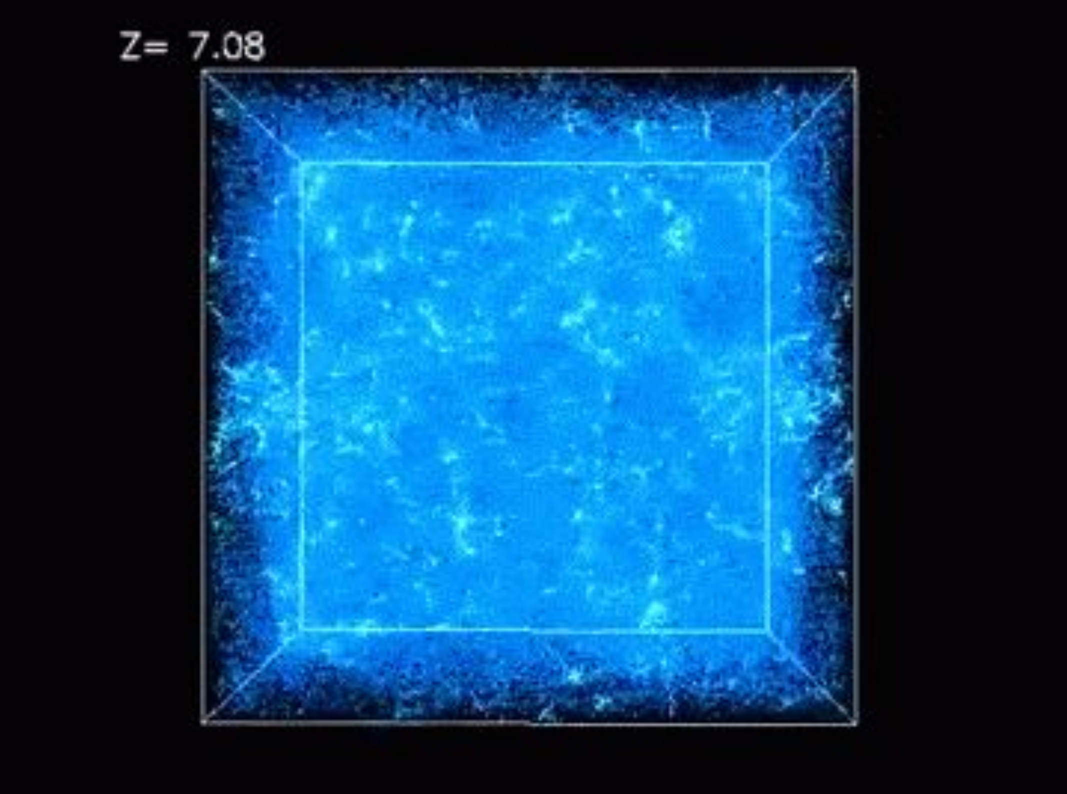
Primordial Fluctuations

+

Gravity and Time

=

Everything We See Today



Primordial Fluctuations

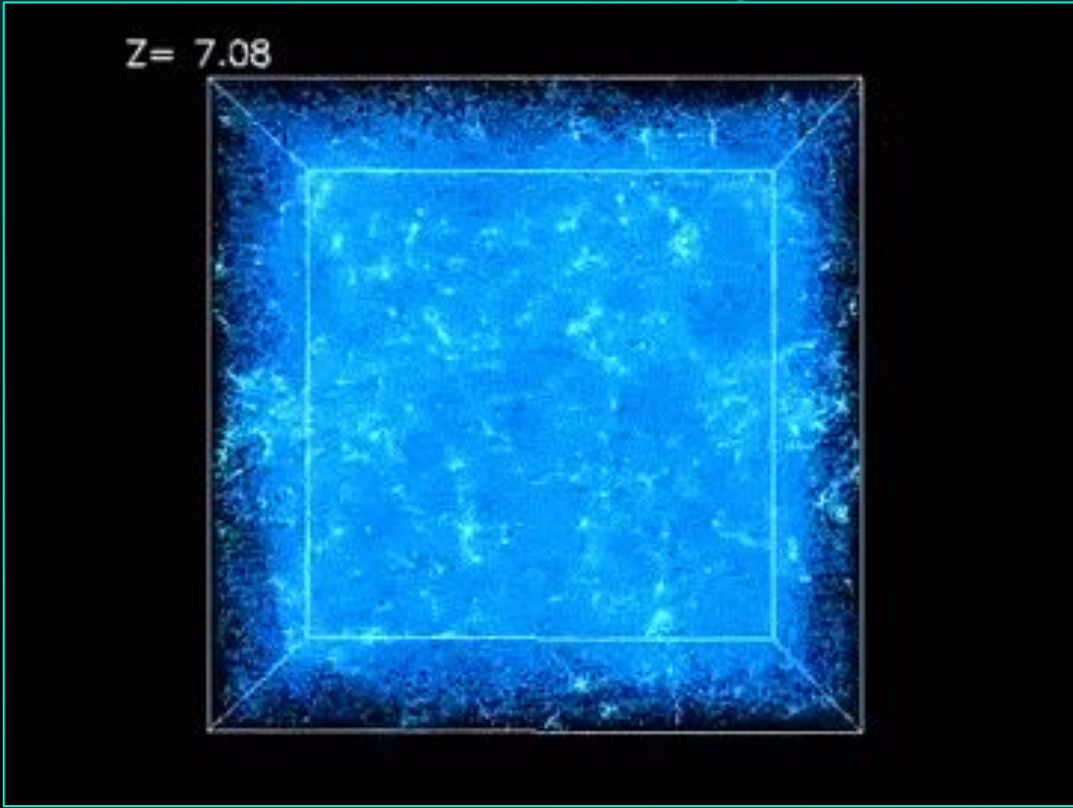
+

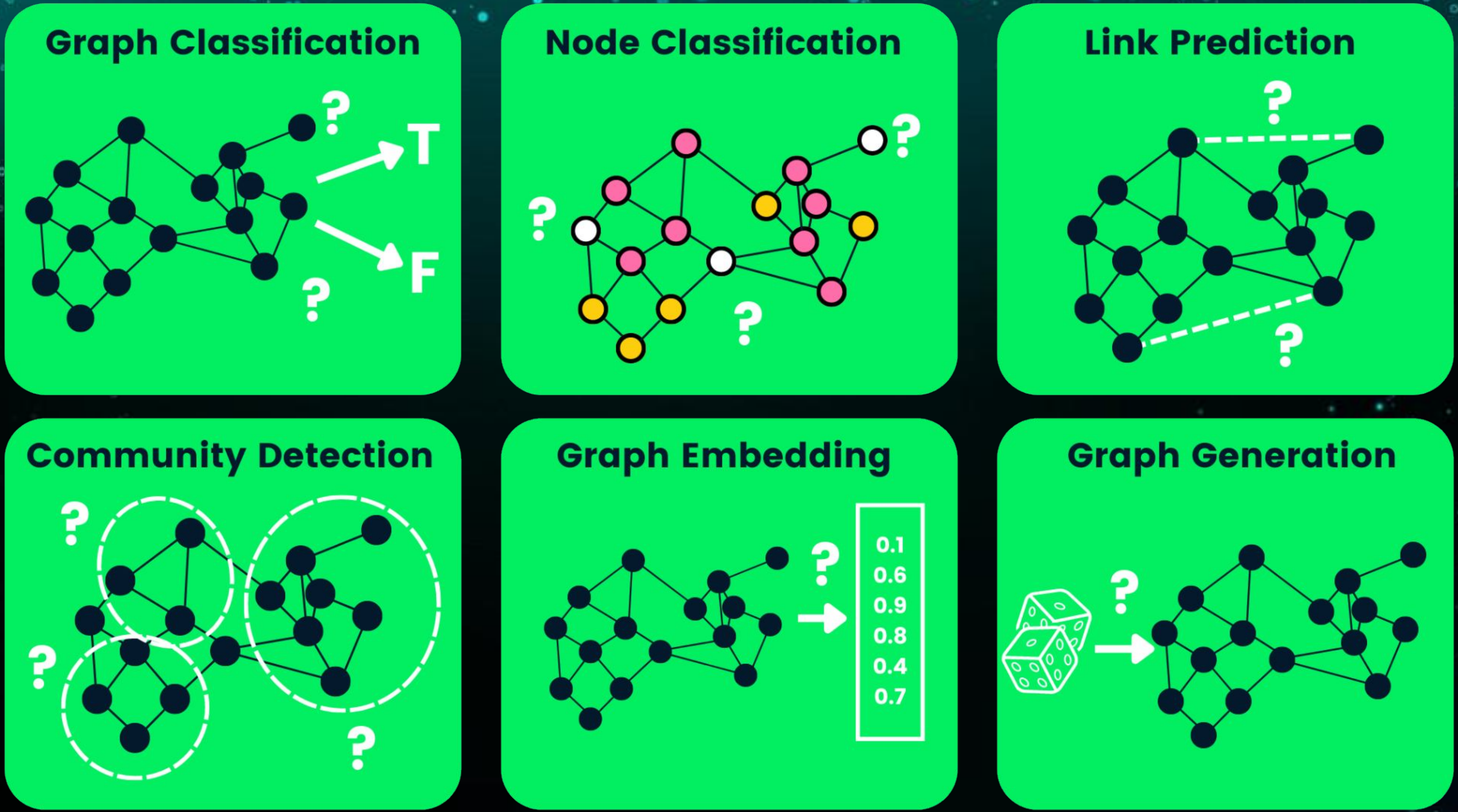
Gravity and Time

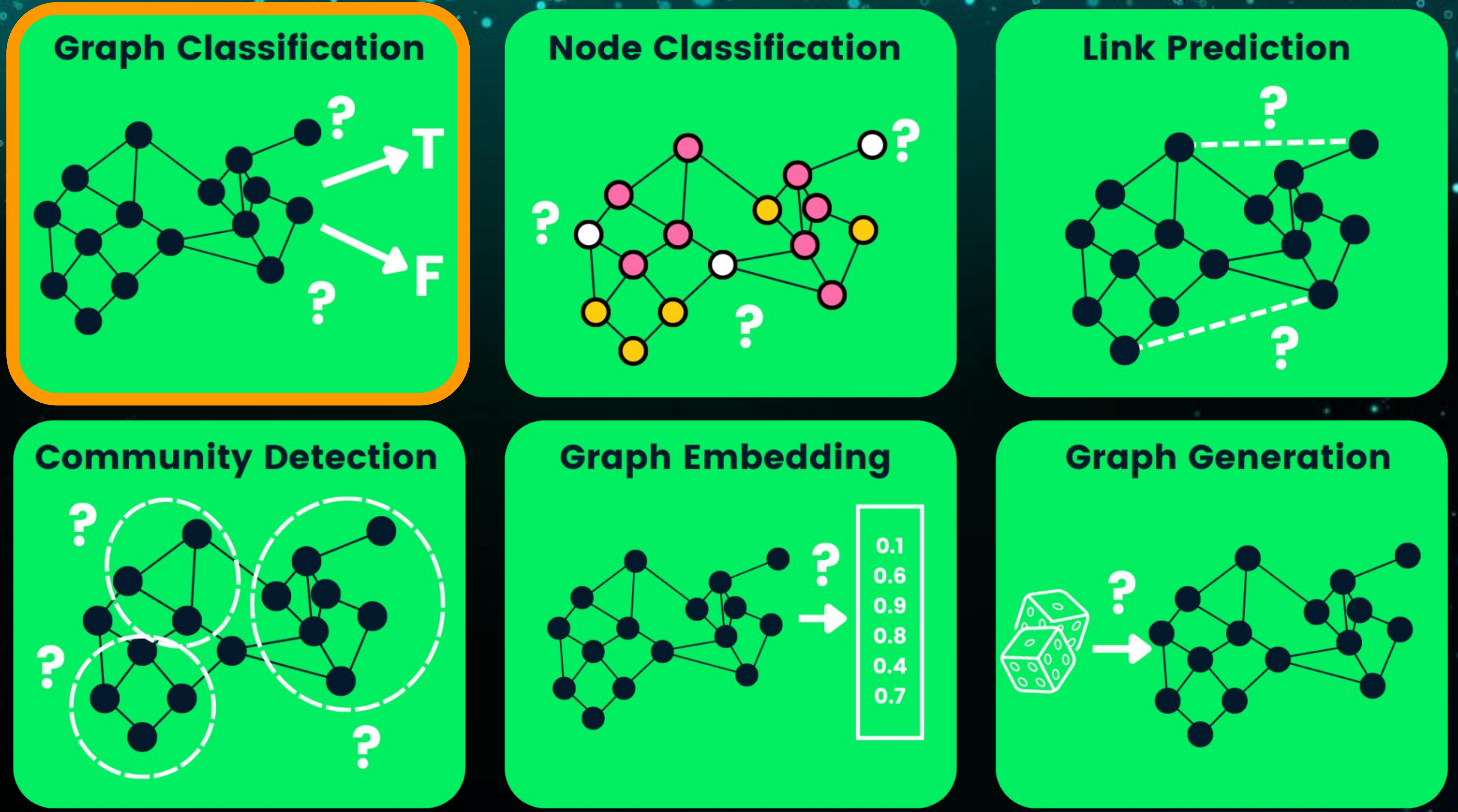
=

Everything We See Today

Can we encode this data into a **Graph**? Each node is a galaxy with its position and properties.




Graph Classification
T
F
Node Classification
Link Prediction
Community Detection
Graph Embedding
0.1
0.6
0.9
0.8
0.4
0.7
Graph Generation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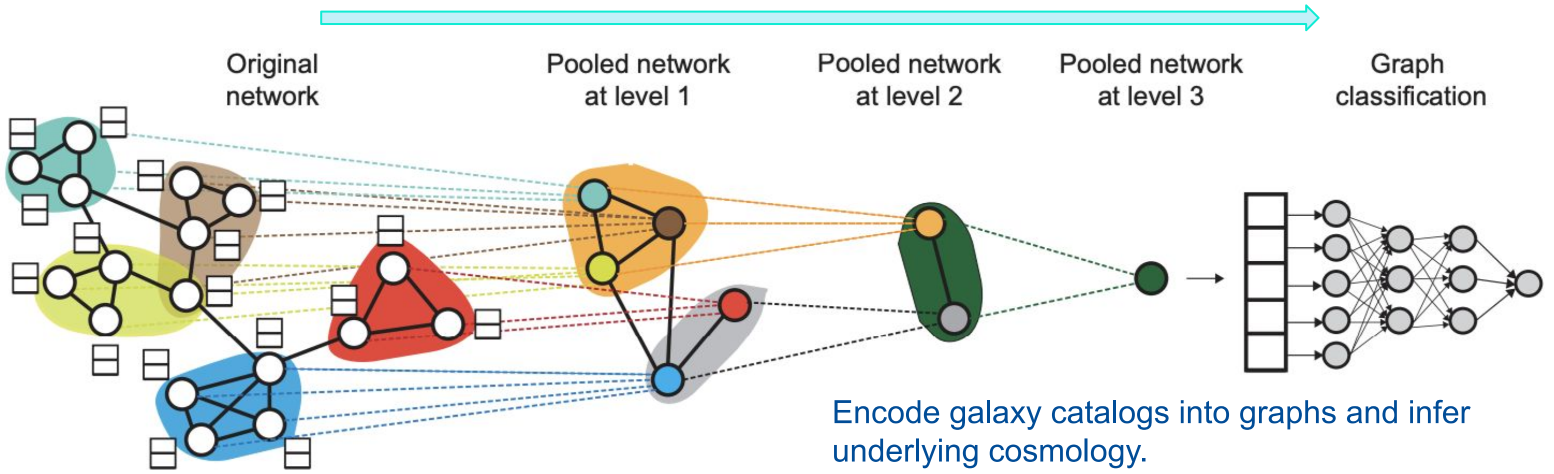
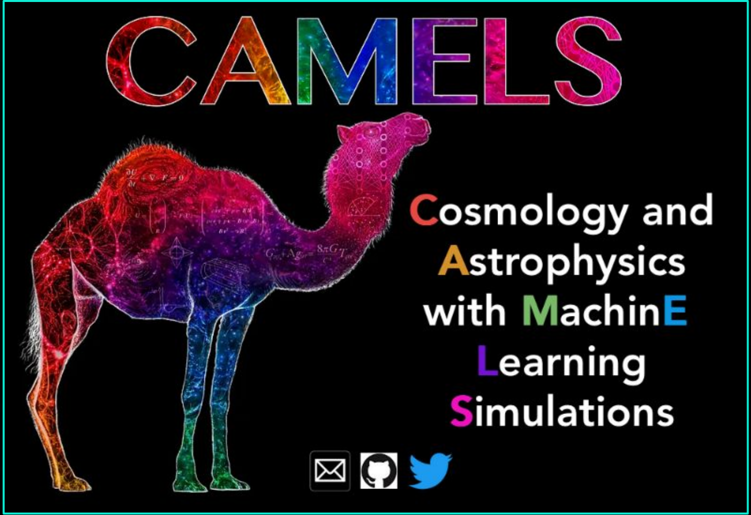
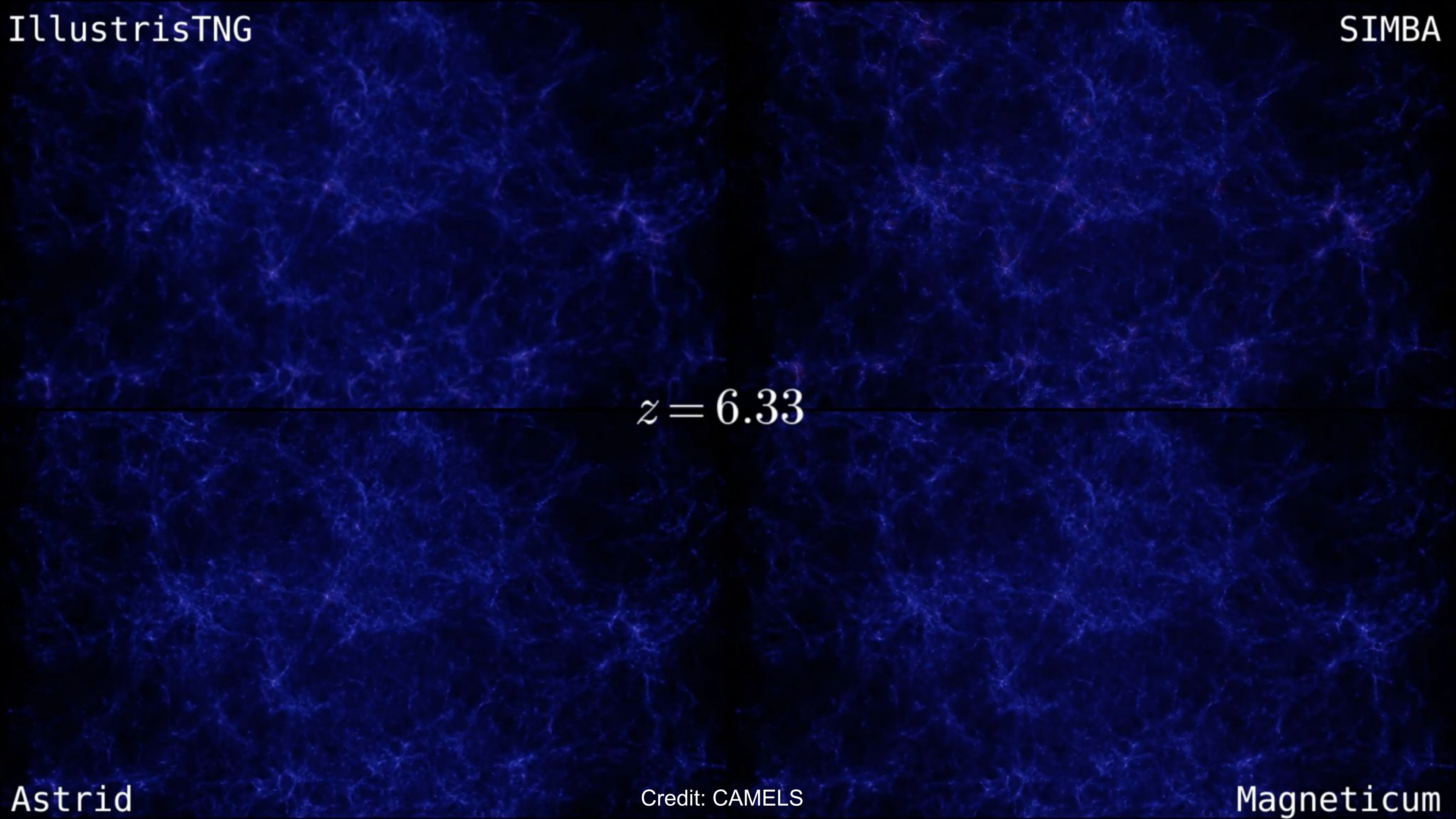
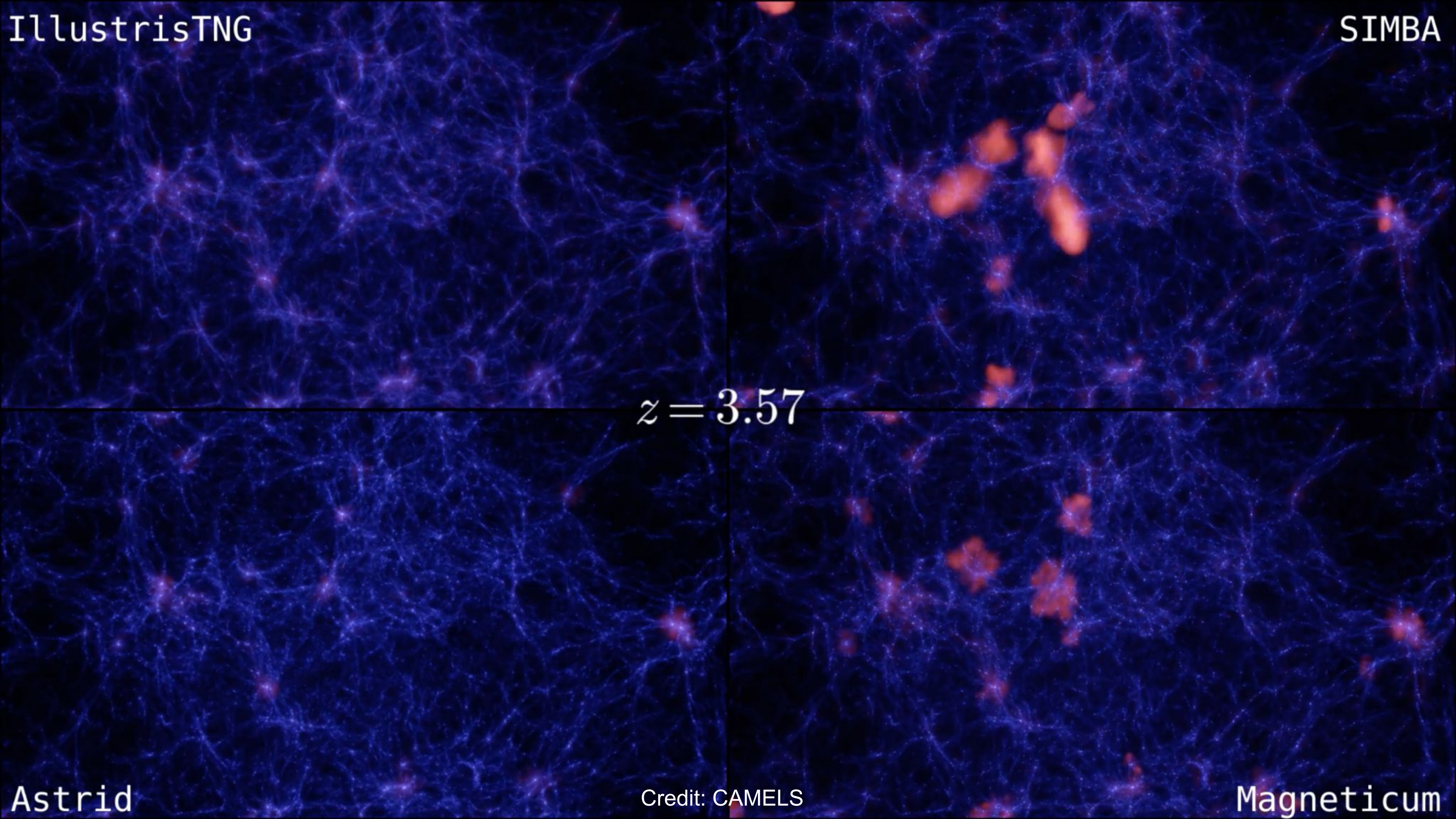


Encode galaxy catalogs into graphs and infer underlying cosmology.



Several great simulations are available. Which one do we choose?


IllustrisTNG
SIMBA
$z = 6.33$
Astrid
Magneticum
Credit: CAMELS



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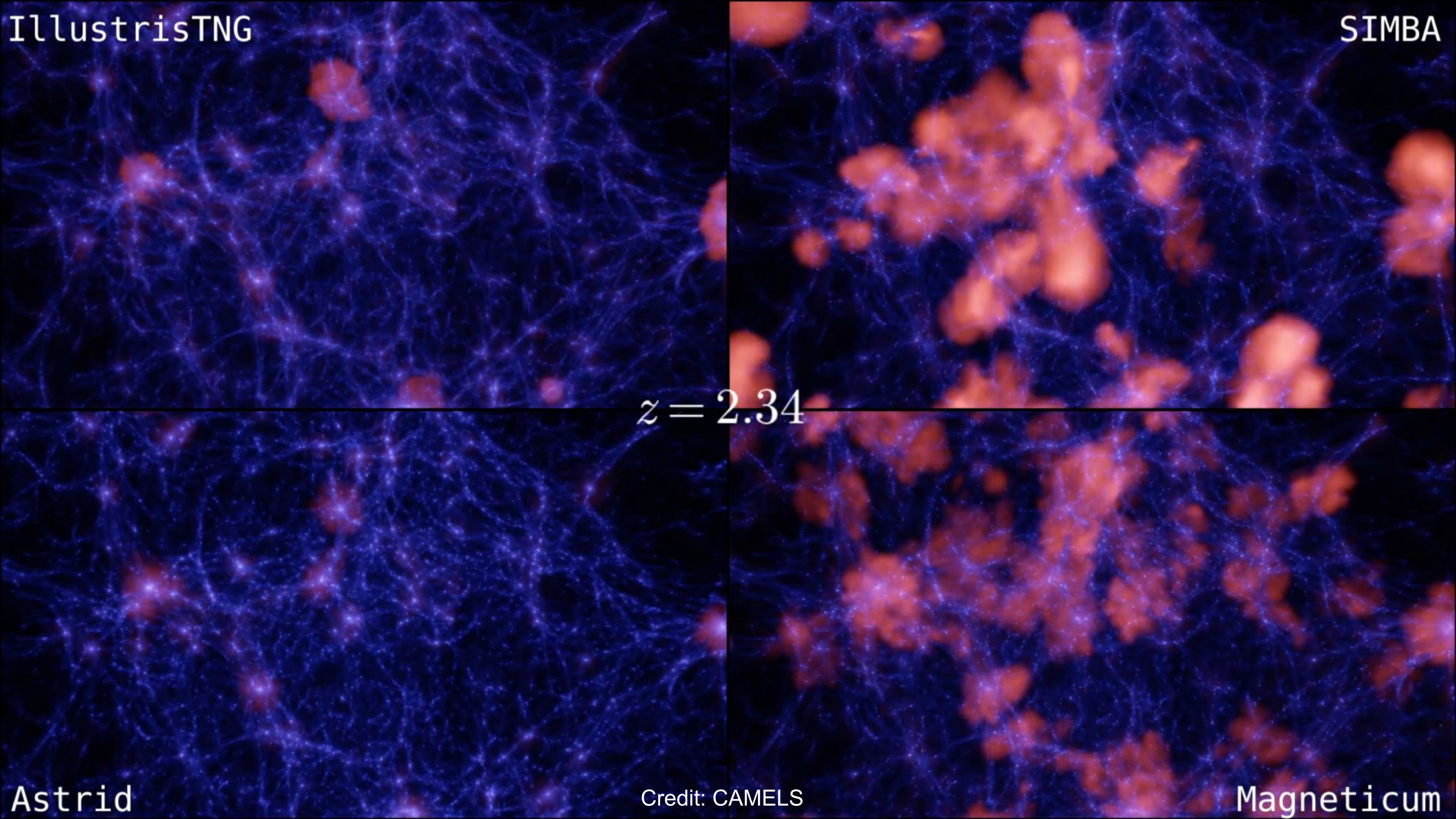

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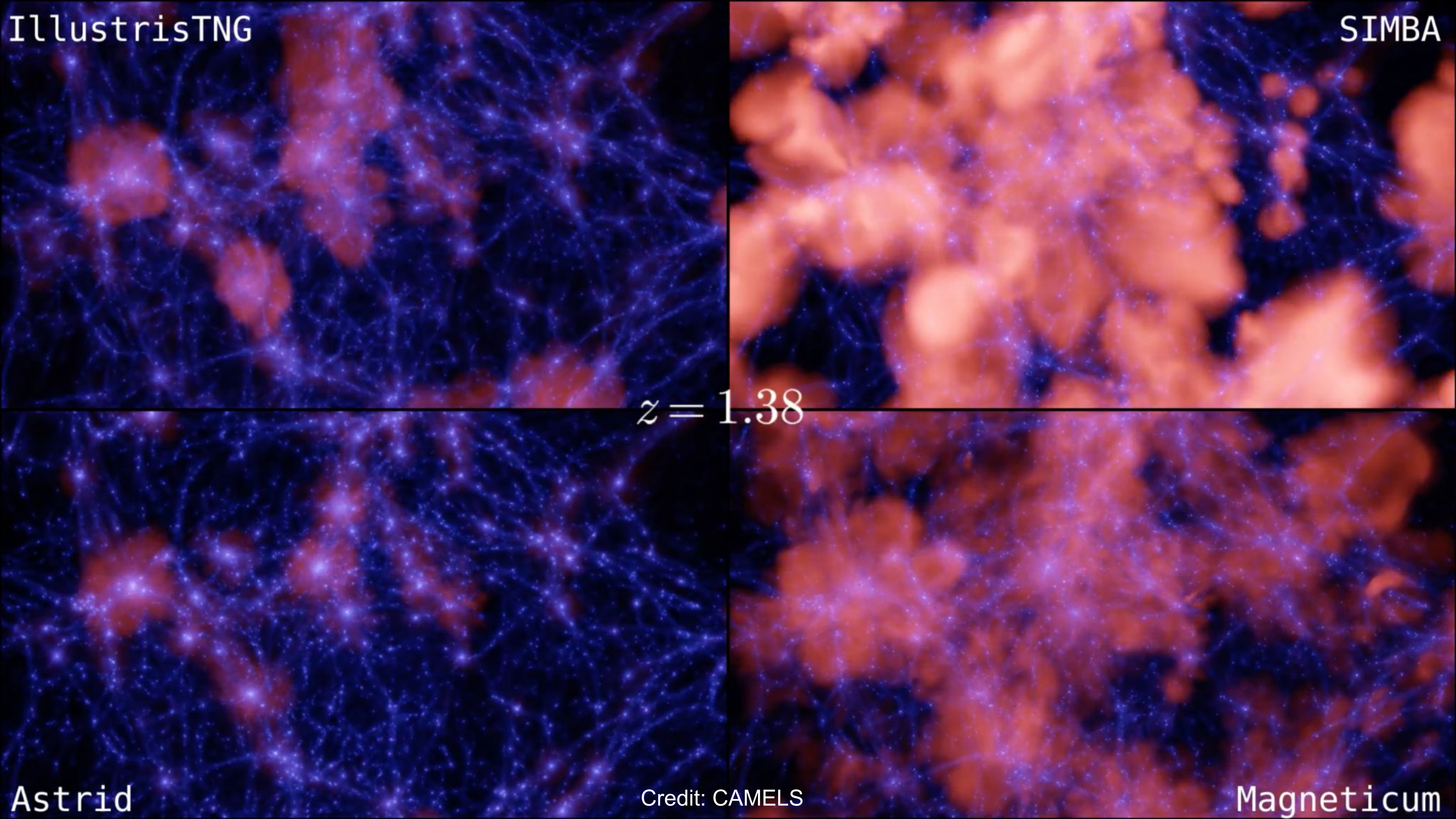

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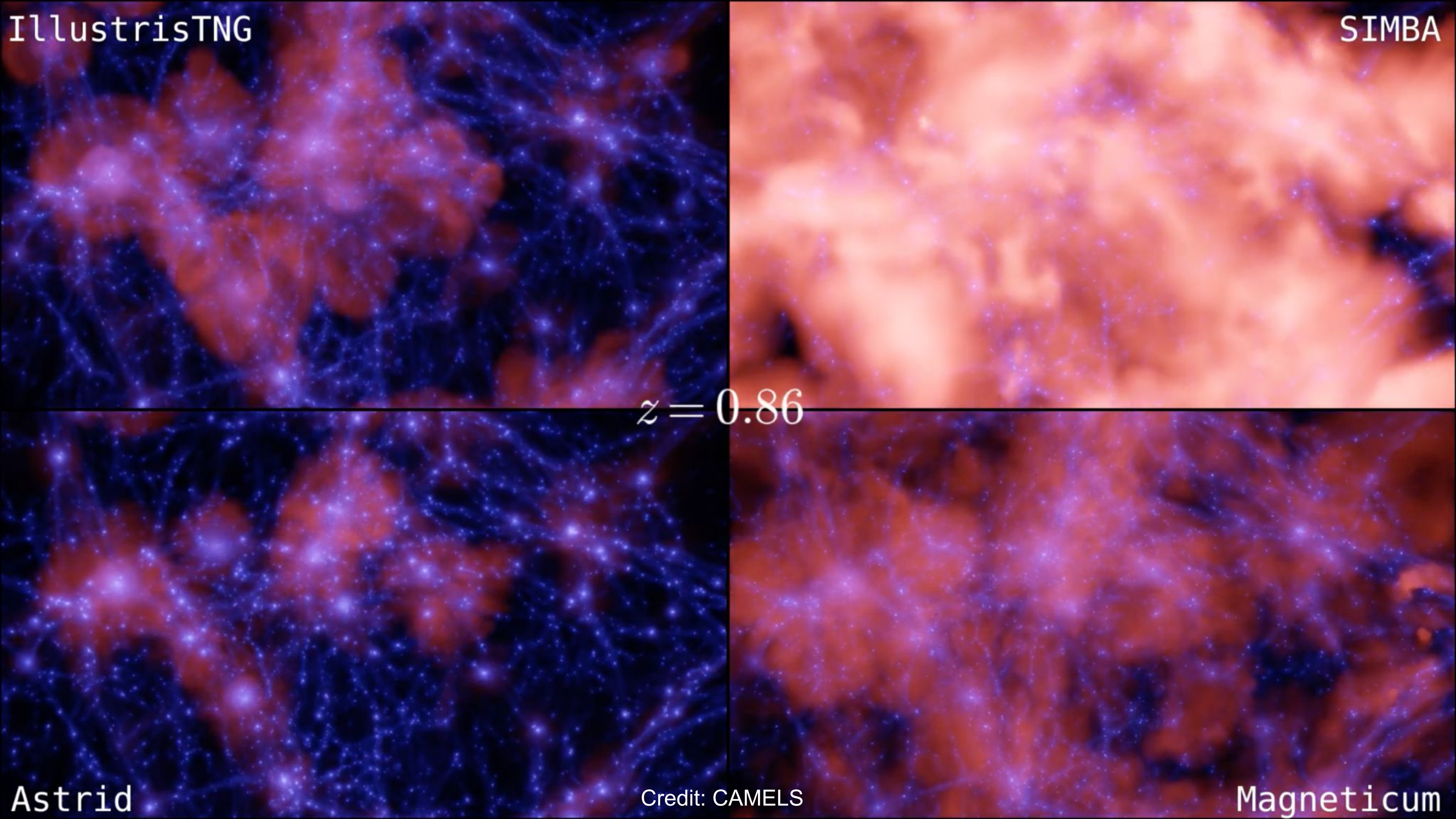

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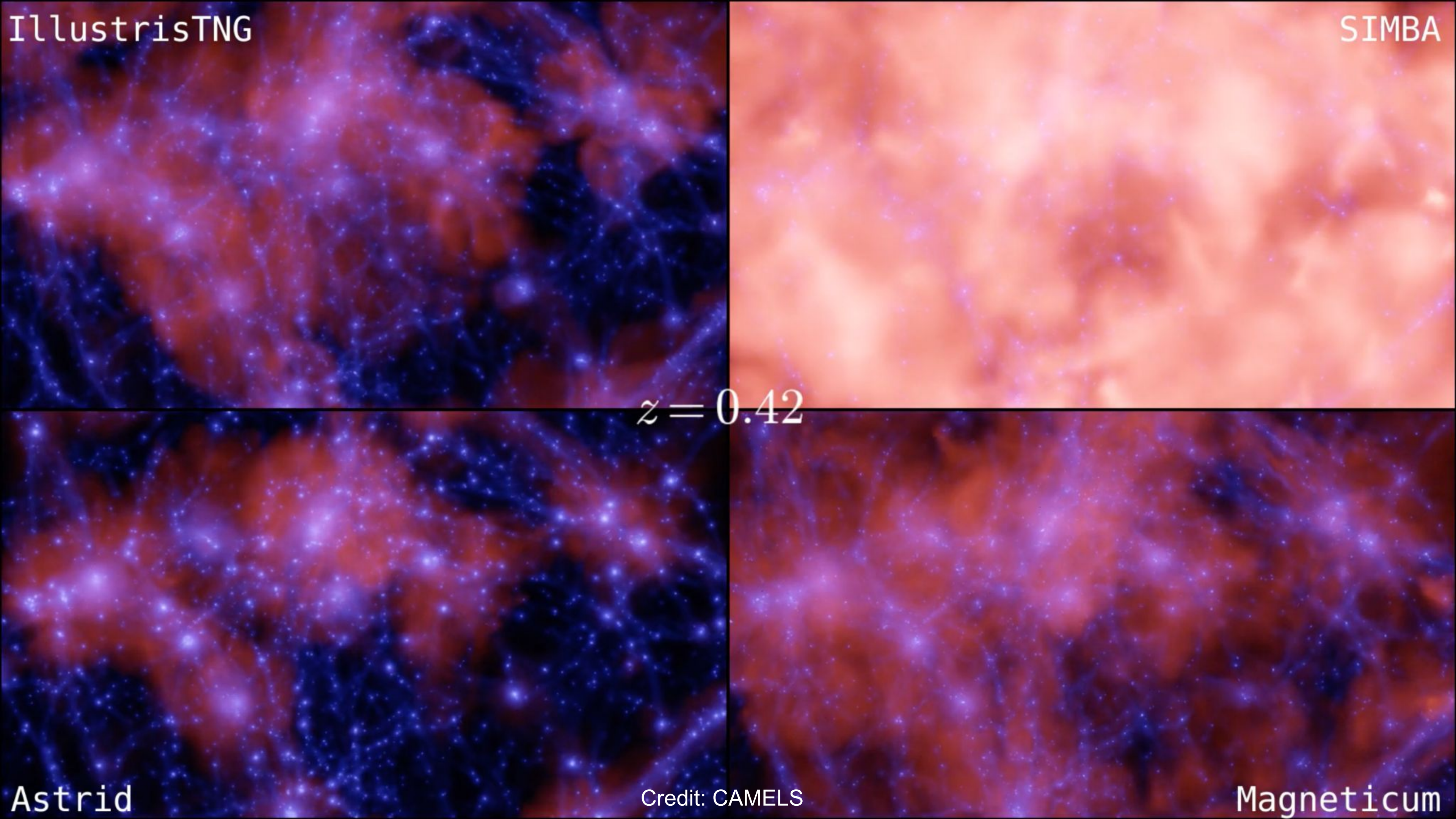
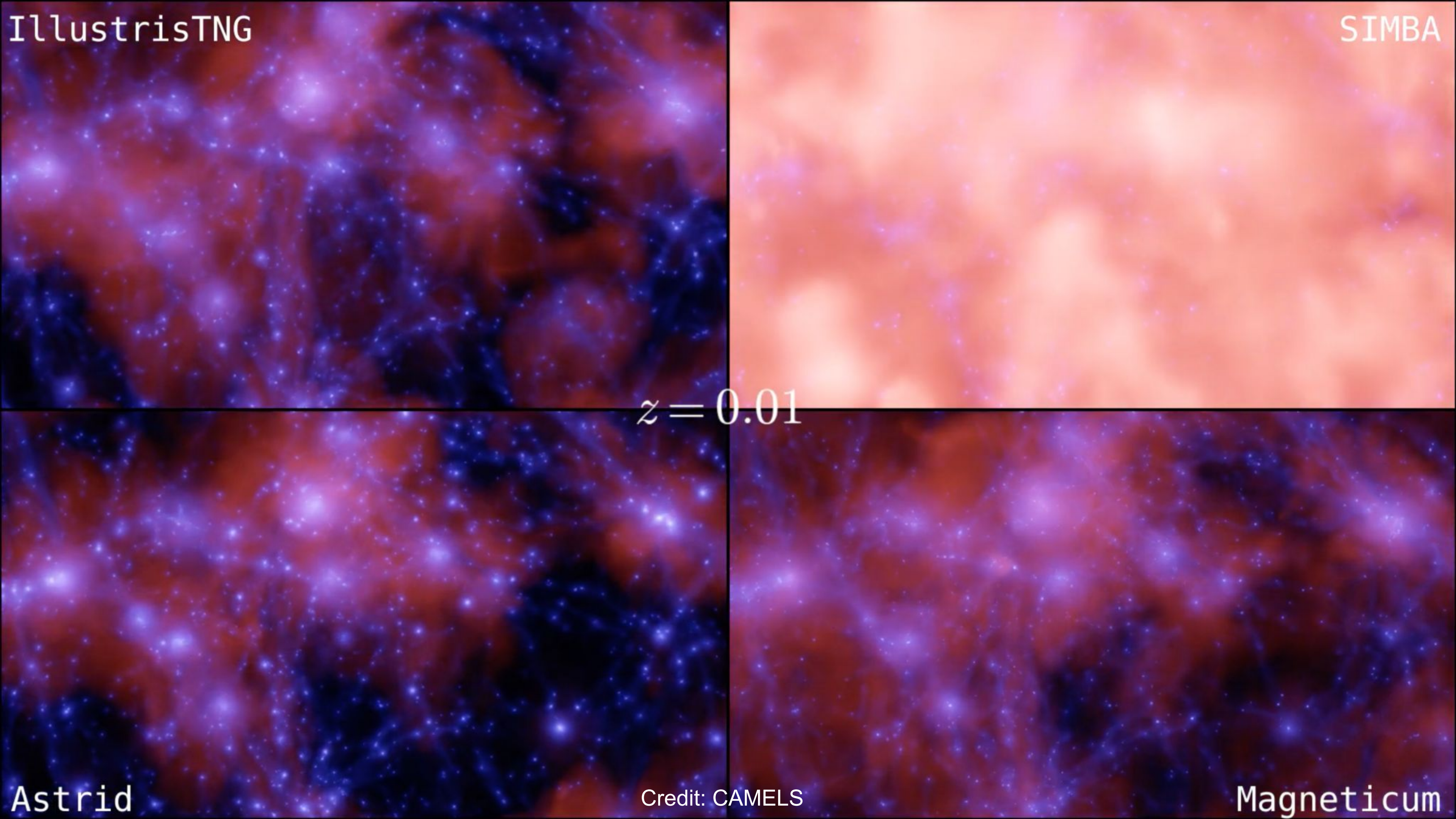

IllustrisTNG
SIMBA
$z = 0.42$
Astrid
Magneticum
Credit: CAMELS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SIMBA
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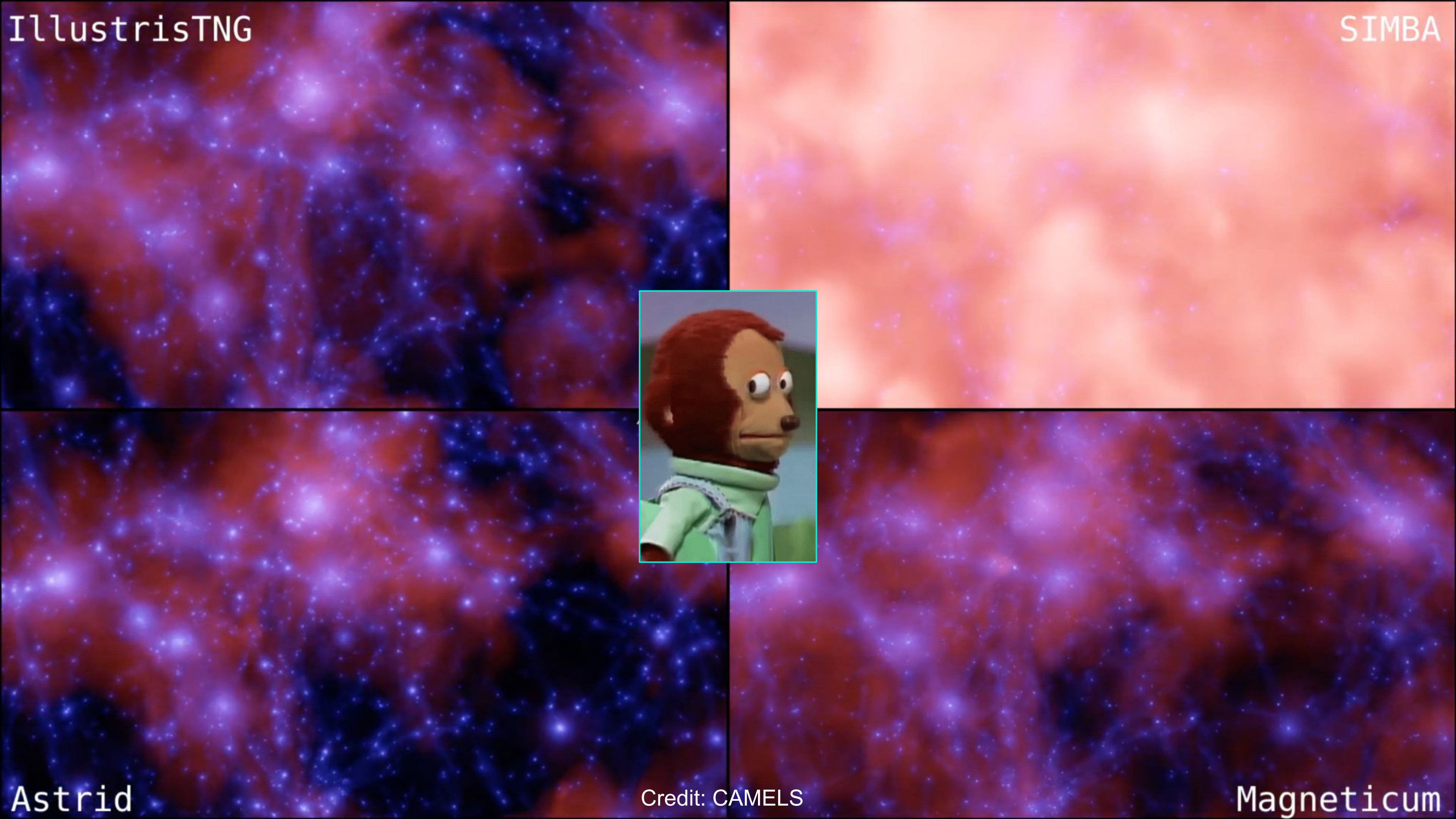
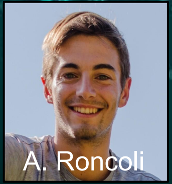
Astrid
Magneticum
Credit: CAMELS



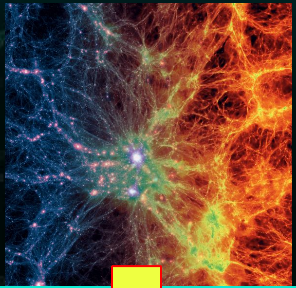
Credit: CAMELS

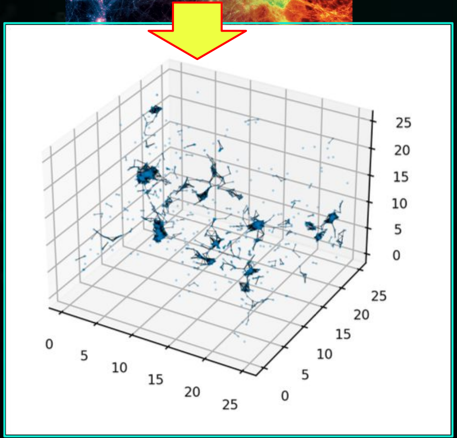
Regression - Cosmology With Graphs

NeurIPS 2023.
Roncoli et al. 2023.

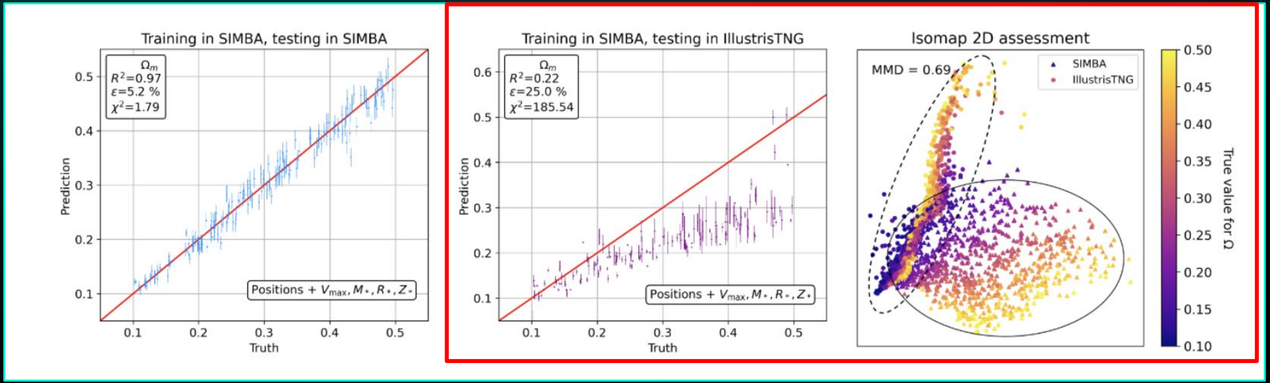


Graph Neural Networks:
ideal for sparse
galaxy catalogs!





SIMBA -> SIMBA   SIMBA->IllustrisTNG



z=0   1000 simulations each

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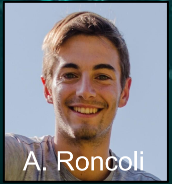

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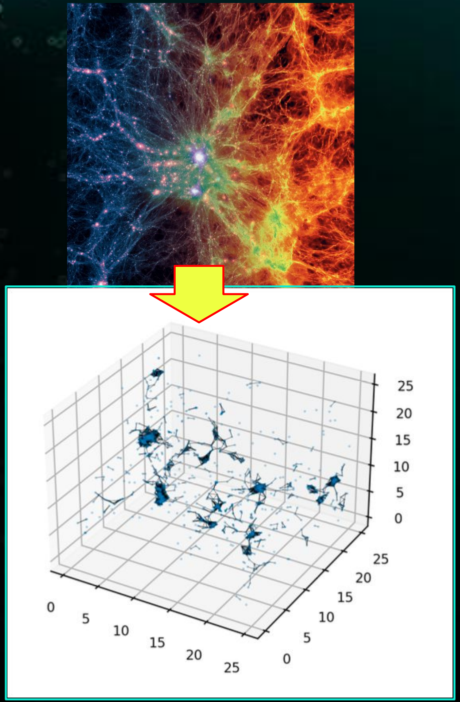
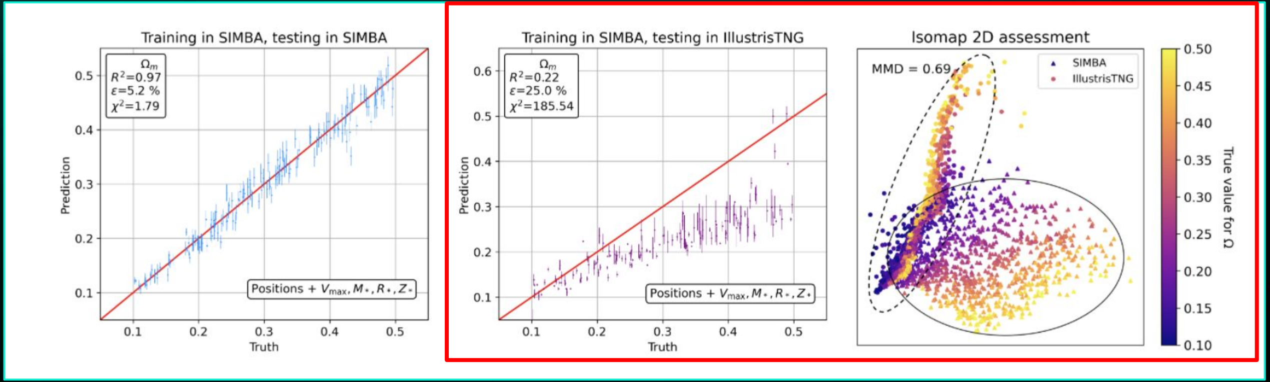


SIMBA -> SIMBA SIMBA->IllustrisTNG



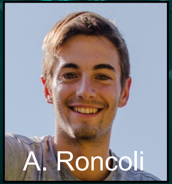
DOMAIN ADAPTATION

Align data distributions in the latent space of the network by forcing the network to **find more robust domain-invariant features**.

z=0 1000 simulations each

Regression - Cosmology With Graphs

NeurIPS 2023.
Roncoli et al. 2023.



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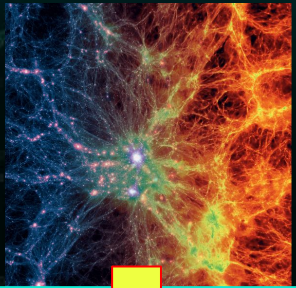
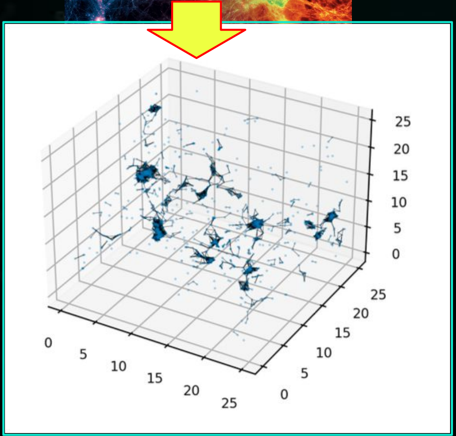
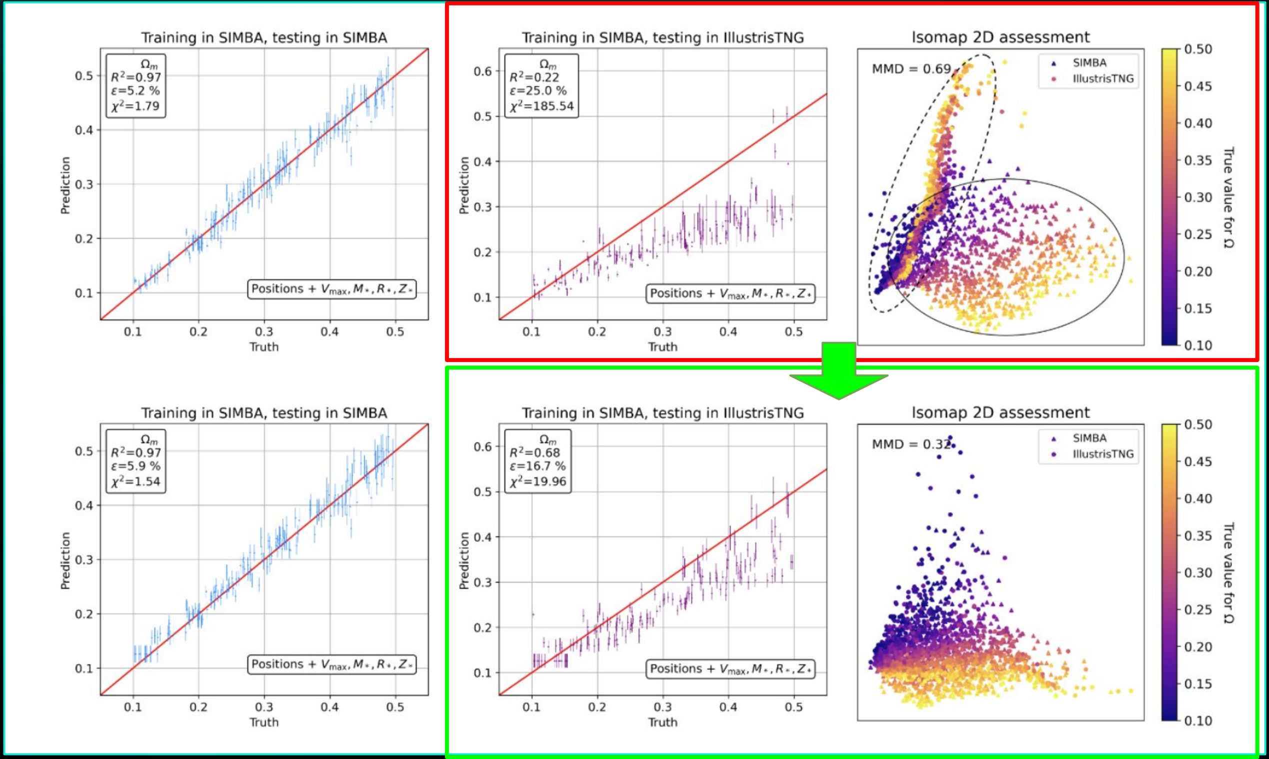




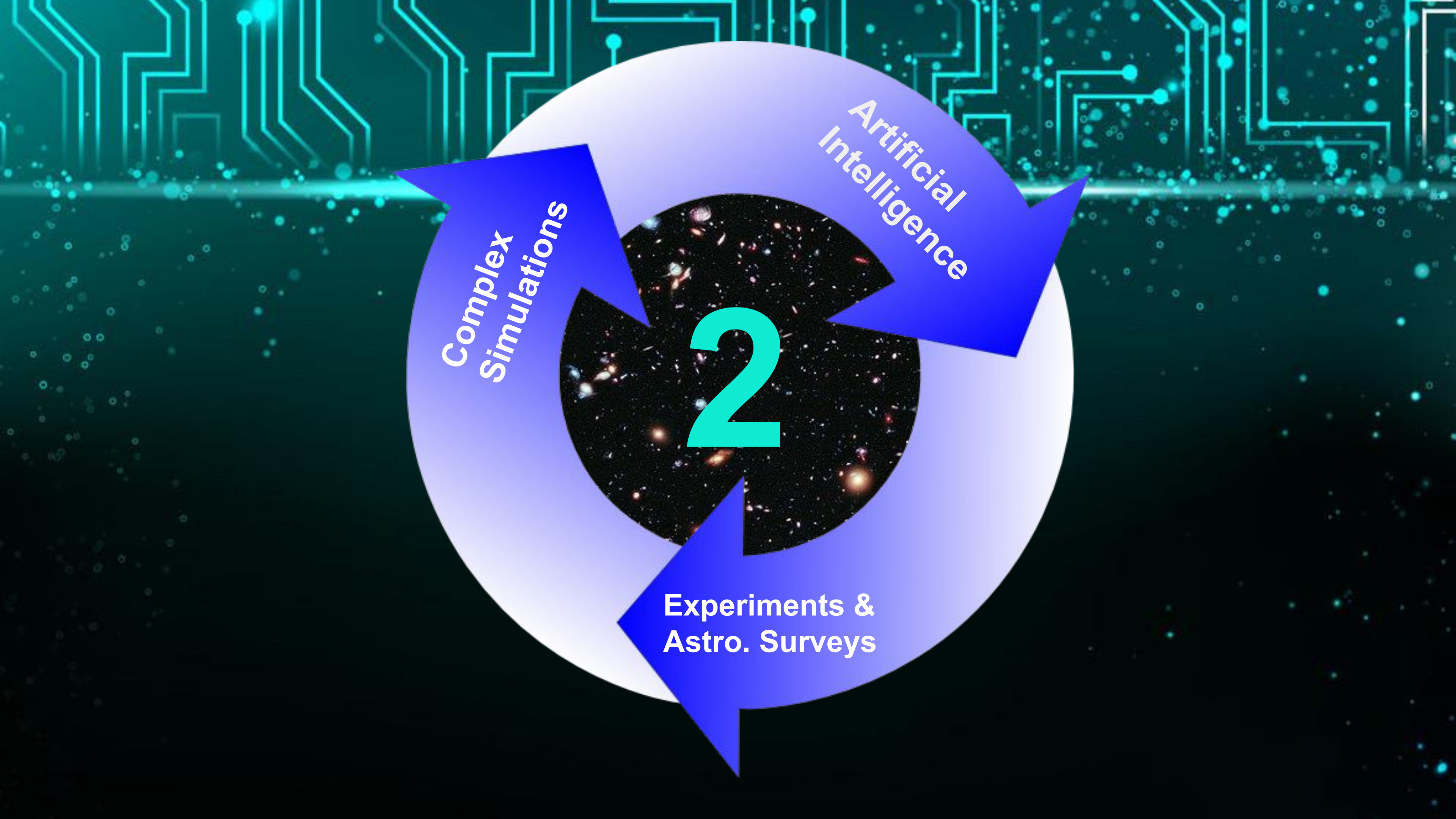
SIMBA -> SIMBA   SIMBA->IllustrisTNG



28% better relative error

order of mag. better χ^2

z=0   1000 simulations each

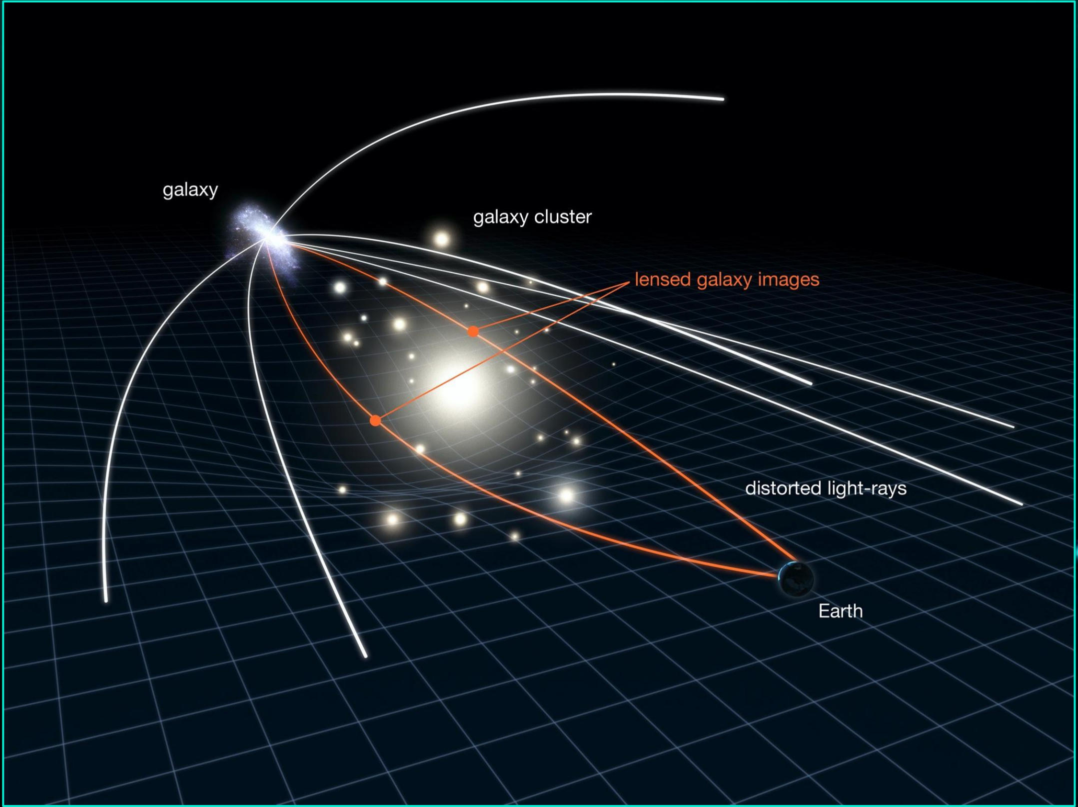

Artificial
Intelligence
Complex
Simulations
2
Experiments &
Astro. Surveys

Strong gravitational lensing

- When light from a distant galaxy pases near a massive galaxy cluster the **light bends** because the space-time has strong curvature near massive objects.

- We **can now see light from a galaxy that would otherwise be obscured** and too distant.

- And use it to infer cosmological parameters (and learn about dark matter)!



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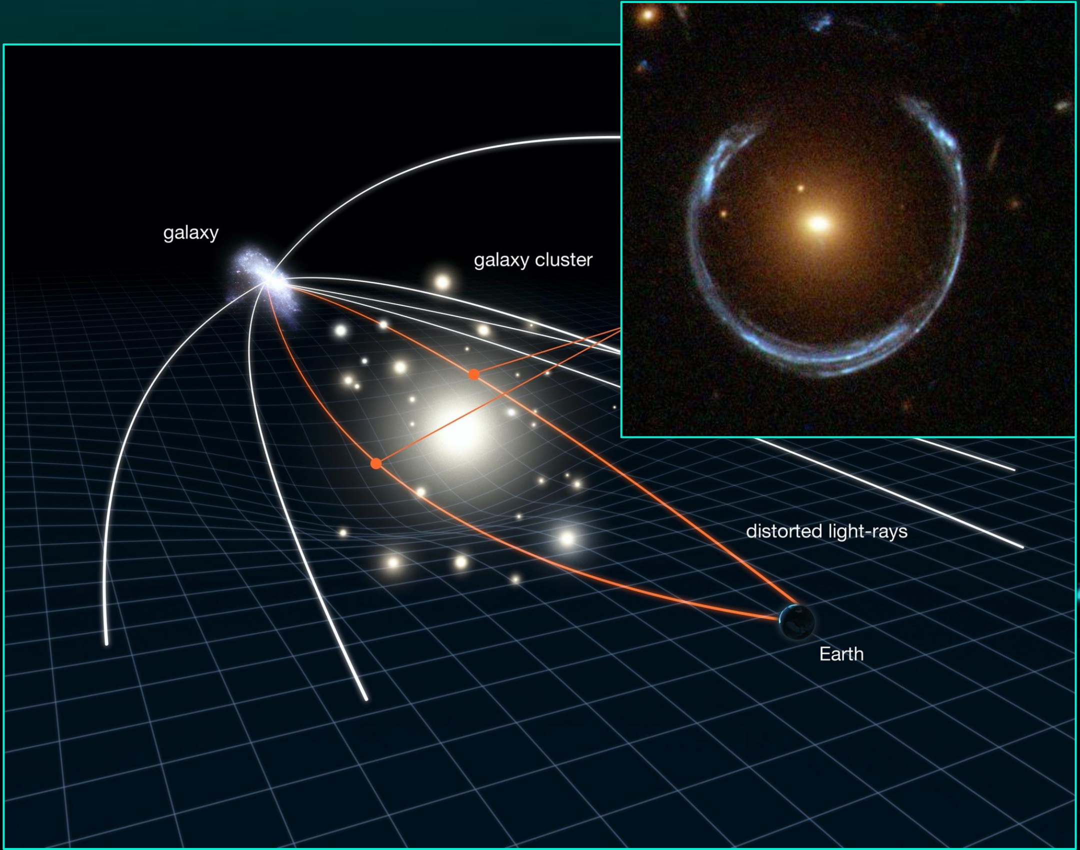

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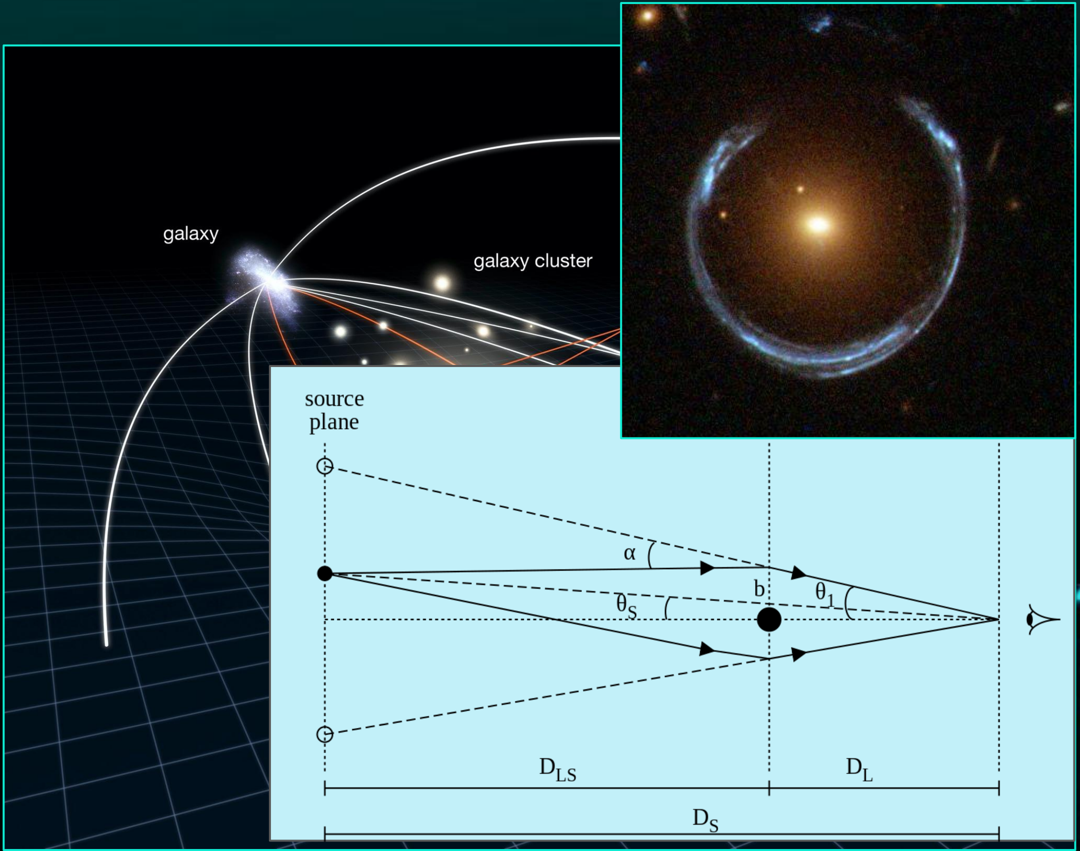

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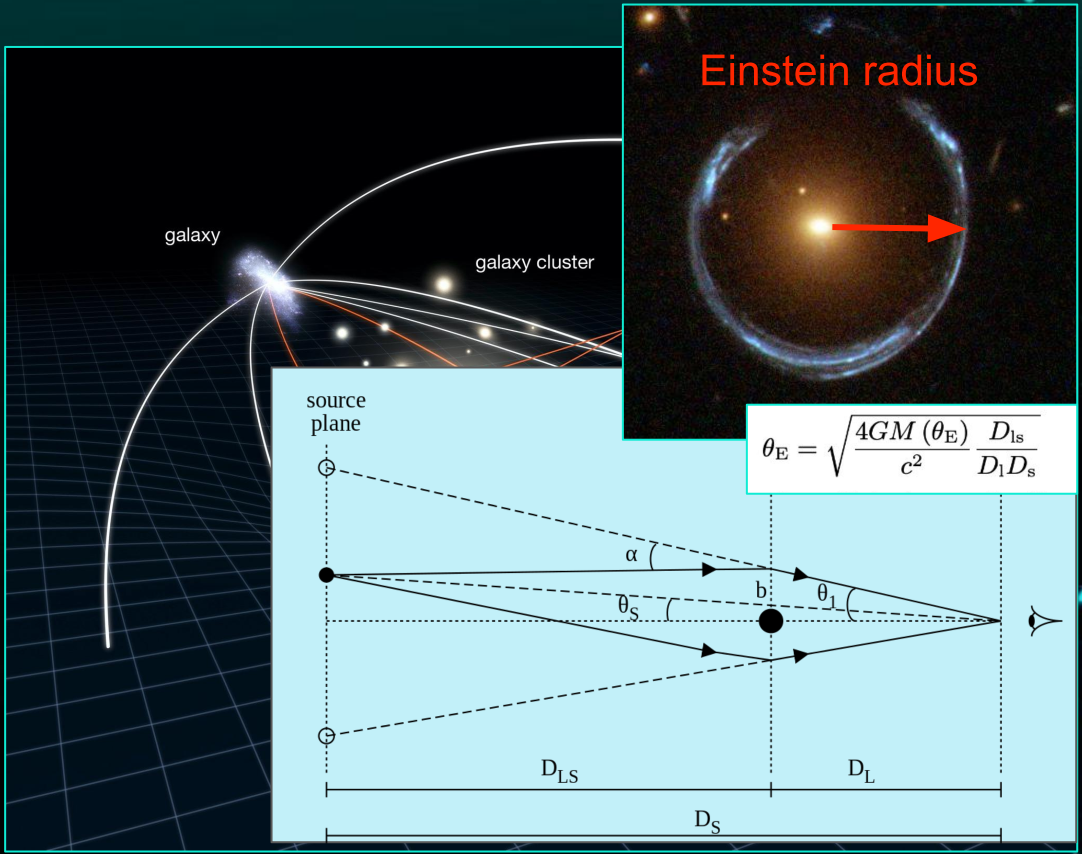

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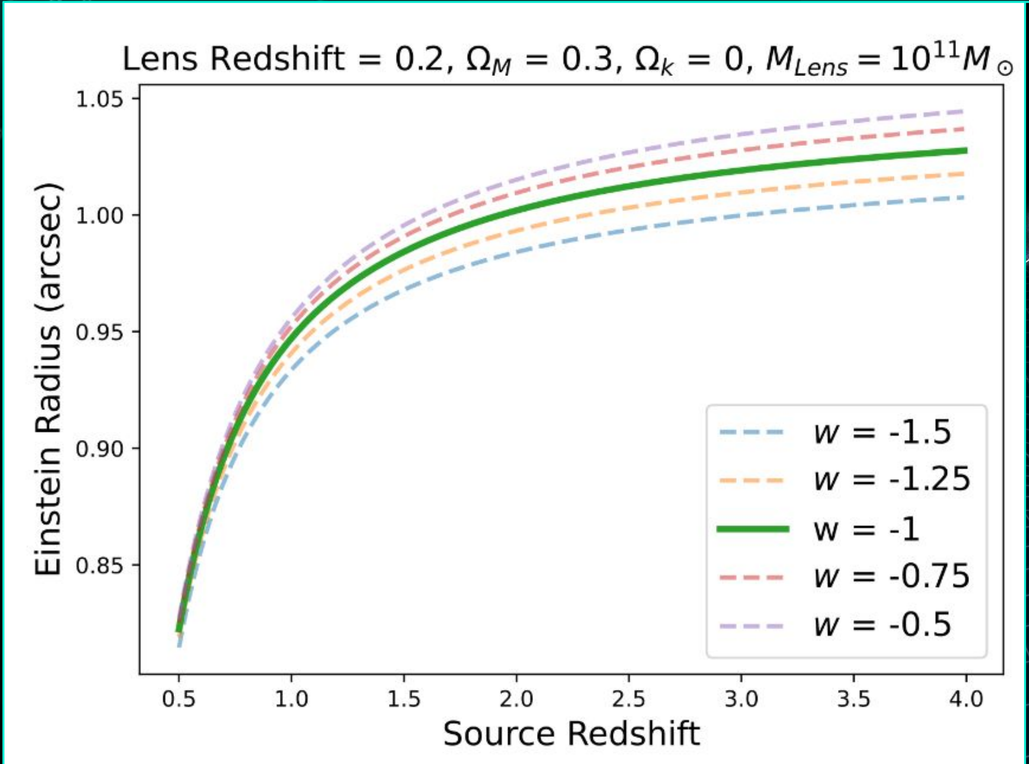
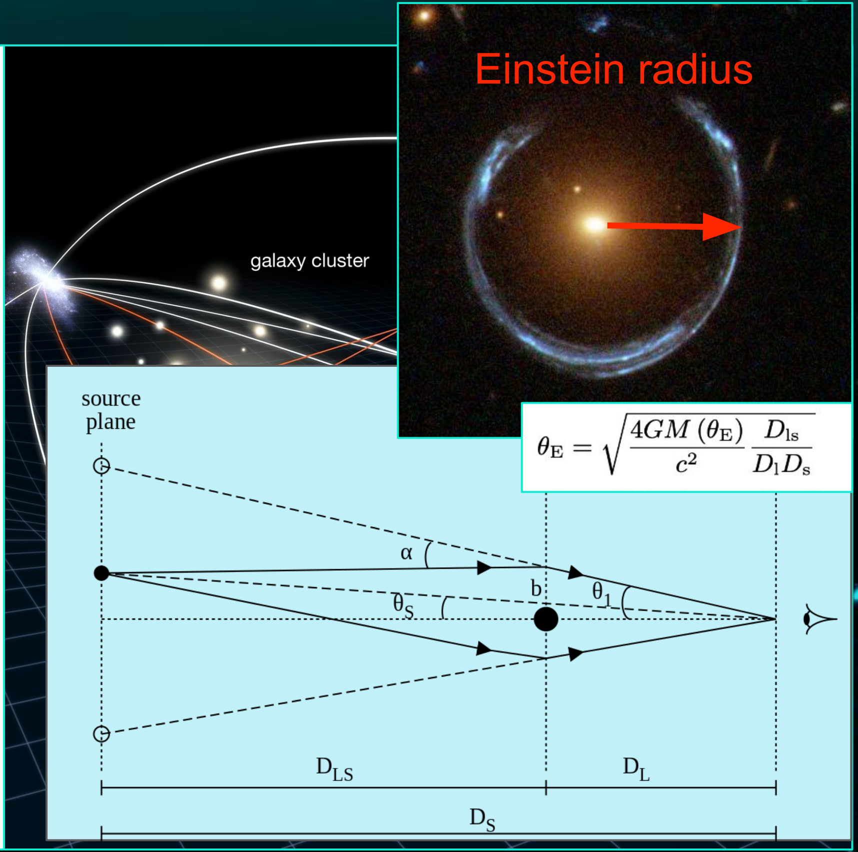
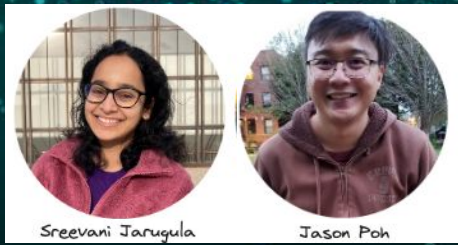


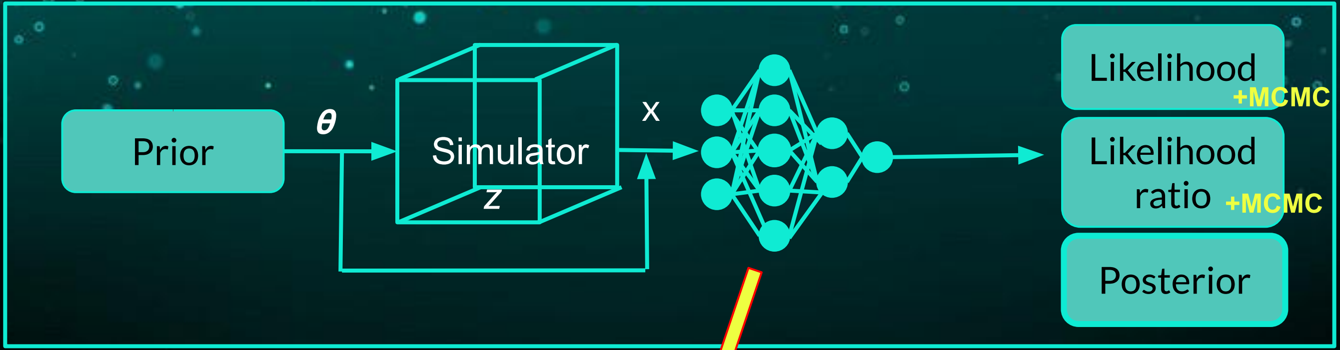
Tian et al. 2023.



$$\theta_E = \sqrt{\frac{4GM(\theta_E)}{c^2}\frac{D_{ls}}{D_l D_s}}$$

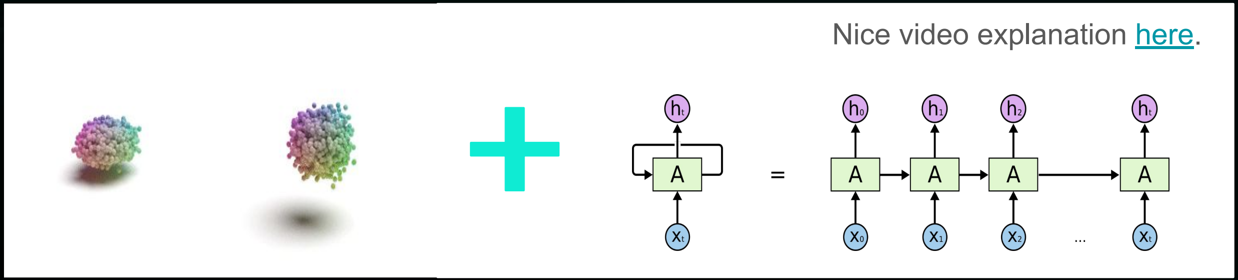
Being Bayesian with AI
Simulation-Based Inference (SBI)





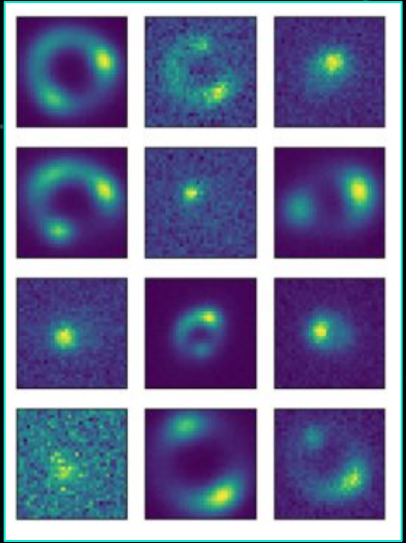
Poh et al. 2022; 2024. in prep
Swierc et al. 2023.
Jarugula et al. 2024.

Masked Autoregressive Flows (MAF)



Normalizing flows

Autoregressive models



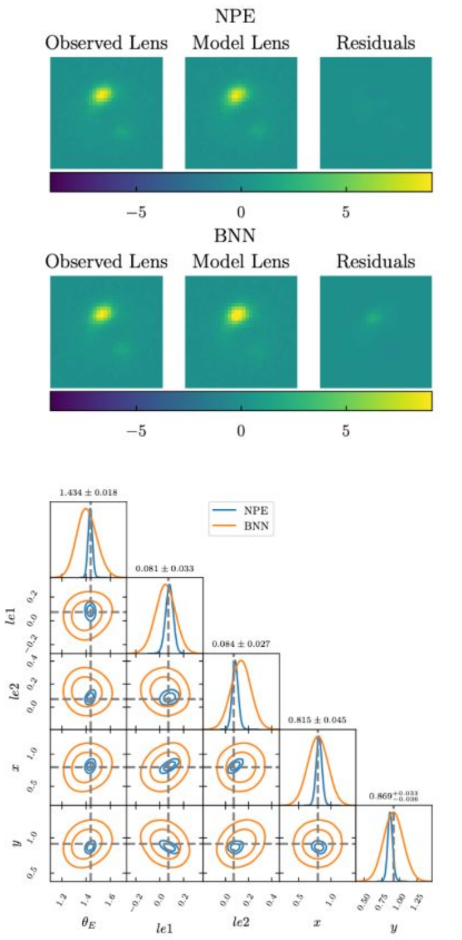
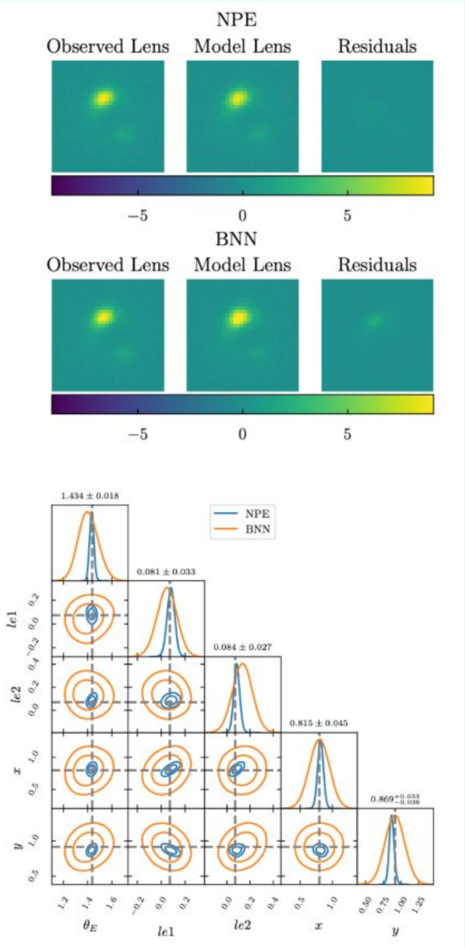


Figure 6. Single Image Inference Example for 5 parameter model.

- Estimate **posteriors of lens parameters** (up tp 12) without the need for slow MCMC and manual modeling.
- NPE is **mode flexible and accurate** than Bayesian NN which have a Gaussian constraint.



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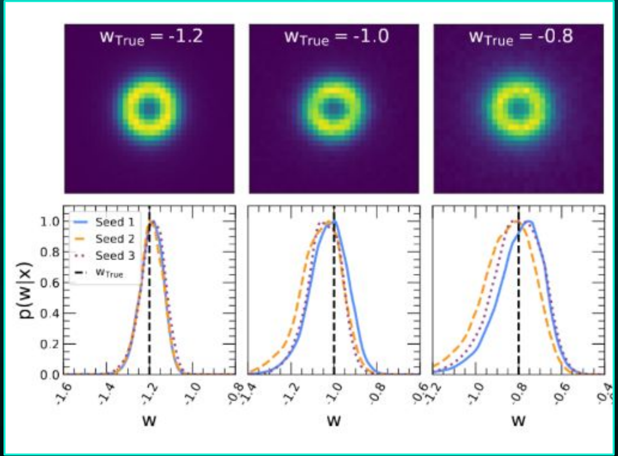
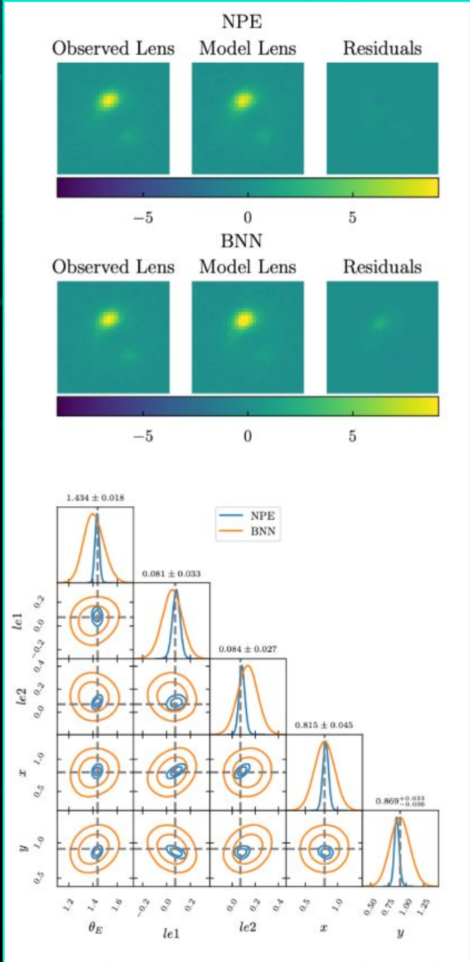


- Use a **regular CNN to estimate likelihood ratio** and then the posterior of w.



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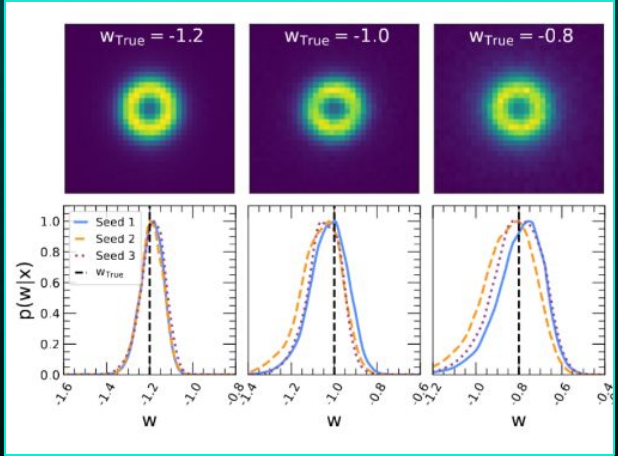
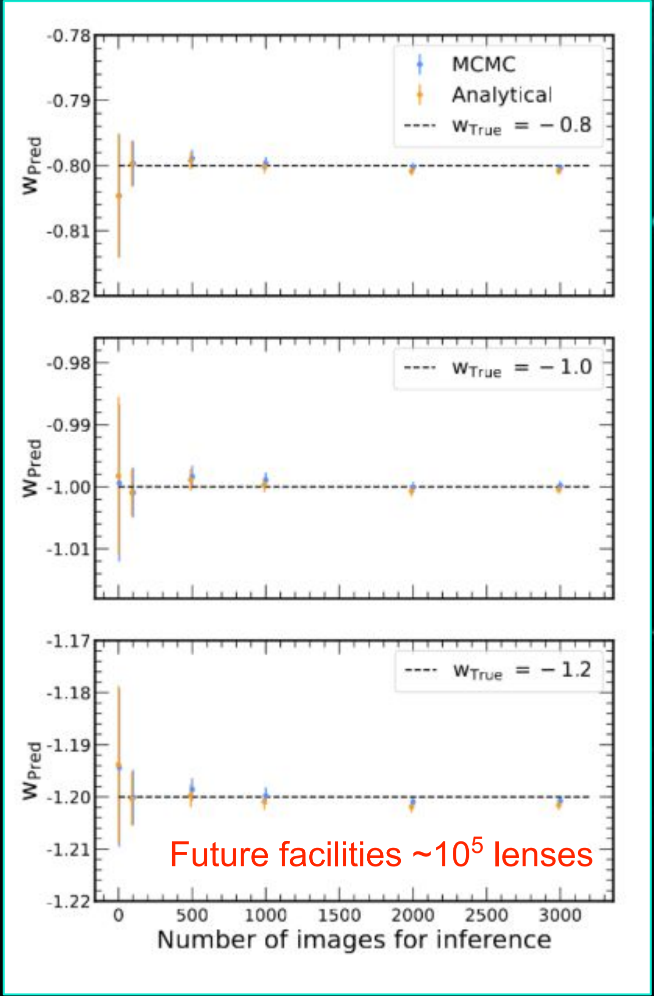
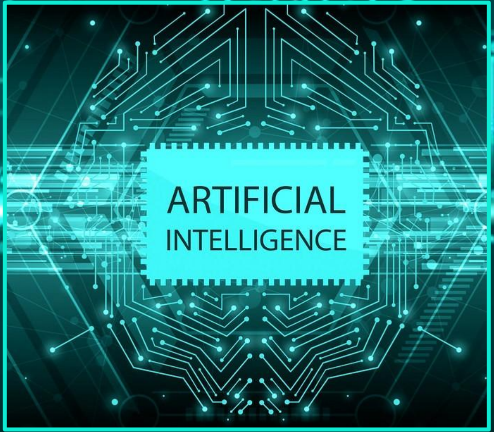


- Use a **regular CNN to estimate likelihood ratio** and then the posterior of w.
- By combining likelihoods from multiple lenses we get **tighter constraints** on the cosmology.



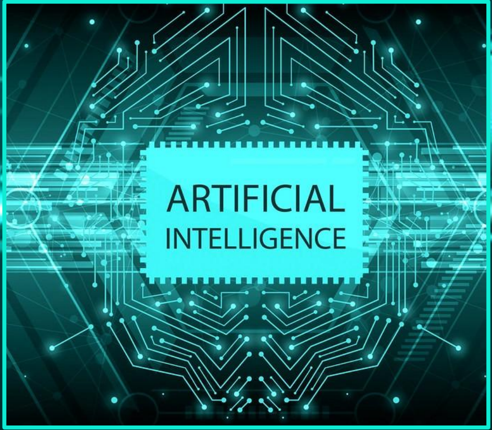


Complex models based on data.

Help constrain cosmology.

PROS

- Enabling work with huge datasets.
- Speed of analysis.
- Avoid compound biases in analysis.
- Help us understand and work with multi-dimensional data.
- Models include details, no need for approximations.



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- Help us understand and work with multi-dimensional data.
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CONS

- Model is as good as the data.
- Watch out for biased data!
- Often do not work for out-of-distribution data.
- We have to carefully think about the data and how to apply AI methods.
- It will learn even the biases we are not aware of.

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    - Inflation
    - Origin of the matter-antimatter asymmetry
    - Dark energy

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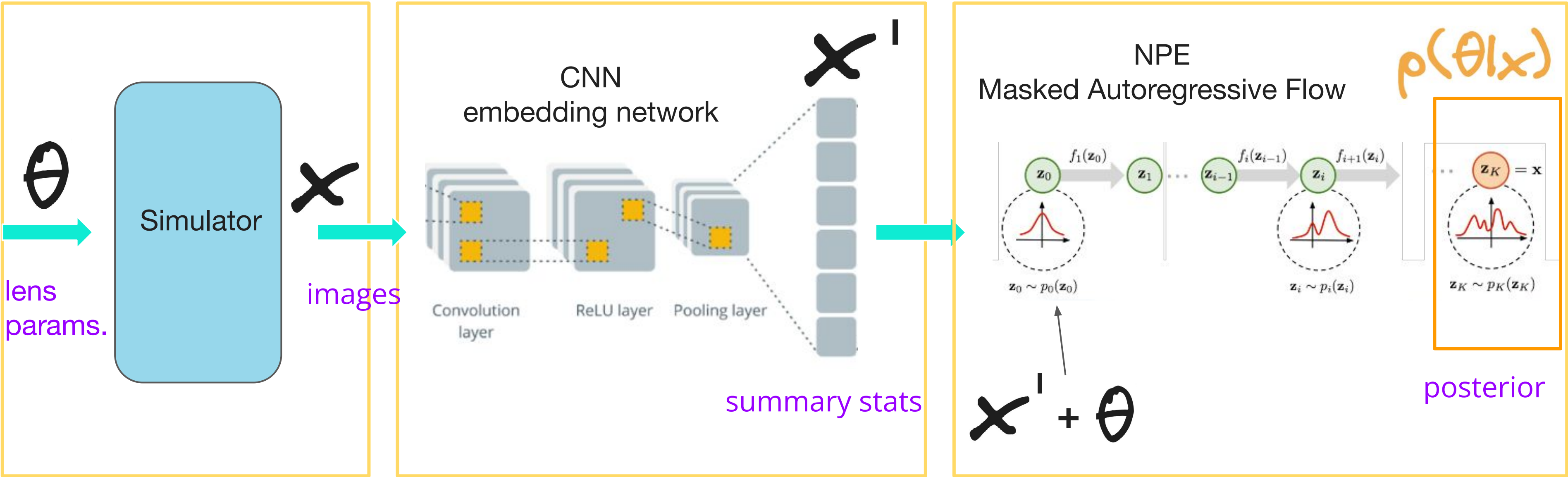
THANK YOU!

aleksand@fnal.gov

SBI setup



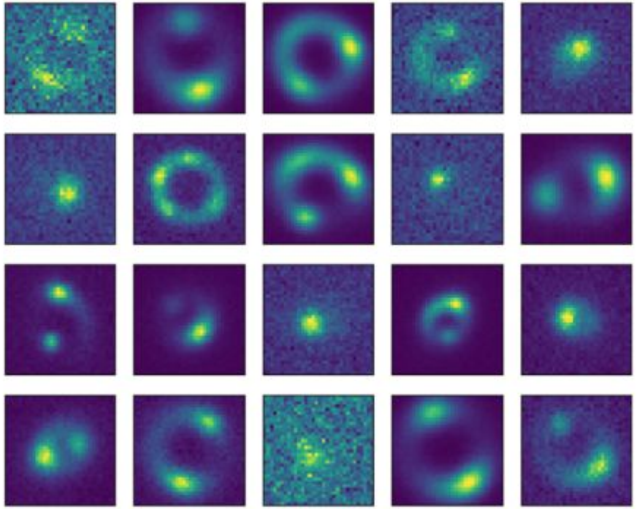
Poh et al. 2022 (NeurIPS 2022) arXiv:2211.05836
Poh et al. 2024 - coming very soon!

Data - DES mocks (ground-based observations)

PRELIMINARY

	Parameter	Applicable Models	Training Set Priors
Einstein radius	θ_E('')	1,5,12	$\mathcal{U}(0.3, 4.0)$
Ellipticity components	le_2	5,12	$\mathcal{U}(-0.8, 0.8)$
	le_2	5,12	$\mathcal{U}(-0.8, 0.8)$
	x_c ('')	5,12	$\mathcal{U}(-2, 2)$
lens-source offset	y_c ('')	5,12	$\mathcal{U}(-2, 2)$
external shear	γ_1	12	$\mathcal{U}(-0.8, 0.8)$
	γ_2	12	$\mathcal{U}(-0.8, 0.8)$
Sersic profile with: apparent magnitude	m_s	12	$\mathcal{U}(18, 25)$
half-light radius	R ('')	12	$\mathcal{U}(0.1, 3.0)$
Sersic index	n	12	$\mathcal{U}(0.5, 8.0)$
	se_1	12	$\mathcal{U}(-0.8, 0.8)$
ellipticity components	se_2	12	$\mathcal{U}(-0.8, 0.8)$

1, 5, 12 parameter models

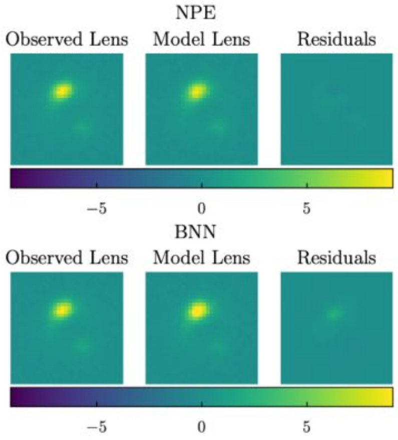


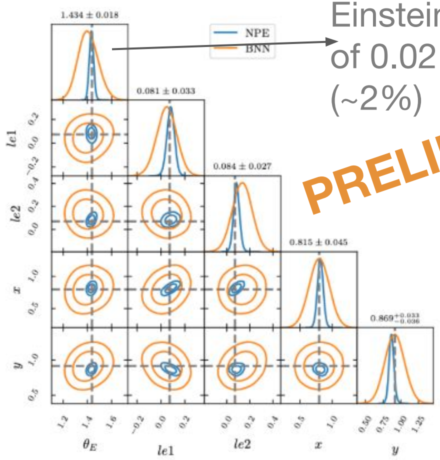
Model	Training	Test
1-parameter	200, 000	1000
5-parameter	400, 000	1000
12-parameter	800, 000	1000

Test Set Priors	OOD Priors Test Set 1	OOD Priors Test Set 2	OOD Priors Test Set 3
Lens Mass Parameters			
$\mathcal{U}(0.5, 3.0)$	$\mathcal{N}(2.0, 0.2)$	$\mathcal{N}(1.0, 0.2)$	$\mathcal{N}(1.0, 0.2)$
$\mathcal{U}(-0.2, 0.2)$	$\mathcal{N}(-0.2, 0.2)$	$\mathcal{N}(-0.1, 0.2)$	$\mathcal{N}(-0.2, 0.2)$
$\mathcal{U}[-0.2, 0.2]$	$\mathcal{N}(-0.2, 0.2)$	$\mathcal{N}(-0.1, 0.2)$	$\mathcal{N}(0.2, 0.2)$
$\mathcal{U}(-1, 1)$	$\mathcal{N}(0.2, 0.2)$	$\mathcal{N}(-0.1, 0.2)$	$\mathcal{N}(-0.2, 0.2)$
$\mathcal{U}(-1, 1)$	$\mathcal{N}(-0.2, 0.2)$	$\mathcal{N}(-0.1, 0.2)$	$\mathcal{N}(0.2, 0.2)$
Lens Environment Parameters			
$\mathcal{U}(-0.05, 0.05)$	$\mathcal{N}_{\log}(-3, 1)$	$\mathcal{N}(0.00, 0.05)$	$\mathcal{N}(0.00, 0.01)$
$\mathcal{U}(-0.05, 0.05)$	$\mathcal{N}_{\log}(-3, 1)$	$\mathcal{N}(0.00, 0.05)$	$\mathcal{N}(0.00, 0.01)$
Source Light Parameters			
$\mathcal{U}(19, 24)$	$\mathcal{N}(22, 1)$	$\mathcal{N}(21, 1)$	$\mathcal{N}(21.0, 0.5)$
$\mathcal{U}(0.5, 1.0)$	$\mathcal{N}(0.7, 0.1)$	$\mathcal{N}(1.0, 0.2)$	$\mathcal{N}(0.8, 0.1)$
$\mathcal{U}(2, 4)$	$\mathcal{N}(4, 1)$	$\mathcal{N}(3.0, 0.5)$	$\mathcal{N}(5.0, 0.1)$
$\mathcal{U}(-0.2, 0.2)$	$\mathcal{N}(-0.2, 0.2)$	$\mathcal{N}(-0.1, 0.2)$	$\mathcal{N}(0.1, 0.1)$
$\mathcal{U}(-0.2, 0.2)$	$\mathcal{N}(-0.2, 0.2)$	$\mathcal{N}(0.1, 0.2)$	$\mathcal{N}(-0.1, 0.1)$

- We also run tests for:
  - 3 OOD tests sets
  - 3 initial random seeds

5-parameter results





Einstein radius error of 0.02 arcsec (~2%)

PRELIMINARY

Figure 6. Single Image Inference Example for 5 parameter model.

Fermilab

5-parameter results

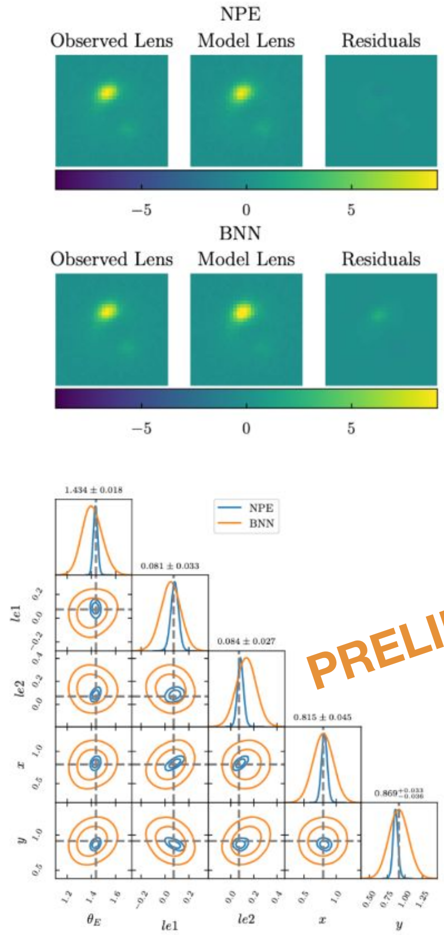


Figure 6. Single Image Inference Example for 5 parameter model.

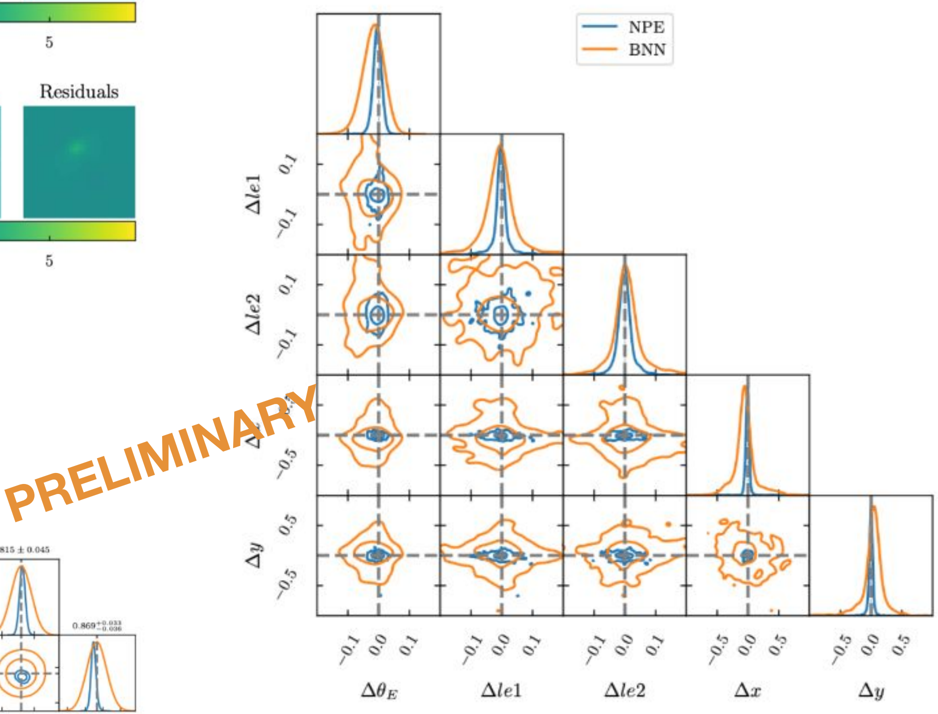
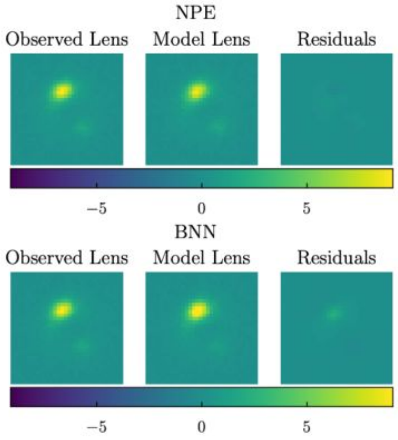
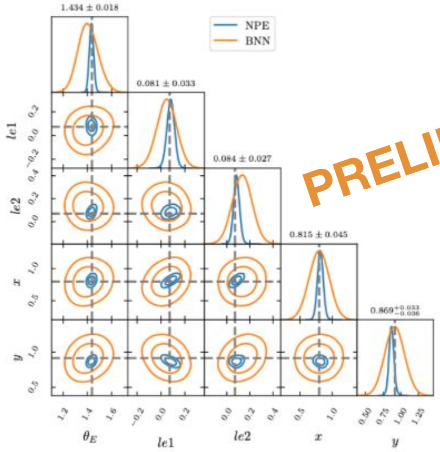


Figure 8. 5 parameter error corner plot.

5-parameter results





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PRELIMINARY

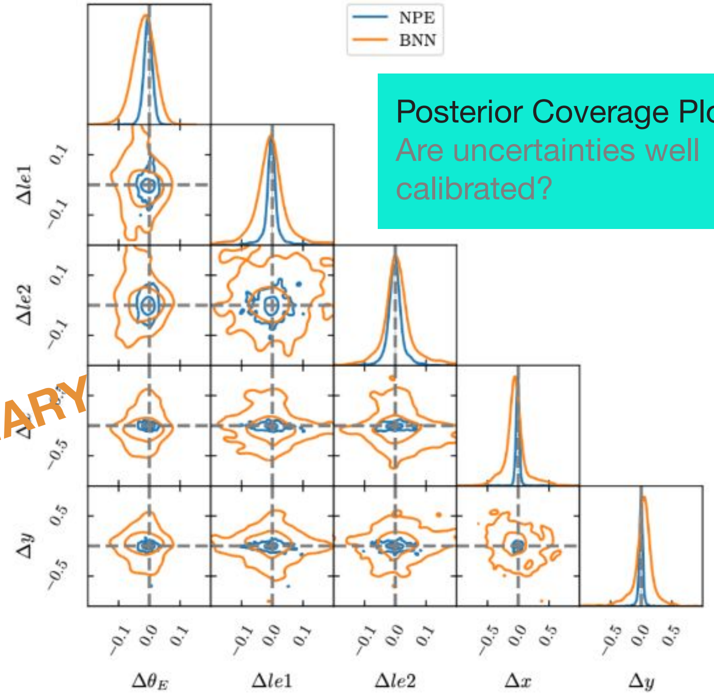
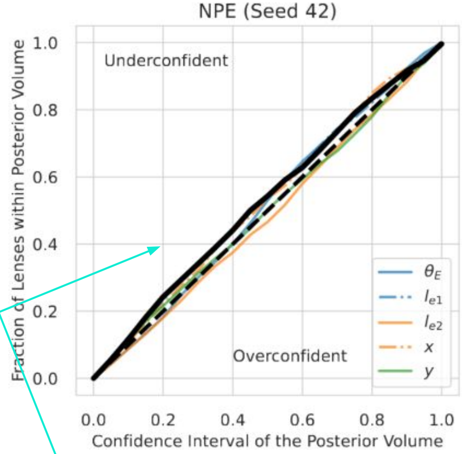
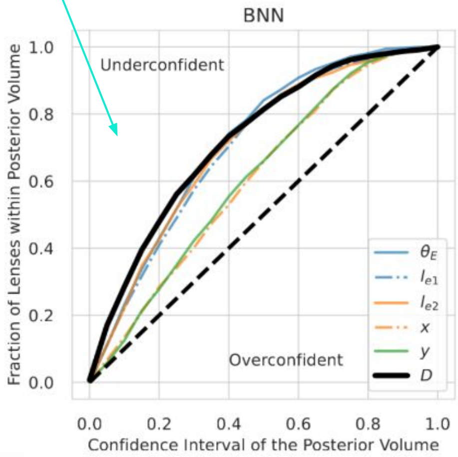


Figure 8. 5 parameter error corner plot.

Posterior Coverage Plot

Are uncertainties well calibrated?





Solving the Friedmann Equation

Expansion rate → $$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{Kc^2}{a^2} + \frac{\Lambda}{3}$$ ← Density measures

In order to solve it, we also need to define the behavior of the mass/energy density $\rho(a)$ of any given mass/energy component. Recall the basic GR paradigm:

> Density determines the expansion
> Expansion changes the density

Each component will lead to a different evolution in redshift

We already saw that:

$$\rho_{\mathrm{m}}(t) = \rho_{\mathrm{m},0}\, a^{-3}(t)$$
$$\rho_{\mathrm{r}}(t) = \rho_{\mathrm{r},0}\, a^{-4}(t)$$
$$\rho_{\mathrm{v}}(t) = \rho_{\mathrm{v}} = \mathrm{const.}$$

Credit: Caltech

The Equation of State

- Defines the dependence of the density vs. volume for a given matter/energy component, to enter in the Friedman eq.
- Usually written as $\boldsymbol{p = w\,\rho}$
- This is not necessarily the best way to describe the matter / energy density; it implies a fluid of some kind… This may be OK for the matter and radiation we know, but maybe it is not an optimal description for the dark energy
- Special values:

  $w = 0$ means $p = 0$, e.g., non-relativistic matter

  $w = 1/3$ is radiation or relativistic matter

  $w = -1$ looks just like a cosmological constant

  … but it can have in principle any value, and it can be changing in redshift

Credit: Caltech

Matter dominated ($w = 0$): $\rho \sim a^{-3}$

Radiation dominated ($w = 1/3$): $\rho \sim a^{-4}$

Dark energy ($w \sim -1$): $\rho \sim constant$

- Radiation density decreases the fastest with time
  - Must increase fastest on going back in time
  - Radiation must dominate early in the Universe
- Dark energy with $w \sim -1$ dominates last; it is the dominant component now, and in the (infinite?) future

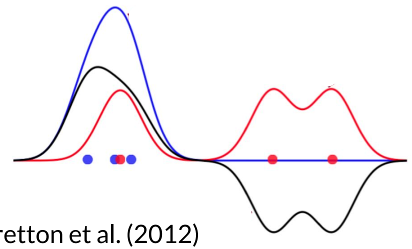
Credit: Caltech

Combining Datasets

DOMAIN ADAPTATION

Align data distributions in the latent space of the network by forcing the network to find more robust domain-invariant features.

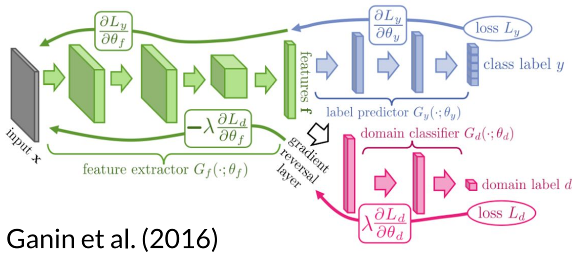
Distance-based methods



Gretton et al. (2012)

Training = Task Loss + DA Loss

Adversarial methods



Ganin et al. (2016)

Combining Datasets

DOMAIN ADAPTATION

Align data distributions in the latent space of the network by forcing the network to **find more robust domain-invariant features.**

Distance-based methods

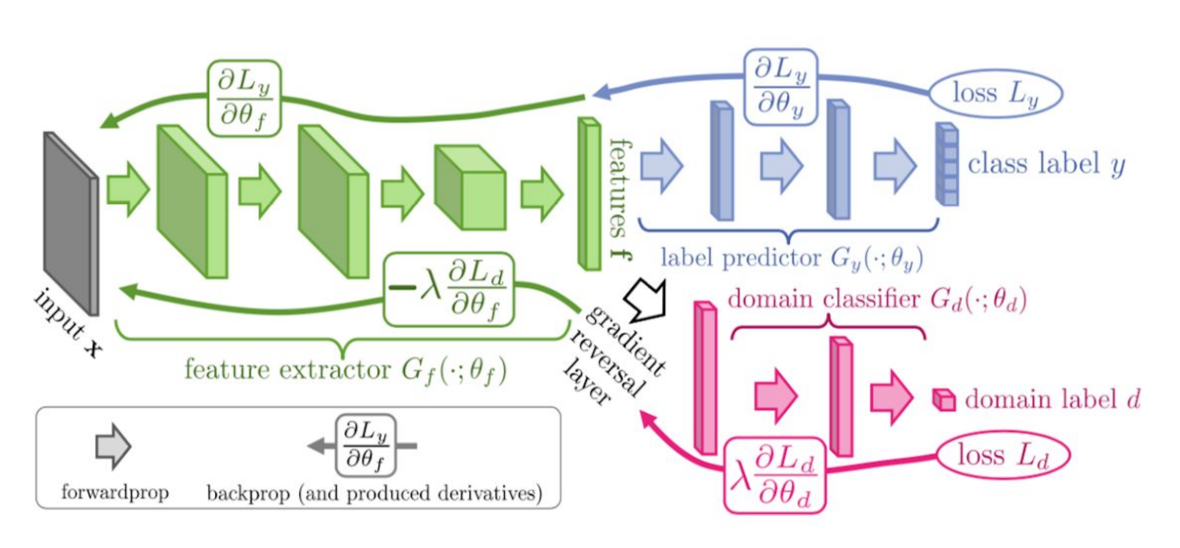
Adversarial methods

Works on **unlabeled target domain**!
Can be applied to **new data**, no need for scientists to label anything.

Domain Adversarial Neural Networks - DANNs

DANN - feature extractor + label predictor + domain classifier

- **Gradient reversal layer** - multiplies the gradient by a negative constant during the backpropagation.
- Results in the extraction of **domain-invariant features**.
- Only source domain images are labeled during training.



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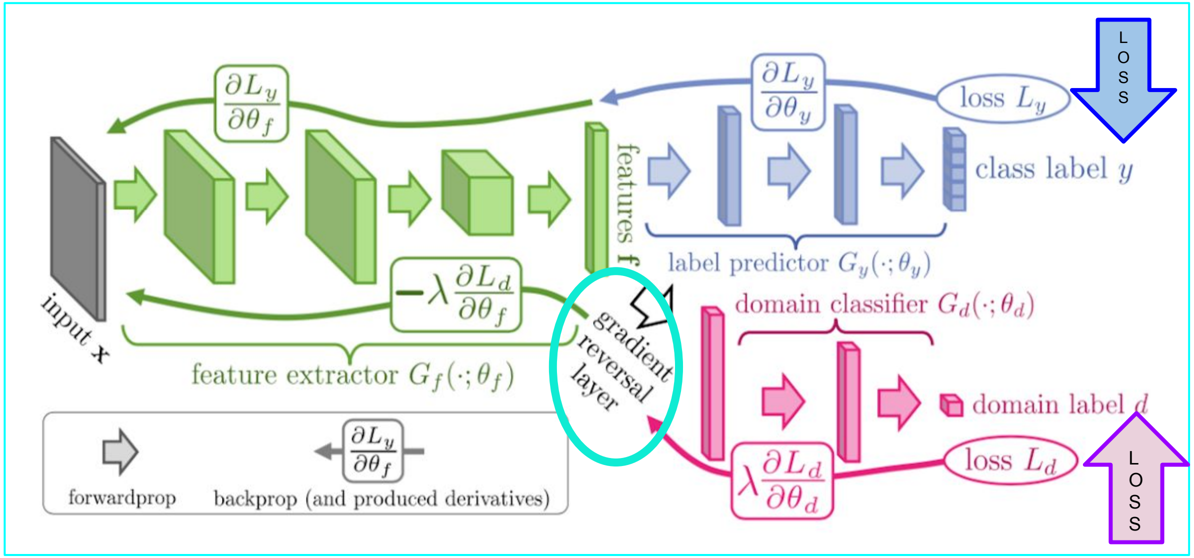
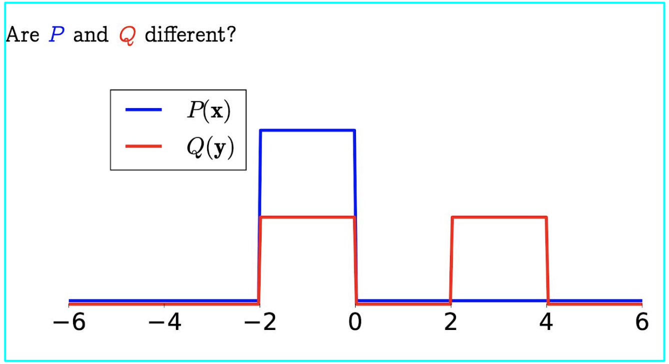
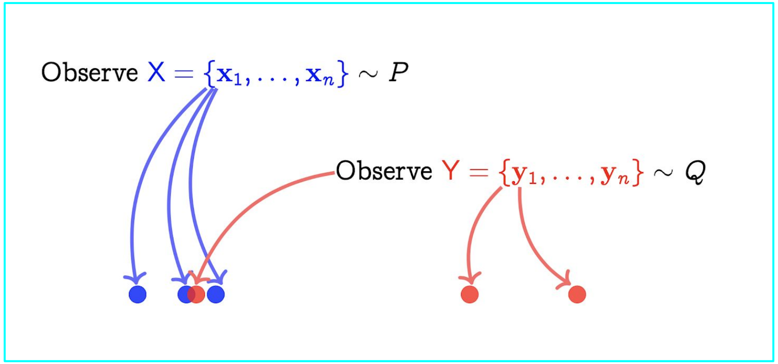


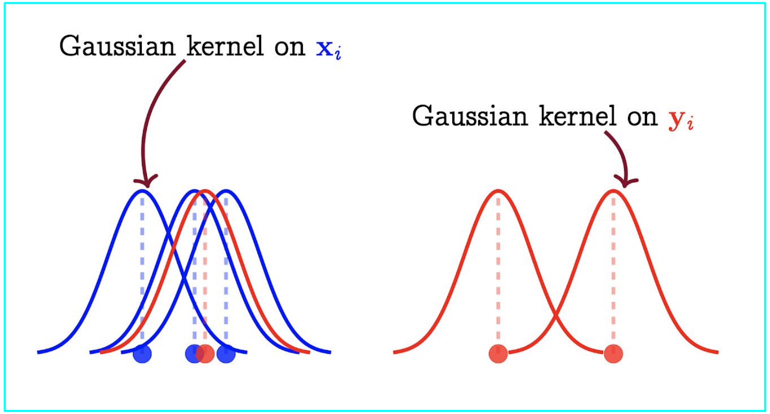
Ganin et al. (2016)

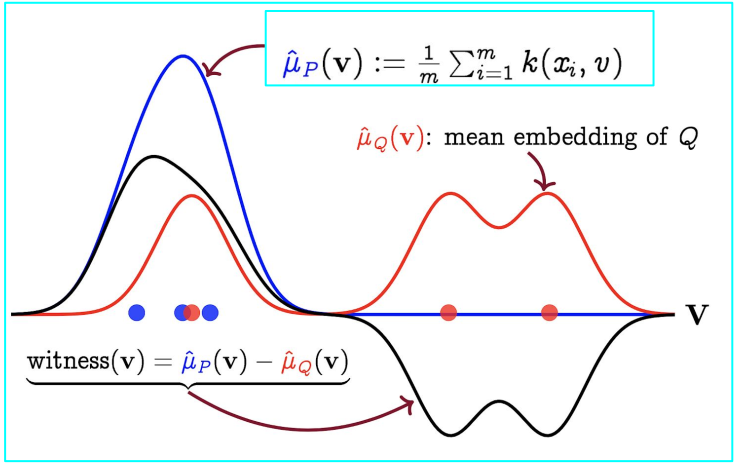
Maximum Mean Discrepancy - MMD

Smola et al. (2007)
Gretton et al. (2012)









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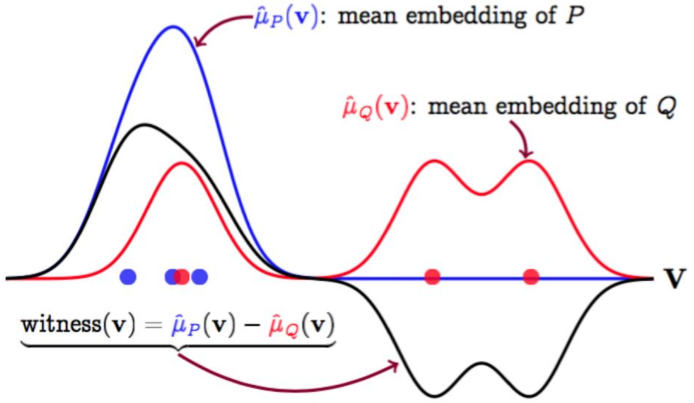
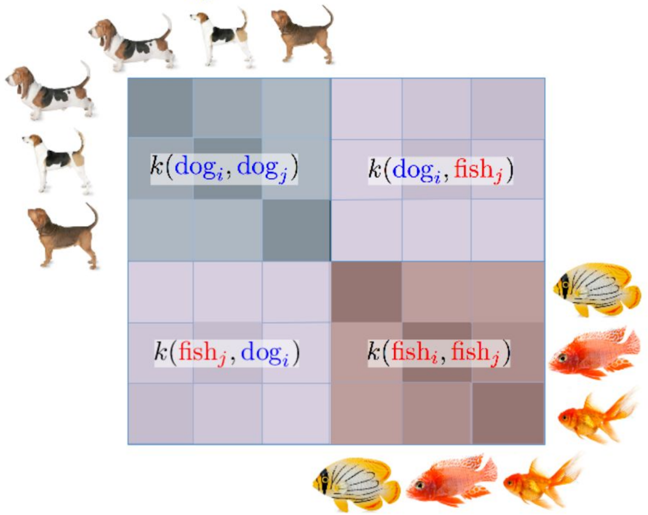


$$\widehat{MMD}^2 = ||\text{witness}(\mathbf{v})||^2_{\mathcal{F}}$$
$$= \frac{1}{n(n-1)} \sum_{i \neq j} k(x_i, x_j) + \frac{1}{n(n-1)} \sum_{i \neq j} k(y_i, y_j) - \frac{2}{n^2} \sum_{i,j} k(x_i, y_j)$$

$$\widehat{MMD}^2 = \frac{1}{n(n-1)} \sum_{i \neq j} k(\text{dog}_i, \text{dog}_j) + \frac{1}{n(n-1)} \sum_{i \neq j} k(\text{fish}_i, \text{fish}_j) - \frac{2}{n^2} \sum_{i,j} k(\text{dog}_i, \text{fish}_j)$$



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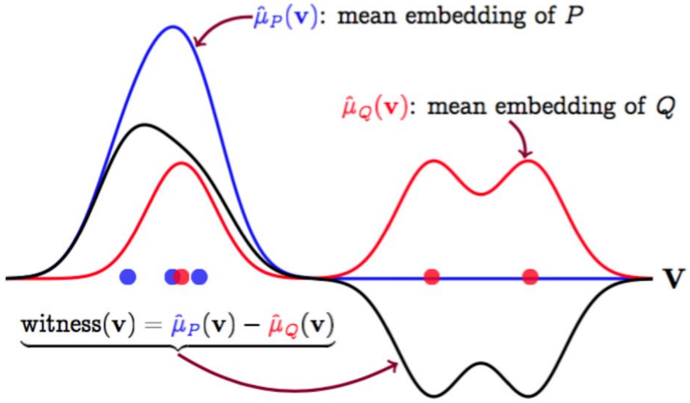

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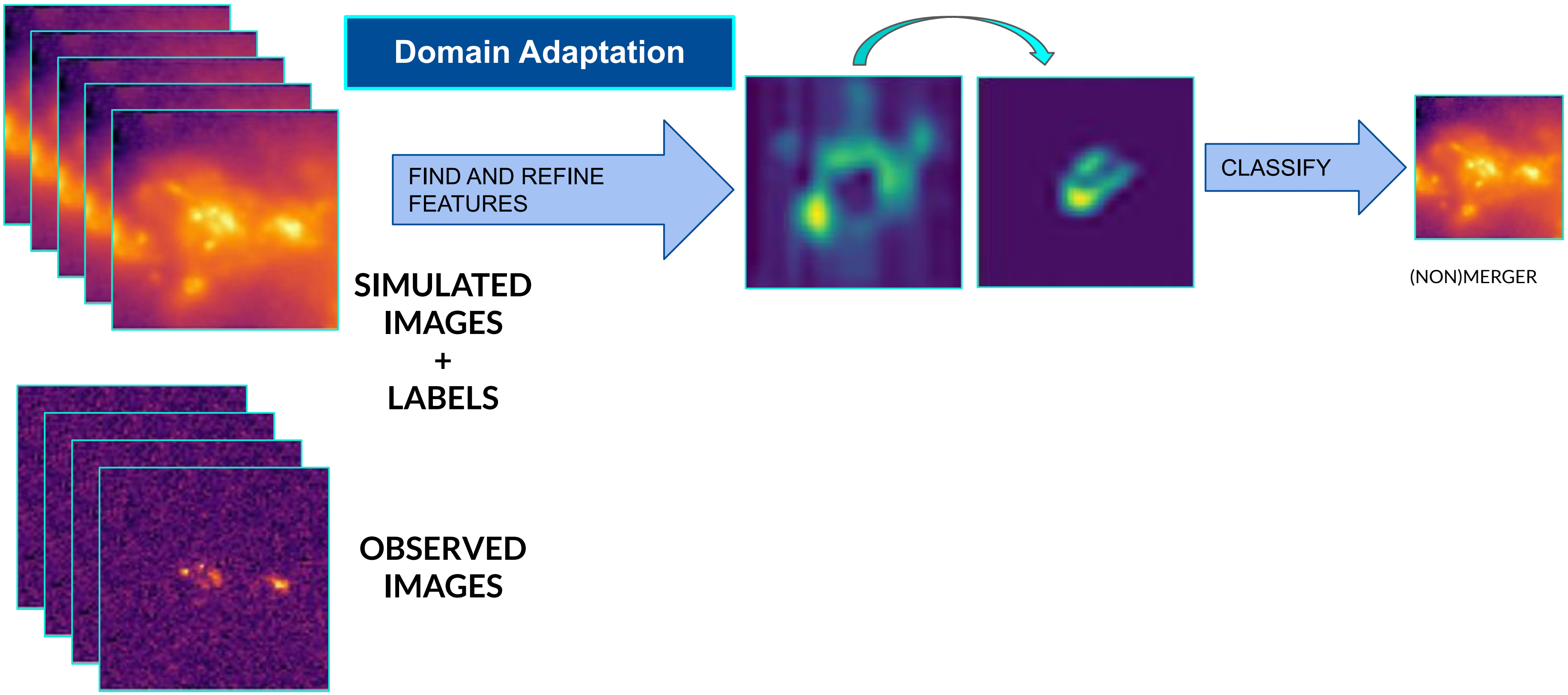
$$- \frac{2}{n^2} \sum_{i,j} k(x_i, \mathrm{y}_j)$$

Combining Datasets



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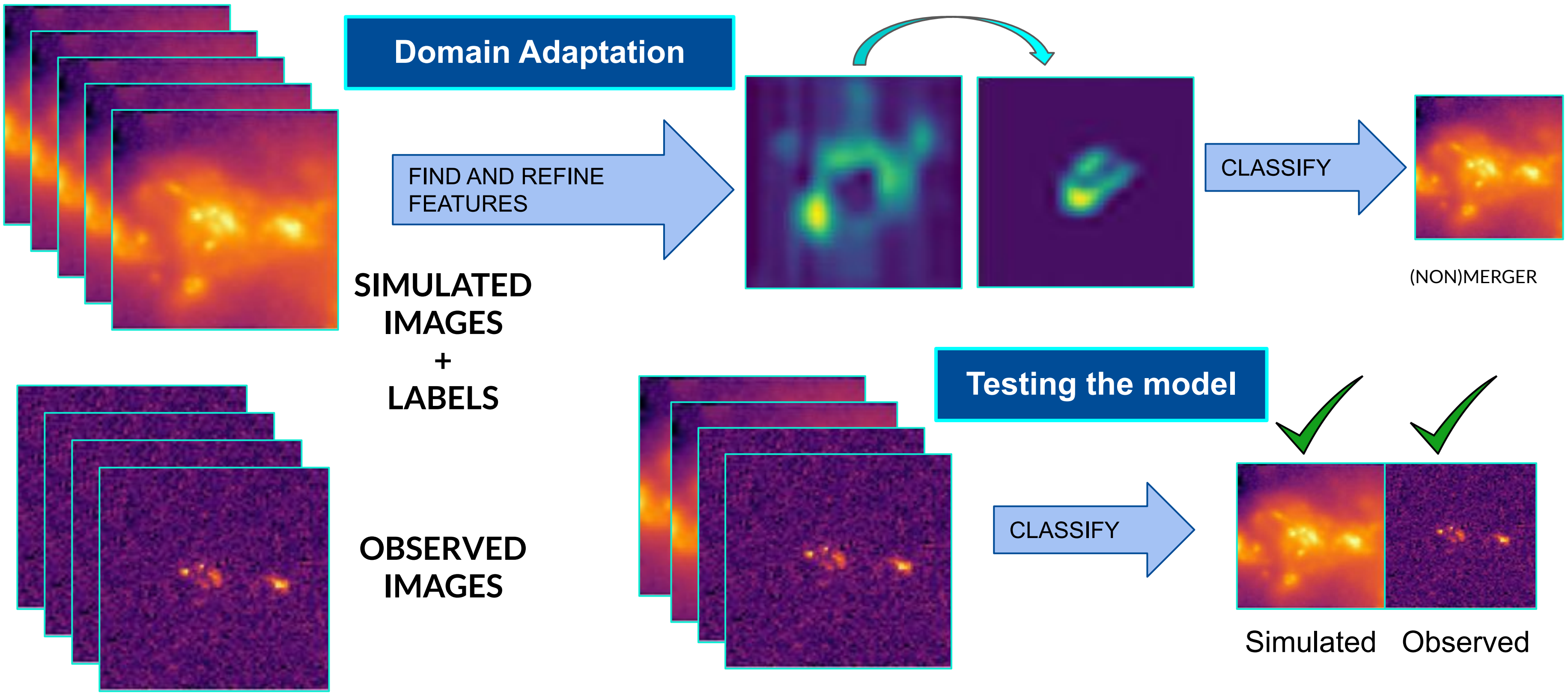
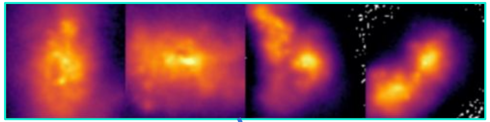
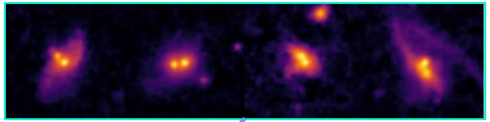


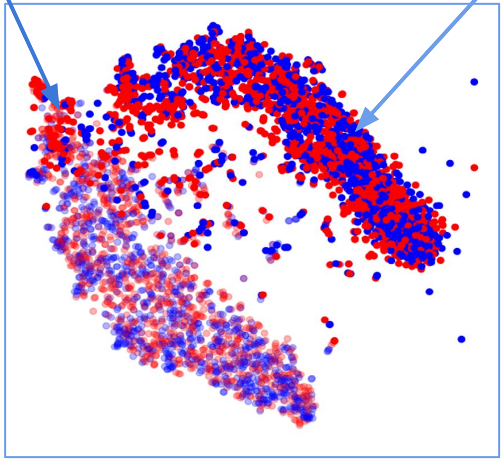
Combining Datasets

Source - Illustris



Target - SDSS observations



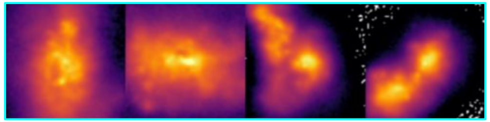


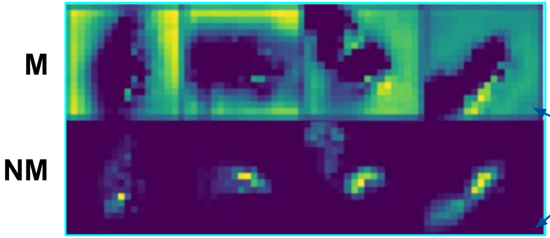
This is how the network sees the data.
2D representation of network's latent space.

Ćiprijanović et al. 2020.
Ćiprijanović et al. 2021.

Combining Datasets

Source - Illustris





Important regions are highlighted!

Regular Training

Ćiprijanović et al. 2020.
Ćiprijanović et al. 2021.

Combining Datasets

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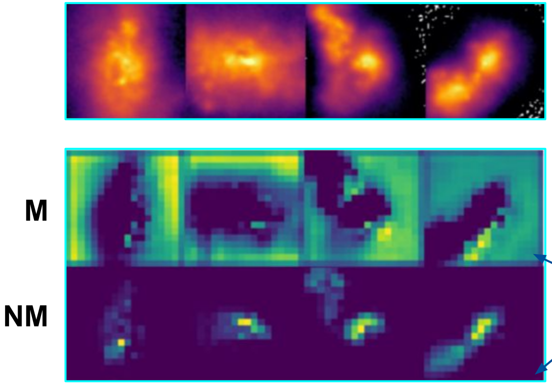

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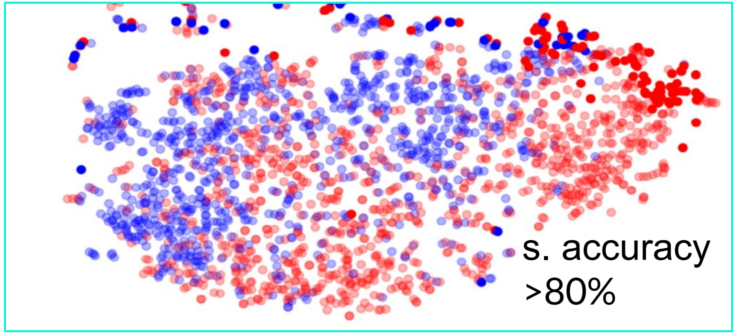


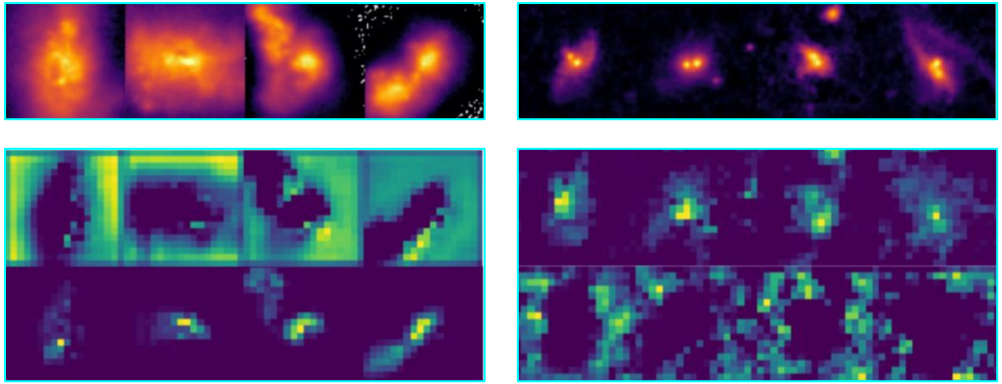
Ćiprijanović et al. 2020.
Ćiprijanović et al. 2021.

Combining Datasets

Source - Illustris **Target - SDSS observations**

M

NM



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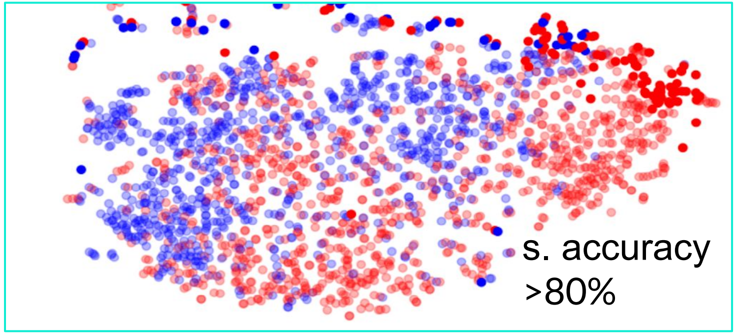

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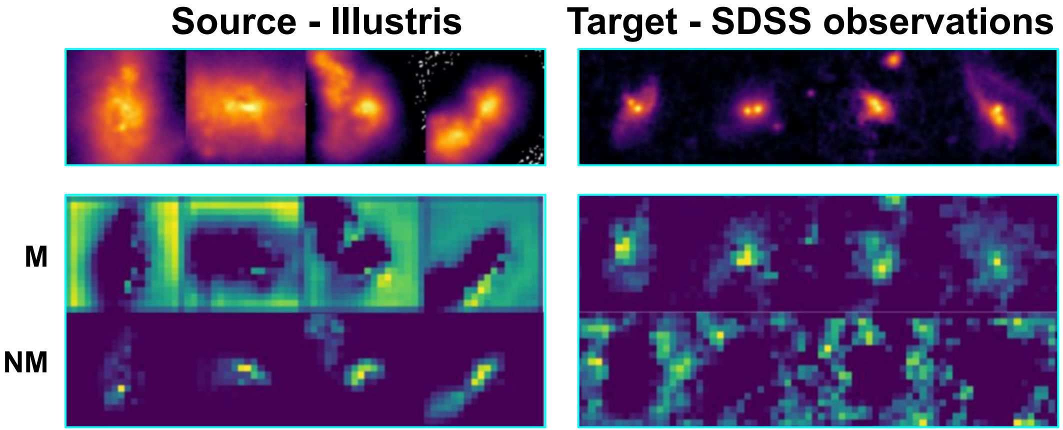

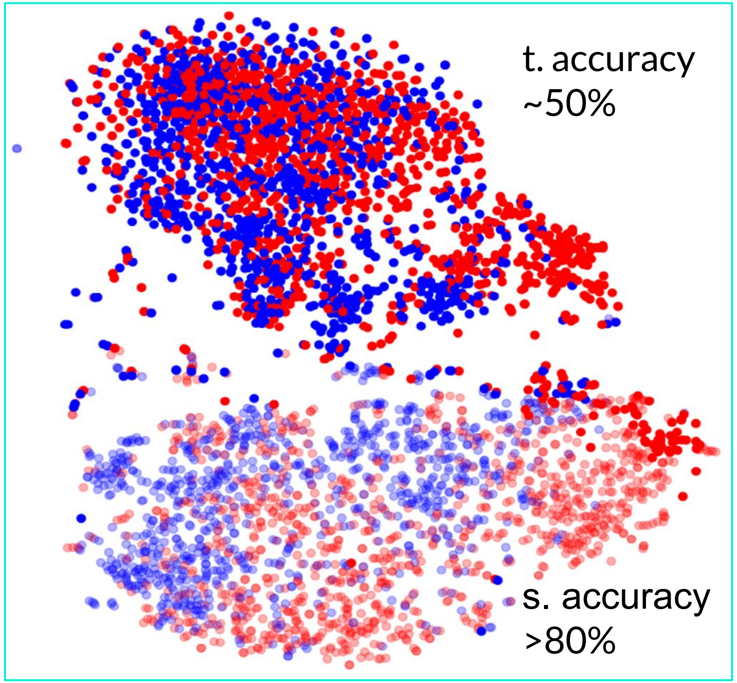

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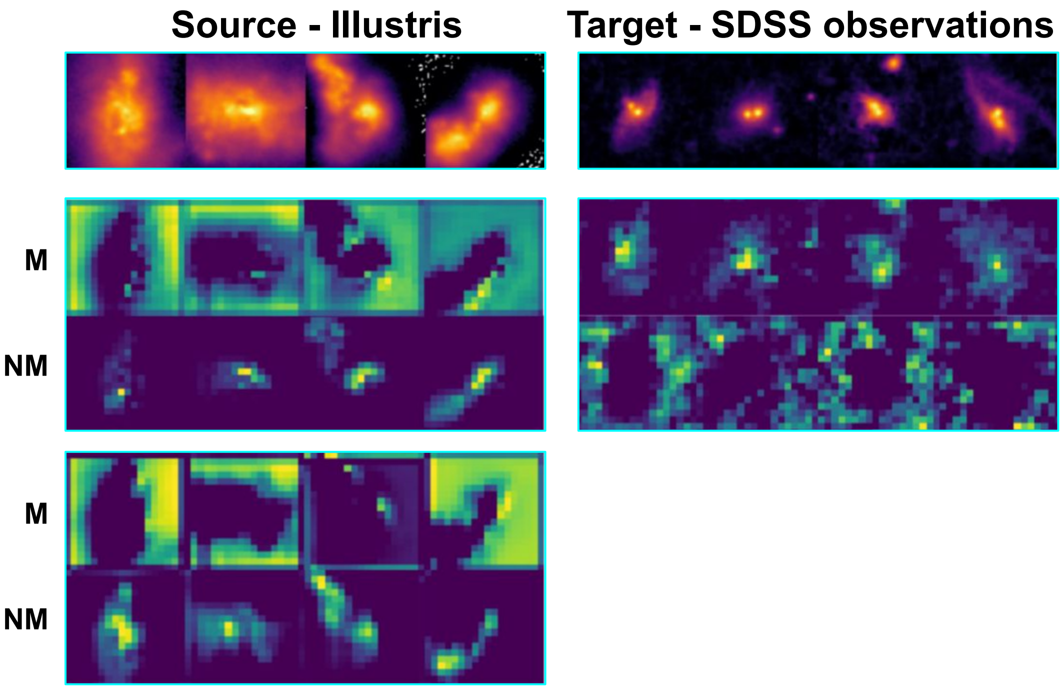

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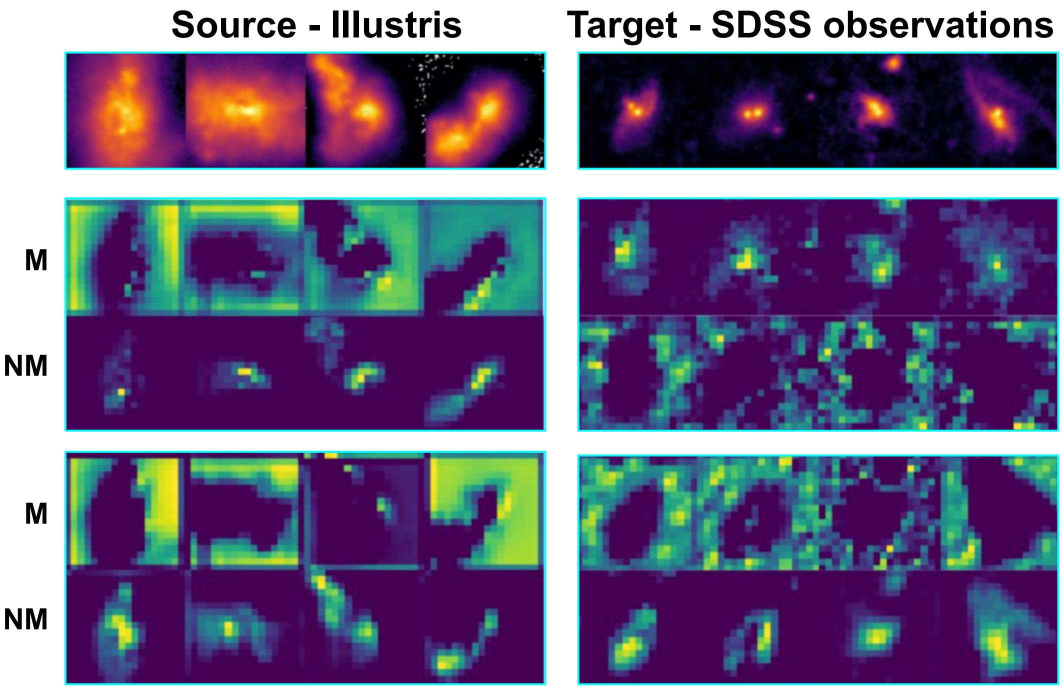
Domain Adaptation

Combining Datasets



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Domain Adaptation

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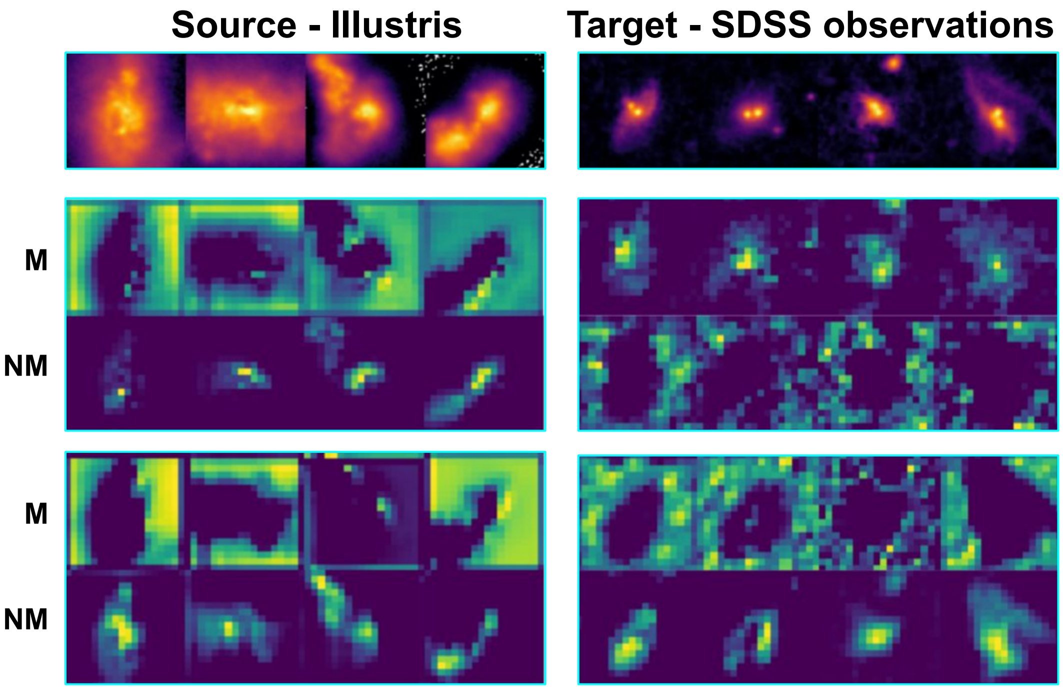

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Up to 30% increase!