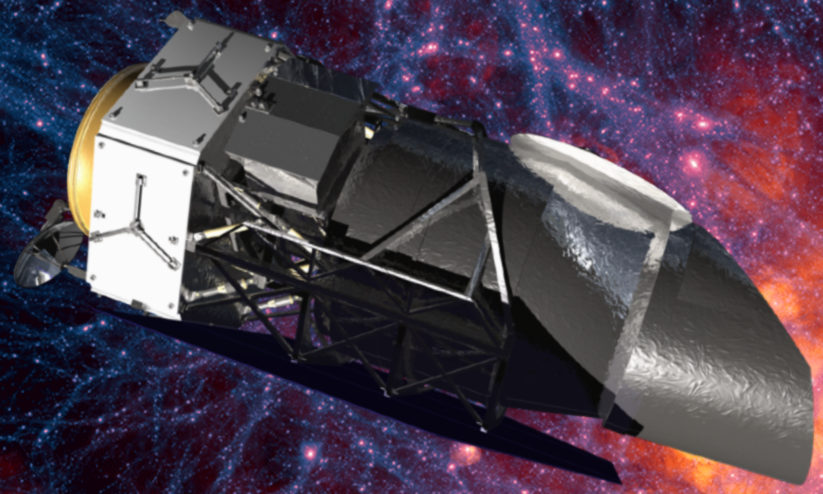
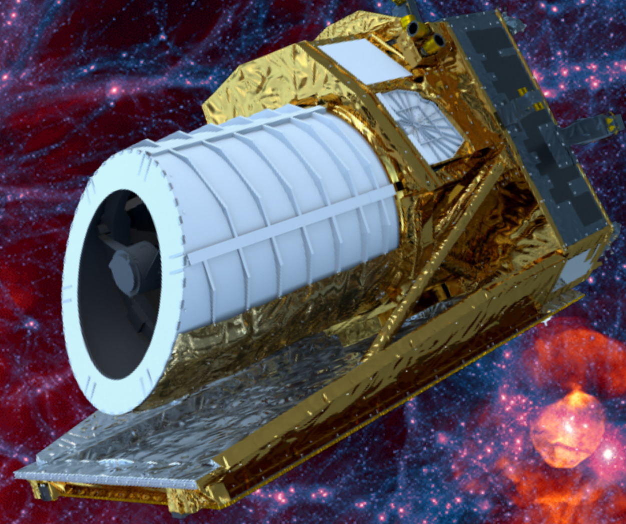
Jet Propulsion Laboratory
California Institute of Technology





Cosmology in Space

Observing the far reaches of the cosmos with space telescopes

Dr Katarina "Dida" Markovič, 04.02.2021, at RAeS Hamburg (on Zoom)

Images: artist's impressions of the Nancy Grace Roman and Euclid Space Telescopes on the Illustris Simulation

About me

- scientist at NASA’s Jet Propulsion Laboratory in Pasadena, CA
- PhD at LMU in Munich
- cosmologist working on:
  - preparations for the **Euclid** Space Telescope science
  - and the Nancy Grace Roman Space Telescope science
  - independent science projects studying **dark energy**
  - (sometimes) on projects that intersect art and science

Image credit: Milan Kreuschitz-Markovič

Cosmology in Space

This talk

- cosmology = a branch of astronomy that studies the universe as its subject

- some astronomy basics
- a bit of history
- quite a bit on the science
- a space telescope

- focus:
  - dark energy
  - Euclid space telescope
- level:
  - some basic concepts
  - some advanced concepts
  - it will fluctuate

Satellite: Herschel and Planck
Copyright: ESA-CNES-Arianespace / Photo Optique Video CSG

Astronomy basics

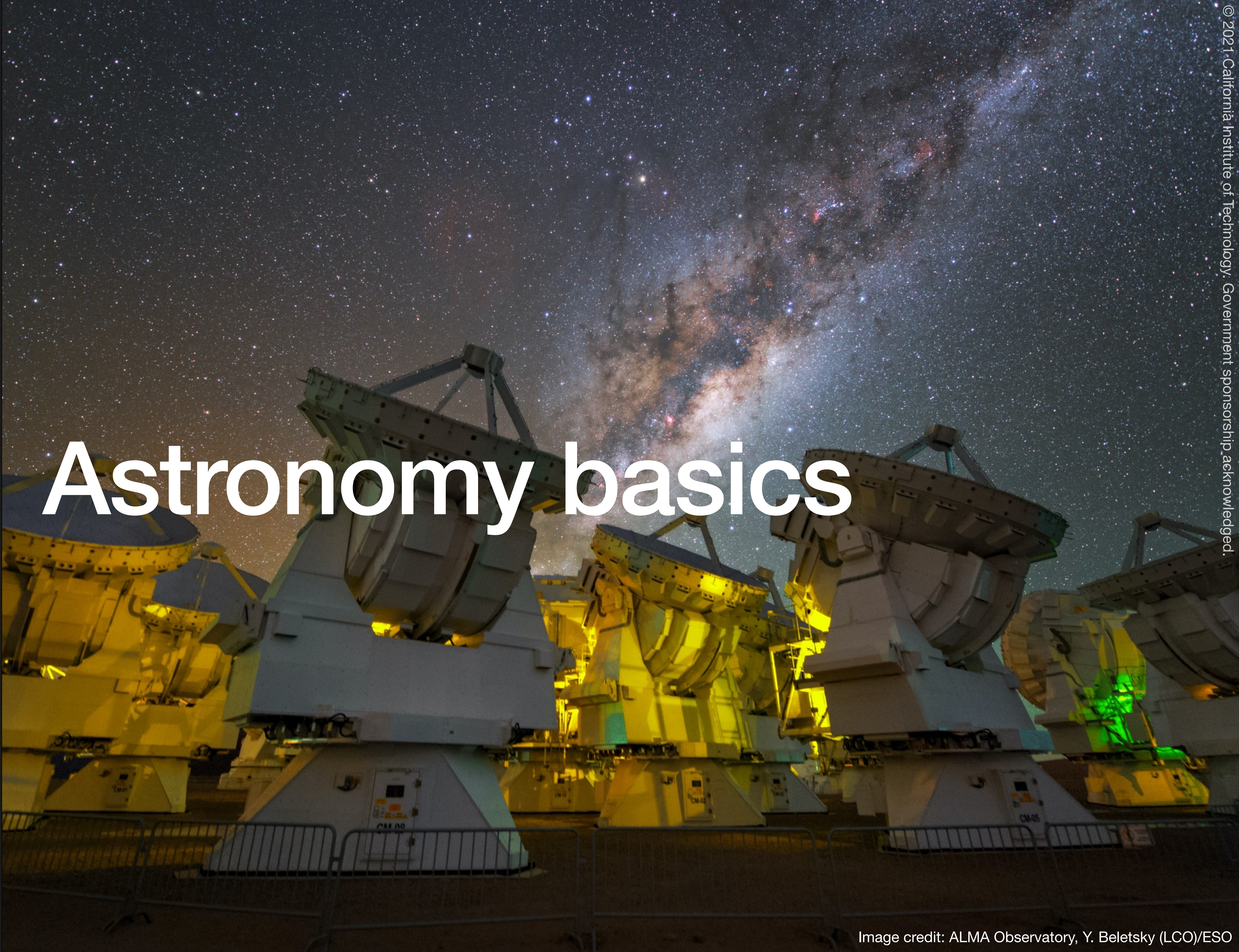


Image credit: ALMA Observatory, Y. Beletsky (LCO)/ESO

Astronomy = detective work

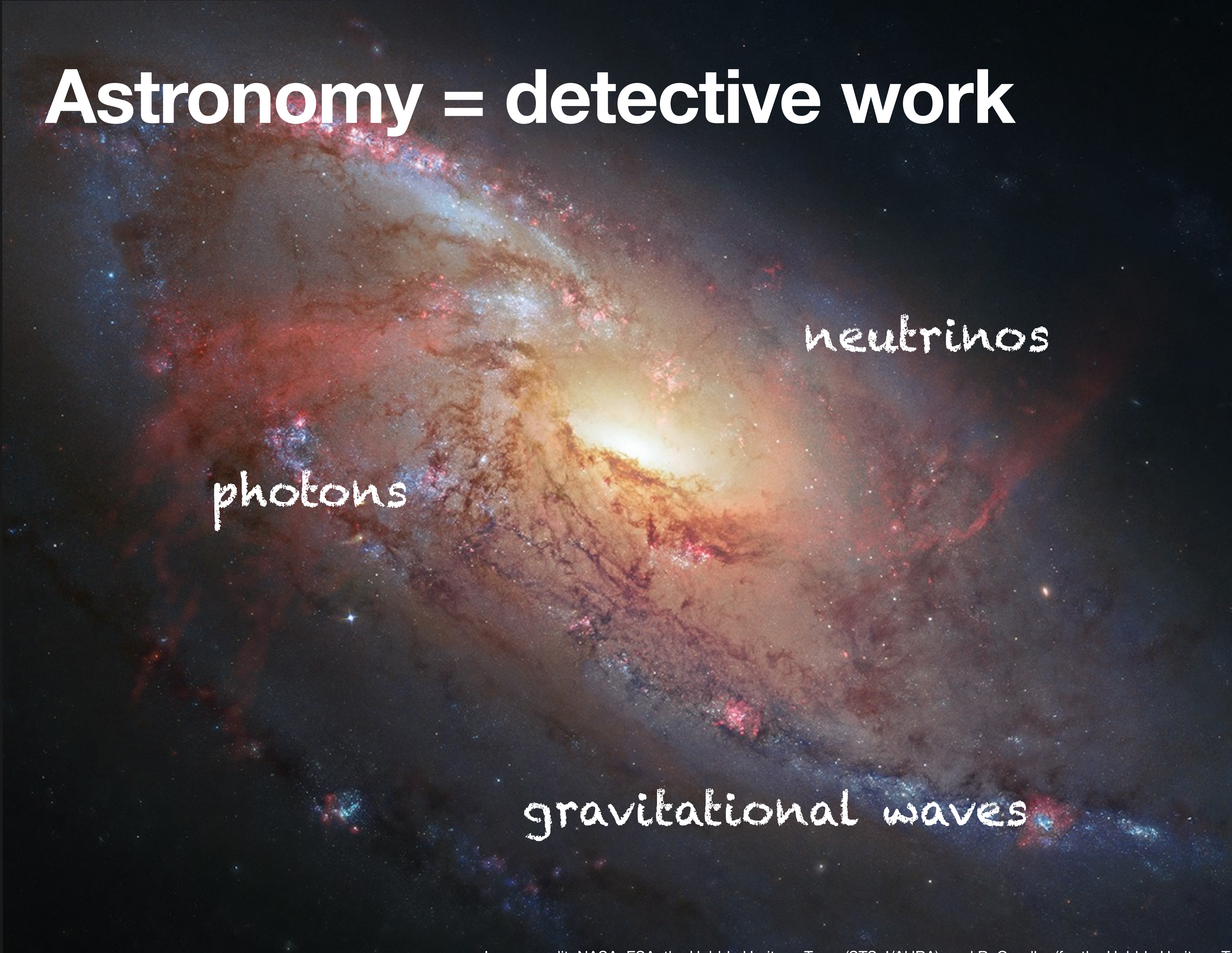
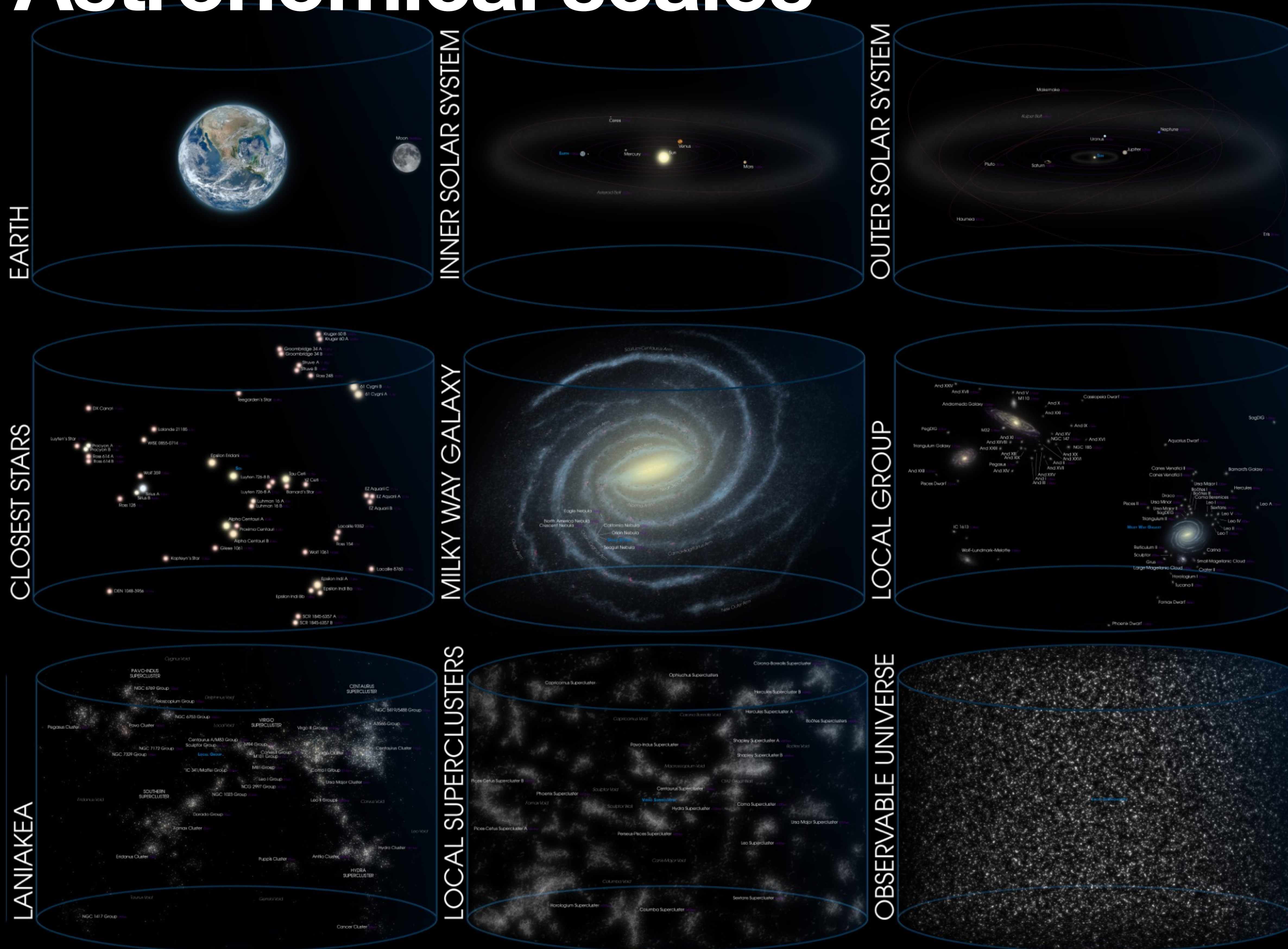


Image credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), and R. Gendler (for the Hubble Heritage Team)

Astronomical scales



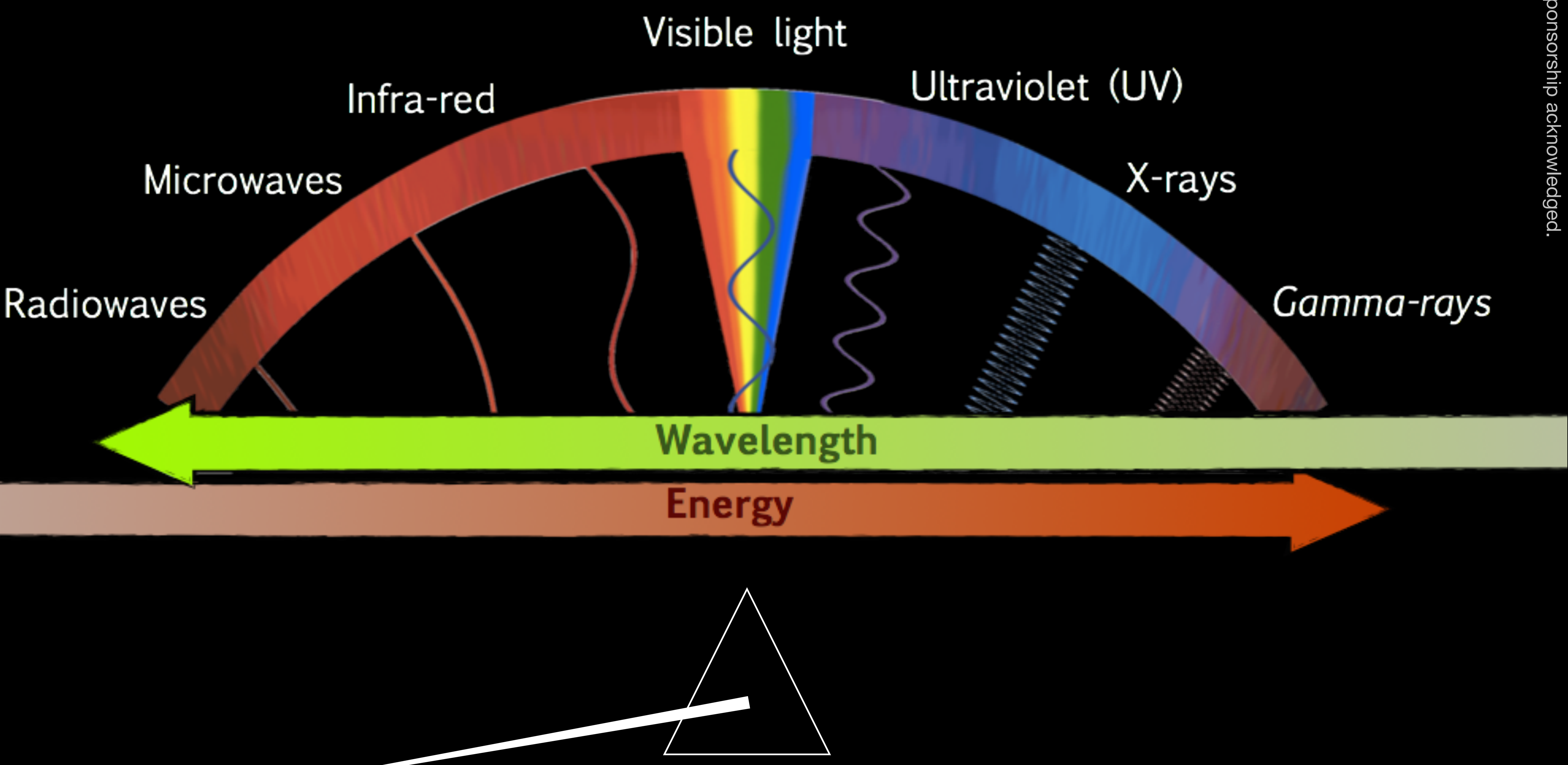
Graphic credit: Andrew Z. Colvin on Wikipedia

Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

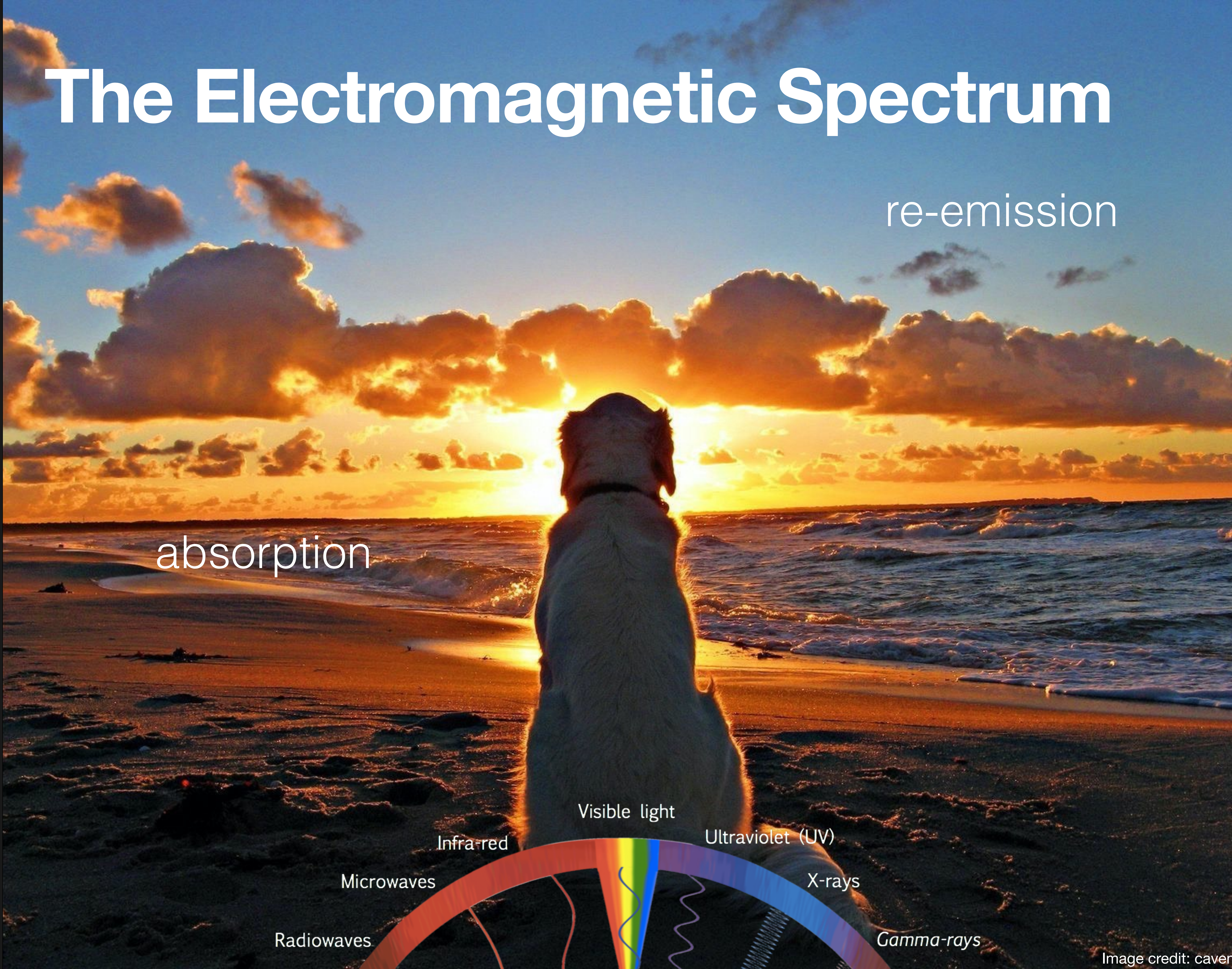
Astronomical distances

Image credit: Kai Pilger

The Electromagnetic Spectrum



The Electromagnetic Spectrum



The Electromagnetic Spectrum

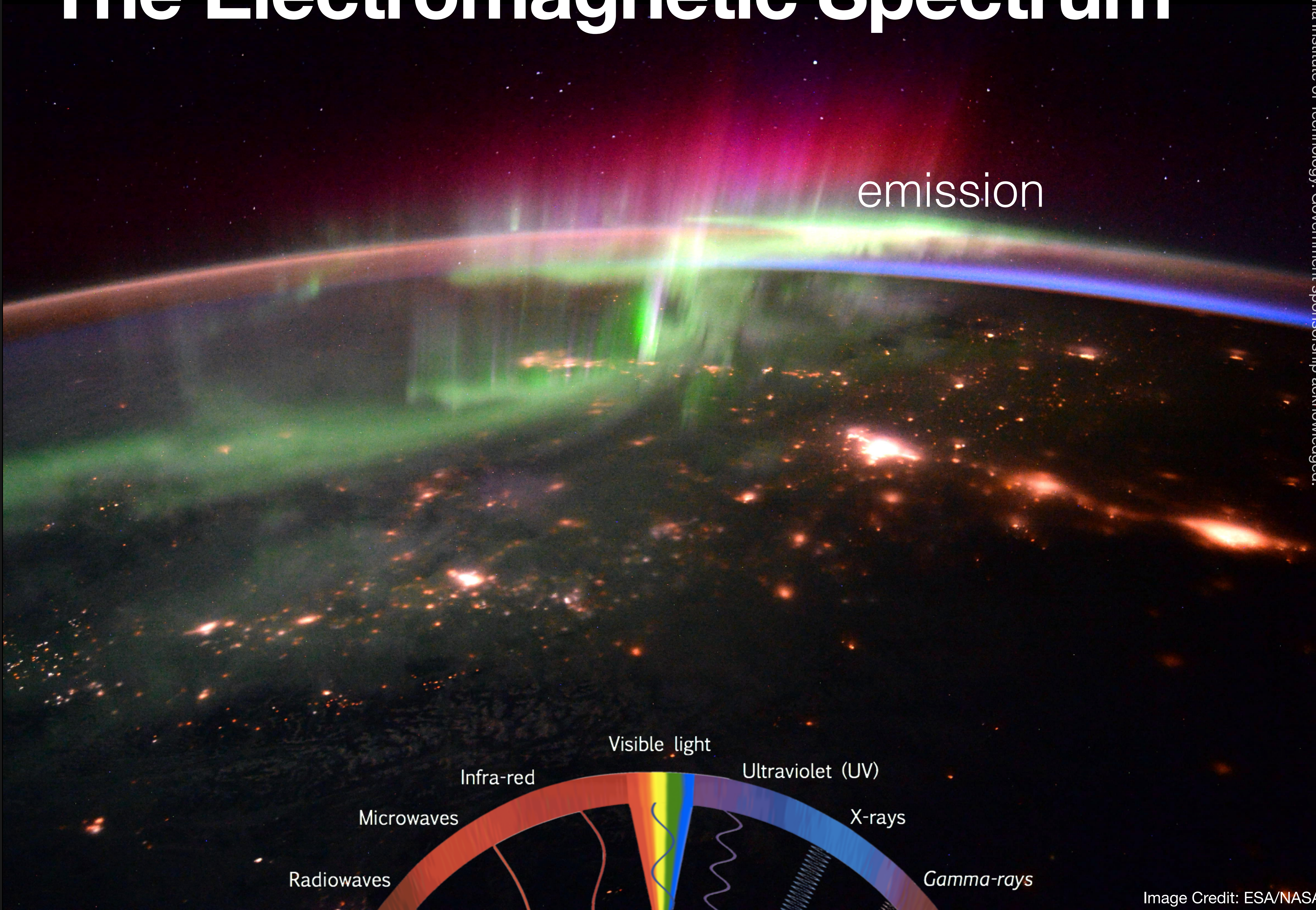
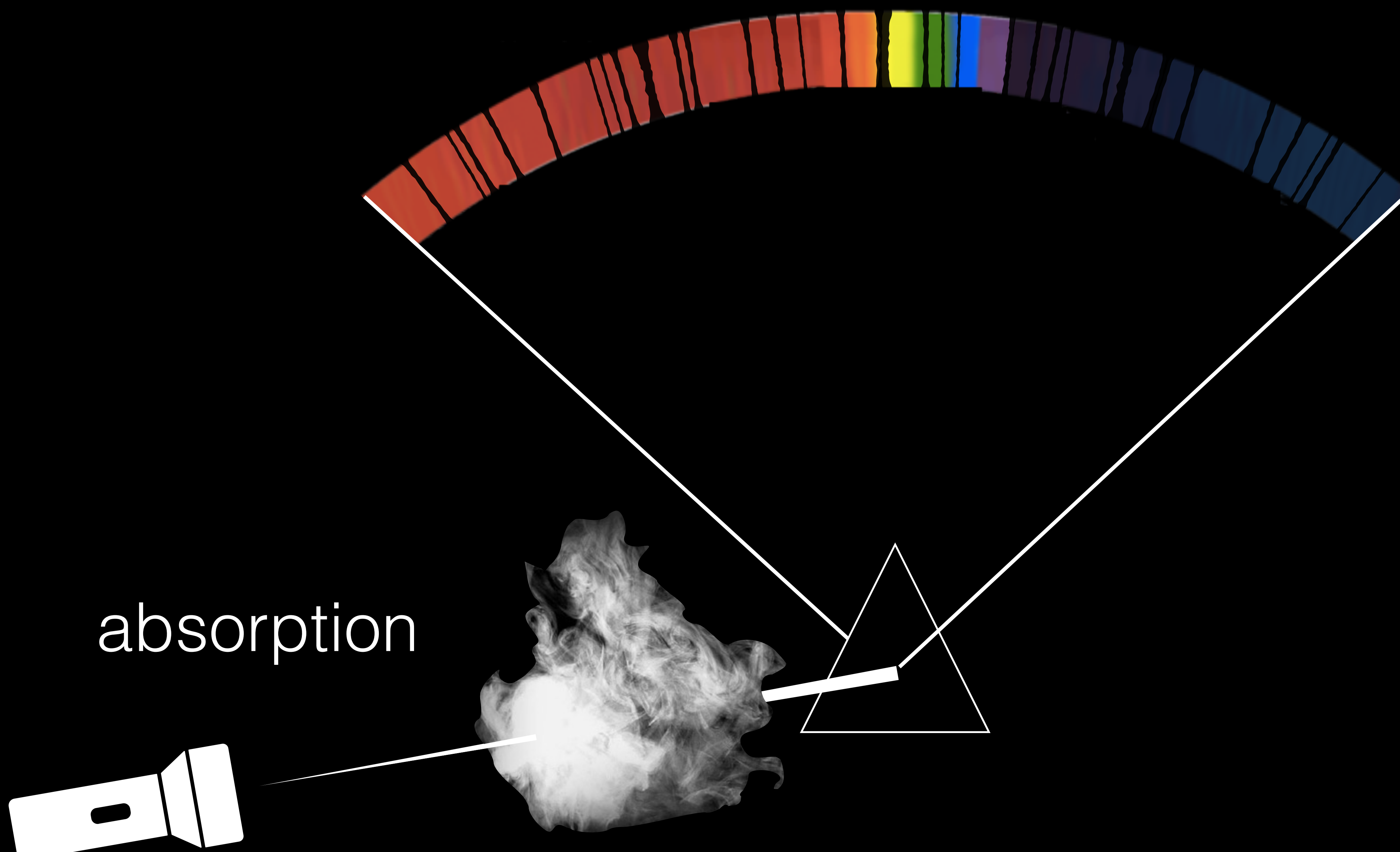


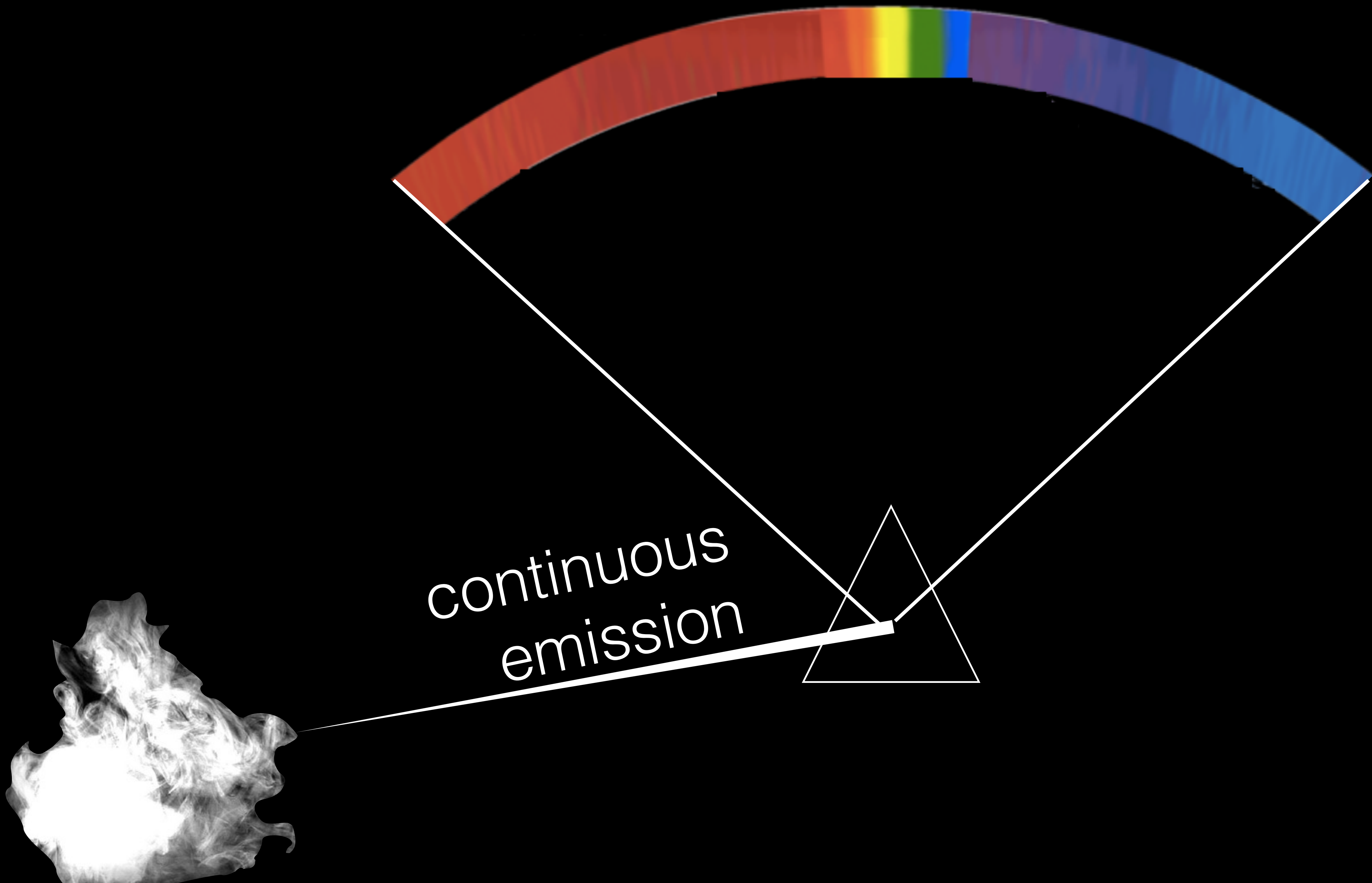
Image Credit: ESA/NASA

The Electromagnetic Spectrum

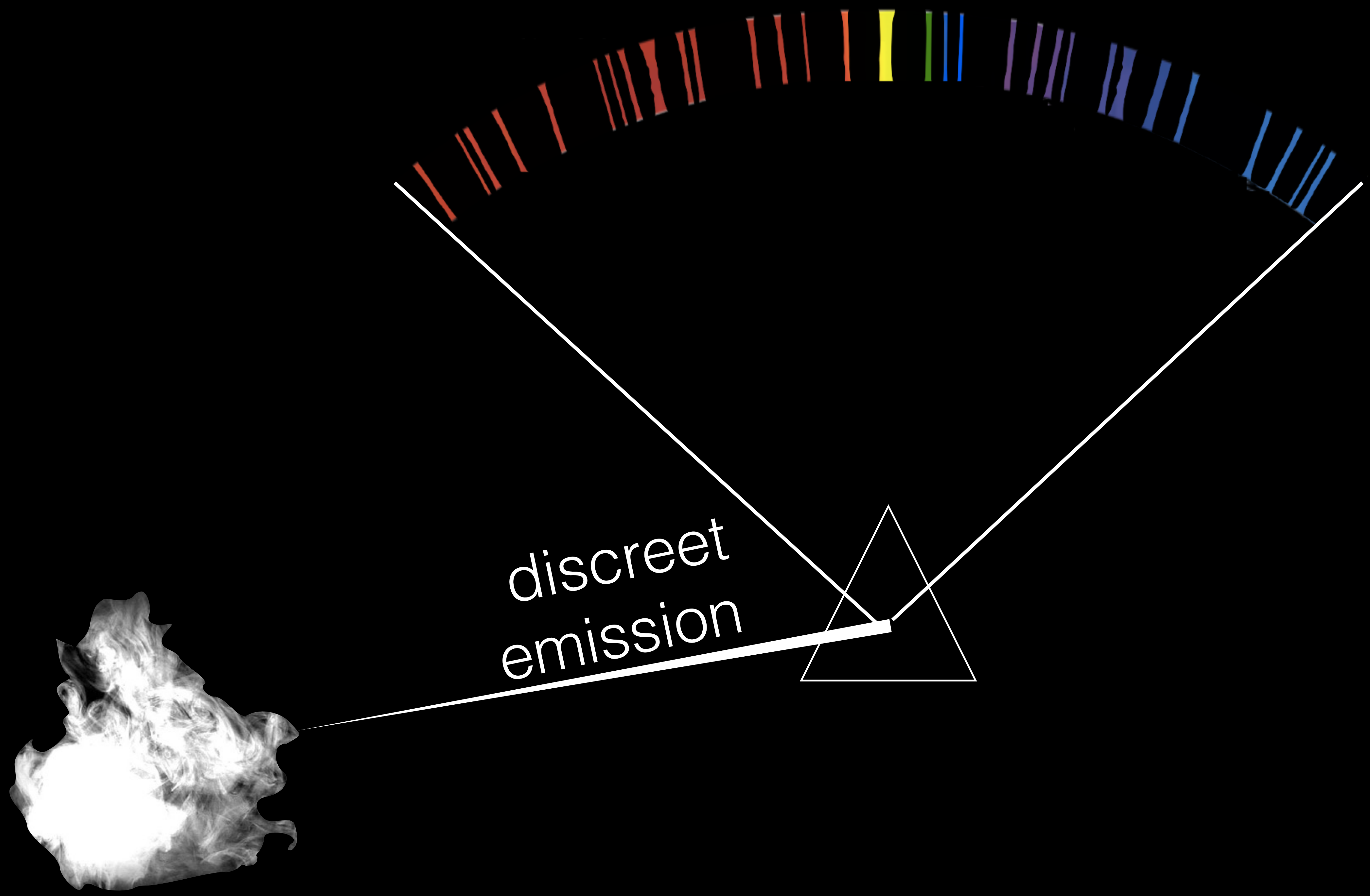


Dr Dida Marković: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

The Electromagnetic Spectrum

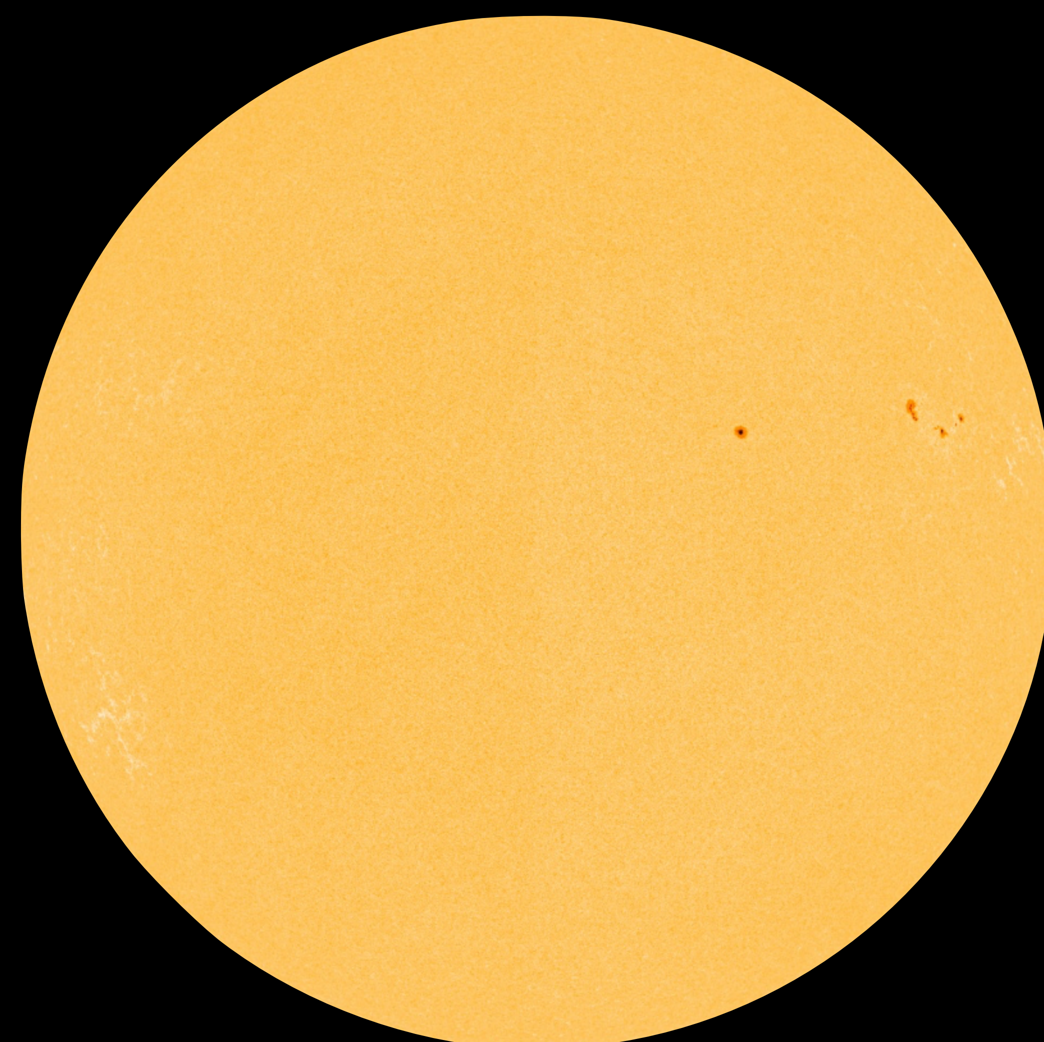


The Electromagnetic Spectrum



Seeing the Invisible:

The Sun



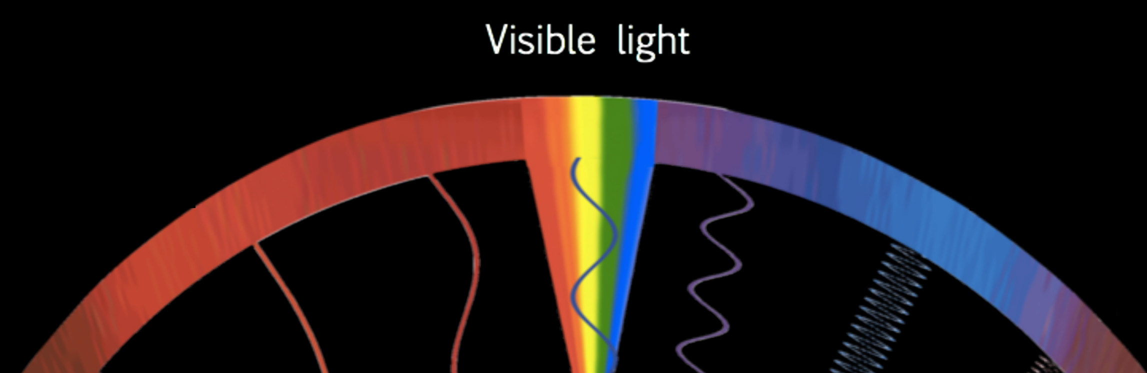
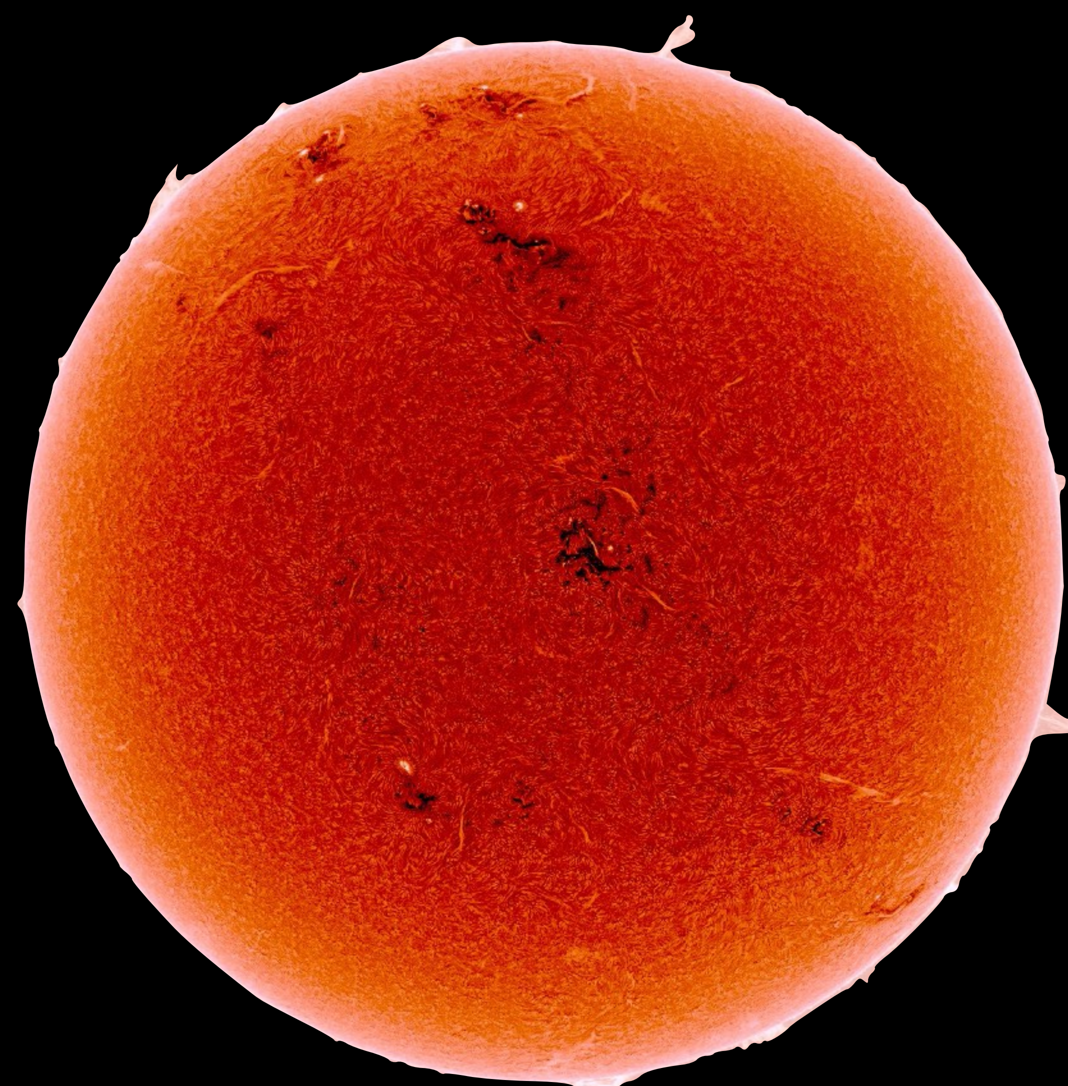


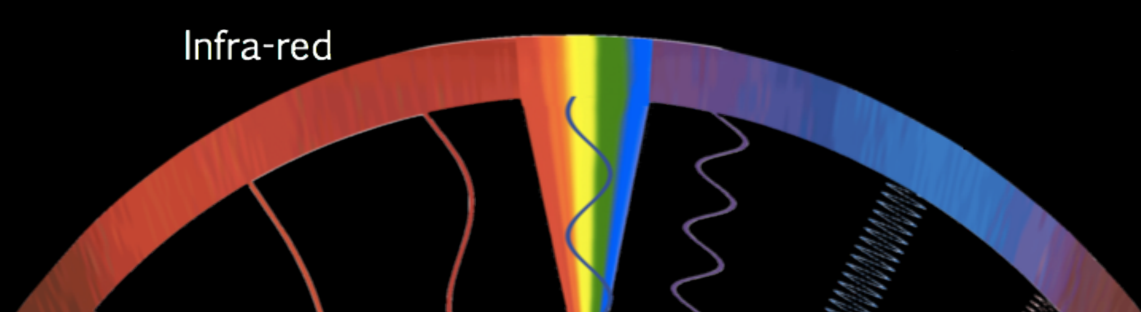
Image credit: Big Bear Solar Observatory

Dr Dida Marković: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Seeing the Invisible:

The Sun

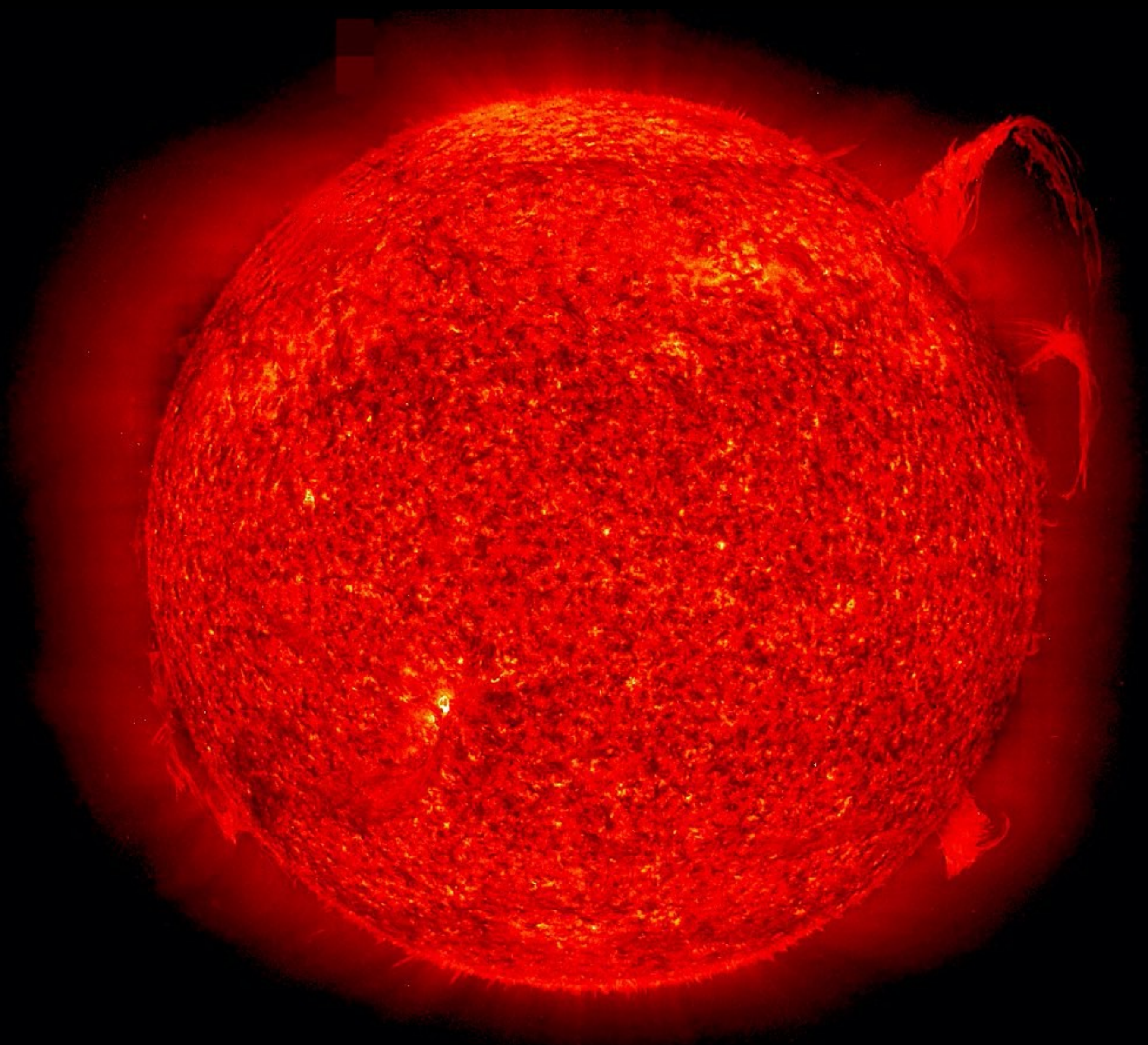


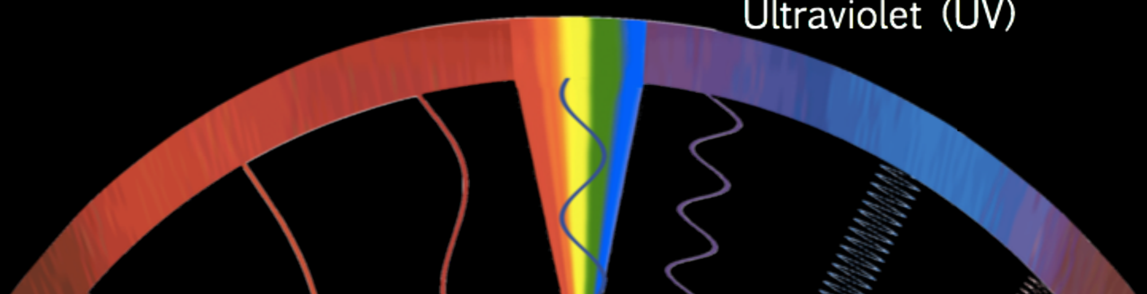


Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Seeing the Invisible:

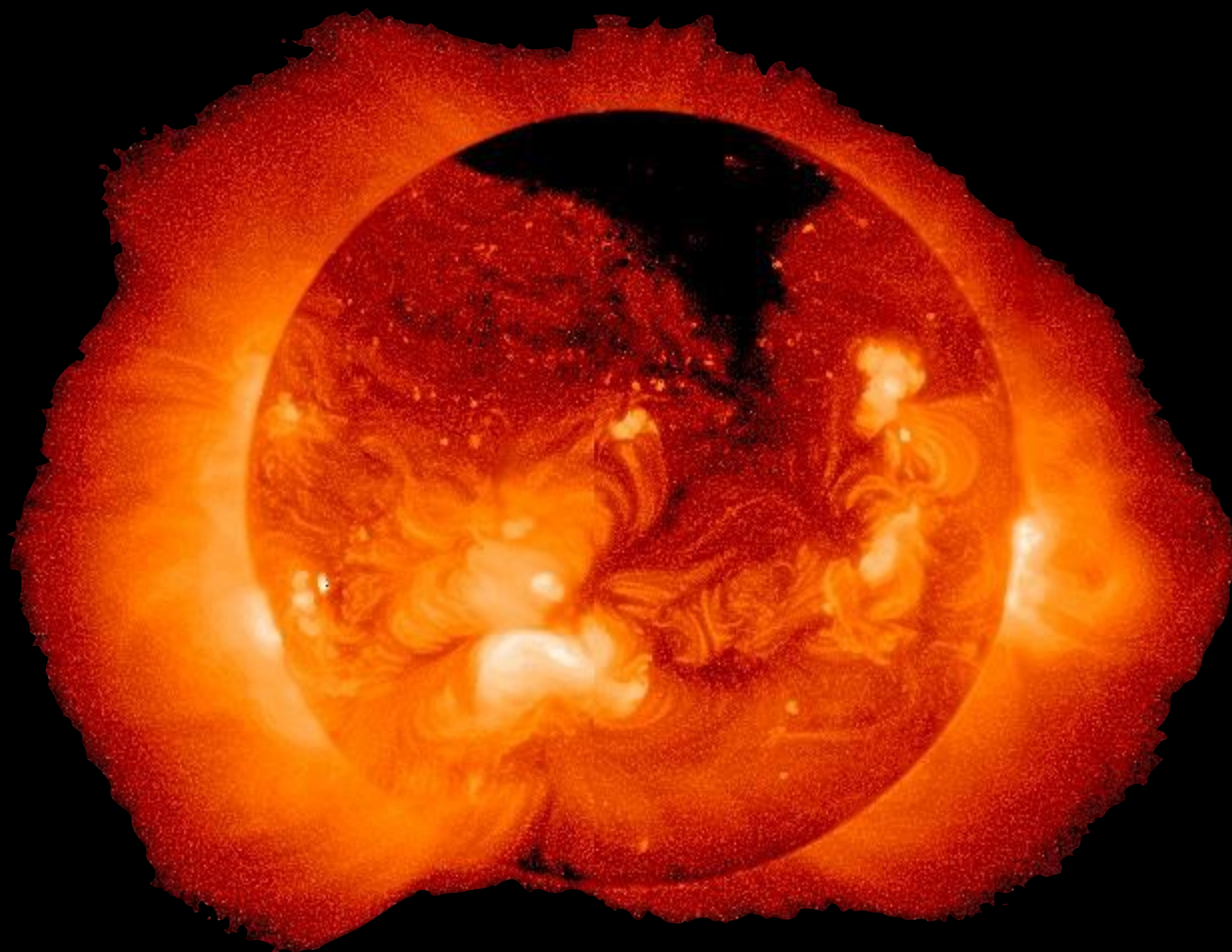
The Sun

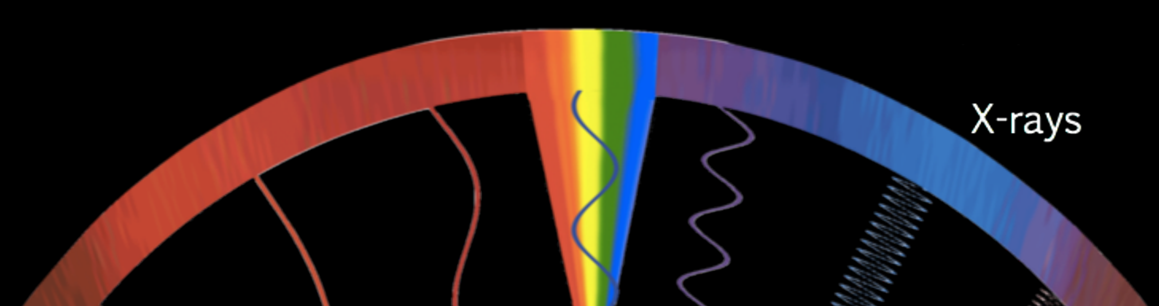




Seeing the Invisible:

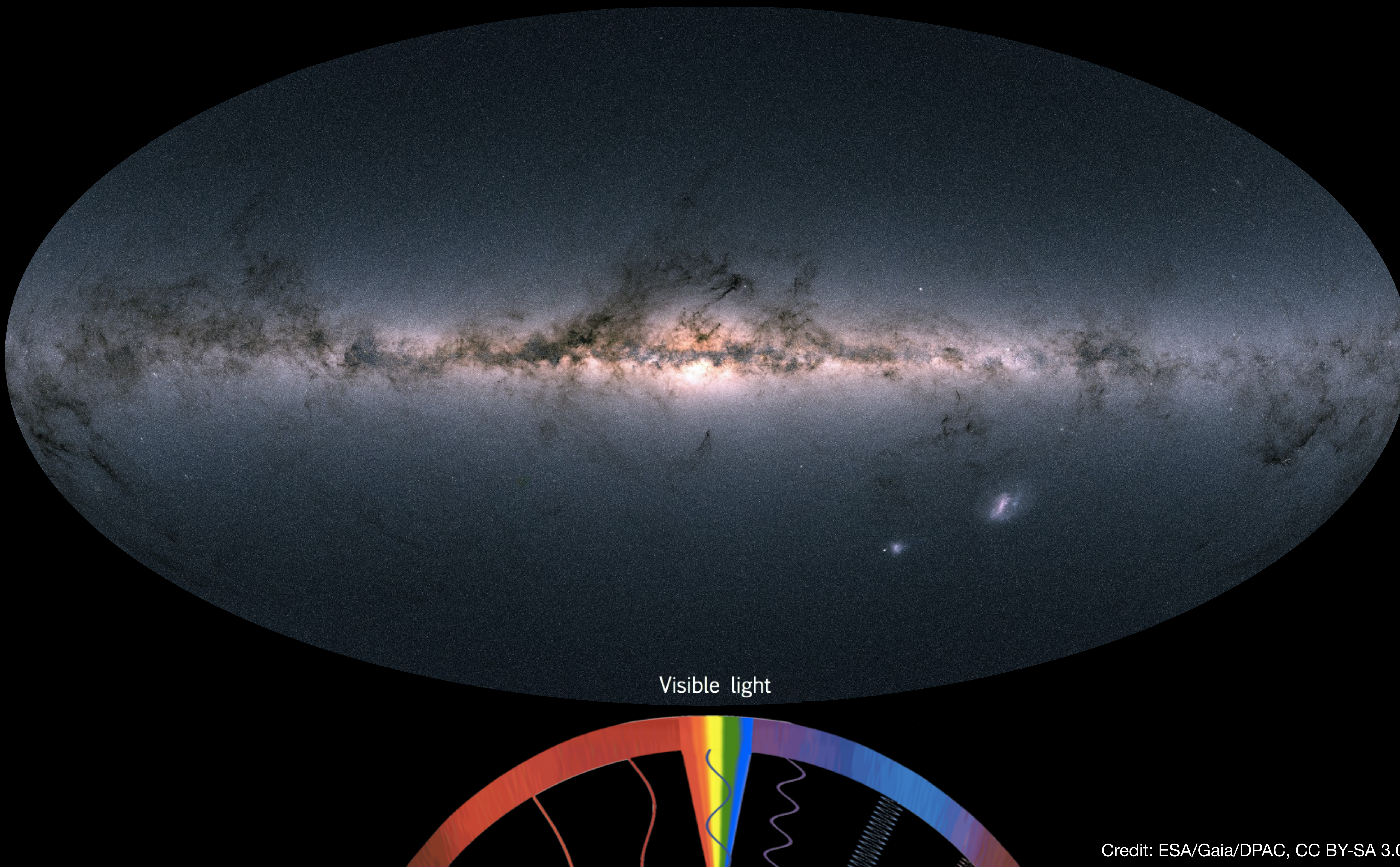
The Sun





Seeing the Invisible:

The Milky Way

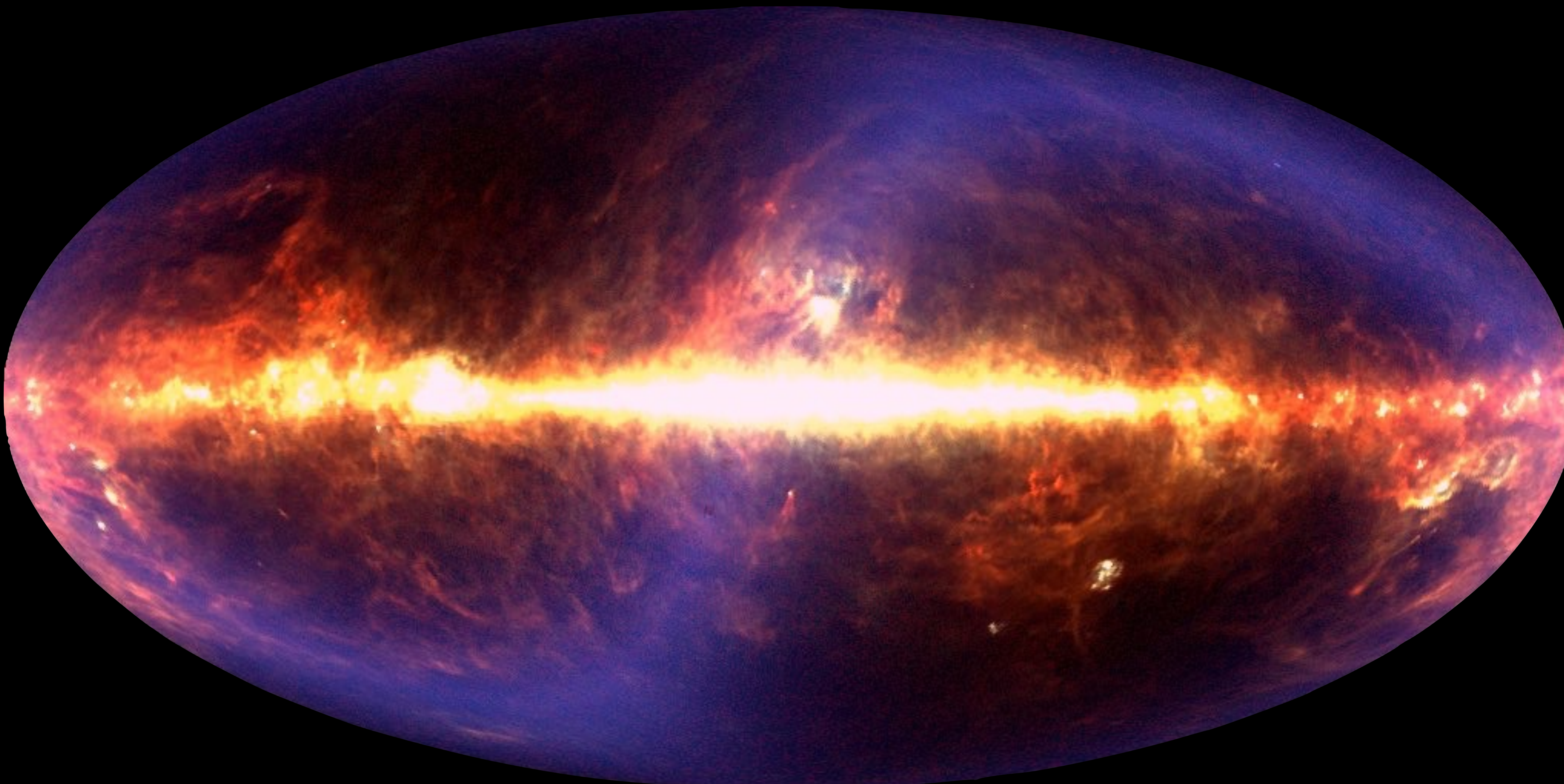


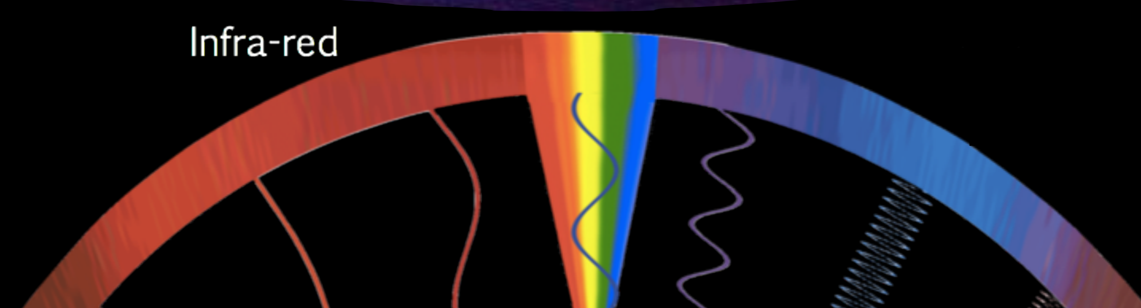
Credit: ESA/Gaia/DPAC, CC BY-SA 3.0 IGO

Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Seeing the Invisible:

The Milky Way

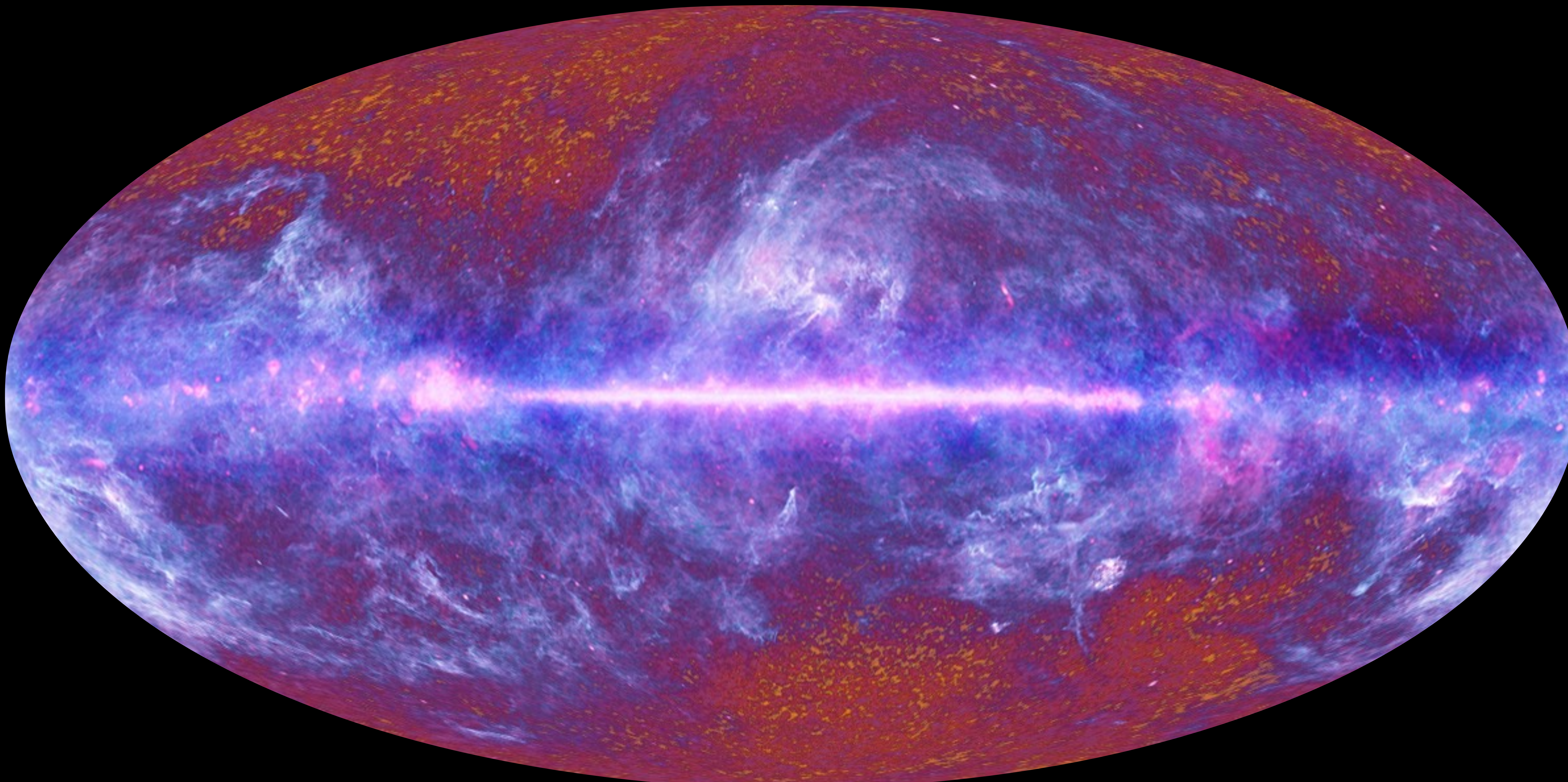




Credit: DIRBE Team, COBE, NASA

Seeing the Invisible:

The Milky Way



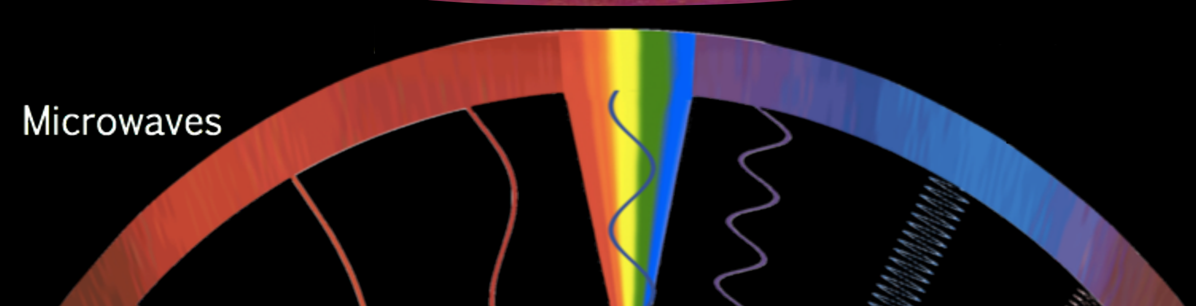
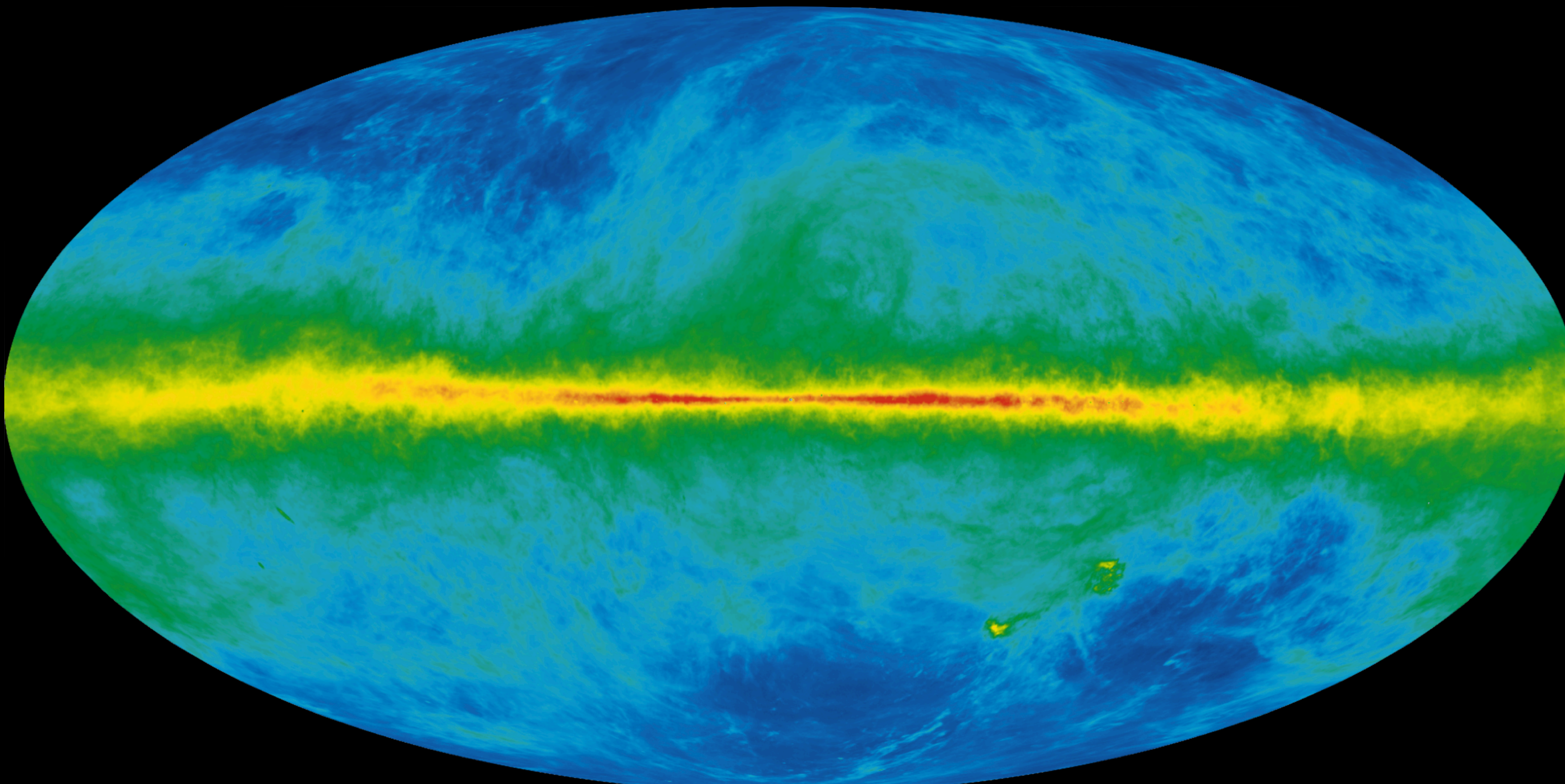


Image credit: ESA, HFI & LFI consortia

Seeing the Invisible:

The Milky Way



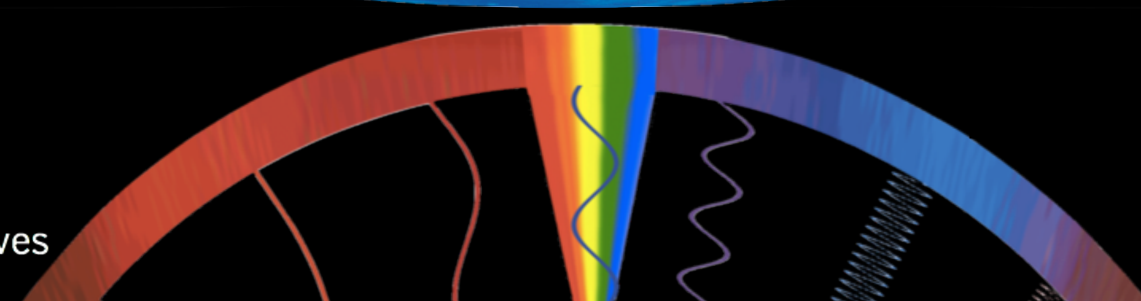
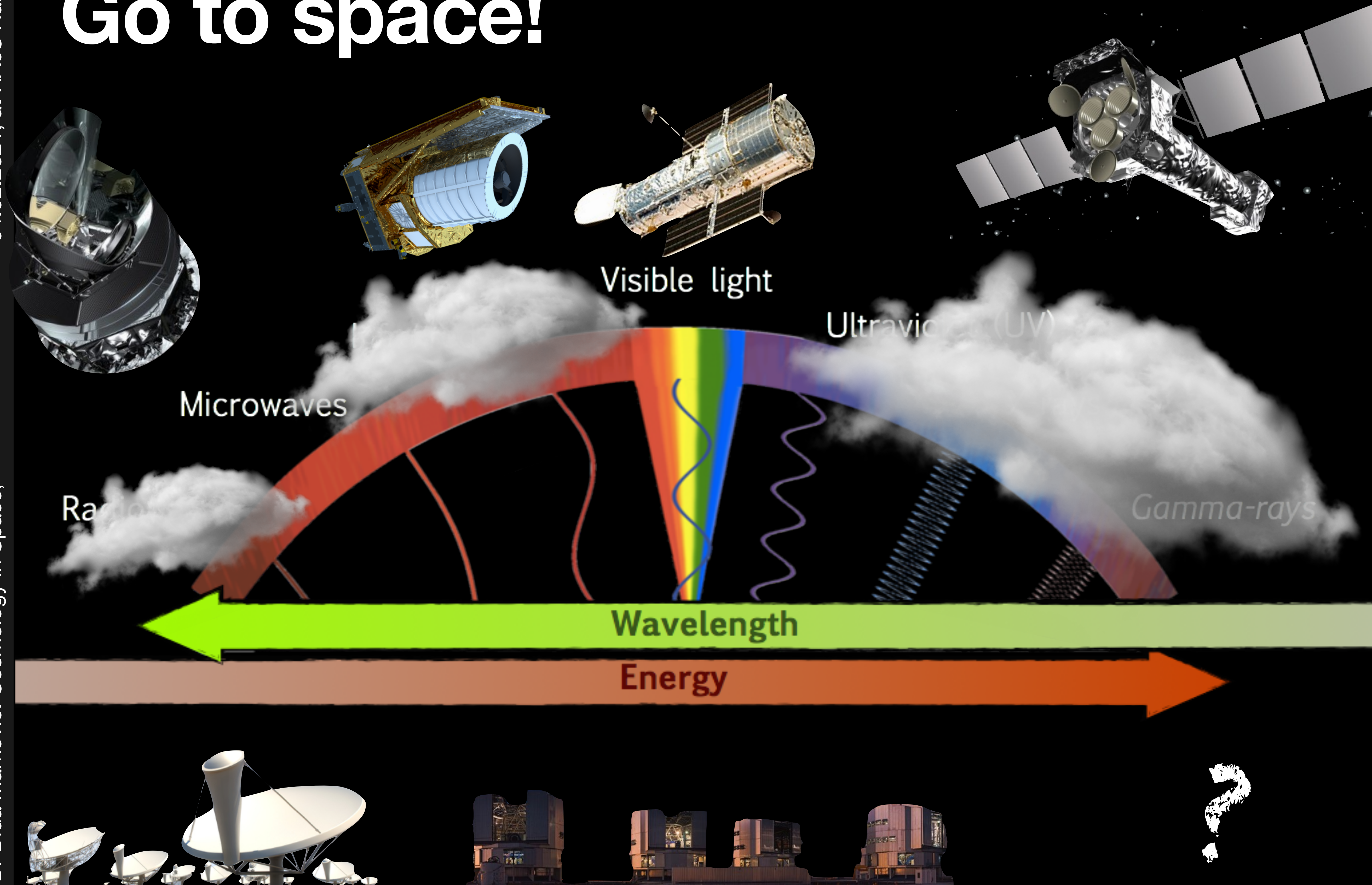


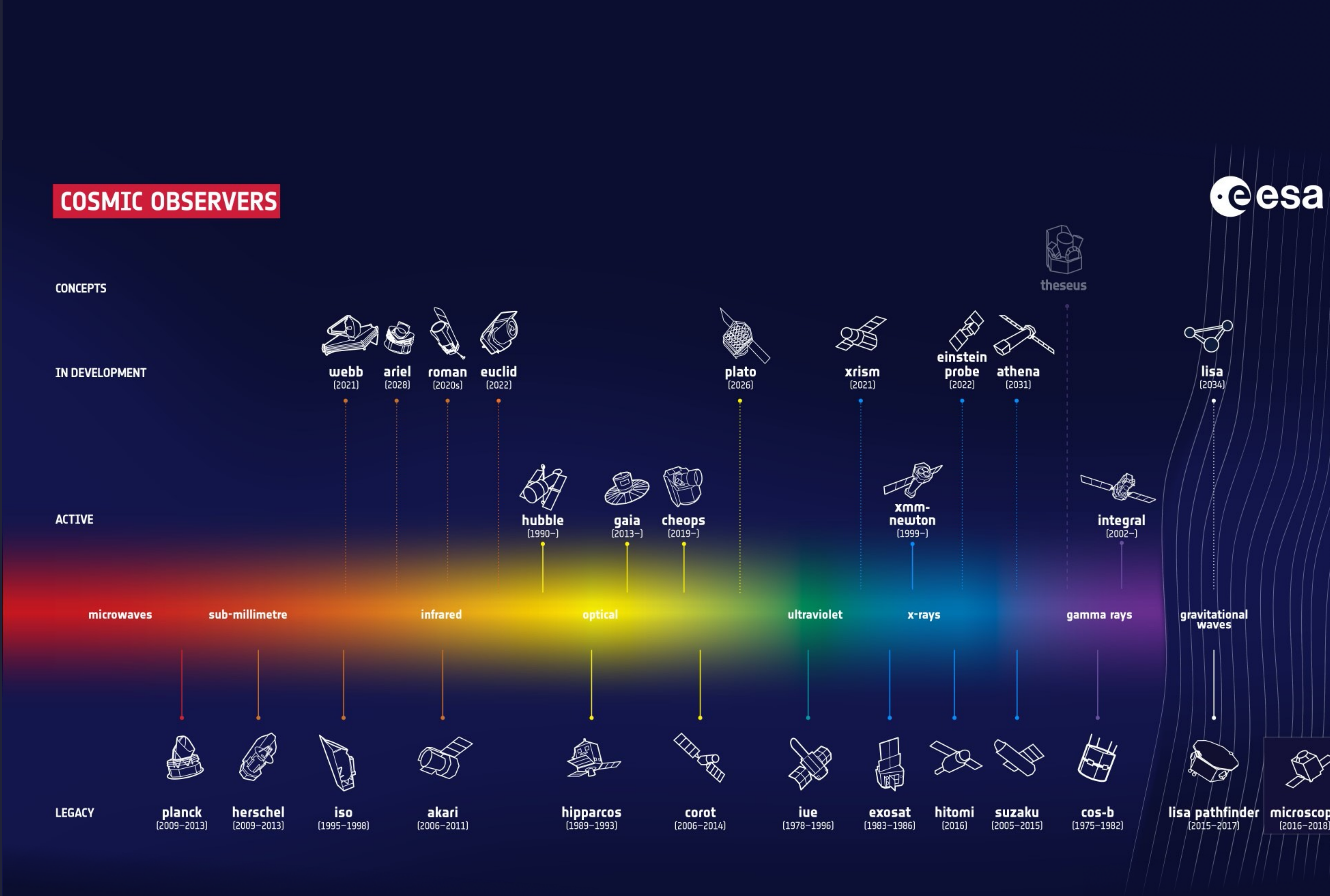
Image credit: HI4PI Collaboration & LAMBDA

Want to see the invisible?
Go to space!



Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Dr Dida Marković: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

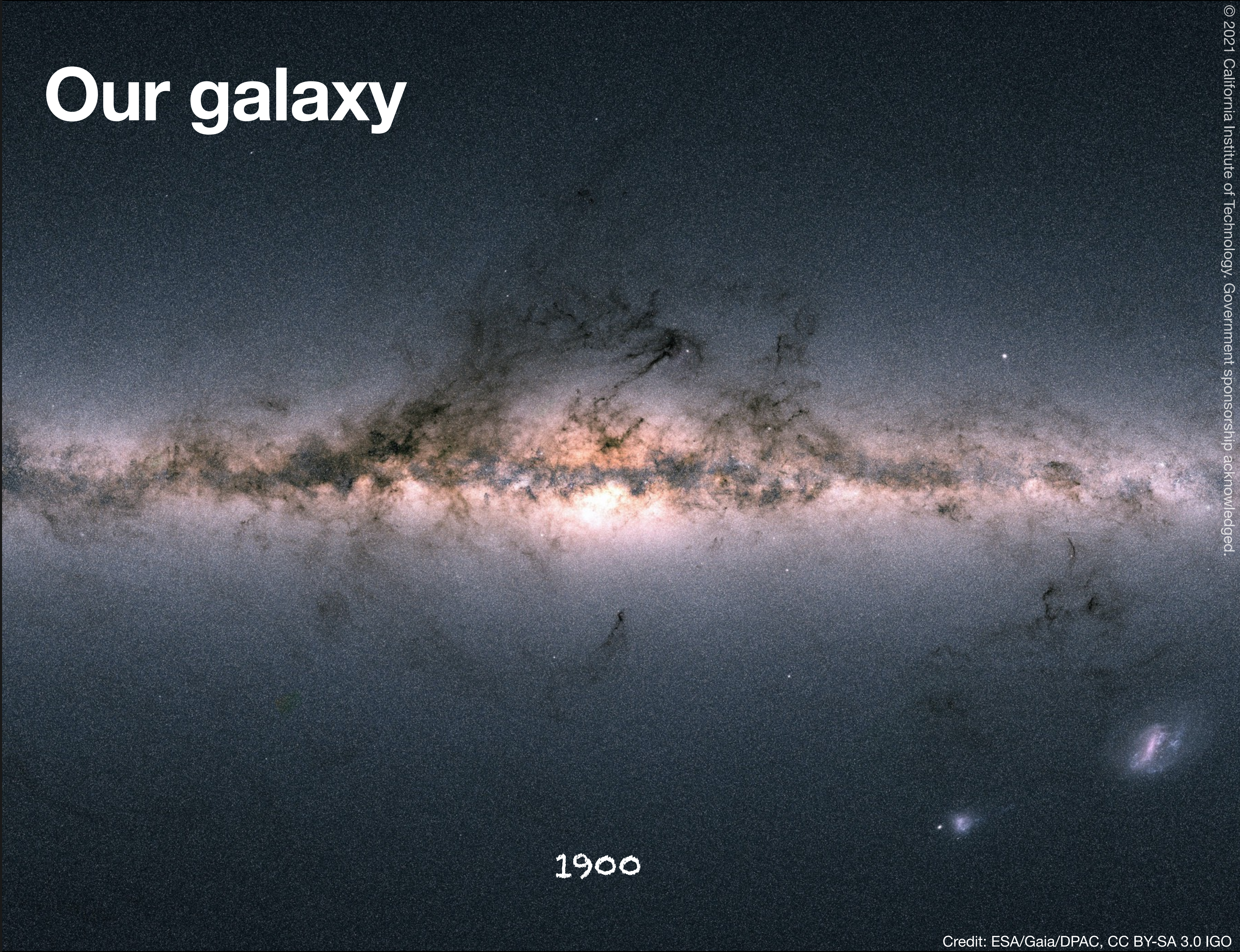


https://sci.esa.int/web/home/-/61106-esa-s-fleet-of-cosmic-observers

History of discovery

Image credit: A. Sonrel,15-inch Great Refractor telescope at Harvard College Observatory

Our galaxy



Credit: ESA/Gaia/DPAC, CC BY-SA 3.0 IGO

Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

“Extragalactic nebulae”

Levitt’s Law

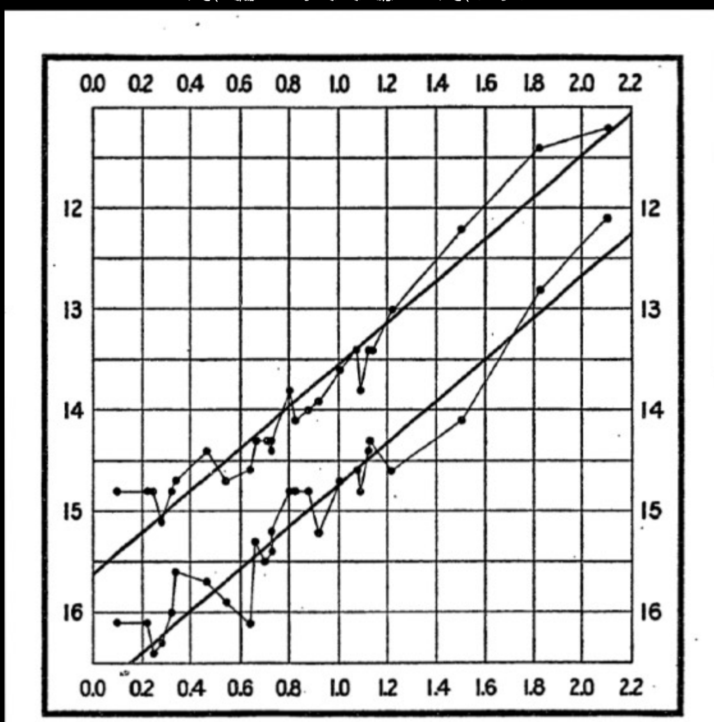
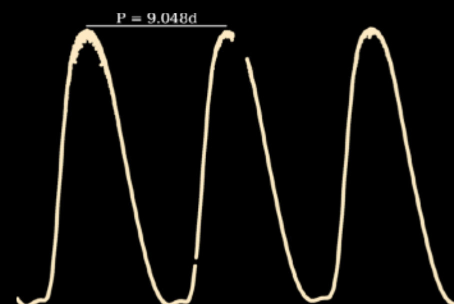
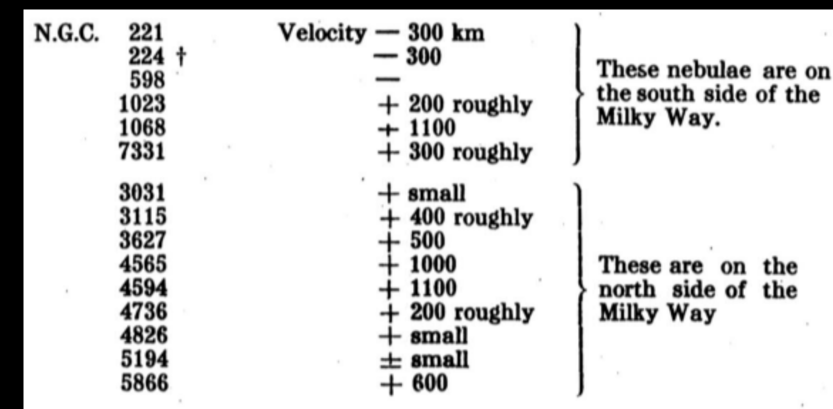


FIG. 2.

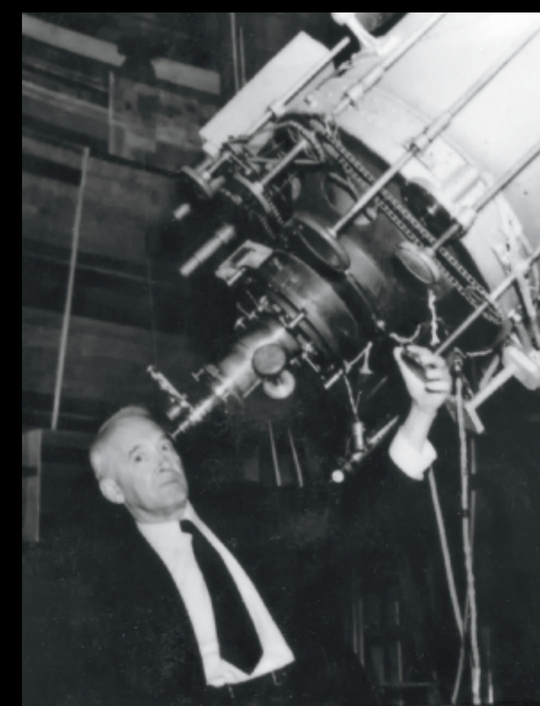
Cepheid apparent magnitude

logarithm of the Cepheid’s period





N.G.C. 221	Velocity — 300 km		These nebulae are on the south side of the Milky Way.
224 †	— 300		
598	—		
1023	+ 200 roughly		
1068	+ 1100		
7331	+ 300 roughly		
3031	+ small		These are on the north side of the Milky Way
3115	+ 400 roughly		
3627	+ 500		
4565	+ 1000		
4594	+ 1100		
4736	+ 200 roughly		
4826	+ small		
5194	± small		
5866	+ 600		



Slipher, 1912:
Spectrographic observations of nebulae

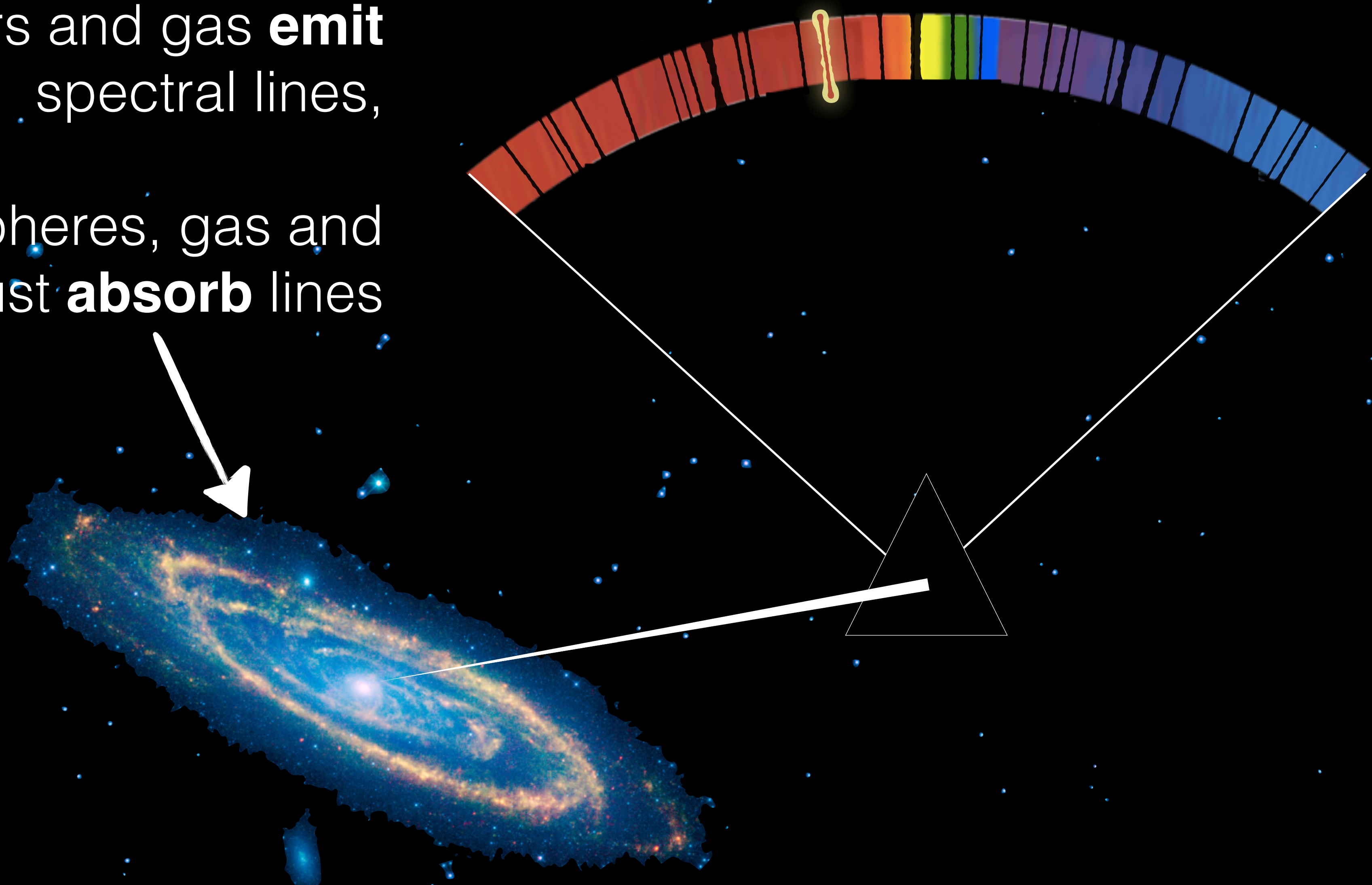
1912–1915

Images from Wikipedia (public domain) and Astronomy magazine.

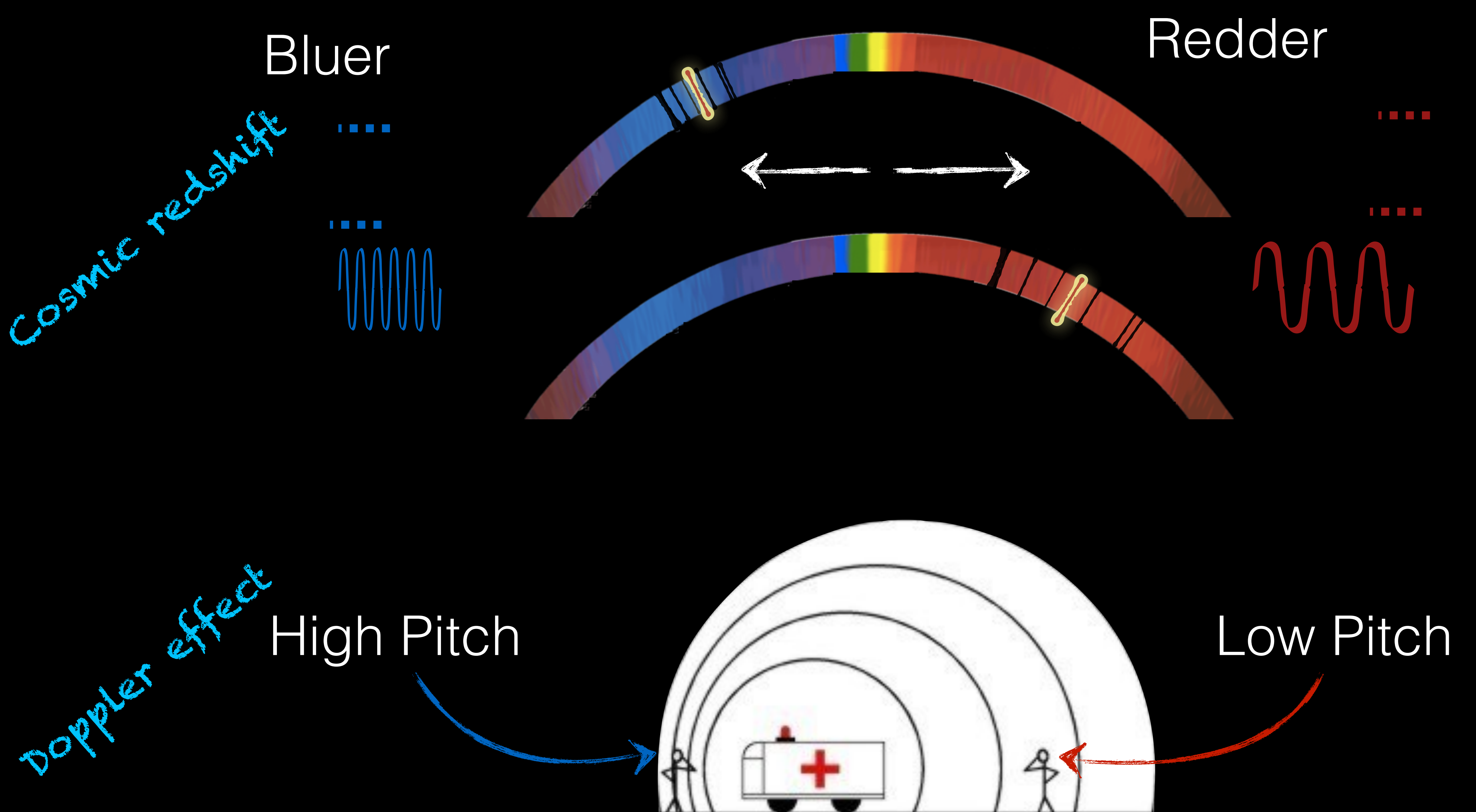
Galactic Spectra

stars and gas **emit** spectral lines,

atmospheres, gas and dust **absorb** lines



Redshift



Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Geometry and Matter

Einstein's Field Equations

- Poisson equation: $\Delta\phi_{\mathrm{N}} = 4\pi G\rho$
- Einstein's first attempt - Ricci tensor $R_{ab} = \frac{8\pi G}{c^4}T_{ab}$ (since $R_{ab} = 0$ in a vacuum), but $\nabla_a R^{ab} \neq 0$!
- Einstein's second attempt - Einstein tensor $G_{ab} = R_{ab} - \frac{R}{2}g_{ab} = \frac{8\pi G}{c^4}T_{ab}$ 4D metric
- Einstein-Hilbert action: $S_{\mathrm{EH}} = \frac{c^4}{16\pi G}\int R\sqrt{-g}\,d^4x$ 4D volume (Riemann curvature tensor, R^d_{abc})
- FLRW metric: only 1 unknown function!

$$ds^2 = -dt^2 + a(t)^2\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

- get $a(t)$, p_i and ρ_i

$$G_{ab} = \frac{8\pi G}{c^4}T_{ab}$$

1915

Image: Official 1921 Nobel Prize in Physics photograph

Dr Dida Marković: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

The Cosmological Constant

Einstein's "biggest blunder"

EFE

$$G_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

1st Friedmann

$$H(t)^2 = \frac{\dot{a}(t)^2}{a(t)^2} = \frac{8\pi G}{3}\rho(t) + \frac{\Lambda c^2}{3} - \frac{kc^2}{a(t)^2}$$

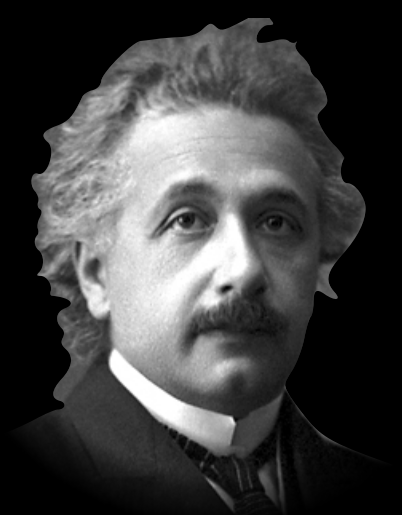
deceleration parameter

$$q_0 = -\frac{\ddot{a}(t)}{a(t)H(t)^2}$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}\left[\rho(t) + \frac{3p(t)}{c^2}\right] + \frac{\Lambda c^2}{3}$$

2nd Friedmann

no curvature!

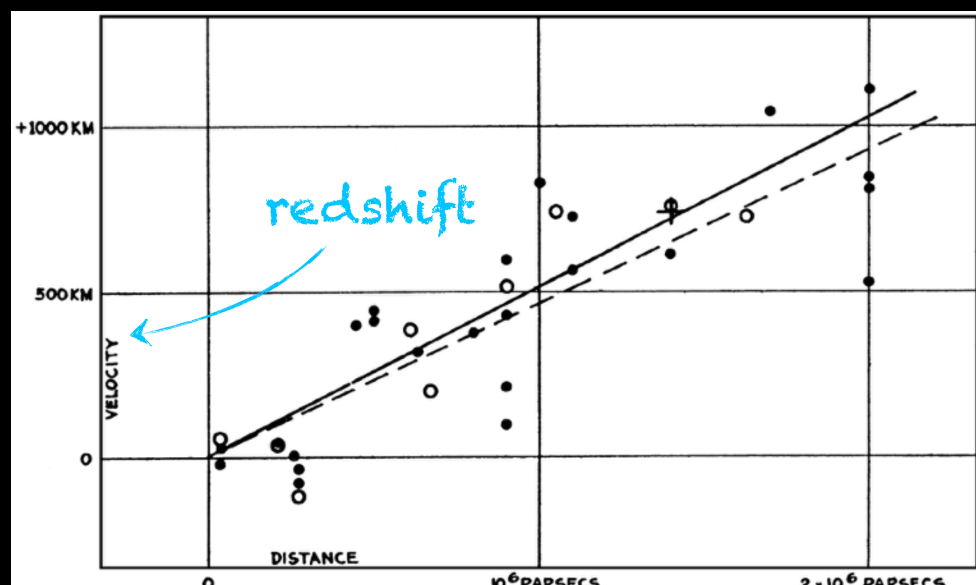


1917–1922

Image: Official 1921 Nobel Prize in Physics photograph

The Expanding Universe

Hubble, 1929:
A relation between distance and radial velocity among extra-galactic nebulae



holds for small v and d (non-relativistic)

- Hubble and Lemaitre used measurements of recession velocities via redshift, $z \equiv \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} - 1 = \left[\frac{1 + v/c}{1 - v/c}\right]^{0.5} - 1 \approx \frac{v}{c}$.
- Hubble got the values pretty wrong, but it was enough to convince the astronomical community that the **universe was expanding**: $z = \frac{a_{\text{obs}}}{a_{\text{emit}}} - 1 = \frac{1}{a_{\text{emit}}} - 1$

can derive from null geodesic assuming a metric (no need for EFE)

comoving distance

- The Hubble-Lemaitre law, $v = \frac{d(ax)}{dt} = \dot{a}x = H_0 d$, holds at small distances (low redshifts).

1927–1931

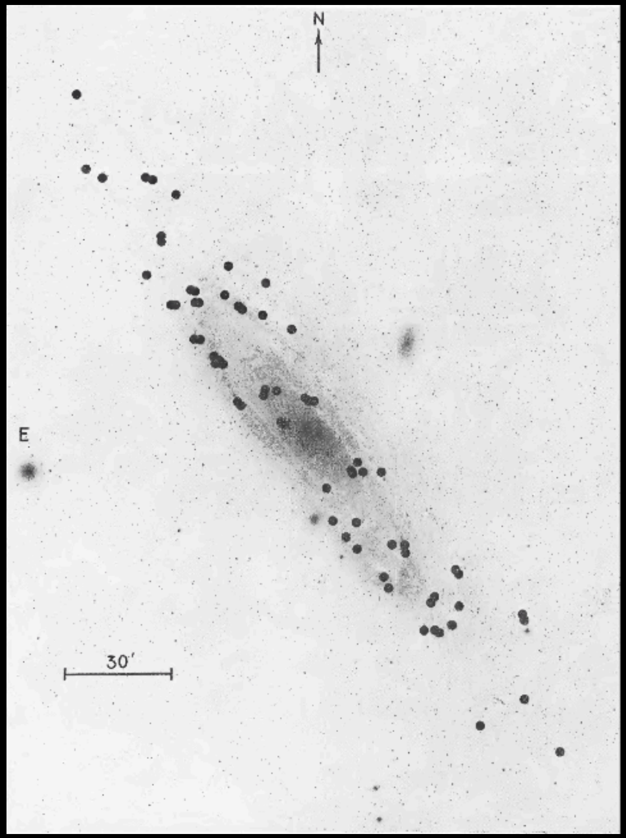
All images from Wikipedia (public domain).

Galaxies have dark haloes

dark matter

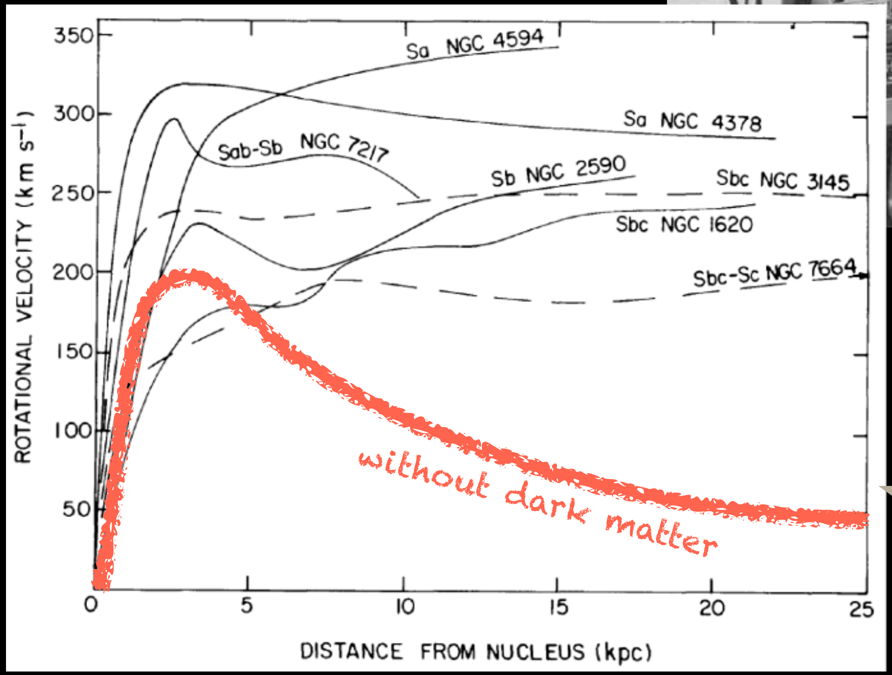
Galaxy rotation curves:

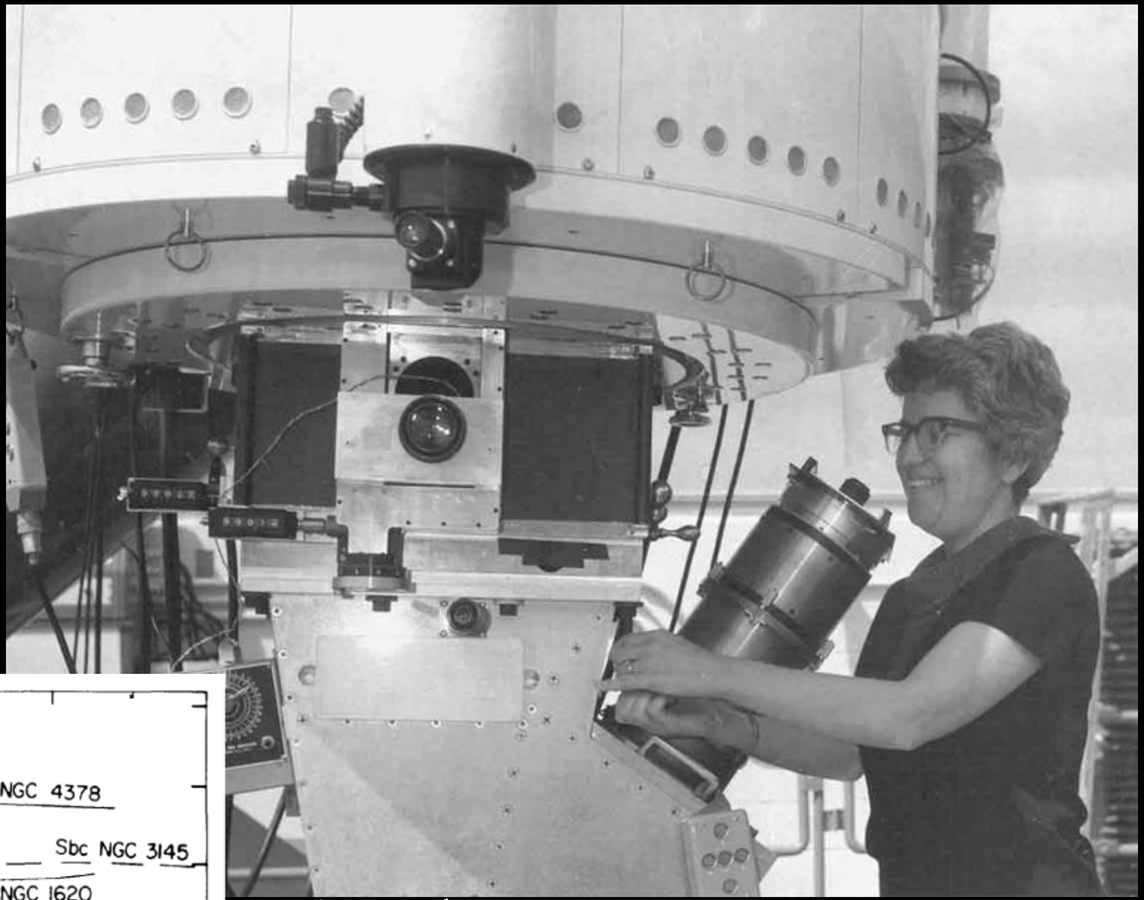
- spectra of emission regions in galaxy
- redshift to get velocity
- stars on outskirts orbit too quickly for mass we see



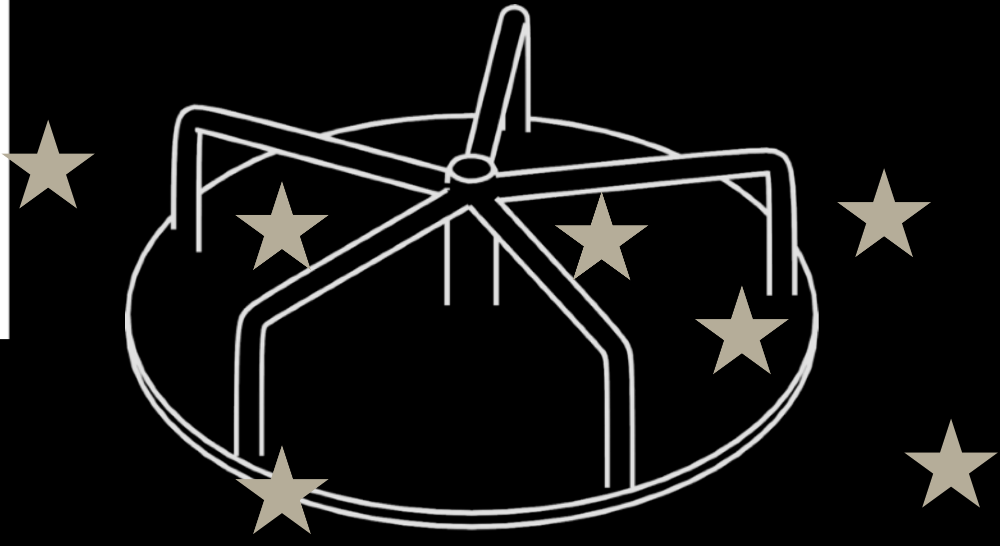
Andromeda Galaxy (M31) in UV
Rubin & Ford, 1970

Galaxy rotation curves
Rubin et al. 1978





Vera Rubin operating the 2.1-meter telescope at Kitt Peak National Observatory



1970

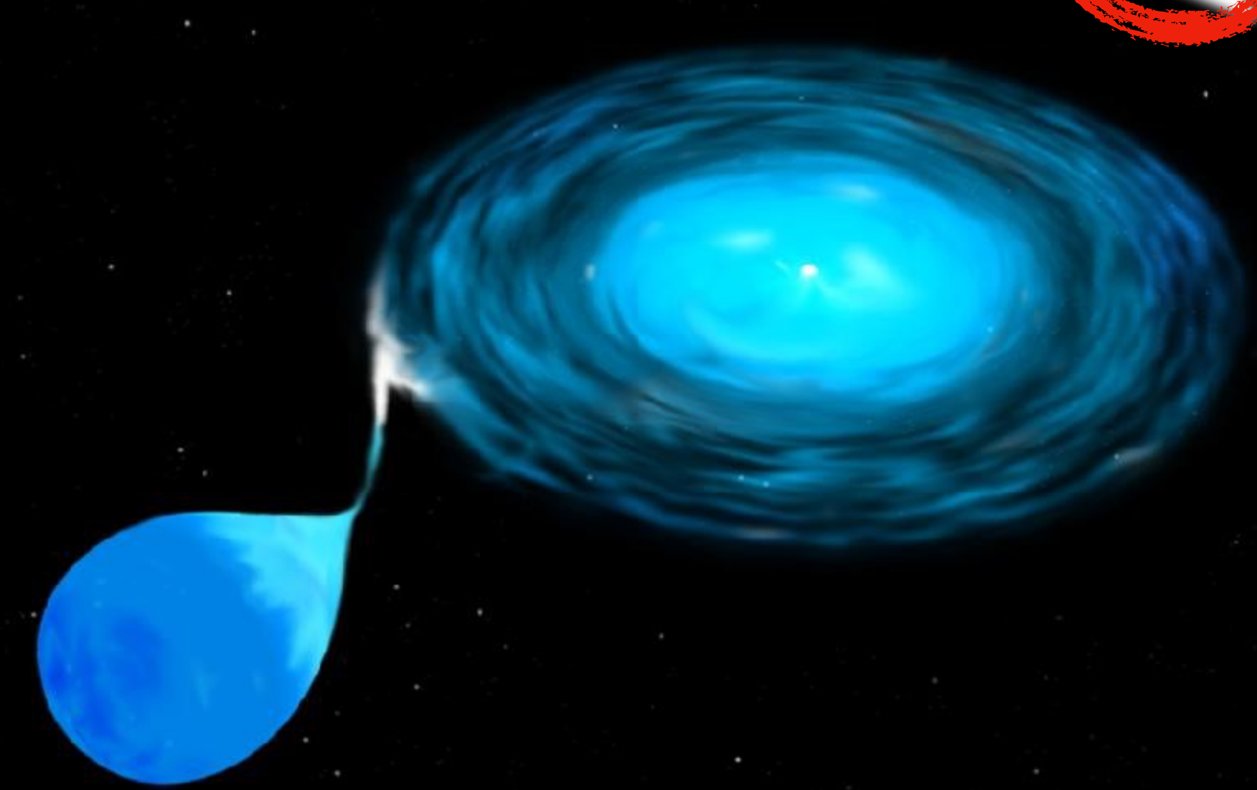
Image credit: NOAO/AURA/NSF

Type Ia Supernovae

“standard candles”

- in the 30s: SNe to measure distances?
- in the 80s: several groups defined Type Ia
- to probe cosmology needed:
  - larger detectors
  - faster telescopes
  - new data reduction techniques
- wanted to:
  - measure H_0 at low z (z<0.1)
  - measure q_0 at high z!

$$q_0 = -\frac{\ddot{a}(t)}{a(t)H(t)^2}$$

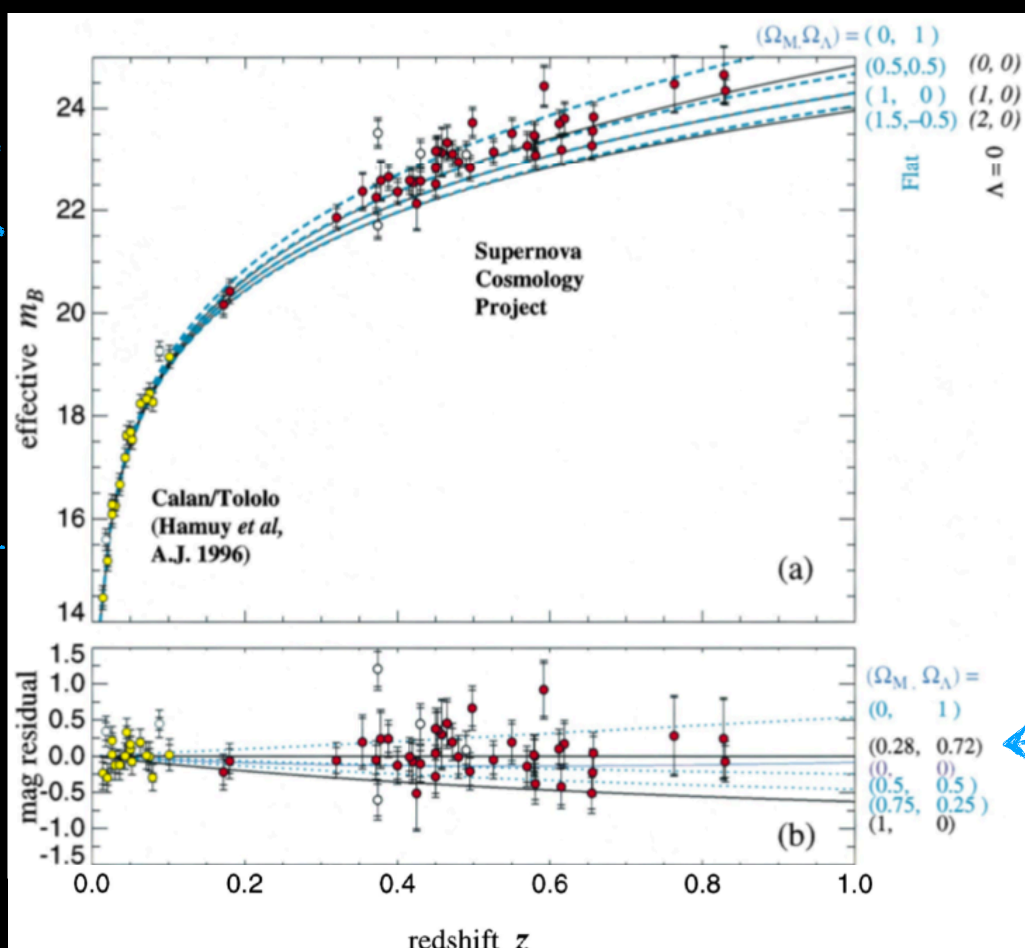


1985

Image credit: STScI

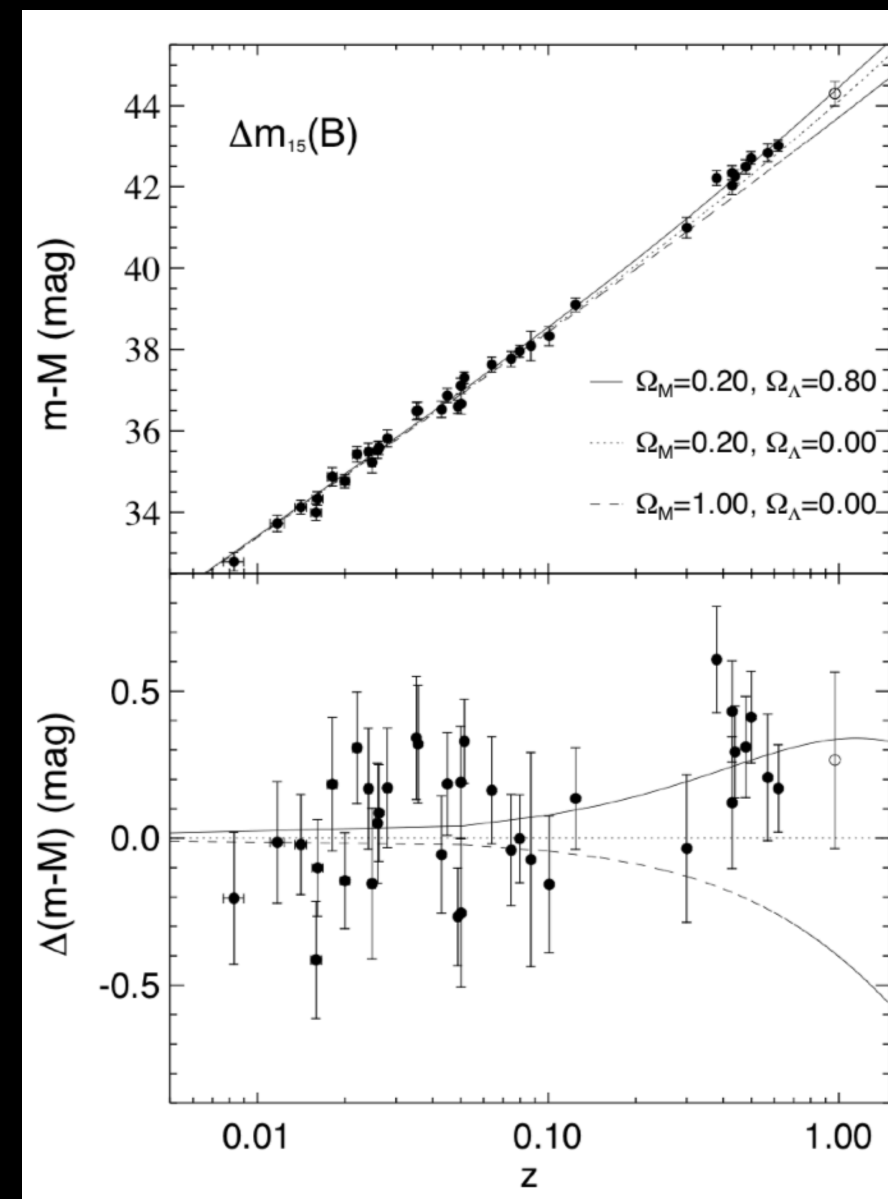
reduces to Hubble's law at small z

$$D_{\mathrm{L}} = c\,(1+z)\int_0^z \frac{dz'}{H(z)} \quad \text{(when } k = 0\text{)}$$



Perlmutter et al, 1999 (Supernova Cosmology Project)

Best fit!



Riess et al, 1998 (High-z team)

1998–1999

The Cosmic Energy Budget

Added to handout - not presented in lecture.

Λ

- 1st Friedmann equation

$$H(t)^2 = \frac{8\pi G}{3}\rho(t) + \frac{\Lambda c^2}{3} - \frac{kc^2}{a(t)^2}$$

$$\frac{kc^2}{a(t)^2 H(t)^2} = \frac{8\pi G}{3H(t)^2}\rho(t) + \frac{\Lambda c^2}{3H(t)^2} - 1$$

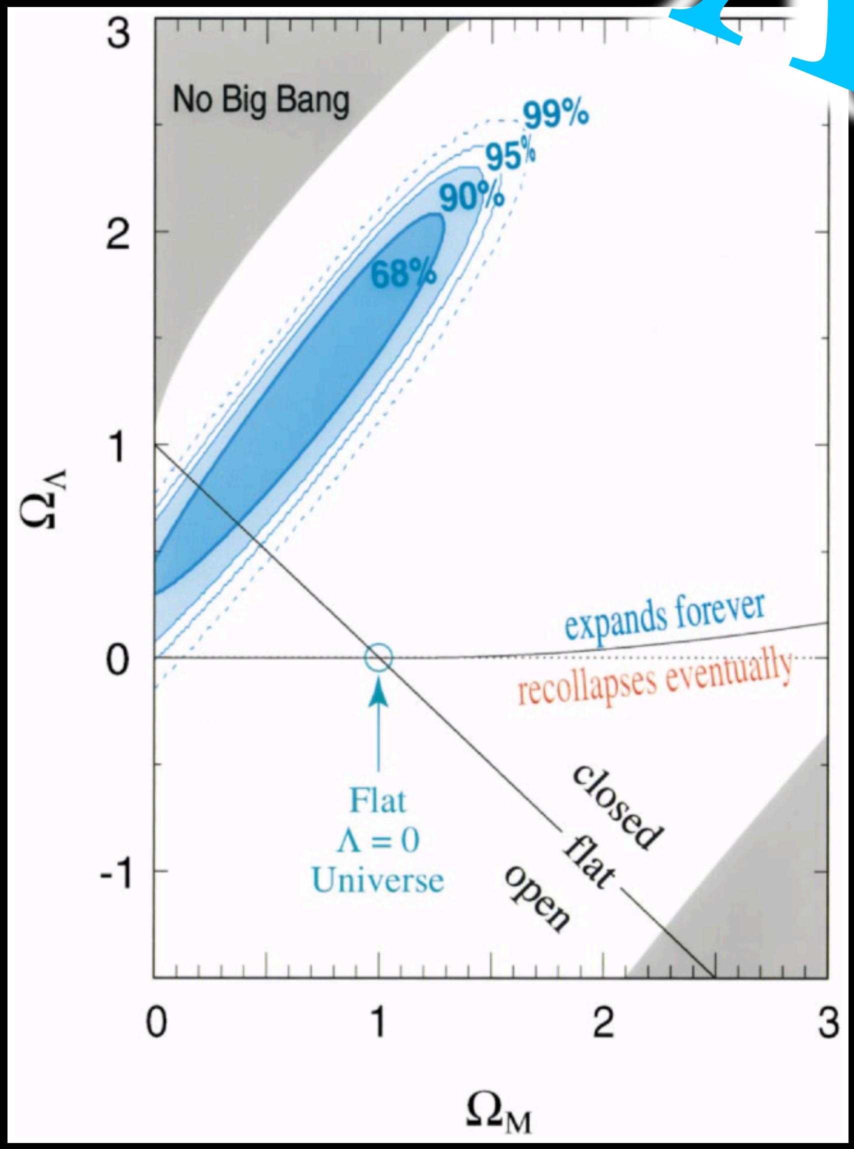
$$\Omega_{i,0} = \frac{8\pi G}{3H_0^2}\rho_{i,0} = \frac{\rho_{i,0}}{\rho_{\mathrm{crit},0}}$$

- write Λ term as an energy density, assume flatness, neglect radiation

$$\frac{H(z)^2}{H_0^2} = \Omega_{\mathrm{m},0}(1+z)^3 + \Omega_{\Lambda,0}$$

$$\rho_{\mathrm{m}} = \rho_{\mathrm{m},0}(1+z)^3$$

- $$D_{\mathrm{L}} = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_{\mathrm{m},0}(1+z')^3 + \Omega_{\Lambda,0}}}$$ (when $\Omega_{\mathrm{K}} = 0$)



Perlmutter et al, 1999 (Supernova Cosmology Project)

From constant to perfect fluid with equation of state $p = w\rho c^2$.
$w = -1$ is the cosmological constant, $w \neq -1$ is Dark Energy!

So, what could be causing this acceleration?

Vacuum/zero-point energy?

Added to handout - not presented in lecture.

- A hand-wavy QM "prediction": $\rho_{\rm vac}^{\rm QM} c^2 \sim \dfrac{(10^{28}\ {\rm eV})^4}{(\hbar c)^3}$

- Cosmological observations: $\Lambda = 3\Omega_\Lambda \left(\dfrac{H_0}{c}\right)^2 \approx 10^{-52}\ {\rm m}$

$1\ {\rm eV} = 1.6 \times 10^{-19}\ {\rm J}$

$1\ {\rm m} = 5.08\ \hbar c \times 10^{-6}\ {\rm eV}^{-1}$

$$\rho_{\rm vac} c^2 = \frac{\Lambda}{8\pi G} \approx \frac{(2 \times 10^{-3}\ {\rm eV})^4}{(\hbar c)^3}$$

- The worst fine-tuning problem in physics: $\dfrac{\rho_{\rm vac}}{\rho_{\rm vac}^{\rm QM}} \sim 10^{-123}$!

- A quantum theory of gravity might make better prediction.
  So-far unsuccessful attempts: string theory, loop quantum gravity…

negative lab tests so far

- Anthropic principle

Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Scalar fields

Dark Energy

Added to handout - not presented in lecture.

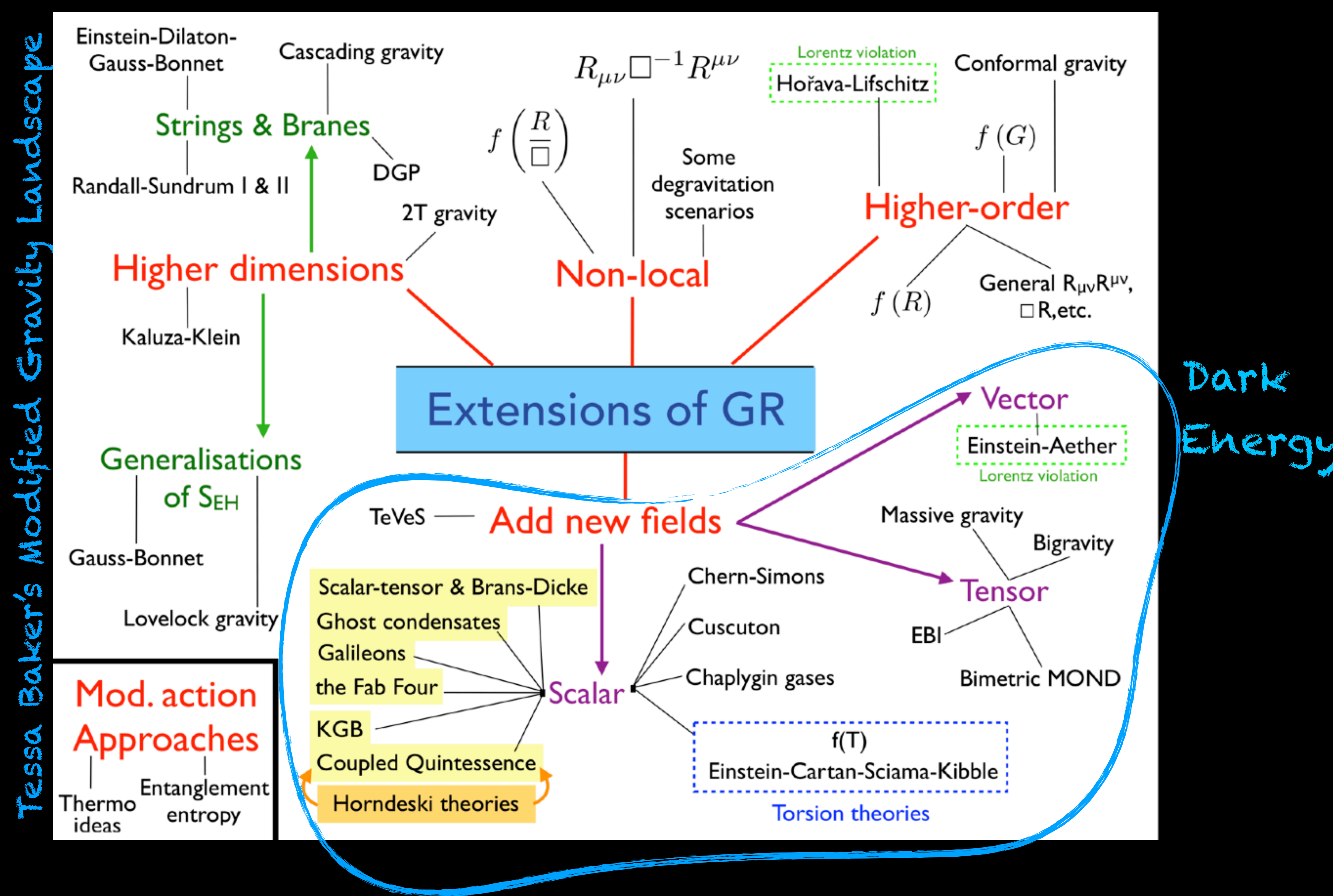
"the fifth element"

- quintessence: $S = \int d^4x \sqrt{-g} \left[-\frac{1}{2} \left(\nabla \phi \right)^2 - V(\phi) \right]$
  - equation of state: $w_\phi = \frac{p}{\rho} = \frac{\dot{\phi} - 2V(\phi)}{\dot{\phi} + 2V(\phi)}$
  - continuity equation: $\rho = \rho_0 \exp \left[- \int 3(1 + w_\phi) \frac{da}{a} \right]$
  - Linder parametrisation: $w(a) = w_0 + w_\mathrm{a}(1 - a)$
- many possibilities: K-essence, tachyon, ghosts, phantoms…

if $w = -1$, we recover Λ
if $w \neq -1$, get dynamical dark energy!

null test: $w_\mathrm{a} \neq 0$ and $w_0 \neq -1$
via $\Omega_{\mathrm{DE},0}(1+z)^{3(1+w_0+w_\mathrm{a})\exp\left[-3w_\mathrm{a}\frac{z}{1+z}\right]}$

Dark Energy or Modified Gravity?



- add to the stuff in the universe: Dark Energy: $G_{ab} = \frac{8\pi G}{c^4}T_{ab} + \Lambda g_{ab}$

- add to space-time geometry, and modify gravity: $G_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4}T_{ab}$

How are we going to figure this out?

Distance-redshift relation

redshift

co-moving distance

$$D_C = c \int_0^z \frac{dz'}{H(z)}$$

Hubble function:
all the physics

Need standard(isable) objects:

- standard candles: SNe…
- standard rulers: BAO…

Astronomical distances

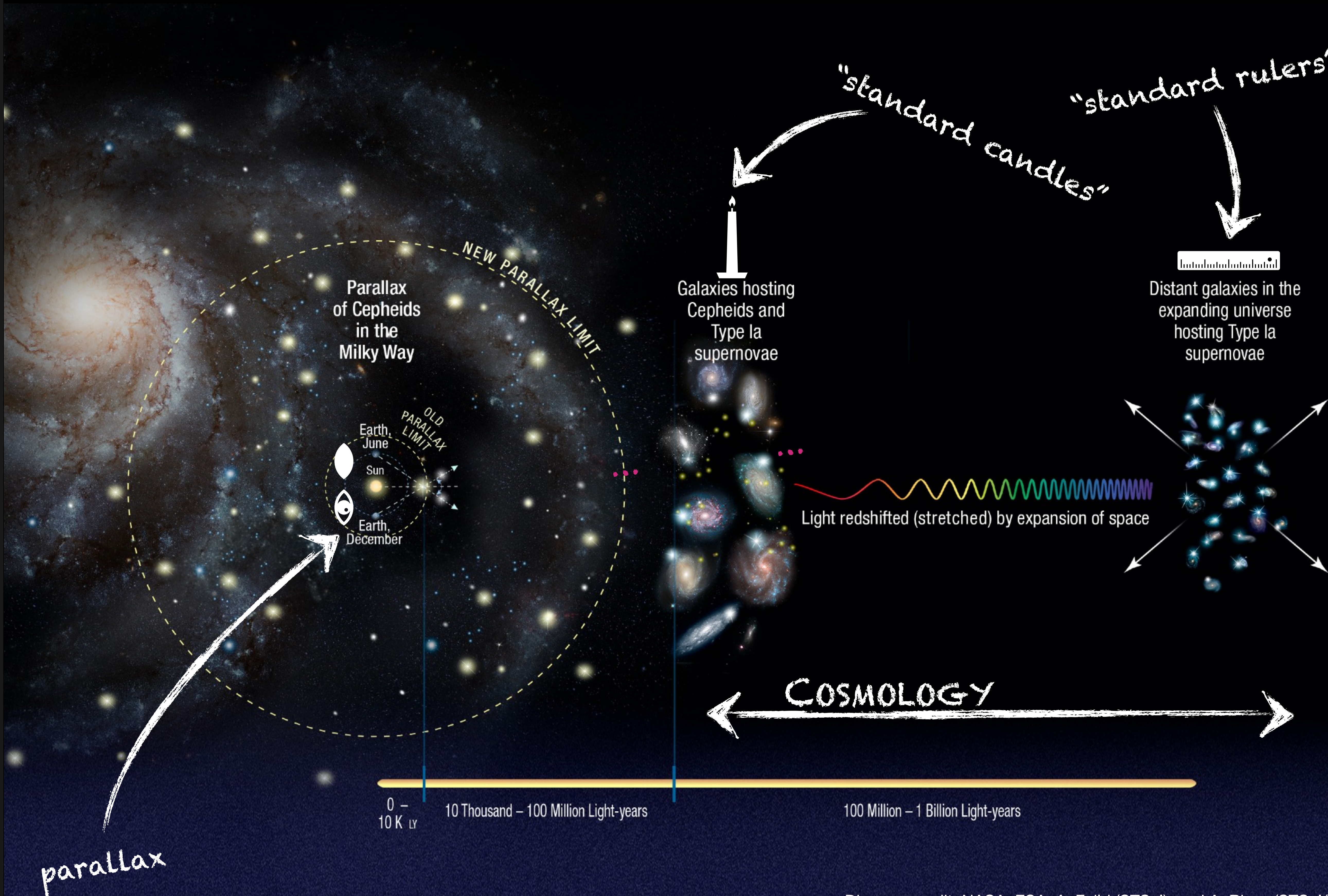
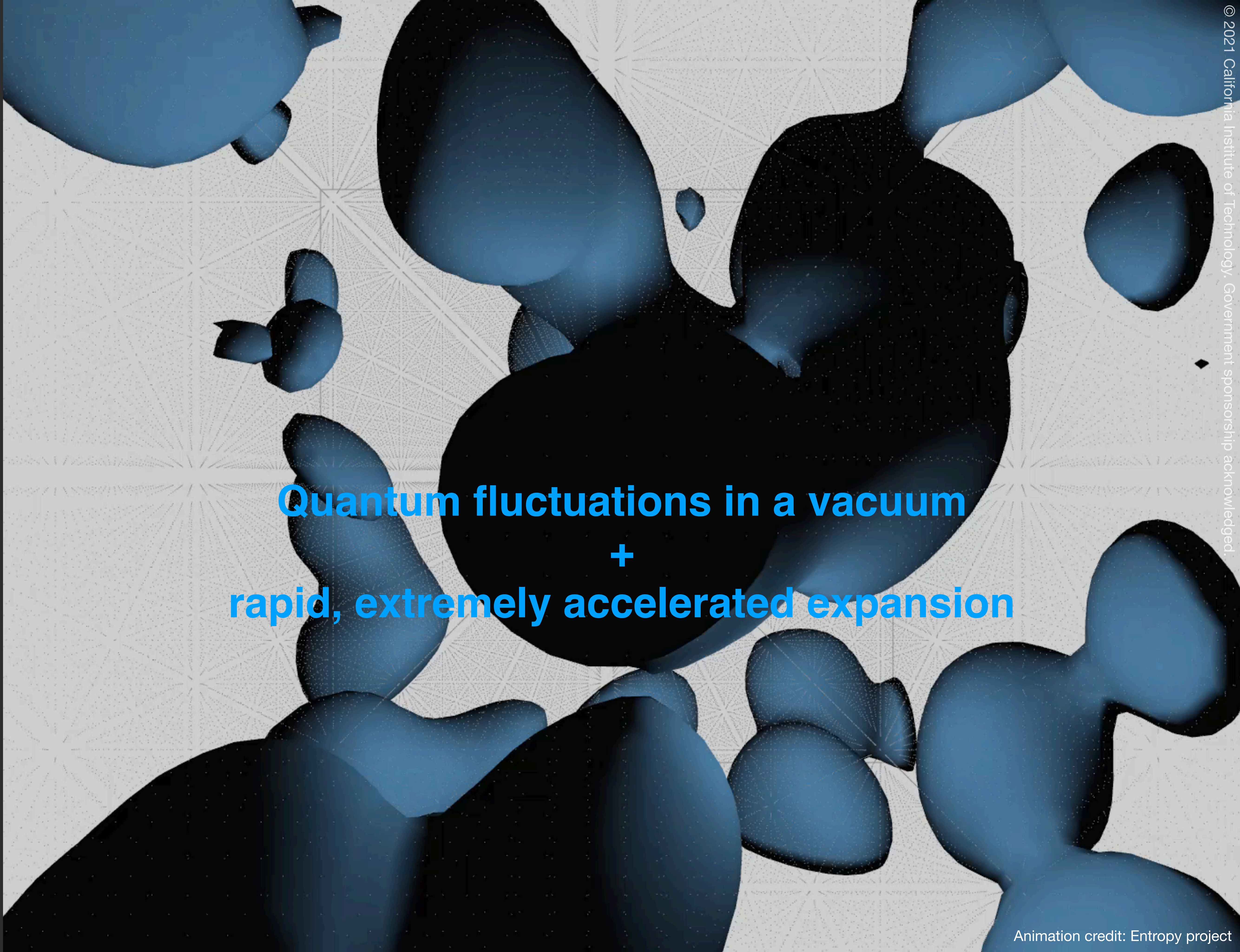


Diagram credit: NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)

A walk down memory lane…

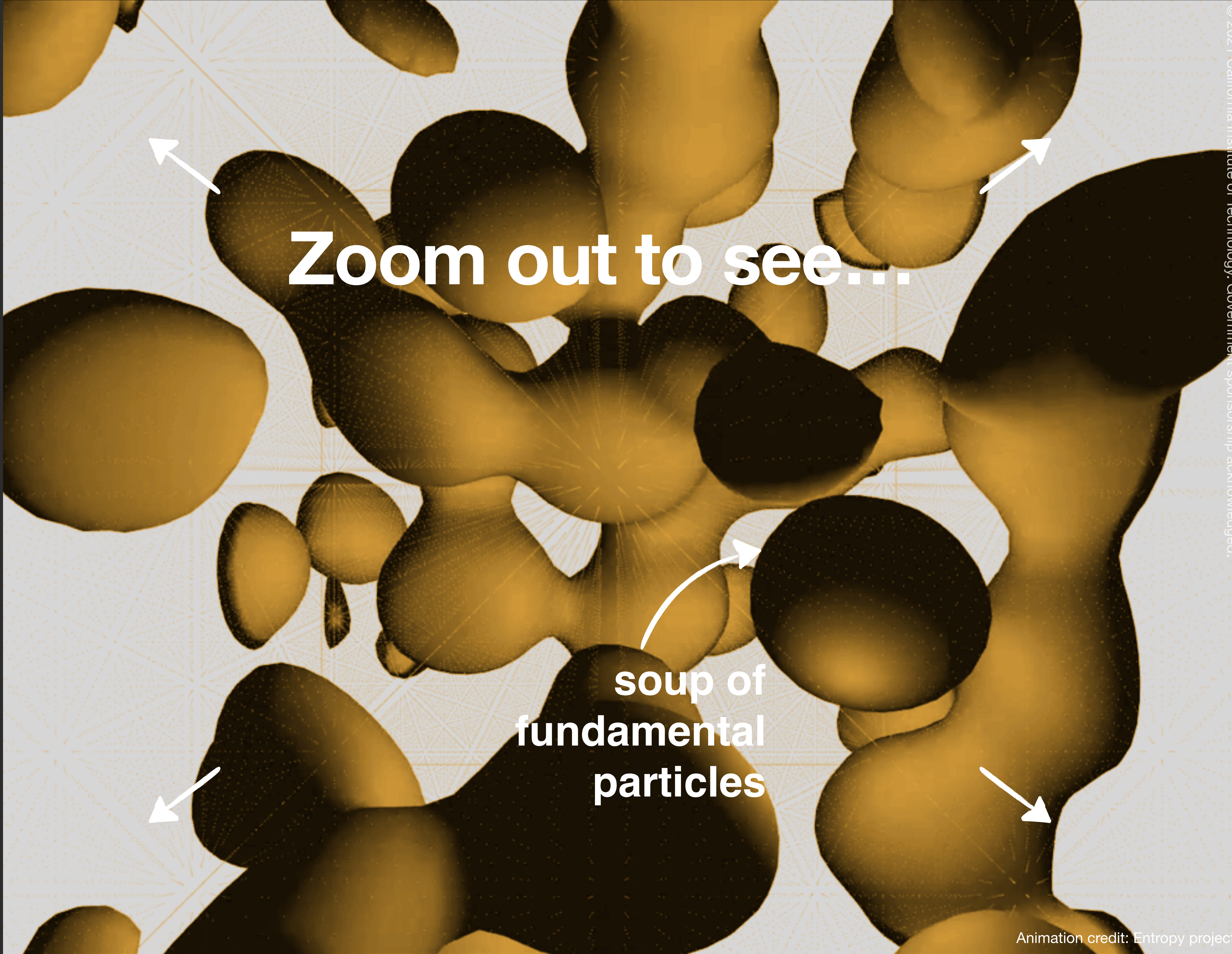


Quantum fluctuations in a vacuum

+

rapid, extremely accelerated expansion

Animation credit: Entropy project



Animation credit: Entropy project

Cosmic Microwave Background

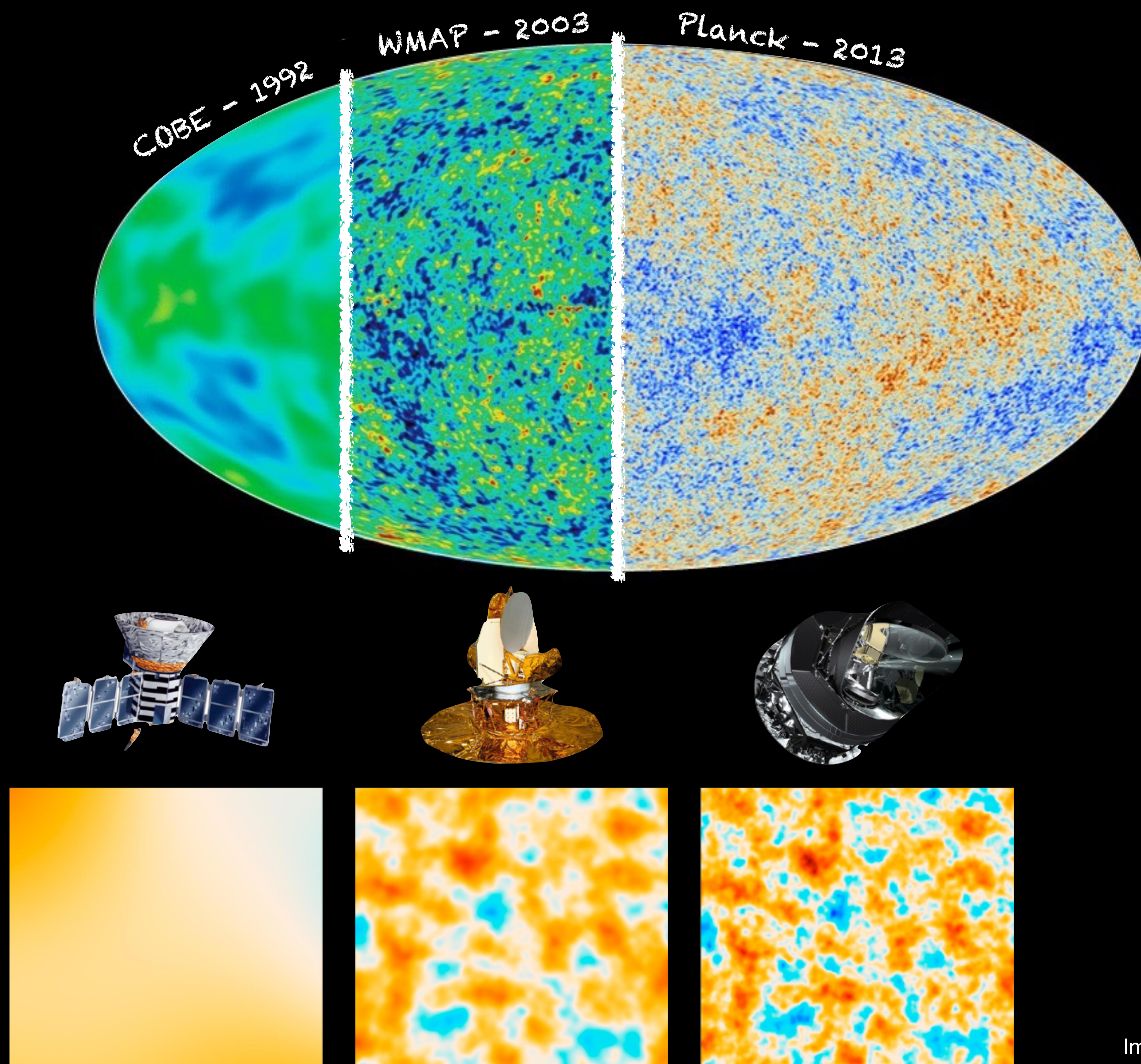
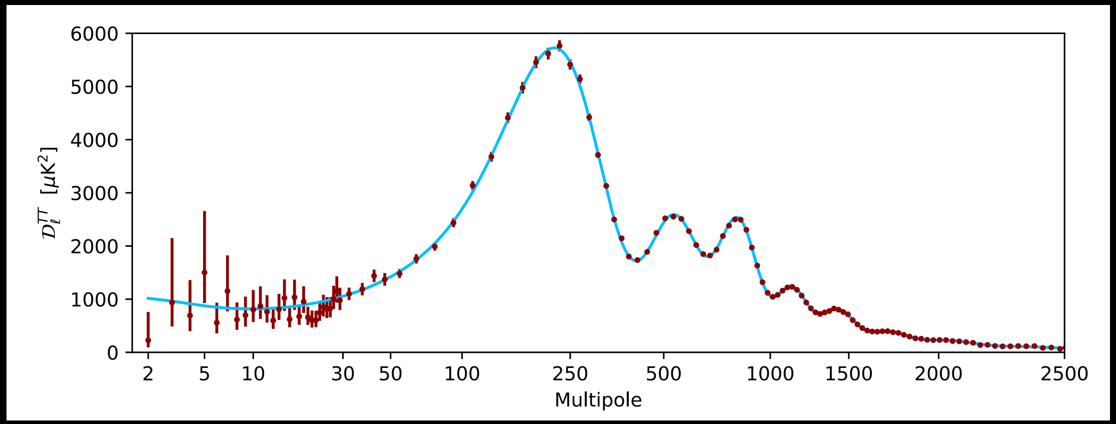


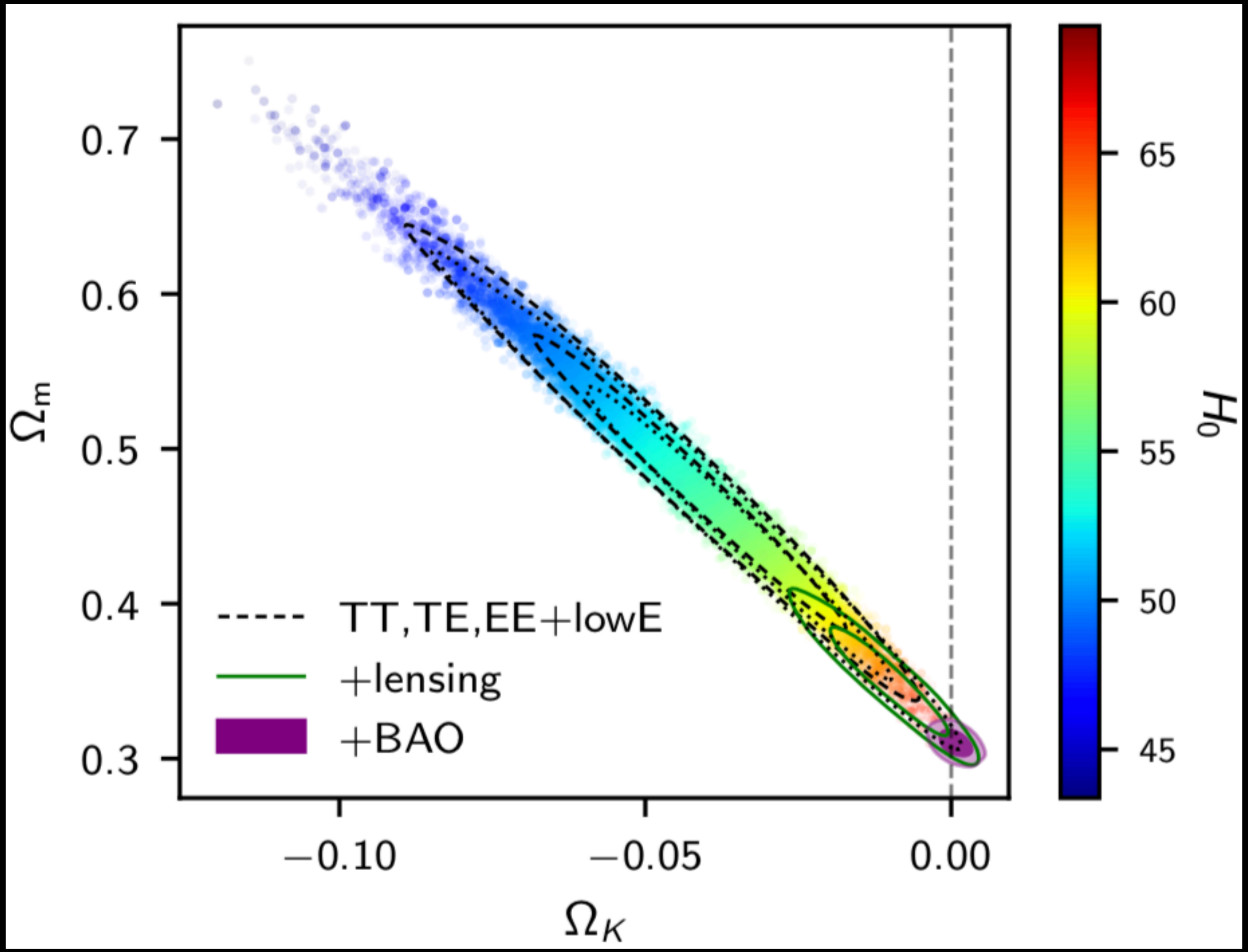
Image: NASA/JPL-Caltech/ESA

Cosmic Microwave Background

Added to handout - not presented in lecture.

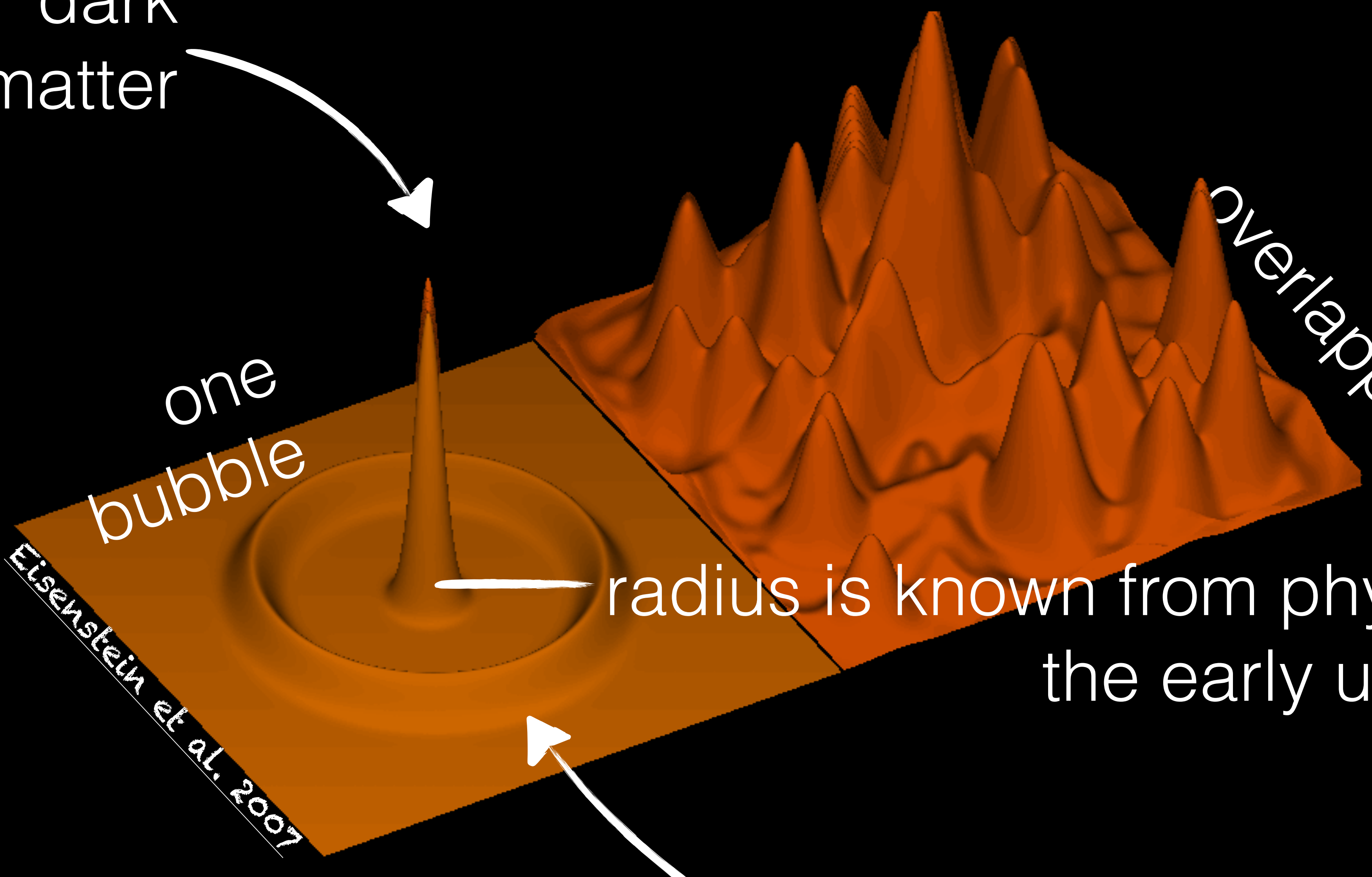


- measure of the primordial sound horizon at z=1100
- critical density universe preferred
- BUT need too much matter for LSS and CMB observations if that's all there is

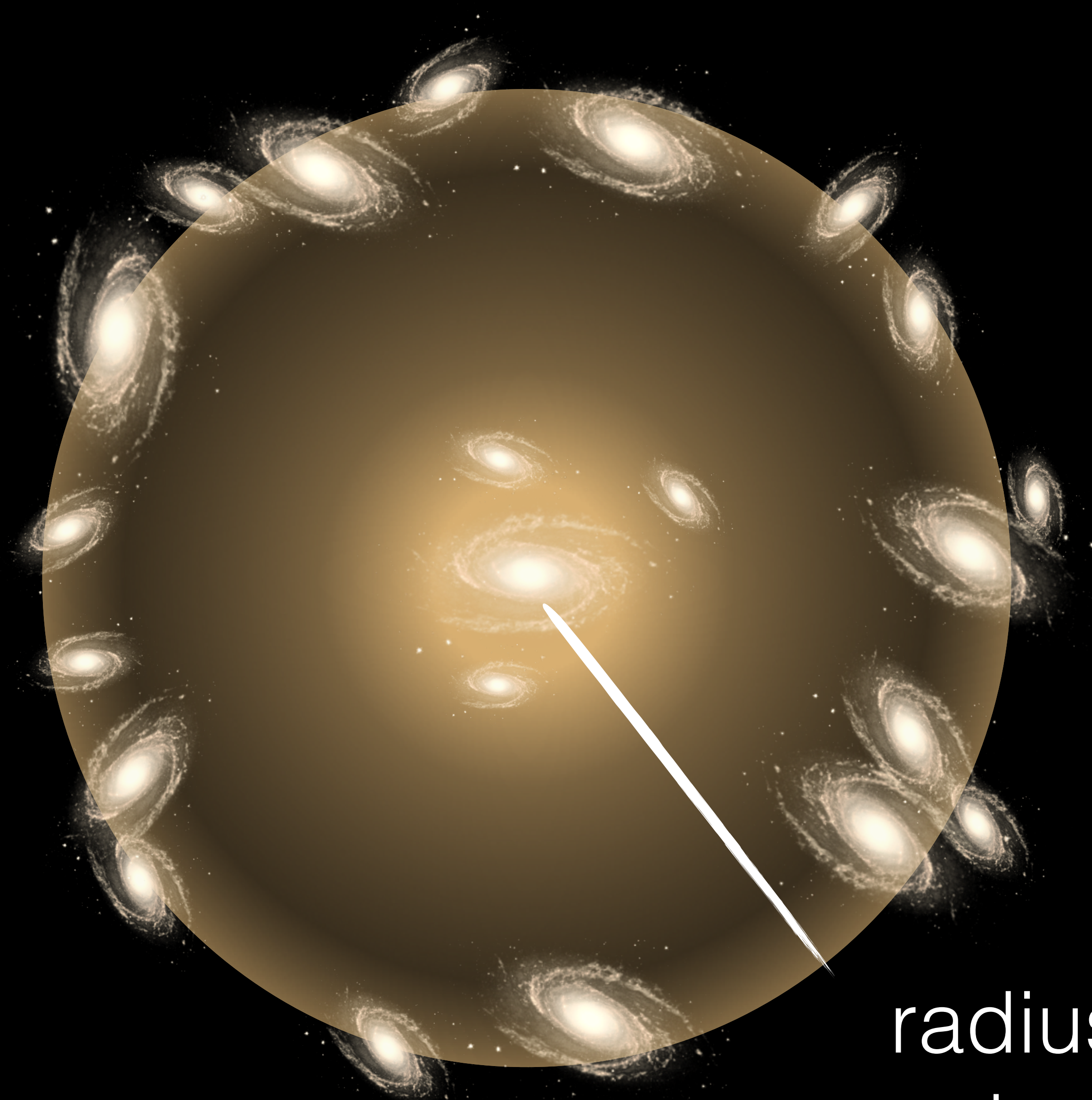


Planck Collaboration, VI (2018)

Acoustic Bubbles



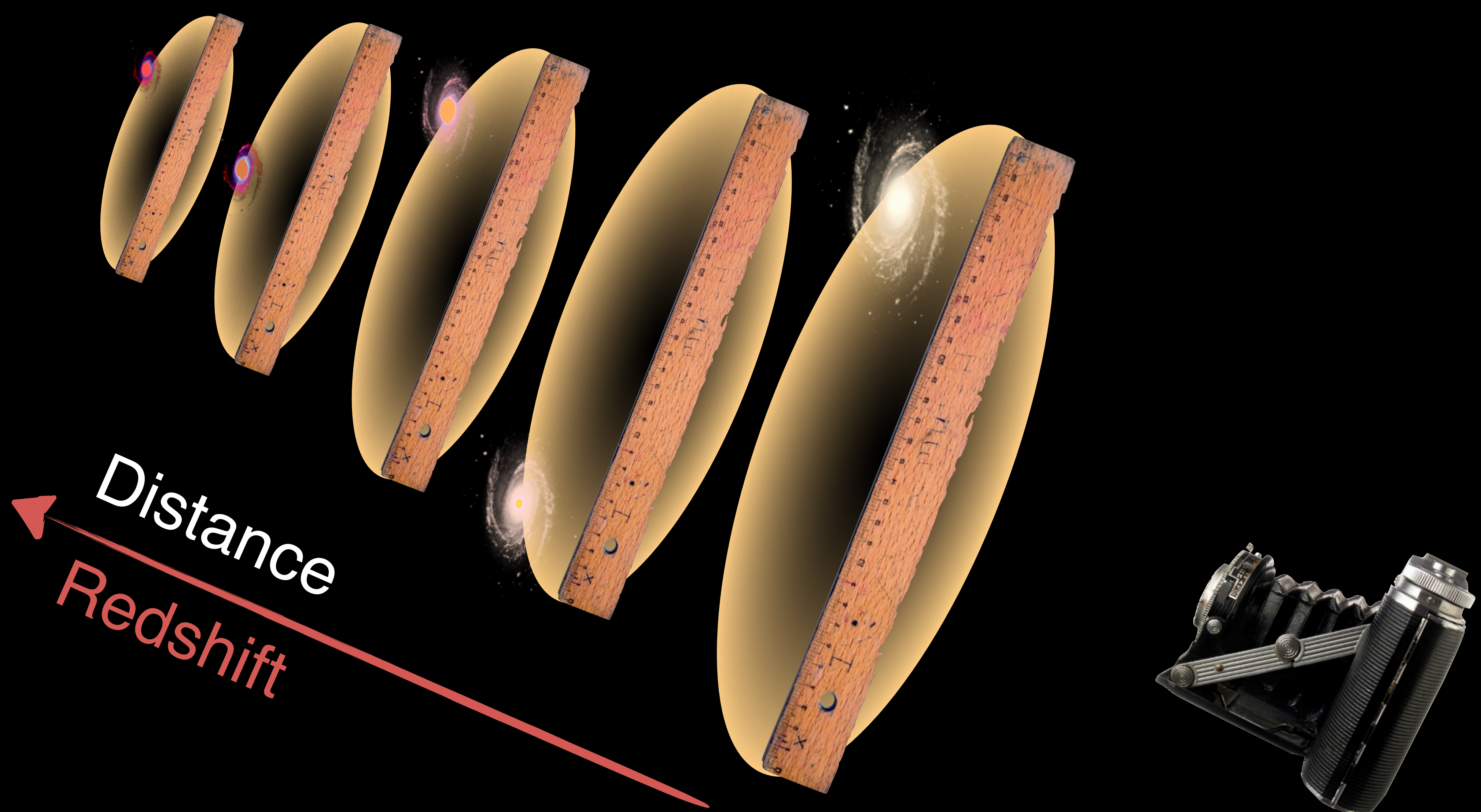
Acoustic Bubbles



radius is known from physics of the early universe

A Standard Ruler

Baryon Acoustic Oscillations

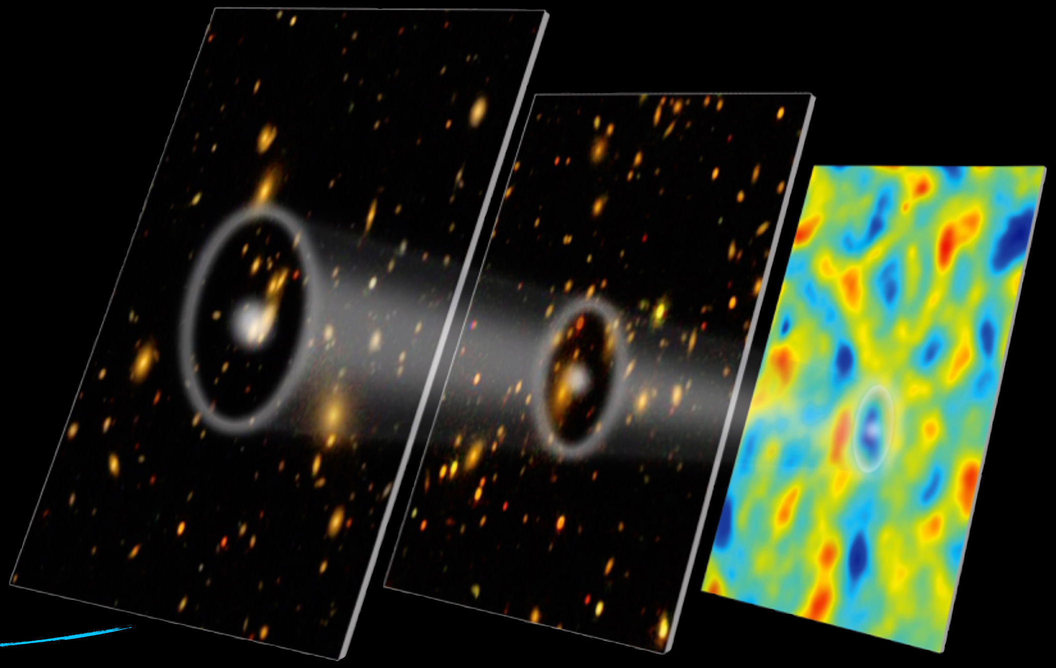


Distance-redshift relation

Added to handout - not presented in lecture.

- comoving distance, $D_C = c\int_0^z \frac{dz'}{H(z)}$ (when $k = 0$)
- Cosmic Distance Ladder:
  parallax → variable stars (RR Lyrae & Cepheids) → SNe
- Inverse Distance Ladder:
  CMB sound horizon → BAO →SNe
- CMB and SNe independent techniques:
  Deuterium abundance (D/H) + BBN theory → baryon density → BAO

anything that is not radiation or dark
(i.e. things made of quarks,
sometimes includes leptons in cosmology)



E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian

The Cosmic Web

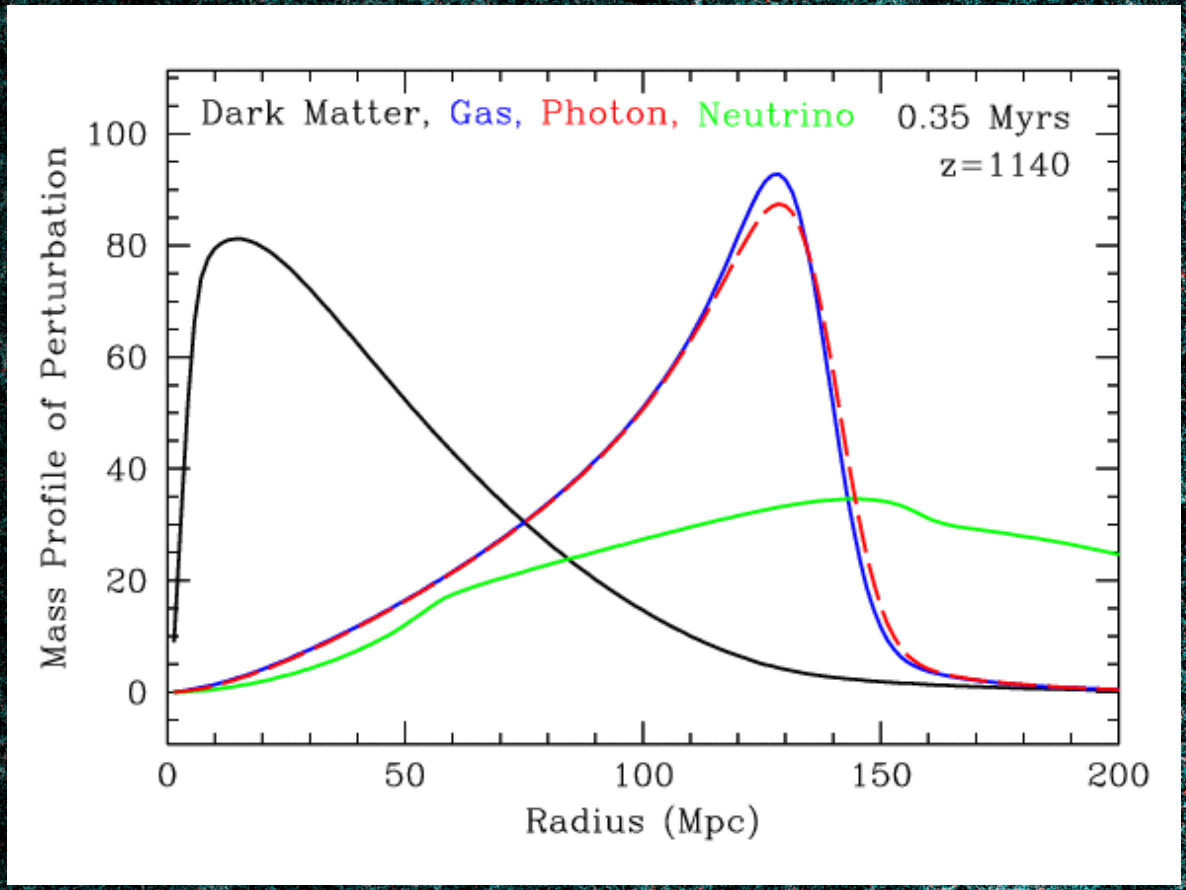
Added to handout – not presented in lecture.

power spectra

n-point correlation functions

number counts

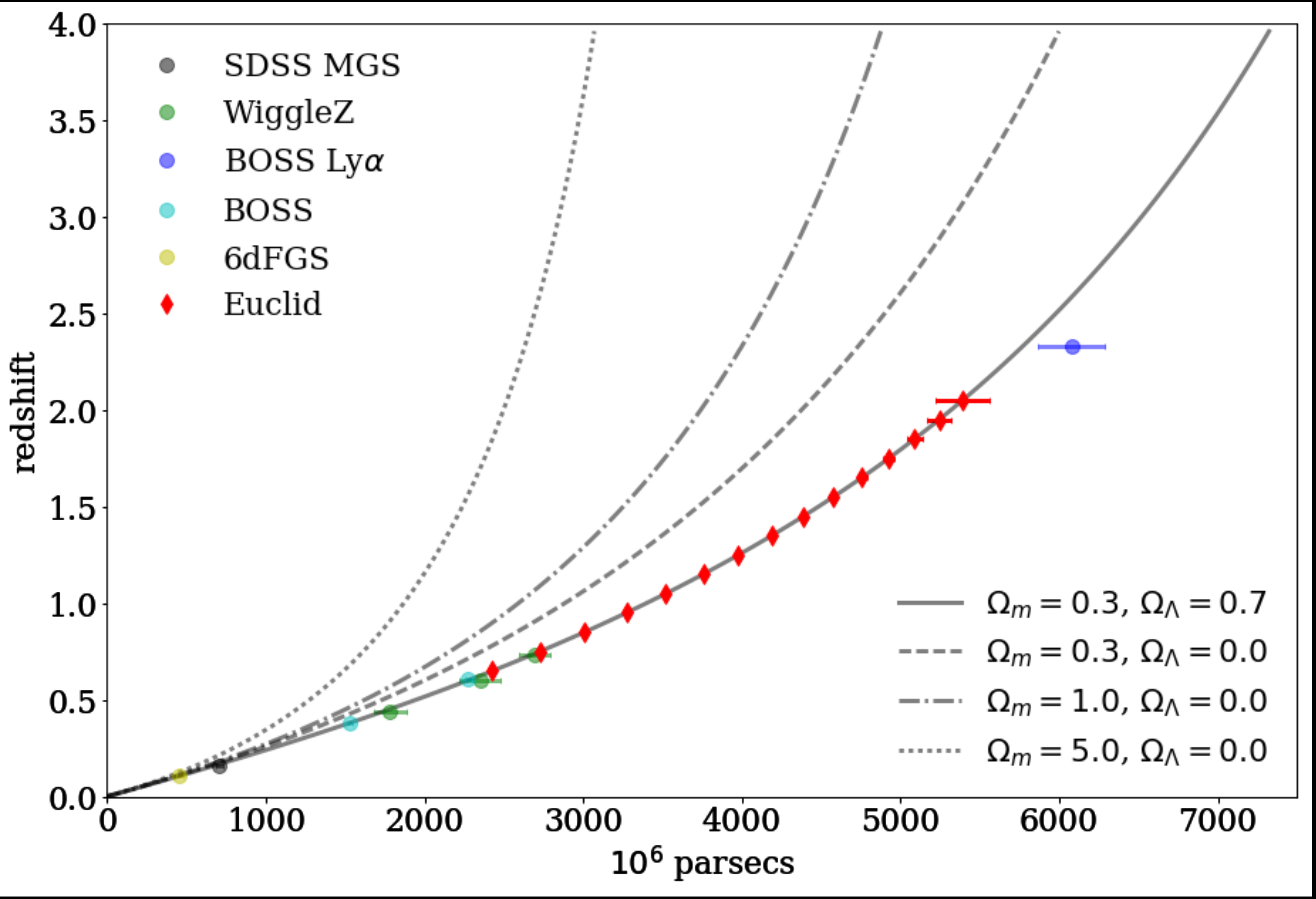
- probes $H(z)$ via BAO for example
- probes gravity via the growth of structure
- probes light paths via gravitational lensing
- probes gravity and expansion via galaxy cluster abundances
- probes expansion via non-linear late-time Integrated Sachs-Wolfe effect (aka Rees-Sciama effect)
- ...



Eisenstein et al. 2007

Euclid Flagship simulation, 2017

The Hubble Diagram



Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

The cosmic constituents

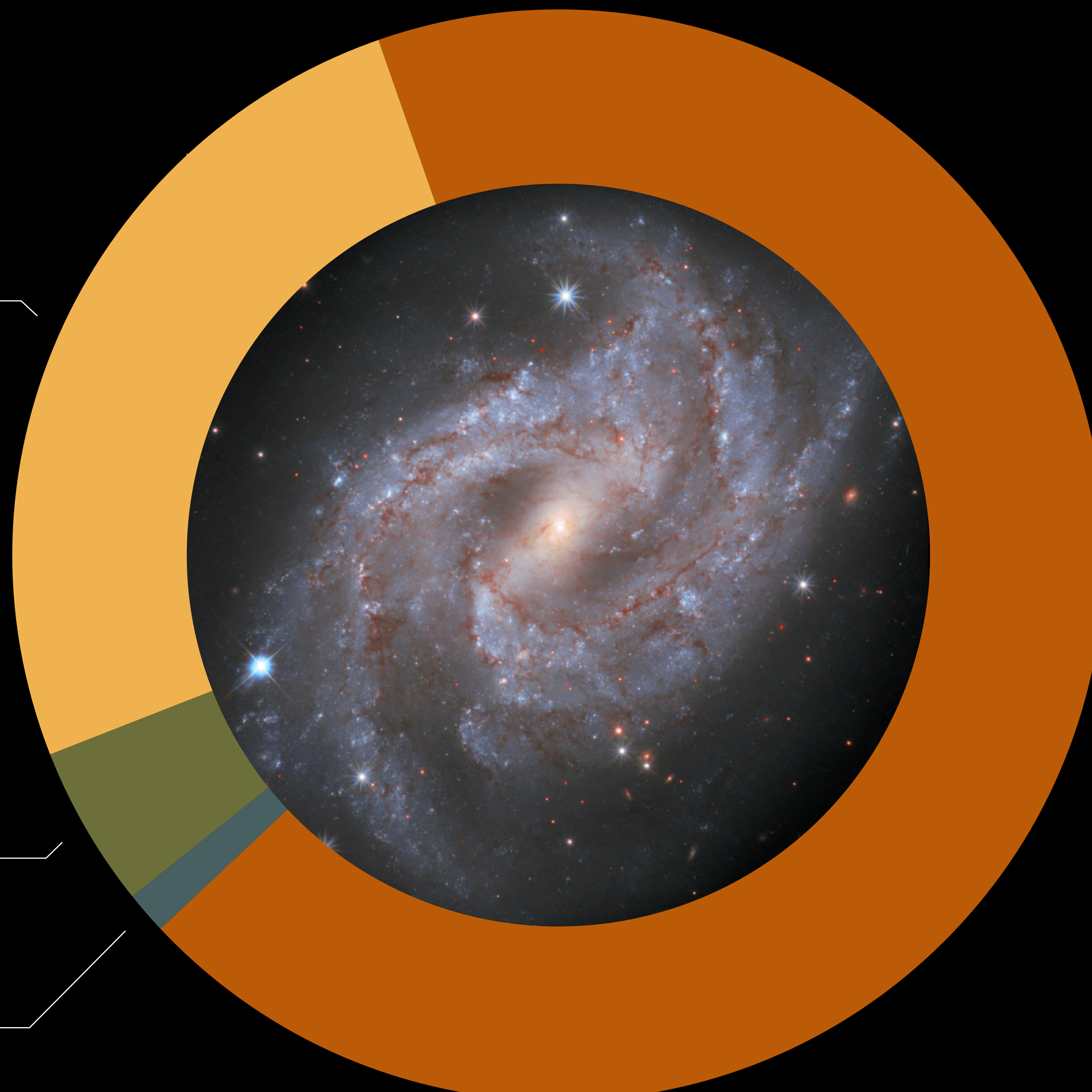
ΛCDM

Dark matter
26%

- too much gravity
- doesn't interact with light
  - neither emit
  - nor reflect
  - nor absorb

Baryons
5%

Neutrinos
1%



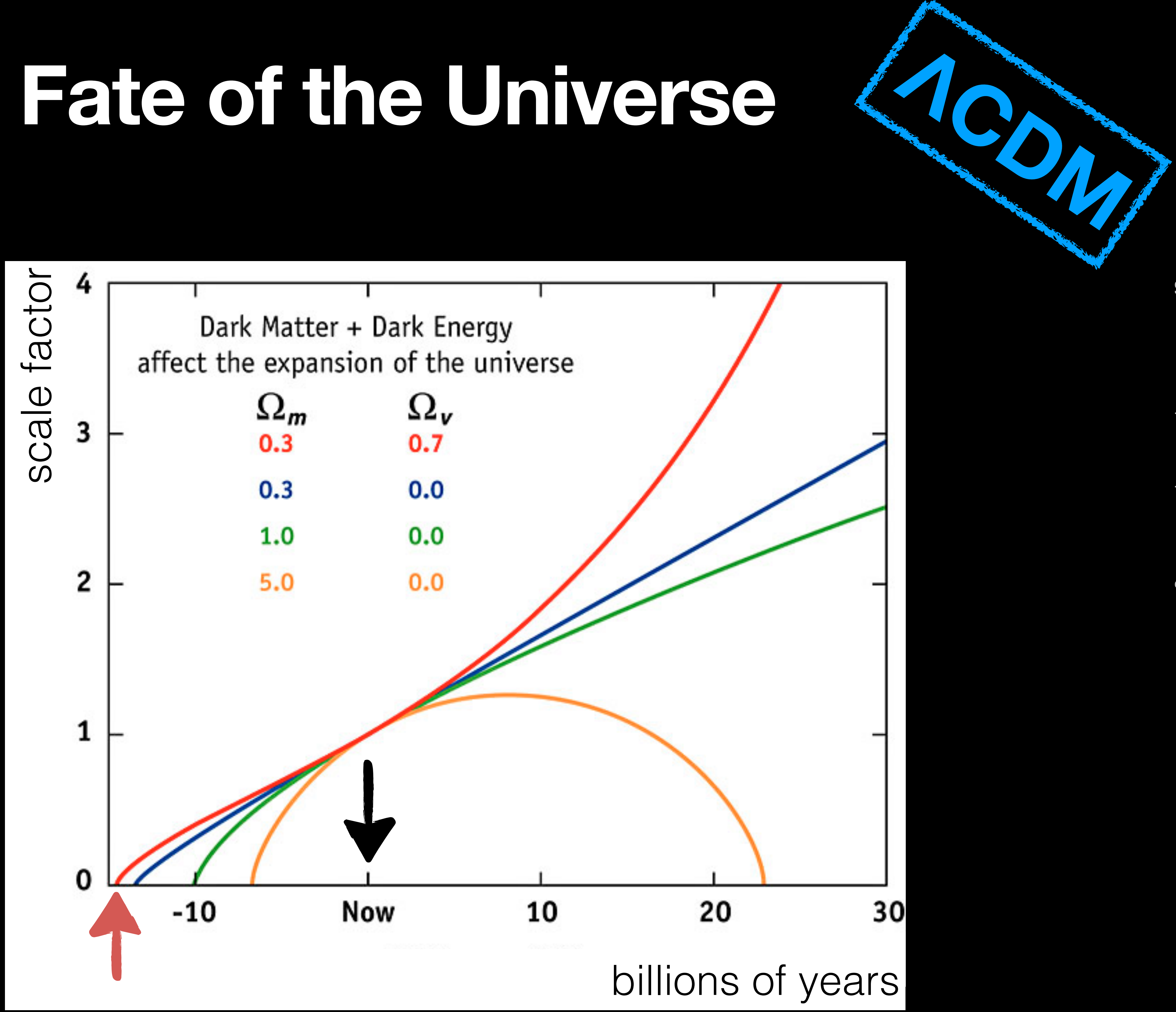
Dark energy
68%

- not enough gravity??
- just a name for an unknown phenomenon:
  - accelerated expansion of the universe

Galaxy image credits: NASA, ESA, and A. Riess (STScI/JHU) and the SH0ES team

Dr Dida Marković: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

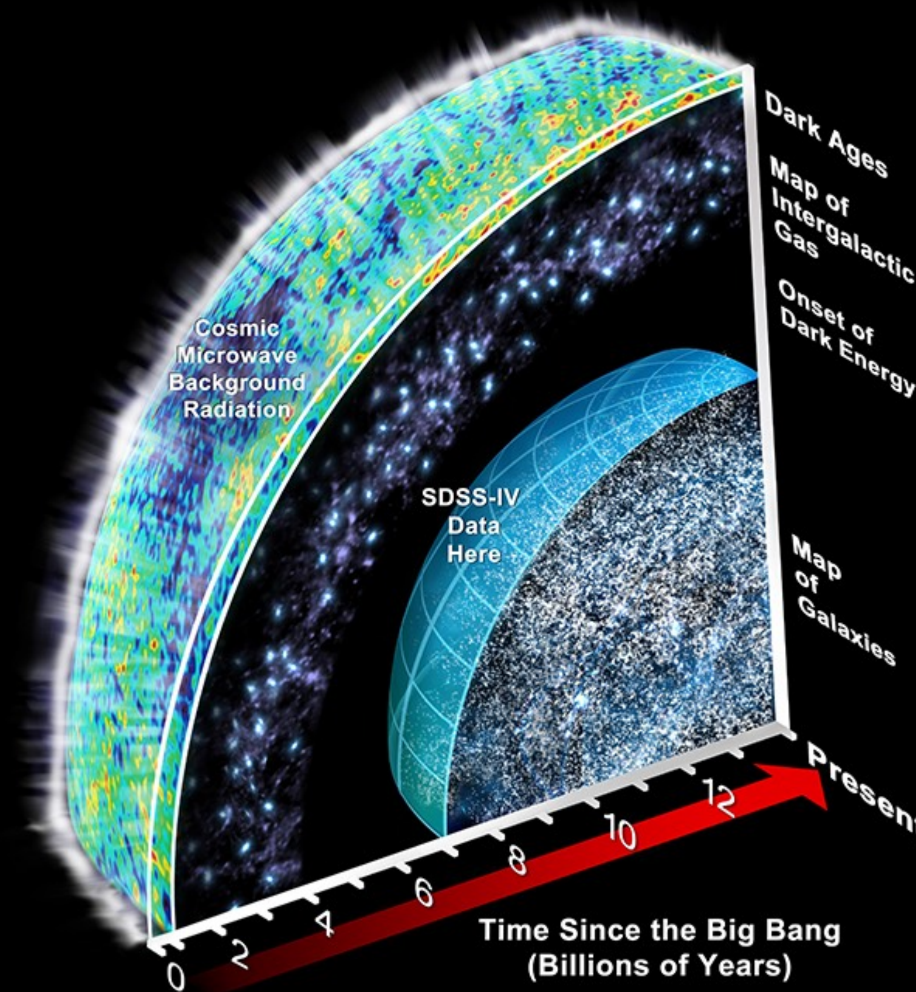
The Fate of the Universe



Dr Dida Marković: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Many experiments

- Early days: **COBE**, SNe surveys
- 2000s: **WMAP**, SDSS & BOSS, **HST** programs
- 2010s: **Planck**, eBOSS (SDSS), HETDEX, CFHTLS, KIDS, PFS on Subaru, DES, DESI, SPT, BINGO, MeetKAT, GBT, Pan-STARRS, VIPERS, VIRGO, LIGO
- 2020s: Rubin (fka LSST), **Euclid**, **Roman** (fka WFIRST), SKA, CHIME, **SPHEREx**…
- 2030s: **LISA**…

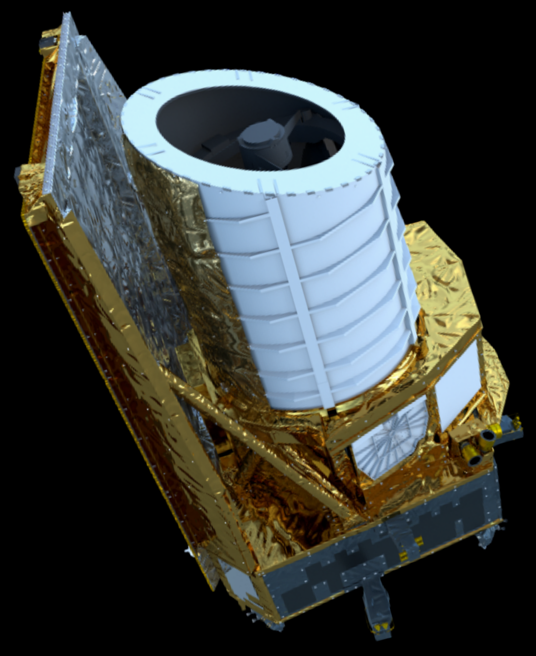


SDSS

focus: large-scale structure & gravitational waves

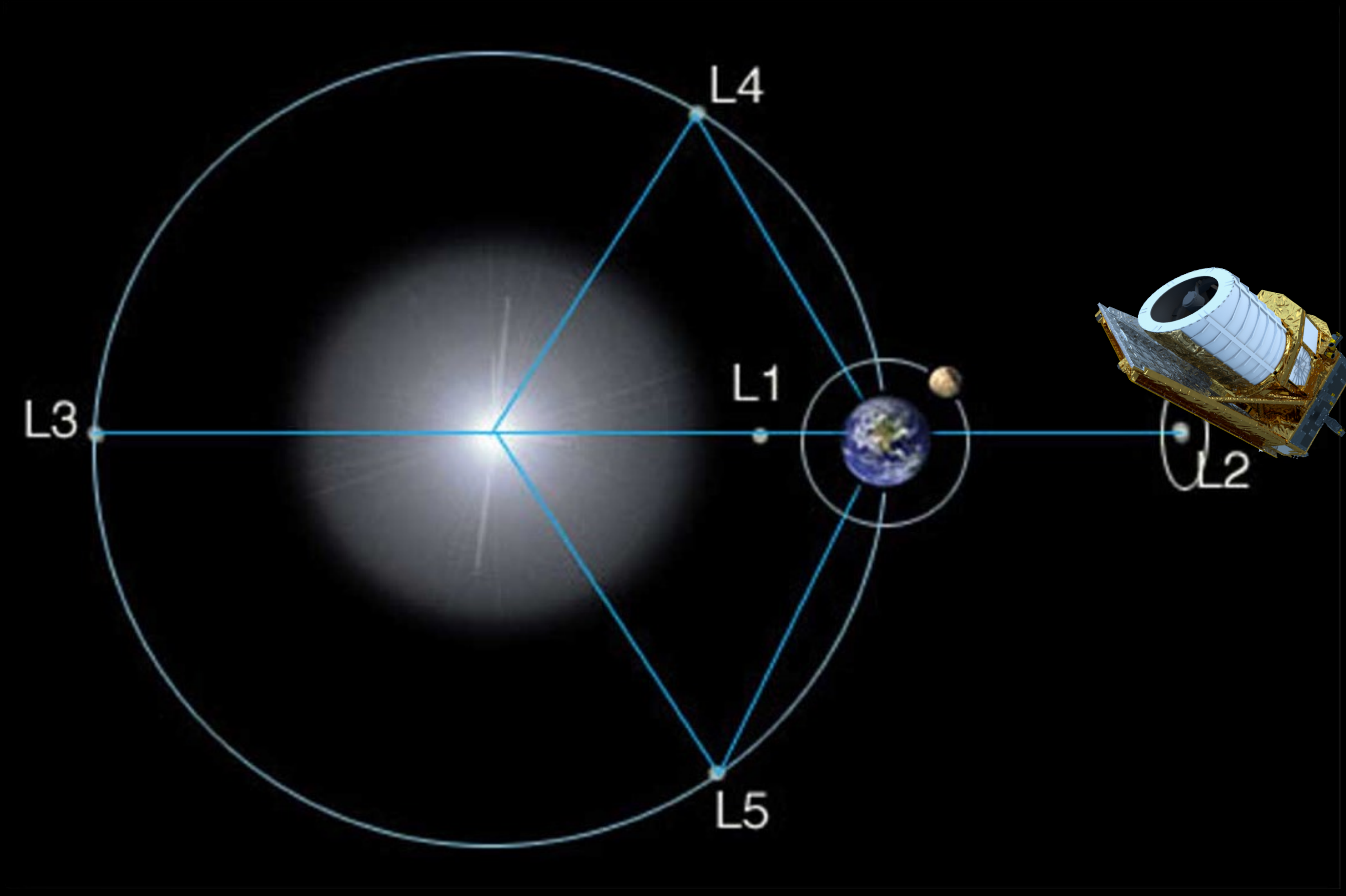
eBOSS graphic

Let’s talk about Euclid



Euclid Space Telescope

- launch:
  - 2022
  - Europe's Spaceport, Kourou, French Guiana
  - Soyuz rocket, ST 2-1b launch vehicle

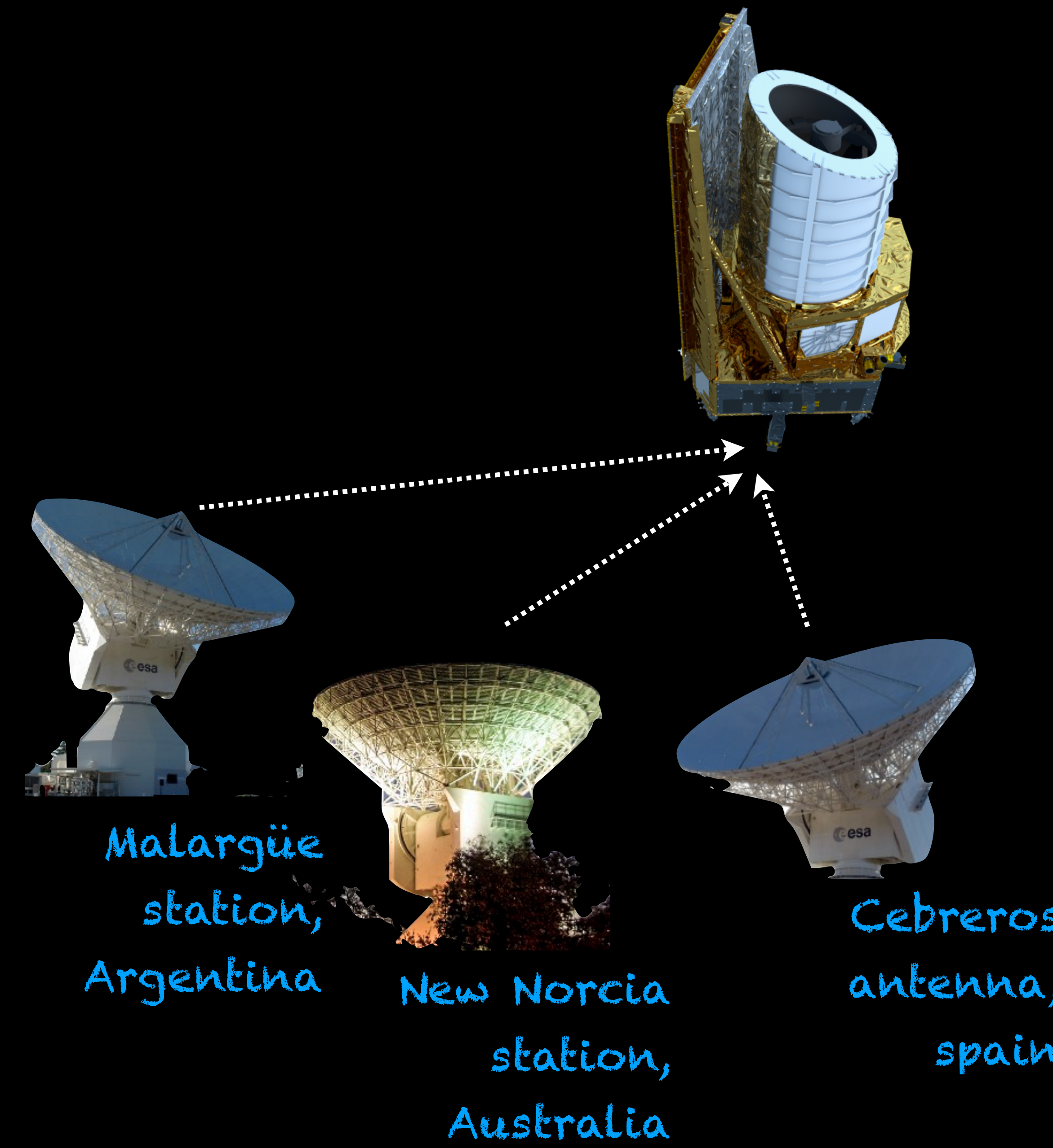


- transfer phase: 30 days commissioning start

- orbit: 2nd Lagrangian point (1.5M km away)

Staying in touch

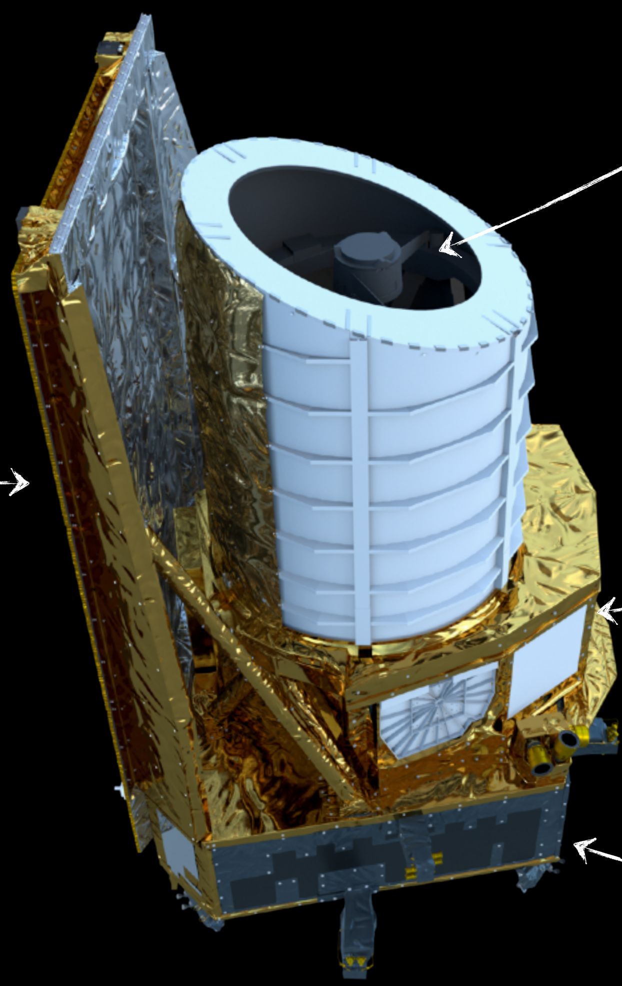
- K-band: downlink
  - science & telemetry
  - high-rate: up to 73.85 Mbit/s
  - vulnerable to weather
- X-band: up- & downlink
  - telecommunication & housekeeping
  - low-bandwidth: max 26 kbit/s
  - works in adverse weather conditions



ESA's deep space antennas

Euclid Payload

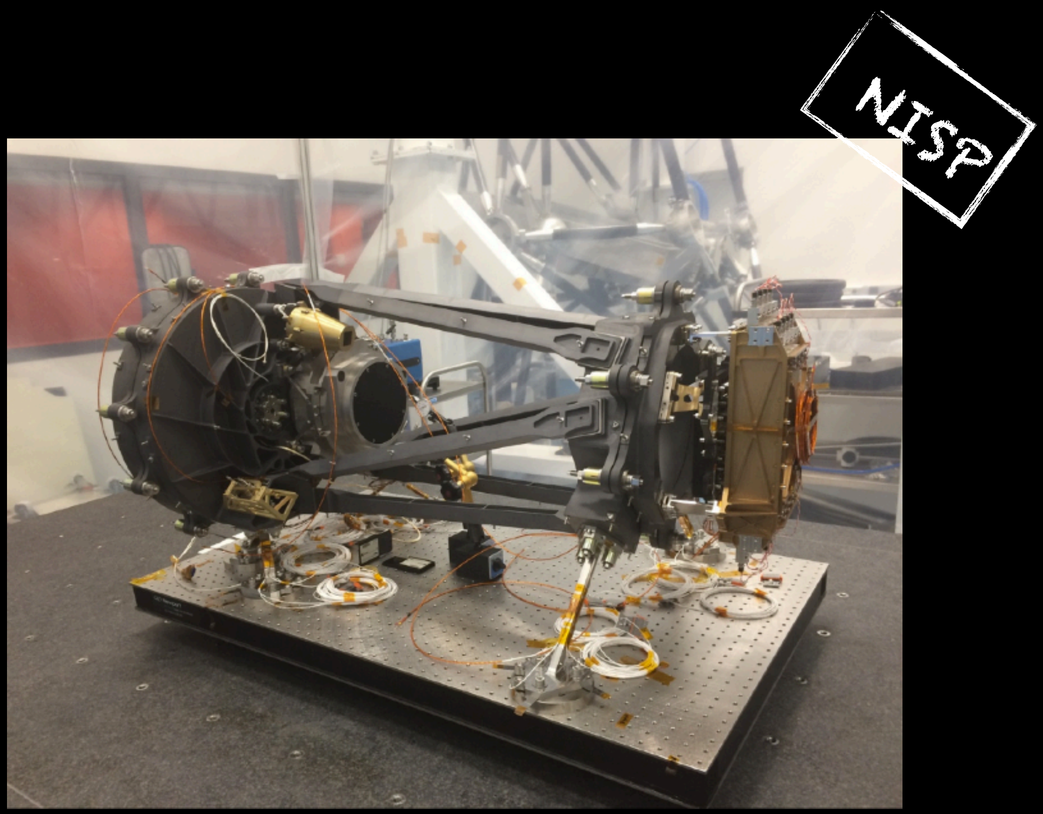
- launch mass: 2100 kg (payload +service module)
- nominal mission lifetime ~ 6 years



Euclid VIS + NISP

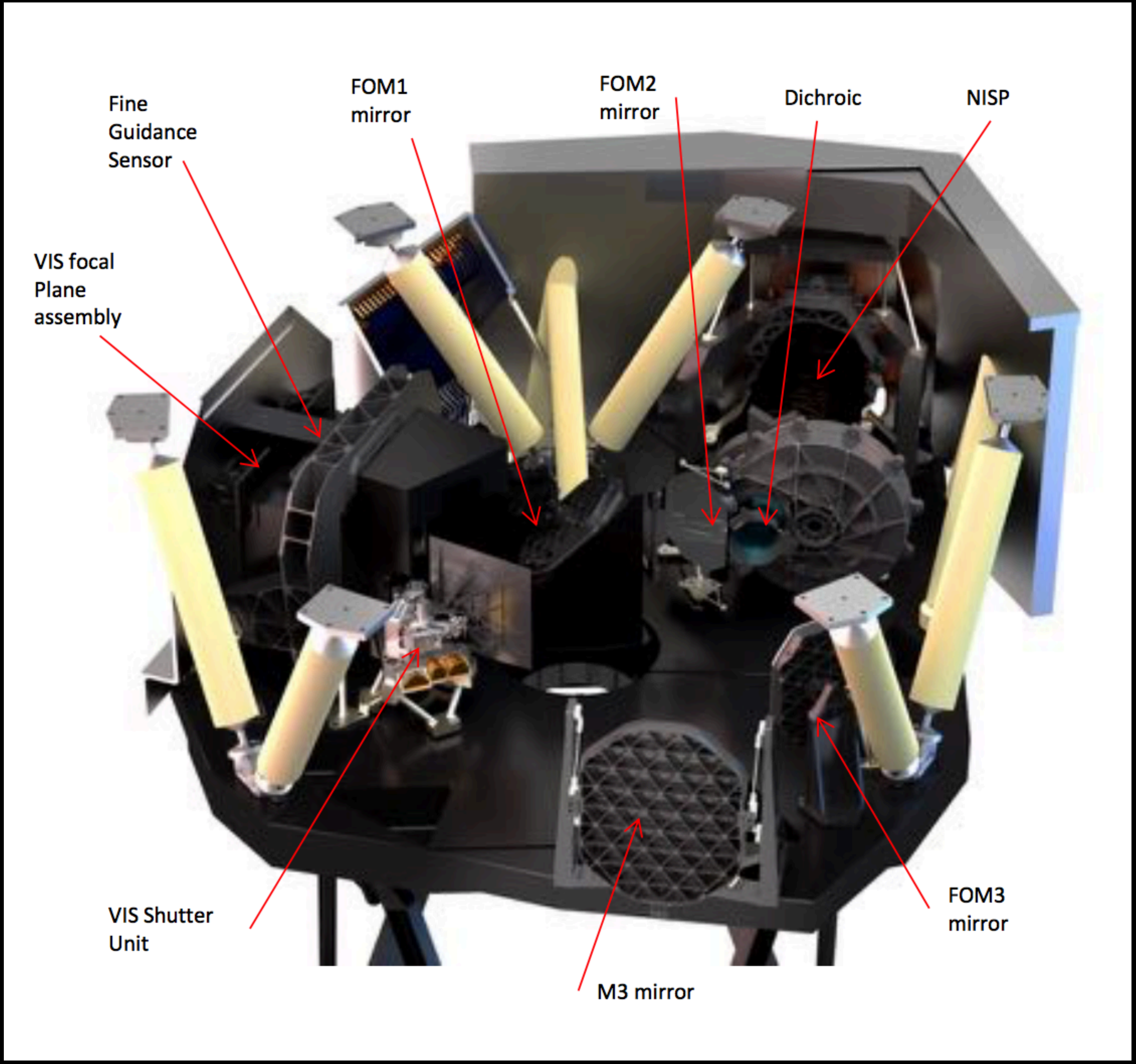
the detector instruments

- VIS CCDs: built by e2v in the UK, tested at MSSL

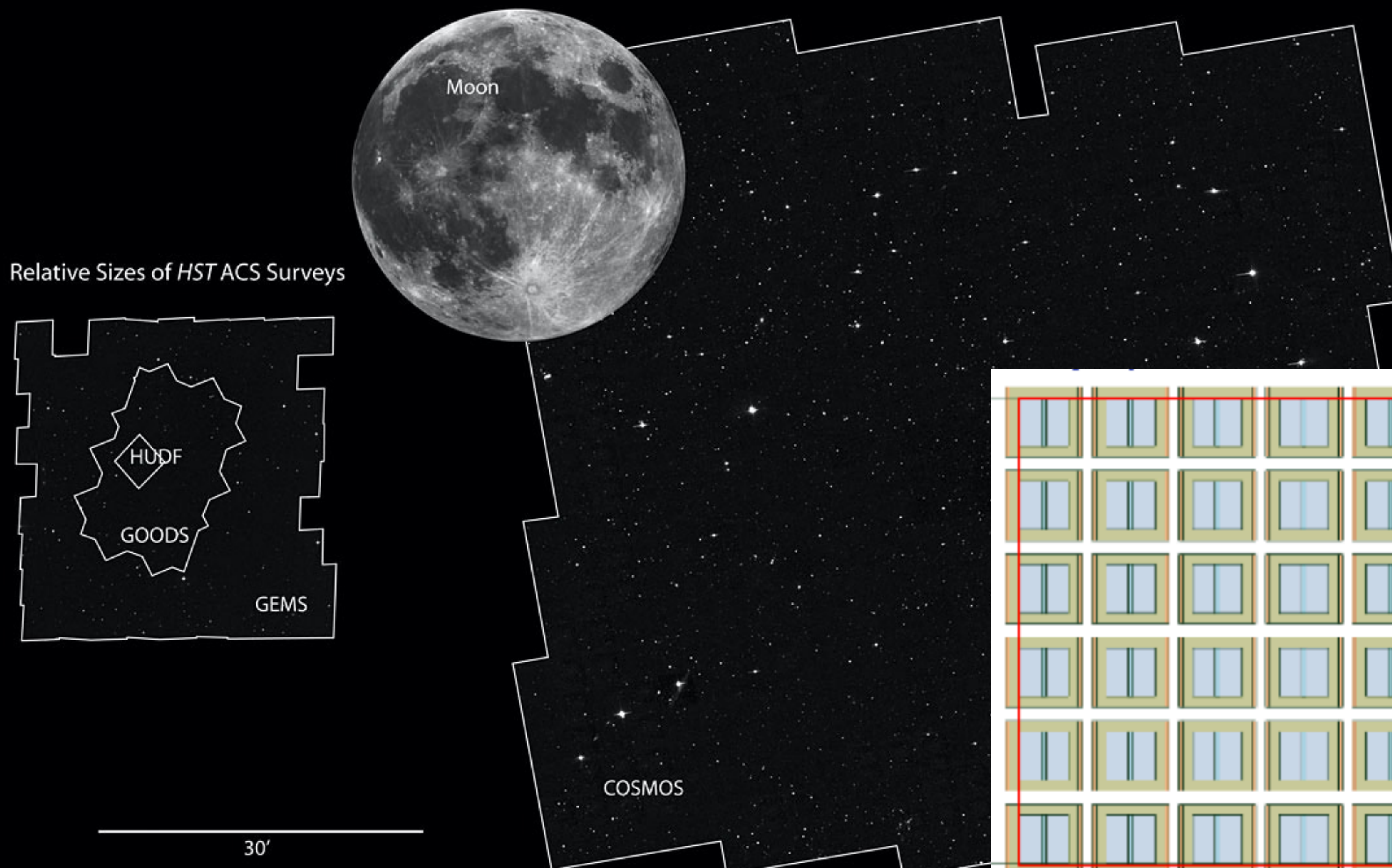


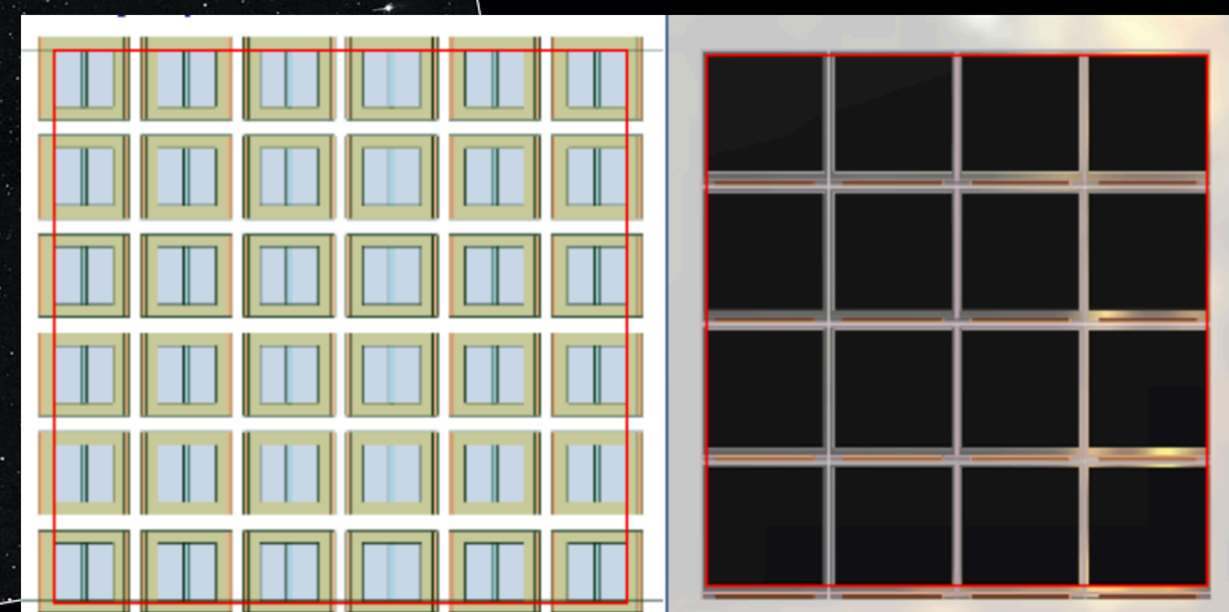
- NISP IR detectors: built by Teledyne, tested at JPL+Goddard, USA

Euclid Focal Plane



Euclid Footprint





	“VIS”	“NISP”
Detectors	36 4096×4132	16 2040x2040
Pixel size	0.1”	0.3”
Dispersion	-	13.4 A/pixel

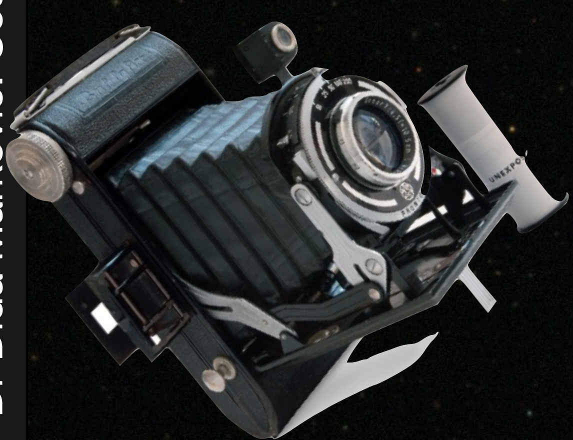
Euclid VIS

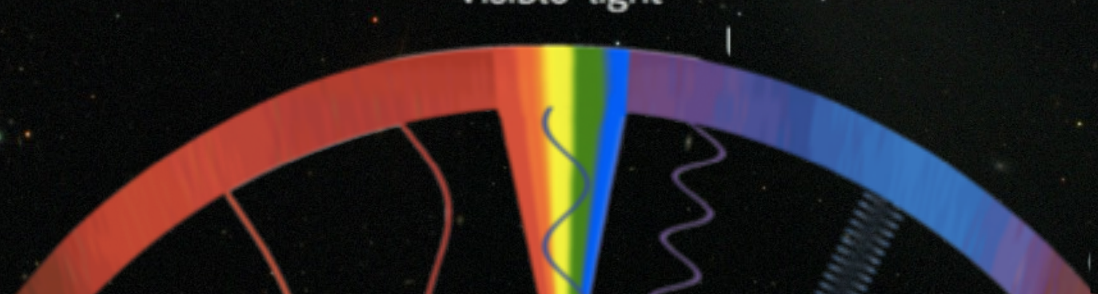
Simulation

- Shapes + Photo-z : **1.5x10⁹** galaxies
- Spectroscopic redshifts: **2.0x10⁷** galaxies

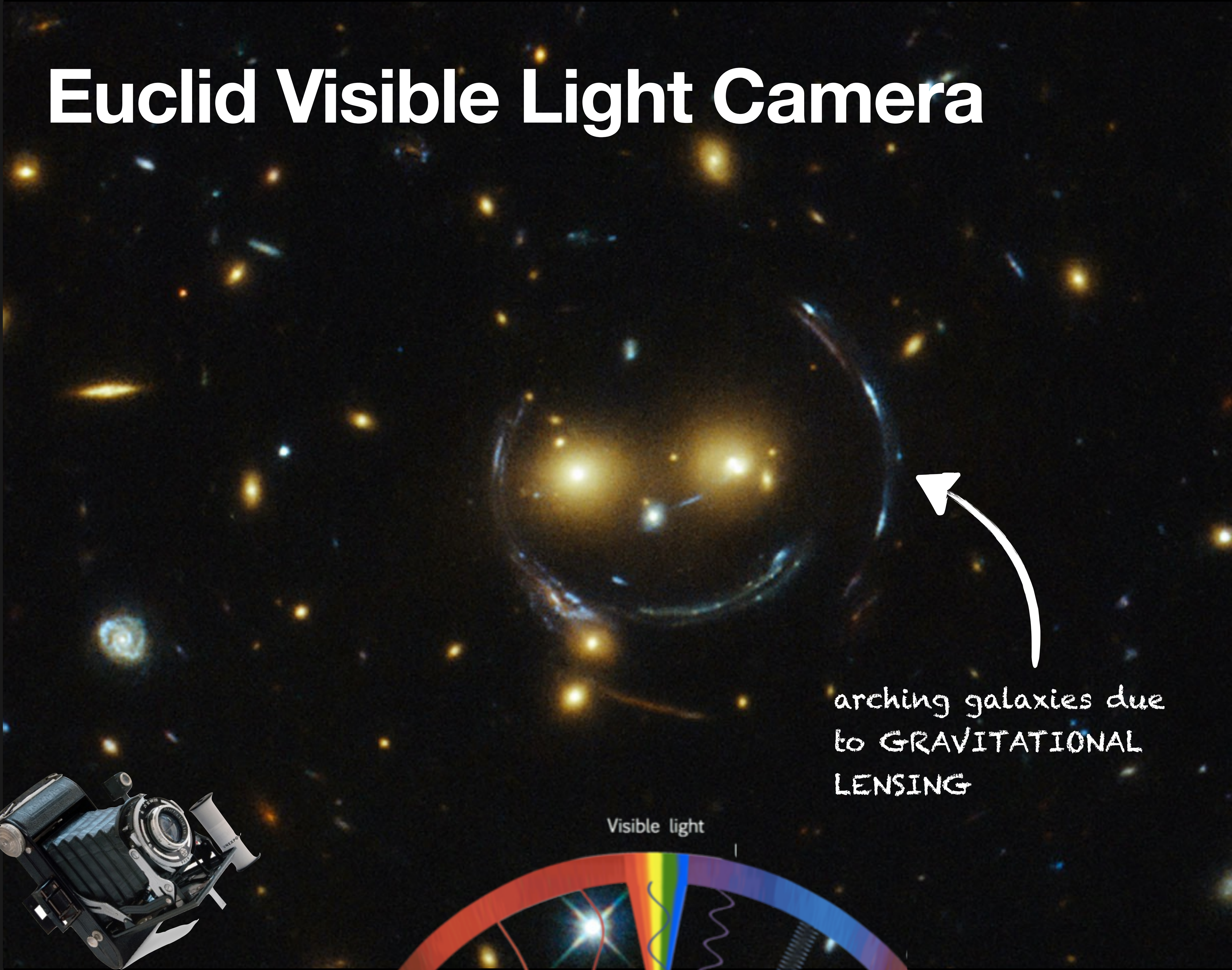
H. J. McCracken and OU-VIS team

Euclid Visible Light Camera





Euclid Visible Light Camera



Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Gravitational Lensing:

Bending Light Paths

Added to handout - not presented in lecture.

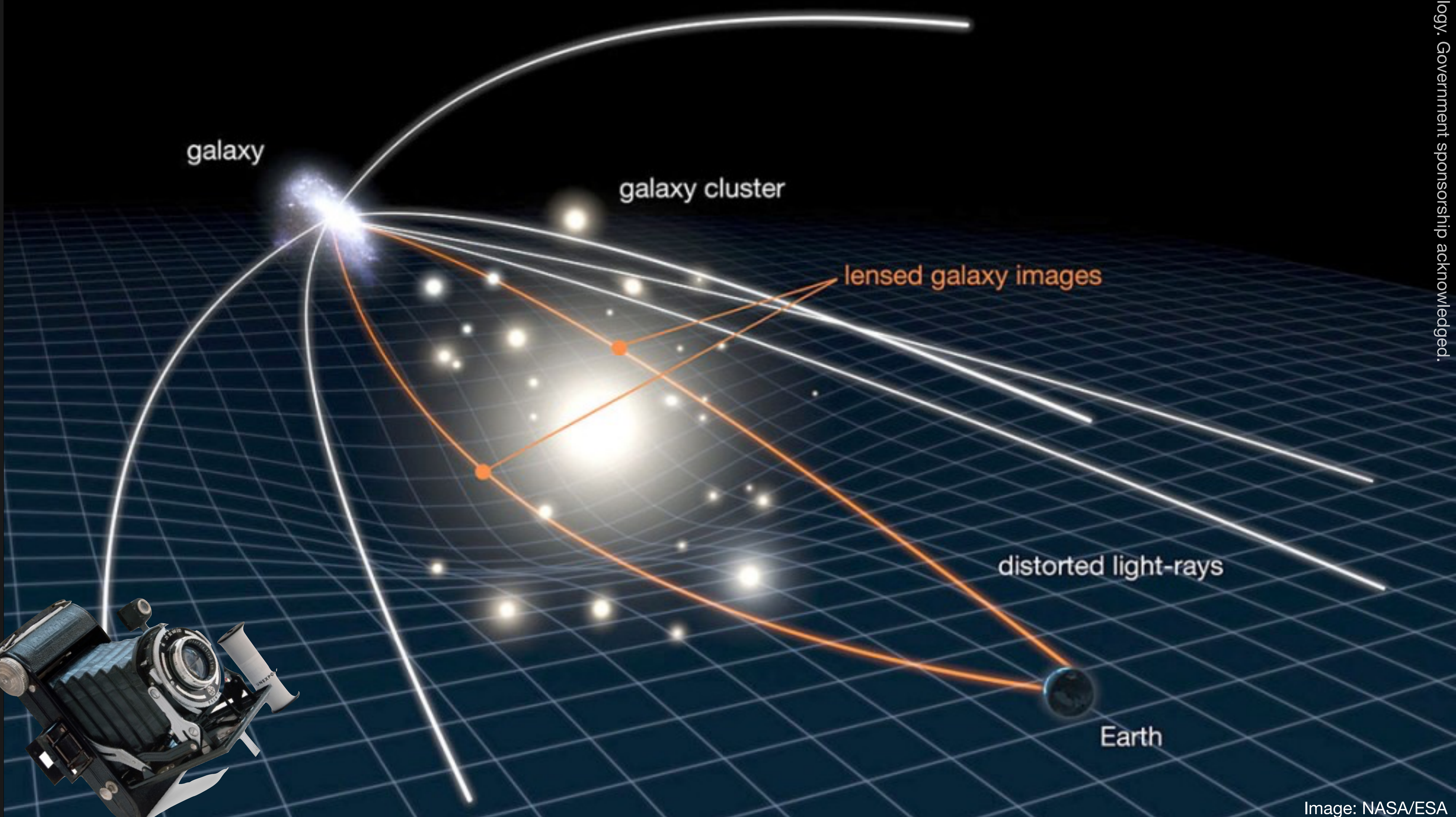
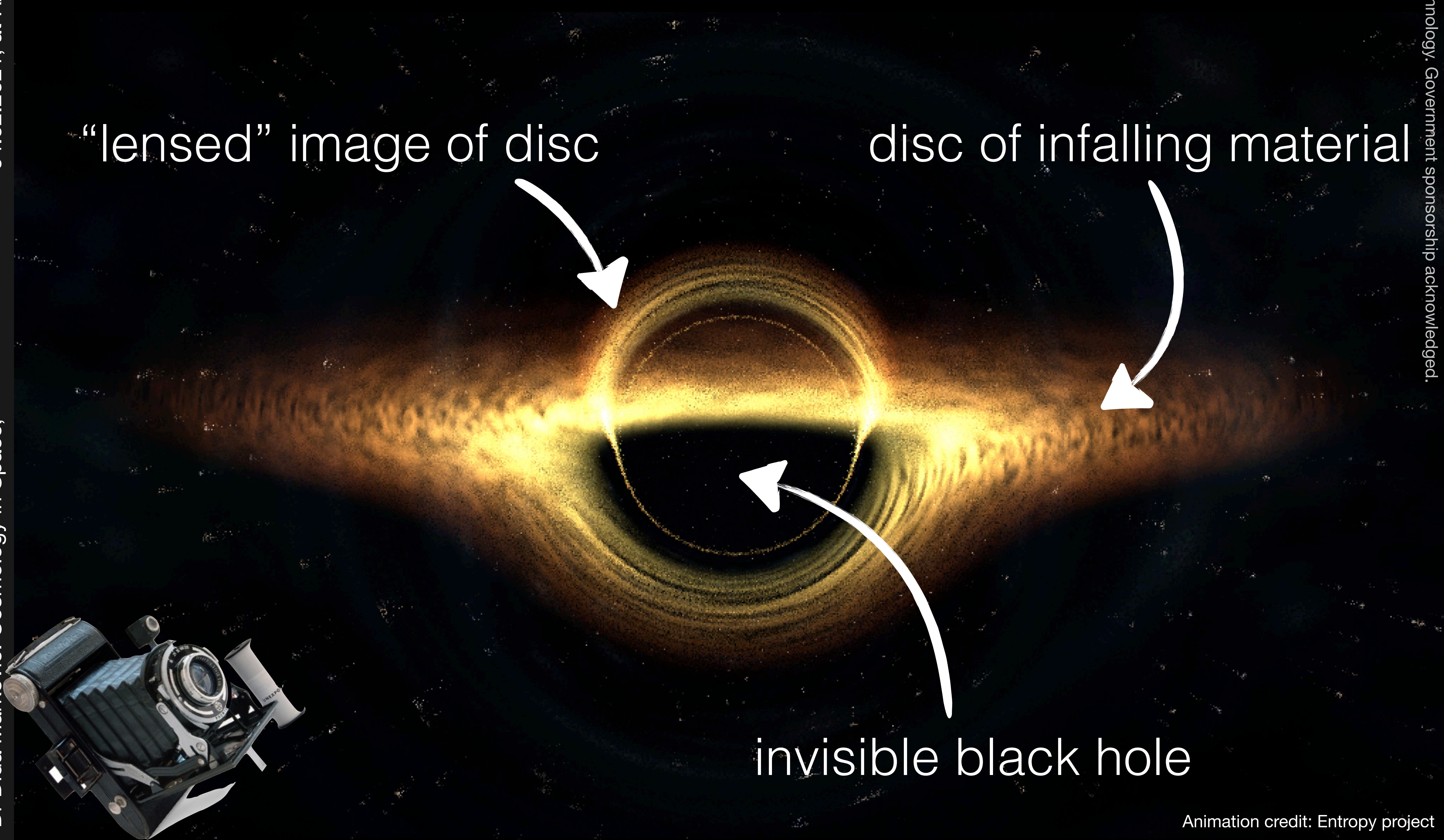


Image: NASA/ESA

Strong Gravitational Lensing:

Black Hole Eddition

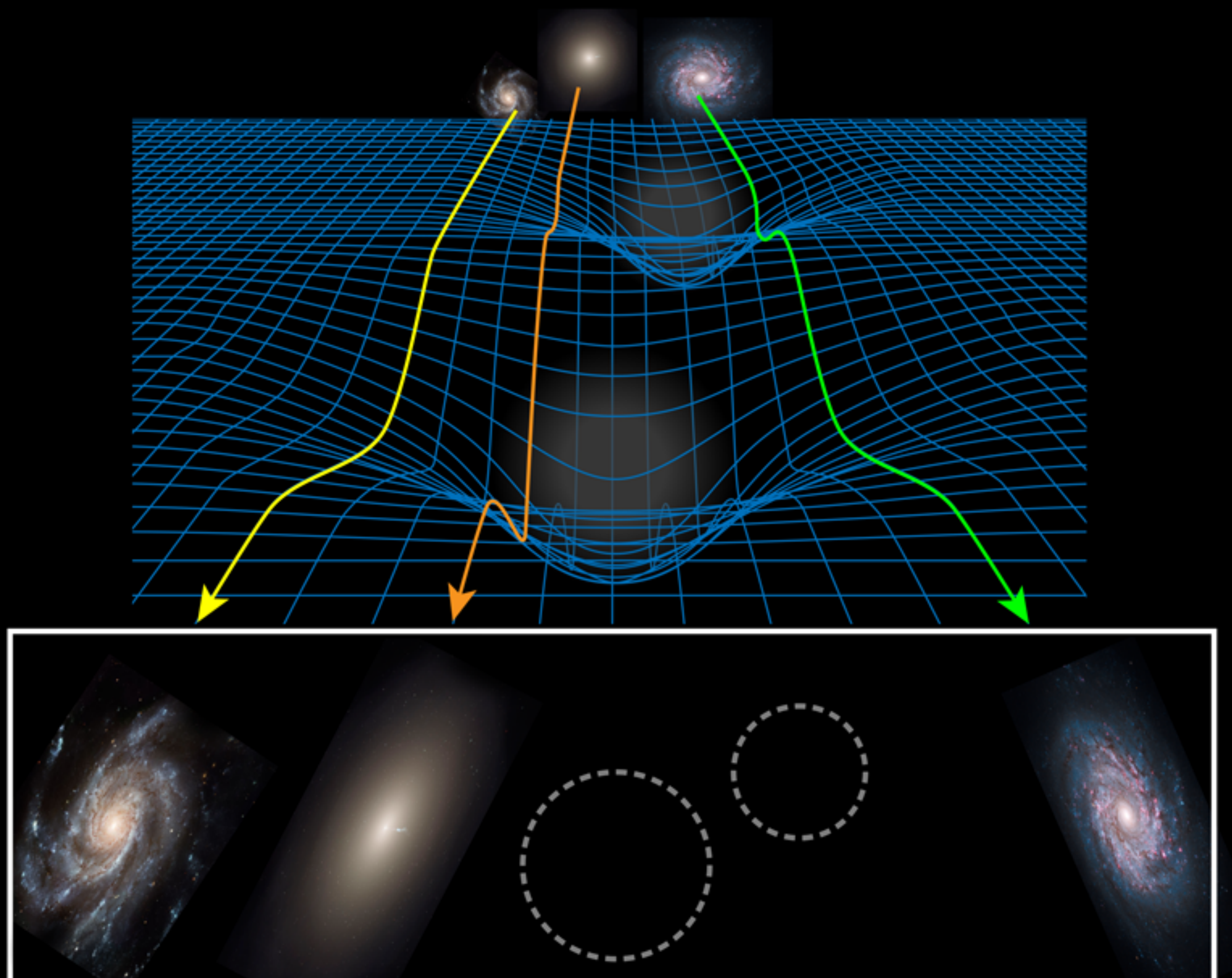


Animation credit: Entropy project

Credit: APS/Alan Stonebraker; galaxy images from STScI/AURA, NASA, ESA, and the Hubble Heritage Team

Gravitational Lensing:

Bending Light Paths



Weak Gravitational Lensing:

Dark Matter Edition

Added to handout - not presented in lecture.

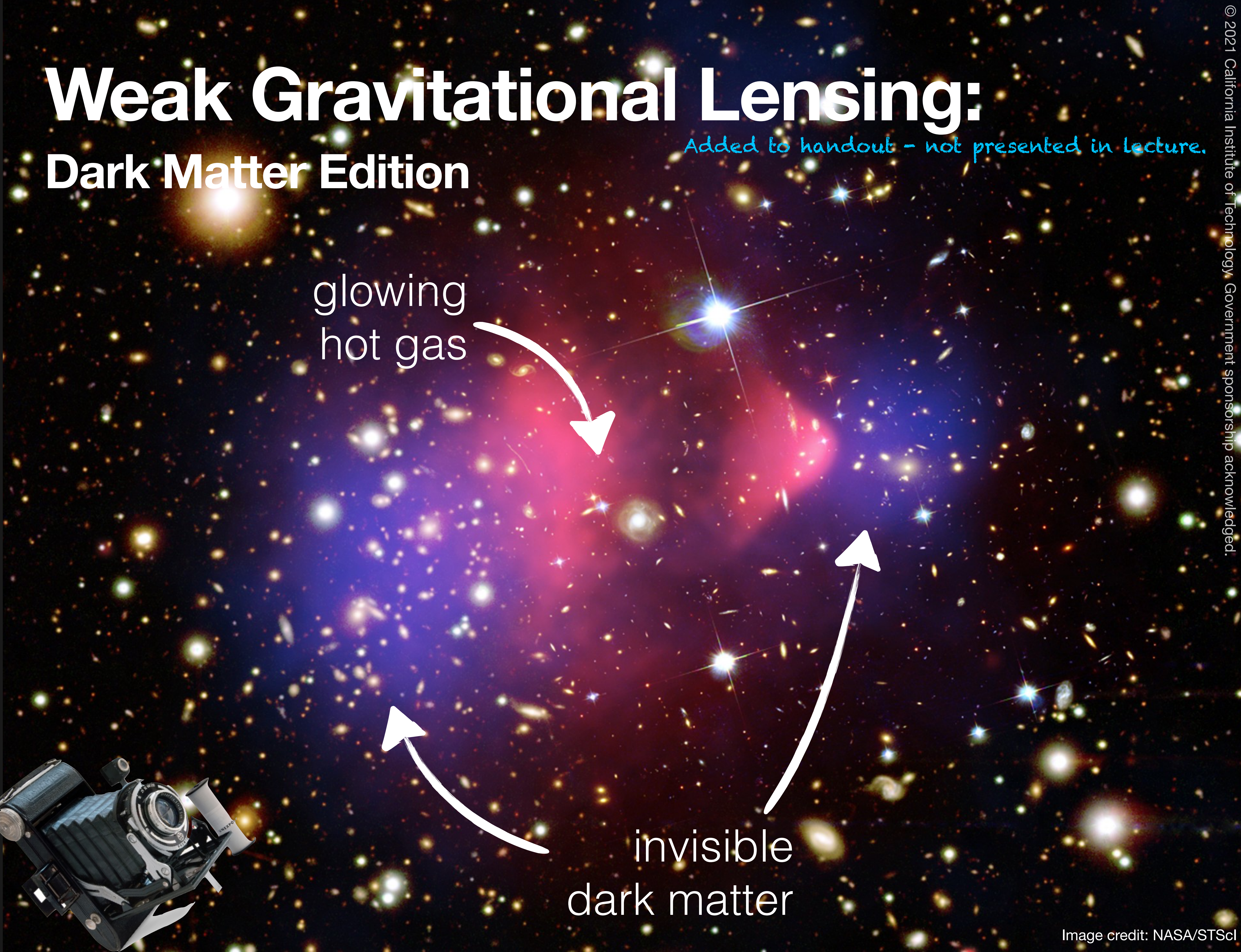
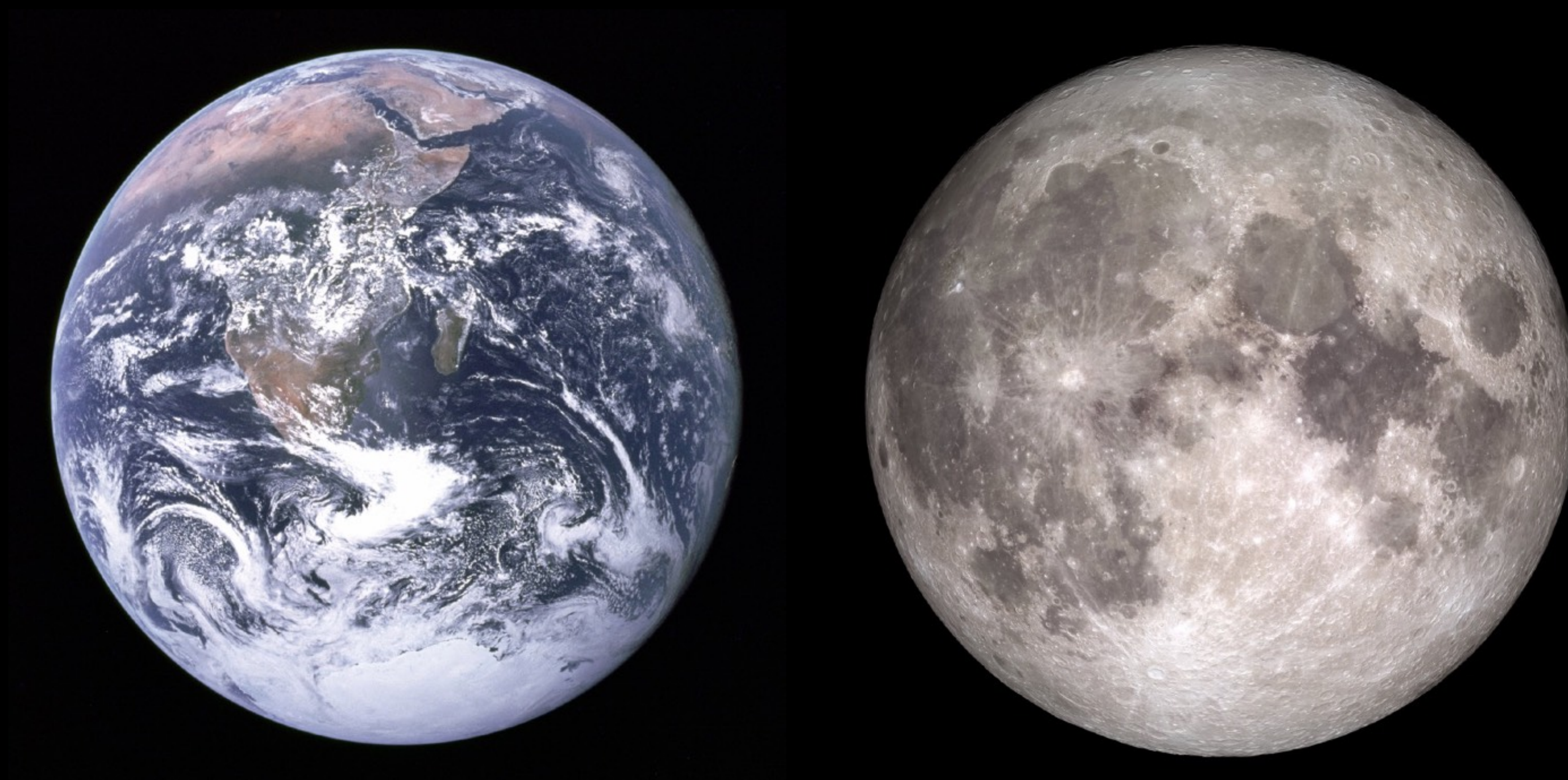


Image credit: NASA/STScI

Gravitational Lensing:

Bending Light Paths

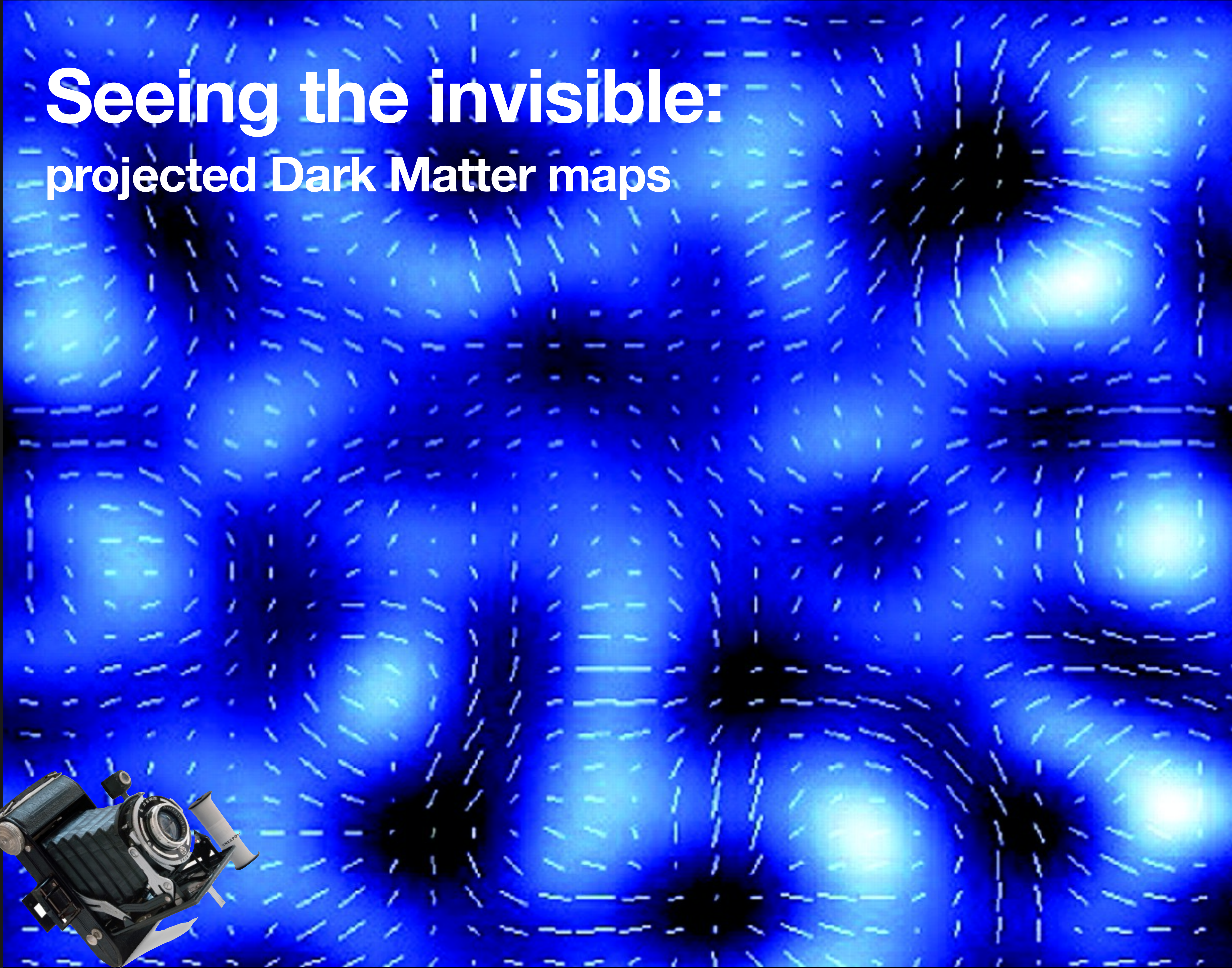
Added to handout - not presented in lecture.



- average shear distortion equivalent to difference in ellipticity between Earth and Moon
- VIS imaging allows shape measurements for 30-40 gals/arcmin^2

Seeing the invisible:

projected Dark Matter maps



Dr Dida Marković: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Seeing the invisible:
projected Dark Matter maps

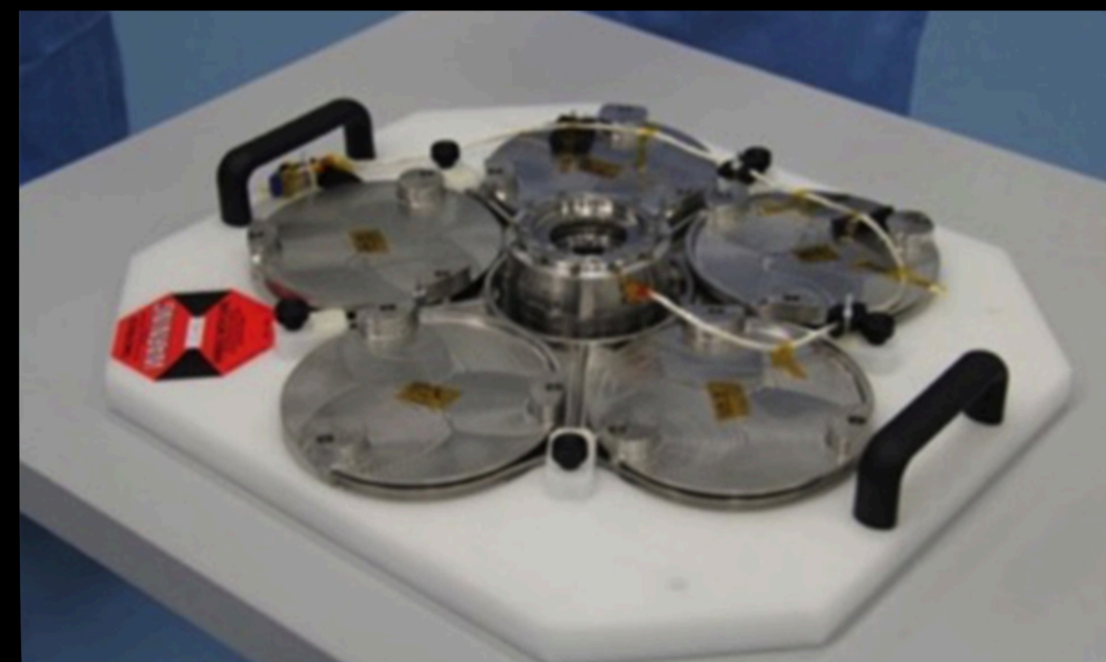
Dr Dida Markovič: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Euclid NISP

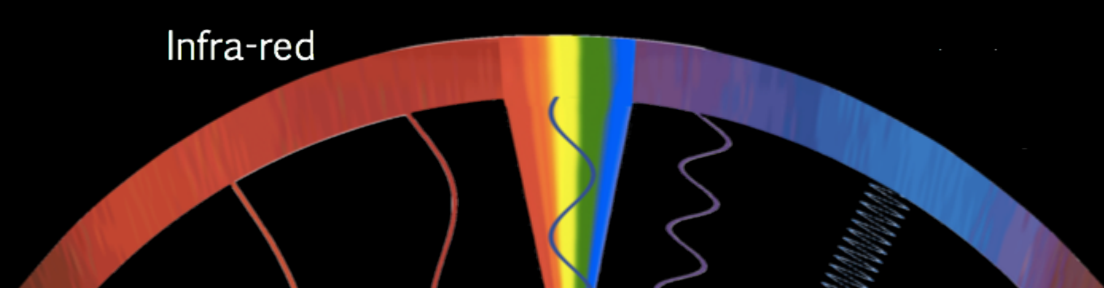
@EuclidNISP

Filter wheel: Y, J, H

grism wheel: red 0, 90, 180, blue 0



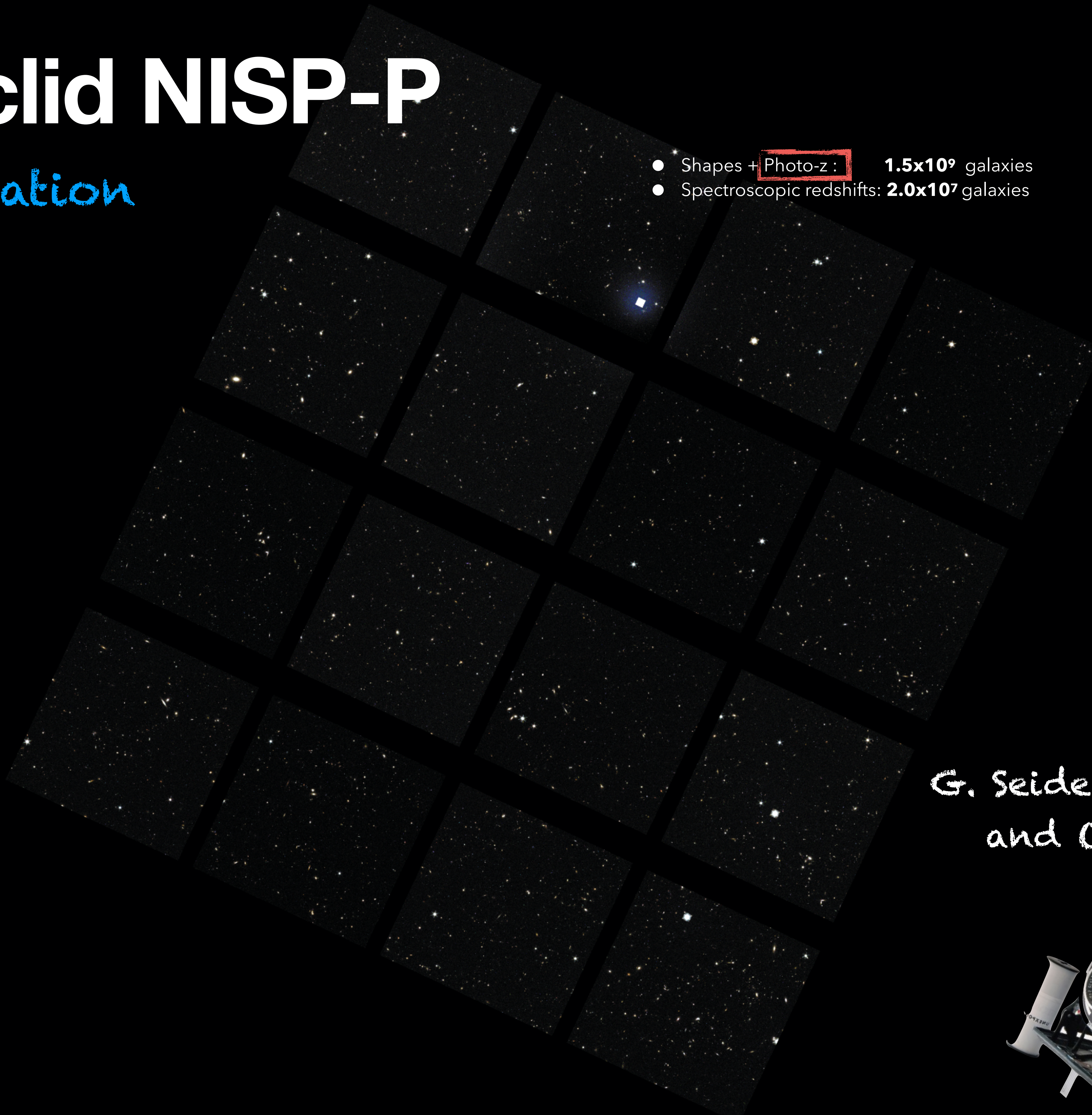
	VIS	Y	J	H	GRISM
Wide	24.5	24	24	24	$2\text{x}10^{-16}$ erg/s/cm^2
Deep	26.5	26	26	26	$2\text{x}10^{-17}$ erg/s/cm^2



Euclid NISP-P

Simulation

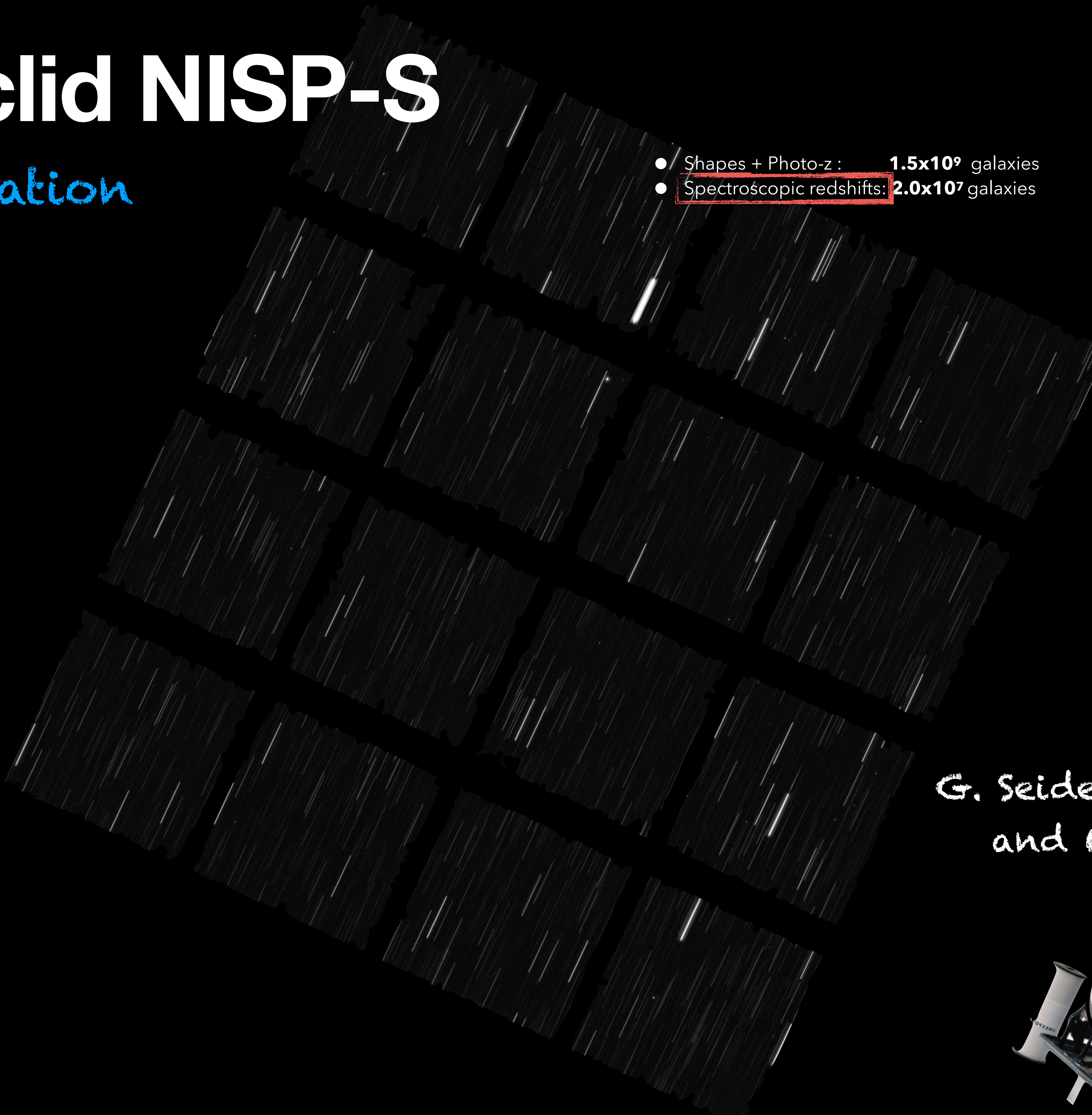
- Shapes + Photo-z : **1.5x10⁹** galaxies
- Spectroscopic redshifts: **2.0x10⁷** galaxies



G. Seidel, S. Serrano and OU-SIM team

Euclid NISP-S

Simulation

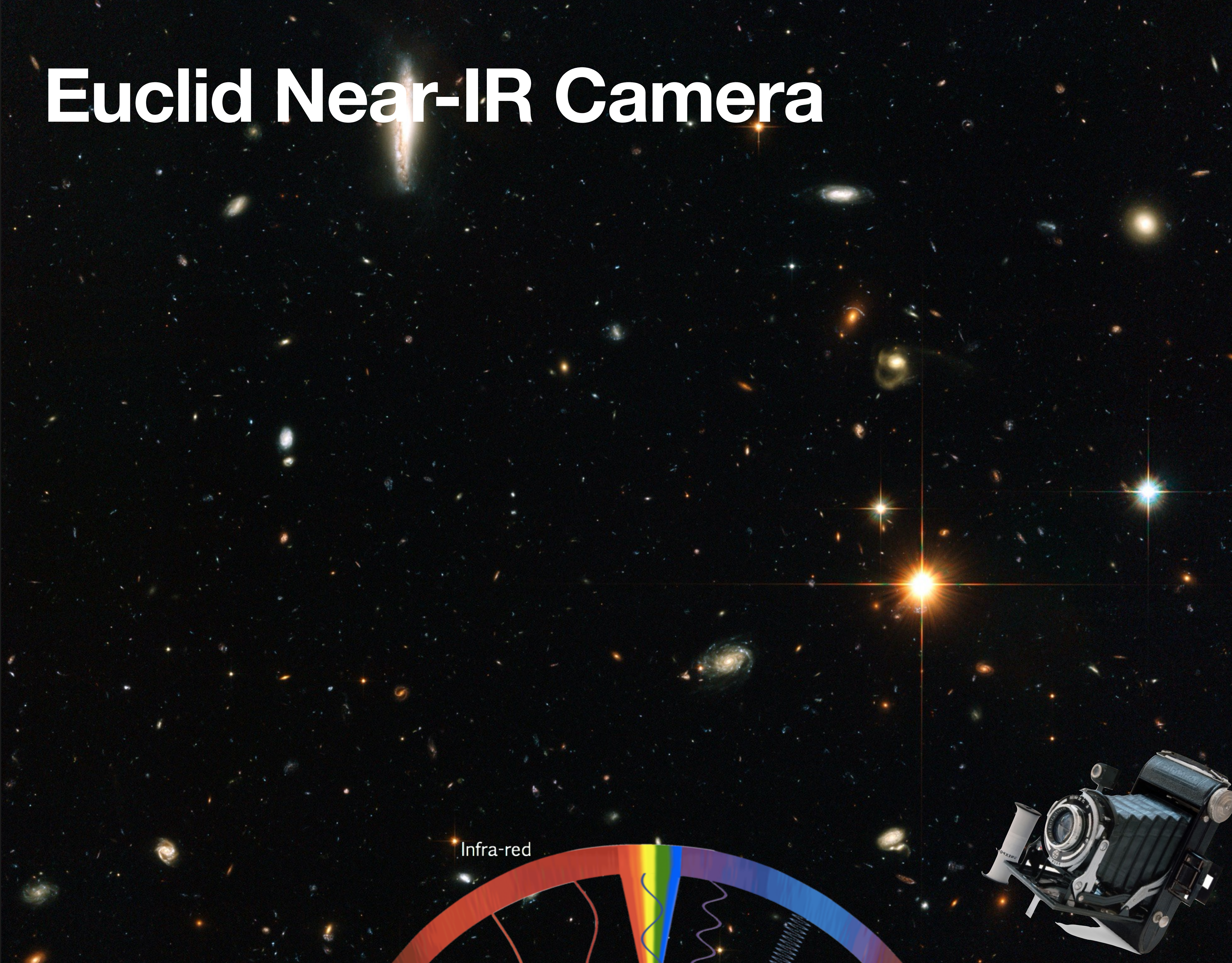


- Shapes + Photo-z : **$1.5\text{x}10^9$** galaxies
- Spectroscopic redshifts: **$2.0\text{x}10^7$** galaxies

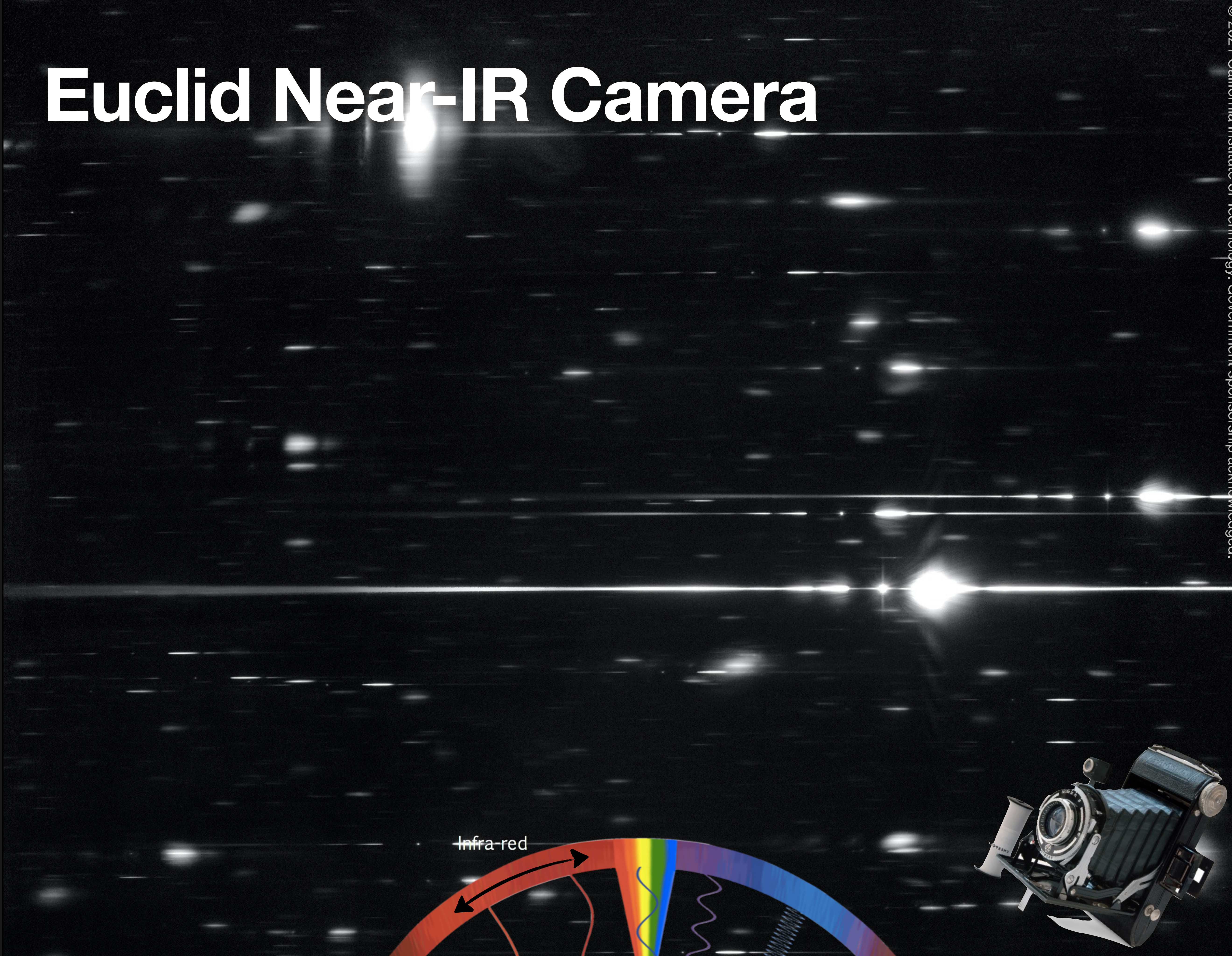
G. Seidel, S. Serrano and OU-SIM team

Dr Dida Marković: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Euclid Near-IR Camera

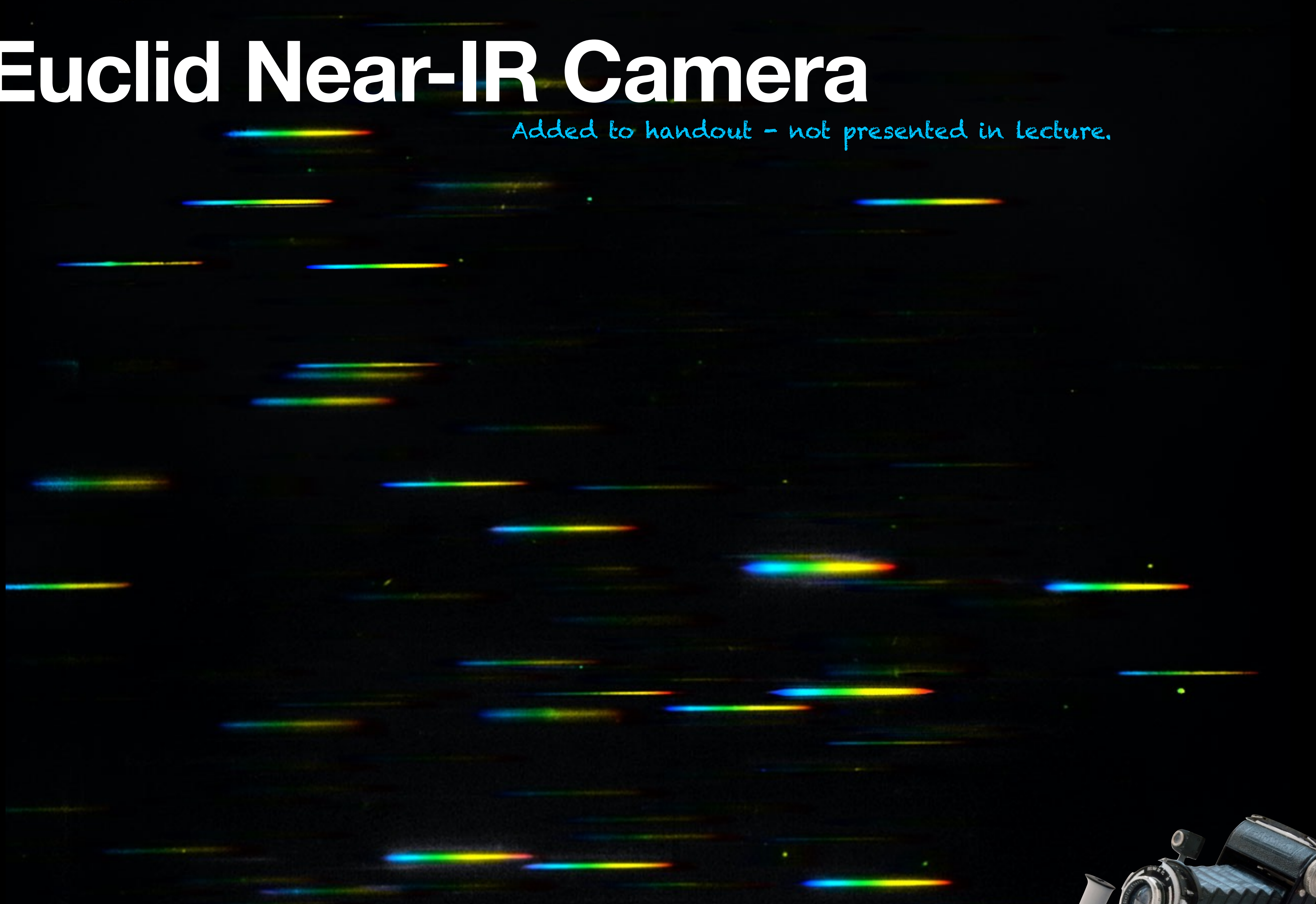


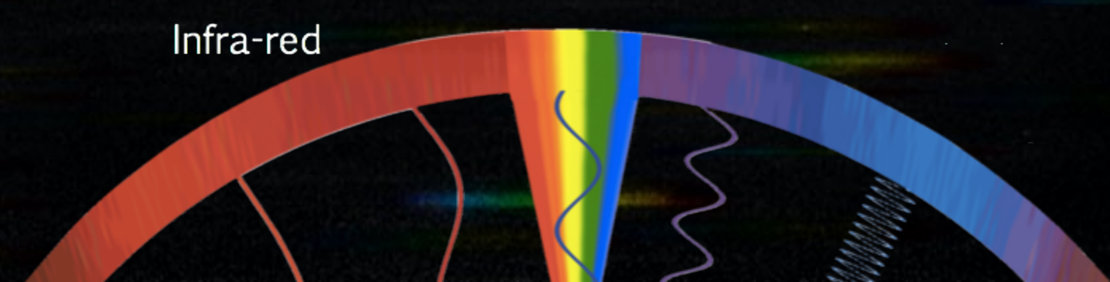
Euclid Near-IR Camera



Euclid Near-IR Camera

Added to handout – not presented in lecture.



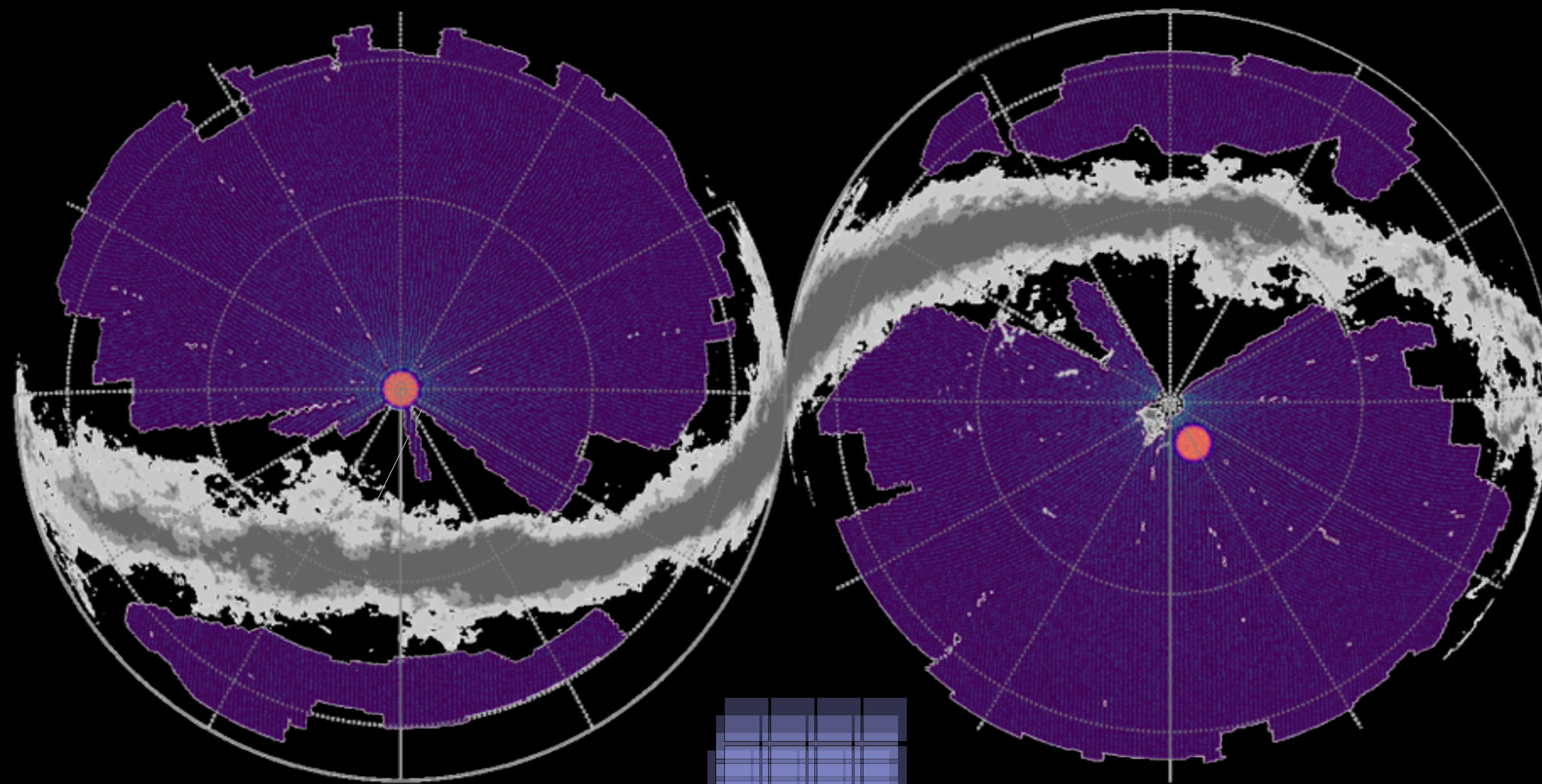


Euclid Survey

- wide survey: 15,000 deg^2
- deep survey: 40 deg^2

- step-and-stare
- 4 dither pointings

- Shapes + Photo-z : **1.5x10^9** galaxies
- Spectroscopic redshifts: **2.6x10^7** galaxies



plot from Roberto Scaramella (mission scientist)

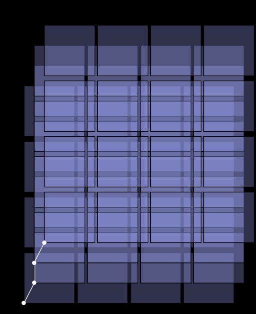
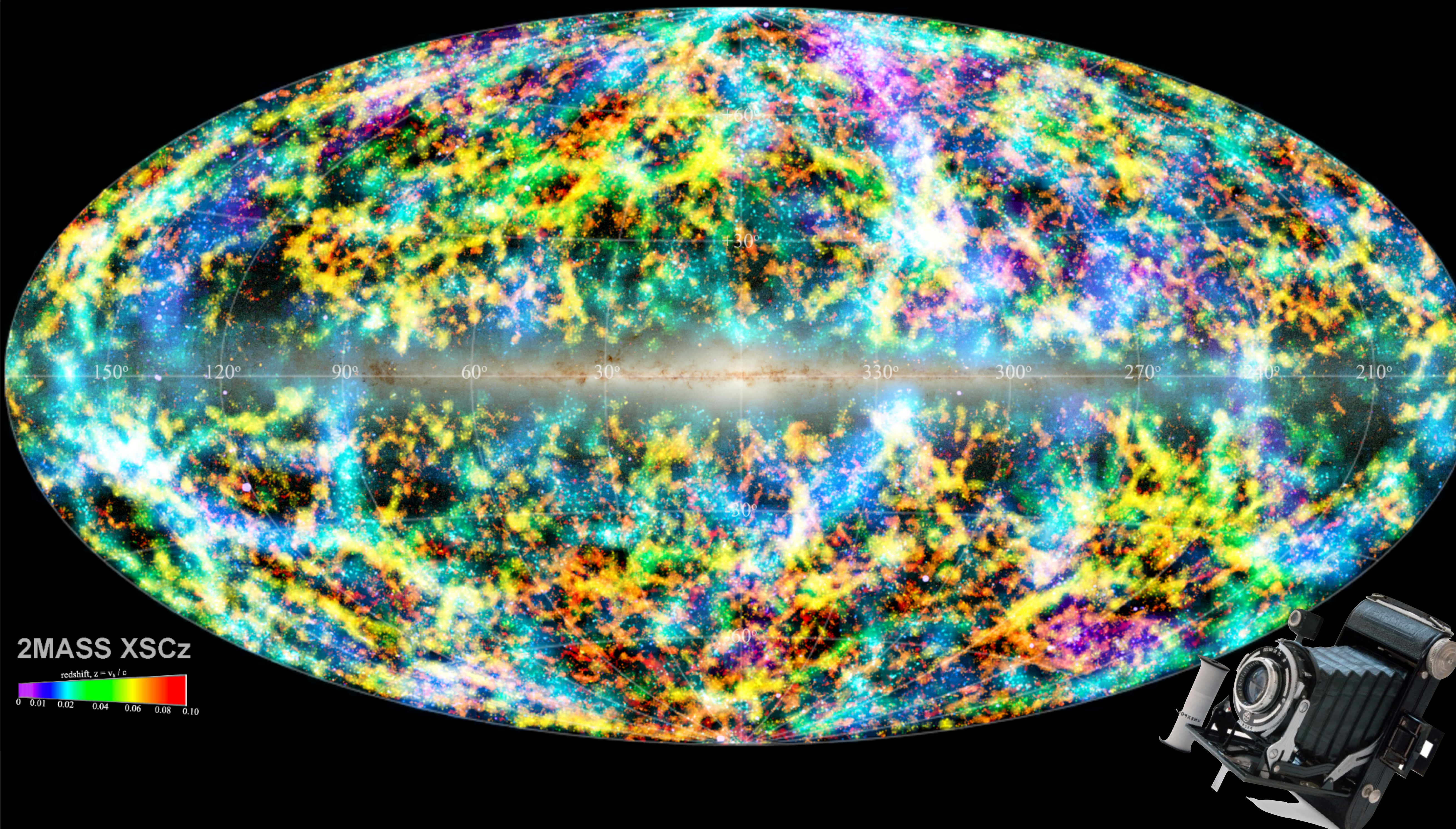


illustration of dithering (in reality covers chip gaps)

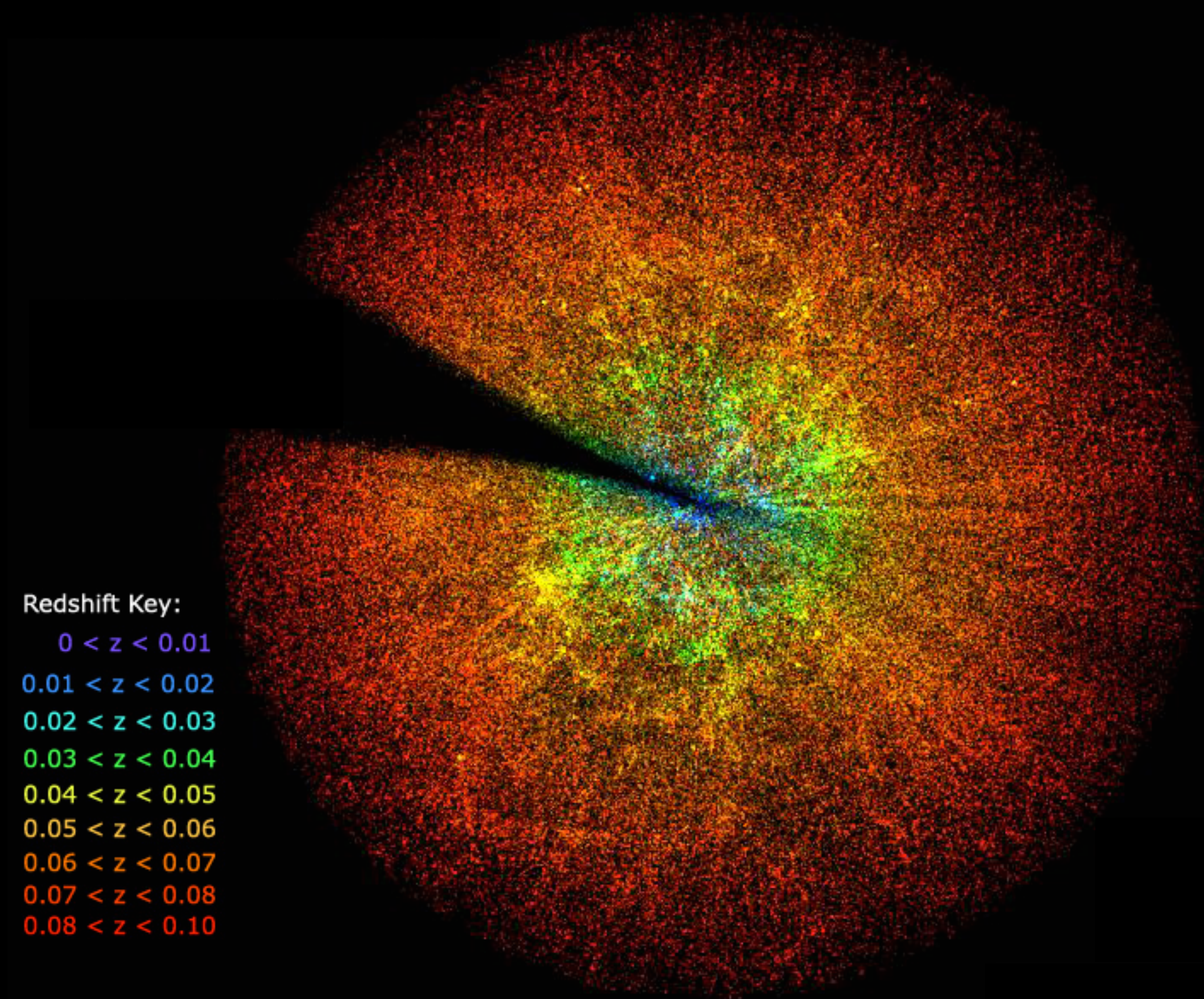
Seeing the invisible:

Redshift



Dr Dida Marković: Cosmology in Space, 04.02.2021, at RAeS Hamburg (on Zoom)

Redshift in our **expanding universe**

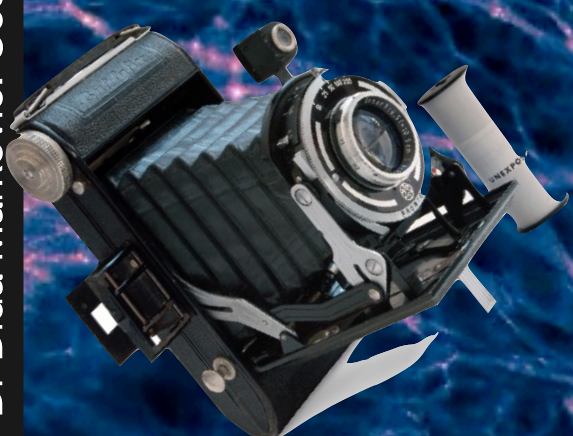


Seeing the invisible:

The Cosmic Dark Matter Web

Biggest maps of galaxies in the universe are coming up over the next decade.

Contain clues about dark matter, dark energy, the beginning of time…



Animation credit: Illustris SImulation

Summary

- Messengers: photons, neutrinos, GWs.
- Photos of different wavelengths carry all kinds of information.
- Distances are challenging, but informative!
- Discoveries unexpected at every step:
  - Einstein wanted a static universe
  - we thought we could see all kinds of matter
  - in the 20th century, deceleration was expected
- The universe is expanding.
- The expansion is accelerating.
- Most matter is dark. Most of the stuff in the universe is invisible.
- Many ground-based and space-based experiments to come in the next decade.

This is a golden age of cosmology.

Image credit: Hubble Space Telescope