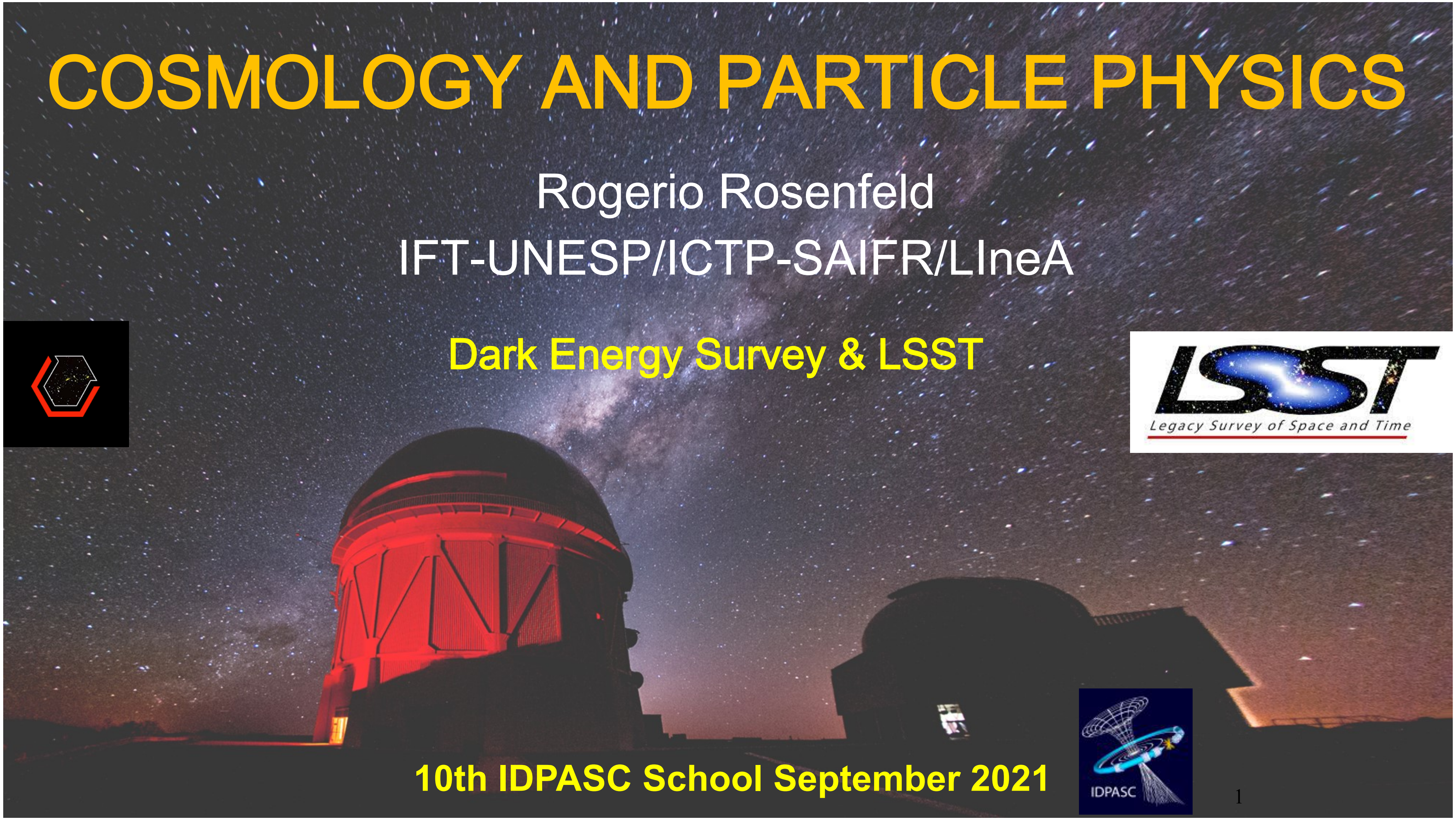

COSMOLOGY AND PARTICLE PHYSICS

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IFT-UNESP/ICTP-SAIFR/LIneA

Dark Energy Survey & LSST

Legacy Survey of Space and Time

IDPASC

10th IDPASC School September 2021

Three lectures on Cosmology and Particle Physcics

Lecture I: Dynamics of the average Universe

Lecture II: Distances and thermal history

➡ Lecture III: Neutrinos in cosmology

Plan for Lecture III:

III.1 – Preliminaries from Particle Physics

III.2 – Neutrino decoupling and temperature

III.3 – Neutrino abundance and N_{eff}

III.4 – Neutrinos and the growth of structure

III.5 – BSM neutrino physics and the Hubble tension

CONCLUSIONS

III.1 – Preliminaries from Particle Physics

In the Standard Model (SM) there are 3 massless neutrinos, ν_e, ν_μ , ν_τ

Only the left-handed neutrinos have weak interactions and are included in SM.

Neutrino oscillations experiments have determined that neutrinos are NOT massless – SM is incomplete!

Mass eigenstates are denoted by m_1, m_2 and m_3 (superposition of flavor eigenstates)

We still do not know whether neutrinos are Dirac or Majorana particles (neutrinoless double beta decay experiments)

Right-handed neutrinos (if they exist) are singlet under SM interactions – no interactions – also called sterile neutrinos.

Oscillation experiments are sensitive only to the squared-mass differences:

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Data shows a hierarchy in the mass diferences:

$$\Delta m_{21} << |\Delta m_{31}| \sim |\Delta m_{32}|$$

It is still an open question the ordering (or hierarchy) of the neutrino mass eigenstates:

Global analysis of oscillation data (1811.05487) in eV^2 :

$$\Delta m^2_{21} = 7.39^{+0.21}_{-0.20}\times10^{-5};\ \ \Delta m^2_{31} = 2.525^{+0.033}_{-0.032}\times10^{-3}(\mathrm{NH});\ \ \Delta m^2_{32} = -2.512^{+0.034}_{-0.032}\times10^{-3}(\mathrm{IH})$$

Cosmology is sensitive to the sum of neutrino masses:

$$\Sigma = \sum_{i=1}^{3} m_i$$

Easy to show that:

$$\sum m_\nu = m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} \qquad \text{(NH)},$$

$$\sum m_\nu = m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} \qquad \text{(IH)}.$$

where m_0 is the lightest mass state ($m_0 = m_1$ for NH and $m_0 = m_3$ for IH)

Taking the lightest mass state to be zero one obtains a lower bound on the sum of neutrino masses (1907.12598):

$$\sum > 58.85^{+0.45}_{-0.44}\ meV$$ Normal ordering

$$\sum > 100^{+0.70}_{-0.67}\ meV$$ Inverse ordering

Hence, oscillation experiments gives a firm lower bound on the sum of neutrino masses:

$\Sigma > 0.06$ eV

Cosmology can determine the mass ordering of neutrinos if it can determine that $\Sigma < 0.1$ eV! More later...

Study of the end of the electron energy spectra in tritium beta decay:

“scale of neutrino mass” m_ν <1.1 eV (90%CL) - 1909.06048

III.2 – Neutrino decoupling and temperature

Different particles are in thermal equilibrium when they can interact efficiently. There are 2 typical rates that can be compared:

• rate of particle interactions:

$$\Gamma(T) = n\langle\sigma v\rangle$$

Number density

Thermal averaged cross section x velocity

• expansion rate of the Universe:

$$H(T)$$

When

$$\Gamma(T) \gg H(T)$$

particles are in thermal equilibrium.

As a first estimate particles decouple when $\Gamma(T) \sim H(T)$

More precise estimate requires solving a Boltzmann equation .

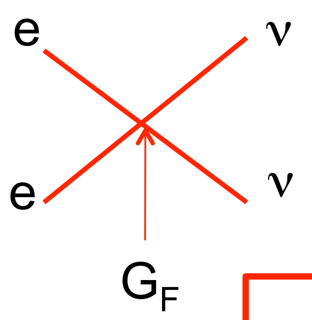
Decoupling of neutrinos from the thermal bath

Weak interactions:

$$\nu_e + \bar{\nu}_e \leftrightarrow e^+ + e^-$$

$$e^- + \bar{\nu}_e \leftrightarrow e^- + \bar{\nu}_e$$

Low energy cross section (4-Fermi interaction):



$G_F = 10^{-5}$ GeV^{-2}: Fermi constant

$$\sigma \sim G_F^2 T^2;\ n_\nu \sim T^3 \Rightarrow \Gamma_\nu(T) \sim G_F^2 T^5$$

$$H(T) \sim T^2/M_{\rm Pl}$$

$$T_{\nu,\rm dec} = \left(\frac{1}{G_F^2 M_{\rm Pl}}\right)^{1/3} \sim 1\ \rm MeV$$

Neutrinos produced in the early universe decouple when the universe had a temperature of around 1 MeV and was only around 1 second old!

Neutrinos decouple while relativistic and are stable neutral particles –
hot dark matter

After decoupling the number of neutrinos does not change anymore –
their density decreases as a^3.

After decoupling from the termal bath they cool down as the universe expands ($T \alpha 1/a$) but do not need to share the same temperature with photons.

In fact, when the threshold for the electron mass is crossed at around m_e = 0.5 MeV the photons get heated up (see previous lecture).

Temperature of cosmic neutrino background is then smaller than cosmic photon backround today.

It can be computed from entropy conservation:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.95\,K = 1.7 \times 10^{-4}\ \text{eV}$$

From neutrino oscillation data at least 2 neutrinos are nonrelativistic today. They transition from relativistic to nonrelativistic during the history of the universe.

III.3 – Neutrino abundance after decoupling and N_{eff}

If neutrinos are relativistic (see previous lecture), after e^+e^- annihilation:

$$\rho_\nu = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\ \rho_\gamma$$

N_{eff} is used to describe extra (beyond photons) relativistic degrees of freedom.
In the SM, with 3 relativistic neutrinos: $N_{eff} = 3.045$ (arXiv:1606.06986)
(neutrinos were not completely decoupled at e+e- annih

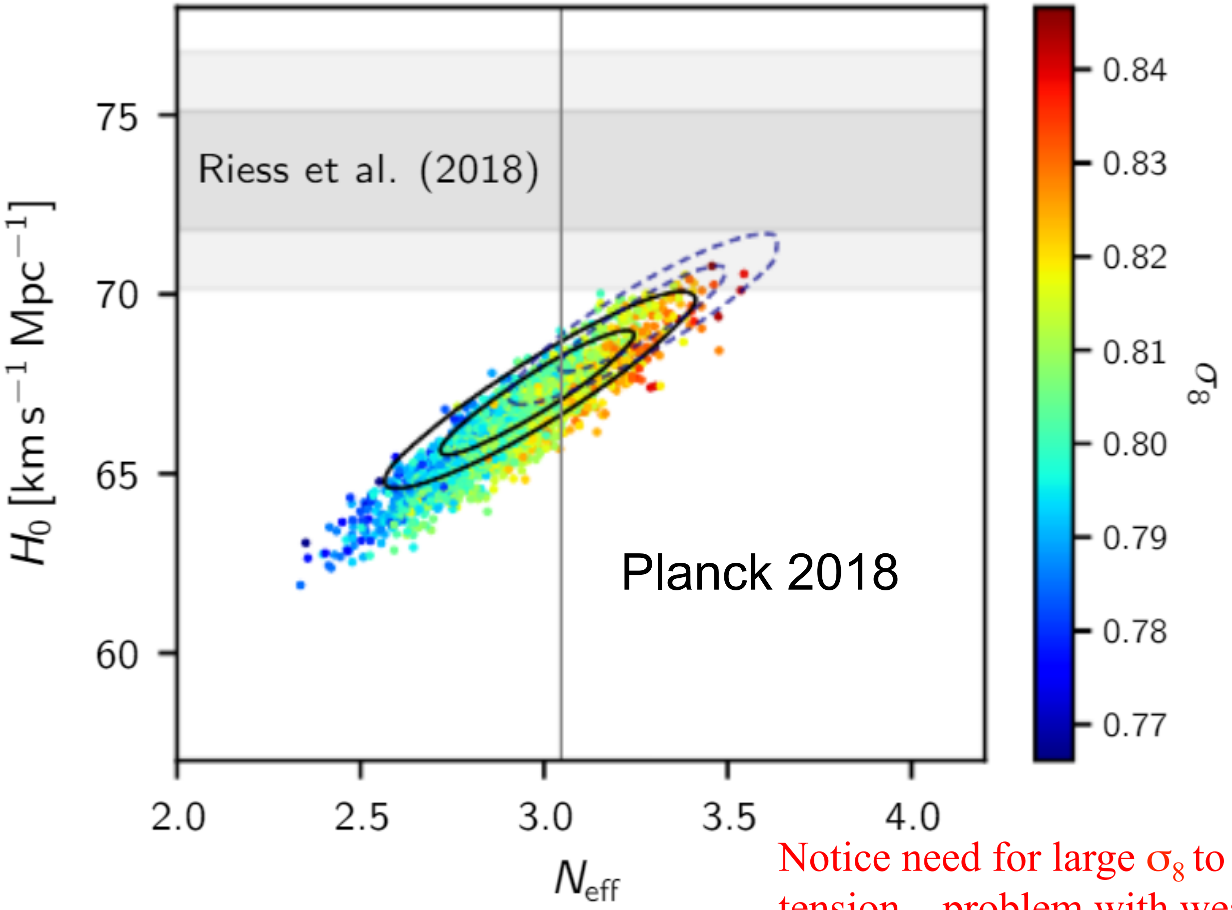
$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad (95\%, \text{TT,TE,EE+lowE+lensing+BAO})$$ Planck 2018

Additional relativistic degrees of freedom are called dark radiation.

Number of Neutrino Types PDG 2021

Number $N = 2.996 \pm 0.007$ (Standard Model fits to LEP-SLC data)

Degeneracy between H_0 and N_{eff} (see previous lecture)



Notice need for large σ_8 to alleviate Hubble tension – problem with weak lensing

Number density of neutrinos is comparable to photons:

$$n_\nu = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma = \frac{3}{11} n_\gamma$$

Number density of relic neutrinos today:

$$n_\gamma^{(0)} = 422\ \mathrm{cm}^{-3} \to n_\nu^{(0)} = 115\ \mathrm{cm}^{-3}$$

If relic neutrinos are non-relativistic today:

$$\rho_\nu^{(0)} = \sum_i m_{\nu,i} n_{\nu,i}^{(0)} \rightarrow \Omega_\nu^{(0)} = \frac{\sum_i m_{\nu,i}}{45\ eV}$$

Gerstein-Zeldovich (1967)
Cowsik-McClelland (1972)

$$\sum_i m_{\nu,i} < 45\ eV$$

We will see next that there are stronger upper bounds from the effects of neutrinos on the growth of structure.

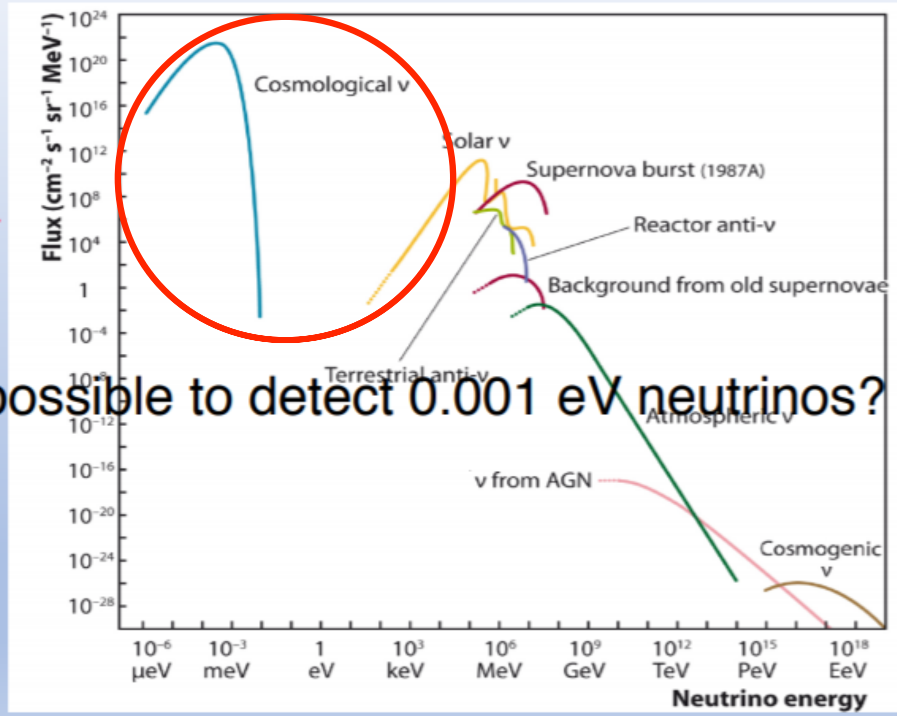
We know that $m_\nu < 1$ eV (KATRIN) and hence: $\Omega_\nu < 0.07$
Probably much smaller as we will see later from cosmology.

Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield
PTOLOMY

Neutrino flow

$T \approx 1.9\ K \Rightarrow p_\nu \approx 0.001\ eV$

$n \approx 56\ cm^{-3} \times 6$



Is it possible to detect 0.001 eV neutrinos?

Marcello Messina, ICHEP-2020

III.4 – Neutrinos and the growth of structure

Structure in the universe (such as galaxies) arise from the growth of the small perturbations generated by quantum fluctuations of the inflaton field.

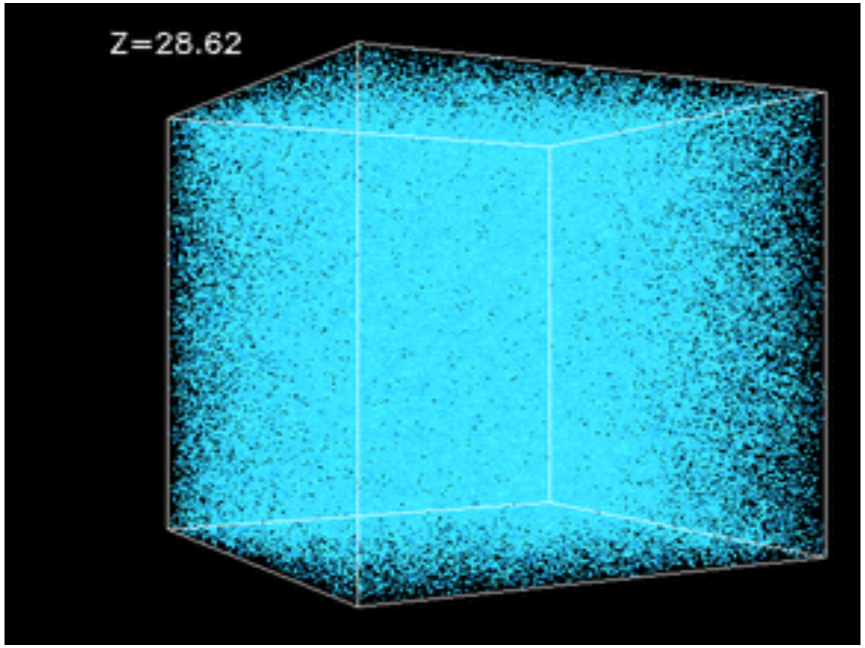
The growth is due to action of gravity and has to be studied in the context of GR taking into account EM interactions when necessary (baryons).

A linearization of GR can be used to study the growth of perturbations when they are small - this is done in codes such as:

CAMB - **Code for Anisotropies in the Microwave Background**
https://camb.info/
CLASS – **Cosmic Linear Anisotropy Solving System**
https://lesgourg.github.io/class_public/class.html

Nonlinear growth of large scale structure: N-body simulations

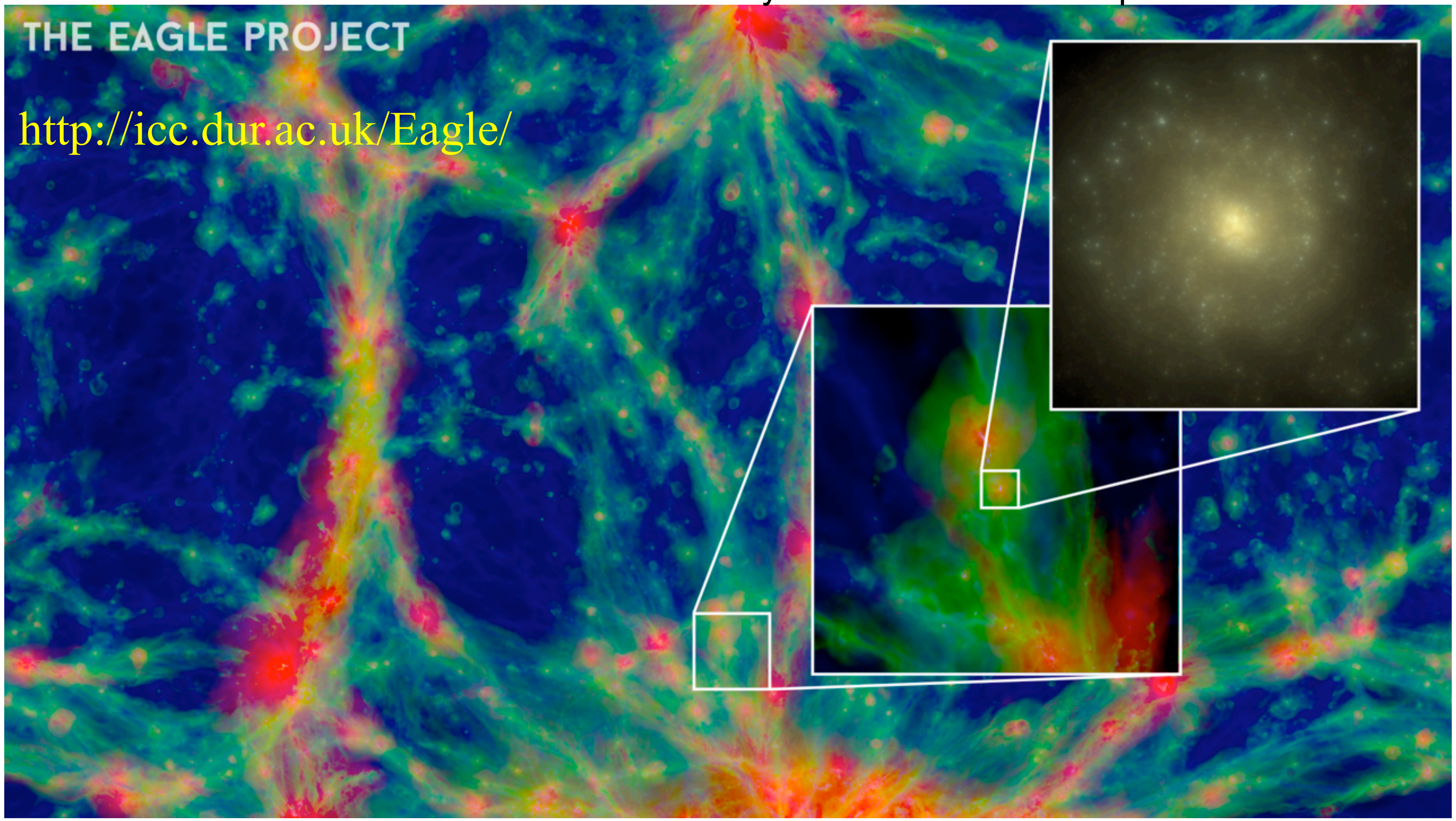
Universe in a box (A. Kravtsov)



http://cosmicweb.uchicago.edu/filaments.html

The movie illustrates the formation formation of clusters and large-scale filaments in the Cold Dark Matter model with dark energy. Evolution of structures in a 43 Mpc box from redshift of 30 to the present epoch . At the initial epoch (z=30), when the age of the Universe was less than 1% of its current age, distribution of matter appears to be uniform. As time goes on, the fluctuations grow resulting in a wealth of structures from the smallest bright clumps which have sizes and masses similar to those of galaxies to the dark large filaments.

The EAGLE simulation is one of the largest cosmological hydrodynamical simulations ever, using nearly 7 billion particles to model the physics.The image below is a slice through the simulation volume, with the intergalactic hot gas with T> 100,000K, and is contained with dark matter structures that host galaxies. Such hot gas can be detected in X-rays. The insets zoom into a galaxy like the Milky Way, showing first its gas, and then its beautiful stellar disc: it looks remarkably similar to observed spirals.



There are two main effects of neutrinos on the growth of structure:

- Neutrinos do contribute to nonrelativistic dark matter density today:

$\Omega_m = \Omega_{cdm} + \Omega_b + \Omega_\nu$

Can affect recente expansion rate.

- Free-streaming

Neutrinos decouple while relativistic. They free-stream until becoming non-relativistic. They affect structure formation by smoothing out density perturbations.

The scale below which this smoothing occurs is called free-streaming length:

$$\lambda_{fs} \approx 350\left(\Omega_m h^2\right)^{-1/2}\left(\frac{m_\nu}{1\ \mathrm{eV}}\right)\ \mathrm{Mpc}$$

The growth of matter perturbations is suppressed at scales smaller than λ_{fs} due to the effect of the time neutrinos were relativistic particles.

This is the reason neutrinos can not be the total dark matter. Only very large structures could have formed (“pancakes”) that would later break down into smaller structures – top-down models.

Simulations later showed that structure formation is a bottom-up process. Hot dark matter was discarded...

OBS: sterile neutrinos with mass in the keV range, a prototype of **warm dark matter**, are still allowed.

III.4.1 – Bounds on neutrino mass from CMB

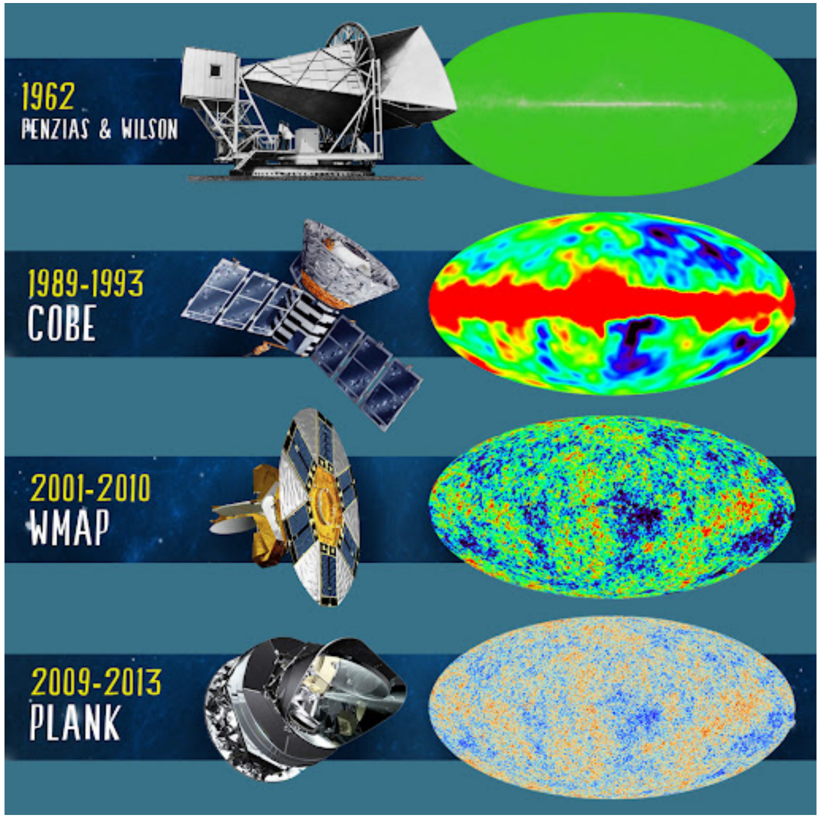
Fluctuations in the CMB are generated during inflation and evolved until photon decoupling. One measures the angular power spectrum C_l defined as:

$$\frac{\delta T}{T}(\hat{\theta}) = \sum_{lm} a_{lm} Y_{lm}(\hat{\theta})$$

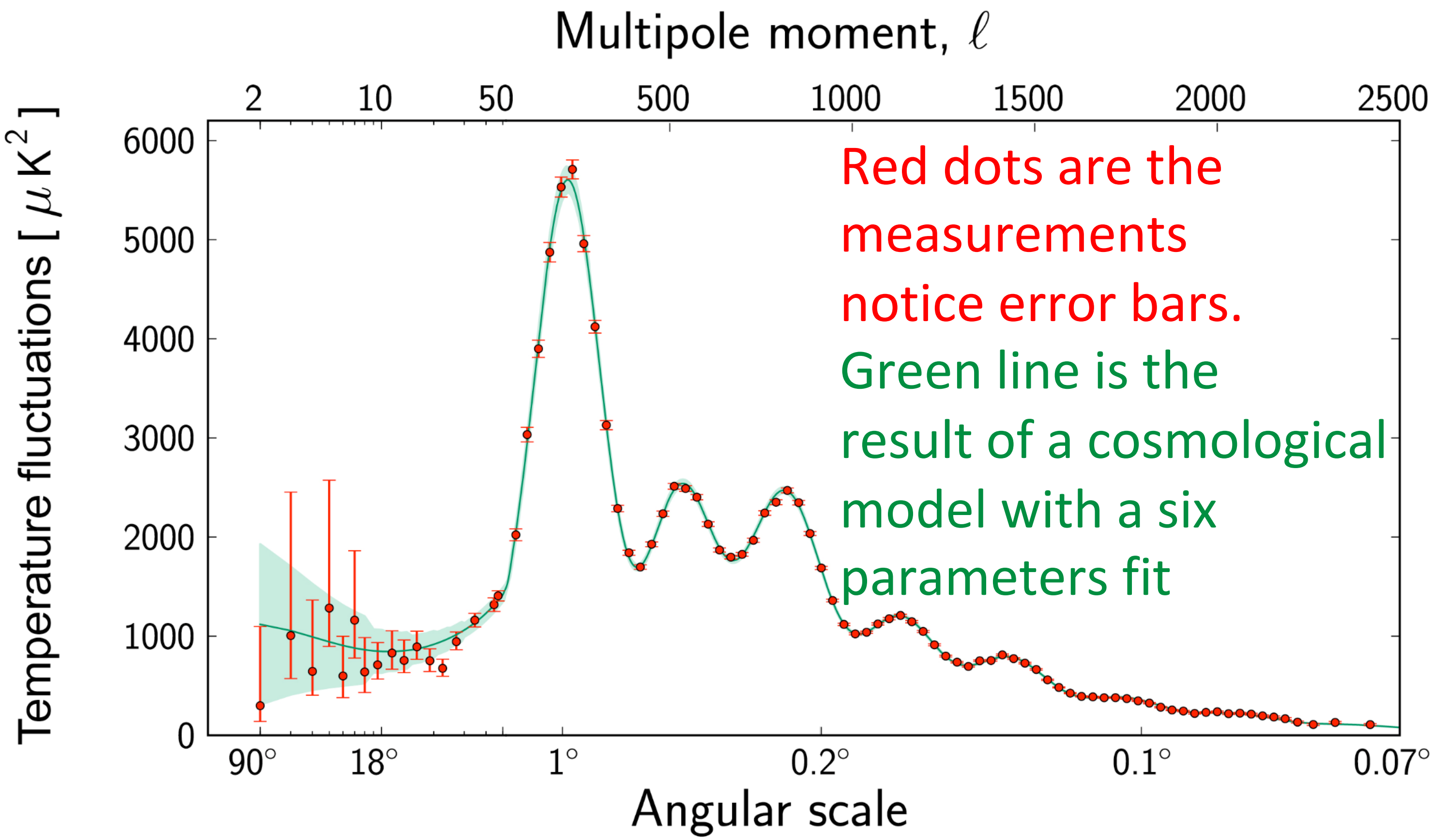
$$\langle a_{lm} a^*_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_l$$

$$C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2$$

Measured with ever increasing precision: COBE, WMAP, PLANCK



Planck 2018



Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
Red dots are the measurements notice error bars.
Green line is the result of a cosmological model with a six parameters fit

Precision cosmology

6 parameters in Planck base ΛCDM fit

Derived parameters

Parameter	Plik best fit	Plik [1]
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031
τ	0.0543	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014
n_s	0.96605	0.9649 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073
Age [Gyr]	13.7971	13.797 ± 0.023
σ_8	0.8120	0.8111 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013
z_{re}	7.68	7.67 ± 0.73
$100\theta_*$	1.041085	1.04110 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26

The Planck base-ΛCDM model assumes $\Sigma\, m_\nu$ = 0.06 eV with only one massive neutrino.

Neutrino mass bounds from CMB:

(from Planck 2018 - 1807.06209)

$\sum m_\nu < 0.24$ eV (95 %, TT,TE,EE+lowE+lensing). Planck-only

$\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO). Planck + BAO
BAO breaks degeneracies

$\Sigma m_\nu < 0.11$ eV (95%, Planck TT,TE,EE+lowE+lensing+BAO+Supernovas)

Caveats: model dependence (ΛCDM), degeneracies among parameters

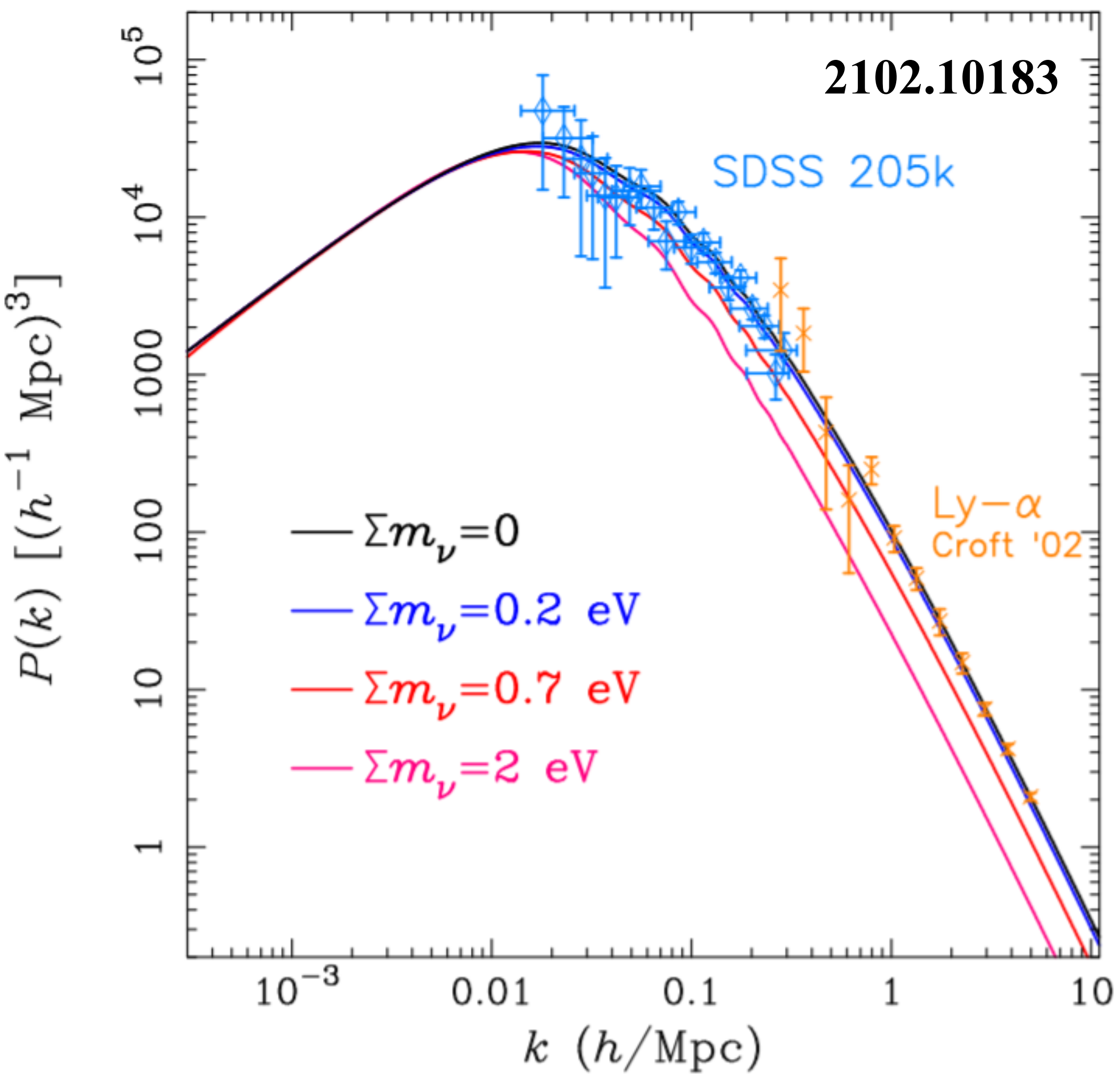
III.4.2 – Bounds on neutrino mass from galaxy surveys

Two main types of galaxy surveys:

- Spectroscopic: take spectra of galaxies
- Photometric: take pictures of galaxies with different color filters

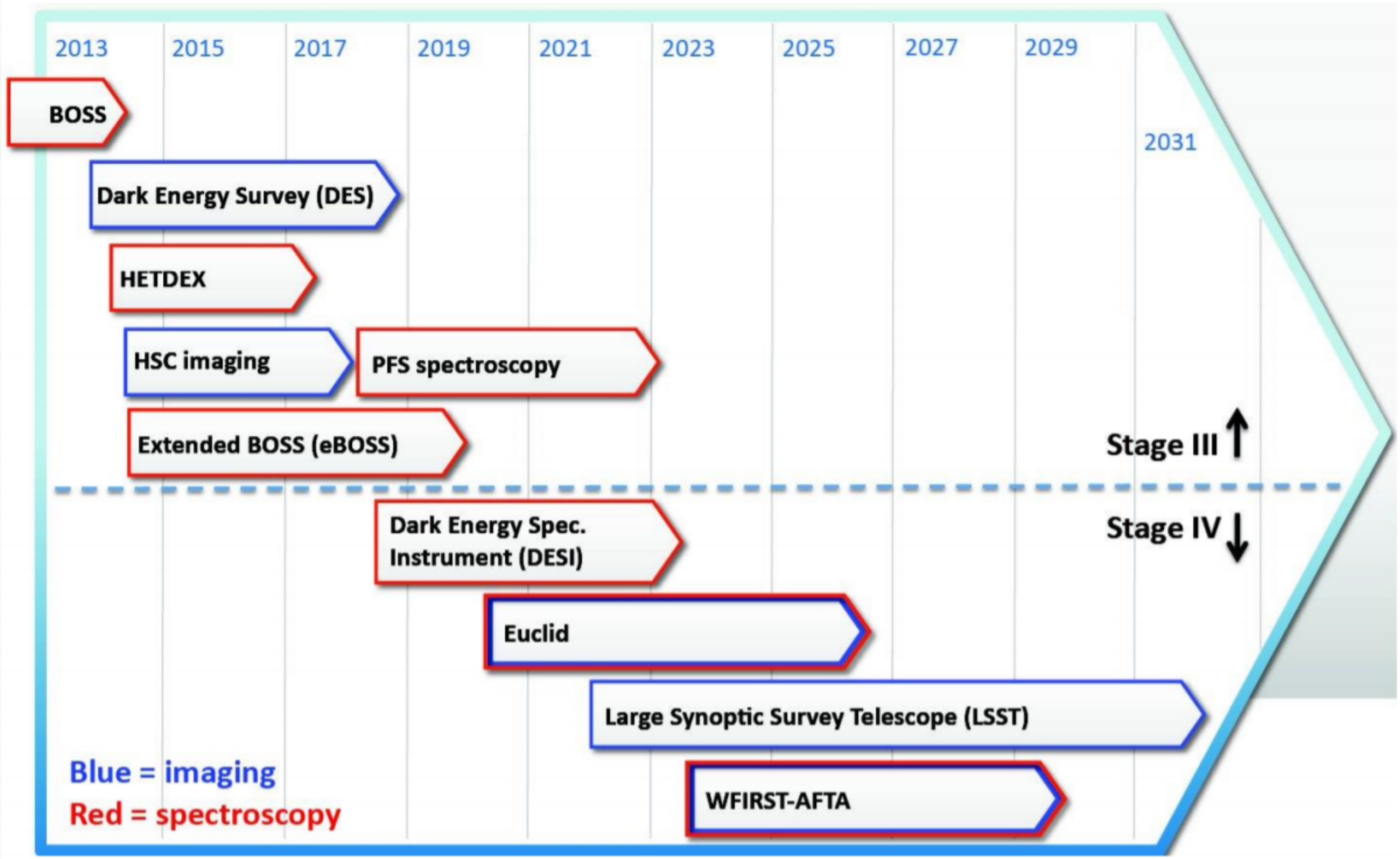
The growth of matter perturbations is suppressed at scales smaller than λ_{fs} due
The suppression is proportional to Ω_ν

The larger Σ m_ν the larger the suppression of the power spectrum.



2102.10183
SDSS 205k
Ly−α
Croft '02
Σm_ν=0
Σm_ν=0.2 eV
Σm_ν=0.7 eV
Σm_ν=2 eV
$P(k)$ [$(h^{-1}$ Mpc$)^3$]
k (h/Mpc)

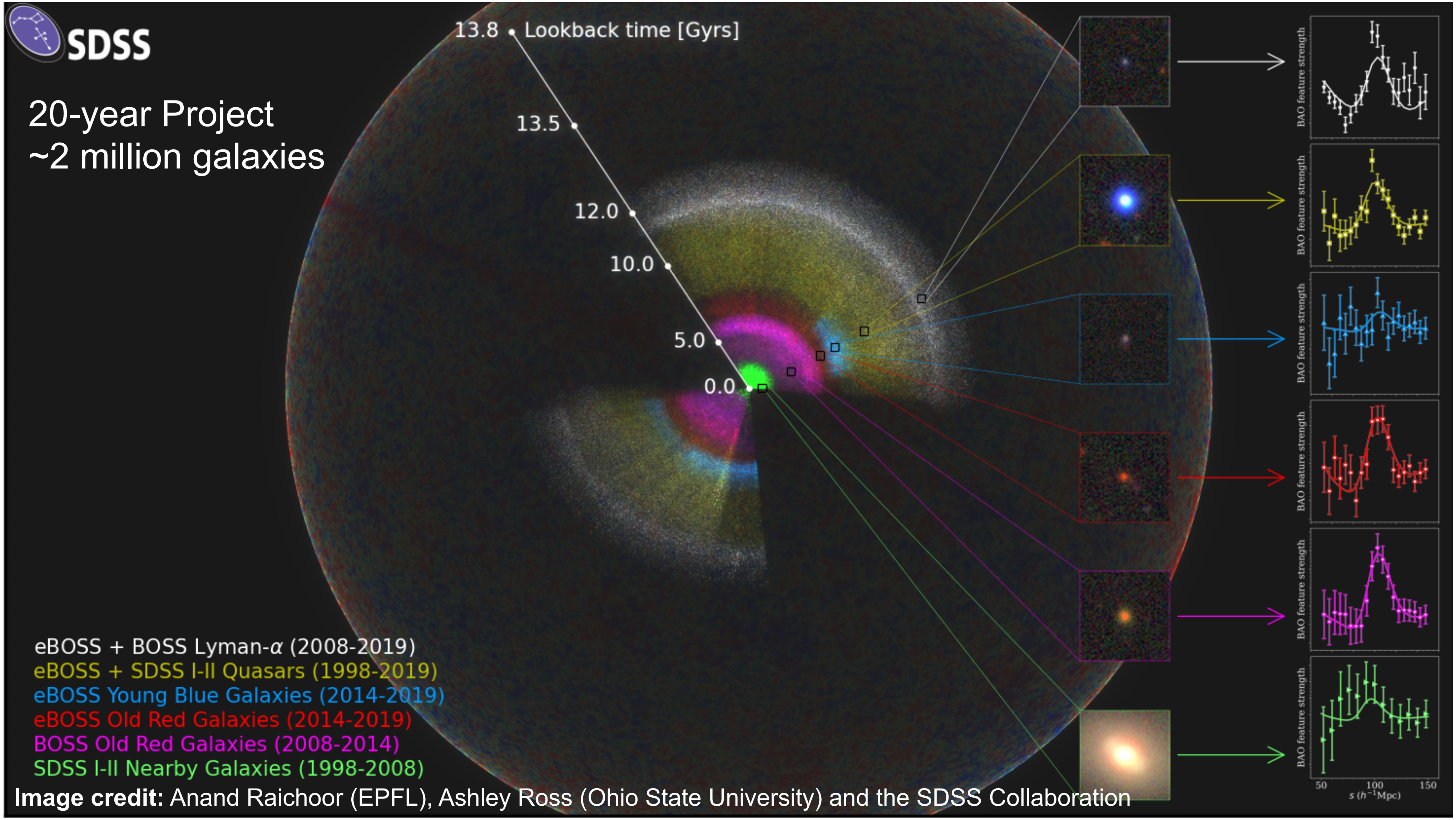
A somewhat outdated schedule of surveys

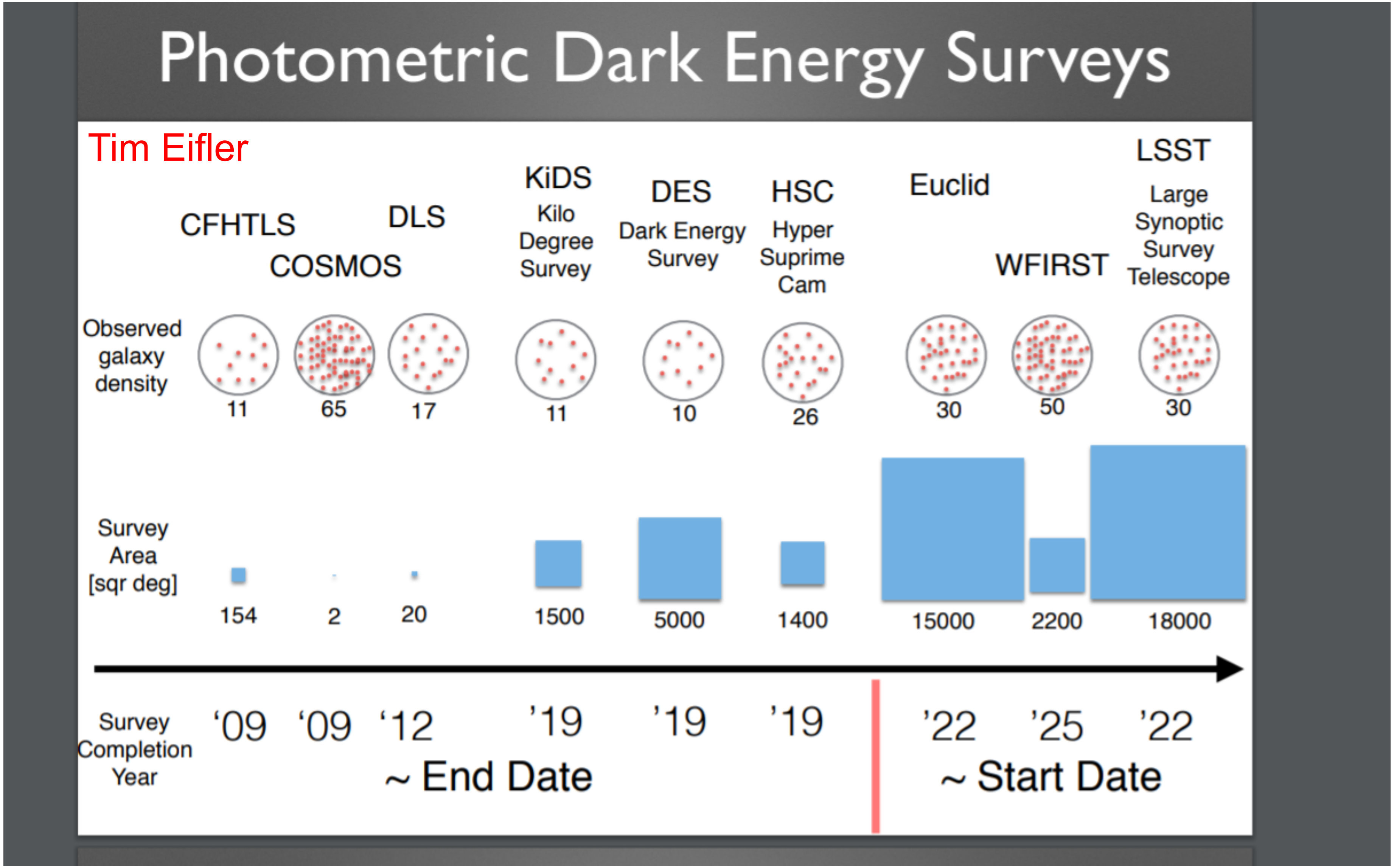


arXiV: 1401.6085

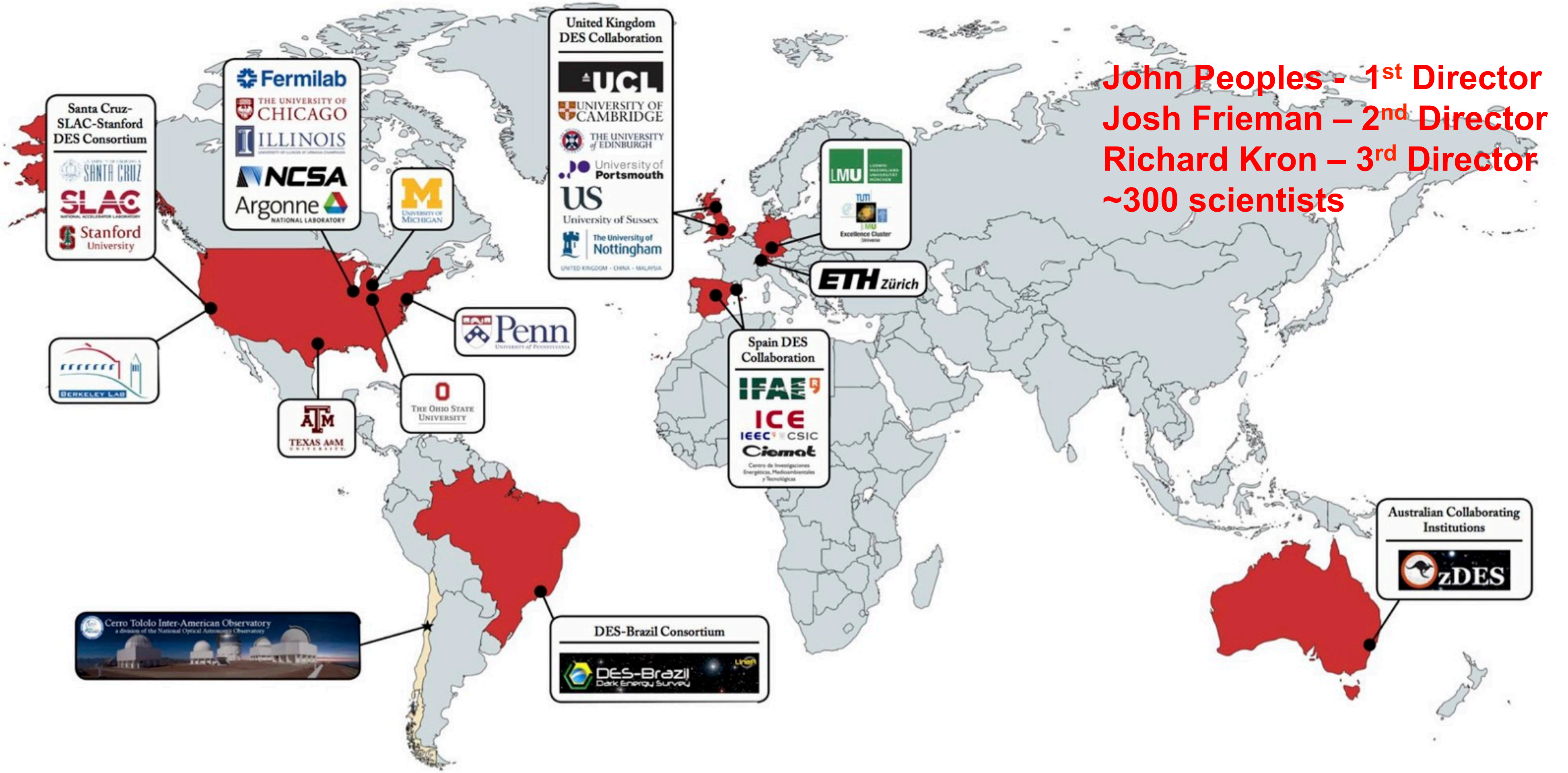
Accelerators ↔ Large scale galaxy surveys analogy:

- Energy ↔ redshift
- Luminosity ↔ area & observation time
- Energy resolution ↔ redshift errors
- Energy calibration ↔ objects with known redshifts
- p_T cuts, etc ↔ magnitude cuts, mask, etc
- Final data set ↔ value added catalogs
- Higgs bump hunting ↔ BAO bump hunting
- PT ok at high E ↔ PT ok at high z


SDSS
20-year Project
~2 million galaxies
13.8 Lookback time [Gyrs]
13.5
12.0
10.0
5.0
0.0
BAO feature strength
50
100
150
s (h⁻¹Mpc)
eBOSS + BOSS Lyman-α (2008-2019)
eBOSS + SDSS I-II Quasars (1998-2019)
eBOSS Young Blue Galaxies (2014-2019)
eBOSS Old Red Galaxies (2014-2019)
BOSS Old Red Galaxies (2008-2014)
SDSS I-II Nearby Galaxies (1998-2008)
Image credit: Anand Raichoor (EPFL), Ashley Ross (Ohio State University) and the SDSS Collaboration


Photometric Dark Energy Surveys
Tim Eifler
CFHTLS
COSMOS
DLS
KiDS
Kilo Degree Survey
DES
Dark Energy Survey
HSC
Hyper Suprime Cam
Euclid
WFIRST
LSST
Large Synoptic Survey Telescope
Observed galaxy density
11
65
17
11
10
26
30
50
30
Survey Area [sqr deg]
154
2
20
1500
5000
1400
15000
2200
18000
Survey Completion Year
'09
'09
'12
'19
'19
'19
'22
'25
'22
~ End Date
~ Start Date

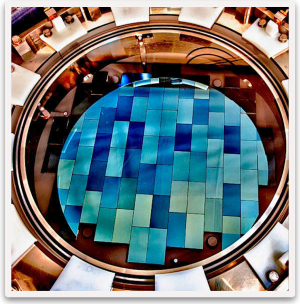
The Dark Energy Survey Collaboration

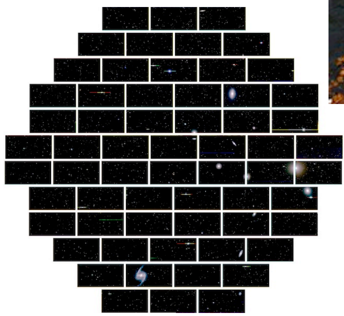


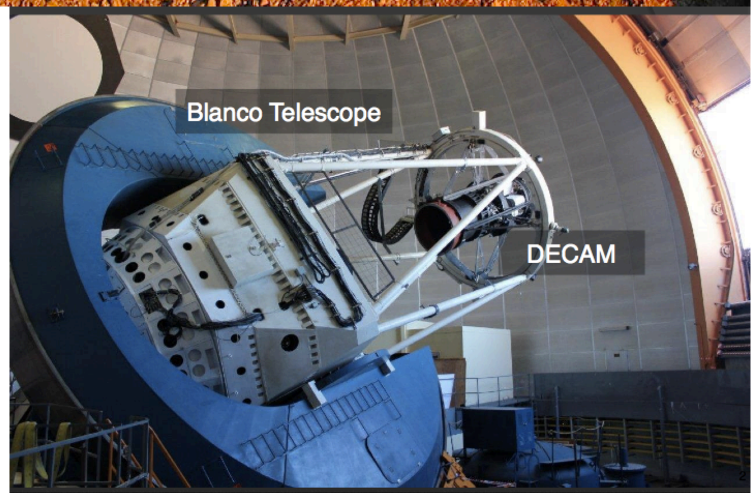
John Peoples - 1st Director
Josh Frieman – 2nd Director
Richard Kron – 3rd Director
~300 scientists

The Dark Energy Survey (DES)

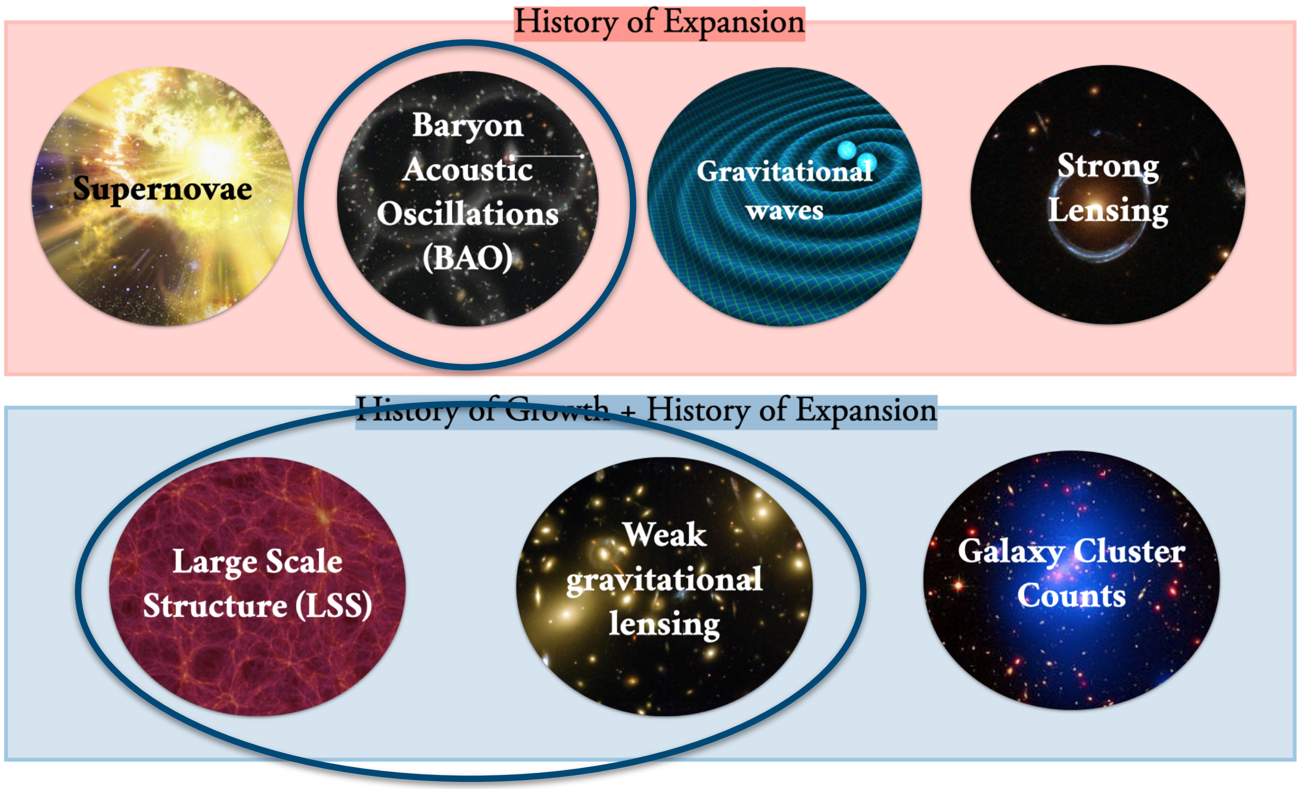
- >400 members, 25 institutions, 7 countries
- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey, ~5.5Y. 2013-2019 (Y3 2013-16).
- **Wide field:** 5000 sq. deg. in 5 bands grizY. ~23 magnitude.
- DES Y3: Positions and shapes of > 100M galaxies.







Cosmic probes within DES



Dark Energy Survey Year 3 results – more than 30 papers

THE DARK ENERGY SURVEY

THE DES PROJECT RESULTS & PAPERS DATA ACCESS NEWS & MEDIA EDUCATION CONTACT US

DES Year 3 Cosmology Results: Papers

Announced on May 2021

www.darkenergysurvey.org/des-year-3-cosmology-results-papers/

3x2pt cosmology main result

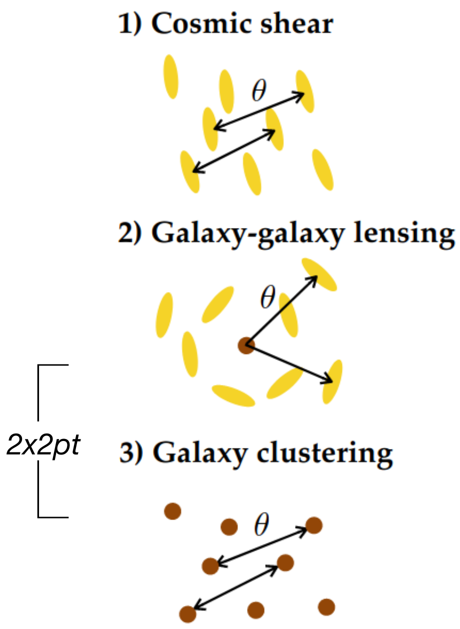


Image credit: Chihway Chang

- Cosmic shear most sensitive to clustering amplitude.
- Galaxy clustering and tangential shear more sensitive to total matter density.

A factor of 2.1 improvement in signal-to-noise from DES Year 1.

ΛCDM	$S_8 = 0.776^{+0.017}_{-0.017}$	(0.776)
	$\Omega_m = 0.339^{+0.032}_{-0.031}$	(0.372)
	$\sigma_8 = 0.733^{+0.039}_{-0.049}$	(0.696)
ωCDM	$\Omega_m = 0.352^{+0.035}_{-0.041}$	(0.339)
	$w = -0.98^{+0.32}_{-0.20}$	(−1.03)

Key result: DES + External low z (SNe Ia, BAO, RSD) + CMB

In ΛCDM:

$$S_8 = 0.812^{+0.008}_{-0.008} \quad (0.815)$$

$$\Omega_{\rm m} = 0.306^{+0.004}_{-0.005} \quad (0.306)$$

$$\sigma_8 = 0.804^{+0.008}_{-0.008} \quad (0.807)$$

$$h = 0.680^{+0.004}_{-0.003} \quad (0.681)$$

$$\sum m_\nu < 0.13 \text{ eV } (95\% \text{ CL})$$

In *w*CDM:

$$\sigma_8 = 0.810^{+0.010}_{-0.009} \quad (0.804)$$

$$\Omega_{\rm m} = 0.302^{+0.006}_{-0.006} \quad (0.298)$$

$$w = -1.03^{+0.03}_{-0.03} \quad (-1.00)$$

III.4.3 – Bounds on neutrino mass from joint LSS, SNIa, CMB analysis

Using data from eBOSS (BAO + RSD from emission line galaxies and quasars), Pantheon sample of SNIa and Planck a recent analysis obtains (2106.15267):

$$\sum < 90\, meV \,@\, 95\% CL$$

"highly compromises the viability of the inverted mass ordering as the underlying neutrino mass pattern in nature"

Caveats: model-dependence, degeneracies among parameters, prior dependence in Bayesian analysis

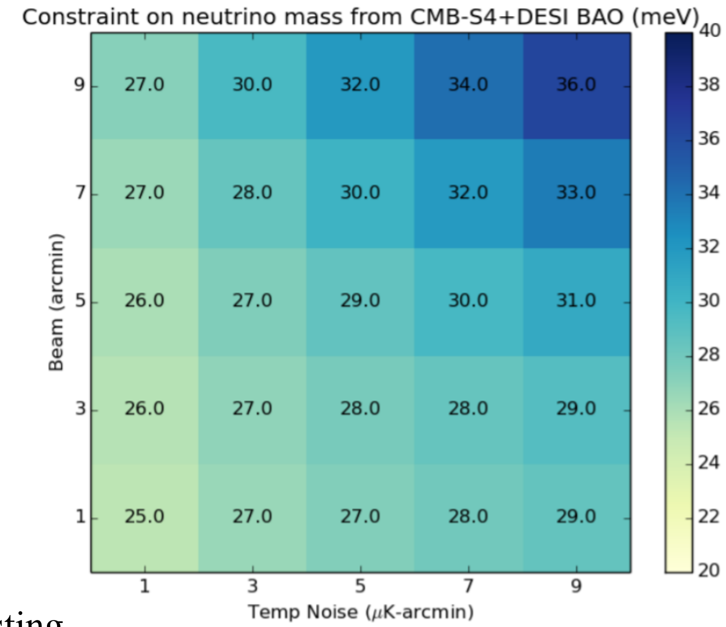
Intriguing question: what if from cosmological data one finds that

$$\sum < 60\, meV\ @\ 95\% CL\ ??$$

This would imply a serious tension between cosmology and neutrino oscillation experiments!

III.4.4 – Future bounds on neutrino mass

CMB-S4 + DESI BAO (similar to Simons Observatory + DESI BAO):
sensitivity to $\Sigma\, m_\nu$ <0.04 eV



cmb-s4.uchicago.edu/wiki/index.php/Forecasting
The Simons Observatory: Science goals and forecasts - 1808.07445

Astro2020 Science White Paper

Neutrino Mass from Cosmology: Probing Physics Beyond the Standard Model

optimal combination of next-generation CMB and LSS surveys has the potential to reach a sensitivity of $\sigma(\Sigma m_\nu) \sim 14$ meV, corresponding to a nearly-4σ detection of the minimal mass scenario.

1903.03689

Cosmology can probe $\Sigma\, m_\nu$ but it will not be possible to directly measure the individual neutrino masses in the foreseeable future (2003.03354, 2006.09395)

III.5 – BSM neutrino physics and the Hubble tension

New interactions in the neutrino sector can ameliorate the Hubble tension. I'll briefly discuss 2 examples.

III.5.1 – The case of "secret" neutrino interactions

1704.06657, 1902.00534, 1905.02727, 2012.07519, 2012.11830 and many more

Main idea: non-standard neutrino scenarios can delay the onset of neutrino free-streaming until close to the epoch of matter-radiation equality and naturally accommodate a larger value for the Hubble constant.

Simple model: new four-fermion interaction.

$$\mathcal{L} = G_{eff}(\bar{\nu}\nu)(\bar{\nu}\nu)$$

G_{eff} has dimensions of $[E]^{-2}$ just like Fermi's constant.

Increasing G_{eff} would further delay the neutrino free-streaming.

Change Boltzmann code to include extra interaction.

Extension of ΛCDM model to include variations of the parameters:

$$\Lambda\mathrm{CDM} + \log_{10}\left[\mathrm{G_{eff}MeV^2}\right] + \mathrm{N_{eff}} + \sum m_\nu$$

A bi-modal posterior distribution was found in the parameter G_{eff}:

“strongly” and “moderately” interacting neutrinos.

In spite of initial positive results, recent analysis claim this is no longer a solution.

Initial results from 1902.00534

TABLE II: TT + lens + BAO + H_0 Constraints: Parameter 68% Confidence Limits

Parameter	Strongly Interacting Neutrino Mode	Moderately Interacting Neutrino Mode
$\Omega_b h^2$	$0.02245^{+0.00029}_{-0.00033}$	0.02282 ± 0.00030
$\Omega_c h^2$	$0.1348^{+0.0056}_{-0.0049}$	$0.1256^{+0.0035}_{-0.0039}$
$100\theta_{MC}$	1.04637 ± 0.00056	$1.04062^{+0.00049}_{-0.00056}$
τ	0.080 ± 0.031	$0.127^{+0.034}_{-0.029}$
$\sum m_\nu$ [eV]	$0.42^{+0.17}_{-0.20}$	$0.40^{+0.17}_{-0.23}$
N_{eff} Problematic	4.02 ± 0.29	3.79 ± 0.28
$\log_{10}(G_{eff} MeV^2)$	$-1.35^{+0.12}_{-0.066}$	$-3.90^{+1.0}_{-0.93}$
$\ln(10^{10} A_s)$	3.035 ± 0.060	$3.194^{+0.068}_{-0.056}$
n_s	0.9499 ± 0.0098	$0.993^{+0.013}_{-0.012}$
H_0 [km/s/Mpc]	72.3 ± 1.4	71.2 ± 1.3
Ω_m	0.3094 ± 0.0083	0.3010 ± 0.0080
σ_8	0.786 ± 0.020	$0.813^{+0.023}_{-0.020}$
$10^9 A_s$	$2.08^{+0.11}_{-0.13}$	2.44 ± 0.15
$10^9 A_s e^{-2\tau}$	1.771 ± 0.016	$1.892^{+0.019}_{-0.017}$
r_* [Mpc]	136.3 ± 2.4	139.1 ± 2.3
$100\theta_*$	1.04604 ± 0.00056	$1.04041^{+0.00058}_{-0.00064}$
D_A [Gpc]	13.03 ± 0.23	13.37 ± 0.21
r_{drag} [Mpc]	138.8 ± 2.5	141.6 ± 2.3

Updated constraints - 2012.07519

		TT+lowE	CMB	CMB+EXT	CMB+R19
$\Omega_b h^2$	NIν	$0.02194^{+0.00072}_{-0.00078}$	$0.02223^{+0.00044}_{-0.00043}$	$0.02235^{+0.00037}_{-0.00037}$	$0.02276^{+0.00035}_{-0.00035}$
	MIν	$0.02191^{+0.00070}_{-0.00078}$	$0.02222^{+0.00043}_{-0.00043}$	$0.02236^{+0.00035}_{-0.00035}$	$0.02278^{+0.00035}_{-0.00033}$
	SIν	$0.02226^{+0.00074}_{-0.00081}$	$0.02232^{+0.00046}_{-0.00045}$	$0.02236^{+0.00035}_{-0.00035}$	$0.02287^{+0.00033}_{-0.00034}$
$\Omega_c h^2$	NIν	$0.1200^{+0.0078}_{-0.0079}$	$0.1183^{+0.0060}_{-0.0057}$	$0.1179^{+0.0055}_{-0.0056}$	$0.1234^{+0.0057}_{-0.0056}$
	MIν	$0.1201^{+0.0086}_{-0.0080}$	$0.1184^{+0.0061}_{-0.0059}$	$0.1182^{+0.0055}_{-0.0055}$	$0.1238^{+0.0057}_{-0.0055}$
	SIν	> 0.126	$0.1161^{+0.0061}_{-0.0057}$	$0.1156^{+0.0060}_{-0.0052}$	$0.1220^{+0.0065}_{-0.0060}$
Σm_ν	NIν	< 0.705	< 0.297	< 0.122	< 0.105
	MIν	< 0.771	< 0.290	< 0.117	< 0.0917
	SIν	< 0.848	< 0.325	< 0.152	< 0.105
$N_{\rm eff}$	NIν	$2.95^{+0.59}_{-0.59}$	$2.91^{+0.39}_{-0.37}$	$2.96^{+0.33}_{-0.35}$	$3.38^{+0.30}_{-0.30}$
	MIν	$2.96^{+0.61}_{-0.59}$	$2.91^{+0.38}_{-0.38}$	$2.97^{+0.34}_{-0.33}$	$3.41^{+0.31}_{-0.30}$
	SIν	$4.00^{+0.80}_{-0.82}$	$2.74^{+0.38}_{-0.35}$	$2.73^{+0.34}_{-0.31}$	$3.22^{+0.32}_{-0.30}$
$\log_{10} G_{\rm eff}$	NIν				
	MIν	< -3.04	< -3.47	< -3.37	< -3.27
	SIν	$-1.13^{+0.20}_{-0.21}$	$-1.69^{+0.27}_{-0.31}$	$-1.71^{+0.27}_{-0.31}$	$-1.58^{+0.29}_{-0.37}$
n_s	NIν	$0.957^{+0.029}_{-0.030}$	$0.959^{+0.017}_{-0.017}$	$0.963^{+0.014}_{-0.014}$	$0.981^{+0.012}_{-0.013}$
	MIν	$0.954^{+0.028}_{-0.031}$	$0.958^{+0.017}_{-0.017}$	$0.963^{+0.014}_{-0.014}$	$0.981^{+0.013}_{-0.013}$
	SIν	$0.944^{+0.028}_{-0.029}$	$0.928^{+0.015}_{-0.015}$	$0.929^{+0.012}_{-0.011}$	$0.947^{+0.011}_{-0.011}$
H_0	NIν	$64.6^{+6.3}_{-8.2}$	$65.9^{+3.3}_{-3.8}$	$67.3^{+2.2}_{-2.2}$	$70.5^{+2.1}_{-2.0}$
	MIν	$64.6^{+7.0}_{-8.1}$	$66.0^{+3.5}_{-3.6}$	$67.4^{+2.2}_{-2.1}$	$70.7^{+2.2}_{-2.1}$
	SIν	73^{+9}_{-10}	$66.4^{+3.7}_{-3.7}$	$66.7^{+2.2}_{-2.1}$	$71.0^{+2.2}_{-2.1}$

No evidence that significantly higher H_0 values can be allowed by adding neutrino self-interactions.

In addition, there are problems with the UV completion of the model. Interactions of the necessary size imply the existence of a force-carrier particle with a large neutrino coupling and mass in the keV – 100 MeV range. This mediator is subject to stringent cosmological and laboratory bounds, and nearly all realizations of such a particle are excluded by existing data – see 1905.02727

III.5.2 – The case of neutrino-assisted early dark energy

Coupling between neutrinos and the dark energy field (quintessence field) can lead to mass-varying neutrinos (eg astro-ph/0309800, 0803.3142).

More recently, there has been an interesting suggestion that the transition from relativistic to non-relativistic regime of neutrinos (which is tantalizing close to the scale of CMB at around 0.3 eV) can give a “quick” to a dark energy field through a coupling to the trace of the energy-momentum tensor (1911.11760, 2011.09895):

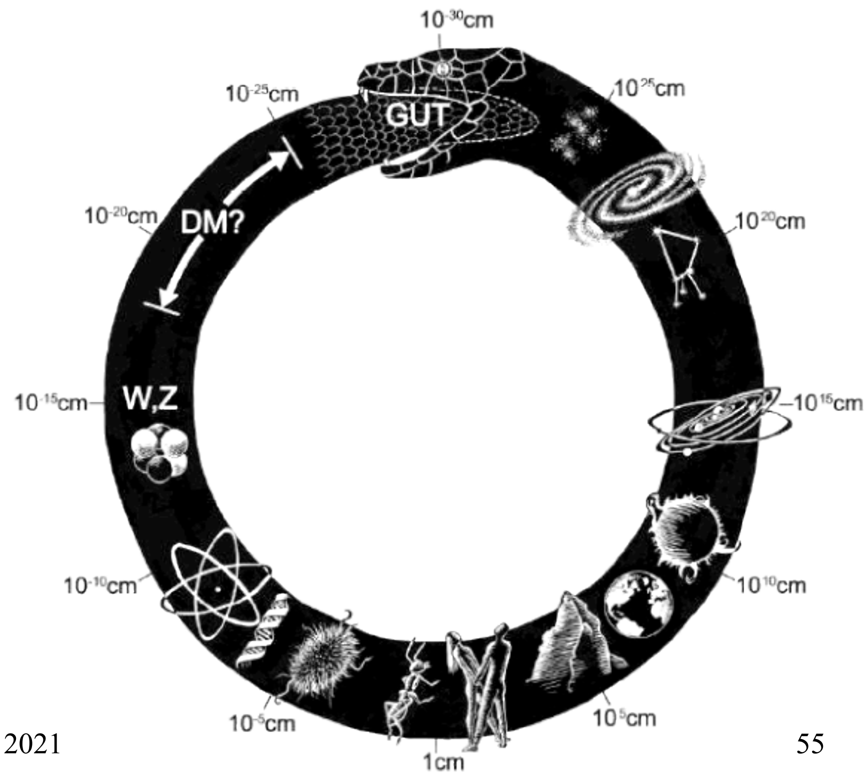
$$\frac{\phi}{f} T^{\mu}_{\mu}$$

More detailed investigations are necessary to determined if this model passes all observational tests.

End of third lecture

Conclusions

- Properties of elementar particles affect the Universe: particle physics and cosmology are intertwined



- This “marriage” has a long history: Lemaître, Gamow, ...

The Beginning of the World from the Point of View of Quantum Theory.

Lemaître – Nature 1931 – The primeval atom hypothesis
First attempt to use the then recently cretaed quantum mechanics in cosmology.
Quantum origin of the universe!!

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

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AND

H. BETHE
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AND

G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt}=f(t)(\sigma_{i-1}n_{i-1}-\sigma_i n_i) \quad i=1,2,\cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm³.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho \leqq 10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty}(10^6/t^2)dt \leqq 5\times 10^4, \qquad (2)$$

which gives us $t_0 \leqq 20$ sec. and $\rho_0 \leqq 2.5\times 10^5$ g sec./cm³. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^5 g sec./cm³ which can possibly be understood if we

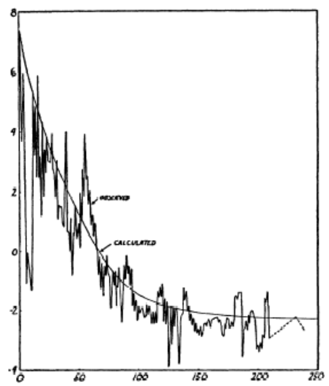
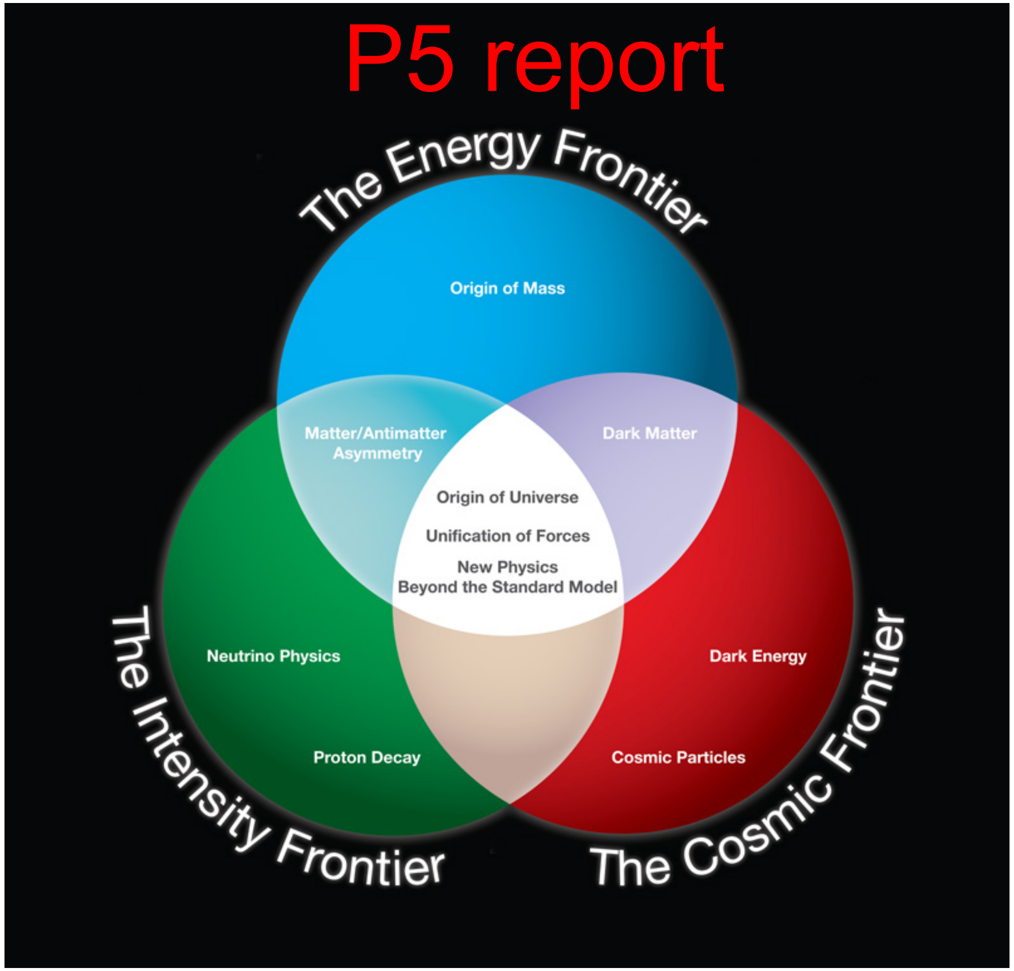


FIG. 1.

Log of relative abundance

Atomic weight

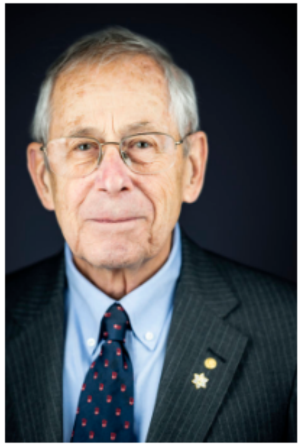
- This “marriage” must be considered in Strategic Planning



- Cosmology has became a precision Science in the past ~20 years

Nobel prizes for CMB discovery (1978), detection of its fluctuations (2006), discovery of the accelerated expansion (2011) and

The Nobel Prize in Physics 2019



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James Peebles

Prize share: 1/2

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Michel Mayor

Prize share: 1/4

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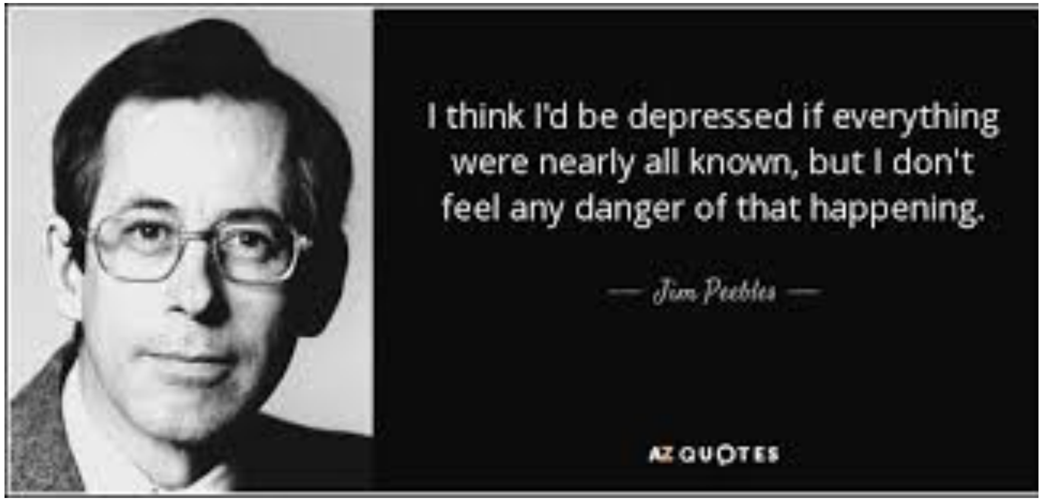
Didier Queloz

Prize share: 1/4



The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos" with one half to James Peebles "for theoretical discoveries in physical cosmology", the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

- High precision measurements reveal tensions in standard ΛCDM

New physics vs systematic errors: jury is still out

- BSM models have to pass cosmological tests

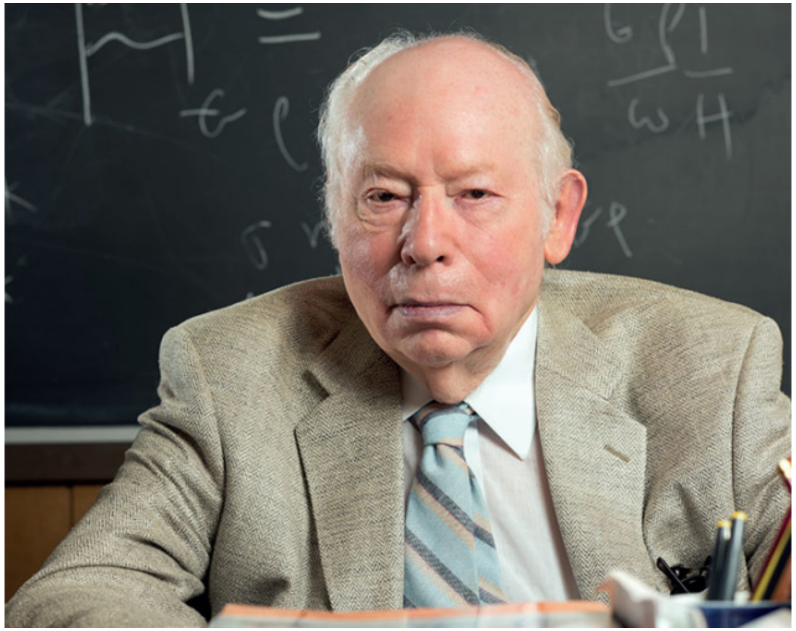
- Exciting times with new cosmological experiments:

  DESI, LSST, Euclid, Simons Observatory, CMB-S4 ...

"The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy. "

— Steven Weinberg (1933-2021)

(last sentence in "The first three minutes")



Steven Weinberg is among the very few individuals who, during the course of the history of civilisation, have radically changed the way we look at the universe.

Gian Giudice *CERN.*


Hope to meet you in-person someday!
Thank you!
Cosmology
You after these lectures