Recent developments in neutrino cosmology **for the layperson**

Sunny Vagnozzi

The Oskar Klein Centre for Cosmoparticle Physics, Stockholm University

sunny.vagnozzi@fysik.su.se

PhD thesis discussion
Stockholm, 10 June 2019

D'où venons-nous? Que sommes-nous ? Où allons-nous?

Courtesy of Paul Gauguin

The oldest questions...

- *Where do we come from*?
- *What are we made of*?
- *Where are we going*?

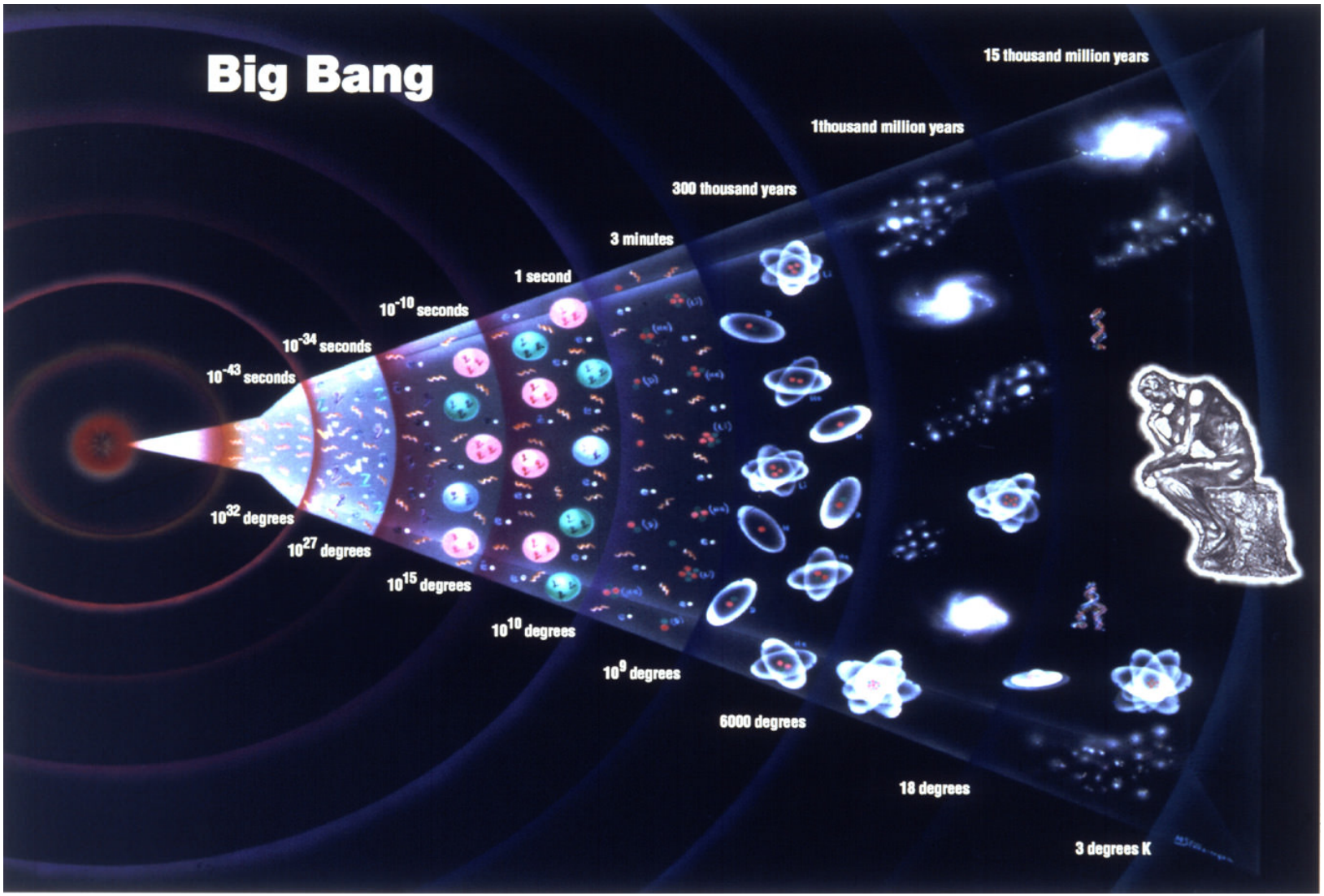
...and the modern versions of these questions

- *Where do we come from*? $\longrightarrow$
- *What are we made of*? $\longrightarrow$
- *Where are we going*? $\longrightarrow$

- *What were the Universe's initial conditions*?
- *What is the Universe made of*?
- *How will the Universe evolve*?

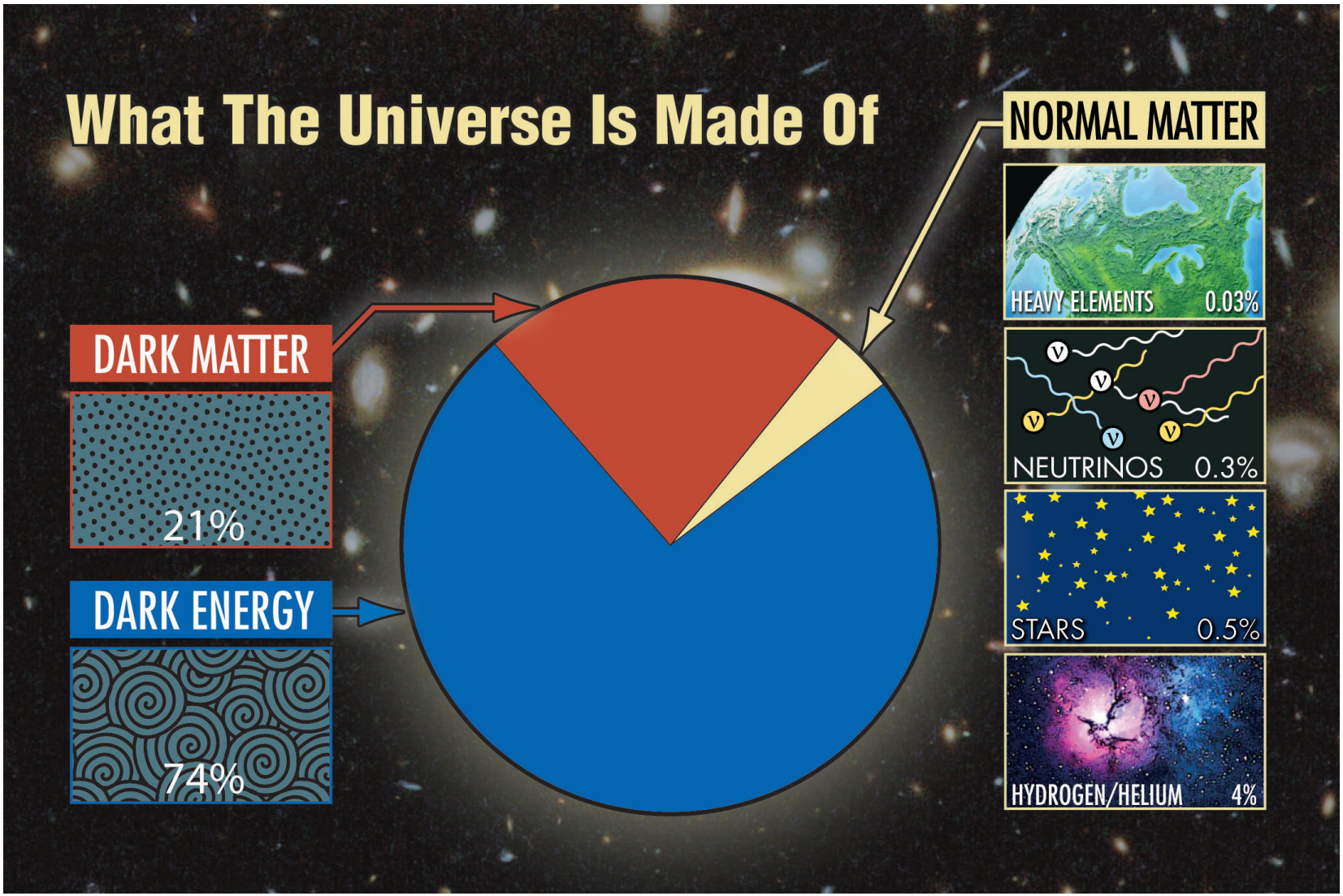
Where do we come from?

Cosmic inflation aka *(Hot) Big Bang*?



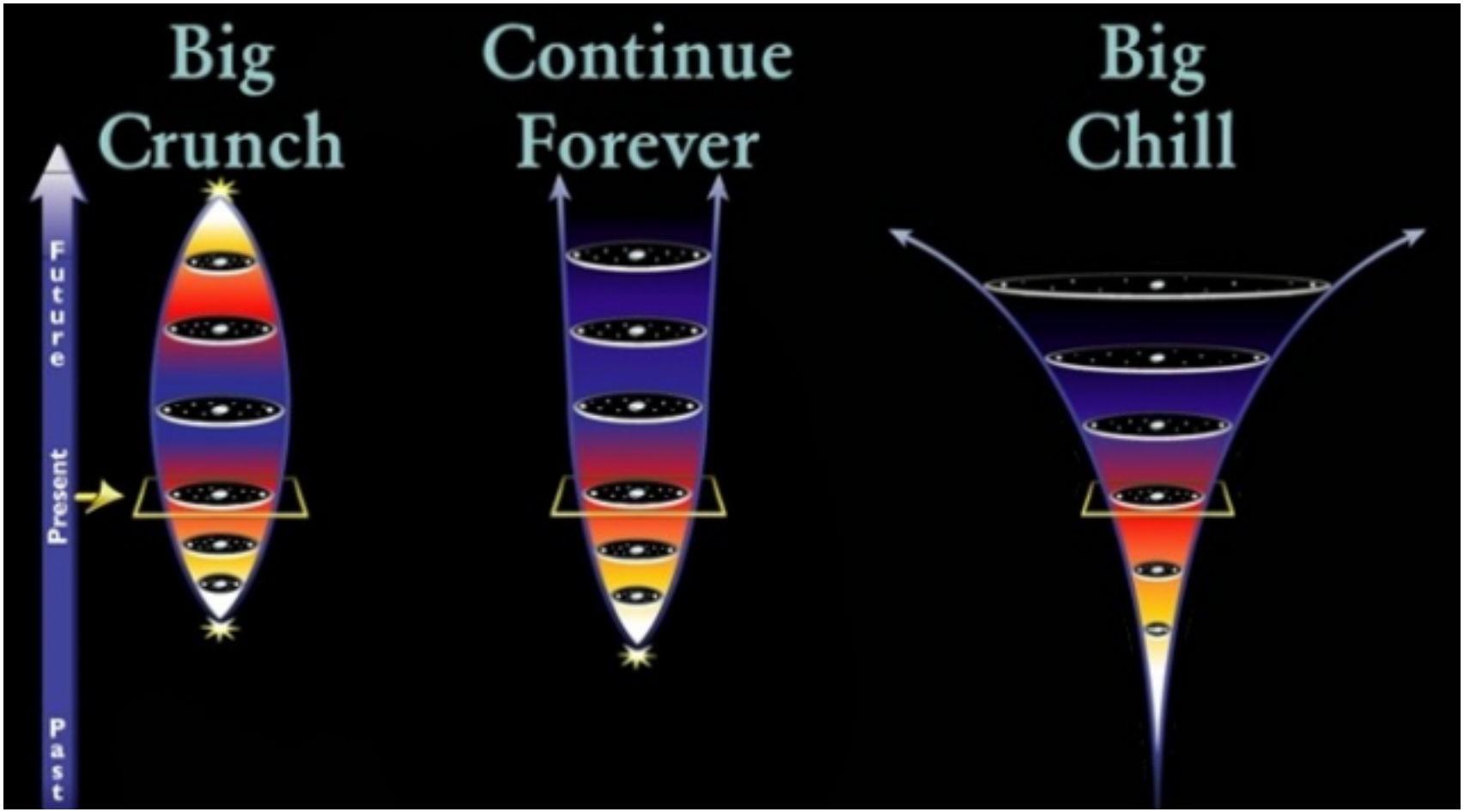
What are we made of?

Mostly dark stuff (and a bit of neutrinos)

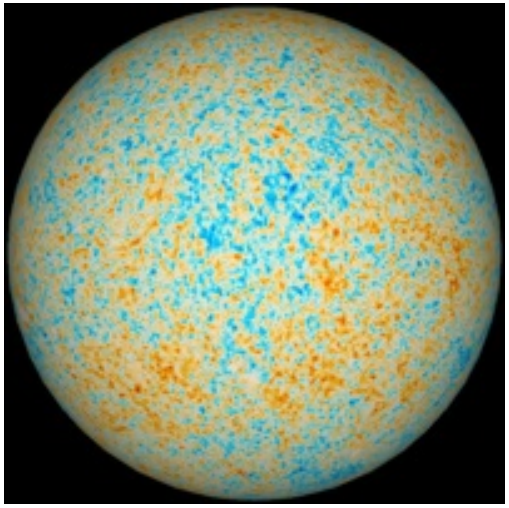


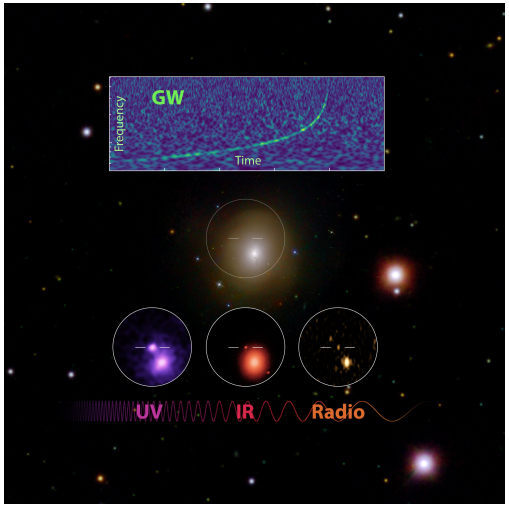
Where are we going?

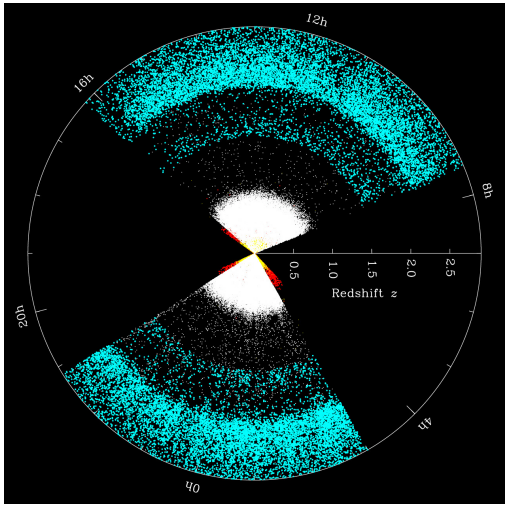
Depends on what dark energy is?

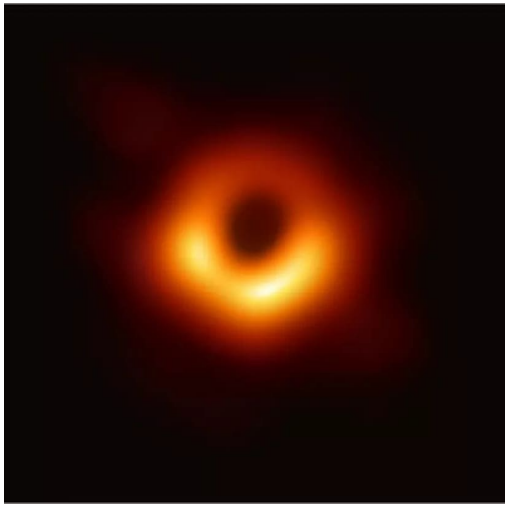


Lots of astrophysical and cosmological data to test theories for the origin/composition/fate of the Universe:

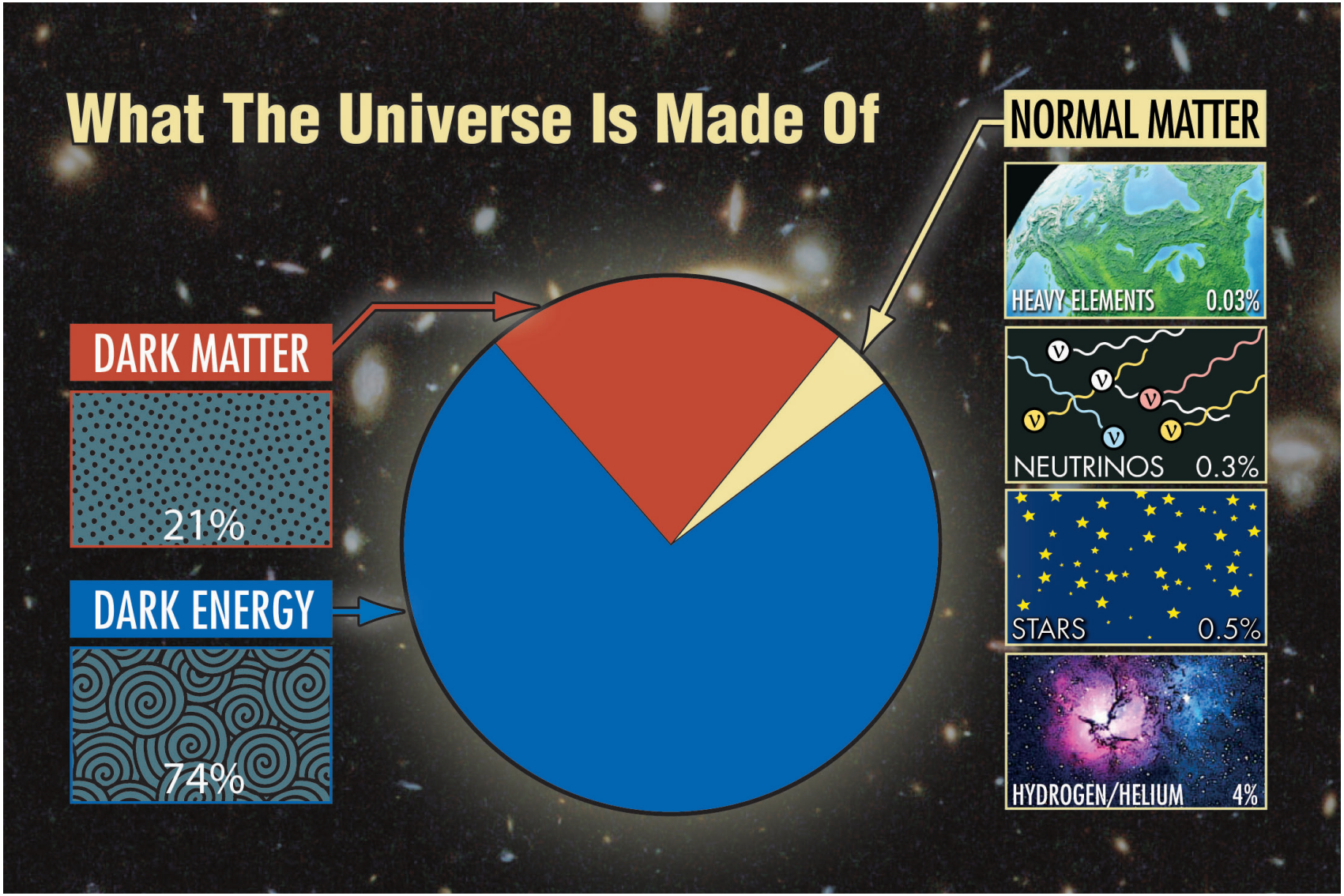




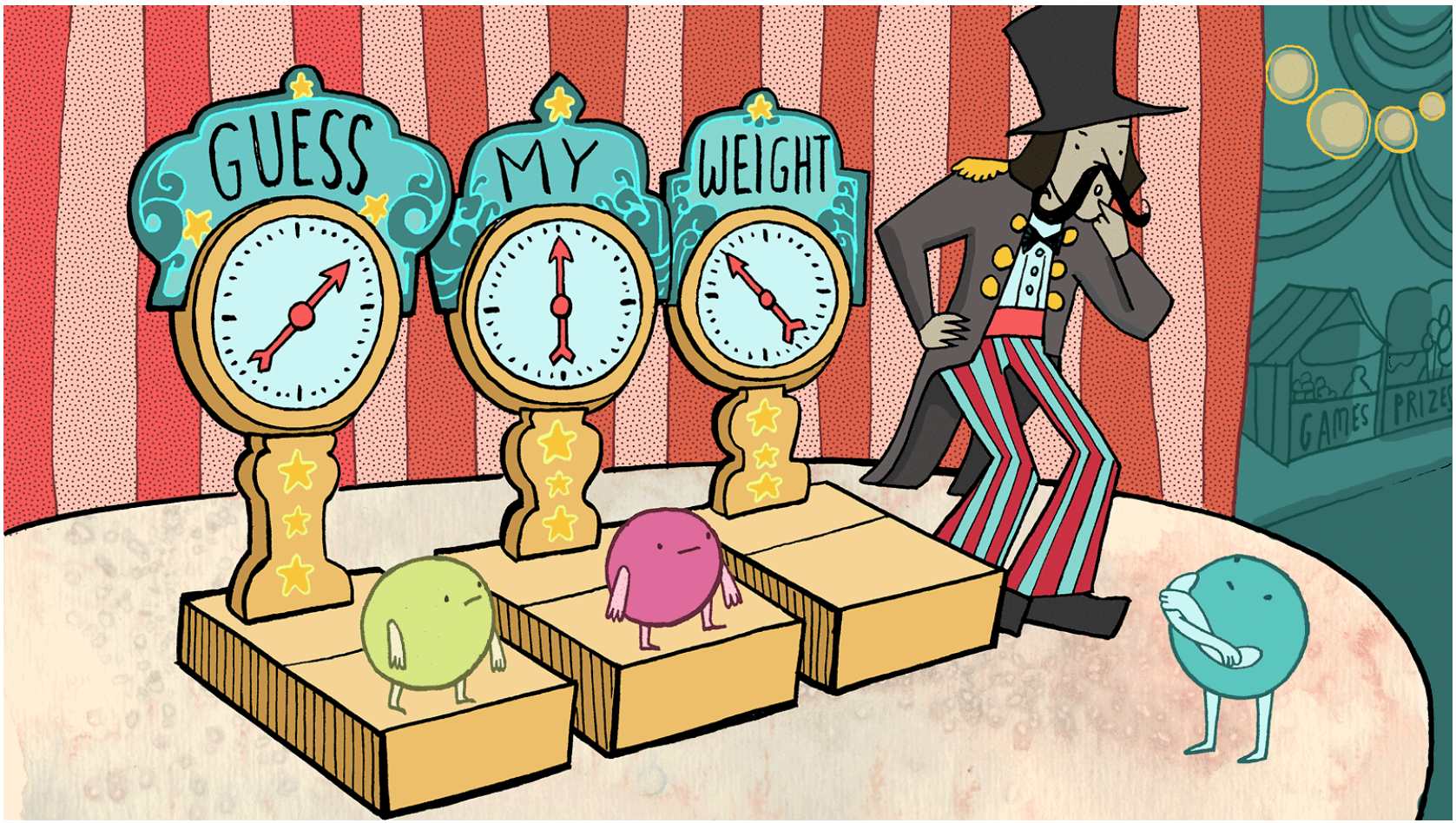




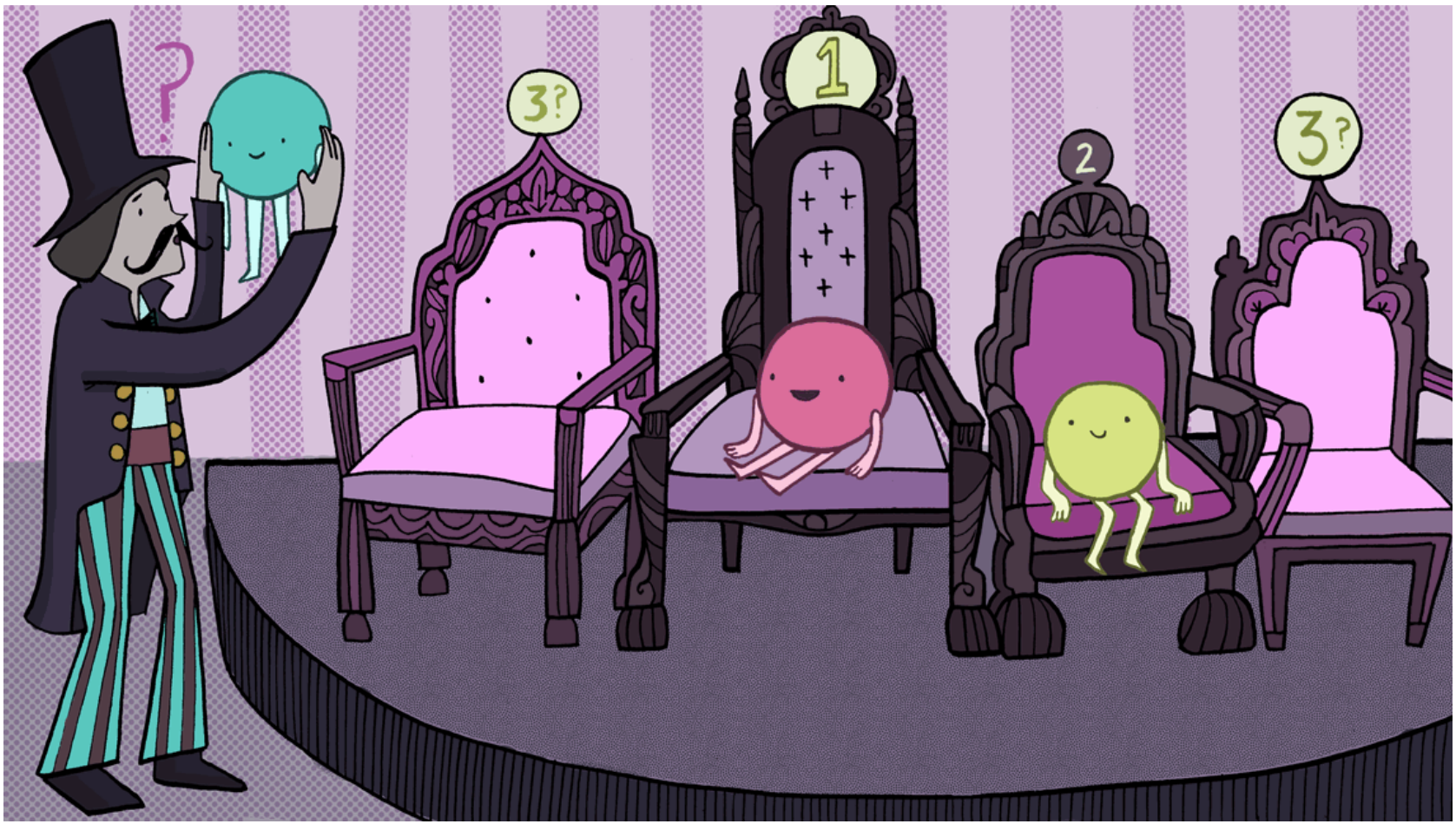
Neutrinos


What The Universe Is Made Of
NORMAL MATTER
HEAVY ELEMENTS 0.03%
NEUTRINOS 0.3%
STARS 0.5%
HYDROGEN/HELIUM 4%
DARK MATTER
21%
DARK ENERGY
74%

Neutrino masses



Neutrino mass ordering



Paper I

Sunny Vagnozzi, Elena Giusarma, Olga Mena, Katie Freese, Martina Gerbino, Shirley Ho, Massimiliano Lattanzi, *Phys. Rev.* D **96** (2017) 123503 [arXiv:1701.08172]

What does current data tell us about the neutrino mass scale and mass ordering? How to quantify how much the normal ordering is favoured?

Unveiling ν secrets with cosmological data: Neutrino masses and mass hierarchy

Sunny Vagnozzi, Elena Giusarma, Olga Mena, Katherine Freese, Martina Gerbino, Shirley Ho, and Massimiliano Lattanzi

Phys. Rev. D **96**, 123503 – Published 1 December 2017

ABSTRACT

Using some of the latest cosmological data sets publicly available, we derive the strongest bounds in the literature on the sum of the three active neutrino masses, M_ν, within the assumption of a background flat ΛCDM cosmology. In the most conservative scheme, combining Planck cosmic microwave background temperature anisotropies and baryon acoustic oscillations (BAO) data, as well as the up-to-date constraint on the optical depth to reionization (τ), the tightest 95% confidence level upper bound we find is $M_\nu < 0.151$ eV. The addition of Planck high-ℓ polarization data, which, however, might still be contaminated by systematics, further tightens the bound to $M_\nu < 0.118$ eV. A proper model comparison treatment shows that the two aforementioned combinations disfavor the inverted hierarchy

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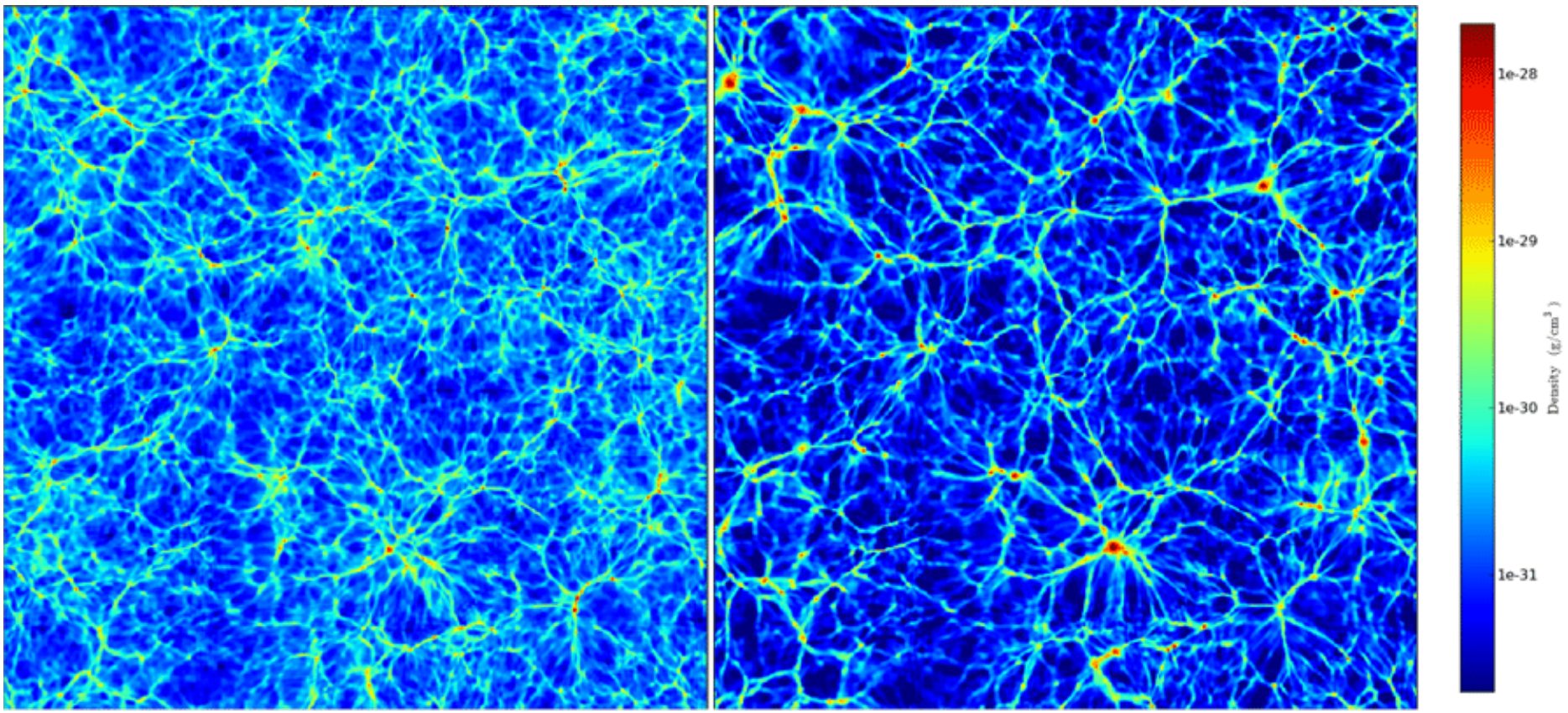
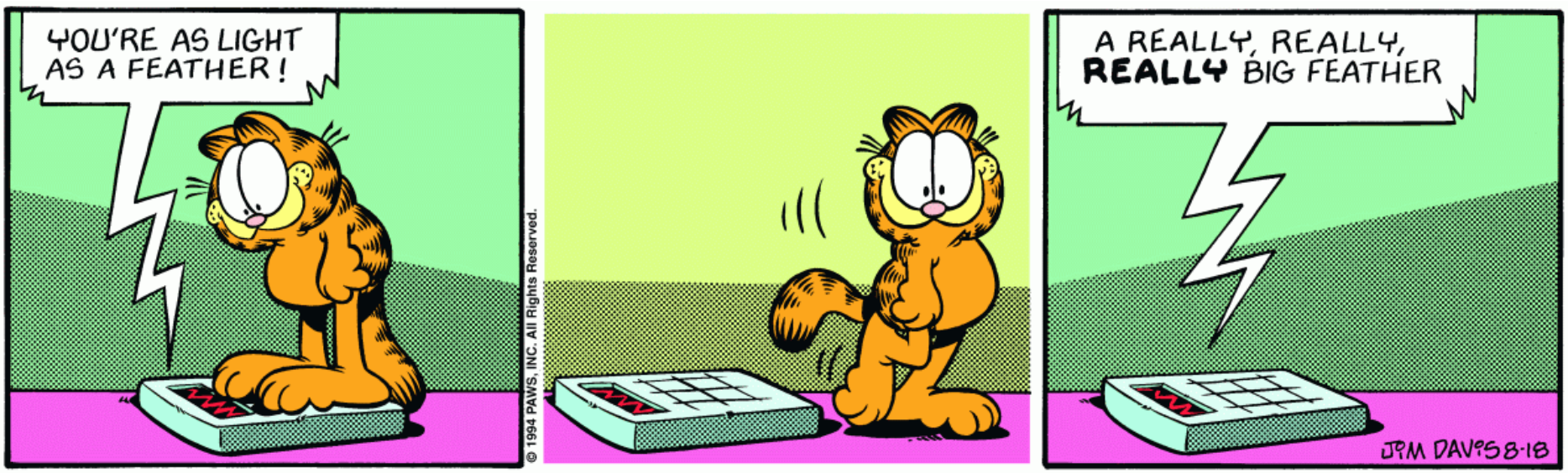
Paper I

Even a small amount of massive neutrinos leaves a huge trace in the distribution of galaxies on the largest observables scales



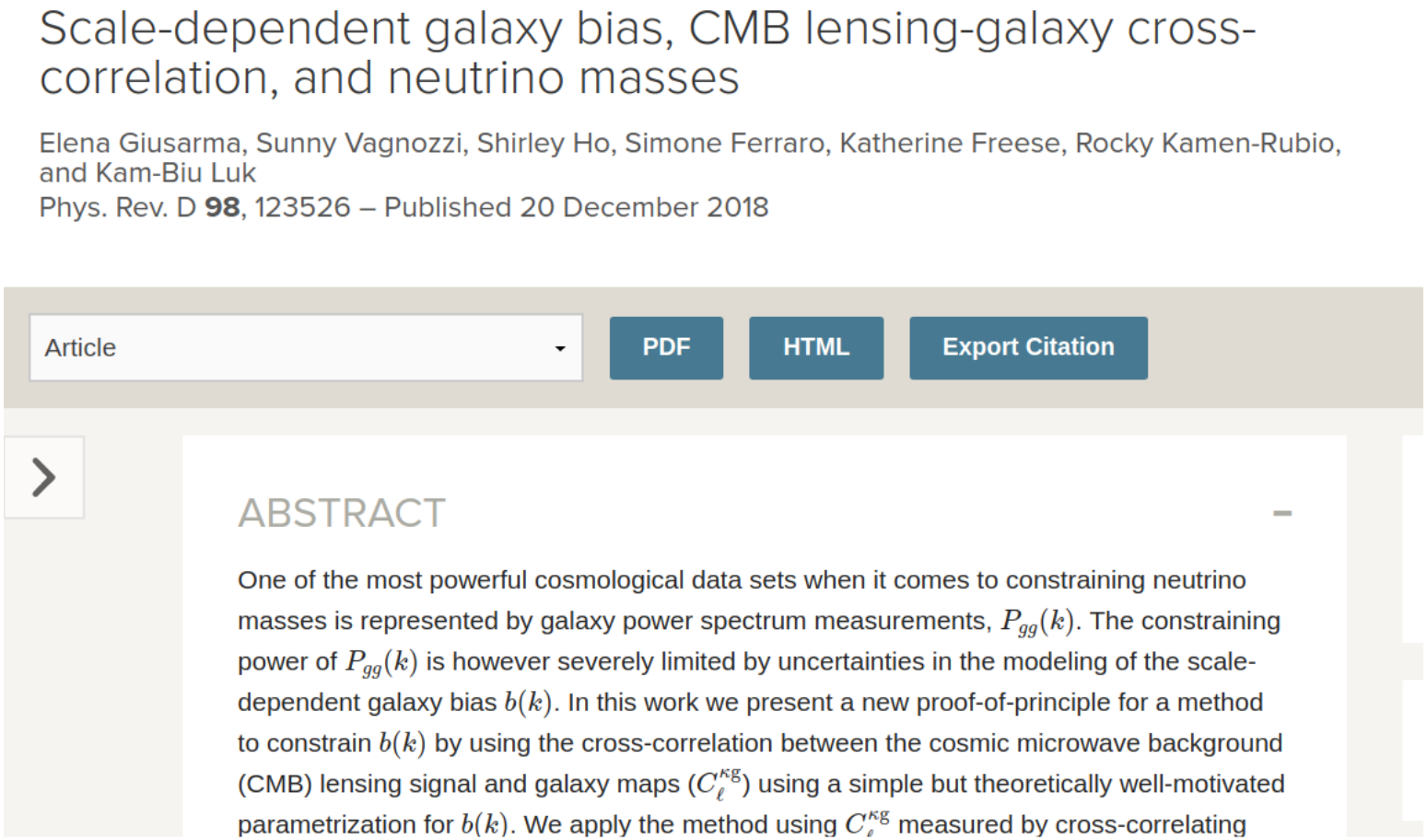
Paper I

$$M_\nu < \frac{1}{100000000000000000000000000000000} \text{ kg}$$



Paper II

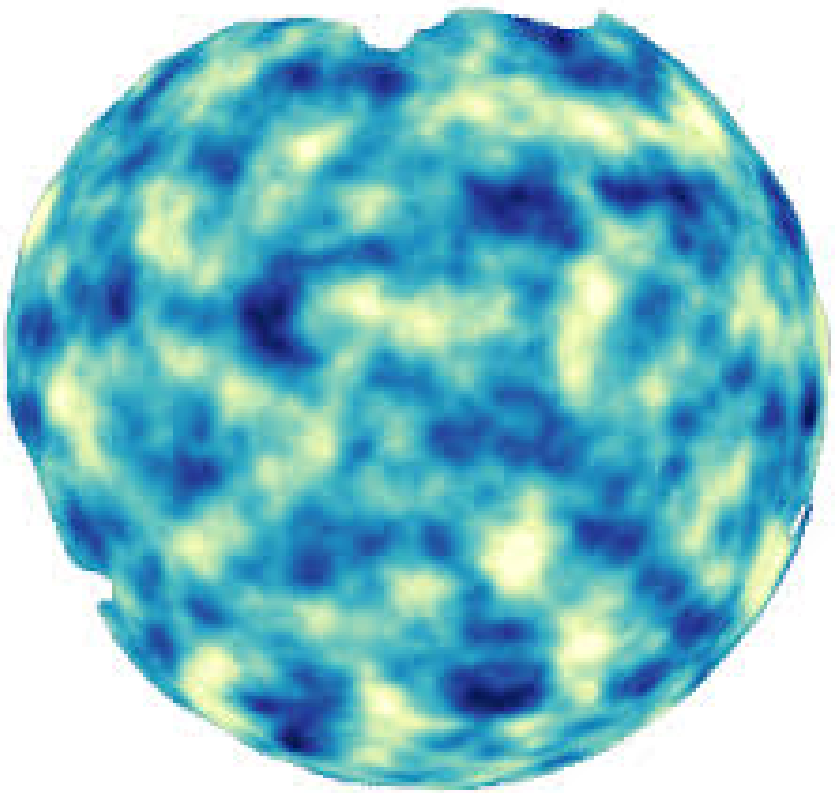
Elena Giusarma, **Sunny Vagnozzi**, Shirley Ho, Simone Ferraro, Katie Freese, Rocky Kamen-Rubio, Kam-Biu Luk, *Phys. Rev.* D **98** (2018) 123526 [arXiv:1802.08694]
Scale-dependent galaxy bias: can we nail it through CMB lensing-galaxy cross-correlations and learn more about neutrinos?



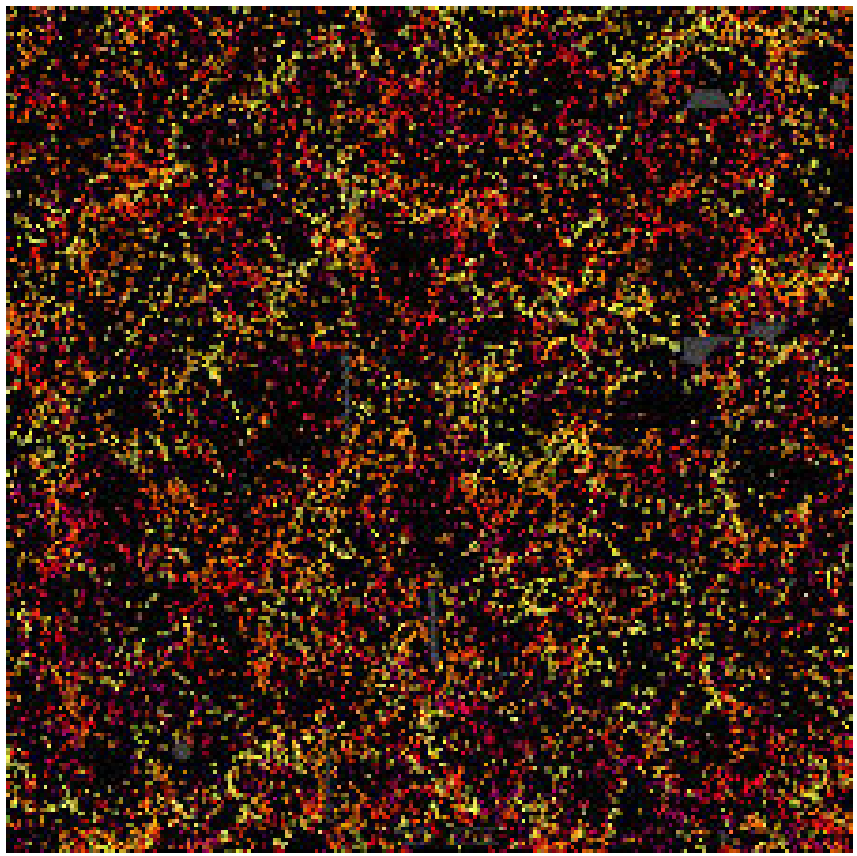
Paper II

Galaxy bias

CMB lensing-galaxy cross-correlation



$\times$



Paper III

Sunny Vagnozzi, Thejs Brinckmann, Maria Archidiacono, Katie Freese, Martina Gerbino, Julien Lesgourgues, Tim Sprenger, *JCAP* **1809** (2018) 001 [arXiv:1807.04672]
Scale-dependent galaxy bias induced by neutrinos: why we should worry, and a simple correction implemented in CLASS

SISSA

Bias due to neutrinos must not uncorrect'd go

Sunny Vagnozzi[a,b], Thejs Brinckmann[c], Maria Archidiacono[c], Katherine Freese[a,b,d], Martina Gerbino[a], Julien Lesgourgues[c] and Tim Sprenger[c]

Published 3 September 2018 • © 2018 IOP Publishing Ltd and Sissa Medialab
Journal of Cosmology and Astroparticle Physics, Volume 2018, September 2018

Article PDF

+ Article information

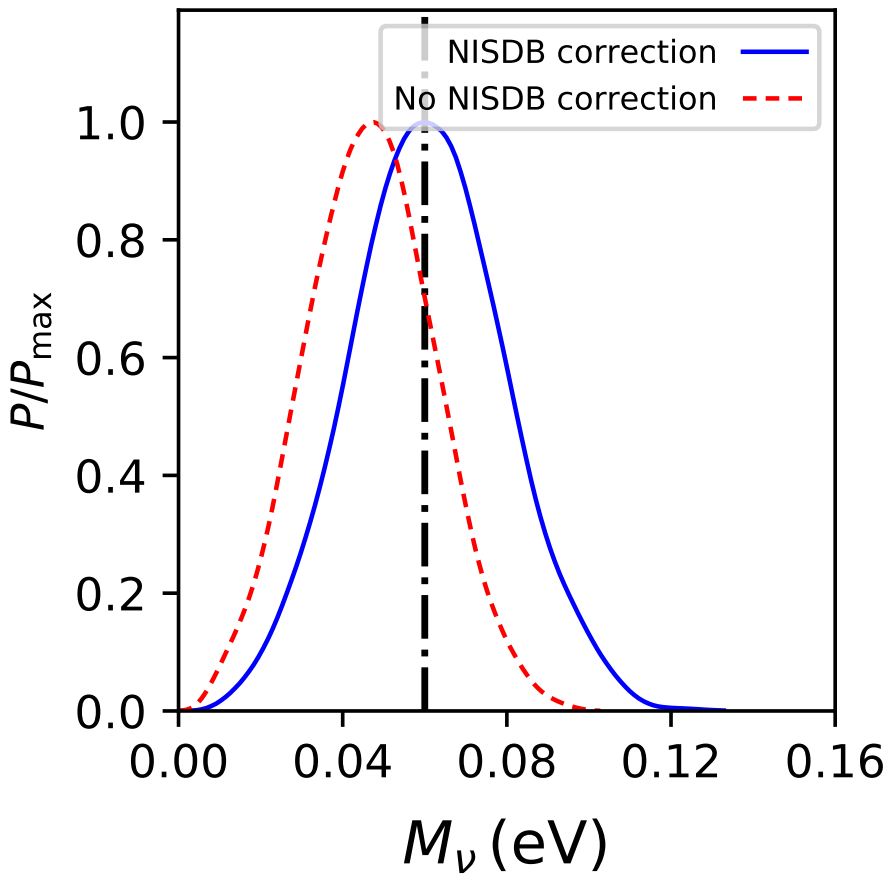
Abstract

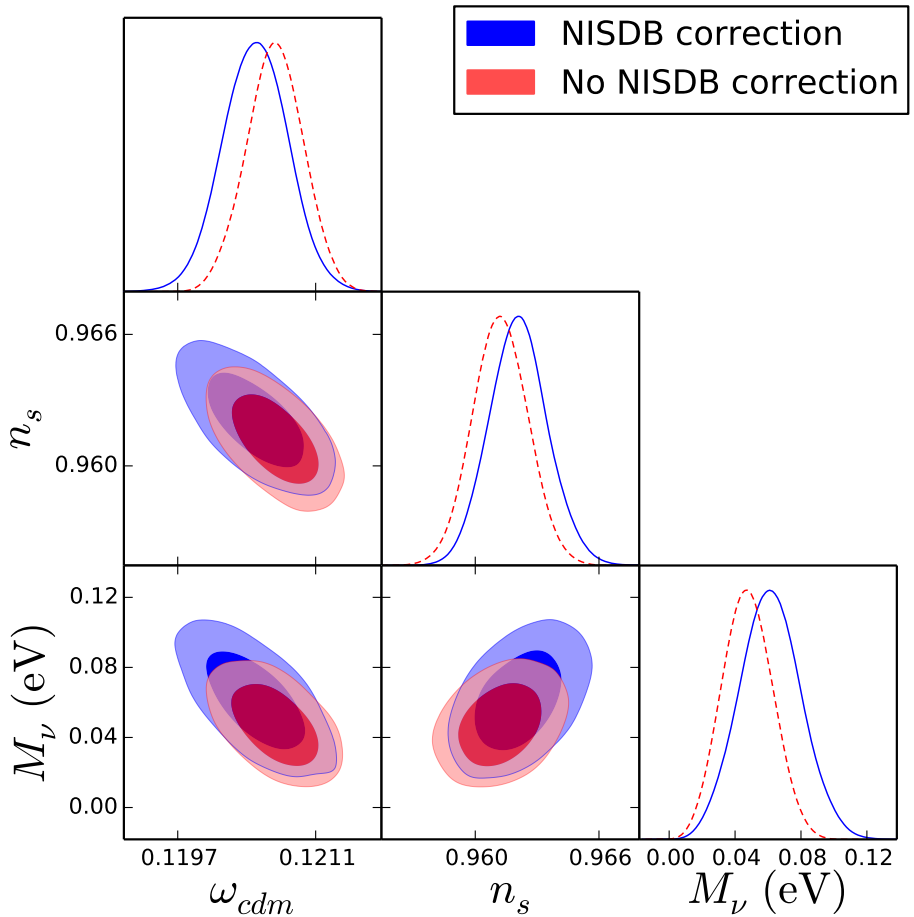
Abstract

It is a well known fact that galaxies are biased tracers of the distribution of matter in the Universe. The galaxy bias is usually factored as a function of redshift and scale, and approximated as being scale-independent on large, linear scales. In cosmologies with massive neutrinos, the galaxy bias defined with respect to the total matter field (cold dark matter, baryons, and non-relativistic neutrinos) also depends on the sum of the neutrino masses M_ν, and becomes scale-dependent even on large scales. This effect has been usually neglected given the sensitivity of current surveys. However, it becomes a severe systematic

Paper III

Paper III


NISDB correction
No NISDB correction
1.0
0.8
0.6
0.4
0.2
0.0
$P/P_{\max}$
0.00
0.04
0.08
0.12
0.16
M_ν (eV)


NISDB correction
No NISDB correction
n_s
0.966
0.960
M_ν (eV)
0.12
0.08
0.04
0.00
0.1197
0.1211
ω_{cdm}
0.960
0.966
n_s
0.00
0.04
0.08
0.12
M_ν (eV)

Paper IV

Sunny Vagnozzi, Suhail Dhawan, Martina Gerbino, Katie Freese, Ariel Goobar, Olga Mena, *Phys. Rev.* D **98** (2018) 083501 [arXiv:1801.08553]

Can the neutrino mass ordering and laboratory experiments tell us something about dark energy and the fate of the Universe ("*Where are we going?*")?

Constraints on the sum of the neutrino masses in dynamical dark energy models with $w(z) \geq -1$ are tighter than those obtained in ΛCDM

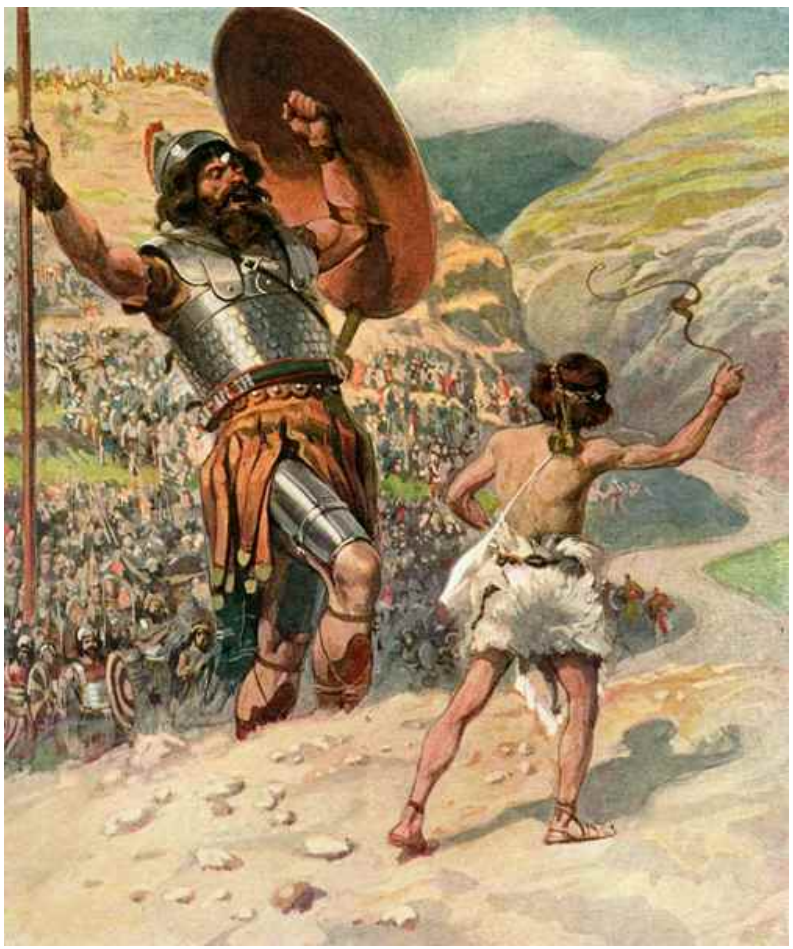
Sunny Vagnozzi, Suhail Dhawan, Martina Gerbino, Katherine Freese, Ariel Goobar, and Olga Mena
Phys. Rev. D **98**, 083501 – Published 1 October 2018

Article | PDF | HTML | Export Citation

ABSTRACT

We explore cosmological constraints on the sum of the three active neutrino masses M_ν in the context of dynamical dark energy (DDE) models with equation of state (EoS) parametrized as a function of redshift z by $w(z) = w_0 + w_a z/(1+z)$, and satisfying $w(z) \geq -1$ for all z. We make use of cosmic microwave background data from the Planck satellite, baryon acoustic oscillation measurements, and supernovae Ia luminosity distance measurements, and perform a Bayesian analysis. We show that, within these models, the bounds on M_ν *do not degrade* with respect to those obtained in the ΛCDM case; in fact, the bounds are slightly tighter, despite the enlarged parameter space. We explain our

Paper IV




UEFA CHAMPIONS LEAGUE
QATAR
Jeep
JUVENTUS 3-0 BARCELONA
BARCELONA HAVE CONCEDED 7 TIMES IN THEIR LAST TWO AWAY CHAMPIONS LEAGUE MATCHES

Paper IV

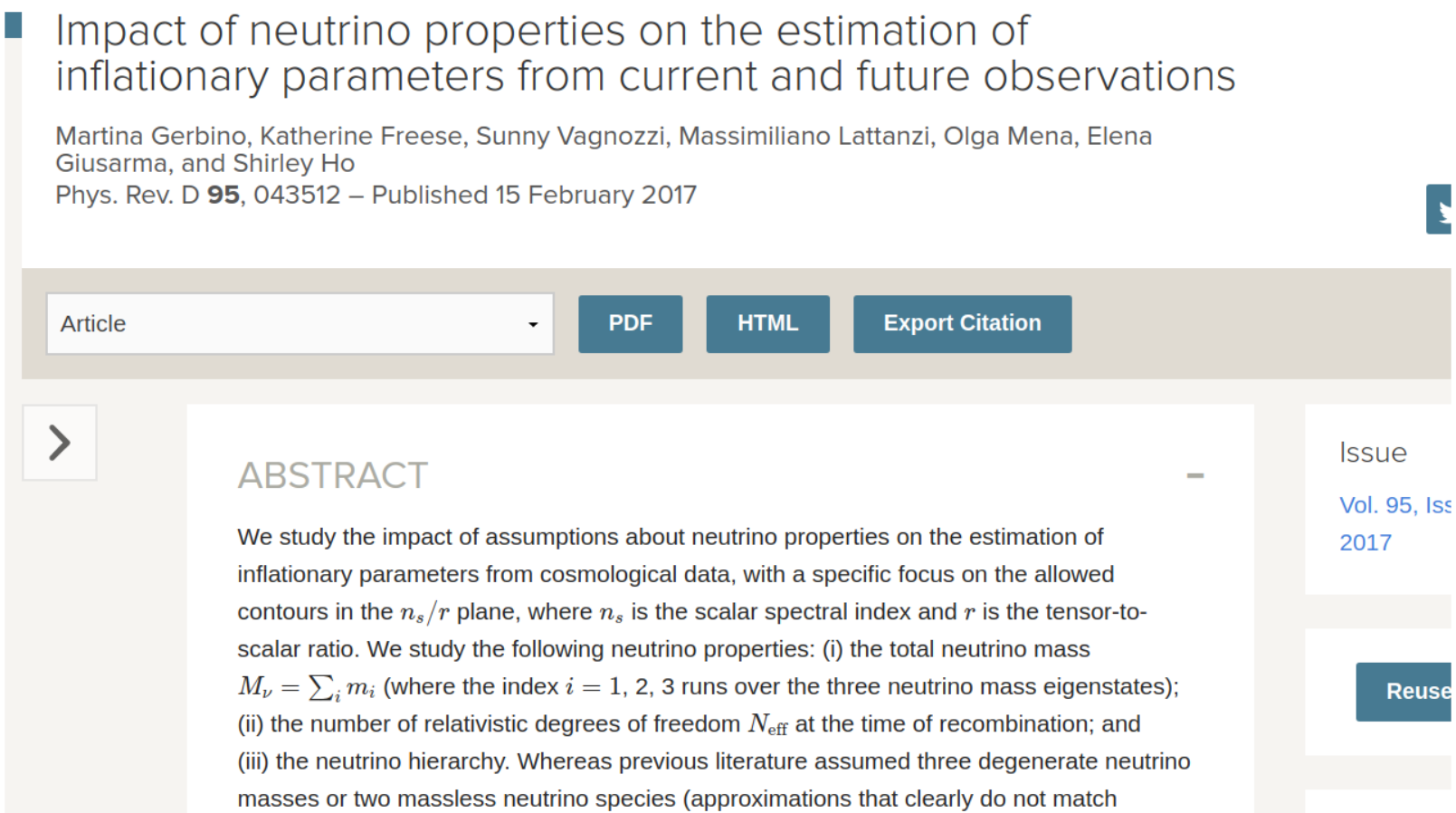
Rules of the game:

- Choose your favourite dark energy model (Goliath).
- Compute upper limit on M_ν using *only* cosmological information (David).
- If limit does not contract lower limit from oscillations ($0.06\,\mathrm{eV}$), your model is not ruled out (yet), else you have a problem!

Paper V

Martina Gerbino, Katie Freese, **Sunny Vagnozzi**, Massimiliano Lattanzi, Olga Mena, Elena Giusarma, Shirley Ho, *Phys. Rev.* D **95** (2017) 043512 [arXiv:1610.08830]

Neutrinos as a nuisance: can they mess up our conclusions about inflation and the initial conditions of the Universe ("*Where do we come from?*")?



Impact of neutrino properties on the estimation of inflationary parameters from current and future observations

Martina Gerbino, Katherine Freese, Sunny Vagnozzi, Massimiliano Lattanzi, Olga Mena, Elena Giusarma, and Shirley Ho

Phys. Rev. D **95**, 043512 – Published 15 February 2017

Article | PDF | HTML | Export Citation

ABSTRACT

We study the impact of assumptions about neutrino properties on the estimation of inflationary parameters from cosmological data, with a specific focus on the allowed contours in the n_s/r plane, where n_s is the scalar spectral index and r is the tensor-to-scalar ratio. We study the following neutrino properties: (i) the total neutrino mass $M_\nu = \sum_i m_i$ (where the index $i = 1, 2, 3$ runs over the three neutrino mass eigenstates); (ii) the number of relativistic degrees of freedom $N_{\rm eff}$ at the time of recombination; and (iii) the neutrino hierarchy. Whereas previous literature assumed three degenerate neutrino masses or two massless neutrino species (approximations that clearly do not match

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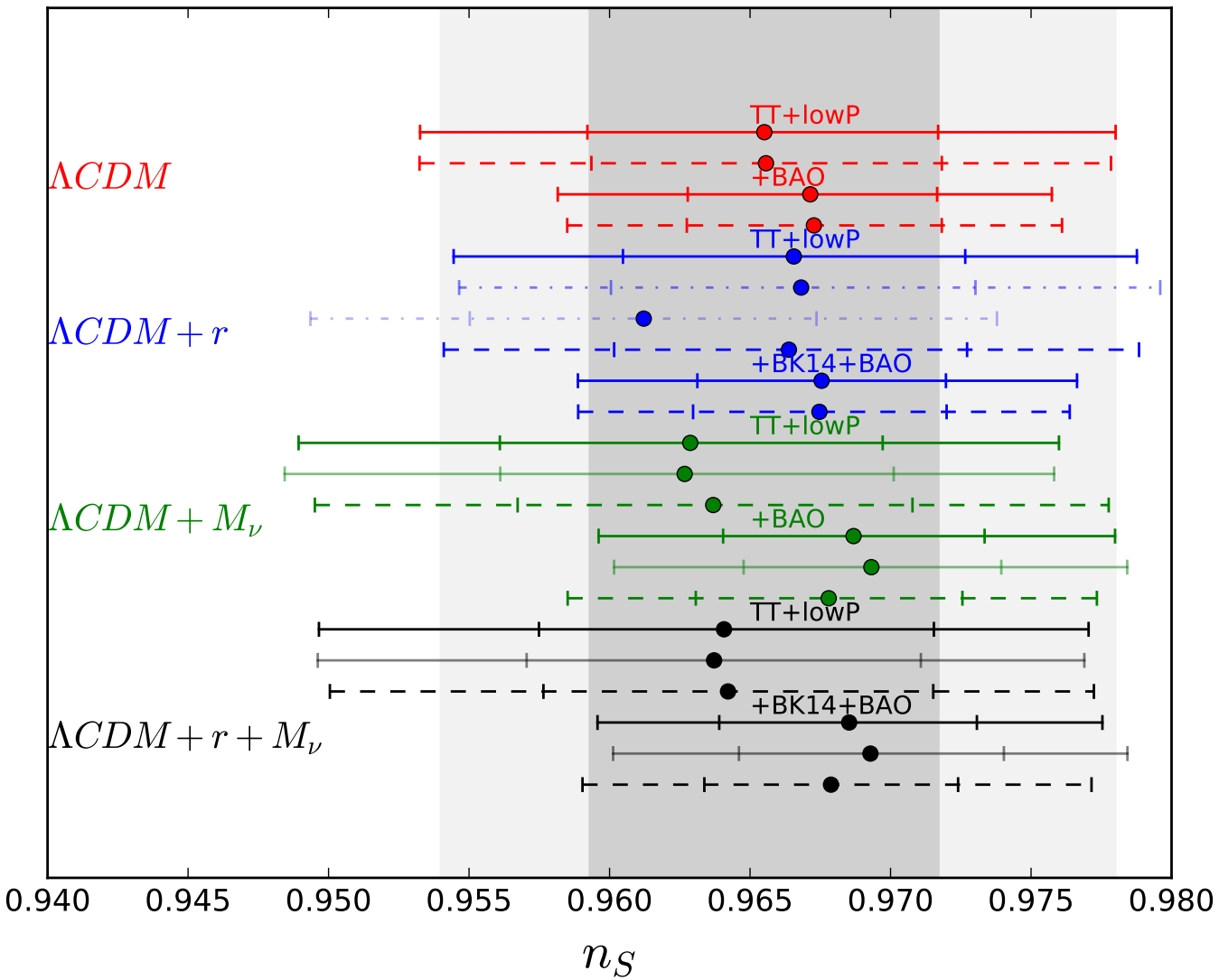
Reuse

Paper V

Big Bang sets initial conditions for the Universe...

...something (apparently) messes them up?

Paper V

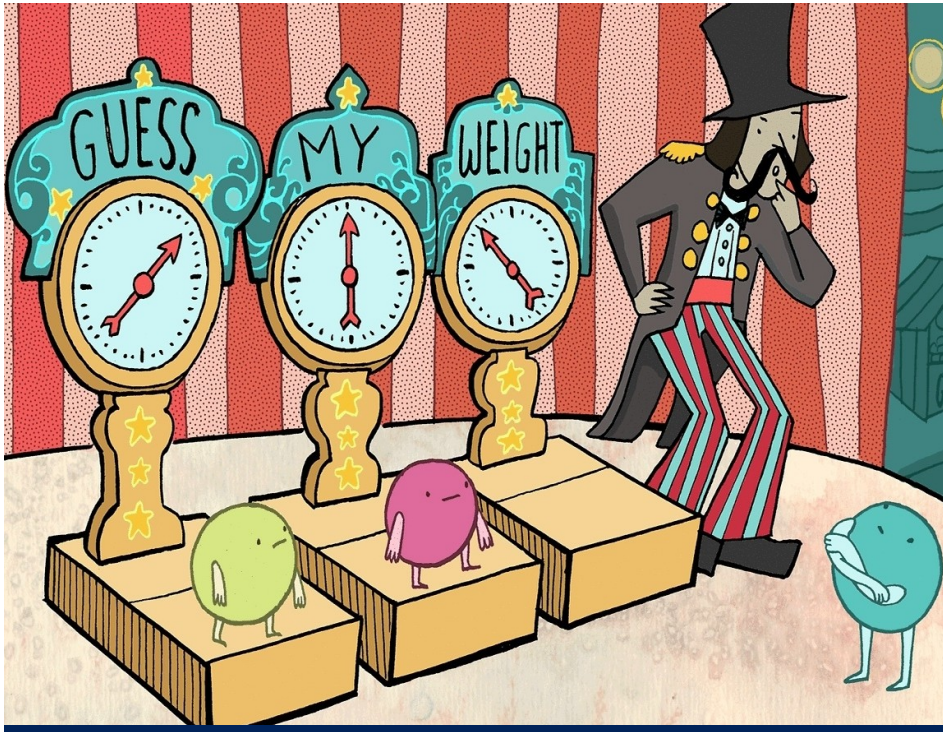

ΛCDM
$\Lambda CDM + r$
$\Lambda CDM + M_\nu$
$\Lambda CDM + r + M_\nu$
TT+lowP
+BAO
TT+lowP
+BK14+BAO
TT+lowP
+BAO
TT+lowP
+BK14+BAO
0.940
0.945
0.950
0.955
0.960
0.965
0.970
0.975
0.980
n_S

Stockholm University

Weigh them all!

Cosmological searches for the neutrino mass scale and mass ordering

Sunny Vagnozzi



Doctoral Thesis in Theoretical Physics at Stockholm University, Sweden 2019

Thank you!