Hubble tension, dark matter and neutrino

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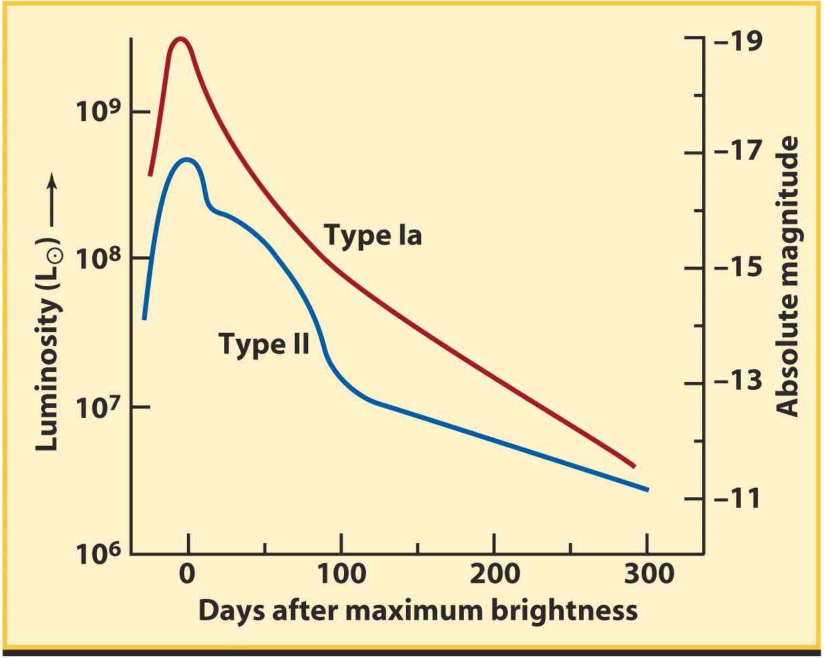
Type Ia supernova

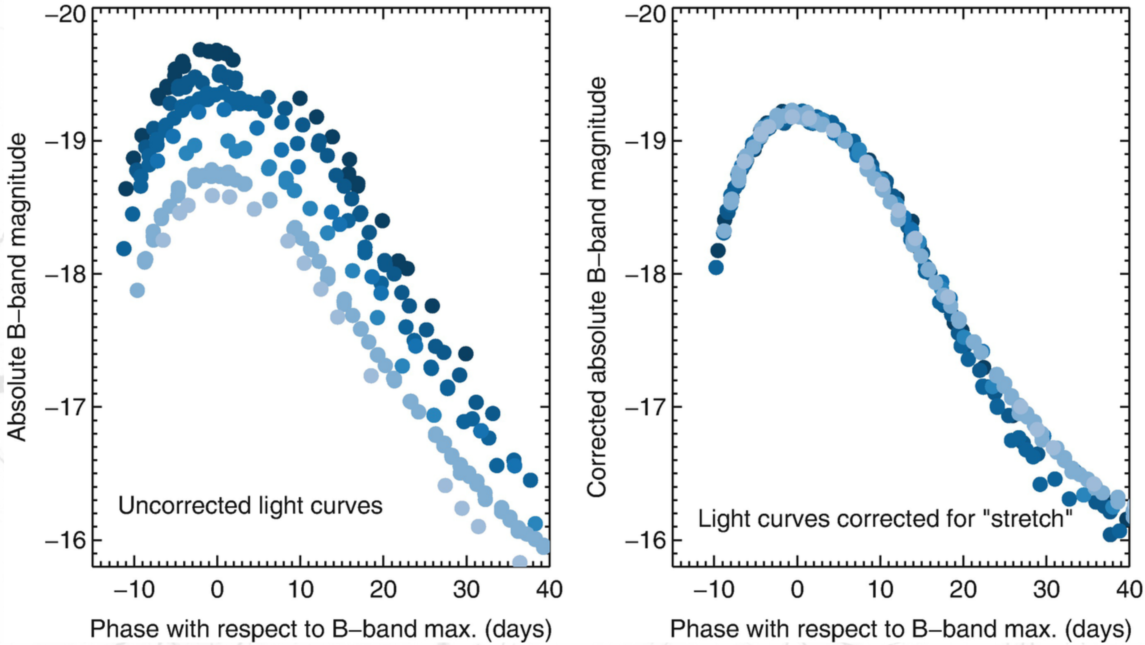
- A Type Ia supernova, also known as a “type one-A” supernova, is a type of supernova that happens in binary systems, or pairs of stars that orbit each other, where one of the stars is a white dwarf. The other star could be anything from a big star to a white dwarf, which is even smaller.
- The mass of slow-rotating carbon-oxygen white dwarfs is less than 1.44 $M_{\odot}$ (solar masses).
- The general hypothesis is that a white dwarf’s core will achieve the ignition temperature for carbon fission as it approaches the Chandrasekhar mass if it gradually absorbs mass from a binary companion or merges with a second white dwarf.
- A significant fraction of the white dwarf’s material undergoes a runaway reaction shortly after nuclear fusion begins, releasing enough energy to break the star and cause a supernova explosion.

Use of type Ia supernovae

- Perlmutter, Schmidt, and Reiss received the Nobel Prize in Physics in 2011 for their finding that the universe is expanding faster than previously thought.
- The research, which was based on studies of far-off supernovae, supported the notion that the cosmos contains both dark energy and dark matter.
- Especially Type Ia supernovae, whose steady light curves serve as benchmark candles for calculating cosmic distances.
- Now, a fresh investigation into more than 1,500 supernovae proves the existence of dark energy and dark matter while also casting doubt on our current cosmological models.



Luminosity ($L_\odot$) ⟶
10^9
10^8
10^7
10^6
Type Ia
Type II
0
100
200
300
Days after maximum brightness
−19
−17
−15
−13
−11
Absolute magnitude


Absolute B−band magnitude
−20
−19
−18
−17
−16
−10
0
10
20
30
40
Phase with respect to B−band max. (days)
Uncorrected light curves
Corrected absolute B−band magnitude
Light curves corrected for "stretch"

Type Ia supernovae measurements

- The study is based on datasets known as Pantheon+ and SH_0ES (Supernovae and H_0 for the Equation of State of dark energy).
- It contains 1,701 light-curve measurements of 1,550 Type Ia supernovae spanning two decades of observations and a cosmic period of 10 billion years.
- It is the most comprehensive survey of dark energy supernova measurements ever made.
- The data set covers the transition from the early universe, which was dominated by dark matter, to the modern universe, which is dominated by dark energy. Thus, it confirms the effects of both of these.
- The data set is so detailed that it also gives us a measure of the Hubble parameter with an accuracy of five sigma, which rules out systematic errors in the measurements.
- According to this information, our universe is made up of roughly two thirds dark energy, one third matter, and one third dark matter.

Different Hubble parameters

- A measurement of the speed at which the universe is expanding is the Hubble parameter, sometimes known as the Hubble constant.
- But this is where things start to get weird. We have analyzed the effects of dark matter and dark energy in a variety of ways over the years.
- In addition to supernova observations, we also detect gravitational waves, the long-term clustering of galaxies, microwave laser light, and variations in the cosmic background.
- They all portray a universe where dark matter and dark energy predominate. However, they don't precisely tell the same tale.
- This is most clearly seen from the discrepancies in the values of the Hubble parameters.

Hubble tension

- Since 2001, we have known that the Hubble parameter ranges from 64 to 80 (km/s)/Mpc, indicating that the universe is 12.5 to 15.6 billion years old. We were not really clear on the precise value at the time.
- Since then, as we have improved the accuracy of our observations, the value has been reduced to roughly 70 (km/s)/Mpc, or 14 billion years.
- The issue is that observations of supernovae provide a value greater than 70, while measurements of the cosmic background produce a value slightly below 70.
- It was believed that more accurate observations would settle this dispute, known as the Hubble tension.
- However, the current experimental investigation demonstrates that it is both real and persistent.

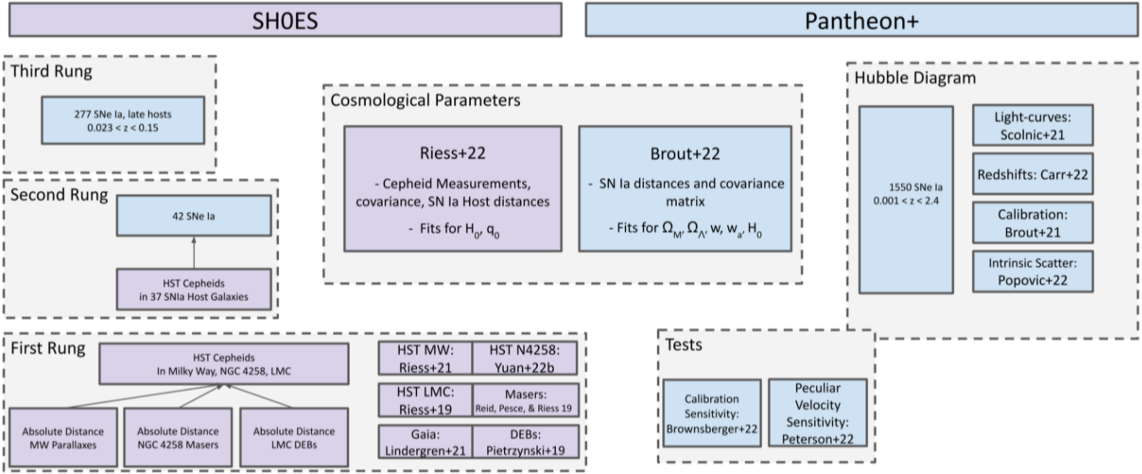
Hubble tension still there

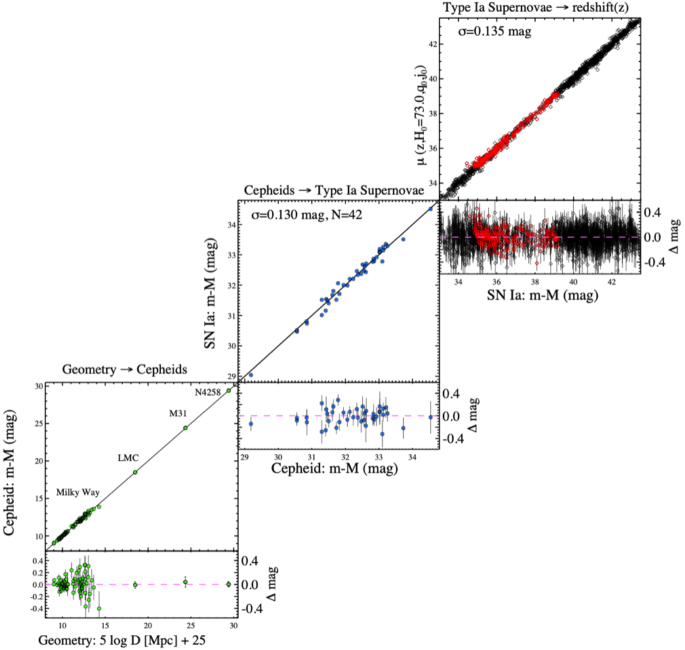
- Pantheon+ data were recently used to examine two different outcomes.
- The Pantheon+ SH_0ES supernova estimate yields a Hubble parameter of 72-74 (km/s)/Mpc.
- The Pantheon+ Planck cosmic background measurement yields a Hubble parameter of 66-68 (km/s)/Mpc.
- Both are very accurate, but they are in conflict with one another.
- The research supports the existence of the Hubble tension.
- We cannot argue that one or the other is incorrect because there is no measurement error involved.

Hubble tension still holds (October, 2022)

- Recent analysis (Focus on Consistently Calibrated Cosmic Distances from Pantheon+ SH_0ES):

  Brout, Dillon, et al.
  "The Pantheon+ Analysis: Cosmological Constraints",
  The Astrophysical Journal, **938** *no.2, 110 (2022),*
  arXiv:2202.04077,
  doi:10.3847/1538-4357/ac8e04


SH0ES
Pantheon+
Third Rung
277 SNe Ia, late hosts
0.023 < z < 0.15
Second Rung
42 SNe Ia
HST Cepheids
in 37 SNIa Host Galaxies
First Rung
HST Cepheids
In Milky Way, NGC 4258, LMC
Absolute Distance
MW Parallaxes
Absolute Distance
NGC 4258 Masers
Absolute Distance
LMC DEBs
HST MW:
Riess+21
HST N4258:
Yuan+22b
HST LMC:
Riess+19
Masers:
Reid, Pesce, & Riess 19
Gaia:
Lindergren+21
DEBs:
Pietrzynski+19
Cosmological Parameters
Riess+22
- Cepheid Measurements, covariance, SN Ia Host distances
- Fits for H_0, q_0
Brout+22
- SN Ia distances and covariance matrix
- Fits for Ω_M, Ω_Λ, w, w_a, H_0
Hubble Diagram
1550 SNe Ia
0.001 < z < 2.4
Light-curves:
Scolnic+21
Redshifts: Carr+22
Calibration:
Brout+21
Intrinsic Scatter:
Popovic+22
Tests
Calibration
Sensitivity:
Brownsberger+22
Peculiar
Velocity
Sensitivity:
Peterson+22



Type Ia Supernovae → redshift(z)
σ=0.135 mag
μ (z,H0=73.0,q0,j0)
Δ mag
SN Ia: m-M (mag)
Cepheids → Type Ia Supernovae
σ=0.130 mag, N=42
SN Ia: m-M (mag)
Δ mag
Cepheid: m-M (mag)
Geometry → Cepheids
N4258
M31
LMC
Milky Way
Cepheid: m-M (mag)
Δ mag
Geometry: 5 log D [Mpc] + 25

How can the findings of particle physics be useful?

- Primarily, if we find out anything about dark matter, it might make us rethink how we interpret our observations in general, possibly in a way we hadn't considered because dark matter might be hot rather than cold or something else that interacts in entirely new ways.
- An alternative possibility is neutrinos. There are neutrinos that don't behave as predicted by the Standard Model but nonetheless match the CMB measurements in some scenarios.

How can the findings of particle physics be useful?

- Before the Hubble tension, the hope was to claim that we have this fantastic cosmological model that fits incredibly well and shows that our universe is extremely dull.
- Then, by restricting neutrino masses or the temperature of dark matter, for instance, we could have utilized that to eventually make the connection to particle physics.
- However, we must exercise caution when playing this game if the cosmos is not maximally uninteresting, as it may be considerably more interesting than we had thought.

H_0 measurements and sterile neutrino property reconstruction from a model-independent joint analysis

- We discovered that the extra radiation in active neutrinos produced just before Big Bang nucleosynthesis by an unstable sterile neutrino with mass $m_s = O(1-3)\ eV$ can reduce this discrepancy with $\sin^2 2\theta = 0.2$ to 0.45 and $N_{eff} \simeq 3.05$.
- A stricter upper limit for the sum of active neutrino masses of 0.09 eV is obtained in a 2021 analysis that includes redshift space distortion measurements from the SDSS-IV (Sloan Digital Sky Survey) eBOSS (The Extended Baryon Oscillation Spectroscopic Survey) survey.

Di Valentino, Eleonora; Gariazzo, Stefano; Mena, Olga
"On the most constraining cosmological neutrino mass bounds",
Physical Review D **104** *083504 (2021),*
arXiv:2106.15267,
doi:10.1103/PhysRevD.104.083504

Confirming BEST and Neutrino-4 experiments

- The Baksan Experiment on Sterile Transitions (BEST):
  $\Delta m^2 = 3.3^{+\infty}_{-2.3}\ eV^2$ and $\sin^2 2\theta = 0.42^{+0.15}_{-0.17}$

  V.V. Barinov, et al.
  "A Search for Electron Neutrino Transitions to Sterile States in the BEST Experiment",
  Physical Review C ***105*** *065502 (2022),*
  arXiv:2201.07364,
  doi:10.1103/PhysRevC.105.065502

Confirming BEST and Neutrino-4 experiments

- The Neutrino-4 Experiment, SM-3 reactor (Dimitrovgrad, Russia):
  $\Delta m^2_{14} = 7.3 \pm 1.7$ eV^2 and $\sin^2 2\theta_{14} = 0.36 \pm 0.12_{\mathrm{stat}}$ (2.9σ)
  Assuming $m^2_4 \approx \Delta m^2_{14}$, $m_4 = 2.70 \pm 0.22$ eV

  A.P. Serebrov, et al.
  "Preparation of the Neutrino-4 experiment on search for sterile neutrino and the obtained results of measurements",
  Physical Review D **104** *032003 (2021),*
  arXiv:2005.05301,
  doi:10.1103/PhysRevD.104.032003

In addition to removing the Hubble tension, our theoretical findings also support the results of two Russian neutrino experiments.