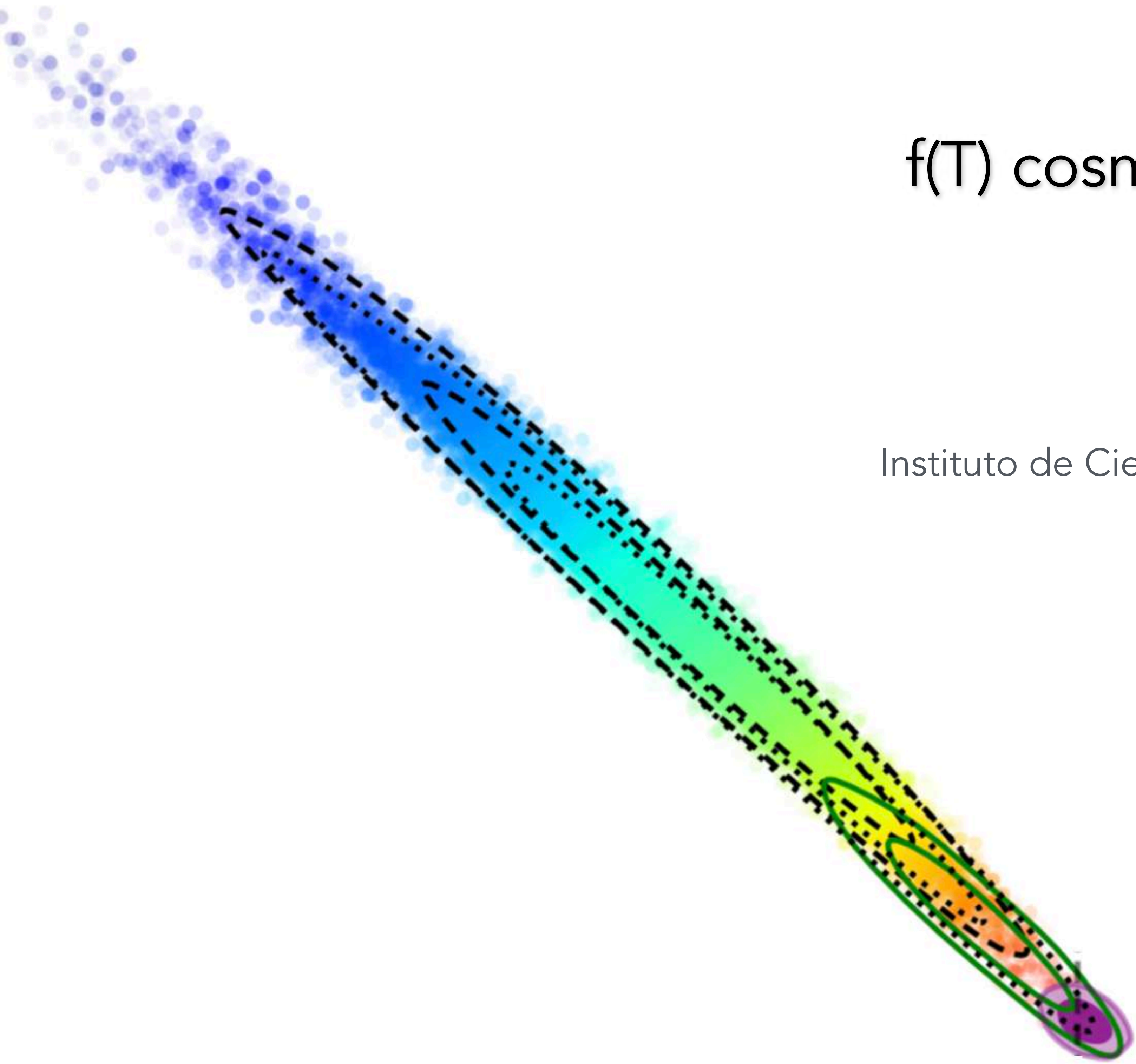
f(T) cosmology in the regime of quasar observations



Celia Escamilla-Rivera
Instituto de Ciencias Nucleares (ICN UNAM, Mexico)
Royal Astronomical Society (RAS, UK)

Workshop on Tensions in Cosmology
September 6-13 2023. Corfu, Greece

http://celrivera.wix.com/cosmology | celia.escamilla@nucleares.unam.mx

Outline

Setting the scene:

- **Cosmology Intertwined: the state-of-art**

The precision problem:

- Beyond the standard cosmology

The work:

- Beyond Einstein's gravity and its constraints

LCDM gravity model
(GR+FLRW)

+

Data
(CMB, SN, BAO, GW,…)

=

Inconsistency : Dark matter + Dark energy

Issues: Cosmological Tensions

New Physics?

Initial Conditions	Cosmic Structure	Late acceleration
Inflation	Dark Matter	Λ
Primordial GWs?	Ultra-light/Axion? Primordial BHs?	Modified Gravity?

Cosmology Intertwined: Snowmass Collaboration

Perspectives for the next decade
[E. Di Valentino, et al. Astropart.Phys. 131 (2021) 102606]

The Hubble constant tension
[E. Di Valentino, et al. Astropart.Phys. 131 (2021) 102605]

The age of the universe and its curvature
[E. Di Valentino, et al. Astropart.Phys. 131 (2021) 102607]

$f\sigma_8$ and S_8
[E. Di Valentino, et al. Astropart.Phys. 131 (2021) 102604]

Cosmological models to solve S_8 (and H_0) tension

Early times

- Decaying dark matter

Late times

- Interacting dark energy
- Running vacuum models

Beyond

★ Modified and Extended Gravity models
- Beyond-FLRW framework

★ Topic treated in this talk

Cosmology Intertwined: Snowmass Collaboration and Cosmoverse

Perspectives for the next decade
[E. Di Valentino, et al. Astropart.Phys. 131 (2021) 102606]

The Hubble constant tension
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$f\sigma_8$ and S_8
[E. Di Valentino, et al. Astropart.Phys. 131 (2021) 102604]

★ Improve our understanding of systematic uncertainties

★ Maximize the amount of information that can be extracted from the data

• Improve our understanding of the physics on non-linear scales

★ *De-standardize* some of the LCDM assumptions.

★ Topic treated in this talk

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Two paths to infer/measure H_0...

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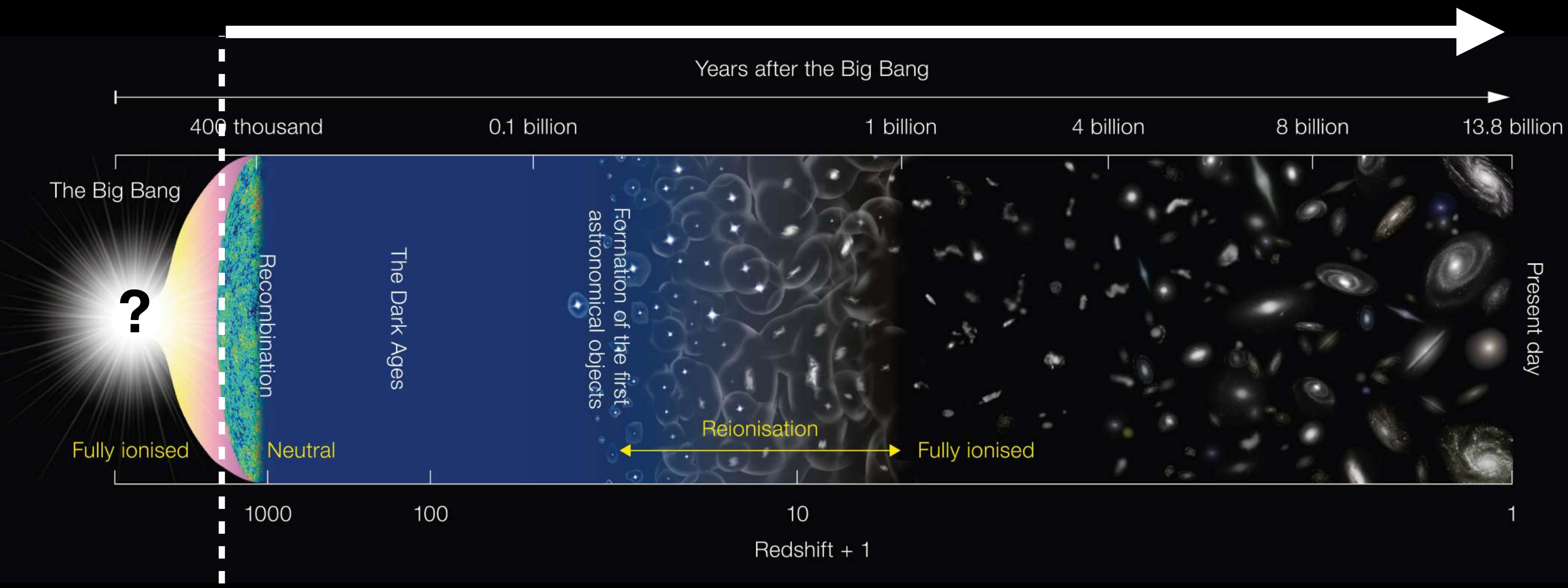
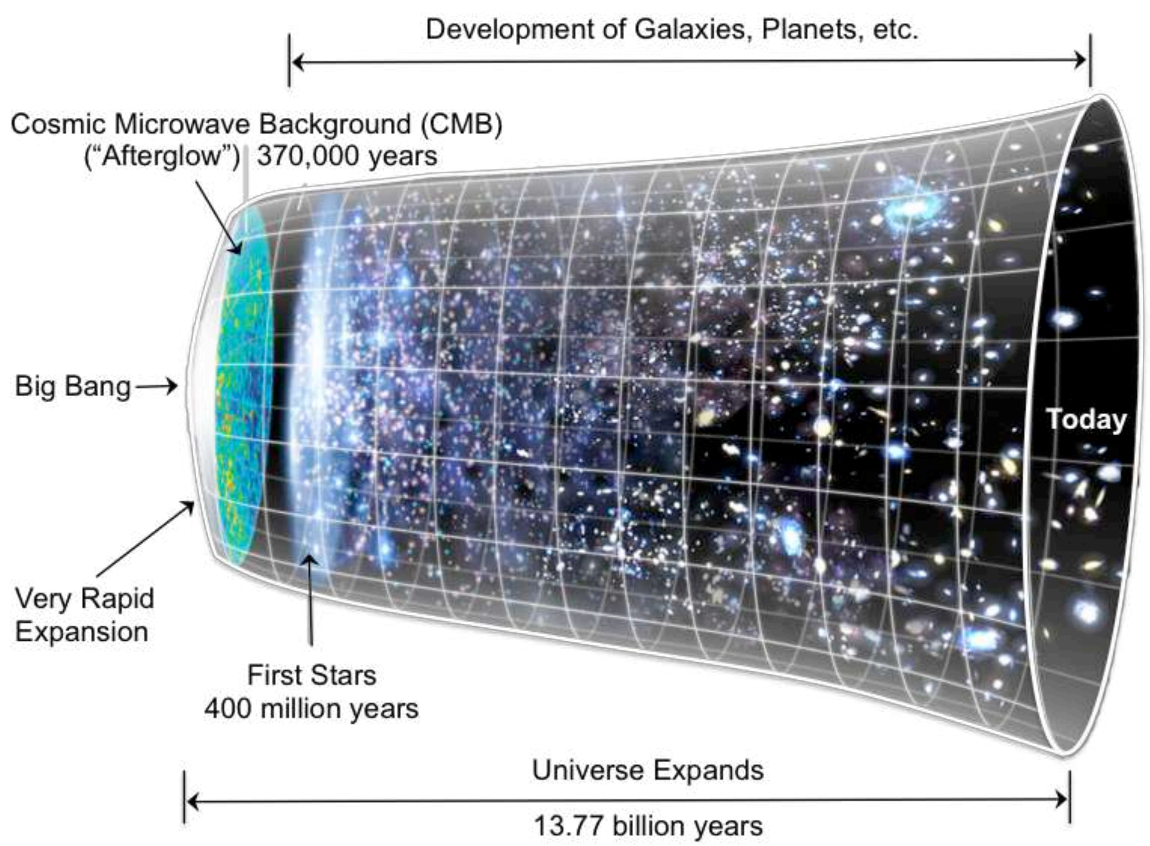
From early cosmic times until today



Cosmic Microwave Background Radiation (CMB)

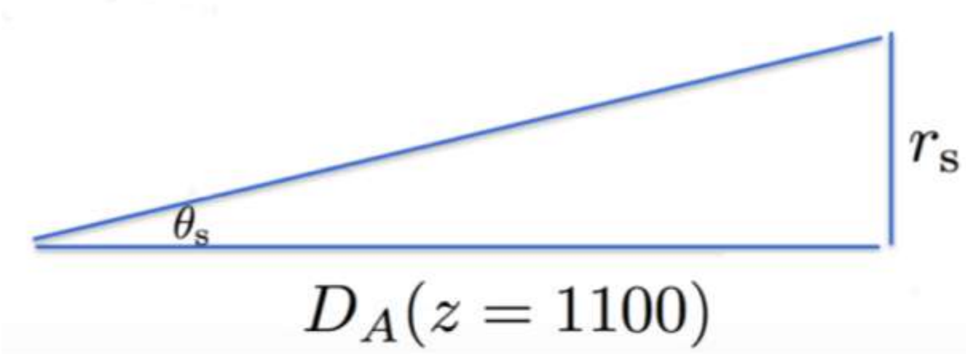
$$d_A(z) = \frac{1}{1+z}\frac{1}{H_0\sqrt{\Omega_K}}\sinh\left[H_0\sqrt{\Omega_K}\int_0^z \frac{dz'}{H(z')}\right]$$



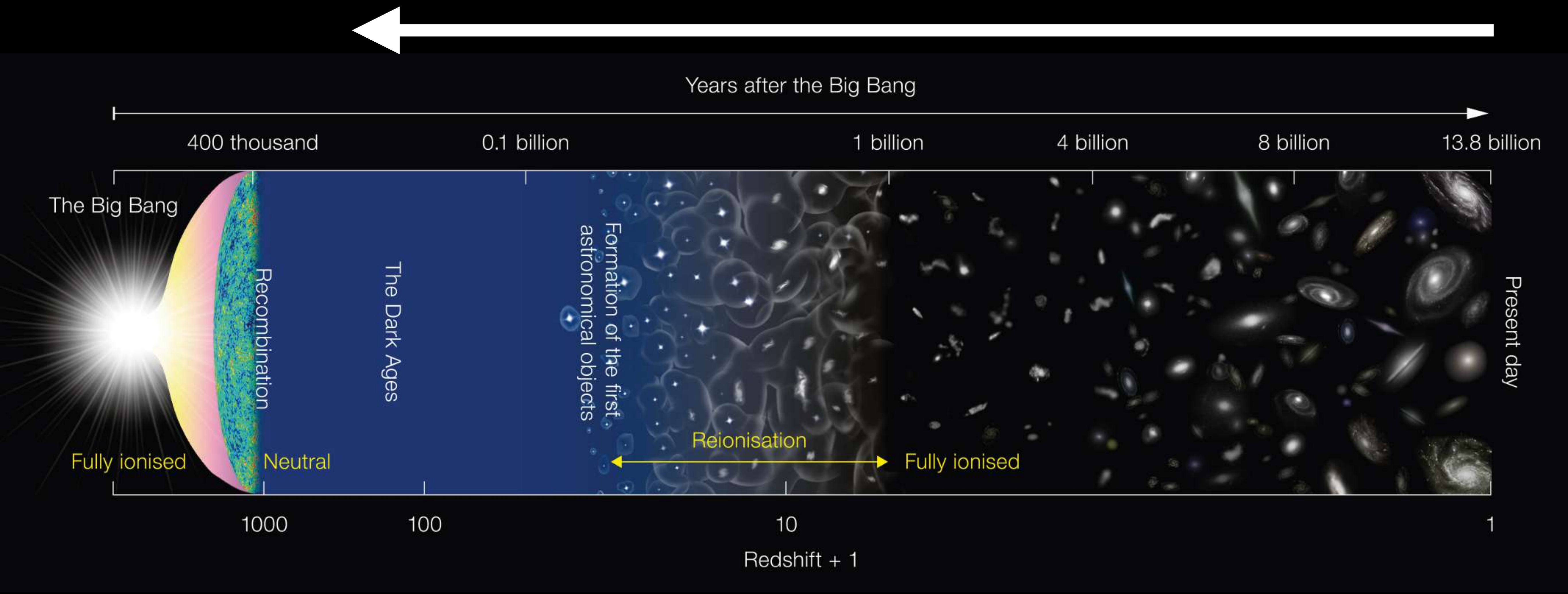
Nobel Prize in Physics 2019

"for theoretical discoveries in cosmology" and "for the discovery of an exoplanet orbiting a solar-type star".

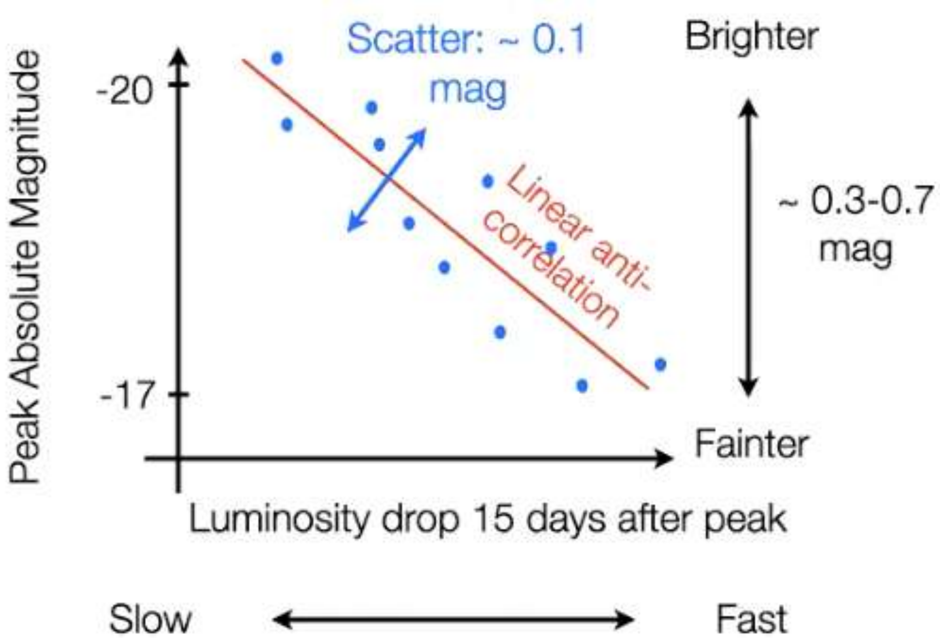
The CMB as a (self-calibrated) standard ruler



From today up to early cosmic times



Supernovae Type Ia

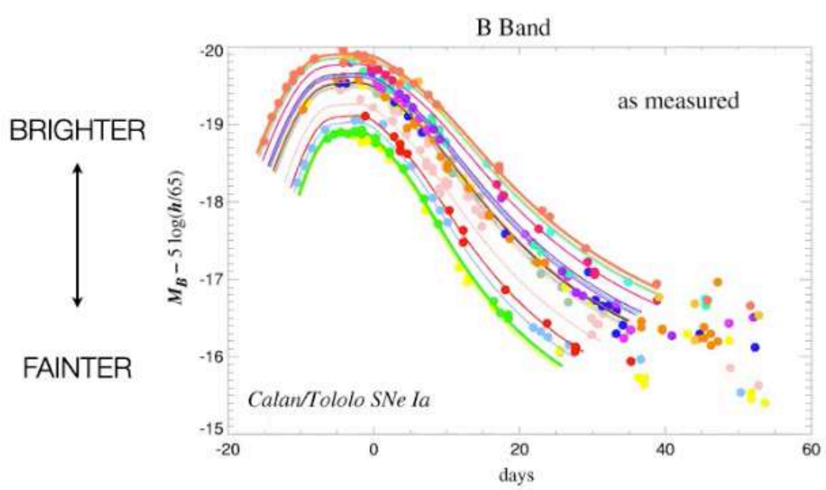


$$d_L(z) = (1+z)\frac{1}{H_0\sqrt{\Omega_K}} \sinh\left[H_0\sqrt{\Omega_K}\int_0^z \frac{dz'}{H(z')}\right]$$

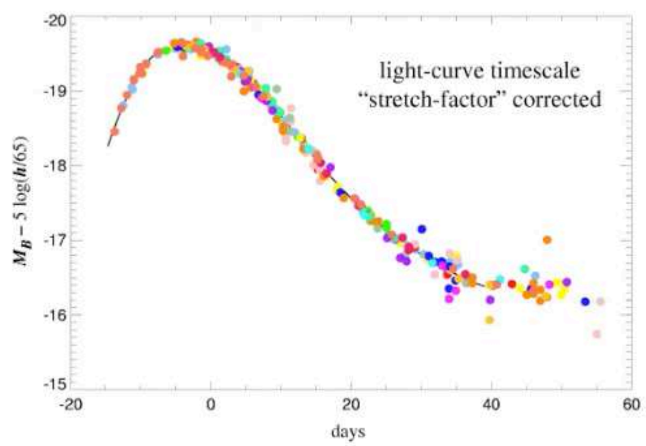
Nobel Prize in Physics 2011

"for the discovery of the accelerated expansion of the Universe through observations of distant supernovae"

BEFORE CORRECTION



AFTER CORRECTION



© The Nobel Foundation. Photo: U. Montan

Saul Perlmutter

Prize share: 1/2

© The Nobel Foundation. Photo: U. Montan

Brian P. Schmidt

Prize share: 1/4

© The Nobel Foundation. Photo: U. Montan

Adam G. Riess

Prize share: 1/4

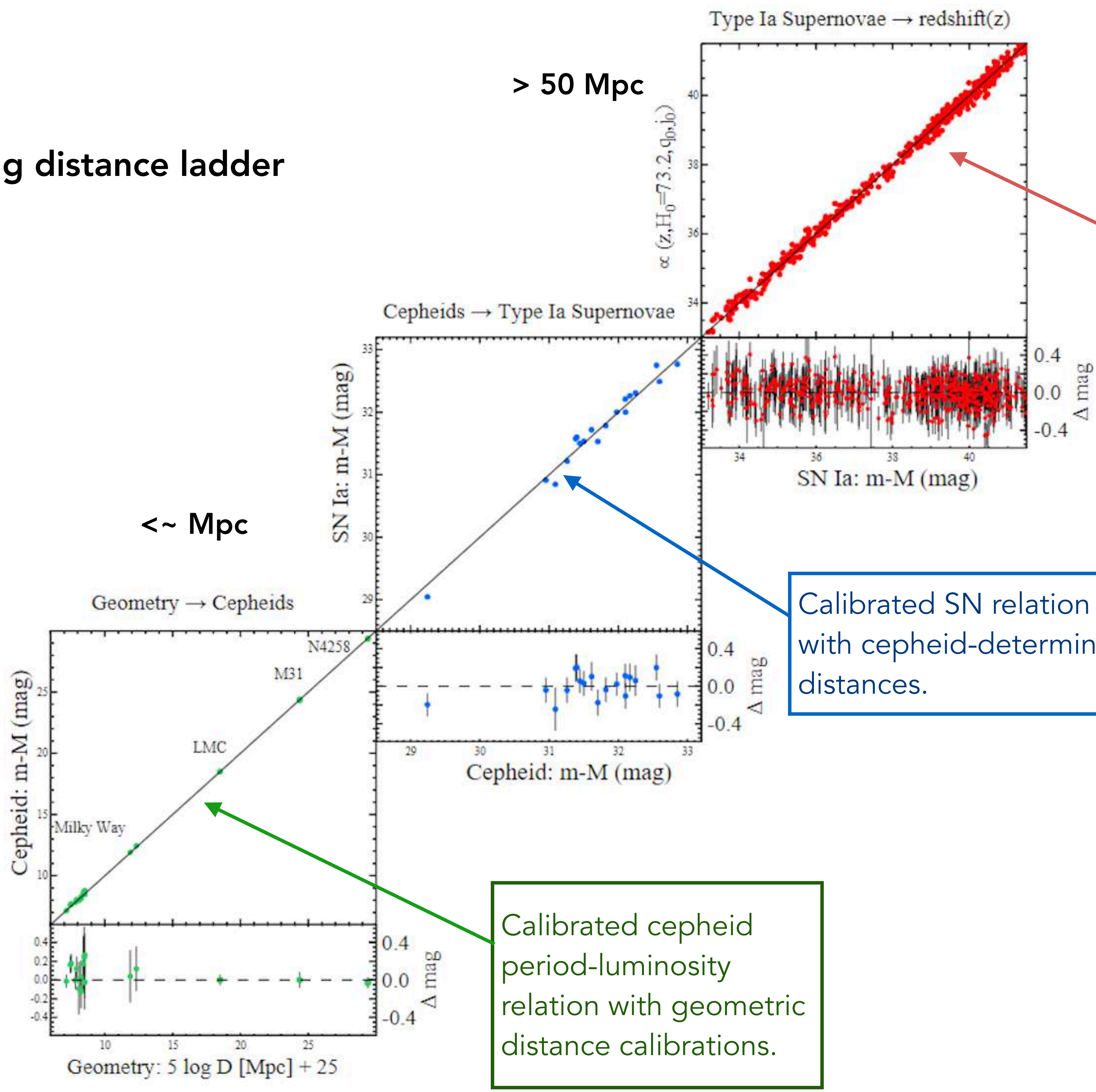
$$\mu = m_B - M - \alpha x_1 - \beta c$$

[Philips, ApJ 413 (1993)]

3-rung distance ladder

> 50 Mpc

<~ Mpc

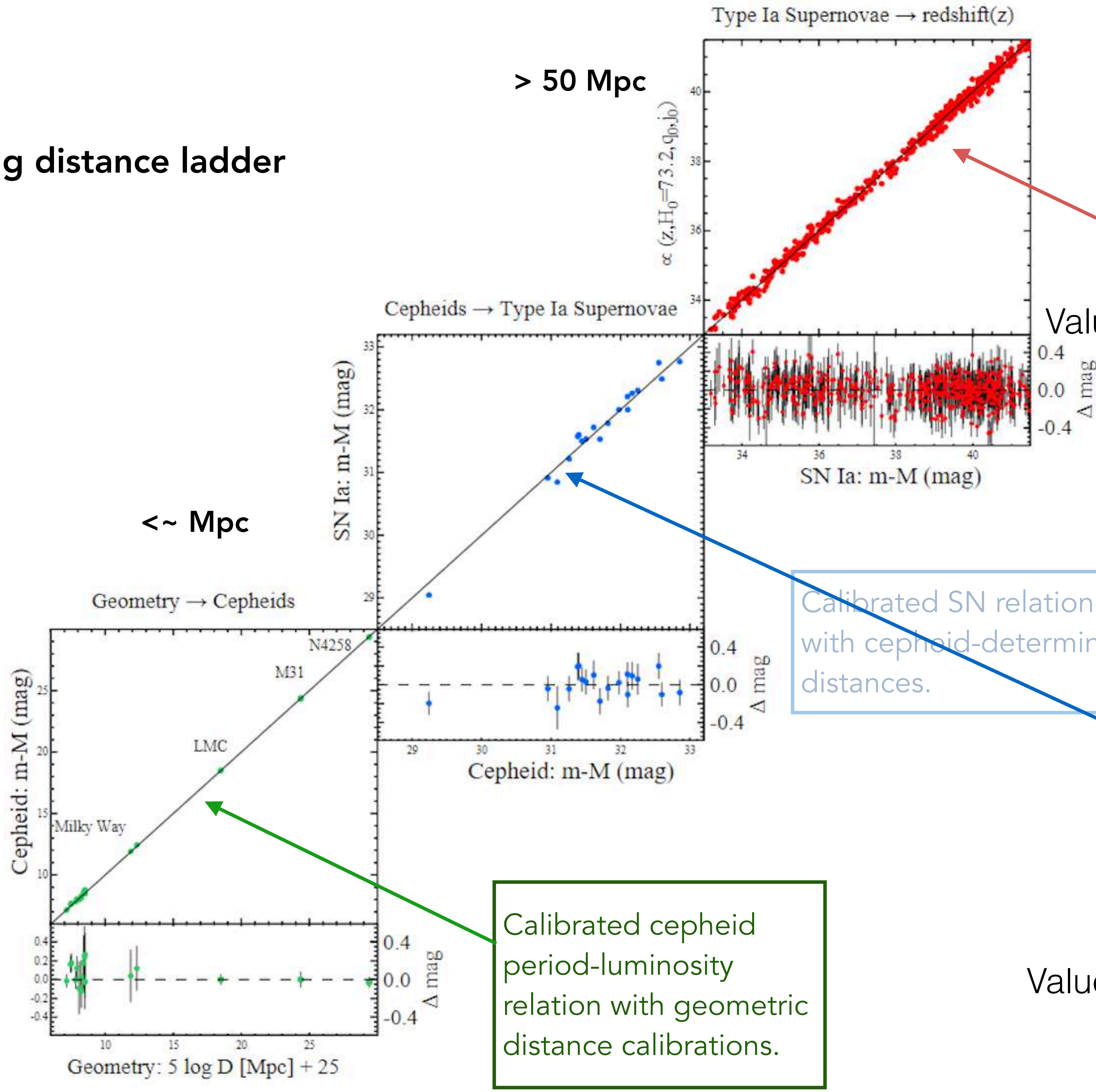


Supernovae magnitude-distance relation.

Calibrated SN relation with cepheid-determined distances.

Calibrated cepheid period-luminosity relation with geometric distance calibrations.

3-rung distance ladder



Supernovae magnitude-distance relation.

Value: $H_0 = 73.5 \pm 1.1$ km/s/Mpc

[Brout+ 2022]

Calibrated SN relation with cepheid-determined distances.

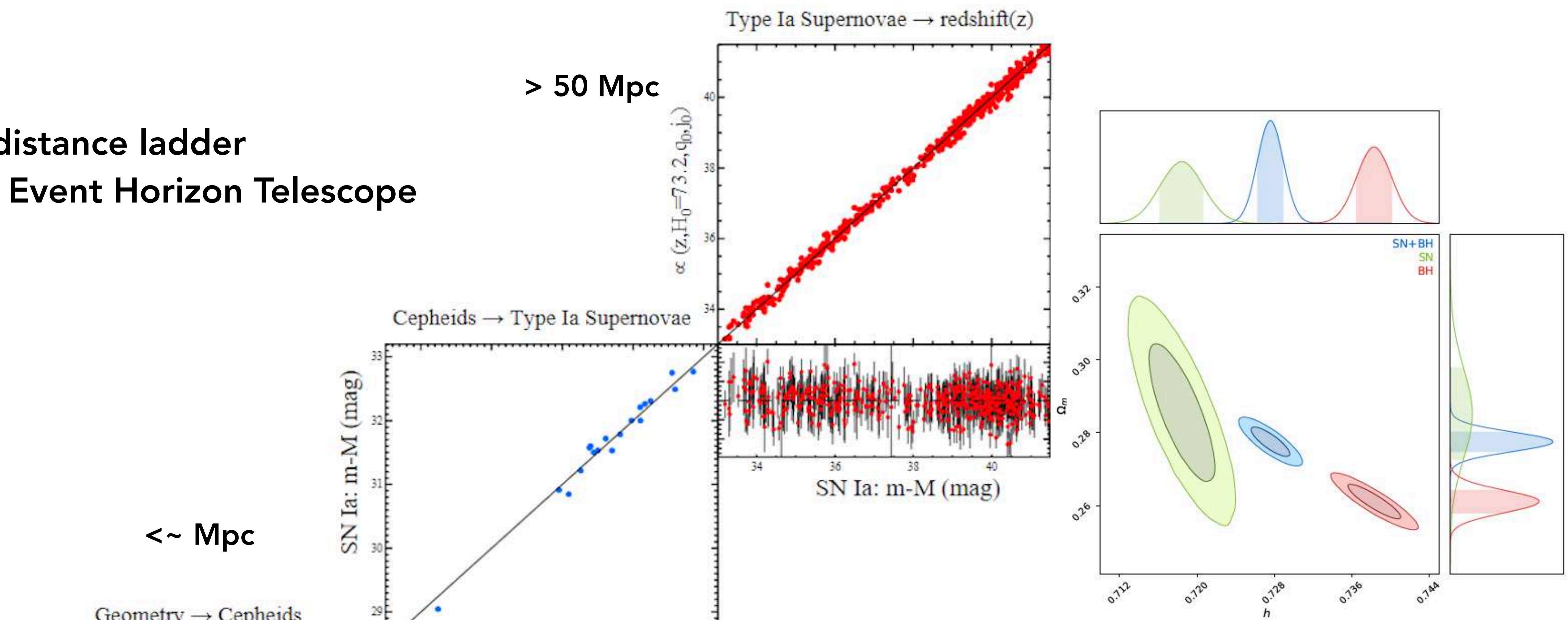
Calibrated cepheid period-luminosity relation with geometric distance calibrations.

Replace second rung of distance ladder using **Tip of the Red Giant Branch** (TRGB) as distance indicator instead of Cepheids.

Value: $H_0 = 71.8 \pm 1.5$ km/s/Mpc

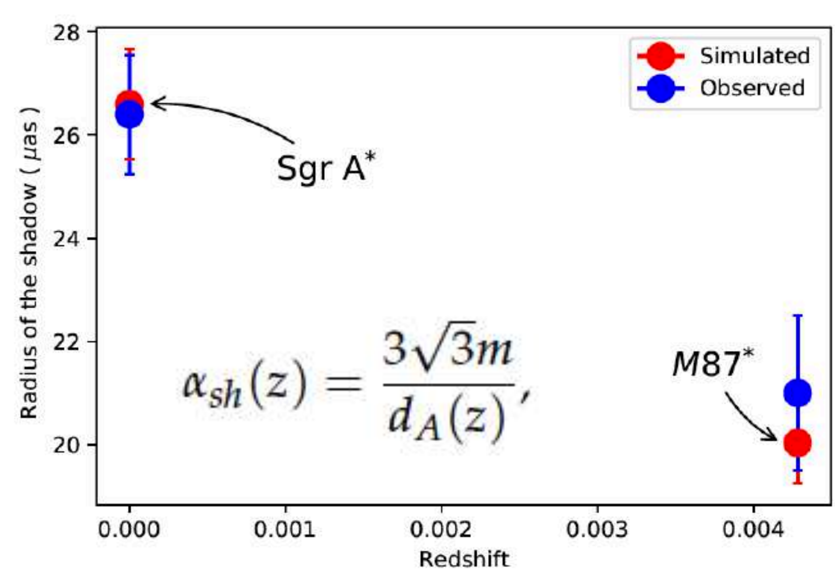
[Anderson+ 2023]

1-rung distance ladder and the Event Horizon Telescope



Value: $H_0 = 72.8 \pm 3.4$ km/s/Mpc

[**C. Escamilla-Rivera**+ 2023]



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Two paths to infer/measure H_0... we have work to do!

The work:

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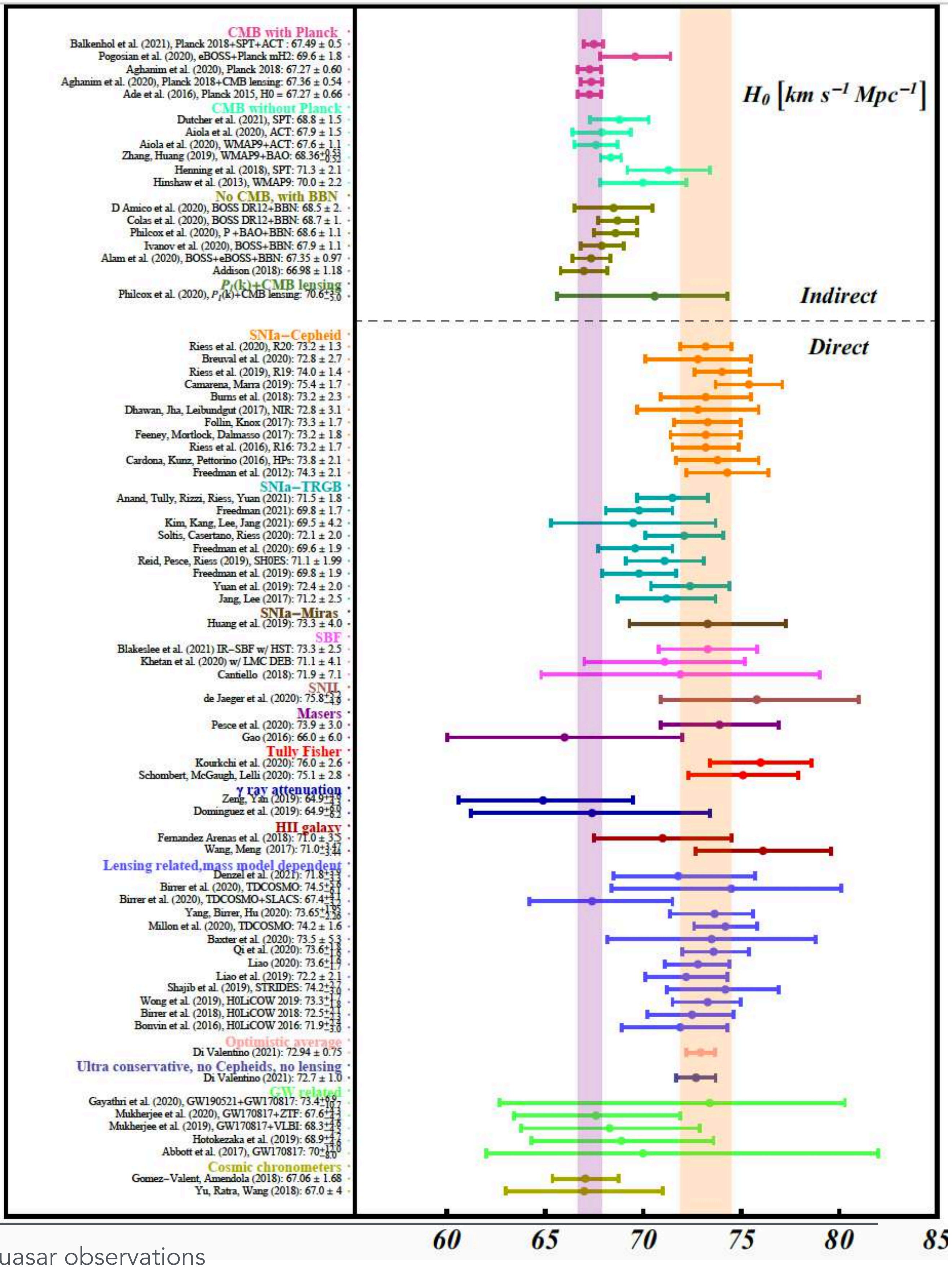
The work:

- **Beyond Einstein's gravity and its constraints**

Possible solutions of H_0

[Cosmology Intertwined: A Review of the Particle Physics, Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies. J. High En. Astrophys.(2022)]



Lovelock's theorem (1971) [version from Clifton+ Phys.Rept. 513 (2012)]

"The only **second-order**, **local** gravitational field equations **derivable from an action** containing **solely the 4D metric tensor** (plus related tensors) are the Einstein field equations with a cosmological constant"

$$S_{grav} = \frac{M_{\rm Pl}^2}{2}\int\sqrt{-g}\,d^4x[R]$$

$$S_{grav} = \frac{M_{\rm Pl}^2}{2}\int\sqrt{-g}\,d^4x\left[\phi R - \frac{\omega(\phi)}{\phi}(\nabla\phi^2) - 2V(\phi)\right]$$

$$S_{grav} = \frac{M_{\rm D}^2}{2}\int\sqrt{-\gamma}\,d^Dx[\mathscr{R} + \alpha\mathscr{G}]$$

$$S_{grav} = \frac{M_{\rm Pl}^2}{2}\int\sqrt{-g}\,d^4x[R + \beta_1 R\nabla_\mu\nabla^\mu R + \beta_2\nabla_\mu R_{\beta\gamma}\nabla^\mu R^{\beta\gamma}]$$

$$S_{grav} = \frac{M_{\rm Pl}^2}{2}\int\sqrt{-g}\,d^4x\left[R + f\left(\frac{1}{\Box}R\right)\right]$$

$$S_{grav} = ?!$$

Hubble tension from the Lovelock's theorem break

"The only **second-order**, **local** gravitational field equations **derivable from an action** containing **solely the 4D metric tensor** (plus related tensors) are the Einstein field equations with a cosmological constant"

$$S_{grav} = \frac{M_{\rm Pl}^2}{2}\int\sqrt{-g}d^4x\left[\phi R - \frac{\omega(\phi)}{\phi}(\nabla\phi^2) - 2V(\phi)\right]$$

Value: $H_0 = 69.9^{+0.84}_{-0.86}$ km/s/Mpc

[M. Gonzalez et al. JCAP 10 (2021) 028]

$$S_{grav} = \frac{M_{\rm D}^2}{2}\int\sqrt{-\gamma}d^Dx[\mathscr{R} + \alpha\mathscr{G}]$$

Value: $H_0 = 68.8 \pm 0.9$ km/s/Mpc

[D. Wang and D. Mota. Phys.Dark Univ. 32 (2021)]

$$S_{grav} = \frac{M_{\rm Pl}^2}{2}\int\sqrt{-g}d^4x[R + \beta_1 R\nabla_\mu\nabla^\mu R + \beta_2\nabla_\mu R_{\beta\gamma}\nabla^\mu R^{\beta\gamma}]$$

Value: $H_0 = 69.22^{+0.66}_{-0.73}$ km/s/Mpc

[S. Odintsov et al. Nucl.Phys.B 966 (2021)]

$$S_{grav} = \frac{M_{\rm Pl}^2}{2}\int\sqrt{-g}d^4x\left[R + f\left(\frac{1}{\Box}R\right)\right]$$

Value: $H_0 = 68.74^{+0.59}_{-0.51}$ km/s/Mpc

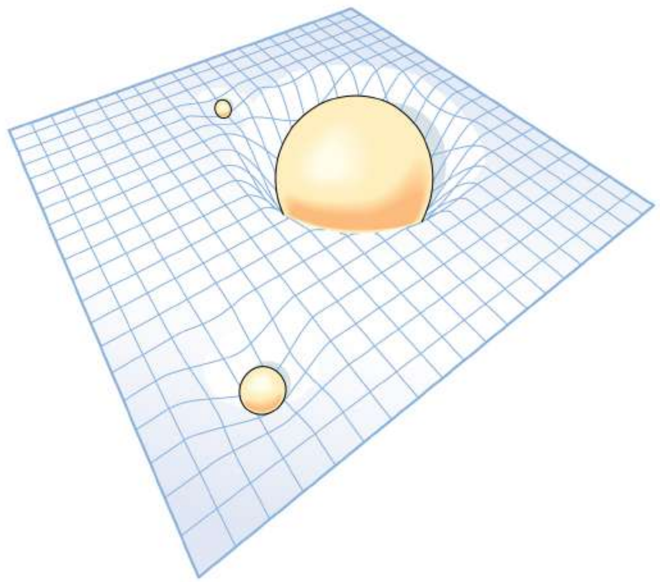
[E. Belgacem et al. JCAP 04 010 (2020)]

$$S_{grav} = ?!$$

Value: $H_0 = 69.8 \pm 2.0$ km/s/Mpc

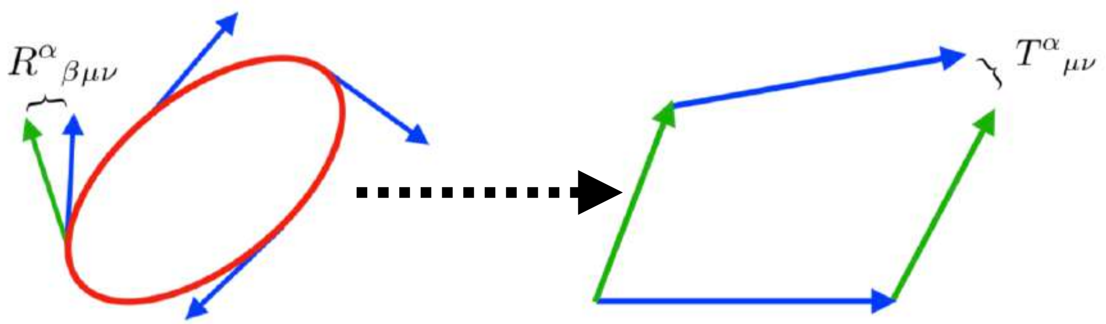
[**C. Escamilla-Rivera** and J. Fabris Universe 2021]

Rethinking the connection…



Space-time tells matter how to move; matter tells space-time how to curve. — *J. Wheeler*

Curvature is a property of the connection not of the space-time



If a manifold is differentiable ········▶ We can define **tetrads**

(gives basis for vector on the tangent space)

Two "completely" equivalent ways of understading gravity:

GR —-> Levi-Civita connection —-> Curvature with vanishing torsion

TEGR —-> Weitzenböck connection —-> Torsion with vanishing curvature

$$\tilde{\Gamma}^{\rho}_{\mu\nu} = E^{\rho}_{a}\left(\partial_{\mu} e^{a}_{\nu} + w^{a}_{b\mu} e^{b}_{\nu}\right)$$

$$T^{\rho}_{\mu\nu} = \tilde{\Gamma}^{\rho}_{\nu\mu} - \tilde{\Gamma}^{\rho}_{\mu\nu}$$

[S.Bahamonde, K. Dialektopoulos, **C. Escamilla-Rivera**, G. Farrugia, V. Gakis, M. Hendry, M. Hohmann, J. Levi Said, J. Mifsud and E. Di Valentino. Rept.Prog.Phys. 86 (2023)]

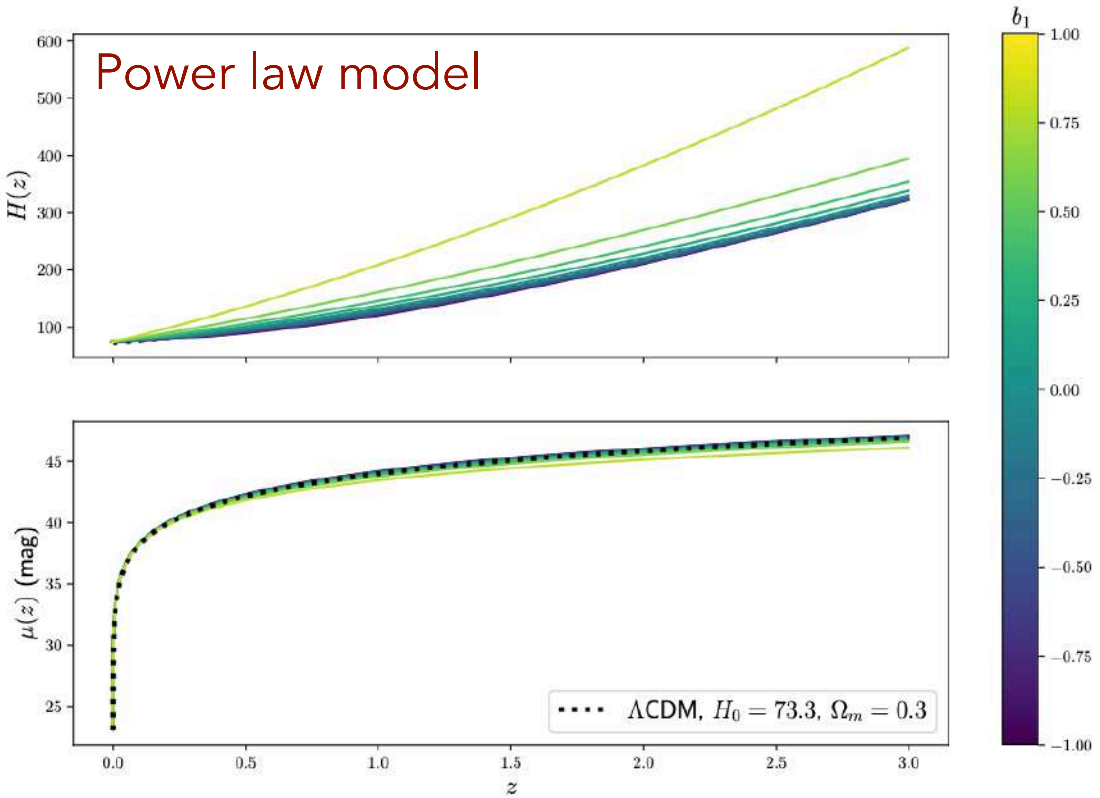
Popular models of f(T)*	Cosmological behaviour		Maturity		Test: Late-time		Test: Early-time
$f(T) = (-T)^{b_1}$	Stability	✓	Reproduces LCDM	✓ (partial)	SNeIa	✓	[Aguilar, **C. Escamilla-Rivera**, J. Levi Said, J. Mifsud. In preparation (2023)] ☢
$f(T) = T_0\left[1 - \mathrm{Exp}\left(-b_2\sqrt{T/T_0}\right)\right]$	Fine-tuning	✓	Reproduces w(z)CDM	✓	BAO	✓	
$f(T) = T_0\sqrt{T/b_4T_0}\,\log(b_4T_0/T)$	Cosmic acceleration	✓			H(z)	✓	

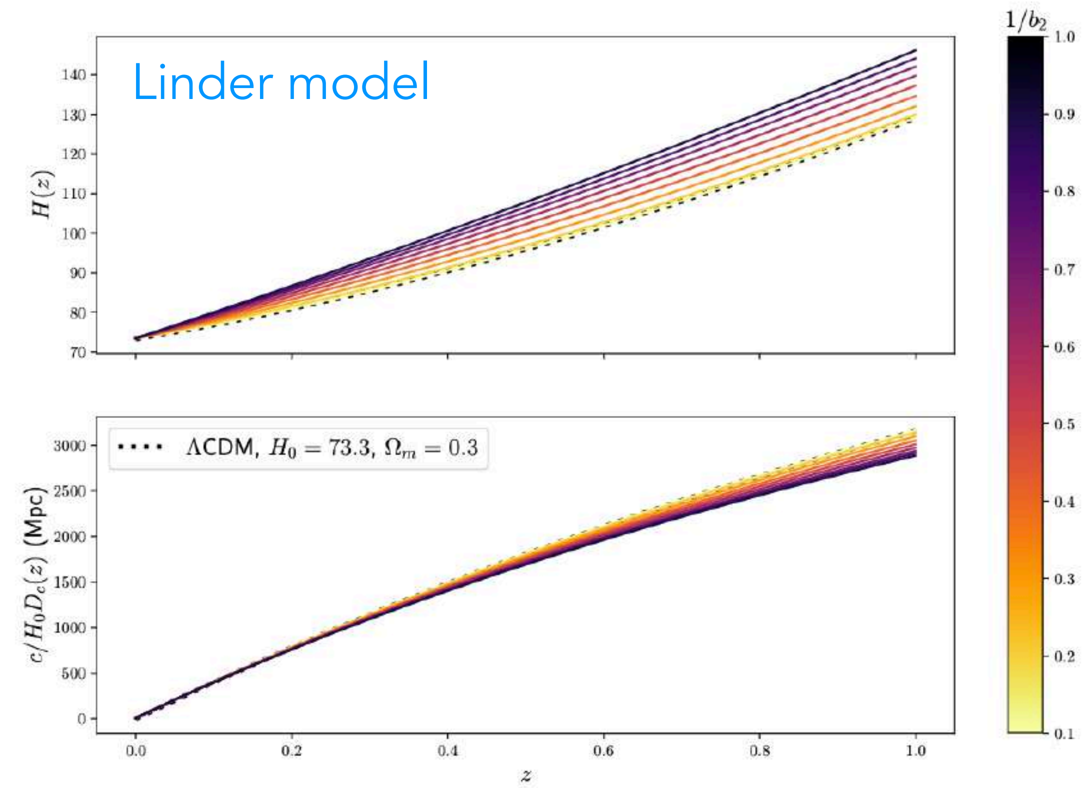
$$S = \frac{1}{2\kappa^2}\int d^4x e[-T + f(T)] + \int d^4x e \mathscr{L}_m$$

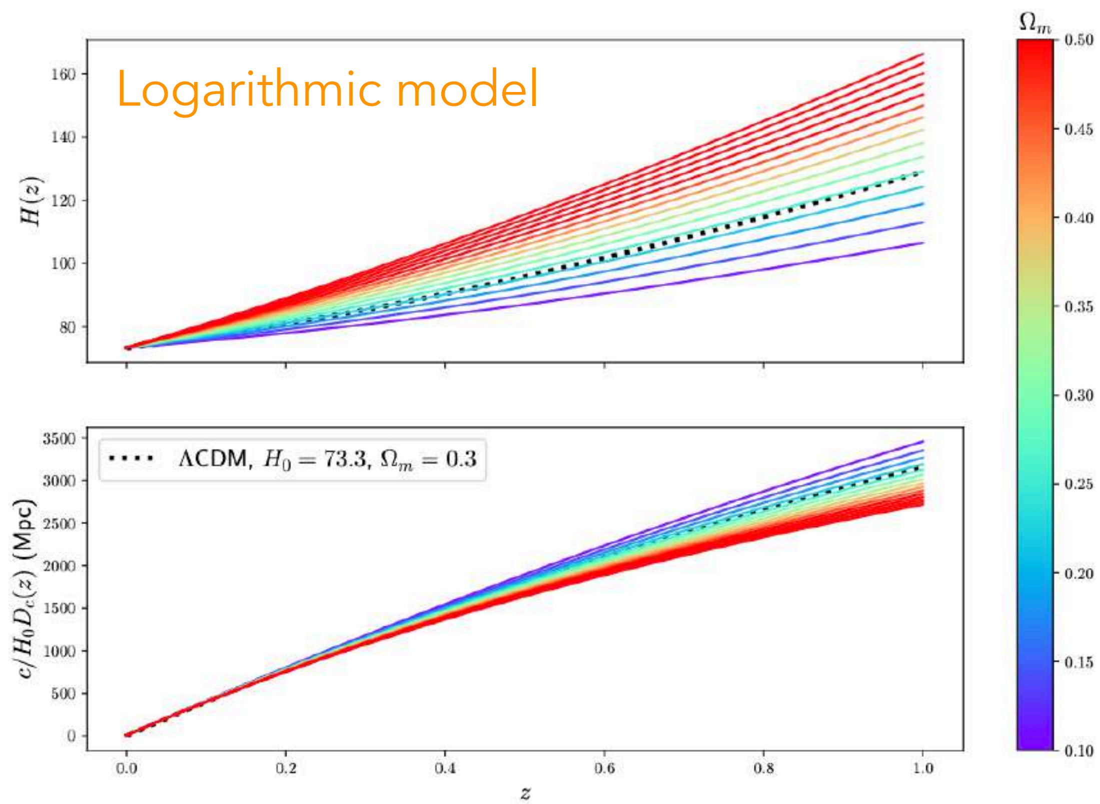
* Power law model — Linder model — Logarithmic model

$$H^2 + \frac{T}{3}f_T - \frac{f}{6} = \frac{\kappa^2}{3}\rho\,,$$

$$\dot{H}\left(1 - f_T - 2Tf_{TT}\right) = -\frac{\kappa^2}{2}(\rho + p)\,,$$


Power law model
$H(z)$
$\mu(z)$ (mag)
ΛCDM, $H_0 = 73.3$, $\Omega_m = 0.3$
z
b_1


Linder model
$H(z)$
$c/H_0 D_c(z)$ (Mpc)
ΛCDM, $H_0 = 73.3$, $\Omega_m = 0.3$
z
$1/b_2$

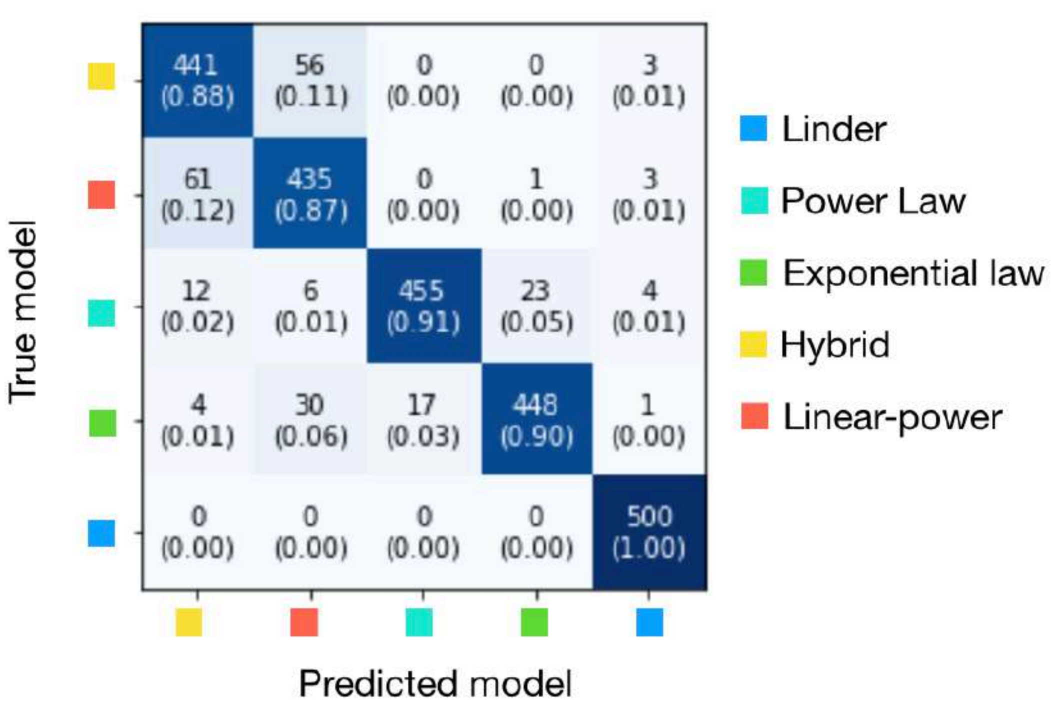

Logarithmic model
$H(z)$
$c/H_0 D_c(z)$ (Mpc)
ΛCDM, $H_0 = 73.3$, $\Omega_m = 0.3$
z
Ω_m

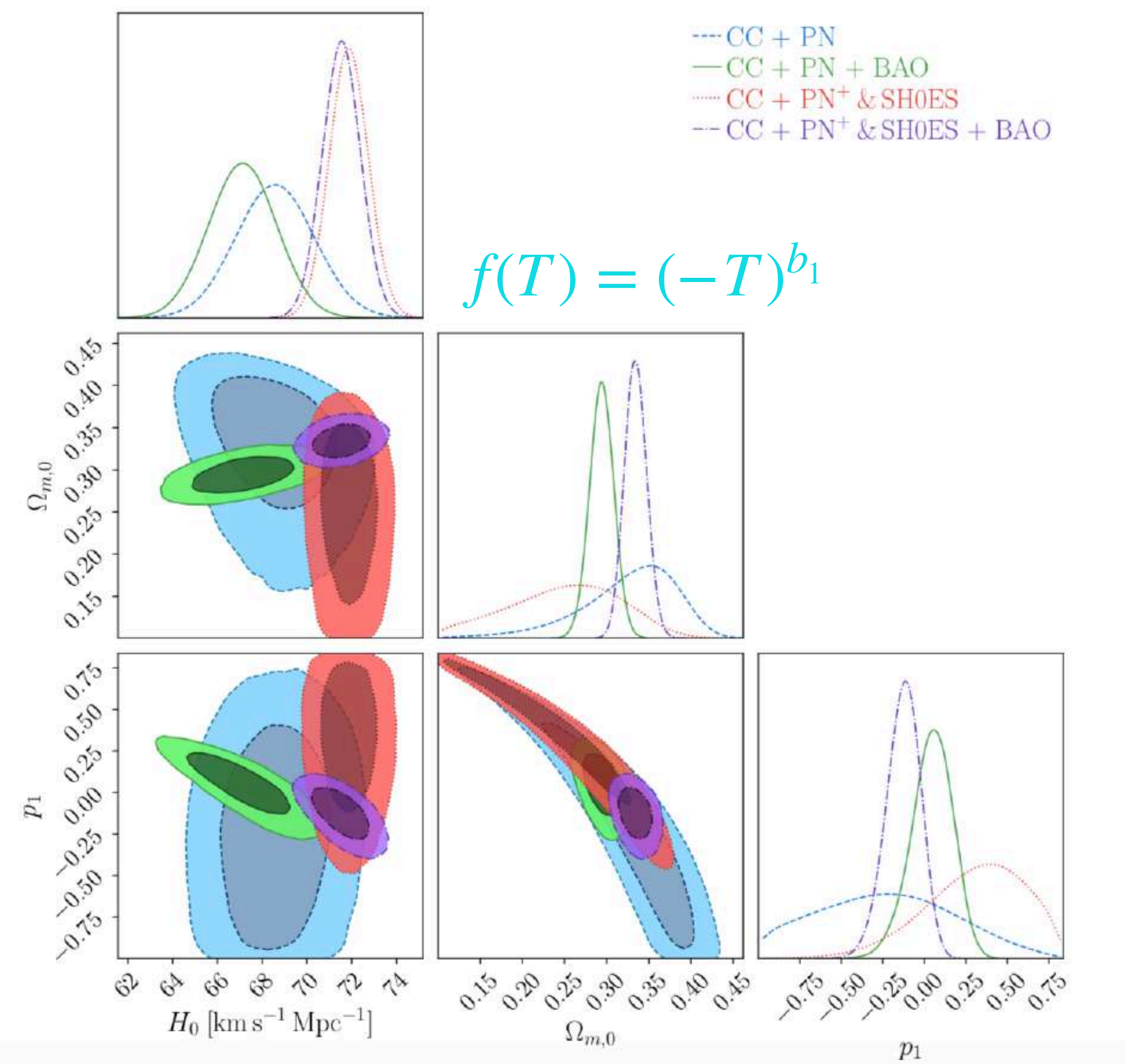
Constraints on f(T) Cosmology with Pantheon+

[R. Briffa, **C. Escamilla-Rivera**, J. Levi Said and J. Mifsud. MNRAS 552 (2023)]

$$H_0 = 70.79 \pm 0.21 \text{ km/s/Mpc}$$

- SNeIa (Pantheon+) [Scolnic+ 2021]
- BAO [6dFGS, SDSS DR7/DR14, BOSS DR12]
- H(z) measurements [Moresco+ 2020]





f(T) cosmology in the regime of quasar observations

[R. Sandoval, **C. Escamilla-Rivera,** R. Briffa, and J. Levi Said, 2309.03675 (2023)]

- ✓ SNeIa (Pantheon+) + BAO + H(z)
- ✓ Quasars

XA sample [Negrete+ 2014-2018, Marziani+ 2018,]

~ 250 objects

1. Radiate near the Eddington limit (relation between this limit and the BH mass)
2. BH mass can be obtained through the virialized relation
3. Using an ionization parameter we can reach an expression for the luminosity

$$L(\mathrm{FWHM}) = 7.88 \times 10^{44} (\mathrm{FWHM})^4_{1000},$$

$$\mu = 2.5[\log L - \log(f_\lambda \lambda)] - 100.19 + 5\log(1+z),$$

$$\chi^2_{\mathrm{XA}} = -\frac{1}{2}\sum_i \left[\frac{(\mu_i - \mu(z_i,\Theta))^2}{\delta\mu_i^2} + \ln(\delta\mu_i^2)\right]$$

f(T) cosmology in the regime of quasar observations

[R. Sandoval, **C. Escamilla-Rivera,** R. Briffa, and J. Levi Said**,** 2309.03675 (2023)]

- ✓ SNeIa (Pantheon+) + BAO + H(z)
- ✓ Quasars

X-UV (nUVX) sample [Lusso+ 2020]

- 2421 objects (0 < z < 7.54)
- Cosmological candle: $F_{UV} - F_X$

$$\log(d_L) = \frac{[\log F_{\rm X} - \gamma F_{\rm UV}]}{2(\gamma - 1)} + \beta',$$

$$\mu = \frac{5}{2(\gamma - 1)}(\log F_{\rm X} - \gamma F_{\rm UV}) + 5\beta',$$

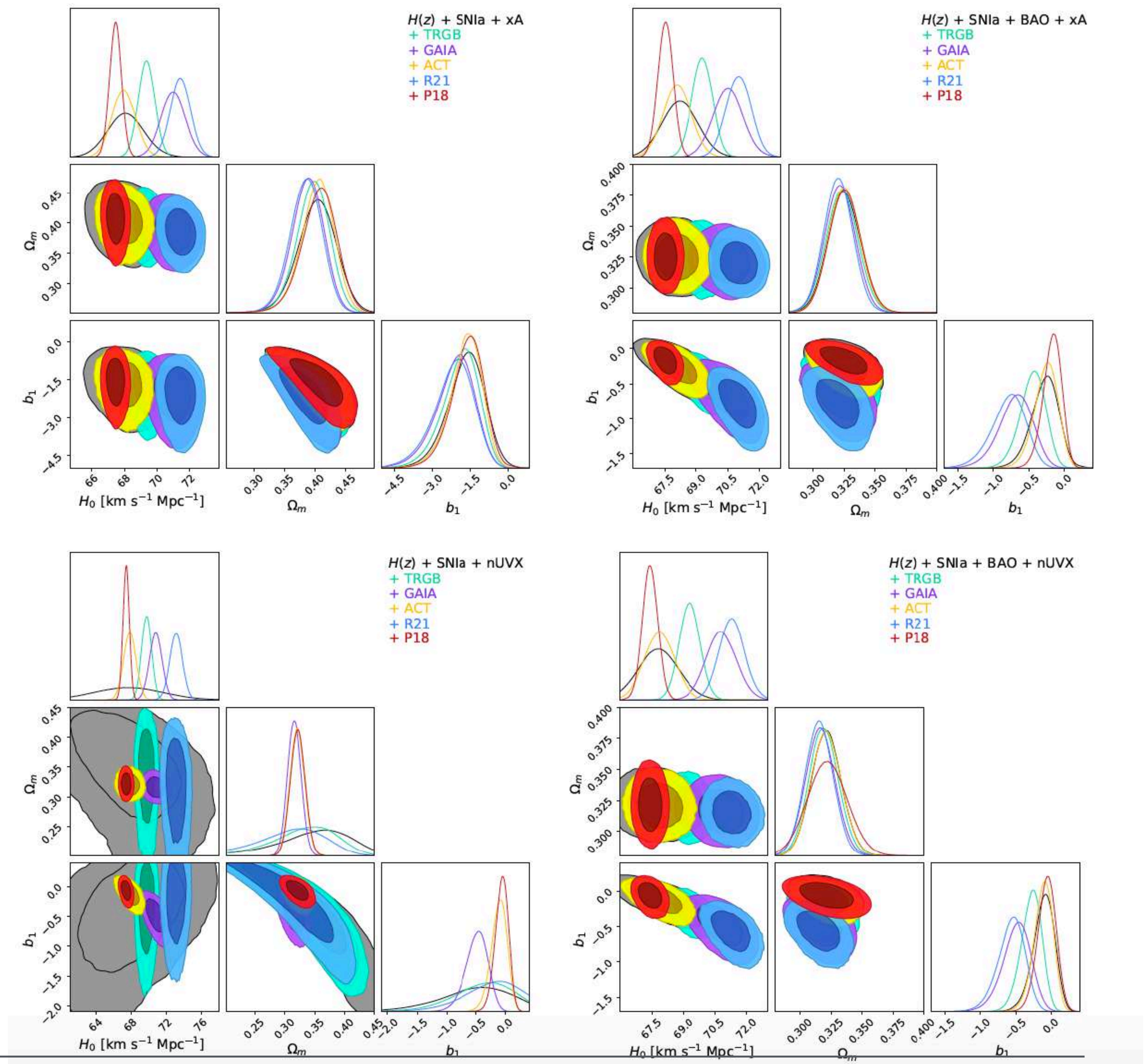
$$\mu = \frac{5}{2(\gamma - 1)}(\log F_{\rm X} - \gamma F_{\rm UV}) + 5\beta',$$

f(T) cosmology in the regime of quasar observations

[R. Sandoval, **C. Escamilla-Rivera,** R. Briffa, and J. Levi Said, 2309.03675 (2023)]

- SNeIa (Pantheon+)
- BAO
- H(z) measurements
- Quasars

$$f(T) = (-T)^{b_1}$$



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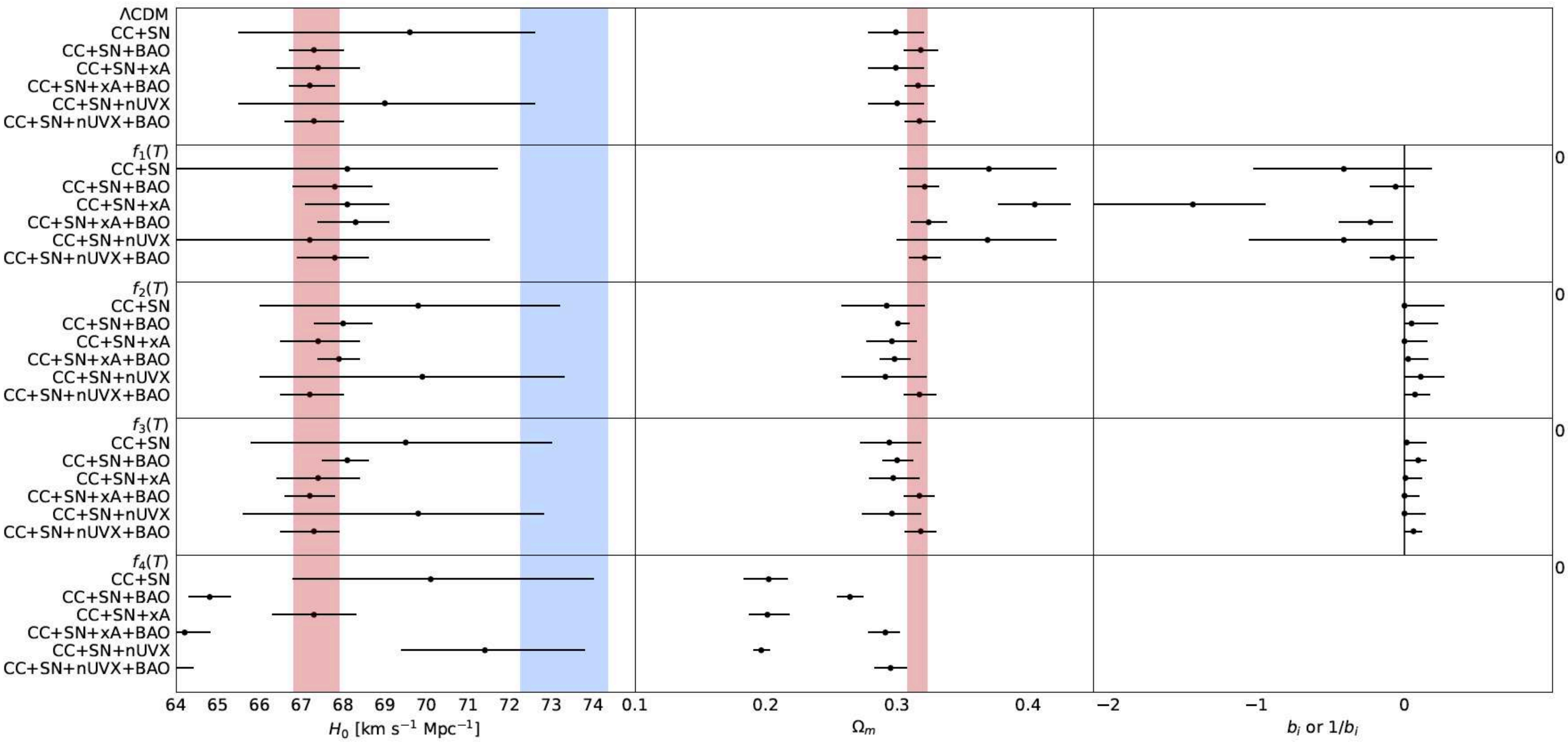
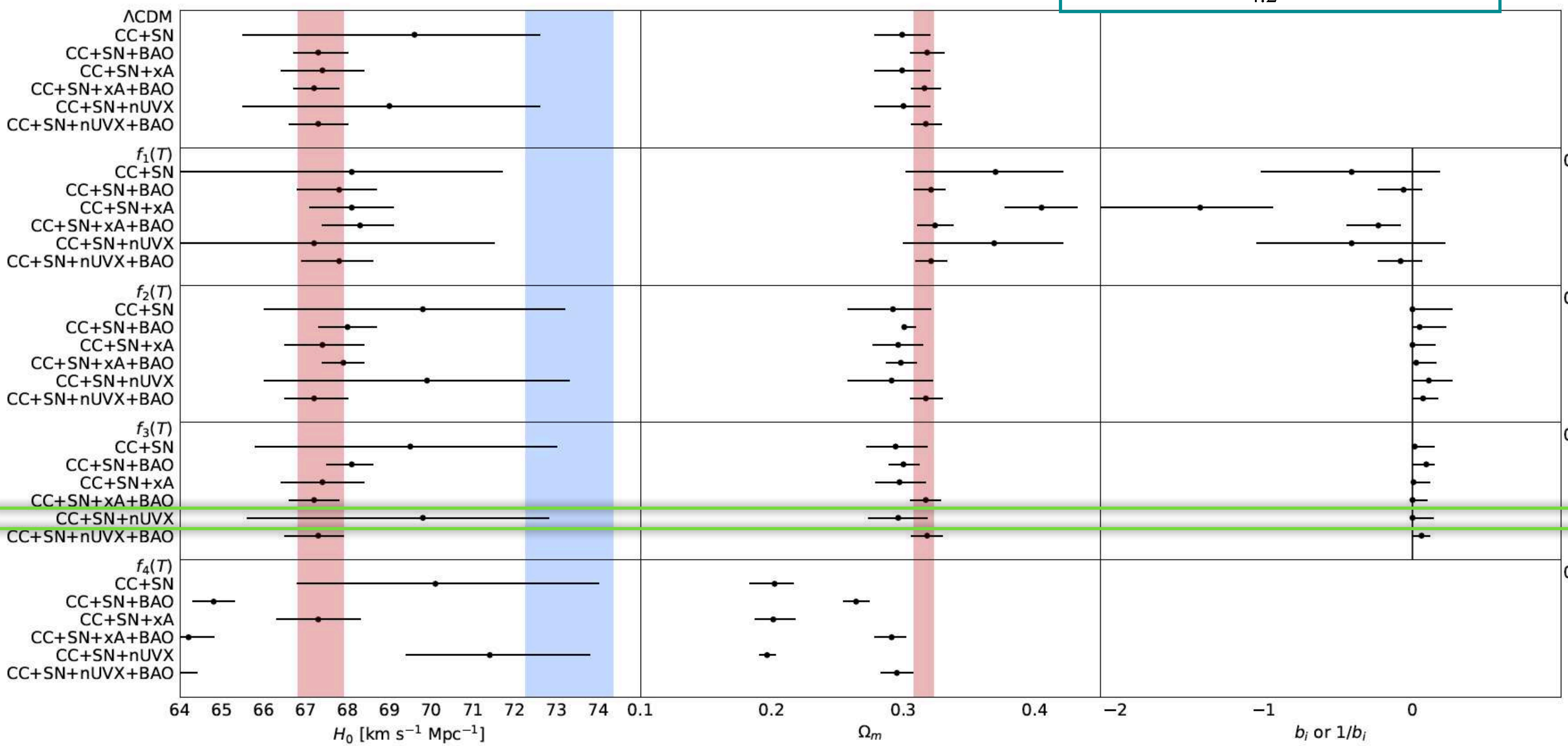


f(T) cosmology in the regime of quasar observations

[R. Sandoval, **C. Escamilla-Rivera,** R. Briffa, and J. Levi Said**,** 2309.03675 (2023)]

$$f(T) = T_0\left[1 - \mathrm{Exp}\left(-b_2\sqrt{T/T_0}\right)\right]$$

$$H_0 = 70.1^{+3.0}_{-4.2}\ \text{km/s/Mpc}$$



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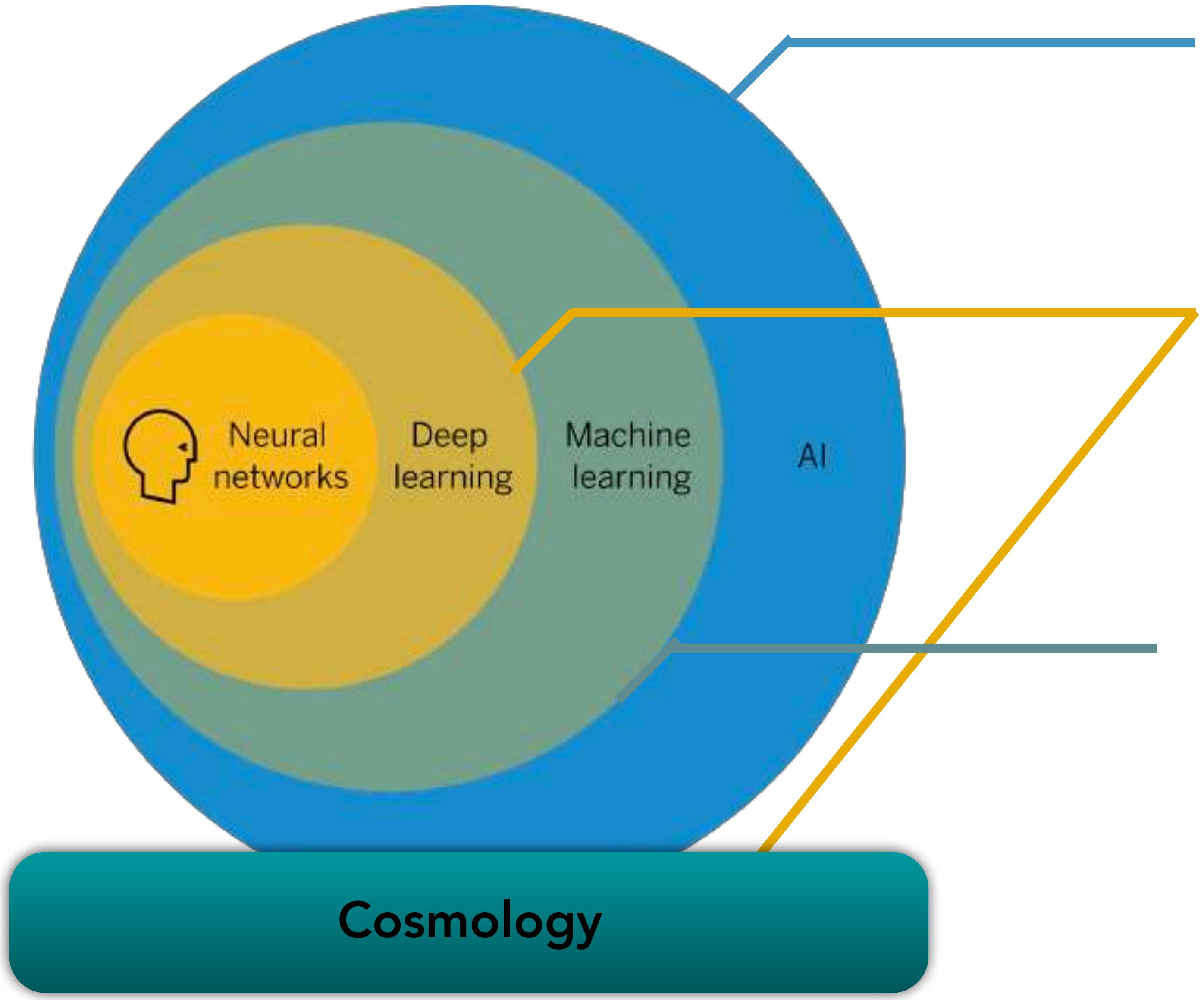
and beyond: Machine Learning

Nonparametric and model independent reconstructions approaches					
Method	Assumption of prior/models	Binned	Low efficiency at high z	Underestimation of errors z	High computational cost
Principal Components Analysis (PCA)	✓	✗	✓	✓	✓
Nonlinear Inverse Approach (NIA)	✓	✗	✓	✗	✓
Dipole of the Luminosity Distance method (DLD)	✗	✗	✓	✗	✗
Nodal Reconstruction (NR)	✓	✗	✗	✗	✗
Genetic Algorithms (GA)	✗	✗	✗	✓	✗
Reconstructions of the Expansion History (MIR-I,II,III)	✗	✗	✗	✓	✓
Gaussian Processes (GP)	✓	✗	✗	✓	✓

[**C. Escamilla-Rivera**+ *JCAP* 10 (2021) 016]

In which stage is "NN" Cosmology?

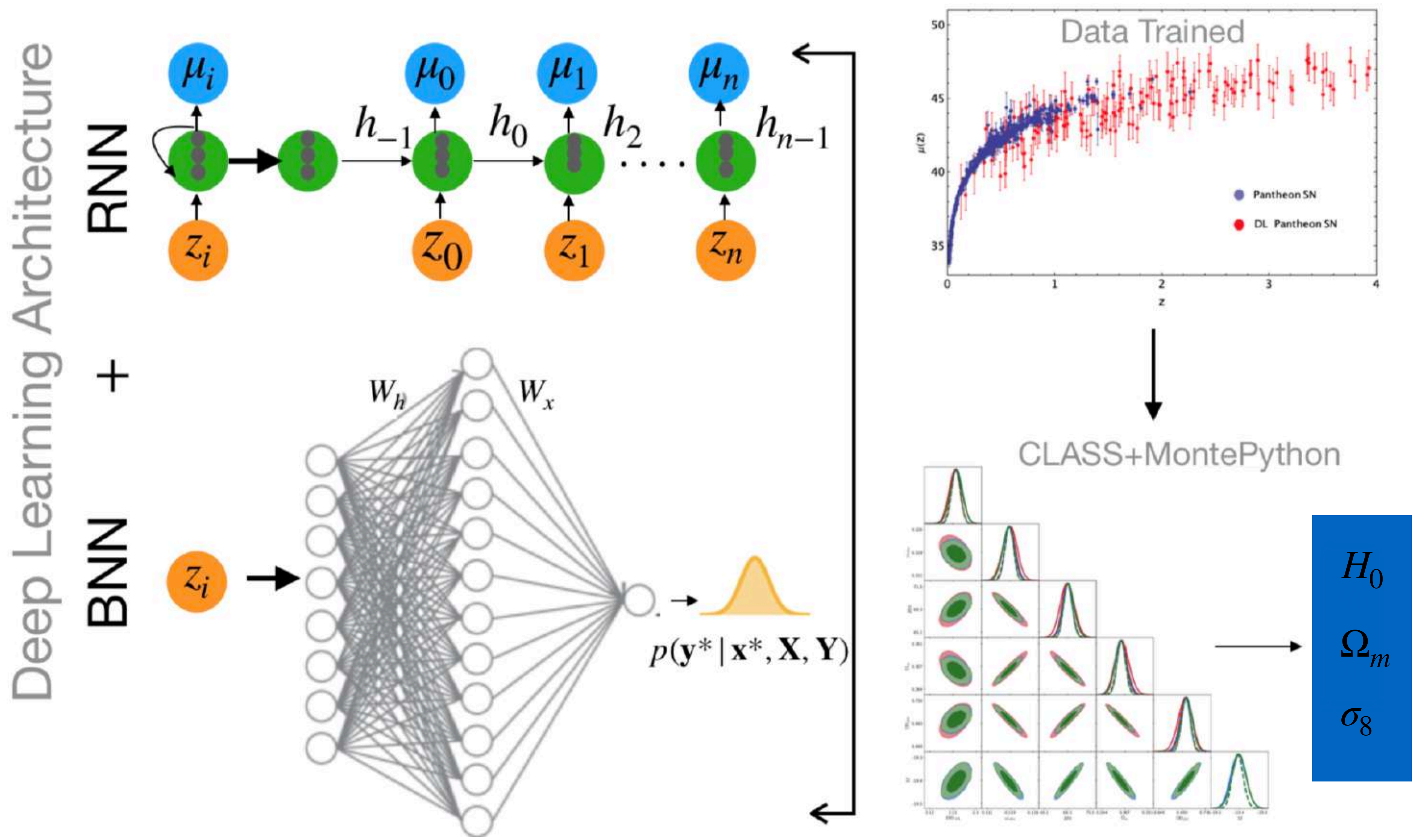


Artificial Intelligence: perceive their environment and define a course of action.

Deep learning: tasks are organised in consecutive layers, builded on the output of previous ones. Mimics the distributed approach to problem-solving.

Machine learning: tasks are complete without being explicitly programmed to do so.

Maping from observations to theory

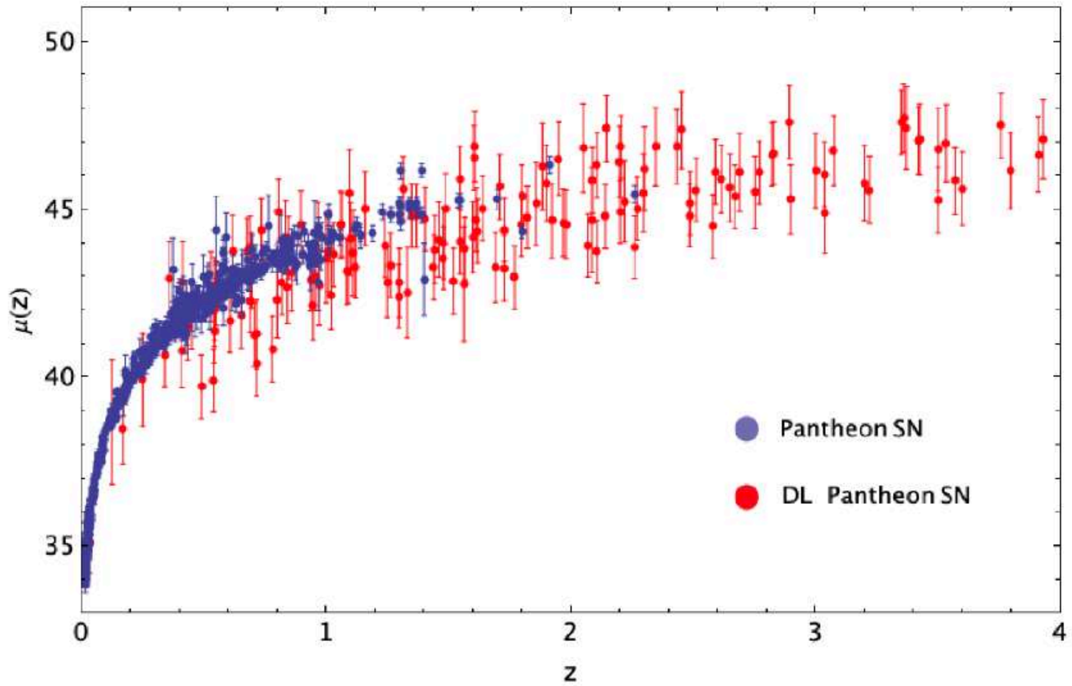


[**C. Escamilla-Rivera,** *PoS* AISIS2019 (2020)]

Architecture	Neurons Iterations	Batch size Random Walkers	Epochs Rates of Convergence	Dropout Bins of a Sample
1	200	5	100	0.7
2	200	10	150	0.7

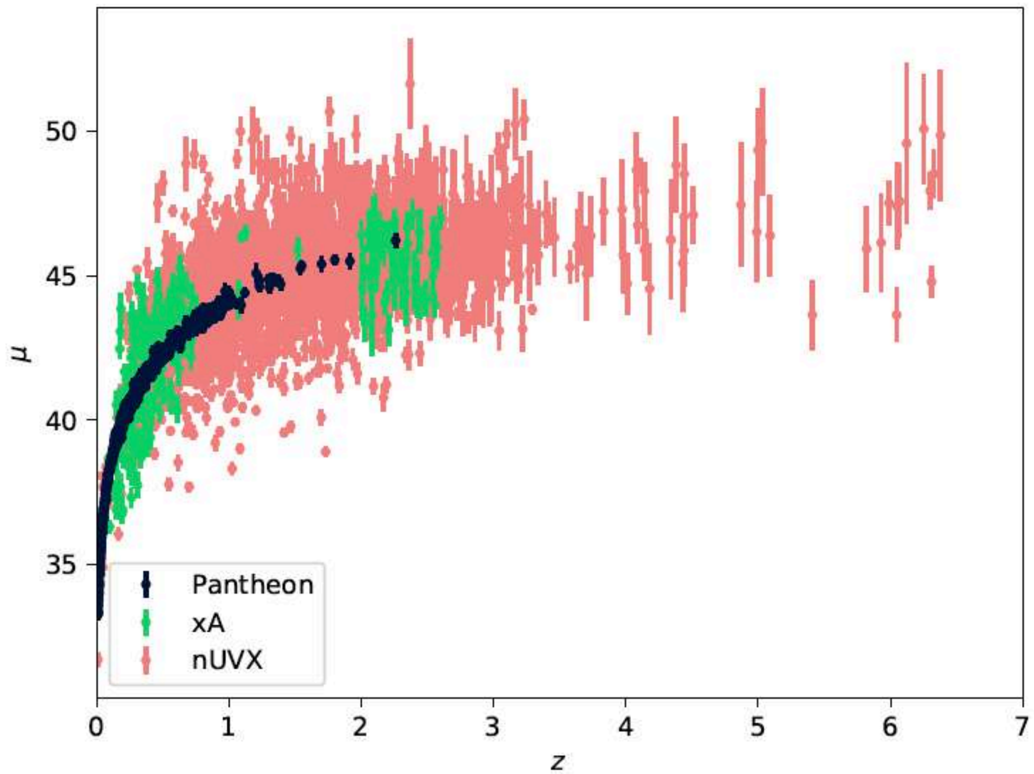
Table 1. Choice of hyperparameters in both RNN architectures and their association with Bayesian cosmology processing language.

Observations data mining results



A deep learning approach to cosmological dark energy models

[**C. Escamilla-Rivera,** M.Carvajal and S. Capozziello. JCAP (2020)]
[**C. Escamilla-Rivera** and C. Zamora. JCAP (2020)]
[**C. Escamilla-Rivera,** M.Carvajal, C. Zamora and M. Hendry. JCAP (2022)]



Constraints on dark energy using deep learning training for quasars and JWST forecasting

[P. Maldonado, **C. Escamilla-Rivera** and R. Sandoval, in preparation (2023)]

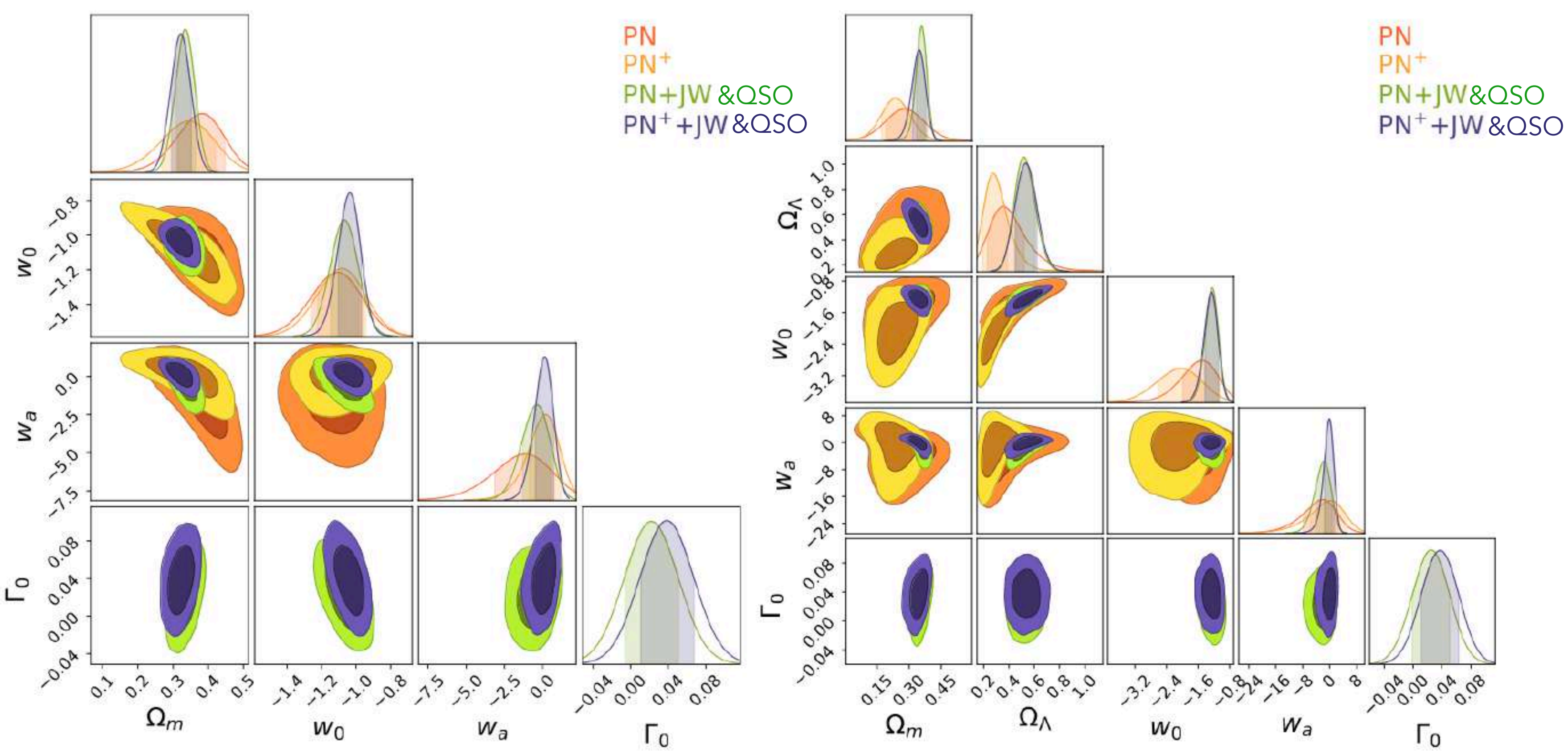
Constraints on dark energy using deep learning training for quasars

[P. Maldonado, **C. Escamilla-Rivera** and R. Sandoval, in preparation (2023)]

- SNIa (Pantheon+)
- Quasars
- JWST SNeIa forecasting
- H(z) measurements (CC)

Flat CPL EoS

Non-flat CPL EoS



Conclusions

- Teleparallel Cosmology is maturing fast
- Quasars can help to relax local tensions (!)
- We can now classify models (likelihood free inference) using training data
- Data + NN can improve constraints on cosmological parameters, e.g H_0

Thanks for your kind attention