Extended theories of gravity to explain the Hubble -Lemaitre tension

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- Hubble-Lemaitre tension state-of-art
- Precision Cosmostatistics for Extended Theories of Gravity (ETG)
- Frontiers in ETG using Precision Cosmology

- **Hubble-Lemaitre tension state-of-art**
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LCDM gravity model

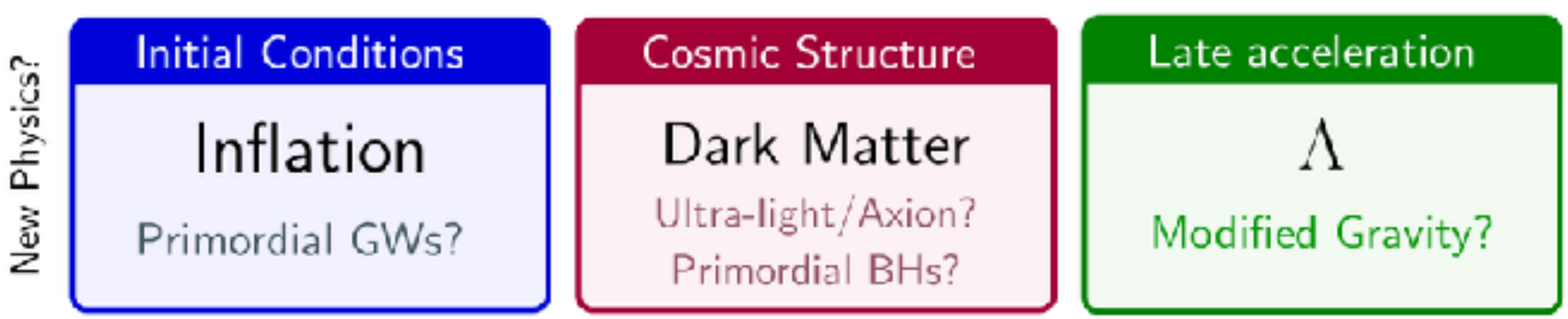
+

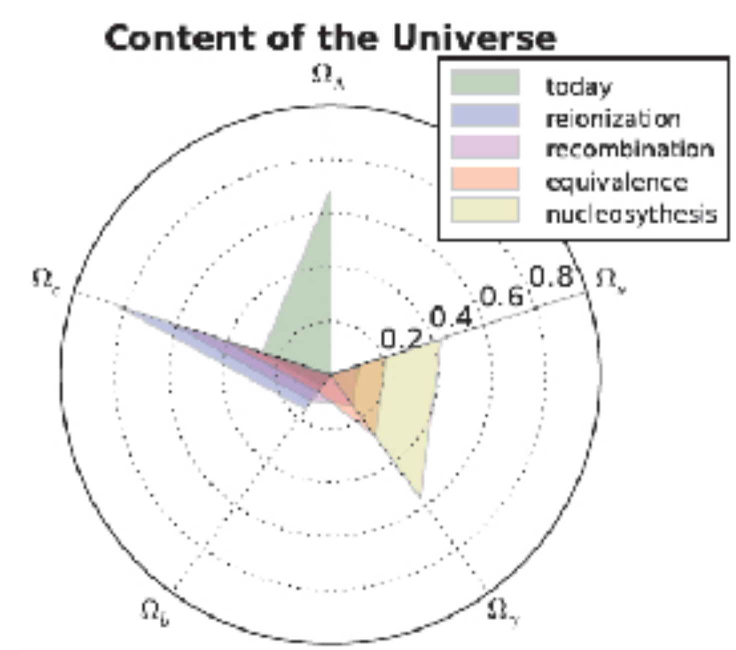
Data
(CMB, SN, BAO, GW, RSD…)

=

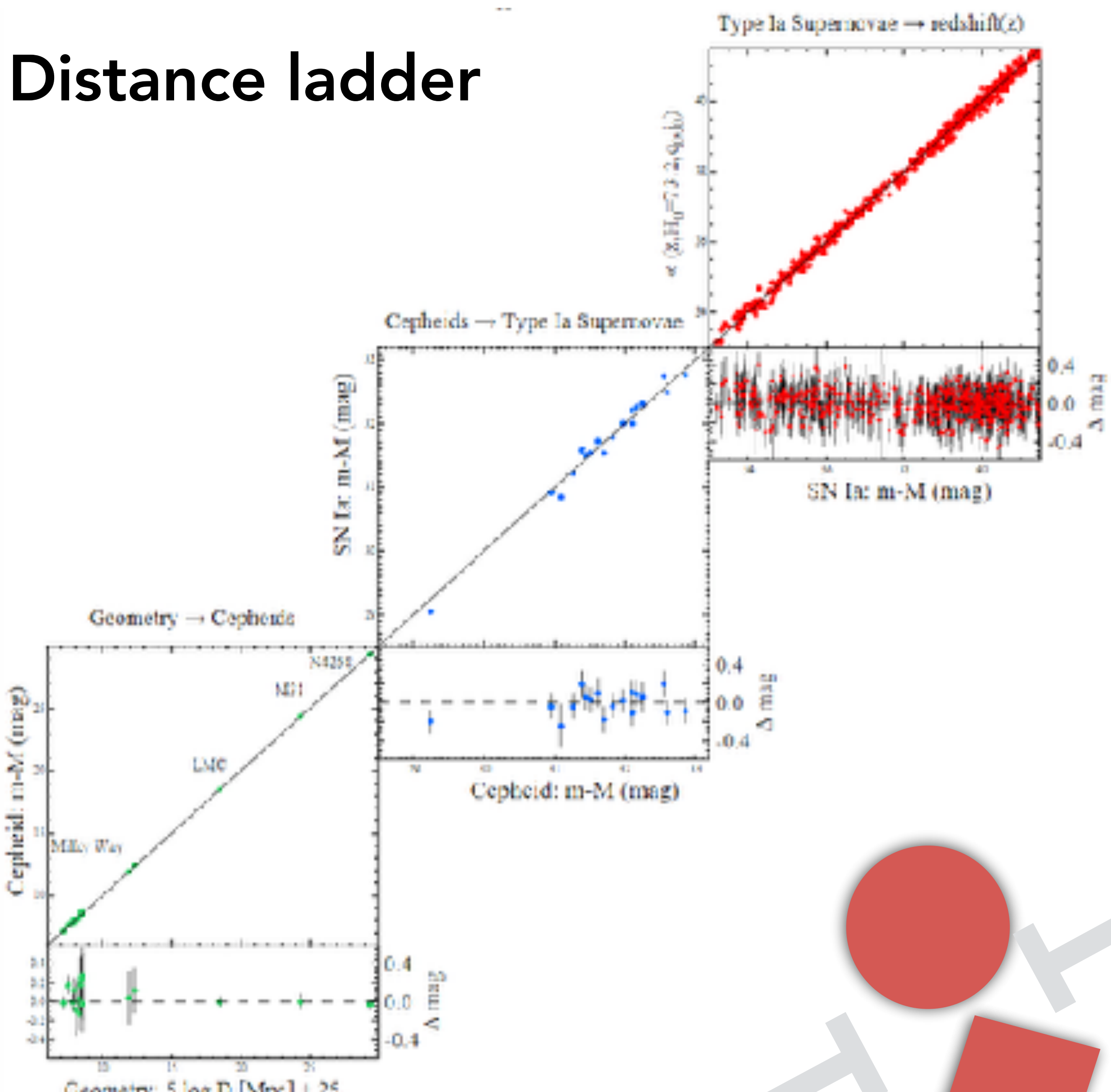
Inconsistency : Dark matter + Dark energy

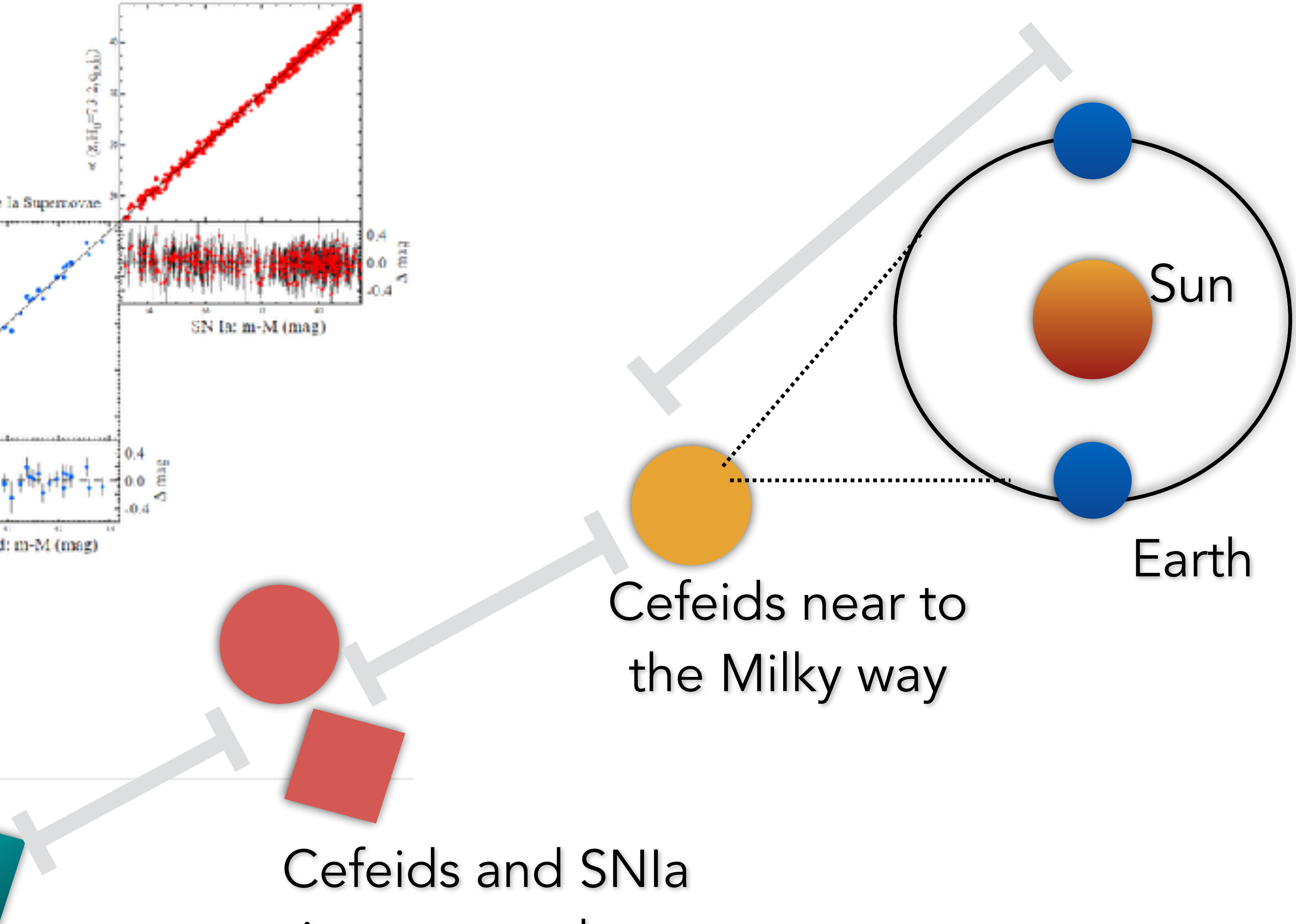
Problems: H_0, and σ_8 tensions





Distance ladder

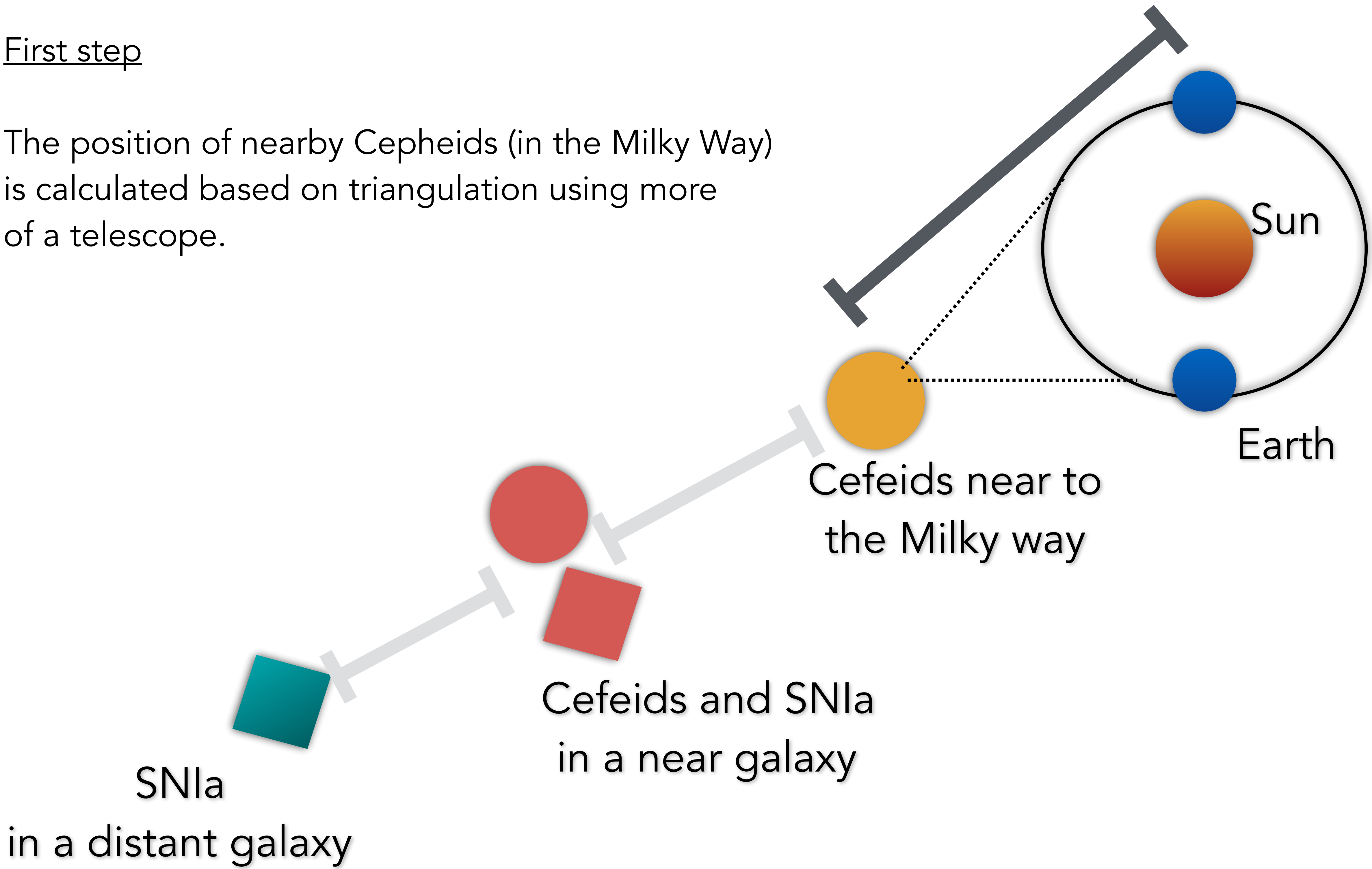




Climbing the "distance ladder"

First step

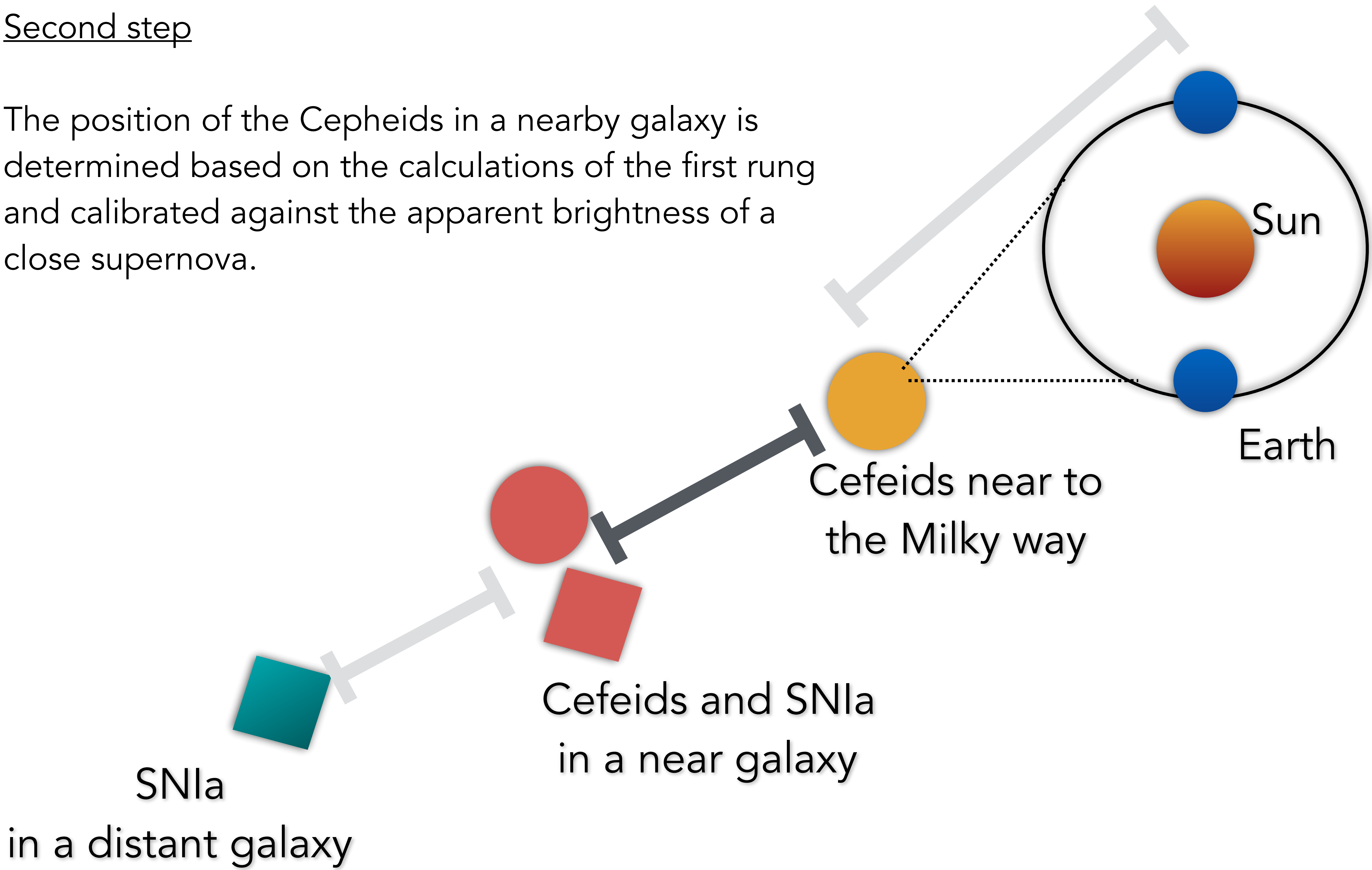
The position of nearby Cepheids (in the Milky Way) is calculated based on triangulation using more of a telescope.



Climbing the "distance ladder"

Second step

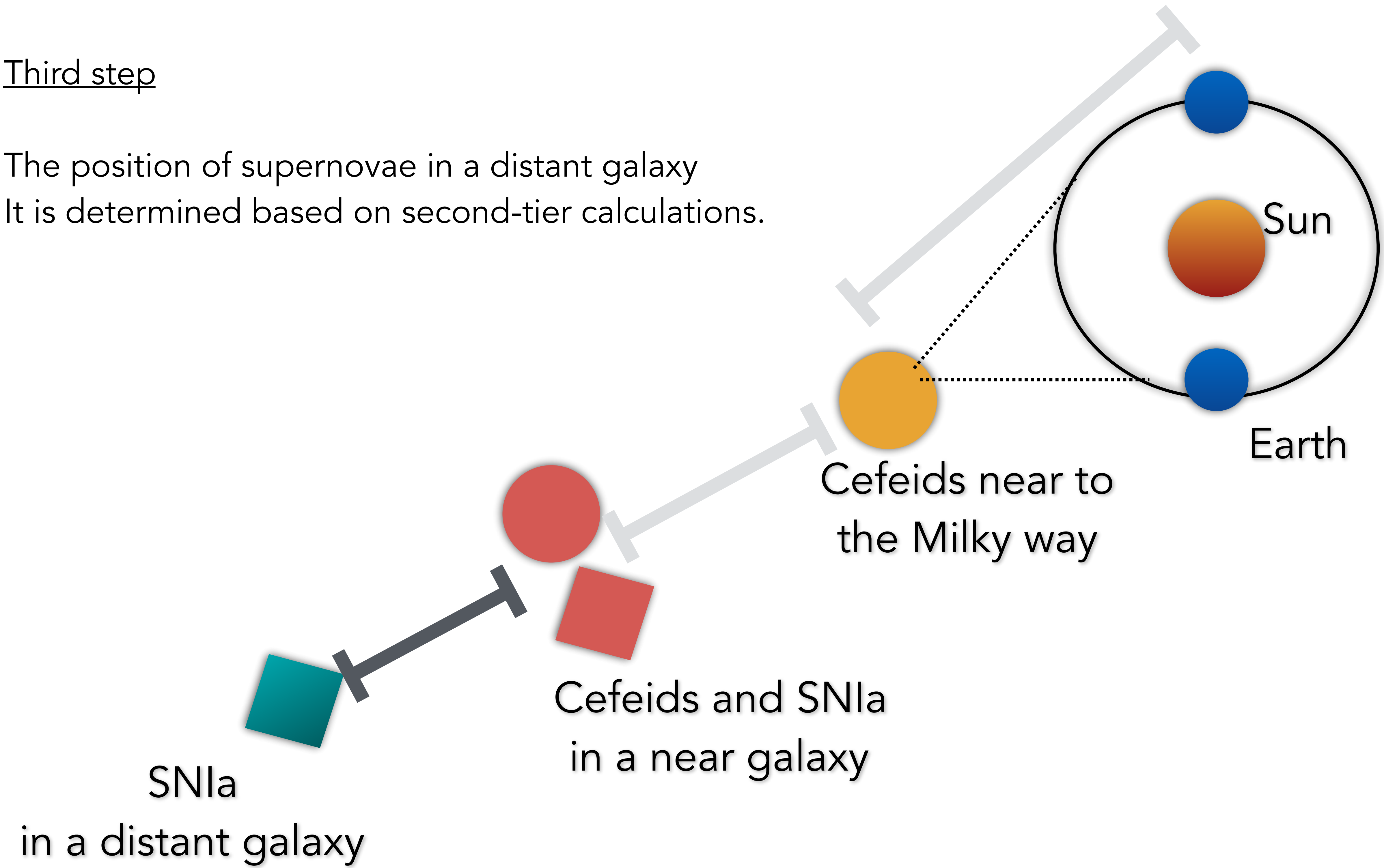
The position of the Cepheids in a nearby galaxy is determined based on the calculations of the first rung and calibrated against the apparent brightness of a close supernova.

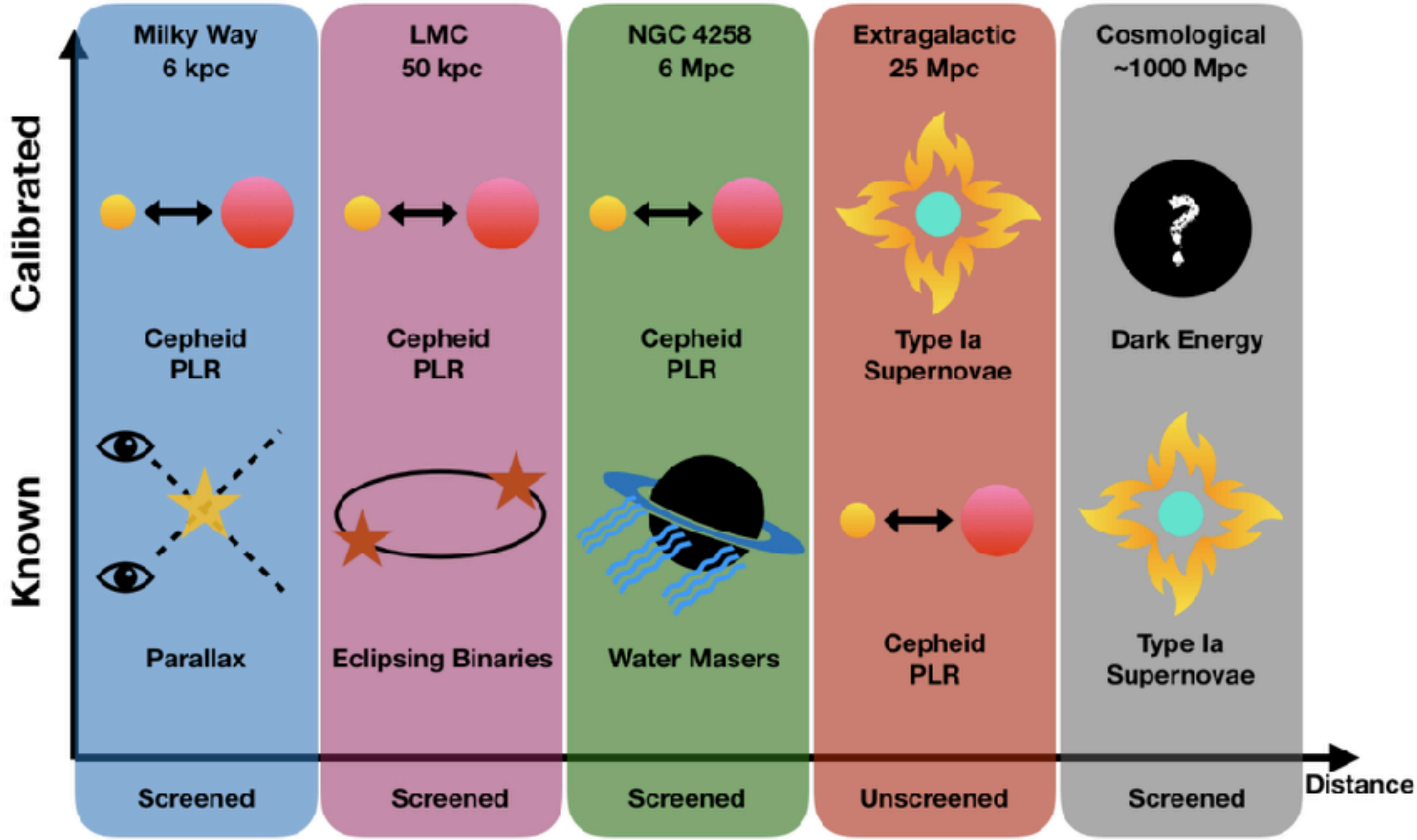


Climbing the “distance ladder”

Third step

The position of supernovae in a distant galaxy
It is determined based on second-tier calculations.




Milky Way
6 kpc
LMC
50 kpc
NGC 4258
6 Mpc
Extragalactic
25 Mpc
Cosmological
~1000 Mpc
Calibrated
Known
Cepheid
PLR
Cepheid
PLR
Cepheid
PLR
Type Ia
Supernovae
Dark Energy
Parallax
Eclipsing Binaries
Water Masers
Cepheid
PLR
Type Ia
Supernovae
Screened
Screened
Screened
Unscreened
Screened
Distance

Two main roots to determining H_0

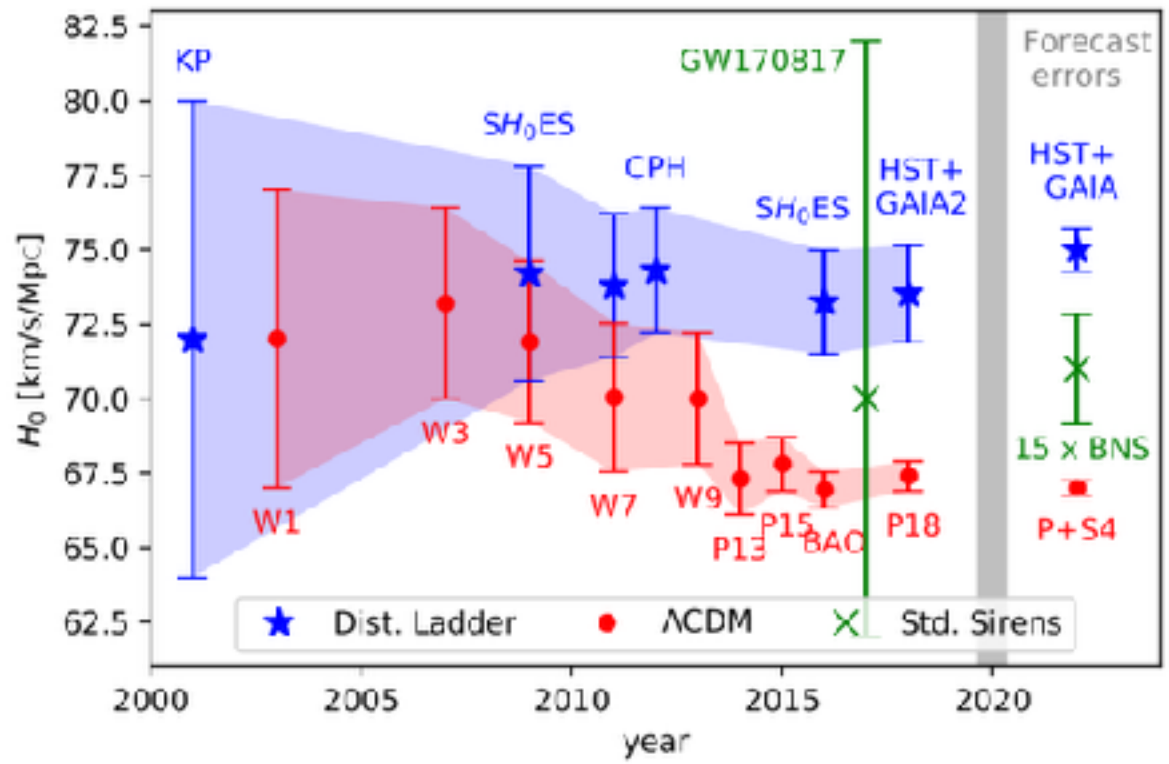
(1) **Distance ladder method**: Cepheids and TRGBs (calibrated to geometric anchor distances)

Improved: from 10% (2001) to < 2% (2019)

Value: $H_0 = 74.03 \pm 1.42$ km/s/Mpc

(2) **Via sound horizon observed from CMB**: not constrained directly. Using data at z ~ 1100 and extrapolated to z ~ 0, based on the physics of the early universe.

Value: $H_0 = 67.4 \pm 0.5$ km/s/Mpc



Novel measurements of H_0

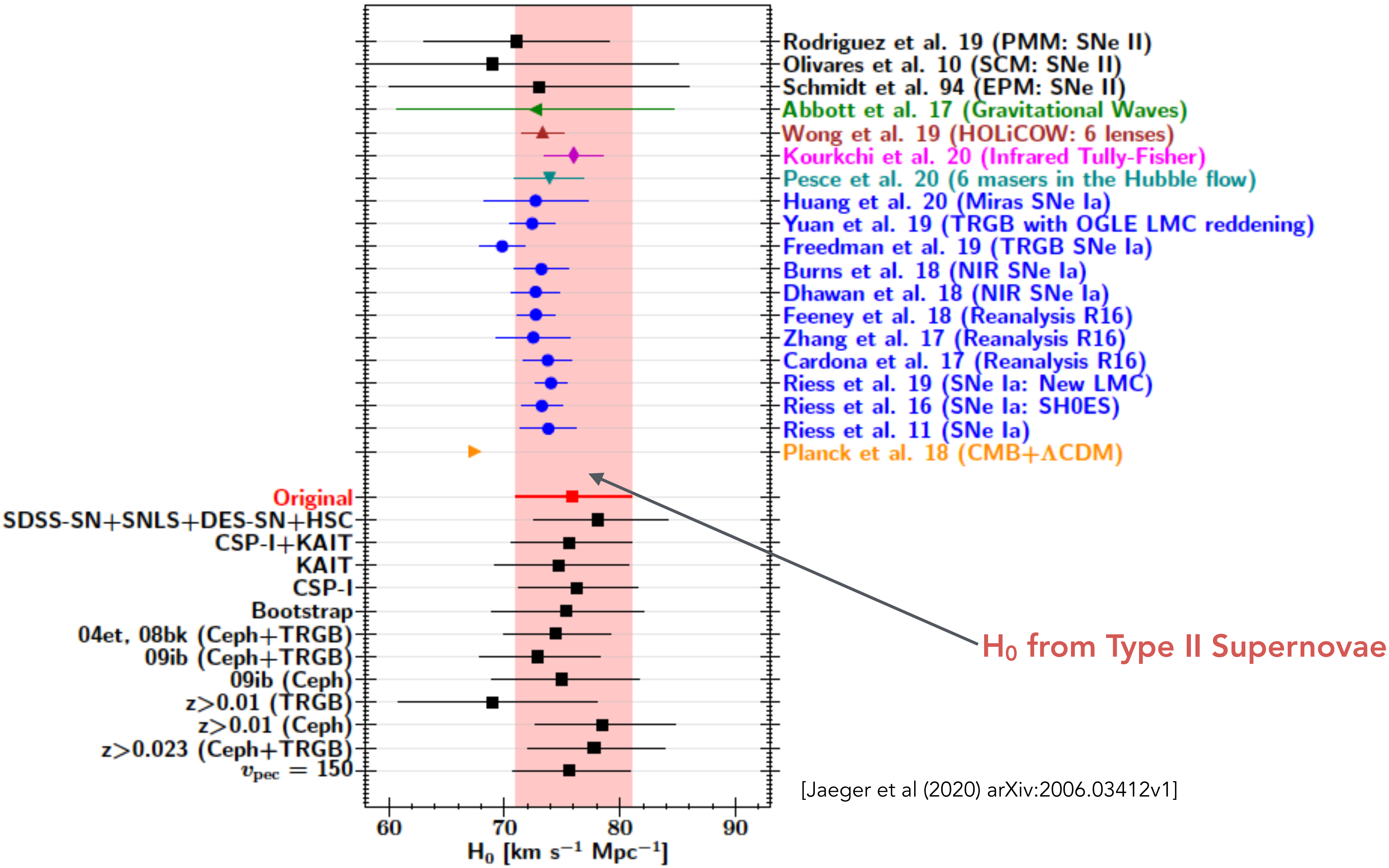
- Quasars strongly gravitationally lensed: H0LiCOW collaboration [Bonvin et al 2017]

Value: $H_0 = 73.3^{+1.7}_{-1.8}$ km/s/Mpc

- Geometric distantes measurements to megamaster-hosting galaxies:

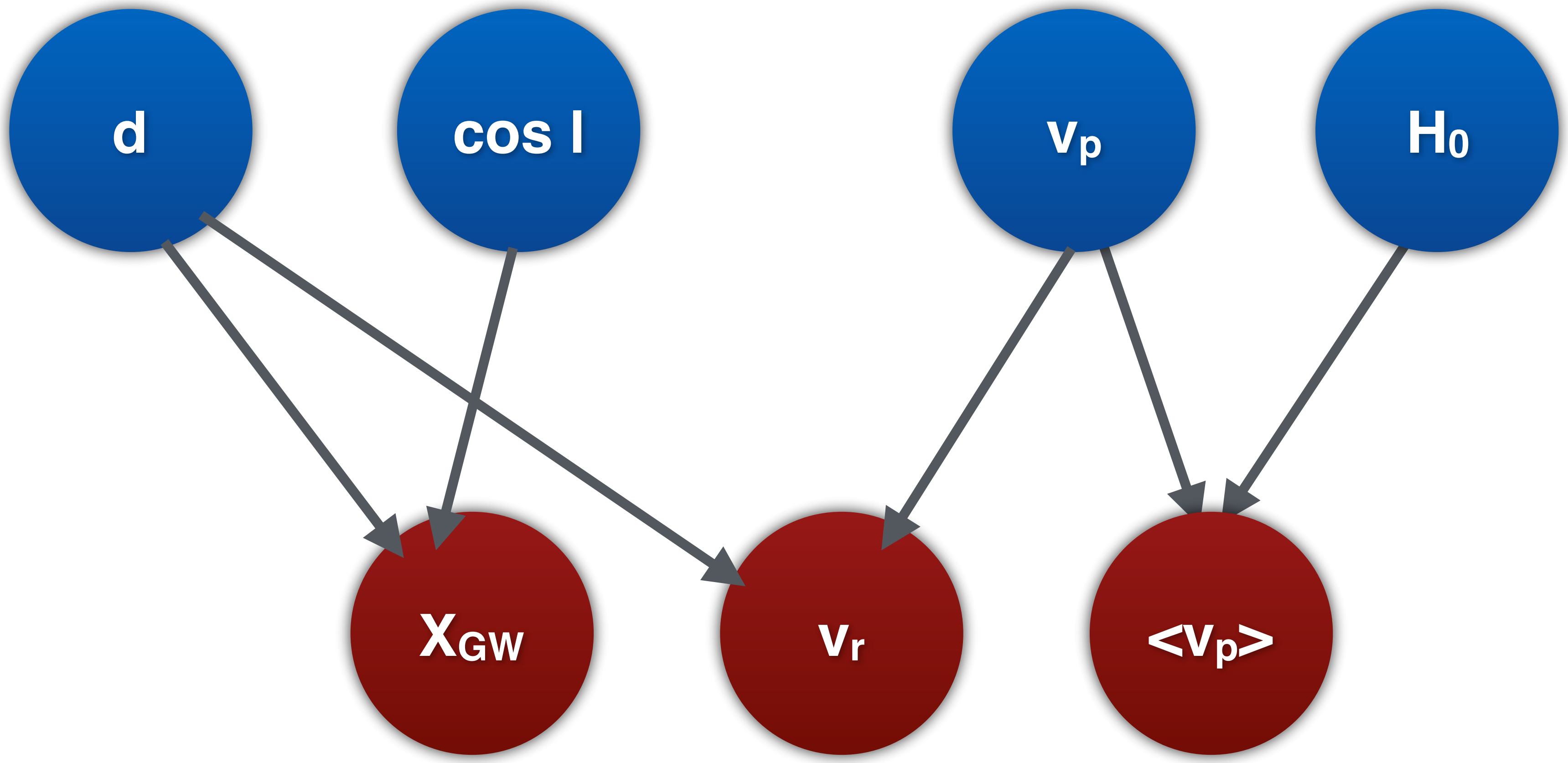
  Megamaster Cosmology Project [Pesce et al 2020]

Value: $H_0 = 73.9 \pm 3.0$ km/s/Mpc



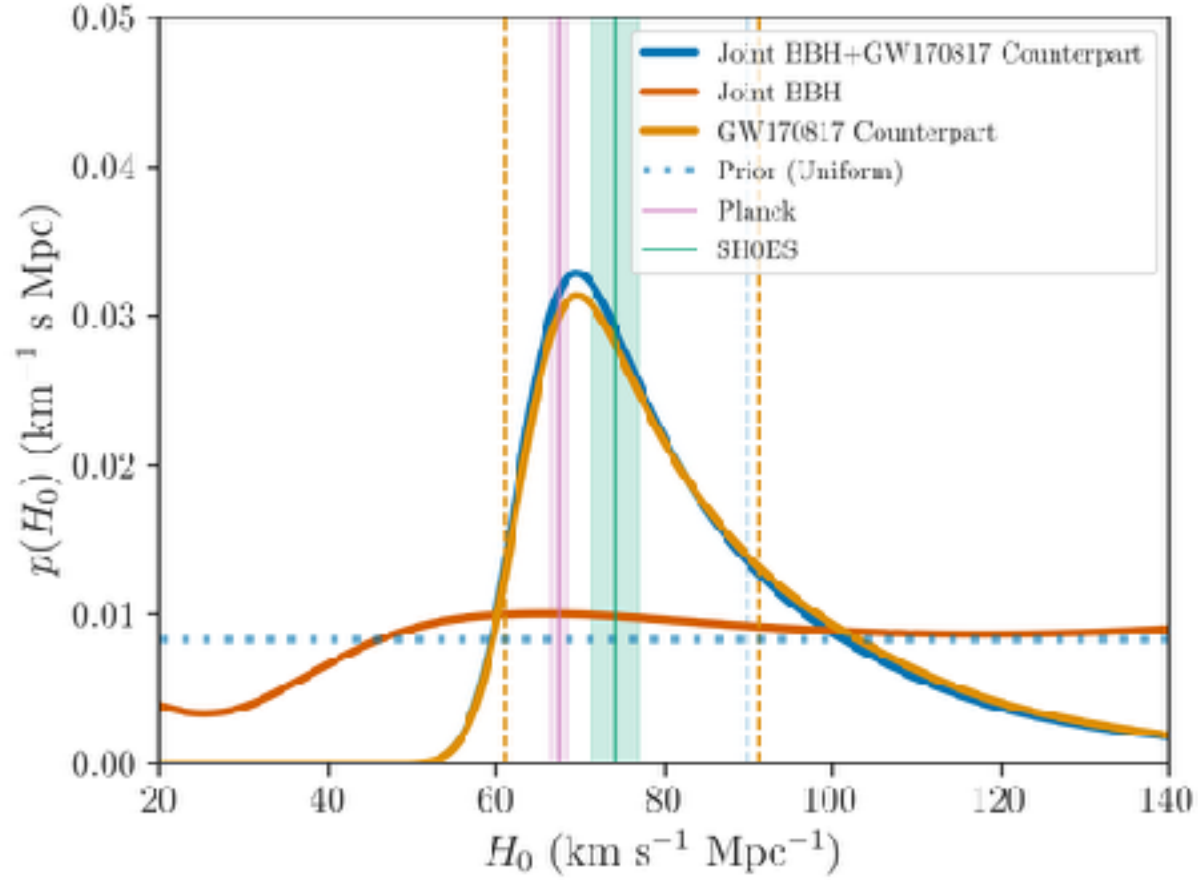
[Jaeger et al (2020) arXiv:2006.03412v1]

Novel measurements of H_0 : How we can compute H_0 from Standard Sirens?

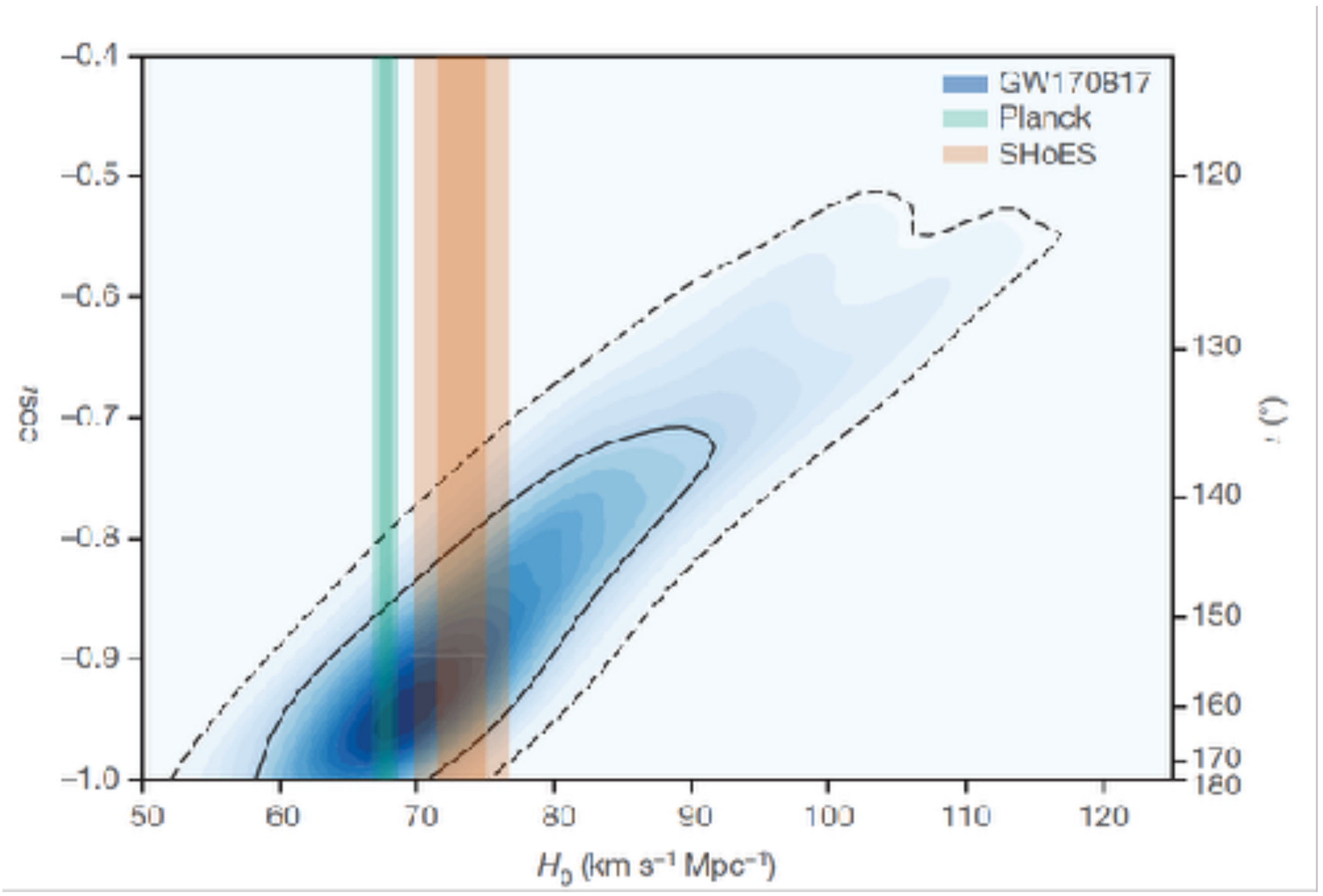


$$p(H_0, z, \cos\iota, v_p \mid x_{\rm GW}, v_r, \langle v_p\rangle) \propto \frac{p(H_0)}{\mathcal{N}_s(H_0)} p(x_{\rm GW} \mid d = cz/H_0, \cos\iota)\, p(v_r \mid z, v_p) \times p(\langle v_p\rangle \mid v_p)\, p(z)\, p(v_p)\, p(\cos\iota),$$

Novel measurements of H_0 : How we can compute H_0 from Standard Sirens?



[LIGO-VIRGO. (2021)]



[LIGO-VIRGO. Nature 24471 (2017)]

Novel measurements of H_0 : Update of H_0 from Standard Sirens

- Modelling early data on the GRB170817 jet [Guidorzi et al 2017]

  Value: $H_0 = 74^{+11.5}_{-7.5}$ km/s/Mpc

- Late-time GRB170817 jet superluminical motion [Hotkezaka et al 2019]

  Value: $H_0 = 70.3^{+5.3}_{-5.0}$ km/s/Mpc

- Dark siren GW170814 BBH merger [Soares et al 2019]

  Value: $H_0 = 75^{+40}_{-32}$ km/s/Mpc

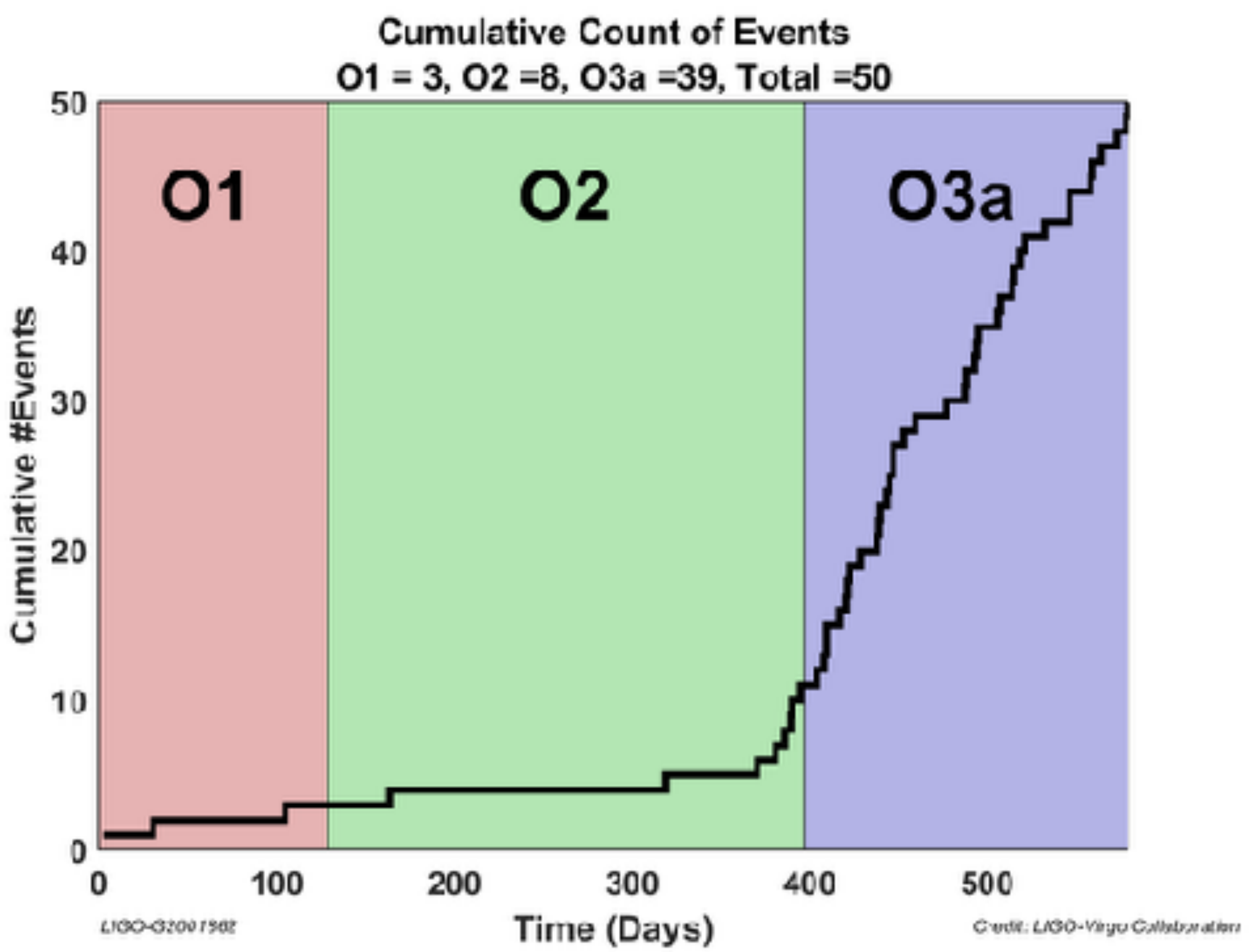
- GW170817 and 4 BBH from O1 and O2 [Abbott et al 2019]

  Value: $H_0 = 68^{+14}_{-7}$ km/s/Mpc

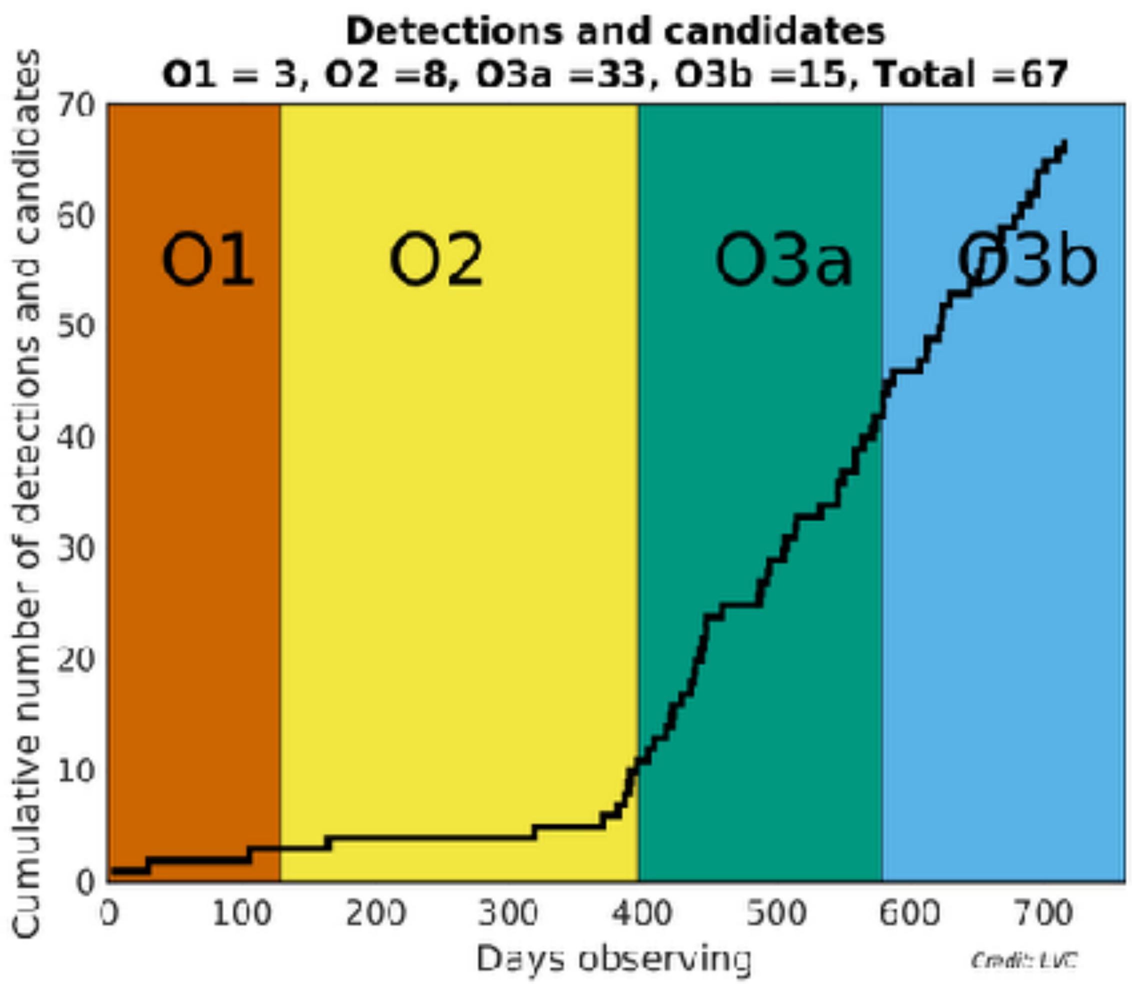
- GW190814 and GW170817 [Abbott et al 2020]

  Value: $H_0 = 70^{+17}_{-8}$ km/s/Mpc

(October 27 2020)



From Today (Nov 3 2020 -> March 2021)

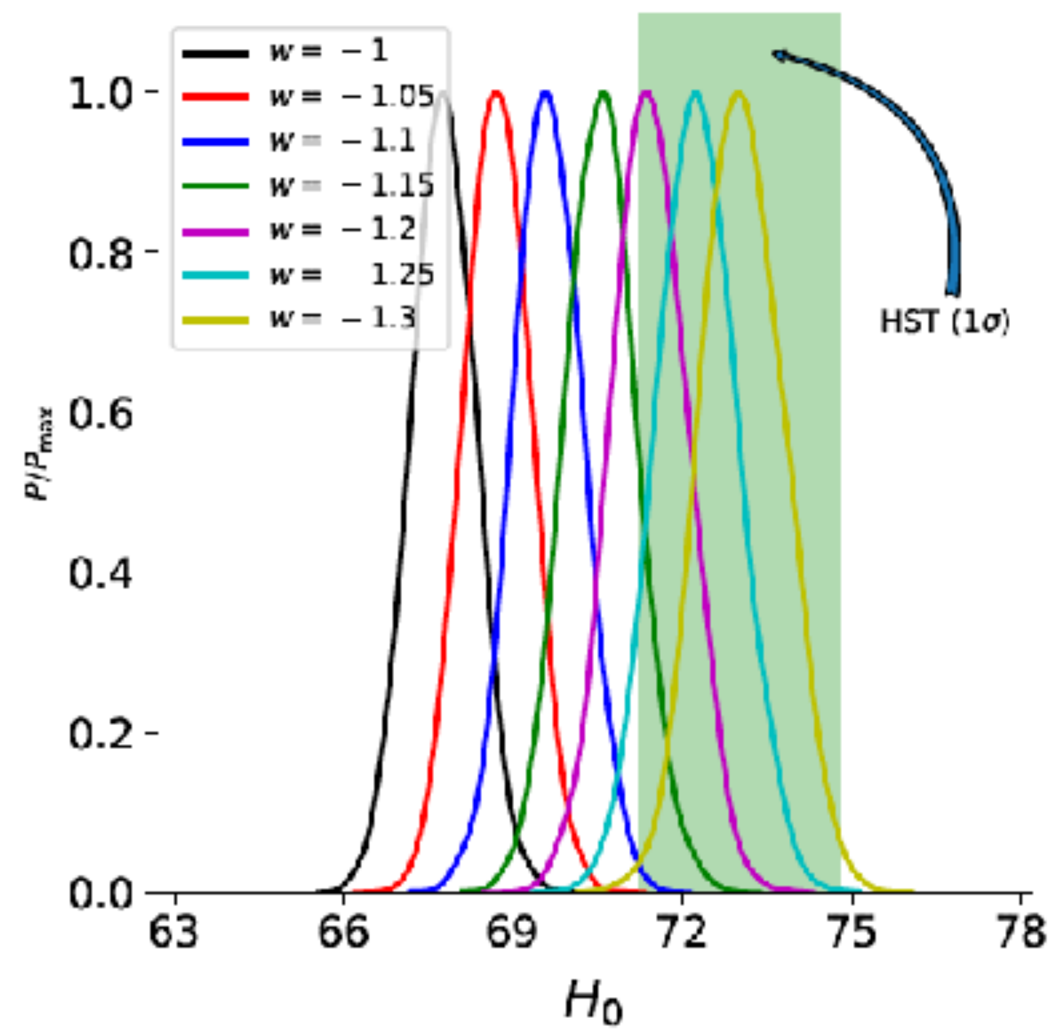


Novel measurements of H_0 : Possible solutions

Physics beyond the canonical LCDM:

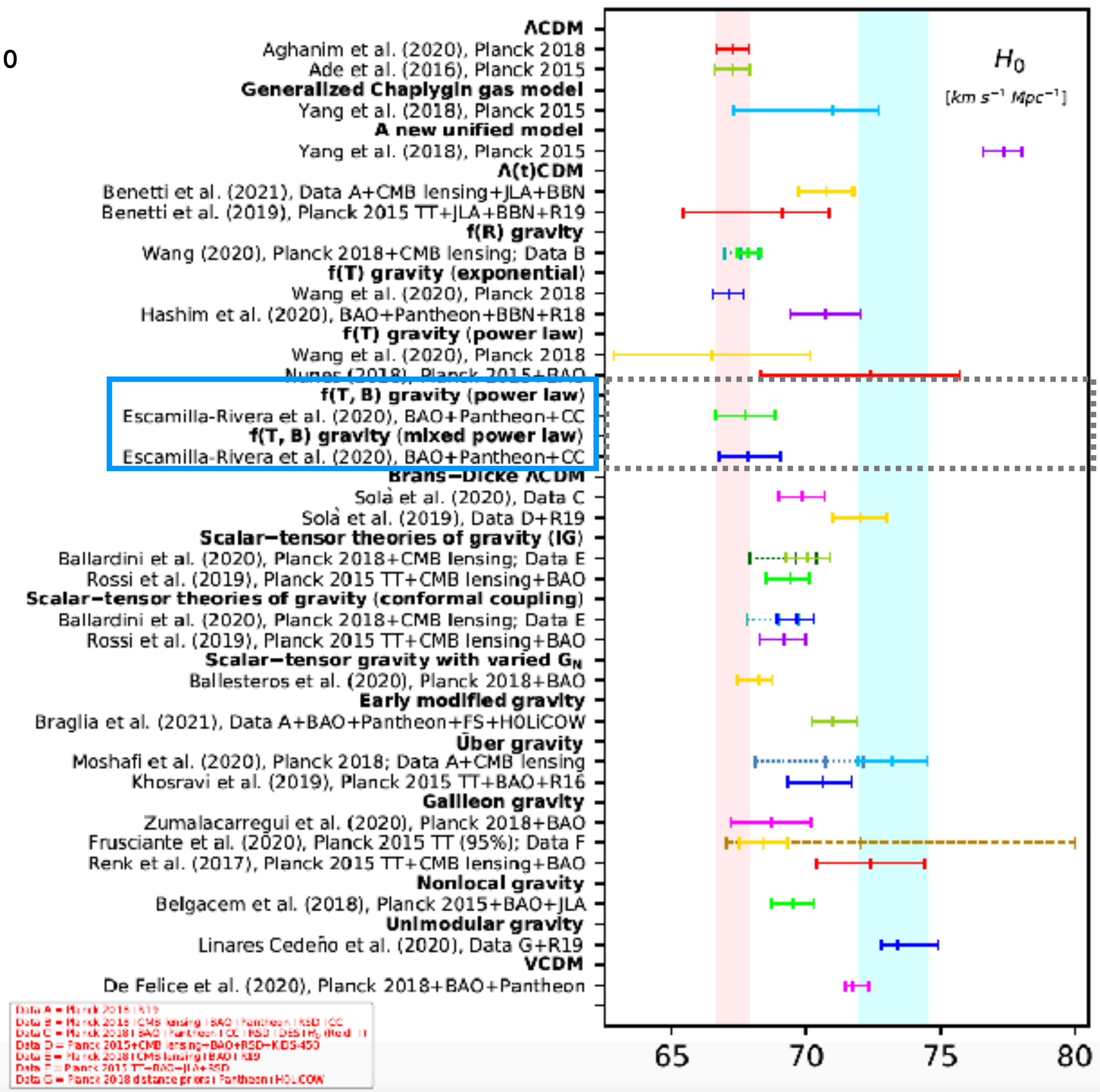
- phantom dark energy,
- dark radiation,
- dynamical dark energy,
- holographic dark energy,
- non-linear parametric dark energy,
- extended dark energy components

with massive neutrinos, …



Novel possible solutions of H_0

[Di Valentino et al (2021)]



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Lovelock's theorem (1971) [version from T. Clifton, et al 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"

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

Lovelock's theorem (1971) [version from T. Clifton, et al 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"

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

Lovelock's theorem (1971) [version from T. Clifton, et al 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"

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

Lovelock's theorem (1971) [version from T. Clifton, et al 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"

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

Lovelock's theorem (1971) [version from T. Clifton, et al 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"

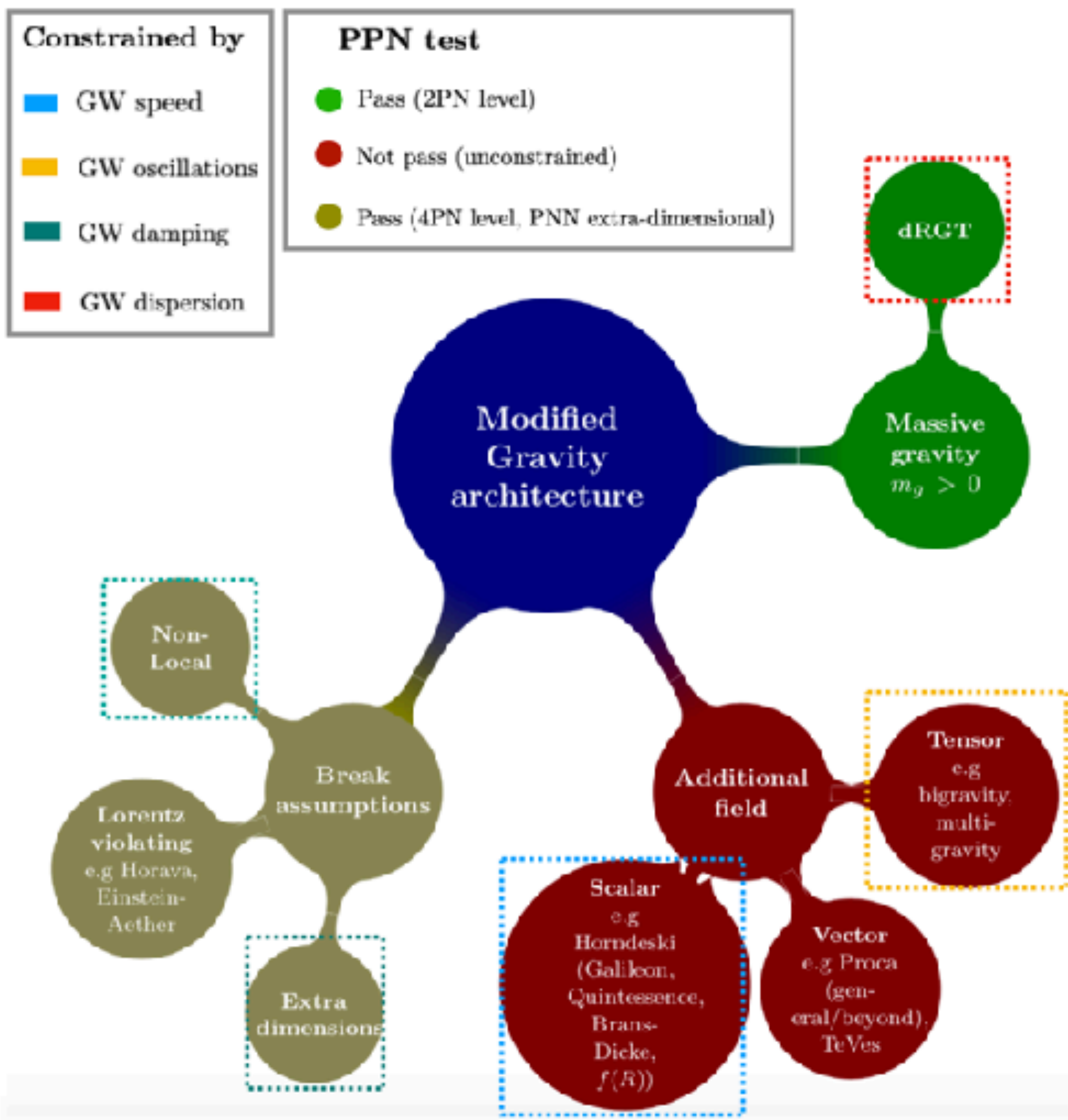
$$S_{grav} = \frac{M_{\mathrm{Pl}}^2}{2}\int\sqrt{-g}\,d^4x\left[R + f\left(\frac{1}{\Box}R\right)\right]$$

Lovelock's theorem (1971) [version from T. Clifton, et al 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"

? ? ? ? ? ?

[**C. Escamilla-Rivera**, Júlio Fabris. 2005.09739 (2021)]



[**C. Escamilla-Rivera**, Júlio Fabris. 2005.09739 (2021)]

Viable after GW170817

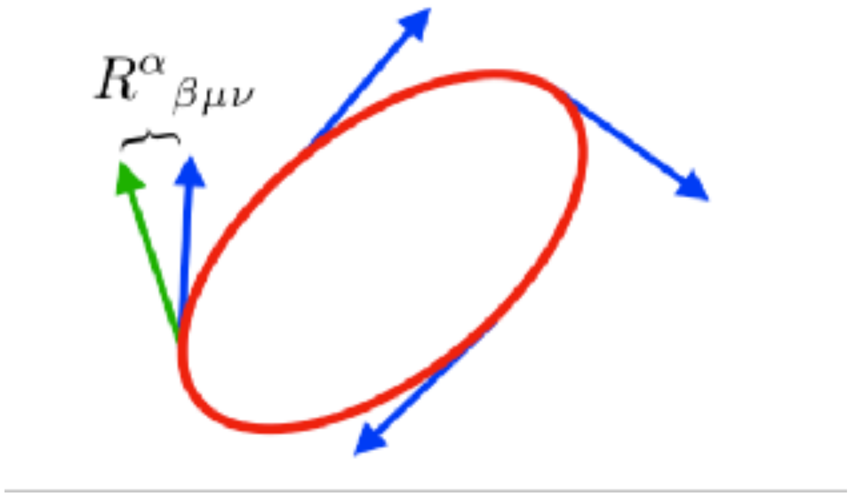
$c_g = c$	$c_g \neq c$
General Relativity Quintessence/k-essence Brans-Dicke/$f(R)$ Kinetic Gravity Braiding	Quartic/quintic Galileons Fab Four de Sitter Horndeski $G_{\mu\nu}\phi^\mu\phi^\nu$, $f(\phi)$.Gauss-Bonnet
Derivative Conformal Disformal Tunning Quadratic DHOST with $A_1 = 0$	Quartic/quintic GLPV Quadratic DHOST with $A_1 \neq 0$ Cubic DHOST

Non-viable after GW170817

General Relativity [A. Einstein (1915)]

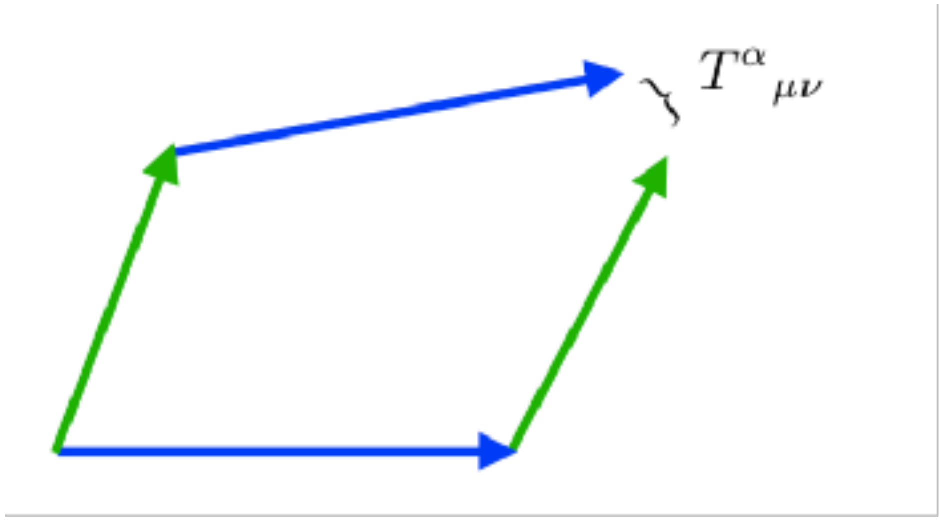
Energy-momentum: source of curvature

Levi-Civita connection: zero torsion, metricity



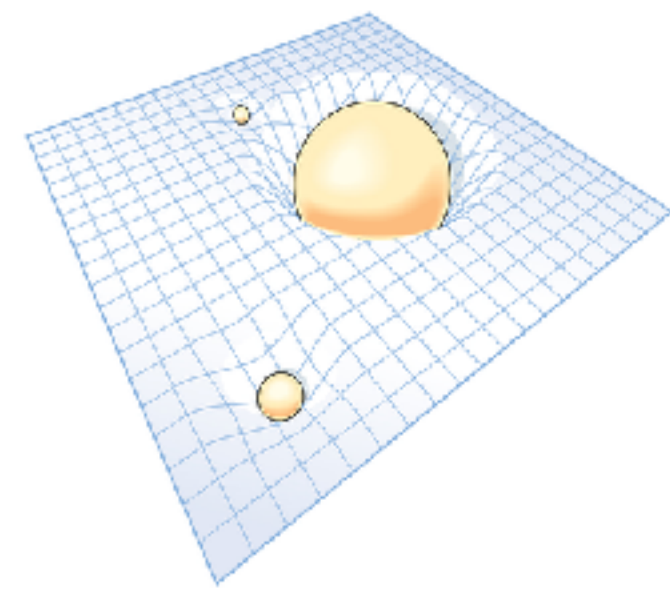
Teleparallel Equivalent of GR [A. Einstein (1928)]

Weitzenböck connection: zero curvature, metricity



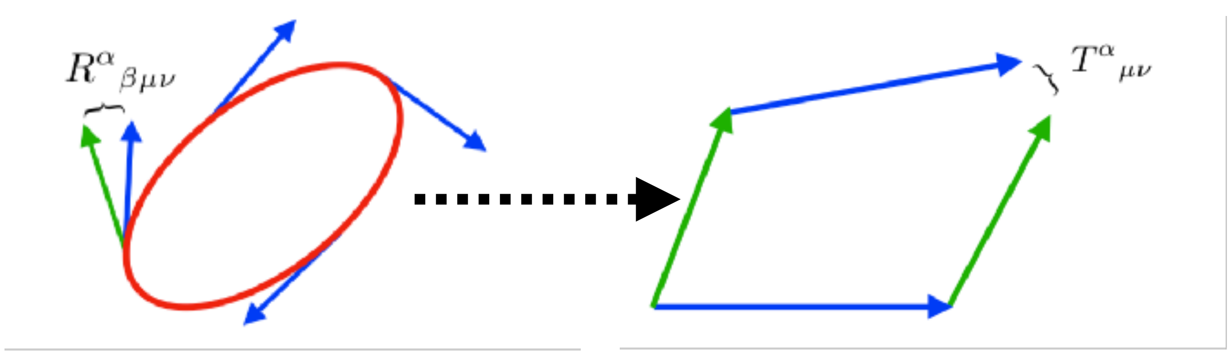
[Beltran et al 1903.06830 (2019)]

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



f(T,B) gravity design

Curvature-Torsion relation : $\mathscr{R} = -T + B$

Naturally, $f(T) \neq f(-T+B) = f(\mathscr{R})$

f(T,B) *organically* decouples second-order (T) and fourth-order (B) contributions

Only linear **B** is a boundary term

f(T,B) gravity : Generalizing f(R) gravity $S = \frac{1}{16\pi G}\int d^4x e[-T + f(T,B)] + S_{\text{matter}}$

Popular models of f(T,B)*	Motivation	Maturity	Late-time test	Early-time test
$f(T,B) = \alpha B^n + \beta T^m$	Stability ✓	Reproduces LCDM ✓	SNeIa ✓	
$f(T,B) = \alpha B^n T^m$	Fine-tuning ✓		BAO ✓	☢
$f(T,B) = \alpha \log B + \beta T$	Cosmic acceleration ✓	Reproduces w(z)CDM ✓	H(z) ✓	
$f(T,B) \propto f(0) + T + B + TB + T^2 + B^2 + \mathcal{O}(TB, T^2, B^2)$				

* Linear power law like — Mixed power law like — Logarithm like — Taylor series like

f(T,B) theory as solution to the Hubble tension

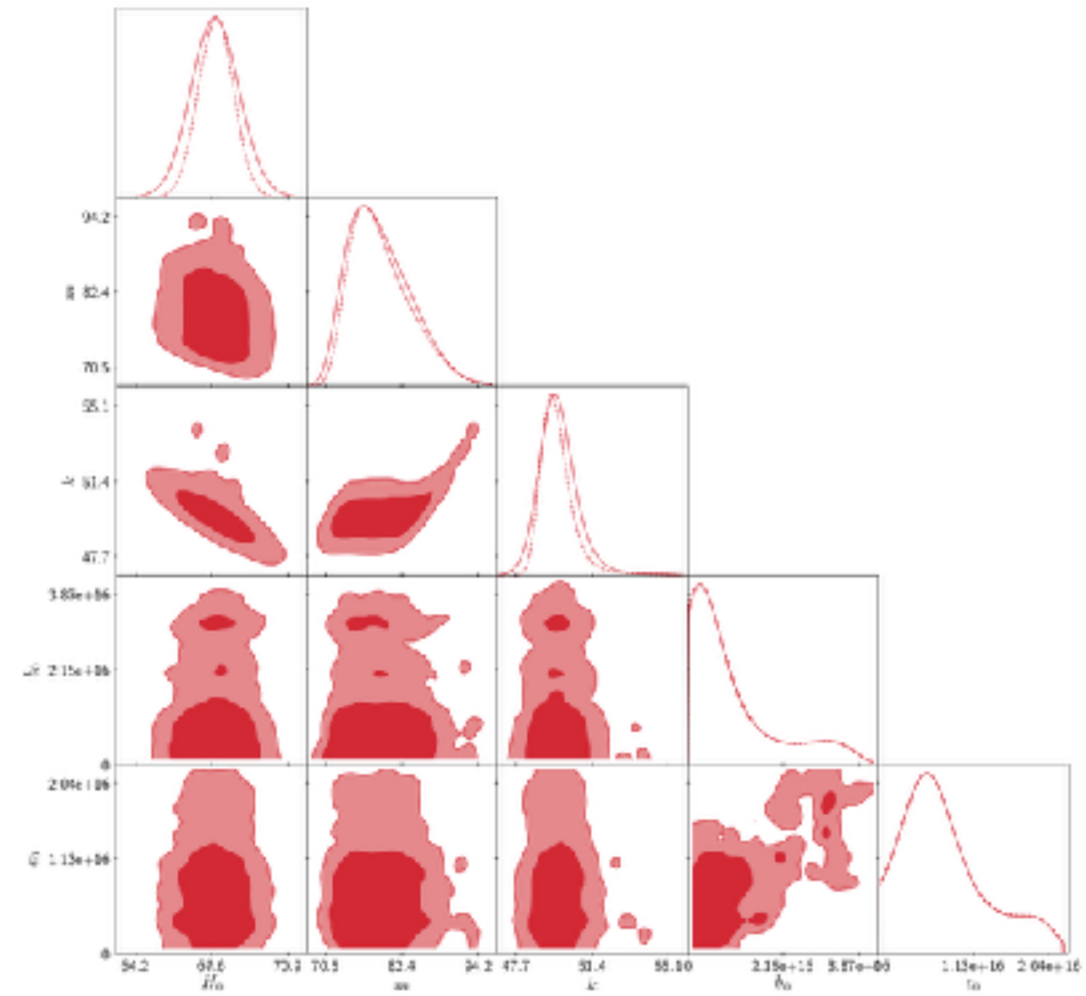
[**C. Escamilla-Rivera** and Jackson Said Levy. Class.Quant.Grav. 37 (2020) 16]

$$e^a_\mu = \text{diag}(1, a(t), a(t), a(t)),$$

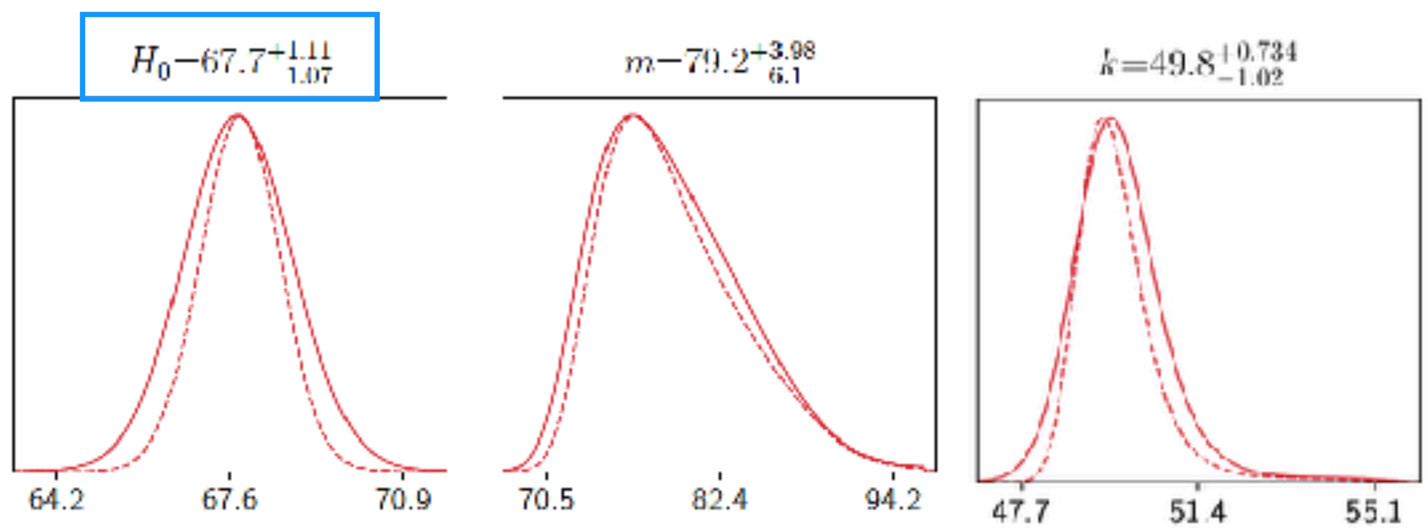
$$T = 6H^2, \quad \text{and} \quad B = 6(3H^2 + \dot{H}),$$

$$\tilde{f}(T,B) \rightarrow -T + f(T,B),$$

$$w_{\text{eff}} = -1 + \frac{\ddot{f}_B - 3H\dot{f}_B - 2\dot{H}f_T - 2H\dot{f}_T}{3H^2(3f_B + 2f_T) - 3H\dot{f}_B + 3\dot{H}f_B - \frac{1}{2}f}.$$



C.L using SN + CC + BAO



$$f(T,B) \propto B^k + T^m$$

Stability analysis for cosmological models in f(T,B) gravity

[G. Rave, **C. Escamilla-Rivera** and J. Said Levy. Eur.Phys.J.C 80 (2020) 7]

In order to construct the dynamical system for f(T,B) Friedmann equations we can write

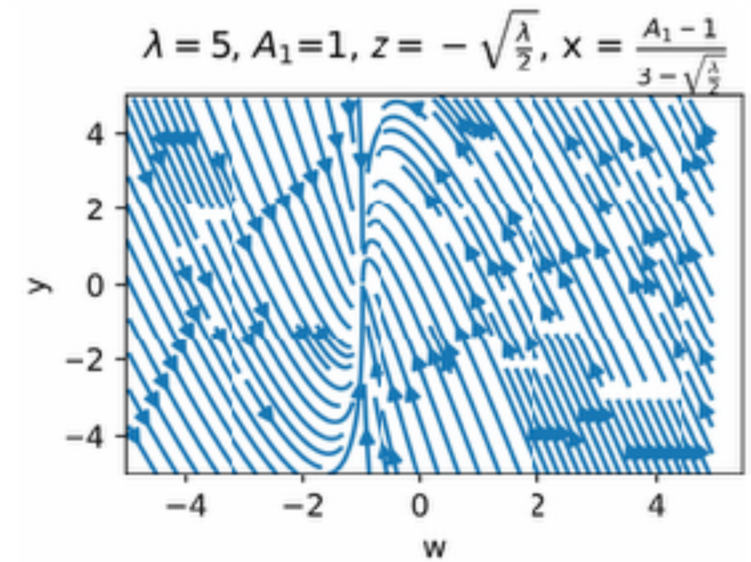
$$\lambda = \frac{\ddot{H}}{H^3} = \text{constant}$$

[S. Odintsov et al, Phys. Rev. D 98, 024013 (2018)]

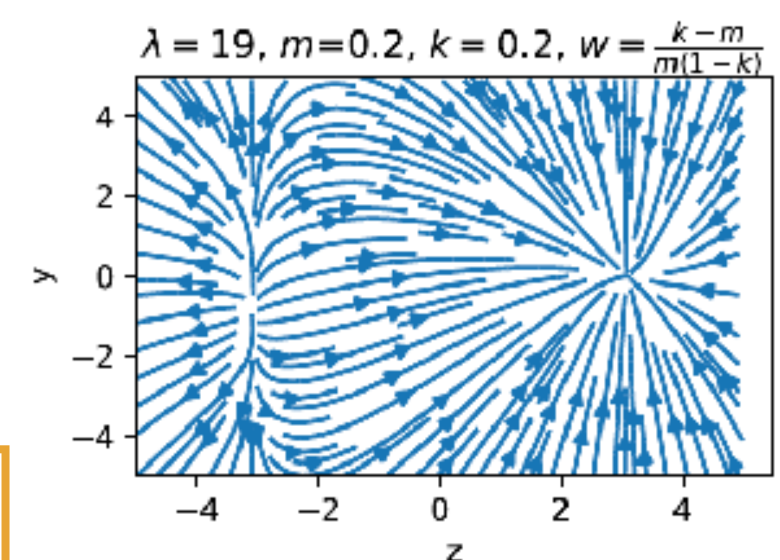
$$3+2\left(\frac{H'}{H}\right) = -\frac{3f}{6H^2} + 9f_B + 6f_T + 3\left(\frac{H'}{H}\right)f_B + 2\left(\frac{H'}{H}\right)f_T + 2f'_T - \left(\frac{H'}{H}\right)f'_B - f''_B\,,$$

$$\Omega_{\rm eff} = 3f_B + 2f_T - f'_B - \frac{f}{6H^2} + \left(\frac{H'}{H}\right)f_B\,,$$

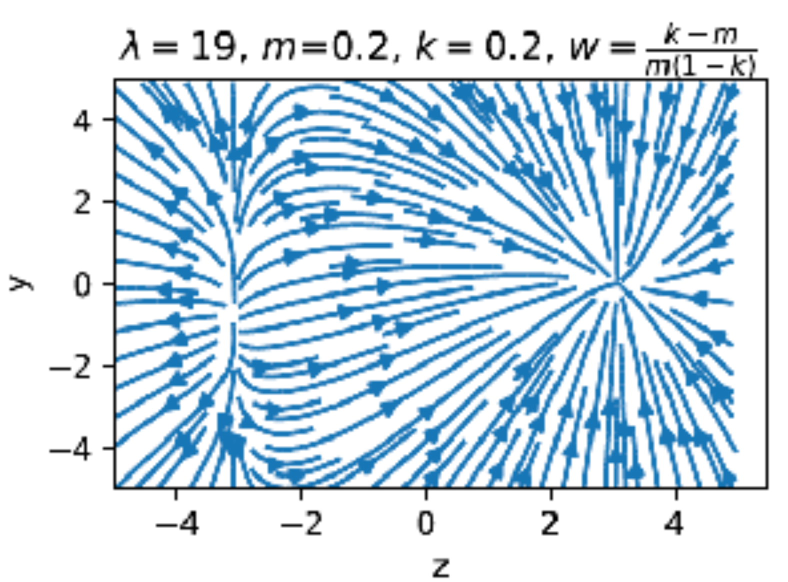
Taylor series like



Power law like



$$\omega_{\rm eff} = -1 \mp \frac{2}{3}\sqrt{\frac{\lambda}{2}}\,.$$



$$\omega_{\rm eff} \xrightarrow{\omega\to 0} -1 \mp \frac{2}{3}(k+m)\sqrt{\frac{\lambda}{2}}\,.$$

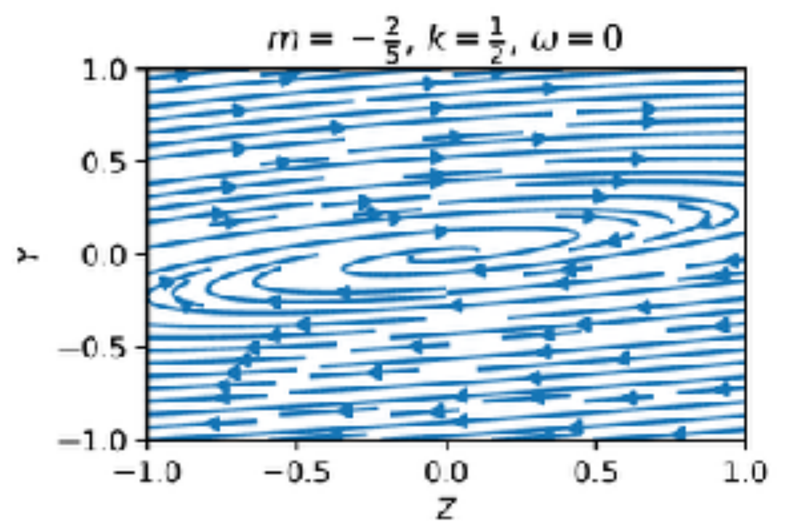
Mixed power law like

Stability analysis: Phenomenological hints on Hubble tension from the generic f(T,B)

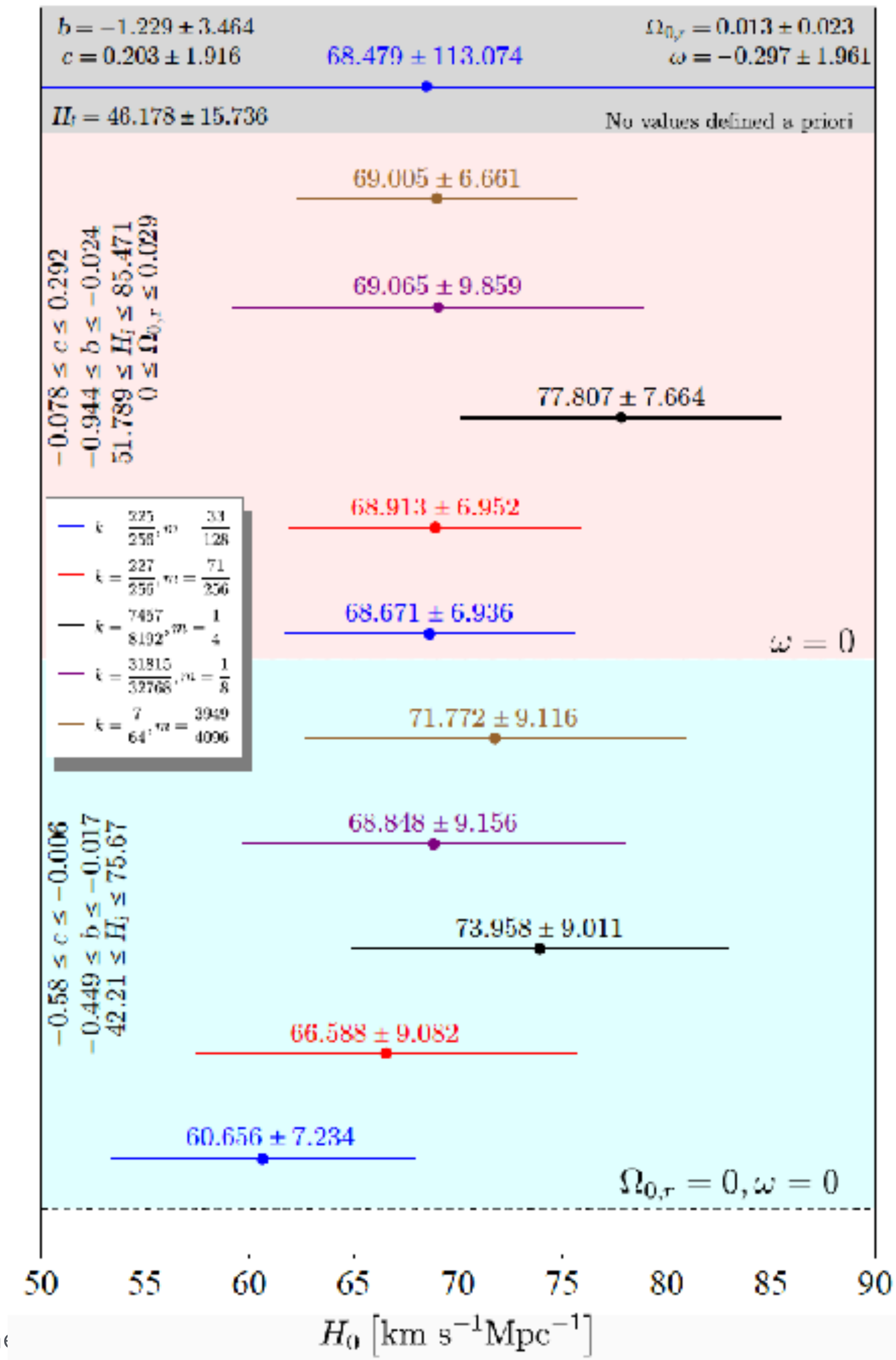
[G. Rave, **C. Escamilla-Rivera** and J. Said Levy. Accepted in PRD (2021)]

$$\lambda = \frac{\ddot{H}}{H^3} \neq \text{constant}$$

$$\lambda = \frac{1}{1-k}\left(6kZ + 2(m-1)(Z+3)Z - \frac{Y(Z+3)}{X} + 2Z^2\right)$$



Mixed power law like



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Current methods: Performing cosmostatistics and statistical diagnostics

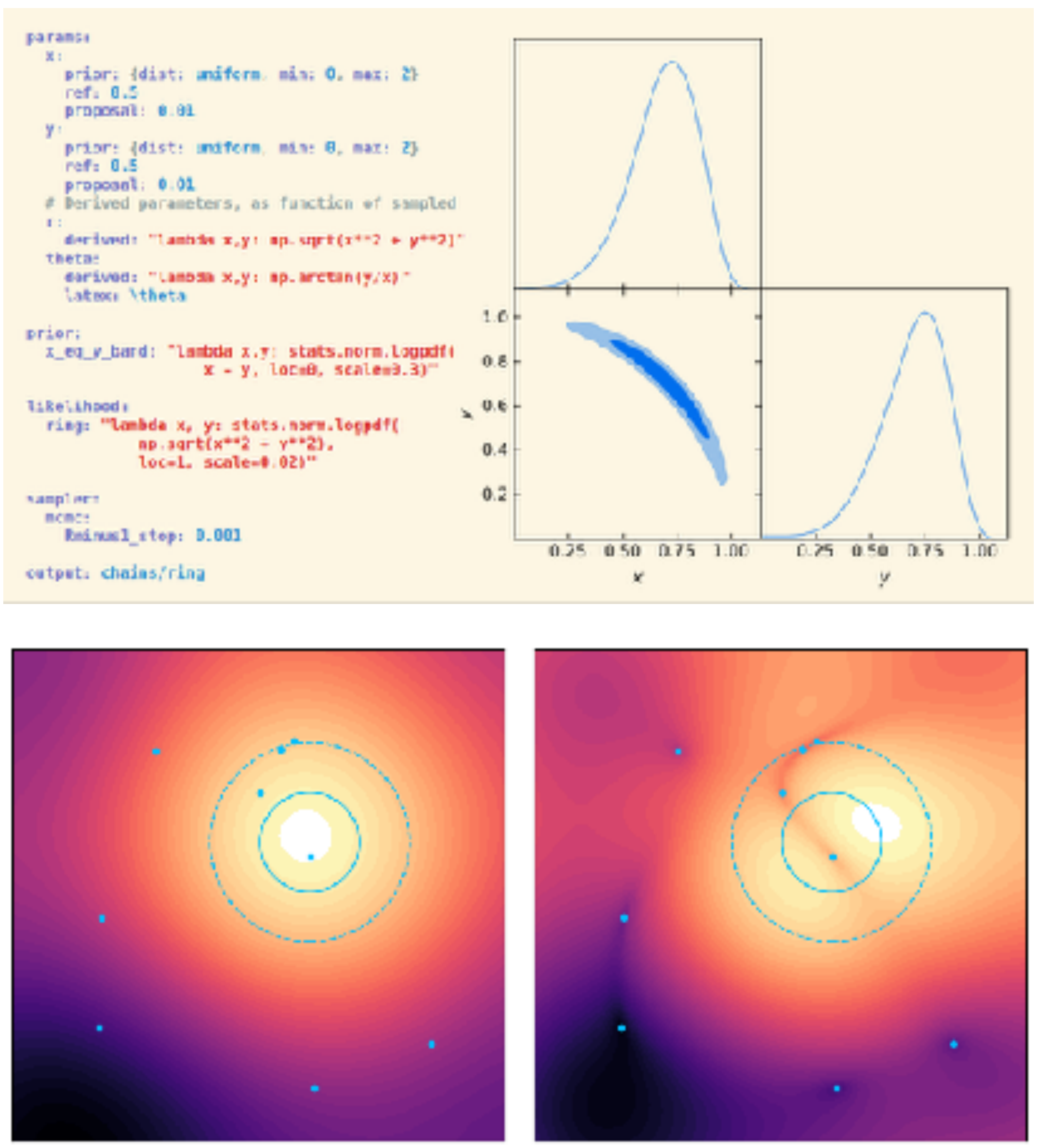
CAMB, CLASS, CosmoMC, MontePython, CosmoSIS, hiCLASS…

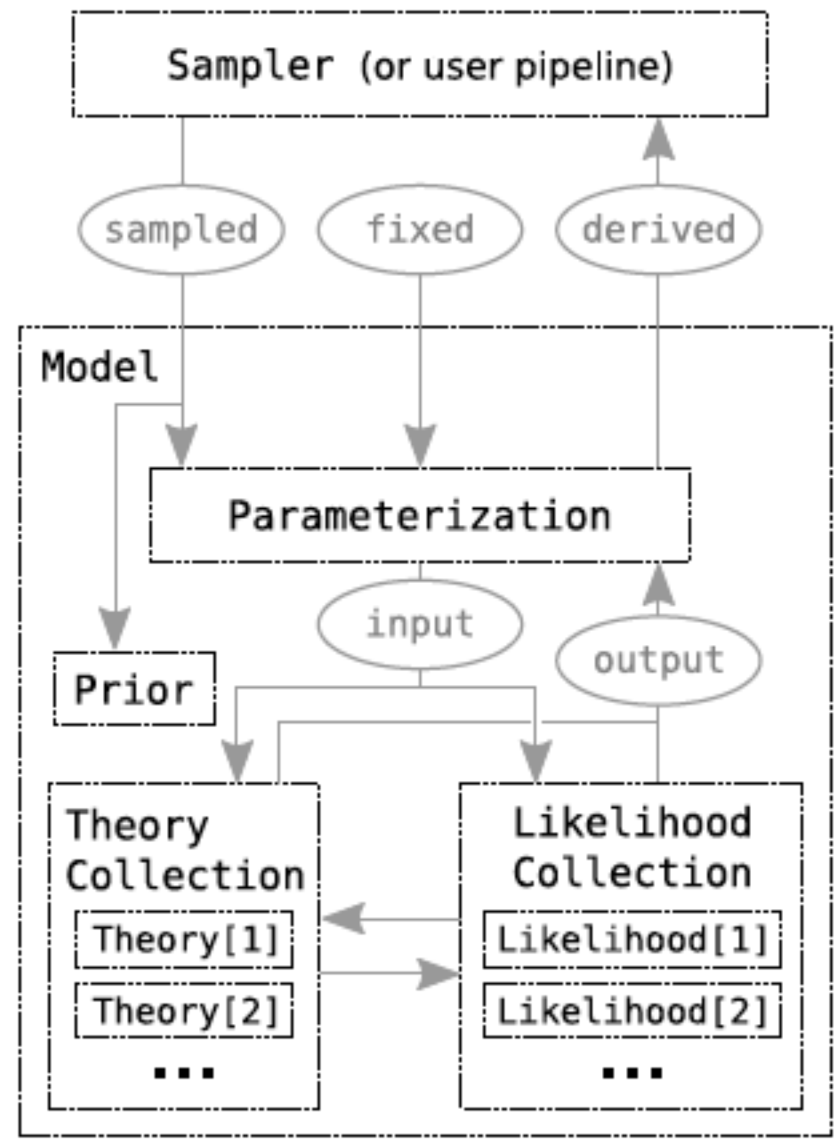
To obtain:

- C.L phase-constraints and likelihoods (evidence) of the cosmological parameters and free model parameters
- Model reconstructions: Gaussian Processs, Principal Component Analysis, Smooting Method [T. Holsclaw et al 2010, Huterer, et al 2010, A. Shafieloo et al 2006]
- Non-parametric approaches: Loess-Simex [Escamilla-Rivera, C et al 2014]
- Power spectra (matter, scalar, tensor)

Future (already here!) methods: Performing cosmostatistics and statistical diagnostics

Cobaya: Code for Bayesian Analysis of hierarchi physical models



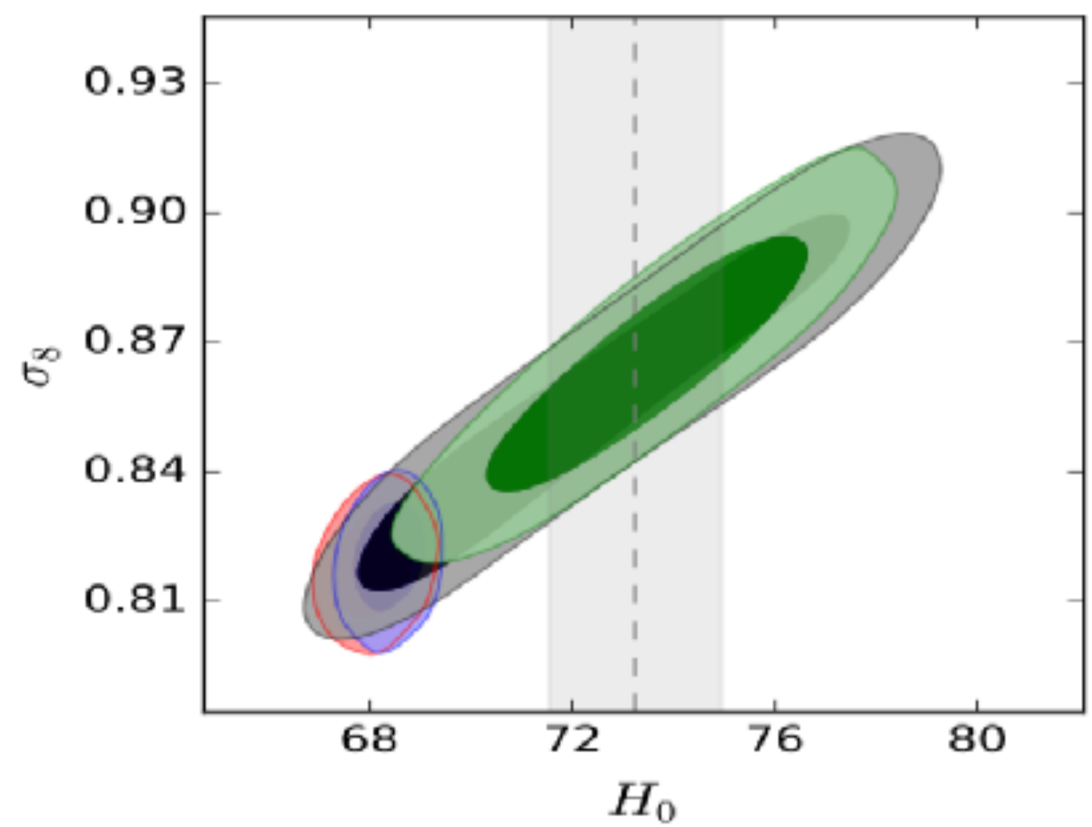


[Torrado J and A. Lewis (2020)]

f(T) precision cosmology

- SNeIa (Pantheon)
- BAO (SDSS)
- H(z) (passive old galaxies)
- CMB (Planck 2018)

Linear power law like



[Nunez, R et al JCAP 05 (2018)]

f(T) precision cosmology

- SNeIa (Pantheon)
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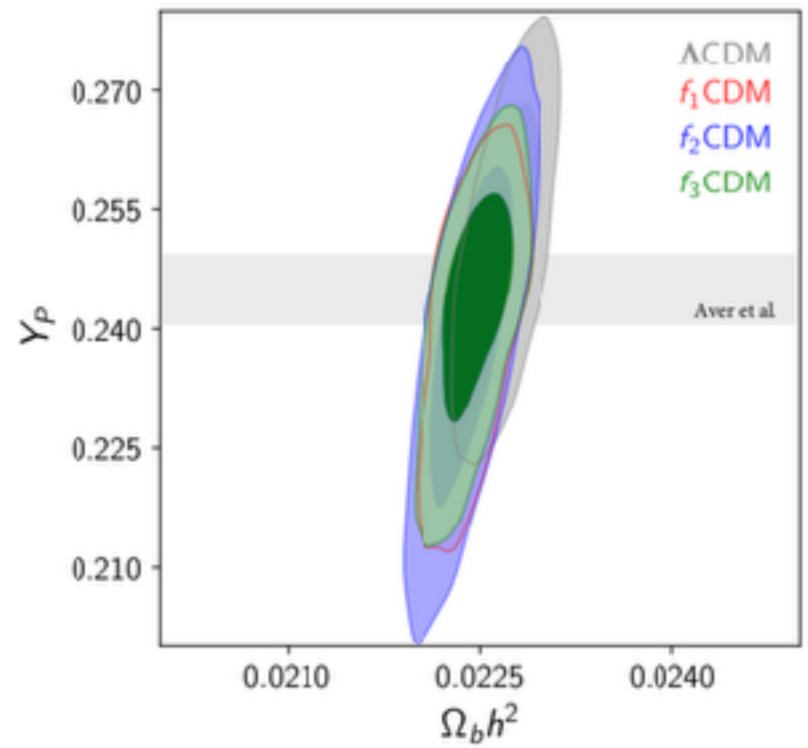
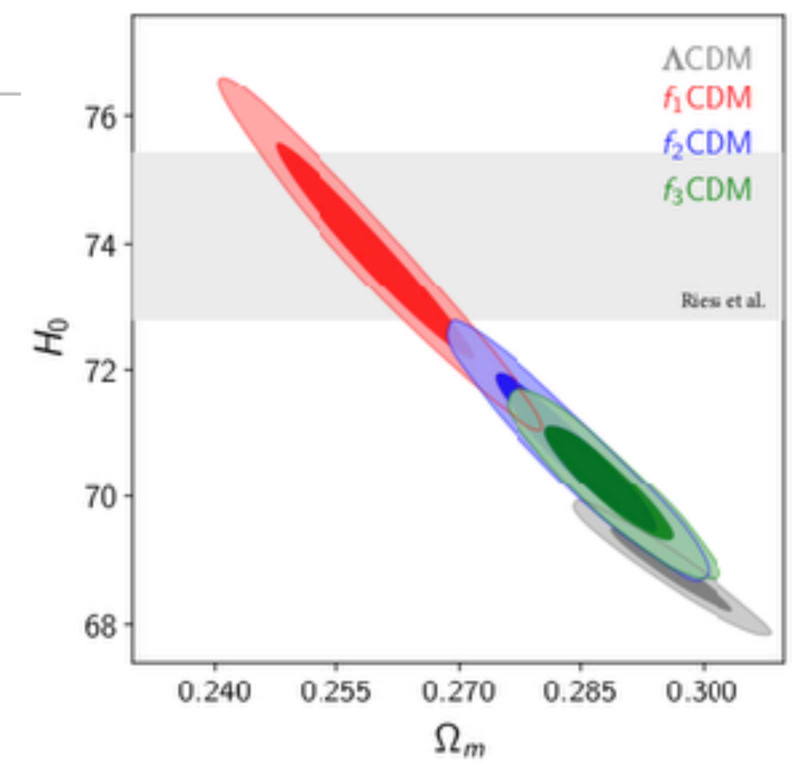


Linear power law like
Exponential
Square-root exponential

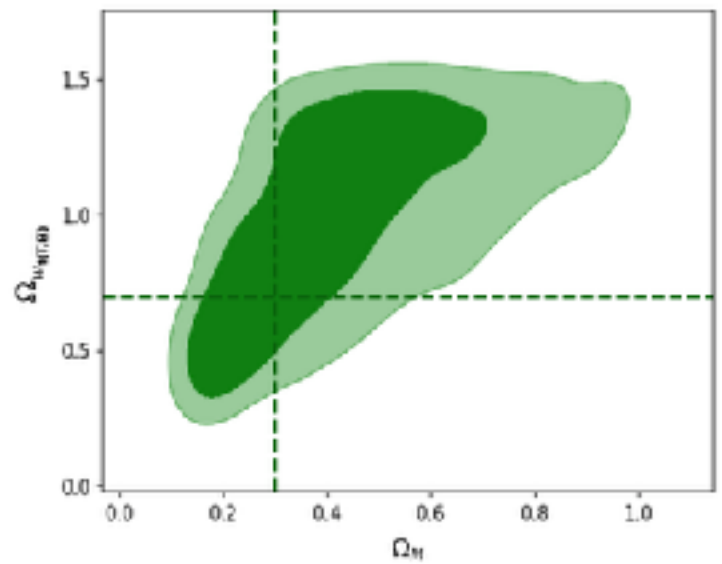


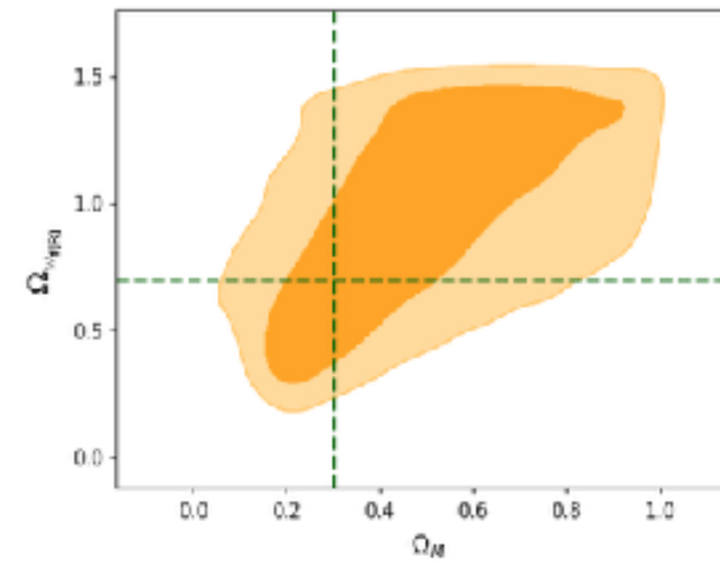
[Benetti, N et al MNRAS staa3368 (2020)]

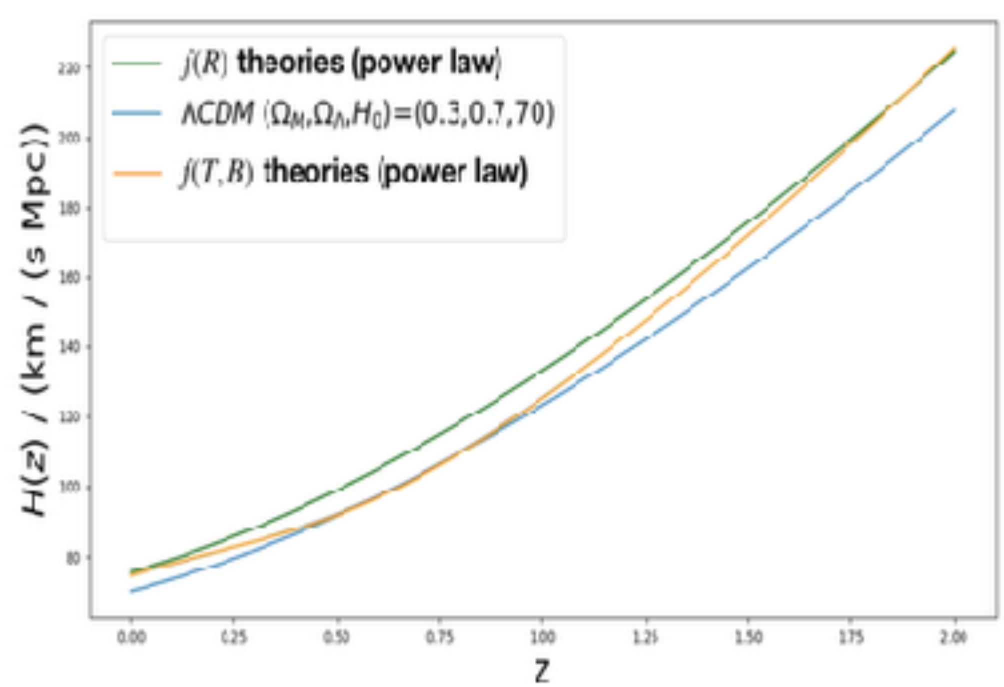
f(T,B) precision cosmology

[**C. Escamilla-Rivera.** Astronomische Nachrichten (2021)]

- SNeIa (Pantheon)
- BAO (SDSS-DR7, DR10, DR11)
- H(z) (passive old galaxies)
- CMB (Planck 2018)







Linear power law like
Mixed power law like
Logarithm like

f(T,B) precision cosmology

[**C. Escamilla-Rivera.** In progress (2021)]

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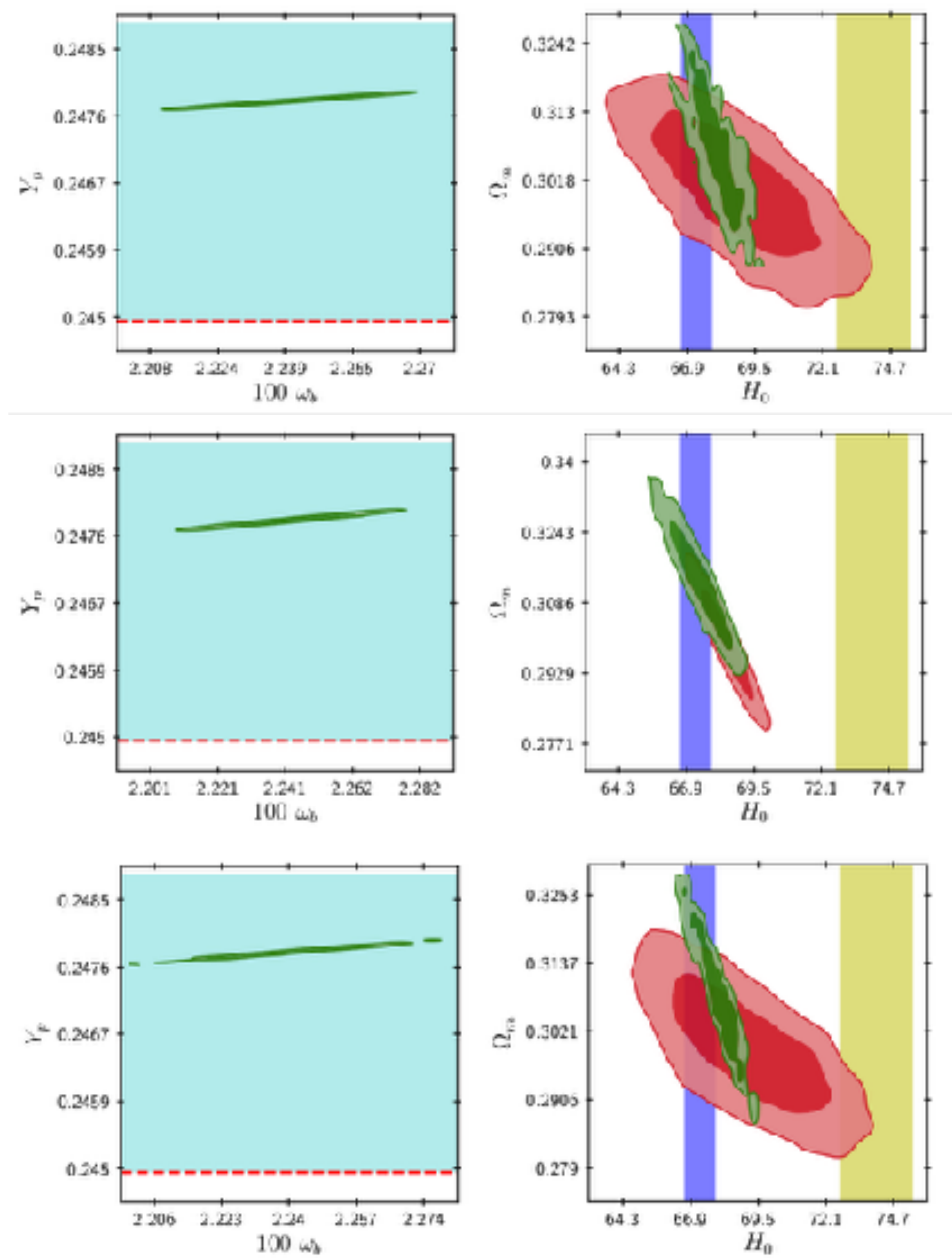
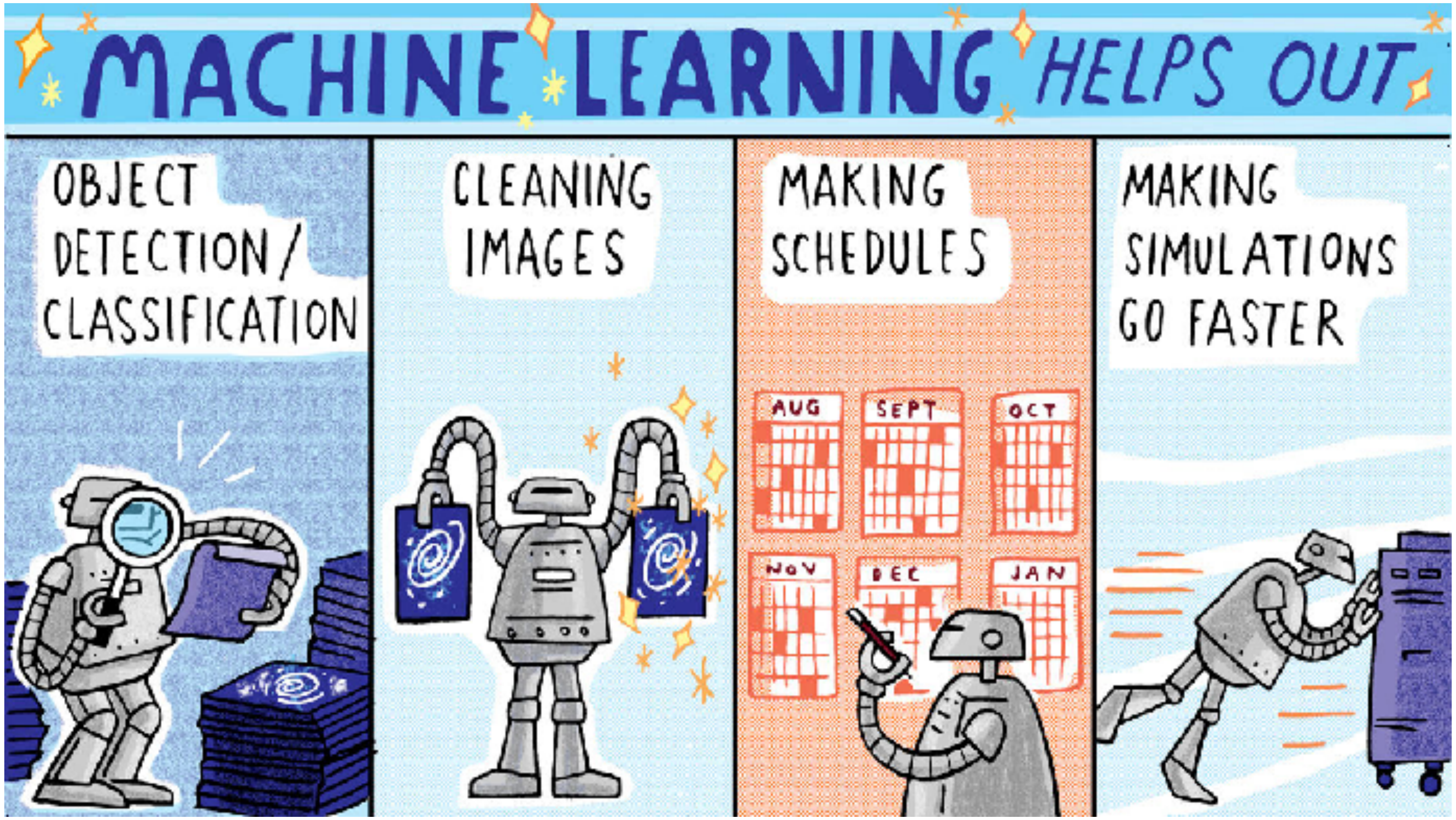
Linear power law like
Mixed power law like
Logarithm like

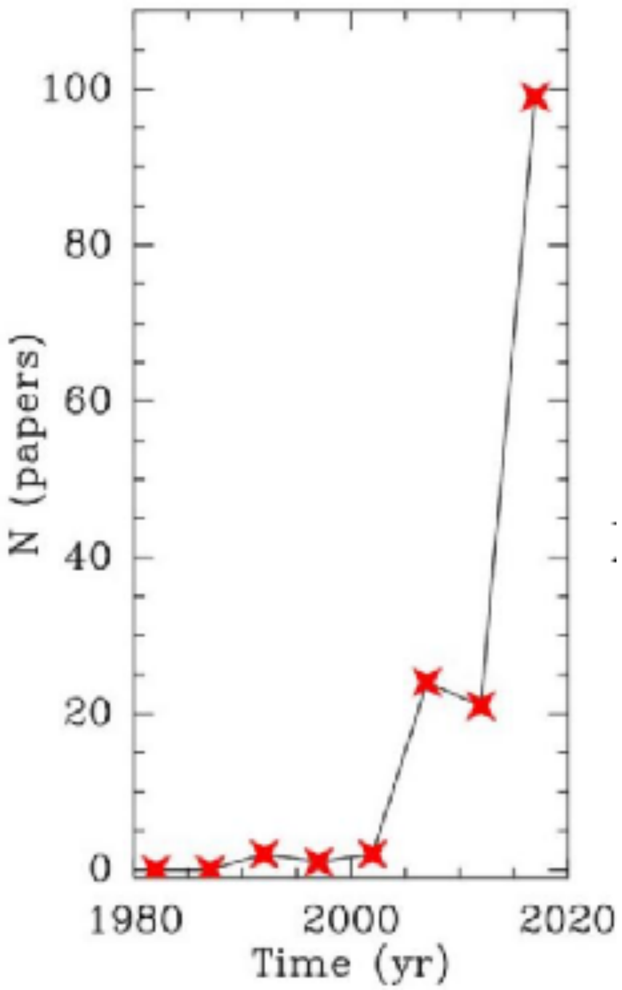


- Hubble-Lemaitre tension state-of-art
- Precision Cosmostatistics for Extended Theories of Gravity (ETG)
- **Frontiers in ETG using Precision Cosmology**

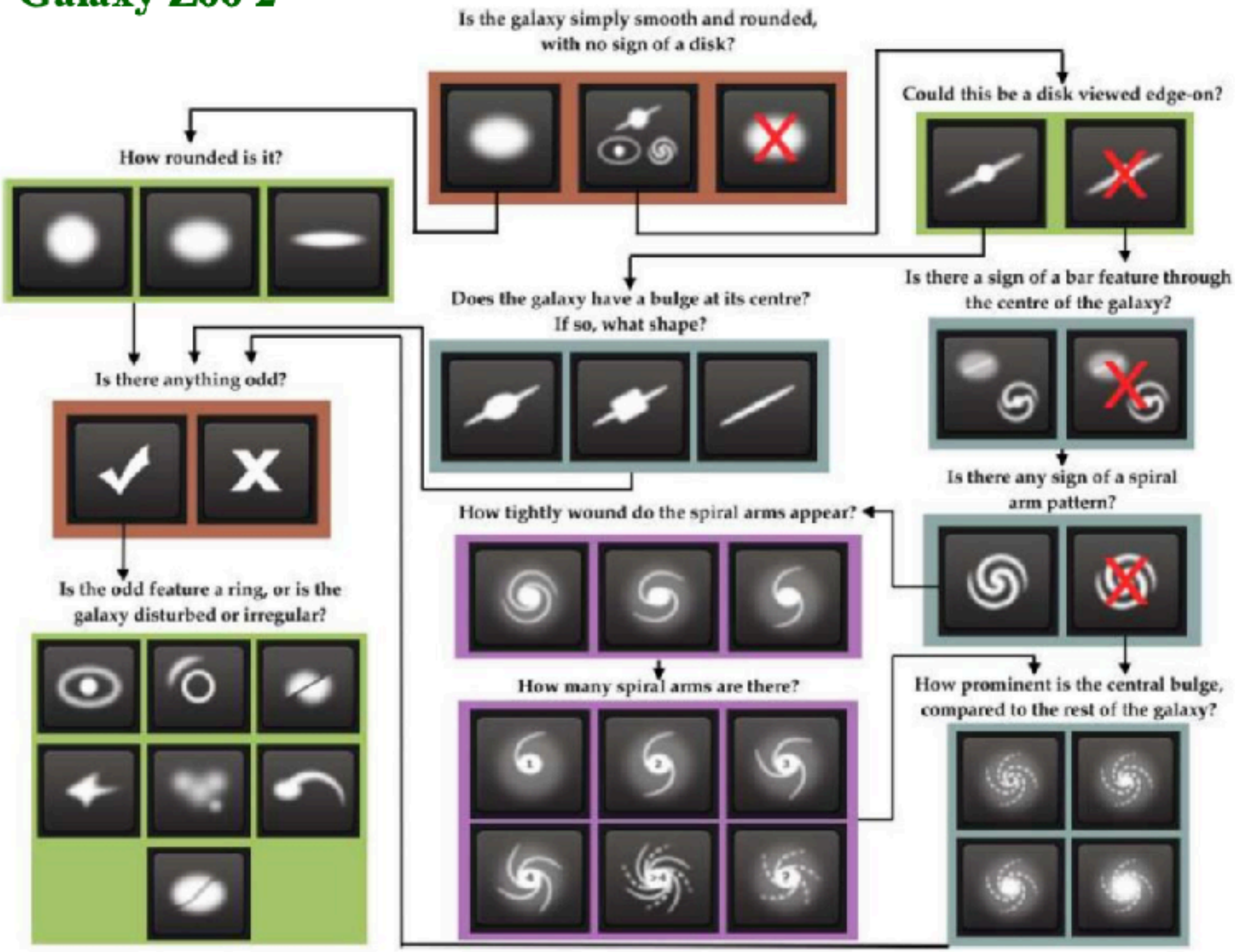
↓

More than Precision Cosmology…Machine Learning


MACHINE LEARNING HELPS OUT
OBJECT DETECTION / CLASSIFICATION
CLEANING IMAGES
MAKING SCHEDULES
AUG
SEPT
OCT
NOV
DEC
JAN
MAKING SIMULATIONS GO FASTER

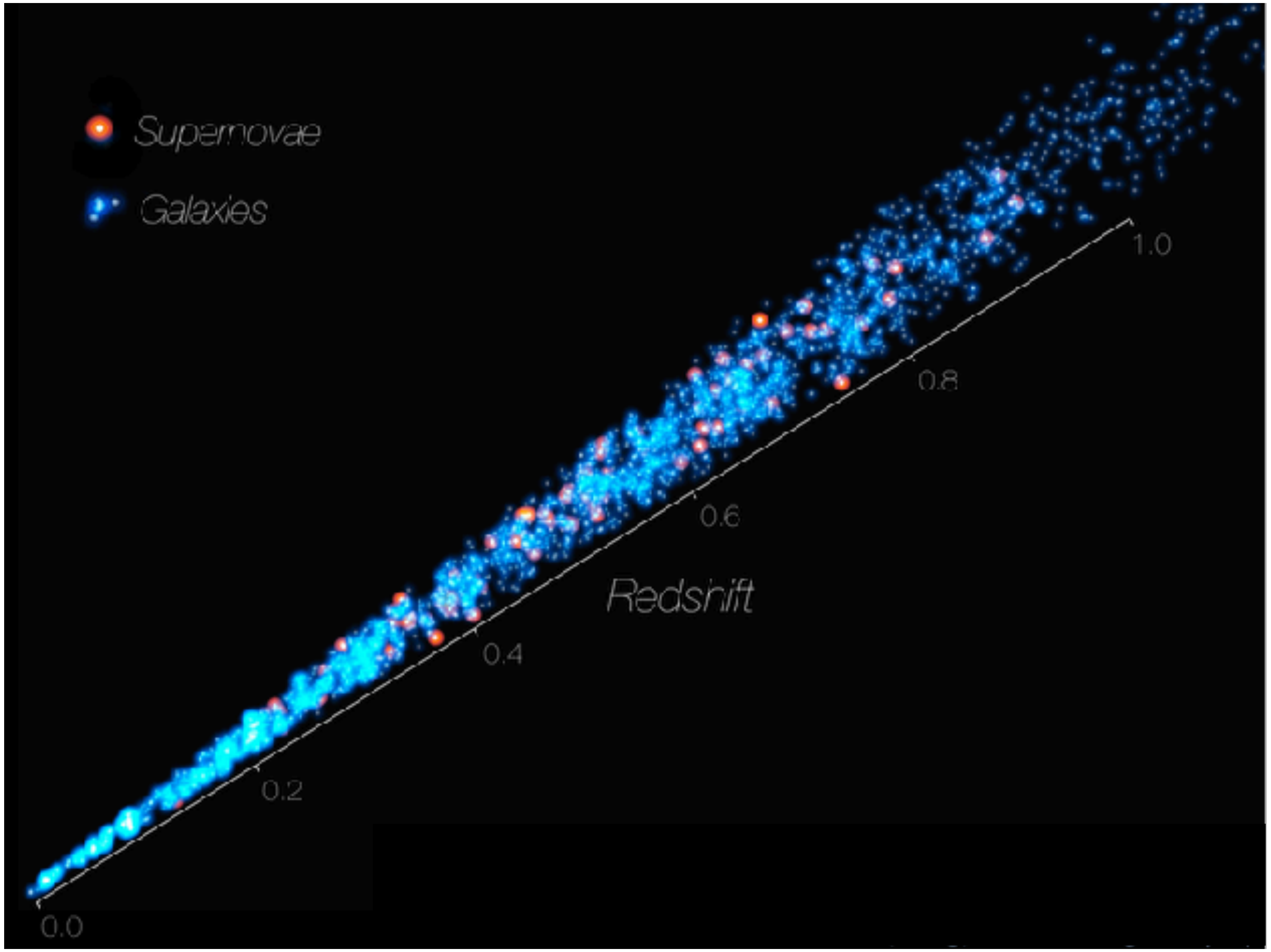

N (papers)
0
20
40
60
80
100
1980
2000
2020
Time (yr)

Galaxy Zoo 2



[Willett et al (2013)]

Why Deep Learning?



[MICE simulation (2013)]

Why Tensorflow?

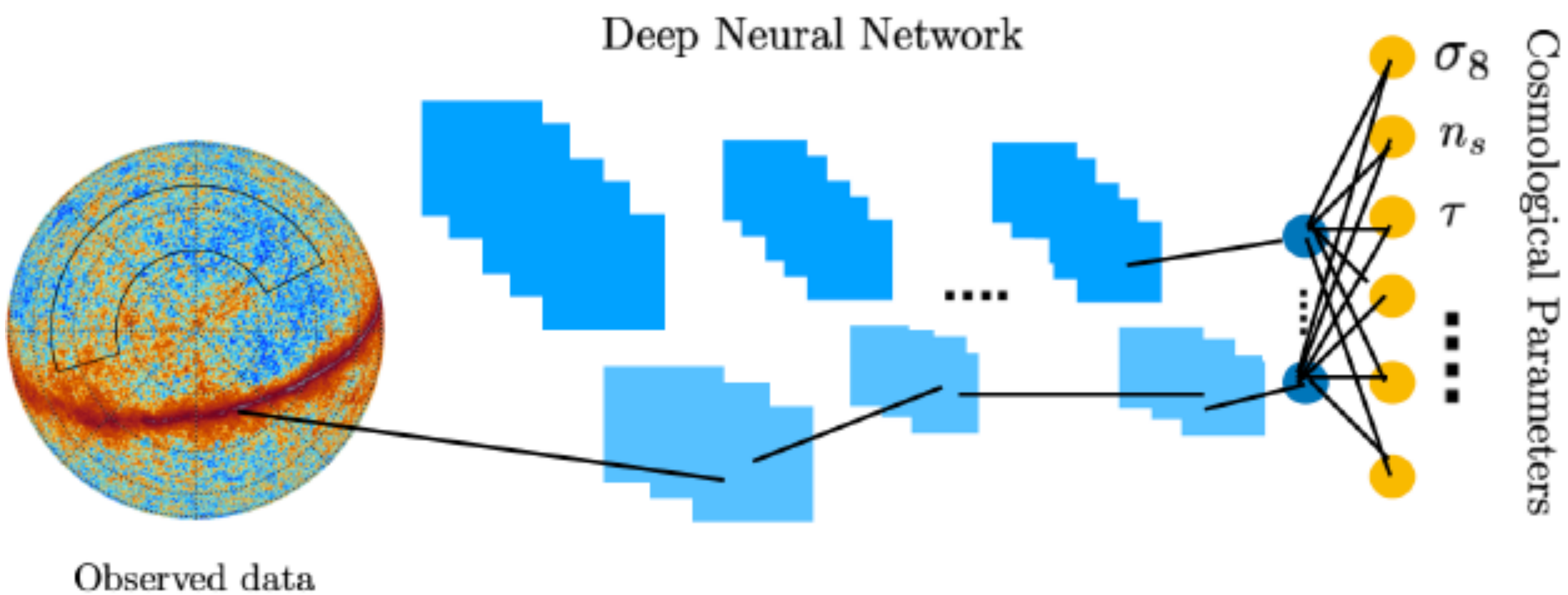
- Highly efficient C++ backend to do its computation.
- Tensorflow has been used in several major companies
- Only recently released to the public
- Makes neural network design simple!
  - High level library that avoids low-level details
  - Flexible architecture
  - Very fast performance
- GoogleBrain is investing a lot into making thi the best CNN library

DLCosmo for gravity: Code for Bayesian Neural Networks Analysis of gravity models

[**Escamilla-Rivera, C.,** Carvajal M., Capozziello, S. JCAP 03 (2020) 008]

Working Team:

CosmoNag ICN-UNAM

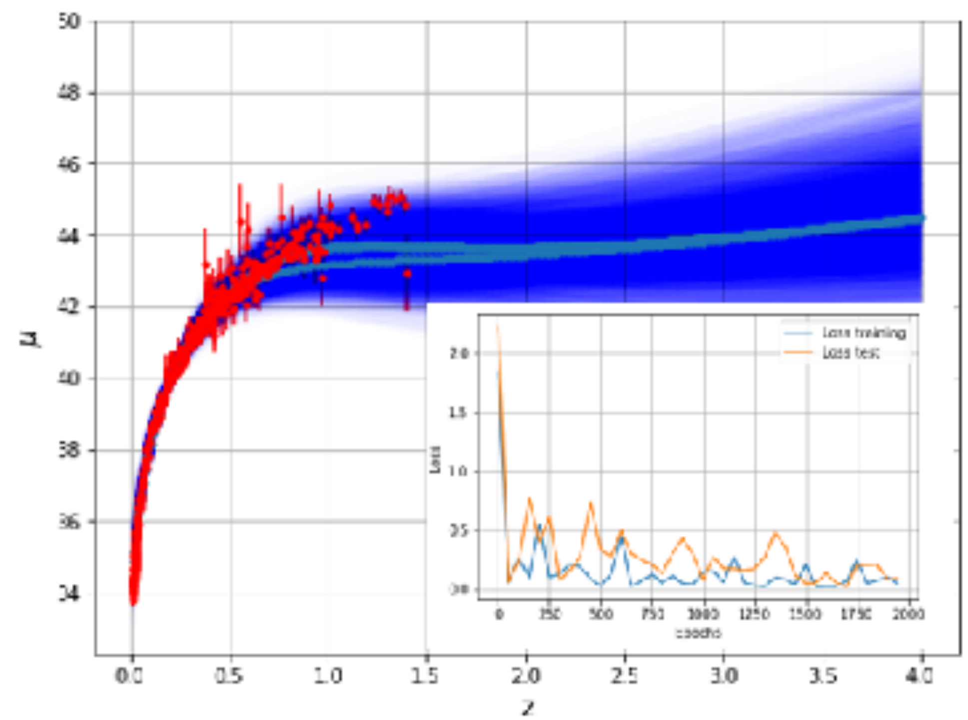


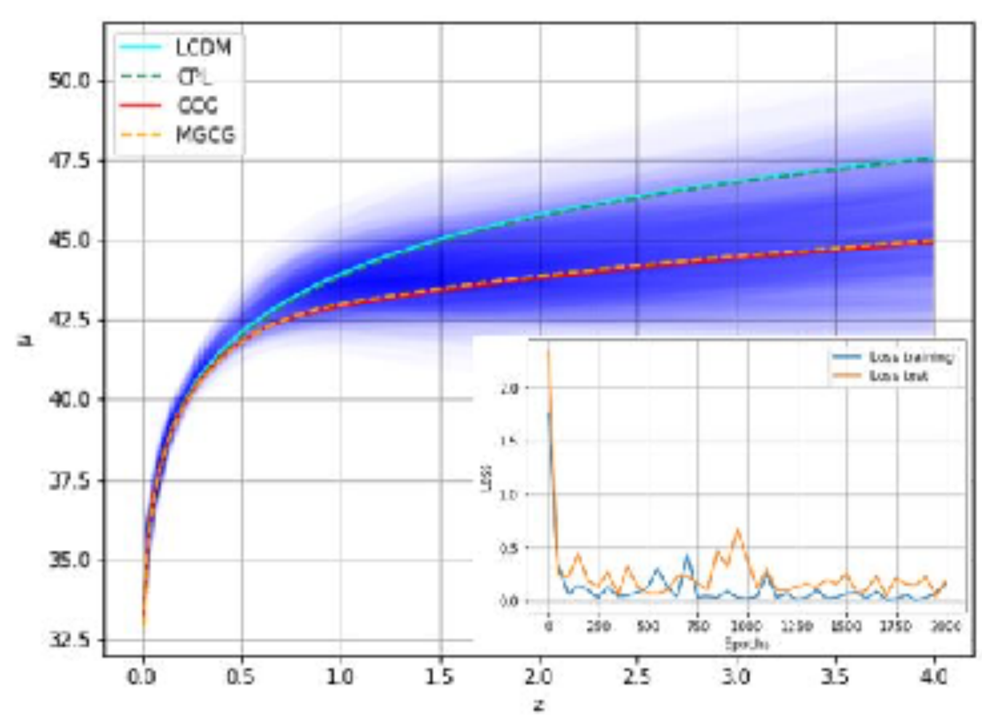
[**Escamilla-Rivera, C.** Cosmology 2020 Book 10.5772]

DLCosmo for gravity: Code for Bayesian Neural Networks Analysis of gravity models

[**Escamilla-Rivera, C.,** Carvajal M., Capozziello, S. JCAP 03 (2020) 008]

- SNeIa (Pantheon)
- BAO (SDSS-DR7, DR10, DR11)
- H(z) (passive old galaxies)
- CMB (Planck 2018)



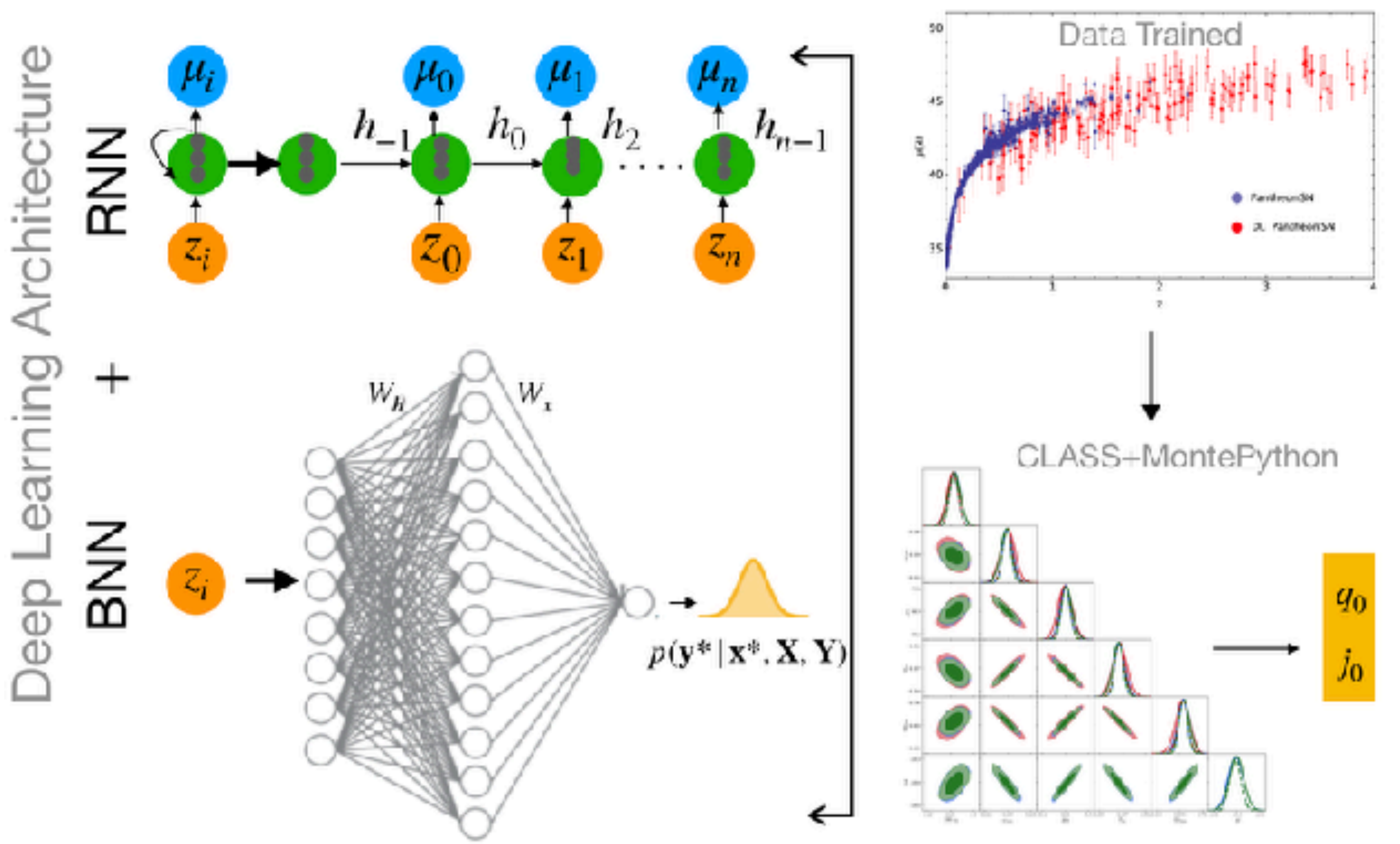


DLCosmo for cosmography

[Zamora, C. **Escamilla-Rivera, C.** JCAP 12 (2020) 007]

Working Team:

CosmoNag ICN-UNAM and U. Glasgow-LIGO/VIRGO/LISA



DLCosmo for cosmography

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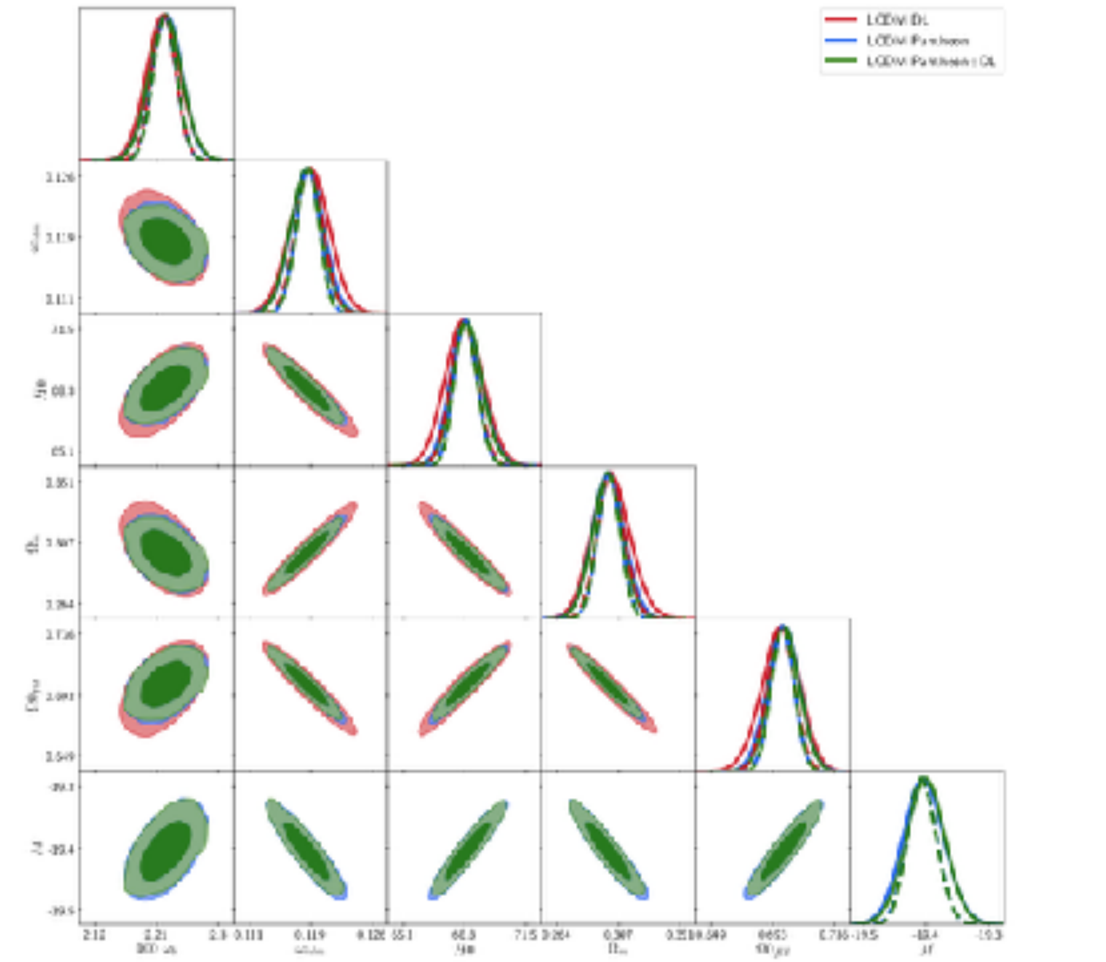
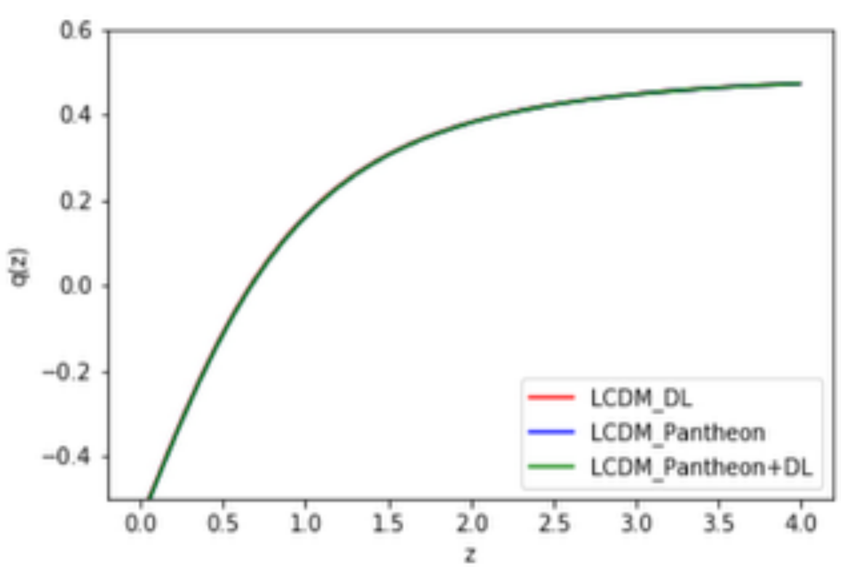
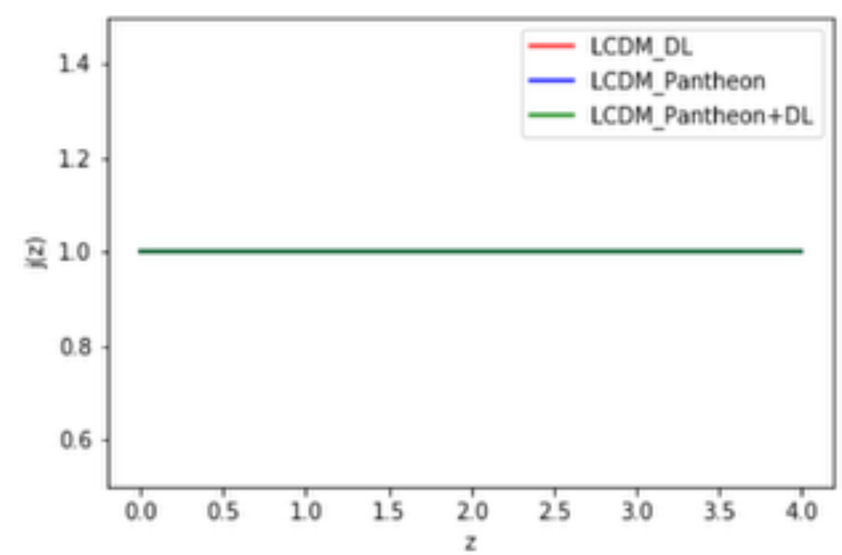


- ✅ SNeIa (Pantheon)
- ☢ BAO (SDSS-DR7, DR10, DR11)
- ✅ GRB [**Escamilla-Rivera, C et al.** In progress (2021)]
- ✅ H(z) (passive old galaxies)
- ☢ CMB (Planck 2018)





Modified gravity (sterile neutrino) from deep learning

[Peel et al Phys. Rev. D 100, 023508 (2018)]

- SNeIa (Pantheon)
- BAO (SDSS-DR7, DR10, DR11)
- H(z) (passive old galaxies)
- CMB (Planck 2018)

Prediction

Truth ($\sigma_{noise} = 0$)	ΛCDM	$f_5(R)$ $M_\nu = 0.15$ eV	$f_5(R)$ $M_\nu = 0.1$ eV	$f_5(R)$ $M_\nu = 0$ eV
ΛCDM	0.98	0.02	0.00	0.00
$f_5(R)$ $M_\nu = 0.15$ eV	0.01	0.90	0.08	0.00
$f_5(R)$ $M_\nu = 0.1$ eV	0.00	0.09	0.72	0.19
$f_5(R)$ $M_\nu = 0$ eV	0.00	0.00	0.17	0.83

Truth ($\sigma_{noise} = 0.35$)	ΛCDM	$f_5(R)$ $M_\nu = 0.15$ eV	$f_5(R)$ $M_\nu = 0.1$ eV	$f_5(R)$ $M_\nu = 0$ eV
ΛCDM	0.79	0.18	0.03	0.00
$f_5(R)$ $M_\nu = 0.15$ eV	0.22	0.59	0.18	0.01
$f_5(R)$ $M_\nu = 0.1$ eV	0.02	0.17	0.54	0.26
$f_5(R)$ $M_\nu = 0$ eV	0.00	0.01	0.22	0.76

Truth ($\sigma_{noise} = 0.7$)	ΛCDM	$f_5(R)$ $M_\nu = 0.15$ eV	$f_5(R)$ $M_\nu = 0.1$ eV	$f_5(R)$ $M_\nu = 0$ eV
ΛCDM	0.44	0.36	0.18	0.02
$f_5(R)$ $M_\nu = 0.15$ eV	0.32	0.47	0.19	0.02
$f_5(R)$ $M_\nu = 0.1$ eV	0.12	0.18	0.39	0.31
$f_5(R)$ $M_\nu = 0$ eV	0.02	0.04	0.24	0.69

f(T) from deep learning

[**Escamilla-Rivera, C.** et al In progress (2021)]

- SNeIa (Pantheon)
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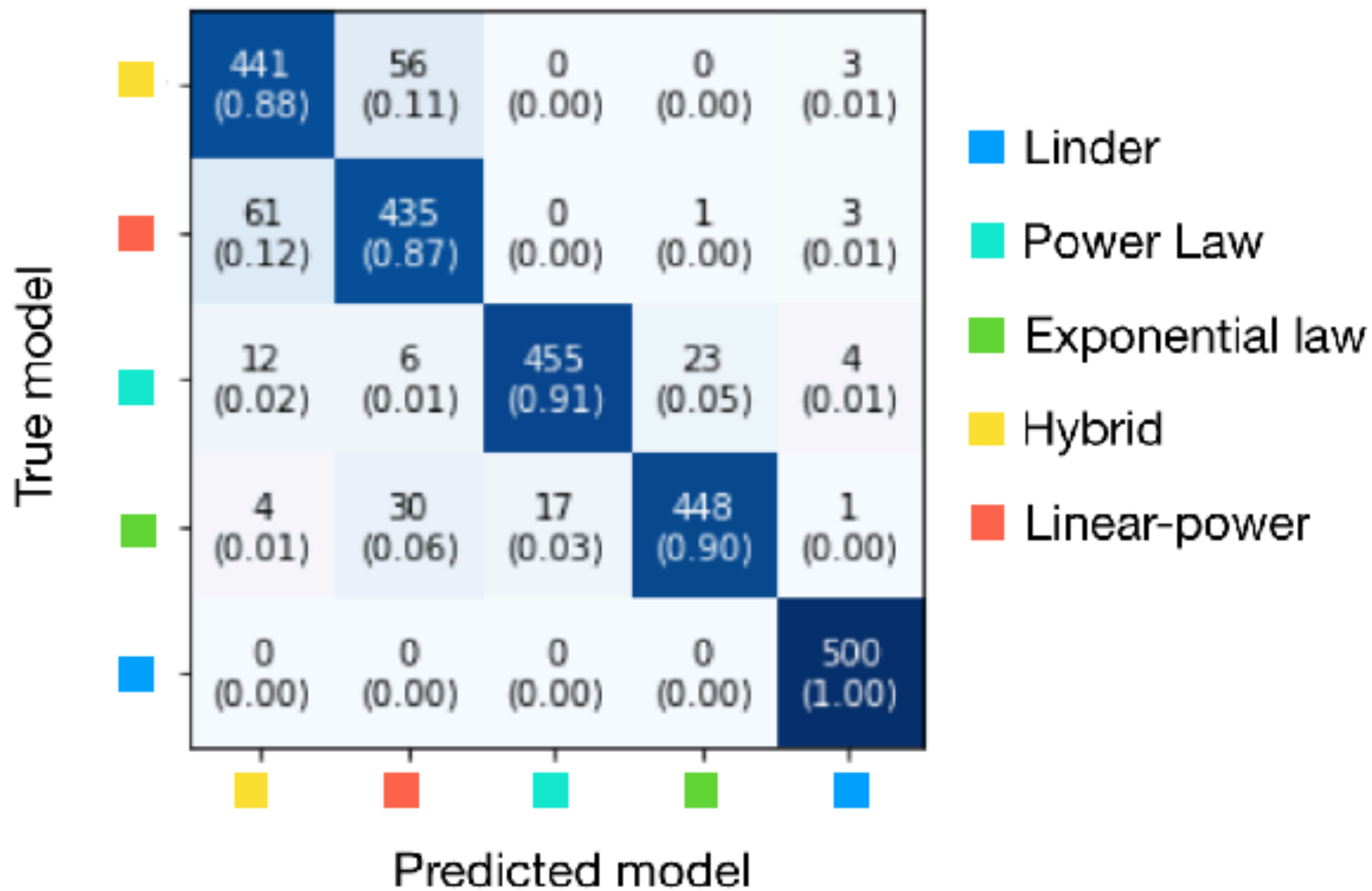

Projects :

- Hordenski TG cosmography tested with multi-messenger observations [Starting…]

- Primordial Gravitational waves in f(T,B) using current and forecast GW
  [In process: A. Aguilar, J. Mifsud C. Escamilla-Rivera and J. Said Levi]

- Training a Neural Network with TG to understand the early universe (some light on the cosmological perturbations)
  [Starting…]

Obrigada!

COST is supported by the EU Framework Programme Horizon 2020