NATIONAL CENTRE
FOR NUCLEAR RESEARCH
ŚWIERK

Special Colloquium
of
Fundamental Research Department

27 June 2022

Future prospects to shed light on cosmic mysteries

Marek Biesiada
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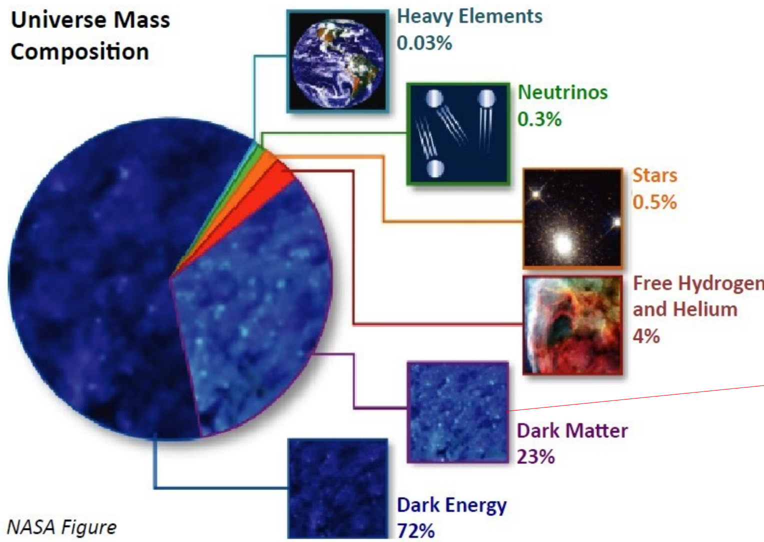
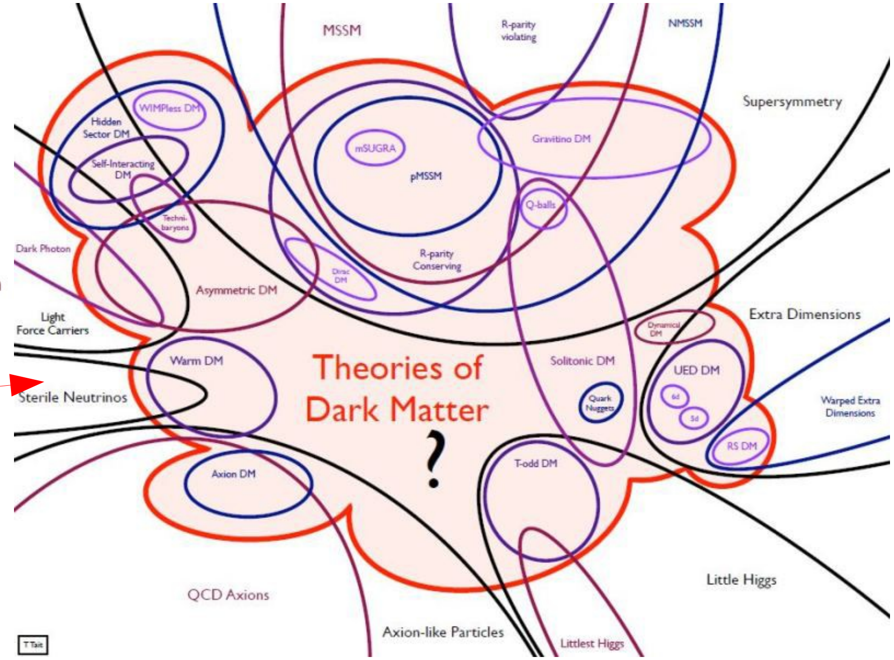
Cosmic mysteries





?

\+ Cracks in the concordance cosmological model - ΛCDM

There is a crack, a crack in everything
That's how the light gets in

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **502,** L16–L20 (2021) doi:10.1093/mnrasl/slaa205
Advance Access publication 2020 December 26

Measuring the viscosity of dark matter with strongly lensed gravitational waves

Shuo Cao,[1]★ Jingzhao Qi,[2] Marek Biesiada,[1,3]★ Tonghua Liu,[1] Jin Li[4] and Zong-Hong Zhu[1]★

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Hubble diagram at higher redshifts: model independent calibration of quasars

Xiaolei Li,[1]★ Ryan E. Keeley,[2]★ Arman Shafieloo,[2,3]★ Xiaogang Zheng,[4] Shuo Cao,[5] Marek Biesiada[5,6] and Zong-Hong Zhu[5]

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Measurements of the Hubble constant and cosmic curvature with quasars: ultracompact radio structure and strong gravitational lensing

Jing-Zhao Qi,[1] Jia-Wei Zhao,[1] Shuo Cao,[2]★ Marek Biesiada[3] and Yuting Liu[2]

Dark matter (satellite) halo **mass deficit?**

1. **Dark matter cores** of kpc size are preferred by observed circular velocities in dwarf/low-surface-brightness (LSB) galaxies, while simulations suggest cusps [Moore 1994; Burkert 1995, …].

   (core/cusp problem)

2. **Non-observation of very massive satellite halos** predicted by simulations in our Milky Way [M.Boylan-Kolchin et al. 2011, 2012] and others [Ferrero et al. 2011].

   (too-big-to-fail problem)

3. Given the long lifetime of dwarfs, some globular/star clusters are expected to be destroyed, or sink to the center **if their host halos are cuspy** [J. Binney & S.Tremaine 2008, F. Contenta et al. 2017, P. Boldrini et al. 2018, …].

   (GC timing problem)

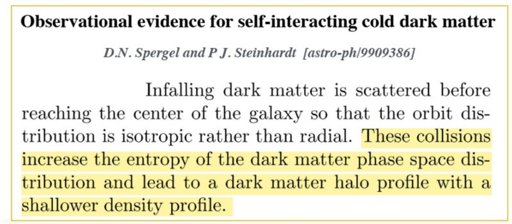
More heat/entropy needed in halo centre (if confirmed)

Heat needed to make a kpc dark core: $10^{53} - 10^{55}$ erg

- Baryonic effects? heated by supernova / in-falling clumps.

  Each supernova deposits $\sim 10^{51}$ erg in interstellar medium *[e.g. Madau, Shen, Governato 2014, …]*

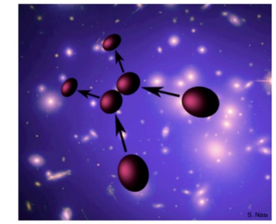
- Self-interacting dark matter? (also decaying / fuzzy dark matter, ….)



Observational evidence for self-interacting cold dark matter

D.N. Spergel and P J. Steinhardt [astro-ph/9909386]

Infalling dark matter is scattered before reaching the center of the galaxy so that the orbit distribution is isotropic rather than radial. These collisions increase the entropy of the dark matter phase space distribution and lead to a dark matter halo profile with a shallower density profile.



O(1) scattering per (central) particle → $\frac{\sigma_{SI}}{m_{DM}} \sim 0.5 - 10\mathrm{cm}^2/\mathrm{g}$

- Self-interacting dark matter (SIDM)?

- Stronger self-scattering **needed** for (dwarf-sized) halos

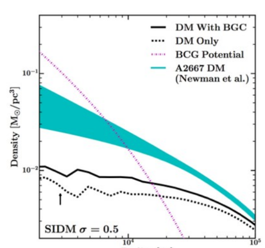
  [O. D. Elbert et al. 2016, K. Bondarenko 2016,….]

  😄 $\frac{\sigma_{SI}}{m_{DM}} \sim 0.5 - 10\mathrm{cm}^2/\mathrm{g}$ at dwarf scales of DM velocity ~ 10 km/s

- Weaker self-scattering **favored** by cluster merging/halo profiles etc.

  [O. D. Elbert et al. 2016, K. Bondarenko 2016,….]

  😭 $\frac{\sigma_{SI}}{m_{DM}} \leq 0.2 - 1\mathrm{cm}^2/\mathrm{g}$ at cluster scales of DM velocity ~ 1000km/s

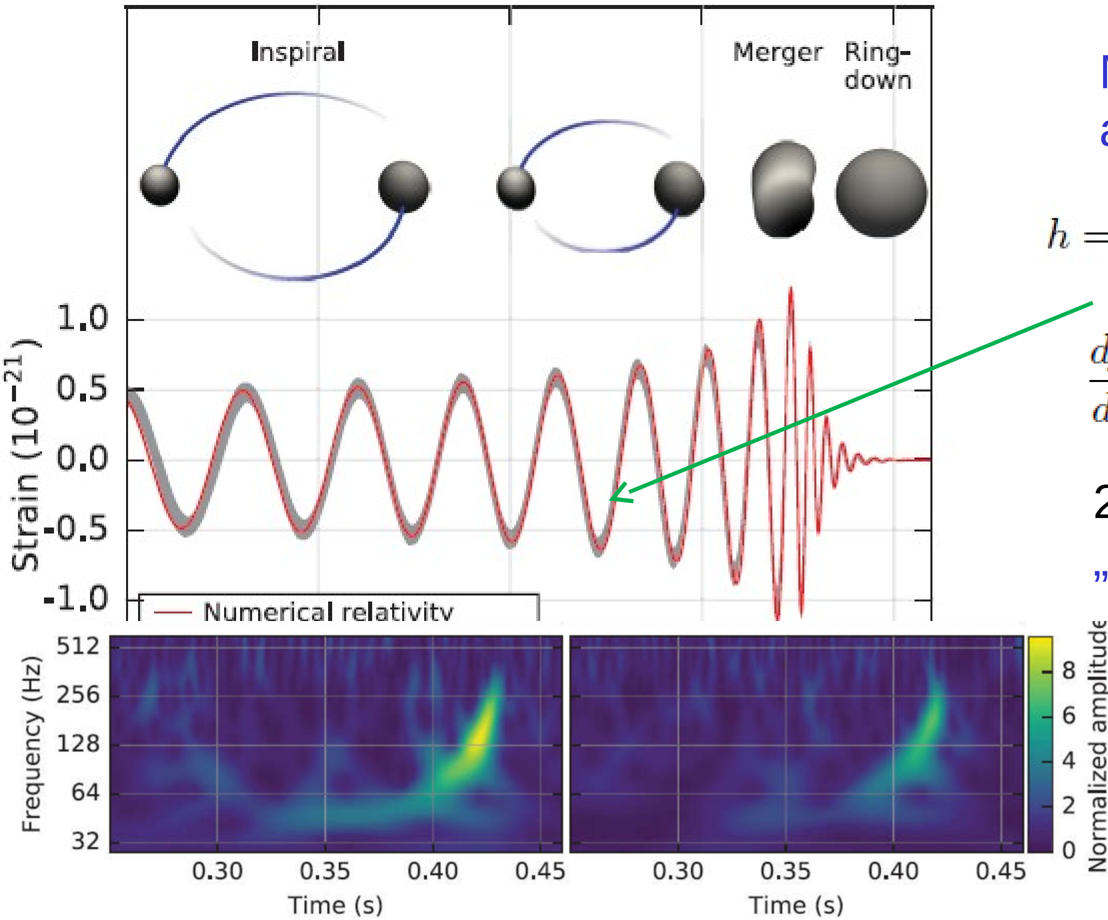


Plane GW Traveling Through Homogeneous Matter

- **Fluid:**
  - GW shears the fluid, (rate of shear) = $\sigma_{jk} = \frac{1}{2}\dot{h}^{GW}_{jk}$
  - no resistance to shear, so no action back on wave
  - Viscosity $\eta \sim \rho v s = (\text{density})(\text{mean speed of particles})(\text{mean free path})$ produces stress $T_{jk} = -2\eta\sigma_{jk} = -\eta\dot{h}^{GW}_{jk}$ **NOTE:** s must be $< \lambda\!\!\!^{-}$
  - Linearized Einstein field equation: $\Box h^{GW}_{jk} = -16\pi(T_{jk})^{TT} = 16\pi\eta\dot{h}^{GW}_{jk}$
  - Wave attenuates: $h^{GW}_{jk} \sim \exp(-z/\ell_{att})$ where $\ell_{att} = \frac{1}{8\pi\eta} = \frac{1}{8\pi\rho v s}$

The idea of „standard sirens”

B. Schutz 1986
B.Schutz, A. Królak 1987



Measure the strain h(t)
and frequency drift df/dt

$$h = \frac{4\pi^{2/3}(G\mathcal{M})^{5/3}}{c^4 D} f(t)^{2/3} \cos\left[\int_0^t f(t')\,dt'\right]$$

$$\frac{df}{dt} = \frac{96\pi^{8/3}}{5}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

2 equations for 2 unknowns:
„chirp mass” *M* & distance D

$$\mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96\pi^{8/3}}\frac{df}{dt}\right)^{3/5} f^{-11/5}$$

$$D = \frac{4c}{\pi^2 h}\frac{df(t)}{dt} f^{-3} \cos\left(\int_0^t f(t')\,dt'\right)$$

$$M_c \rightarrow (1+z) M_c$$

$$t \rightarrow (1+z)\,t$$

$$f \rightarrow \frac{1}{1+z} f$$

$$\frac{df}{dt} \rightarrow \frac{1}{(1+z)^2}\frac{df}{dt}$$

for cosmological sources

The distance inferred is the **luminosty distance**

$$D_L = (1+z)\,D$$

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Measuring the viscosity of dark matter with strongly lensed gravitational waves

Shuo Cao,[1★] Jingzhao Qi,[2] Marek Biesiada,[1,3★] Tonghua Liu,[1] Jin Li[4] and Zong-Hong Zhu[1★]
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$$h_{\alpha,\mathrm{visc}} = h_\alpha \mathrm{e}^{-\beta D/2}$$

attenuated wave leads to biased luminosity distance

$$D_{\mathrm{L,eff}}(z,\beta) = D_{\mathrm{L}}(z)\mathrm{e}^{\beta D(z)/2}$$

lensed transitents (GW, SNIa) signal leads to very precise determination of „time delay distance"

$$\Delta t_{i,j} = \frac{D_{\Delta t}(1+z_1)}{c}\Delta\phi_{i,j}$$

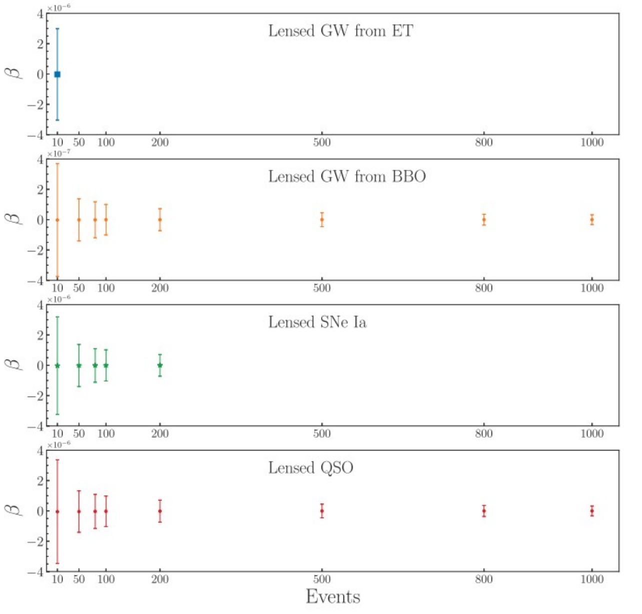
$$D_{\Delta t}(z_l, z_s) \equiv \frac{D_A(z_l) D_A(z_s)}{D_A(z_l, z_s)}$$

To be determined by unlensed standard sirens

$$D_{\Delta t} = \frac{D_{\mathrm{L}}(z_l) D_{\mathrm{L}}(z_s)}{(1+z_l)^2 D_{\mathrm{L}}(z_s) - (1+z_s)(1+z_l) D_{\mathrm{L}}(z_l)}$$

$$\chi^2 = \sum_{i=1}^{i} \frac{\left(D^{lens}_{\Delta t,i}(z_{l,i}, z_{s,i}) - D^{unlens}_{\Delta t,i}(z_{l,i}, z_{s,i}; \beta)\right)^2}{\sigma^2_{i,\text{lens}} + \sigma^2_{i,\text{unlens}}}$$

objective function fitted for beta



relation with DM physical parameters

$$\frac{\langle \sigma_\chi \rangle}{m_\chi} = \frac{6.3\pi G \langle v \rangle}{c^3 \beta}$$

Table 1. Summary of the constraints obtained from different observations. Type I and II, respectively, correspond to the two cases of self-interacting DM in galaxies and galaxy clusters.

Data	$\Delta\beta$	$\Delta(\sigma_\chi/m_\chi)(I)$	$\Delta(\sigma_\chi/m_\chi)(II)$
GW (lensed; ET) + GW (unlensed)	10^{-6} Mpc^{-1}	10^{-4} cm^2 g^{-1}	10^{-3} cm^2 g^{-1}
GW (lensed; BBO) + GW (unlensed)	10^{-8} Mpc^{-1}	10^{-6} cm^2 g^{-1}	10^{-5} cm^2 g^{-1}
QSO (lensed; LSST) + GW (unlensed)	10^{-7} Mpc^{-1}	10^{-5} cm^2 g^{-1}	10^{-4} cm^2 g^{-1}
SNe Ia (lensed; LSST) + GW (unlensed)	10^{-6} Mpc^{-1}	10^{-4} cm^2 g^{-1}	10^{-3} cm^2 g^{-1}

it would be able to DM viscosity and differentiate cluster and small scale scenarios

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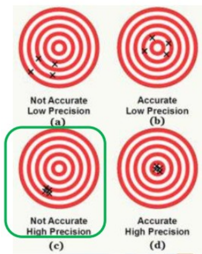
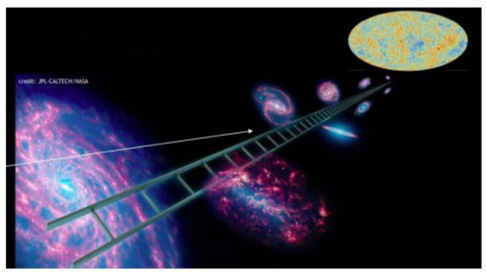
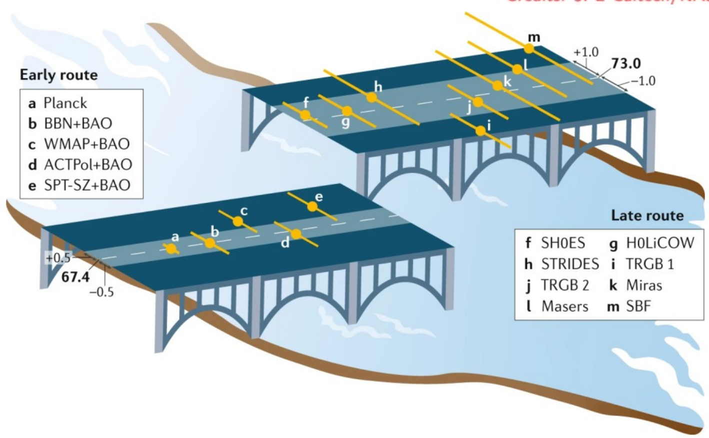


H_0 tension



Credits: JPL-Caltech/NASA and Dillon Brout

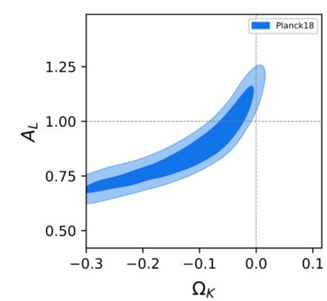


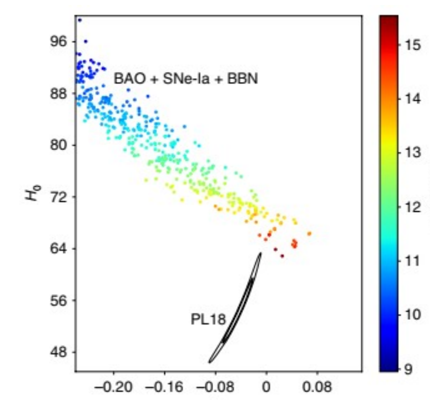
Credits: Riess, Nat. Rev. Phys. 2 (2020) 10

ARTICLES
https://doi.org/10.1038/s41550-019-0906-9
nature astronomy

Planck evidence for a closed Universe and a possible crisis for cosmology

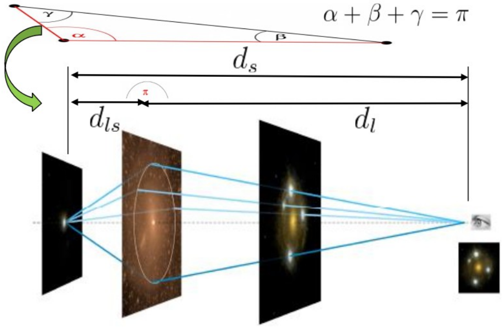
Eleonora Di Valentino[1], Alessandro Melchiorri[2*] and Joseph Silk[3,4,5]





the preference at 3.4σ for a closed Universe

$$\Omega_K = -0.044^{+0.018}_{-0.015}$$



$$d_{ls} = \sqrt{1+\Omega_k d_l^2}\; d_s - \sqrt{1+\Omega_k d_s^2}\; d_l$$

One can obtain Ω_k and H_0 if

d_l, d_s, d_{ls} are known

Observations:
z_l , z_s – known

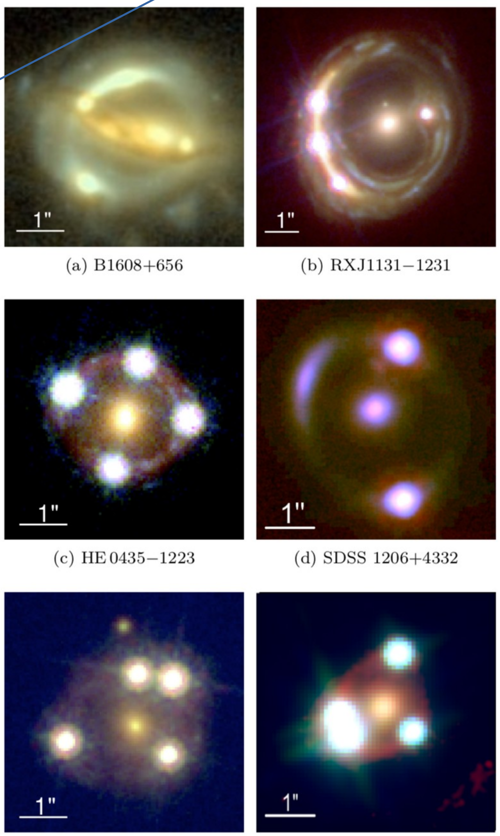
Time delays -- > $d_l d_s / d_{ls}$

=================

$d_{l,}$ d_s – standard candle or **ruler matched by redshift**

H0LICOW six well studied lenses

$$D_{\Delta t} = \frac{c\Delta t_{i,j}}{\Delta\phi_{i,j}} = \frac{c}{H_0}\frac{d_l d_s}{d_{ls}}$$



(a) B1608+656 (b) RXJ1131−1231
(c) HE 0435−1223 (d) SDSS 1206+4332
(e) WFI2033−4723 (f) PG 1115+080

$$0.654 < z_s < 2.375.$$

$$\frac{d_l d_s}{d_{ls}} = \frac{1}{\sqrt{1/d_l^2 + \Omega_K} - \sqrt{1/d_s^2 + \Omega_K}}.$$

Instead of simple matching by z we used d(z) reconstructed from ILQSO

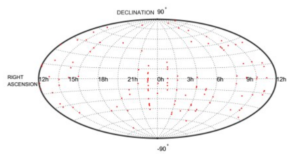
A&A 606, A15 (2017)
DOI: 10.1051/0004-6361/201730551

Astronomy & Astrophysics

Ultra-compact structure in intermediate-luminosity radio quasars: building a sample of standard cosmological rulers and improving the dark energy constraints up to $z \sim 3$

Shuo Cao[1], Xiaogang Zheng[1,2], Marek Biesiada[1,2], Jingzhao Qi[1], Yun Chen[3], and Zong-Hong Zhu[1]

Compact radio sources



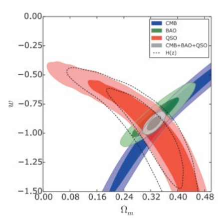
120 compact radio sources (QSOs) at 2 GHz

Steps:
1. expansion rate reconstruction from H(z) data (cosmic chronometers)

2. robust selection of luminosity sample

3. calibration of standard rulers l = 11.03 ±0.25 pc

4. $D_A(z)$ reconstruction (GP) from binned ILQSO data or use of calibrated ILQSO for cosmological parameter inference



$$\theta(z) = \frac{l_m}{D_A(z)}$$

17

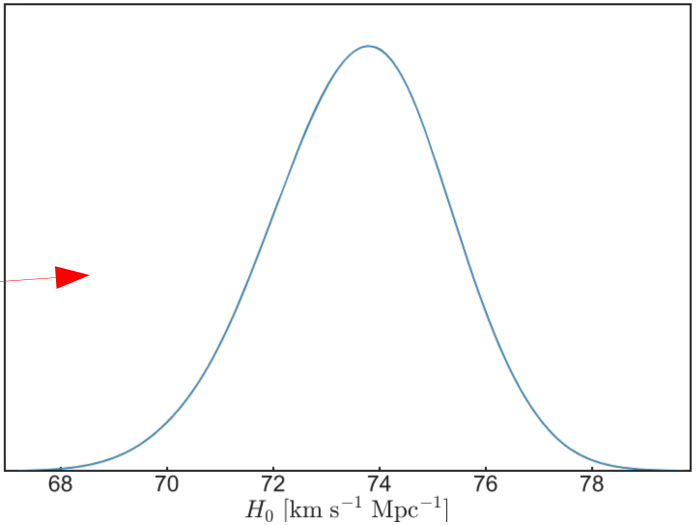
$$\chi^2_{QSO} = \sum_i^{120} \frac{[\theta(z_i; d(z_i)) - \theta_{oi}]^2}{\sigma_i^2}$$

$$\mathcal{L}_{QSO} \sim \exp(-\chi^2_{QSO}/2)$$

$$\ln\mathcal{L} = \ln(\mathcal{L}_{QSO}) + \ln(\mathcal{L}_{\Delta t})$$

Table 1. Summary of the best-fitting values and the corresponding BIC for the Hubble constant (H_0), cosmic curvature (Ω_K), and the coefficients of third-order polynomial expansion (a_1, a_2), with strongly lensed and unlensed radio quasars in the framework of distance sum rule.

$H_0(\mathrm{km\,s^{-1}\,Mpc^{-1}})$	Ω_K	a_1	a_2	BIC
78.3 ± 2.9	0.49 ± 0.24	-0.365 ± 0.037	0.069 ± 0.014	492.2
73.6 ± 1.7	0 (fixed)	-0.404 ± 0.030	0.077 ± 0.013	491.0
74.03 (fixed)	$0.22^{+0.14}_{-0.17}$	-0.412 ± 0.018	0.084 ± 0.010	489.3



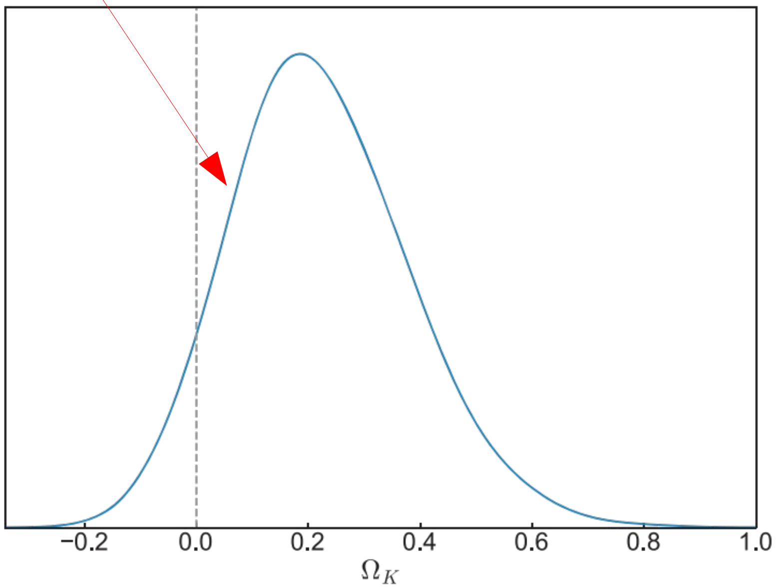
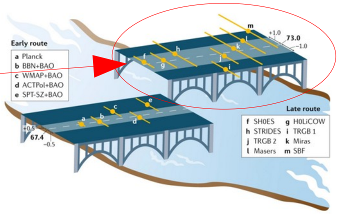


Table 3. Summary of the best-fitting values for the Hubble constant (H_0), matter density parameter (Ω_m) and cosmic curvature (Ω_K), with strongly lensed and unlensed radio quasars in the framework of non-flat ΛCDM and flat ΛCDM model.

	$H_0(\mathrm{km\,s^{-1}\,Mpc^{-1}})$	Ω_K	Ω_m
Non-flat ΛCDM	72.5 ± 1.6	$-0.09^{+0.13}_{-0.15}$	0.287 ± 0.055
Flat ΛCDM	$73.1^{+1.5}_{-1.3}$	–	$0.254^{+0.027}_{-0.035}$



Our results confirm SH0ES local measurements of H_0
results for curvature depend on the approach ΛCDM vs. model-independent reconstructions

to be clarified …

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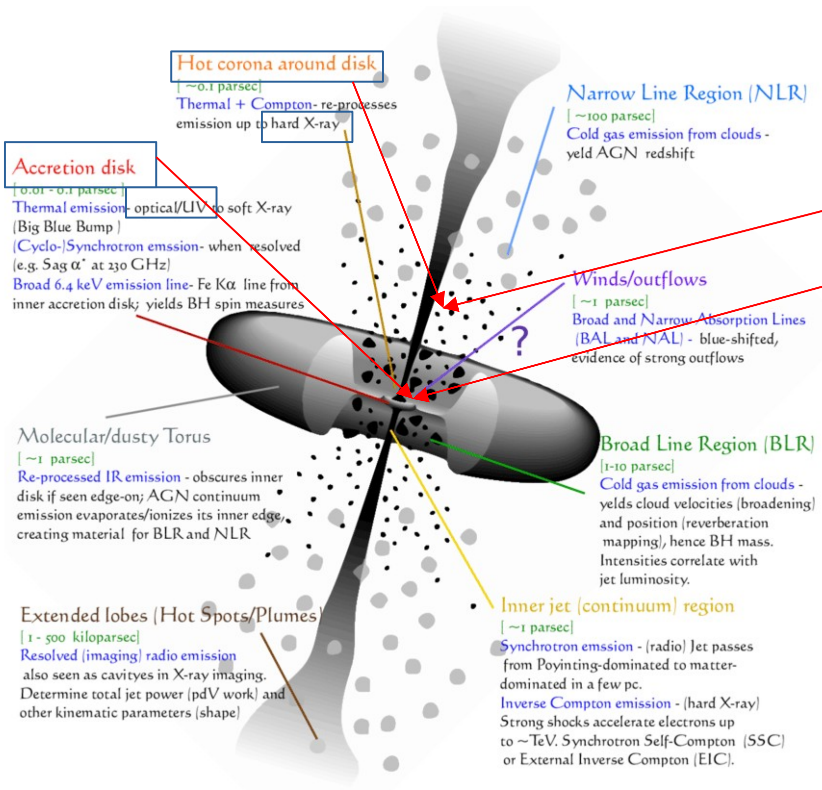


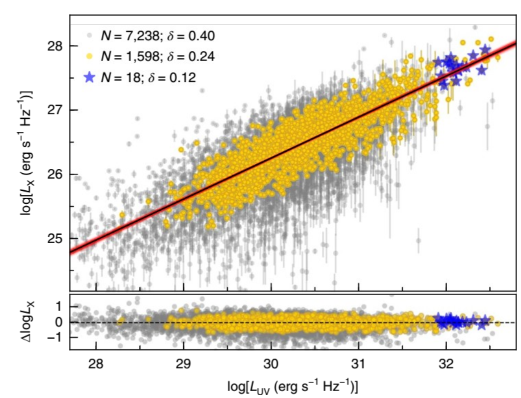
Credit: https://www.researchgate.net/publication/344342737_Numerical_Models_of_AGN_Feedback/figures?lo=1

$$\log(L_X) = \gamma \log(L_{UV}) + \beta_1$$

γ from fluxes in redshift bins

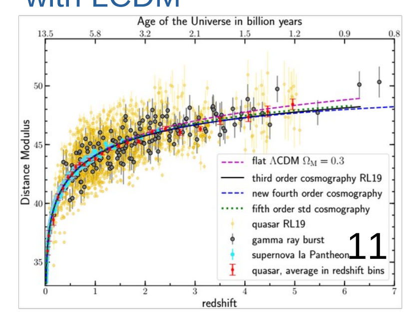
$$\log(F_X) = \gamma \log(F_{UV}) + (2\gamma - 2)\log(D_L) + \beta_2$$

Risaliti & Lusso 2019
Nature Astronomy



$$\beta_2 = \gamma \log(4\pi) - \log(4\pi) + \beta_1,$$

Lusso et al. 2019
A&A Lett. - tension
with LCDM



Gaussian Processes reconstruction of cosmic expansion history H(z) from SN Ia Pantheon sample

$$\langle \varphi(s_i)\varphi(s_j)\rangle = \sigma_f^2 \exp\left(-\frac{|s_i - s_j|^2}{2\ell^2}\right)$$

$$\varphi(z) = \ln\left(H^{\rm mf}(z)/H(z)\right)$$

$$D_L H_0(z) = (1+z)\int_0^z \mathrm{d}z \frac{c}{h(z)}$$

$$\log(F_{\rm X})^{\rm SN} = \gamma \log(F_{\rm UV}) + (2\gamma - 2)\log(D_{\rm L}H_0) + \beta,$$

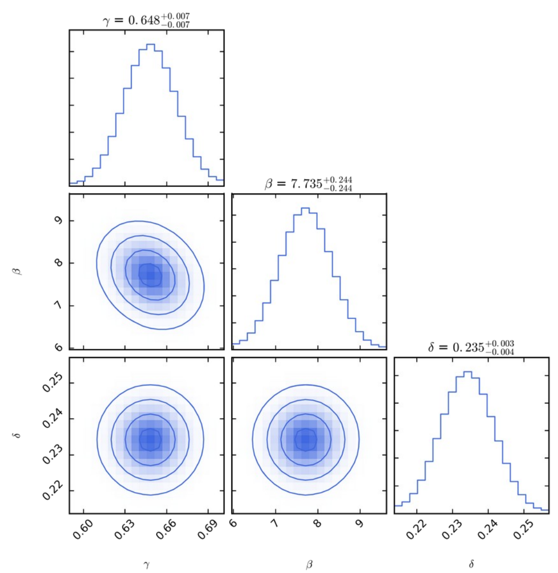
(i) Draw 1000 unanchored luminosity distances $D_{\rm L}H_0$ from supernovae data,
(ii) Calculate the predicted quasar X-ray flux corresponding to these unanchored luminosity distances,
(iii) Define the likelihood of the quasar parameters,
(iv) Calculate the posterior distribution of the quasar parameters.

$$\chi^2 = \sum_i \left[\frac{\left(\log(F_{\rm X}(\gamma,\beta))_i^{\rm SN} - \log(F_{\rm X})_i^{\rm QSO}\right)^2}{s_i^2} + \ln\left(s_i^2\right)\right]$$

$$s_i^2 = \sigma^2_{\log(F_{\rm X})} + \gamma^2\sigma^2_{\log(F_{\rm UV})} + \delta^2.$$

$$\gamma = 0.649 \pm 0.007 \text{ and } \delta = 0.235 \pm 0.04$$

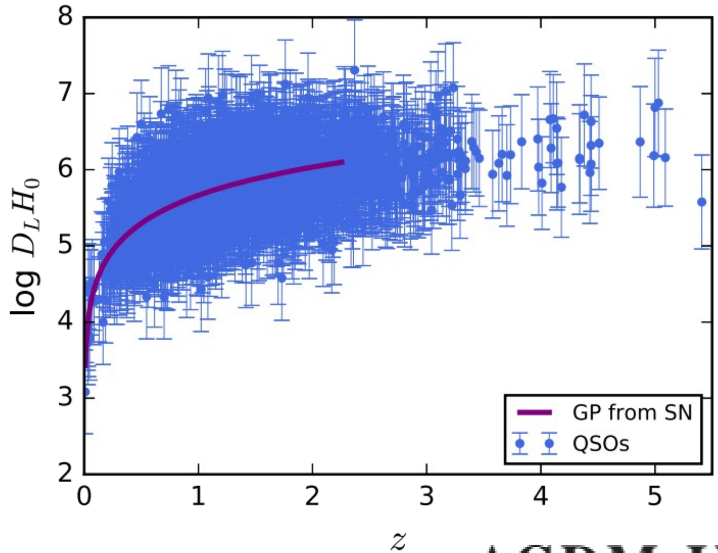
Model independent calibration of quasars



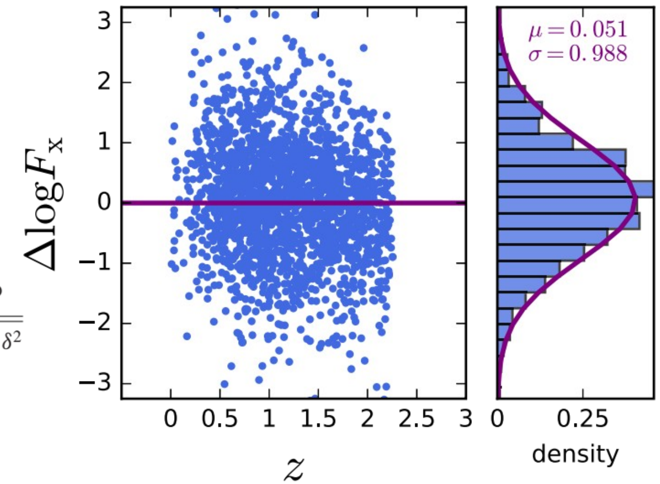
Lusso et al. 2020

$$\gamma = 0.586 \pm 0.061,\ \delta = 0.21 \pm 0.06$$

INTERNAL CONSISTENCIES



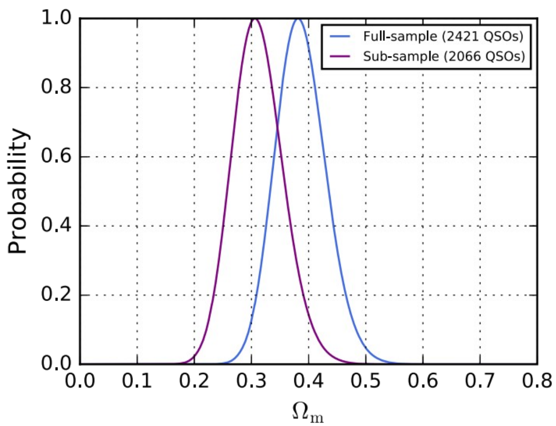
$$\Delta \log(F_{\rm X}) = \frac{\log(F_{\rm X})^{\rm SN} - \log(F_{\rm X})^{\rm QSO}}{\sqrt{\sigma^2_{\log(F_{\rm X})} + \gamma^2 \sigma^2_{\log(F_{\rm UV})} + \delta^2}}$$

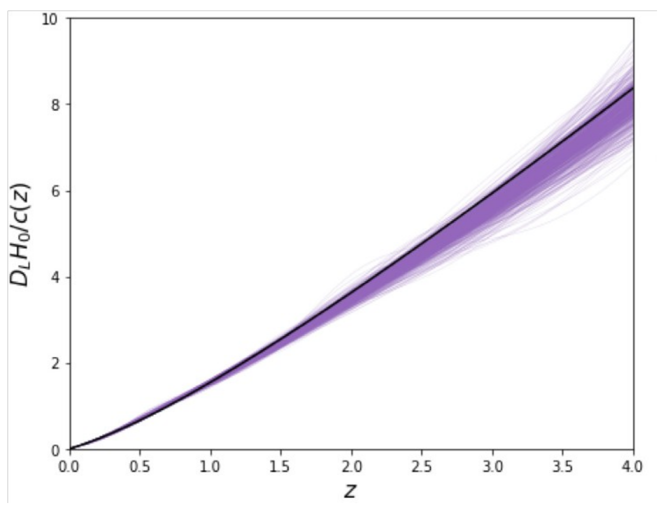


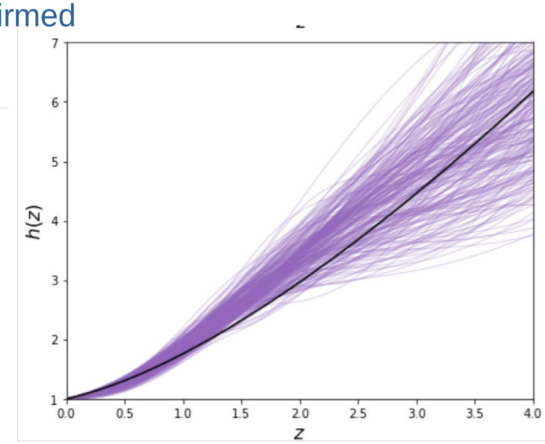
ΛCDM INFERENCES

$$\ln \mathcal{L} = -\frac{1}{2} \sum_i \left[\frac{\left(\log(D_{\rm L} H_0(\Omega_m))_i^{\Lambda\rm CDM} - \log(D_{\rm L} H_0)_i^{\rm QSO} \right)^2}{\sigma^2_{\log(D_{\rm L} H_0);i}} \right]$$

Deviation from ΛCDM seen in Lusso, Risaliti et al. confirmed







Summary:

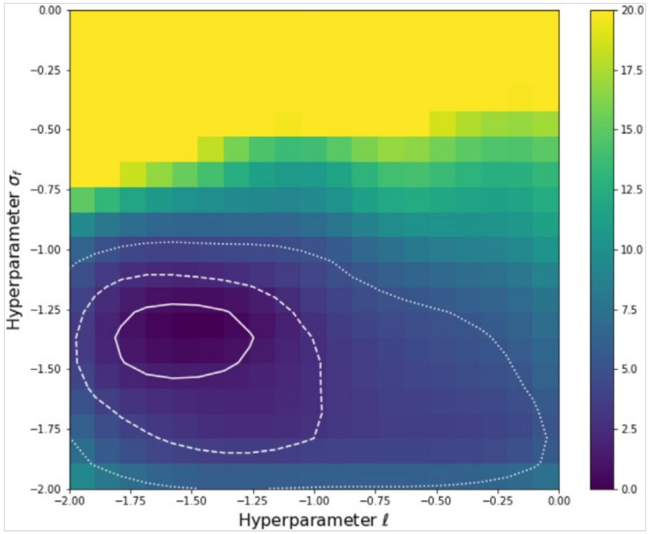
* We calibrated QSO UV-X relation with a new model-independent method

* We confirmed that quasars can be used as new standardizable candles

* For the full sample we found the deviations from the ΛCDM as in Lusso et al.

* The 2-3σ preference of beyond-ΛCDM evolution is supported by posterior distribution of GP hyper-parameters – σ_f >0 indicates that data Hold more information than can be modeled by input mean function (here assumed ΛCDM)

Further studies are underway



Thank you !