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The Large Scale Structure and Fast Radio Bursts

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

GERMAN CENTRE FOR COSMOLOGICAL LENSING

ORIGINS Excellence Cluster

Robert Reischke
with Steffen Hagstotz

Cosmology from Home | 2023

Overview

1. Fast Radio Bursts 101
2. Distance scale
3. Effects of the LSS

Overview

1. **Fast Radio Bursts 101**
2. Distance scale
3. Effects of the LSS

Fast Radio Bursts

- Mechanism unknown
- First discovered in archival data 2007
- Short (~ms), bright (~Jy) radio transients
- Frequencies 300 Mhz - 8 Ghz
- Extragalactic
- About 600 known events, soon several 1000s
- Some repeating?

Proposed Mechanisms

A Living Theory Catalogue for Fast Radio Bursts

E. Platts[a,*], A. Weltman[a], A. Walters[b,c], S. P. Tendulkar[d], J.E.B. Gordin[a], S. Kandhai[a]

arXiv 1810.05836

www.frbtheorycat.org

FAST RADIO BURST THEORY CATALOGUE

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Hosted by the Institut Spatial de McGill / McGill Space Institute in collaboration with University of Cape Town, University of KwaZulu-Natal / Inyuvesi Yakwazulu-Natali

Proposed Mechanisms

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Neutron stars? Mergers? AGN?

Article | Published: 04 November 2020

A bright millisecond-duration radio burst from a Galactic magnetar

The CHIME/FRB Collaboration

Nature **587**, 54–58(2020) | Cite this article

A repeating fast radio burst source in a globular cluster

F. Kirsten (Chalmers), B. Marcote (JIVE), K. Nimmo (ASTRON, University of Amsterdam), J. W. T. Hessels (U
University), S. P. Tendulkar (TIFR, NCRA), A. Keimpema (JIVE), J. Yang (Chalmers), M. P. Snelders (Universi
University, Caltech), C. J. Law (Caltech), W. M. Peters (NRL), M. Giroletti (INAF), D. M. Hewitt (University of
Burgay (INAF), S. T. Buttaccio (INAF), J. E. Conway (Chalmers), A. Corongiu (INAF), R. Feiler (NCU), O. Fors
(MPIfR), M. A. Kharinov (IAA RAS), M. Lindqvist (Chalmers), G. Maccaferri (INAF), A. Melnikov (IAA RAS), O

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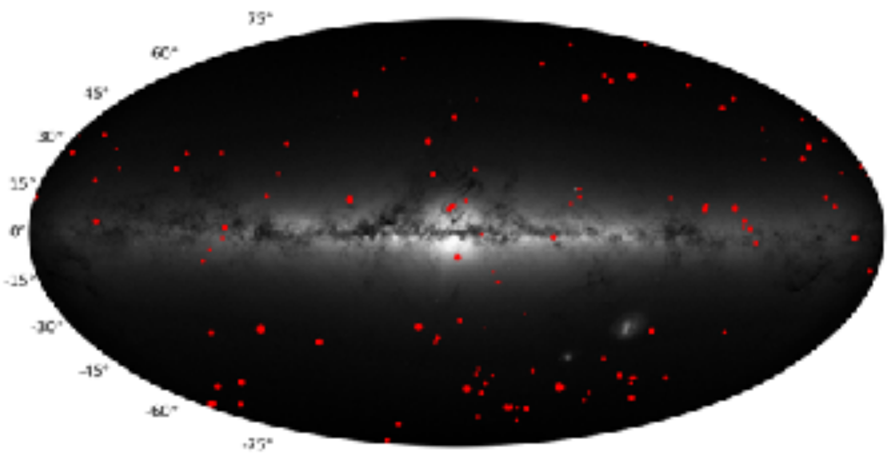
Known FRBs



- Until now: detections mostly incidental
- Expect rates of $10^3 - 10^4$ / sky / night
- Now: dedicated searches ongoing

CHIME

ASKAP

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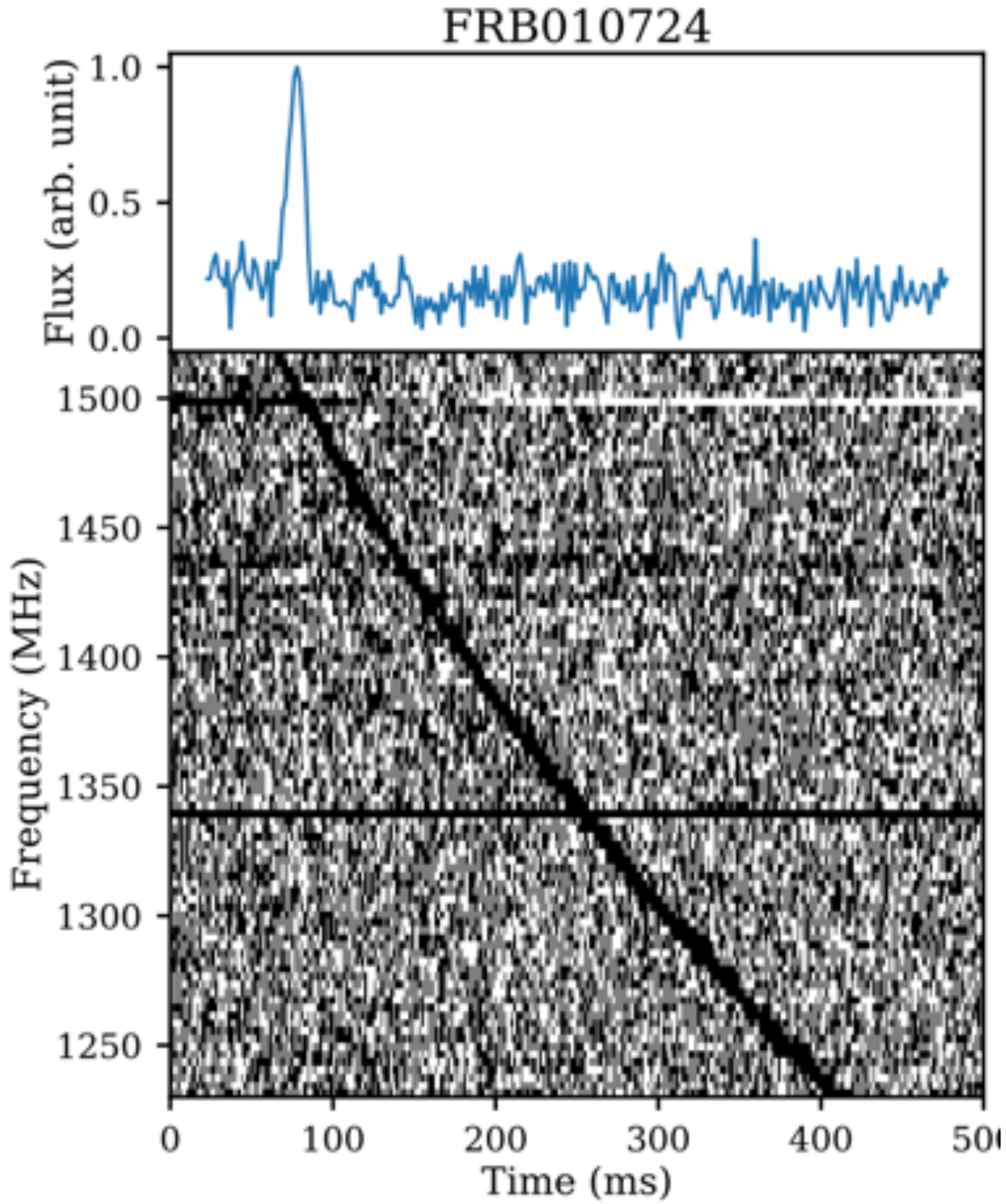
Dispersion measure



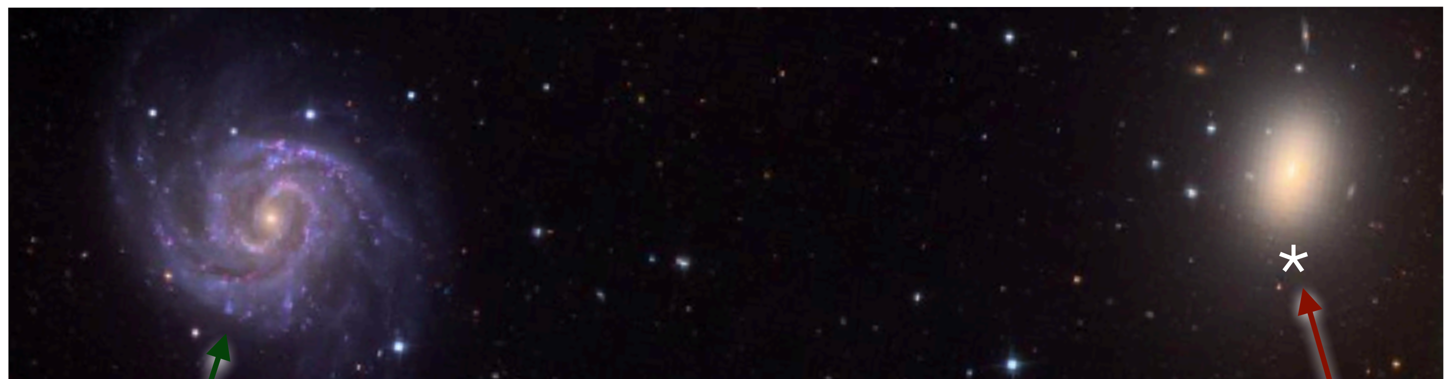
Lorimer et al 2007
Cordes & Chatterjee 2019

- Radio signals undergo dispersion
- Pulse delay $\Delta t \sim \nu^{-2}$
- Depends on integrated electrons along LoS

$$\mathrm{DM} = \int \frac{n_e}{1+z} \mathrm{d}l$$

Dispersion measure

$$\mathrm{DM_{tot}}(z) = \mathrm{DM_{MW}} + \mathrm{DM_{LSS}}(z) + \mathrm{DM_{host}}(z)$$



LSS

Milky Way models
Can be checked with Pulsars
Quite accurate!

Host halo models
Depends on galaxy types?
Location of FRBs?

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Redshift scaling:

const.

$$\propto \int^{z} \frac{1+z'}{E(z')} \mathrm{d}z'$$

$$\propto \frac{1}{1+z}$$

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Statistics can tell contributions apart

Dispersion measure

Dispersion measure has several contribution:

$$\mathrm{DM_{tot}}(z) = \mathrm{DM_{MW}} + \mathrm{DM_{LSS}}(z) + \mathrm{DM_{host}}(z)$$

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Density field

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Ionisation history

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Baryon fraction

$$n_e \approx F(z)\frac{\rho_b}{m_p} = F(z)\frac{\bar{\rho}_b}{m_p}\left[1 + b_e\delta_m\right]$$

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Need redshifts

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FRB distance scale

Mean LSS dispersion:

$$\langle \mathrm{DM_{LSS}} \rangle(z) = \int \mathrm{d}l \, \frac{n_e}{1+z}$$

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FRB distance scale

Mean LSS dispersion:

$$\langle \mathrm{DM}_{\mathrm{LSS}} \rangle (z) = \int \mathrm{d}l \, \frac{n_e}{1+z}$$

$$n_e \approx \chi_e \frac{\bar{\rho}_{\mathrm{b}}}{m_p}$$

FRB distance scale

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$$\langle \mathrm{DM_{LSS}} \rangle(z) = \int \mathrm{d}l \, \frac{n_e}{1+z}$$

$$= \frac{3\Omega_\mathrm{b} H_0}{8\pi G m_\mathrm{P}} \chi_\mathrm{e} f_\mathrm{IGM} \int^z \frac{1+z'}{E(z')} \mathrm{d}z'$$

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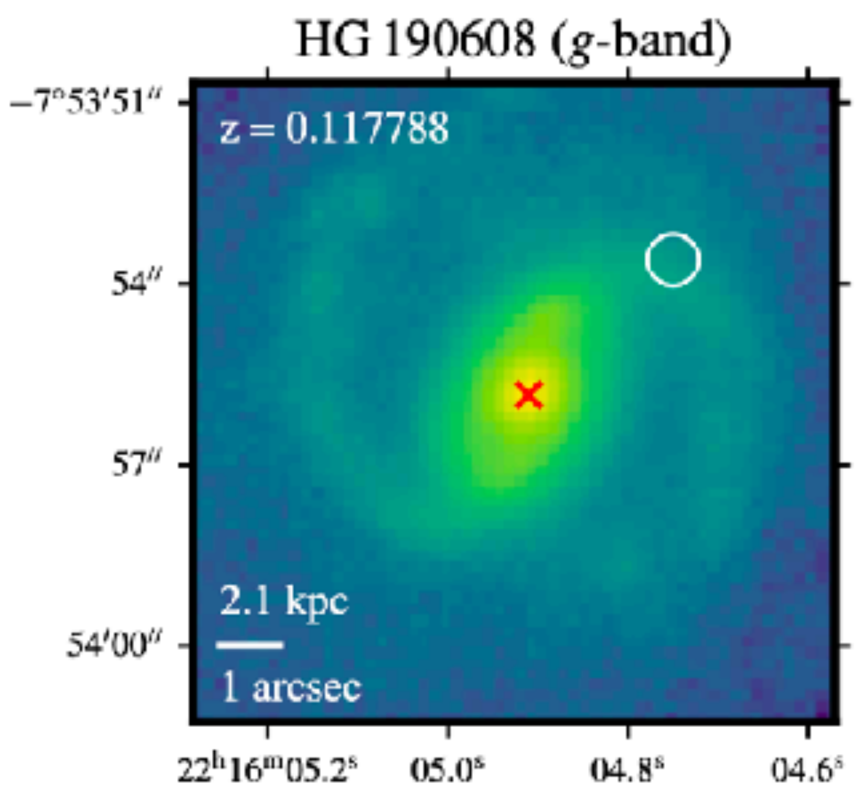
- Perfect degeneracy at the background level
- Combine with prior on baryon density $\Omega_\mathrm{b} h^2$ (from CMB or BBN)

Host ID



VLT + ASKAP (Macquart et al 2020)

- Dedicated FRB searches from radio arrays
- Long baselines, excellent angular resolution
- Optical follow-up allows host ID and redshift

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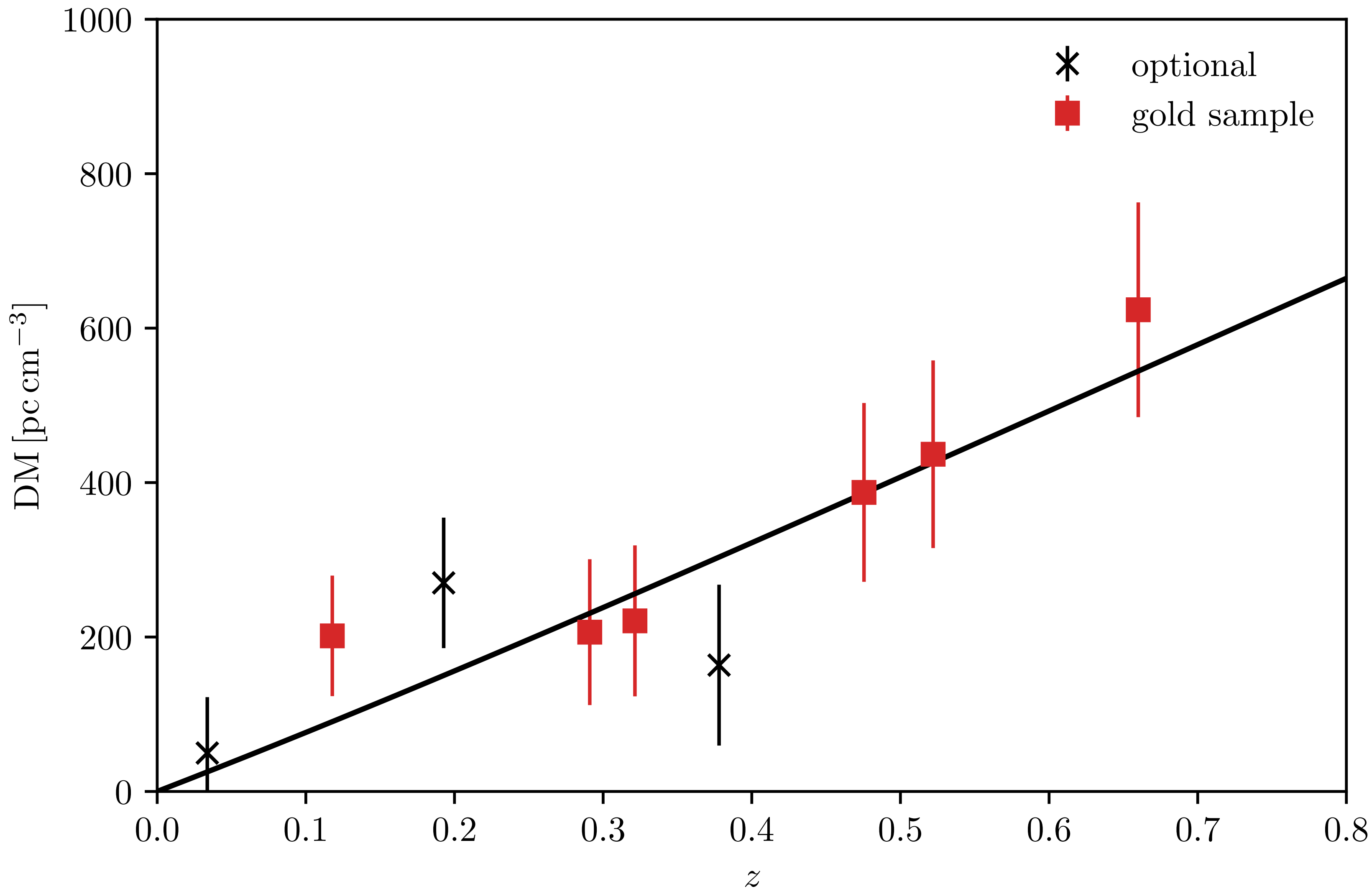
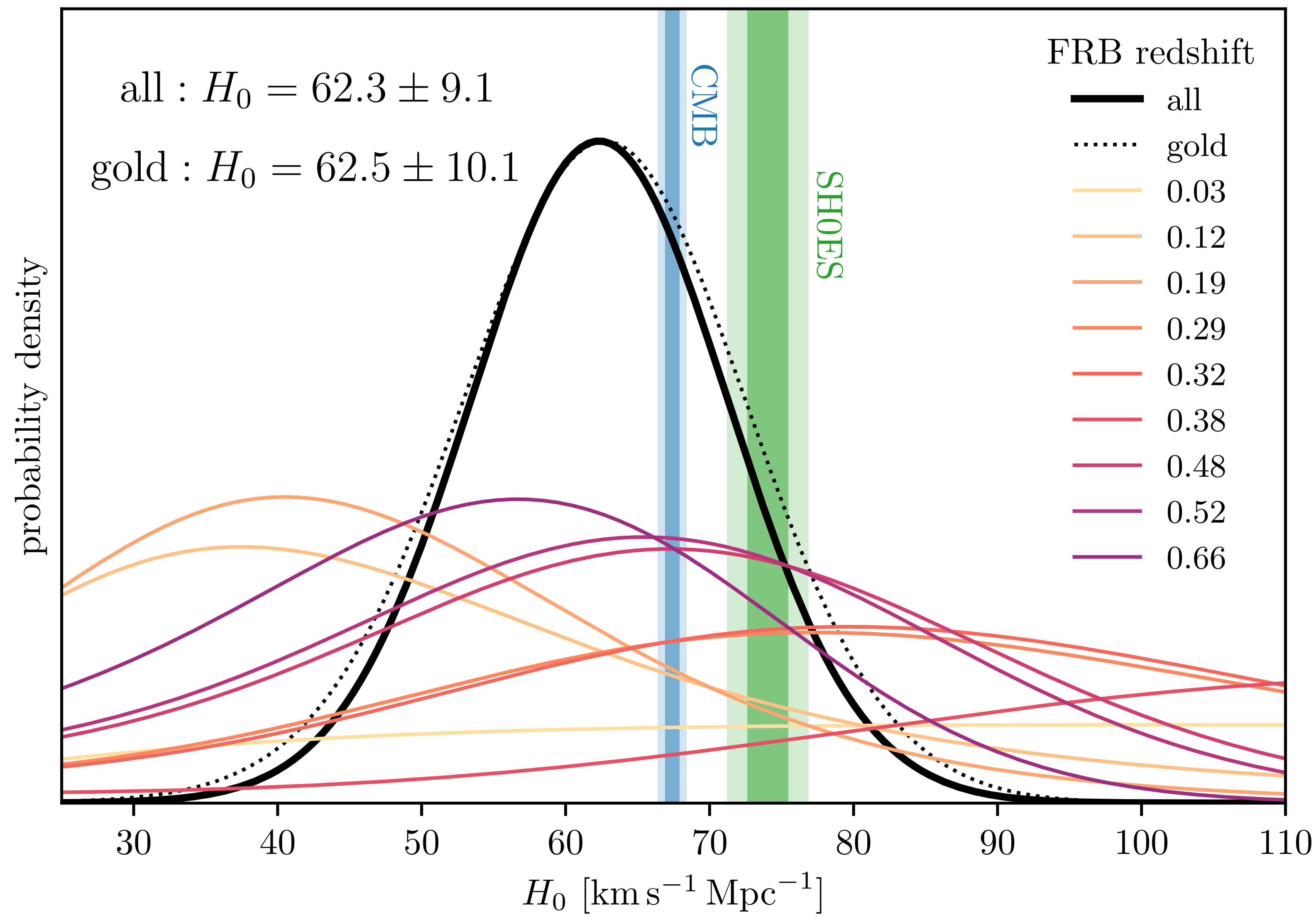
FRB distance scale



- Compile DM-z diagram similar to SNe Ia
- Absolute calibration via subtraction of host & MW DM
- Additional “gold sample” of high quality events

Hubble constant



Events at large z most important

Uncertainty in host DM dominates error

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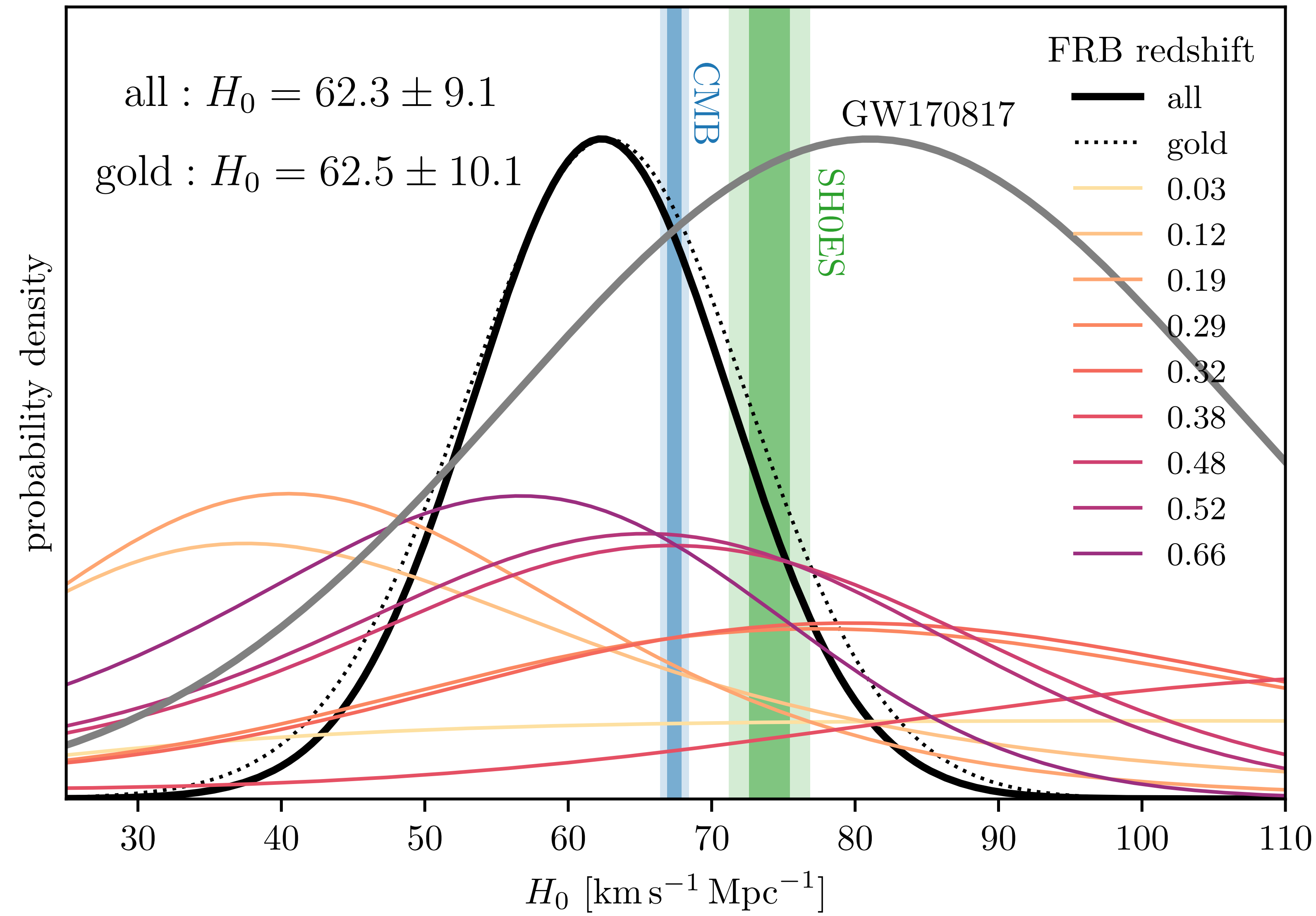
Hubble constant



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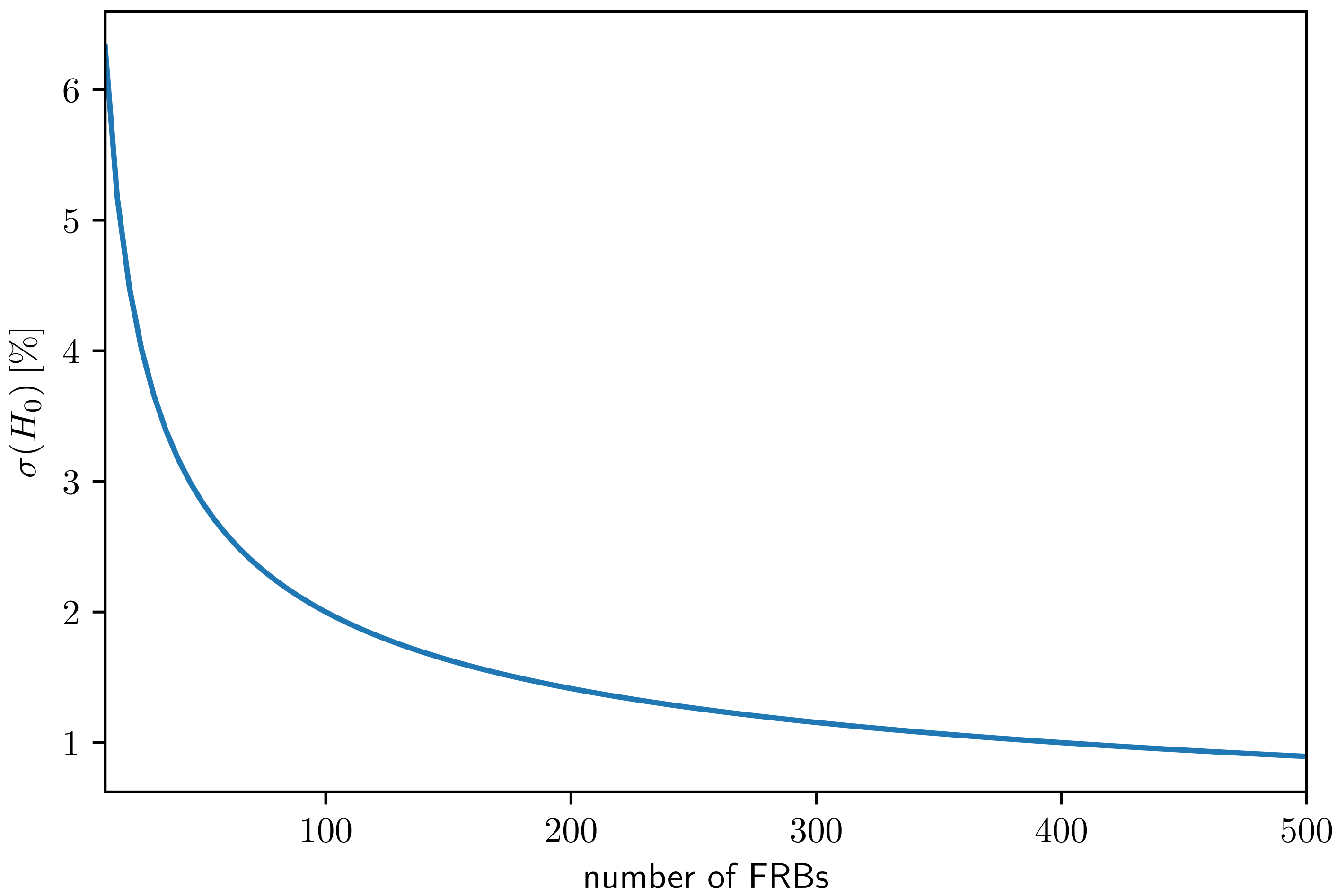
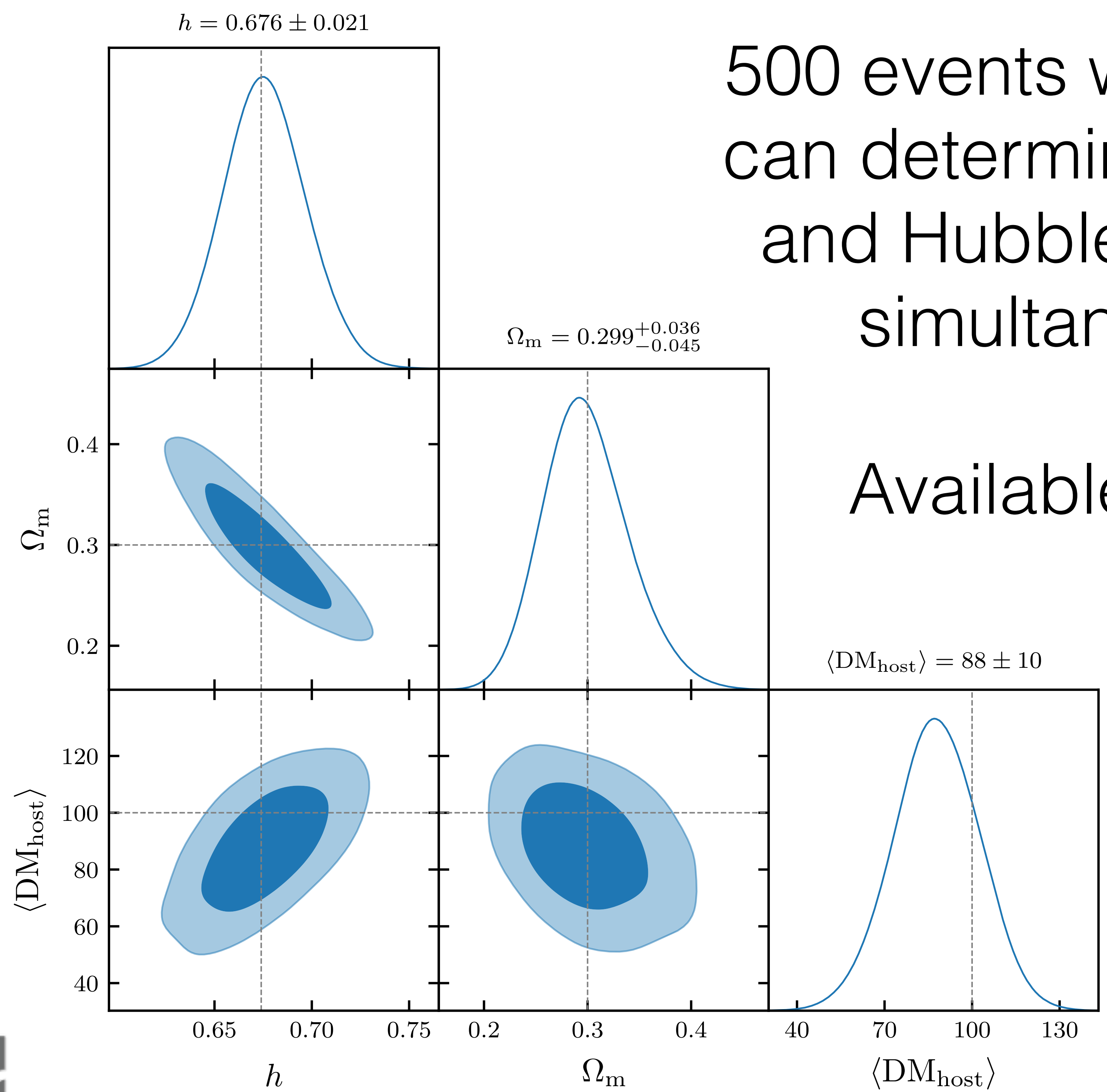
The Future

When can FRBs be competitive?



- A few hundred events with host ID get to ~1% precision
- Can we relax some assumptions with larger samples?

Forecast



500 events with host ID can determine host DM and Hubble constant simultaneously

Available soon!

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Correlated events

Nearby lines of sight
traverse similar structures
→ correlated DM

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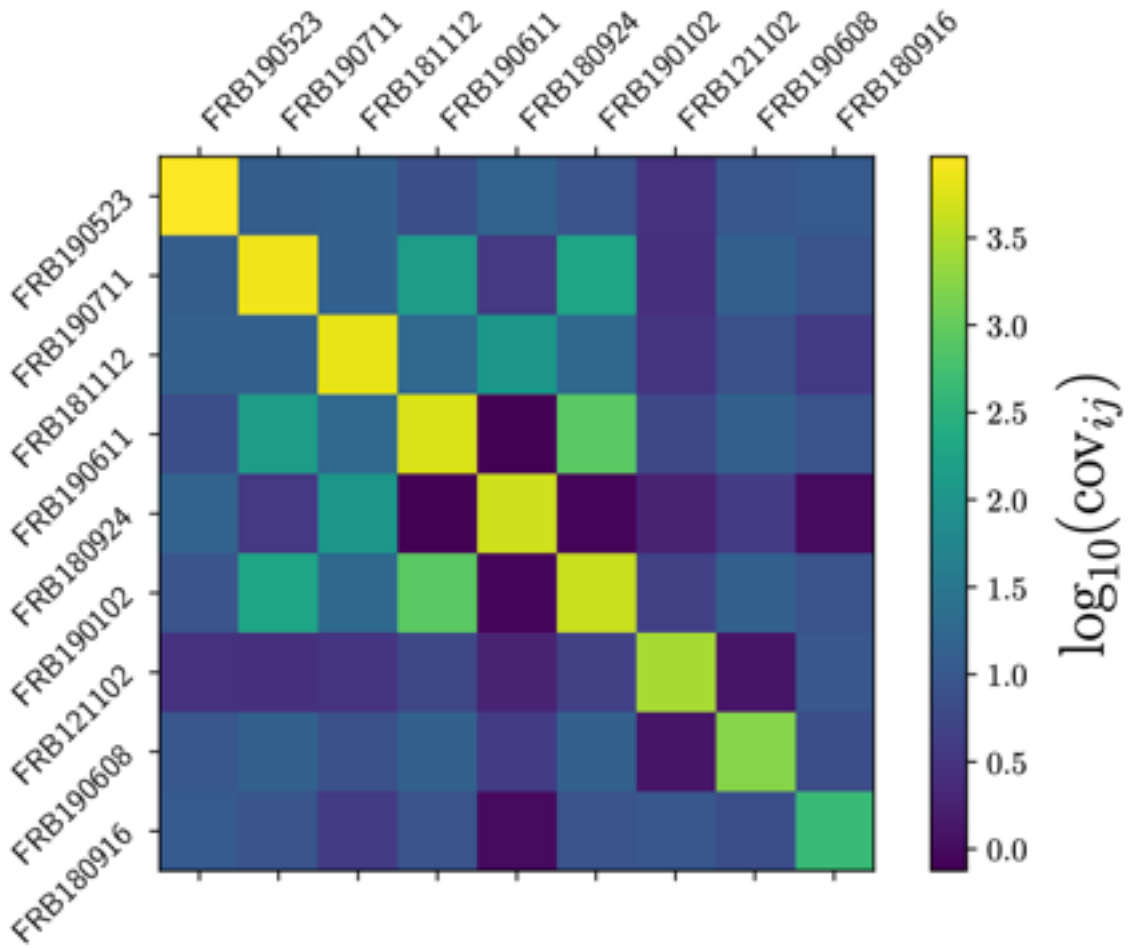

Reischke & Hagstotz, 2301.03527

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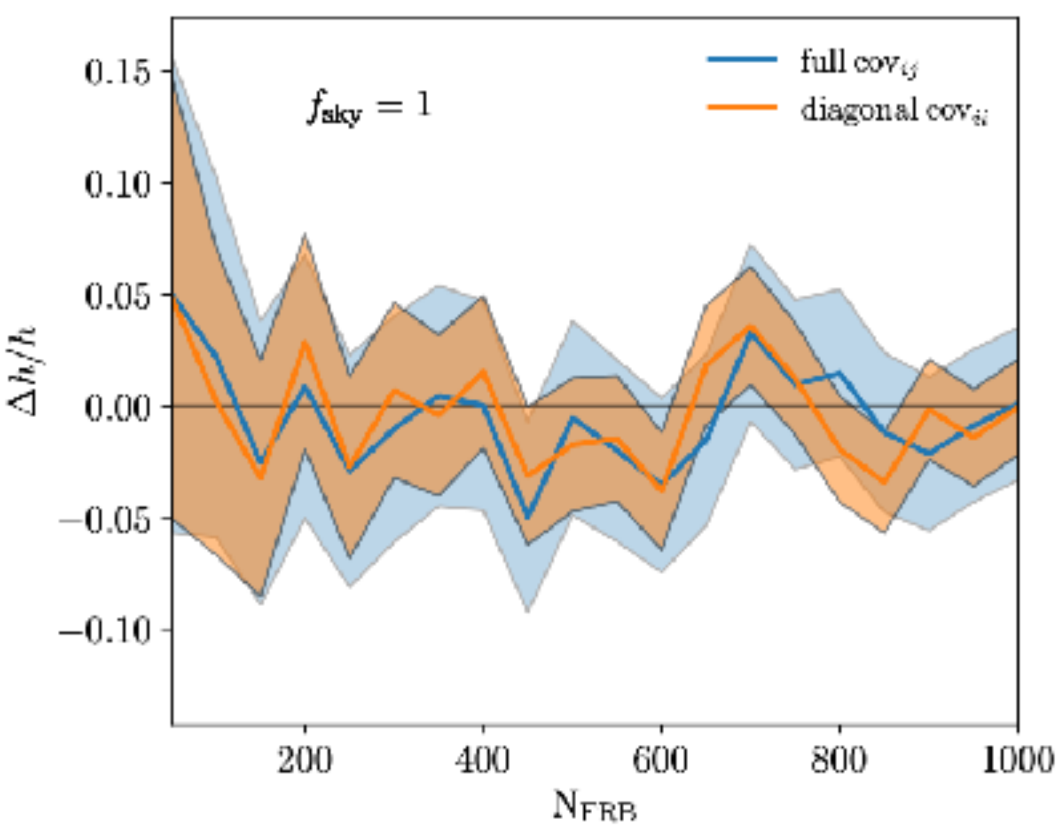
Correlated events



Correlation becomes important for few 100s FRBs/sky..

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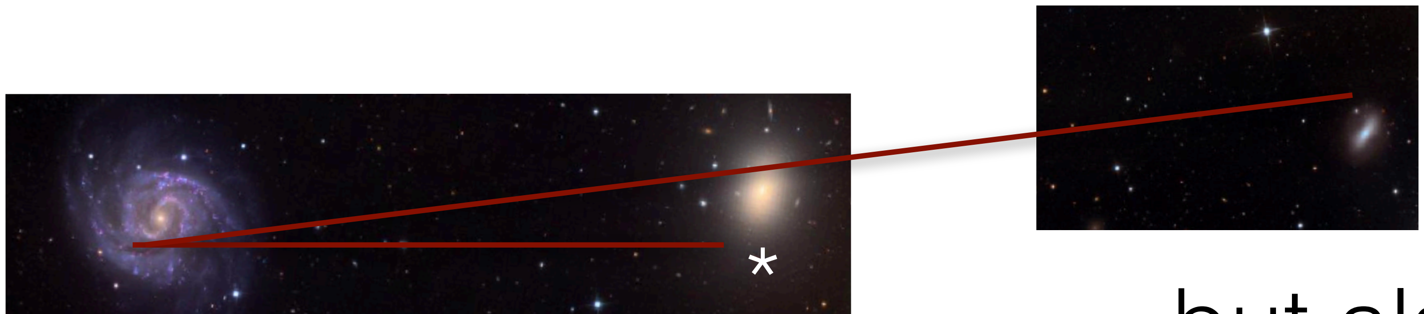
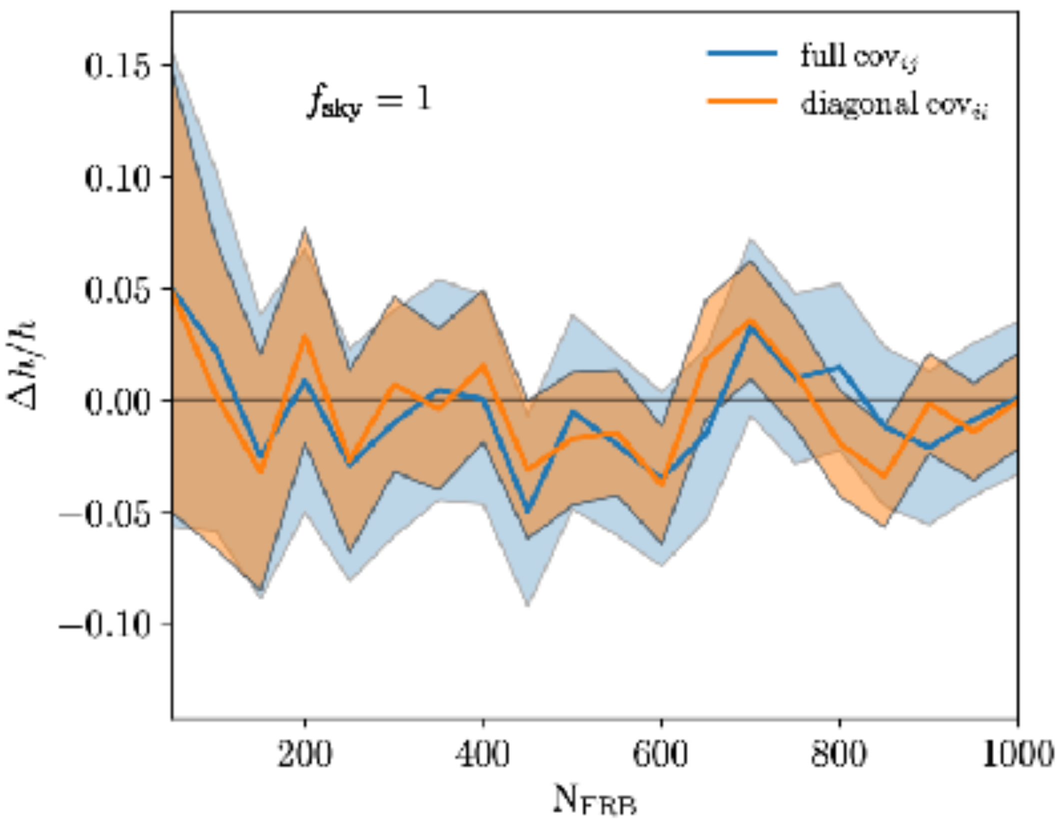
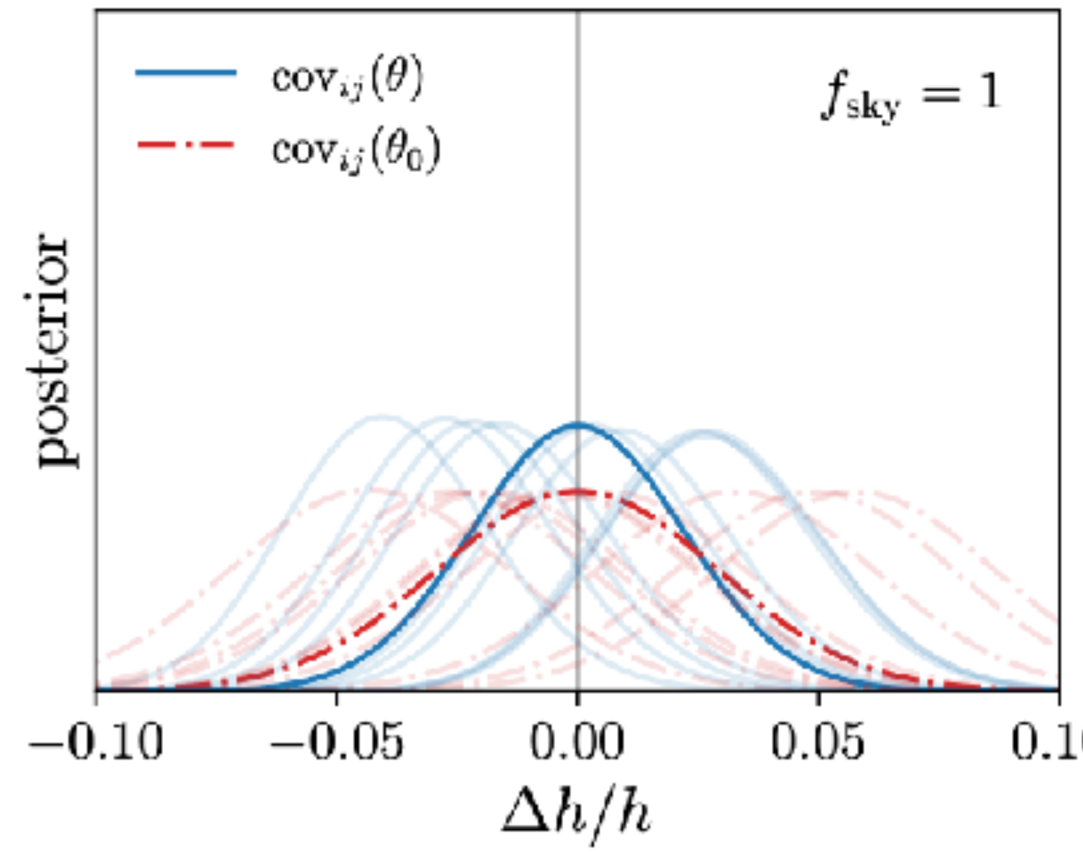
Reischke & Hagstotz, 2301.03527

Correlated events



…but also is a source of information





Correlation becomes important for few 100s FRBs/sky..

$$\mathrm{cov}(H_0, \Omega_m, \ldots)$$

Reischke & Hagstotz, 2301.03527

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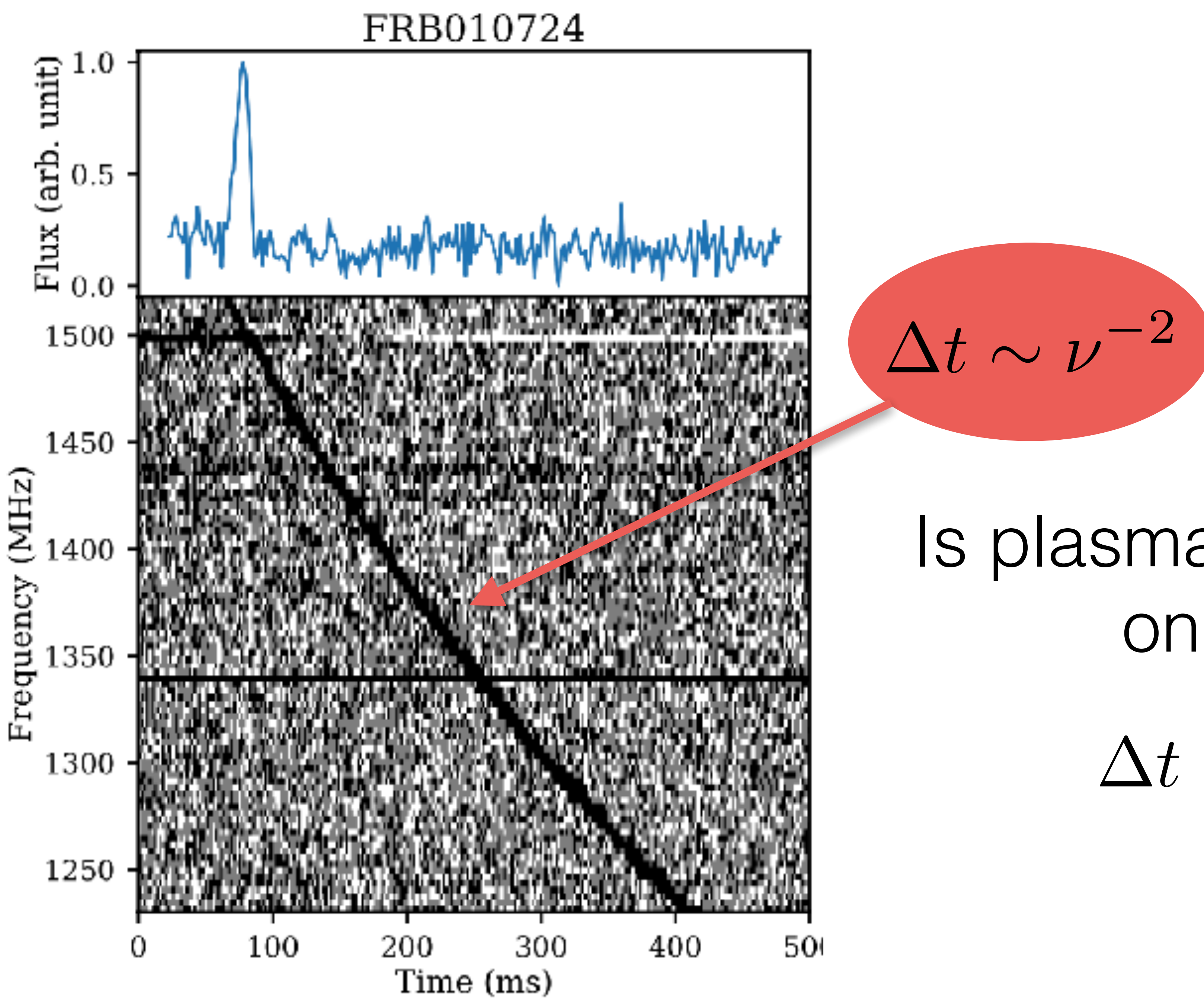
Pulse dispersion?



Lorimer et al 2007
Cordes & Chatterjee 2019

Is plasma dispersion the only effect?

$$\Delta t \sim \nu^2 + \nu^\alpha$$

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Equivalence principle

- If EP is broken, photons of different frequencies would pick up an additional (to ν^{-2} scaling) delay

$$\Delta t = \Delta t_{\rm DM} + \Delta t_{\rm grav}$$

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$$\Delta t = \Delta t_{\rm DM} + \Delta t_{\rm grav}$$

- So far what has been assumed is the classical Shapiro delay expression

$$t_{\rm grav} = -\frac{1+\gamma}{c^3}\int_{\boldsymbol{r}_{\rm e}}^{\boldsymbol{r}_{\rm o}} {\rm d}\lambda\, U(\boldsymbol{r}(\lambda))$$

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- Idea: assume to know a subset of potentials along line-of-sight

- Put upper limits on $\Delta\gamma$

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Problems

- Adding structure increases the limit monotonically
- In a cosmological setting the standard expression diverges due to boundary conditions

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- Adding structure increases the limit monotonically
- In a cosmological setting the standard expression diverges due to boundary conditions
- Should rather use

$$\Delta t_{\mathrm{grav}} = \frac{\Delta\gamma}{c^3} \int \mathrm{d}\chi a(\chi) \phi(\hat{\boldsymbol{x}}\chi)$$

- New problem: no longer upper bound since ϕ fluctuates

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Equivalence principle tests

- True observable: time delay between frequency arrival $\Delta t = \Delta t_{\rm DM} + \Delta t_{\rm grav}$

- Shapiro delay

Possible frequency dependence

$$\Delta t_{\rm grav} = \frac{\Delta\gamma}{c^3}\int \mathrm{d}\chi a(\chi)\phi(\hat{\boldsymbol{x}}\chi)$$

- Can imprint additional correlations when interpreted as DM signal

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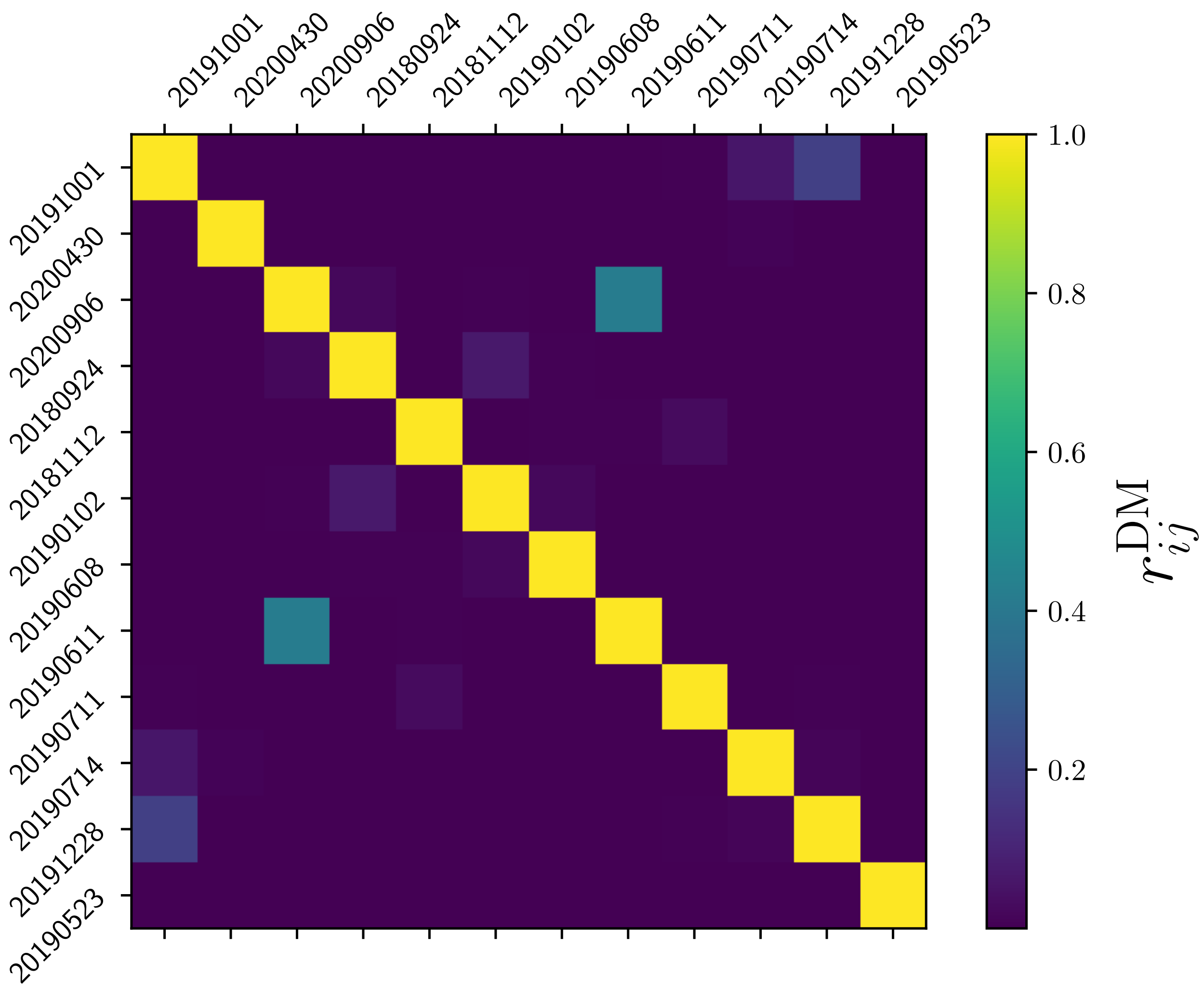
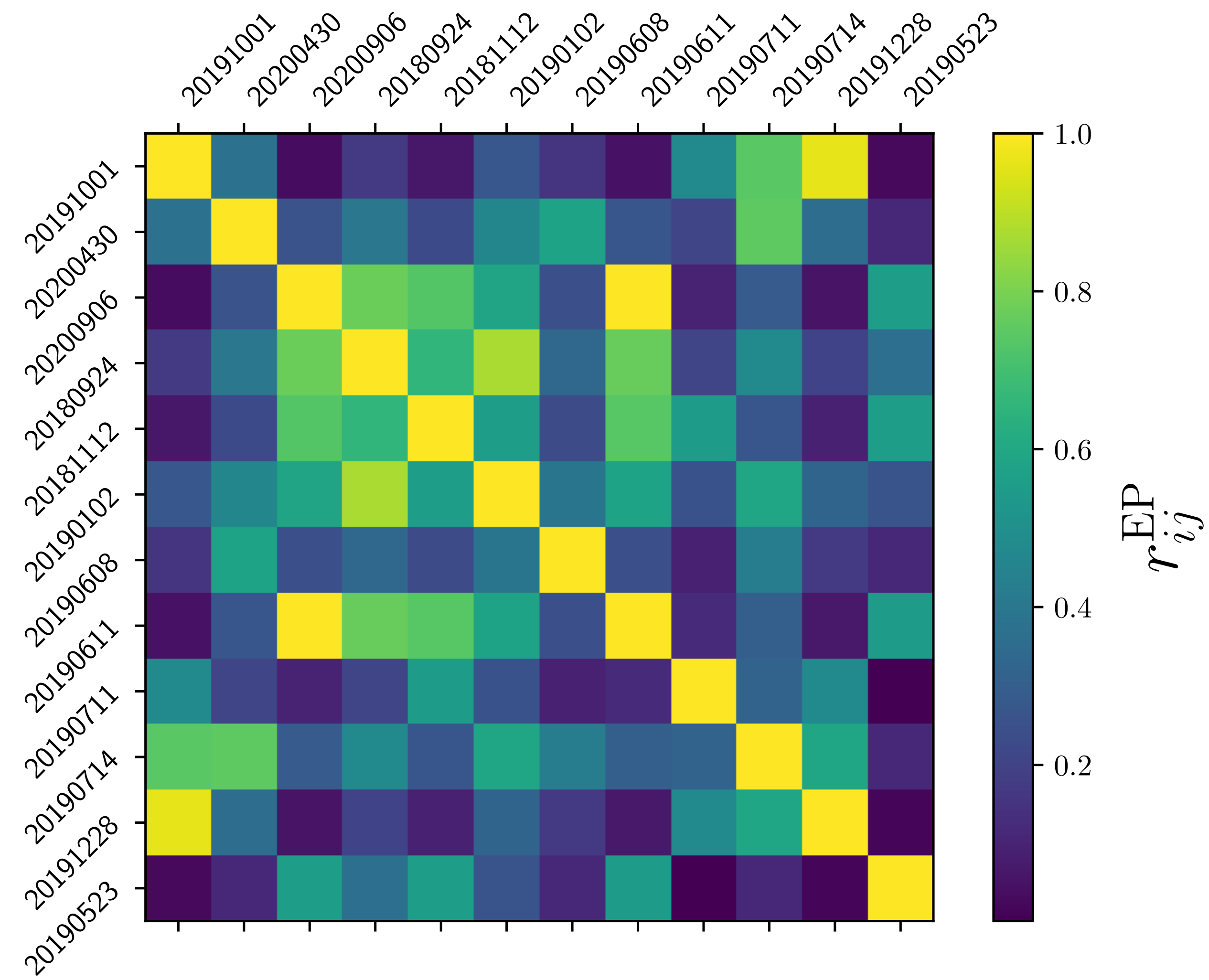
Equivalence principle tests





Reischke, Hagstotz 2302.10072

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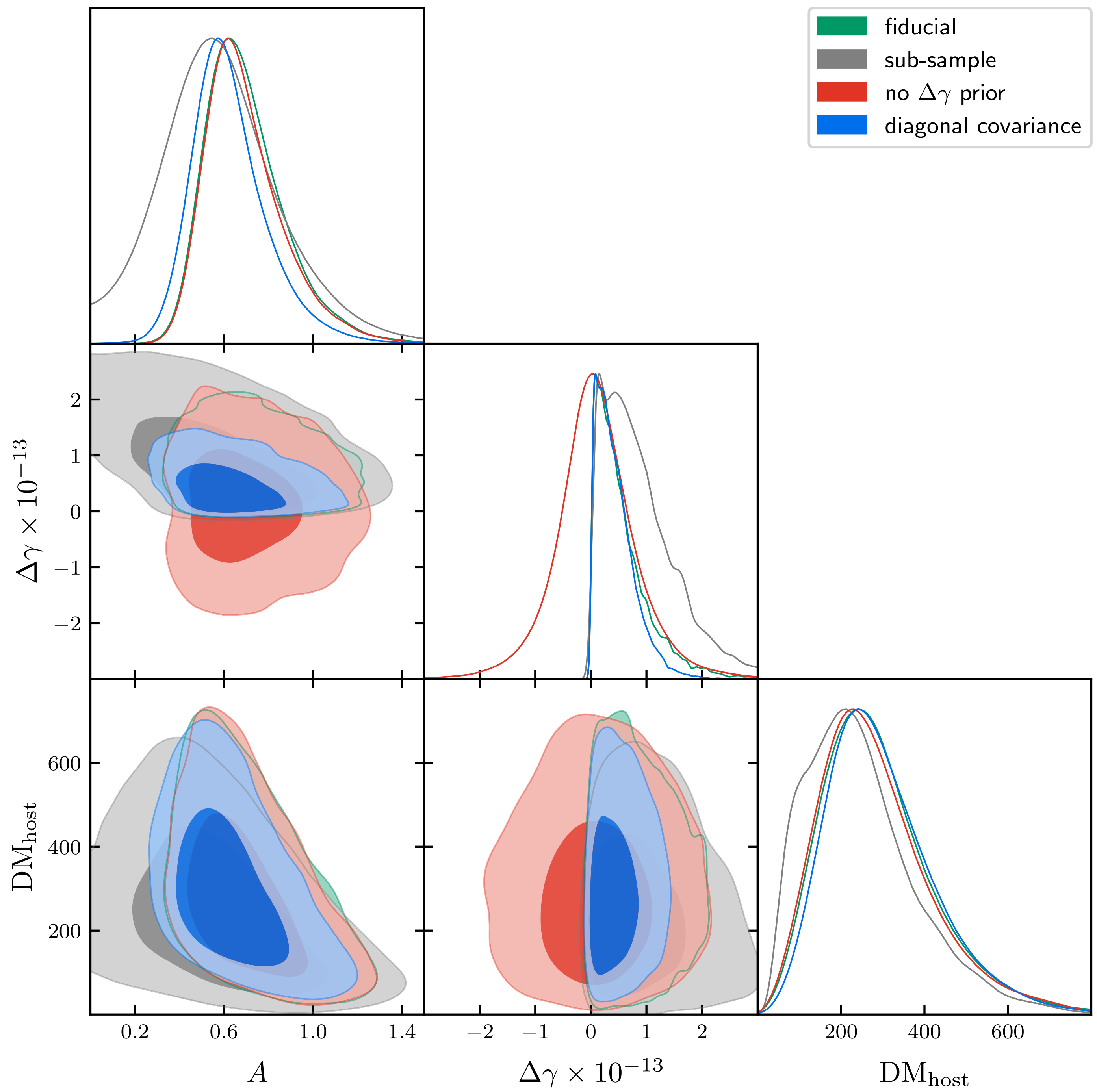

Reischke, Hagstotz 2302.10072

FRB statistics

Redshifts in general not known: consider angular clustering

Correlate dispersion measure

weak lensing on steroids*

$$C_\ell = \langle \mathrm{DM}_\ell \, \mathrm{DM}_{\ell'} \rangle \sim \int \mathrm{d}\chi \Big[\ldots P_{ee}(k) \Big] + \frac{\sigma^2_{\mathrm{host}}}{\bar{n}}$$

*(but still sparse)

signal >> noise

Because $\mathrm{DM}_{\mathrm{LSS}}(z) \gg \mathrm{DM}_{\mathrm{host}}$

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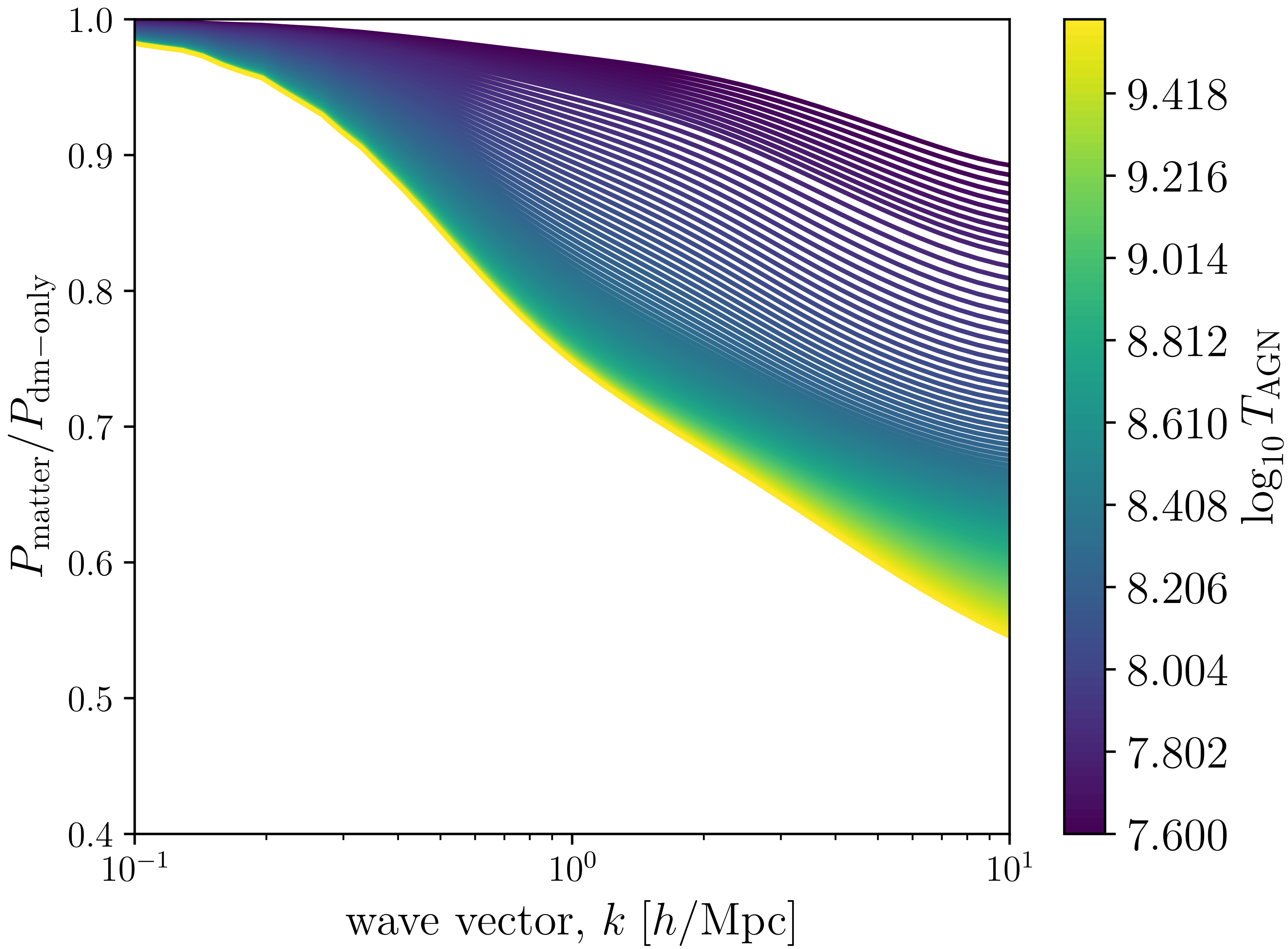
Baryonic Feedback



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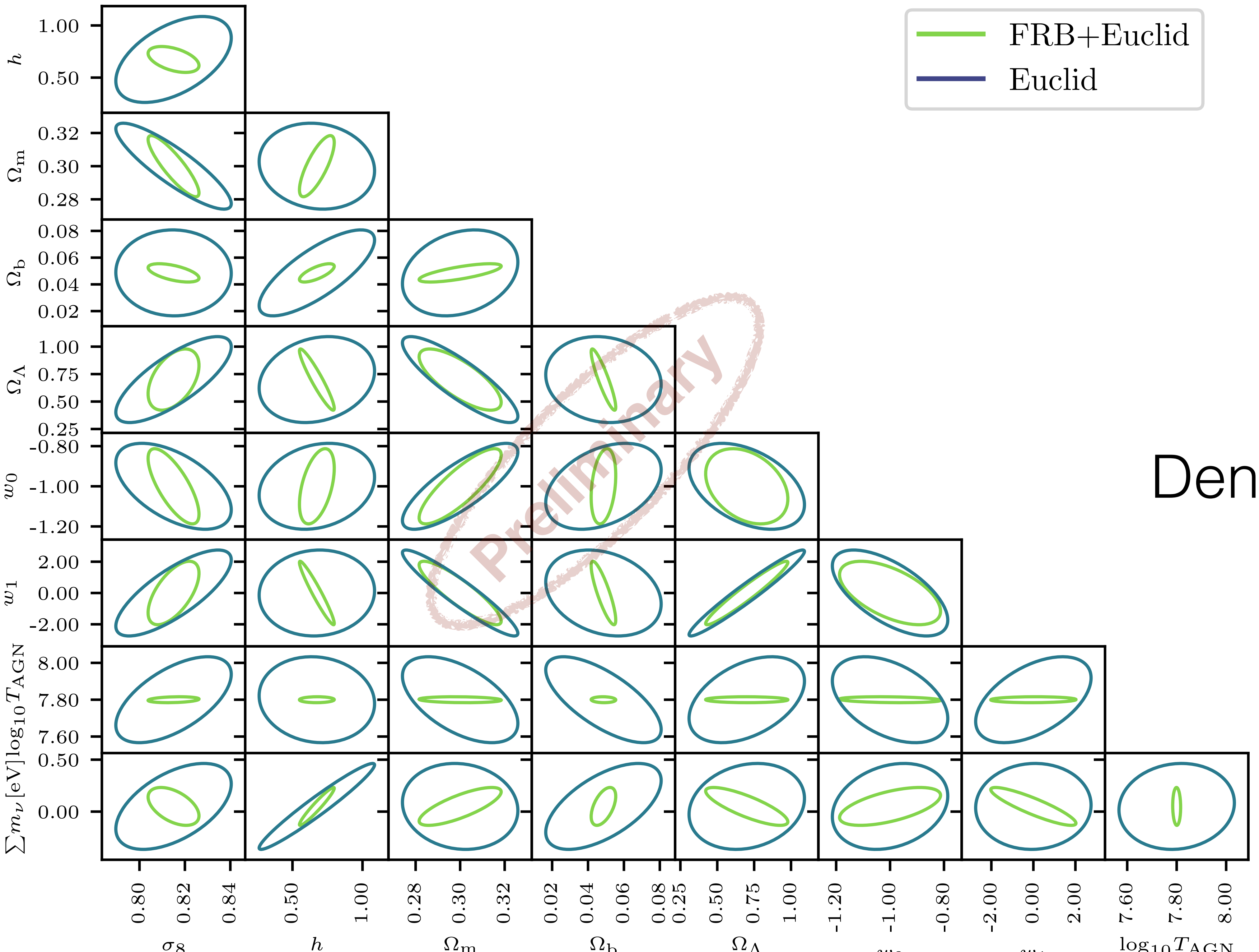

Dennis Neumann

Summary

- Mechanism of the bursts unknown
- FRBs can provide independent* measurement of the Hubble constant $H_0 = 62.3 \pm 9.1$
- Currently limited by statistics, many more events are coming from CHIME/ASKAP/HIRAX
- Correlations allow powerful tests of fundamental physics
- Direct measurement of baryons to constrain feedback