Cosmology with Fast Radio Bursts

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Steffen Hagstotz
with Robert Reischke, Alexander Theis,
Dennis Neumann

Kigali I July 13 I 2023

Fast Radio Bursts

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- Mechanism unknown
- First discovered in archival data 2007
- Short (~ms), bright (~Jy) radio transients
- Frequencies 300 Mhz - 8 Ghz
- Extragalactic
- About 500 known events, soon several 1000s
- Some events are repeating

Proposed Mechanisms

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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

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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
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Proposed Mechanisms

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A Living Theory Catalogue for Fast Radio Bursts

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1 Welcome to

Fast Radio Bursts from Extragalactic Light Sails

Manasvi Lingam, Abraham Loeb

We examine the possibility that Fast Radio Bursts (FRBs) originate from the activity of extragalactic civilizations. Our analysis shows that beams used for powering large light sails could yield parameters that are consistent with FRBs. The characteristic diameter of the beam emitter is estimated through a combination of energetic and engineering constraints, and both approaches intriguingly yield a similar result which is on the scale of a large rocky planet. Moreover, the optimal frequency for powering the light sail is shown to be similar to the detected FRB frequencies. These `coincidences' lend some credence to the possibility that FRBs might be artificial in origin. Other relevant quantities, such as the characteristic mass of the light sail, and the angular velocity of the beam, are also derived. By using the FRB occurrence rate, we infer upper bounds on the rate of FRBs from extragalactic civilizations in a typical galaxy. The possibility of detecting fainter signals is briefly discussed, and the wait time for an exceptionally bright FRB event in the Milky Way is estimated.

millisecond-duration radio burst from a Galactic magnetar

The CHIME/FRB Collaboration

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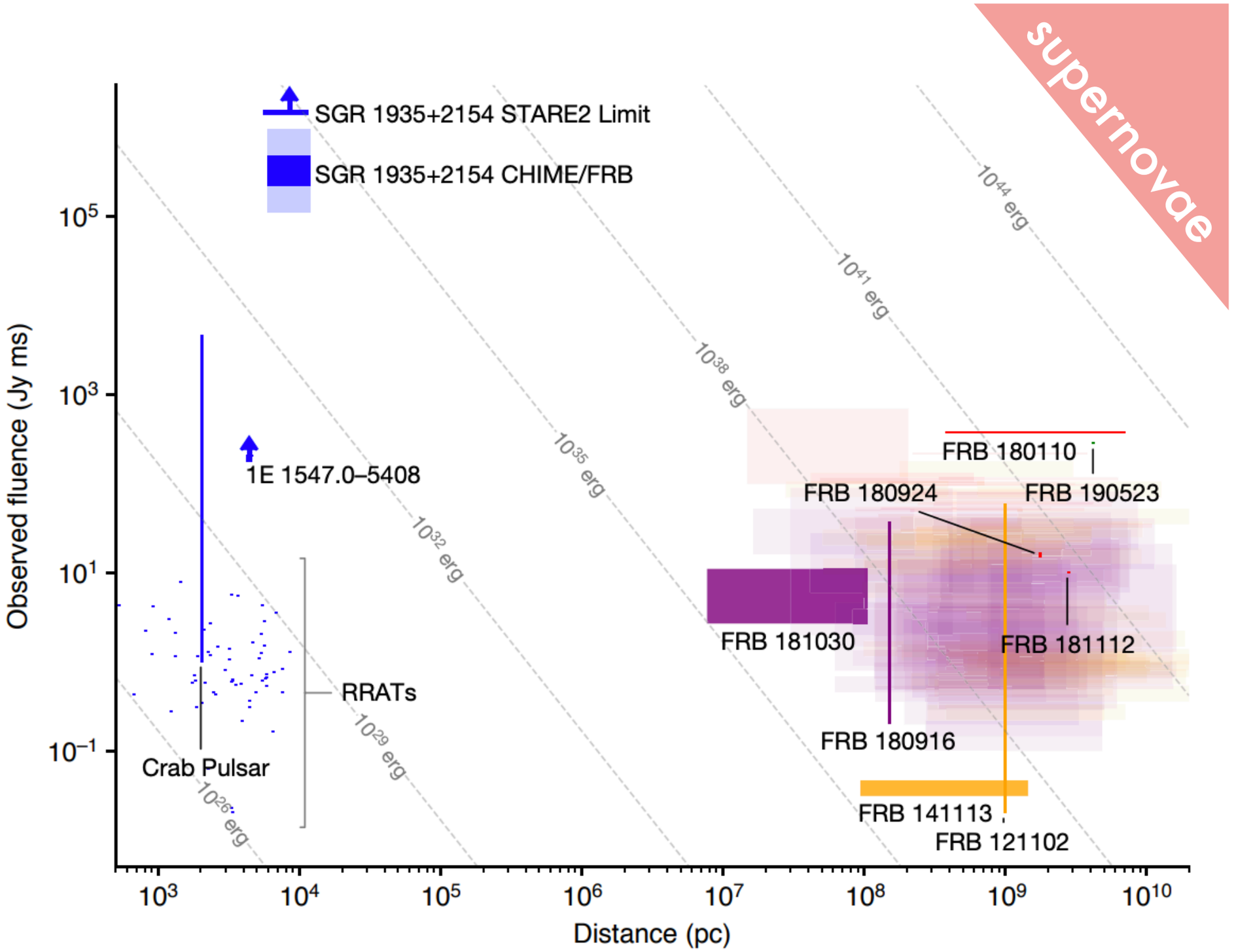
Energy



CHIME/FRB collaboration, Nature 587, 54-58(2020)

Known FRBs

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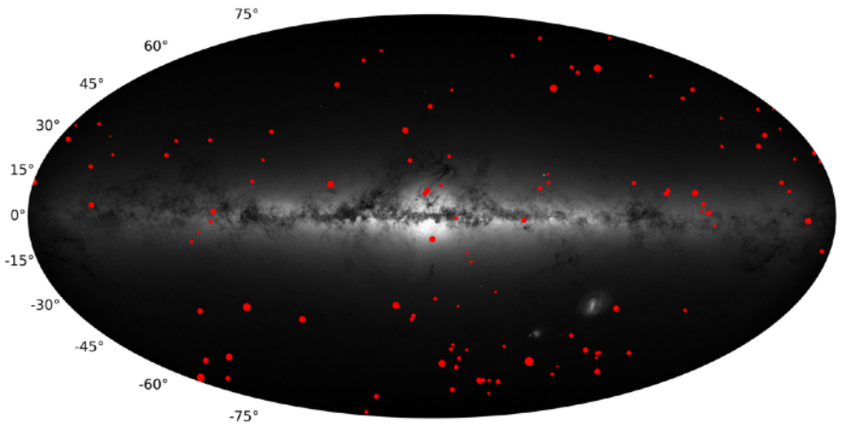
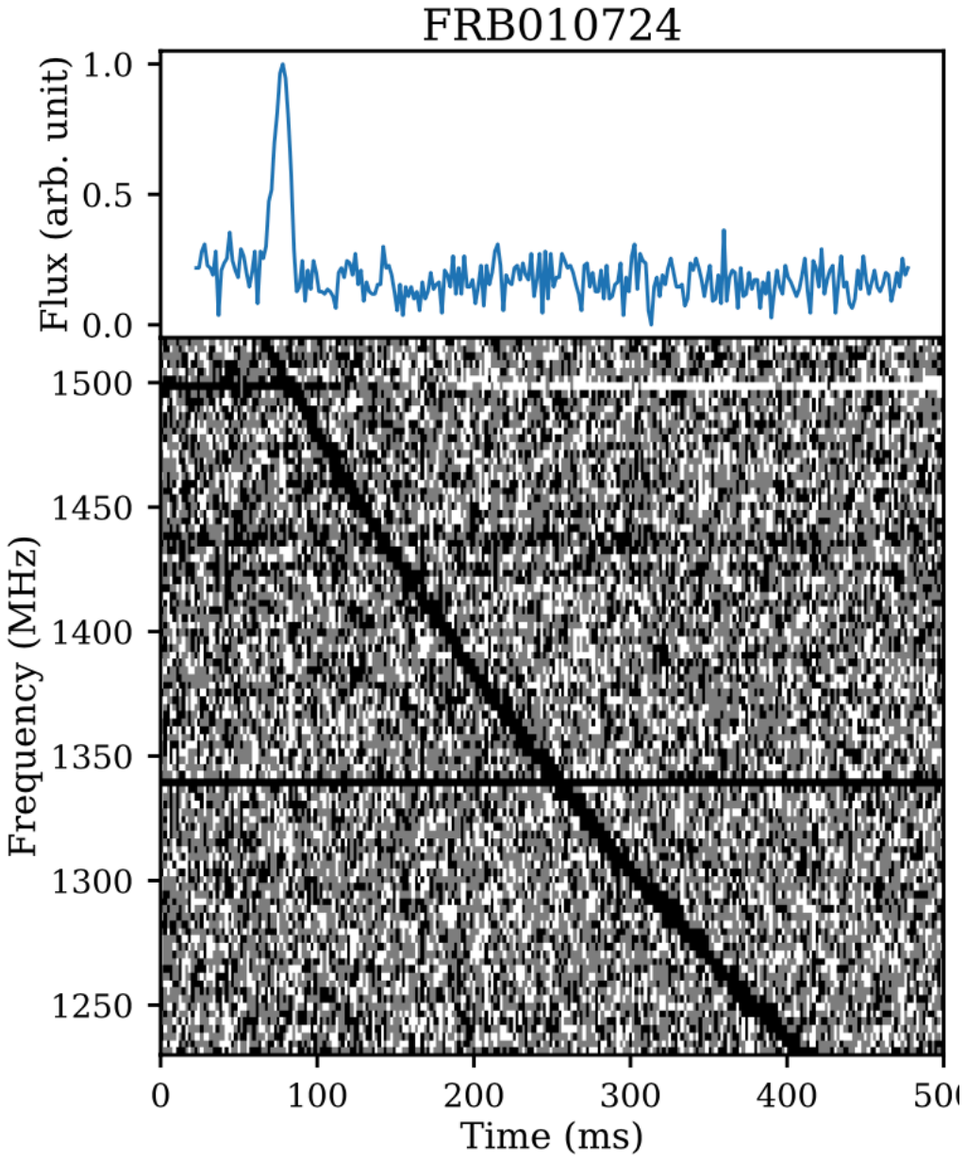


- Until now: detections mostly incidental
- Expect rates of $10^3 - 10^4$ / sky / night
- Now: dedicated searches ongoing

CHIME

ASKAP

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

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

Pulse structure

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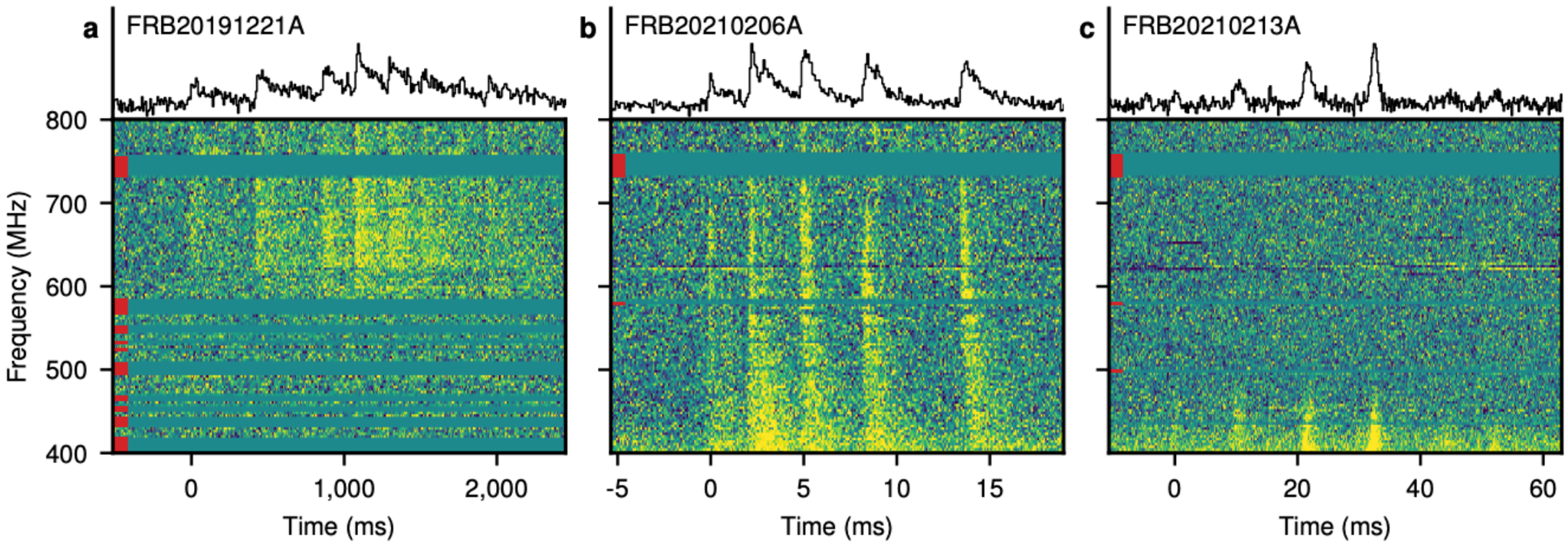

Puls substructure at the ms level -> source not bigger than O(100) km

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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?

Dispersion measure

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Depends on galaxy types?
Location of FRBs?

Redshift scaling:

const.

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

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

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

Dispersion measure

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Ionisation history

Density field

Dispersion measure

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Distance measure

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Density field

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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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Baryon fraction
Need redshifts

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

Distance measure
Need redshifts

Ionisation history
Need redshifts

Density field

Dispersion measure

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Distance measure
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Ionisation history
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Nature, volume 581, 391–395(2020)

Article

A census of baryons in the Universe from localized fast radio bursts

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Distance scales

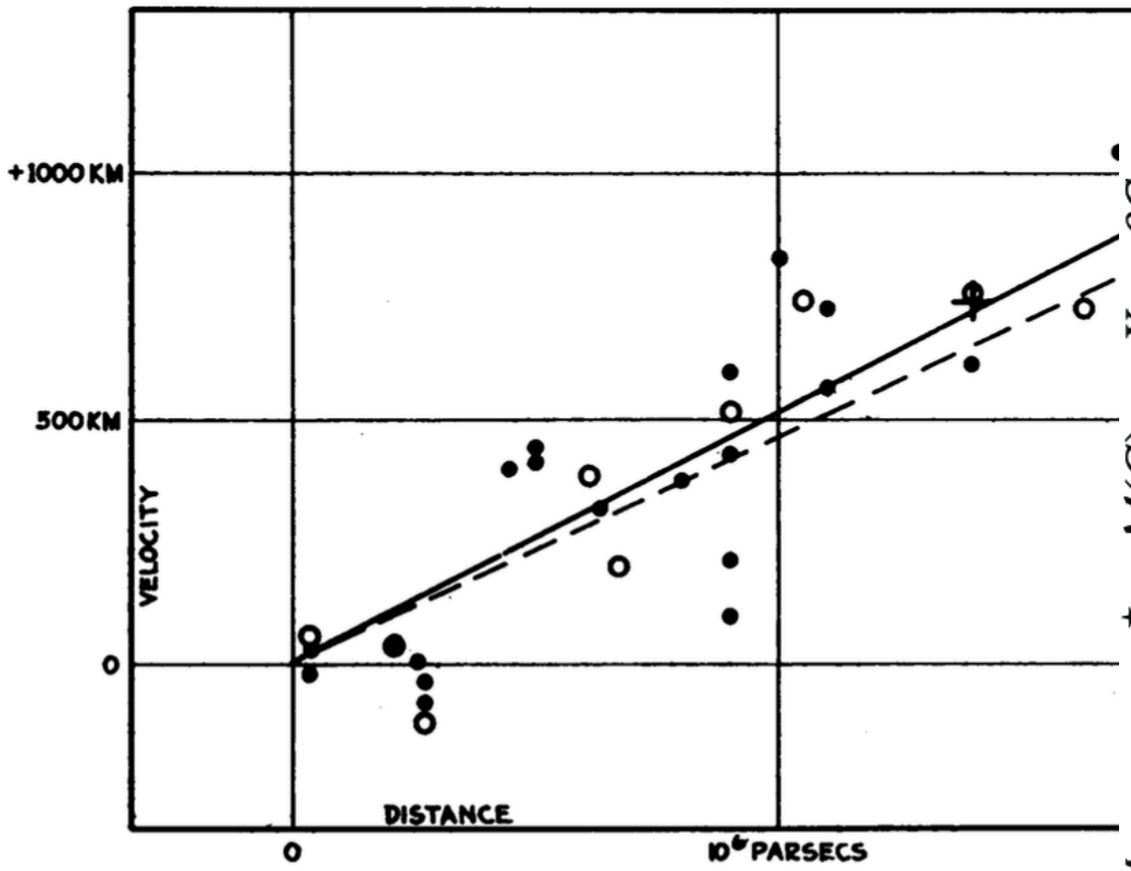
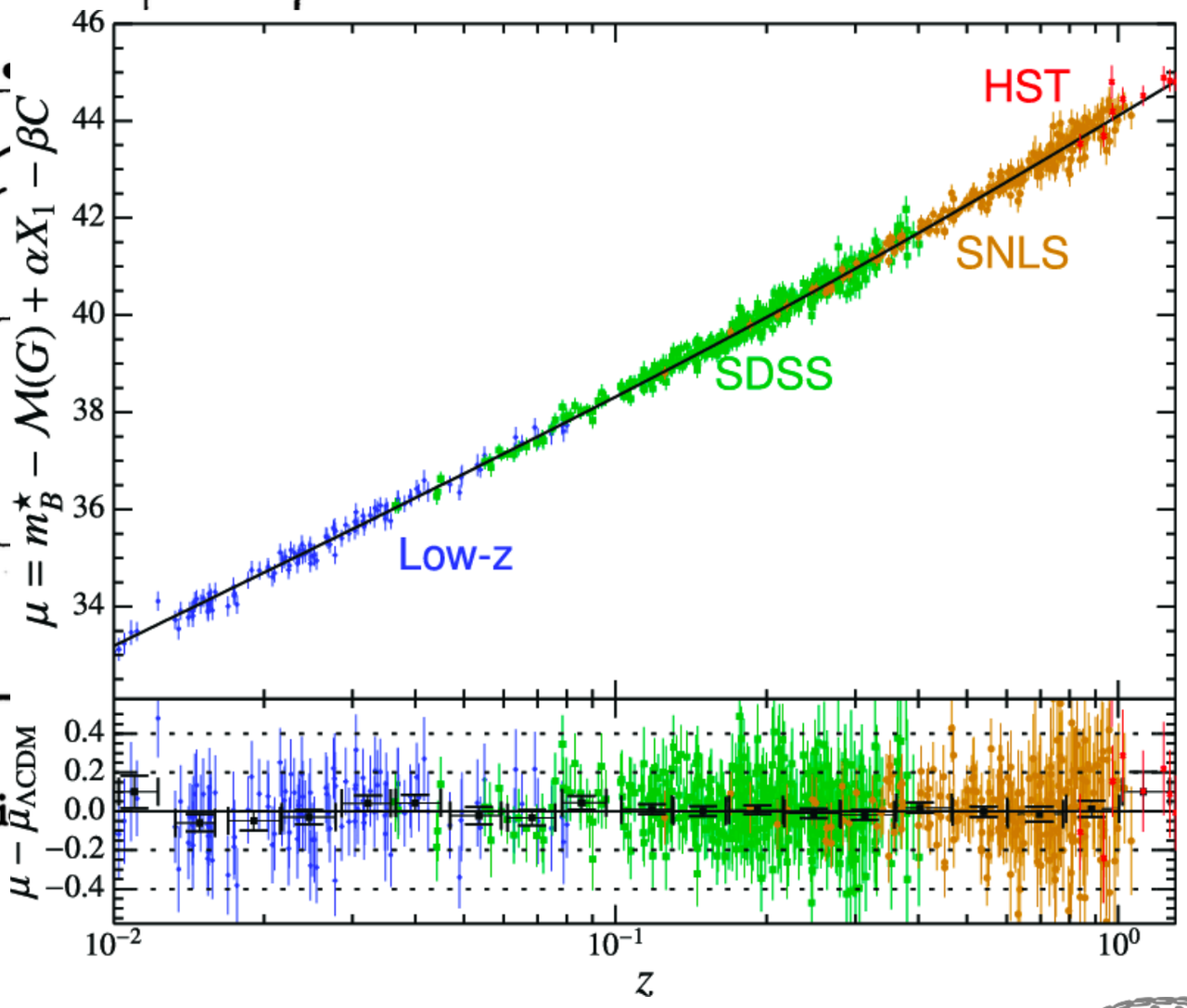


FIGURE 1

Velocity-Distance Relation among Extra-Galacti



Bahcall 2015

FRB distance scale

Mean LSS dispersion:

$$< \mathrm{DM_{LSS}} > (z) = \int \mathrm{d}l \frac{n_e}{1+z}$$

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FRB distance scale

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

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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)

Known FRBs

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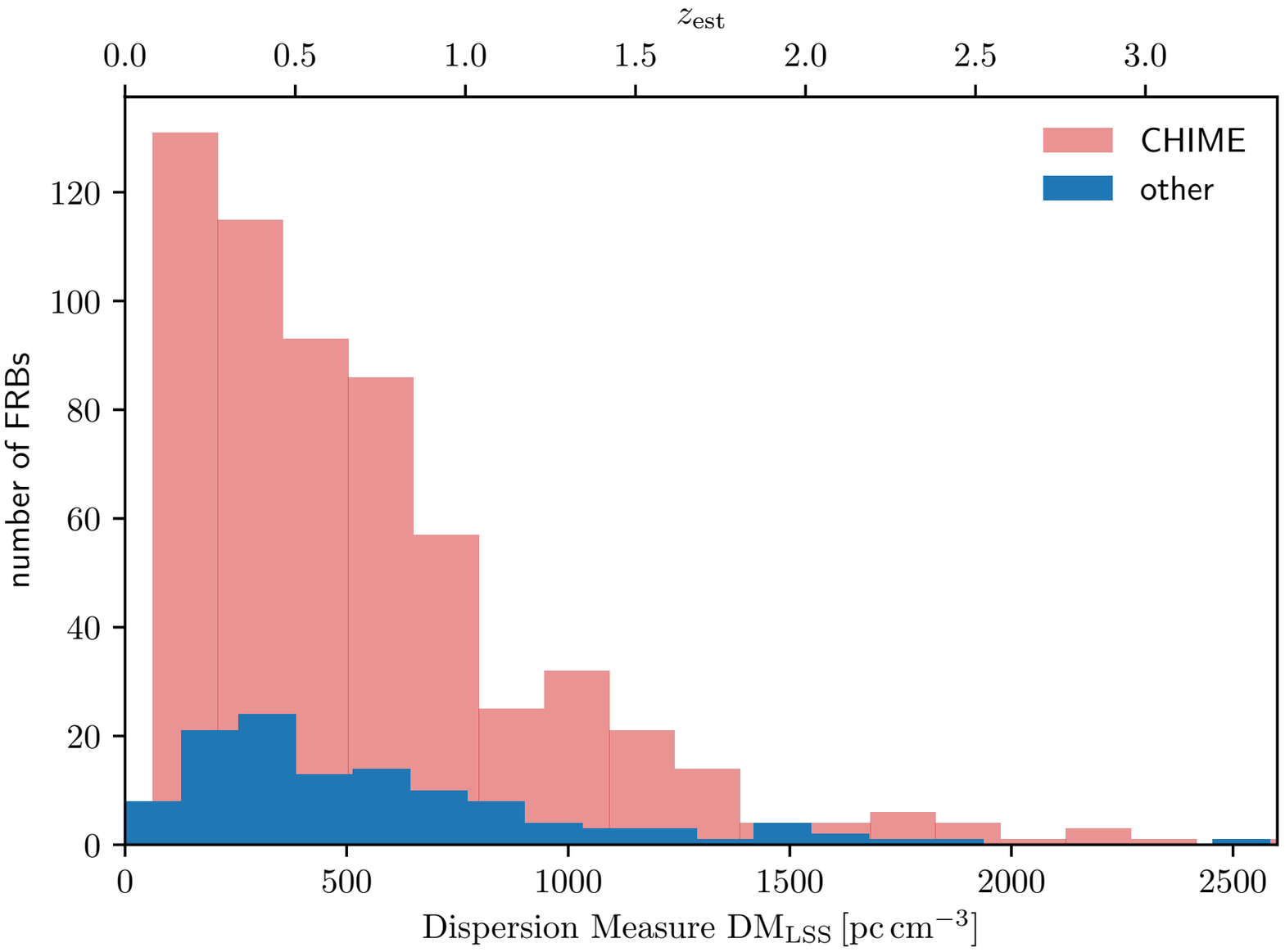
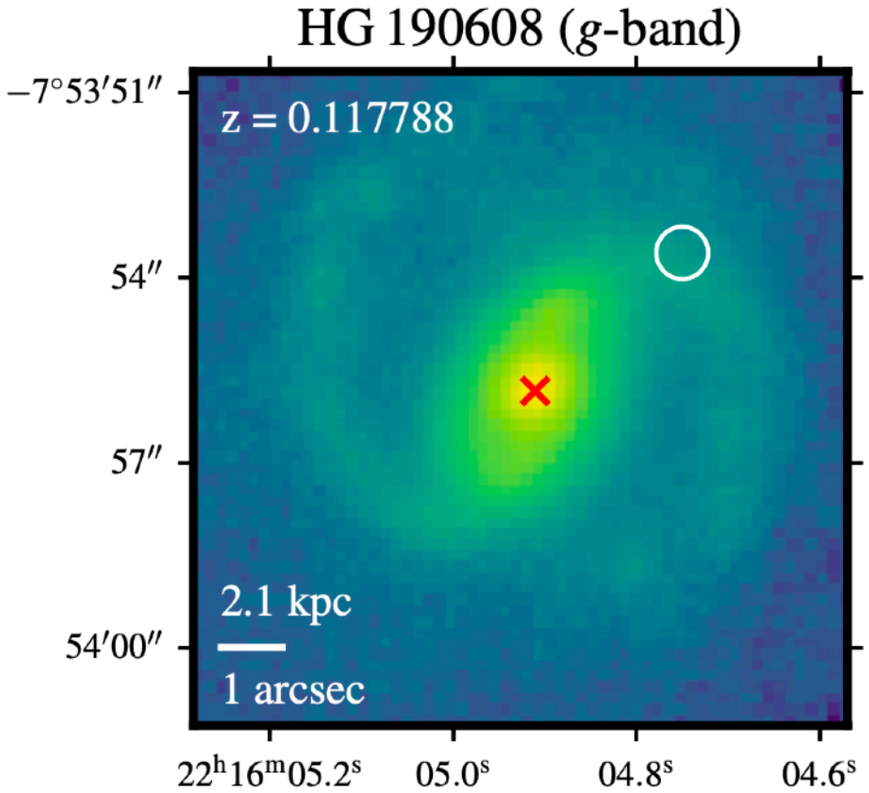


- True FRB population not well known
- Detections up to z~2 possible
- Maybe beyond? Reionisation studies?

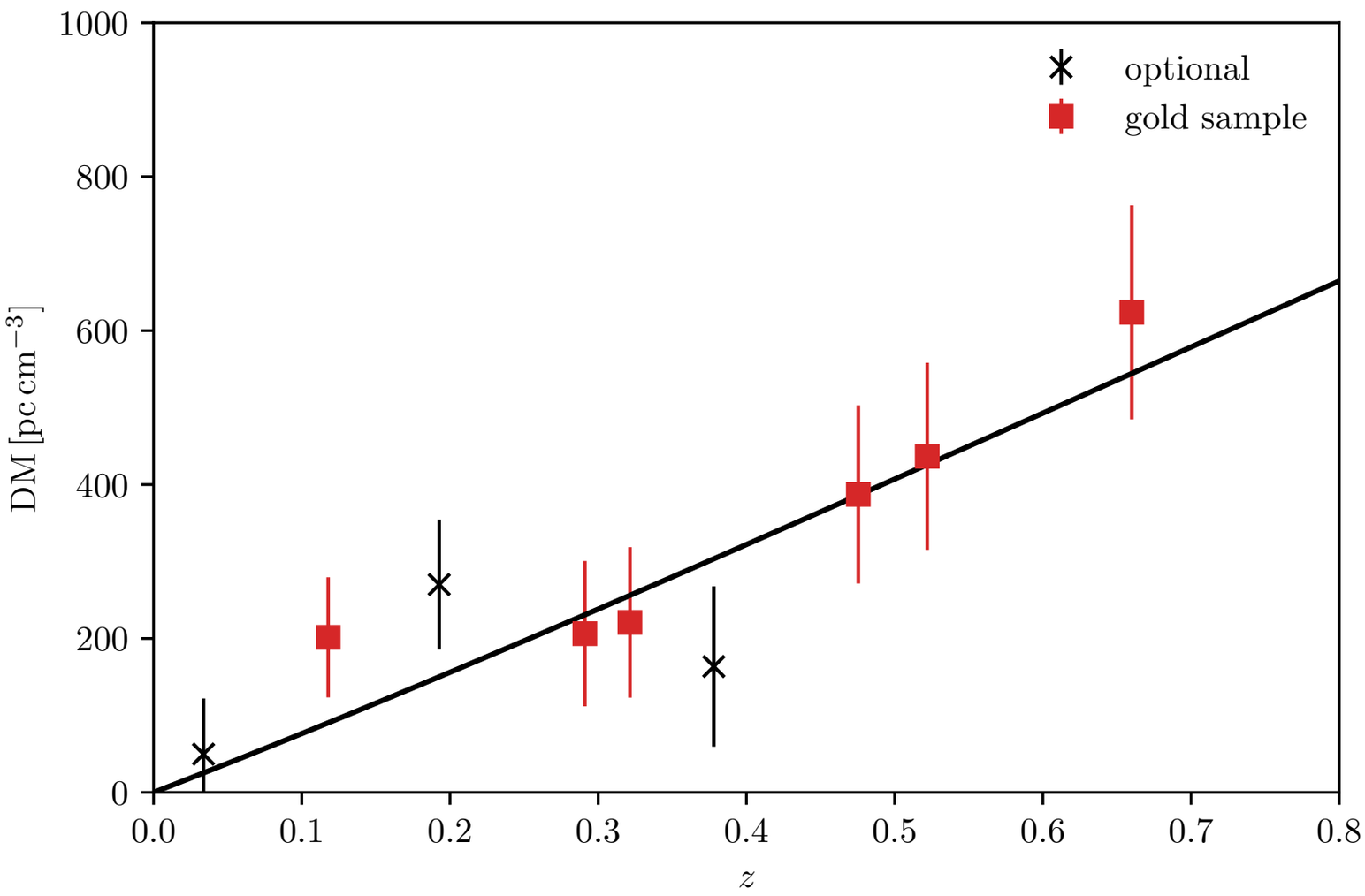
Host ID



VLT + ASKAP (Macquart et al 2020)

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

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

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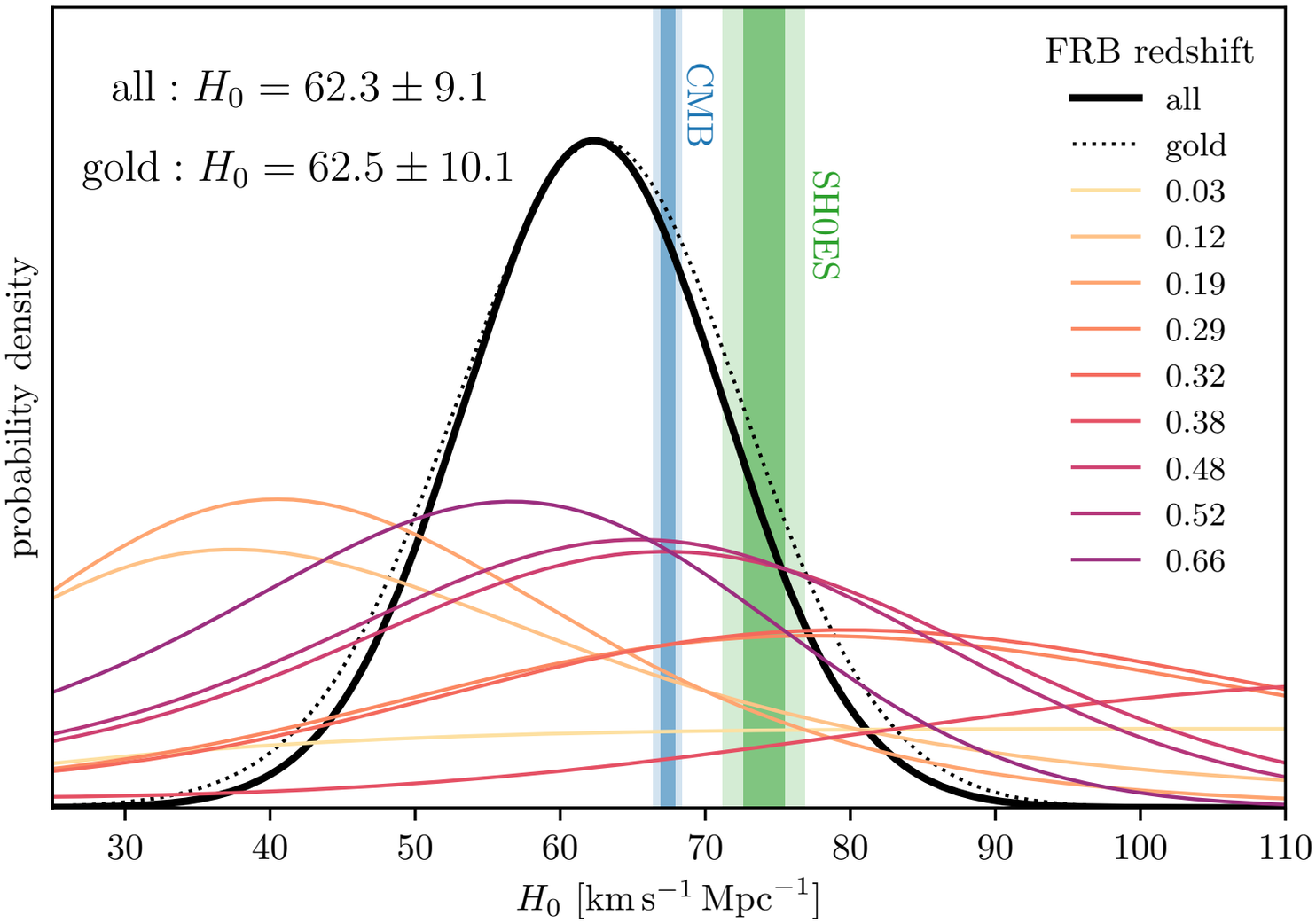
Hubble constant

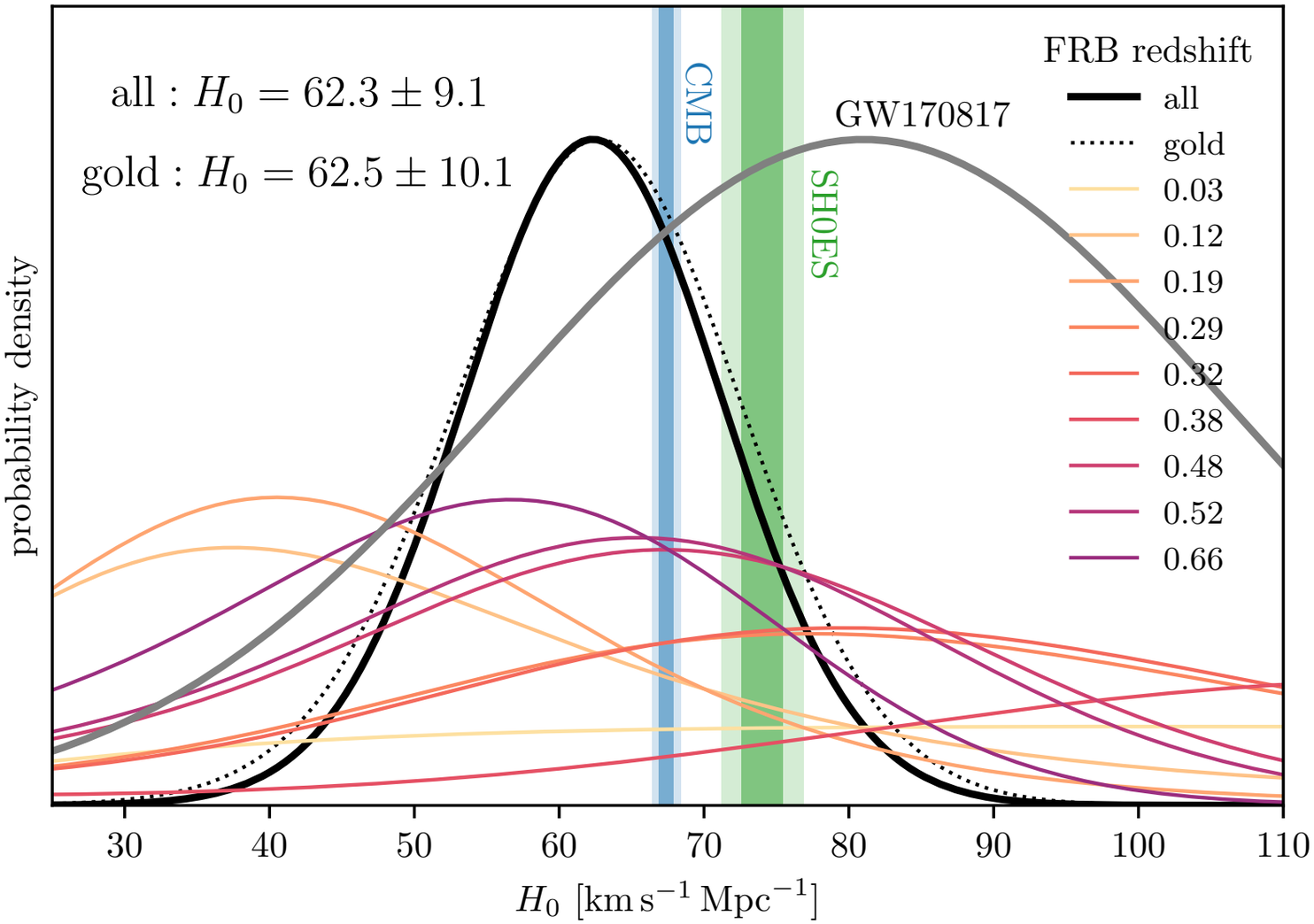


Events at large z most important

Uncertainty in host DM dominates error

SH, Reischke & Lilow arXiv 2104.04538

Hubble constant



Events at large z most important

Uncertainty in host DM dominates error

The Future

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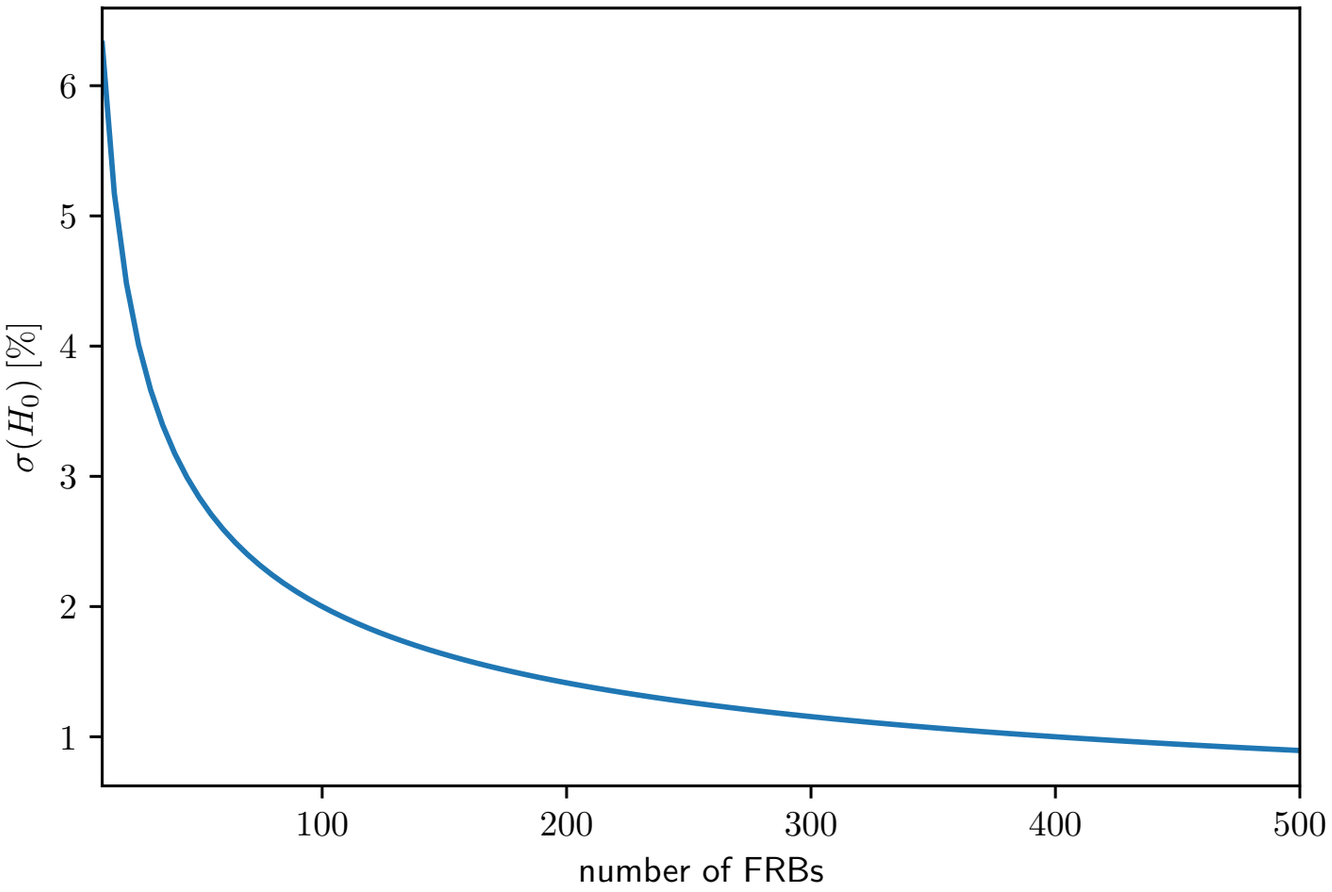
When can FRBs be competitive?



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

Dispersion measure

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LSS

Milky Way models
Can be checked with Pulsars
Quite accurate!

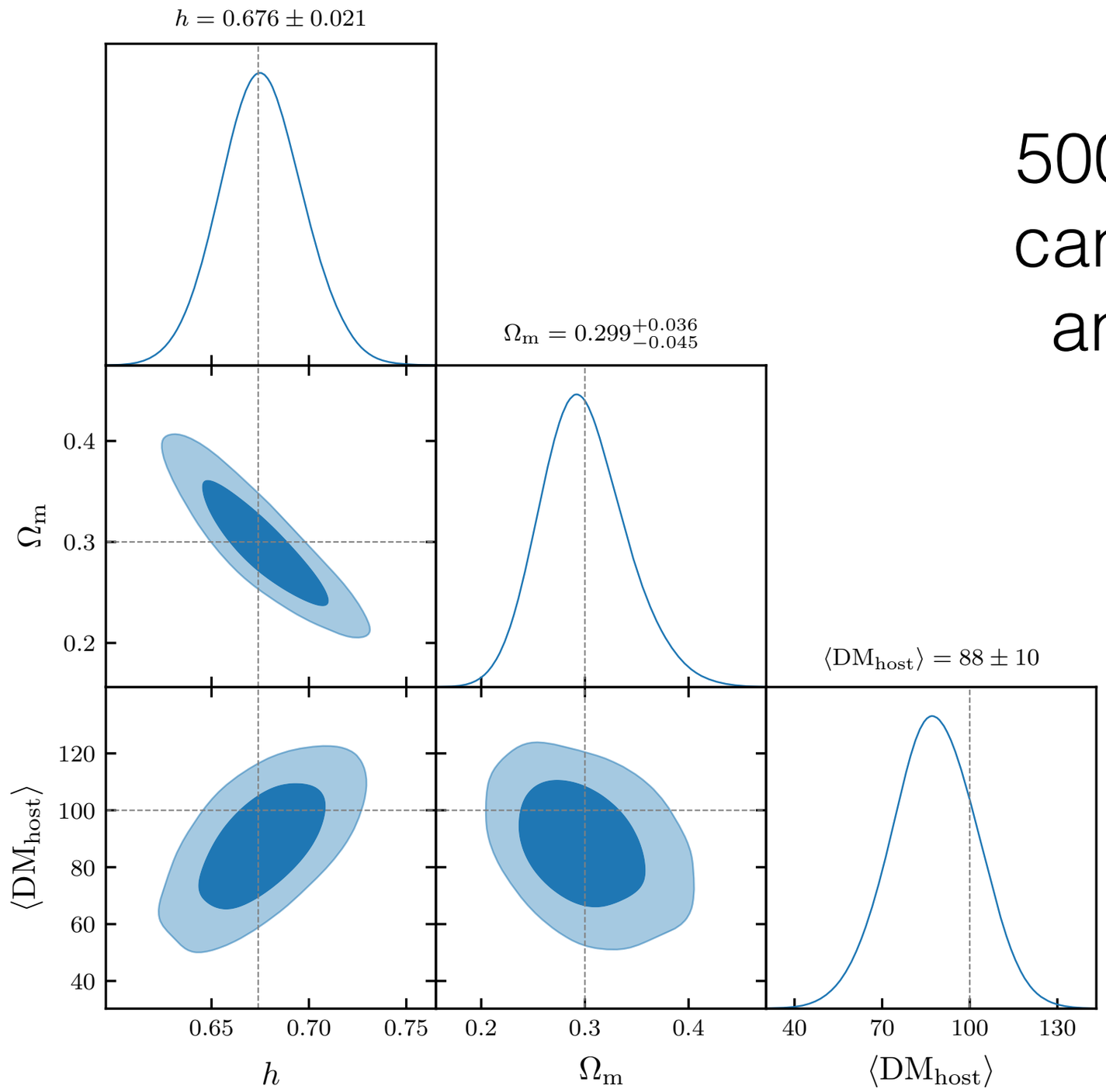
Host halo models
Depends on galaxy types?
Location of FRBs?

Redshift scaling:

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

Statistics can tell contributions apart

Forecast



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

Available soon!

SH, Reischke & Lilow arXiv 2104.04538

Standard Beacons?

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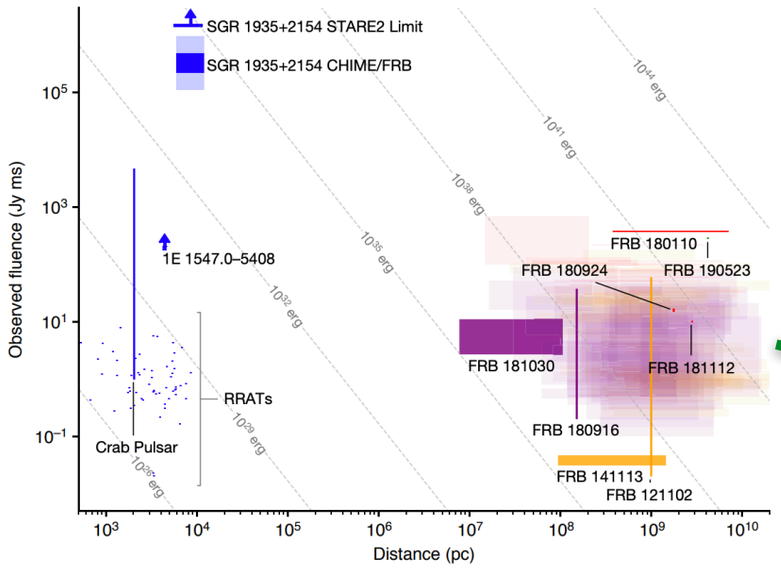

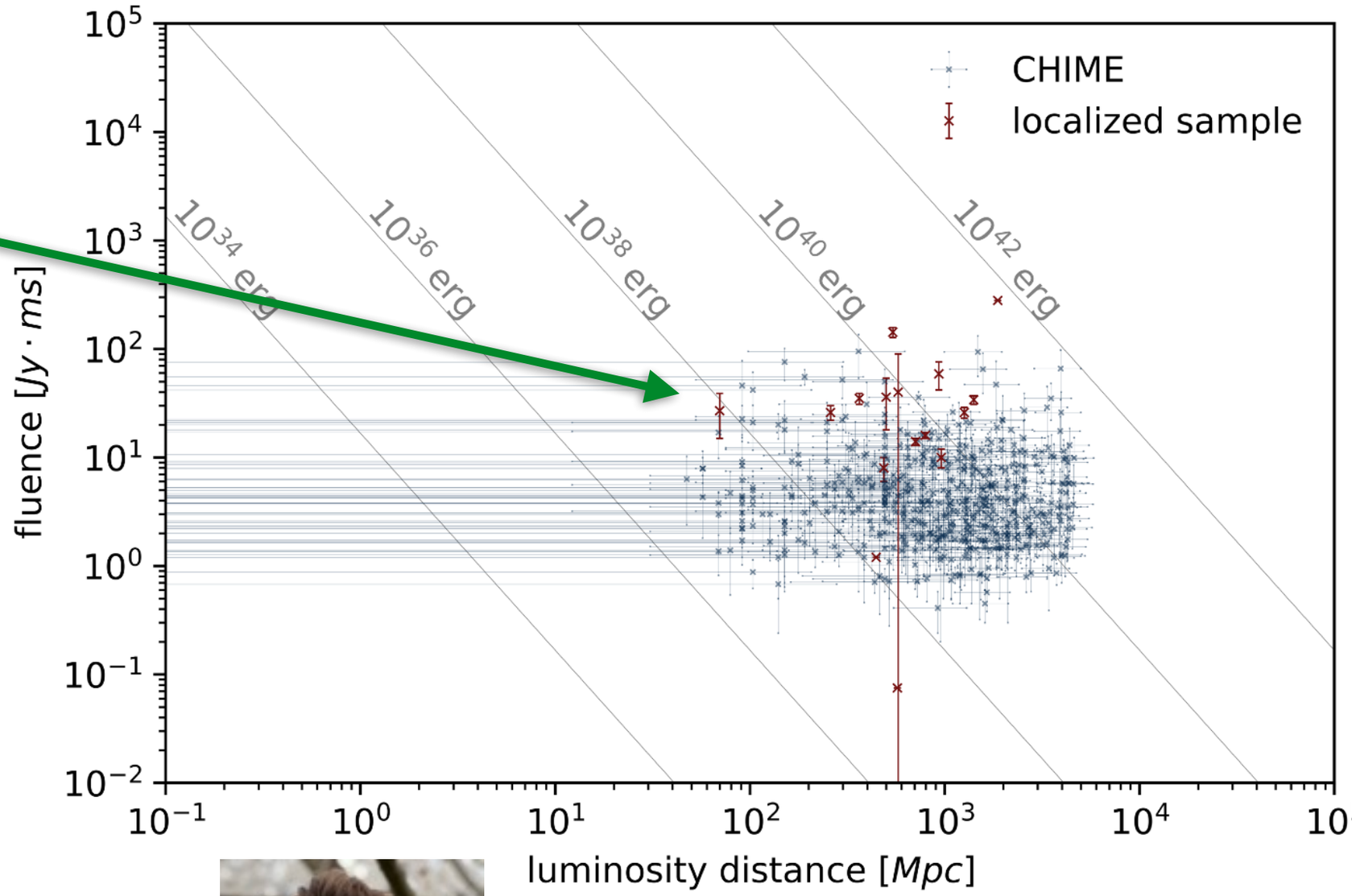

No clear spectral information, but distribution should have characteristic energy

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Steffen Hagstotz

Standard Beacons?

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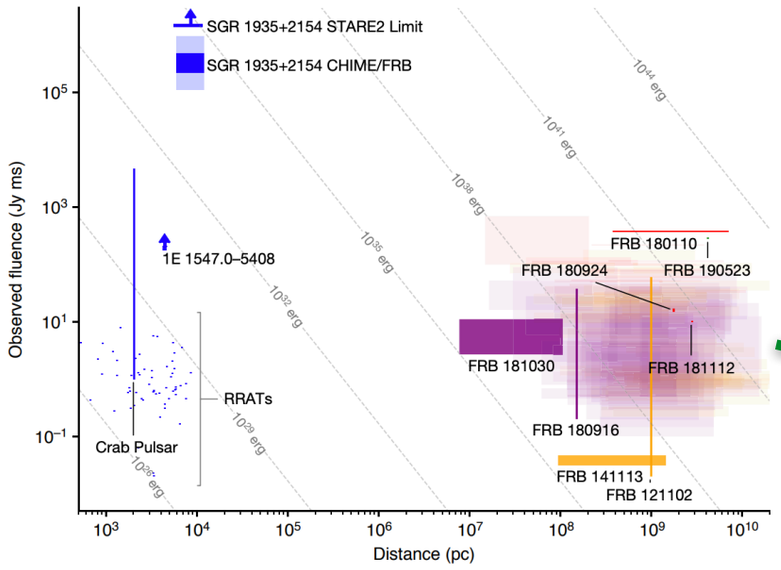

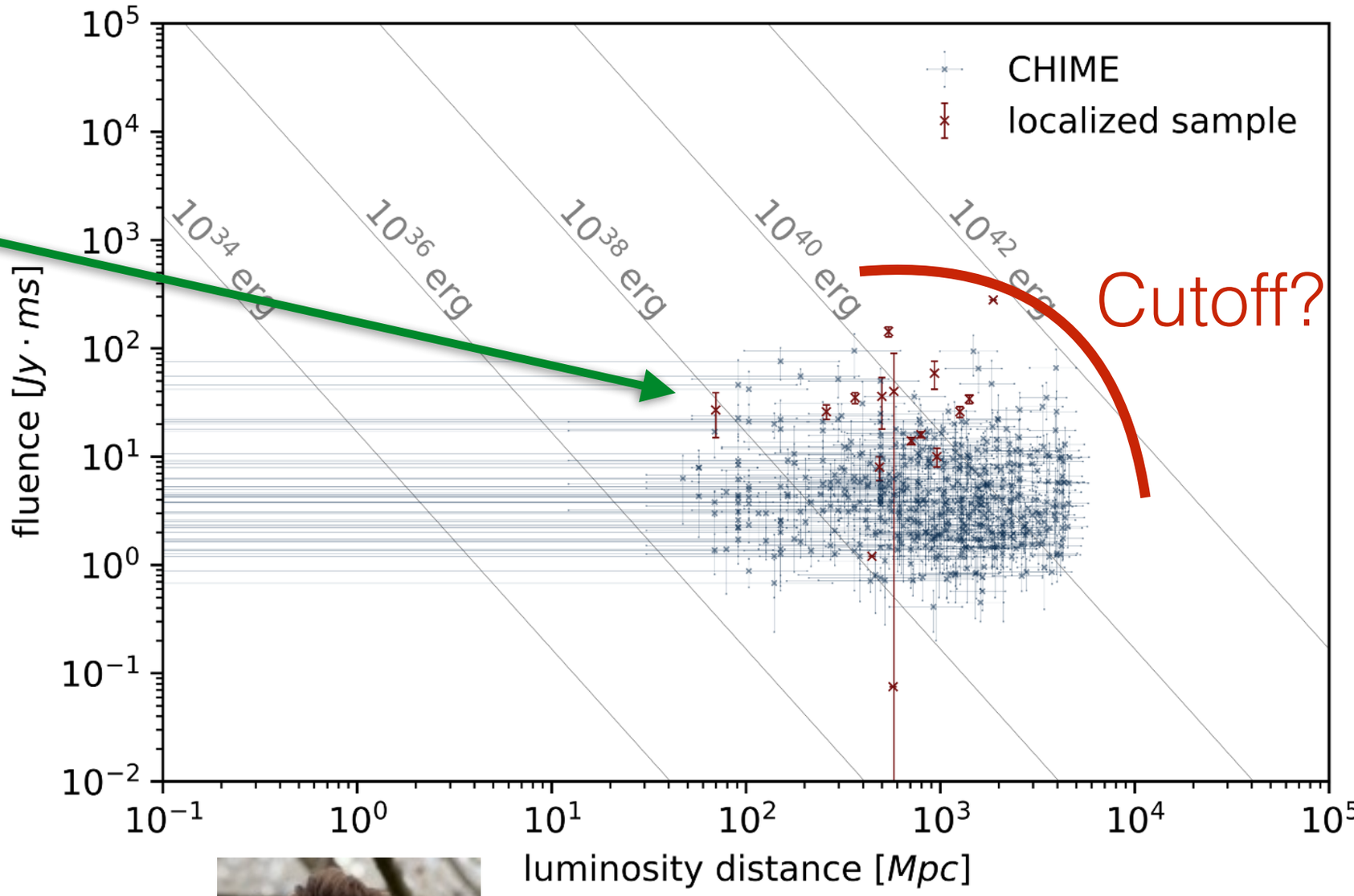

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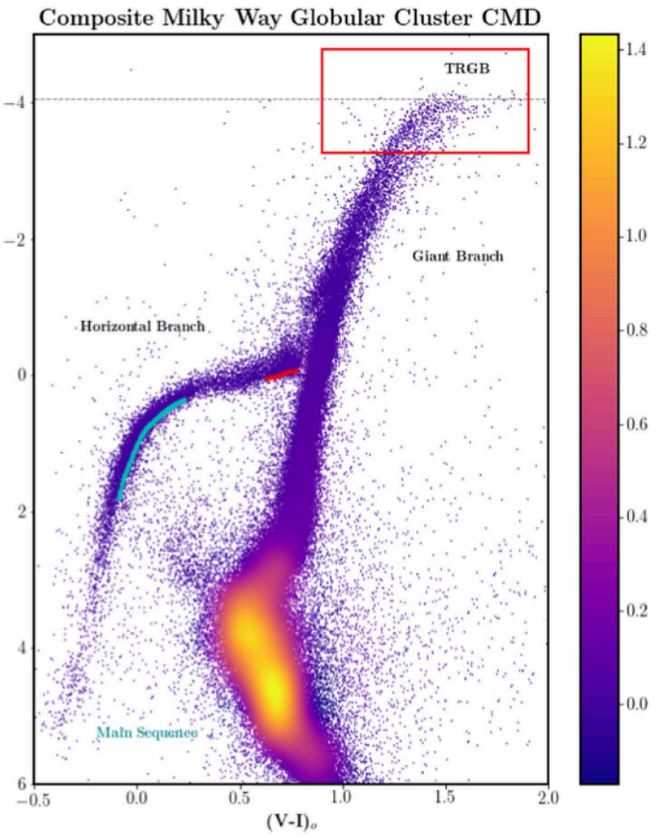
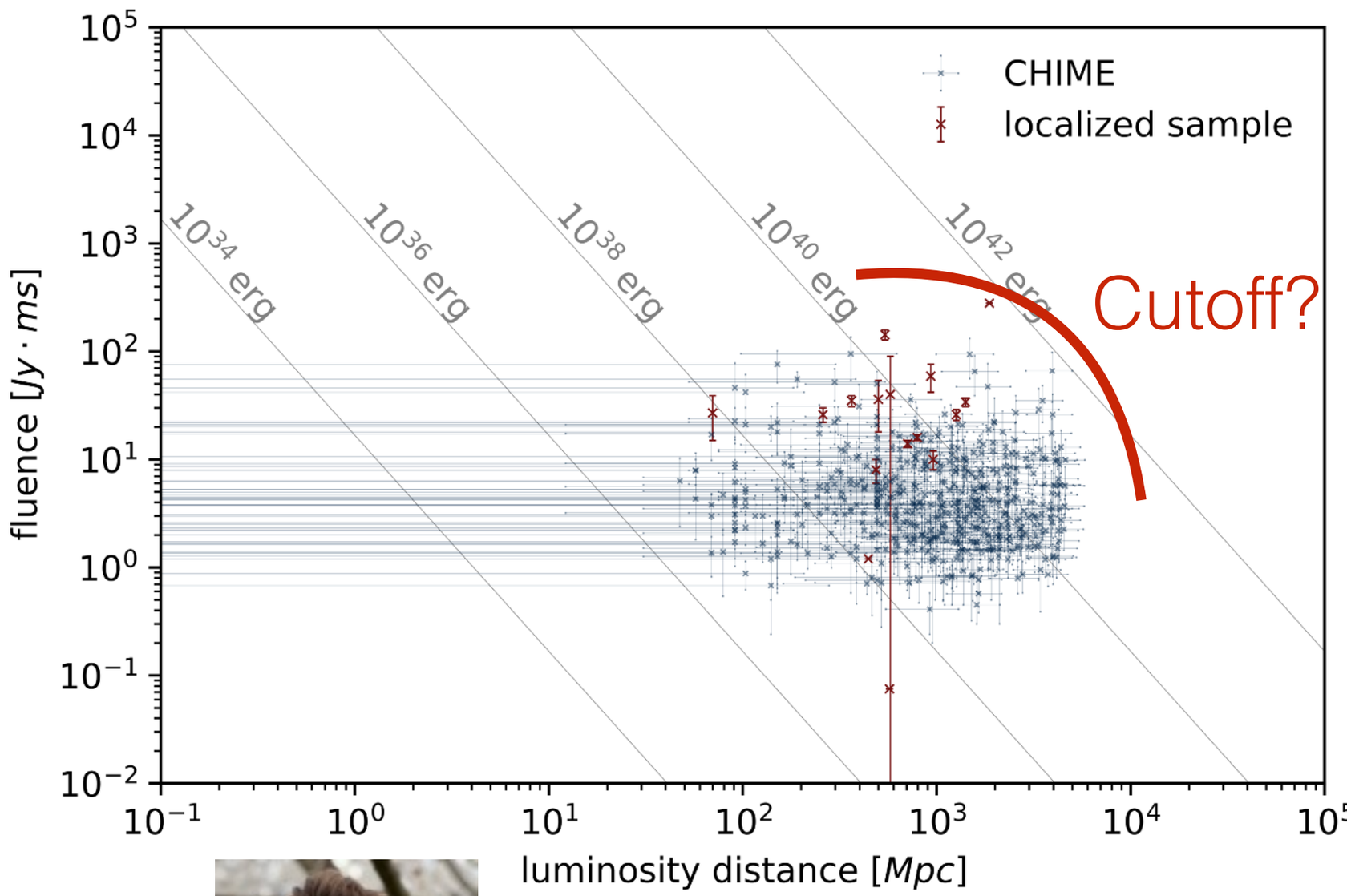


Freedman 2022



Tip of the FRB luminosity as distance proxy?

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Alexander Theis

FRB statistics

Redshifts in general not known: consider angular clustering

Correlate FRBs

$$C_\ell = \langle \delta_\ell^{\mathrm{FRB}} \, \delta_{\ell'}^{\mathrm{FRB}} \rangle$$

Sparse, noisy distances, shot-noise dominated

FRB statistics

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Correlate dispersion measure

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

FRB statistics

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signal >> noise

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

FRB statistics

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Super weak lensing*

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Correlate dispersion measure

Super weak lensing*

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

*(but still sparse)

signal >> noise

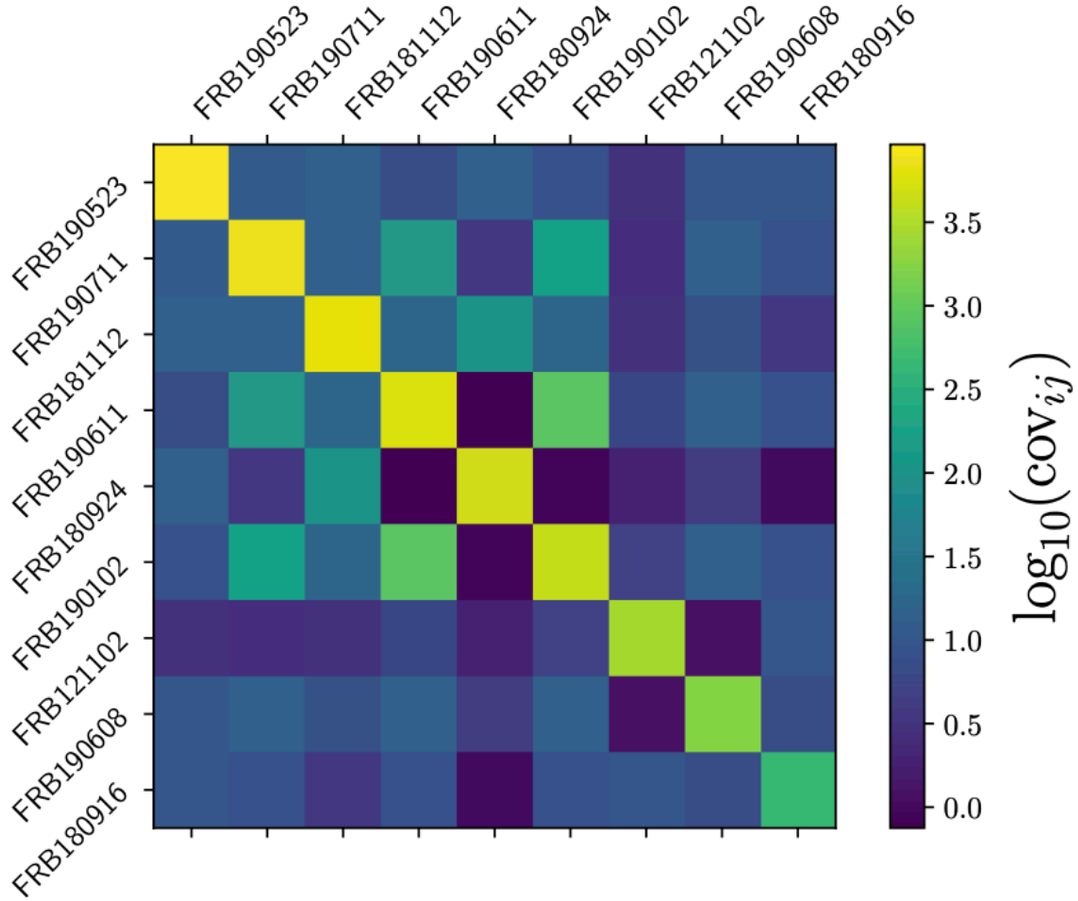
Because $\quad {\rm DM}_{\rm LSS}(z) \gg {\rm DM}_{\rm host}$

Correlated events

Nearby lines of sight
traverse similar structures
→ correlated DM

Correlated events

Nearby lines of sight traverse similar structures → correlated DM



Reischke & Hagstotz, 2301.03527

Correlated events

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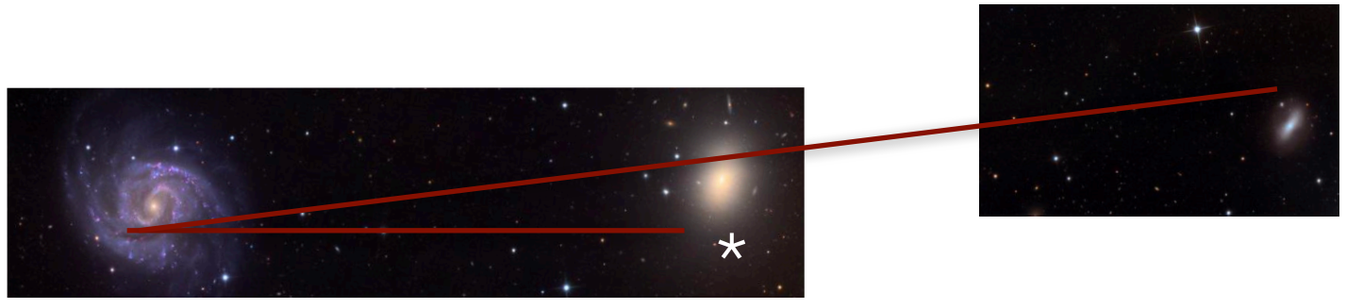
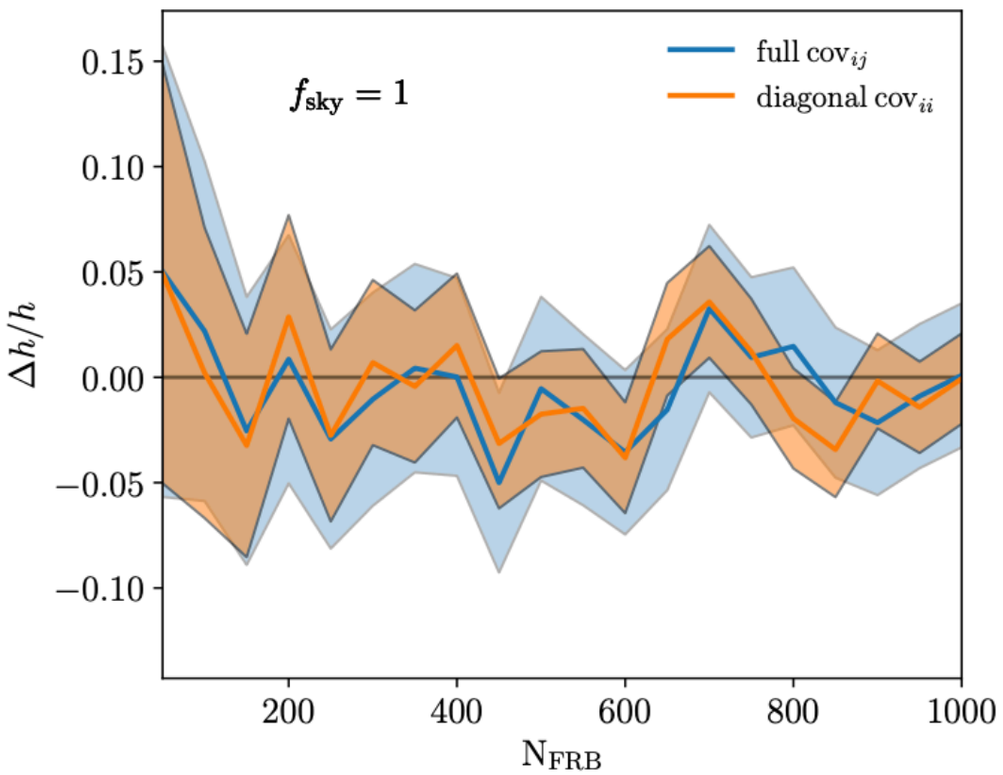
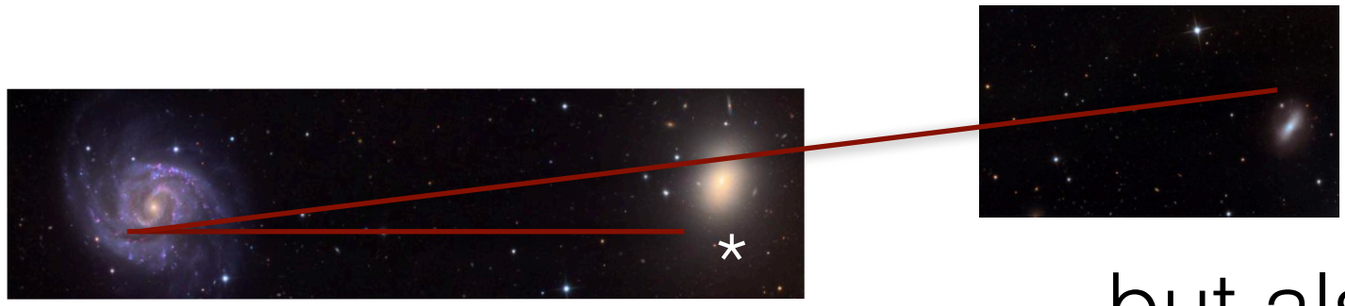




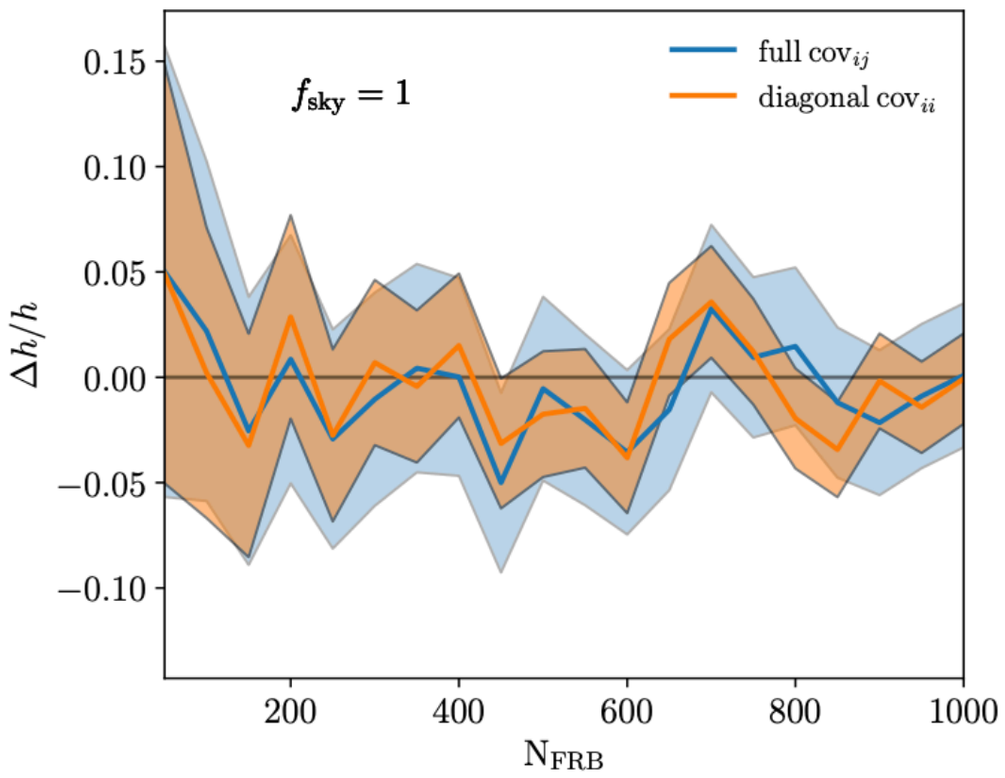
Correlation becomes important for few 100s FRBs/sky..

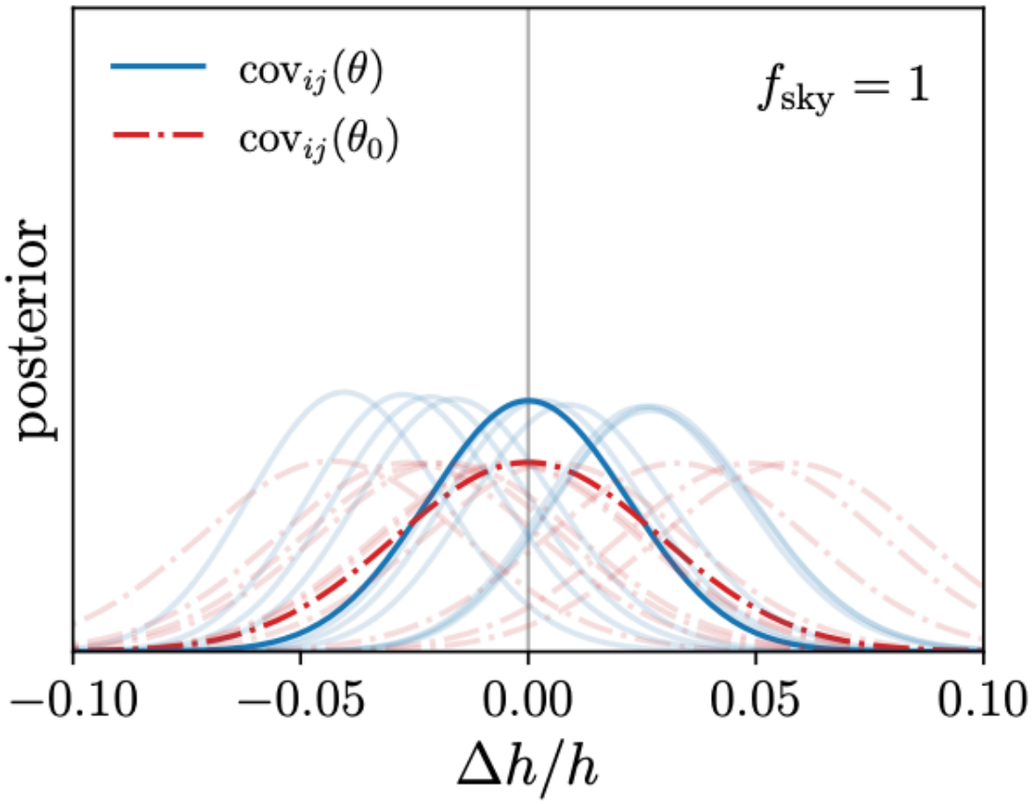
Reischke & Hagstotz, 2301.03527

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

FRB statistics

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Correlate dispersion measure

$$C_\ell = \langle \mathrm{DM}_\ell \, \mathrm{DM}_{\ell'} \rangle$$

Great for signals on large scales!

- Primordial non-Gaussianity

  Reischke, SH, Lilow arXiv 2007.04054

- Equivalence principle tests with Shapiro delay

  Reischke, SH, Lilow arXiv 2102.11554

  Reischke & Hagstotz arXiv 2302.10072

- <your idea goes here>

Baryonic Feedback

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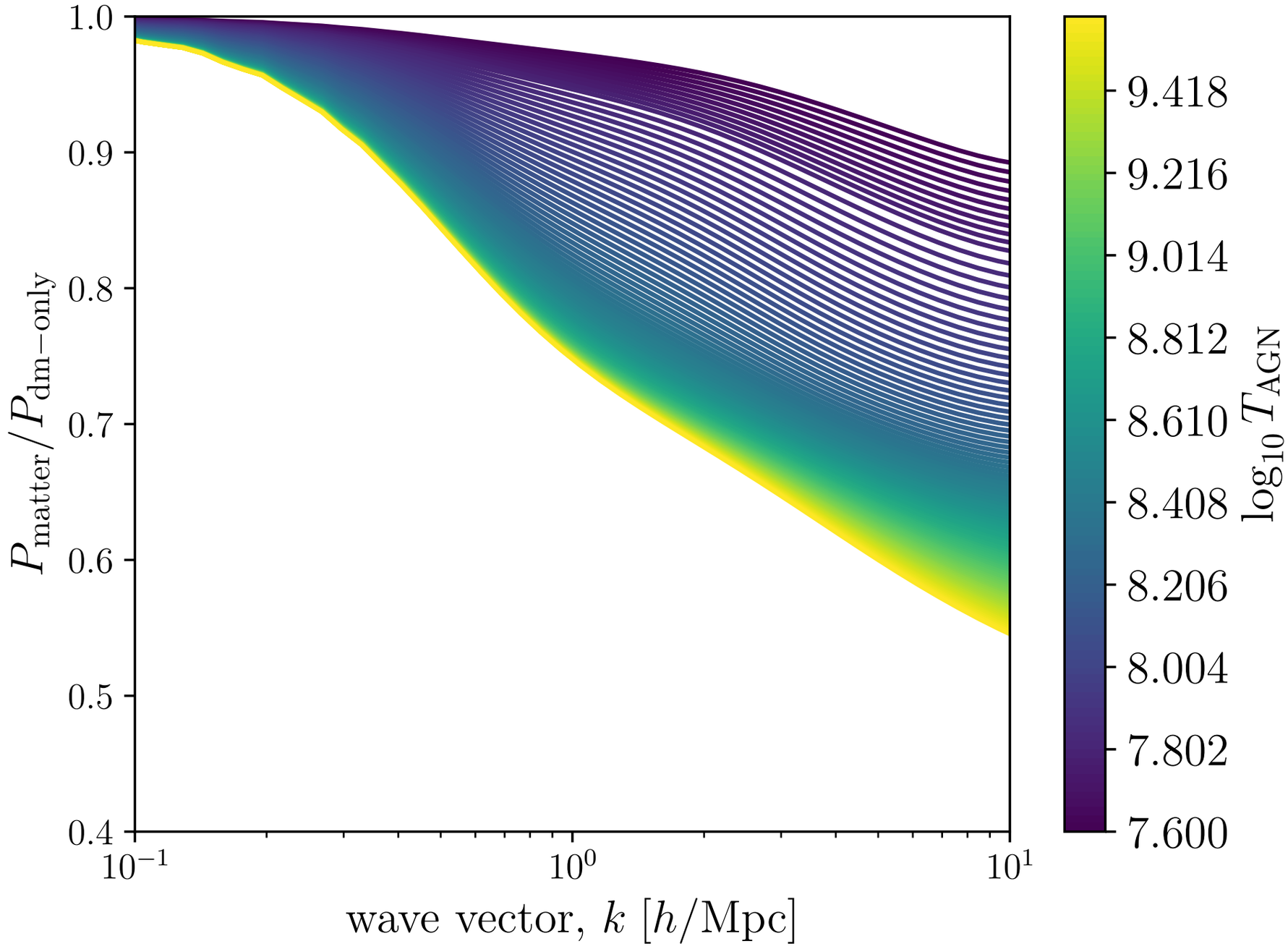

Steffen Hagstotz

Baryonic Feedback

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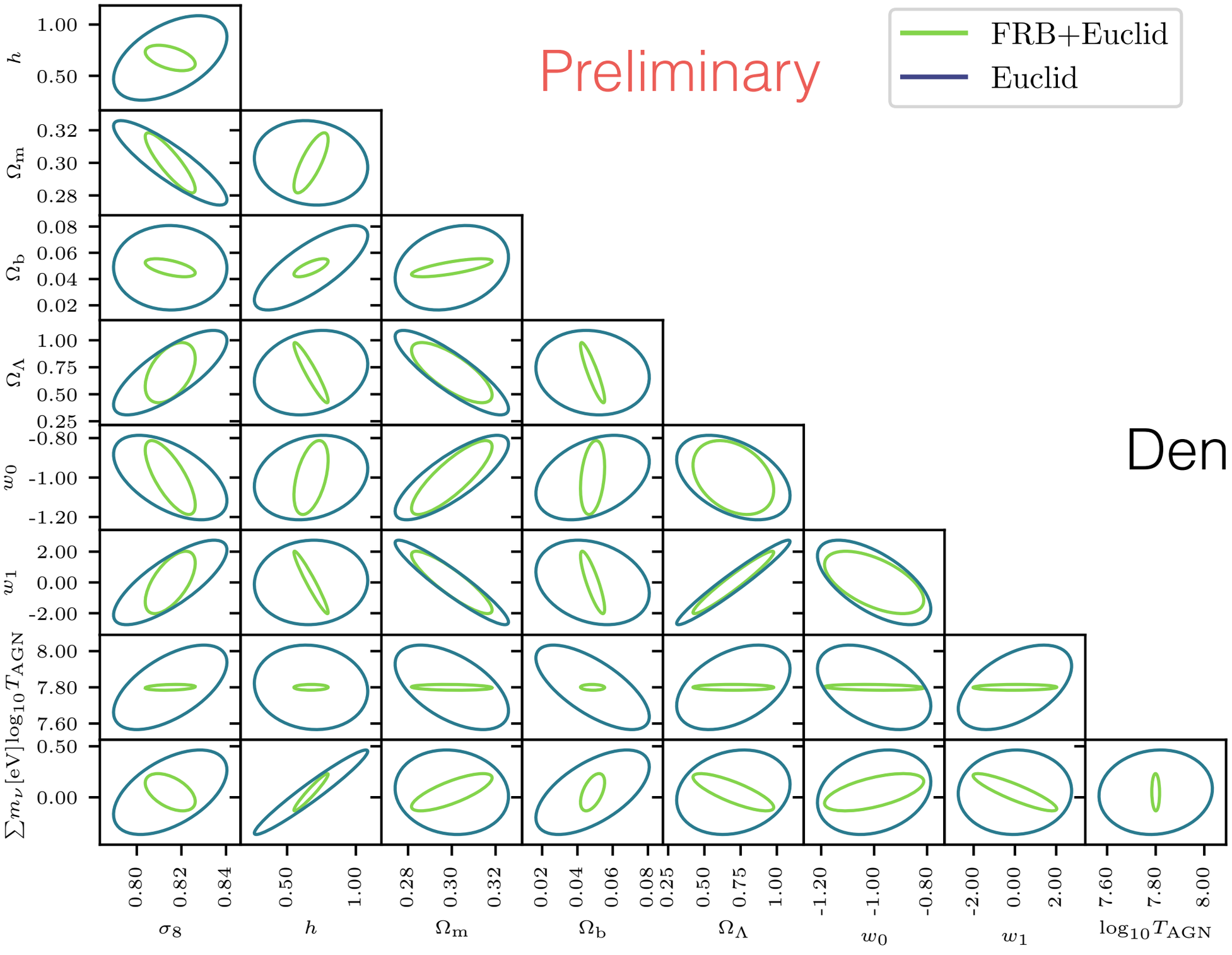
Preliminary



Dennis Neumann

Baryonic Feedback

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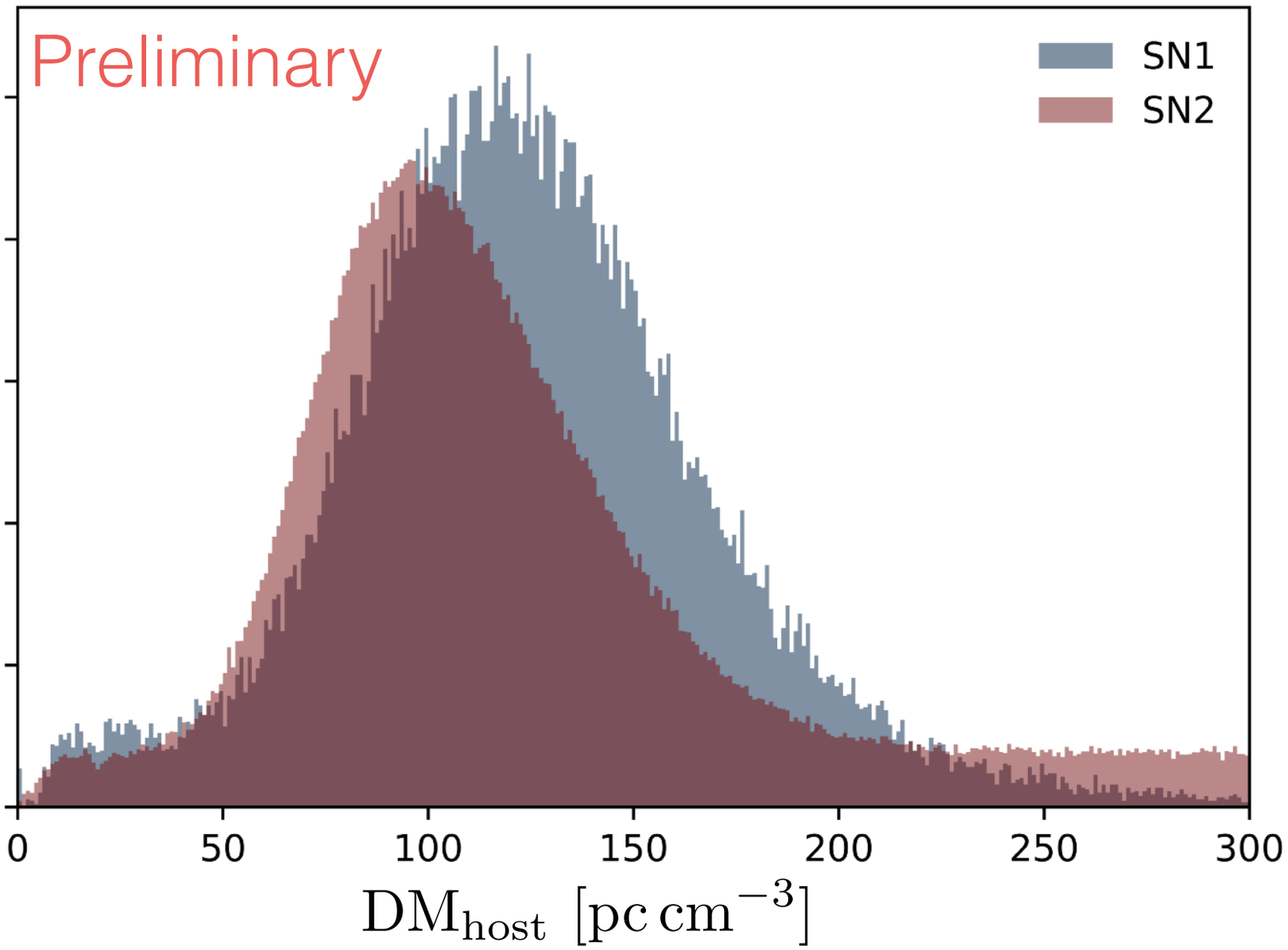

Measure $\mathrm{DM_{host}}$ to constrain feedback?

Alexander Theis

Steffen Hagstotz

Summary

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- Mechanism of the bursts unknown

- FRBs can provide independent* measurement of the Hubble constant $H_0 = 62.3 \pm 9.1$ km/s/Mpc

- Currently limited by statistics, many more events are coming from CHIME/ASKAP/HIRAX

- FRBs can do many more things for cosmology!

  Primordial non-Gaussianity

  Equivalence principle

  Calibrating baryonic effects