PUMA: The Next Generation Intensity Mapping Experiment

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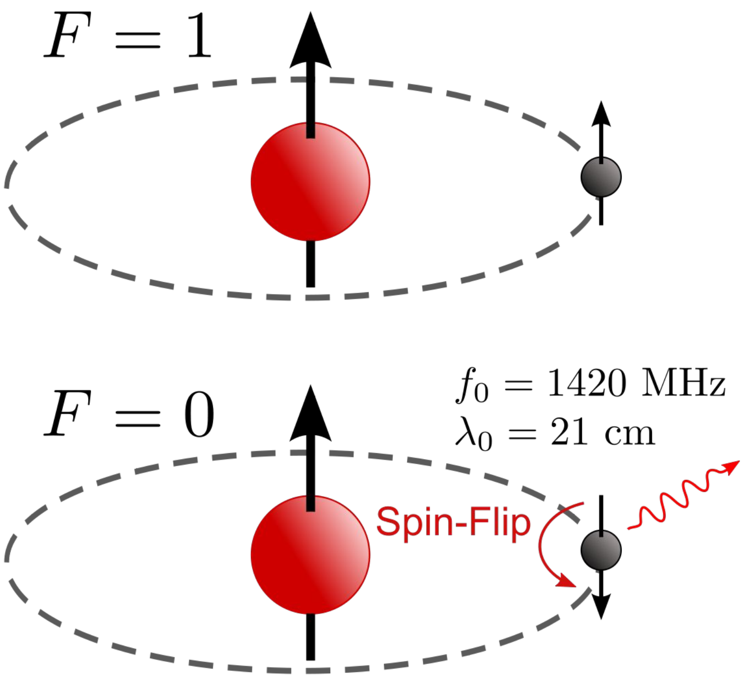
PUMA packed ultra-wideband mapping array

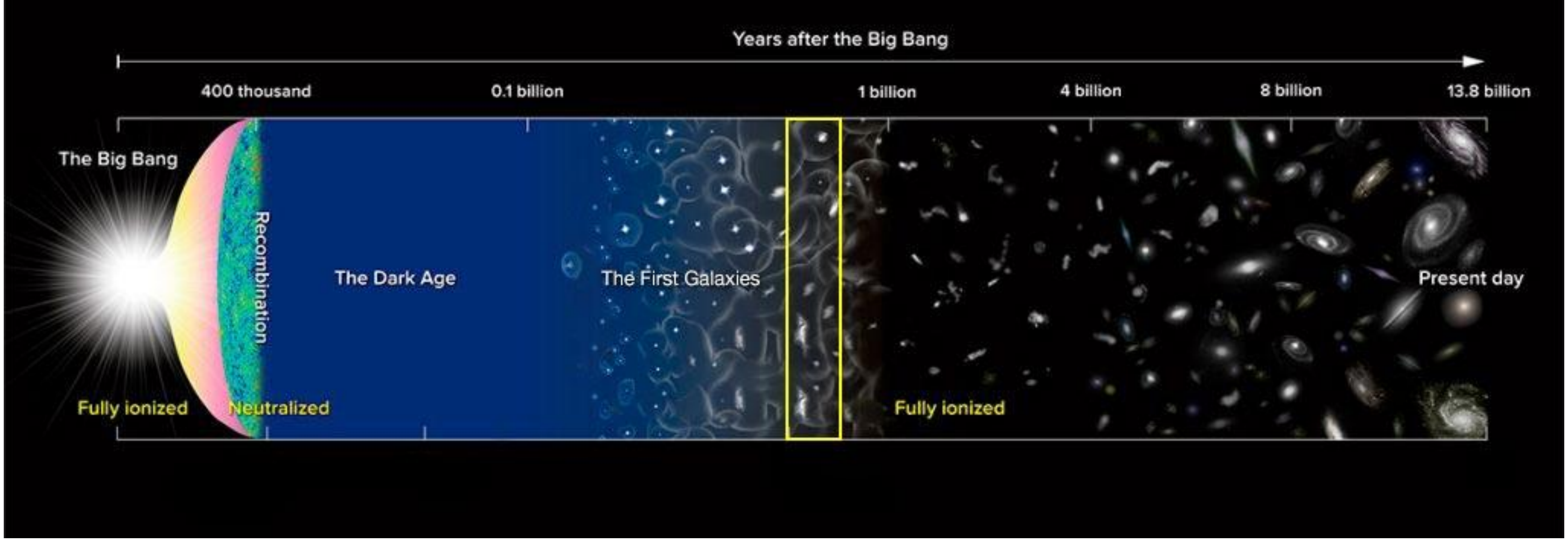
PUMA in one slide

- Transformational radio telescope
- Characterized by having thousands of dishes closed together (**Packed**): static, transit array
- Employing latest in RF technology advances driven by telecom industry (**Ultra wide-band**) radio array
- Geared towards intensity **Mapping**
- Harnesses the digital signal processing at all levels, hence an interferometer (**Array**)
- The point of this talk:
  - This is the future
  - You should think about it!

21cm emission

- Hyperfine transition in neutral hydrogen at ν=1420MHz, λ=21.1cm;
- This is the **only** transition around -- if you see a line at 710MHz, it is a z=1 galaxy;
- (not true in optical)
- Universe is mostly hydrogen (75%), but at low redshift we are sensitive to pockets of neutral hydrogen in galaxies;
- **21cm surveys are galaxy surveys in radio frequencies**





Dark Ages	Epoch of Reionization	Low redshift
$20 \lesssim z \lesssim 150$	$6 \lesssim z \lesssim 20$	$z \lesssim 6$

Dark Ages ($20 \lesssim z \lesssim 150$)

- Pristine primordial density field
- Still linear universe
- Like CMB in 3D: amazing science
- Observationally extremelly difficult
- 30 years from now

Epoch of Reionization ($6 \lesssim z \lesssim 20$)

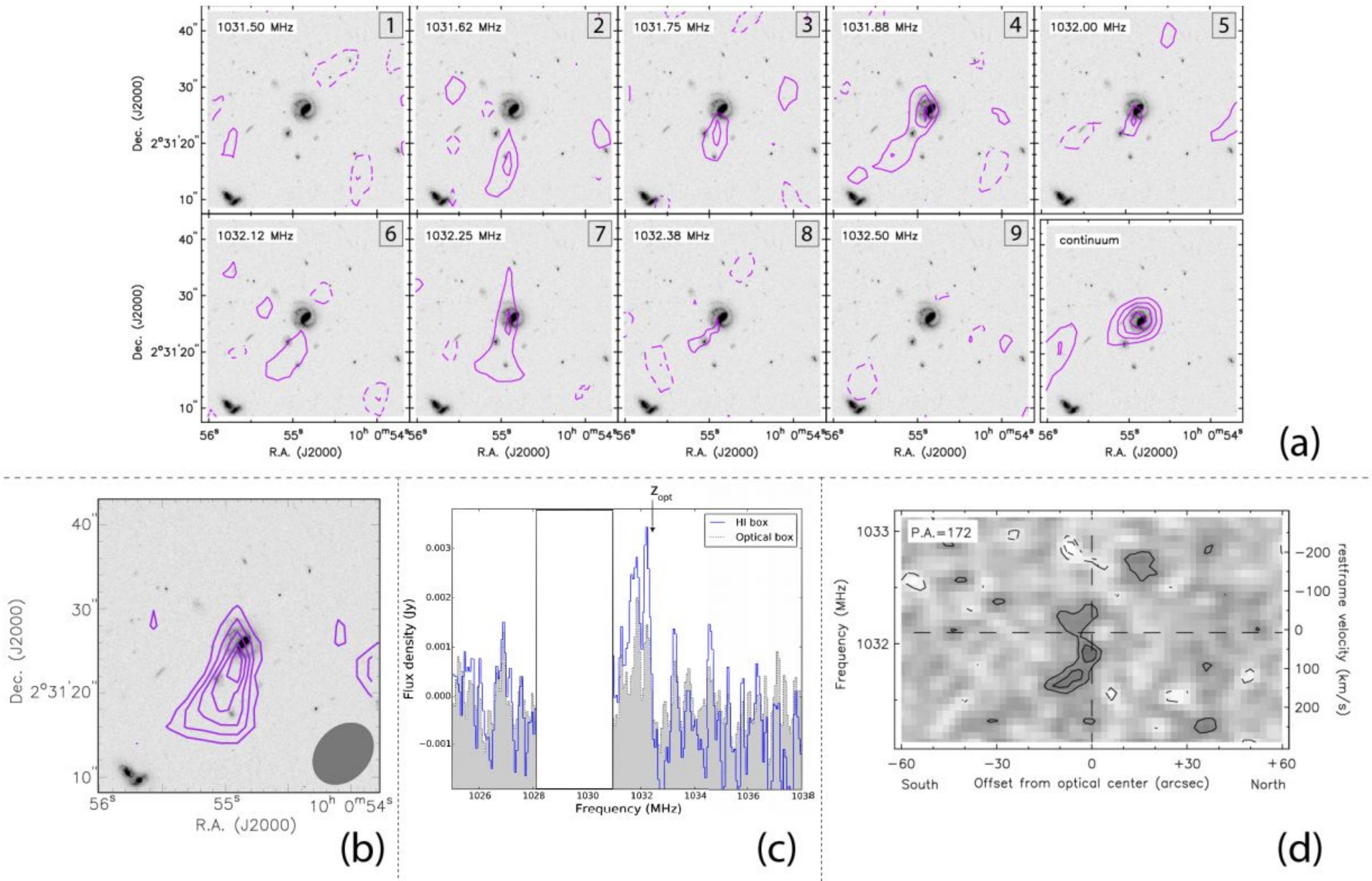
- First stars and galaxies are reionizing universe
- Large bubbles of ionized gas among neutral medium
- Signal driven by astrophysics
- Non-DOE science

Low redshift ($z \lesssim 6$)

- Universe is reionized
- pockets of neutral hydrogen in galaxies
- Very similar science to standard galaxy surveys
- We don’t aim to go after individual galaxies

Galaxies in 21cm

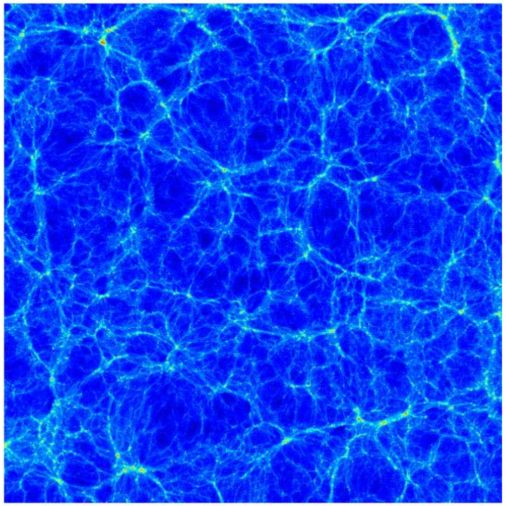
This is a weak transition, 21-cm detection redshift record is z=0.376 using 178 hours of VLA data (Fernández et al, 2016)

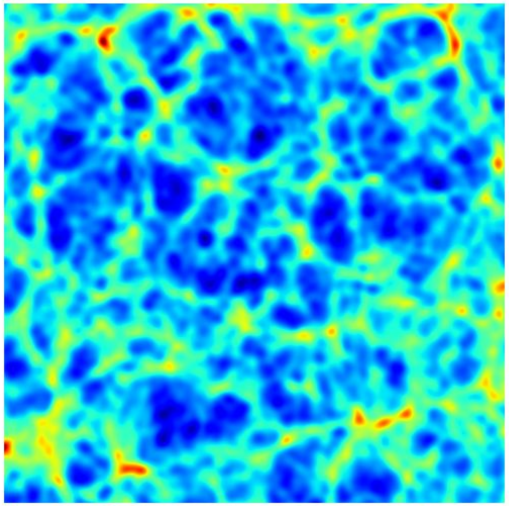


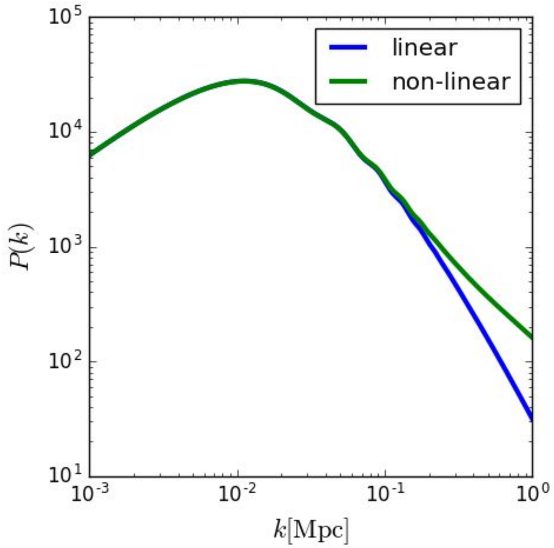
21cm Intensity mapping

The main idea is to give up on resolving individual galaxies:

- For scales much bigger than individual galaxies, the overall signal will still trace the underlying number density of galaxies
- Put SNR where you really need it -- linear large scale modes
- Sounds easy, no?



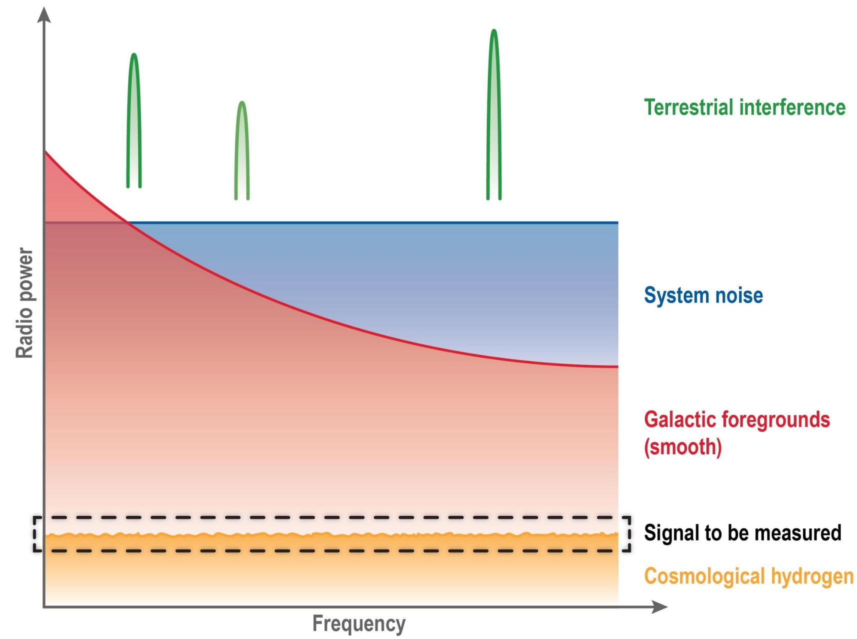




Easy peasy, build a radio telescope

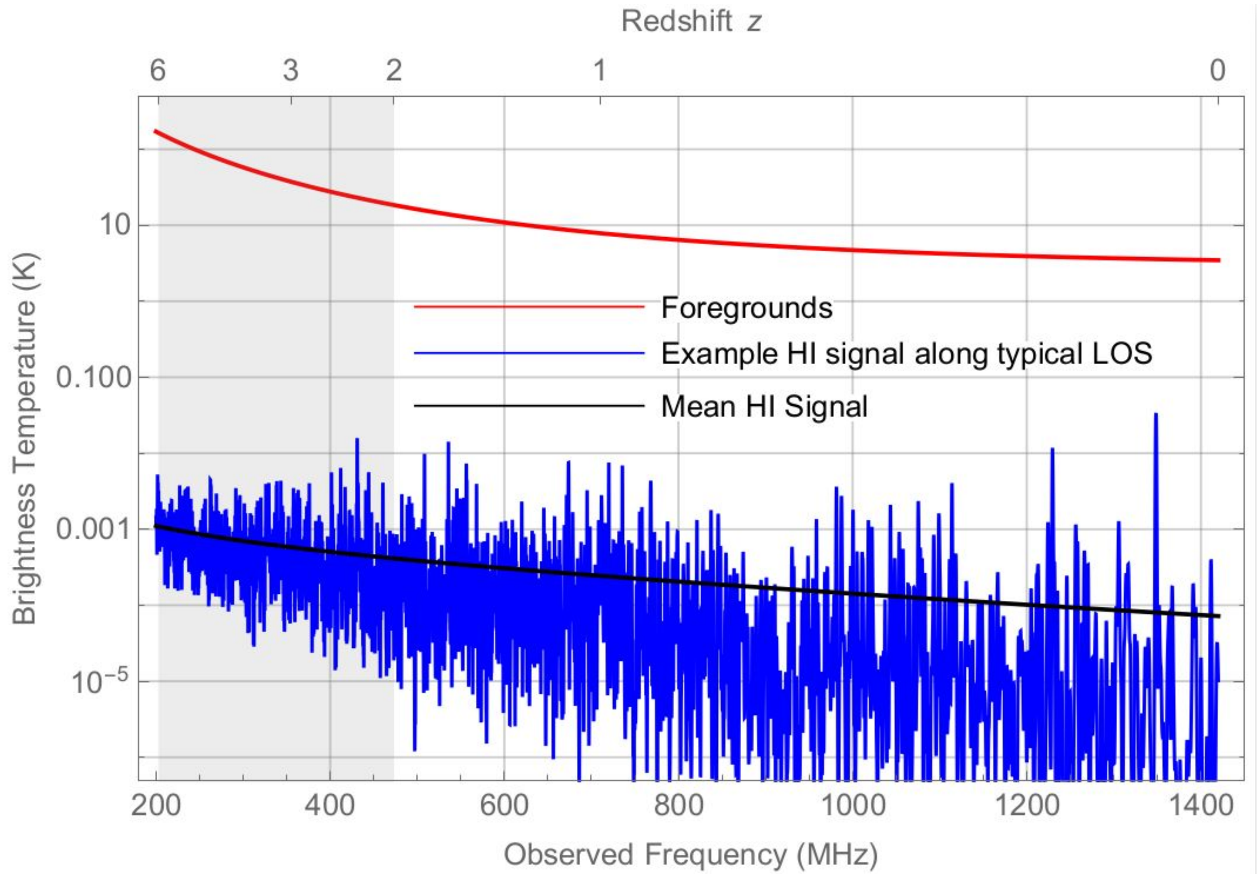
- There foregrounds that are orders of magnitude brighter than the signal
- Luckily they are spectrally smooth
- Need telescope with exquisite systematics control

Can this ever work?



- *Optimist*: “In CMB we regularly observe microK fluctuations on top of 3K monopole. We regularly observe polarization signals that 1000 times weaker than temperature signal.”
- *Pessimist*: “Analogy with CMB is fallacious: we are differencing in frequency not space.”
- *Realist*: “Doable, but requirest care.”

But 21cm is not the only radio signal...

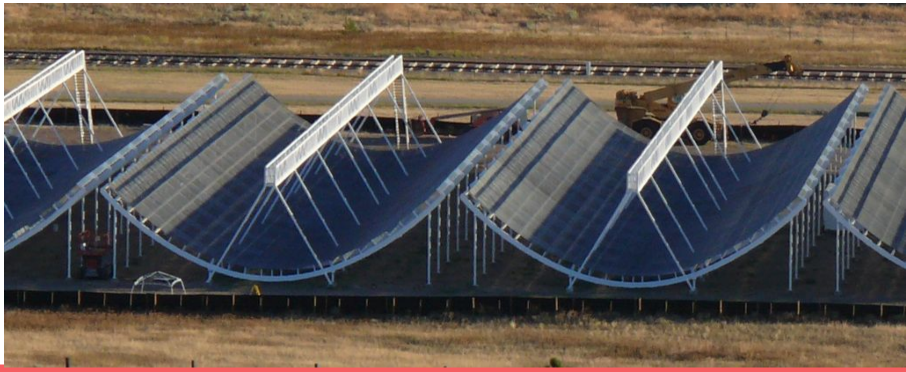


- Signal is subdominant, but the only non-smooth component.
- Of course, instrument can have non-smooth, time-varying response too!

What kind of instrument do you need?

- Traditional radio telescopes are interferometers
- Dish size determines field of view
- Longest baseline determines resolution
- For intensity mapping one typically wants:
    - compact array
    - favor number of baselines over ability to track
- **Traditional radio telescopes do not cut it**
- **(SKA does not cut it)**

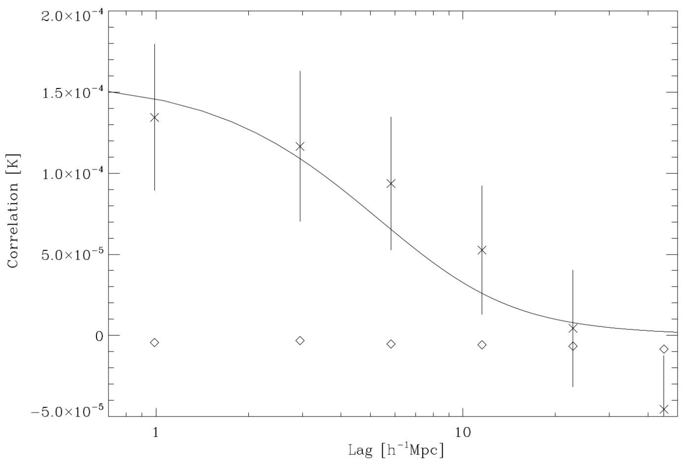
VLA



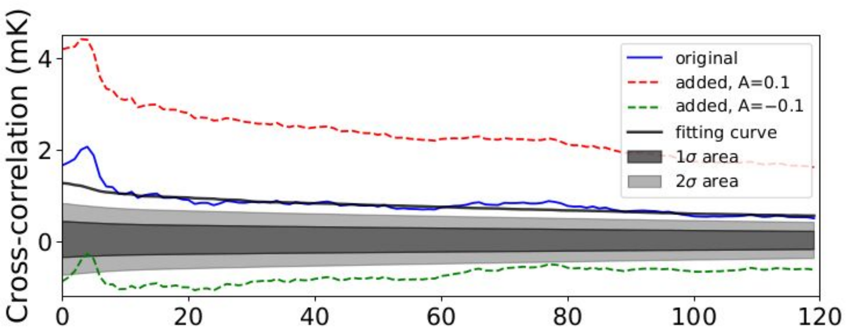
CHIME

Curren Status of the field

- The intensity mapping signal in 21cm has been detected in cross-correlation using single-dish experiments.
- Pioneering work Tzu-Ching Chiang in late 2000s
- Similar work has been repeated in many iterations with various instruments
- Still no published results in either:
  - Auto-correlation
  - Using interferometers



Tzu-Ching Chiang et al, 2010
(GBT x Deep-2)



Lee et al, 2020
(Parkes x Wiggle-Z)

Current status of experiment worldwide

Outside DOE:

- CHIME – Canadian experiment, starting first light with full array – should detect BAO z=0.75-2
- HIRAX – South African experiment, seed funded and being prototyped
- FIRST: 500m single dish Chinese experiment
- BINGO, partly funded Brazillian experiment

Inside DOE:

- Tianlai involvement at Fermilab
- BMX testbed at BNL

All these experiments will, in the next 5 years, demonstrate the promise of the technique.

CHIME telescope in Canada

BMX testbed at BNL

Step 1: WhitePaper on why this is a good idea

- Published in Fall 2018, https://arxiv.org/abs/1810.09572
- Made some basic calculations and forecasts about the promises of the project and potential difficulties

Cosmic Visions Dark Energy:
Inflation and Early Dark Energy with a Stage II
Hydrogen Intensity Mapping Experiment
(Cosmic Visions 21 cm Collaboration)

Réza Ansari,[1] Evan J. Arena,[2,3] Kevin Bandura,[4,5] Philip Bull,[6,7] Emanuele Castorina,[8] Tzu-Ching Chang,[9,10] Shi-Fan Chen,[8] Liam Connor,[11] Simon Foreman,[12] Josef Frisch,[13] Daniel Green,[14] Matthew C. Johnson,[15,16] Dionysios Karagiannis,[17] Adrian Liu,[6,7,18] Kiyoshi W. Masui,[19] P. Daniel Meerburg,[20,21,22,23,24] Moritz Münchmeyer,[16] Laura B. Newburgh,[25] Andrej Obuljen,[26,27,28] Paul O'Connor,[2] Hamsa Padmanabhan,[12] J. Richard Shaw,[29] Chris Sheehy,[2] Anže Slosar,[2,*] Kendrick Smith,[16] Paul Stankus,[30] Albert Stebbins,[31] Peter Timbie,[32] Francisco Villaescusa-Navarro,[33] Benjamin Wallisch,[14,34] and Martin White[6]

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[2] *Brookhaven National Laboratory, Upton, NY 11973, USA*

Step 2: Decadal Survey submission

Packed Ultra-wideband Mapping Array (PUMA):
A Radio Telescope for Cosmology and Transients

Thematic Areas: Ground Based Project

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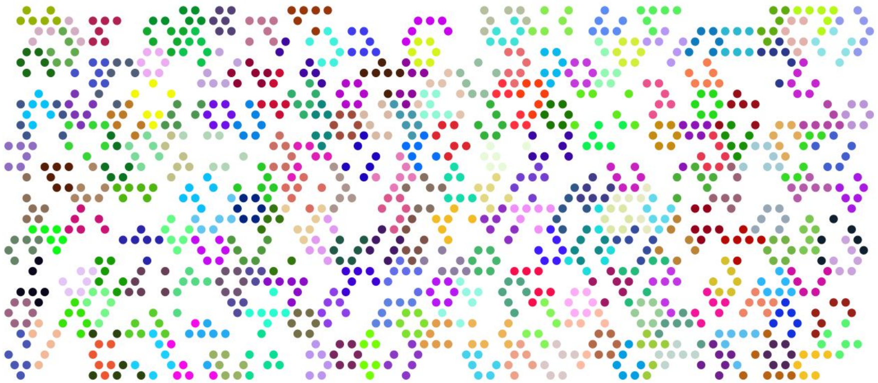
- July 2019
- Now with a name and a logo
- Full parametric costing
- Refined concept with Petite and Full arrays
- More realistic forecasts

Step 3: Decadal Request for information

Packed Ultra-wideband Mapping Array (PUMA*):
A Radio Telescope for Cosmology and Transients

Emanuele Castorina[1,2], Simon Foreman[3], Adrian Liu[4], Kiyoshi W. Masui[5], P. Daniel Meerburg[6], Laura B. Newburgh[7], Paul O'Connor[8], Andrej Obuljen[9], Hamsa Padmanabhan[10], J. Richard Shaw[11], Anže Slosar[8], Paul Stankus[8], Peter T. Timbie[12], Benjamin Wallisch[13,14], Martin White[2,15,16]

RFI2: Submitted for consideration by the Astro2020 Decadal Survey Program Panel Panel on Radio, Millimeter, and Submillimeter Observations from the Ground (RMS)



Distribution of elements in PUMA array showing a subset of 1296 elements. Elements are distributed on hexagonal lattice with 50% occupancy rate. Clusters of 6 elements that could share the same base station with synchronized clock and a channelizer are painted in the same color.

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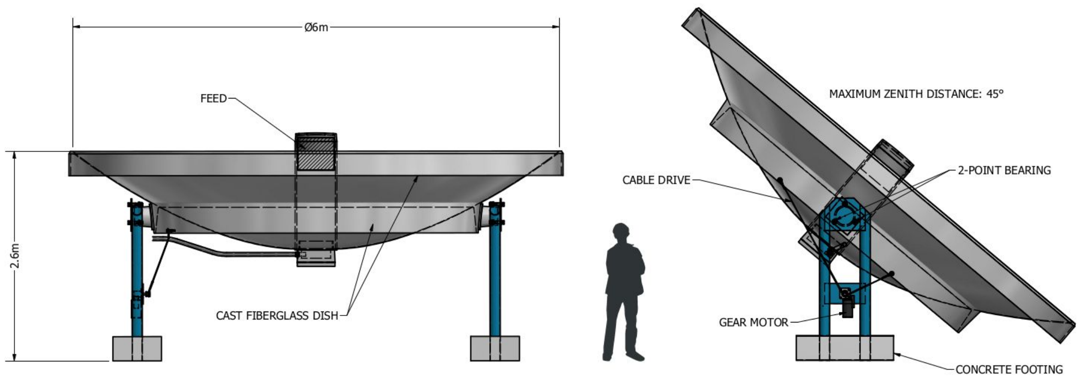
- Decadal Committee sent us a set of questions
- We responded in a third document (without page limit), Dec 2019
- Followed up by zoom telecon with the committee
- Wrt to the APC submission, it forced us to think the R&D phase through
- Petite and Full array became PUMA-5K and PUMA-32K
- A much better thought out R&D plan:
  - Lab work
  - Computer sims
  - PUMA prototypes: PUPs



Main take-home messages

Science:

- Go after as much volume as possible
- Expansion history / growth across cosmic volume
- Inflation using primordial non-Gaussianity and search for features
- Non-DOE science:
    - Fast Radio Bursts
    - Pulsar timing

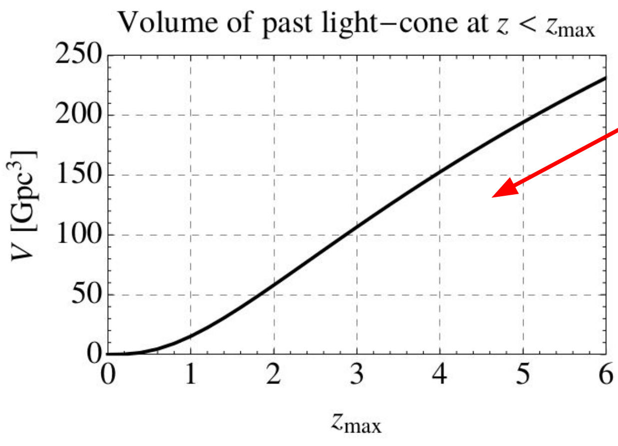
Technology:

- Development of ultra-wideband feeds allow a single instrument to reach $0.3<z<6$
- Development of RF technology for telecom industry DSP
- Development of power-efficient computing enables large-scale “software telescope”

Programatics:

- It’s hard -- need DOE HEP style collaboration to do it
- Requires lots of compute resources -- DOE knows how to do this efficiently
- It’s requires management: thousands of identical elements that require industrial scale production and project management

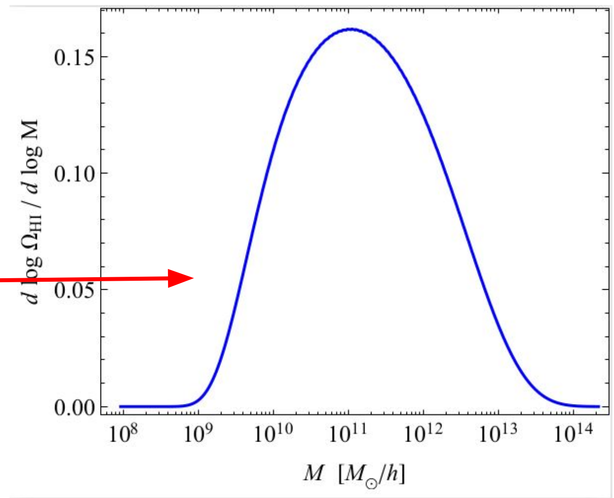
Why high redshift: volume and linear modes



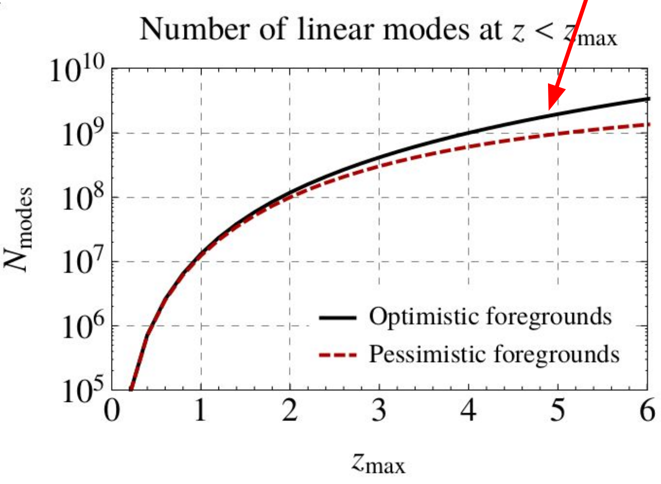
- Lots of volume
- High redshift less non-linear universe
- Galaxies in small halos -- very small shot noise, easier to model

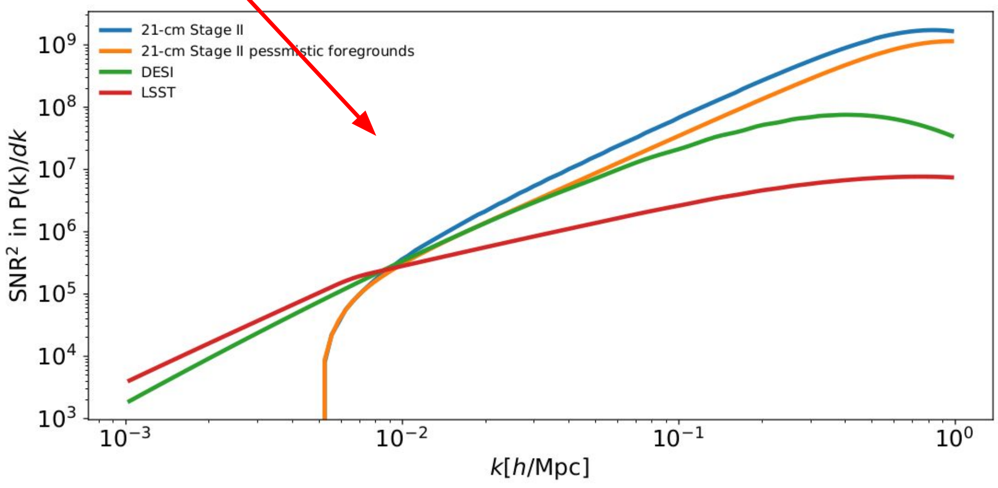
Ergo:

- Very good sensitivity to power spectrum



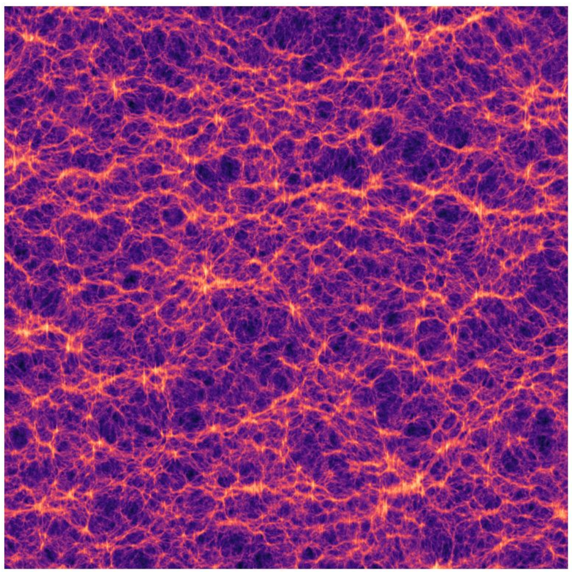
From Castorina et al 2017



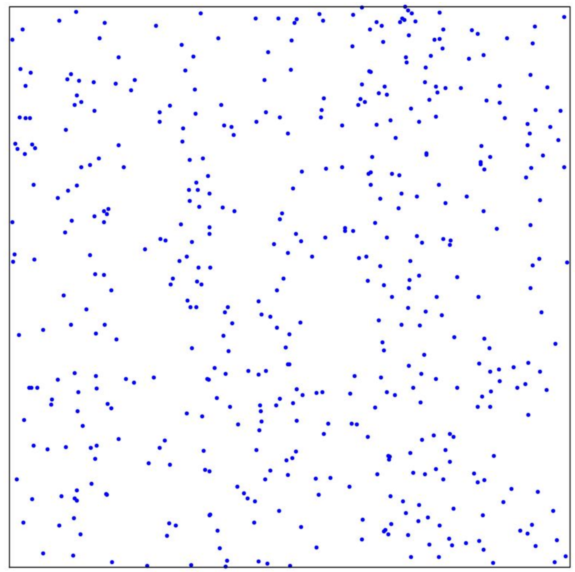


The Universe at z=3

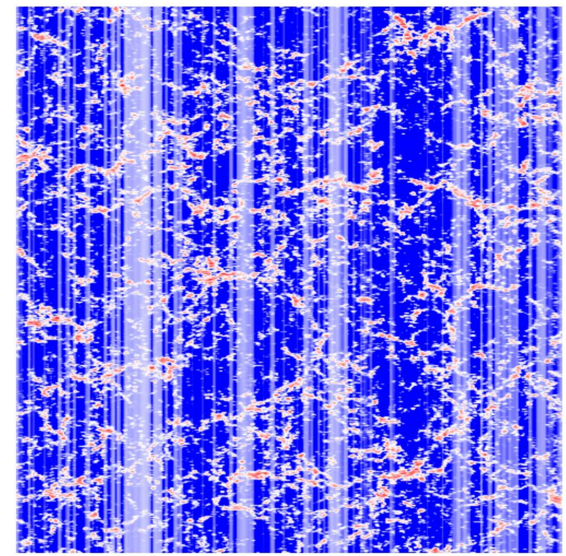
Mass



LSST galaxies
(w redshifts)

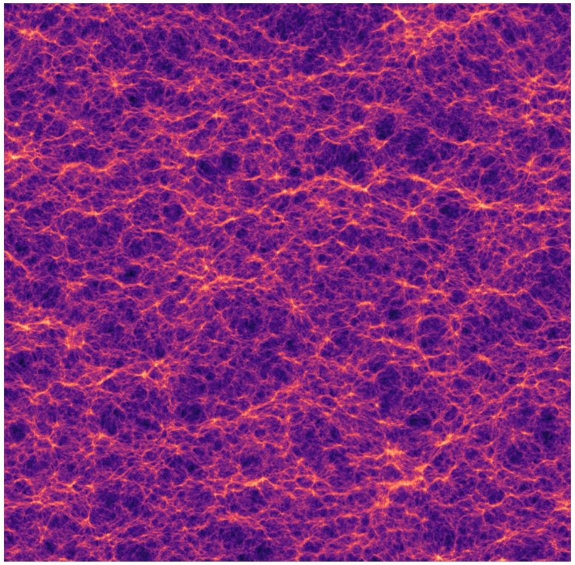


Stage II

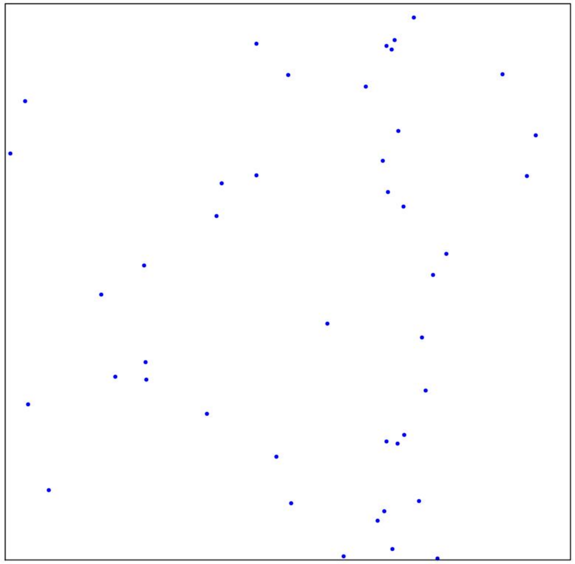


The Universe at z=5

Mass



LSST galaxies
(w redshifts)



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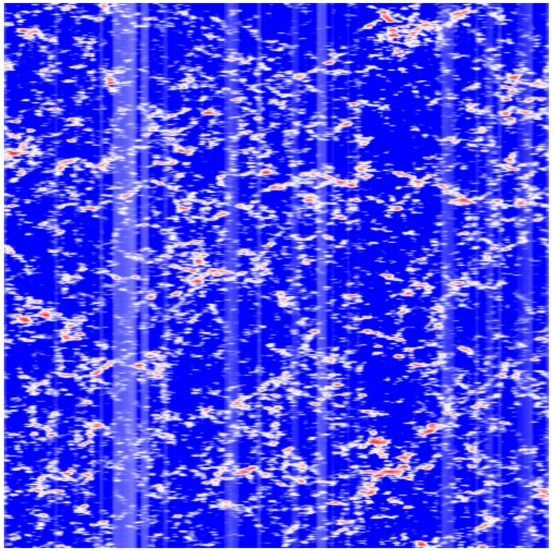
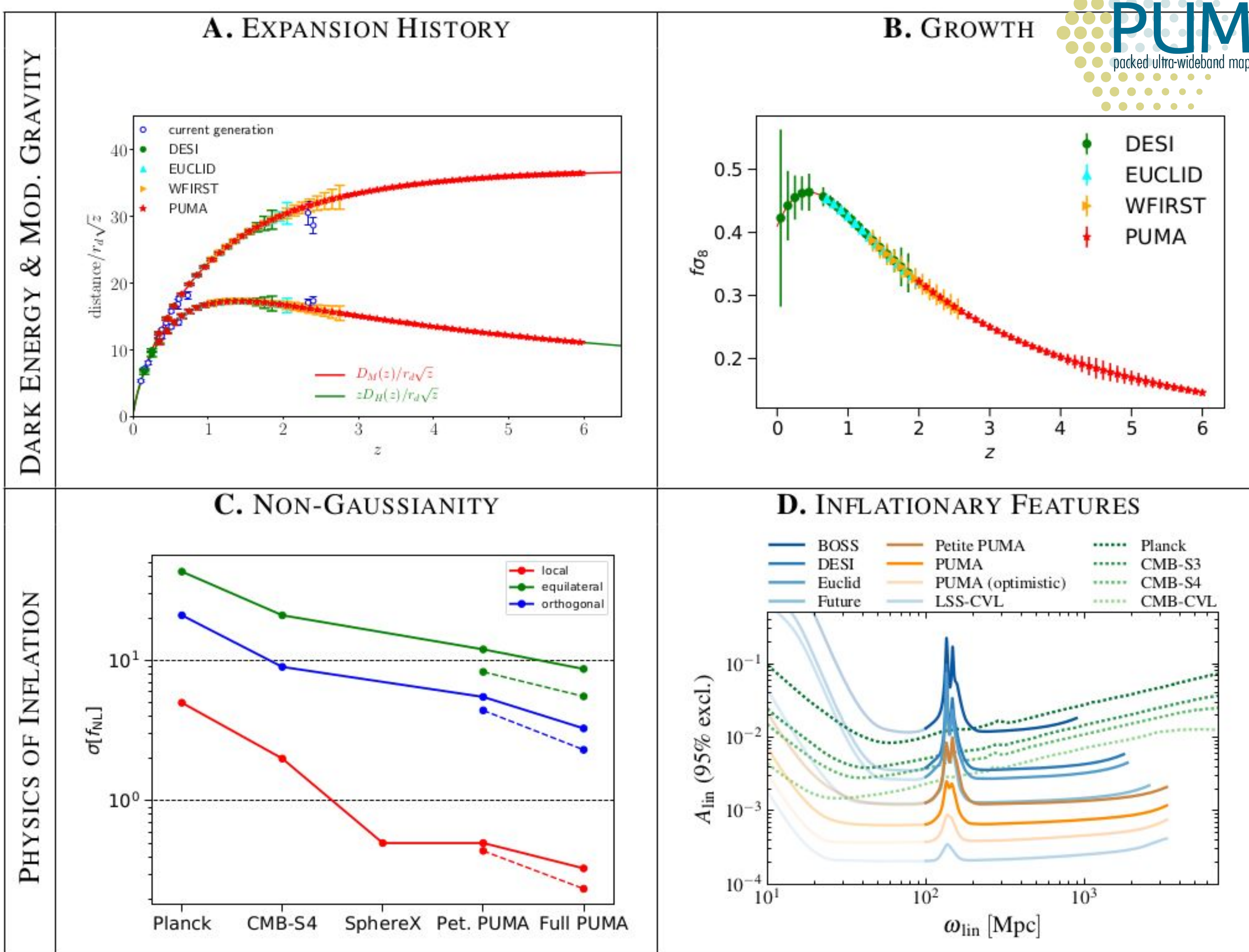
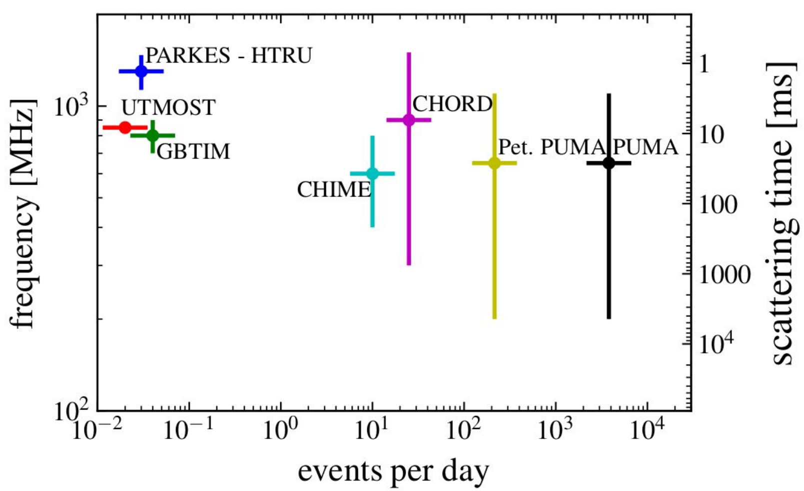



Dark Energy & Mod. Gravity
Physics of Inflation
A. Expansion History
current generation
DESI
EUCLID
WFIRST
PUMA
distance/$r_d\sqrt{z}$
$D_M(z)/r_d\sqrt{z}$
$zD_H(z)/r_d\sqrt{z}$
z
B. Growth
DESI
EUCLID
WFIRST
PUMA
$f\sigma_8$
z
C. Non-Gaussianity
local
equilateral
orthogonal
$\sigma[f_{NL}]$
Planck
CMB-S4
SphereX
Pet. PUMA
Full PUMA
D. Inflationary Features
BOSS
DESI
Euclid
Future
Petite PUMA
PUMA
PUMA (optimistic)
LSS-CVL
Planck
CMB-S3
CMB-S4
CMB-CVL
$A_{\rm lin}$ (95% excl.)
$\omega_{\rm lin}$ [Mpc]

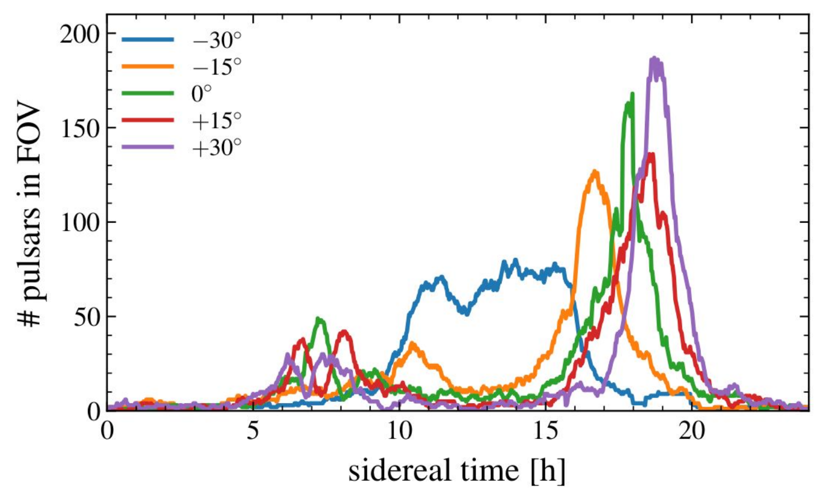
Parameter	LSST + DESI + Planck	CMB S4	PUMA + Planck	LSST + DESI + PUMA + Planck	CMB-S4 + PUMA	All experiments combined
$\sum m_\nu$ [meV]	38	59	31 / 27	25 / 22	24 / 21	15 / 14
$\sum m_\nu + \tau$ prior	—	15	—	—	14 / 13	10.4 / 10.2
$\sum m_\nu$ (free w)	50	—	33 / 29	26 / 23	—	—
N_{eff}	0.050	0.026	0.043 / 0.037	0.033 / 0.030	0.014 / 0.013	0.012 / 0.011
w (free $\sum m_\nu$)	0.017	—	0.006 / 0.005	0.005 / 0.004	—	—

TRANSIENT RADIO SKY

E. FAST RADIO BURSTS



F. PULSARS



From Science to Instrument Design

- Our Science naturally sets the basic instrument parameters:
  - start with a compact array that need to be big enough
  - need sufficient sensitivity proportional to NxD
  - Dishes need to be small enough for short baselines and big enough for systematics control

- Result:
  - 6m elements that can move N-S
  - Hexagonally closely-packed with 50% fill factor
  - Small version: 5000 dishes (~600m), large version 32000 dishes (~1600m)
  - Massive bandwith: 200-1100 MHz (z = 6-0.3)

- Requires significant advances in instrumentation and systematics control:
  - Exquisite sub-ps clock distribution across km
  - On-dish digitization and channelization
  - FFT-correlation and real-time calibration
  - Extremely good dish stability and repeatability

PUMA
packed ultra-wideband mapping array

Science Objective	Scientific Measurement Requirement	Measurement Objective	Instrument Requirements
A. Characterize expansion history in the pre-acceleration era *Decadal Science Whitepaper: [11]*	Measure Baryon Acoustic Oscillations to volume-limited accuracy	Measure 21 cm intensity: – over $2 < z < 6$ – to $k \sim 0.4h\text{Mpc}^{-1}$ – with SNR per mode ~ 1 at $k \sim 0.2h\,\text{Mpc}^{-1}$	Bandwidth must include 200-475 MHz Maximum baseline $L_{\text{max}} \gtrsim 600\,\text{m}$ $ND > 25$ km at $L_{\text{max}} = 600\,\text{m}^{\star}$
B. Characterize structure growth in the pre-acceleration era *Decadal Science Whitepaper: [11]*	Measure growth through the 21 cm power spectrum on weakly non-linear scales to volume-limited accuracy	Measure 21 cm intensity: – over $2 < z < 6$ – to $k \sim 1.0\,h\text{Mpc}^{-1}$ – with SNR per mode ~ 1 at $k \sim 0.6\,h\,\text{Mpc}^{-1}$	Bandwidth must include 200-475 MHz Maximum baseline $L_{\text{max}} \gtrsim 1500\,\text{m}$ $ND > 200$ km at $L_{\text{max}} = 1500\,\text{m}^{\star}$
C. Constrain or detect primordial non-Gaussianity *Decadal Science Whitepaper: [13]*	Measure the 21 cm bispectrum to achieve non-Gaussianity sensitivity of: – orthogonal: $\sigma\left[f_{\text{NL}}^{\text{ortho}}\right] < 10$ – equilateral: $\sigma\left[f_{\text{NL}}^{\text{equil}}\right] < 10$	Measure $\gtrsim 10^9$ linear modes with SNR per mode ~ 1	Same as above plus: bandwidth $200-1100$ MHz ($z \sim 0.3-6$) assuming $f_{\text{sky}} \sim 0.5$
D. Constrain or detect features in the primordial power spectrum *Decadal Science Whitepaper: [14]*	Measure the matter power spectrum over all available scales to constrain primordial features with: – $A_{\text{lin}} < 1 \times 10^{-3}$ (95% c.l.)	Sufficient forecasted power spectrum sensitivity	Same as above
E. Fast Radio Burst Tomography *Decadal Science Whitepapers: [16, 19–21]*	Volume limited measurement of electron power spectrum, stellar mass census	– 1 million FRBs – covering two frequency octaves – 3" localization precision	Fluence sensitivity threshold $\lesssim 2.5 f_{\text{sky}}^{2/3}$ Jy ms Provide real-time FRB back-end Provide baseband buffer with triggered readout
F. Monitor pulsars *Decadal Science Whitepapers: [21–26]*	Monitor all pulsars discovered by SKA	Detect all pulsars in current Field of View brighter than $10\,\mu$Jy	$10\,\sigma$ point source sensitivity $> 10\mu$Jy/transit Provide real-time pulsar back-end

Table 1: Science traceability matrix for main science drivers. All derived instrument parameters assume certain fixed system properties such as amplifier temperature, sky background and various efficiency factors as outlined in [3]. The total integration time is assumed to be five years. *At fixed linear dimension of the array, the noise power scales as ND, where N is the number of elements and D is their linear dimension. FRB rates and properties at frequencies below 400 MHz are extrapolations.

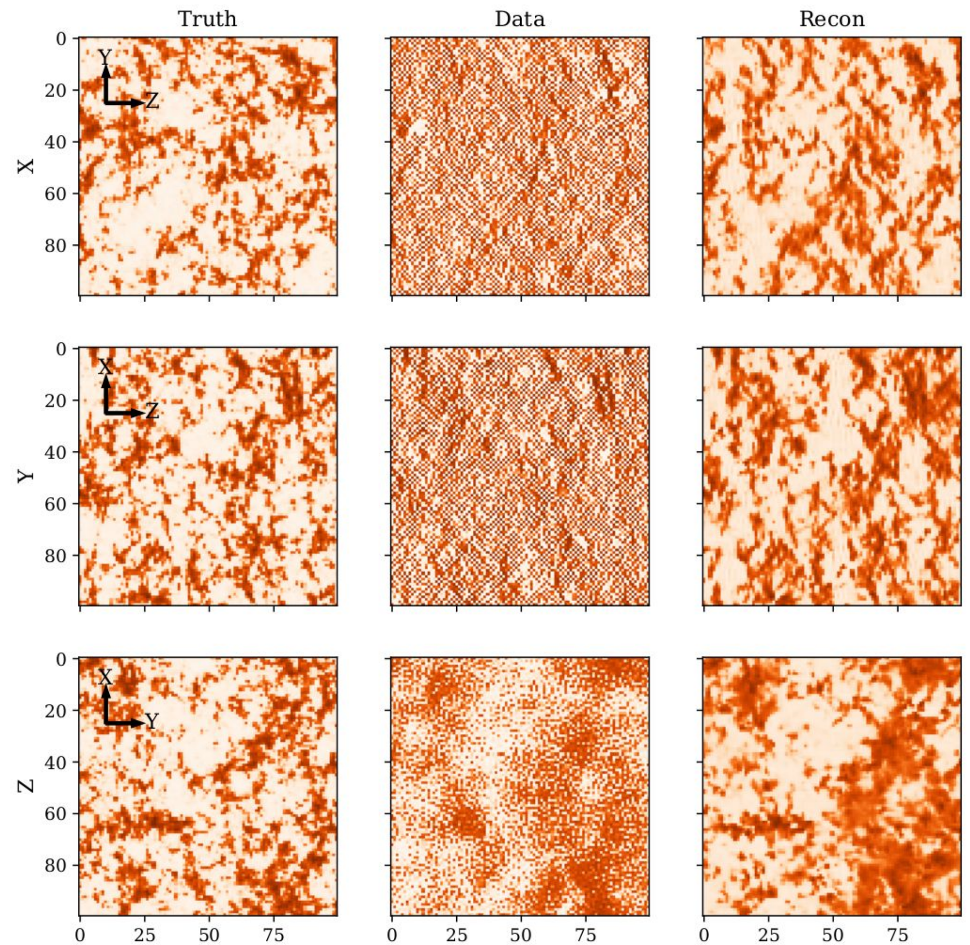
Antenna Array	Hexagonal close-packed transit array		
	Petite	Full	Petite array: Achieve science goals A & F, and $\sim$ 30% of B to E Full array: Achieve all science goals
array diameter	600m	1500m	
fill factor	50%	50%	
number of elements	5,000	32,000	
10σ single transit sens.	8.7μJy	1.3μJy	
Array element	Parabolic on-axis with N-S pointing		transit observations, campaign repointing
dish diameter	6m		shortest possible baselines with $D \gg \lambda_{\text{min}}$
construction	on-site fiber-glass production, mm surface accuracy		better beam control than Stage I for systematics
frequency coverage	$200-1100$ MHz		
OMT	ultra-wide band, dual-pol		
front-end	amplifiers and digitizers integrated with OMT		alternative arrangement to be explored
channelizer	one per 10-100 dishes		helps with corner-turning, alternatives possible
Correlator	FFT correlator with partial N^2 correlations		also non-FFT calibration mode
FRB capability	real-time FRB search engine		
real-time beamforming	10^4 concurrent tracking beams		pulsar, transients, multi-messenger

Survey	
area	50% sky
observing time	5 years on sky, wall-time 7-10 years
equivalent source density	
at $z = 2$, $k = 0.2\,h\,\text{Mpc}^{-1}$	$7.4/2.0 \times 10^{-3}\,h^3\,\text{Mpc}^{-3}$ (full/petite)
total equivalent sources	
at $k = 0.2\,h\,\text{Mpc}^{-1}$	2.9/0.6 billion (full/petite)
at $k = 0.5\,h\,\text{Mpc}^{-1}$	2.5/0.4 billion (full/petite)
FRB rates (expected)	
200-400 MHz	1200/70 per day (full/petite; *uncertain*)
400-700 MHz	1000/60 per day (full/petite)
700-1100 MHz	1300/80 per day (full/petite)
Calibration	
complex amplitude	sky sources
primary beam	per antenna using fixed wing drones
clock distribution	100 fs clock distribution for phase stability

Table 2: Basic instrumental parameters.

Field reconstructions

- Non-linear evolution cascades information from large-scales to smaller scales
- Can use weakly non-linear scales to reconver linear fields:
  - Recovers modes lost to foregrounds
  - Lowers noise below Poisson noise
- Method developed for galaxies, but 21cm is an ideal application (light halos, high redshift)



From Chirag, White, Slosar, Castorina, JCAP 2019

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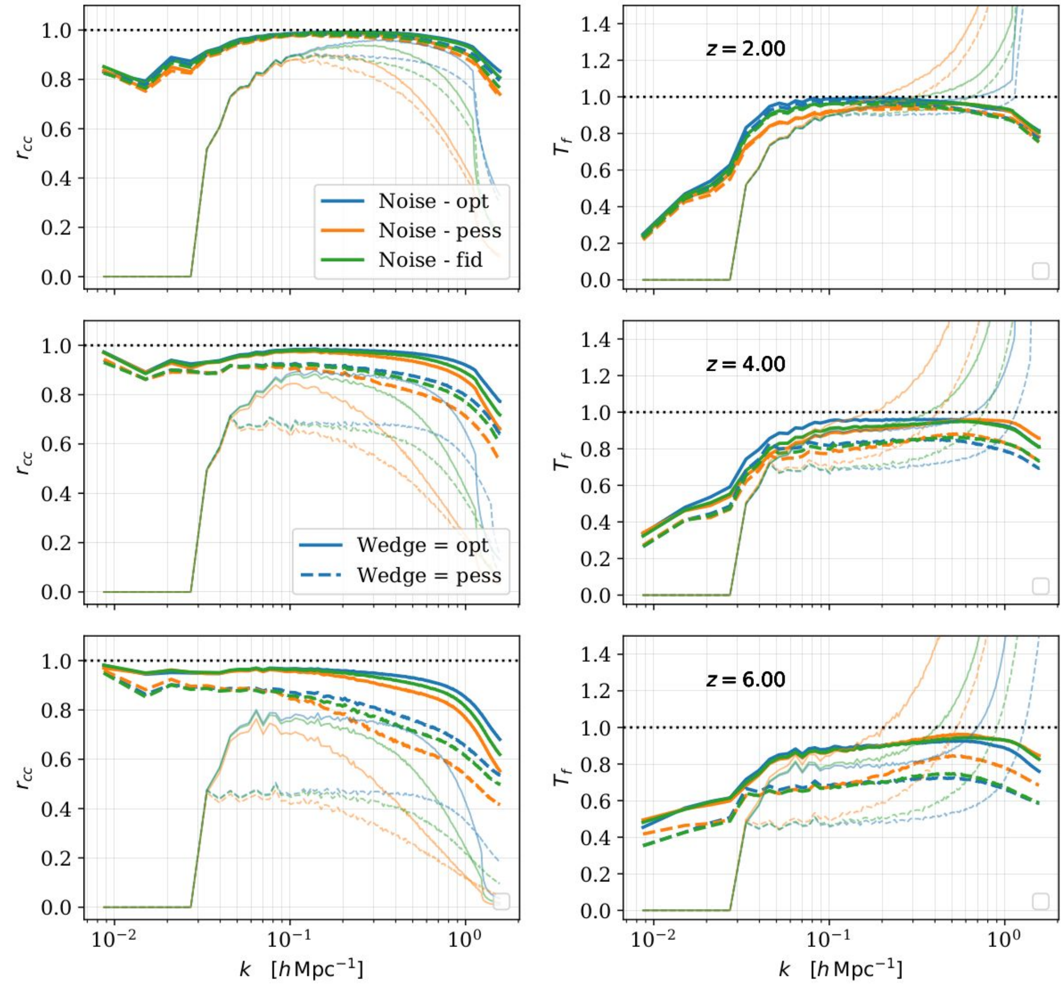
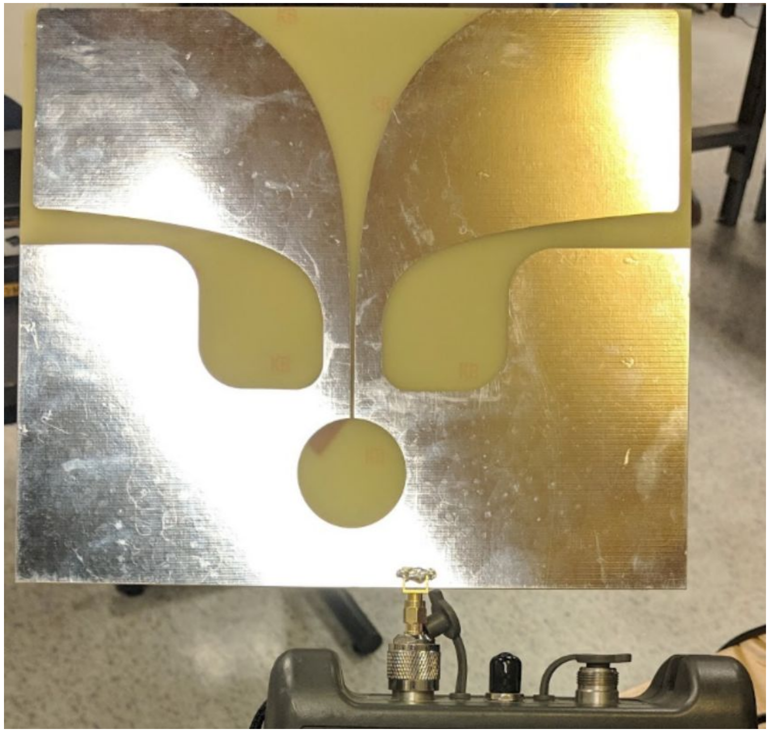


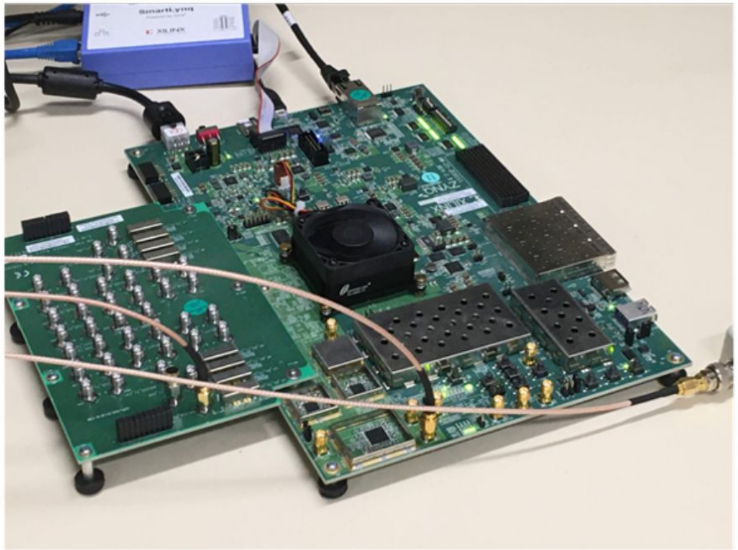
From Chirag, White, Slosar, Castorina, JCAP 2019

Enabling Technologies

- Development of ultra-wide band feeds
  - price is ~10% coupling loss across the band
  - 6:1 frequency ratios achiveable
- Commercial fast digitizers:
  - 5 GS/s rate is becoming feasible
  - Cheaper to oversample than to make analog filtes
  - Integrated OMT/digitizer/channelizer possible
- Networking and Correlation:
  - Off-the-shelf digital network:
  - CHIME built an effectively proprietary FGPA based network
  - You can now use off-the-shelf 10Gb ethernet / switches
  - GPU / ASIC correlations using FFT

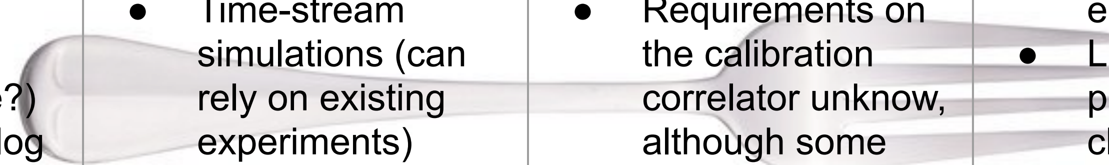


Xilinx ZCU111 RFSoC FPGA digitizer/channelizer



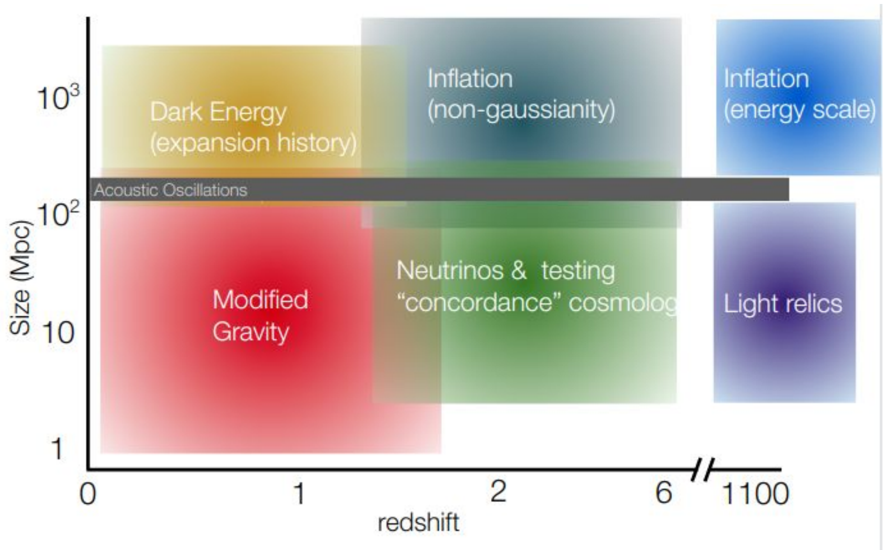
The Four prongs of the R&D Plan

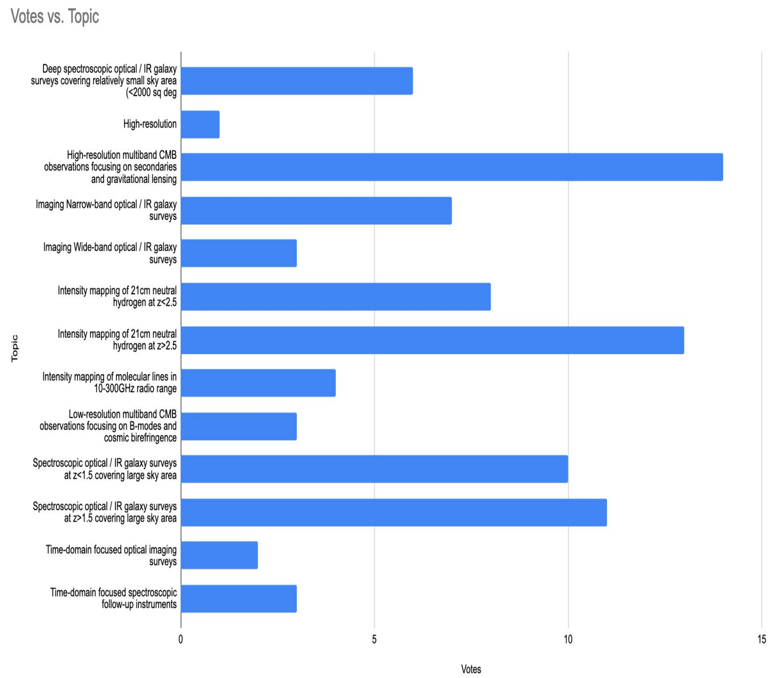
1. Technology Development in the Lab	2. Computing, Software, Pipelines	3. Real-time signal processing and Calibration	4. Path-finder arrays
• Optical and Mechanical Antenna Design • Dish Construction Techniques (fiberglass moulding alla CHORD or something else?) • Integrated Analog and Digitalf ront-end • Clock distribution (White Rabbit likely just not quite good enough) • Primary Beam Calibration (drones)	• Electromagnetic modelling of Array performance (from single-dishes to coupling between dishes) • Time-stream simulations (can rely on existing experiments) • Proto-pipelines to validate the algorithms	• PUMA relies on FFT correlation • A separate calibration correlator will run in parallel • Requirements on the calibration correlator unknow, although some publishes result on possible algorithrms (Gorthi et al 2020) • Demonstration of this subsystem in computer simulations	• PUP engineering prototypes • Ranging from PUP-2 to PUP-60 • A well-defined research goal for each stage • Likely and iterative plan that will change as we learn more



CPAD / BRN Process

- 21cm technology is now part of the process
- Two topics where our needs are represented:
    - “Breaking the picosecond barrier”
    - “Real-time data processing”
- There is some hope for R&D funding, but science needs to lead.

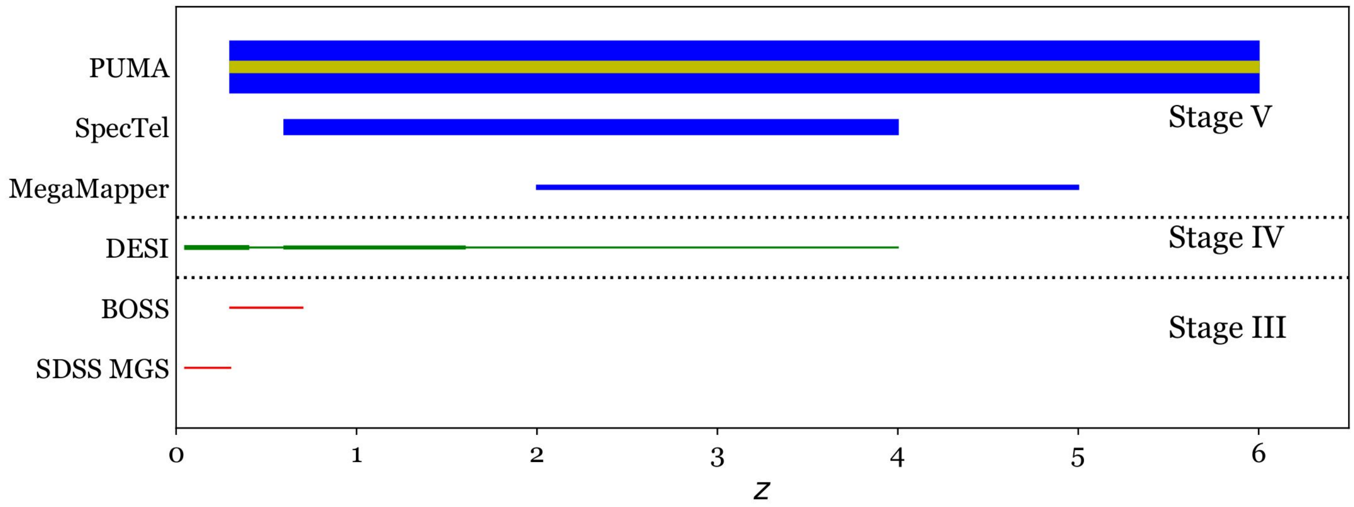




PUMA Collaboration today

- We have around 40 people on the e-mail exploder
- Monthly seminar series that has been very successful
- Aug 18-20:
  - Inaugural Virtual Workshop
  - A great success, over 30 people online
- Next steps:
  - Start real work towards setting the requirements
  - Entire system relies around dividing and controlling the complex gain and beam stability allowance across various subsystems and real-time calibration that keeps it there
  - The dish synchronization requirements are still not absolutely clear, likely around 100fs
  - A lot of headway can be made using relatively simple numerical experiments
- We hope to have a Snowmass WhitePaper which will be an update to Decadal RFI response with hand-wavy bits replaced by real numbers

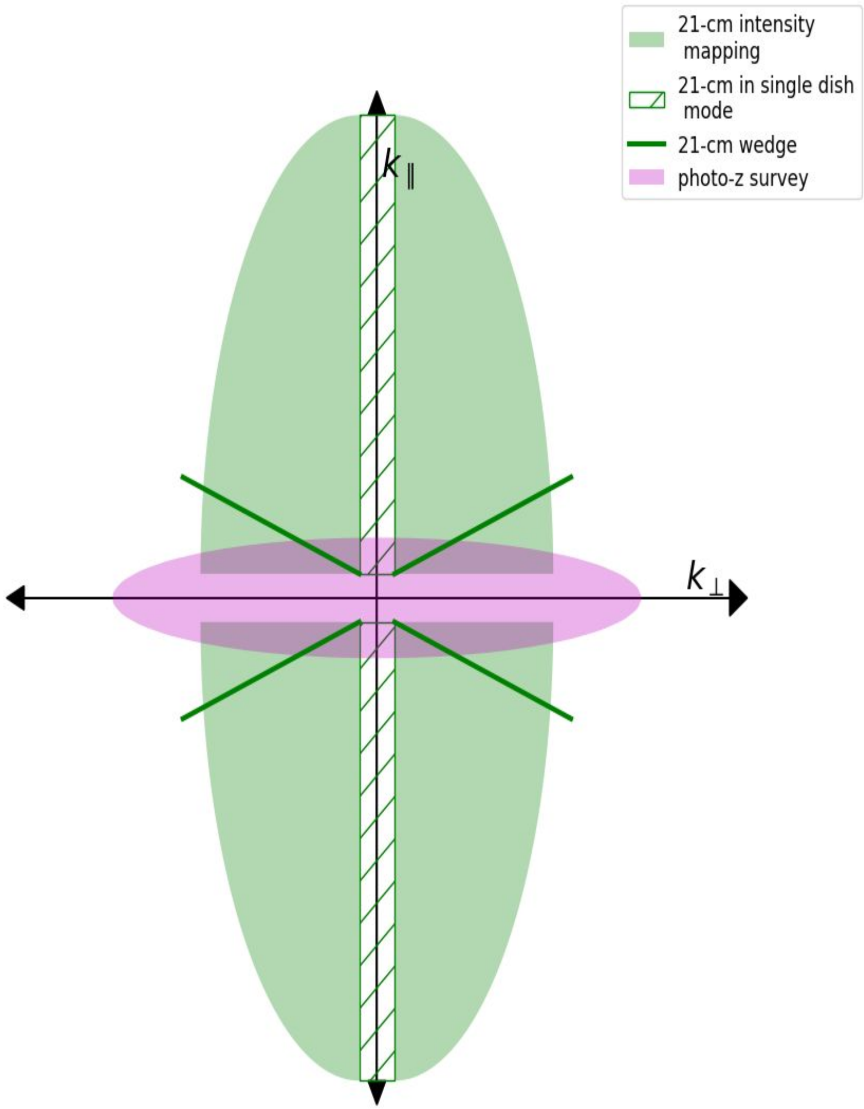
Conclusions



- 21cm intensity mapping is potentially a revolutionary technique
- It allows:
  - Mapping universe across cosmic times with a single instrument
  - Unprecedented signal to noise at affordable cost
  - Riding the wave of technology development for the telecom and computing market
- Nobody has quite managed to make it work:
  - Problems purely technical in nature
  - Our community is capable of solving them
- Let's do it!

BACKUP SLIDES

Main difference with galaxy surveys



- We definitely loose the low $k_{||}$ modes ($k_{||} \lesssim 10^{-2}\,\mathrm{Mpc}^{-1}$) directly
- Low $k_{||}$ modes could be reconstructed using several techniques
- We potentially loose modes inside the wedge, but could get them back with good calibration
- Additionally, we do not know the mean signal, hence redshift-space distortions need additional calibration