Cosmic Frontier Snowmass

BNL Snowmass day

Introduction

Cosmic Frontier encompasses 3 related, but distinct topics:

- Direct Dark Matter Detection (think LZ and LUX): :
    - CF 1 and CF 2
    - A detector, typically deep underground
    - Detect DM through interaction with SM particles
- Traditional Cosmology:
    - CF 4,5,6
    - Constrain Cosmological Model through statistics of cosmic tracers
    - neutrino mass, inflation, etc goes here
    - Includes CMB, galaxy surveys, SN and related techniques:
- Fundamental Physics through astronomical observables:
    - CF 3 (DM), CF 7 (general)
    - stellar streams, modified GR screening, neutron stars, etc
    - I.e. you find some astronomical system that is in some way sensitive to your insane model

CF working groups

- CF1. Dark Matter: Particle-like
- CF2. Dark Matter: Wave-like
- CF3. Dark Matter: Cosmic Probes
- CF4. Dark Energy and Cosmic Acceleration: The Modern Universe
- CF5. Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
- CF6. Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
- CF7. Cosmic Probes of Fundamental Physics

- All groups have “solicited whitepapers”
- Additional whitepapers are possible.
- Significant overlap and scope division a continuous source of confusion

4 Key Opportunities

Large N_{linear}: [Anze, Martin, Simone] -- overlap with static sky of "joint analysis WP"

- Implies large volume, high z
- Target Science (e.g. Martin White + Simone Ferraro Paper z>2 paper):
  - Inflation
  - Parameters
  - Neutrinos
  - Expansion history, Early Dark Energy
- DESI-2, MegaMapper, MSE
- Later: PUMA, CO Line Intensity Mapping

Large nP: [K Dawson, Heitmann, Hearin]

- Implies low-z, smaller sky area
- Target Science:
  - Dark Matter Physics
  - Modified Gravity
  - Small Scale primordial power spectrum?
  - Primordial field recovery (?)
  - Unknown physics from a very rich dataset
- DESI-2, MegaMapper, MSE with a different strategy
- Later: ATLAS

High precision in Astrophysics [A Gonzalez, S Chakrabarti, M Pierce]

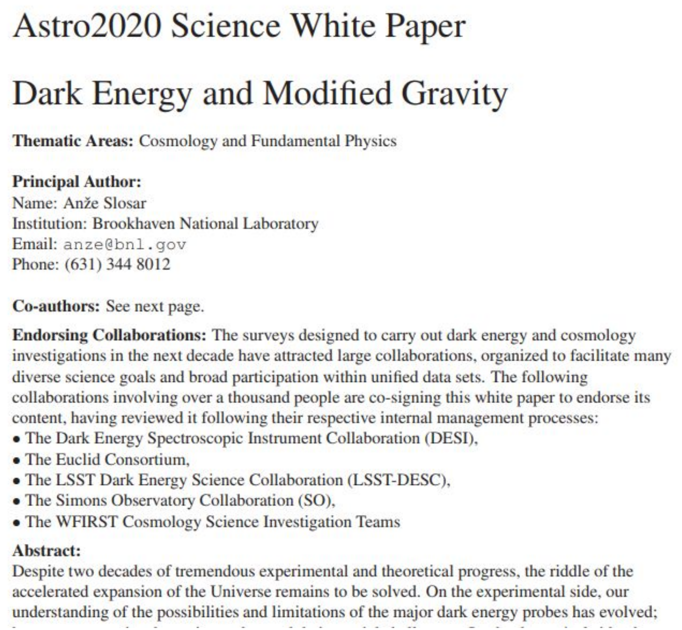
- Large spectroscopic precision
- Large astrometric precision
- Target Science:
  - Direct expansion measurements
  - Dark Matter Physics
  - Modified Gravity
  - GW, multi-messenger
- … list expts

Enabling flagship experiments to reach their potential: [Jeff, Peter N, Alex K, Dickinson M (ELT)] -- overlap with transient sky of "joint analysis WP"

- Many needs: spare fibers + smaller facilities for bright targets; small-area programs with next gen telescopes/instruments; deep high-multiplex spectroscopy
- Target Science:
  - Supernova follow-up + peculiar velocities
  - Strong lens follow-up
  - Photometric Redshift training and calibration
  - Intrinsic Alignment constraints
  - Galaxy cluster studies

Snowmass and Decadal Survey

- Cosmological Survey Experiments need typically to be endorsed both by the **Decadal Survey of Astronomy and Astrophysics** as well as Snowmass
- Decadal survey is federally mandated for NASA, but NSF and DOE join forces
- Run by National Academy of Sciences
- Very NASA and NSF focused
- Decadal Survey accepted both Science and Project Whitepapers
- We participated in both.
- The report came out in Oct 2021:
  - not terribly exciting for Cosmology
  - not terribly supportive of PUMA



Astro2020 Science White Paper

Dark Energy and Modified Gravity

Thematic Areas: Cosmology and Fundamental Physics

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Institution: Brookhaven National Laboratory
Email: anze@bnl.gov
Phone: (631) 344 8012

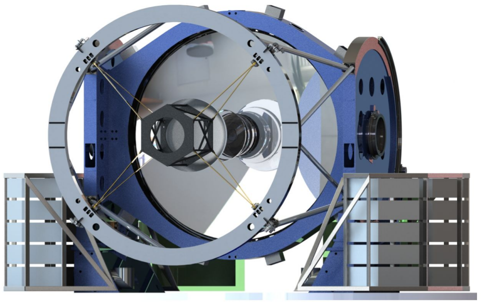
Co-authors: See next page.

Endorsing Collaborations: The surveys designed to carry out dark energy and cosmology investigations in the next decade have attracted large collaborations, organized to facilitate many diverse science goals and broad participation within unified data sets. The following collaborations involving over a thousand people are co-signing this white paper to endorse its content, having reviewed it following their respective internal management processes:
- The Dark Energy Spectroscopic Instrument Collaboration (DESI),
- The Euclid Consortium,
- The LSST Dark Energy Science Collaboration (LSST-DESC),
- The Simons Observatory Collaboration (SO),
- The WFIRST Cosmology Science Investigation Teams

Abstract:
Despite two decades of tremendous experimental and theoretical progress, the riddle of the accelerated expansion of the Universe remains to be solved. On the experimental side, our understanding of the possibilities and limitations of the major dark energy probes has evolved;

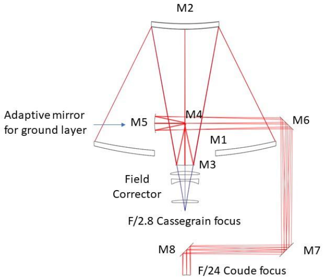
MegaMapper

- Large volume redshift survey (0<z<3.5)
- Goals: High redshift dark energy science, inflation and neutrinos, structure growth in accelerating regime
- Potential partnership with Carnegie Observatories, NSF, university partners
- Southern site targeting LSST
- Construction cost ~$50M (focal plane + instrument)



SpecTel

- High density galaxy redshift survey (0<z<3.5)
- Cosmology goals: High redshift dark energy science, inflation and neutrinos, structure growth in accelerating regime
- Astrophysics goals: near-field cosmology and galaxy evolution
- Potential partnership with ESO, NSF, other non-US agencies
- Construction cost ~$400M (but depends on scale of focal plane)



PUMA

- Intensity mapping in 21cm at z=0.3-6 (optimized for 2-6)
- Goals: High redshift dark energy science, physics of inflation, auxiliary science FRB, pulsars
- Requires R&D in streaming DAQ, timing synchronization, calibration
- Potential partnership with NSF, NRAO, non-US agencies
- Construction cost $330M ($55 M for descoped version)

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**)

Successes and Failures of PUMA

Successes:

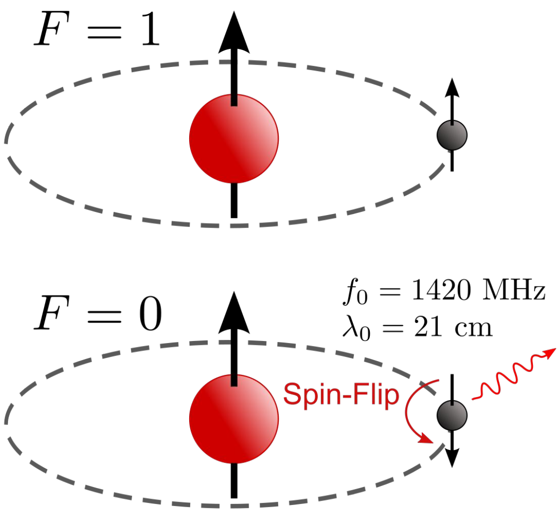
- A compelling concept
- Good forecasts
- Science Driven Instrument Design
- 1 DOE whitepaper, 2 Decadal Submissions
- Cited in literature
- DOE management aware of this effort

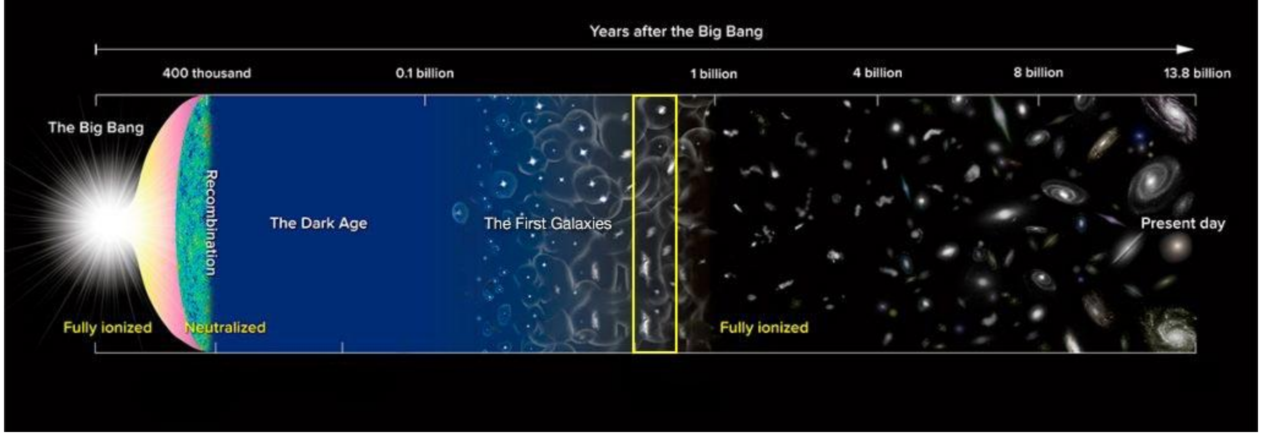
Failures:

- Did not manage to convince the wider HEP community
- Did not manage to convince the traditional radio astronomy community
- Decal seemed very positive initially (RFI and presentation to the committee), but ultimately did not resoundingly endorse this project
- precursor experiments failed to live to expectations

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

$20 \lesssim z \lesssim 150$

- 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

LuSEE Concept at BNL

- Backstory is almost comical
- Top-down effort to get DOE and NASA work together again
- Commercial Lunar Payload Services - CLPS will pay to get your experiment to the far side of the Moon
- Many experiments would be much better off in orbit, but this is not an option
- BNL has been chosen as the lead lab for the LuSEE at Night - a Dark Ages pathfinder:
    - but funding not awarded yet by congress, so if you talk about it, I will have to fly to LI and kill you
    - The experiment is unlikely to see the real signal, but it will teach us what we need to do in order to see it

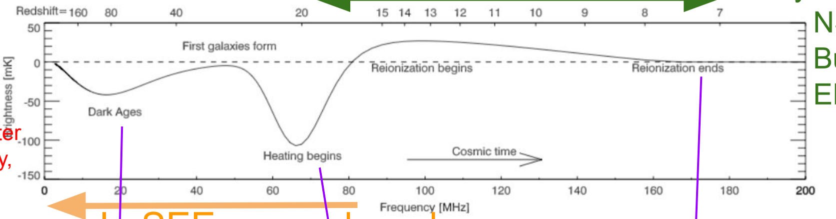
Science

Essentially impossible from the ground

- Dark Ages through.is a cosmic calorimeter
- Measures something adding or taking energy from hydrogen fluid
- Constrains physics like dark matter-baryon scattering, millicharged dark matter, dark matter annihilation, axions, neutrino decay, charge sequestration, quark nuggets, dark photons, interacting dark energy

Optical galaxy surveys

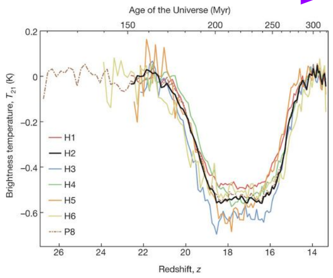
z<6 21-cm

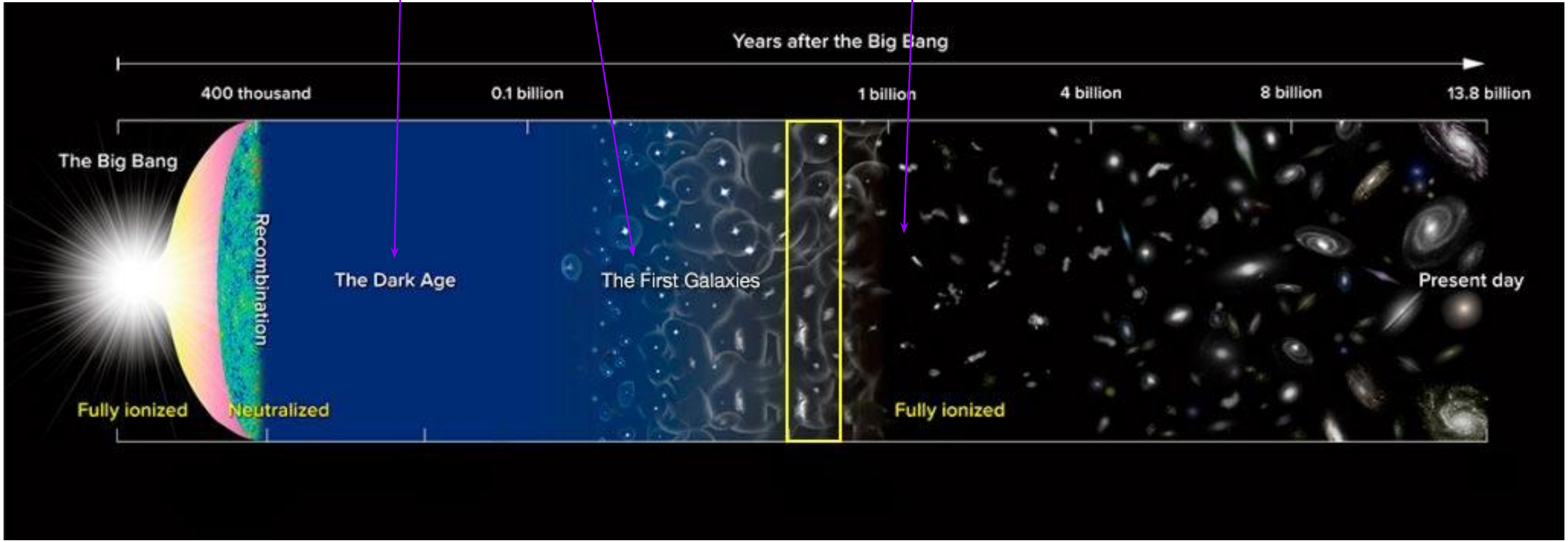


LuSEE somewhere here

Mostly astrophysics, NSF funded, But note recent EDGES result ->

- Second through much bigger than expected
- Could be exotics
- Likely systematics
- Very cheap
- Can do from Earth





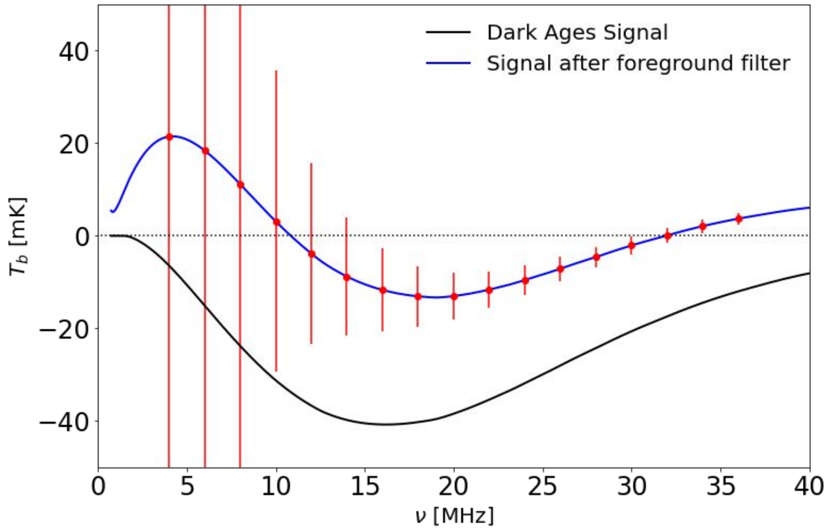
Science objectives

Baseline science:

- Constrain the presence of the dark ages monopole at ~1000 mK precision and thus rule out the non-standard cooling models
- Characterize the radio sky and properties of foreground emission at 0.1-120MHz at percent precision

Threshold science:

- Demonstrate feasibility of radio observations from the lunar surface
- Characterize the lunar RF environment
- Characterize the radio sky and properties of foreground emission at 0.1-40MHz at percent precision



Preliminary estimate of signal achieved after 11 lunar nights on a single polarization directional antenna with 100% effective spectrometer and perfect calibration and a simplified foreground model.

Agency Scopes

DOE scope (new funds <$10 mil):
- Experiment electronics
- Antenna design, characterisation and simulations

DOE scope (existing science lines, with potential small augmentation)
- Science pipelines: small team, 3-5 people from all labs

NASA scope:
- Lander
- Systems, mechanical and thermal engineering
- Relay communication

NASA led scope with DOE participation:
- Systems engineering
- Flight qualification
- Instrument integration & testing
- Mission operations

TBD scope:
- Communication system (purchased commercially, ~$1m)
- Batteries, solar panels, power delivery and conditioning

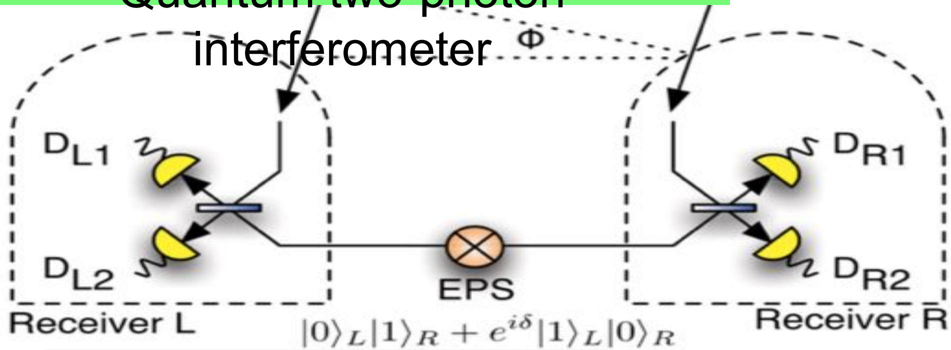
Extreme Precision Astrometry Using Two Photon Amplitude Interferometry

A.Nomerotski, A.Slosar, P.Stankus, S.Vintskevich *et.al.*

Classical interferometer

- Measure phase difference by bringing light together from two stations
- Baselines limited to 100 m (CHARA, VLTI)

Quantum two-photon interferometer



D.Gottesman et al, PRL 109, 070503 (2012)

Sensitive to features on angular scale:

$$\Delta\theta \sim \frac{\lambda}{b}$$

- Measure phase difference by *teleporting the sky photon* to the other station
- Decouples two stations and *enables long baselines* to improve astrometric precision by orders of magnitude

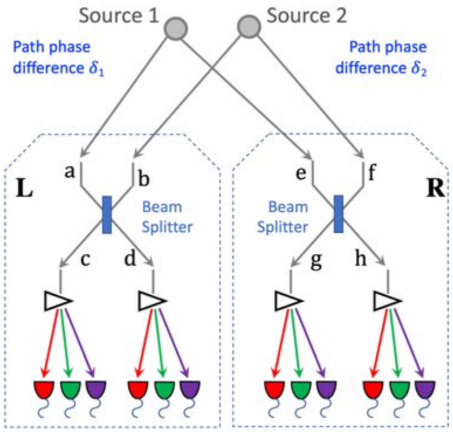
Possible Impacts on Astrophysics and Cosmology

If successful: orders of magnitude better astrometry/resolutions

- Imaging of black holes □ General relativity
- Parallax: improved distance ladder □ SN science □ DE
- Proper motions □ local DM patterns
- Microlensing □ see motions and shape changes, DM hunting
- Coherent motions of stars □ Gravitational Waves
- Coincidence nulling □ Exoplanets

Quantum Astrometry Project

Idea: phase sensitivity for two-photon interference using **two sky sources**



$$\Psi^{\text{Initial}} = \psi_1\psi_2 = \frac{1}{2}\underbrace{(\hat{a}^\dagger + e^{i\delta_1}\hat{e}^\dagger)}_{\text{sky photon 1}}\underbrace{(\hat{b}^\dagger + e^{i\delta_2}\hat{f}^\dagger)}_{\text{sky photon 2}}$$

Phase difference $\delta_1 - \delta_2$ is extracted from coincidence rates of four single photon counters; *directly sensitive to opening angle* between sources.

BNL QuantISED project, started in Sept 2019

Goals: theoretical and experimental exploration of the idea

- A conceptual paper on two-photon amplitude in review, a follow-up paper being written
- Experimenting in the lab on HOM interference and spectroscopic binning for thermal sources, plan to perform on-sky observations for bright stars

Results will define a path towards a small experiment

Aligned with BNL plans on quantum networks

A.Nomerotski et al, *Sensors* **2020**, *20*, 3475
Y Zhang et al, Phys.Rev.A 101 (5), 053808 **(2020)**

Conclusions

- The field is quite active with many ideas and little coalescence around a single project
- Optical spectroscopy is too much “more of the same” in my view, but is most likely to emerge as the consensus option
- 21cm of various kinds provides interesting options forward
- Dark Ages is perhaps the most difficult of them all and yet it might be the first to get some experimental attention from DOE.