UNIVERSITY OF SÃO PAULO

Whispers of the Universe: theoretical and observational developments, gravity and cosmology

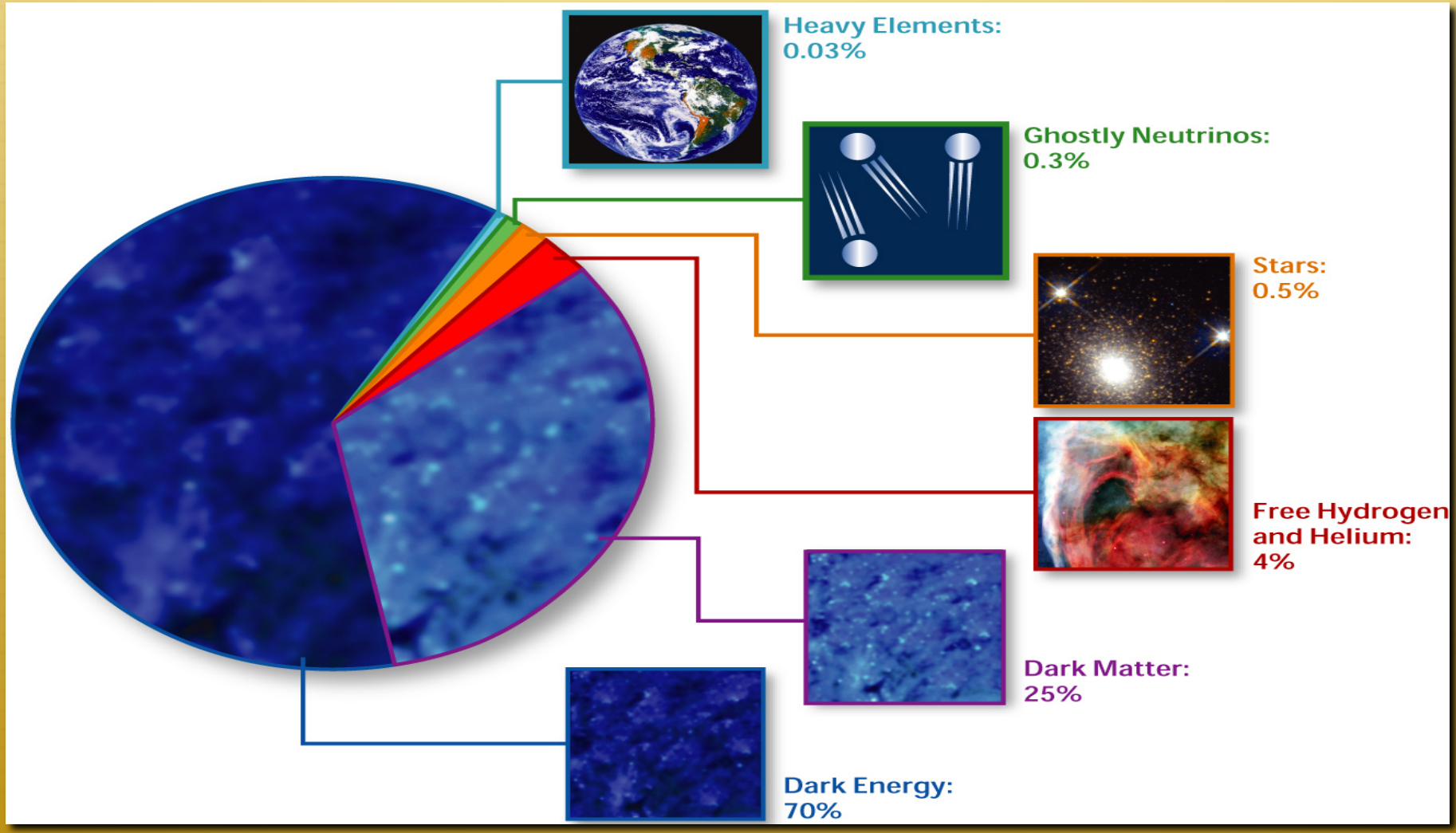
Elcio Abdalla
2017

Gravity

- Black Hole formation in an expanding Universe (E.A., Elefterious Papantonopoulos (Athens), Bertha Cuadros (EEL), Leonardo Werneck (PhD project), Carlos Eduardo Pellicer (Natal))
- Pontos de Lagrange em Relatividade Geral (E.A., Diego Shibata Obregon (MSc), Cecilia Chirent (UFABC))
- Galileon Black Holes (E.A., Bertha Cuadros (EEL), Alan Pavan (Itajubá), Jeferson Oliveira (UFMT), Carlos E. Pellicer (Natal))
- Horndeski Model in Gravity and Cosmology (E.A., Papantonopoulos, Bertha Cuadros, Fabrizio Bernardi (PhD), R. Rhavia (PhD))

Standard Cosmological Model

Composition of the Universe



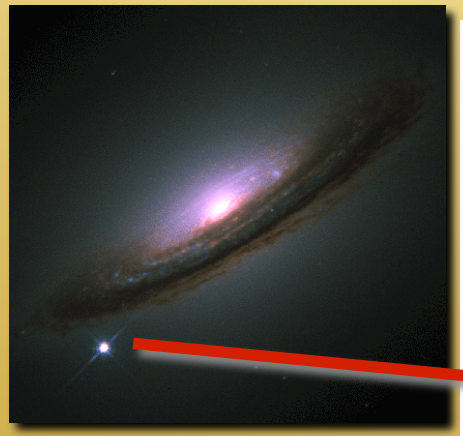
http://en.wikipedia.org/wiki/Image:Cosmological_composition.jpg source and rights]

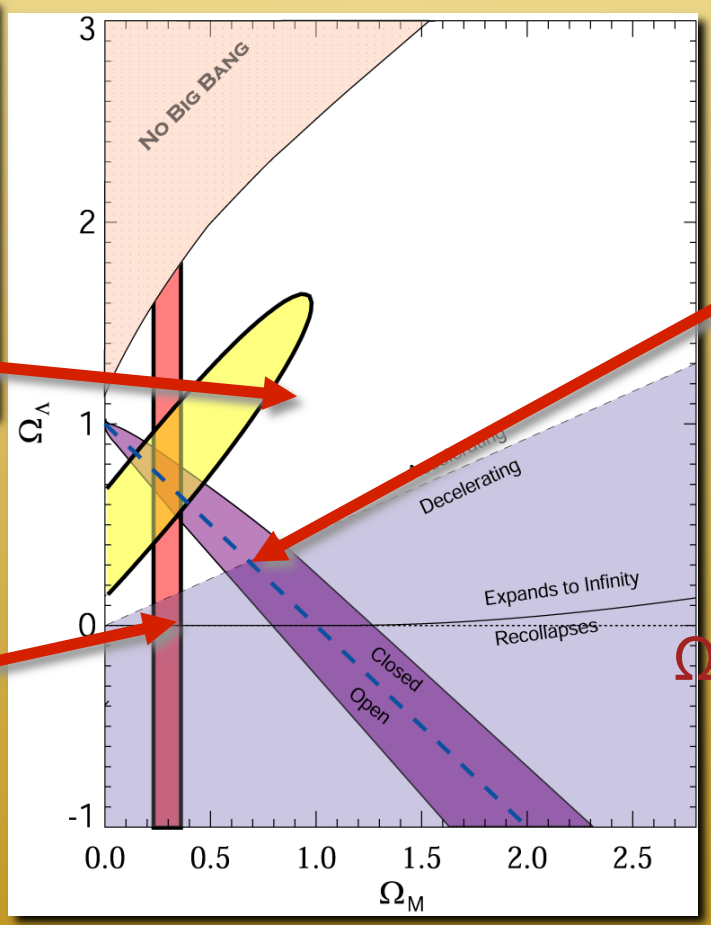
What is Dark Energy?

The Evidence:

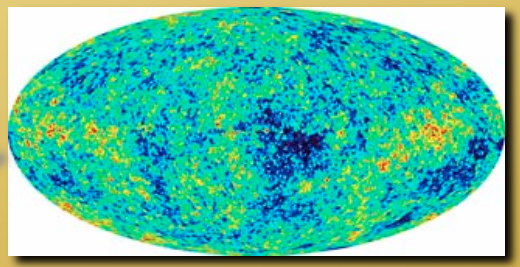
98's: The universe is expanding in an accelerated way.

SNe Ia

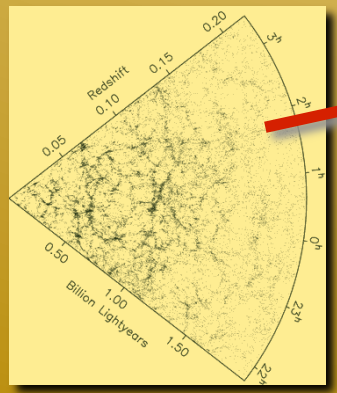




CMB



LSS



Ω_{DE}=0.721±0.025 (WMAP)

WMAP

Ω_{DE}=0.685±0.013 (Planck)

Source: S. Tsujikawa, "**Dark Energy and Modified Gravity**"

What is causing the acceleration?

From the Friedmann equations:

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho + 3p)$$

$$p < -\frac{\rho}{3} \rightarrow \omega < -\frac{1}{3}$$

Source: de Rahm & Tolley, 2008

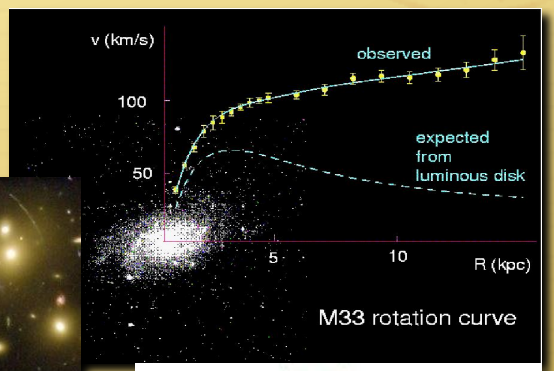
What is Dark Matter?

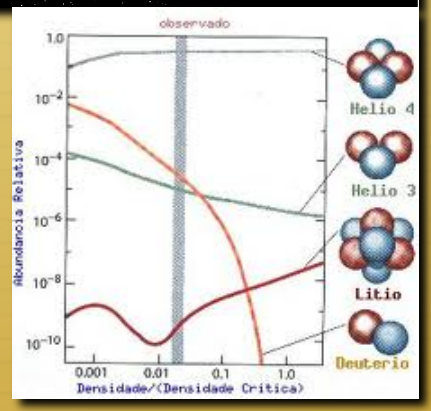
Evidences for Dark Matter

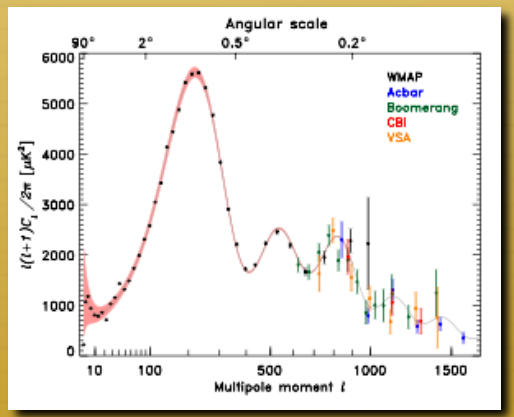
- Huge amount of evidences indicating that dark matter exists. One of the biggest unsolved, but very well measured, problems in physics.

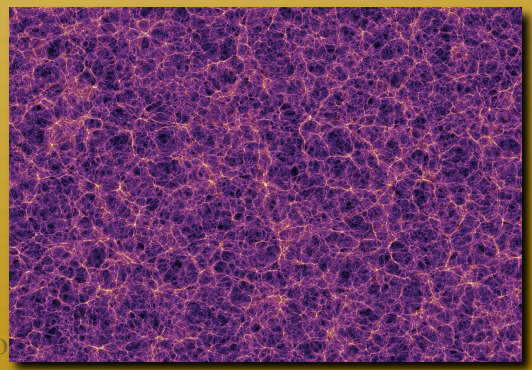
- Observations indicate that DM interacts mainly gravitationally.

- So far, we have no (non-contradictory) observations that DM was detected by any non-gravitational mechanism.









Candidates

- Neutralinos (higgsino, bins, winos, singlinos)
- Axinos
- Gravitinos
- Sneutrinos
- Axions
- Sterile neutrinos
- 4th generation neutrinos
- Kaluza-Klein photons
- Kaluza-Klein gravitons
- Brane world dark matter/D-matter
- Little higgs dark matter
- Light scalars
- Superheavy states (ie. “WIMPzillas”)
- Self-interacting dark matter
- Super-WIMPs
- Asymmetric dark matter
- Q-balls (and other topological states)
- CHAMPs (charged massive particles)
- Cryptons, …

DE/DM Interaction

Each component is not conserved alone anymore. Cosmological equations:

$$\dot{\rho}_m + 3H\rho_m = -Q,$$

$$\dot{\rho}_\phi + 3H(1+w_\phi)\rho_\phi = Q,$$

Many many models in the literature:

- Phenomenological (For a classification see [Koyama, Maartens, Song, 0907.2126])

  - Interaction depending on DM

  - Interaction depending on DE

  - Interaction depending on DM and DE

Constant coupling or Time varying coupling

Coupling must be small : constraints from observations!

In general no analytic solution!

New Evidence Against ΛDCM

Baryon Acoustic Oscillations in the Lyα forest of BOSS DR11 quasars.

T. Delubac et al. [BOSS Collaboration] – A&A 574, A59 (2015), arXiv: 1404.1801

- From adjusting the BAO peaks and combining with the ΛCDM fiducial values from Planck+ WMAP:

$$H(z = 2.34) = (222 \pm 7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}) \times \frac{147.4\,\mathrm{Mpc}}{r_d}$$

$$D_A(z = 2.34) = (1662 \pm 96\,\mathrm{Mpc}) \times \frac{r_d}{147.4\,\mathrm{Mpc}},$$

$r_d = 147.4$ Mpc

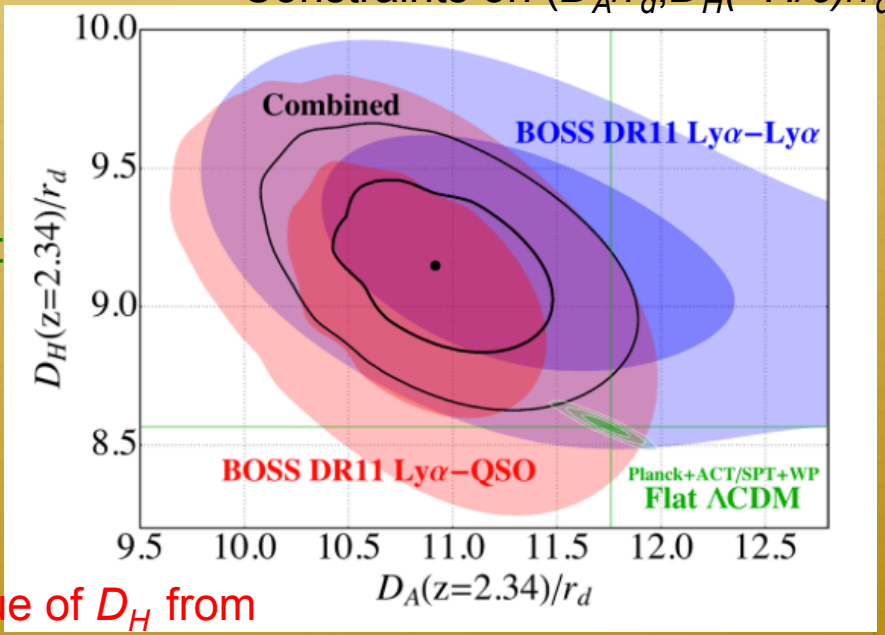
- Blue contours represent the Lyα forest autocorrelation and in red the quasar Lyα forest cross- correlation (Font-Ribera et al., 2014), and the combined constraints (black).

- Green contours are CMB from Planck+WP +SPT+ACT (Ade et al., 2013) assuming a flat ΛCDM

- Values differ: 1.8σ from Planck+WP;

  1.6σ from WMAP9+ACT+SPT

Constraints on (D_A/r_d,$D_H(=H/c)/r_d$)



Conclusion: Approximately 2σ below the value of D_H from autocorrelation and 2σ above the value of D_A from cross-correlation compared to the ΛCDM prediction.

New Evidence Against ΛDCM

Baryon Acoustic Oscillations in the Lyα forest of BOSS DR11 quasars.
T. Delubac et al. [BOSS Collaboration] – A&A 574, A59 (2015), arXiv: 1404.1801

Consequences in cosmology:

- Assuming flat space and universe with only dark energy and dark matter, and using the parameter values from Table I:

$$\frac{8\pi G}{3}\rho_{\rm de}(z) = H^2(z) - H_0^2\Omega_M(1+z)^3 \,.$$

$$\frac{\rho_{\rm de}(z=2.34)}{\rho_{\rm de}(z=0)} = -1.2 \pm 0.8 \,.$$

~2.5σ difference from the expected from ΛDCM!

- Deviation from ΛDCM! Need to be revised!!
- Simplest generalization, dynamical dark energy, does not work!
- Negative values for the energy density of DE.
  - Requires exotic forms of DE, e.g., phantom DE.
- We propose a simpler model that can accommodate this new result:

Interacting dark energy

Table I: Parameters from Planck+WMAP for ΛDCM

Parameter	Bestfit	σ
h	0.706	0.032
$\Omega^0_{DM}h^2$	0.143	0.003
Ω^0_{DE}	0.714	0.020
$\Omega^0_b h^2$	0.02207	0.00033

Hidrogênio

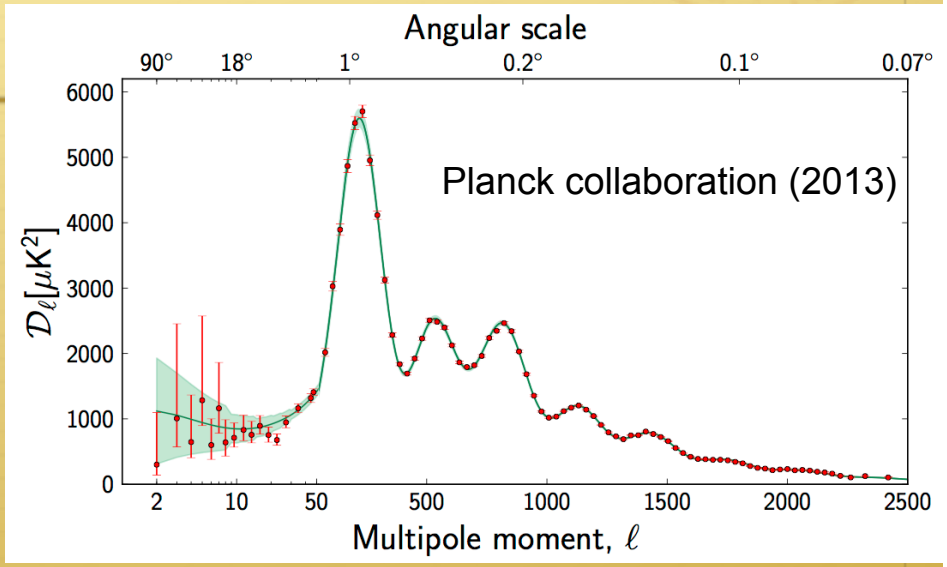
- 75% da massa do Universo visivel (baryons) é Hidrogênio (24% Hélio, o resto é quase nada!)
- De acordo com a Mecânica Quântica, a diferença entre os níveis de energia de spins (p,e) paralelos ou antiparalelos, é correspondente à transição hiperfina.
- A linha de radiação correspondente tem comprimento de onda de 21cm

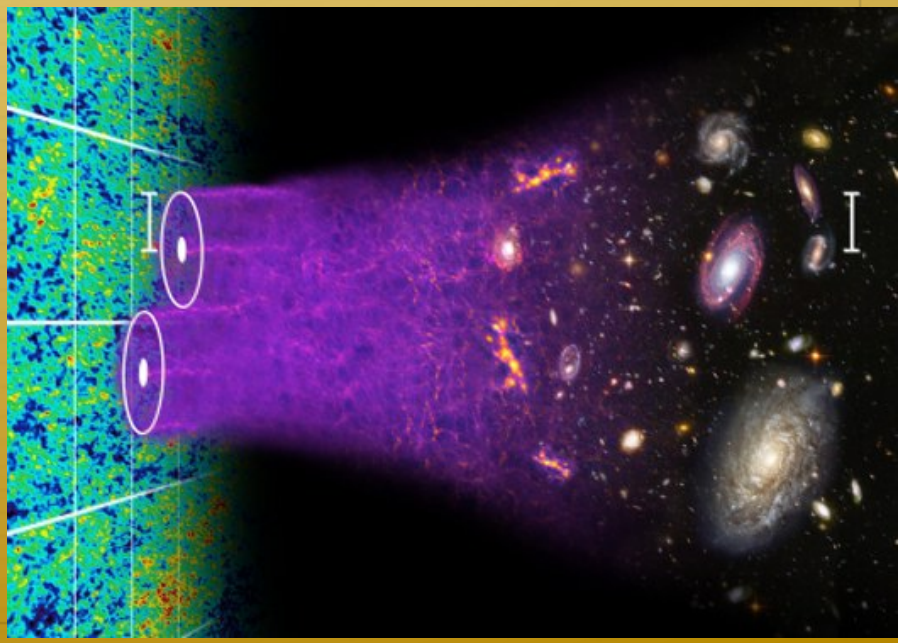
Hidrogênio

- Portanto a linha de 21 cm nos fornece um mapa da distribuição de Hidrogênio no Universo.
- O mapa de Hidrogênio, por sua vez, indica um mapa de distribuição de matéria.
- As ondas de matéria são identificadas, as chamadas BAO (Baryonic Acoustic Oscillations)
- Temos então vínculos sobre os parâmetros

Baryon Acoustic Oscillations (BAOs)

- Ondas acústicas formadas na Radiação de Fundo 380,000 anos depois do Big Bang
- A escala acústica é a distância luminosa atravessada naquele tempo
  - Conhecida do espectro de CMB
- A escala de BAO está impressa em todo o conteúdo material do Universo
  - Pode ser usada como régua padrão para medir a expansão
  - Vincula modelos do Setor Escuro do Universo!!!

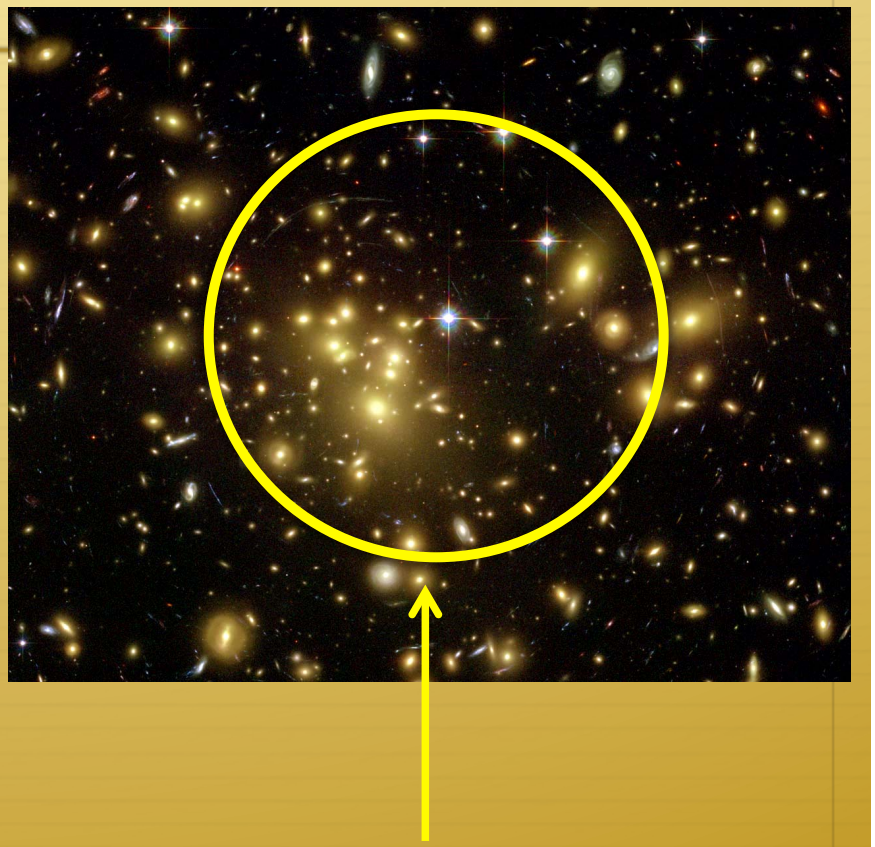




Mapeamento de Intensidade HI (linha de 21cm)

First proposed by Peterson (2006) and proof-of-concept with GBT (Chang et al. 2010; Switzer et al. 2013)

- Alternativa eficiente de medir miliões de galáxias individualmente (e.g. BOSS, Euclid, SKA…)
  - Redshift diretamente da frequency
  - Não há linhas de absorção
  - HI mede massas em grandes escalas
  - Grandes setores do céus
  - Mede fluduações de HI (power spectrum como função da f frequência)
- BAOs em z≈0.3: **BINGO**
  - Único (CHIME em z≈1)
  - Complementar aos óticos
  - Dados adicionais de BAO

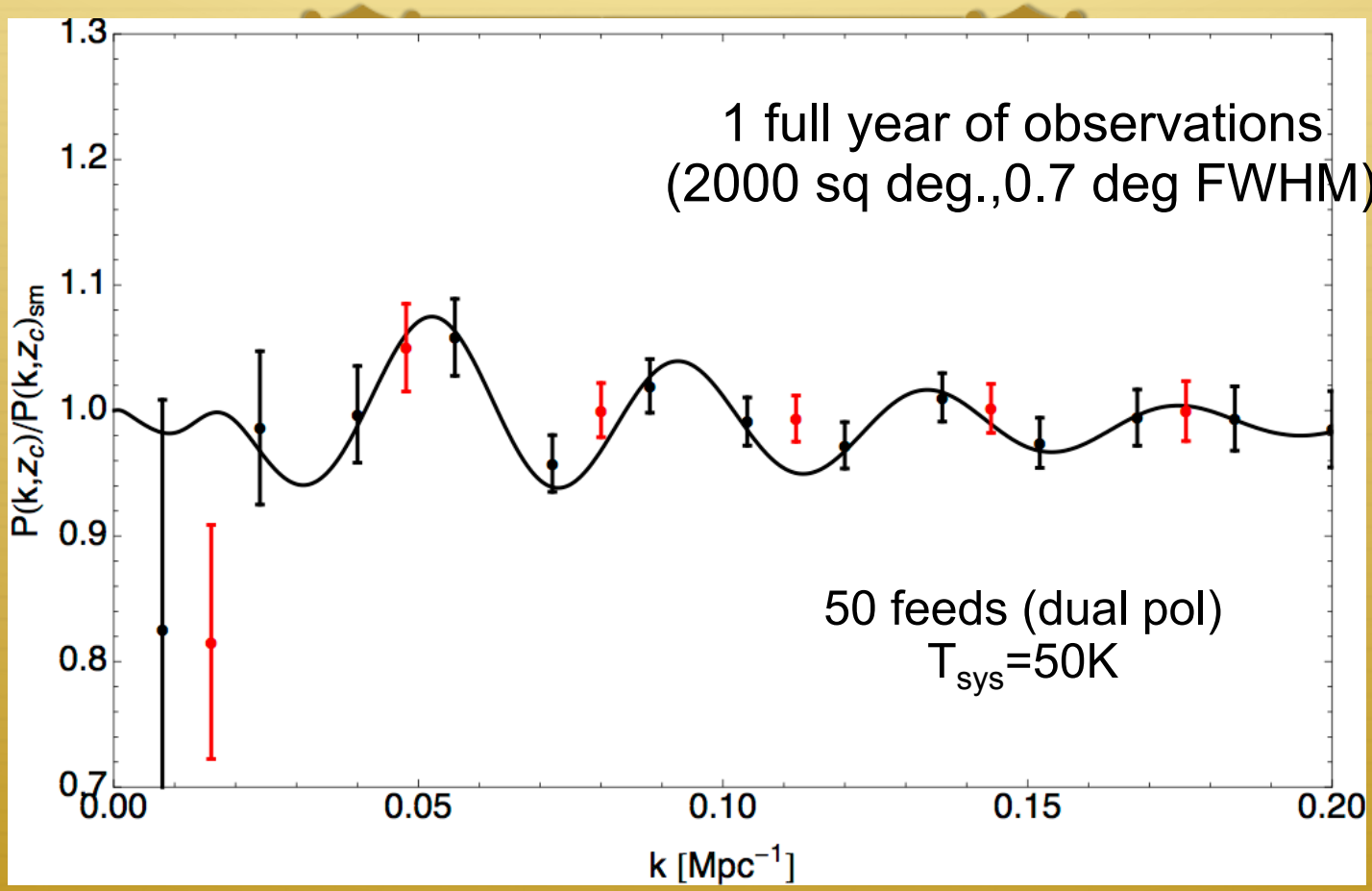


Large beam on the sky (≈1 deg) contains large number of galaxies

Battye, Browne, Dickinson, Heron, Maffei, Pourtsidou
2013 MNRAS, 434, 1239 [arXiv:1209.0343]

Detecção Projetada de BAO

≈5 sigma detection should be achievable in 1 year on sky (probably 2 years real time)
(we have been conservative in our error budget)



Medida da escala acústica $\delta k_A/k_A \approx 0.024$ (2.4%)

•Projected constraint on dark energy $\delta w/w \approx 0.16$

BINGO concept

- *BAO from Integrated Neutral Gas Observations (21 cm Hidrogen line)*
- *Brazil, UK, Switzerland, Uruguay, China*
- *0.96 GHz to 1.26 GHz, be of a two-mirror compact range design with a 40 m diameter primary and have no moving parts*

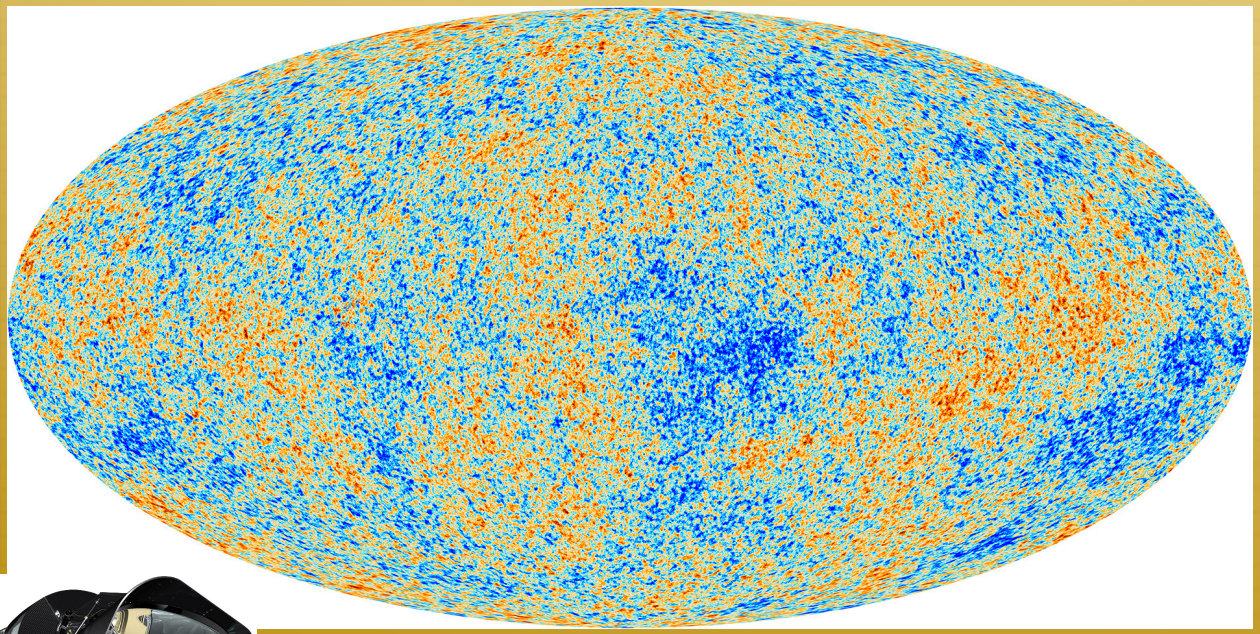
MANCHESTER 1824
The University of Manchester

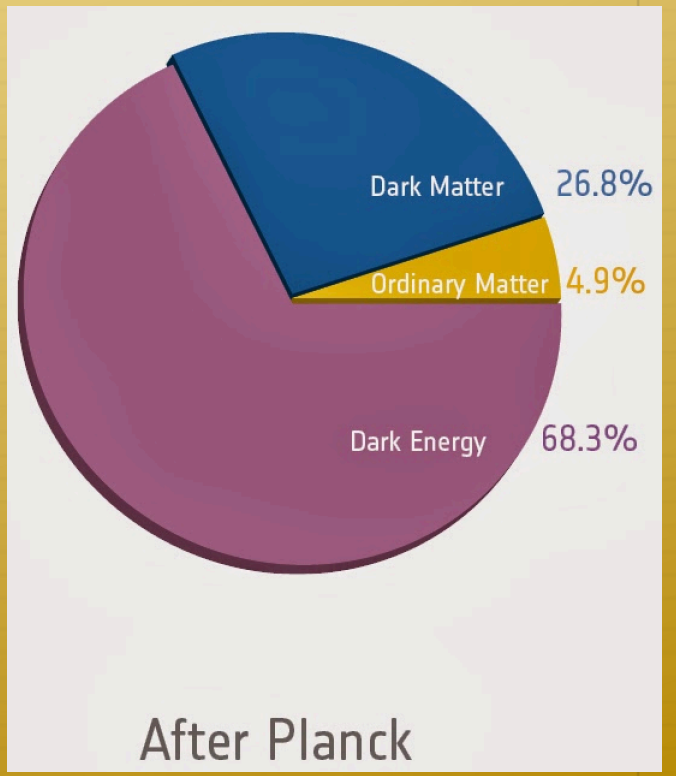
Cosmology with future ultra-deep radio astronomy surveys:
HI intensity mapping with BINGO

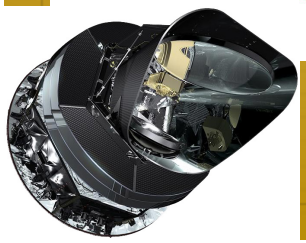
BINGO team

Era of precision cosmology

- Cosmology is now in a golden area
  - Standard ΛCDM model appears to be correct so far!
- But still major questions! E.g.
  - Inflation ($t<10^{-32}$ s)
  - Dark energy



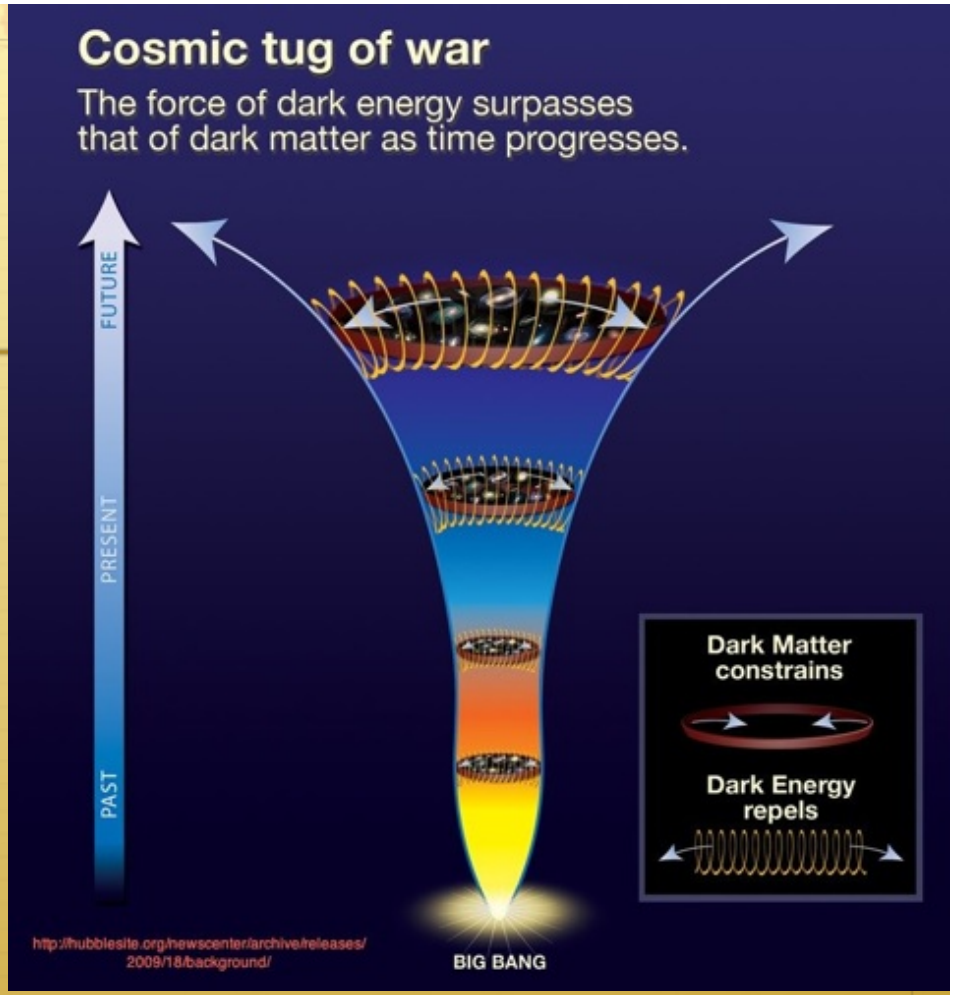




CMB map from Planck collaboration et al. (2013)

Dark Energy

- Dark Energy is beginning to dominate the Universe!
- Accelerated expansion since z≈1
  - Nobel Prize 2011
- Very little is known



$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

acceleration — gravity — cosmological constant

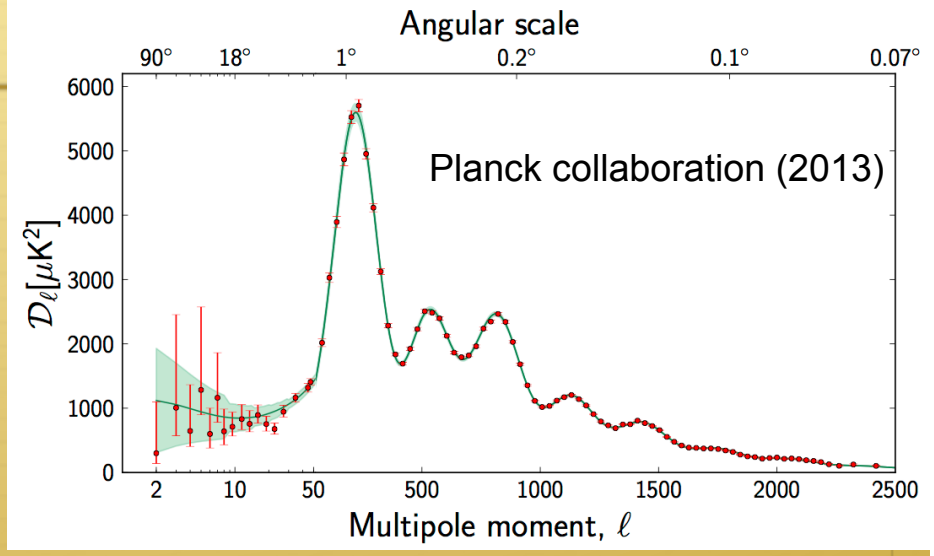
slows down expansion — speeds up expansion

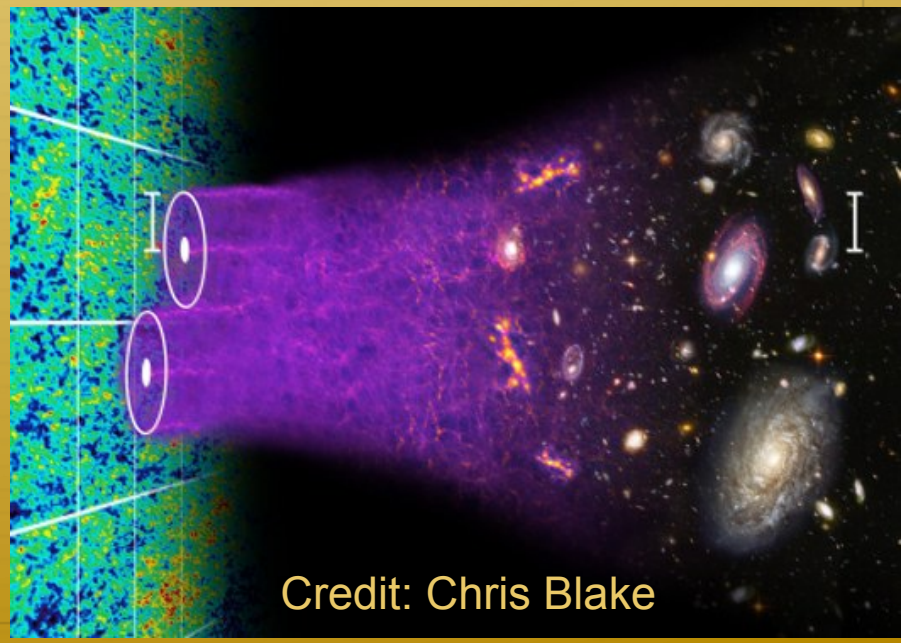
$$w = \frac{P}{\rho} < -1/3$$

(w=-1 is a cosmological constant)

Baryon Acoustic Oscillations (BAOs)

- Acoustic waves imprinted on CMB 380,000 years after Big Bang
- Acoustic scale set by distance light travelled at that time
  - Known precisely from CMB power spectrum
  - D=147.4 ± 0.6 Mpc
- BAO scale imprinted on all matter in the Universe
  - Use as a "standard ruler"





Square Kilometre Array (SKA)

Note: SKA international headquarters at Jodrell Bank Observatory (Manchester)

- SKA will be the world's largest radio telescope
  - 2020 before phase I is complete
- Can measure >10^9 galaxies in HI (21cm line) -> precise BAO measurements!
  - HI expected to be a good tracer of total mass
  - No absorption of the signal along the line-of-sight
  - Get redshifts (distances) for free!

BINGO :

BAOs from

Integrated

Neutral

Gas

Observations

BINGO Players

Bin Wang + others
YangZhou

Also others from Paris, South Africa

Brazil
Elcio Abdalla, Raul Abramo, Alex Wueunsche, Thryso Villela, +engineers (INPE) Luciano Barosi et al (Paraiba)

Manchester:
Ian Browne, Richard Battye, Clive Dickinson, P. Wilkinson, + Jodrell Bank

Saudi Arabia
Yaser Hafez

University College London:
Filipe Abdalla
Also others from england

Uruguay, Gonzalo Tancredi, Manuel Caldas

Zurich (ETH)
Alex Refregier
Adam Amara
Christian Monstein

BINGO (revised) concept

Key specifications

Dish diameter : 40m

Resolution : 2/3 deg

Frequency range : 960 - 1260MHz

Number of feeds : 50 (dual pol.)

No cryogenics : $T_{sys} \approx 50K$

Digital correlation receiver

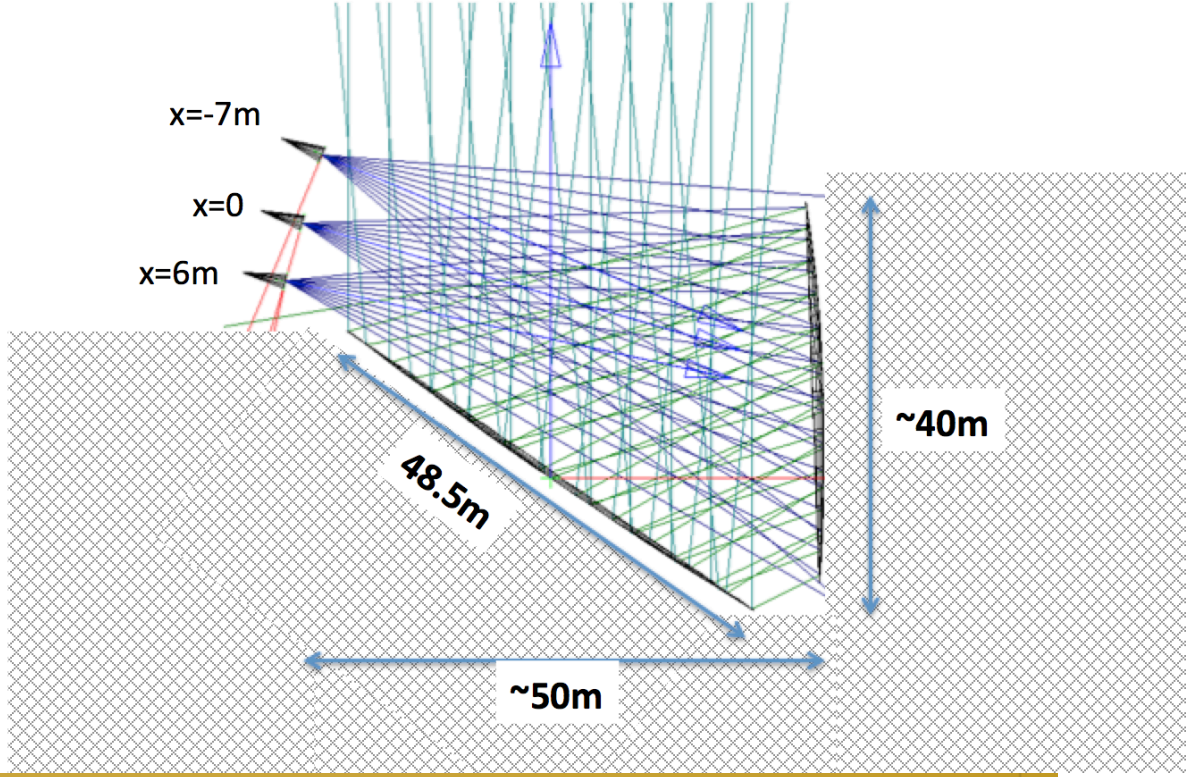
All components are "off-the-shelf"

Survey Design

Observation time : 1 year on source

Area : 10 x 200 deg^2 – drift scan

- Horn aperture diameter ~ 1.7m
- Focal plane size to cover 10x10 deg ~ 14 x 14 m



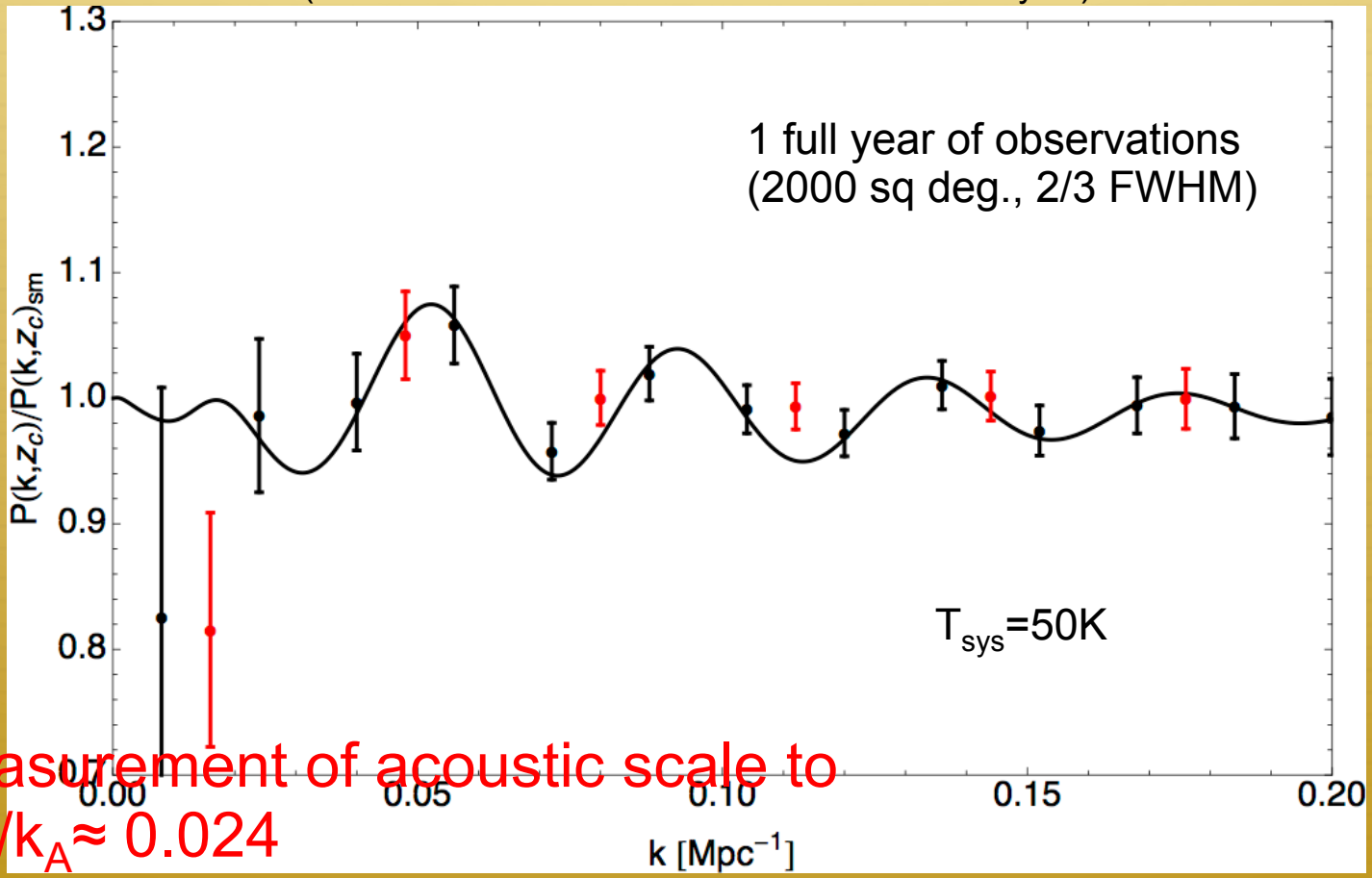
Guiding principle : simplicity !

Static telescope with 2 ~40m dishes
(No moving parts)

After careful design and analysis…

≈5 sigma detection should be achievable in 2 years (real time)

(we have been conservative in our error analysis)



- Measurement of acoustic scale to $\delta k_A/k_A \approx 0.024$
- Projected constraint on dark energy $\delta w/w \approx 0.16$

Additional science with BINGO

(We will have an ultra-deep large-area spectral survey at 960-1260 MHz)

- 1. BAOs contain additional information
  - Matter density
  - Redshift distortions
  - Anisotropic BAOs…
- 2. Life history of hydrogen
- 3. Fast Radio Bursts (FRBs/"Lorimer" bursts)
  - New transient sources discovered (6 up to now)
  - We don't know what they are!
  - BINGO is an ideal survey instrument! (est. 1 detection/ week)
  - In a BINGO phase-2 add outriggers and do astrometry
- 4. Radio recombination lines
- 5. Galactic continuum

Only major challenge: BINGO horns are big!

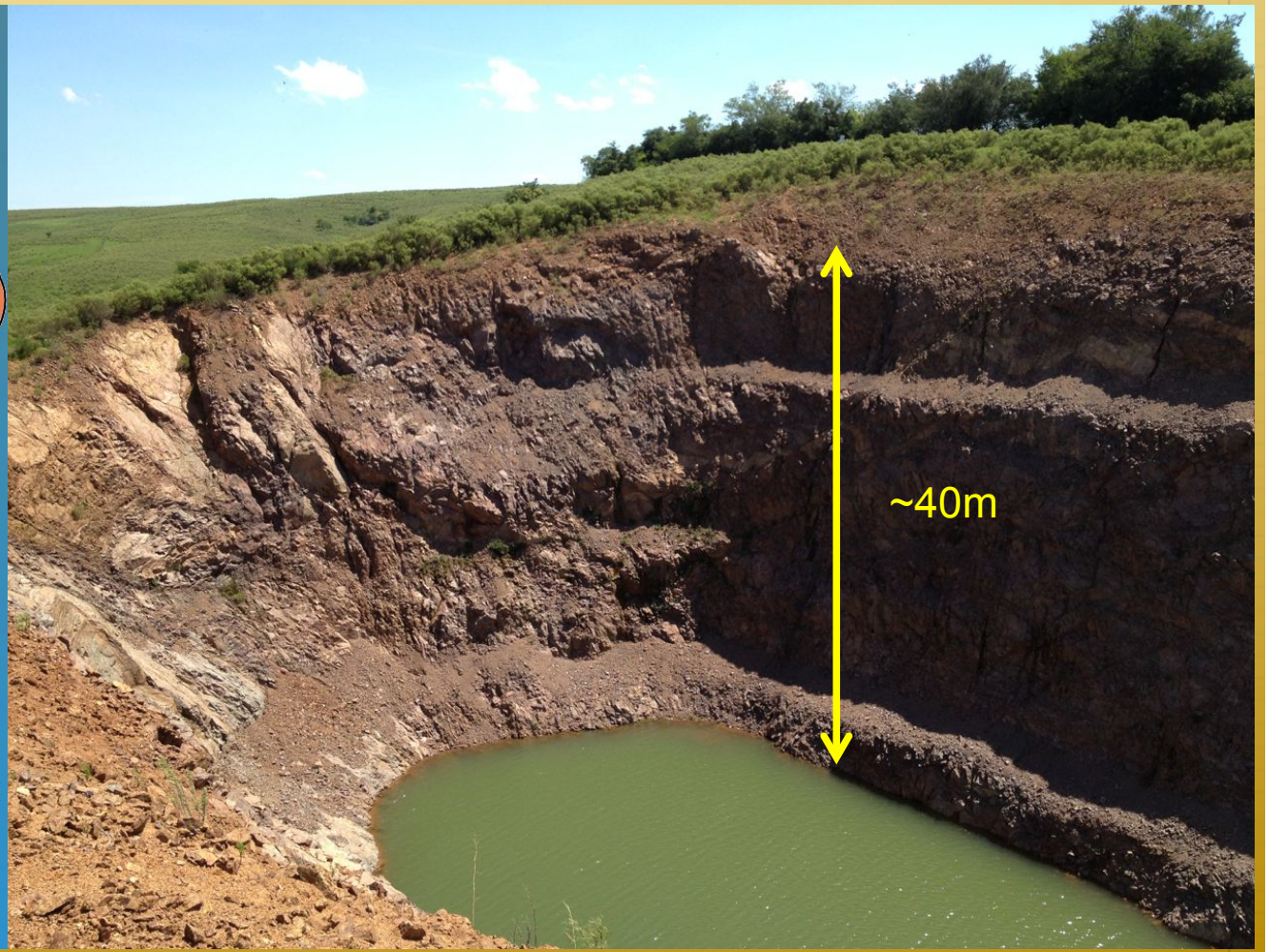
(≈1.7m diameter, ≈4.7m long)

Credit: Ian Browne

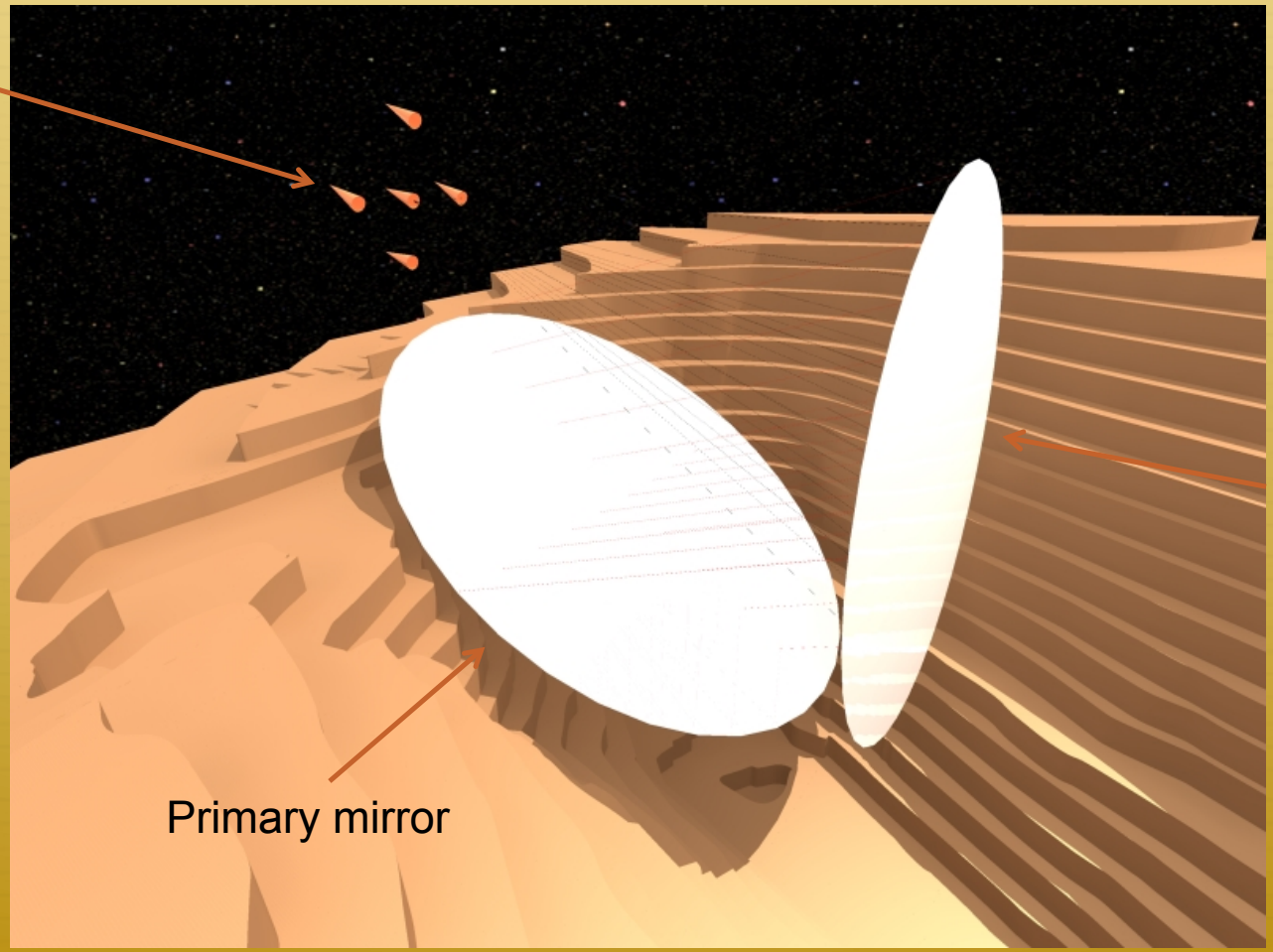
Standard techniques expensive and heavy - alternatives being investigated

1. Foam covered in metal tape (Ian Browne/Manchester)
2. Bend corrugated Aluminium hoops and fix together (INPE)

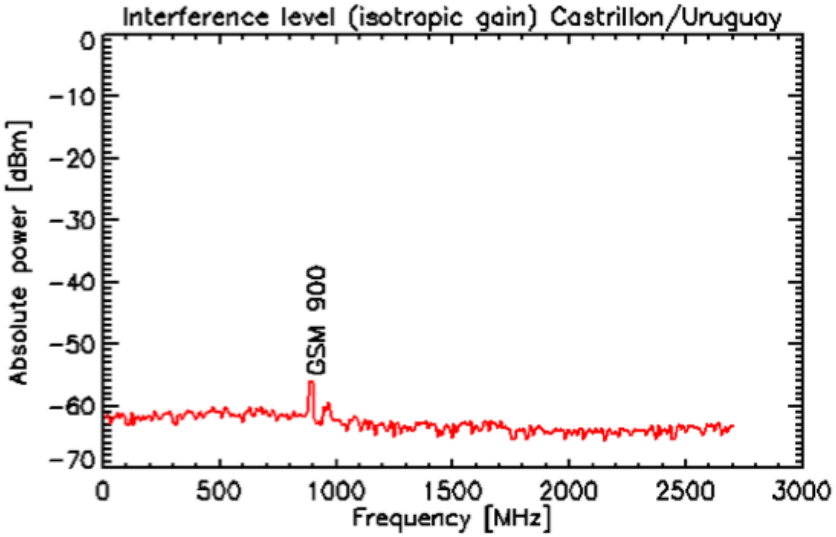
First BINGO site: Quarry Castrillon (N. Uruguay)

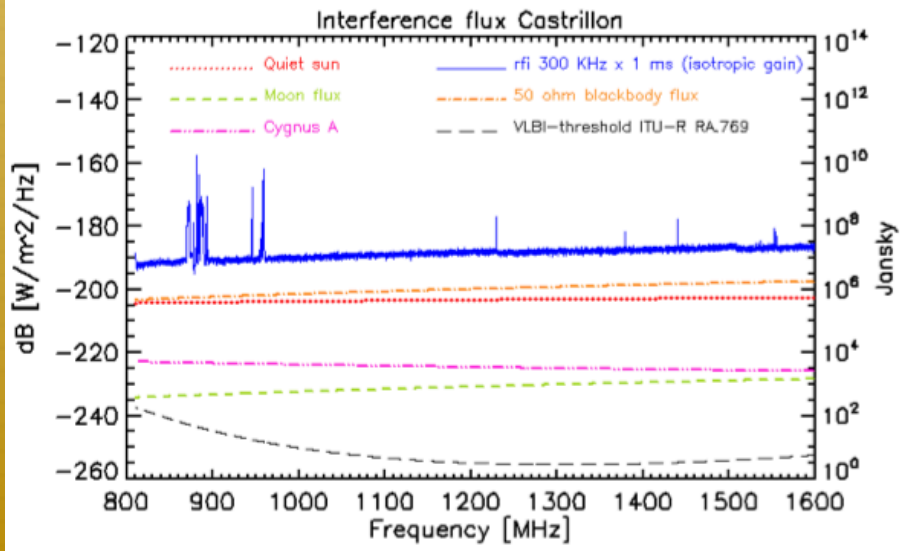


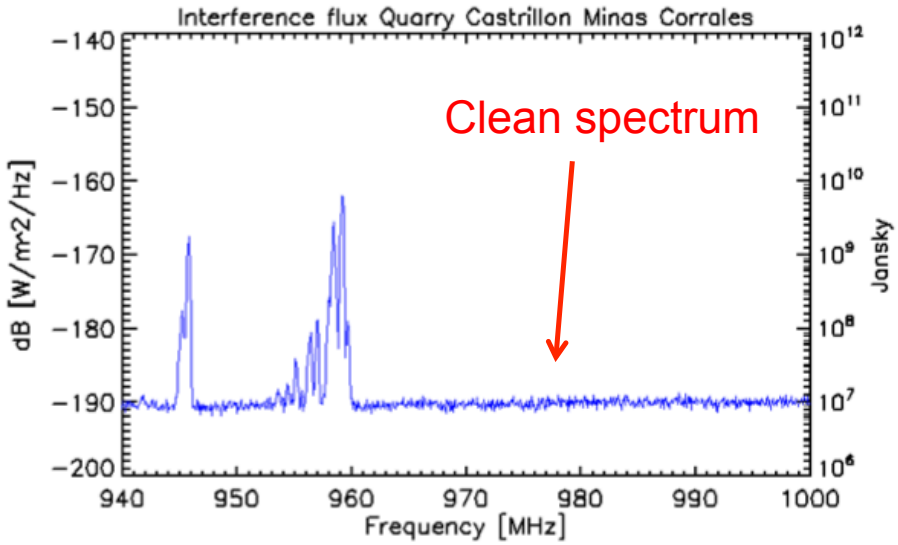
Preliminary 3-D model of optics in Castrillon



Castrillon RFI tests – looked acceptable!





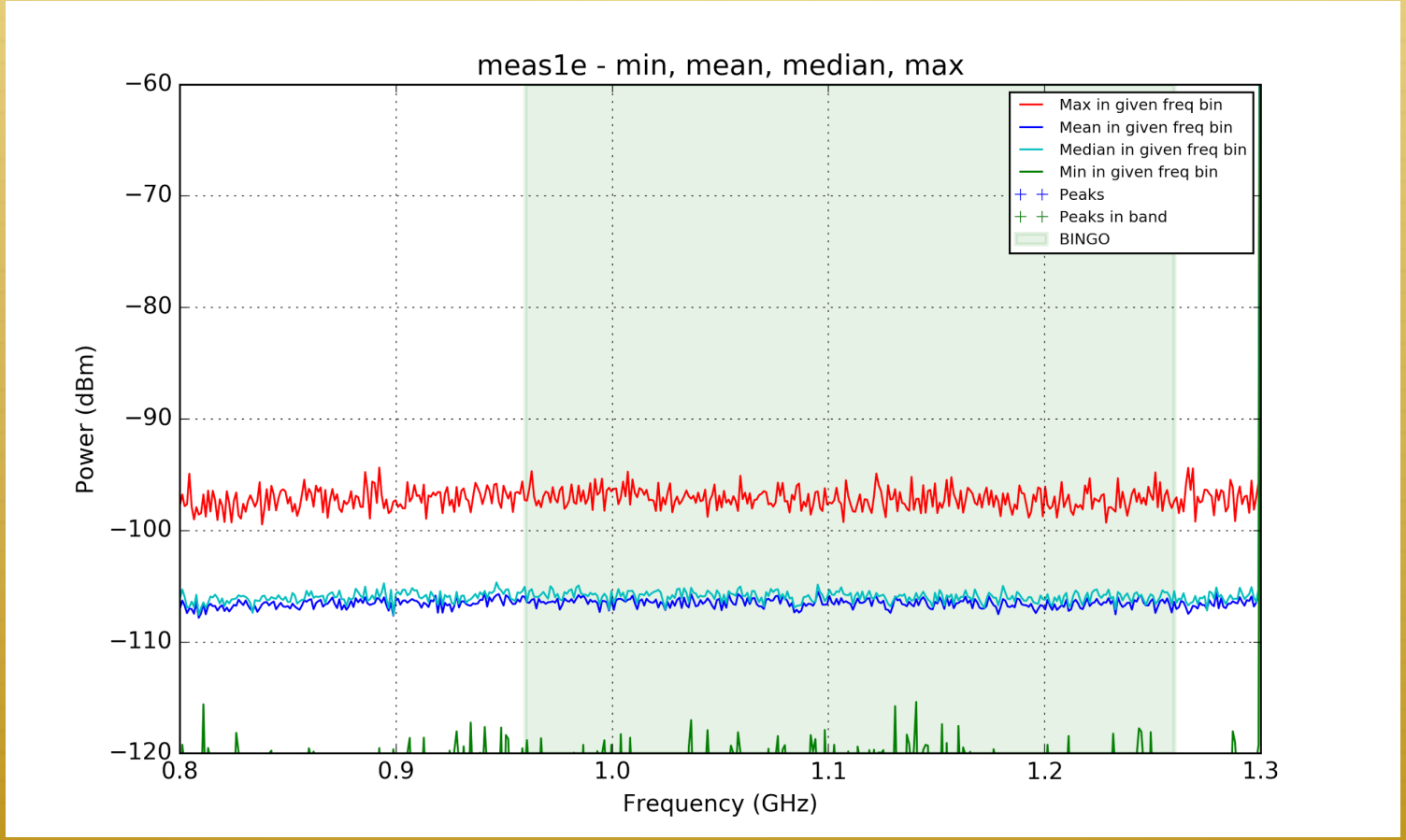


Gold mine Castrillon in Minas Corrales

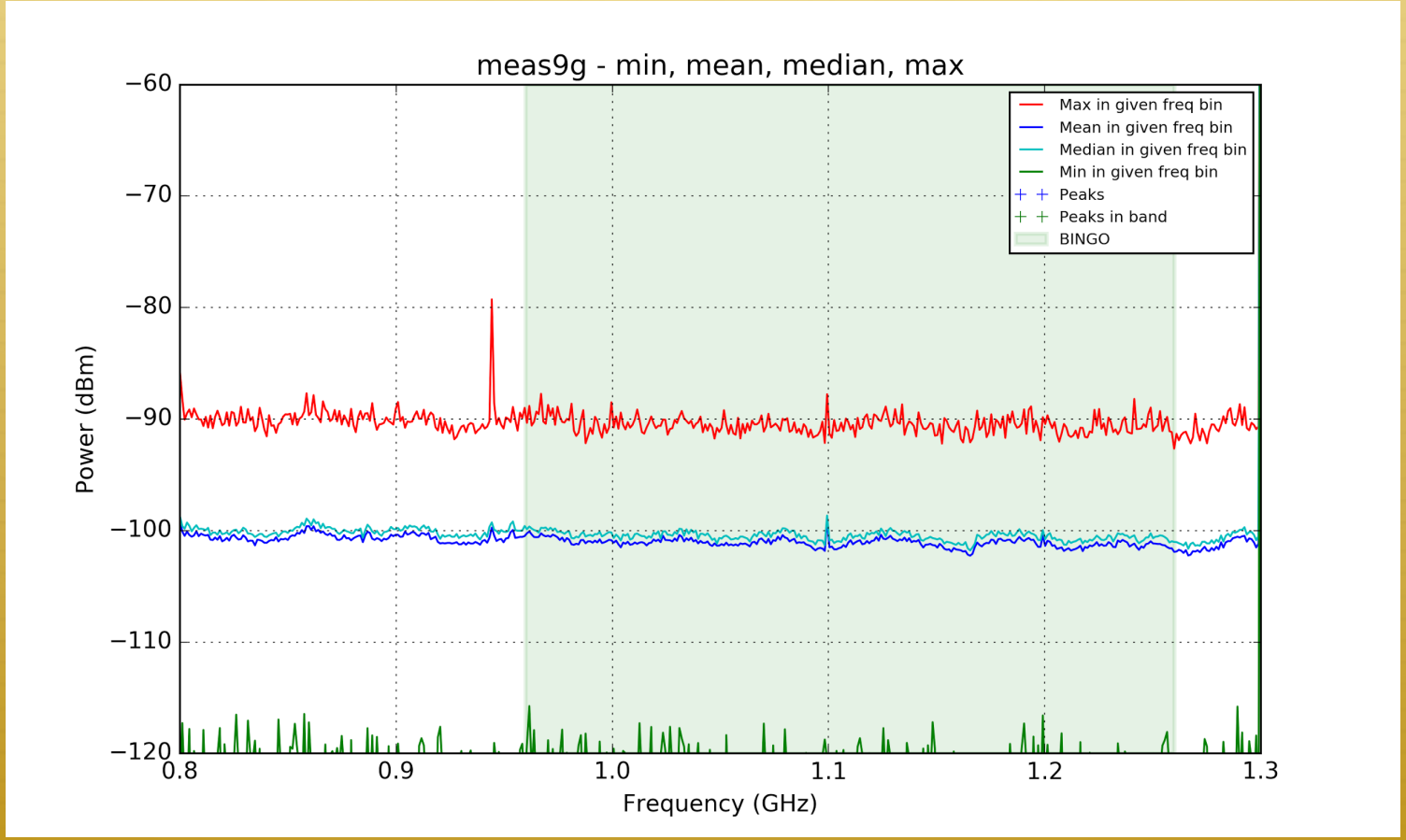
The BINGO project: Paraíba

- **Site 1 - Serrote das Flores - 1 August 2017 07°02’59.97”S, 38°37’57.33”W** - Vão do Gato (Altitude 451m)
- Site appears clean. We need to revisit this site with a better amplifier.
- 
- *Surveying the site - the entrance can be seen at the back, and this is facing the valley opening.*

The BINGO project: Paraíba



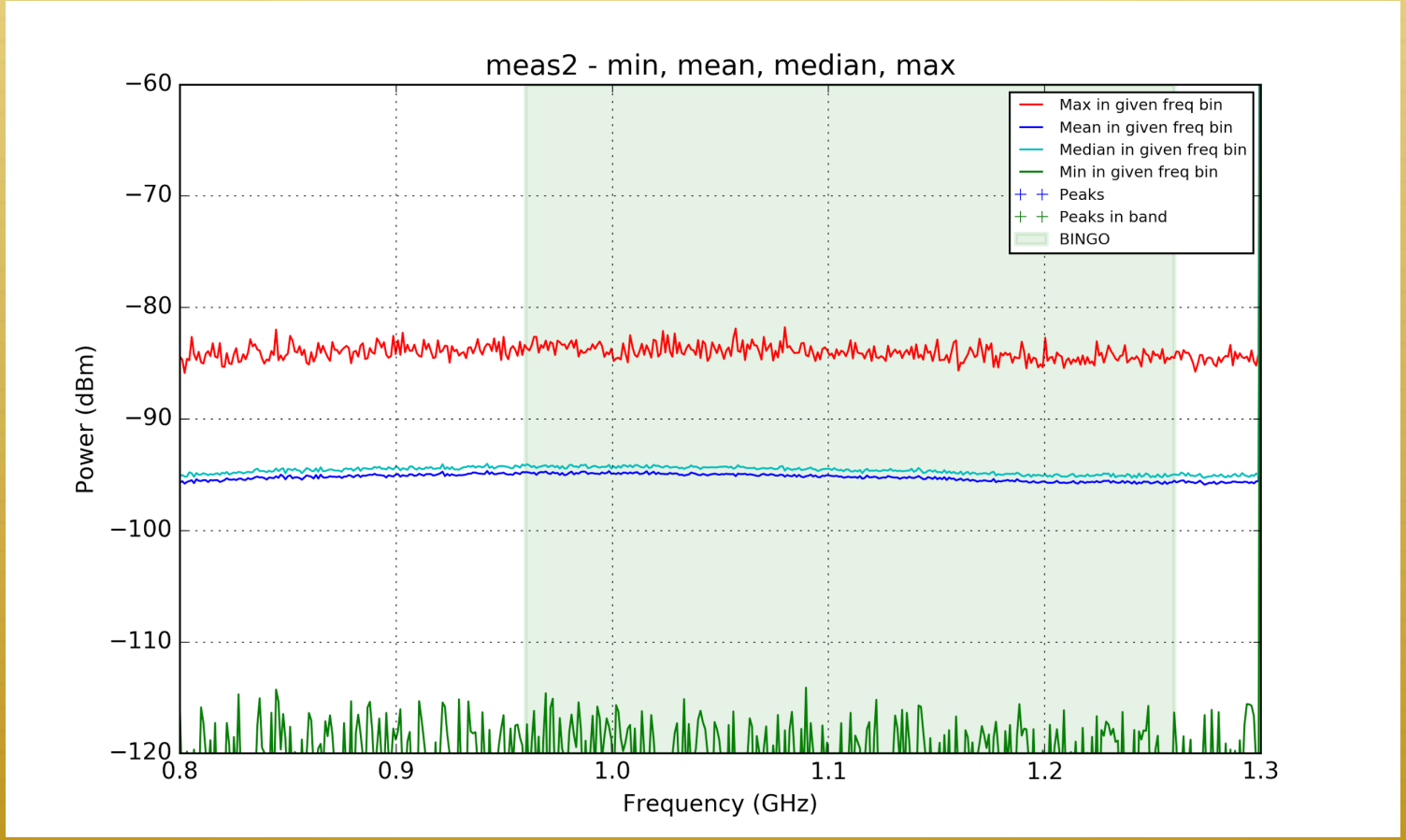
The BINGO project: what is not wanted (Cariri)



The BINGO project

- **(South of Serra da Catarina) - 2 August 2017**
- **07°02’51.82”S, 38°15’34.23”W (Upper location; altitude 318-324m)**
- 
- no signals were seen at this site, but more sensitive measurements are needed before it can be directly compared to other sites.

The BINGO project

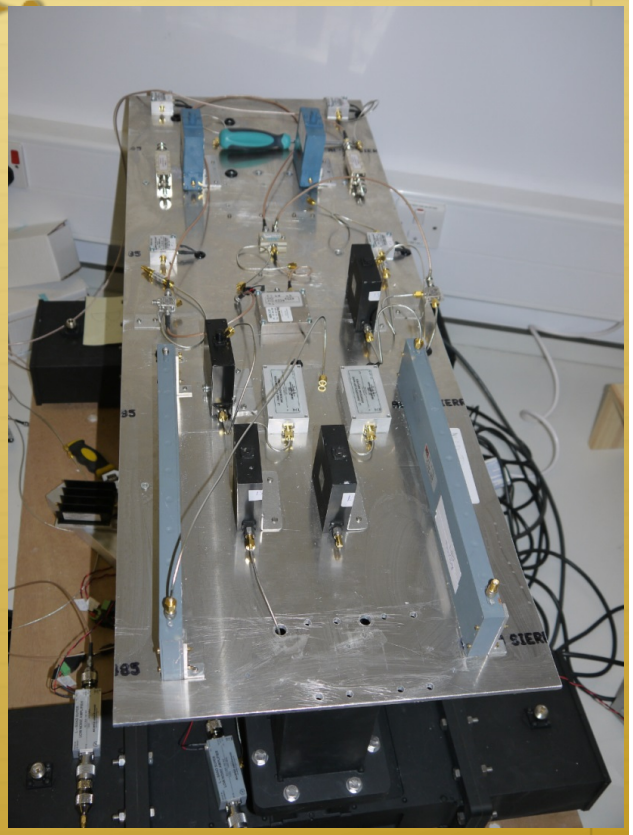


Project status

- We are basically ready to go!
- Strong collaboration has been formed
- We have as expertise
  - Cosmology/astronomy (Sao Paolo/INPE)
  - Receivers, antennas, telescopes, engineering (INPE)
  - 80m antenna range with 5m shielded room (INPE)
- Good site identified
- Lots of student/post-doc interest
  - Students and post docs in Manchester

Funding

- Estimated total cost (all in): US$5.3M
  - Capital cost US$3.5M (conservative estimate)
- FAPESP proposal being evaluated for US $3.0M
- FAPESQ (Paraíba) proposal in negotiation
- Other funding initiatives:
  - STFC SOI submitted (UK)
  - SNSF (Switzerland) LOI sent by ETH Zurich
  - YangZhou University
  - KACST proposal submitted (Saudi Arabia)
  - Proposal to Royal Society (U.K.) for L-BASS project



Prototype receiver being tested at Jodrell Bank

Projects in Cosmology

- ***Field Theory Models of DE and DM*** (E.A., Ricardo Landim (PD, leader), Fabrizio Bernardi (PhD), Bertha Cuadros (EEL))
- ***Comparison with phenomenological Data, CMB, BAO*** (E.A., Andre Alencar da Costa (PD, leader), R. Pinheiro, (MSc), A. Marins (MSc), W. de Paula (MSc), W. Ribeiro (MSc), D. Taschetto (IC), R. Rhavia (PhD), L. Olivari (future PD), R. Landim (PD)).
- ***JPAS related activities (forecast, DE/DM interactions)*** (E.A., Raul Abramo, A. A. Costa (PD), R. Landim (PD), Rafael Marcondes (colaborador))

Projects in Cosmology

- ***Instrumentation in BINGO*** (E.A., C. A. Wuensche (INPE, leader), M. Peel (young researcher, leader), Andreia Souza (engineer), Renato Branco (INPe, Engineer), Karin Fornazier (INPE, PD) Sonia Anton (Visiting Professor), Reitano (INPE)

- ***Noise in BINGO and related questions*** (E.A., C. A. Wuensche (INPE, leader), M. Peel (young researcher) Sambit Roychaudury (Manchester), Sonia Anton (Visiting Professor), Christianne Morais (MSc), D. Soler (MSc)

- ***Forecast in BINGO*** (E.A., Raul Abramo, Andre Alencar, XiaoDong Xu, Bin Wang, R. Landim, F. Bernardi, A. Marins, W. Ribeiro, W. de Paula, R. Rhavia

- ***BINGO construction*** (E.A. (leader), C. A. Wuensche (INPE, leader), Thyrso Vilela (INPE), Sonia Anton, Andreia Souza, Renato Branco, Reitano

Conclusion: BINGO project

- BINGO is an exciting new radio astronomy project
- Fundamental cosmology and much more!
- Design is ready and site selected
- Powerful collaboration in place

Some potential papers from 1st year observations

- 1. BINGO project paper
- 2. Simulations and systematics
- 3. Component separation techniques/algorithms
- 4. Data analysis and calibration
- 5. Beam modeling, measurements and testing
- 6. Cosmological constraints on w_0, w_1, Ω_m
- 7. Combination of cosmological probes
- 8. HI matter power spectrum and spin temperature
- 9. Constraints on f(R) models, DE/DM interactions
- 10. Transients and the variable sky
- 11. FRB detections/statistics and interpretation
- 12. Radio Recombination Line survey and Warm Ionized Medium
- 13. Galactic continuum components – synchrotron spectrum
- … + many more!!!