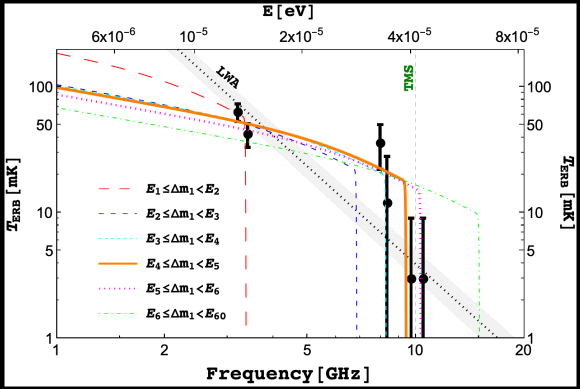
NEHOP 2024 –
New Horizons in Primordial Black Hole Physics
Edinburgh, 17-20 June 2024

Relic neutrino decay solution to the excess radio background mystery



(B. Dev, PDB, I. Soler-Martinez, R. Roshan, JCAP 04 (2024) 046, 2312.03082)

Pasquale Di Bari
(University of Southampton)

HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

UNIVERSITY OF Southampton

Why new physics?

Even barring:

- ❑ (more or less) compelling theoretical motivations
- ❑ Experimental anomalies (e.g., $(g-2)_\mu$, 95 GeV excess,….)

Standard physics (SM+GR) cannot explain:

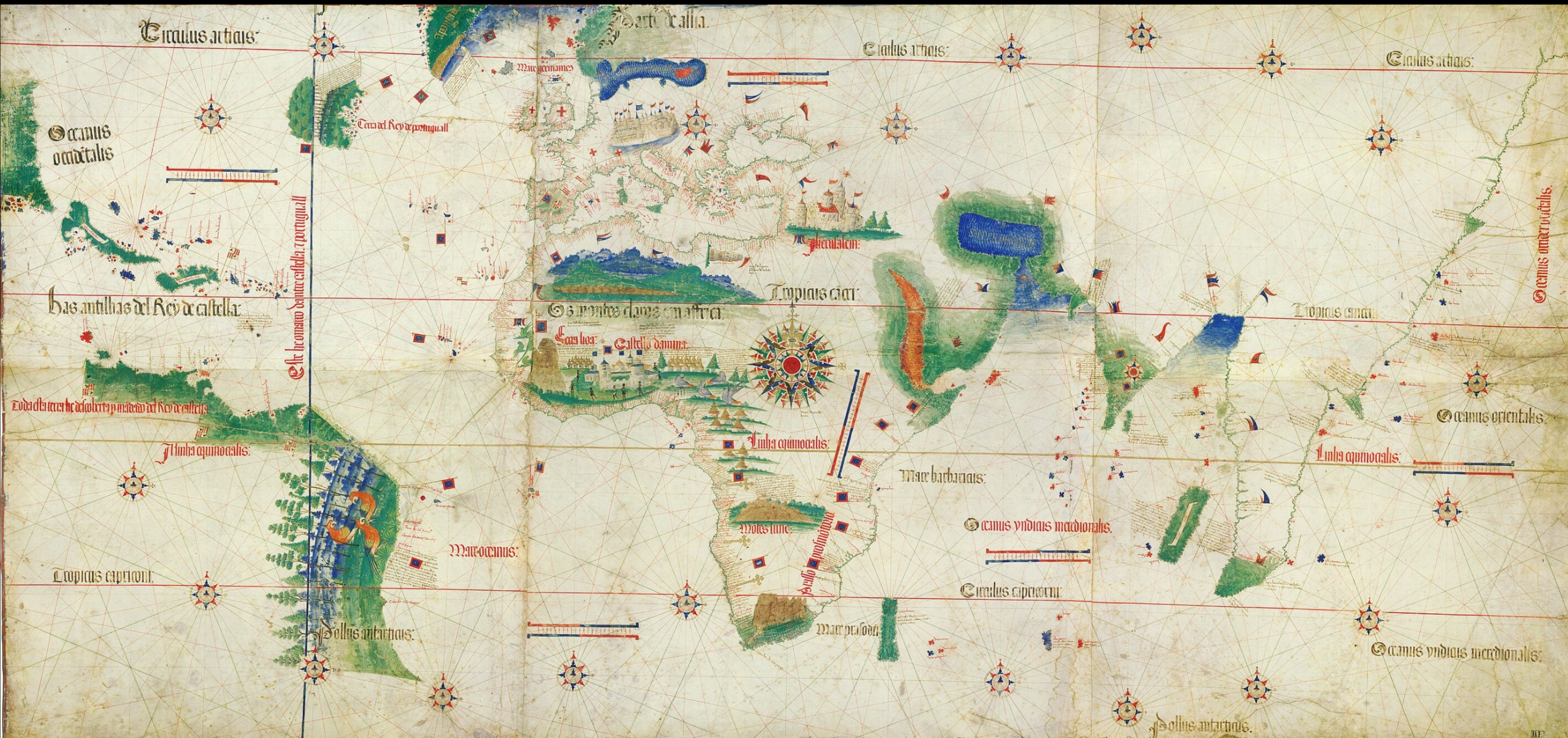
- ***Cosmological Puzzles*** :

1. Dark matter
2. Matter - antimatter asymmetry
3. Inflation
4. Accelerating Universe at present

problem of the origin of matter in the universe

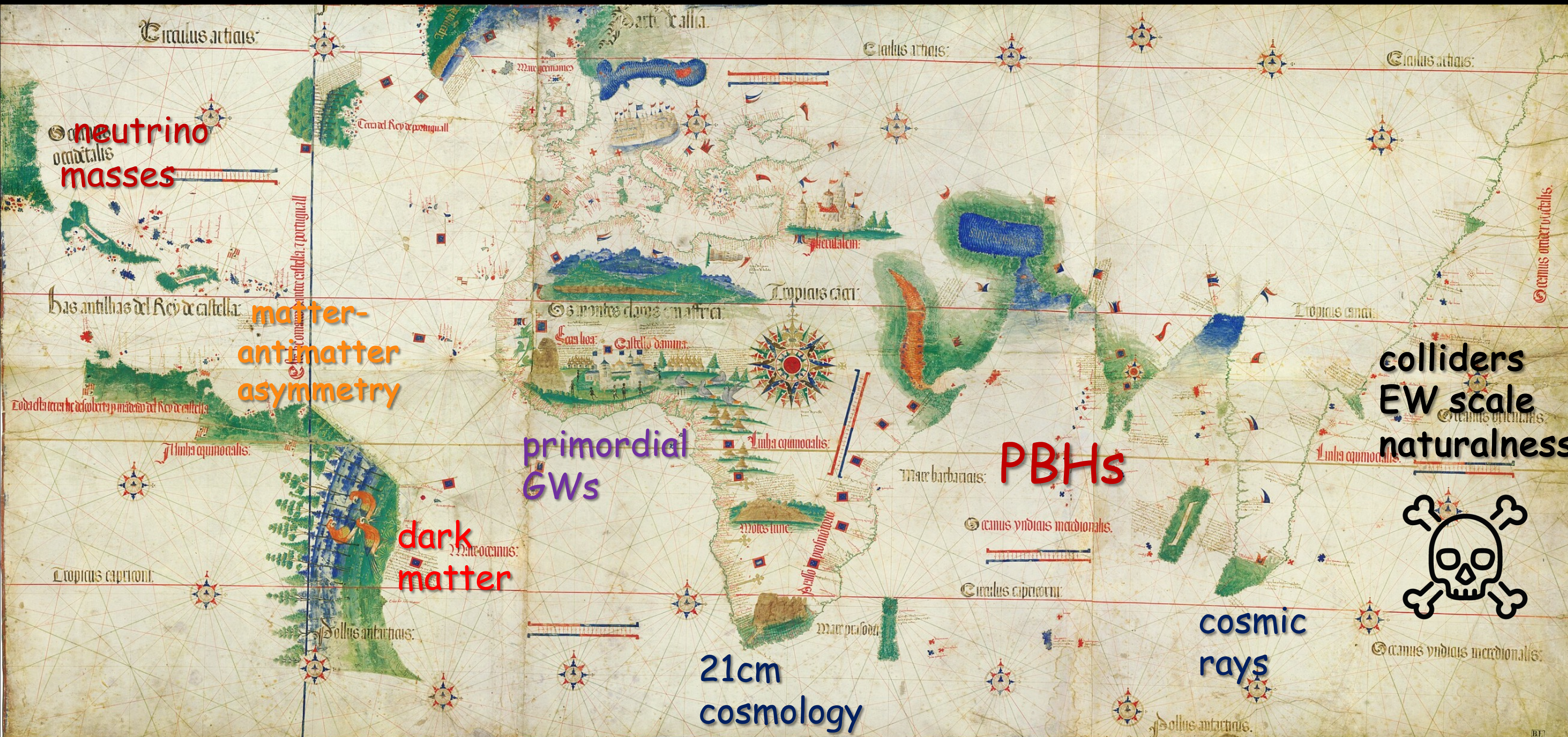
- ***Neutrino masses and mixing***

A map to new physics?



(Cantino planisphere, 1502, Biblioteca Estense Modena)

A map to new physics?



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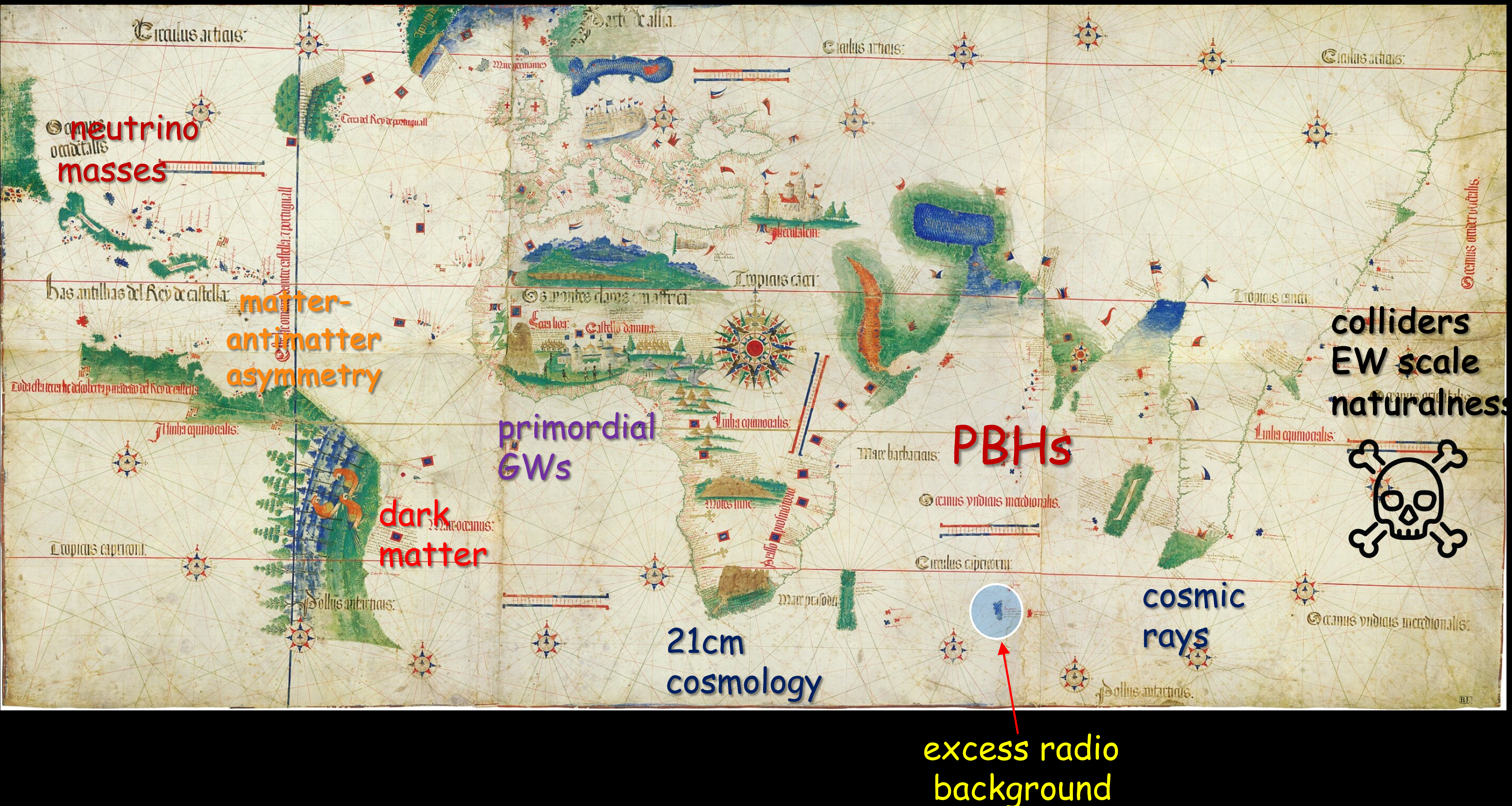
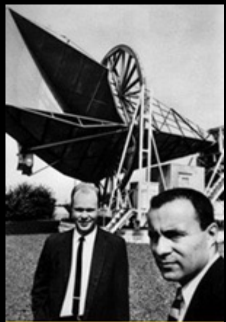


CMB spectrum: the most perfect Planckian



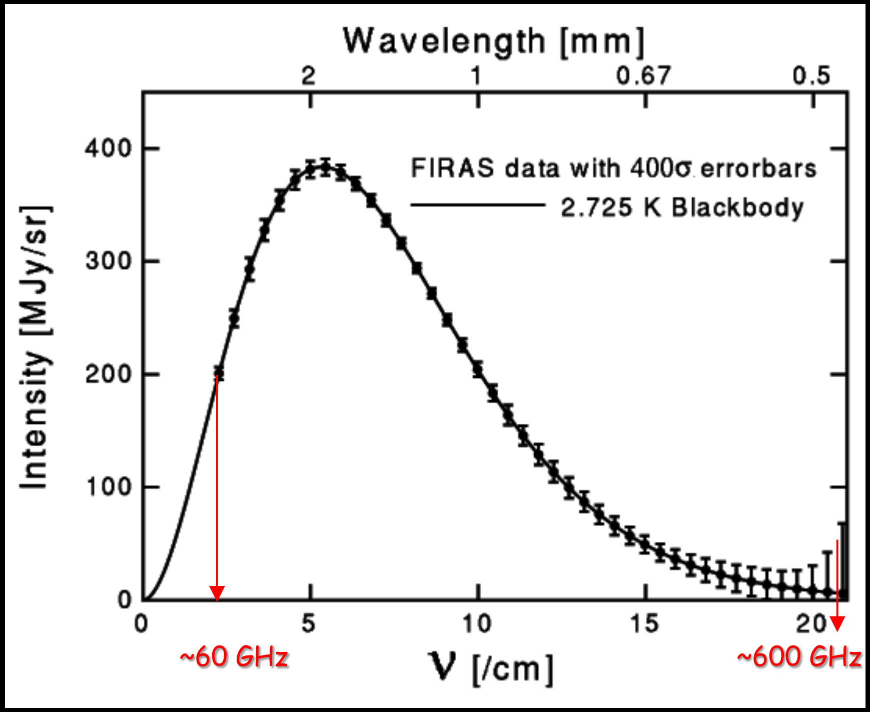
Penzias and Wilson (1965)

$T_{\gamma 0}$= (3.5 ± 1) ^{0}K

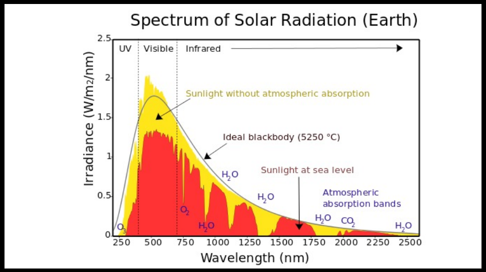
COBE satellite

FIRAS instrument of COBE (1990)

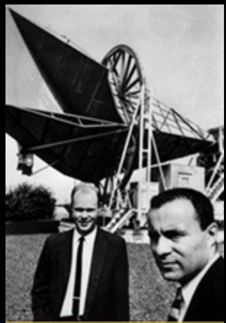
$T_{\gamma 0}$= (2.725 ± 0.001) ^{0}K (Fixsen and Mather 2002)



for a comparison



The CMB spectrum: most perfect Planckian in nature



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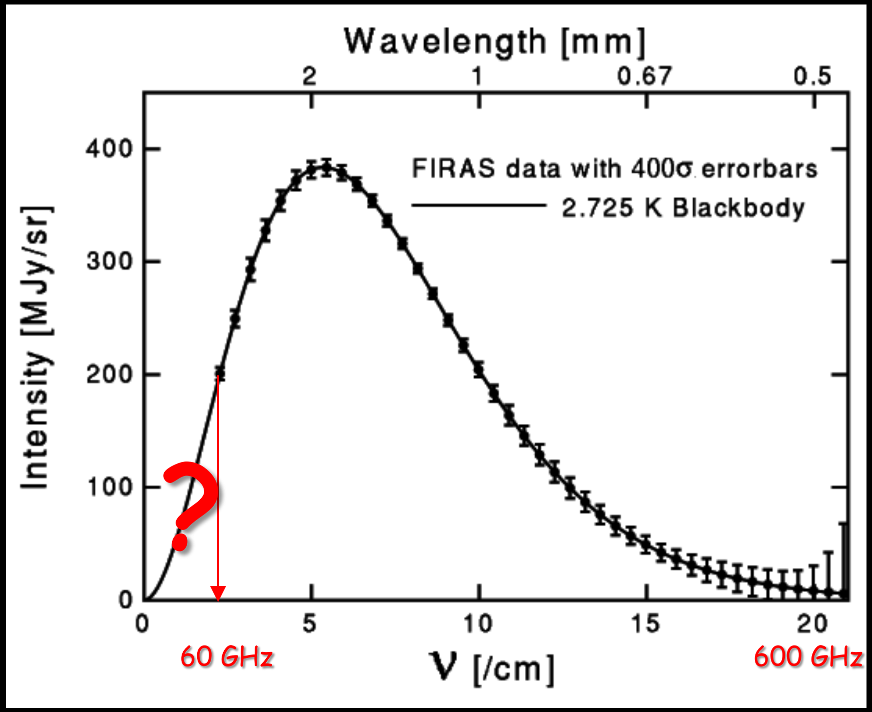
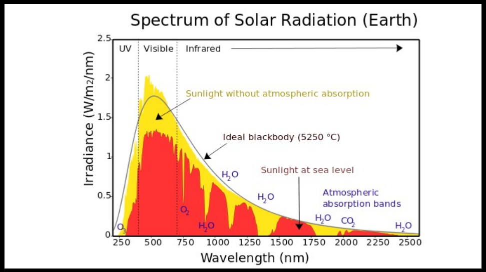


for a comparison

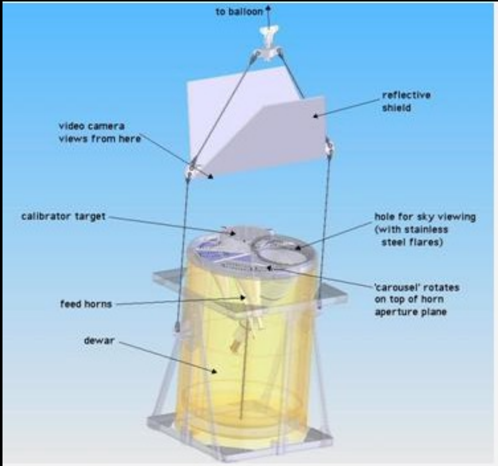


Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission (ARCADE 2)

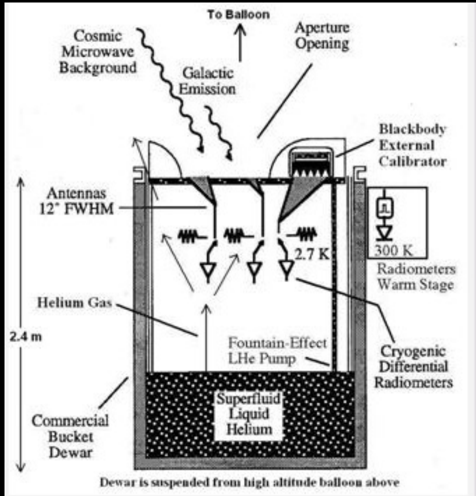
ARCADE 2: The instrument

(Singal, Fixsen, Kogut, Levin, Limon, Lubin, Mirel, Seiffert, Villela, Wollack, Wuensche 0901.0546)

FIG. 5.— Photograph of the ARCADE 2 instrument just prior to 2006 flight. The instrument core is contained within the large (1.5 m diameter, 2.4 m tall) bucket dewar. The lid is shown closed



Schematic of ARCADE 2 instrument, showing the big dewar, the suspension structure above, the horns hanging inside to form the core.



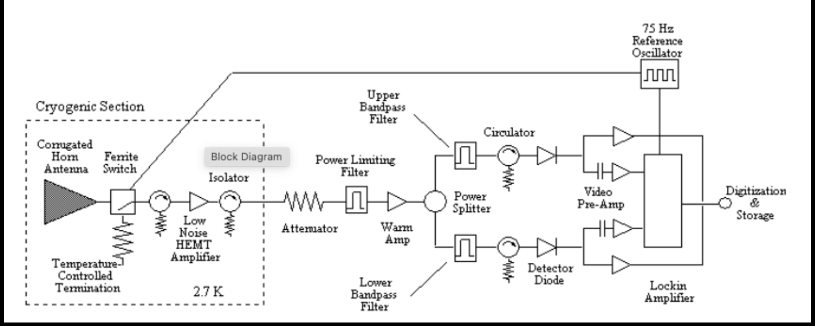
Schematic of ARCADE 2 instrument, highlighting the radiometric and thermal features.

- Balloon-borne instrument with 7 (Dicke) radiometers mounted in a liquid helium bucket dewar
- A cryogenic switch connects the amplification either to a horn antenna or to an internal reference load
- The temperature of the reference load is adjusted in a way to produce zero differential signal, nulling the radiometer output
- The horn can view either the sky or an external blackbody calibrator
- The blackbody temperature can be adjusted to match the sky temperature nulling instrumental offsets (*double nulled instrument*)
- The sky temperature measurement depends critically on the calibrator temperature determination
- Horns are cooled to a nearly constant temperature of ~1.5 K

ARCADE 2: The radiometers

(Singal, Fixsen, Kogut, Levin, Limon, Lubin, Mirel, Seiffert, Villela, Wollack, Wuensche 0901.0546)

Would you buy a radiometer from this man?



5 GHz radiometer back end

- ARCADE consists of 7 Dicke cryogenic radiometers covering a poorly-measured centimeter band between full-sky surveys at radio frequencies (f< 3 GHz) and the FIRAS millimeter and sub-mm measurements (f > 60 GHz)

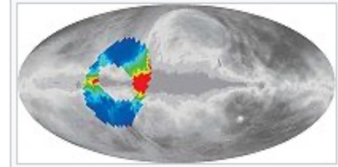
ARCADE Receiver Summary

	3 GHz	5 GHz	7 GHz	10 GHz	30 GHz*	90 GHz
Lower Freq (GHz)	3.1	5.2	7.8	9.5	28.5	87.5
Upper Freq (GHz)	3.5	5.8	8.5	10.7	31.5	90.5
Cold Stage Gain (dB)	40	29	40	40	25	26
System Temperature (K)	7	8	13	12	40	60
Sensitivity (mK Sqrt(s))	0.7	0.7	1.0	0.7	1.5	2.2

ARCADE 2: The 2006 FLIGHT

(Fixsen, Kogut, Levin, Limon, Lubin, Mirel, Seiffert, Singal, Wollack, Villela, Wuensche 0901.0555)

- Launched from Palestine TX (Columbia scientific balloon facility) on a 29 MCF balloon on 22 July 2006 at 1:15 UT
- It reached a float altitude of 37 km at 4:41 UT
- The calibrator was moved 28 times providing at least 8 cycles between calibrator and sky for each of the radiometers
- The entire gondola with the instrument was rotated so that 8.4% of the entire sky was observed
- The most useful observations were from 5:35 to 7:40 UT: with only two hours of balloon flight observations, ARCADE 2 approaches the absolute accuracy of long-duration space missions
- The uncertainty in the sky temperature is dominated by thermal gradients in the calibrator
- One main advantage of balloon flight is that at 37km the instrument is above about 99.7% of the atmosphere and an even larger fraction of water vapour and, second, it is well above the nearest source of any radio transmitters
- The 5 GHz switch failed in flight, so no useful data from that radiometer



ARCADE viewed about 7% of the sky. The observed region is colored on this all-sky radio map. The plane of our galaxy, the Milky Way, runs across the center.

Photograph of the instrument upon landing, 2005. The electronics box and magnetometers which are mounted on the dewar are visible.

Specific intensity of thermal (CMB) and non-thermal radiation

specific intensity of CMB

$$I_{\gamma_{\rm th}}(E,z) \equiv \frac{d\mathcal{F}_E^{\gamma_{th}}}{dA\, dt\, dE\, d\Omega} = \frac{1}{4\pi}\frac{d\varepsilon_{nth}}{dE}\bigg|_{z=z_*} = \frac{1}{4\pi^3}\frac{E^3}{e^{E/T(z)}-1}$$

Here z has to be meant as the redshift at the detection.....in our case we are mainly interested in the case z=0 but there is also the possibility to detect the radiation at z > 0 if the radiation is absorbed (case of 21cm signal)

Rayleigh-Jeans tail limit

$$I_{\gamma_{\rm th}}(E,z) = \frac{1}{4\pi^3}\frac{E^3}{e^{E/T(z)}-1} \xrightarrow{E \ll T(z)} \frac{1}{4\pi^3}T(z)E^2$$

In the case of some additional non-thermal contribution, one can define:

effective (or radiometric) temperature

$$T_{\gamma_{nth}}(E,z) = E\,\ln^{-1}\left(1+\frac{E^3}{4\pi^3 I_{\gamma_{nth}}(E,z)}\right)$$

For $E \ll T_{\gamma \rm nth}$:

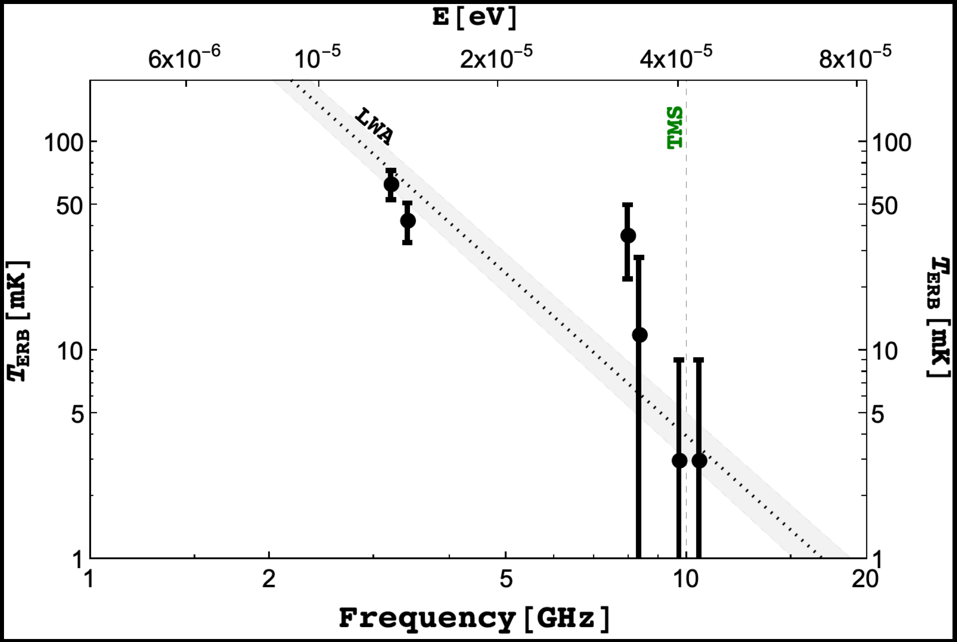
$$T_{\gamma_{\rm nth}}(E,z) \simeq \frac{4\pi^3}{E^2} I_{\gamma_{\rm nth}}(E,z)$$

ARCADE 2: Results

(Fixsen, Kogut, Levin, Limon, Lubin, Mirel, Seiffert, Singal, Wollack, Villela, Wuensche 0901.0555)

$$T_{ERB} \equiv T_{\gamma 0}(\nu) - T_{CMB,0}$$

radiometric temperature



(Figure courtesy of Rishav Roshan)

- The ARCADE 2 measurement of the CMB temperature is in excellent agreement with the FIRAS instrument above 10 GHz
- Below 10 GHz, the detected radio background is brighter than expected
- The Long Wavelength Array (LWA) measured the diffuse radio background in the 40-80 MHz, also finding an excess. In combination with ARCADE 2 data, they find a good fit in terms of a power-law:

$$T_{\rm ERB} = (30.4 \pm 2.6) \left(\frac{\nu}{310\,{\rm MHz}}\right)^{-2.58\pm0.05} {\rm K}\,.$$

The excess radio background mystery

- Part of the excess is due to galactic synchrotron radiation but this galactic contamination is significantly below the measured excess. (N.Fornengo, R.A. Lineros, M. Regis, M. Taoso 1402.2218)

- The excess cannot be explained by known population of sources: they give a contribution to the effective temperature that is 3-10 times smaller than the measured one. (J. Singal et al. 1711.09979)

- Low-redshift populations of discrete extra-galactic radio sources have been also excluded by cross correlating data of the diffuse radio sky with matter tracers at different redshifts provided by galaxy catalogs and CMB lensing. (E.Todarello, et al. 2311.17641)

- Exotic astrophysical explanations have been proposed (supermassive black holes and star forming galaxies) but typically they tend to produce also other (unobserved) signals and more importantly the Australian Telescope Compact Array (ATCA) constrains the contribution to the excess of extended source with angular size below 2 arcmin: the ERB is extremely smooth. (T. Vernstrom et al 1408.4160)

- In order to satisfy this constraint, the source of the excess should be active only at redshifts $z \gtrsim 5$ (G.P. Holder 1207.0856)

- Even explanations in terms of new physics encounter similar difficulty: e.g., excess radiation from dark matter decays and/or annihilations would also produce anisotropies that have not been observed.

- "The radio synchrotron level reported by ARCADE 2 is spatially uniform enough to be considered a BACKGROUND. Thus, it would join the astrophysical backgrounds known in all other regions of the EM spectrum. …the origin of the radio background would be one of the mysteries of contemporary astrophysics". (Singal et al., *The second radio synchrotron background workshop, 2211.16547*)

Can PBHs solve the excess radio background mystery?

- An isotropic excess radio background directly from Hawking emission, even in the extreme case that PBHs make up all of the dark matter, is completely negligible ($T_{ERB} \sim \mathcal{O}(10^{-46})$ K).
  (S. Mittal, G. Kulkarni 2110.11975)

- However, radio emission from gas accretion onto supermassive PBHs can easily explain the excess radio background.
  (S. Mittal, G. Kulkarni 2110.11975)

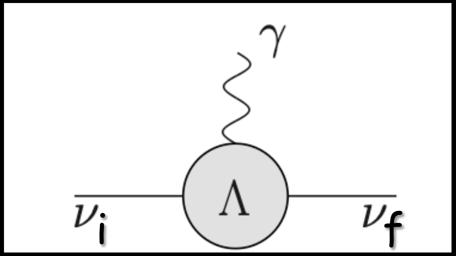
- The problem is that there would be necessarily also an accompanying ultraviolet photon emission that would completely ionize the universe at $z > 6$ in stark contrast with CMB anisotropy observations.
  (S.K. Acharya, J. Dhandha, J. Chluba 2208.03816)

A solution would require some radiation injection from a source that is sufficiently smoothly distributed and that radiates just in the radio frequencies in order not to modify the reionization history probed by CMB anisotropy observations and also to avoid FIRAS constraints!

Relic neutrino decays

(Chianese, Farrag, PDB, Samanta 2018; Dev, PDB, Martinez-Soler, Roshan 2312.03082)

An intriguing possibility is that the source of non-thermal radiation is relic neutrinos decaying radiatively due to the existence of some new physics at some scale Λ:



The decay active-to-active neutrino would induce a neutrino magnetic moment and a stringent upper bound, therefore, rules out the possibility that the neutrino in the final state is an ordinary neutrino…

…but it could be a NEW STERILE neutrino:

$$\nu_f = \nu_{\text{sterile}}$$

Assume decaying and final sterile neutrino quasi-degenerate: $\Delta m_i \equiv m_i - m_s \ll m_i$

Moreover, assume ordinary neutrinos non-relativistic at the decay: with these assumptions the final photon is monochromatic at the decay, at redshift z_D:

$$E_\gamma(z_D) = \Delta m_i$$

…but not at the detection since cosmological expansion will redshift energies:

$$E_\gamma(z) = \Delta m_i \frac{1+z}{1+z_D} \leq \Delta m_i$$

Specific intensity of the radiation from relic neutrino decays

(Chianese, Farrag, PDB, Samanta 2018; Dev, PDB, Martinez-Soler, Roshan 2312.03082)

energy density

$$\varepsilon_{\gamma_{nth}}(z) = \frac{\Delta m_1}{\tau_1} n^{\infty}_{\nu_1}(z) \int_0^a da_D \, \frac{e^{-\frac{t(a_D)}{\tau_1}}}{H(a_D)a}$$

specific intensity

$$I_{\gamma_{\rm nth}}(E,z) = \frac{1}{4\pi} \frac{d\varepsilon_{\gamma_{\rm nth}}}{dE}\bigg|_z = \frac{n^{\infty}_{\nu_1}(z)}{4\pi} \frac{e^{-\frac{t(a_D)}{\tau_1}}}{H(a_D)\tau_1}$$

$\Rightarrow$

effective temperature

$$T_{\gamma_{\rm nth}}(E,z) \simeq \frac{4\pi^3}{E^2} I_{\gamma_{\rm nth}}(E,z)$$

expansion rate at the decay

$$H(a_D) = H_0\sqrt{\Omega_{M0} {a_D}^{-3} + \Omega_{\Lambda 0}} = H_0\sqrt{\Omega_{M0}}\, {a_D}^{-\frac{3}{2}} \left(1 + \frac{{a_D}^3}{{a_{eq}^{M\Lambda}}^3}\right)^{\frac{1}{2}}$$

scale factor at the decay

$$a_D = \frac{1}{1+z_D} = \frac{E}{\Delta m_1 (1+z)}$$

age of the universe at the decay

$$t(a_D) = \frac{2}{3} \frac{H_0^{-1}}{\sqrt{\Omega_{\Lambda 0}}} \ln\left[\sqrt{\left(\frac{a_D}{a_{eq}^{M\Lambda}}\right)^3} + \sqrt{1 + \left(\frac{a_D}{a_{eq}^{M\Lambda}}\right)^3}\right]$$

relic neutrino number density at the detection

$$n^{\infty}_{\nu_1}(z) = \frac{6}{11} \frac{\xi(3)}{\pi^2} T^3(z)$$

Fitting the ARCADE 2 excess radio background

(Dev, PDB, Martinez-Soler, Roshan 2312.03082)

In the case of ARCADE 2, the redshift at the detection is simply z=0:

$$I_{\gamma_{\rm nth}}(E,0) = \frac{n^{\infty}_{\nu_1}(0)}{4\,\pi}\,\frac{e^{-\frac{t(a_{\rm D})}{\tau_1}}}{H(a_{\rm D})\,\tau_1}$$

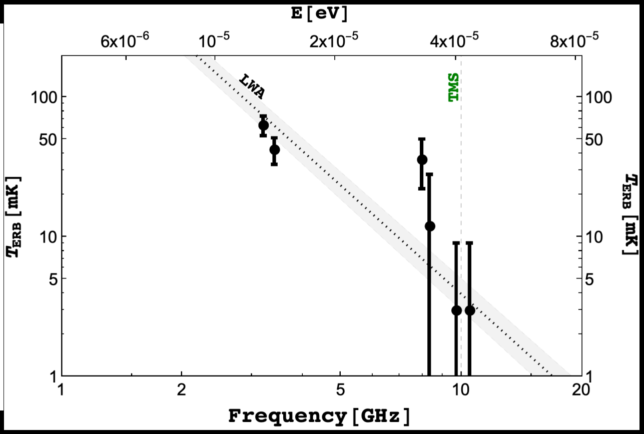
Moreover, we will consider solutions with $\tau_1 \gg t_0$ so that we can neglect the exponential:

$$T_{\gamma_{\rm nth}}(E,0) \simeq \frac{6\,\zeta(3)}{11\,\sqrt{\Omega_{\rm M0}}}\,\frac{T_0^3}{E^{1/2}\,\Delta m_1^{3/2}}\,\frac{t_0}{\tau_1}\,\left(1+\frac{a_{\rm D}^3}{a_{\rm eq}^3}\right)^{-\frac{1}{2}}$$

We have to fit the 6 values of the effective temperature measured by ARCADE 2:

Table 1. ARCADE 2 measurements of the excess radio background effective temperature [1].

i	ν_i (GHz)	E_i (10^{-5} eV)	$T^i_{\gamma 0}$ (K)	$\overline{T}^i_{\rm ERB}$ (mK)	$\delta T^i_{\rm ERB}$ (mK)
1	3.20	1.36	2.792	63	10
2	3.41	1.41	2.771	42	9
3	7.97	3.30	2.765	36	14
4	8.33	3.44	2.741	12	16
5	9.72	4.02	2.732	3	6
6	10.49	4.34	2.732	3	6



Fitting the ARCADE 2 excess radio background

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input

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χ^2

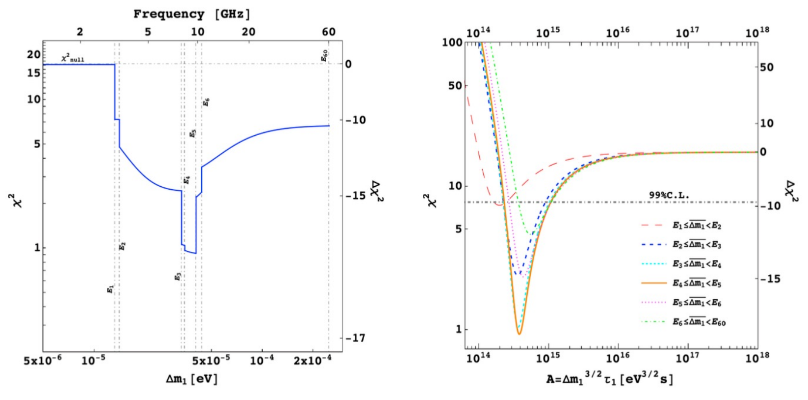
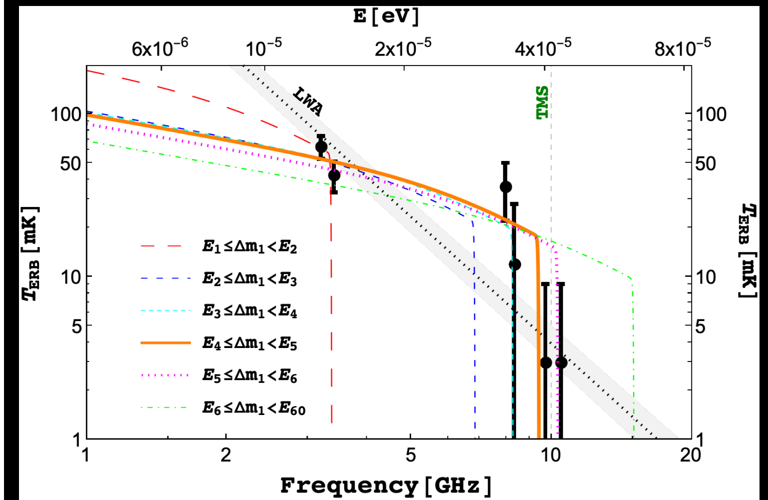


Figure 1. Left panel: χ^2 versus Δm_1 for best fit value of A in each interval as in Table 2. Right panel: χ^2 (4 d.o.f.) as a function of A for the best fit values of Δm_1 in each interval $E_i \leq \Delta m_1 < E_{i+1}$ as in Table 2.



results

Table 2. Results of the fit of ARCADE 2 data. Best fit values, χ^2 and $\Delta\chi^2$ are shown for each interval of Δm_1, corresponding to a frequency interval between two data points.

Interval	$\overline{A}$ (eV$^{3/2}$s)	$\overline{\Delta m_1}$ (eV)	$\overline{\tau}_1$ (s)	$\chi^2_{\rm min}$	$\Delta\chi^2_{\rm min}$
$E_1 \leq \Delta m_1 < E_2$	1.9×10^{14}	1.4×10^{-5}	3.6×10^{21}	7.36	−9.87
$E_2 \leq \Delta m_1 < E_3$	2.3×10^{14}	2.7×10^{-5}	1.6×10^{21}	2.28	−14.95
$E_3 \leq \Delta m_1 < E_4$	3.6×10^{14}	3.4×10^{-5}	1.8×10^{21}	1.06	−16.17
$E_4 \leq \Delta m_1 < E_5$	3.8×10^{14}	4.0×10^{-5}	1.46×10^{21}	0.96	−16.27
$E_5 \leq \Delta m_1 < E_6$	4.2×10^{14}	4.3×10^{-5}	1.49×10^{21}	2.19	−15.04
$E_6 \leq \Delta m_1 < E_{60}$	4.7×10^{14}	2.0×10^{-4}	1.66×10^{20}	3.23	−14.00

Fitting the ARCADE 2 excess radio background

(Dev, PDB, Martinez-Soler, Roshan 2312.03082)

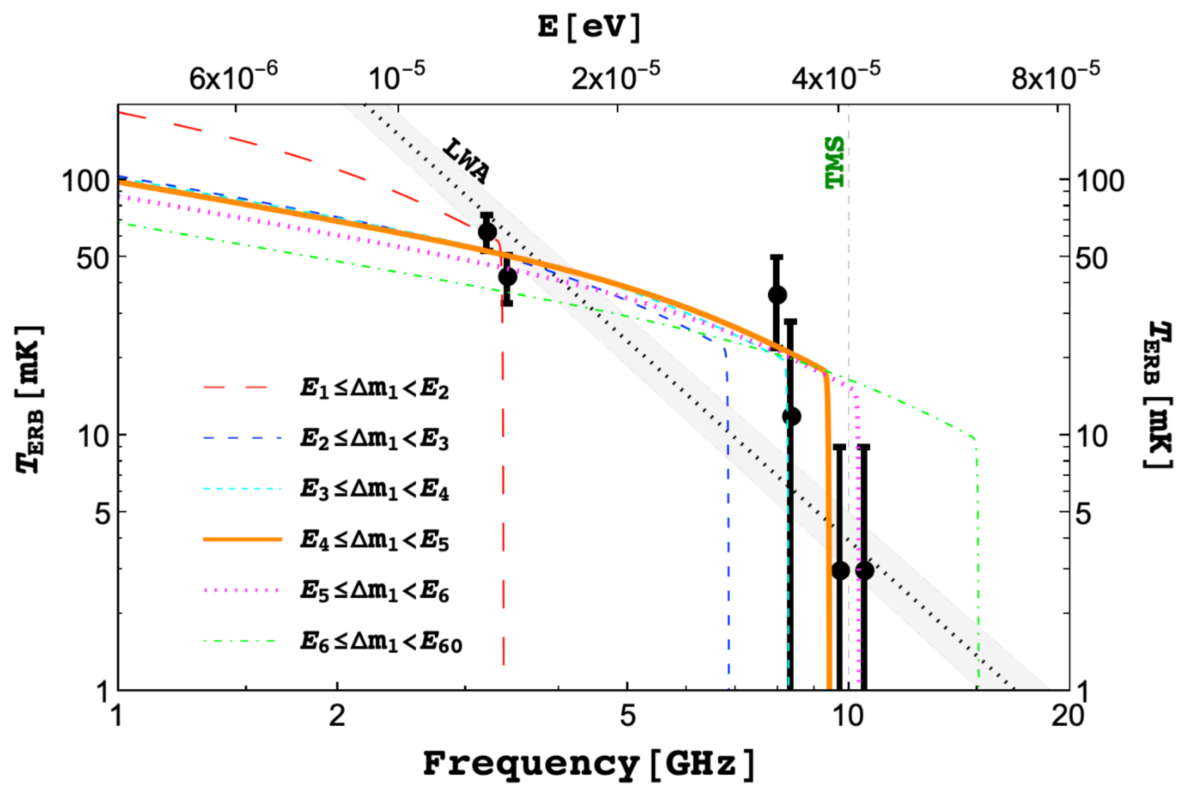


Figure 2. Best fit curves for $T_{\rm ERB}$ obtained with Eq. (3.2). The thick solid orange curve corresponds to a solution very close to the best global fit ($\Delta m_1 = 4.0 \times 10^{-5}$ eV and $\tau_1 = 1.46 \times 10^{21}$ s). The ARCADE 2 data points are taken from Ref. [1], while the power-law fit $\beta = -2.58 \pm 0.05$ (dotted line with grey shade) is from [3].

For our best fit we find $\chi^2/4$d.of. =0.96, to be compared with $\chi^2/4$d.of. =2.5 for the power law

Allowed region (99% C.L.)

(Dev, PDB, Martinez-Soler, Roshan 2312.03082)

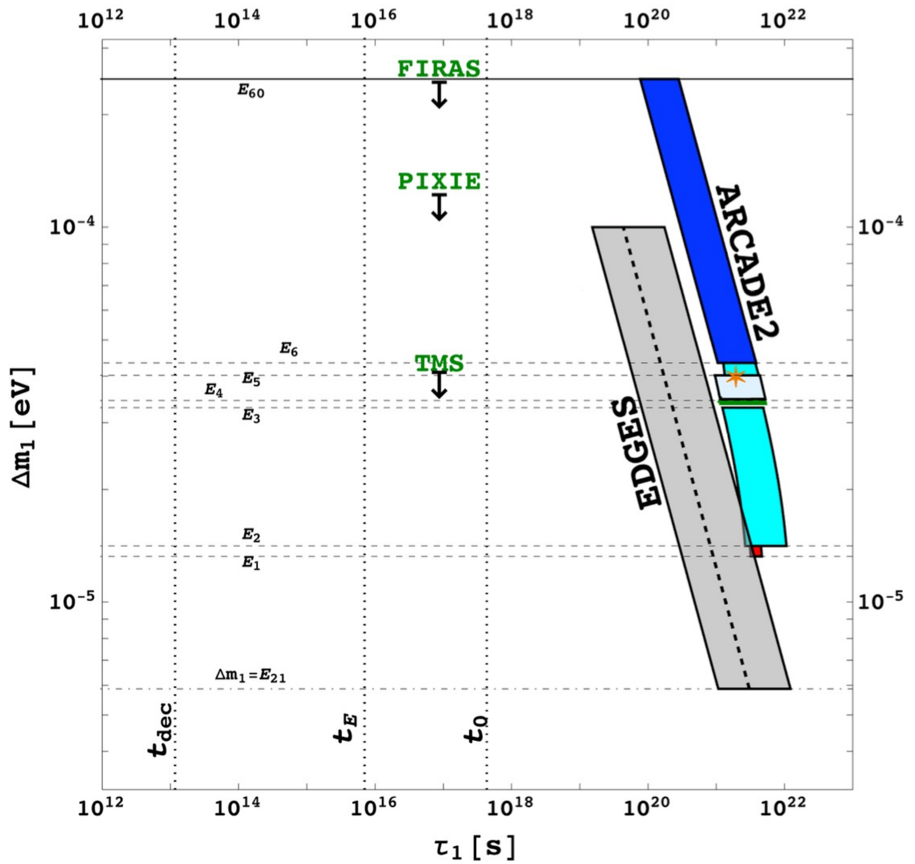


Figure 3. Allowed region in the plane of Δm_1 versus τ_1 (99% C.L.). The orange star indicates the best fit to ARCADE 2 excess found. Colour code: light grey for $\chi^2 < 1$, green for $1 < \chi^2 < 2$, cyan for $2 < \chi^2 < 3$, blue for $3 < \chi^2 < 7$ and red for $7 < \chi^2 < 9$. We also show the best-fit and 99% C.L. region for the EDGES anomaly (dashed line and grey shaded region). The vertical lines show (from left to right) the epochs of CMB decoupling, cosmic dawn and the age of the Universe. The horizontal lines correspond to different photon energies (or frequencies). The region above 60 GHz is disfavored by FIRAS, and this limit can be improved down to 30 GHz with PIXIE, or to 10 GHz by TMS, as shown by the downward arrows.

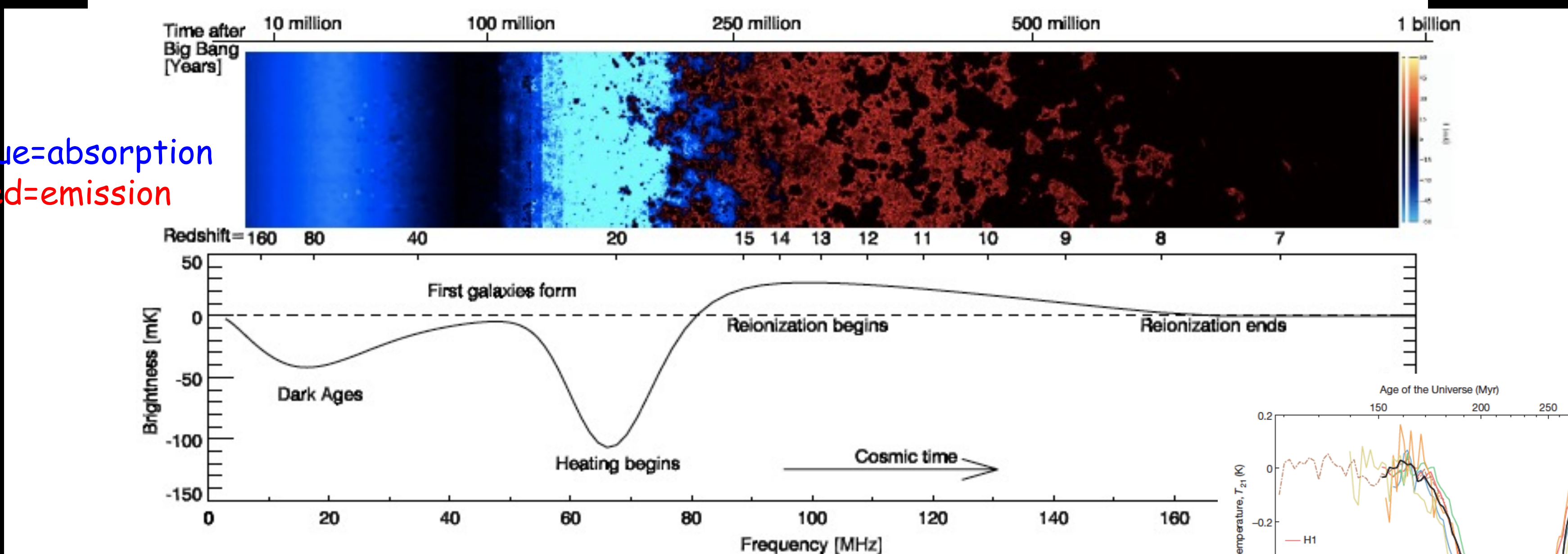
21 cm cosmology (global signal)

- 21 cm line (emission or absorption) is produced by hyperfine transitions between the two energy levels of 1s ground state of Hydrogen atoms. The energy splitting between the two level is $E_{21}=5.87\mu eV$
- The 21cm brightness temperature parametrises the brightness contrast :

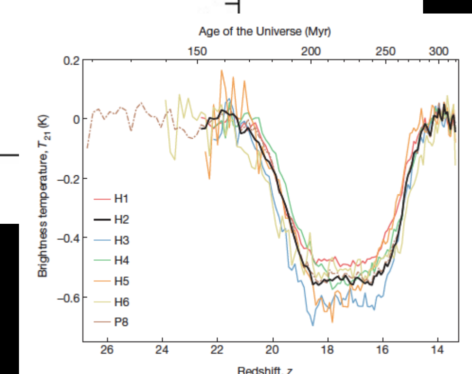
$$T_{21}(z) \simeq 23\,\mathrm{mK}\,(1+\delta_B)\,x_{H_I}(z)\left(\frac{\Omega_B h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_\mathrm{m} h^2}\right)\left(\frac{1+z}{10}\right)\right]^{1/2}\left[1-\frac{T_\gamma(z)}{T_S(z)}\right],$$

spin temperature

Blue=absorption
Red=emission



EDGES (anomalous) signal



EDGES anomaly

21cm brightness contrast temperature

$$T_{21}(z) \simeq 23\,\mathrm{mK}\,(1+\delta_{\mathrm{B}})\,x_{H_I}(z)\left(\frac{\Omega_{\mathrm{B}0}h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_{\mathrm{M}0}h^2}\right)\left(\frac{1+z}{10}\right)\right]^{1/2}\left[1-\frac{T_\gamma(z)}{T_{\mathrm{S}}(z)}\right]$$

spin temperature

$$\frac{n_1}{n_0}(z) \equiv \frac{g_1}{g_0}\,e^{-\frac{E_{21}}{T_{\mathrm{S}}(z)}}$$

When stars form, 21 cm transitions couple to the gas and simply $T_S = T_{gas}$

The EDGES collaboration found an absorption profile signal with minimum at $z_E \simeq 17$ corresponding to $\nu_{21}(z_E)$=78 MHz (at rest ν_{21}=1420 MHz) and

$$T_{21}^{\mathrm{EDGES}}(z_E) = -500^{+200}_{-500}\,\mathrm{mK}\ \ (99\%\ \mathrm{C.L.}).$$

Is this result compatible with the expectation from the ΛCDM model?

The (thermal) relic photon temperature is given by $T_\gamma(\bar{z}_E) = T(\bar{z}_E) = T_0\,(1+\bar{z}_E) \simeq 49.6\,\mathrm{K}$

The gas temperature is found $T_{\mathrm{gas}}(\bar{z}_E) \simeq 7.2\,\mathrm{K}$

Plugging these numbers into the expression for $T_{21}(z_E)$: $T_{21}(\bar{z}_E) \simeq -206\,\mathrm{mK}$

Can relic neutrino decays explain (also) the EDGES anomaly ?

EDGES anomaly and relic neutrino decays

(**Chianese, PDB, Farrag, Samanta, arXiv 1805.11717;** Dev, PDB, Martinez-Soler, Roshan 2312.03082)

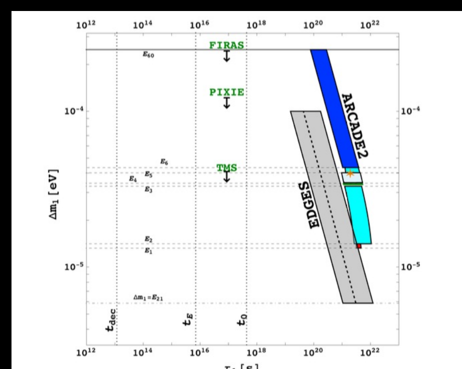
A solution of the EDGES anomaly requires an additional non-thermal photon component with:

$$T_{\gamma_{\rm nth}}^{\rm EDGES}(\bar{z}_E) = (60^{+101}_{-41})\,{\rm K}$$

If we want to reproduce this value with relic neutrino decays we have to use:

$$T_{\gamma_{\rm nth}}(E_{21}, z_E) \simeq \frac{6\,\zeta(3)}{11\,\sqrt{\Omega_{\rm M0}}}\;\frac{T_0^3\,(1+z_E)^{3/2}}{E_{21}^{1/2}\,\Delta m_1^{3/2}}\;\frac{t_0}{\tau_1}$$

And the result is:



As one can see, there is some tension with the solution fitting ARCADE….but not so dramatic!
The ARCADE 2 solution predicts:

$$T_{21}(\bar{z}_E) = -238^{+21}_{-20}\,{\rm mK} \quad (99\%\,{\rm C.L.}).$$

The EDGES result is controversial and many groups think it might be contaminated by some foreground contribution (ionosphere? Ground inhomogeneities? SARAS3 experiment has rebutted EDGES, so we need to wait for more results.

Final remarks

- The excess radio background found by ARCADE 2 is currently unexplained
- The excess cannot be explained by known (or even unknown) population of astrophysical sources
- Relic neutrino decays provide an intriguing solution fitting quite well the ARCADE 2 data but of course more results are needed: Tenerife Microwave Spectrometer (TMS) on the way
- The solution also predicts a stronger 21cm absorption global signal than in ΛCDM….though not as strong as the EDGES anomalous signal (this would be a real smoking gun!)
- The solution can also be mimicked by dark matter decays/deexcitations but one obtains an upper bound of $m_{DM} \lesssim 10$ keV and moreover in this case one obtains an anisotropic background that is ruled out!
- Instead, relic neutrino decay solution is compatible with the observed smoothness of the excess radio background, since neutrinos do not cluster much (neutrino clustering is proportional to the mass….intriguing! (This might provide a way to constraint the absolute neutrino mass scale)
- Relic neutrino decays require new physics so that this solution represents a very exciting opportunity to finally crack the SM of particle physics. Maybe radio observations will succeed where LHC and many other traditional particle physics experiments have failed so far?

A map to new physics?