Workshop on the standard model and beyond - Corfu Summer Institute

25 August – 4 September 2024

Testing an unstable cosmic neutrino background

(see Bhupal Dev, PDB, Ivan Martinez-Soler, Rishav Roshan 2312.03082+new one coming soon)

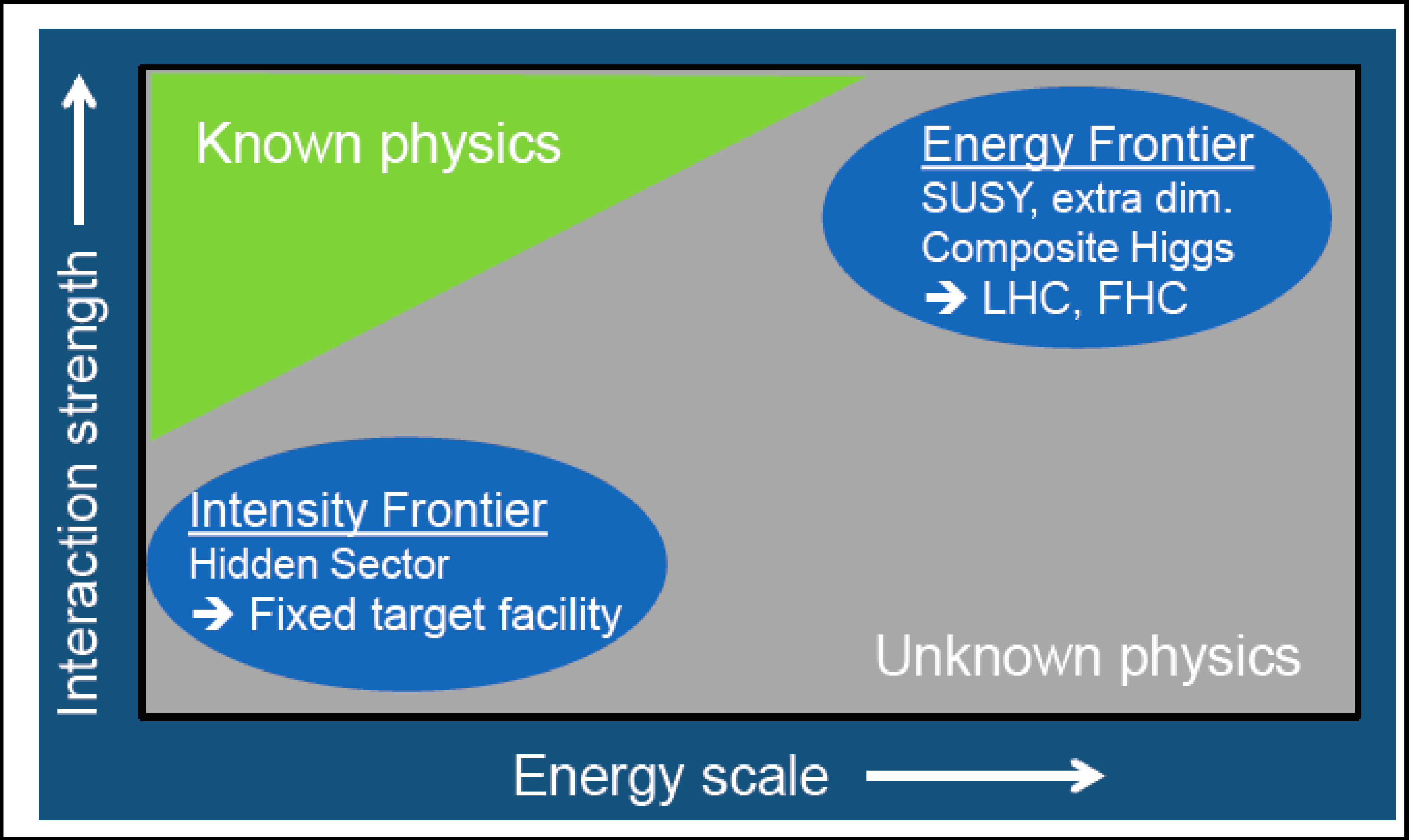
Pasquale Di Bari

HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

UNIVERSITY OF Southampton

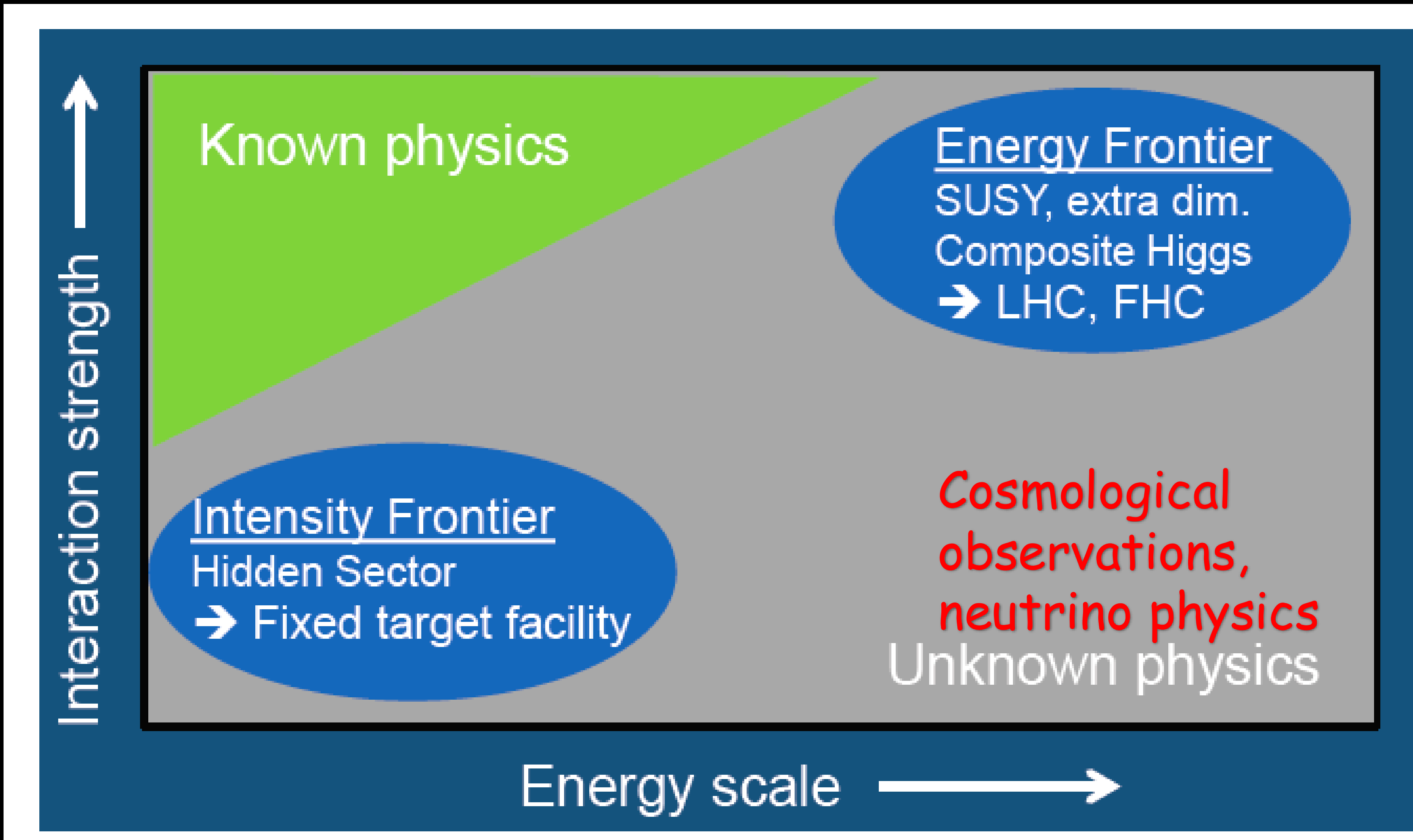
New frontiers

(SHIP proposal, 1504.04855)

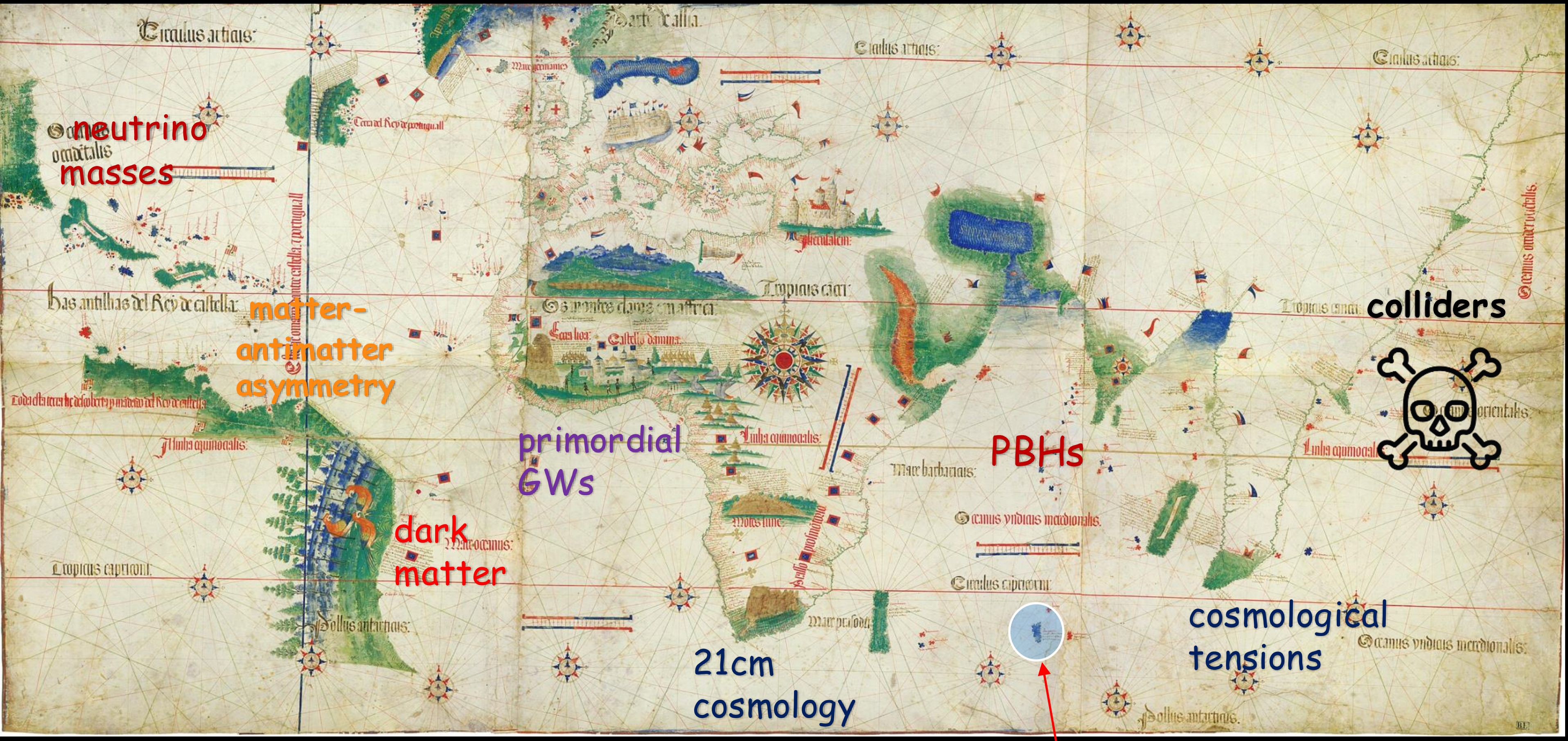


New frontiers

(SHIP proposal, 1504.04855)

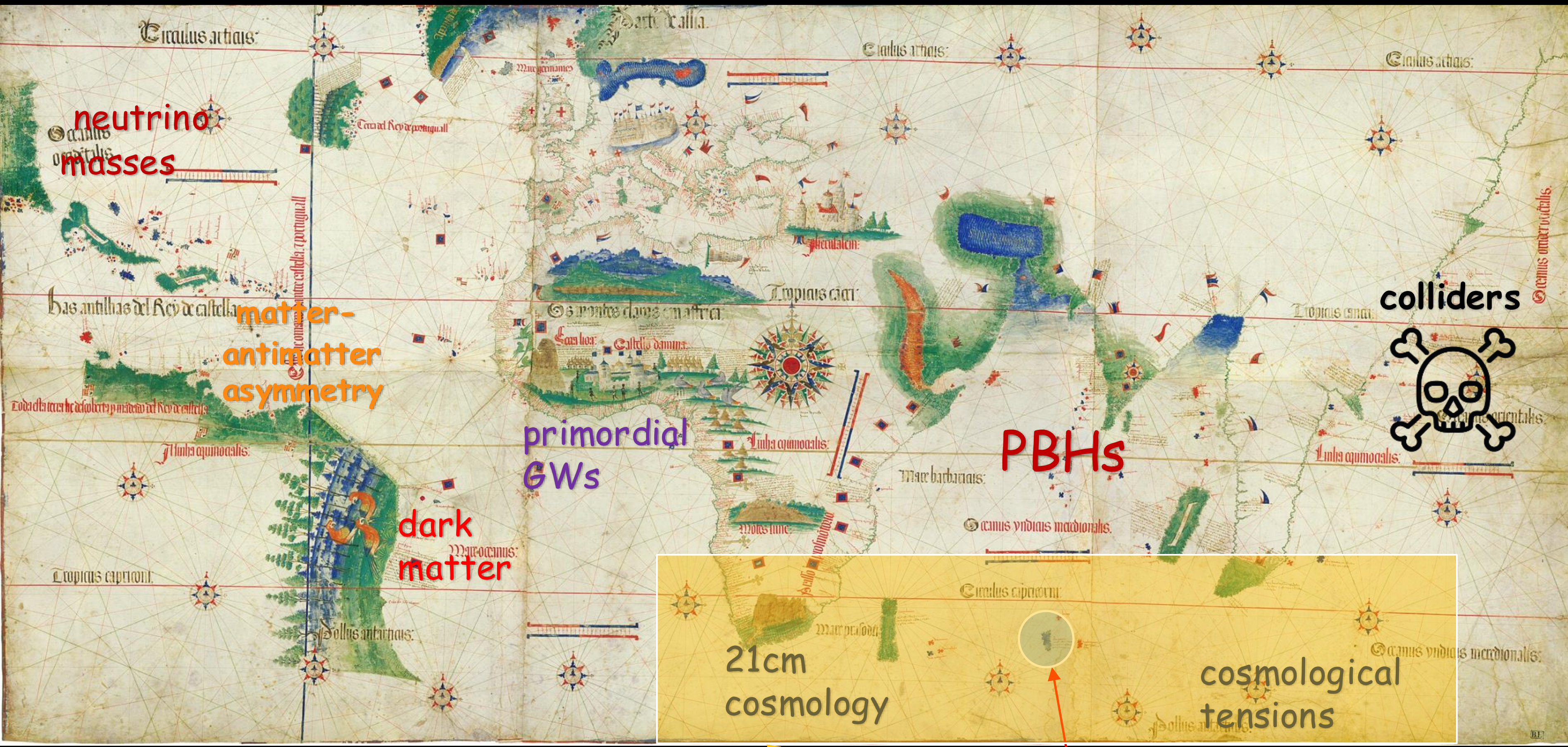


A map to new physics?



excess radio background

A map to new physics?

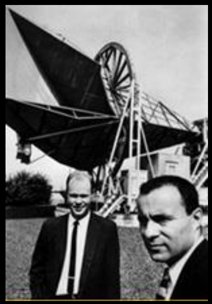


This talk

excess radio background

Constraints from CMB spectrum

CMB spectrum: the most perfect Planckian



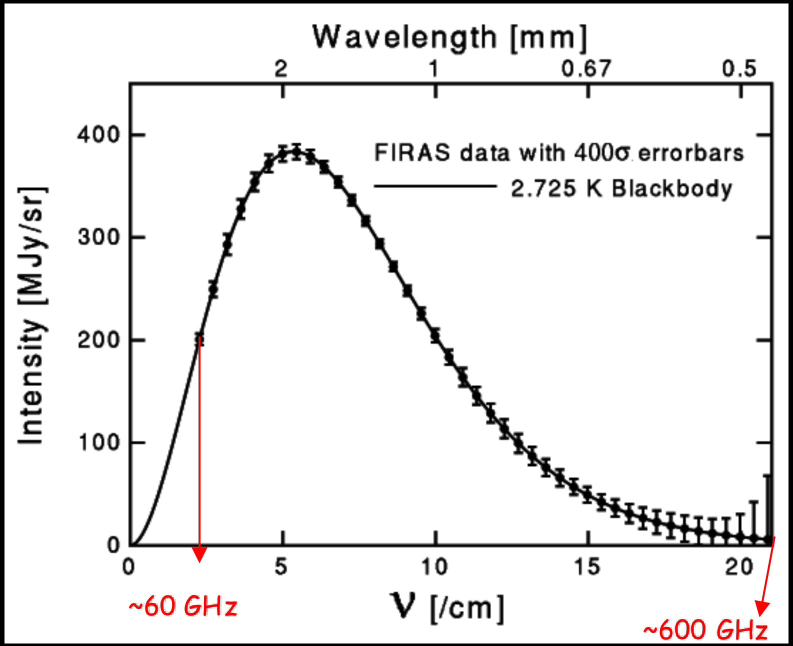
Penzias and Wilson (1965)

$T_{\gamma 0}$= (3.5 ± 1) ^{0}K

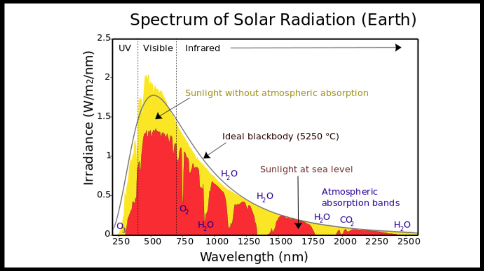
COBE satellite

FIRAS instrument of COBE (1990)

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



for a comparison

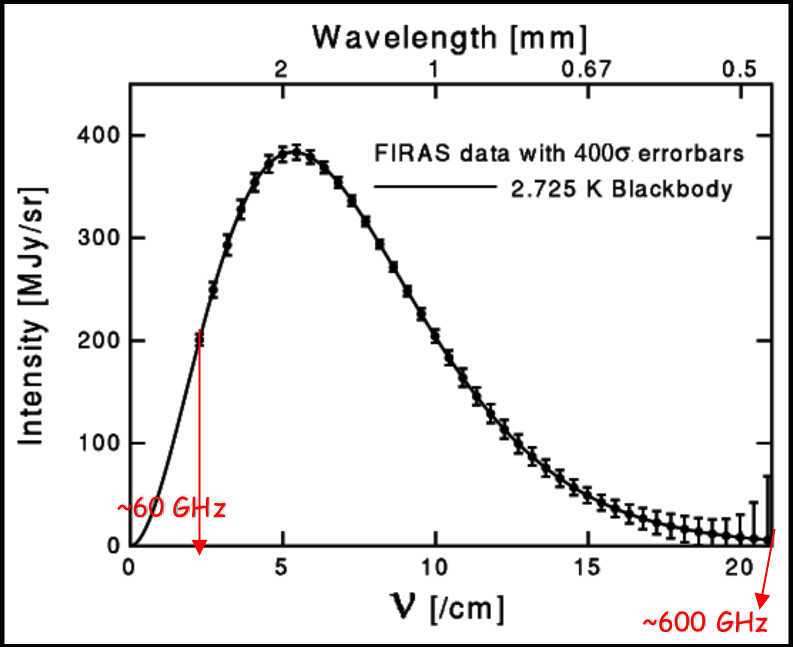


$$2.5 \times 10^{-4}\text{eV} \lesssim E_\gamma^{FIRAS} \lesssim 2.5 \times 10^{-3}\text{eV}$$

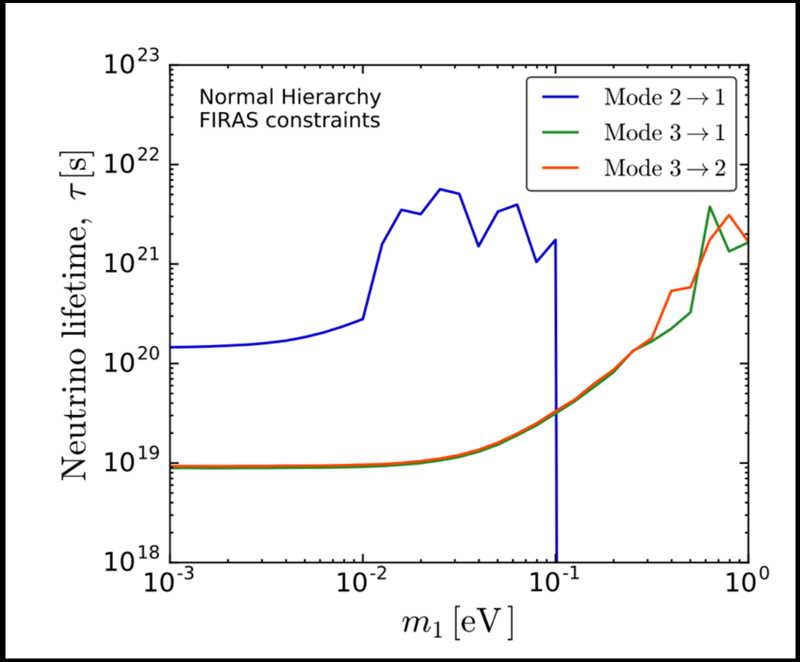
Lower bound on neutrino lifetime from FIRAS

(Aalberts et al. 1803.00588)

- $\nu_j \rightarrow \nu_i + \gamma \ \ (i,j = 1,2,3)\ ;$
- ν_j is also an active neutrino mass eigenstate ;
- The ν_i ' s are assumed to decay non-relativistically (m_i >>T)
- $\Rightarrow\ E_{\gamma 0} = \frac{m_j^2 - m_i^2}{2\, m_j} \frac{1}{1+z_D}$
- Neutrino oscillation experiments fix $m_j^2 - m_i^2$



$2.5 \times 10^{-4}\mathrm{eV} \lesssim E_\gamma^{FIRAS} \lesssim 2.5 \times 10^{-3}\mathrm{eV}$



lower bounds on neutrino lifetime

Upper limit on neutrino effective magnetic moment from FIRAS

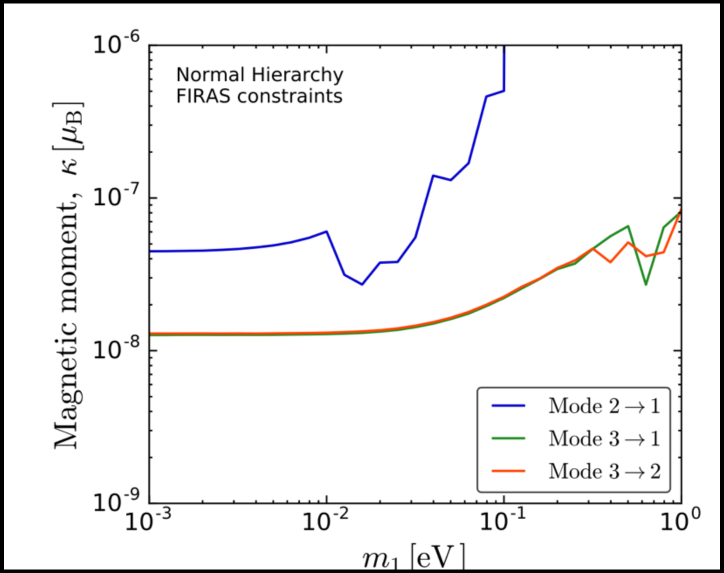
(Aalberts et al. 1803.00588)

- The decay rate can be expressed in terms of the neutrino effective magnetic moment*

$$\mu_{\mathrm{eff},ij} \equiv \sqrt{|\mu_{ij}|^2 + |\epsilon_{ij}|^2}$$

$$\Gamma_{\nu_j \to \nu_i + \gamma} = \frac{\mu^2_{\mathrm{eff},ij}}{8\pi} \left(\frac{m_j^2 - m_i^2}{m_j} \right)^3$$

(Pal, Mohapatra 1982;…;Studenikin, Giunti 2015)



- These upper limits are looser than those placed by:

neutrino-electron scattering experiments $\mu_{\mathrm{eff},ij} \lesssim 3.2 \times 10^{-11}\, \mu_B$ (GEMMA, 1005.2736)

globular cluster stars $\mu_{\mathrm{eff},ij} \lesssim 3 \times 10^{-12}\, \mu_B.$ (Raffelt, 1992)

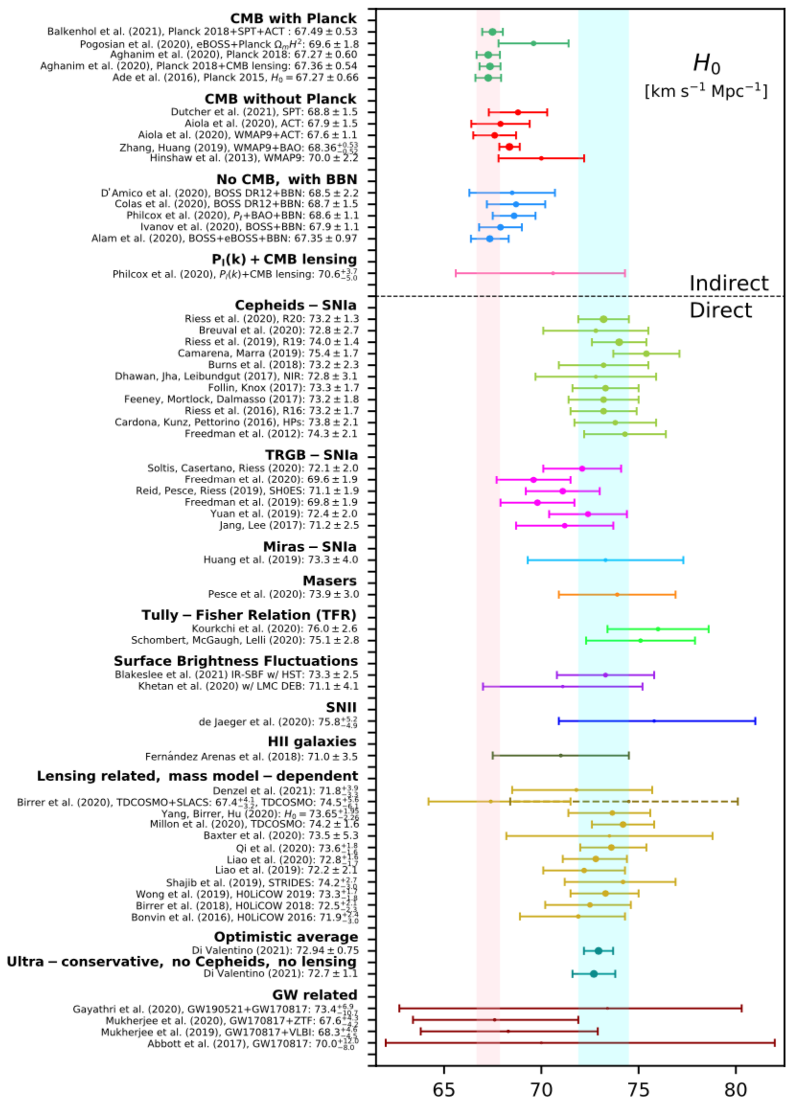
- The Primordial Inflation Explorer (PIXIE) will improve the lower (upper) limit on lifetime (magnetic moment) by 4 (2) orders of magnitude
- It would be then very challenging to explain relic neutrino radiative decays!

* *neglecting a neutrino millicharge*

Cosmological tensions

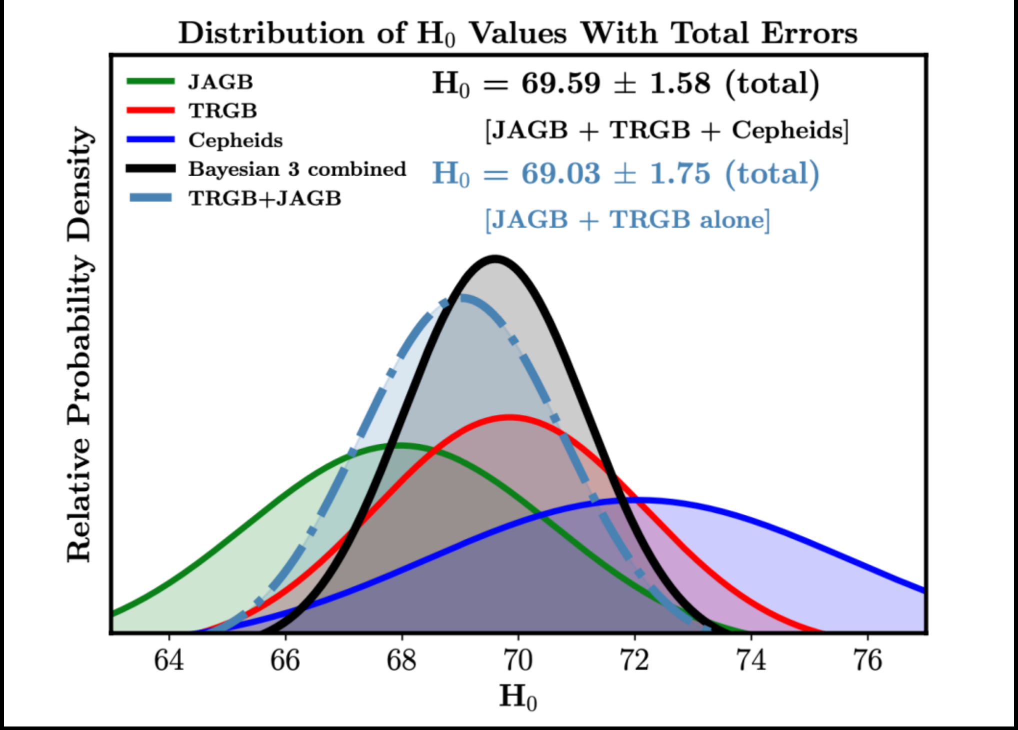
Hubble tension

(E. Di Valentino, O. Mena, S. Pan, L. Visinelli, W. Yang, A. Melchiorri, D.F. Mota, A.G. Riess, J. Silk 2103.0118



New JWST results seem to solve the Hubble tension

(W. Freedman et al., 2408.06153)



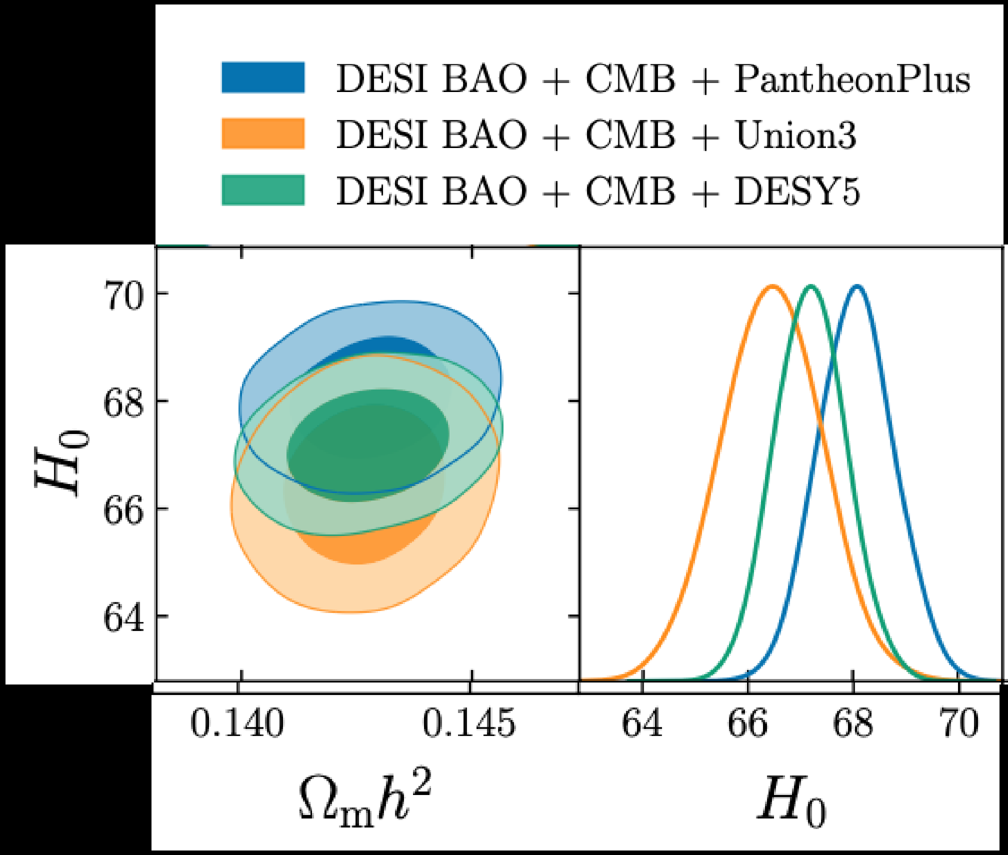
"These data are consistent with the current standard ΛCDM model without the need for the inclusion of additional new physics"

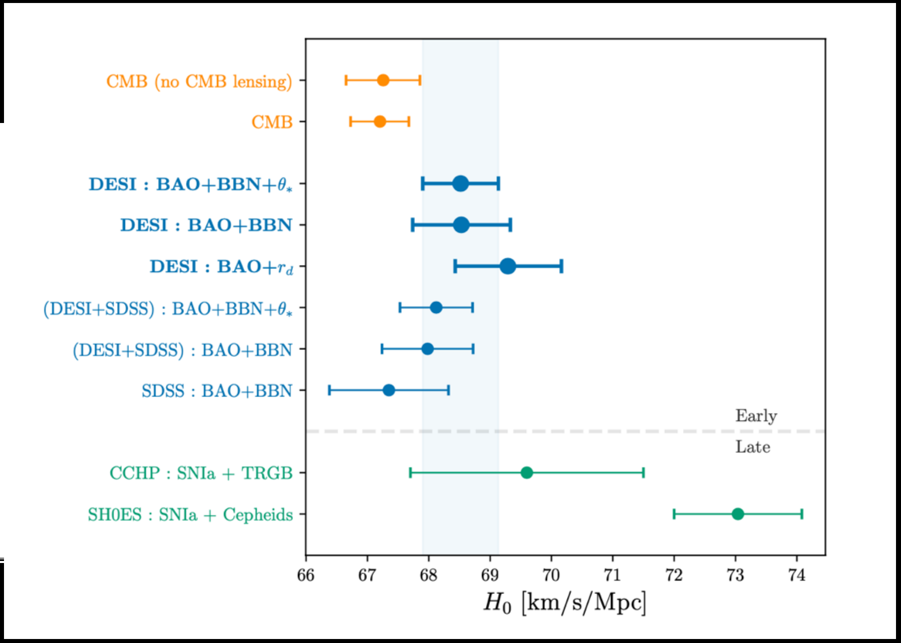
(different conclusion in A. Riess et al. 2408.11770)

DESI 2024: cosmological constraints from the measurements of baryon acoustic oscillations

(DESI collaboration 2404.03002)

Hubble constant

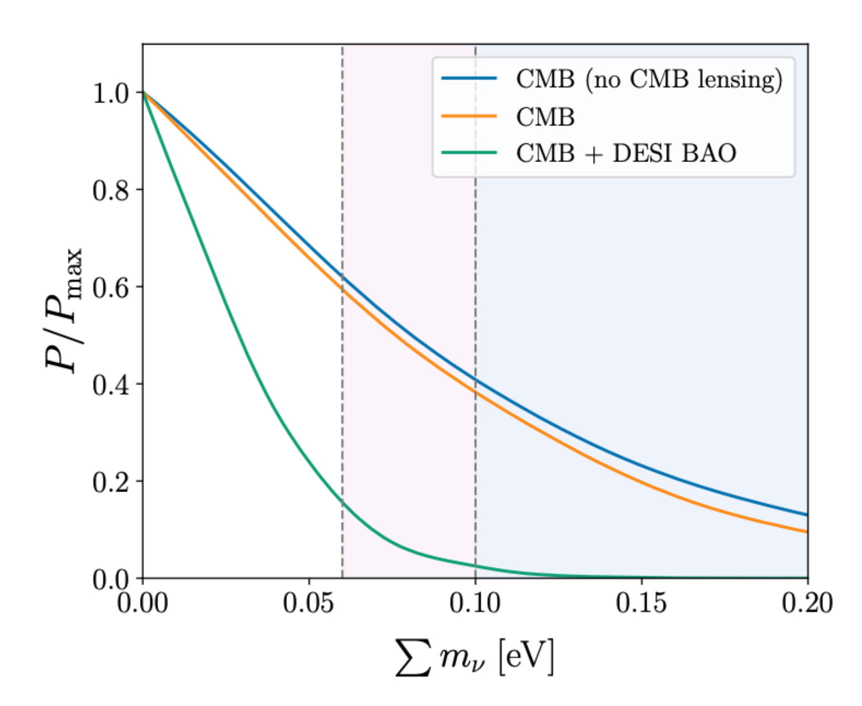




DESI 2024: cosmological constraints from the measurements of baryon acoustic oscillations

(DESI collaboration 2404.03002)

Neutrinos



Planck CMB alone

$$\sum m_\nu < 0.21\,\mathrm{eV} \quad (95\,\%,\ \mathrm{CMB}),$$

DESI BAO + CMB

$$\sum m_\nu < 0.072\,\mathrm{eV} \quad (95\,\%,\ \mathrm{DESI\ BAO{+}CMB}).$$

The best fit is for $\Sigma_i m_{\nu i} = 0$ imposing a prior $\Sigma_i m_{\nu i} \geq 0$

No ν's good news?

(J.F. Beacom, N. Bell. S. Dodelson astro-ph/0404085; P. Serpico astro-ph/0701699; M. Escudero, J. Lopez-Pavon, N. Rius, S. Sandner 2007.04994; N. Craig, D. Green, J. Meyers, S. Rajendran, 2405.00836)

- The upper bound $\Sigma_i m_{\nu i} < 72$ meV (95% C.L.), obtained with a prior $\Sigma_i m_{\nu i} \geq 0$, is in tension with the lower bound $\Sigma_i m_{\nu i} > 58$ meV from neutrino oscillation experiments: they are incompatible at almost 2σ
- This tension can be solved if neutrinos decay with a lifetime lower (at least) than about 1 order of magnitude than the the age of the universe but longer than $\sim 10^9 s(\Sigma_i m_{\nu i}/50\text{meV})^3$ not to clash with CMB anisotropy observations (neutrinos need to free stream at recombination).
- Radiative decays are strongly constrained by the upper bound on CMB spectral distortions $\Rightarrow$ they need to decay invisibly;
- Example:

$$\mathcal{L}_\phi \supset \frac{\lambda_{ij}}{2}\bar{\nu}_i\nu_j\phi + \frac{\tilde{\lambda}_{ij}}{2}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$

(N. Craig, D. Green, J. Meyers, S. Rajendran, 2405.00836)

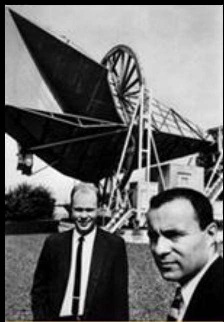
- This results into

$$\tau(\nu_i \to \nu_j\phi) \simeq 7\times 10^{17}\,\text{s}\times\left(\frac{0.05\,\text{eV}}{m_{\nu_i}}\right)\left(\frac{10^{-15}}{\tilde{\lambda}_{ij}^2}\right)^2$$

- *A low scale dark sector destabilizing neutrinos?*

- CAUTION: a recent analysis with new *Planck* lensing likelihoods, relaxes the tension, finding $\Sigma_i m_{\nu i} < 100$ meV (95% C.L.) with best fit $\Sigma_i m_{\nu i} \simeq 40$ meV (Allali and Notari 2406.14554)

The CMB spectrum: most perfect Planckian in ture



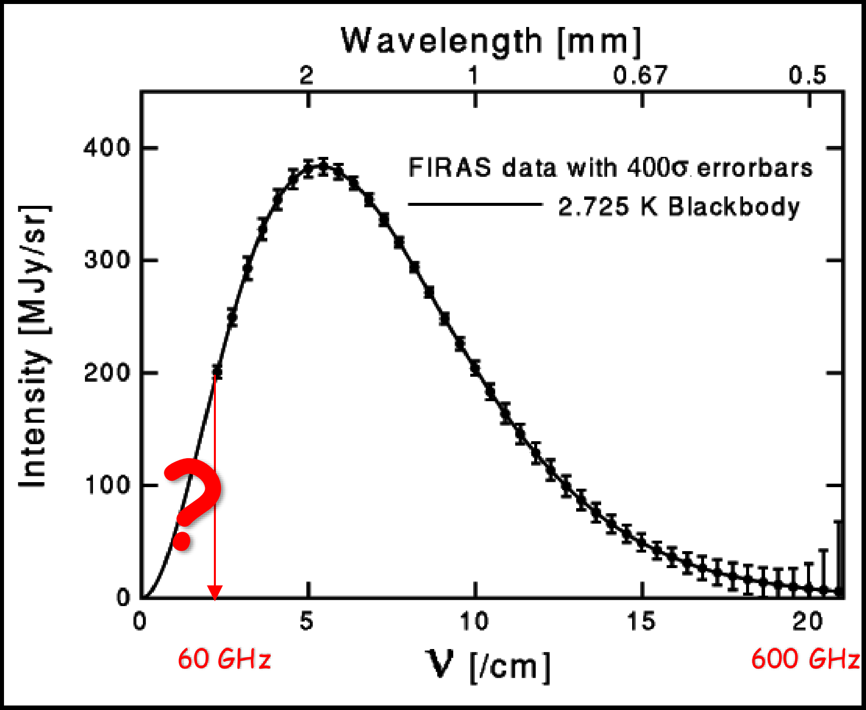
Penzias and Wilson (1965)

$T_{\gamma 0}$= (3.5 ± 1) ^{0}K

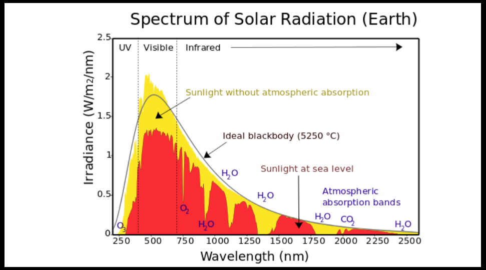
COBE satellite

FIRAS instrument of COBE (1990)

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



for a comparison



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.....the traditional case is 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 $E \ll T_{\gamma nth}$:

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

Specific intensity of the radiation from relic neutrino decays

(Masso,Toldra 1999; 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

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

effective temperature

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

$$E = \Delta m_i \frac{1+z}{1+z_D} \leq \Delta m_i \quad \Longrightarrow \quad a_D \equiv \frac{1}{1+z_D} = \frac{E}{\Delta m_1 (1+z)}$$

scale factor at the decay

expansion rate at the decay

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

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

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

21cm cosmology: shedding light on dark ages

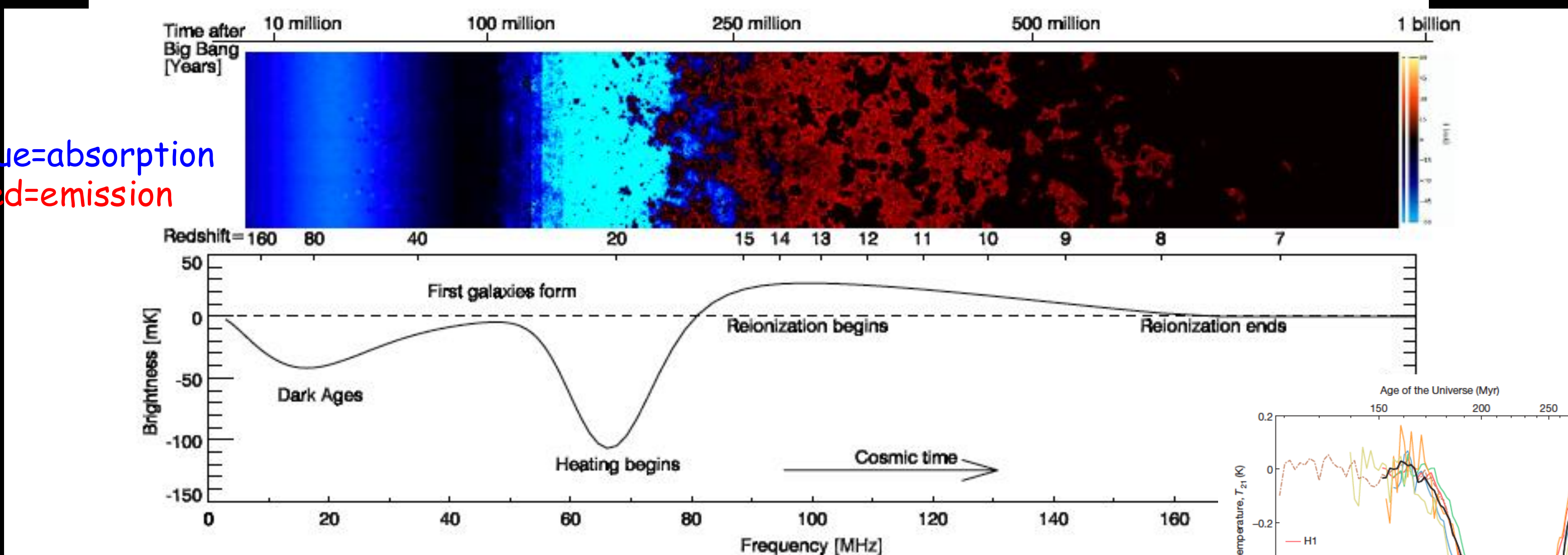
21 cm cosmology (global signal)

- 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 :

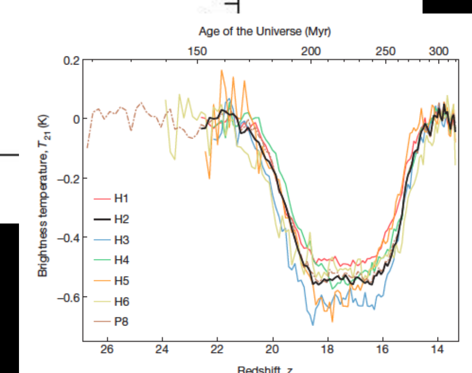
$$T_{21}(z) \simeq 23\,\mathrm{mK}\,(1+\delta_B)\,x_{H_I}(z)\left(\frac{\Omega_B h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_{\rm m} h^2}\right)\left(\frac{1+z}{10}\right)\right]^{1/2}\left[1-\frac{T_\gamma(z)}{T_S(z)}\right],$$

spin temperature

Blue=absorption
Red=emission



EDGES (anomalous) signal



EDGES anomaly and relic neutrino decays

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

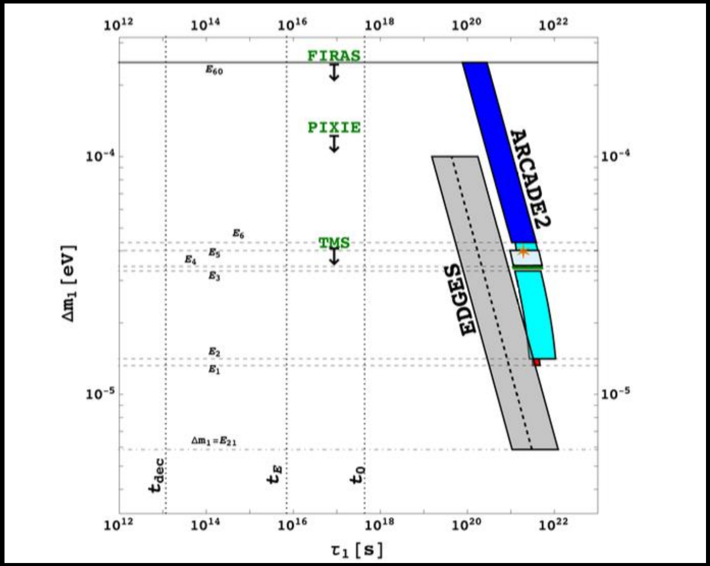
A solution of the EDGES anomaly requires an additional non-thermal photon component with:

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

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:



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. 3 lunar-based experiments (to avoid ionosphere and ground reflection) are planned in a close future

21cm global signal: lunar-based experiments

Lunar Surface Electromagnetic Experiment (LuSEE)

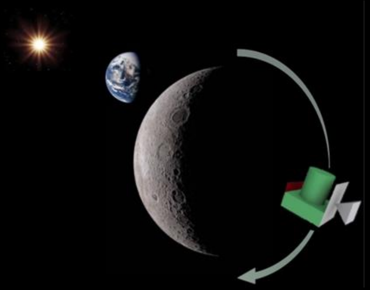
- 4 monopole antennas mounted on a rotating platform;
- 0.1-50 MHz band
- far side of the Moon
- scheduled to land in early 2026;

Discoverying Sky at the Longest wavelength (DSL)

- 1 mother satellite + 8 daughter satellites;
- 2h lunar orbit period;
- high precision in 30-120 MHz band
- mission launch in 2026;

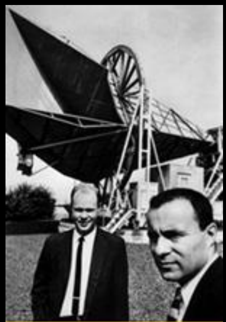
Probing ReionizATion of the Universe using Signal from Hydrogen (PRATUSH)

- Moon-orbiting experiment;
- 40-200 MHz band
- Pre-project funded by the Indian Space Research Organisation



Excess radio background: a new cosmological background?

The CMB spectrum: most perfect Planckian in nature



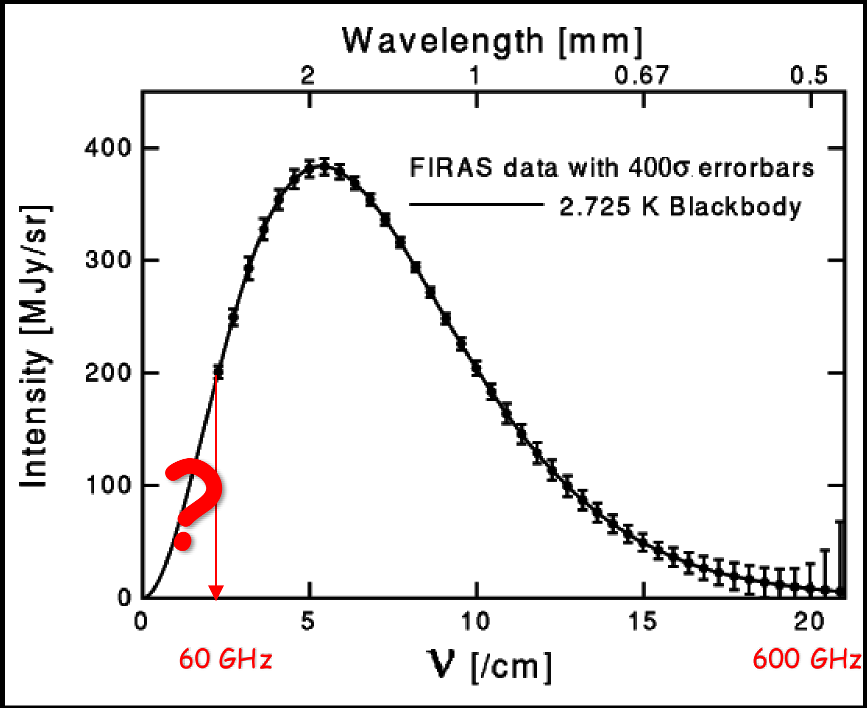
Penzias and Wilson (1965)

$T_{\gamma 0}$= (3.5 ± 1) ^{0}K

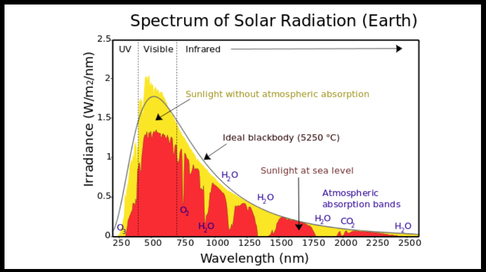
COBE satellite

FIRAS instrument of COBE (1990)

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



for a comparison

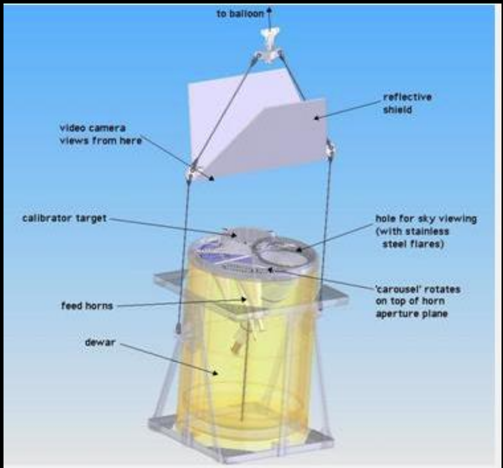


Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission (ARCADE 2)

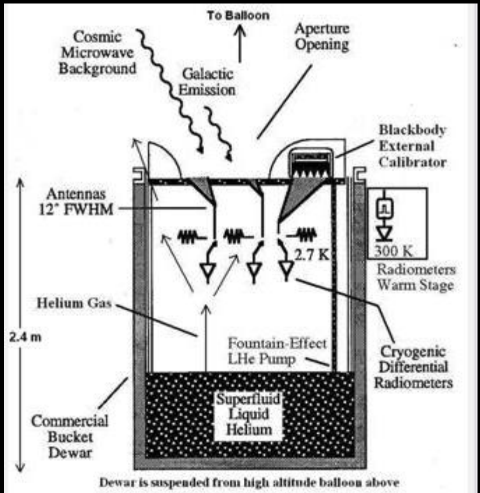
ARCADE 2: The instrument

(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.

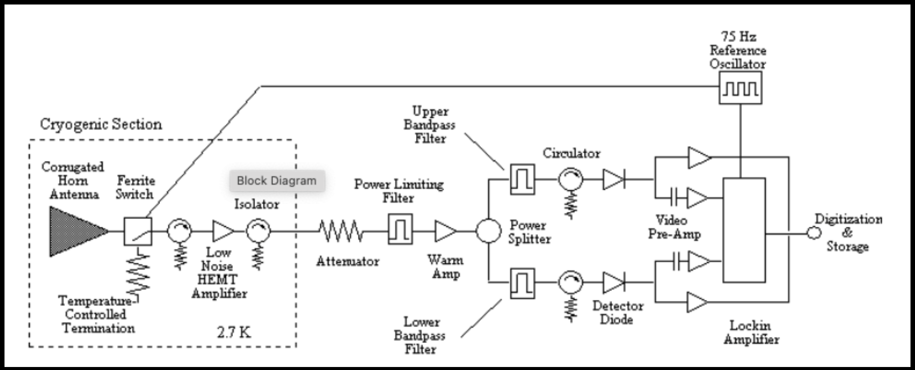


Schematic of ARCADE 2 instrument, highlighting the radiometric and thermal features.

- 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)



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)

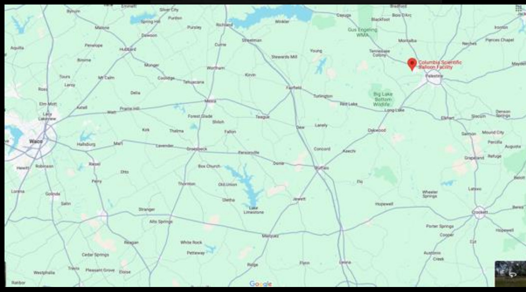
ARCADE Receiver Summary

	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

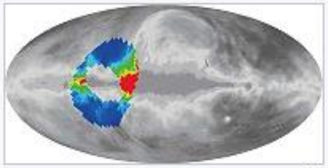
- Only the 3, 7 and 10 GHz radiometers produced useful data points (2 each one: 6 data points)

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.

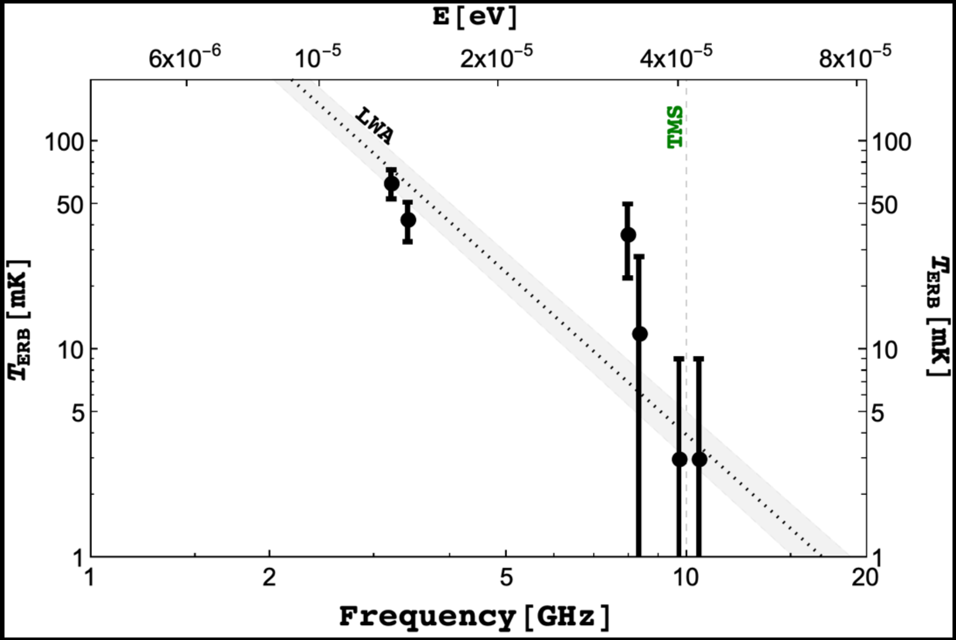
Photograph of the instrument upon landing, 2005. The electronics box and magnetometers which are mounted on the dewar are visible.

ARCADE 2: Results

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

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

effective 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:

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

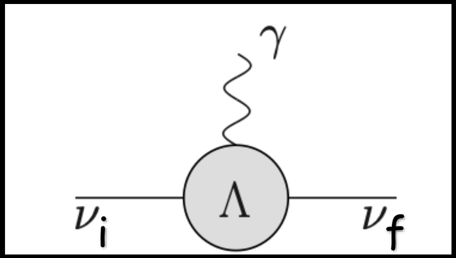
The excess radio background mystery

- 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*)
- “Higly accurate measurements…..The nature of the background is still unknown” (R. Sunayev 2408.01858)

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:



The decay active-to-active neutrino cannot explain the necessary small $\Delta m_i \ll 2.5\times10^{-4}$ eV
Then necessarily the final neutrino needs to be a sterile neutrino:

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

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

Moreover, assume that the ordinary neutrinos decay non-relativistically:
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:

$$E_{\gamma 0} = \frac{\Delta m_i}{1+z_D} \leq \Delta m_i$$

Fitting the ARCADE 2 excess radio background

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

The general expression for the specific intensity gets now specialized into:

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

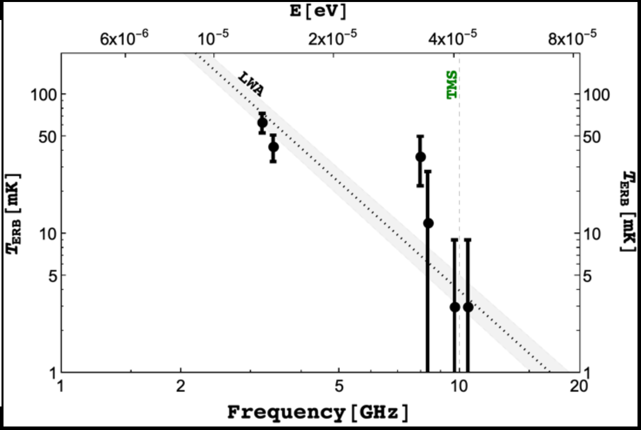
Moreover, we will consider solutions with $\tau_1 \gg t_0$ so that we can neglect the exponential:

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

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)	$T_{\gamma 0}^i$ (K)	$\overline{T}_{\rm ERB}^i$ (mK)	$\delta T_{\rm ERB}^i$ (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

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

input

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

χ^2

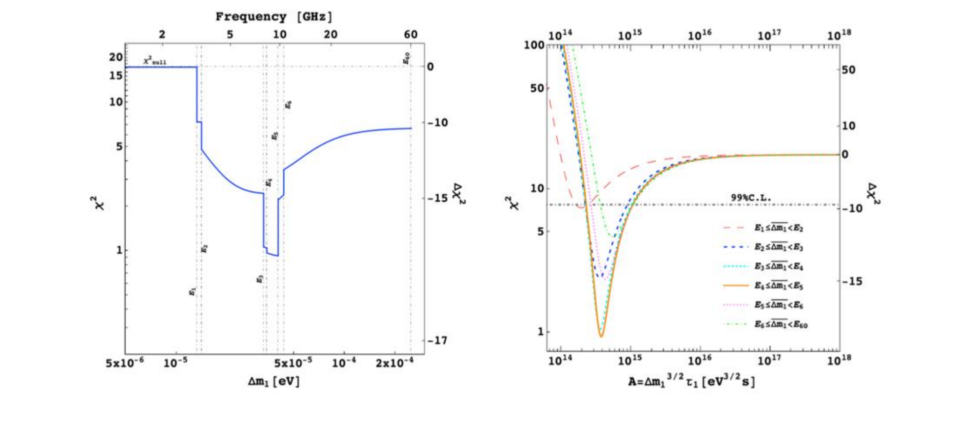
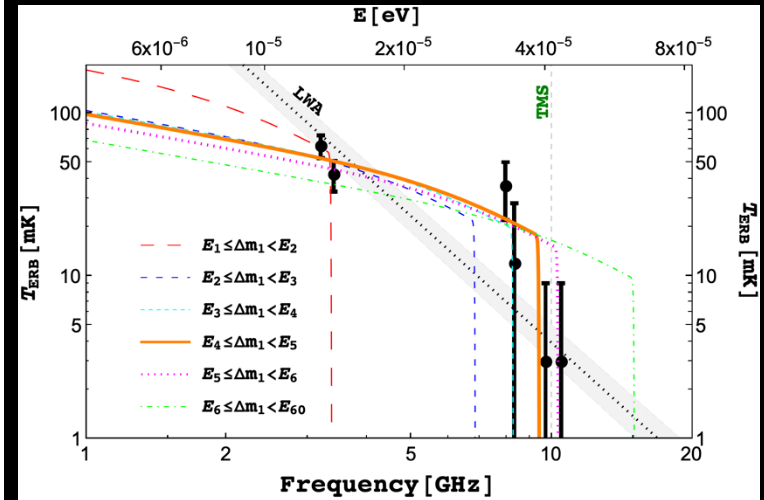


Figure 1. Left panel: χ^2 versus Δm_1 for best fit value of A in each interval as in Table 2. Right panel: χ^2 (4 d.o.f.) as a function of A for the best fit values of Δm_1 in each interval $E_i \leq \Delta m_1 < E_{i+1}$ as in Table 2.



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)

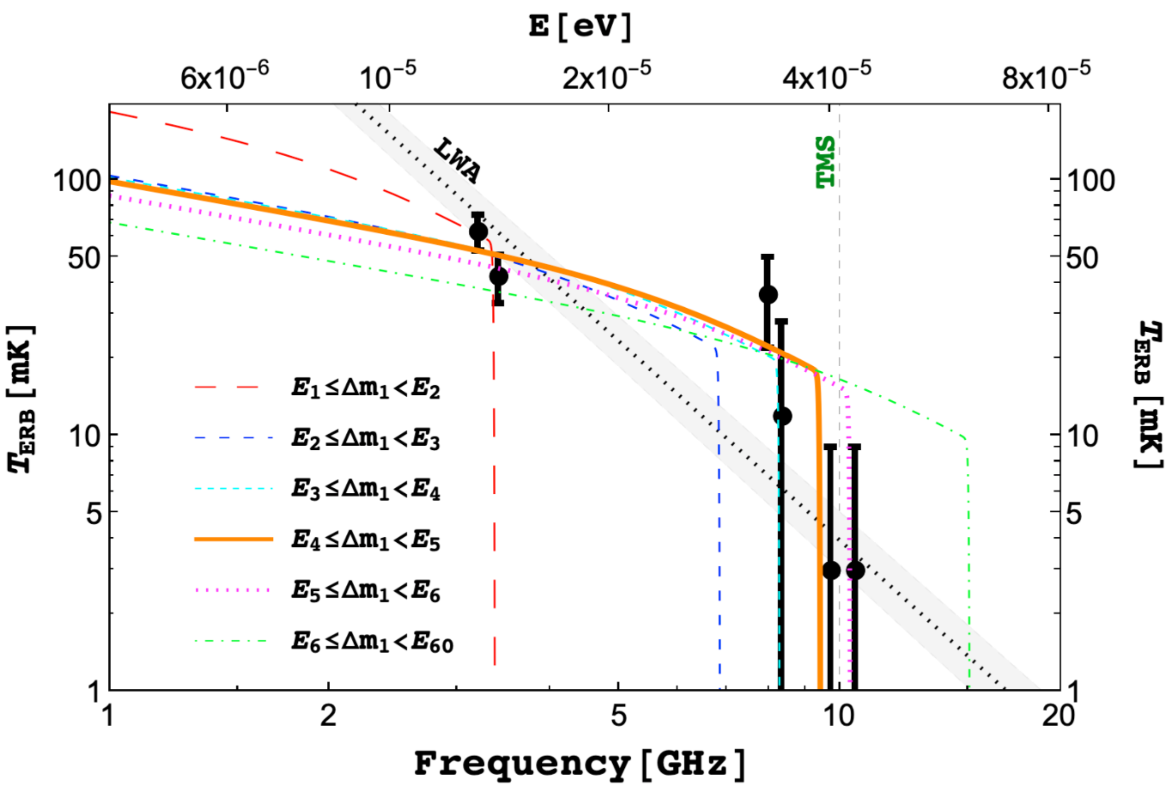
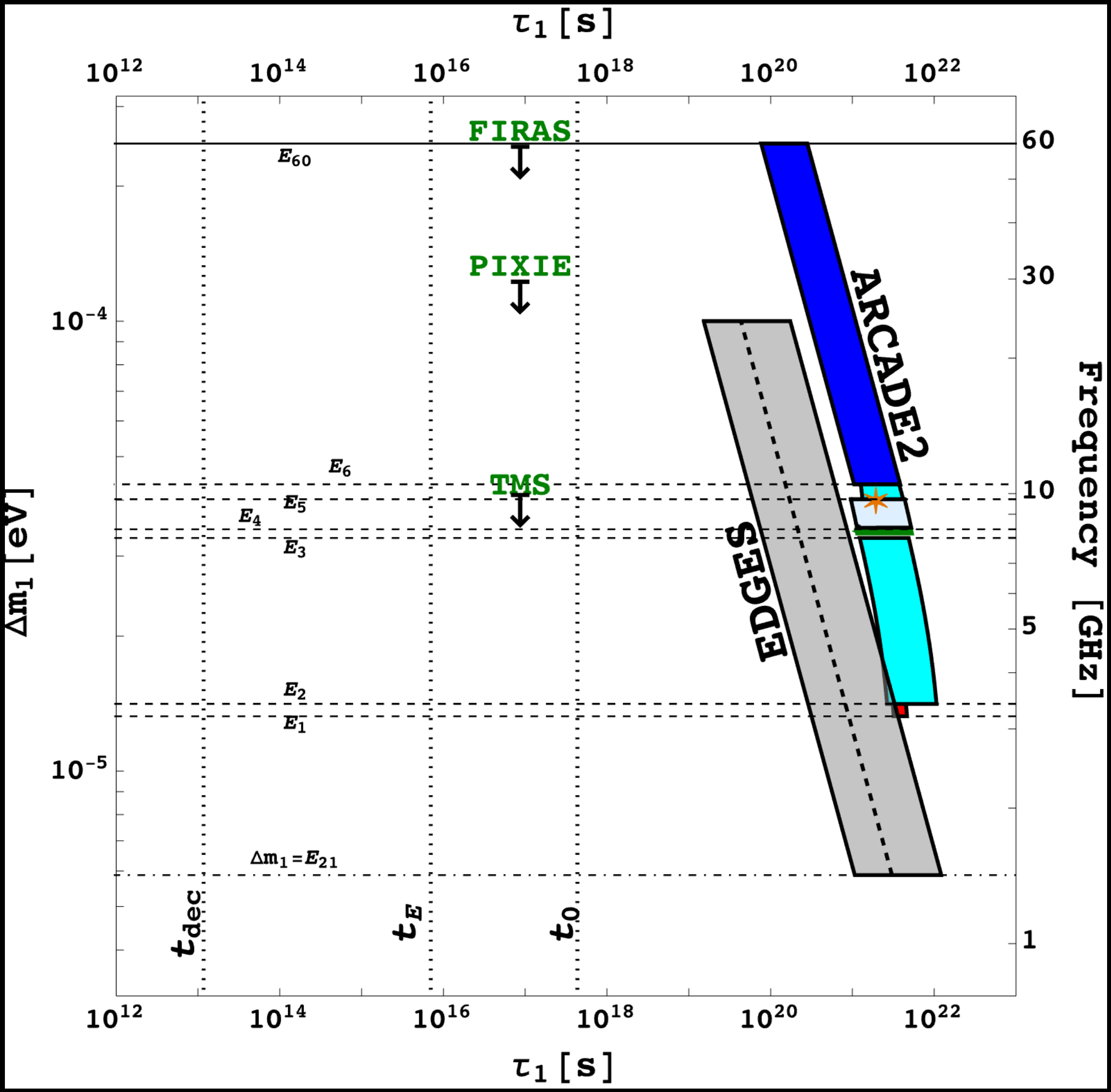


Figure 2. Best fit curves for $T_{\rm ERB}$ obtained with Eq. (3.2). The thick solid orange curve corresponds to a solution very close to the best global fit ($\Delta m_1 = 4.0 \times 10^{-5}$ eV and $\tau_1 = 1.46 \times 10^{21}$ s). The ARCADE 2 data points are taken from Ref. [1], while the power-law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

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

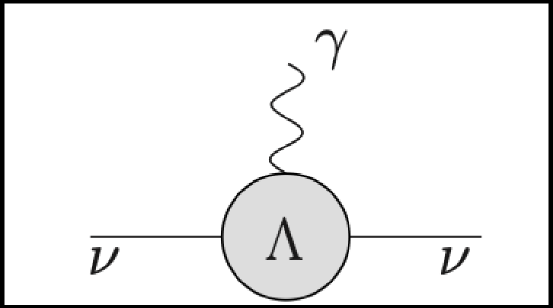
Allowed region (99% C.L.)

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

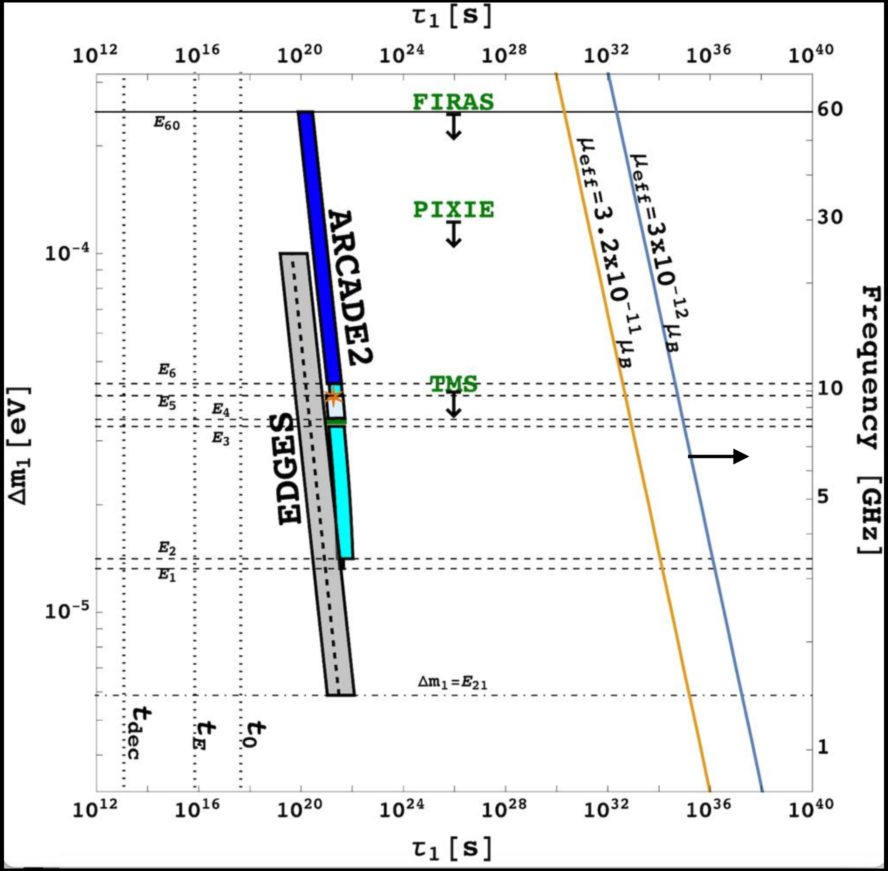


A clash with the upper limits on the effective magnetic moment

(Dev, PDB, Martinez-Soler, Roshan in preparation)



$$\Gamma_{\nu_j \to \nu_i + \gamma} = \frac{\mu^2_{\mathrm{eff},ij}}{8\pi} \left(\frac{m_j^2 - m_i^2}{m_j} \right)^3$$



This clash is very challenging but certainly interesting: which way to solve it? Stay tuned.

Final remarks

- New cosmological tools allow to explore new physics in regimes (energy and coupling) inaccessible to colliders
- At low scales there are interesting mysteries, in particular the excess radio background and relic neutrino decays seem to provide at the moment the most attractive solution
- The "short" requested lifetimes are challenging to explain, and this makes things quite exciting
- Soon there will be new results that can test such an idea, with new measurements both of 21cm cosmological global signal (lunar-based experiments) and excess radio background (TMS).

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!

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 $\nu_{21}=1420$ 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

21cm brightness contrast temperature

$$T_{21}(z) \simeq 23\,\mathrm{mK}\,(1+\delta_{\rm B})\,x_{H_I}(z)\left(\frac{\Omega_{\rm B0}h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_{\rm M0}h^2}\right)\left(\frac{1+z}{10}\right)\right]^{1/2}\left[1-\frac{T_\gamma(z)}{T_{\rm S}(z)}\right]$$

spin temperature

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

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

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

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 $T_{\rm gas}(\bar z_E)\ \simeq\ 7.2\,\mathrm{K}.$

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 ?

Testing an unstable relic neutrino background: a long history of constraints

(Kolb and Turner 1988)

5.5 Neutrino Cosmology 145

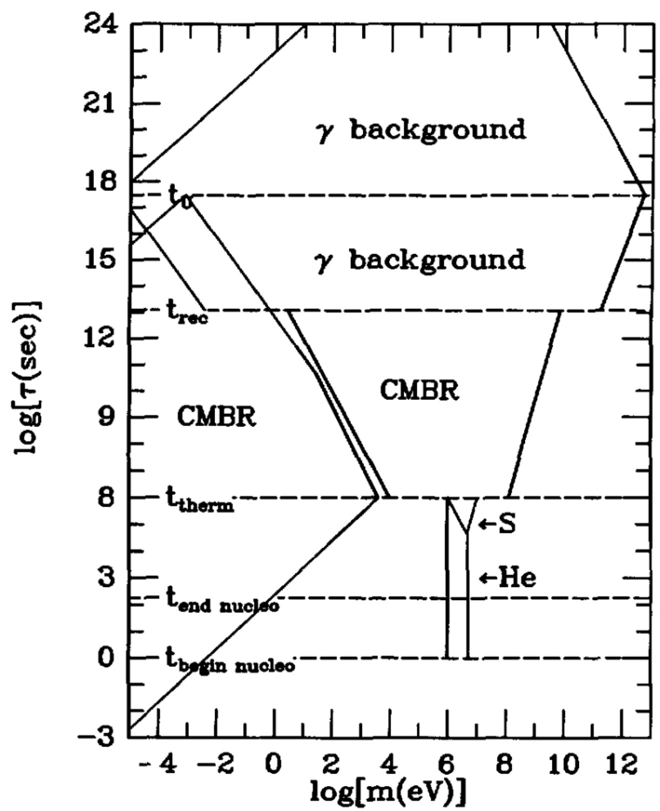


Fig. 5.6: Cosmological limits to the mass and lifetime of an unstable neutrino species that decays radiatively.

Testing an unstable relic neutrino background: a long history of constraints

(Kolb and Turner 1988)

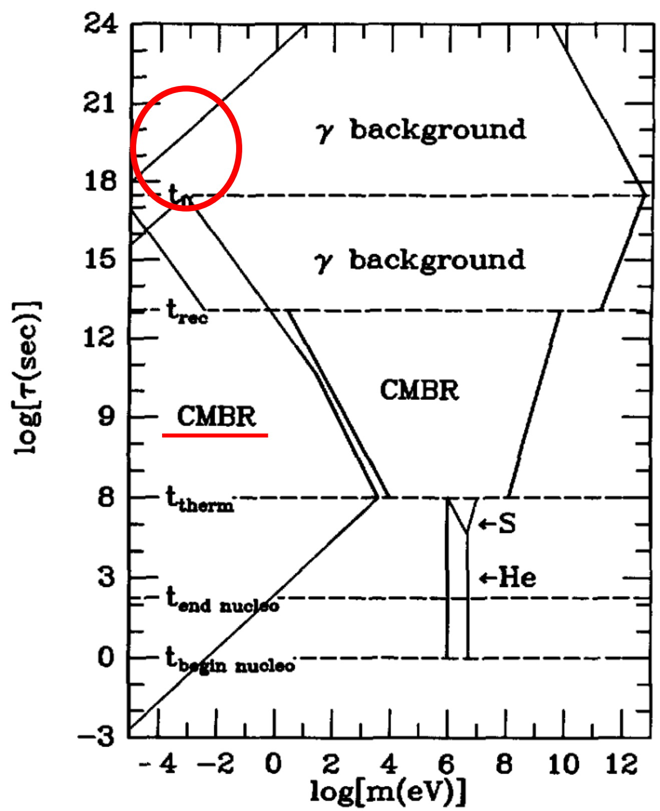


Fig. 5.6: Cosmological limits to the mass and lifetime of an unstable neutrino species that decays radiatively.