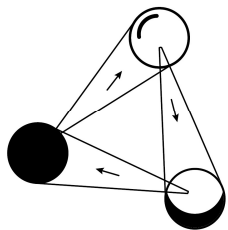


Detection of extremely weak signals at room temperature for radioastronomy and Earth observation applications



**MILLIMETER AND
SUBMILLIMETER TEAM**

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Motivación

Electro optic up-converter

Experiment

Sensitivity as radiometer

Conclusions

Consideraciones previas

Otra dificultad para nuestro *ahora*: ¡espacio y tiempo no son constantes! Nuestra velocidad en el tiempo está relacionada con nuestra velocidad en el espacio. Imaginemos nuestra esfera espaciotemporal así:



El límite del amarillo y el azul se mueve según nuestra velocidad.

Cuanto más deprisa se desplace un objeto en el espacio, **más se ralentiza en el tiempo**. En la esfera, la superficie amarilla aumenta; la azul disminuye:



Al ganar velocidad en el espacio, el piloto pierde en velocidad temporal. El tictac de su reloj se ralentiza...

... comparado con el tictac del reloj de Adam.



Consideraciones previas



Un objeto inmóvil en el universo solo se desplazaría en el tiempo en relación con todos los demás. Por tanto, la esfera sería completamente azul:



Ten en cuenta que tal objeto no existe en el cosmos (... mucho menos un banco sobre una piedra).

Consideraciones previas

Por el contrario, la luz se desplaza a la velocidad máxima. Siempre se aleja de nosotros a 300.000 kilómetros/segundo*, cualquiera que sea nuestra velocidad: está como fuera del tiempo.

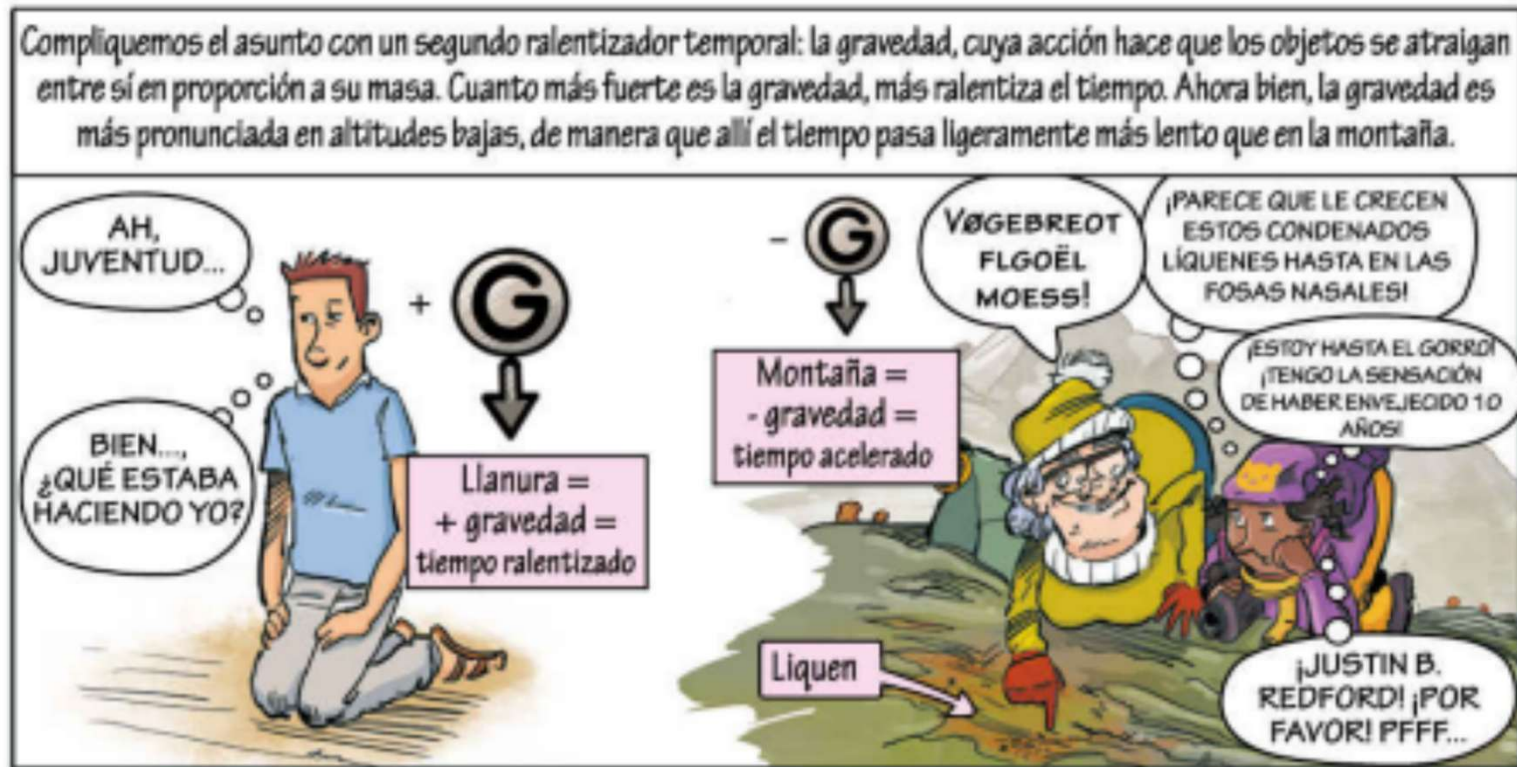
La luz solo se desplaza en «el espacio». ¡Para ella, el tiempo no pasa!



Los fotones transportan la luz. No tienen masa.

* Exactamente: 299.792,458 km/s.

Consideraciones previas



He aquí el problema (aparte de la ausencia de Justin B. Redford). En varios puntos del globo, todos concuerdan en un *ahora* a las 10 h 00 min y 00,0 segundos. Pero una medición más precisa señala el fin de la simultaneidad: en cada uno de esos lugares imperan condiciones distintas de gravedad y de velocidad de desplazamiento. Además, unas centésimas de segundo los separan debido a la velocidad de la luz.

Consideraciones previas

En resumen: el *ahora* de unos difiere en algunos nanosegundos con respecto al *ahora* de otros. Dado que nuestros sentidos son incapaces de percibir el mundo por debajo de alrededor de una décima de segundo, las 10 h 00 min 00,00 s UTC solo nos proporcionan la *ilusión* de un tiempo simultáneo en todos los lugares de la Tierra.



Consideraciones previas



Consideraciones previas



Consideraciones previas



Consideraciones previas

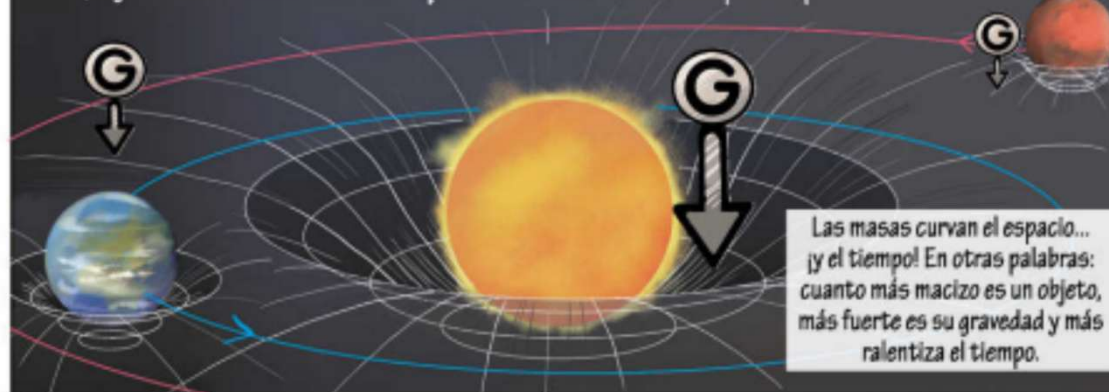


Consideraciones previas

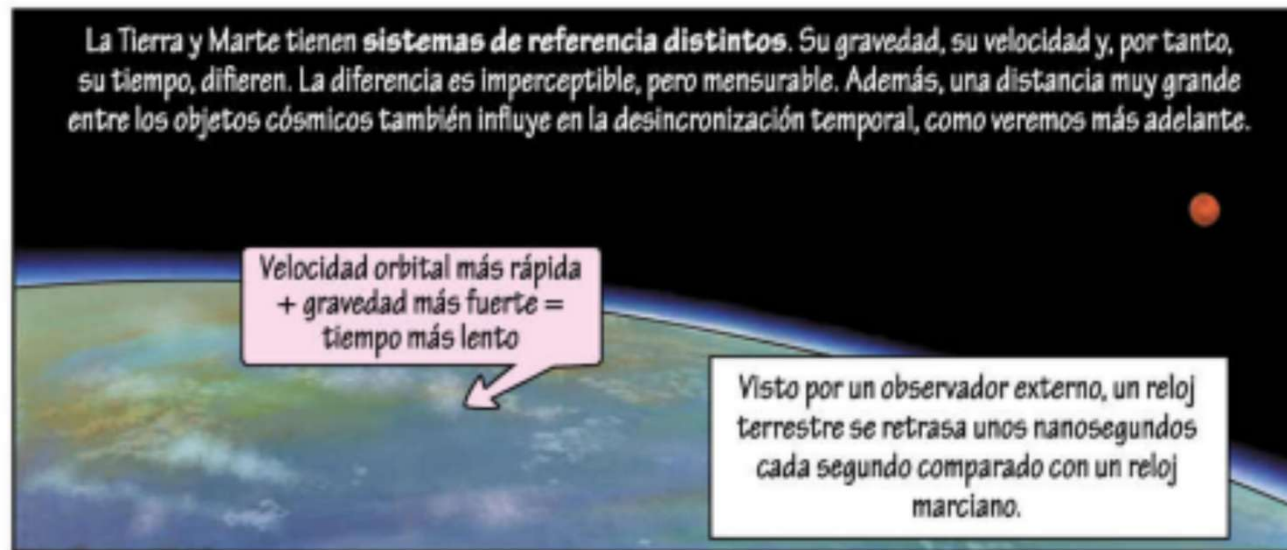
Además, recuerda: un objeto se desplaza en el espacio (en amarillo  en la pequeña esfera), pero también en el tiempo (en azul ). La velocidad combinada de su velocidad en el espacio y en el tiempo equivale a la esfera entera: es la velocidad de la luz, siempre constante. Ahora bien, la Tierra orbita unos miles de km/h más rápido que Marte. Un observador situado en el Sol, por ejemplo, mediría que el tiempo pasa un poco más lentamente en la Tierra que en Marte.



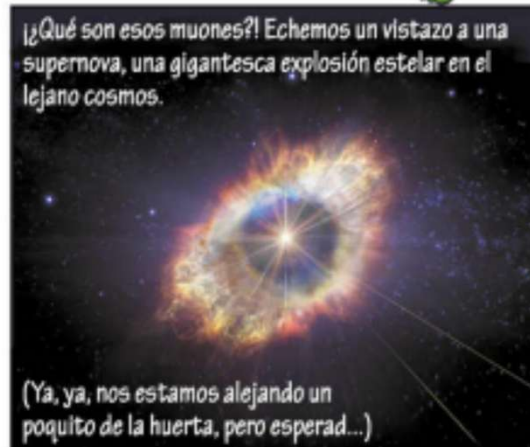
Añadamos un elemento del que ya hemos hablado: la gravedad. Al integrar la gravedad a la relatividad restringida, Albert Einstein descubrió la **relatividad general**. Esta demuestra que todo el espacio-tiempo es blando, algo así como un colchón sobre el que hubiésemos colocado unas pelotas pesadas.



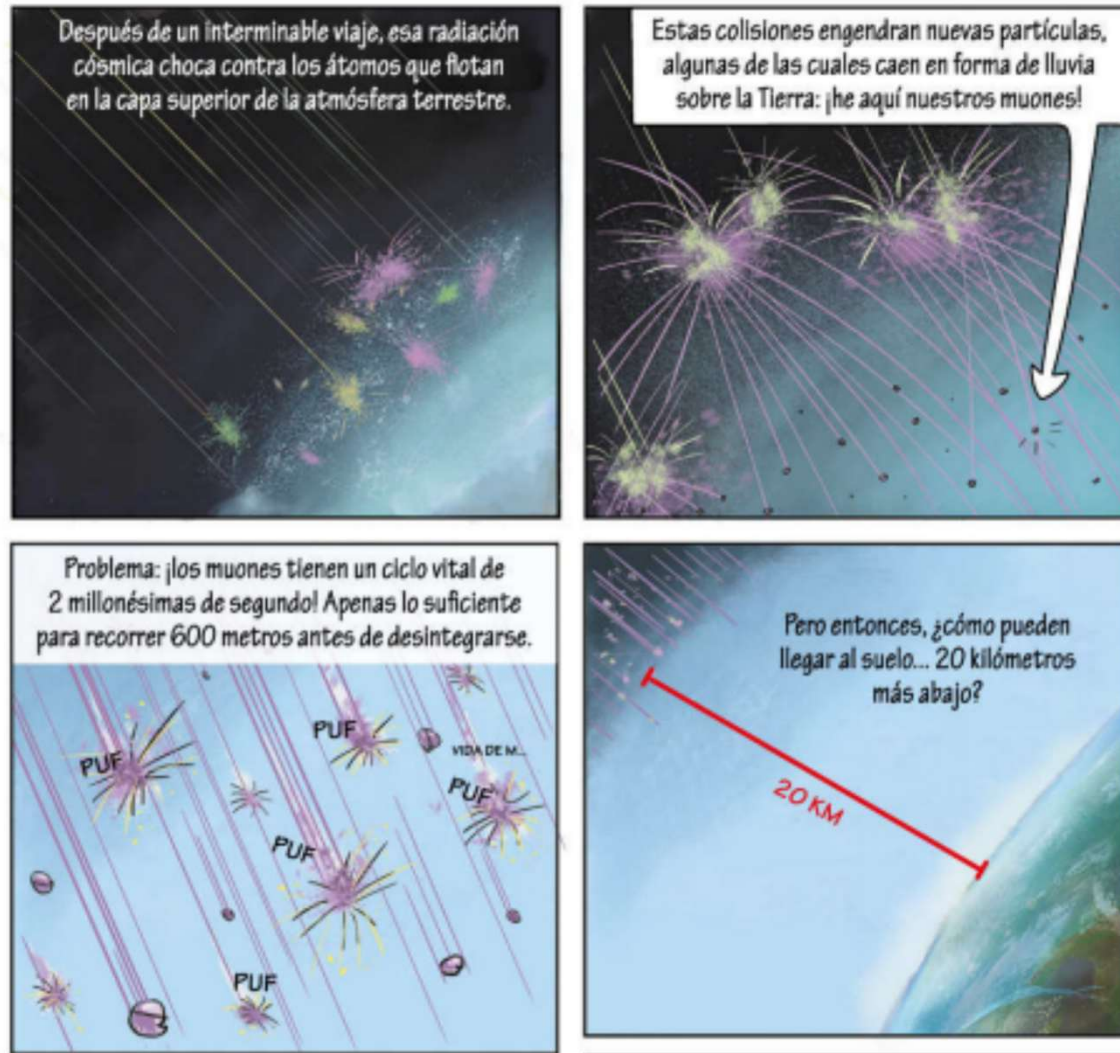
Consideraciones previas



Consideraciones previas



Consideraciones previas



Consideraciones previas



Consideraciones previas

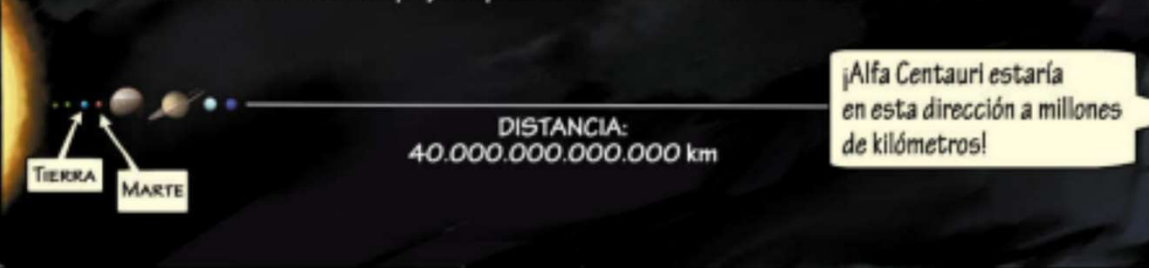


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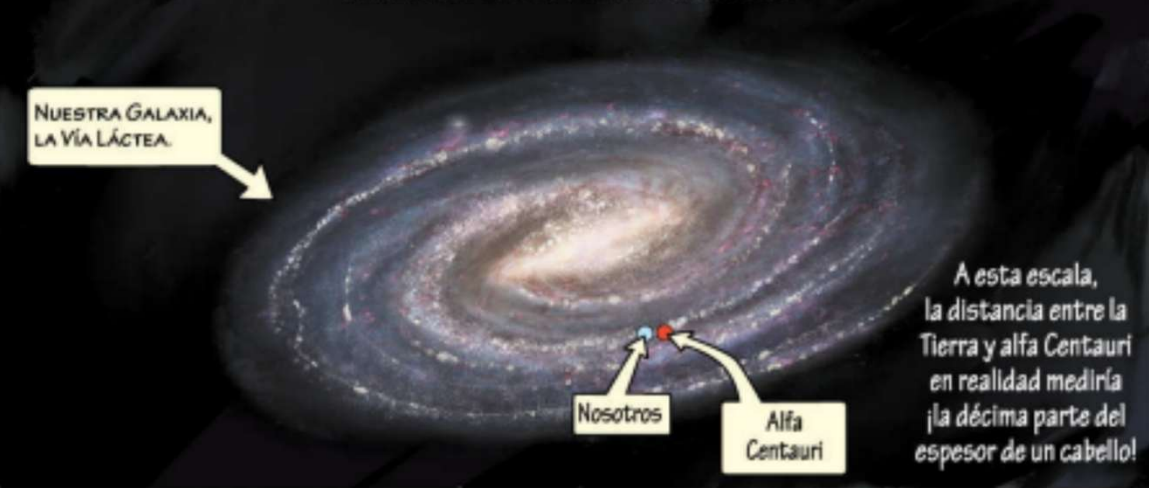


Consideraciones previas

Nuestro mosquito de referencia ha viajado así desde el «garaje de al lado» hasta el otro extremo de la Tierra. En equivalencia cósmica, nuestro insecto habría llegado a la estrella **alfa Centauri**, fuera del Sistema Solar. Esta viñeta es demasiado pequeña para ilustrar a escala la distancia de esta estrella.



En la escala del universo, alfa Centauri es, sin embargo, una vecina: la estrella más próxima al Sistema Solar, a «solo» 4 años luz. ¡Ella y nuestro Sol están a las afueras de una galaxia que cuenta al menos con 100.000 millones de estrellas!



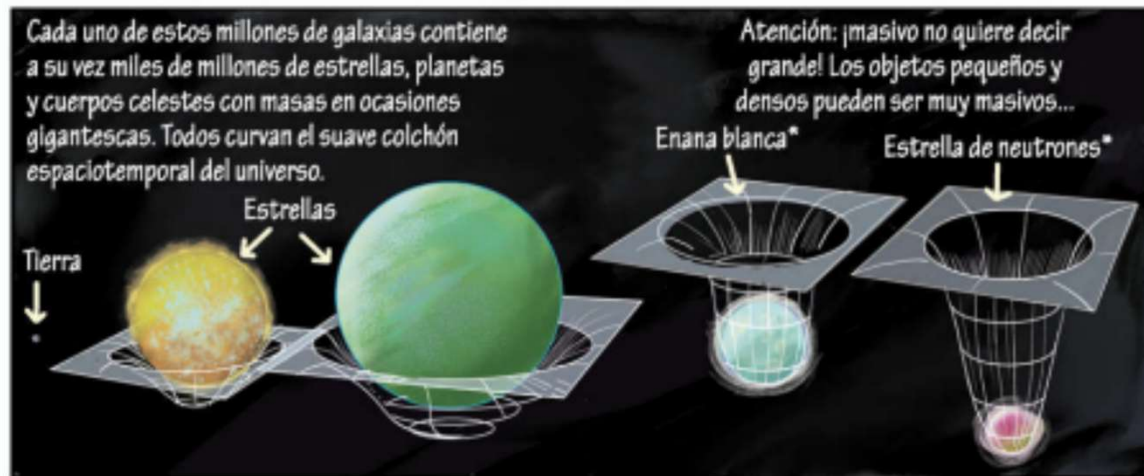
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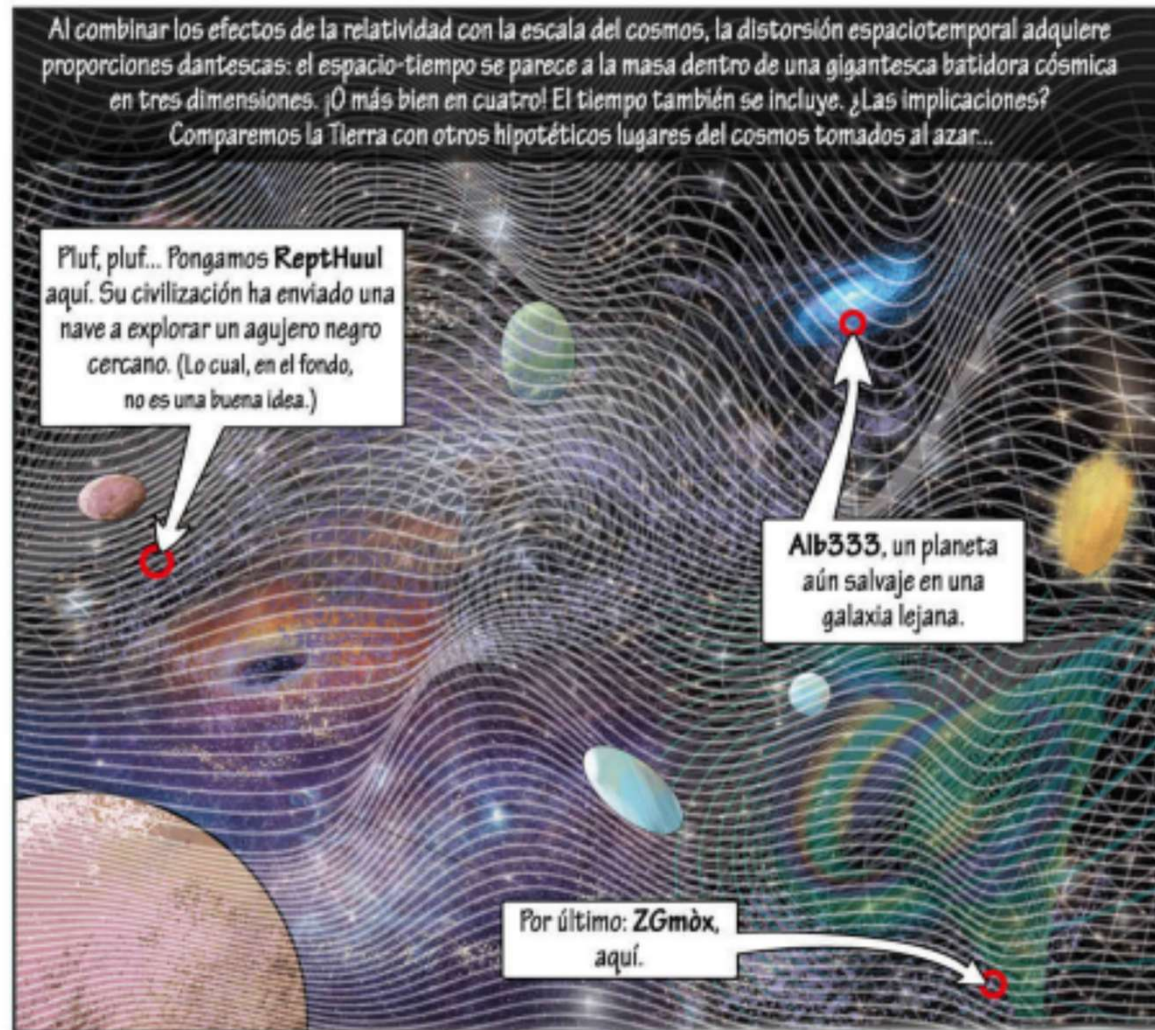
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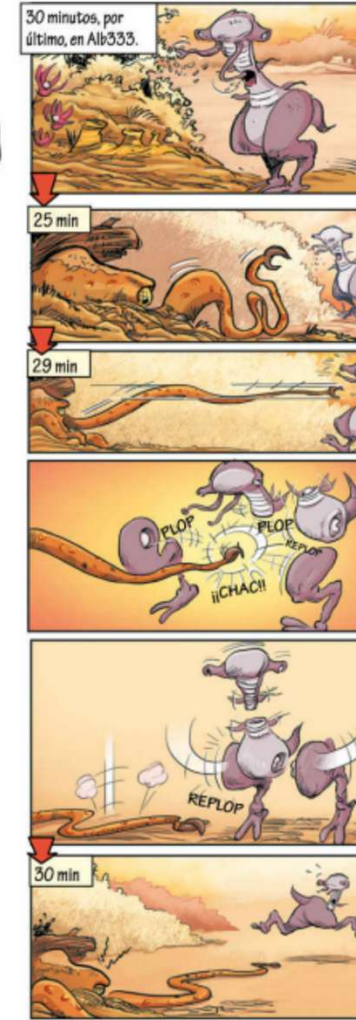
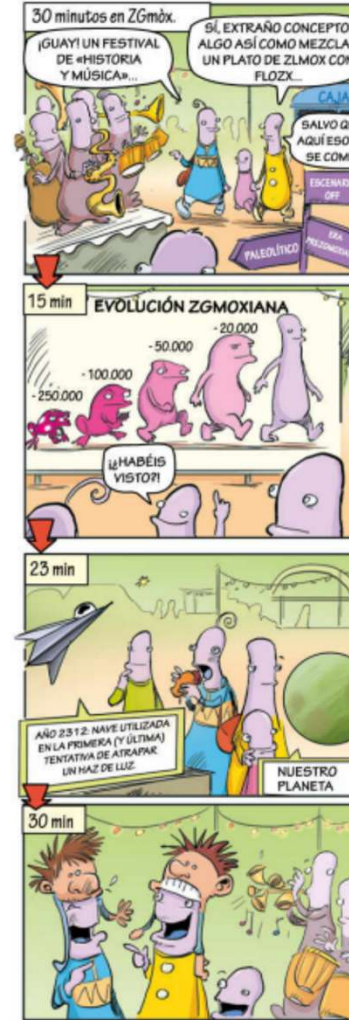
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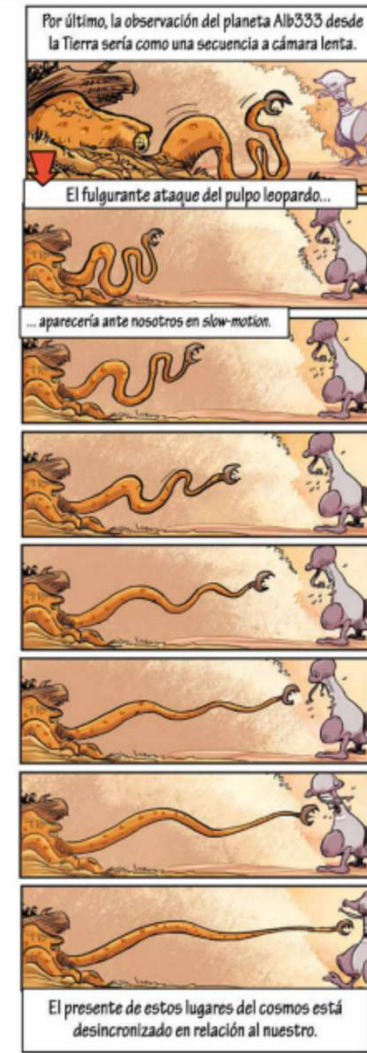
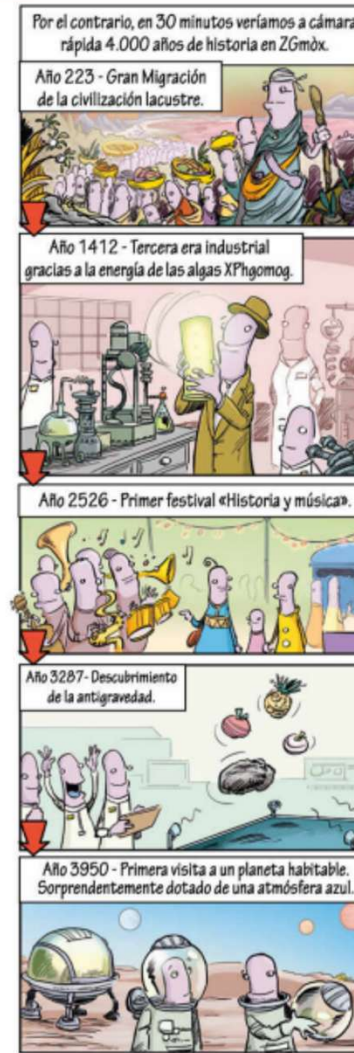
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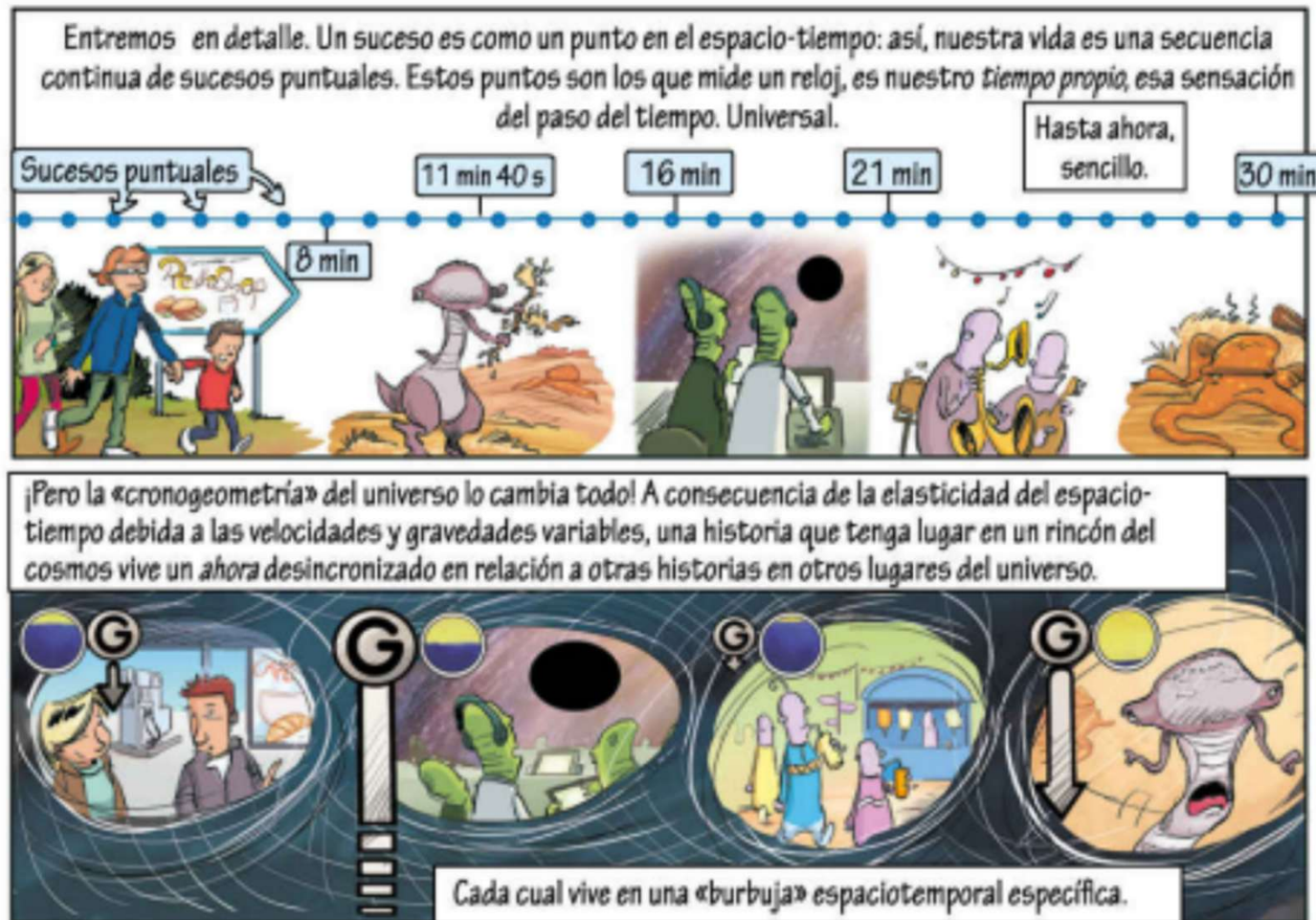
Consideraciones previas



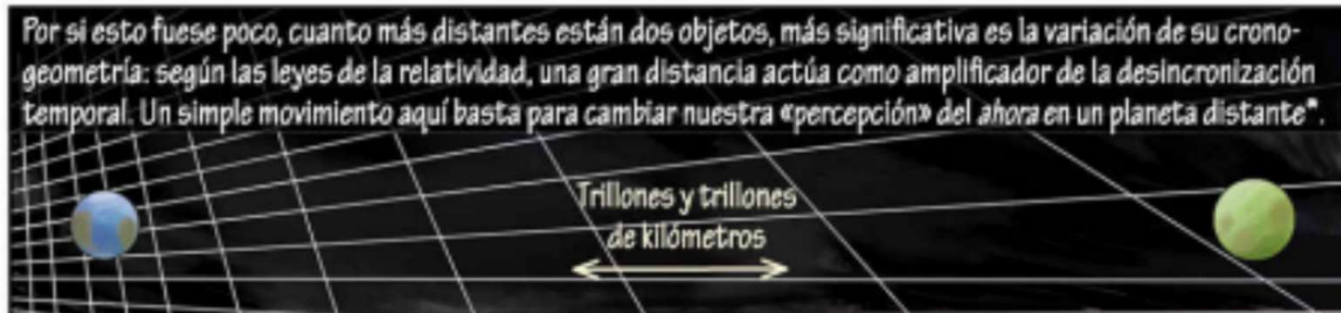
Consideraciones previas



Consideraciones previas



Consideraciones previas



Dicho de otro modo: «El ahora de una galaxia lejana [...] cuando camino puede diferir en miles de años con respecto al ahora de la misma galaxia cuando estoy inmóvil», escribe el astrofísico Trinh Xuan Thuan. Imaginemos que Zoé y Adam pudieran ver el ahora del planeta ZGmòx. En la práctica, es imposible. Pero aceptemos que poseen una especie de visión mágica.



Consideraciones previas



**MILLIMETER AND
SUBMILLIMETER TEAM**

La relatividad de Einstein, ilustrada mediante este «universo pastel», nunca ha sido refutada. Por tanto, sigue siendo en la actualidad la descripción más sólida que tenemos del tiempo, aunque, sin duda, sea incompleta. La mayoría de los investigadores consideran insatisfactoria la idea de un tiempo que se presentaría como un bloque estático. De hecho, resulta difícil admitir la ausencia de tiempo, un futuro predeterminado, sin libre albedrío.

LOS FOTONES,
VECTORES DE LA LUZ
Y DESPROVISTOS
DE MASA, SON
ATEMPORALES.
CARECEN DE SISTEMA
DE REFERENCIA, ESTÁN
FUERA DE CAMPO. ¿UN
FOTÓN NACE Y MUERE
AL MISMO TIEMPO?

AL ENTRAR EN UN AGUJERO NEGRO, EN LA GRAVEDAD «INFINITA», LA TRIPULACIÓN REPTHULLIANA VE COMO LA ETERNIDAD PASA, EN UN INSTANTE: LA VIDA Y LA MUERTE DE LOS QUE SE HAN QUEDADO EN REPTHULL, DE SU PLANETA, DE SU GALAXIA, DEL COSMOS ENTERO. EL TODO EN UNA FRACCIÓN DE SEGUNDO.

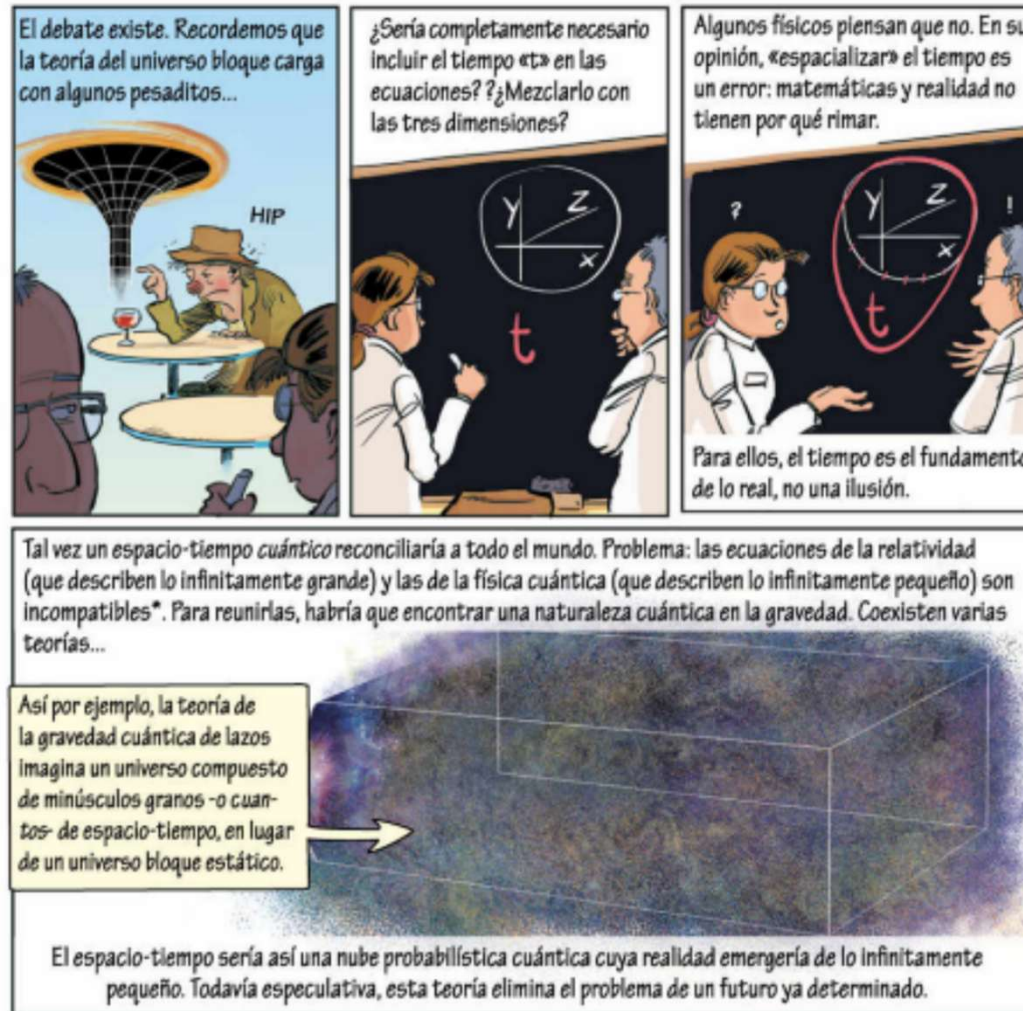
1890: CLÉMENT ADER
A BORDO DEL ÉOLE, UNO DE LOS
PRIMEROS VUELOS CON MOTOR

1877: LUDWIG BOLTZMANN
DEFINE EL ASPECTO
ESTADÍSTICO DE LA ENTROPÍA,
DESCRIBIENDO UN MUNDO QUE
SIEMPRE VA DEL ORDEN AL
DESORDEN.

EL LIBRO LA TEORÍA DEL TODO, EL UNIVERSO SIN SECRETO DESCRIBE CON EXACTITUD EL FUNCIONAMIENTO DEL CONJUNTO DEL COSMOS. SE PUBLICARÁ EN EL AÑO 2552. SI EL UNIVERSO ES UN BLOQUE, ¿QUIZÁ ESTE LIBRO YA EXISTE?

04/12/202

Consideraciones previas



Consideraciones previas

También solucionaría la densidad infinita del agujero negro. Este podría contener en su centro una «estrella de Planck». A modo de recordatorio, he aquí la visión clásica de un agujero negro:

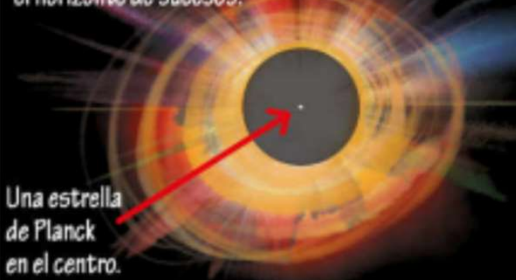
En el medio una singularidad, es decir, una densidad infinita...

... y un ciclo vital de trillones y trillones de años. Pero ¿es este en realidad el caso? ¿Y si...



... un agujero negro fuera de hecho una «explosión»? Su aparente inmovilidad a nuestros ojos solo se debería a la ralentización temporal creada por la gravedad. Como la nave reptHuuliana congelada ante el horizonte de sucesos.

Una estrella de Planck en el centro.



Esta «explosión», un colapso y luego un rebote, sería causada por el franqueamiento de una densidad-límite (por tanto, no infinita) que supondría el paso de un agujero negro...

¡... hacia un agujero blanco!

Una especie de gemelo invertido del agujero negro del que es posible salir pero no entrar.

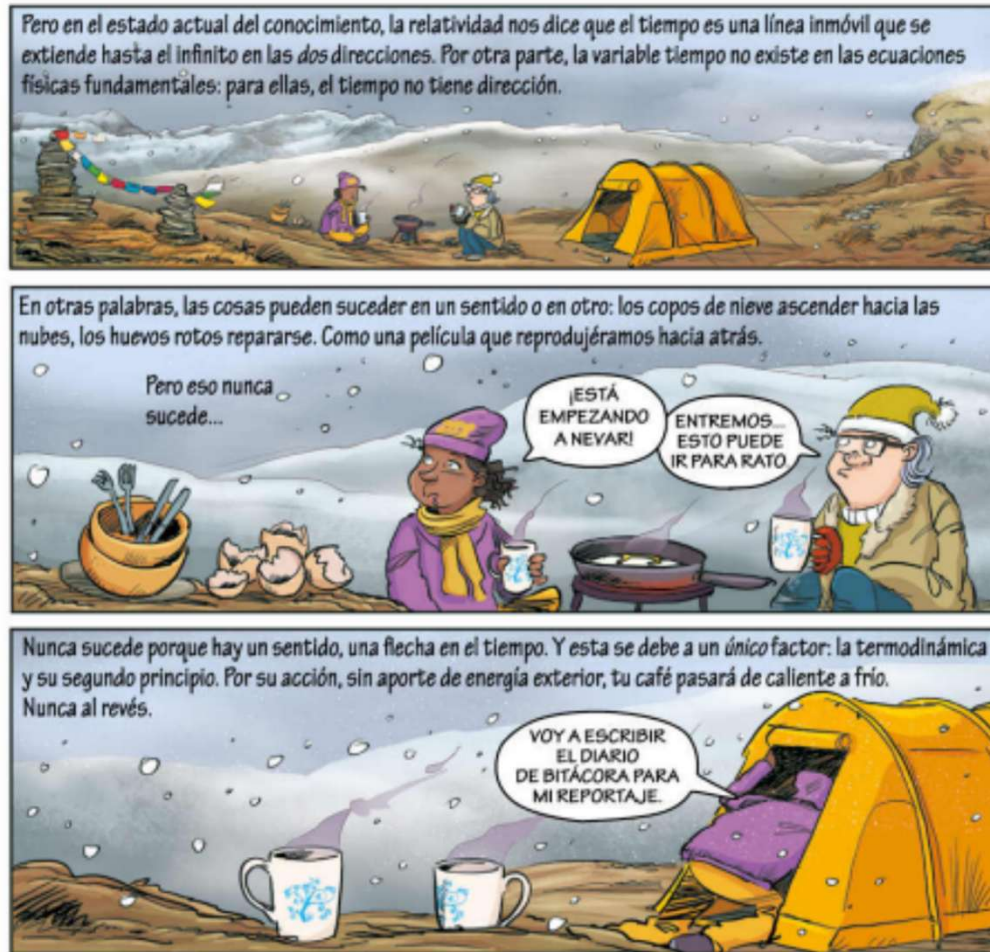


«La relatividad general predice la posibilidad de agujeros blancos», explica el físico Carlo Rovelli, coautor de la teoría.

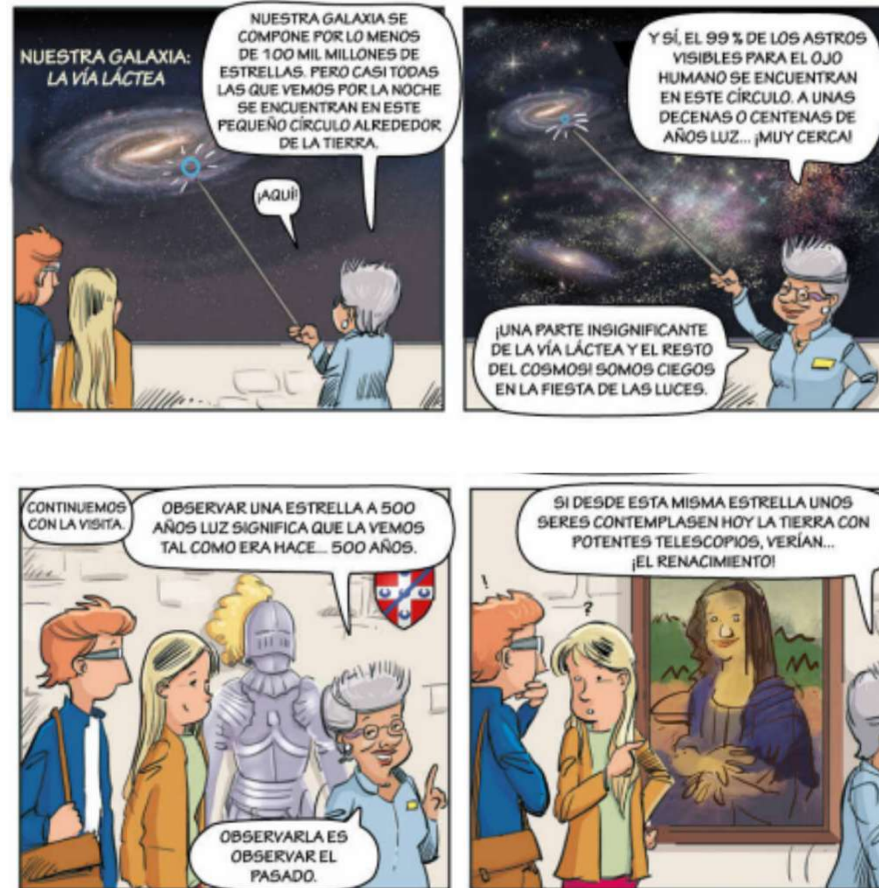


Existen otras hipótesis. Todas tratan de resolver los enigmas de los agujeros negros y el tiempo. Y todas buscan pruebas.

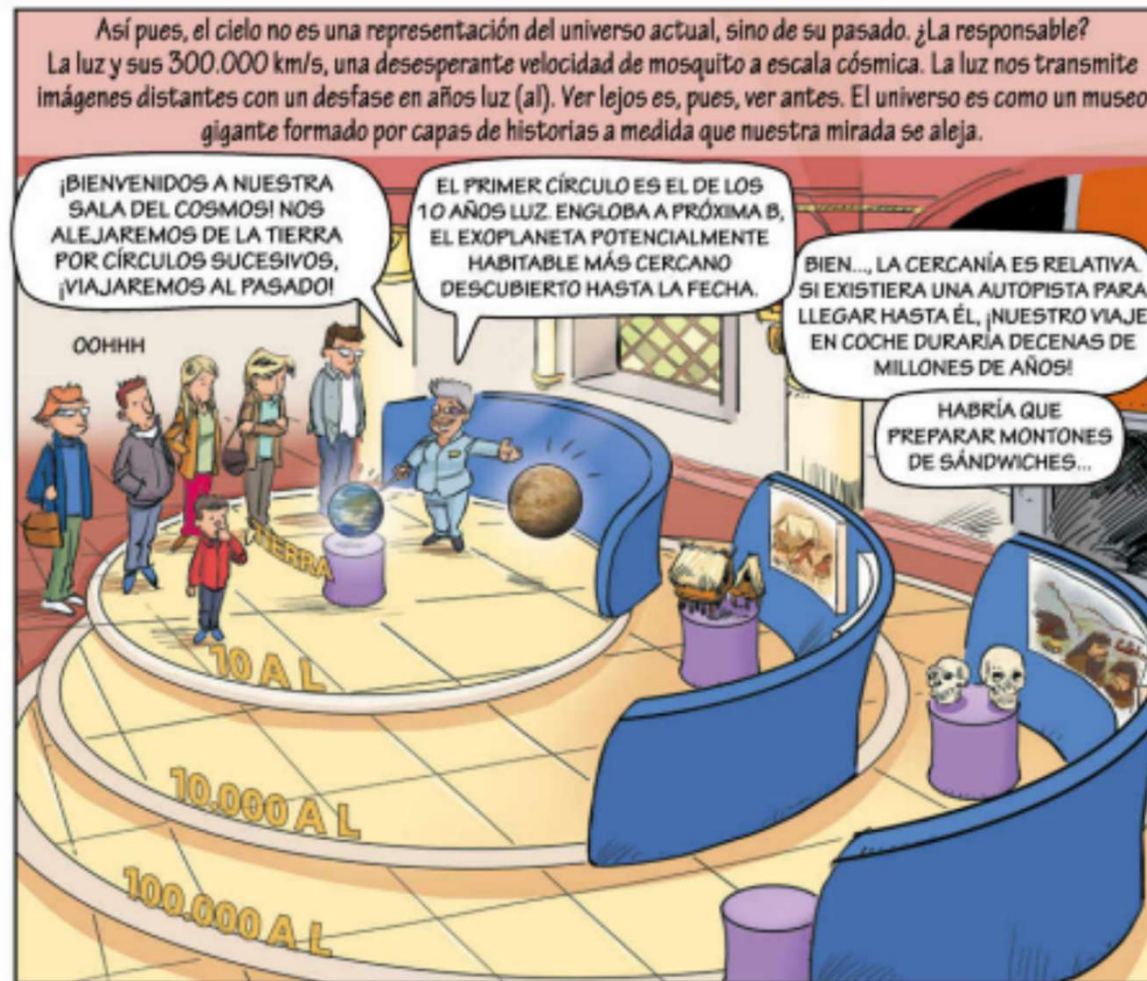
Consideraciones previas



Consideraciones previas



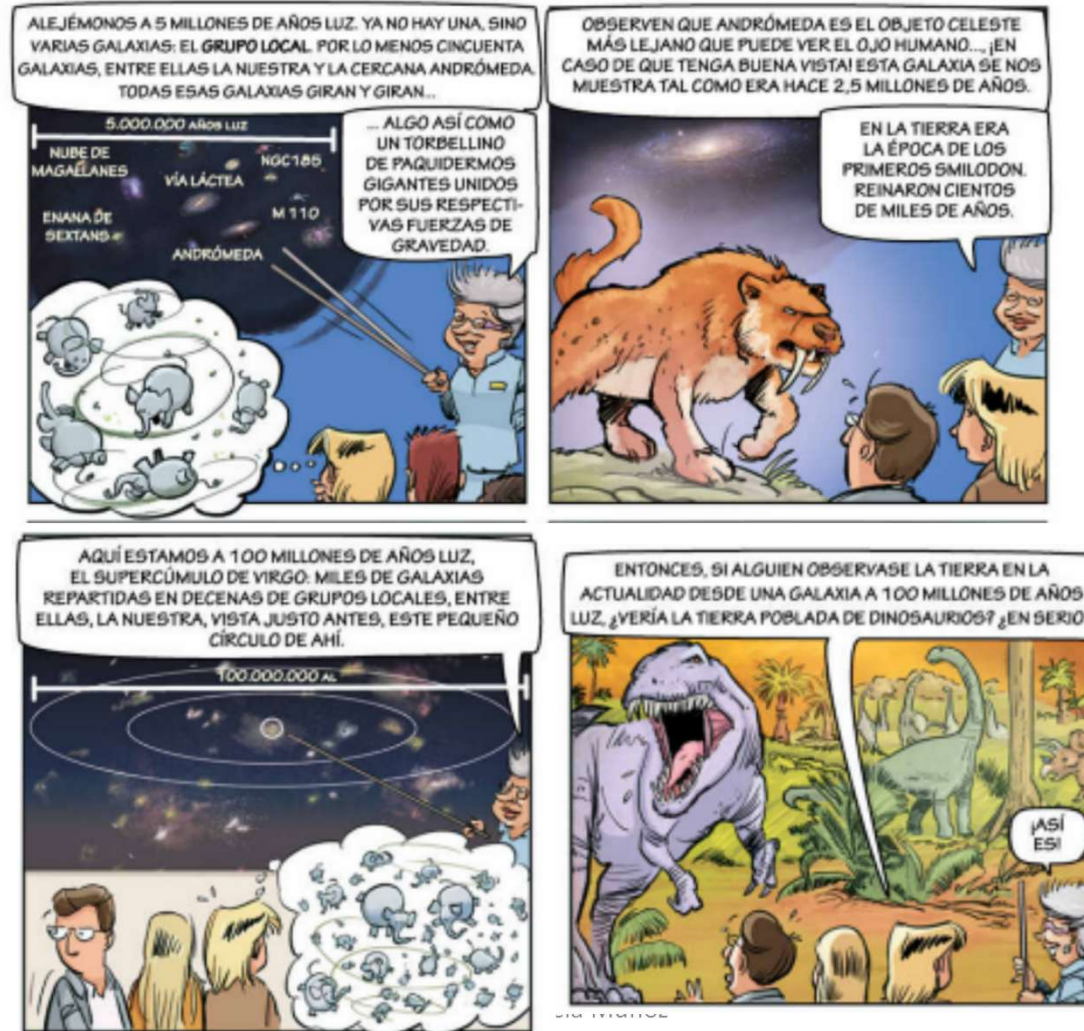
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Consideraciones previas



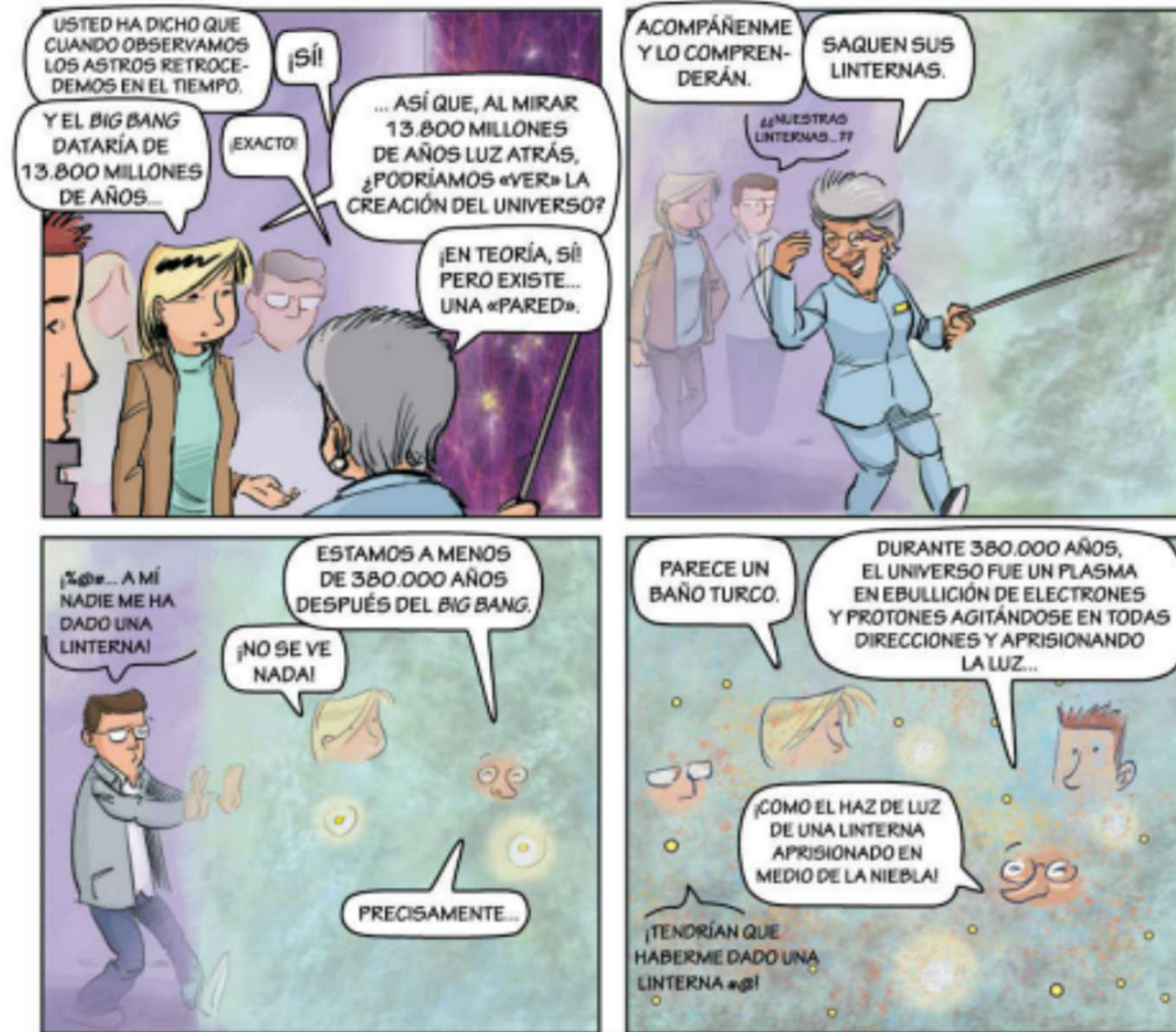
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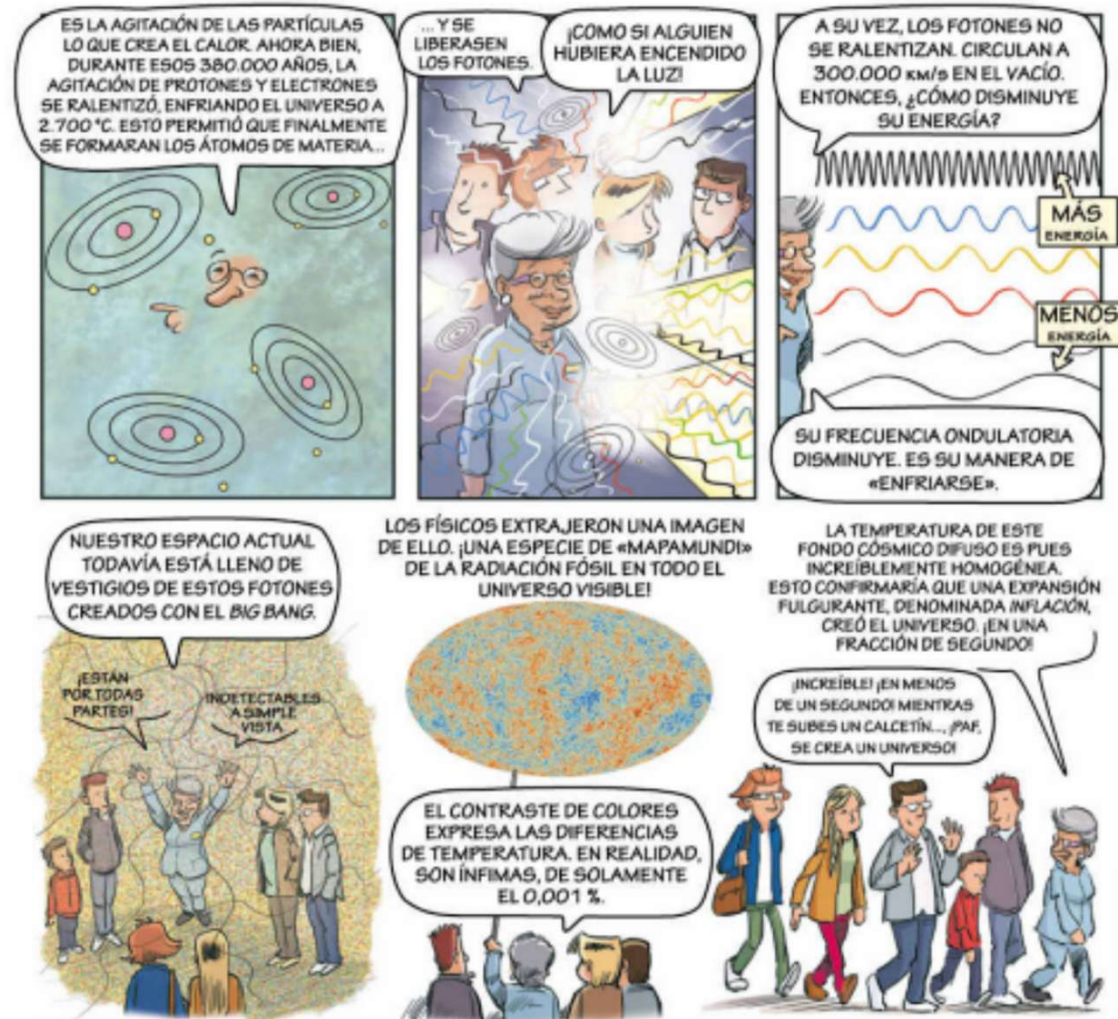
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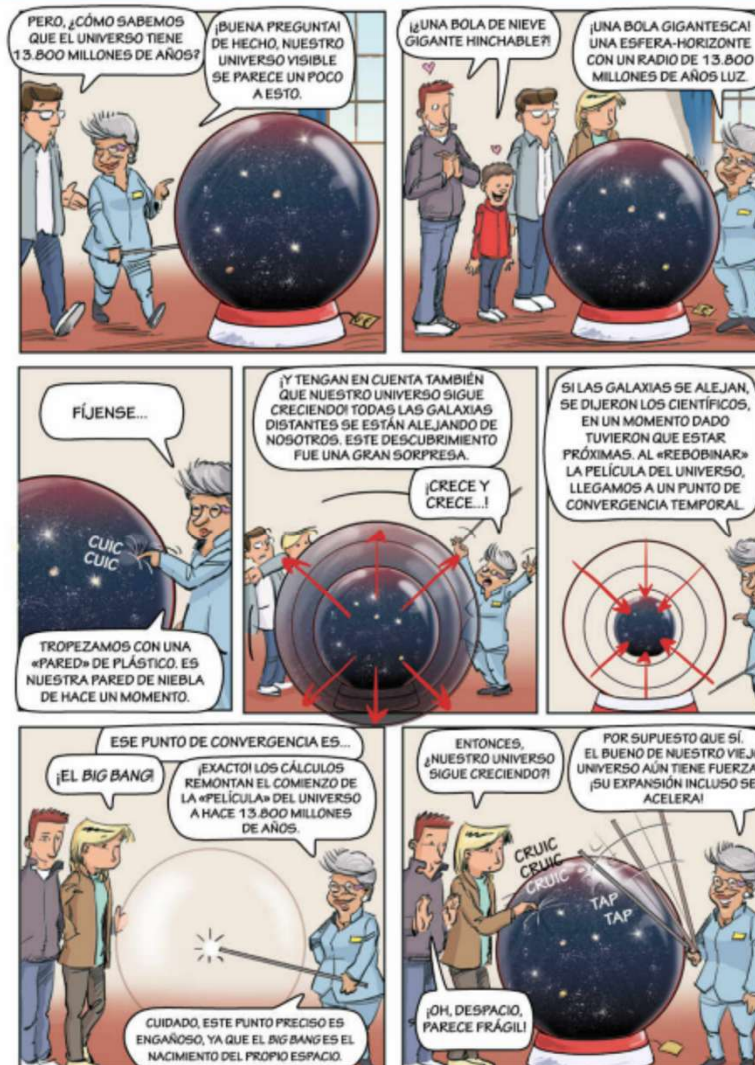
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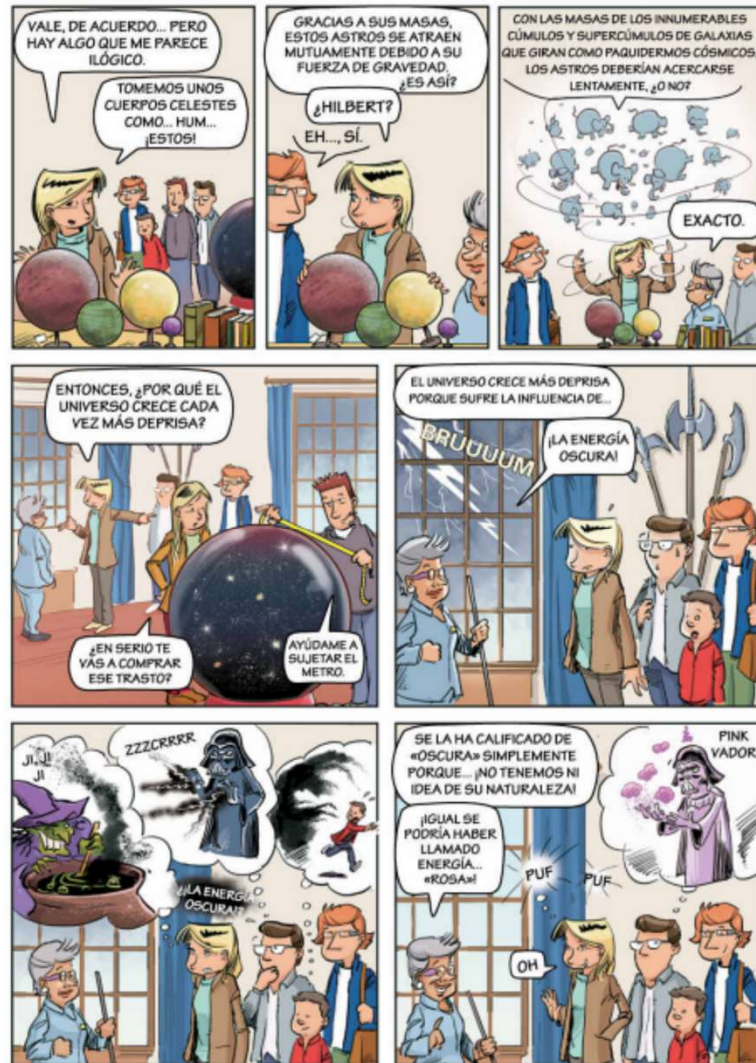
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Consideraciones previas



Consideraciones previas



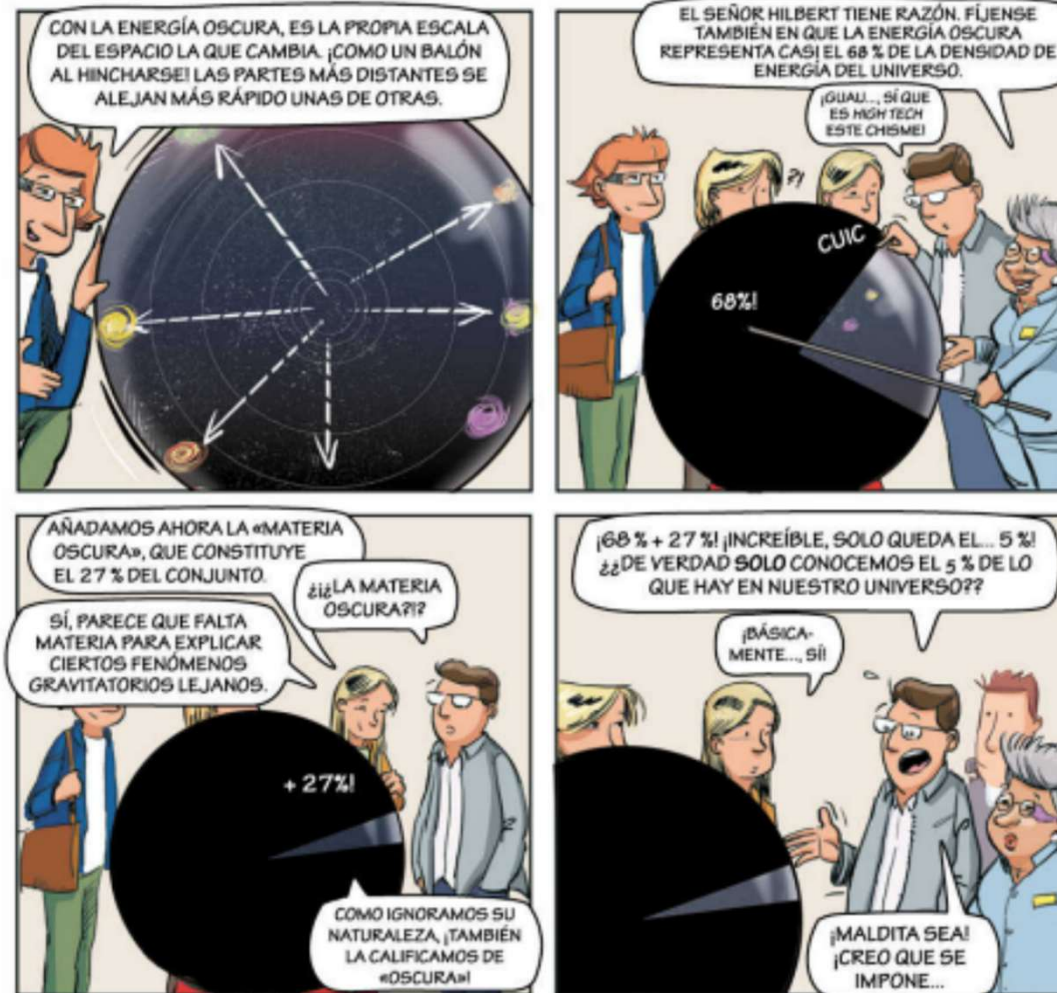
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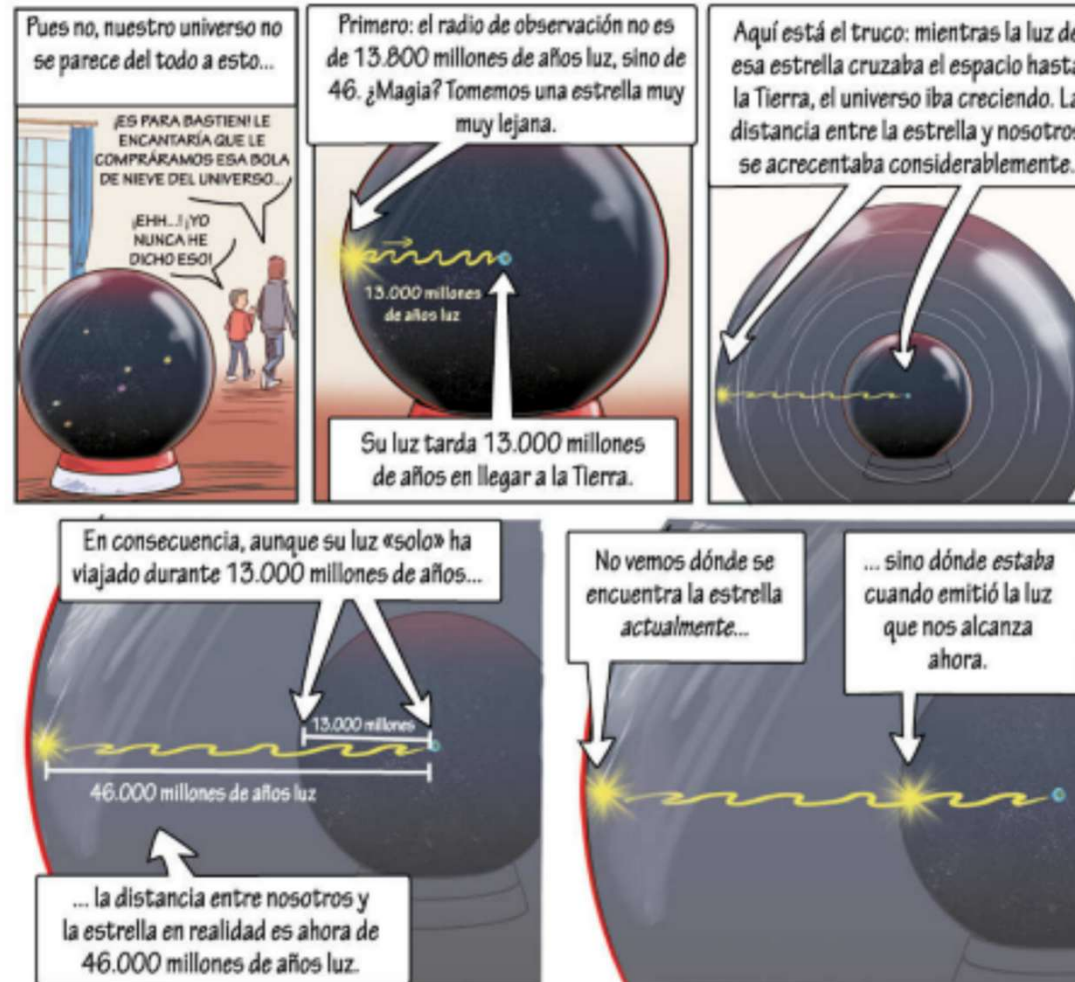


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Consideraciones previas



Consideraciones previas



Consideraciones previas



Consideraciones previas

Aun así, hace falta mucho más para desanimar a los científicos, armados con fórmulas matemáticas, satélites, telescopios y otros artilugios de medición.

Telescopio Fondo cósmico difuso Satélite Fórmulas Artilugio

El estudio conjunto de la densidad del universo y del fondo cósmico difuso brinda importantes pistas.

Así, un triángulo trazado sobre un universo de curvatura positiva, como una patata, vería la suma de sus ángulos superar los 180 grados. Sin energía oscura, la densidad de la materia acabaría provocando que se contrajese sobre sí mismo.

UNIVERSO PATATA

Nuestra esfera-horizonte Suma de los ángulos $> 180^\circ$

Por el contrario, una curvatura negativa se parecería a una silla de montar, abierta y sin límite. El universo crecería sin fin, incluso sin energía oscura y con independencia de su densidad de materia.

UNIVERSO SILLA DE MONTAR

Ángulos $< 180^\circ$

La forma del universo está especialmente determinada por la relatividad general: la **densidad** de materia y energía* presentes puede curvar el universo en una dirección... **ALTA densidad**

... o en otra. **Baja densidad**

También podemos imaginar una especie de triángulo cósmico gigante sobre el fondo cósmico difuso: según la curvatura del universo, la suma de los ángulos varía...

Finalmente, el universo podría ser plano como una caja: de curvatura nula. En este caso, la suma de los ángulos sería de 180 grados, como si el triángulo hubiera sido dibujado sobre una hoja de papel.

UNIVERSO CAJA

Ángulos $= 180^\circ$

Consideraciones previas

Un universo «patata» podría ser finito... ¡pero sin bordes! Caminaríamos sobre él como hormigas cuya mente solo podría captar dos dimensiones.

Variante: el universo dónut. O hipertoro. También en este caso estaríamos en un espacio de dimensiones curvadas sin tener conciencia de ello.

A base de ecuaciones, la ciencia ha imaginado geometrías extrañas, complejas y multidimensionales. He aquí un ejemplo de universo «Calabi-Yau», utilizado en la denominada teoría de cuerdas.

Universo colinabo*

Universo taza*

*Vale, estos dos son extraños (pero reconocamos que la taza va de maravilla con el dónut).

¡ESTE MUSEO ES INTERMINABLE!

En estas complejas geometrías, las salidas estarían conectadas con las entradas. Jamás podríamos irnos. Como si estuviéramos en el juego Pac-Man.

Cafeteria

En la actualidad, la medida de la densidad del universo, así como el análisis preciso del fondo cósmico difuso convergen hacia un universo «caja», es decir, plano.

Cafeteria

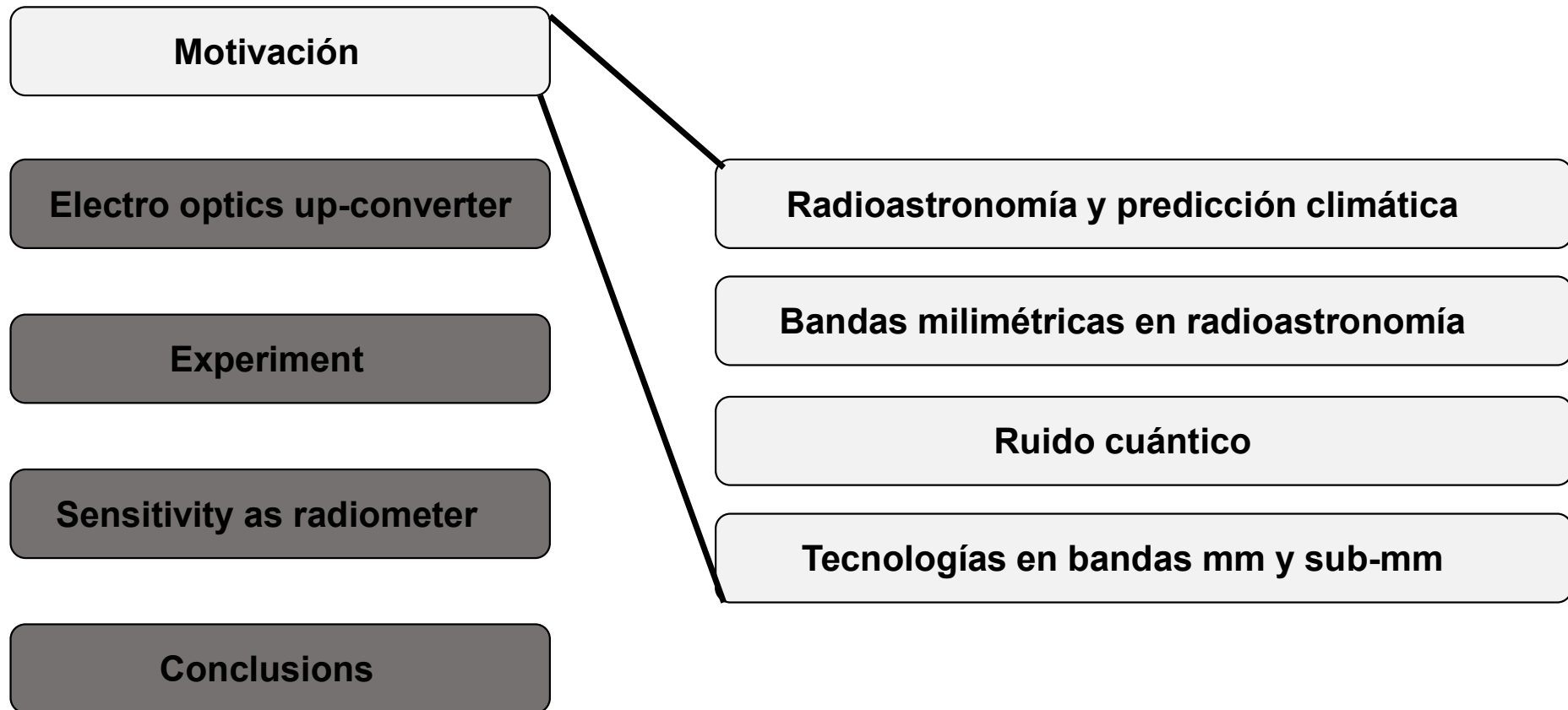
Cada metro cúbico contendría de media una masa equivalente a cinco átomos de hidrógeno, es decir, 10^{-25} gramos. Esta cantidad corresponde a la densidad crítica para que el universo sea casi plano.

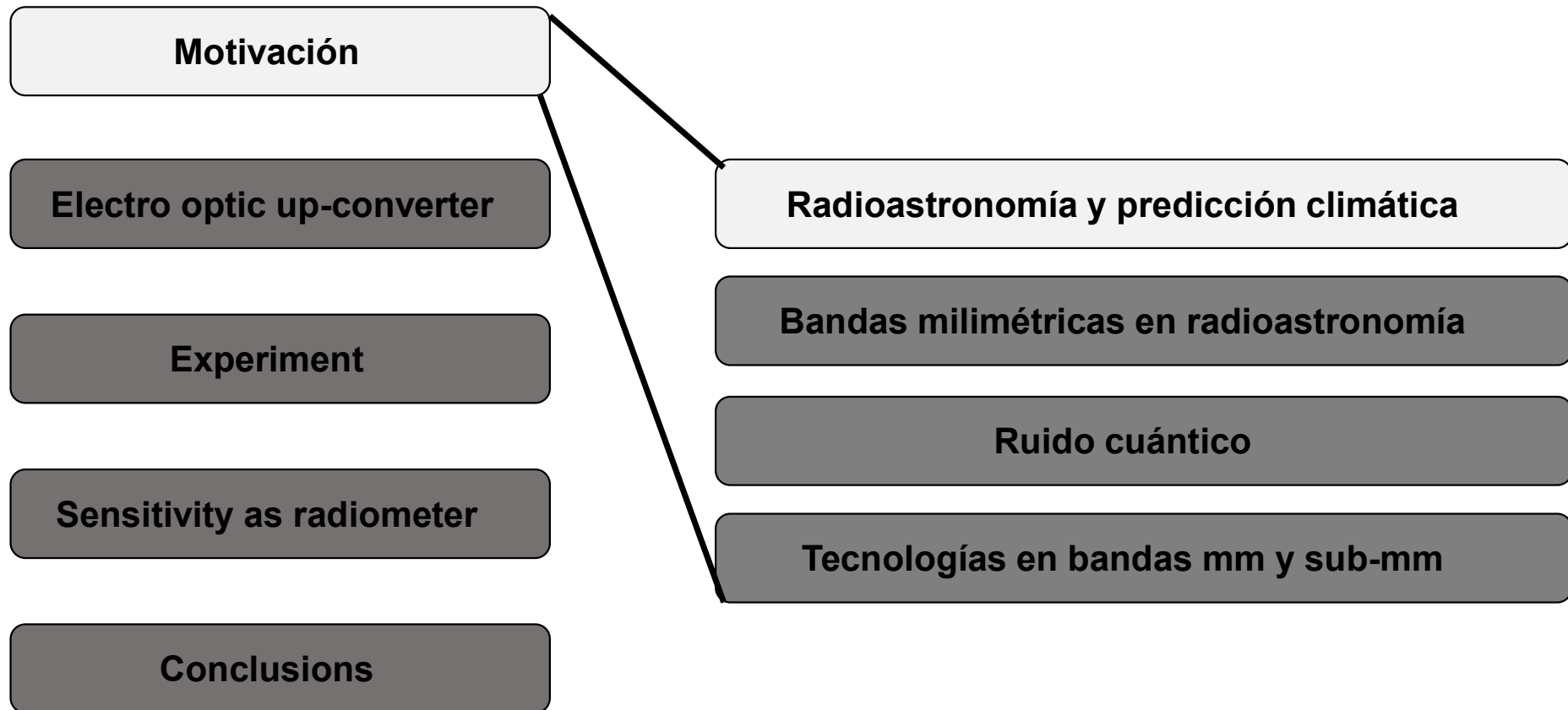
¿DÓNDE VAMOS A PONER TU BOLA DE NIEVE GIGANTE, EH...?

BAH... YA ENCONTRAREMOS UN METRO CÚBICO DONDE COLOCARLA.

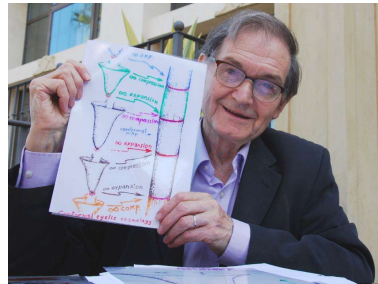
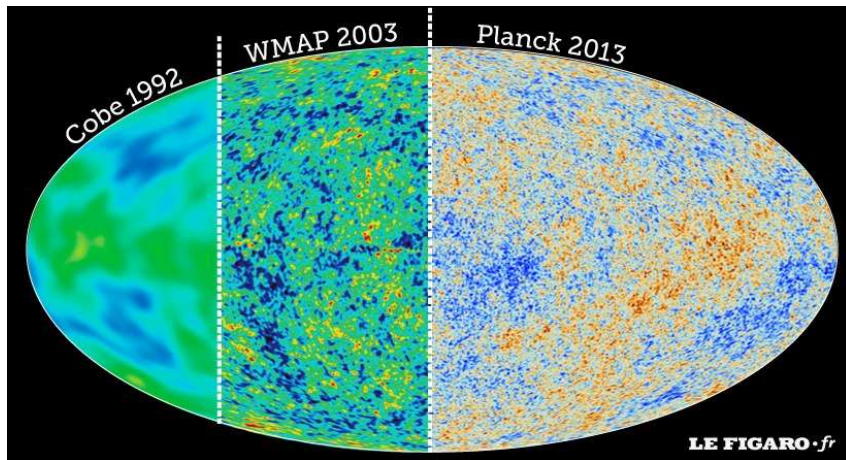
Pero medir la curvatura de un universo no es moco de pavo. Sería algo parecido a intentar calcular la de la Tierra a partir de una pequeña cafetería...

Cafeteria





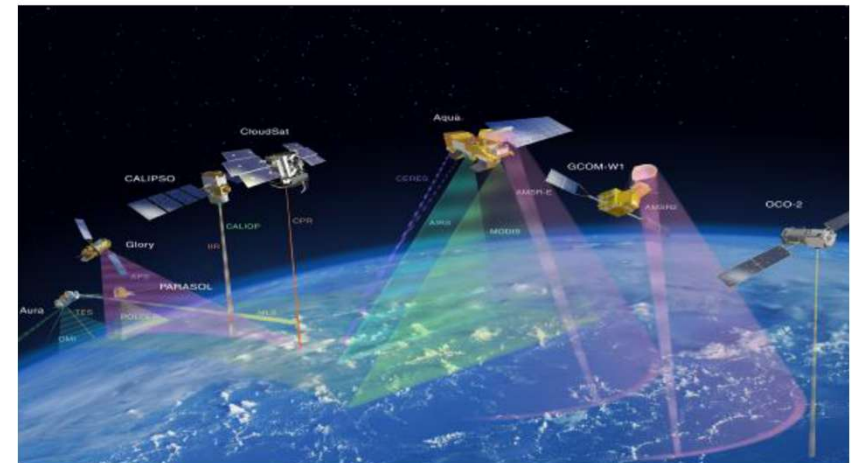
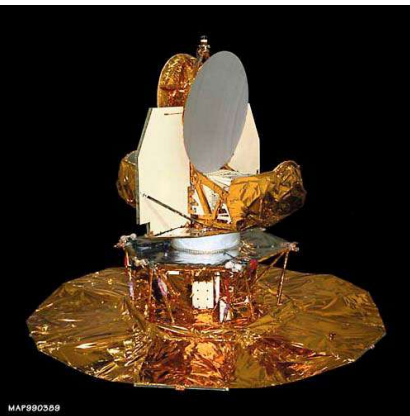
Motivación: radioastronomía y predicción climática



Source: WMAP website

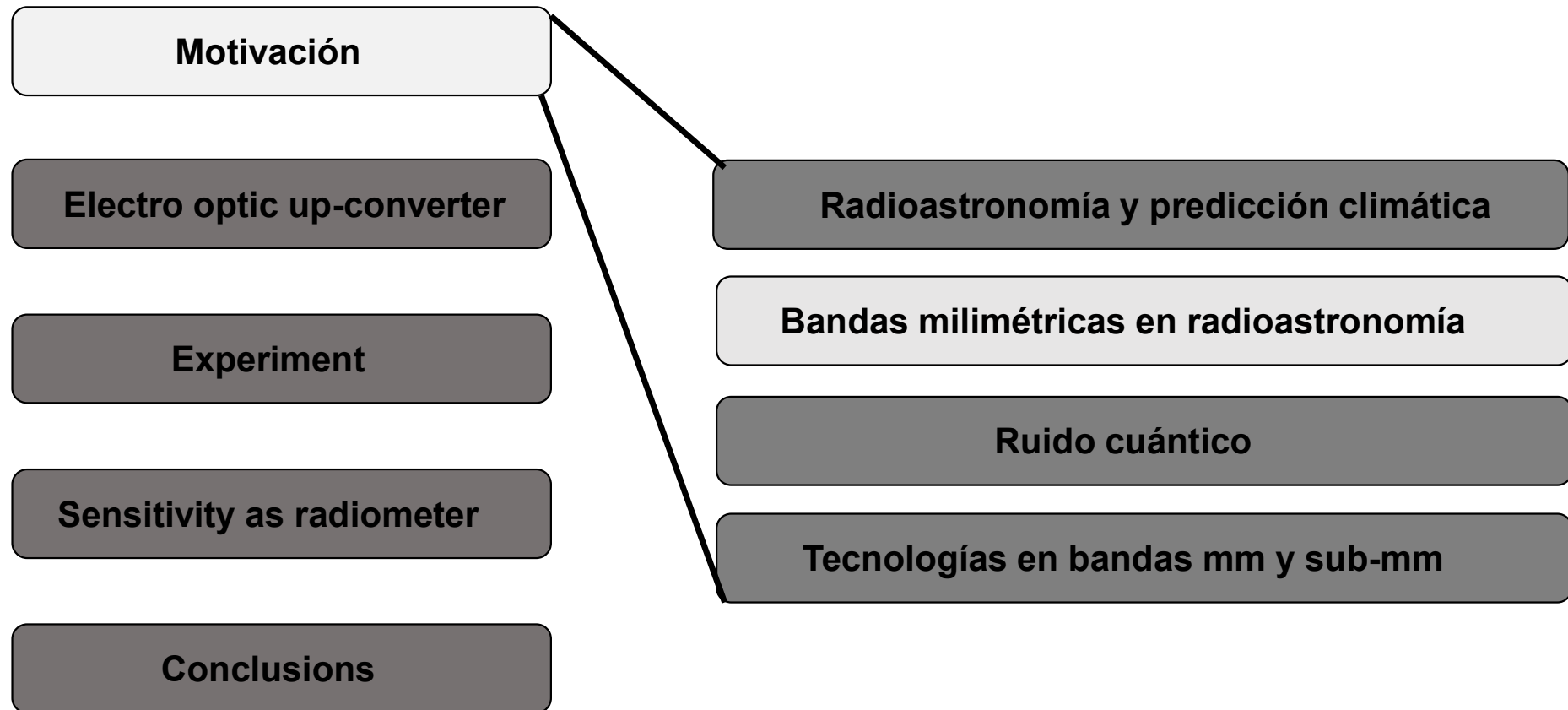
Ultra-low noise instrumentation

Radio astronomy, Earth observation, planetary missions, ...



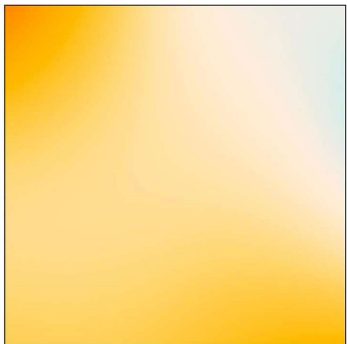
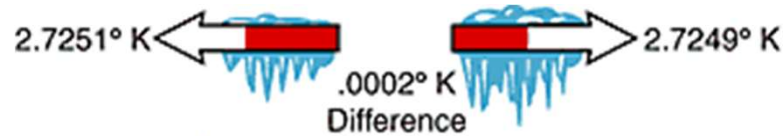
04/12/2025

Luis Enrique García Muñoz

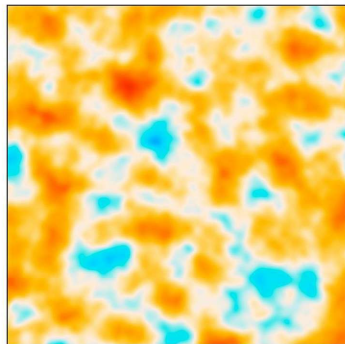
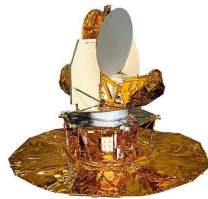


Motivación de las bandas milimétricas en radioastronomía

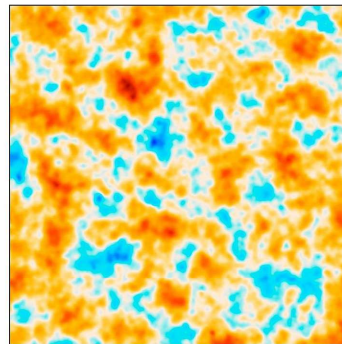
WMAP goal: map the relative CMB temperature over the full sky with a sensitivity of $20 \mu\text{K}$ per 0.3° square pixel.



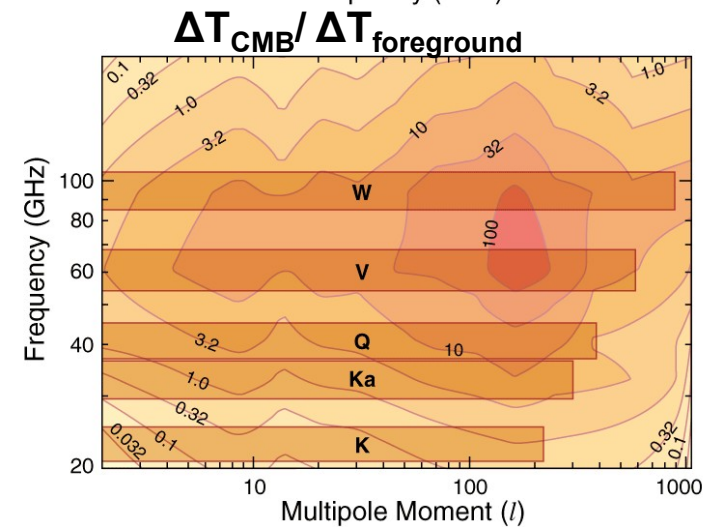
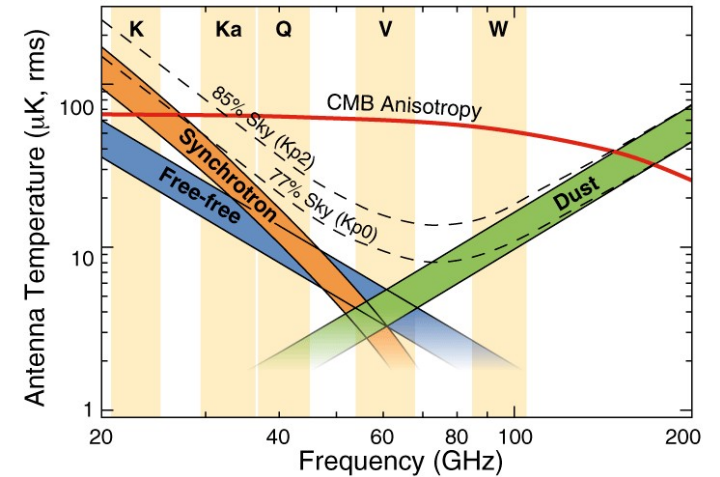
COBE

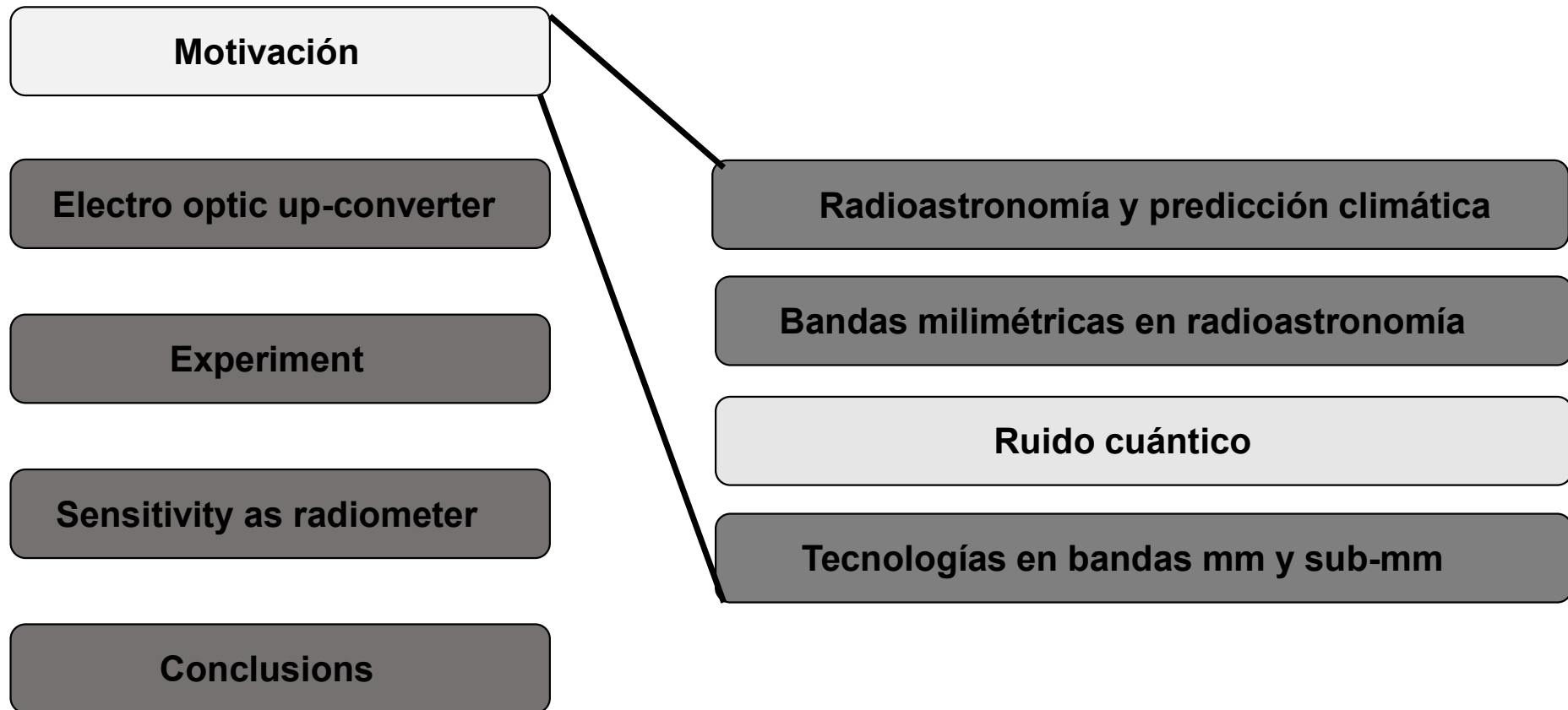


WMAP



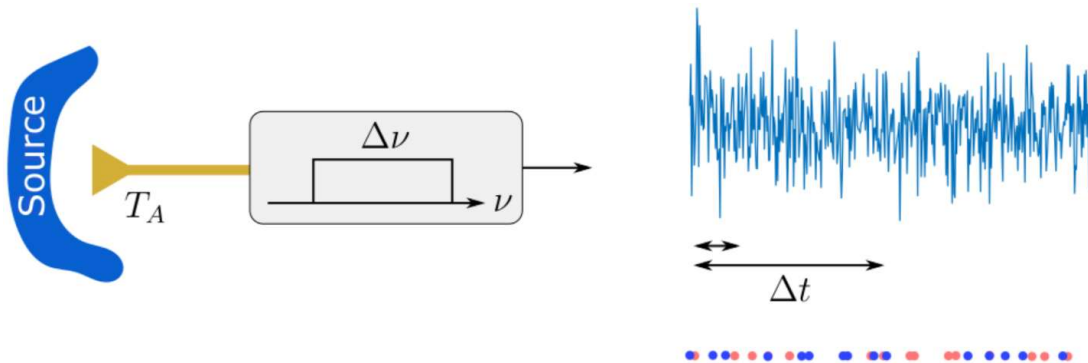
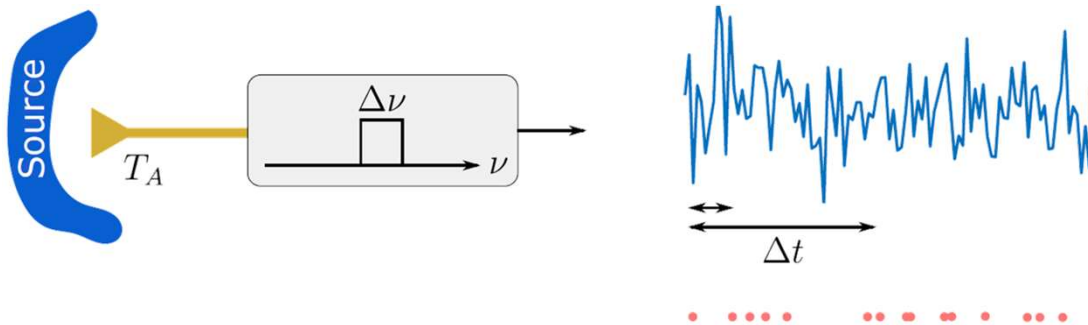
Planck





Motivación: ruido cuántico

“Ideal” radiometer: No noise added, and 100% of photons detected



Mandel's formula



$$\Delta n = \underbrace{\sqrt{\bar{n}}}_{\text{Shot noise}} + \underbrace{\frac{(\bar{n})^2}{\Delta \nu \Delta t}}_{\text{Thermal noise}}$$

$$\Delta t \gg 1/\Delta \nu$$

Planck's formula

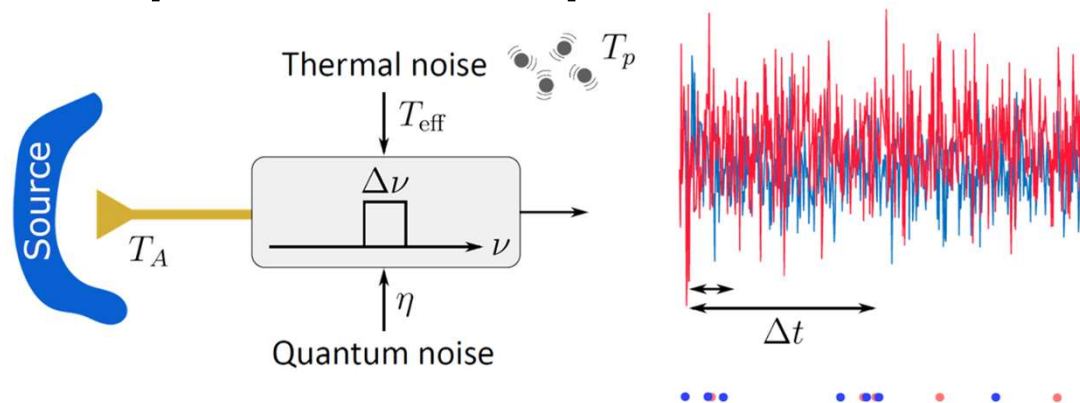
$$\Delta n \rightarrow \Delta T$$

Radiometer equation

$$\Delta T = \underbrace{\frac{T_A}{\sqrt{\Delta t \Delta \nu}}}_{\text{classical}} \underbrace{\sqrt{\frac{h \nu}{k_B T_A} + 1}}_{\text{quantum}}$$

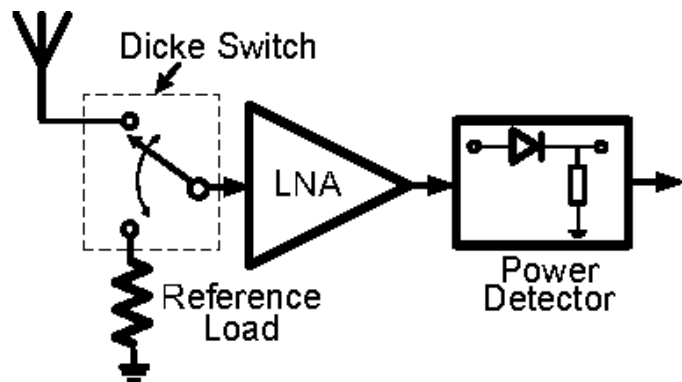
Motivación: ruido cuántico

“Actual” radiometer: Thermal noise added and $\eta < 100\%$, some photons are lost.



Some integration techniques

Dicke switching



THE REVIEW OF SCIENTIFIC INSTRUMENTS

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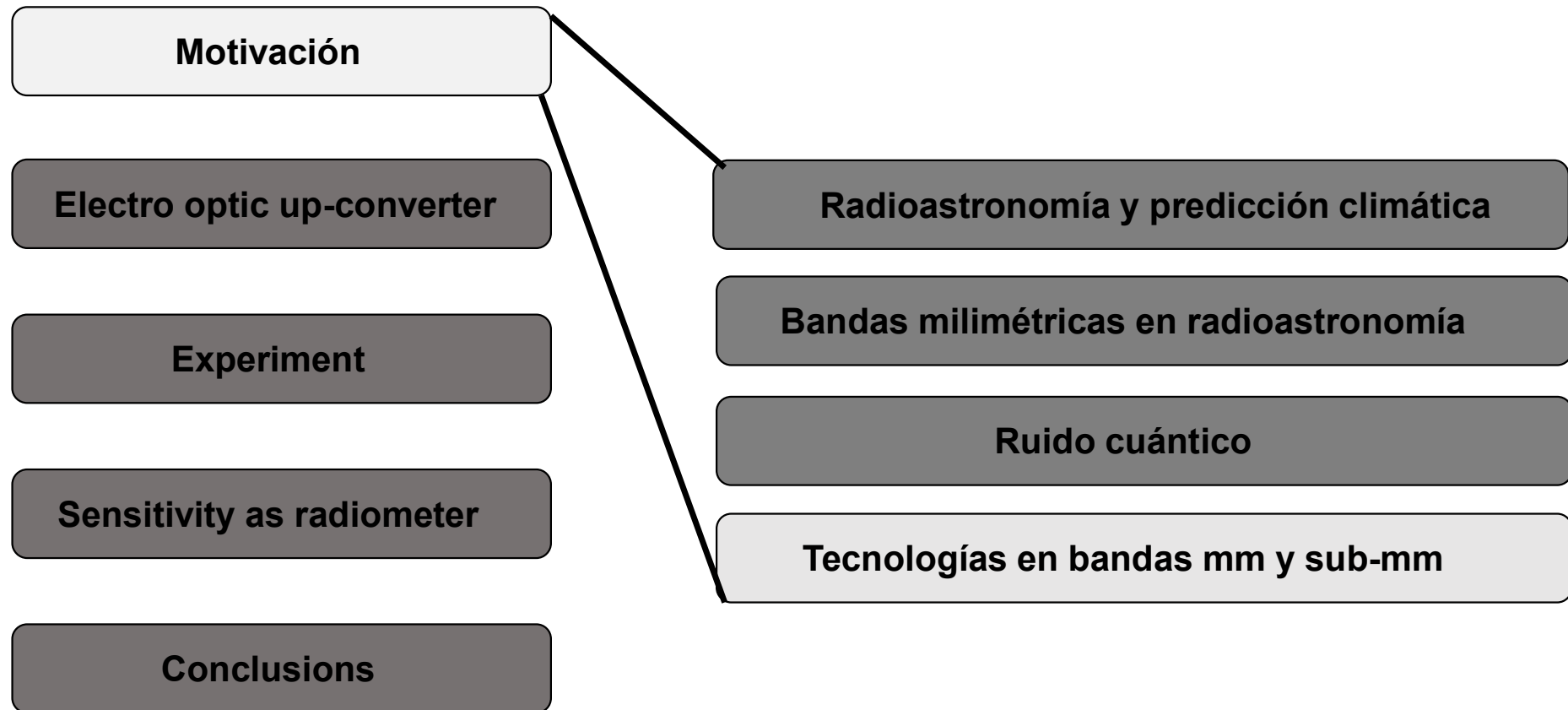
JULY, 1946

The Measurement of Thermal Radiation at Microwave Frequencies

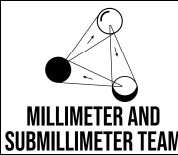
R. H. DICKE*

*Radiation Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts***

(Received April 15, 1946)



Motivación: tecnologías de detección en bandas mm y sub-mm

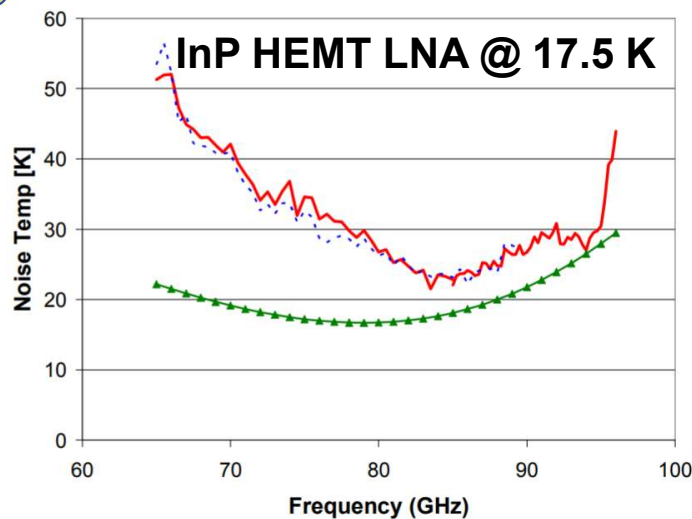


- Bolometric detectors (HEB, TES, ...)
- Superconductor-Insulator-Superconductor (SIS)
- Kinetic Inductance Detectors (KIDs)
- High-electron-mobility transistors (HEMTs)

Cryogenic operation

A W-Band Low-Noise Amplifier with 22K Noise Temperature

Eric W. Bryerton¹, Xiaobing Mei², Young-Min Kim², William Deal², Wayne Yoshida², Mike Lange², Jansen Uyeda², Matthew Morgan¹, and Richard Lai²



04/12/2025

	Type	Temp	Phase	NEP
Golay	thermal	300K	no	150 pW/ $\sqrt{\text{Hz}}$
Pyroelectric	thermal	300K	no	150 pW/ $\sqrt{\text{Hz}}$
HEB	thermal	mK	no	$10^{-19} \text{W}/\sqrt{\text{Hz}}$
TES	thermal	mK	no	$10^{-21} \text{W}/\sqrt{\text{Hz}}$
Schottky	field rectifying	300K	yes	pW/ $\sqrt{\text{Hz}}$
CMOS	FET	300K	yes	pW/ $\sqrt{\text{Hz}}$

Photon-counting detectors require sub-Kelvin cryogenic operation

Extremely Low-Noise Cryogenic Amplifiers for Radio Astronomy: Past, Present and Future

Marian W. Pospieszalski

"I hope, after reading the paper, you will be convinced that there is a limit on the minimum noise temperature of FETs in general (based on their principle of operation) and for InP cryogenic HEMTs that limit is about 4-4.5 time quantum noise. We have practically reached it."

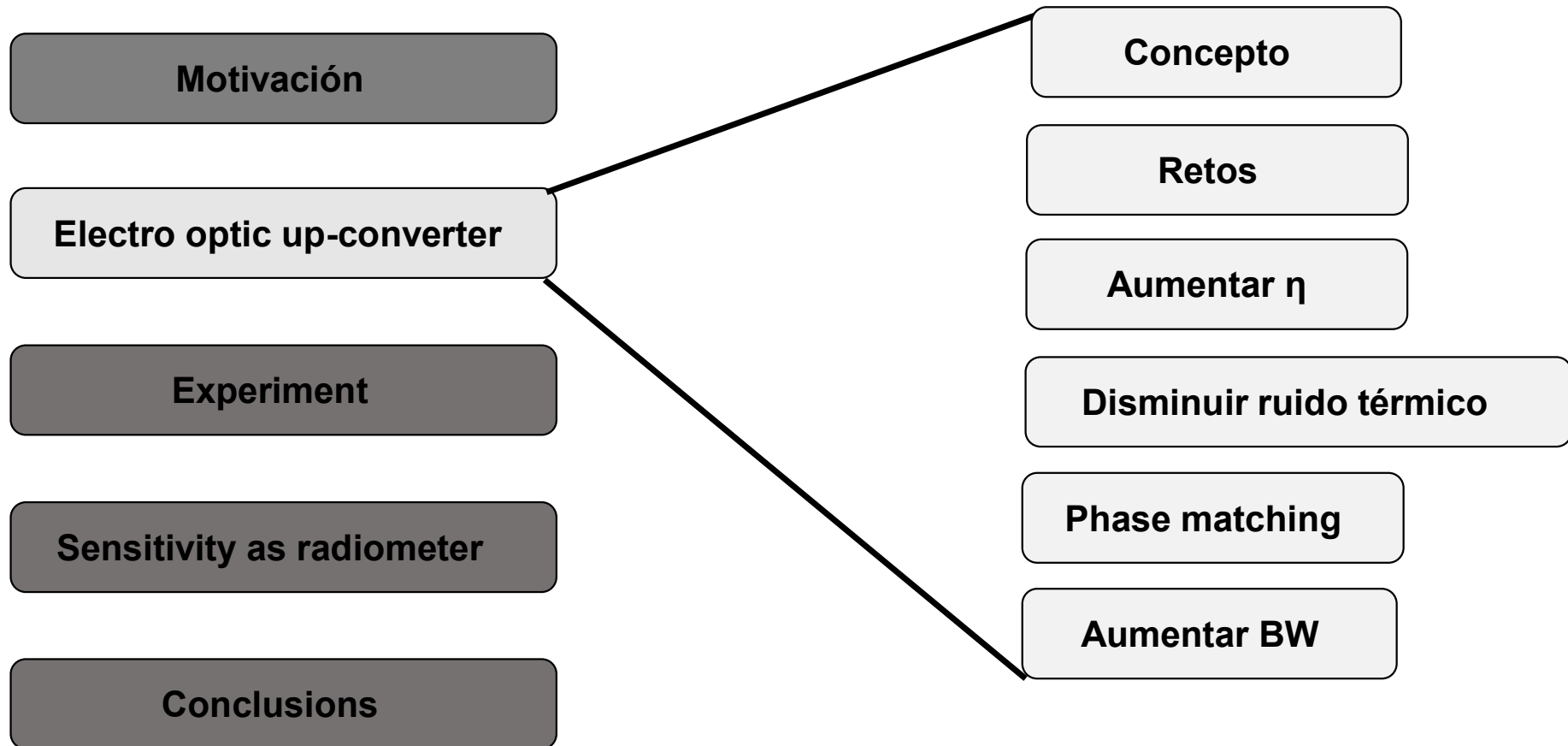


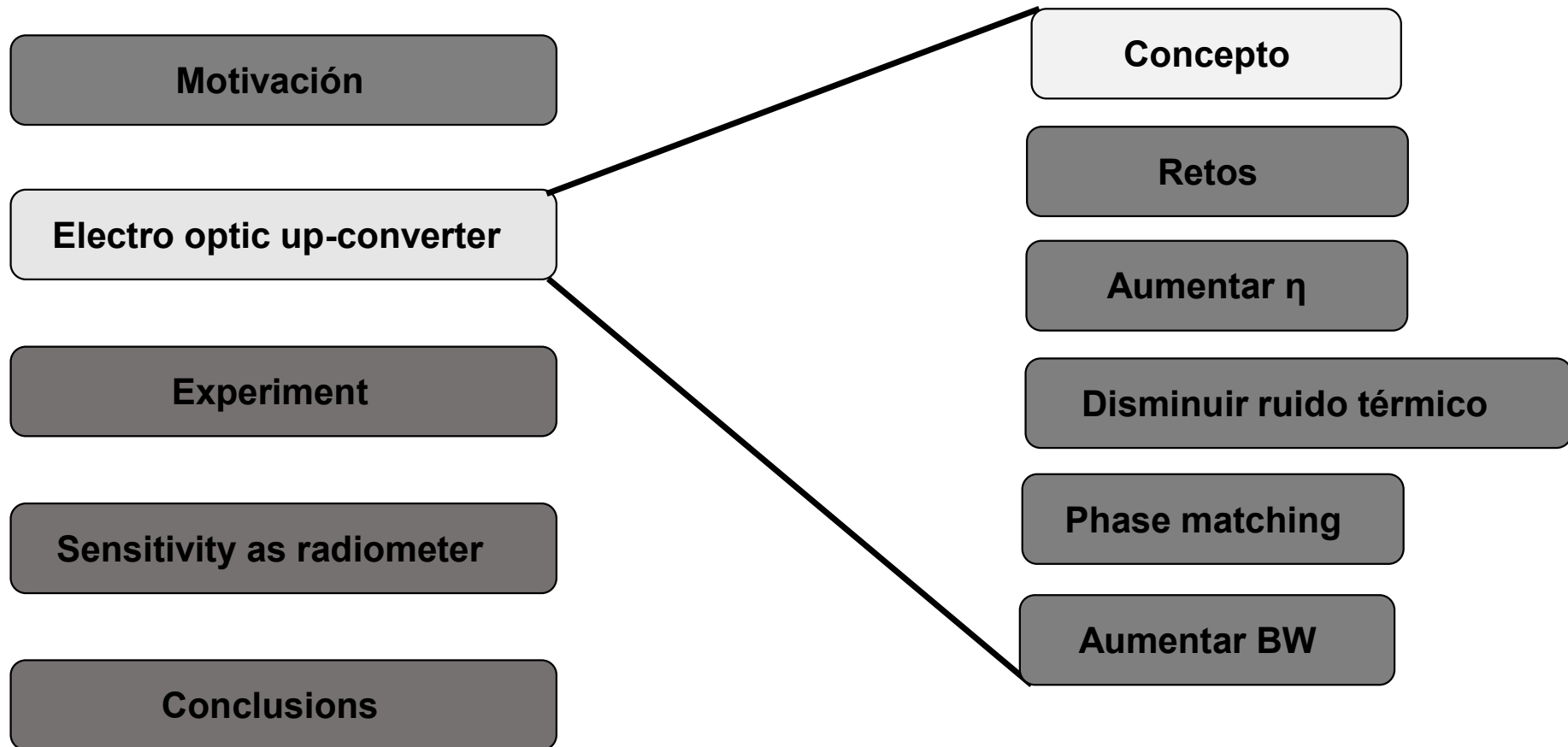

University of Colorado
Boulder

Luis Enrique García Muñoz



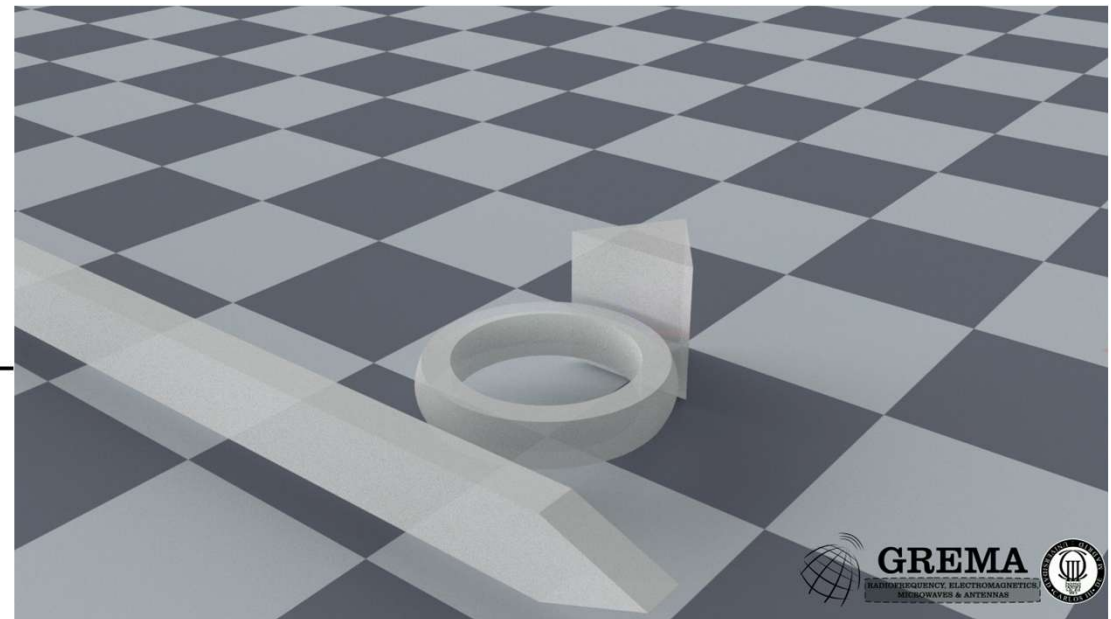
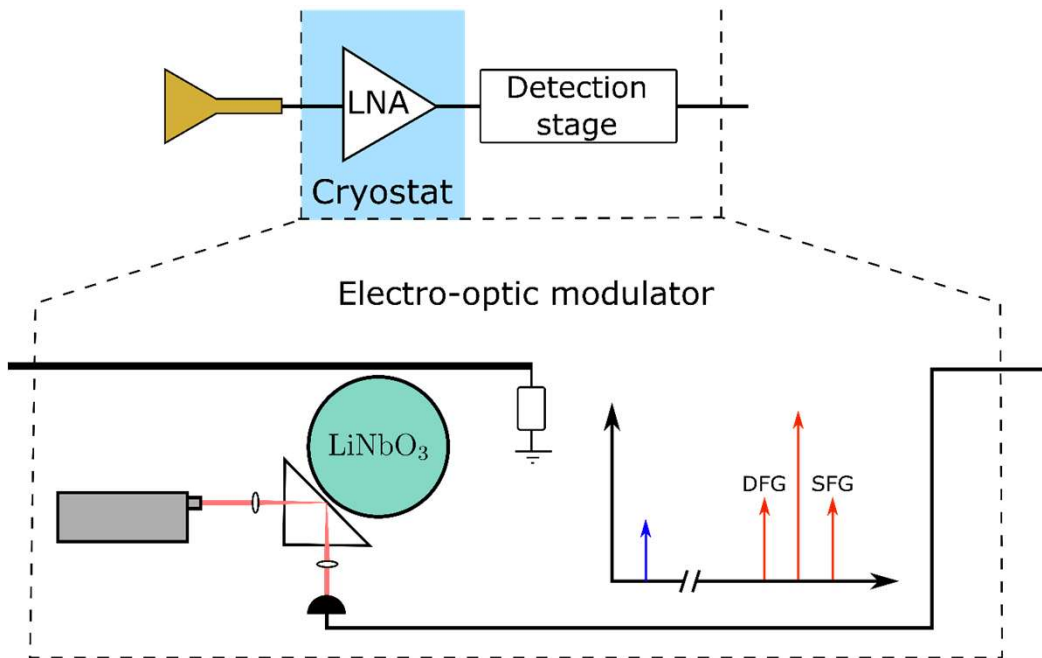
58

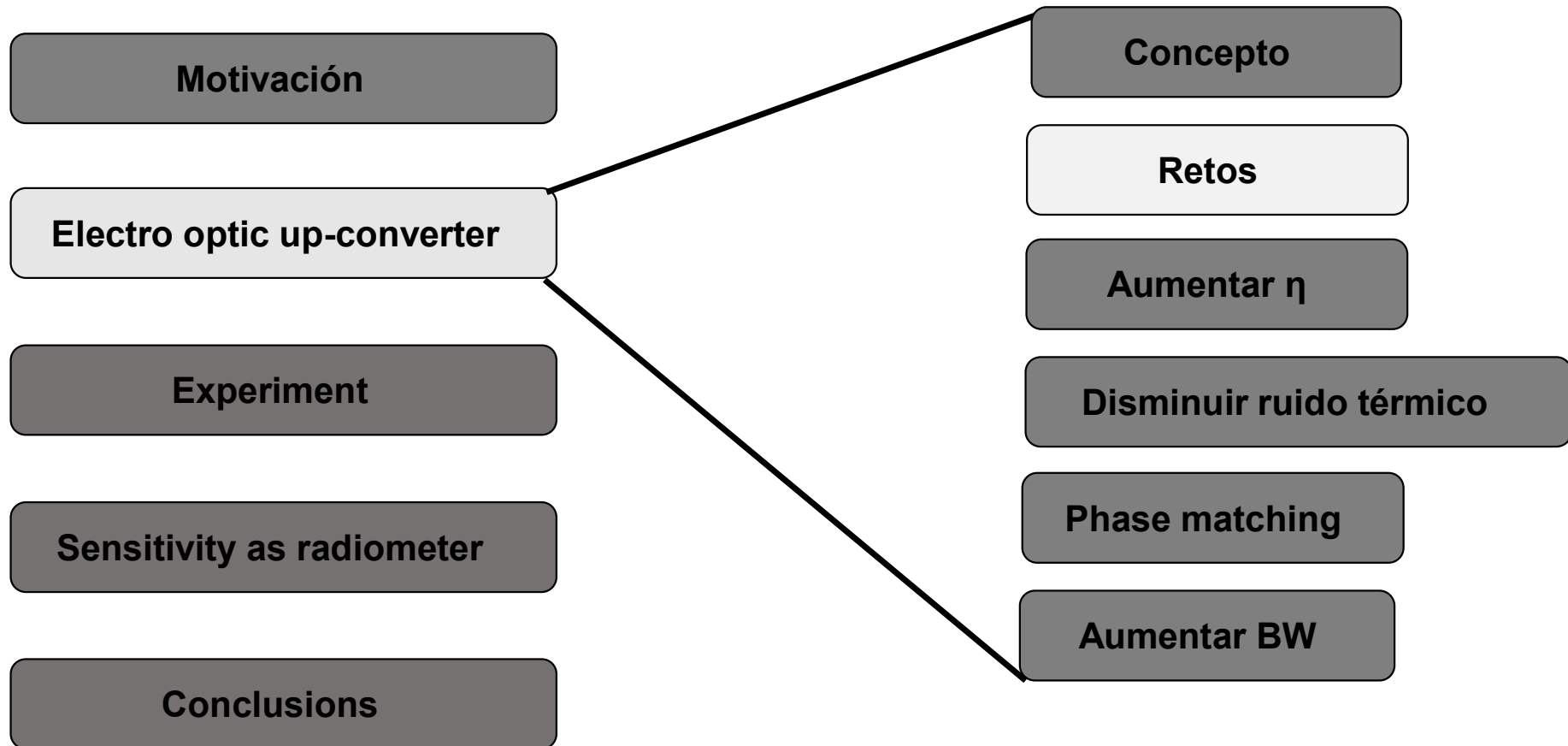




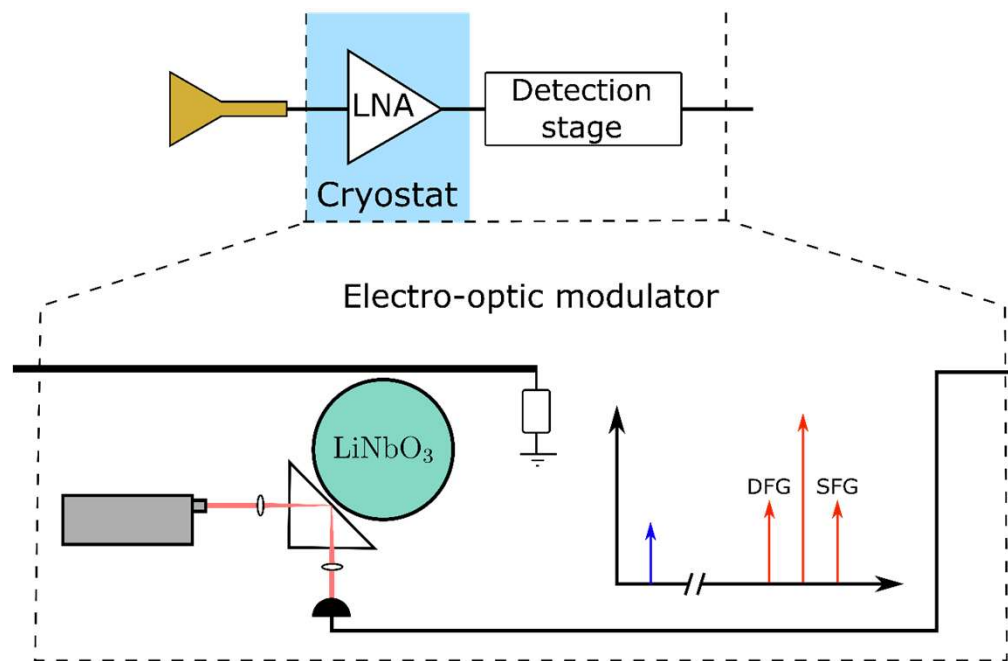
Electro-optic up-converter: concepto

Good candidate for low-noise detection with less strict cooling requirements





Electro-optic up-converter: challenges

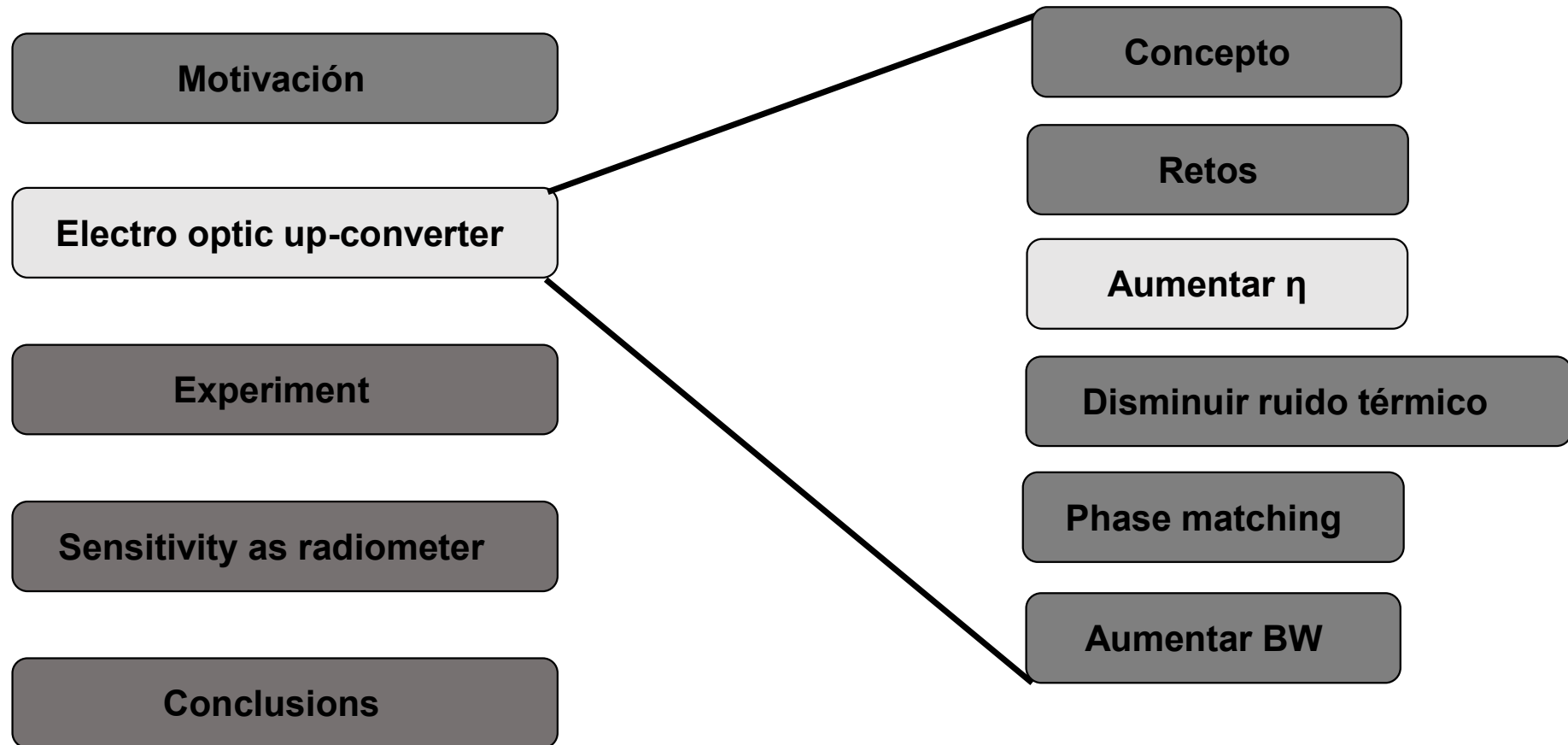


Challenges:

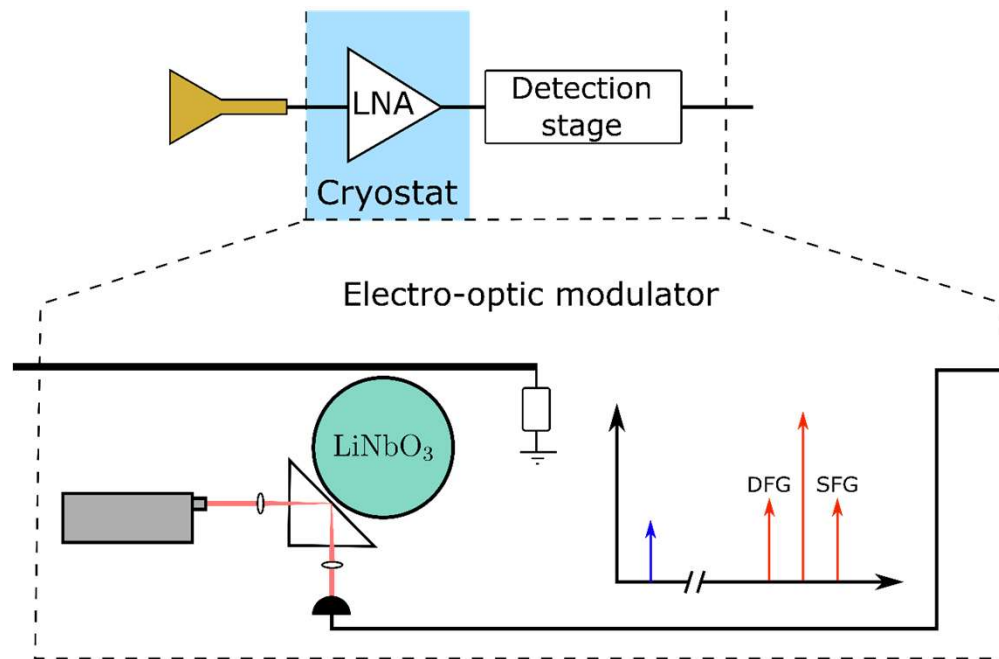
1. High conversion efficiency:

$$\eta = \frac{\# \text{ of upconverted photons}}{\# \text{ of input microwave photons}}$$

2. Avoid thermal noise being upconverted
3. Phase matching
4. High upconversion bandwidth



Electro-optic up-converter: challenges



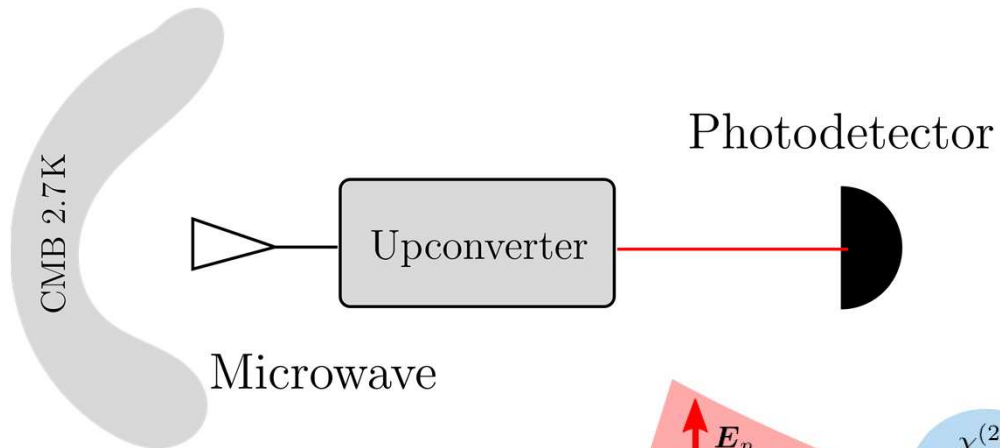
Challenges:

1. High conversion efficiency:

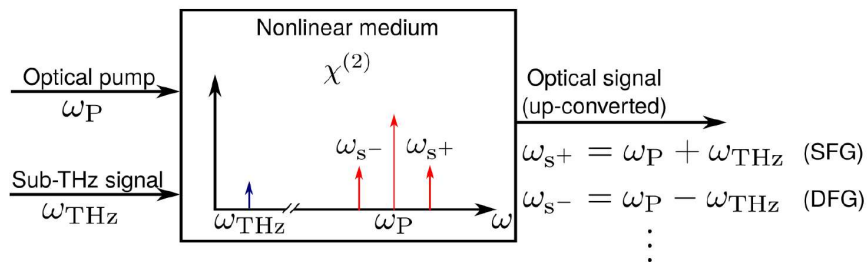
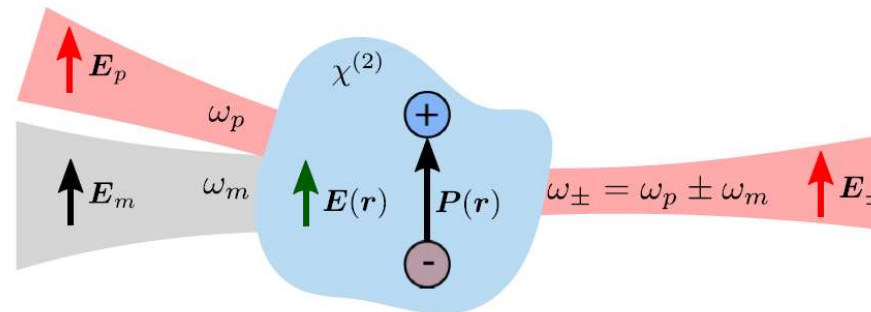
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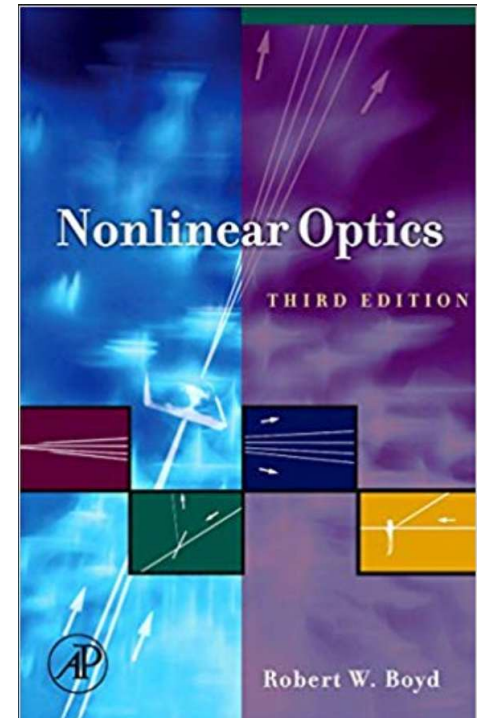
Electro-optic up-converter



The signal is up-converted into the optical domain where it is easier to detect with available high-sensitivity optical receivers.



$$P(r) = \epsilon_0 E(r) + \epsilon_0 \chi^{(2)} E^2(r)$$



Electro-optic up-converter: theory and WGM resonators

Quantum Electronics 32(5) 377–400 (2002)

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REVIEW

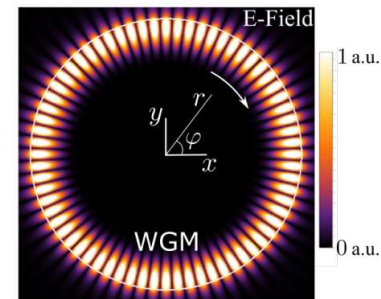
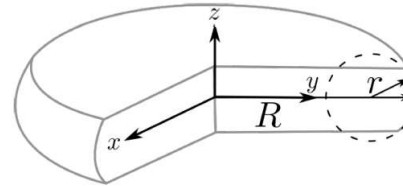
PACS numbers: 42.25.Bs; 42.25.Gy

DOI: 10.1070/QE2001v031n05ABEH002205

Whispering-gallery waves

A.N. Oraevsky

- Travelling-wave resonator
- The circulating power can result significantly higher than the incoming power
- The effective path of the interaction is increased in the WGM resonator
- Three WGMs are excited (optical pump, sub-THz signal, up-converted signal)



Electro-optic up-converter: WGM resonators

Q factors are only limited
by host material

strong confinement
of the light

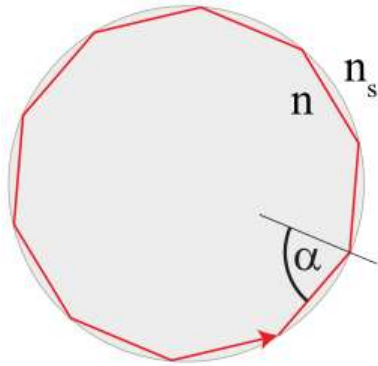
→ great for nonlinear
frequency mixing

resonance condition:

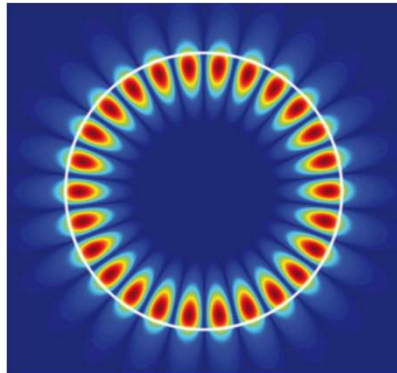
$$2\pi Rn \approx m\lambda$$

total internal reflection:

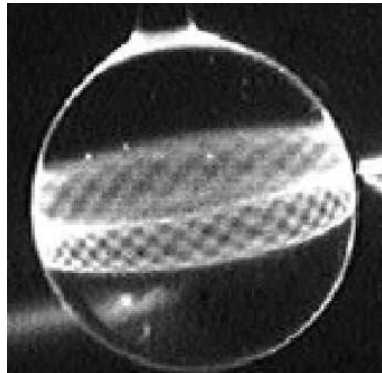
$$\sin \alpha \geq \frac{n_s}{n} \Rightarrow n > n_s$$



wave picture



actual picture



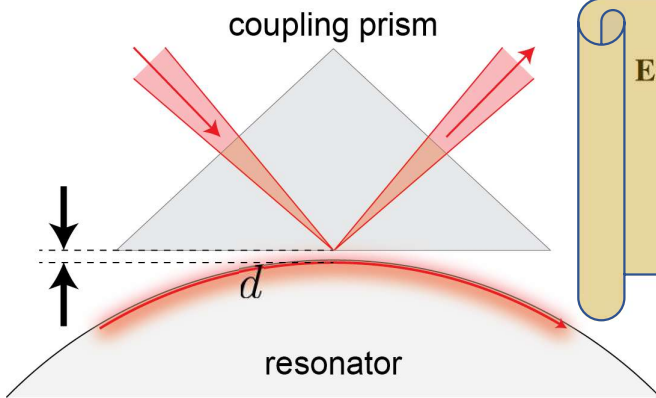
evanescent field

→ interaction with the
environment

Gorodetsky et al,
Opt. Comm. 113, 133-143 (1994)

Electro-optic up-converter: how to couple light in a WGM resonator

Frustrating the TIR by another dielectric



coupling condition

$$n_{\text{prism}} > n_{\text{resonator}}$$

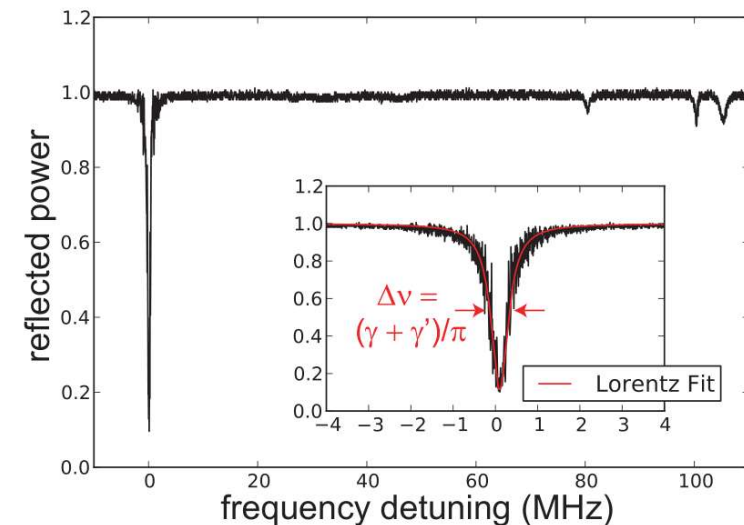
tunable coupling rate: $\gamma \propto e^{-\kappa d}$

- tunable bandwidth
- optimize nonlinear experiments

Efficient and Coherent Conversion of 80 GHz Signals into the Optical Domain Using a Whispering Gallery Mode Resonator

Florian Sedlmeir^{1,2,5}, Alfredo Rueda^{1,2}, Sascha Preu³,
L. Enrique García-Muñoz⁴, Harald G.L. Schwefel⁵

Spectrum in reflection



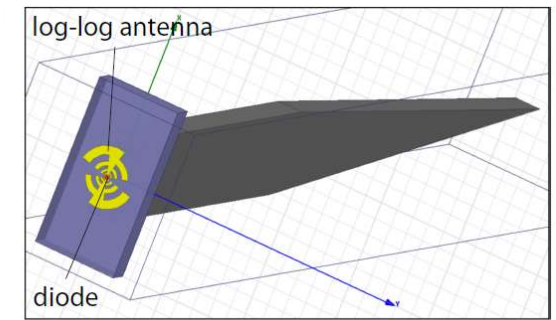
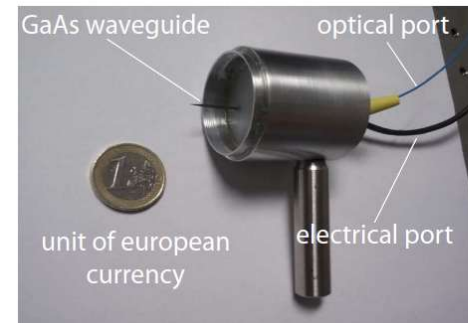
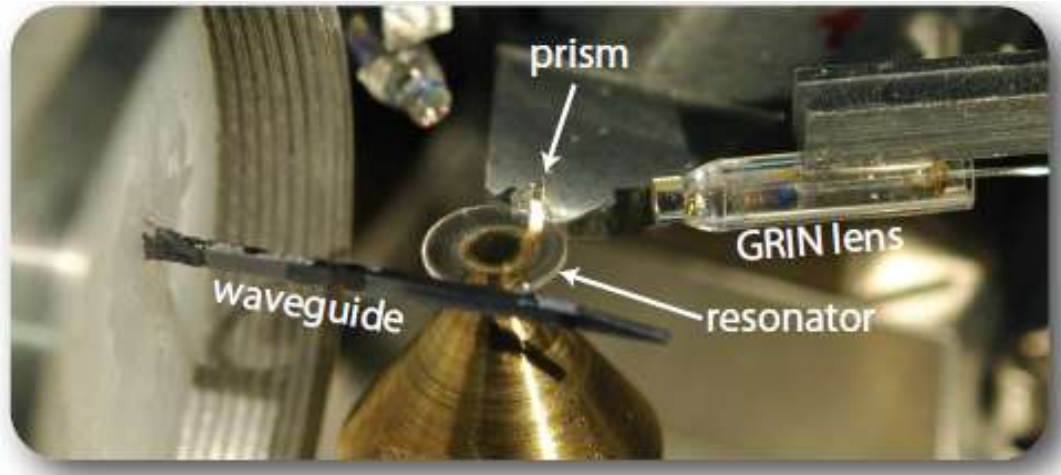
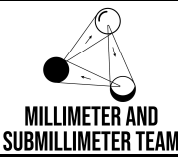
$$Q = \frac{\nu}{\Delta \nu}$$

typical values:

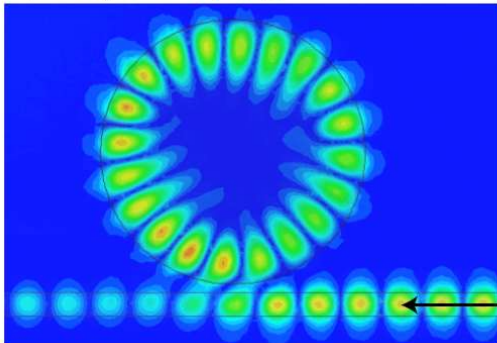
$$Q \approx 10^7 \dots 10^9$$



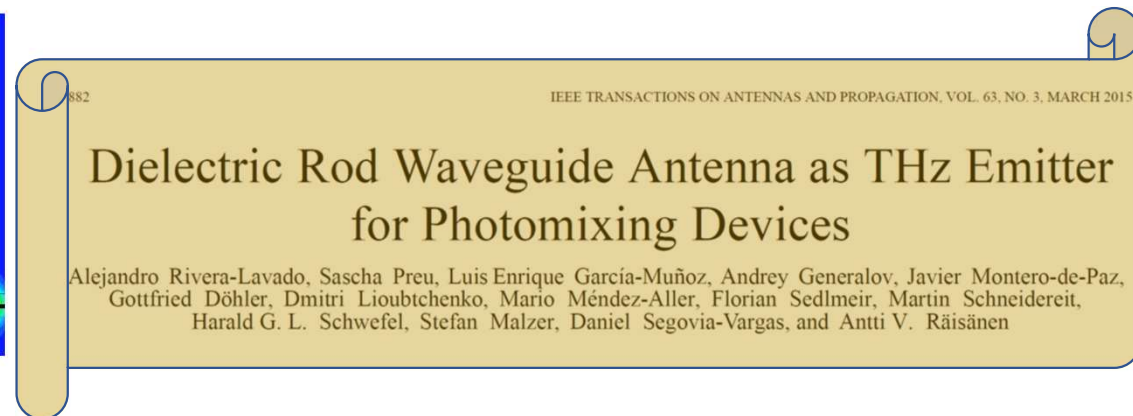
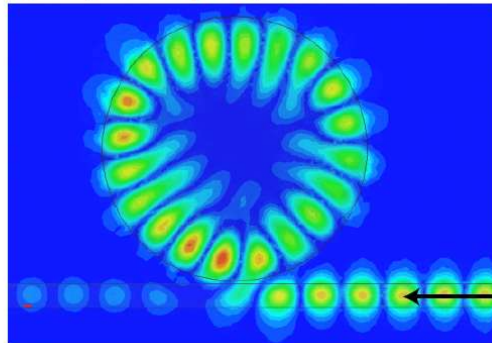
Electro-optic up-converter: how to couple mm-waves in a WGM resonator



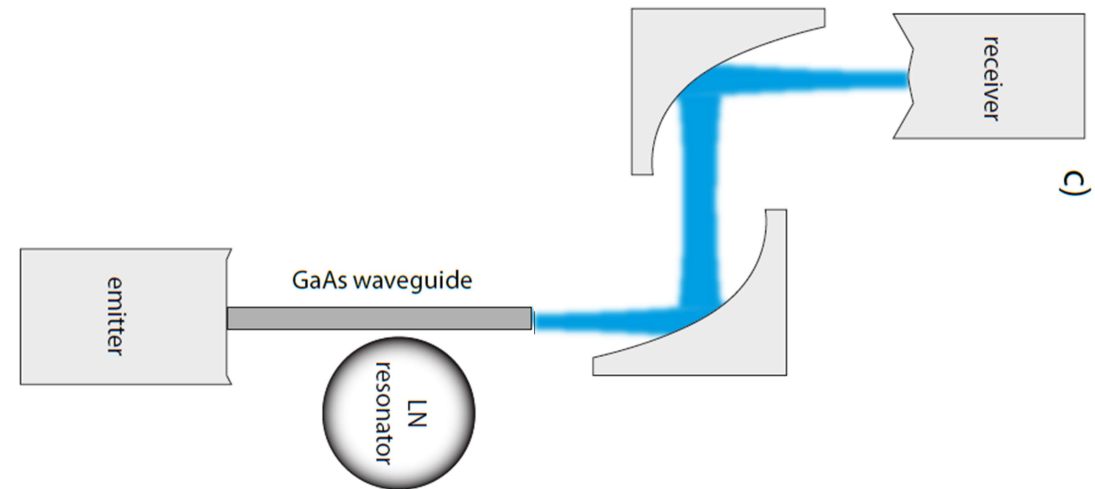
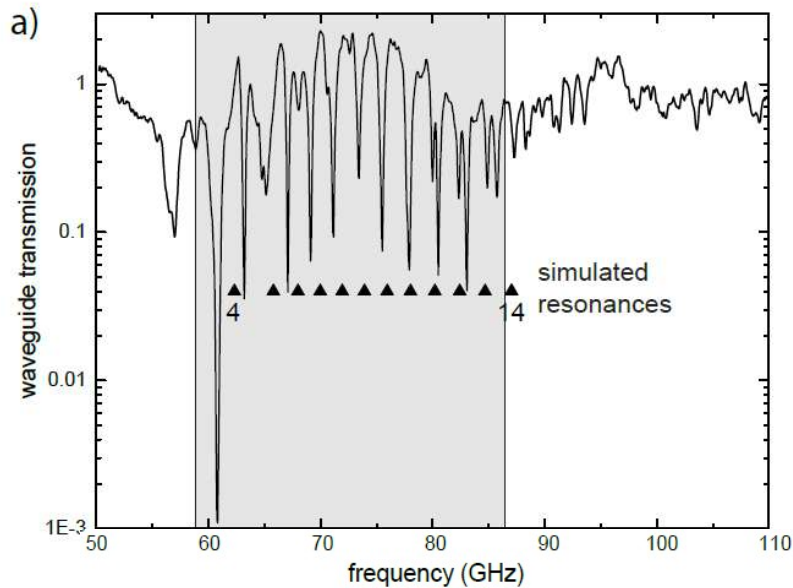
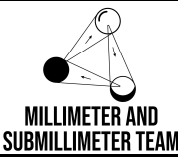
a) 200 μ m coupling distance



b) 20 μ m coupling distance



Electro-optic up-converter: how to couple mm-waves in a WGM resonator



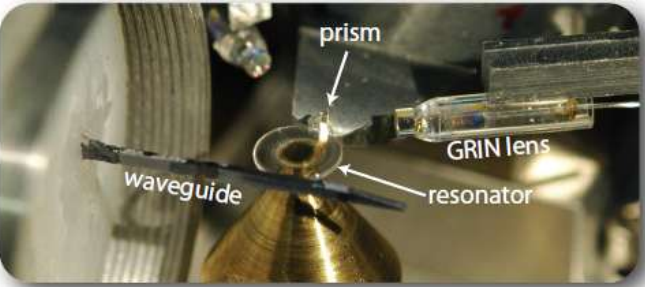
532

IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY, VOL. 3, NO. 5, SEPTEMBER 2013

From Arrays of THz Antennas to Large-Area Emitters

Gottfried H. Döhler, Luis Enrique Garcia-Muñoz, Sascha Preu, Stefan Malzer, Sebastian Bauerschmidt, Javier Montero-de-Paz, Eduardo Ugarte-Muñoz, Alejandro Rivera-Lavado, Vicente Gonzalez-Posadas, and Daniel Segovia-Vargas, *Member, IEEE*

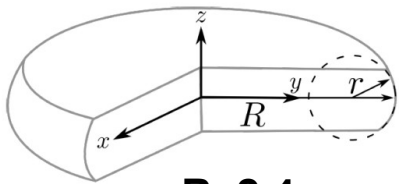
Electro-optic up-converter: experimento



$$n_{\text{prism}} = 2,42$$

$$n_{\text{laser}} = 2,14$$

$$n_{\text{mw}} = 5$$



$$Q_{\text{laser}} = 5 \times 10^6 \quad \text{Finesse} = 300$$

$$Q_{\text{mw}} = 100 \quad \text{BW} = 150 \text{ MHz}$$

$$R = 2,4 \text{ mm} \quad r = 150 \text{ }\mu\text{m}$$

$$1550 \text{ nm laser power} = 2 \dots 5 \text{ mW}$$

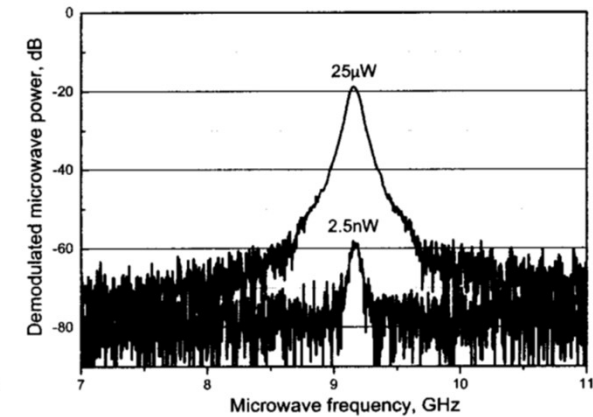
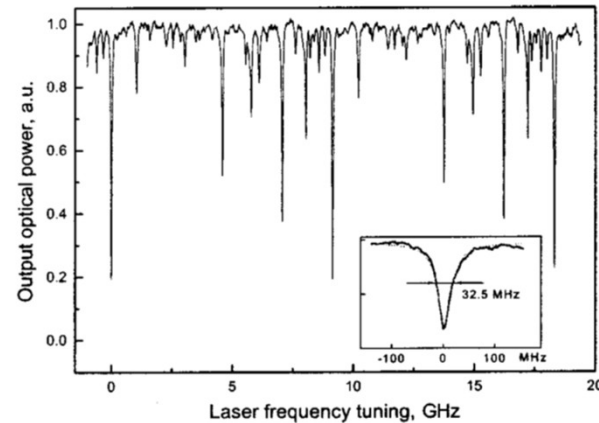
$$\text{Optical output efficiency} = 10 \text{ dB}$$

$$\text{FSR} = 9,155 \text{ GHz}$$

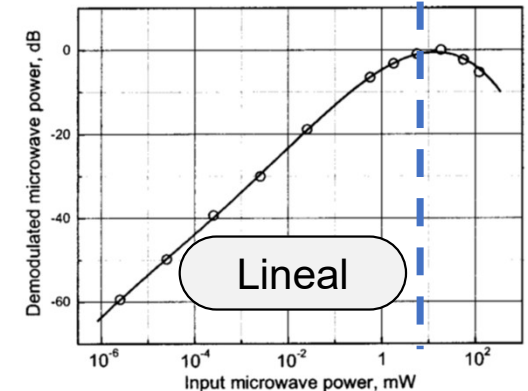
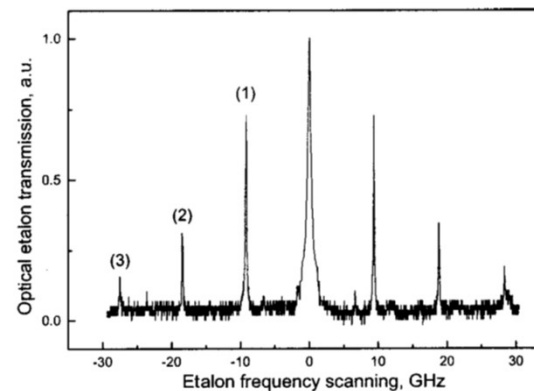
**Efficient and Coherent Conversion of 80 GHz
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Florian Sedlmeir^{1,2,5}, Alfredo Rueda^{1,2}, Sascha Preu³,
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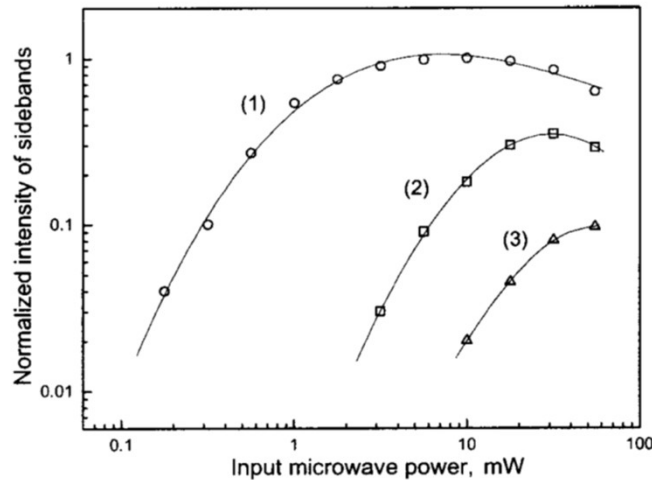
04/12/2025



$$P_{\text{mw minimum}} = 1 \text{ nW}$$

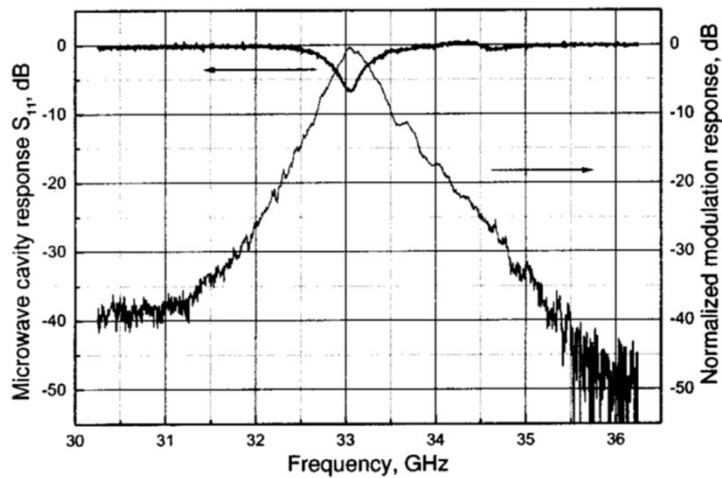


Electro-optic up-converter: experimento



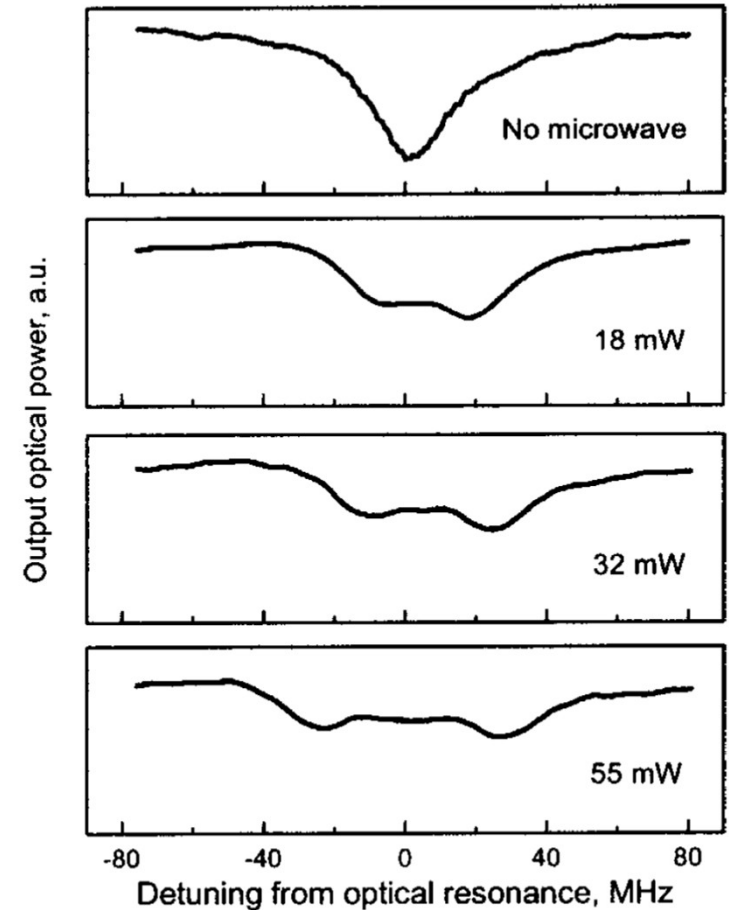
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Maximization of the optical intra-cavity power of whispering-gallery mode resonators via coupling prism

G. A. SANTAMARÍA-BOTELLO,¹ L. E. GARCÍA MUÑOZ,^{1,*} F. SEDLMEIR,² S. PREU,³ D. SEGOVIA-VARGAS,¹ K. ATIA ABDALMALAK,¹ S. LLORENTE ROMANO,¹ A. GARCÍA LAMPÉREZ,¹ S. MALZER,⁴ G. H. DÖHLER,⁴ H. G. L. SCHWEFEL,² AND H. B. WEBER⁴



Electro-optic up-converter: aumentar la eficiencia

$$\eta_{ph} = \frac{2P_p}{\epsilon_0 \omega_{\pm}} \frac{\chi^{(2)^2} Q_p^2 Q_m}{n_p^4 n_m^2} \frac{E_m'^2(\mathbf{r}_p)}{V_m} (1 - S_{11}^2 - S_{21}^2)$$

Research Article Vol. 24, No. 23 | 14 Nov 2016 | OPTICS EXPRESS 26503

Optics EXPRESS

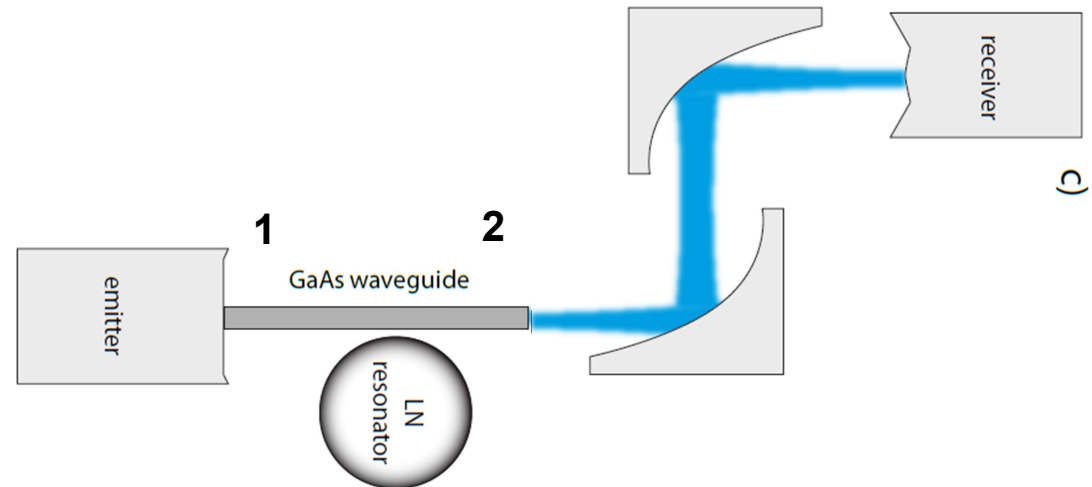
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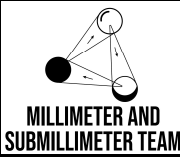
Topical Review

Nonlinear and Quantum Optics with Whispering Gallery Resonators

Dmitry V Strekalov^{1,2}, Christoph Marquardt^{2,3}, Andrey B Matsko⁴, Harald G L Schwefel^{2,3,5} and Gerd Leuchs^{2,3}



Electro-optic up-converter: aumentar la eficiencia



$$\eta_{ph} = \frac{2P_p}{\varepsilon_0 \omega_{\pm}} \frac{\chi^{(2)^2} Q_p^2 Q_m}{n_p^4 n_m^2} \frac{E_m'^2(r_p)}{V_m} (1 - S_{11}^2 - S_{21}^2)$$

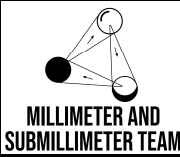
1

Limited to:

The application (frequency)

The maximum optical power
that the resonator can
handle

Electro-optic up-converter: aumentar la eficiencia



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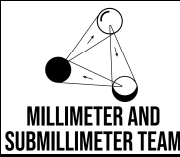
1
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Electro-optic up-converter: aumentar la eficiencia

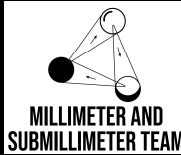


$$\eta_{ph} = \frac{2P_p}{\varepsilon_0 \omega_{\pm}} \frac{\chi^{(2)^2} Q_p^2 Q_m}{n_p^4 n_m^2} \frac{E_m'^2(r_p)}{V_m} (1 - S_{11}^2 - S_{21}^2)$$

2
↓

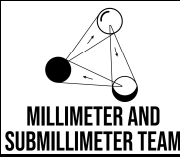
**Depends on the selection of the
material of the WGM resonator**

Electro-optic up-converter: aumentar la eficiencia



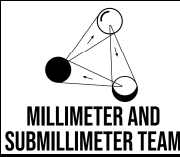
Material	$\chi^{(2)}$ (pm/V)	n_p	n_m	Q_p	Q_m	$\frac{\chi^{(2)^2} Q_p^2 Q_m}{n_p^4 n_m^2}$
Lithium tantalate (LiTaO ₃)	155	2.116	6.29	5.7×10^8	150	1.5×10^{-3}
Lithium Niobate (LiNbO ₃)	151	2.138	4.95	1×10^8	200	8.9×10^{-5}
Quartz (SiO ₂)	0.4	1.536	2.11	5×10^7	5000	8.1×10^{-8}
Aluminium nitride (AlN)	5	2.16	2.88	6×10^5	2000	1.0×10^{-10}
Gallium Arsenide (GaAs)	41.9	3.37	3.59	1×10^5	1000	1.1×10^{-11}
Indium Phosphide (InP)	40	3.165	3.514	1×10^5	1000	1.3×10^{-11}
Zinc selenide (ZnSe)	18	2.45	3.0158	5×10^4	525	1.3×10^{-12}
Zinc telluride (ZnTe)	56.3	2.733	3.1707	1.6×10^3	555	8.0×10^{-15}

Electro-optic up-converter: aumentar la eficiencia



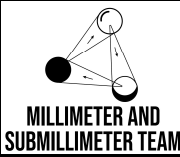
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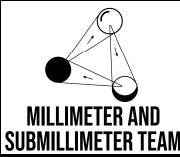
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Electro-optic up-converter: aumentar la eficiencia



Material	$\chi^{(2)}$ (pm/V)	n_p	n_m	Q_p	Q_m	$\frac{\chi^{(2)2} Q_p^2 Q_m}{n_p^4 n_m^2}$
Lithium tantalite (LiTaO ₃)	155	2.116	6.29	5.7×10^8	150	1.5×10^{-3}
Lithium Niobate (LiNbO ₃)	151	2.138	4.95	1×10^8	200	8.9×10^{-5}
Quartz (SiO ₂)	0.4	1.536	2.11	5×10^7	5000	8.1×10^{-8}
Aluminium nitride (AlN)	5	2.16	2.88	6×10^5	2000	1.0×10^{-10}
Gallium Arsenide (GaAs)	41.9	3.37	3.59	1×10^5	1000	1.1×10^{-11}
Indium Phosphide (InP)	40	3.165	3.514	1×10^5	1000	1.3×10^{-11}
Zinc selenide (ZnSe)	18	2.45	3.0158	5×10^4	525	1.3×10^{-12}
Zinc telluride (ZnTe)	56.3	2.733	3.1707	1.6×10^3	555	8.0×10^{-15}

Electro-optic up-converter: aumentar la eficiencia



$$\eta_{ph} = \frac{2P_p}{\varepsilon_0 \omega_{\pm}} \frac{\chi^{(2)^2} Q_p^2 Q_m}{n_p^4 n_m^2} \frac{E_m'^2(\mathbf{r}_p)}{V_m} (1 - S_{11}^2 - S_{21}^2)$$

3
↓

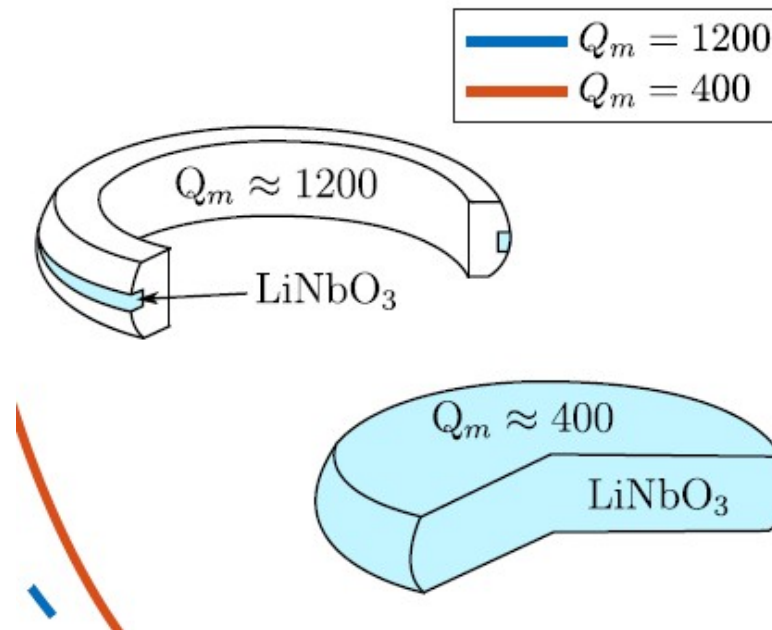
Depends on the geometry of the resonator, the overlap between both input signals needs to be maximized by:

Pushing the microwave mode's maximum intensity towards the rim of the resonator

Decreasing the mode volume of the microwave signal

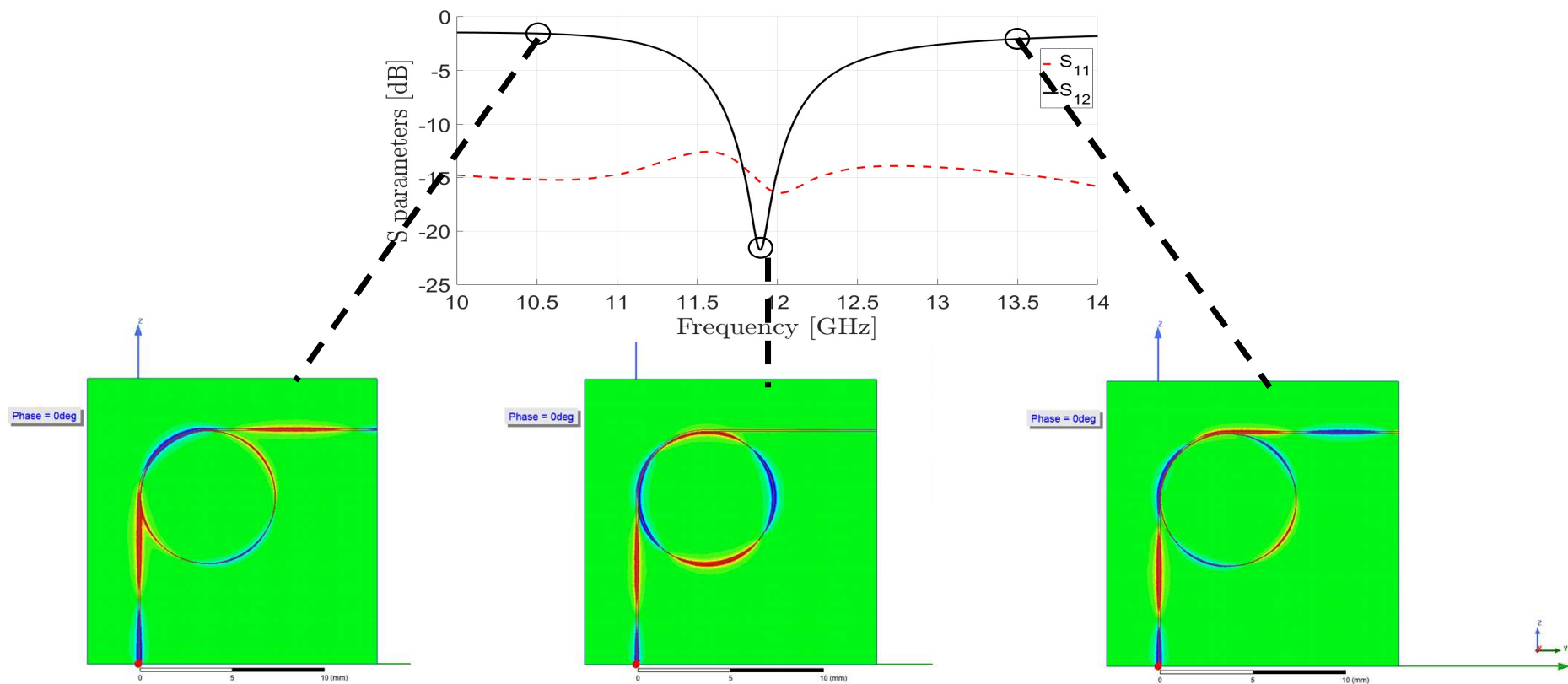
Electro-optic up-converter: aumentar la eficiencia

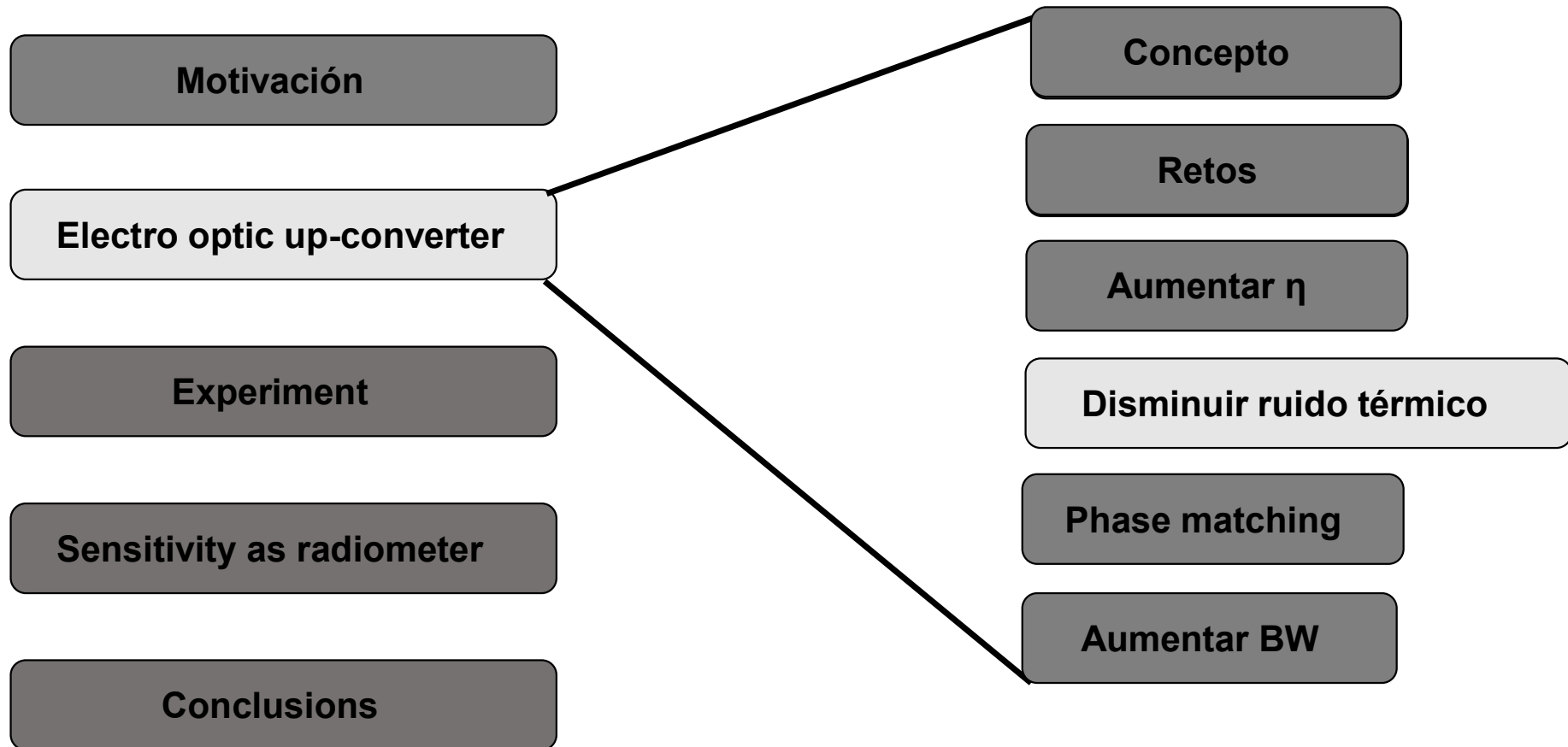
$$\eta_{ph} = \frac{2P_p}{\varepsilon_0 \omega_{\pm}} \frac{\chi^{(2)^2} Q_p^2 Q_m}{n_p^4 n_m^2} \frac{E_m'^2(\mathbf{r}_p)}{V_m} (1 - S_{11}^2 - S_{21}^2)$$



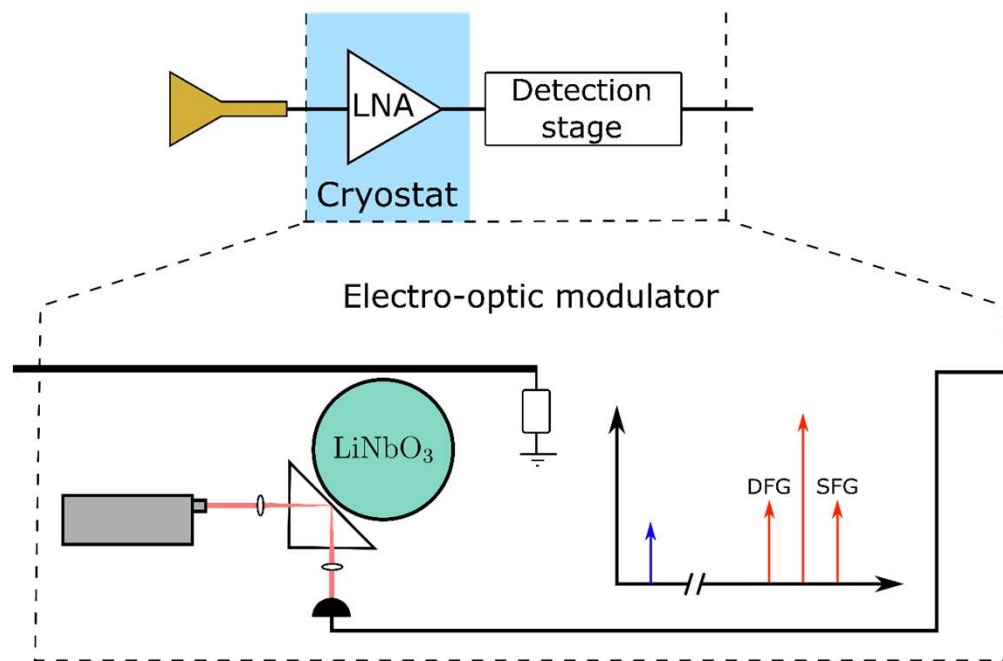
Electro-optic up-converter: aumentar la eficiencia

$$\eta_{ph} = \frac{2P_p}{\epsilon_0 \omega_{\pm}} \frac{\chi^{(2)^2} Q_p^2 Q_m}{n_p^4 n_m^2} \frac{E_m'^2(\mathbf{r}_p)}{V_m} (1 - S_{11}^2 - S_{21}^2)$$





Electro-optic up-converter: challenges



Challenges:

1. High conversion efficiency:

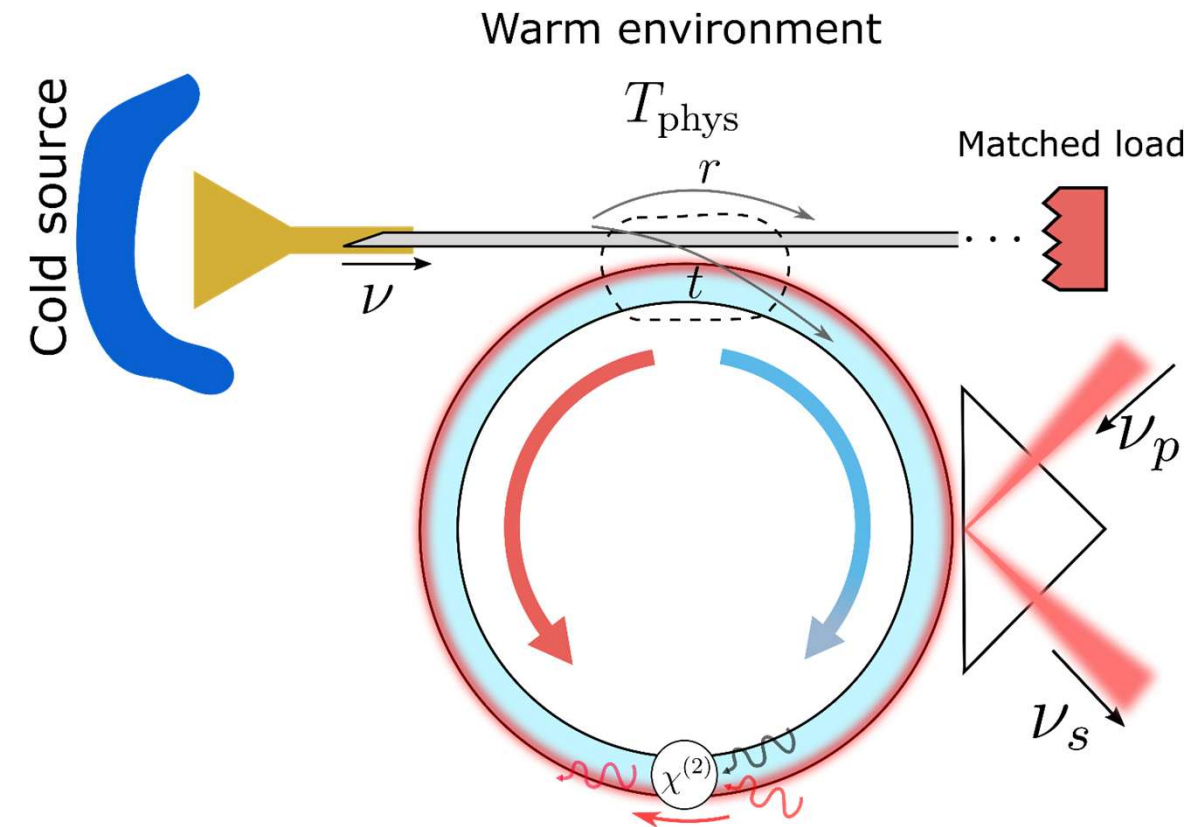
$$\eta = \frac{\# \text{ of upconverted photons}}{\# \text{ of input microwave photons}}$$

2. **Avoid thermal noise being upconverted**

3. Phase matching

4. High upconversion bandwidth

Electro-optic up-converter: ocupación térmica



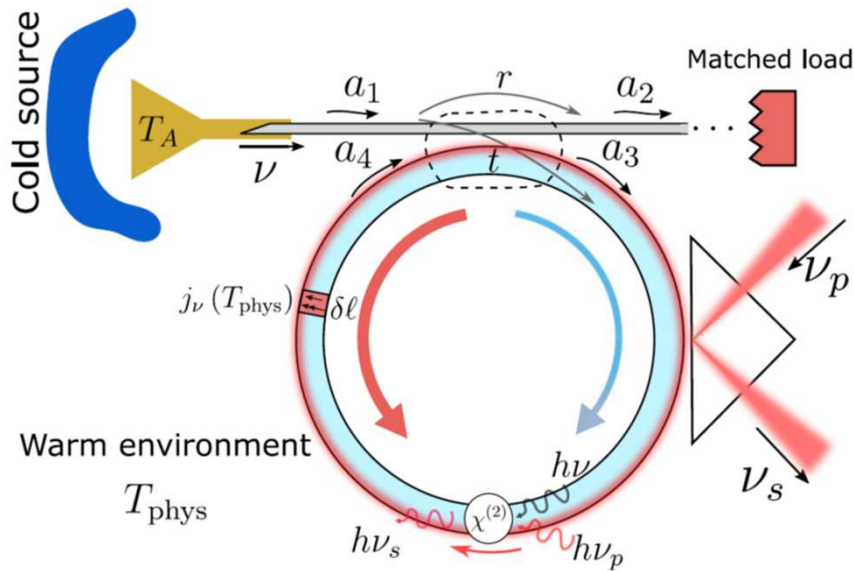
Hot matched load

Thermal noise from thermic bath

Thermal noise from horn+waveguide

Thermal noise from the resonator

Electro-optic up-converter: ruido inherente al resonador



Thermal equilibrium

$$|j_\nu(T_{\text{phys}})|^2 = h\nu(1 - \exp(-2\alpha\delta\ell))\Theta_\nu(T_{\text{phys}}).$$

$$\Theta_\nu(T) = [\exp(h\nu/(k_B T)) - 1]^{-1}$$

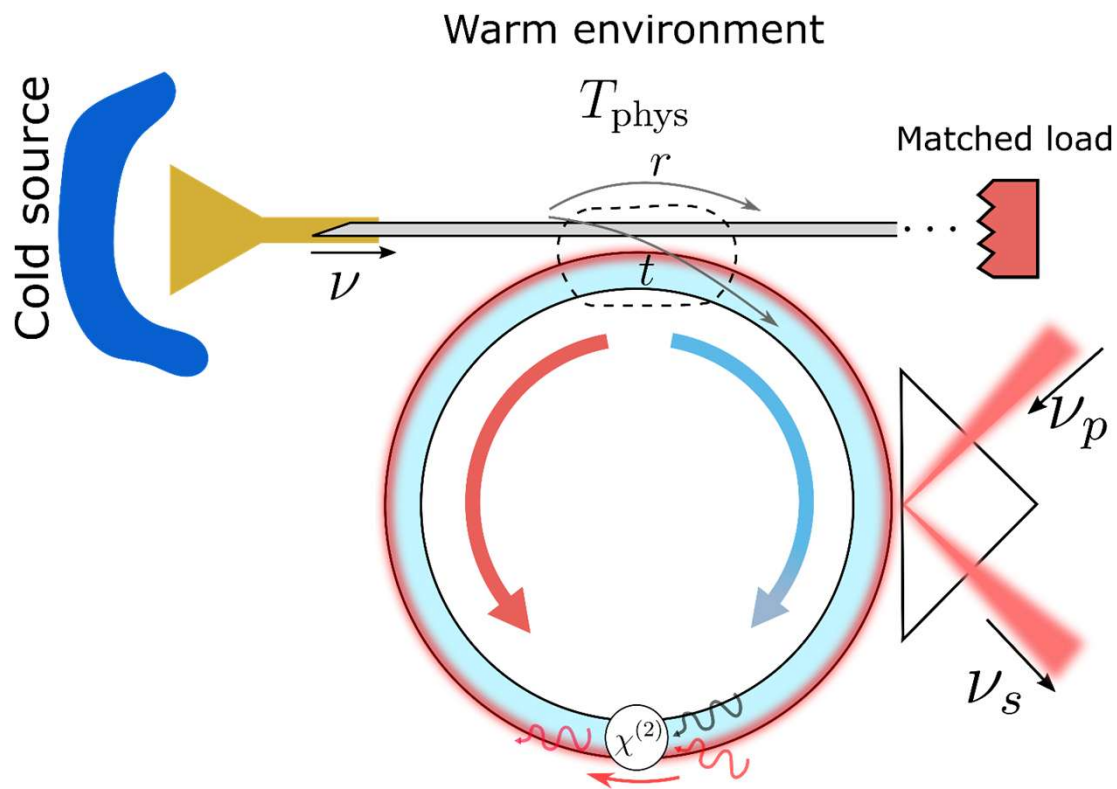
$$|s_T(\nu, \ell_2)|^2 = \underbrace{\frac{a^{2\ell_2/L}(1 - |r|^2)}{|1 - a|r| \exp(i2\pi\tau\delta\nu)|^2} h\nu\Theta_\nu(T_A)}_{\text{Antenna contribution}} + \underbrace{\frac{1 - |r|^2 a^2 - (1 - |r|^2)a^{2\ell_2/L}}{|1 - a|r| \exp(i2\pi\tau\delta\nu)|^2} h\nu\Theta_\nu(T_{\text{phys}})}_{\text{"Hot" resonator contribution}}$$

$$P_s \propto \frac{(1 - a^2)(1 - |r|^2)}{\ln(a^{-2})} h\nu[\Theta_\nu(T_A) + \Theta_\nu(T_{\text{eff}})].$$

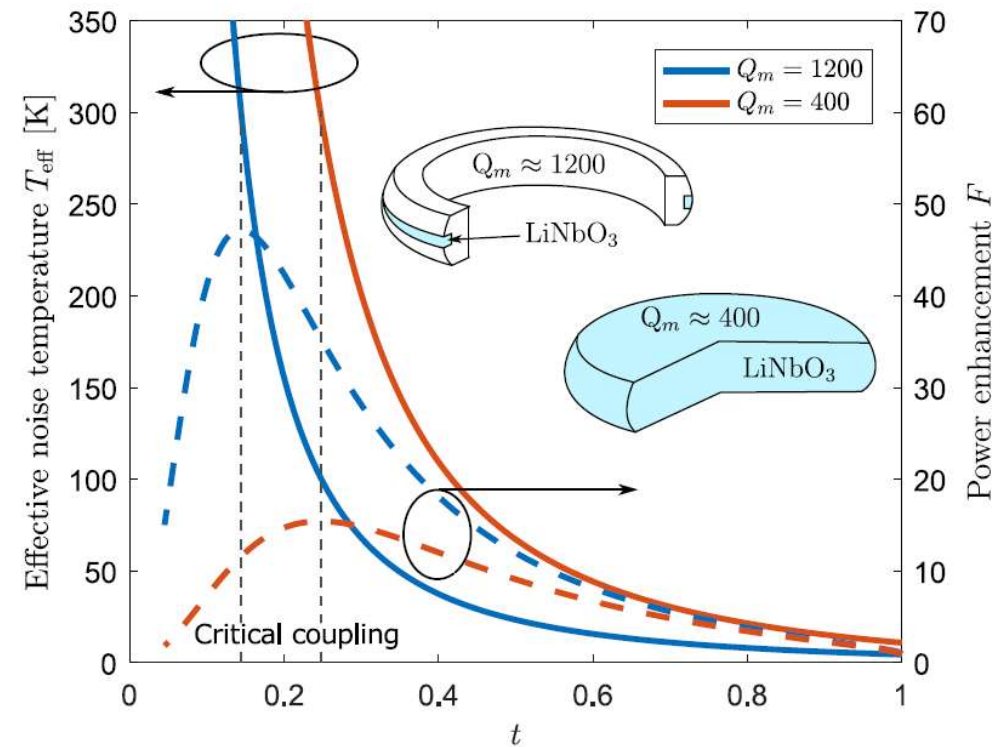
$$\Theta_\nu(T_{\text{eff}}) = \left[\frac{(1 - a^2|r|^2) \ln(a^{-2})}{(1 - a^2)(1 - |r|^2)} - 1 \right] \Theta_\nu(T_{\text{phys}}).$$

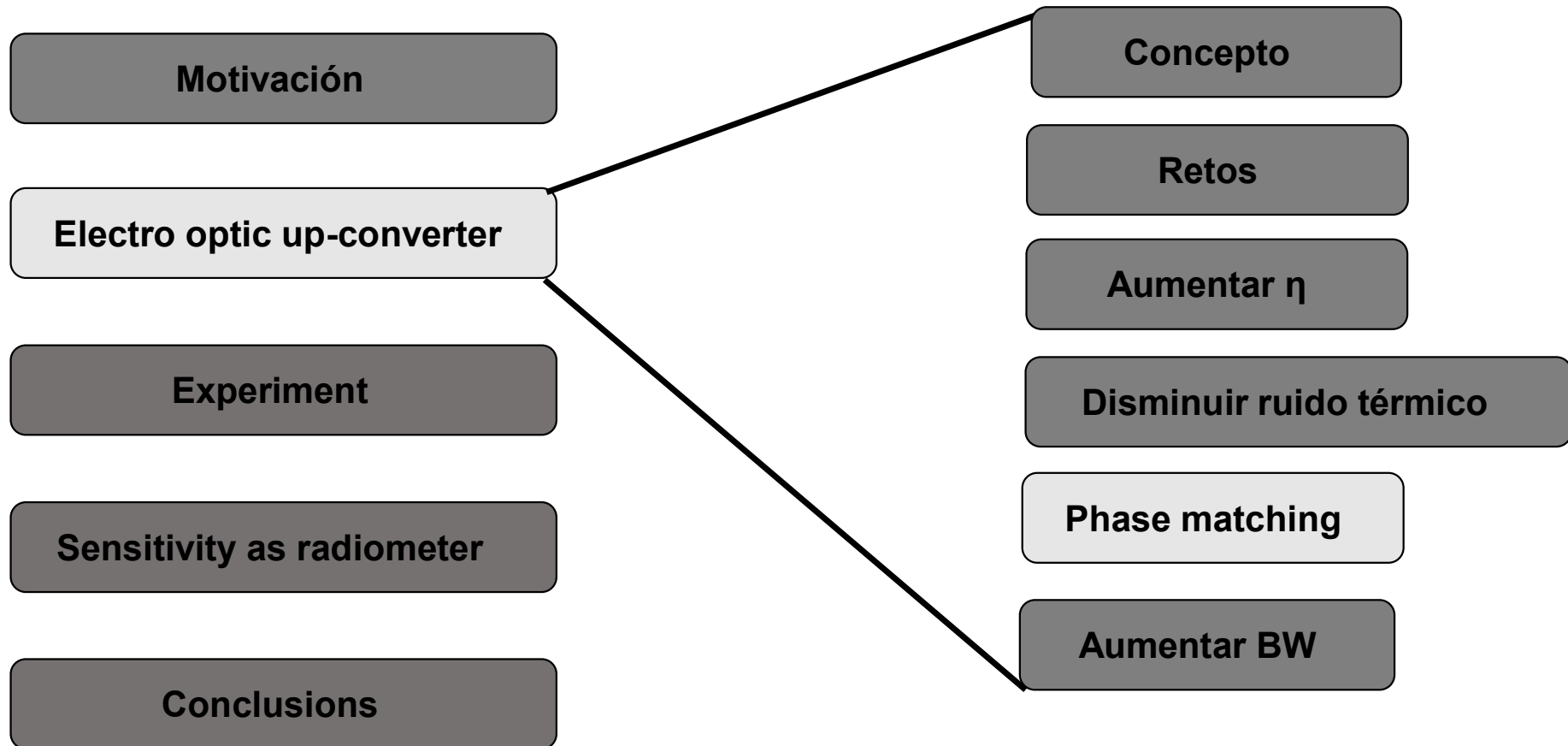
$$T_{\text{eff}} = \left[\frac{(1 - a^2|r|^2) \ln(a^{-2})}{(1 - a^2)(1 - |r|^2)} - 1 \right] T_{\text{phys}}.$$

Electro-optic up-converter: ruido inherente al resonador

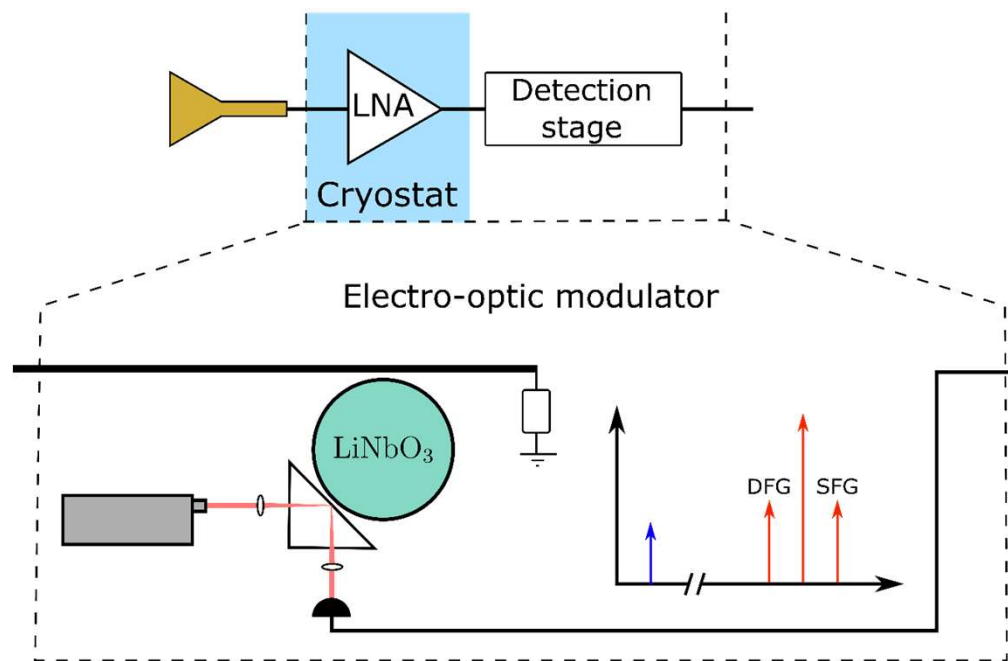


$$T_{\text{eff}} = \left[\frac{(1 - a^2 |r|^2) \ln(a^{-2})}{(1 - a^2)(1 - |r|^2)} - 1 \right] T_{\text{phys}}$$





Electro-optic up-converter: challenges



Challenges:

1. High conversion efficiency:

$$\eta = \frac{\# \text{ of upconverted photons}}{\# \text{ of input microwave photons}}$$

2. Avoid thermal noise being upconverted

3. Phase matching

4. High upconversion bandwidth

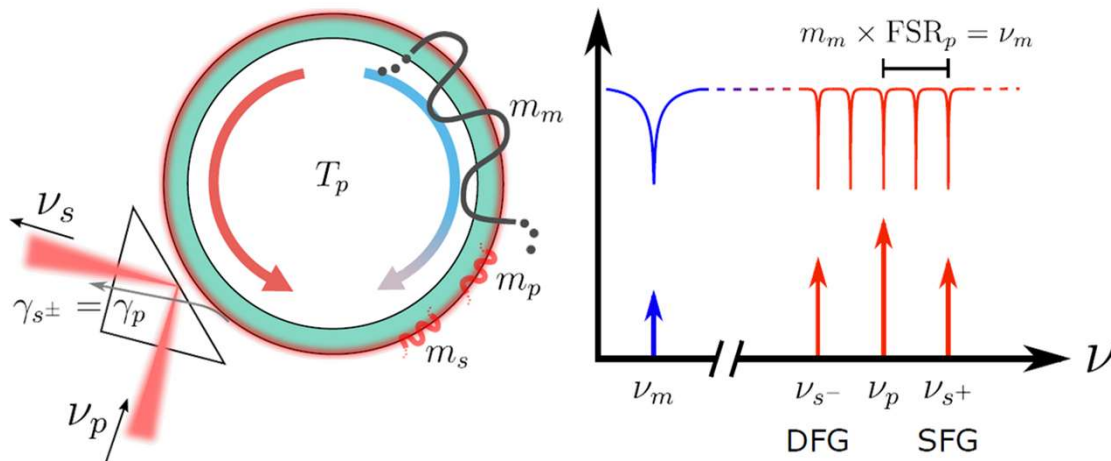
Electro-optic up-converter: realizing phase matching

Momentum conservation constrains mode azimuthal numbers to fulfill the relation:

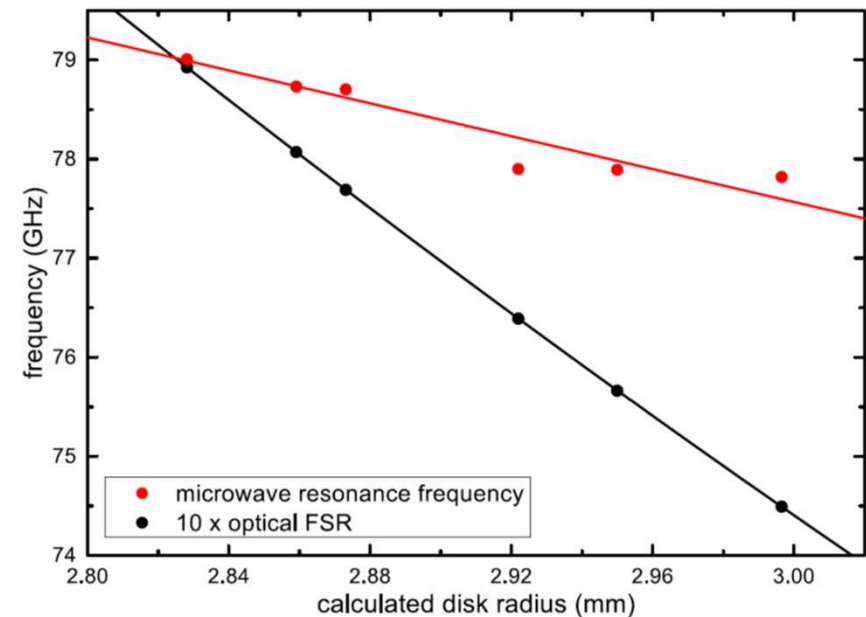
$$m_s = m_p \pm m_m$$

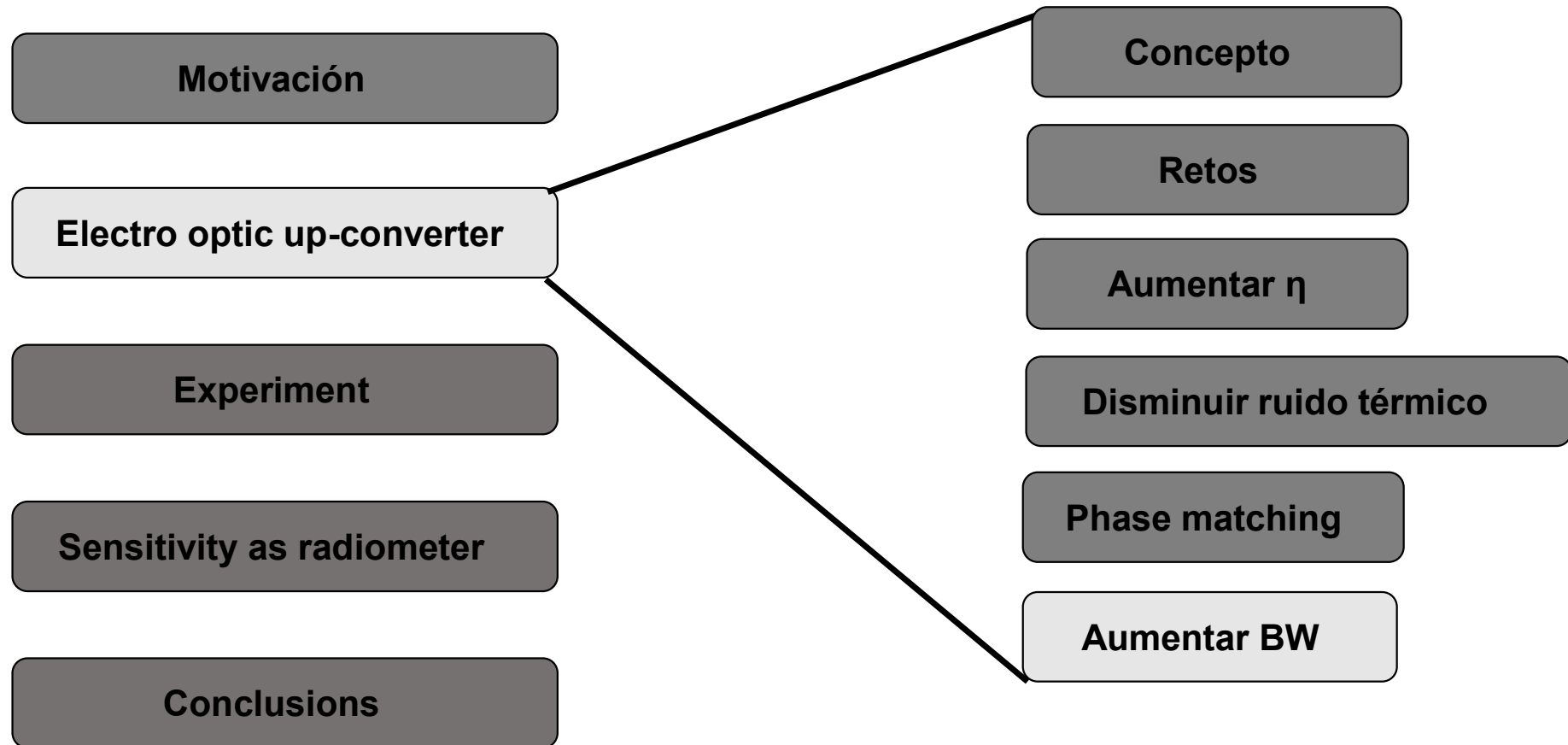
Energy conservation constrains the frequency to fulfill the relation

$$f_s = f_p \pm f_m$$

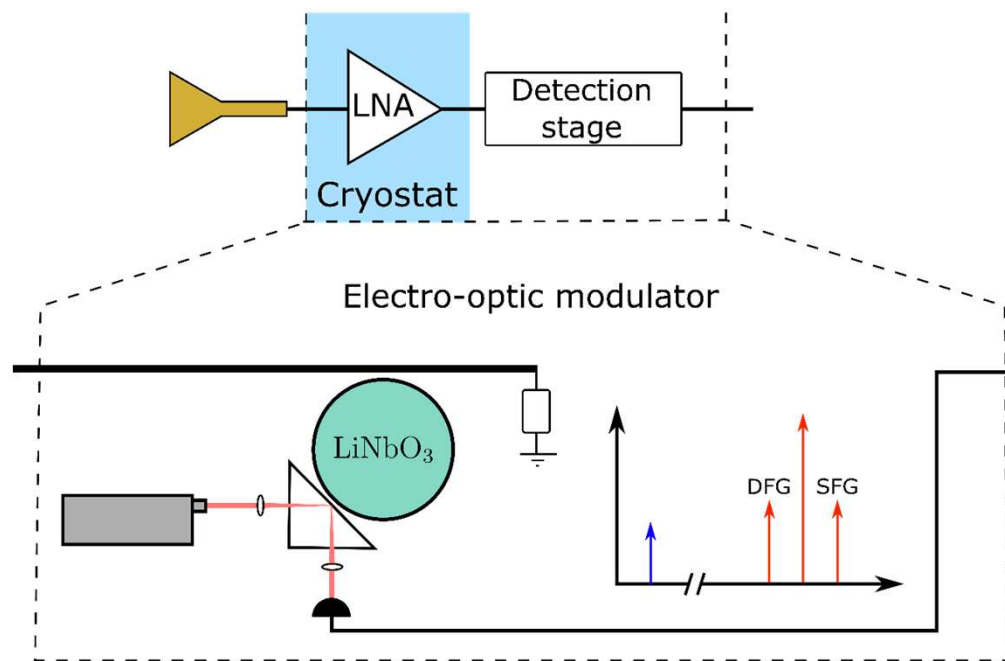


Since the prism couples both optical modes with the same rate, the sideband must also be resonant. Narrowband up-conversion! ≈ 2 MHz for 1550 nm light and $Q \approx 10^8$ cavity





Electro-optic up-converter: challenges



Challenges:

1. High conversion efficiency:

$$\eta = \frac{\# \text{ of upconverted photons}}{\# \text{ of input microwave photons}}$$

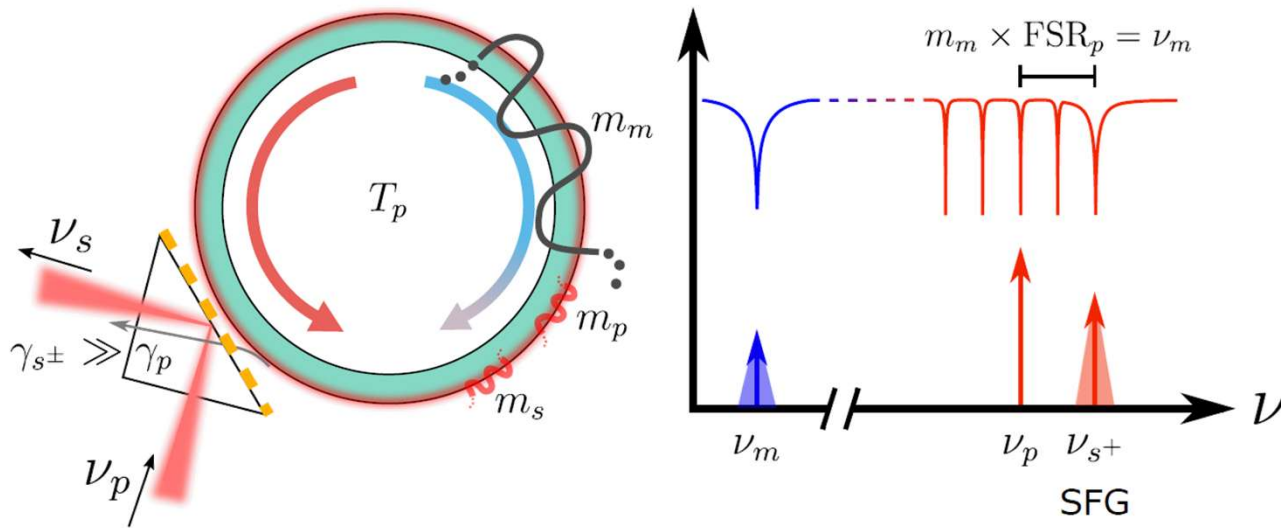
2. Avoid thermal noise being upconverted

3. Phase matching

4. High upconversion bandwidth

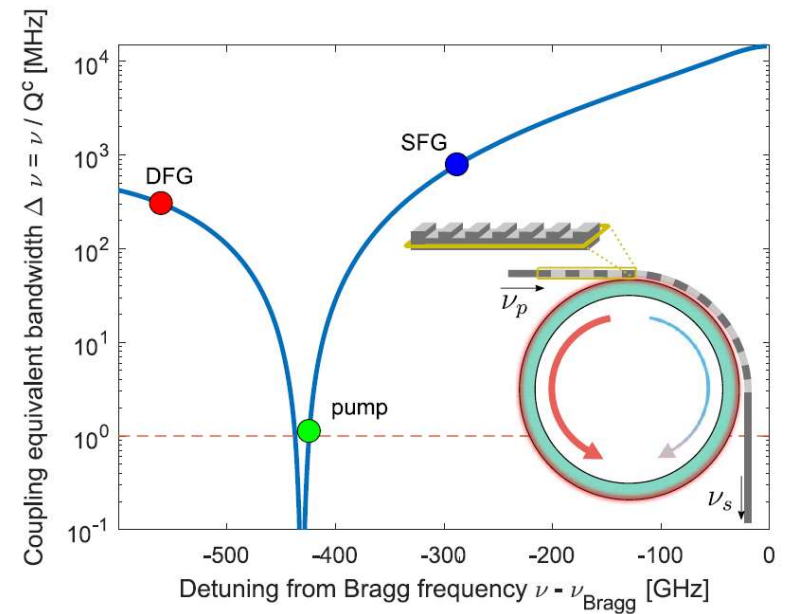
Electro-optic up-converter: increasing bandwidth

Finding a strong mode selective coupler

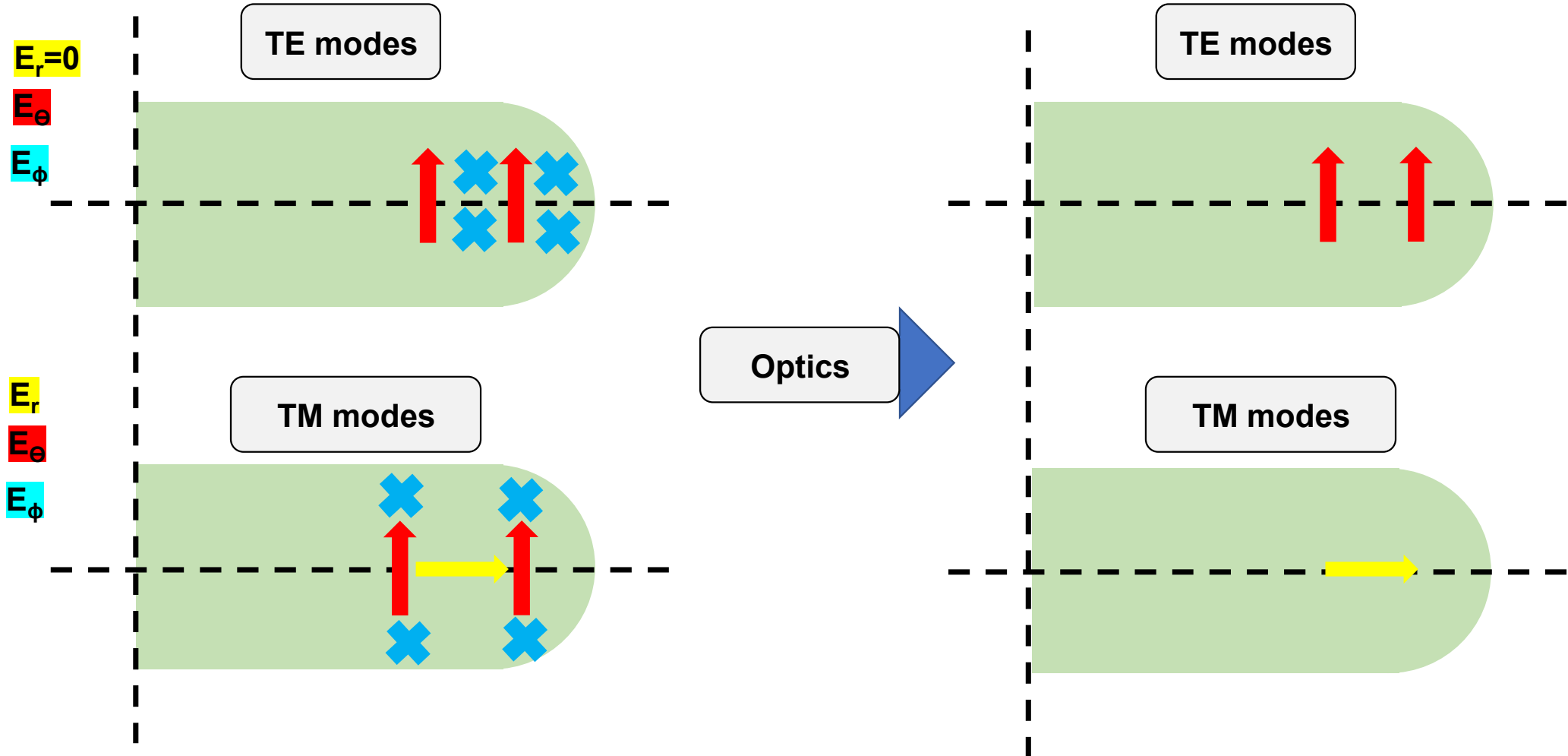


Grating etched in optical silicon coupling waveguide.

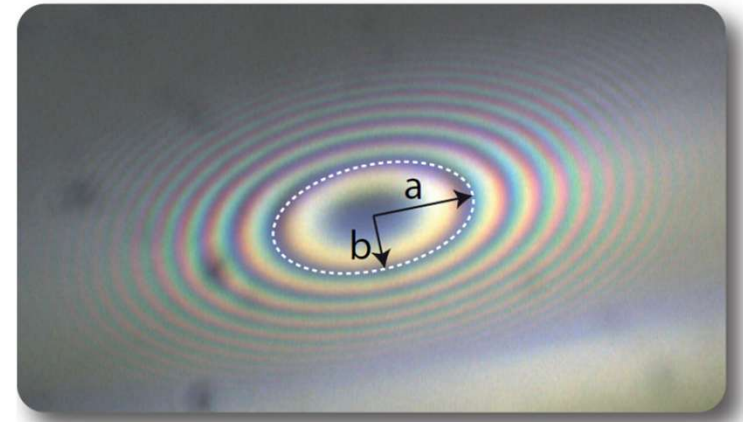
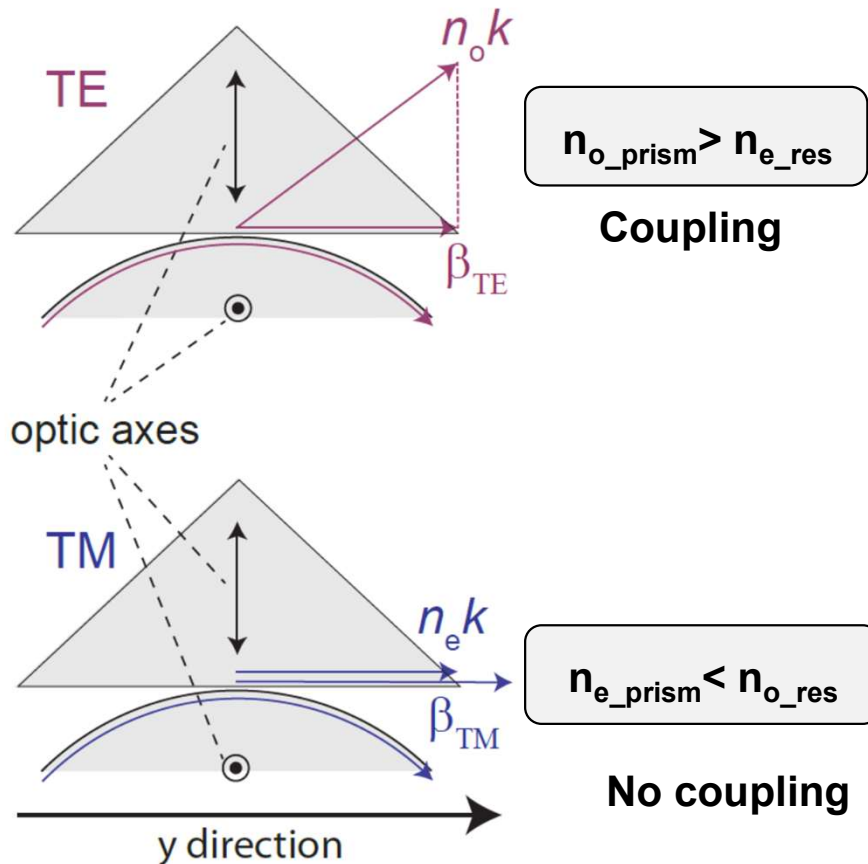
Preliminary theoretical study with coupled-mode theory shows 800 MHz upconversion bandwidth of 130 GHz signals.



Electro-optic up-converter: increasing bandwidth



Electro-optic up-converter: increasing bandwidth



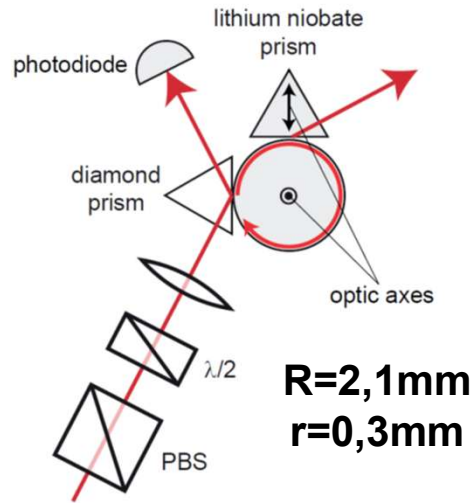
Research Article Vol. 24, No. 23 | 14 Nov 2016 | OPTICS EXPRESS 26503

Optics EXPRESS

Maximization of the optical intra-cavity power of whispering-gallery mode resonators via coupling prism

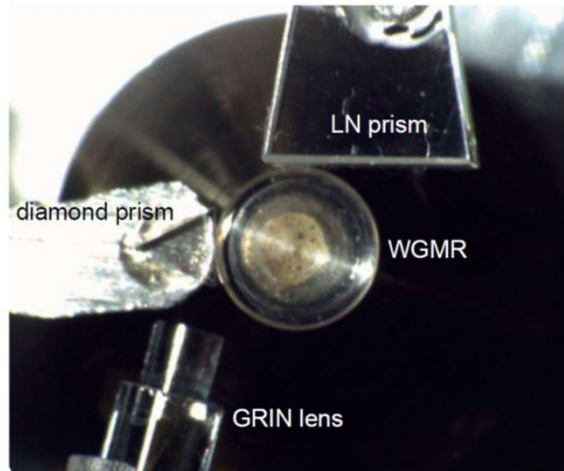
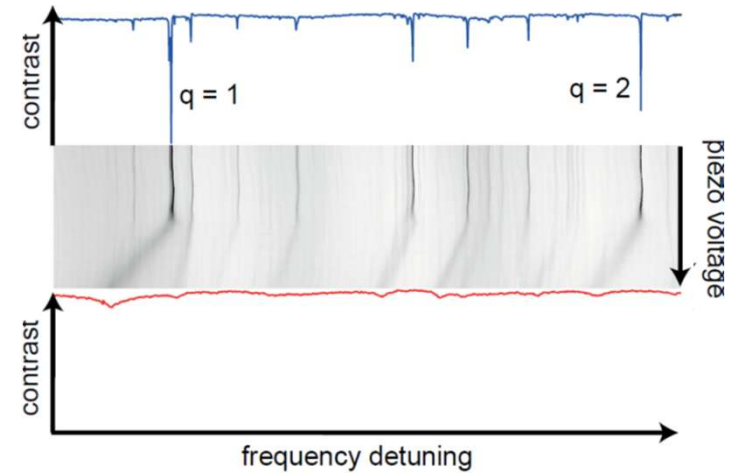
G. A. SANTAMARÍA-BOTELLO,¹ L. E. GARCÍA MUÑOZ,^{1,*} F. SEDLMEIR,² S. PREU,³ D. SEGOVIA-VARGAS,¹ K. ATIA ABDALMALAK,¹ S. LLORENTE ROMANO,¹ A. GARCÍA LAMPÉREZ,¹ S. MALZER,⁴ G. H. DÖHLER,⁴ H. G. L. SCHWEFEL,² AND H. B. WEBER⁴

Electro-optic up-converter: experiment for increasing bandwidth



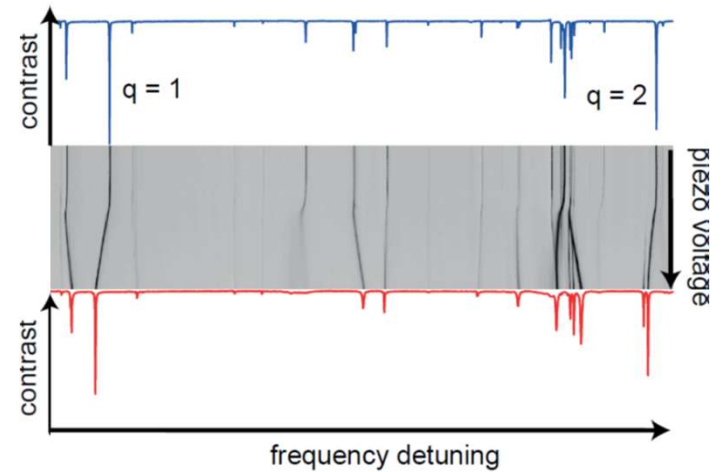
Coupling to the LN prism

TE modes $\left\{ \begin{array}{l} n_{e_res} \\ n_{o_prism} \end{array} \right.$
 $Q=8,8 \times 10^7$
 $\Delta v_{TE}=2,2 \text{ MHz}$



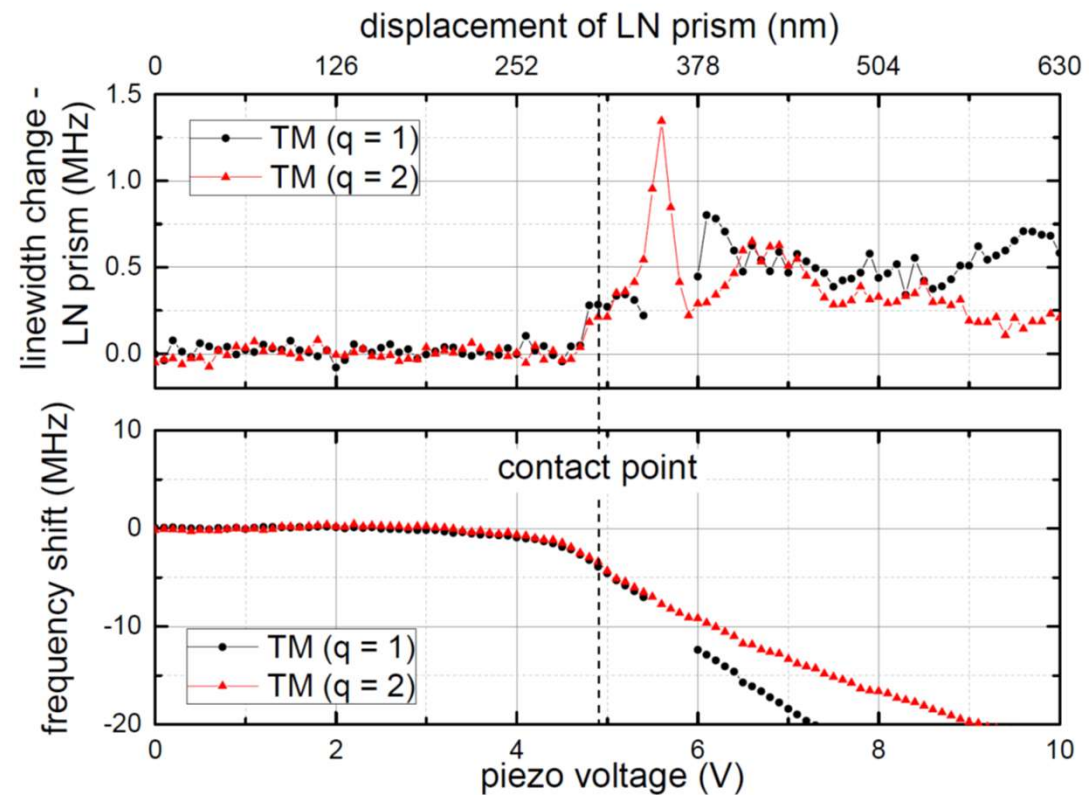
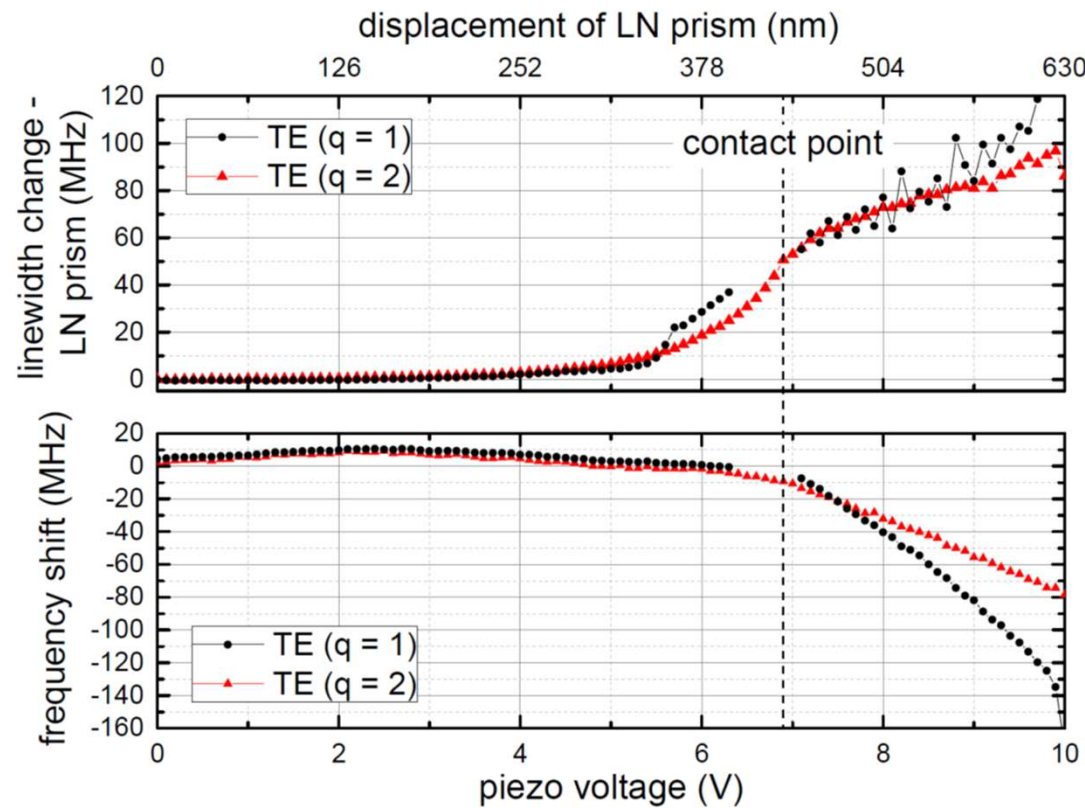
No coupling to the LN prism

TM modes $\left\{ \begin{array}{l} n_{o_res} \\ n_{e_prism} \end{array} \right.$
 $Q=1,9 \times 10^8$
 $\Delta v_{TE}=1 \text{ MHz}$

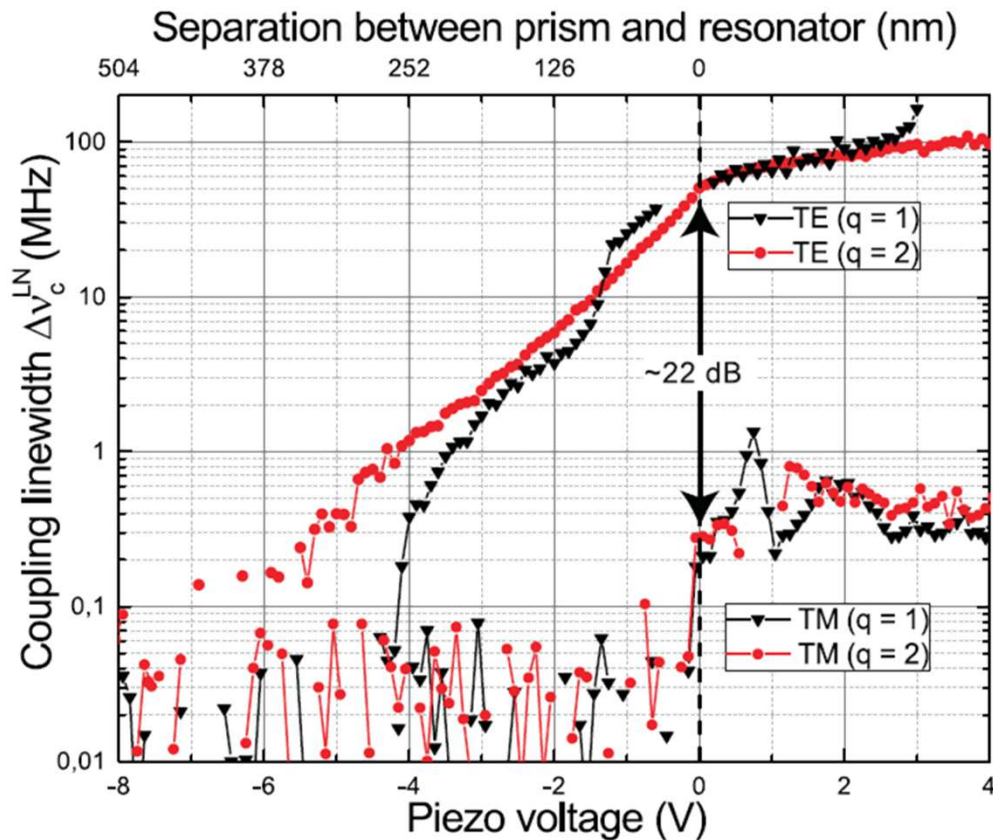


Electro-optic up-converter: experiment for increasing bandwidth

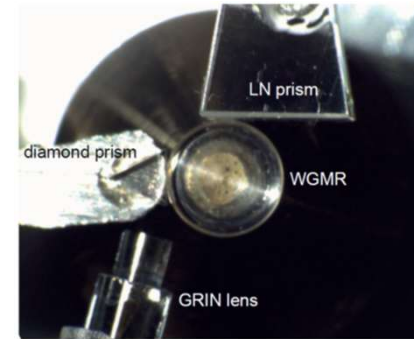
Piezo 0,1V=6,3nm



Electro-optic up-converter: experiment for increasing bandwidth



Up to 100 MHz coupling bandwidth difference between TE and TM modes



Research Article

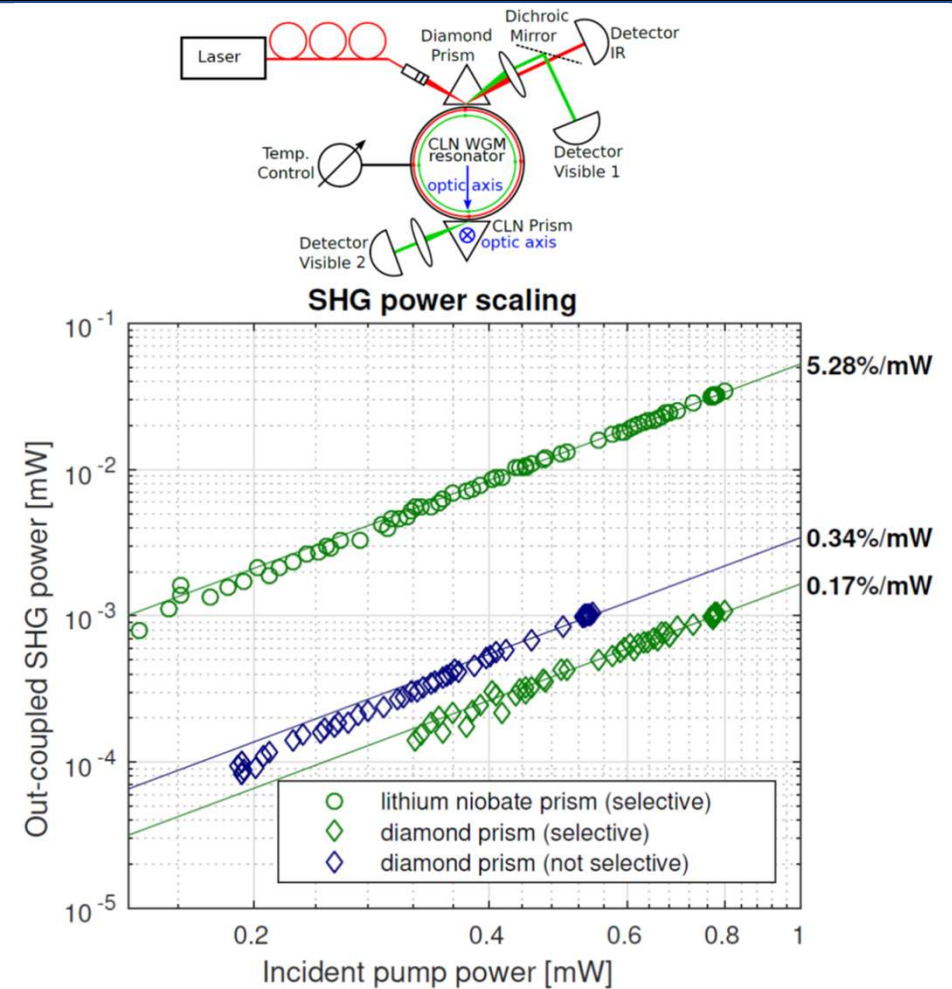
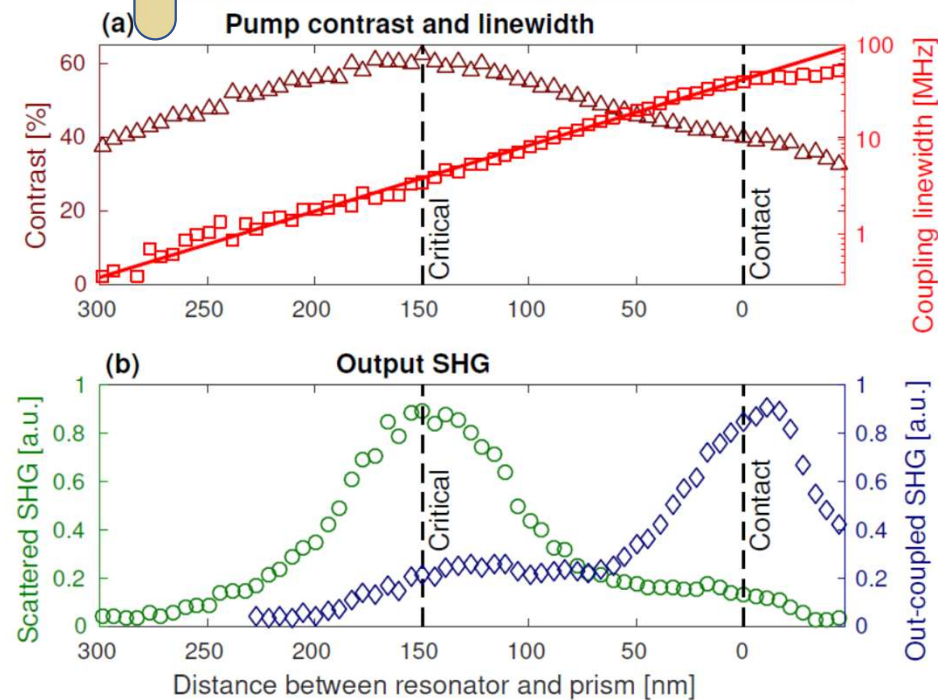
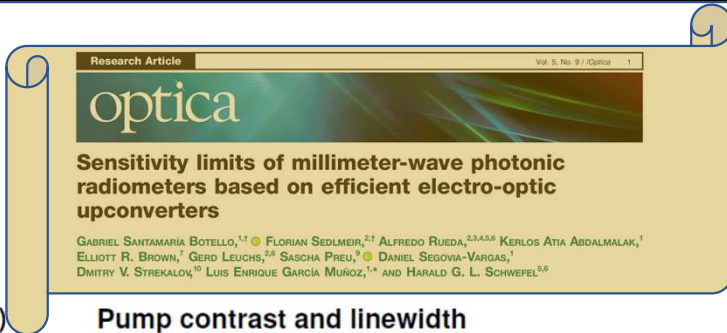
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Optics EXPRESS

Maximization of the optical intra-cavity power of whispering-gallery mode resonators via coupling prism

G. A. SANTAMARÍA-BOTELLO,¹ L. E. GARCÍA MUÑOZ,^{1,*} F. SEDLMEIR,² S. PREU,³ D. SEGOVIA-VARGAS,¹ K. ATIA ABDALMALAK,¹ S. LLORENTE ROMANO,¹ A. GARCÍA LAMPÉREZ,¹ S. MALZER,⁴ G. H. DÖHLER,⁴ H. G. L. SCHWEFEL,² AND H. B. WEBER⁴

Electro-optic up-converter: increasing bandwidth, SHG experiment



Motivación

Electro optic up-converter

Experiment

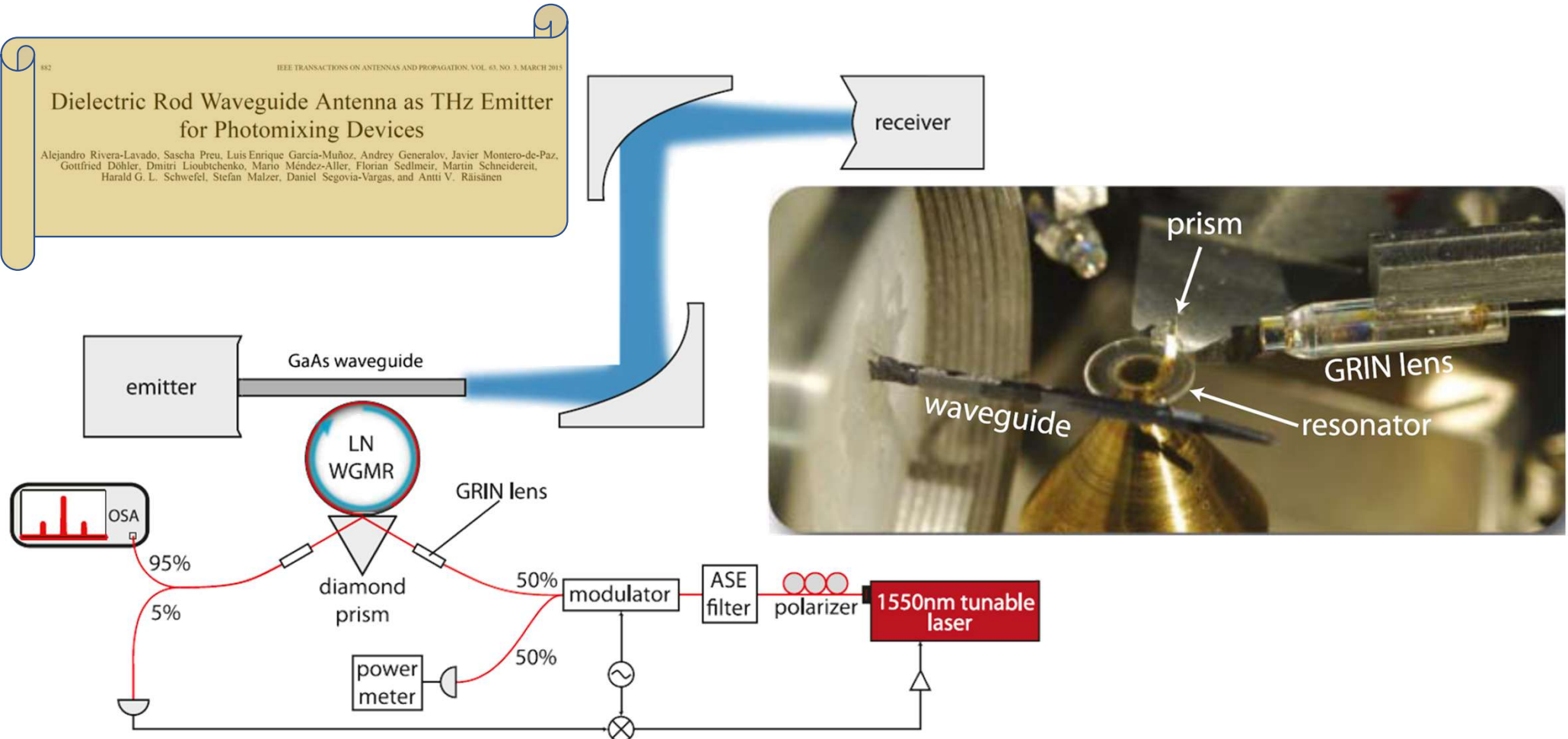
Sensitivity as radiometer

Conclusions

Electro-optic up-converter: Experimental proof of concept

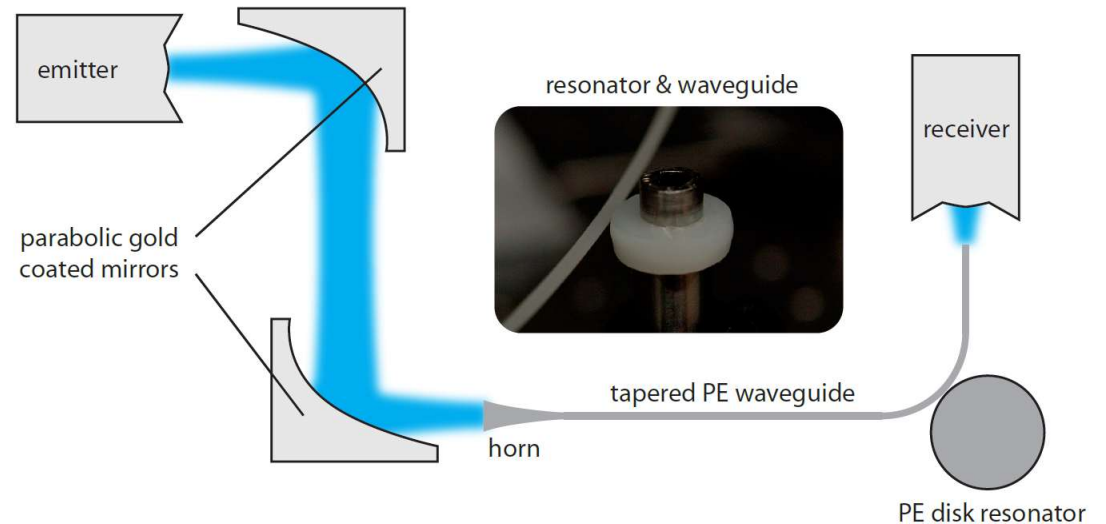
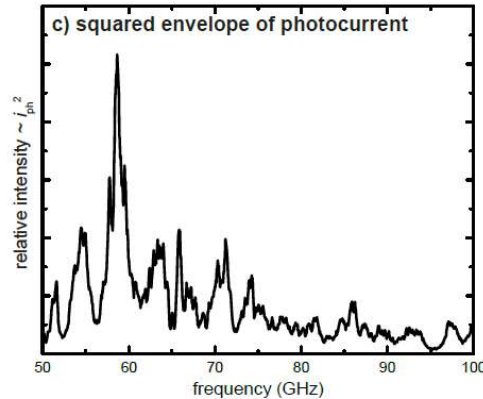
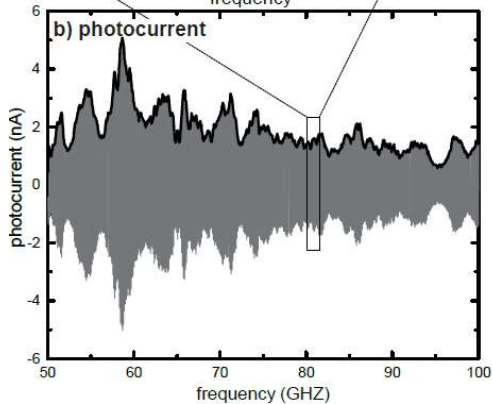
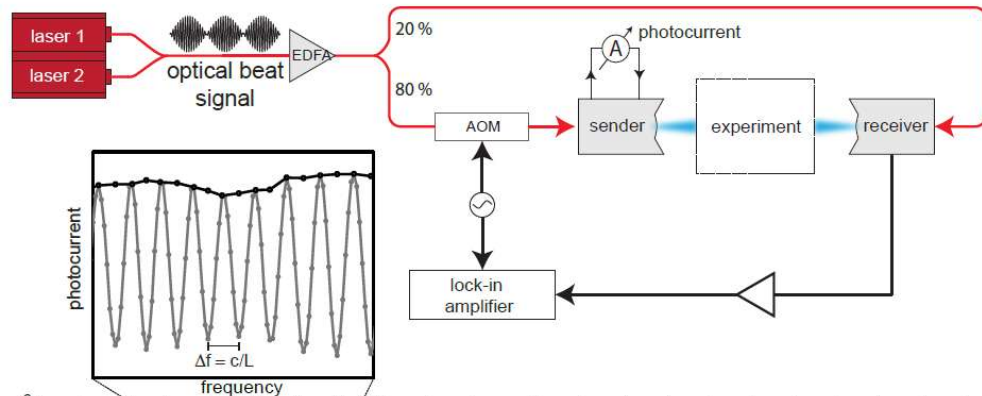
Dielectric Rod Waveguide Antenna as THz Emitter for Photomixing Devices

Alejandro Rivera-Lavado, Sascha Preu, Luis Enrique García-Muñoz, Andrey Generalov, Javier Montero-de-Paz, Gottfried Döhler, Dmitri Lioubtchenko, Mario Méndez-Aller, Florian Sedlmeir, Martin Schneider, Harald G. L. Schwefel, Stefan Malzer, Daniel Segovia-Vargas, and Antti V. Räsänen



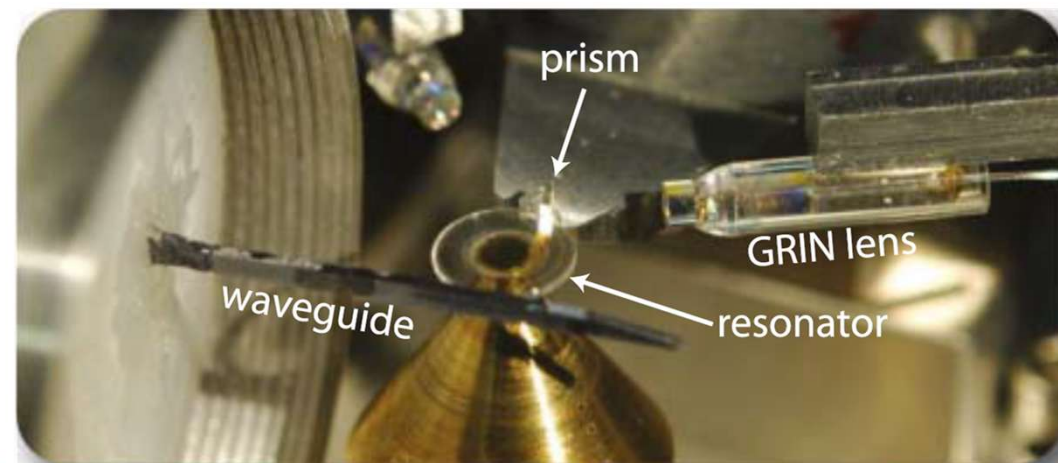
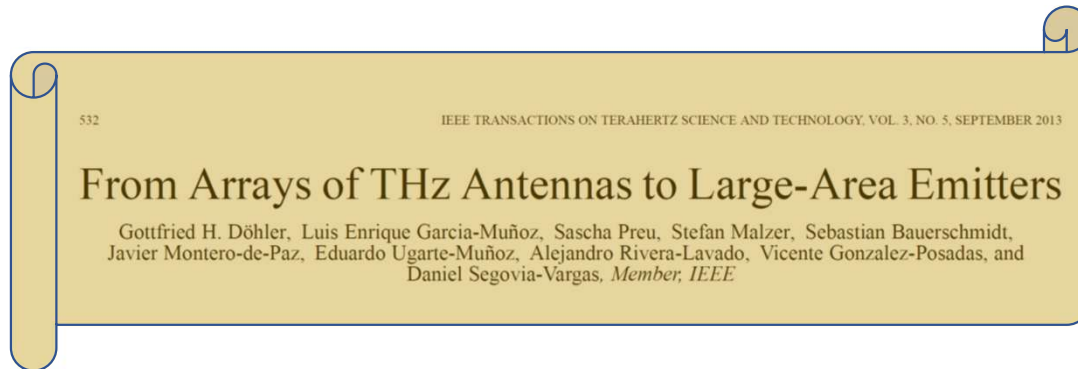
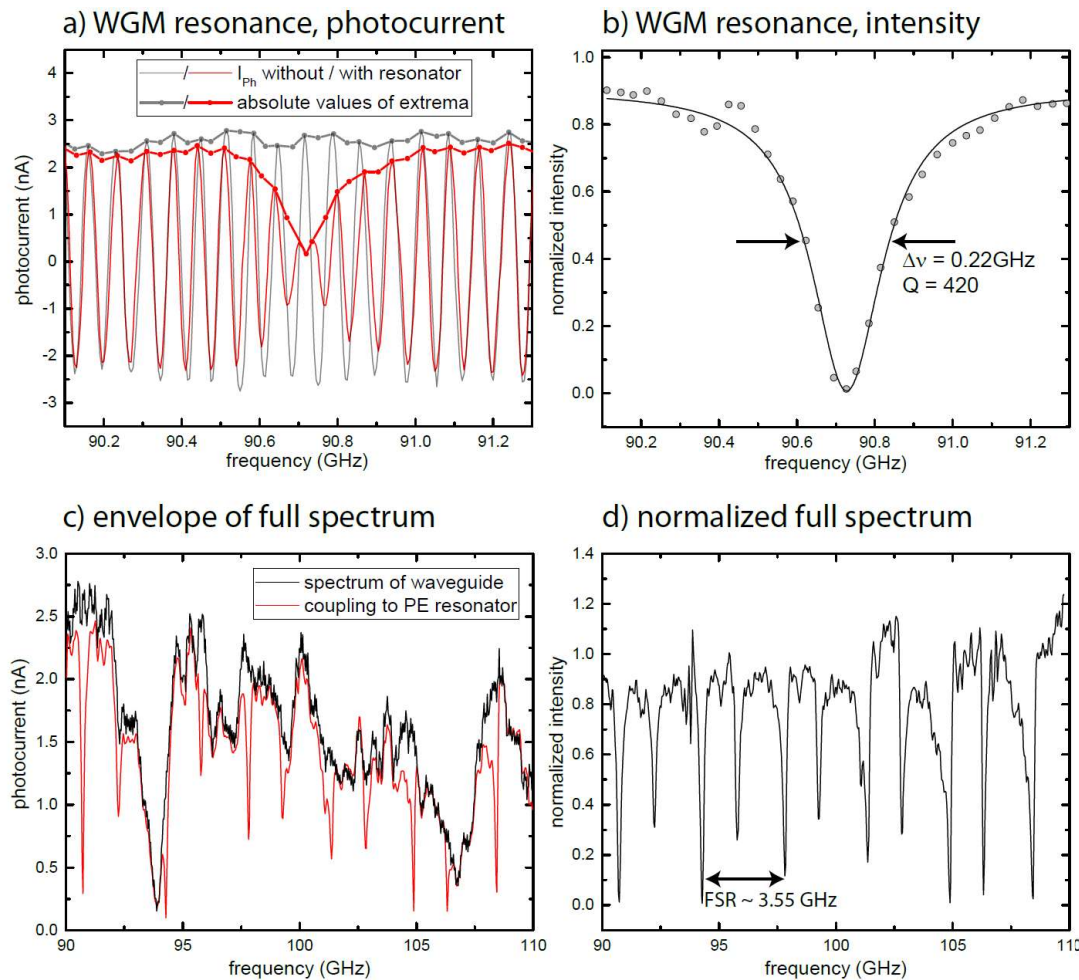
Electro-optic up-converter: Experimental proof of concept

a) schematic of the photomixing setup

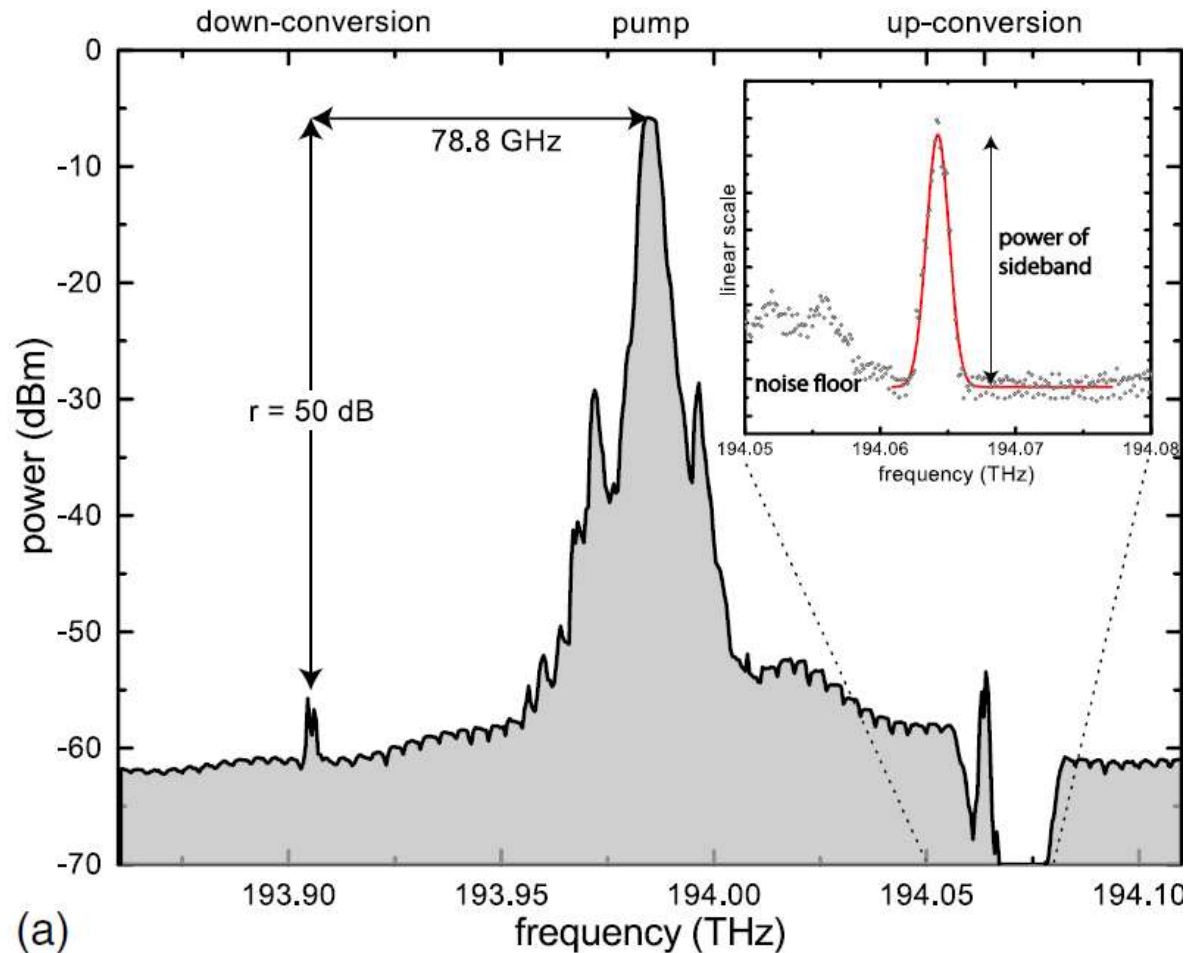


This schematic shows the setup used to couple to a PE resonator ($R = 10$ mm): The microwave from a photomixer emitting to free space is collimated and refocused with two parabolic mirrors into a tapered PE waveguide. The waveguide is bent to improve coupling to the resonator.

Electro-optic up-converter: Experimental proof of concept



Electro-optic up-converter: Experimental proof of concept



Record conversion efficiency $\eta = 2.5 \times 10^{-5}$ per mW pump power

Geometry optimizations from full-wave simulations show about 2 orders of magnitude increase in efficiency

Research Article Vol. 5, No. 9 / Optica 1

optica

Sensitivity limits of millimeter-wave photonic radiometers based on efficient electro-optic upconverters

GABRIEL SANTAMARÍA BOTELLO,^{1,†} FLORIAN SEDLMEIR,^{2,†} ALFREDO RUEDA,^{2,3,4,5,6} KERLOS ATIA ABDALMALAK,¹ ELLIOTT R. BROWN,⁷ GERT LEUCHS,^{2,8} SASCHA PREU,⁹ DANIEL SEGOVIA-VARGAS,¹ DMITRY V. STREKALOV,¹⁰ LUIS ENRIQUE GARCÍA MUÑOZ,^{1,*} AND HARALD G. L. SCHWEFEL^{5,6}

Electro-optic up-converter: Experimental proof of concept



Research Article

Vol. 3, No. 6 / June 2016 / Optica 597

optica

Efficient microwave to optical photon conversion: an electro-optical realization

ALFREDO RUEDA,^{1,2,3,†} FLORIAN SEDLMEIR,^{1,2,3,6,†} MICHELE C. COLLODO,^{1,2,4,5} ULRICH VOGL,^{1,2} BIRGIT STILLER,^{1,2,6} GERHARD SCHUNK,^{1,2,3} DMITRY V. STREKALOV,¹ CHRISTOPH MARQUARDT,^{1,2} JOHANNES M. FINK,^{4,7} OSKAR PAINTER,⁴ GERD LEUCHS,^{1,2} AND HARALD G. L. SCHWEFEL^{5,*}

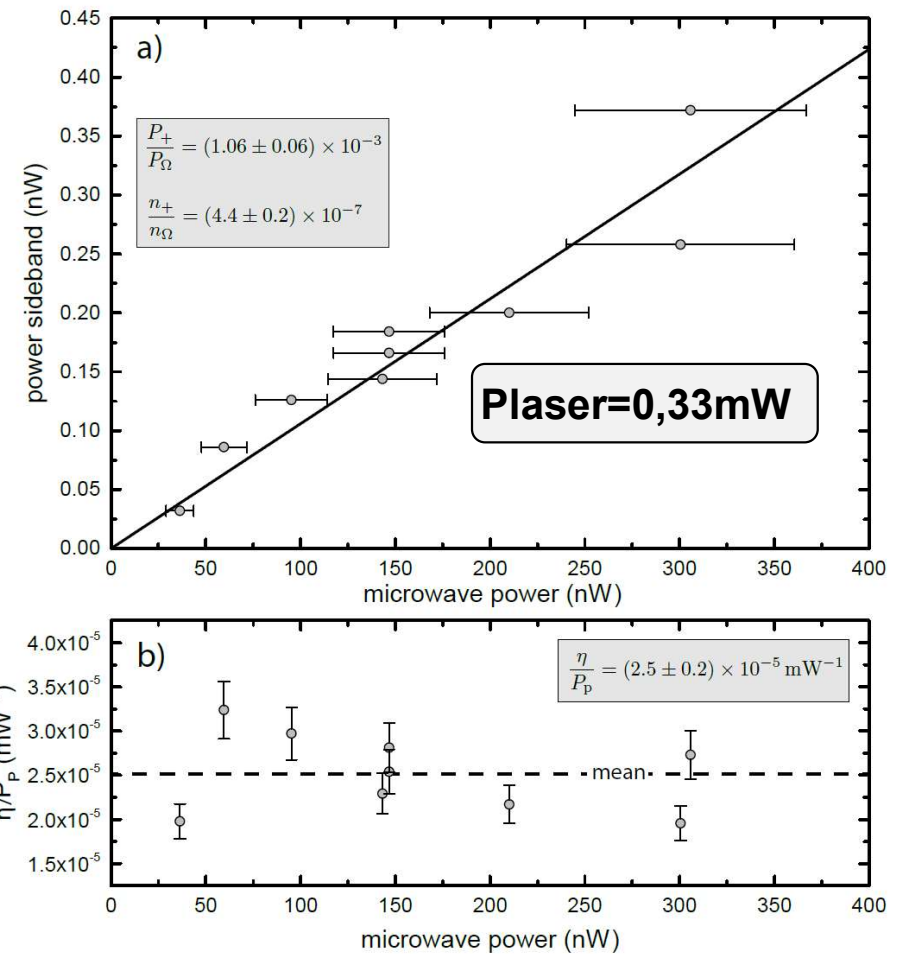
Research Article

Vol. 5, No. 9 / Optica 1

optica

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Motivación

Electro optic up-converter

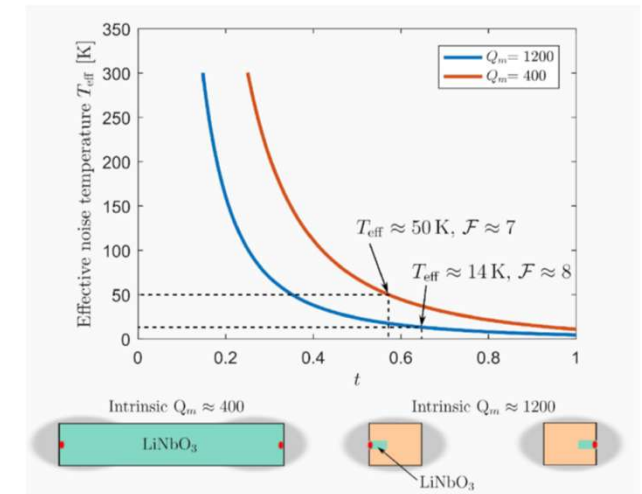
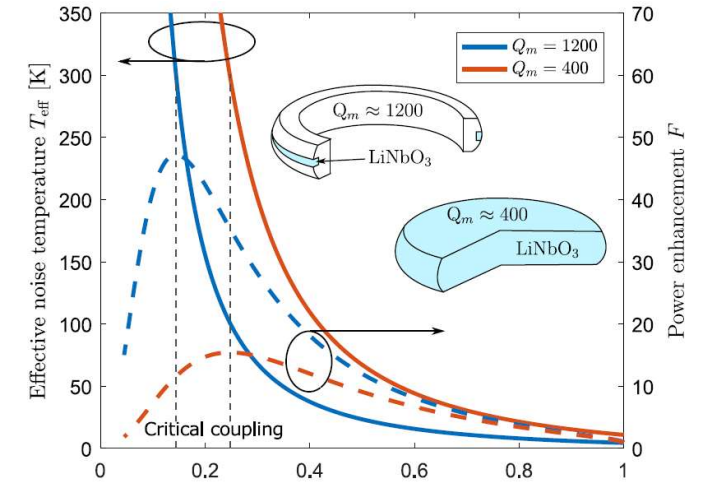
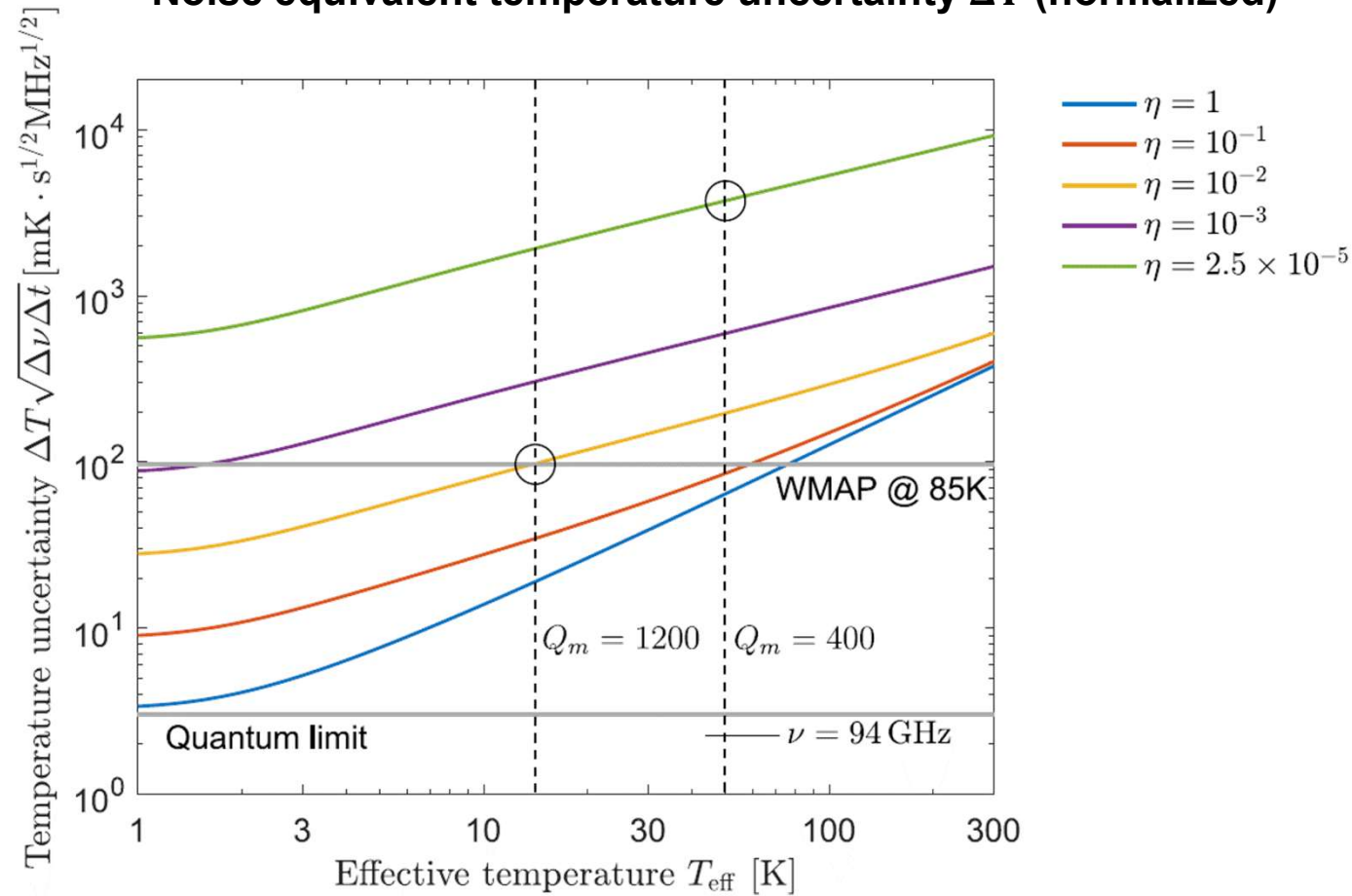
Experiment

Sensitivity as radiometer

Conclusions

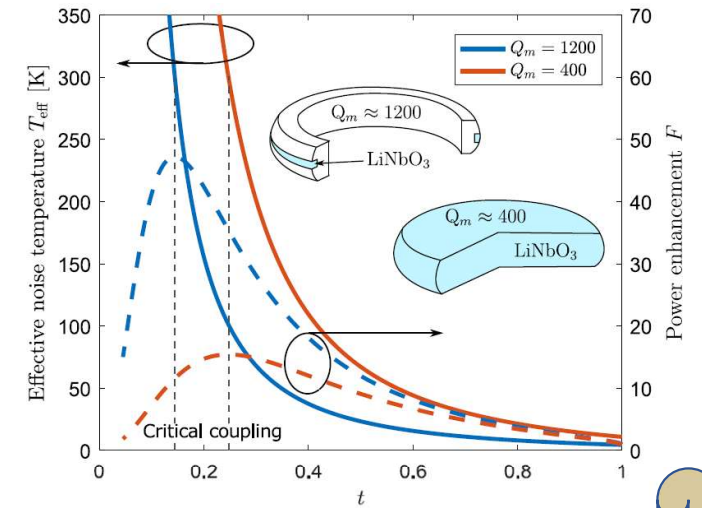
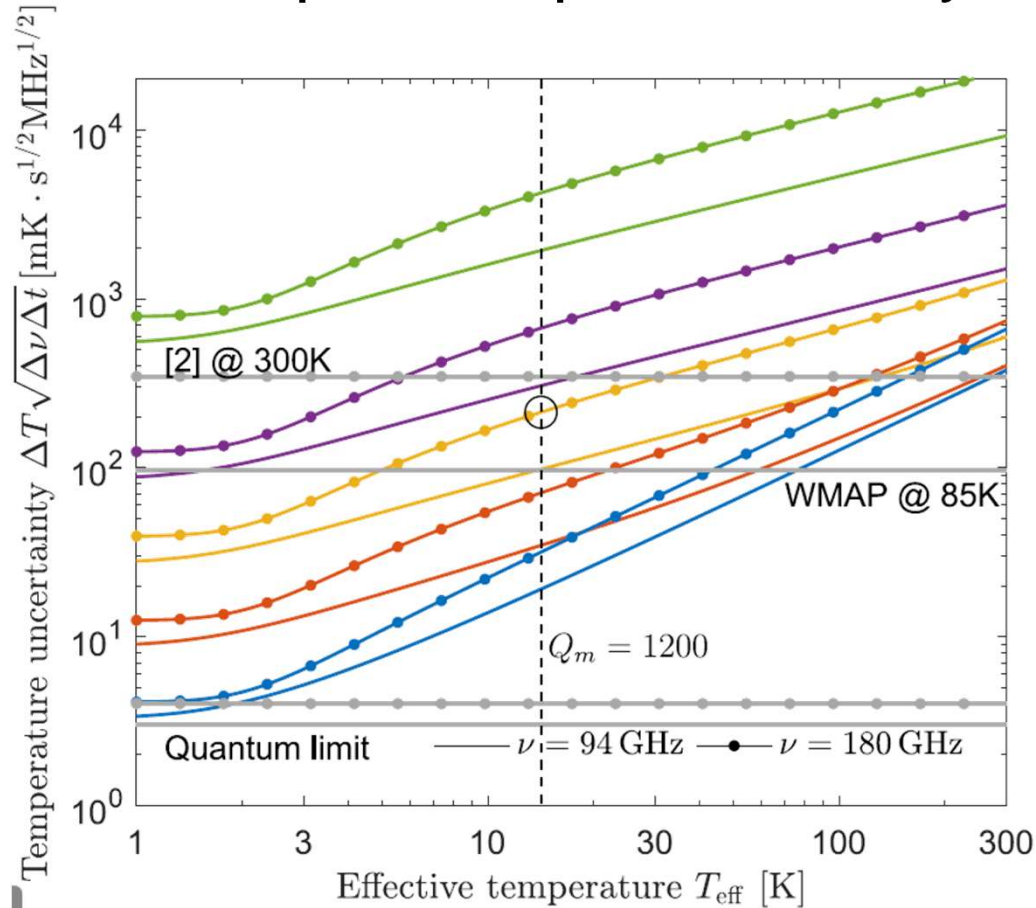
Sensitivity as a radiometer

Noise equivalent temperature uncertainty ΔT (normalized)



Sensitivity as a radiometer

Noise equivalent temperature uncertainty ΔT (normalized)



Research Article

Vol. 3, No. 6 / June 2016 / Optica 597

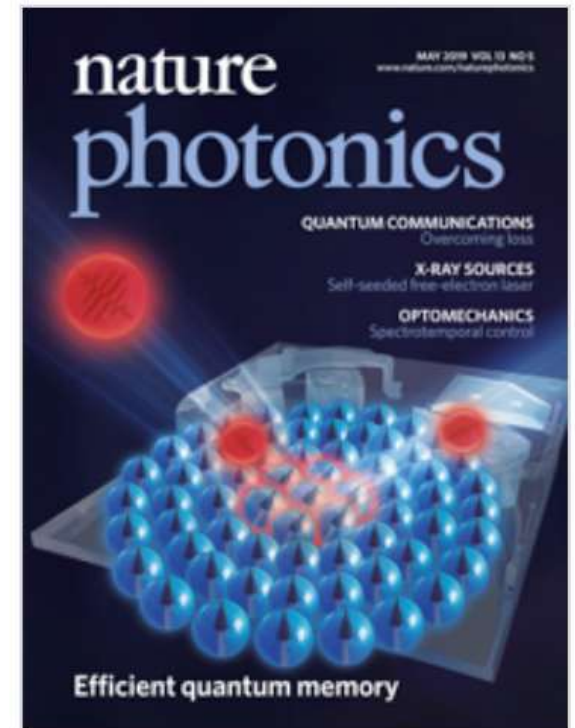
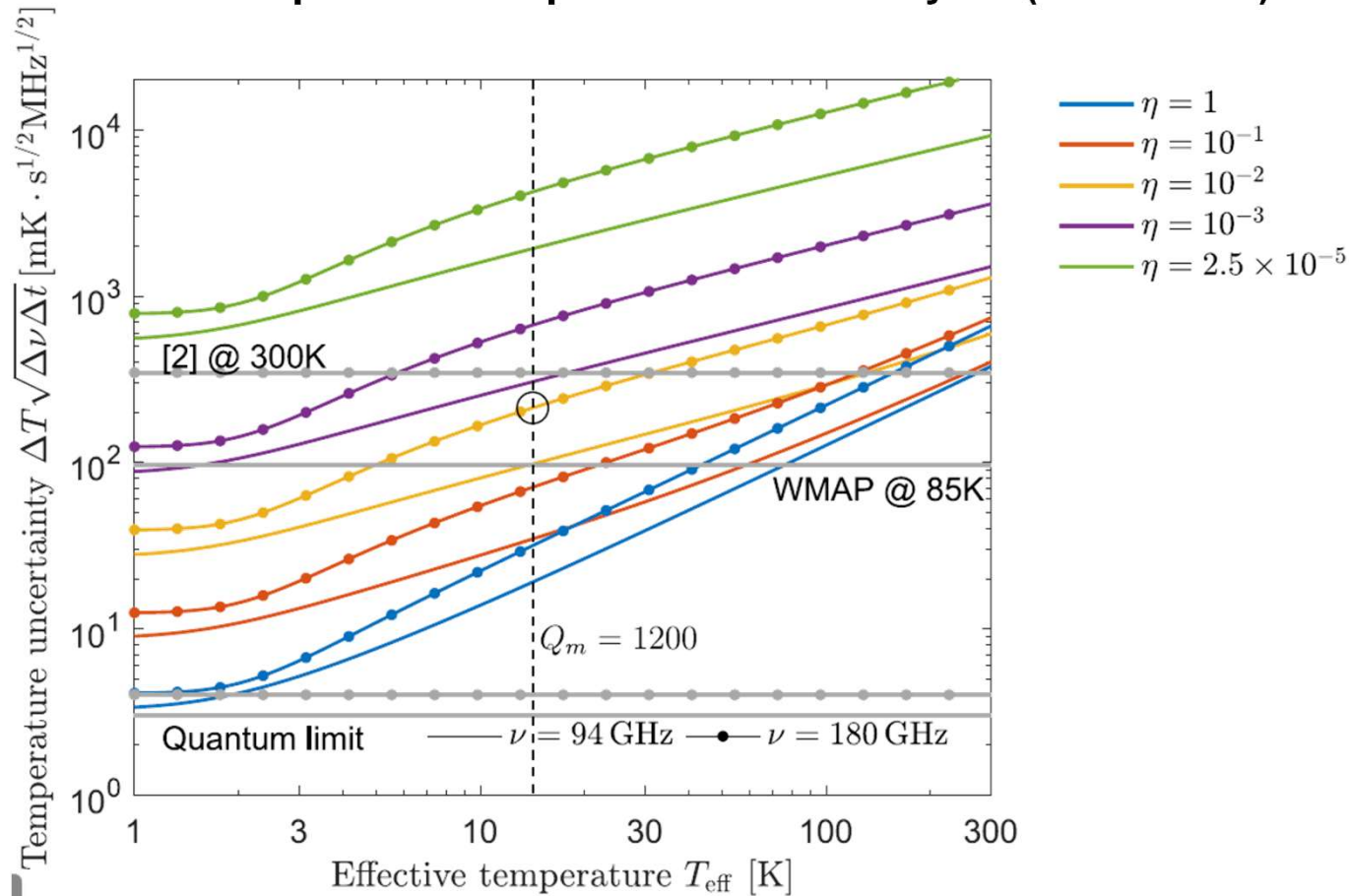
optica

Efficient microwave to optical photon conversion: an electro-optical realization

ALFREDO RUEDA,^{1,2,3,†} FLORIAN SEDLMEIR,^{1,2,3,9,†} MICHELE C. COLLODO,^{1,2,4,5} ULRICH VOGL,^{1,2} BIRGIT STILLER,^{1,2,6} GERHARD SCHUNK,^{1,2,3} DMITRY V. STREKALOV,¹ CHRISTOPH MARQUARDT,^{1,2} JOHANNES M. FINK,^{4,7} OSKAR PAINTER,⁴ GERT LEUCHS,^{1,2} AND HARALD G. L. SCHWEFEL^{8,*}

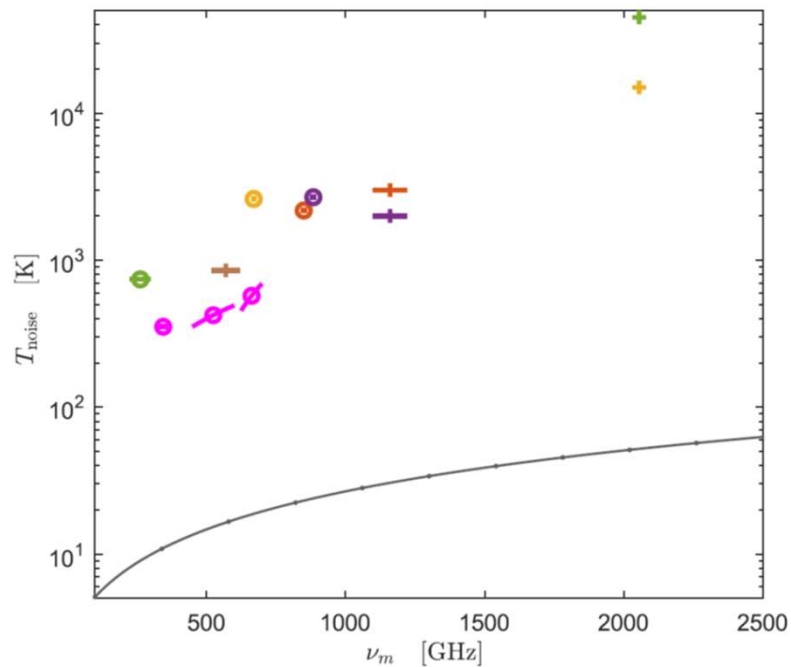
Sensitivity as a radiometer

Noise equivalent temperature uncertainty ΔT (normalized)

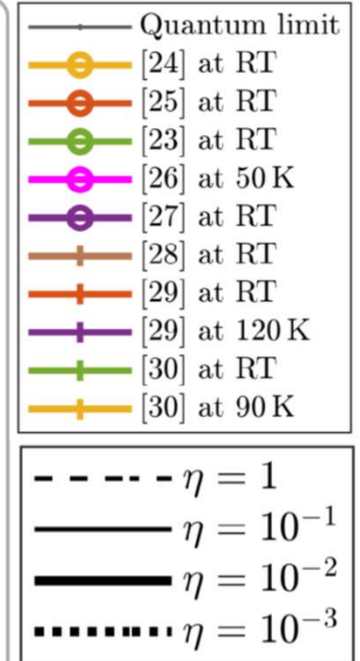
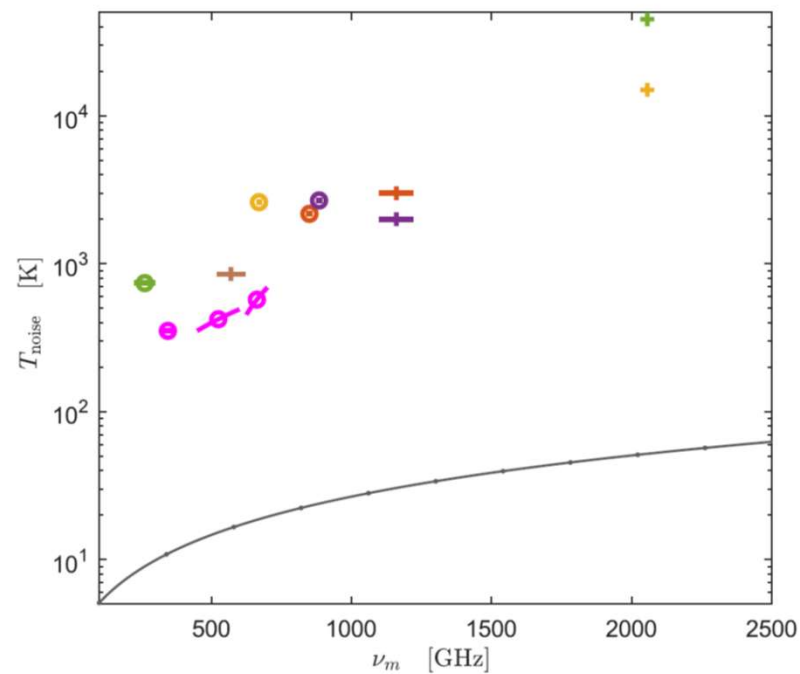


Sensitivity as a radiometer

Direct detection

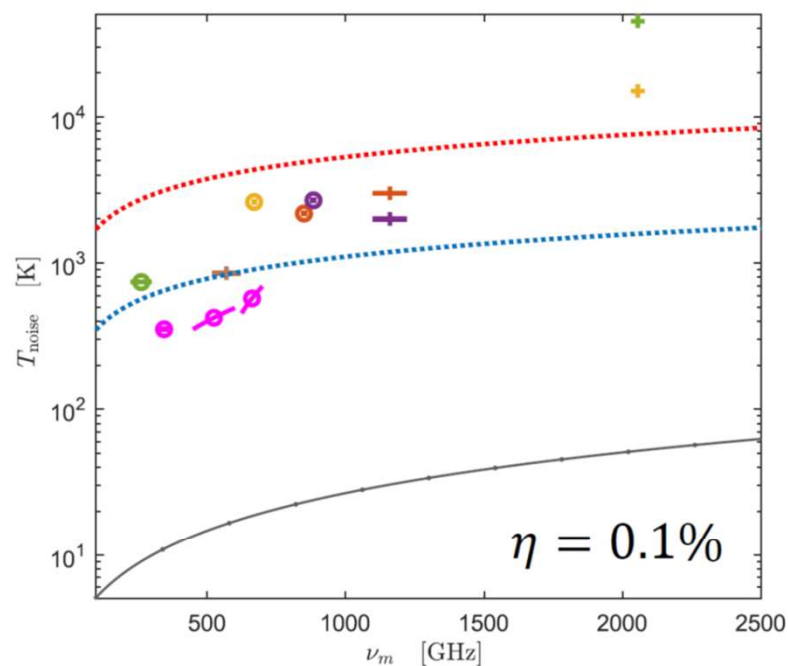


Heterodyne detection

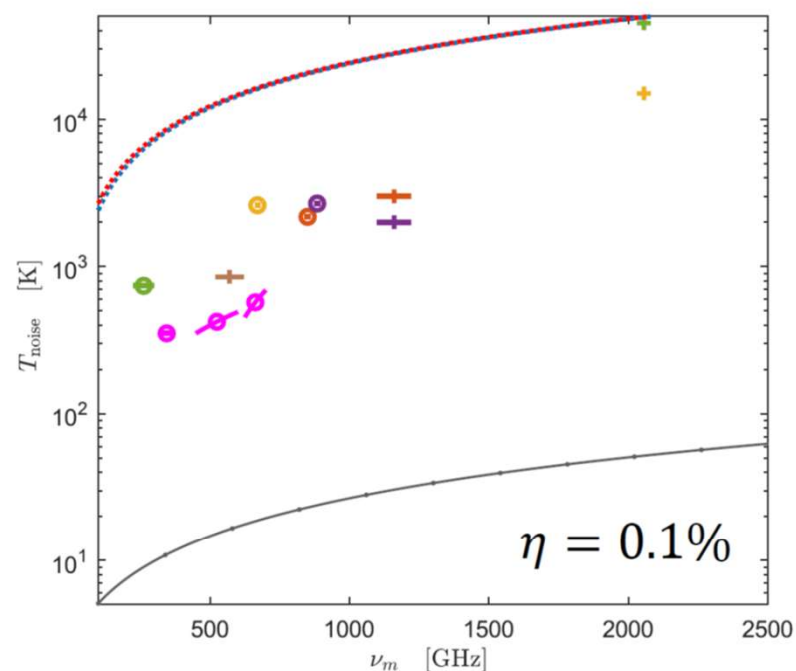


Sensitivity as a radiometer

Direct detection



Heterodyne detection



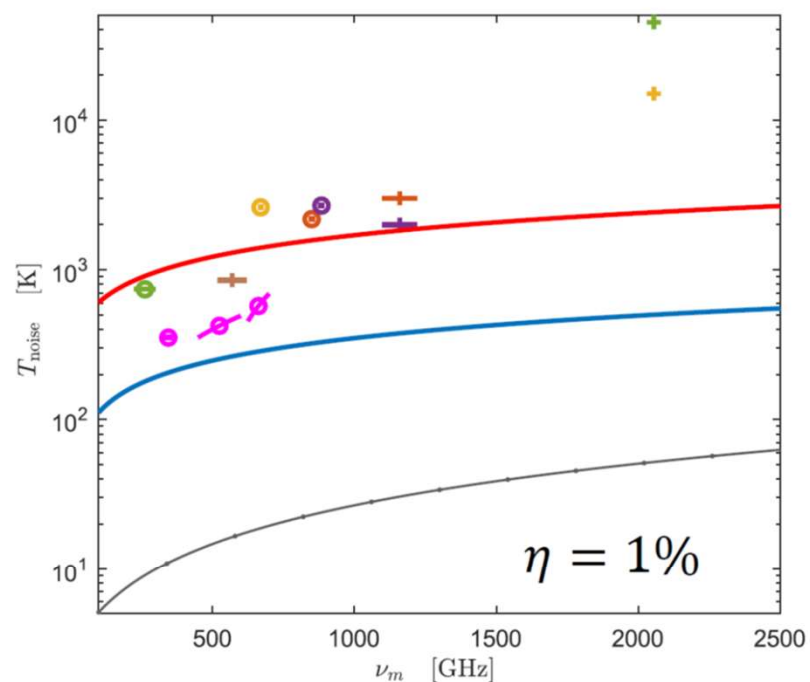
- Quantum limit
- [24] at RT
- [25] at RT
- [23] at RT
- [26] at 50 K
- [27] at RT
- × [28] at RT
- × [29] at RT
- × [29] at 120 K
- + [30] at RT
- + [30] at 90 K

- - - $\eta = 1$
- $\eta = 10^{-1}$
- $\eta = 10^{-2}$
- · · $\eta = 10^{-3}$

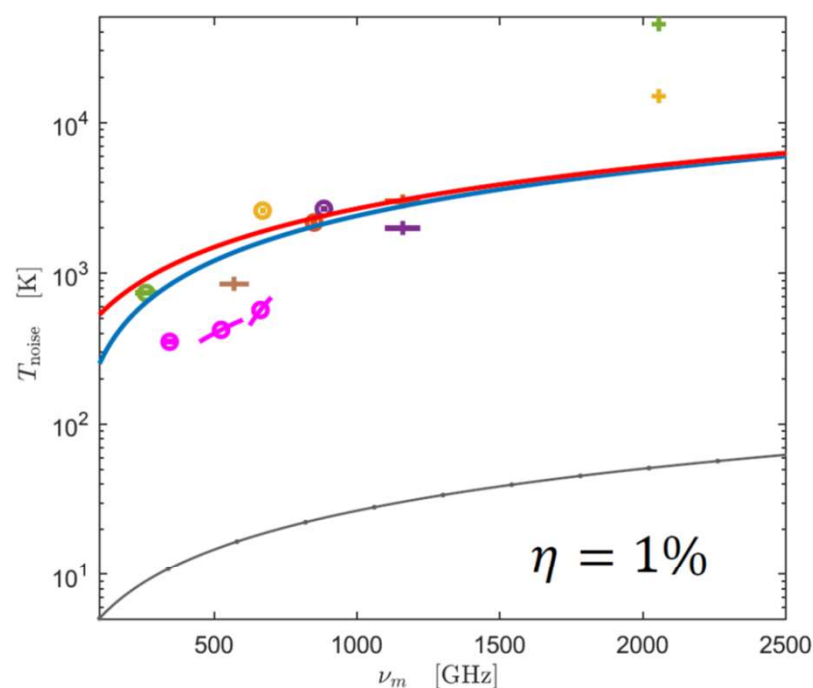
— $T_e = 10$ K ; $Q_{\text{THZ}} \gtrsim 1000$
 — $T_e = 290$ K ; $Q_{\text{THZ}} < 100$

Sensitivity as a radiometer

Direct detection



Heterodyne detection

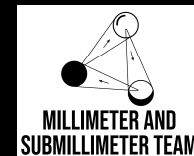


- Quantum limit
- [24] at RT
- [25] at RT
- [23] at RT
- [26] at 50 K
- [27] at RT
- [28] at RT
- [29] at RT
- [29] at 120 K
- [30] at RT
- [30] at 90 K

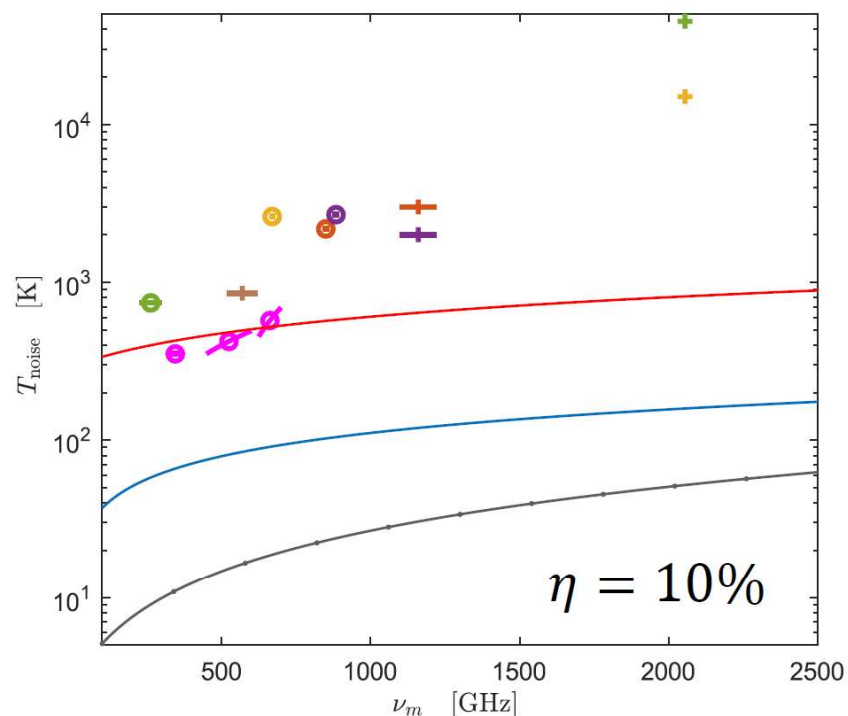
- $\eta = 1$
- $\eta = 10^{-1}$
- $\eta = 10^{-2}$
- $\eta = 10^{-3}$

$T_e = 10 \text{ K} ; Q_{\text{THZ}} \gtrsim 1000$
 $T_e = 290 \text{ K} ; Q_{\text{THZ}} < 100$

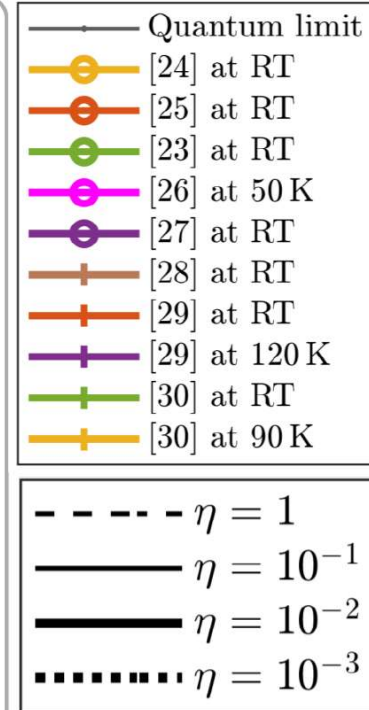
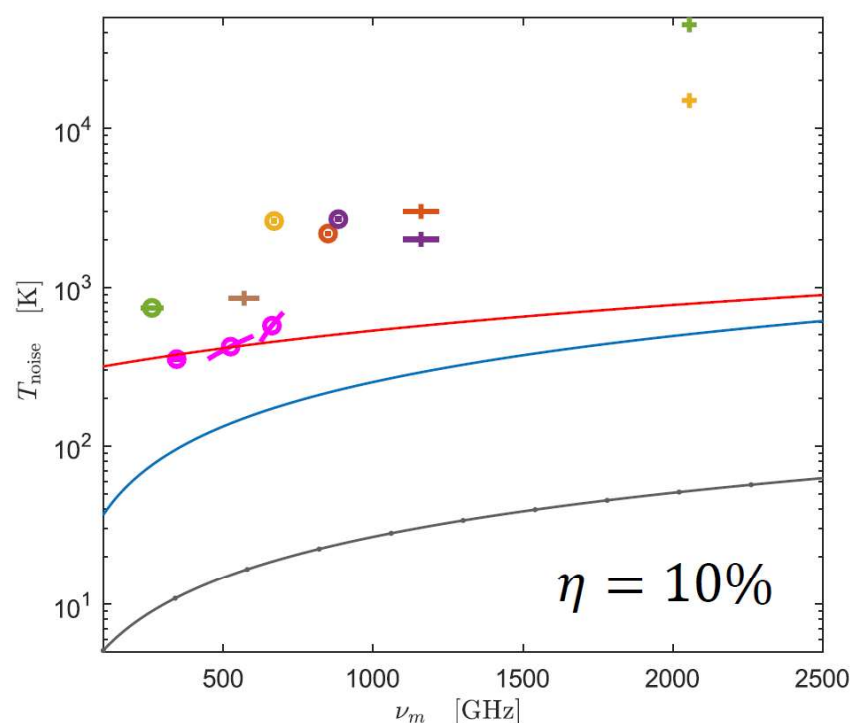
Sensitivity as a radiometer



Direct detection

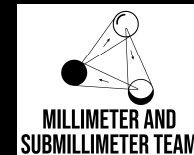


Heterodyne detection

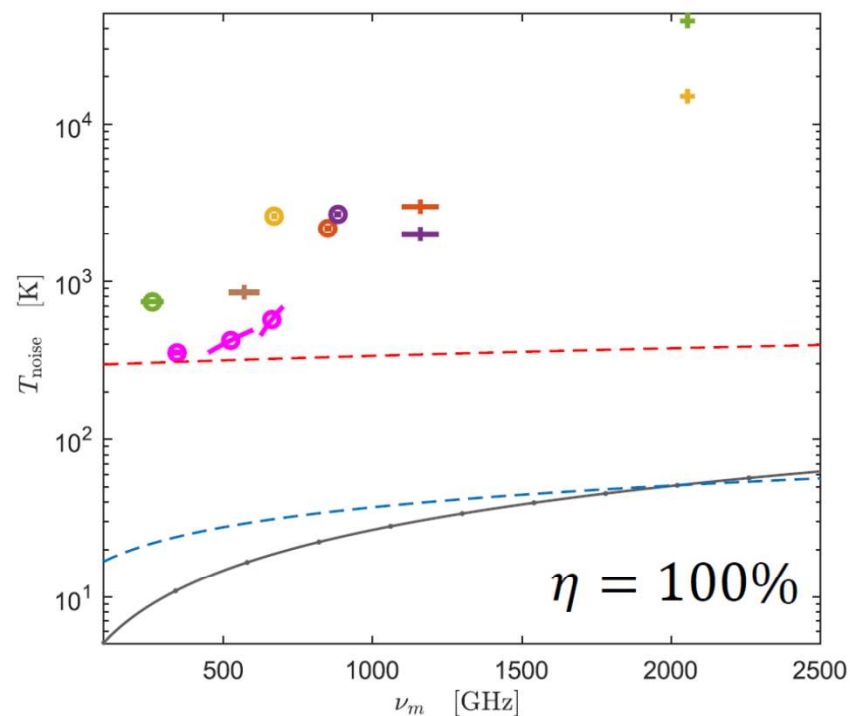


$T_e = 10 \text{ K} ; Q_{\text{THZ}} \gtrsim 1000$
 $T_e = 290 \text{ K} ; Q_{\text{THZ}} < 100$

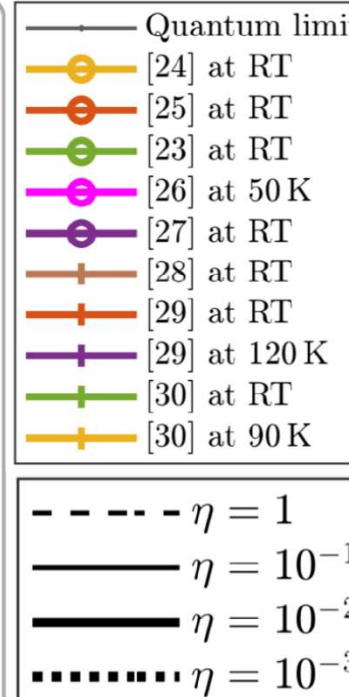
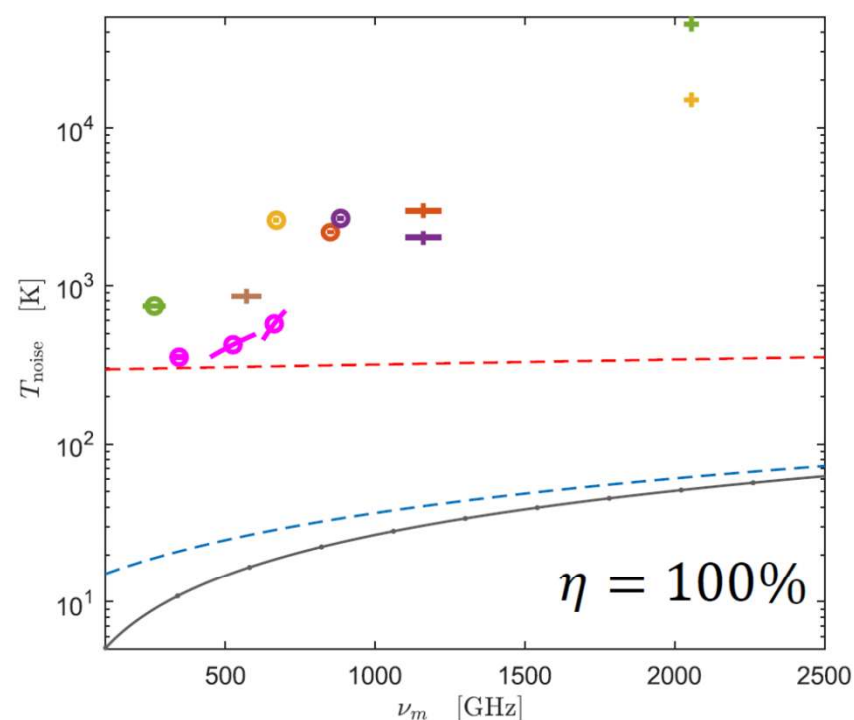
Sensitivity as a radiometer



Direct detection



Heterodyne detection

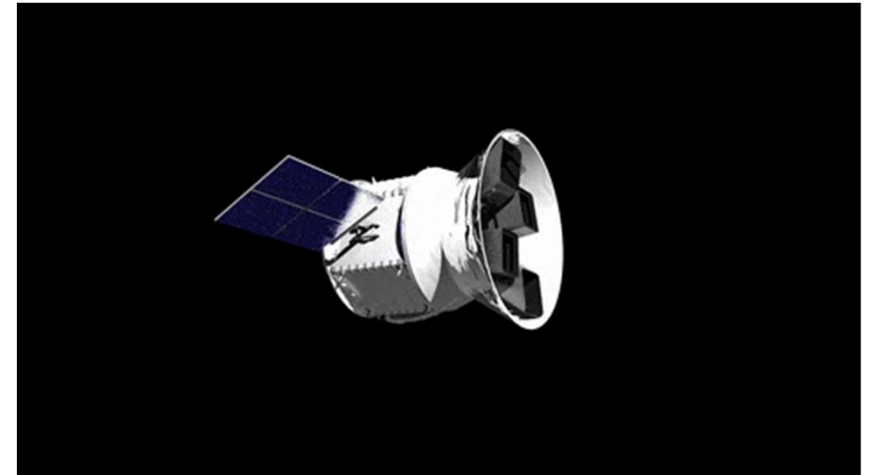


$T_e = 10 \text{ K} ; Q_{\text{THZ}} \gtrsim 1000$
 $T_e = 290 \text{ K} ; Q_{\text{THZ}} < 100$

MARTINLARA CUBESAT



Millimeter wave Array at Room Temperature for Instruments in LEO Altitude Radio Astronomy (MARTINLARA) desarrolla una misión espacial de demostración en órbita integrando en un nanosatélite tecnologías de uso espacial en radioastronomía, observación de la Tierra, fotónica espacial, y propulsión espacial eléctrica.



MARTINLARA CUBESAT



Millimeter wave **A**rray at **R**oom **T**emperature for
INstruments in **L**EO **A**ltitude **R**adio **A**stronomy
(MARTINLARA)

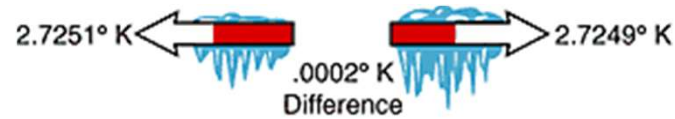
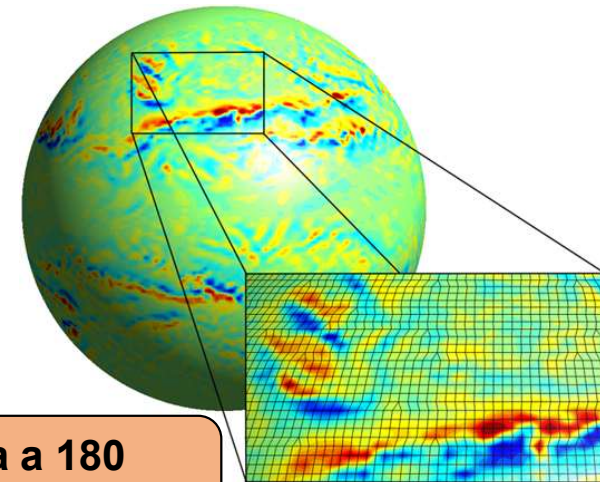
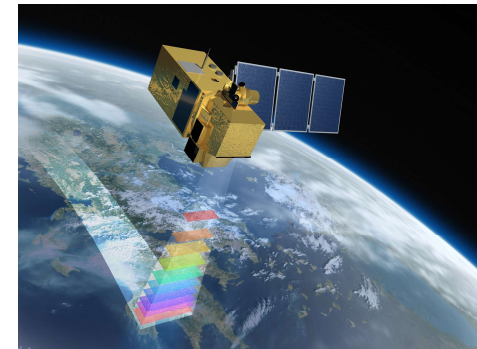


MARTINLARA CUBESAT

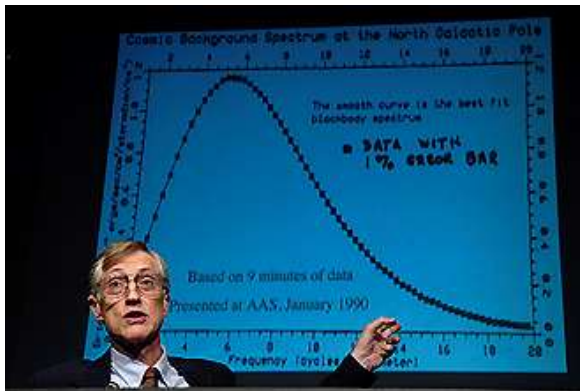
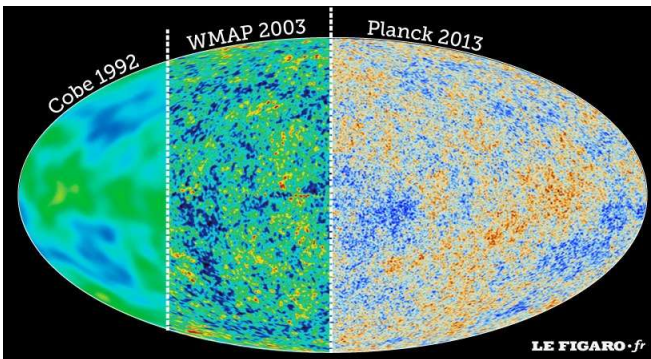
Anisotropías de CMB

CMB a 180, 200 y 250 GHz

“Numerical Weather Prediction”



Vapor de agua a 180
GHz



04/12/2025

Luis Enrique García Muñoz

119

Anisotropías de CMB

CMB a 150, 200 y 250 GHz

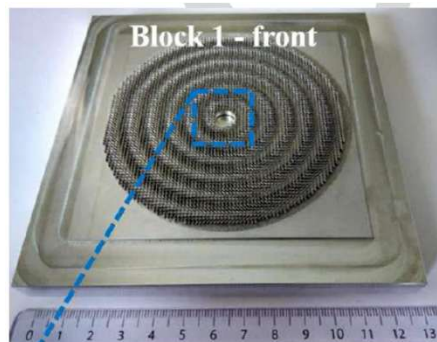
“Numerical Weather Prediction”

NWP a 150, 200 y 250 GHz

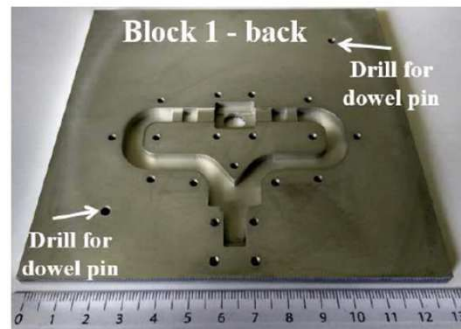
Eficiencia de apertura = 40%
Órbita = 800 km
Directividad = 38 dB
Apertura = $20 \cdot \lambda$
Cielo $\rightarrow 10^\circ$ ($3 \times 3^\circ$)
Tierra $\rightarrow 10^\circ$ (40x40 km de spot)

Diámetro_{150 GHz} = 8 cm
Diámetro_{200 GHz} = 6 cm
Diámetro_{250 GHz} = 4,8 cm

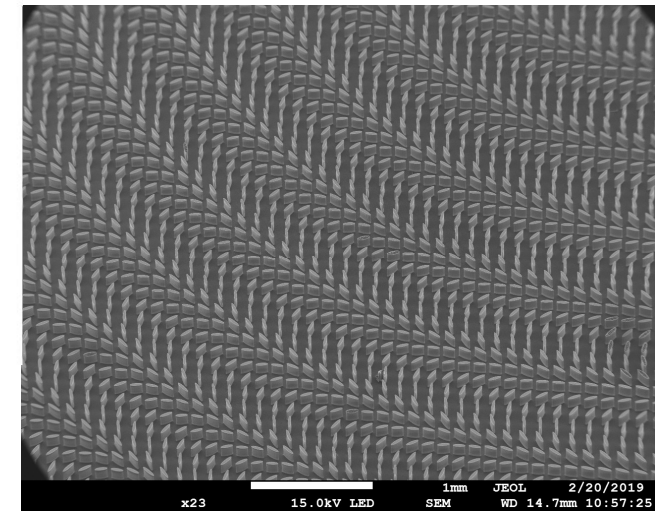
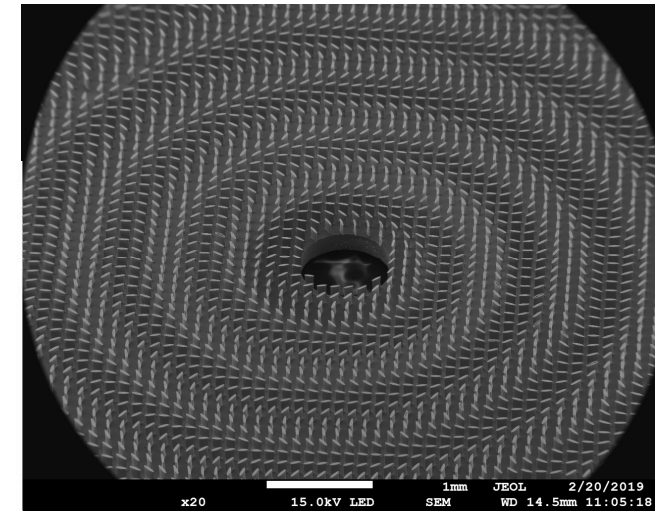
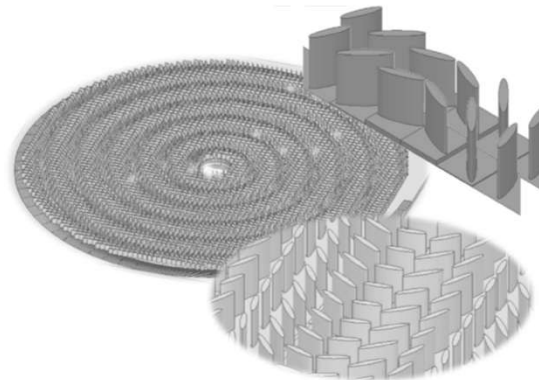
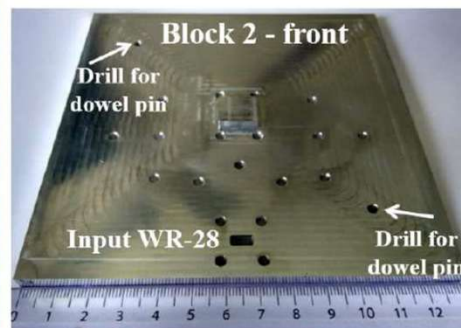
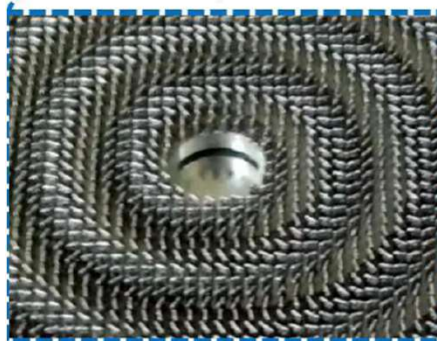
Antenas



a)

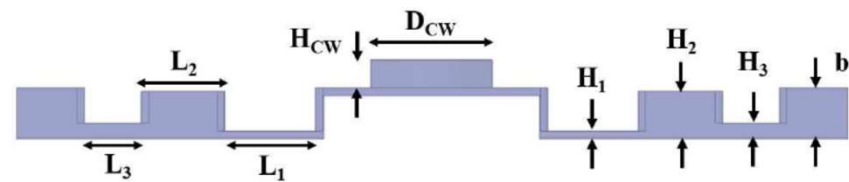
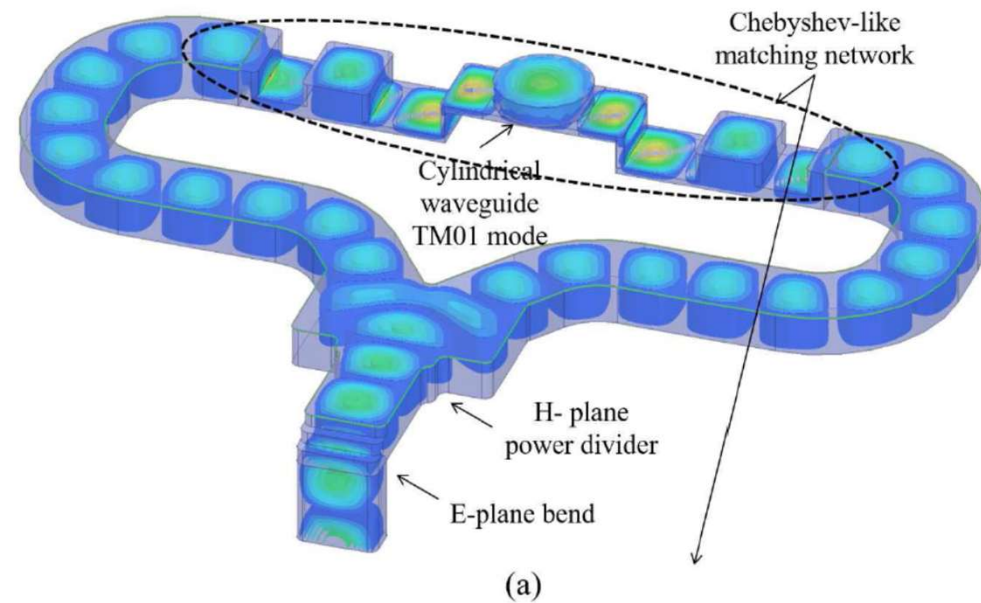
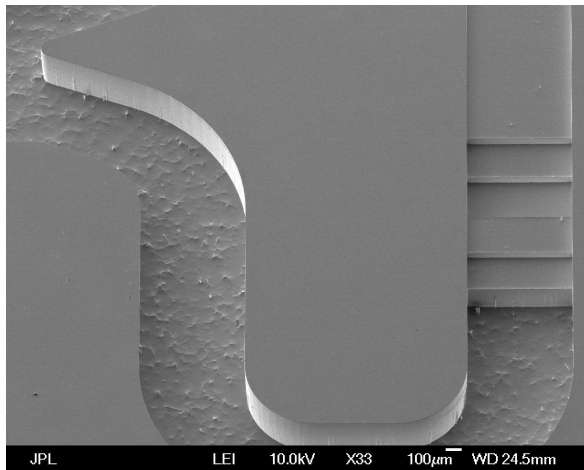
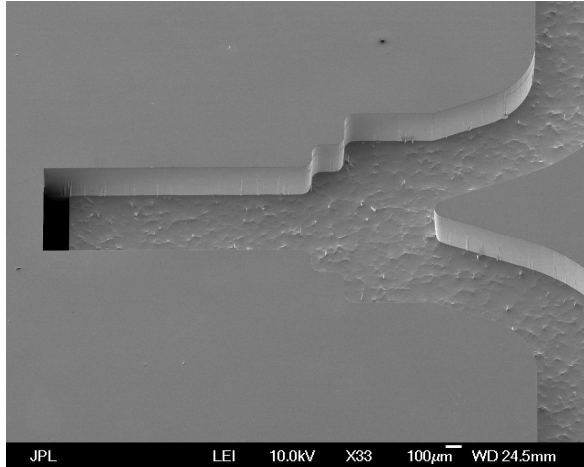


b)



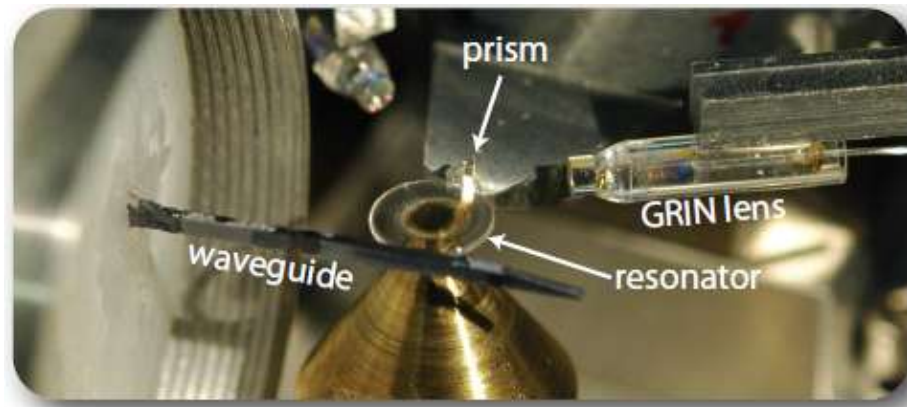
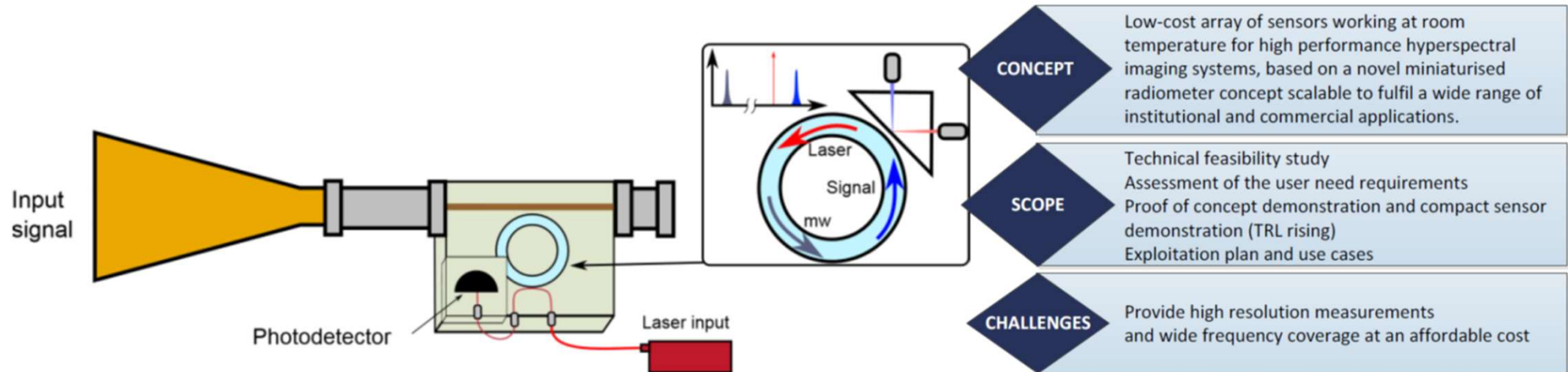
04/12/2025

Antenas



04/12/2025

Radiómetros



Cada radiómetro (sin guía de onda ni antena):

Caja de aluminio de 3 mm de espesor

Peso: 500 g

Volumen: 150 x 80 x 30 mm

Consumo: 10 W

Motivación

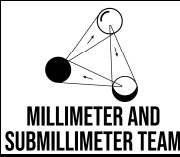
Electro optic up-converter

Experiment

Sensitivity as radiometer

Conclusions

Conclusiones



Currently the experiment is limited by shot noise.

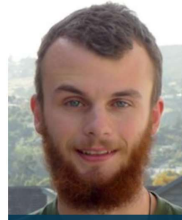
Optimized geometries and structures have to be designed to reduce thermal noise and increase efficiency.

For intrinsic (unloaded) microwave $Q \approx 1500$ and $\eta \approx 10\%$, the sensitivity would be 10 times above the quantum limit at room temperature.

The same concept can be extended to the sub-millimeter range by just scaling the resonator's geometry.

The conversion bandwidth is not fundamentally limited. We are seeking for other ideas and approaches to achieve broadband up-conversion.

Conclusiones: el equipo de trabajo



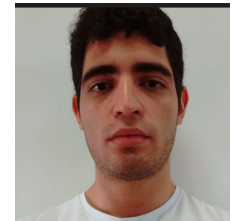
University of Colorado
Boulder



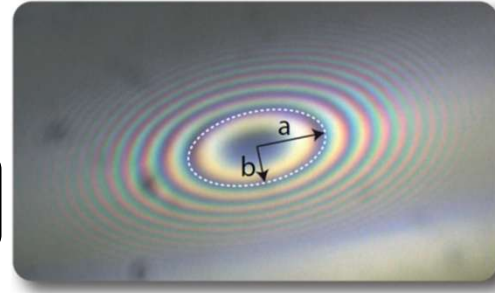
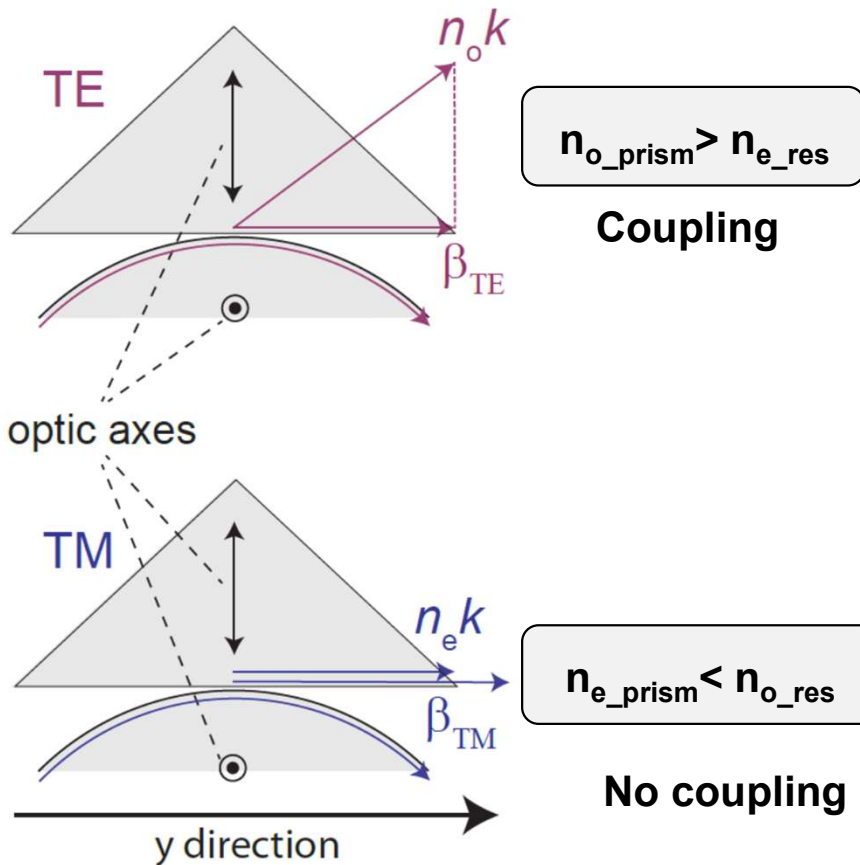
Maynooth University
National University
of Ireland Maynooth



uc3m | **Universidad Carlos III de Madrid**

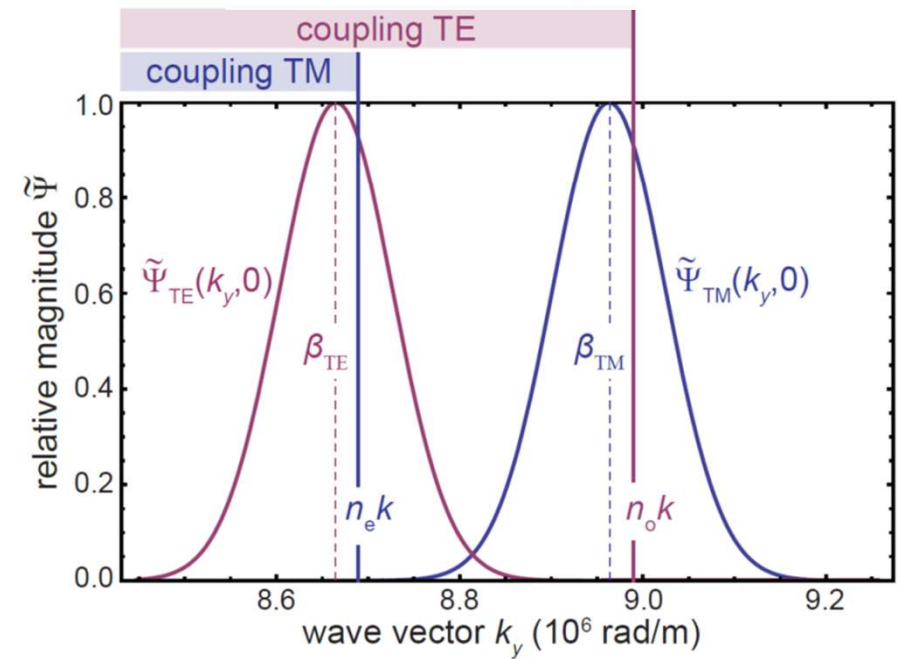


Electro-optic up-converter: increasing bandwidth

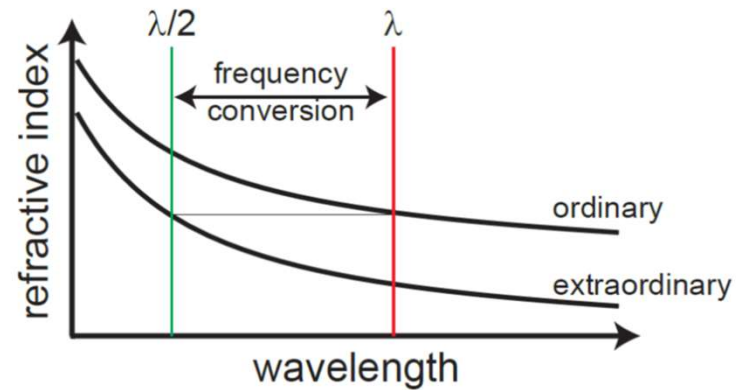


$$\Psi^P(x_p, y, z) \propto \Psi^F(x, y, z) \Big|_{\rho=r} \times \exp \left[-\kappa \left(d + \frac{z^2}{2r} + \frac{y^2}{2R} \right) \right]$$

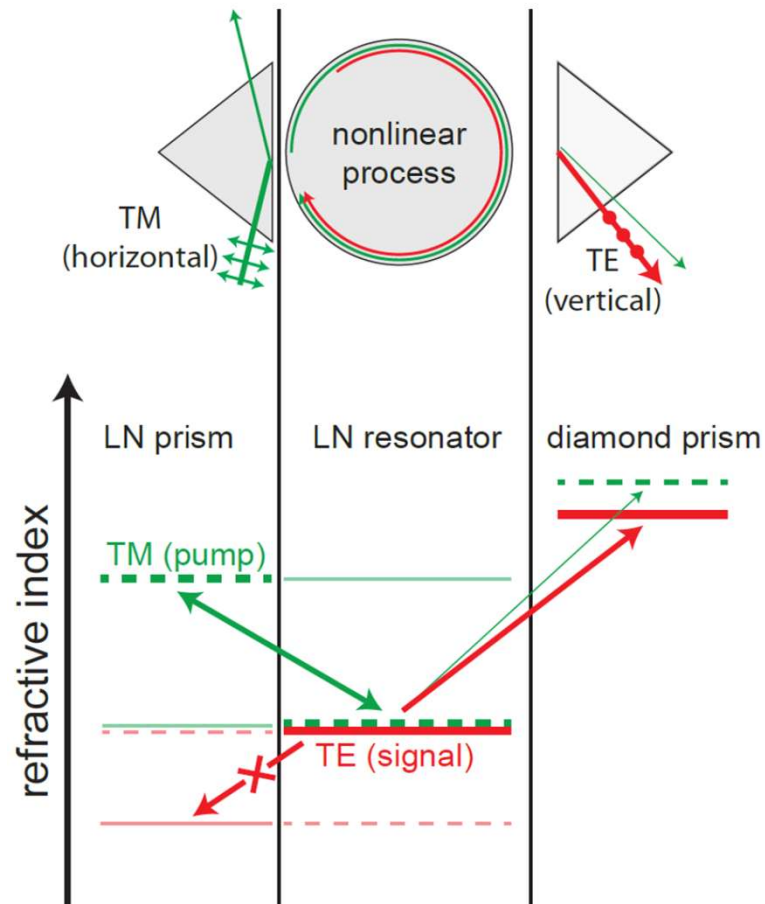
$$|\tilde{\Psi}^P(k_y, k_z)|^2 \propto \exp \left[-\Delta y^2 (k_y - \beta)^2 - \Delta z^2 k_z^2 \right]$$



Electro-optic up-converter: increasing bandwidth



- dashed line: TM polarized
- straight line: TE polarized
- green: pump light
- red: signal light



Second harmonic generation (SHG)