Flavor and Origin of Matter

Sabor y Origen de la Materia

elusives
neutrinos, dark matter & dark energy physics
invisiblesPlus
neutrinos, dark matter & dark energy physics

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

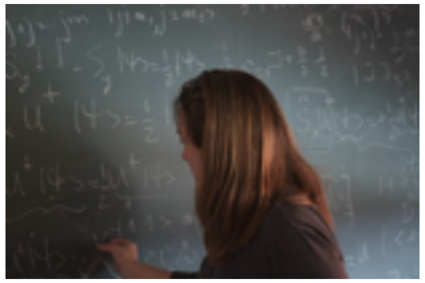
VNIVERSITAT DE VALÈNCIA

EXCELENCIA
SEVERO
OCHOA

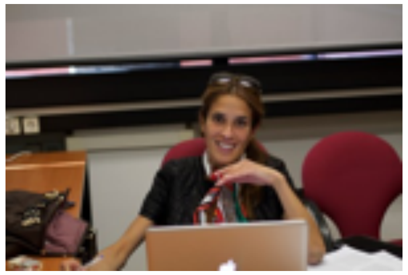
¿QUIENES SOMOS?

Jose Vicente Carrión

Andrea Donini



Pilar Hernández



Olga Mena

Nuria Rius

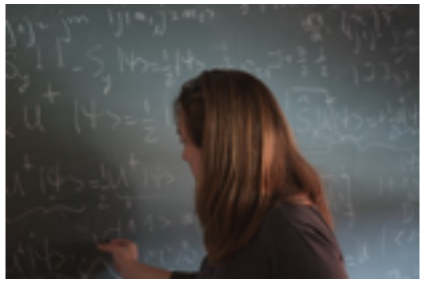
Carlos Peña-Garay

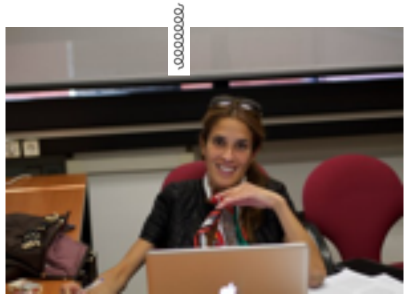
Roberto Ruiz de Austri

¿QUIENES  OS?

Experimento NEXT en el LSC

ANTARES y KM3NeT (ARCA y ORCA)





Detector interno/Física
ATLAS y MoEDAL

Astropartículas y física de altas energías

Partículas elementales: Modelo Estándar y sus extensiones

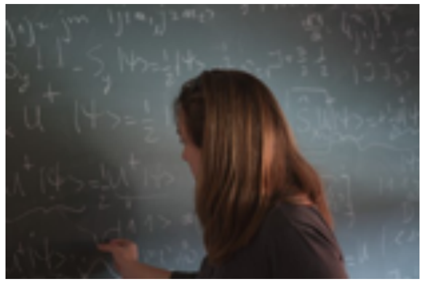
¿QUIENES SOMOS?

Jose Vicente Carrión

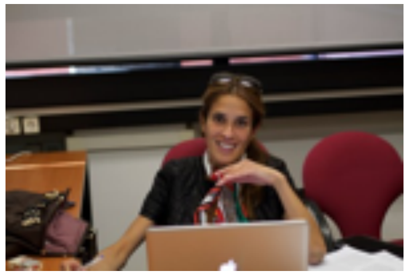
Olga Mena

Nuria Rius

Andrea Donini



Pilar Hernández



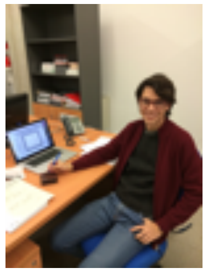
Roberto Ruiz de Austri

Carlos Peña-Garay

Hayato Motohashi

Jordi Salvadó

Marija Kekic



Héctor Ramírez

Miguel Escudero

Jose Manuel Martí

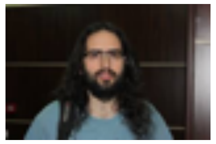
Santiago González-Miramón

Andrea Caputo

Pablo Villanueva

Miguel García Folgado

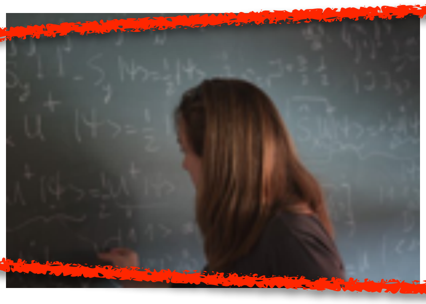
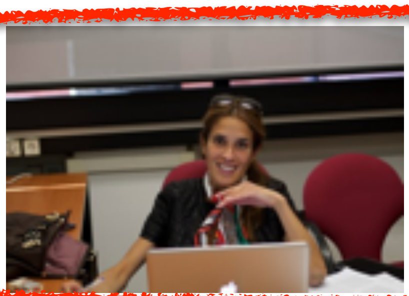
Partículas elementales: Modelo Estándar y sus extensiones (S. Palomares-Ruiz)



¿QUIENES SOMOS?

6 senior

01/12/2018
RyC extension S8A


PhD en Dic'16

Invisibles +
PROMETEO

09/10/2018

SOM FPA

2 postdocs

Elusives

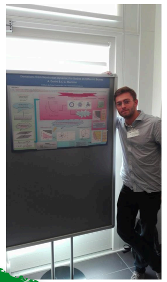
+1 Sept'17

15/01/2019
FPI SOM FPA

16/12/2018
FPU MECD

7 PhD

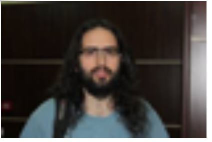
28/02/2017
FPI SOM FPA



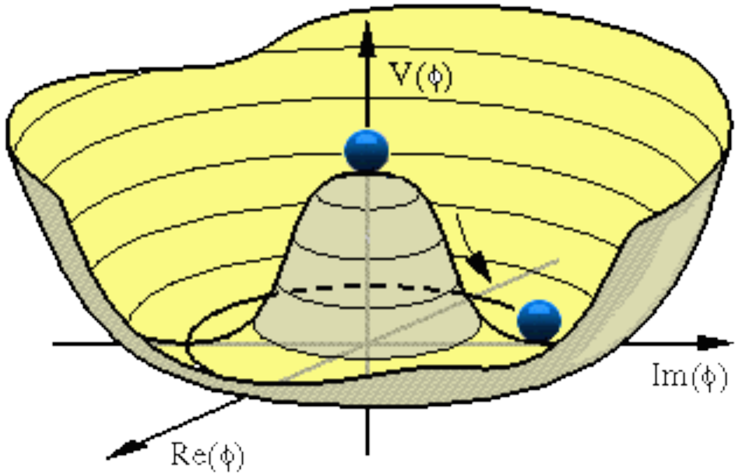
21/09/2019
Elusives

FPI S8A

Prometeo

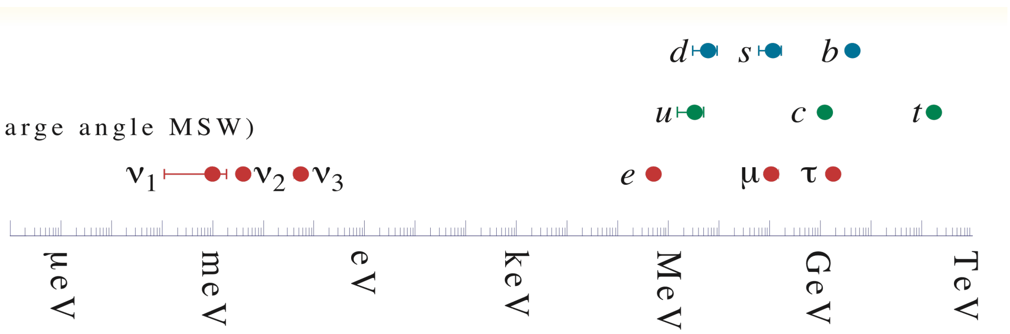


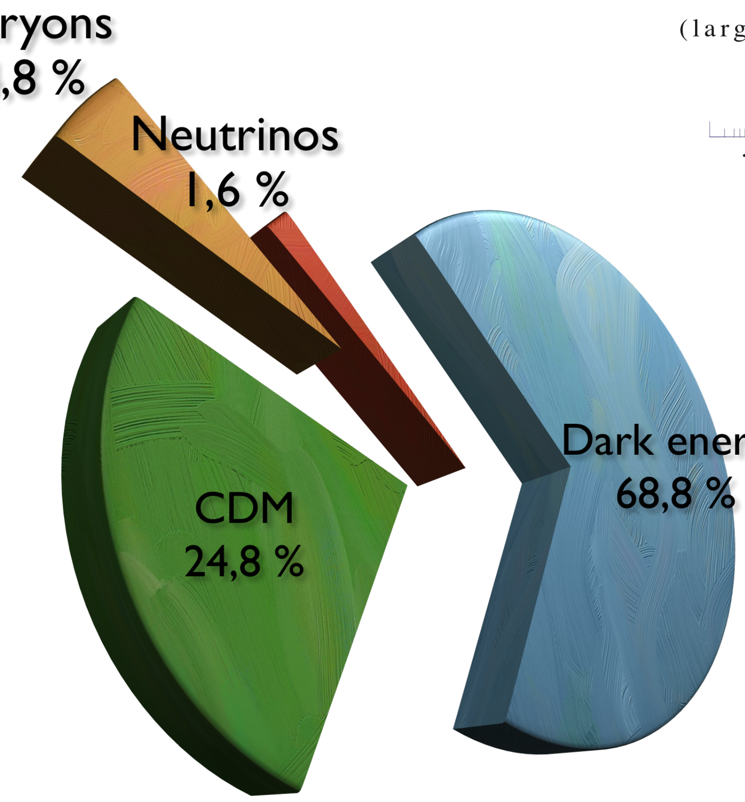
Nuestra motivación principal: entender origen de la materia y su sabor



CRUCIAL: ¡Entender vacío de la teoría!

Puzzle del sabor





Problema de la jerarquía:
Física del Higgs

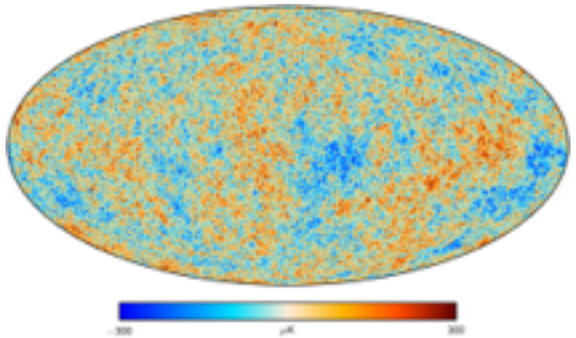
Origen Materia:
Bariogénesis/Leptogénesis

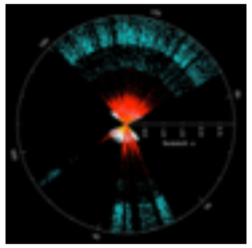
Energía del vacío
¿Constante cosmológica o energía oscura?

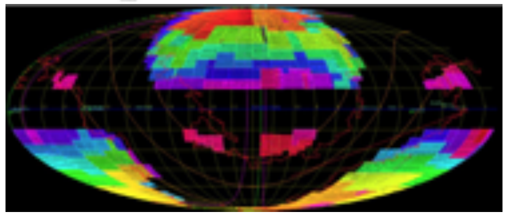
¿Materia oscura?

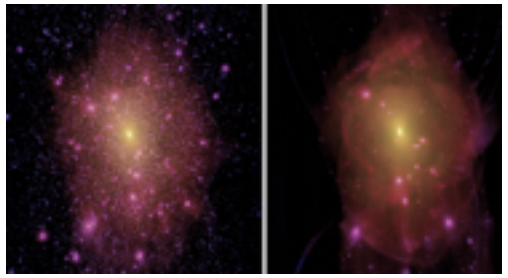
Origen estructuras: Inflación

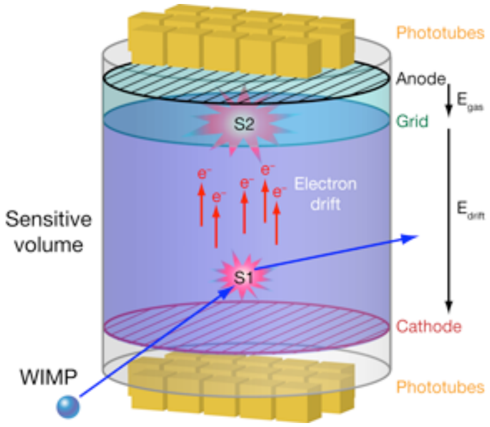
Estrategias: maximizar sinergias!

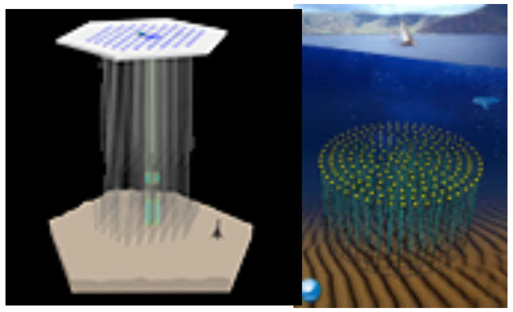


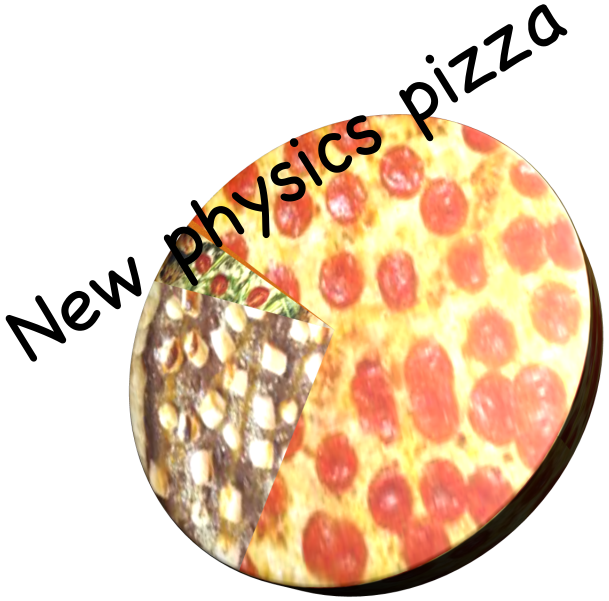


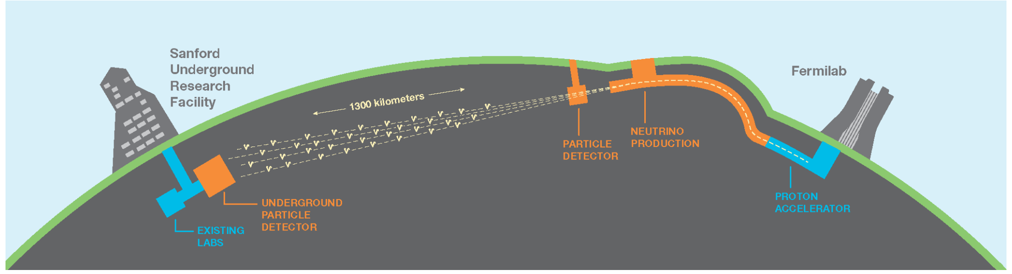


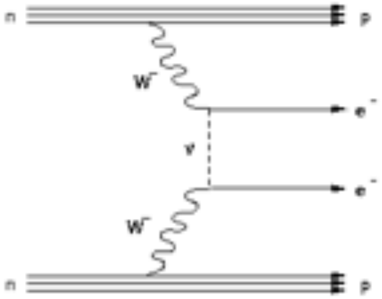


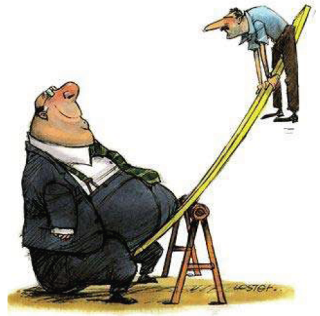




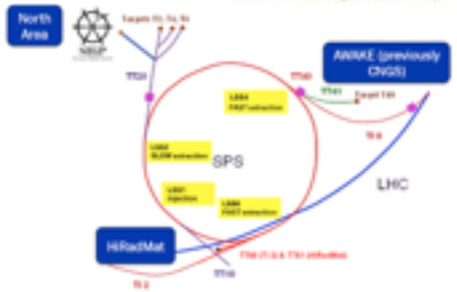


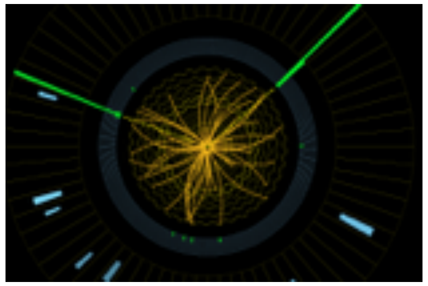






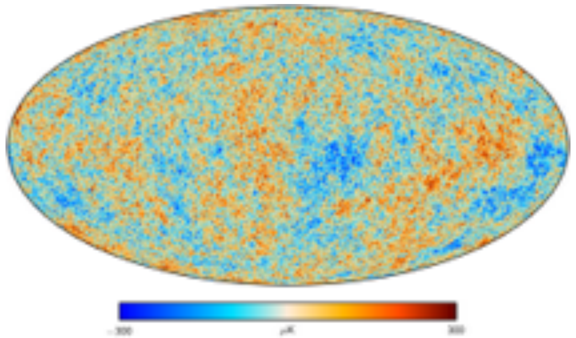
SHiP
Search for Hidden Particles

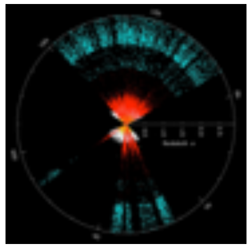


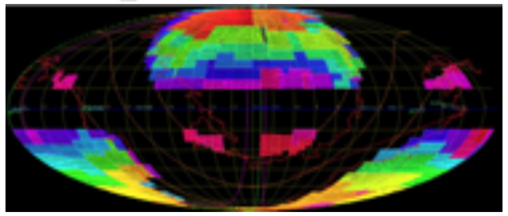


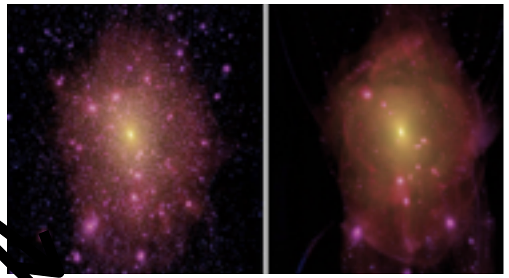
Estrategias: ¡maximizar sinergias!

masa ν's

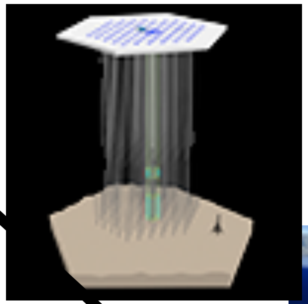


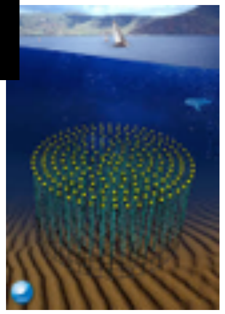


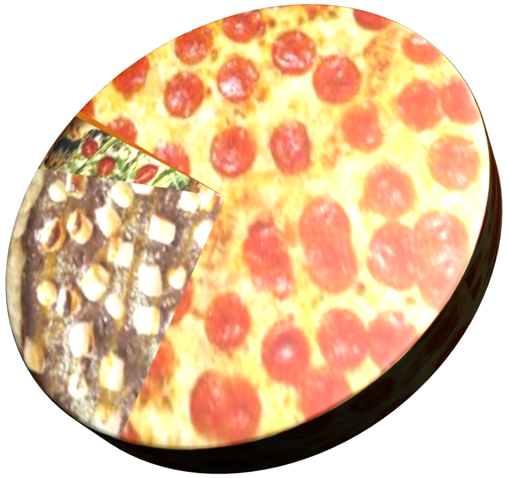


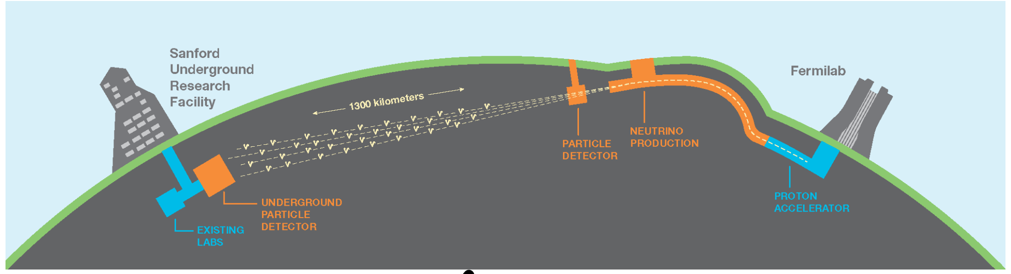


ν's



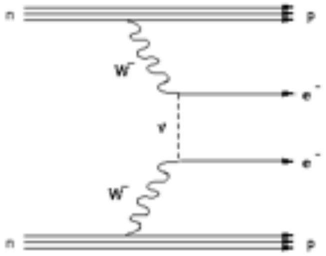


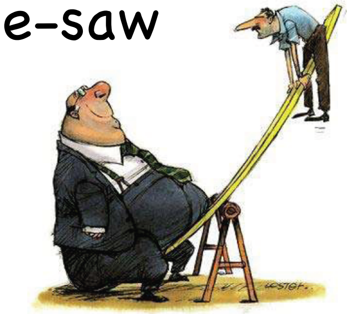




Lepto-Bario

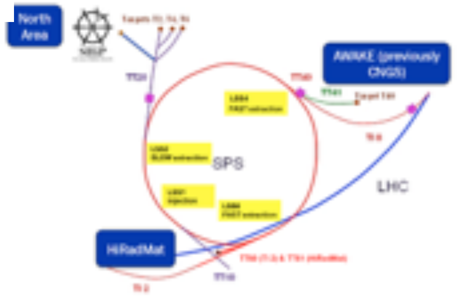
see-saw

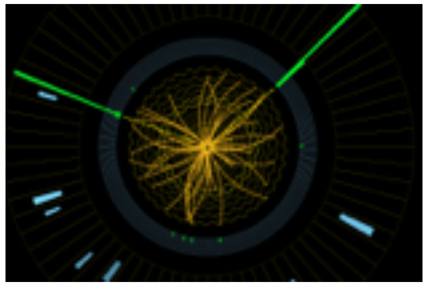




SHiP

Search for Hidden Particles

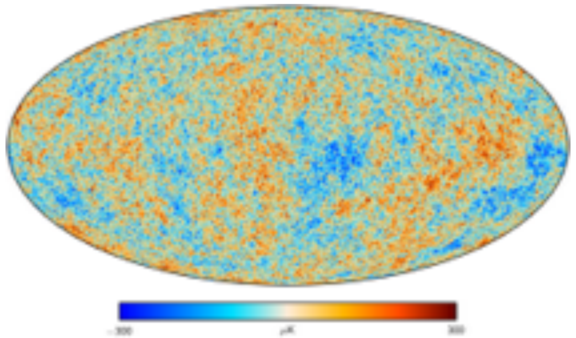


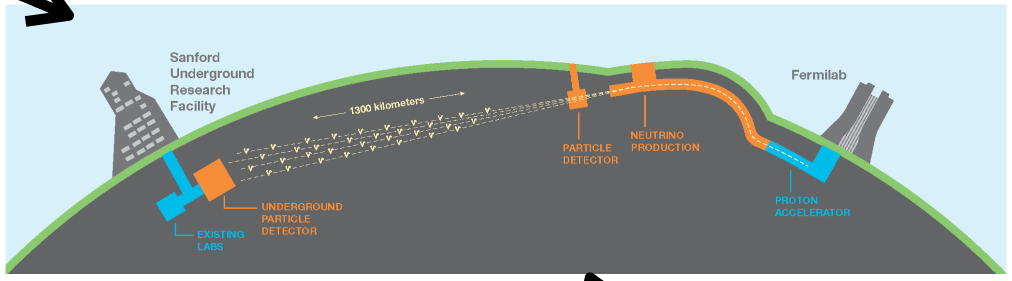


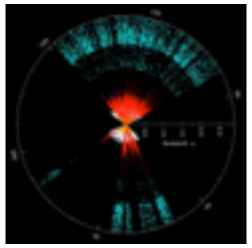
Heavy ν's

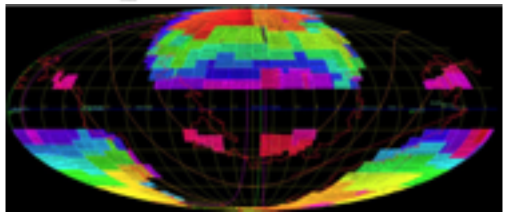
Estrategias: ¡maximizar sinergias!

ν's materia oscura caliente

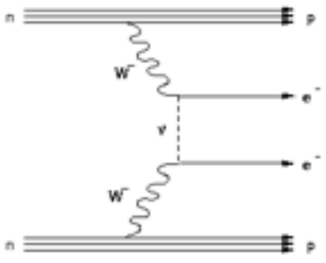


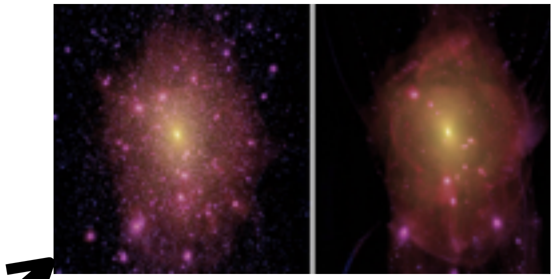




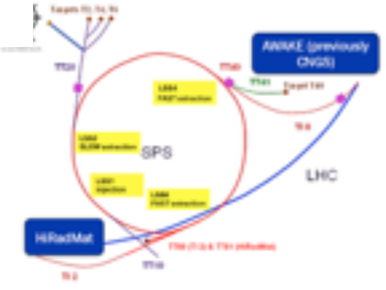


Lepto-Bario
see-saw





LSS



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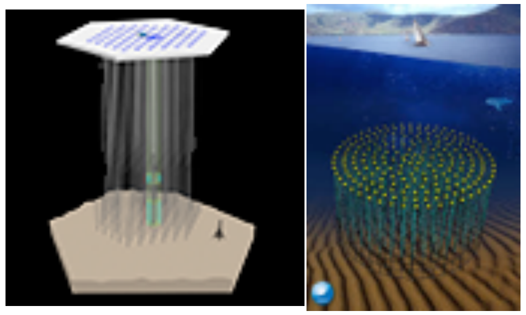
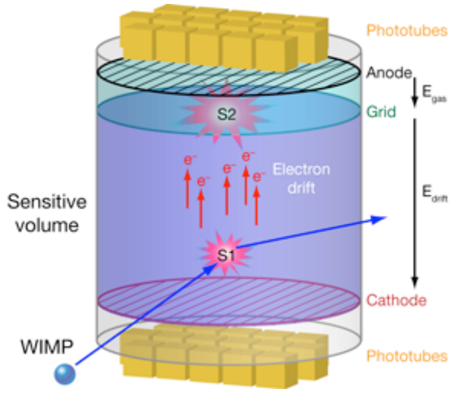
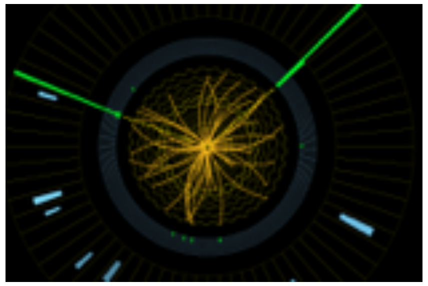


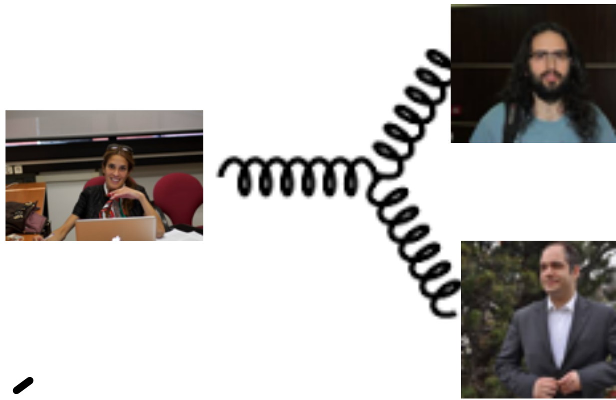
Heavy ν's Materia oscura



Materia oscura



¿QUÉ HACE ?

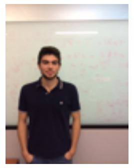


Cosmología: Energía & Materia oscura e Inflación

Energía oscura: expansión acelerada del universo (SNIa, CMB, LSS).

¿ Desviaciones de Relatividad General?
¿Si es una constante cosmológica, como se explica el enorme "fine-tuning"?

Cualquiera de ellas requiere **NUEVA FÍSICA**



Materia oscura: (Curvas rotación galaxias, LSS, Galaxy Clusters, CMB).
¿WIMPS, SUSY, axiones, **neutrinos, sterile neutrinos**, dimensiones extra (LKPs, ….?)

Cualquiera de ellas también requiere **NUEVA FÍSICA**

Inflación: (Universo plano, Generación de perturbaciones primordiales).
Slow-roll: nuevo campo escalar.
"Axion-monodromy", "multi-field", "non standard gravity", "non-canonical kinetic terms"

NUEVA FÍSICA^3

¿QUÉ HACE  ?

Sinergia cosmología-neutrinos:

Situación actual y

logros científicos más relevantes:

Pioneros en el campo en el cálculo de cotas a neutrinos, axiones y otras partículas de materia oscura caliente (+1000 citas)

CIENCIA ›

La masa del neutrino, ni una millonésima de electrón

El CSIC mide las partículas, que suponen menos del 0,6% de la masa-energía del cosmos

EL PAÍS

Madrid - 12 ENE 2012 - 07:05 EST

Distribución de galaxias luminosas realizada por SDSS-III. /DAVID KIRBY

La masa de los neutrinos no excede de 0,26 electronvoltios, dos millones de veces inferior a la masa del electrón, según un grupo de investigadores del Consejo Superior de Investigaciones Científicas (CSIC). El equipo sostiene que la suma de las masas de los tres tipos de neutrinos que existen (electrónicos, muónicos y tauónicos) no representa más del 6 por mil del total de la masa-energía del cosmos, según informó el organismo español.

El análisis se basa en datos obtenidos de una selección de 900.000 galaxias luminosas, utilizadas para estudiar la distribución espacial de galaxias, y los resultados se presentan en la reunión anual de la Sociedad Astronómica Americana, que se celebra hasta el 12 de enero en Austin (Texas).

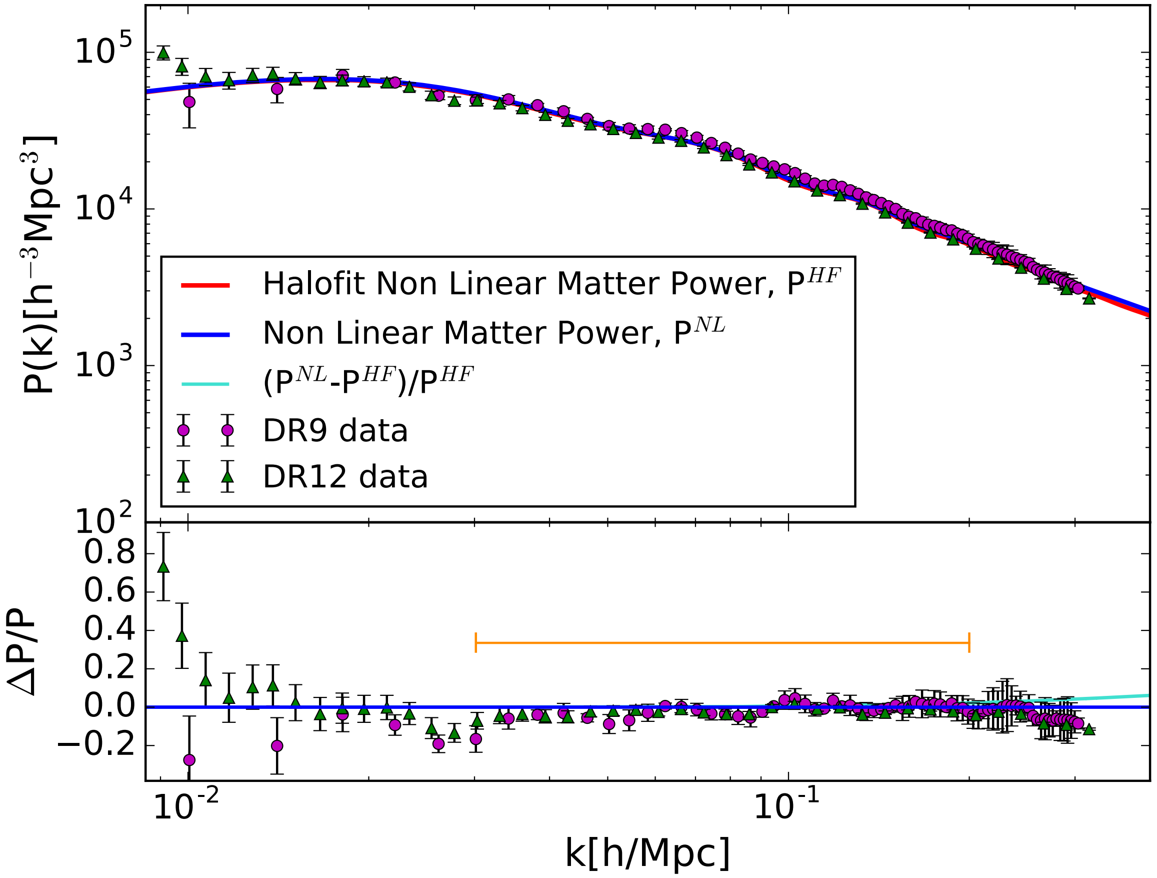
¿QUÉ HACE  ?

Sinergia cosmología-neutrinos:

Situación actual y

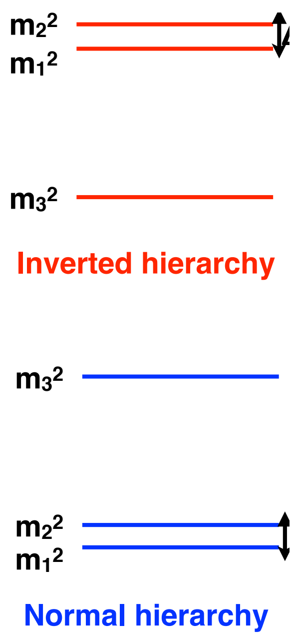
logros científicos más relevantes:

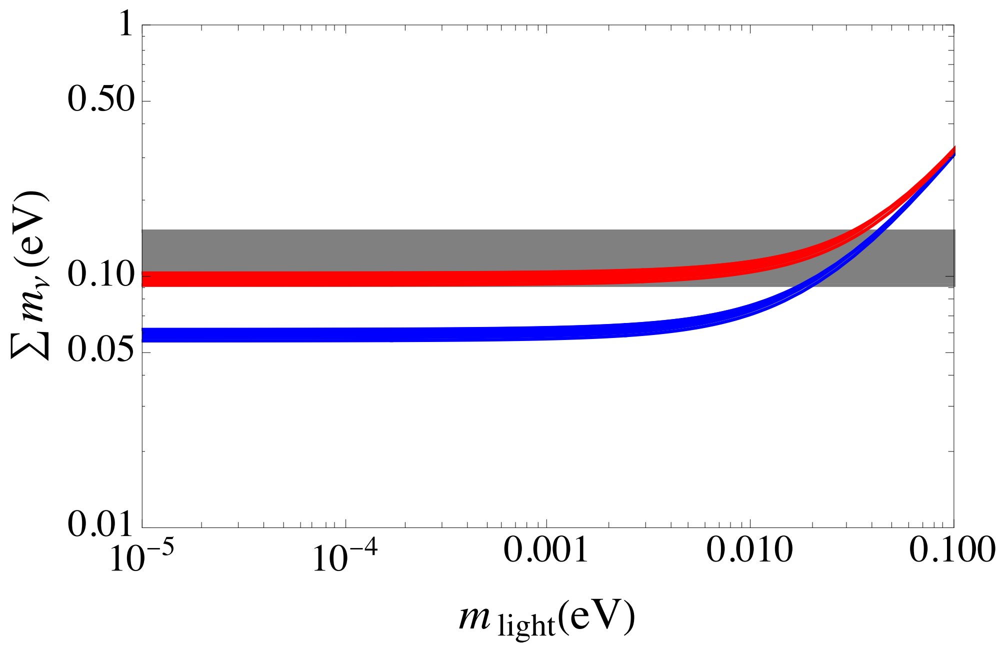
Pioneros en el campo en el cálculo de cotas a neutrinos, axiones y otras partículas de materia oscura caliente (+1000 citas)



$basepolBAO \equiv PlanckTT+lowP+highP+BAOFULL$	< 0.153 eV	81%
$basepolBAO+\tau0p055$	< 0.118 eV	91%
$basepolBAO+H073p02$	< 0.113 eV	92%
$basepolBAO+H073p02+\tau0p055$	< 0.094 eV	96%
$basepolBAO+H073p02+\tau0p055+SZ$	< 0.093 eV	96%

Vagnozzi et al'17



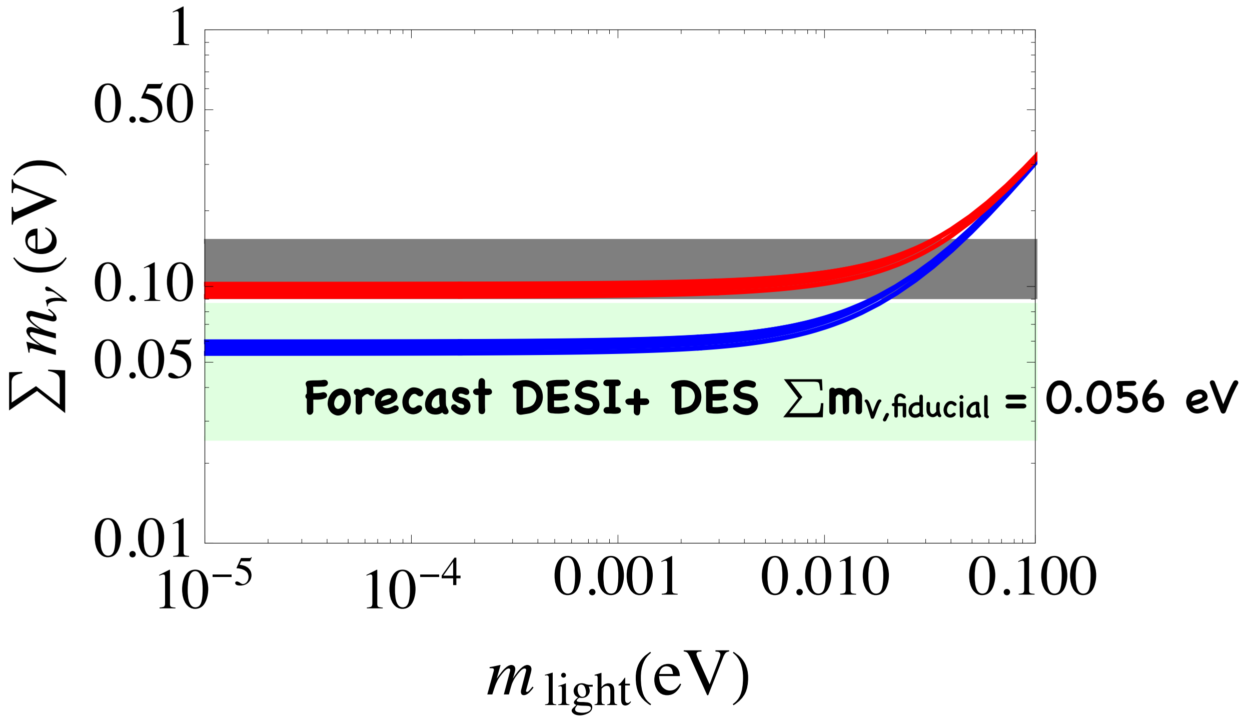


¿QUÉ HAREMOS? (I)

Miembros de BOSS (SDSS III) & SKA

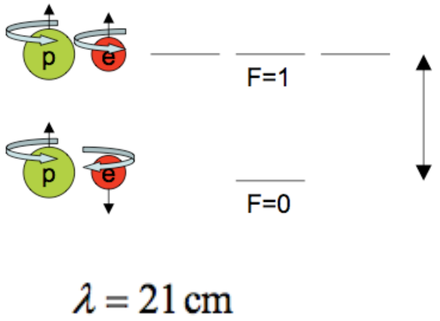
3.3-3.7σ Minimum neutrino mass.

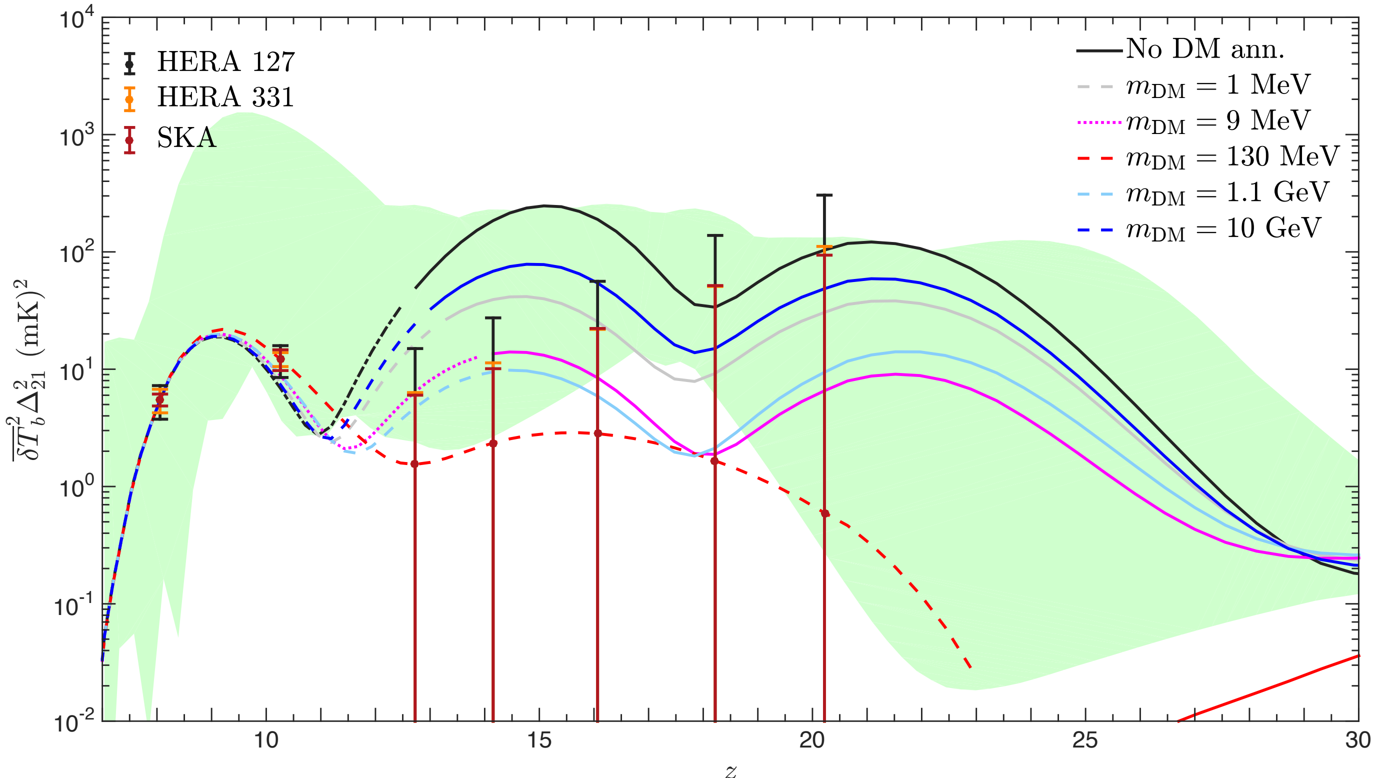
2.6-3.0σ Neutrino mass ordering extraction



Forecast DESI+ DES $\sum m_{\nu,\rm fiducial}$ = 0.056 eV

Cosmología 21 cm (SKA):





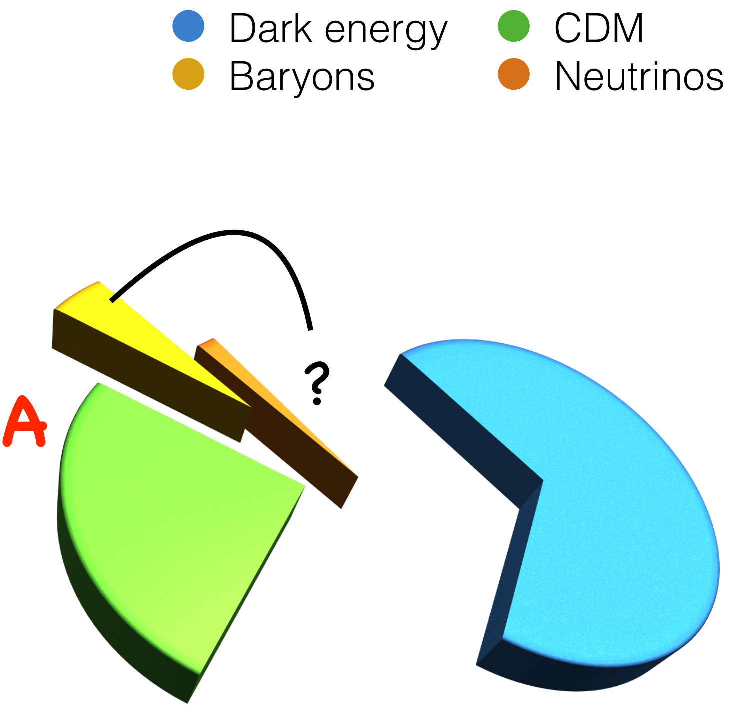
ás abundante del IGM

; de reionización!

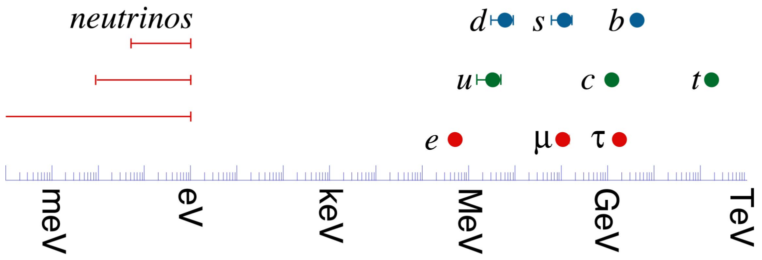
Lopez et al, JCAP'16

¿QUÉ HACE ?

Sinergia cosmología-neutrinos:

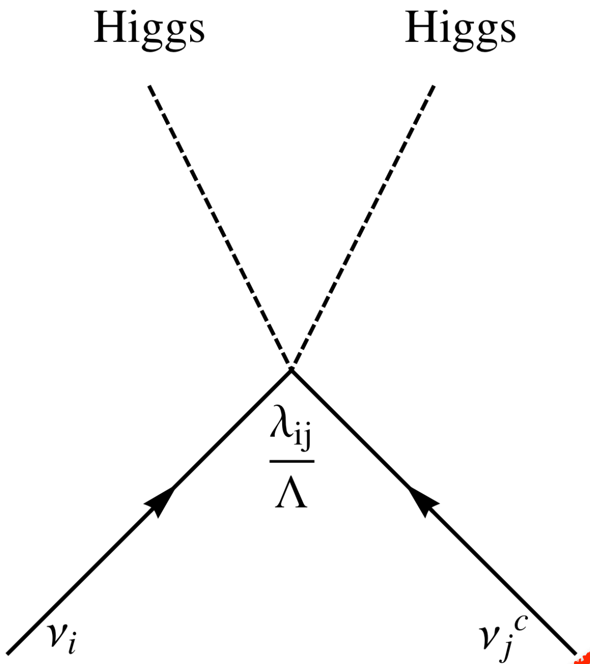


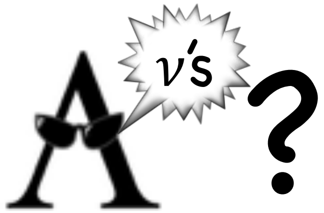
Neutrinos masivos: una nueva perspectiva en el puzzle del sabor

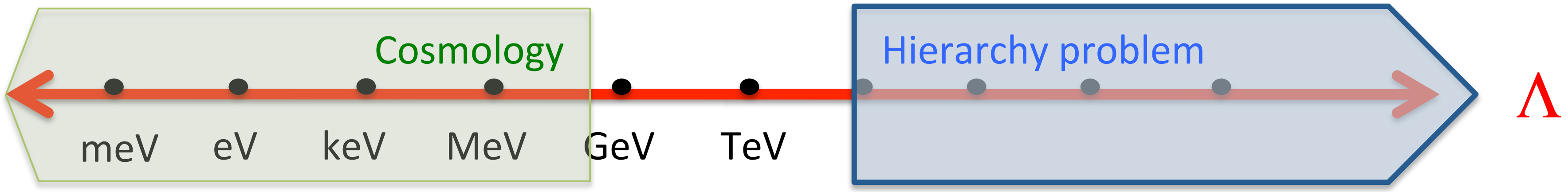


¡MAYOR EVIDENCIA NUEVA FÍSICA EN FÍSICA DE PARTÍCULAS!

FERMI-era via a *Weinberg operator*:







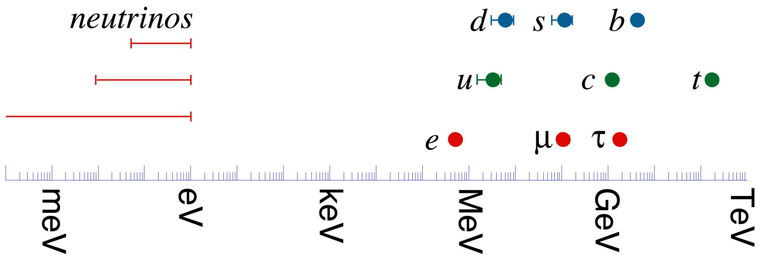
Logros científicos más relevantes:

Hemos encontrado cotas muy fuertes de cosmología a modelos de see-saw con Λ < 100 MeV P. Hernández *et al*, *PRD89'14*, *PRD90'14*

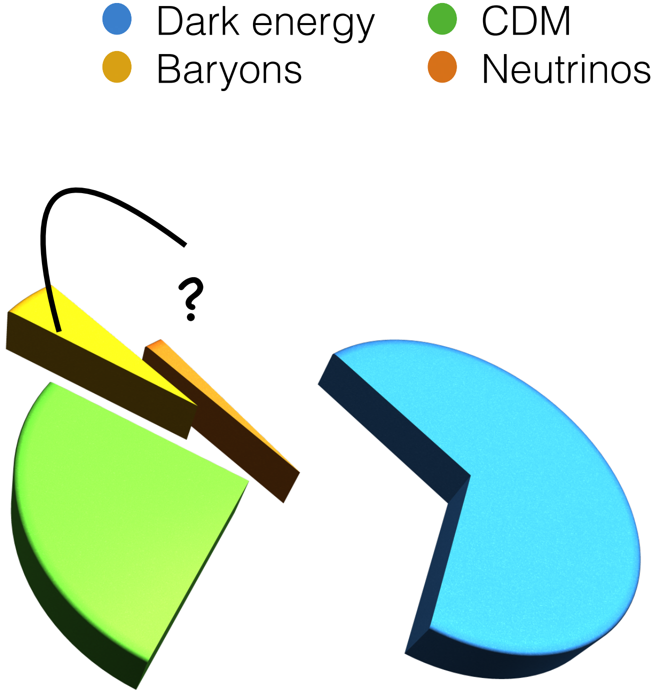
¿QUÉ HACE  ?

Sinergia cosmología-neutrinos:

Neutrinos masivos: una nueva perspectiva en el puzzle del sabor



MAYOR EVIDENCIA NUEVA FÍSICA EN FÍSICA DE PARTÍCULAS!



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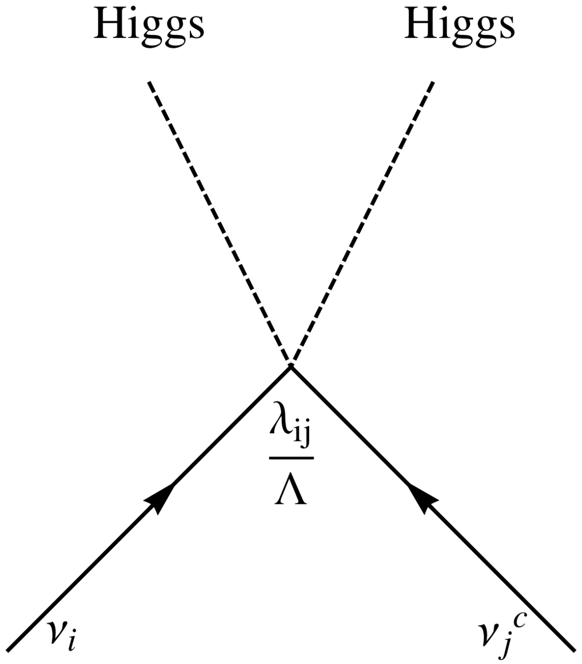
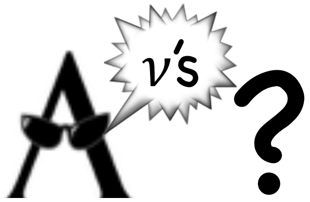
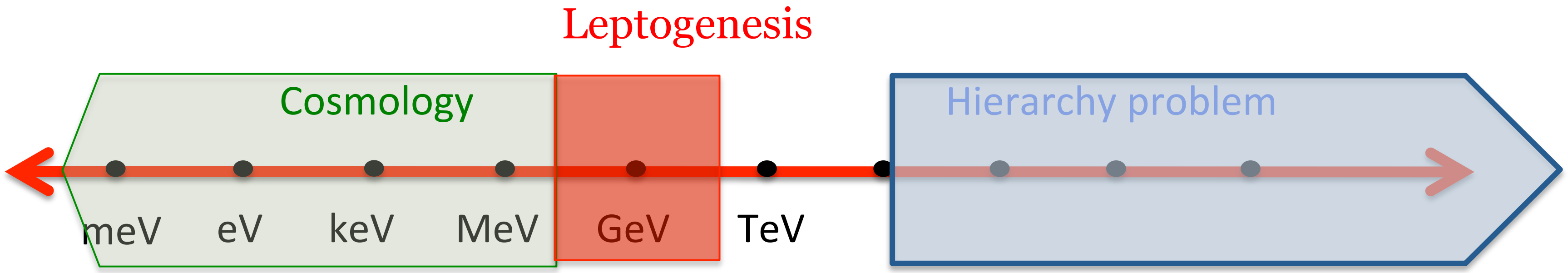






Logros científicos más relevantes:

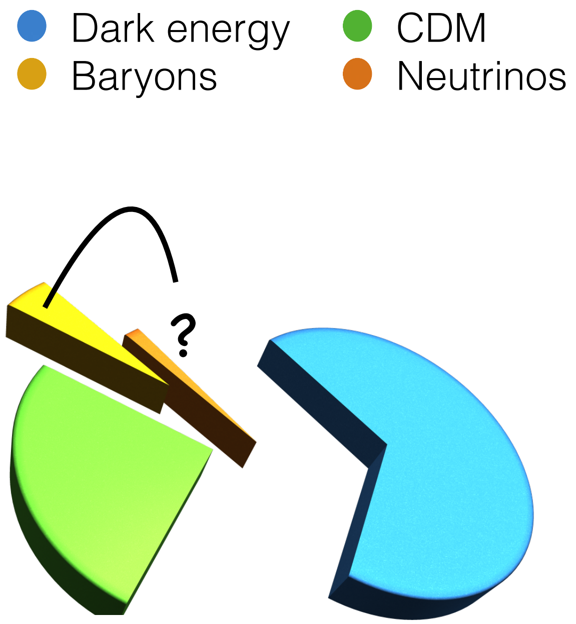
POSIBILIDAD DE EXPLORAR BARIOGÉNESIS

Se puede generar la asimetría barionica en modelos see-saw con

$0.1\ \mathrm{GeV} < \Lambda < 100\ \mathrm{GeV}$

P. Hernández *et al*, *JHEP'15, JHEP'16*

¿QUÉ HACE ?

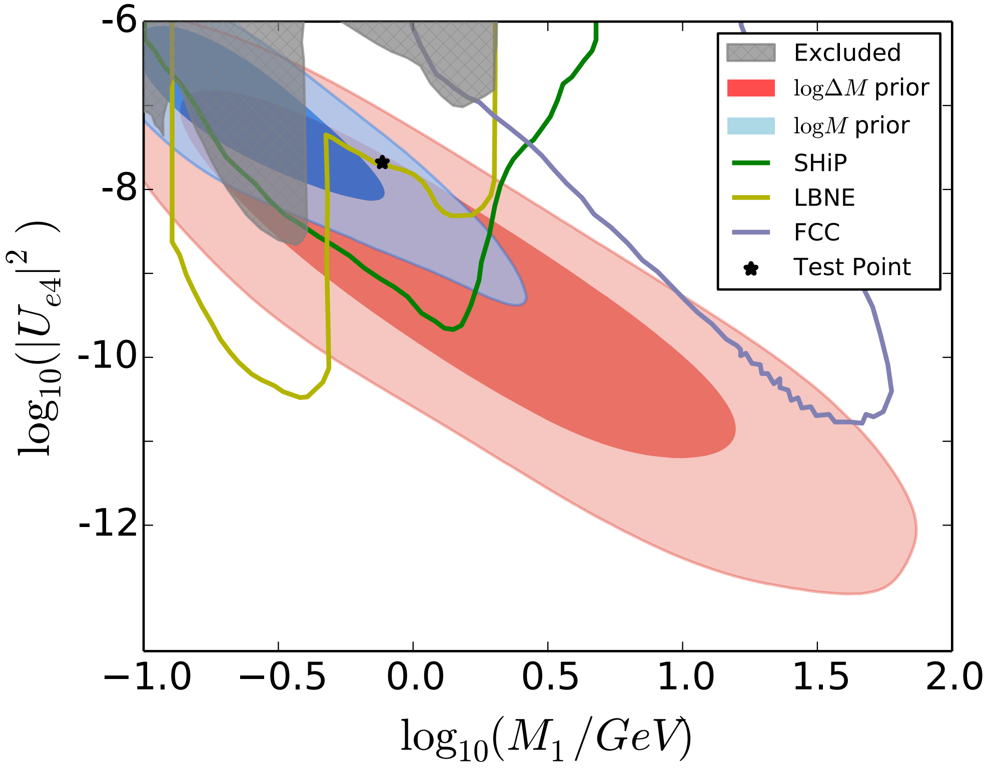


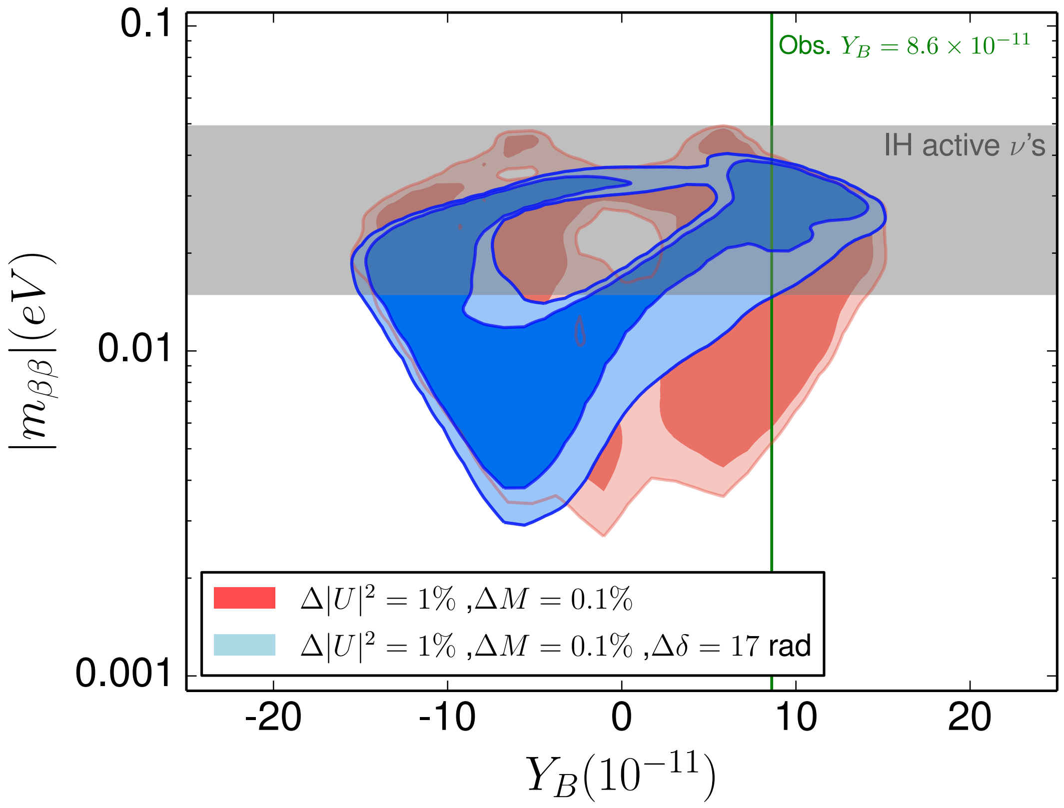
Sinergia cosmología-neutrinos:

POSIBILIDAD DE EXPLORAR BARIOGÉNESIS

P. Hernández *et al, JHEP'15, JHEP'16*

En modelos de see-saw mínimos a la escala del GeV, medidas futuras en SHiP, de CP en Dune/HyperK y en decaimiento beta sin neutrinos pueden proveer información suficiente para reconstruir la asimetría materia-antimateria observada en nuestro universo: **¡The GeV Miracle!**





Futuro, ¿qué haremos?

Extensión a modelos no-mínimos

Sinergia cosmología-neutrinos-materia oscura?

Estudio detallado fenomenología modelos see-saw@GeV

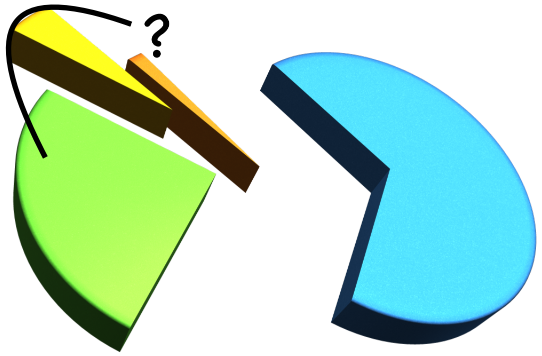
¿QUÉ HACE  ?

● Dark energy ● CDM
● Baryons ● Neutrinos

Sinergia cosmología-neutrinos:

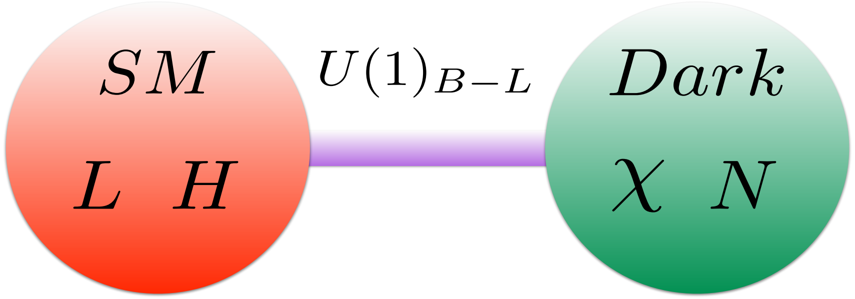
CONEXIÓN MATERIA OSCURA-SEESAW

¿Hay una relación entre la materia oscura tipo WIMP y los neutrinos estériles del modelo see-saw@GeV-TeV?

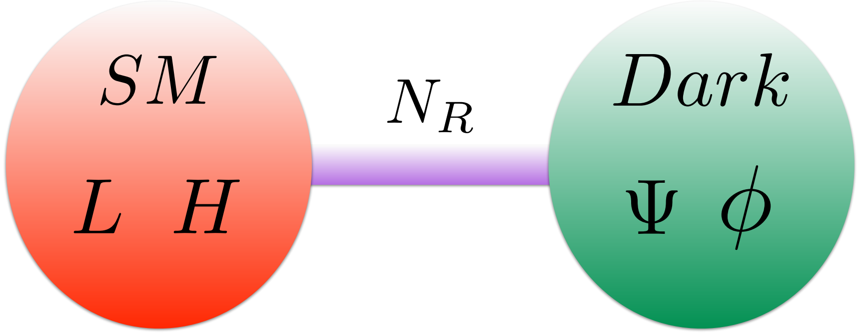


¡Abundancia materia oscura determinada por la interacción con los neutrinos estériles!

a) Materia oscura con número leptónico



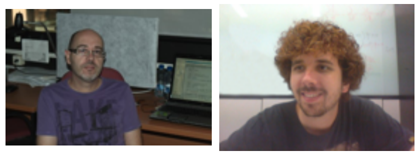
b) Simetría en el sector oscuro



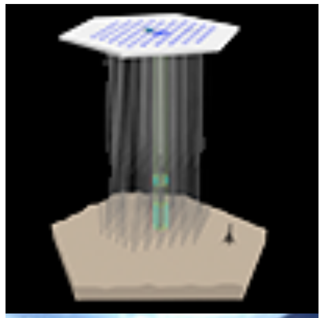
M. Escudero *et al, JHEP'16 (a), JHEP'16 (b)*

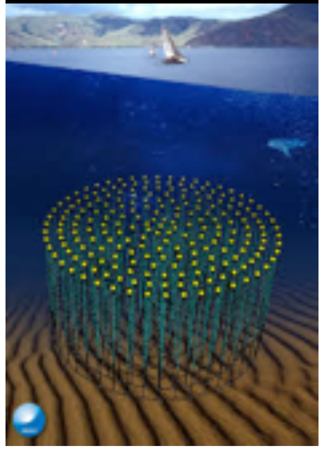
Futuro, ¿qué haremos?

Estudio detallado fenomenológico de esta sinergia:
Espectro de fotones: cotas de detección indirecta



¿QUÉ HACE  ?





ANTARES,
KM3NeT,
ARCA/ORCA

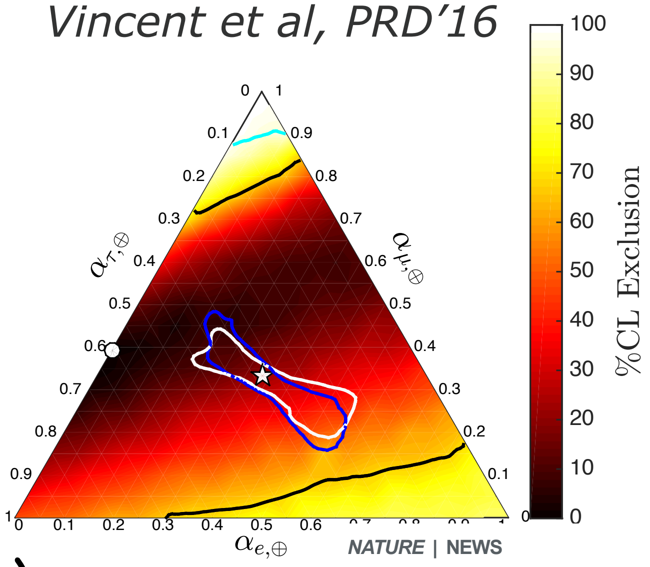
Sinergia astro-neutrinos:

Neutrinos de alta energía

Composición en sabor
(dependencia angular y en energía)

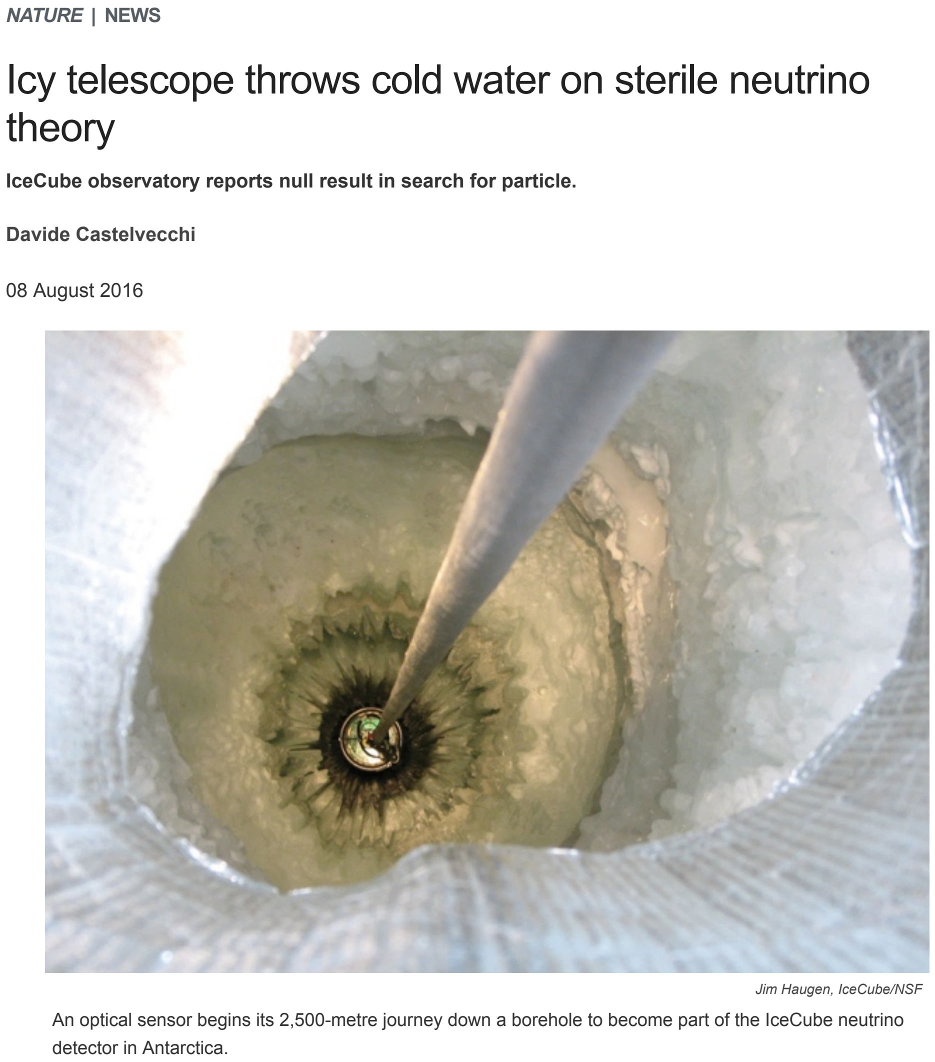
¿NUEVA FÍSICA?

Vincent et al, PRD’16



Neutrinos estériles

Icecube coll. PRL’16



NATURE | NEWS

Icy telescope throws cold water on sterile neutrino theory

IceCube observatory reports null result in search for particle.

Davide Castelvecchi

08 August 2016

Jim Haugen, IceCube/NSF

An optical sensor begins its 2,500-metre journey down a borehole to become part of the IceCube neutrino detector in Antarctica.

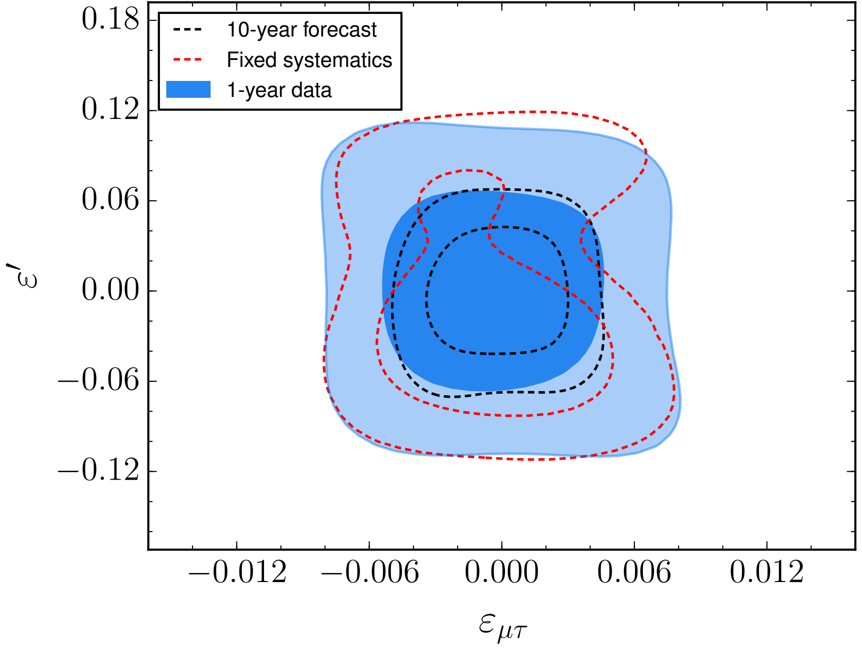
BUSQUEDAS DE NUEVA FÍSICA:

Interacciones no-estándar (neutrinos atmosféricos)

$$H_{\rm mat} = \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon^*_{e\mu} & \epsilon^*_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon^*_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\varepsilon' = \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$$

Salvado et al, JHEP’17



Neutrinos solares

Modelo estándar solar “revisited”:
¿compatibilidad Heliosismología vs. Metalicidad? *JHEP’16,MNRAS’16*

¿QUÉ HACE ?

Sinergia astro-materia oscura-rayos cósmicos:

Rayos cósmicos íntimamente relacionados con BÚSQUEDAS DE **NUEVA FÍSICA**:
Materia oscura podría ser una fuente de rayos cósmicos.

Constituyen un ruido de fondo para búsquedas indirectas de materia oscura:
Fermi-LAT y AMS (!)

Logros científicos más relevantes:

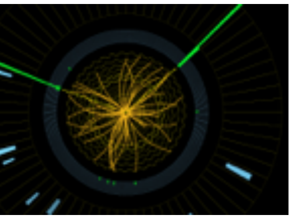
GalpBayes: estudiar modelos de rayos cósmicos empleando sofisticadas técnicas estadísticas, alcanzando la resolución mejor hasta la fecha.

Futuro, ¿qué haremos?

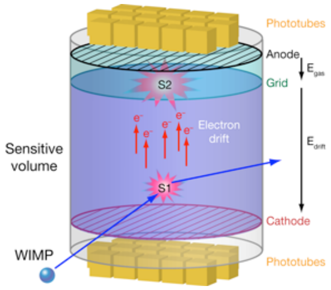
BÚSQUEDAS DE NUEVA FÍSICA:

Sinergia astro-neutrinos: neutrino decay, Lorentz violation, materia oscura@PINGU/ORCA.

materia oscura-rayos cósmicos: materia oscura centro galáctico@Fermi-LAT.



¿QUÉ HACE ?



Sinergia astro-colisionadores de partículas (LHC)

BÚSQUEDAS DE NUEVA FÍSICA:

Ajustes globales: Combinan datos en colisionadores y experimentos de detección directa que permiten inferir estadísticamente señales de **NUEVA FÍSICA.**

Logros científicos más relevantes:

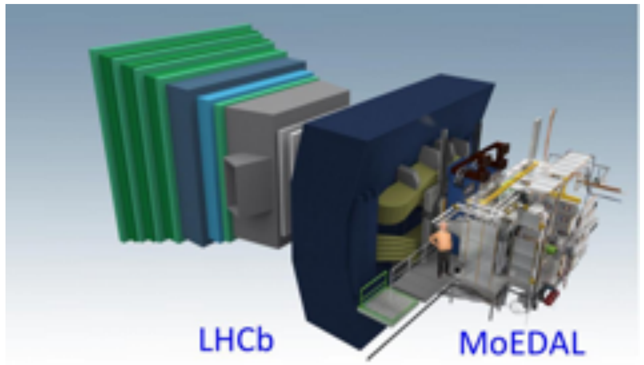
Pioneros en el desarrollo de herramientas de rastreo y aplicaciones para modelos de SUSY, dimensiones extra y EFT.

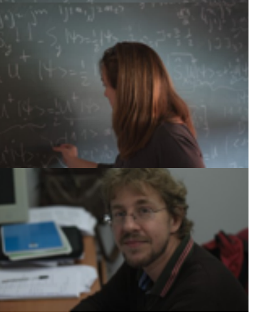
Ello ha dado lugar a una colaboración exitosa y fructífera con el grupo de SUSY en ATLAS.

Futuro, ¿qué haremos?

Proyecto GAMBIT: Formado por más de 30 físicos experimentales (ATLAS, detección de materia oscura) y físicos teóricos para desarrollar herramientas robustas que permitan hacer ajustes globales a modelos de **NUEVA FÍSICA.**

Búsquedas de monopolos magnéticos y "long-living-particles" con el experimento MoEDAL.





¿QUÉ HACE  ?

QCD en el retículo

Desintegraciones débiles de kaones en las cuales se viola el sabor han jugado un papel clave en la construcción del SM.
¿Quizás puedan indicar necesidad de posibles extensiones al SM?:

Violación de CP en las desintegraciones no leptónicas de kaones

$(\varepsilon'/\varepsilon)_{SM} < (8.6 \pm 3.2) \times 10^{-4}$

$(\varepsilon'/\varepsilon)_{exp} = (16.6 \pm 2.3) \times 10^{-4}$

Buras, Gerard, EPJC77 (2017)

¿NUEVA FÍSICA?

La "regla" **ΔI** =1/2

$\mathrm{Re}\, A_0 / \mathrm{Re}\, A_2 = 22.4$

Gell-Mann, Pais, PR 97 (1955)

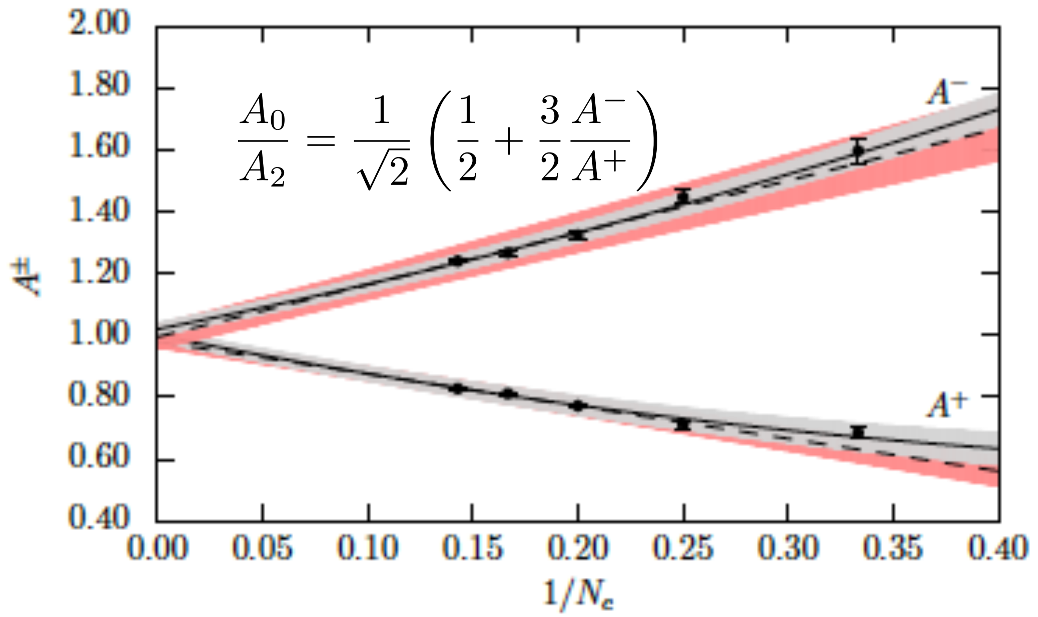
Aún no deducida en QCD

Logros científicos más relevantes:

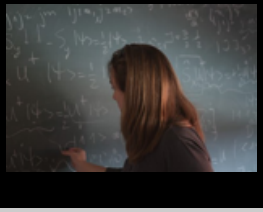
Los análisis fenomenológicos hasta ahora han usado la aproximación de **gran N_c.** Incluso con esta simplificación una predicción de primeros principios requiere la regularización en el retículo.

Hemos llevado a cabo el primer estudio de la dependencia en N_c de estos observables en el retículo.

A. Donini *et al* PRD'16



Labor f🌍rmativa



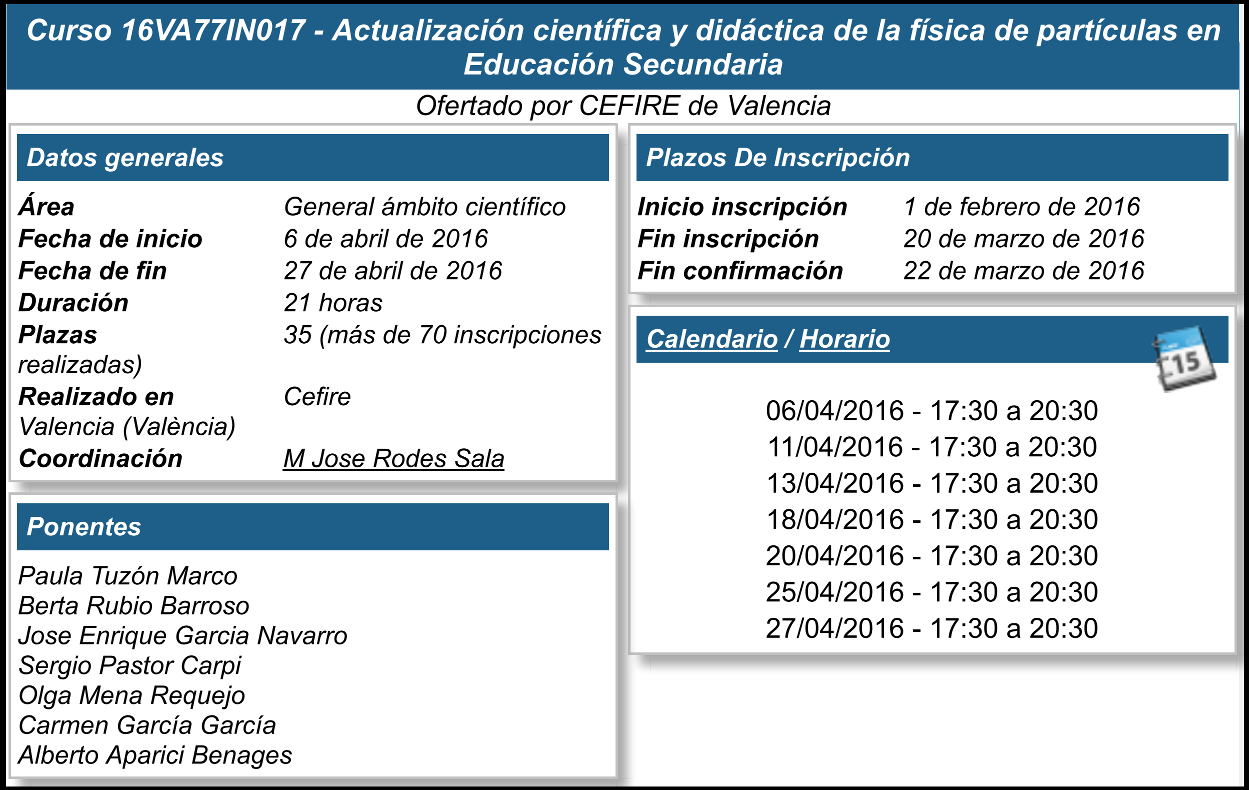
- Nordic Winter School PPC 2013
- Trieste School on Particle Physics & Cosmology 2013
- TASI Lectures 2013
- Hellenic Summer School Corfu 2013
- Scottish Universities St. Andrews 2014
- CERN Latinoamerican School of HEP 2015
- CERN Summer Student Lectures 2016

9 Tesis de Máster en 2012/2016

5 Tesis de doctorado en 2012/2016,
previstas **3** en 2017/2018,
5 en 2019/2020.

Trobadas

Ific seminar



Curso 16VA77IN017 - Actualización científica y didáctica de la física de partículas en Educación Secundaria

Ofertado por CEFIRE de Valencia

Datos generales

Área	General ámbito científico
Fecha de inicio	6 de abril de 2016
Fecha de fin	27 de abril de 2016
Duración	21 horas
Plazas	35 (más de 70 inscripciones realizadas)
Realizado en	Cefire Valencia (València)
Coordinación	M Jose Rodes Sala

Plazos De Inscripción

Inicio inscripción	1 de febrero de 2016
Fin inscripción	20 de marzo de 2016
Fin confirmación	22 de marzo de 2016

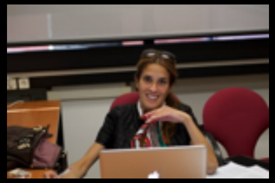
Calendario / Horario

06/04/2016 - 17:30 a 20:30
11/04/2016 - 17:30 a 20:30
13/04/2016 - 17:30 a 20:30
18/04/2016 - 17:30 a 20:30
20/04/2016 - 17:30 a 20:30
25/04/2016 - 17:30 a 20:30
27/04/2016 - 17:30 a 20:30

Ponentes

Paula Tuzón Marco
Berta Rubio Barroso
Jose Enrique Garcia Navarro
Sergio Pastor Carpi
Olga Mena Requejo
Carmen García García
Alberto Aparici Benages

🌍UTREACH

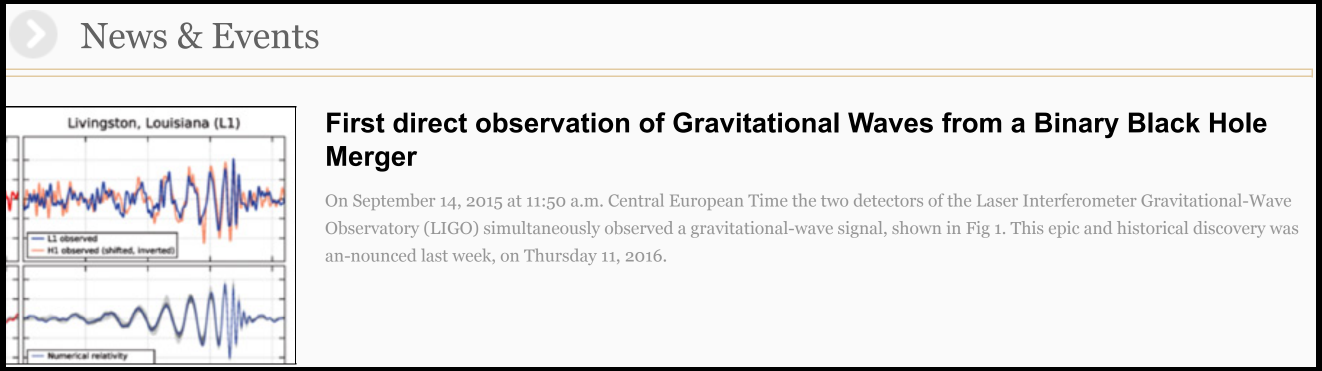


Conferencia Día Internacional de la Mujer

Blog IFIC

UTREACH

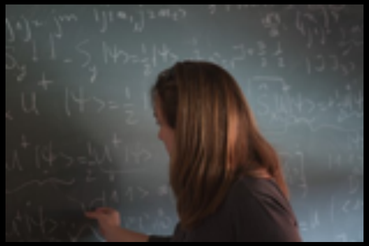
elusiνes
neutrinos, dark matter & dark energy physics
webinars

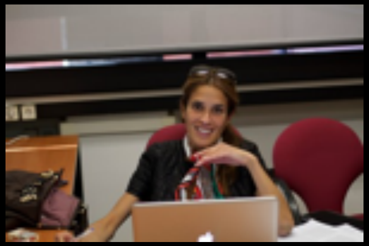


News & Events

First direct observation of Gravitational Waves from a Binary Black Hole Merger

On September 14, 2015 at 11:50 a.m. Central European Time the two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) simultaneously observed a gravitational-wave signal, shown in Fig 1. This epic and historical discovery was an-nounced last week, on Thursday 11, 2016.





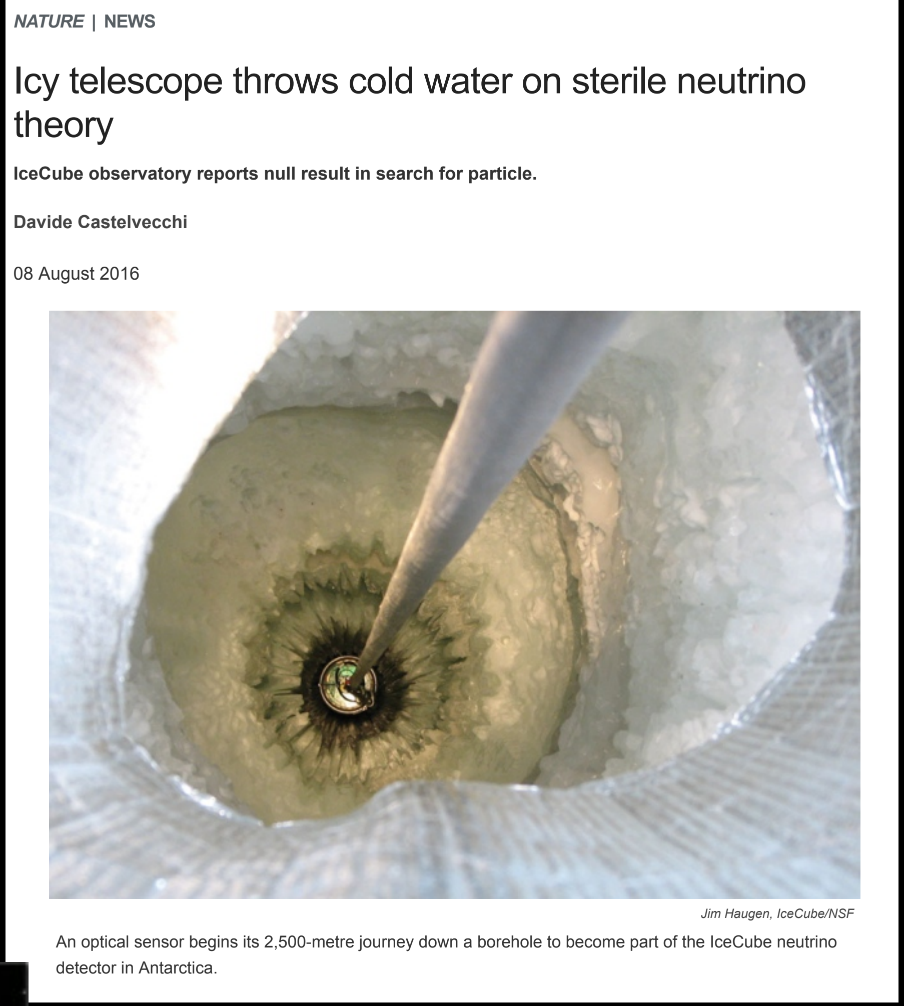
Outreach » Articles & Interviews » **Non-thermal cosmic neutrino background**

Paper of the month: Non-thermal cosmic neutrino background

The Cosmic Neutrino Background (CNB) is a solid prediction of the Standard Models of Particle Physics and Cosmology. In the early universe, neutrinos were formed as part of the thermal bath, a hot plasma filling the universe (thermal production). As the universe expanded and cooled down to MeV temperatures, the neutrinos decoupled from the thermal bath, traveling freely through space ever since. Neutrinos are very weakly interacting particles, which makes the detection of this neutrino background very challenging and so far experimentally inaccessible. However, on the other hand, this same property implies that once we succeed in measuring the cosmic neutrino background, we can not only learn something about the properties of neutrinos but also the CNB is a window to the very early universe, back to the times of the formation of light elements in Big Bang Nucleosynthesis (BBN), when the neutrinos decoupled from the thermal bath at about two minutes after the "Big Bang". For comparison, the cousin of the CNB, the better-known Cosmic Microwave Background (CMB), consisting of background photons instead of neutrinos, had lead to major breakthroughs in modern cosmology. This window however only leads back to temperature around 1 eV, nearly 400,000 years later than the CNB window. This paper discusses how physics beyond the standard model, in particular non-thermally generated right-handed neutrinos, can modify the CNB predictions.

Links

arXiv
http://arxiv.org/abs/1509.00481



NATURE | NEWS

Icy telescope throws cold water on sterile neutrino theory

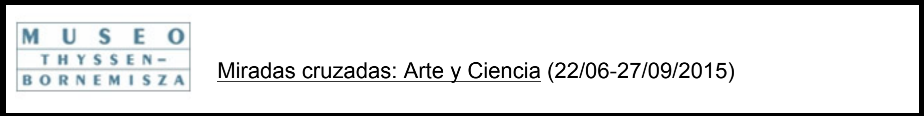
IceCube observatory reports null result in search for particle.

Davide Castelvecchi

08 August 2016

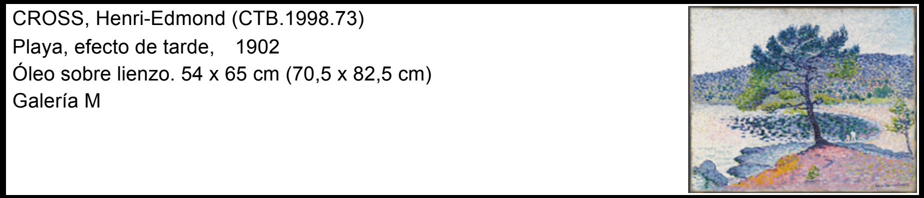
Jim Haugen, IceCube/NSF

An optical sensor begins its 2,500-metre journey down a borehole to become part of the IceCube neutrino detector in Antarctica.

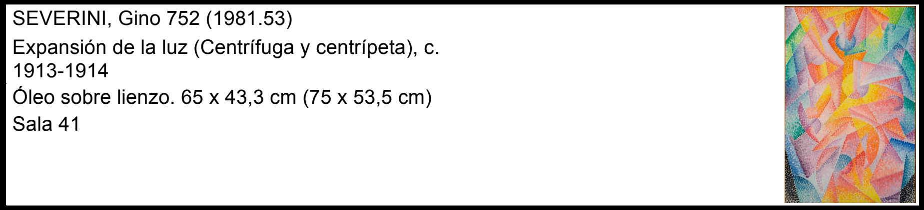


MUSEO THYSSEN-BORNEMISZA

Miradas cruzadas: Arte y Ciencia (22/06-27/09/2015)



CROSS, Henri-Edmond (CTB.1998.73)
Playa, efecto de tarde, 1902
Óleo sobre lienzo. 54 x 65 cm (70,5 x 82,5 cm)
Galería M



SEVERINI, Gino 752 (1981.53)
Expansión de la luz (Centrífuga y centrípeta), c. 1913-1914
Óleo sobre lienzo. 65 x 43,3 cm (75 x 53,5 cm)
Sala 41

DELAUNAY-TERK, Sonia 518 (1976.81)

Invisibles Art Group
Steve Sproates, Chrissie Morgan, Bruce Burn, Catherine Yates, Bill Harris, Dawn Douglas, Michael Grogan, Angela Sandwith, Maggie Parker

ITN Invisibles
Durham University

Invisibles Art
an original exhibition exploring science with art
with the opening by Prof. Sir Arnold Wolfendale FRS
18 July 2013 18:00-19:30
Lumley Castle Hotel, Chester le Street, DH3 4NX

¿CÓMO LO HACEMOS?

PROMETEO 240.330 eur Enero 2014/Diciembre 2017 (N. Rius)

FPA 165.560 eur Enero 2014/Diciembre 2017 (P. Hernández, co: OM)

Proyecto H2020-ITN-ELUSIVES 454.402,92

Abril 2016-Marzo 2020 (P. Hernández)

Proyecto H2020-RISE-InvisiblesPlus

Febrero 2016- Enero 2020

UVEG 198.500 eur (P. Hernández)

IFIC 103.220 eur (O. Mena, nodo coordinador del CSIC)

Severo Ochoa

Esperamos veros a todos en el
Theory post-Xmas meeting toast
Viernes 27 @ 15:30 PM
Seminar Room 0.8 ICMol

+

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Neutrino masses: Weyl, Dirac, Majorana

In general, a massless fermion is described by a two-component Weyl spinor field. It ha certain chirality, left or right. The chirality operators are:

$$P_L = \frac{1-\gamma_5}{2}\,, \qquad P_R = \frac{1+\gamma_5}{2}\,,$$

For massless fermions, chirality and helicity, which is the projection of the spin of the particle on its momentum, are equivalent:

$$P_\pm = \frac{1}{2}\left(1 \mp \frac{\boldsymbol{\sigma}\mathbf{p}}{|\mathbf{p}|}\right)$$

Weak interactions only produce left-handed chirality states:

$$j_\mu = \overline{\nu}\,\gamma_\mu\,(1-\gamma_5)\;e = 2\,\overline{\nu_L}\,\gamma_\mu\,e_L$$

A Dirac neutrino (or fermion) needs independent left and right chiral projections: four independent components

$$\nu = \underset{\substack{\uparrow \\ \text{four} \\ \text{components}}}{\begin{pmatrix} \chi_R \\ \chi_L \end{pmatrix}} \quad \Rightarrow \quad \nu_L = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} \chi_R \\ \chi_L \end{pmatrix} = \underset{\substack{\uparrow \\ \text{two} \\ \text{components}}}{\begin{pmatrix} 0 \\ \chi_L \end{pmatrix}}$$

Weak interactions involve only TWO of the FOUR components of the Dirac neutrino.

Neutrino masses: Weyl, Dirac, Majorana

There are two possible mass terms for fermions: Dirac or Majorana. C is the particle-antiparticle operator (left-handed neutrino->right handed antineutrino), which should not be confused with the charged conjugation operator which will take the left-handed neutrino into a left- handed antineutrino which DOES NOT exist!.

$$\hat{C}: \ \psi \to \psi^c = C\bar{\psi}^T , \qquad C = i\gamma_2\gamma_0 \qquad \nu = \begin{pmatrix} \chi_R \\ \chi_L \end{pmatrix} , \quad \nu^c = \begin{pmatrix} -i\sigma^2\chi_L^* \\ i\sigma^2\chi_R^* \end{pmatrix}$$

There are basically two options: right handed component of the neutrino field is totally independent of the left-handed one: **Dirac mass term couples totally independent left handed and right handed fields!**

$$\psi = \begin{pmatrix} \varphi_R \\ \varphi_L \end{pmatrix} = \begin{pmatrix} 0 \\ \varphi_L \end{pmatrix} + \begin{pmatrix} \varphi_R \\ 0 \end{pmatrix} = \psi_L + \psi_R$$

$$\begin{aligned} \mathcal{L}^{\mathrm{D}} = -m_{\mathrm{D}}\,\overline{\nu}\,\nu = & \ -m_{\mathrm{D}}\,(\overline{\nu_L} + \overline{\nu_R})\,(\nu_L + \nu_R) \\ = & \ -m_{\mathrm{D}}\,(\overline{\nu_L}\,\nu_R + \overline{\nu_R}\,\nu_L) \end{aligned}$$

Or, it can be that the right handed component is the C-conjugate of the left handed part: Majorana fermion $\nu^c = \nu$

To construct a massive Dirac field, one needs two independent Weyl components together with their C conjugates: four degrees of freedom

$$\psi = \psi_L + \psi_R$$

To construct a Majorana mass term one needs only two degrees of freedom, since the right-handed field is the C-conjugate of the left-handed one

$$\psi_R = (\psi_L)^c = (\psi^c)_R \qquad \psi = \psi_L + \eta(\psi^c)_R = \psi_L + \eta(\psi_L)^c$$

Dirac mass term

$$\begin{aligned}\mathcal{L}^{\rm D} = -m_{\rm D}\,\overline{\nu}\,\nu = & -m_{\rm D}\,(\overline{\nu_L}+\overline{\nu_R})\,(\nu_L+\nu_R)\\ = & -m_{\rm D}\,(\overline{\nu_L}\,\nu_R+\overline{\nu_R}\,\nu_L)\end{aligned}$$

Majorana mass term

$$\mathcal{L}^{\rm M} = -\frac{1}{2}\,m\,(\overline{\nu_L^c}\,\nu_L+\overline{\nu_L}\,\nu_L^c)$$

Notice that the Dirac mass term is invariant under the U(1) transformations:

$$\psi \rightarrow e^{i\alpha}\psi\,, \qquad \bar{\psi} \rightarrow \bar{\psi}e^{-i\alpha}\,,$$

so it conserves the corresponding charges (electric charge, lepton or baryon number,...)
Majorana mass term break all the charges by two units, lepton number is BROKEN
Only neutral particles can be Majorana particles (electric charge must be conserved!).
If neutrinos are Majorana particles, the total lepton number is NOT conserved.

Why neutrinos are massless within the SM? :

1) We can not construct a Dirac mass term,

since there is NOT right handed neutrino in the SM!

2) We can not construct a Majorana mass term, $\nu_L^T C \nu_L$

the left handed neutrino has weak isospin projection 1/2,
the Majorana mass will be a component of the isotriplet operator
since there is NOT a Higgs triplet in the SM!

3) We can not add a Majorana mass term HHLL,

since this operator has d=5 and the SM is renormalizable!

4) We can not add the effective operator HHLL/M at some higher loop level,

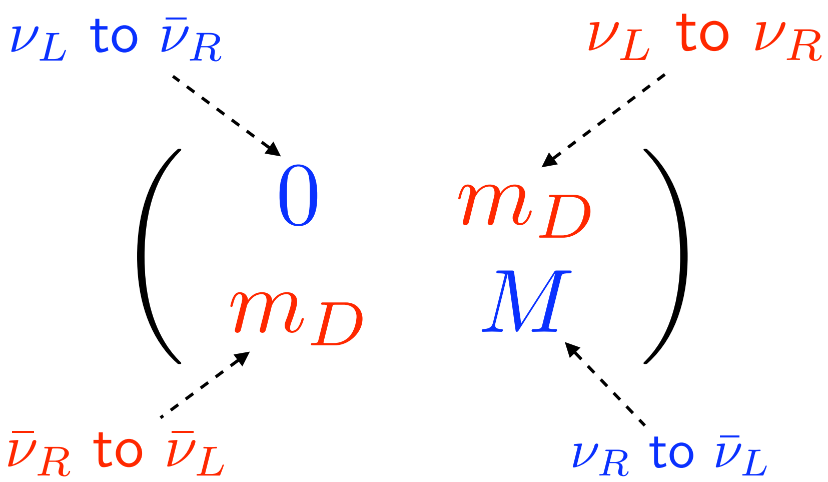
since the total lepton number is conserved in the SM!

Adding a right-handed neutrino singlet under SU(2) x U(1): the complete model

$$\mathcal{L}^{\mathrm{D+M}} = \mathcal{L}^{\mathrm{M}}_{\mathrm{L}} + \mathcal{L}^{\mathrm{M}}_{\mathrm{R}} + \mathcal{L}^{\mathrm{D}} = -\frac{1}{2}\begin{pmatrix}\overline{\nu^c_L} & \overline{\nu_R}\end{pmatrix}\begin{pmatrix} m_L & m_{\mathrm{D}} \\ m_{\mathrm{D}} & m_R \end{pmatrix}\begin{pmatrix}\nu_L \\ \nu^c_R\end{pmatrix} + \mathrm{h.c.}$$

$$= \frac{1}{2} N_L^T \, \mathcal{C}^\dagger \, M \, N_L + \mathrm{h.c.}$$

$$N_L = \begin{pmatrix}\nu_L \\ \nu^c_R\end{pmatrix}, \qquad M = \begin{pmatrix} m_L & m_{\mathrm{D}} \\ m_{\mathrm{D}} & m_R \end{pmatrix}$$

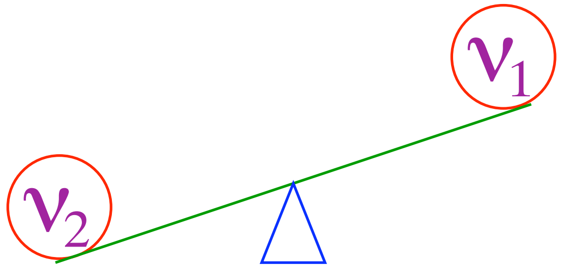


- ν_L to ν_R AND $\bar{\nu}_R$ to $\bar{\nu}_L$ are the Dirac masses.
- ν_L to $\bar{\nu}_R$ forbidden by weak isospin.
- ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected.

If we diagonalize the mass matrix, and we assume that M >>>>> v (WHY?)

Two Majorana neutrinos
with masses m_D^2/M and M

Seesaw:
Yanagida, Gell-man-
Ramond-Slansky



$$L = \underset{\text{doublet}}{\begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}} \leftarrow I_3 = 1/2 \quad , \qquad \mathcal{L}^{\mathrm{M}} \sim \underset{\substack{I_3=1 \\ \text{triplet}}}{\nu_L^T \, \nu_L}$$

$$\underset{\text{non-renormalizable}}{\frac{g}{M} \left(L^T \, L\right) \left(\phi^T \, \phi\right)} \xrightarrow[\text{Breaking}]{\text{Symmetry}} m_L \, \nu_L^T \, \nu_L$$

Effective Lagrangian!

Can we construct a Higgs triplet made out of two Higgs doublets?

The SM could be regarded as an effective low energy theory... effects caused by the New Physics below the New Physics energy scale M are represented by a tower of operators of dimension > 4 and suppressed by powers of 1/M

$$\phi \xrightarrow[\text{Breaking}]{\text{Symmetry}} v \Rightarrow g \left(\phi^T \, \phi\right) \xrightarrow[\text{Breaking}]{\text{Symmetry}} m_{\mathrm{D}}^2 \quad \left(m_\ell^2 \text{ or } m_q^2\right)$$

$$\boxed{m_L \sim \frac{m_{\mathrm{D}}^2}{M}}$$

See-Saw Type

Natural Cut-Off: $M_{\mathrm{P}} \sim 10^{19}\,\mathrm{GeV}$

Even in the SM it is natural to expect small Majorana ν masses given by the see-saw type relation

$$\boxed{m_L \sim \frac{m_{\mathrm{D}}^2}{M_{\mathrm{P}}}}$$

In SM fermion masses are generated through Yukawa couplings:

$$\mathcal{L}_{\mathrm{Y}} = \sum_{\alpha,\beta} y_{\alpha,\beta}\, \overline{L_\alpha}\, \phi\, R_\beta \qquad (\alpha, \beta = e, \mu, \tau)$$

The coefficients $y_{\alpha,\beta}$ are parameters of the model

$\Downarrow$

Their explanation must come from new physics BSM

$\Downarrow$

All fermion masses give info on new physics BSM

Smallness of ν masses is additional mystery

$\Downarrow$

More info on new physics BSM

Known natural explanations of smallness of ν masses:

$\star$ See-Saw Mechanism

$\star$ Effective Lagrangian

$$\text{Both imply} \begin{cases} \text{Majorana } \nu \text{ masses!} \\ \boxed{m_{\text{light}} \sim \dfrac{m_{\mathrm{D}}^2}{M}} \end{cases}$$

Dolci!: Leptogenesis

The SM of elementary particles can not explain the observed matter-antimatter asymmetry of the universe:

$$Y_{\mathcal{B}}^{\rm obs} \equiv \frac{n_B - n_{\overline{B}}}{s} = (8.7 \pm 0.3) \times 10^{-11}$$

The simplest explanation is baryogenesis: this asymmetry was produced at some point in the expansion history of the universe due to particle processes which violate B

There are three conditions which have to be met in order that a dynamical generation of baryogenesis becomes possible (Sakharov conditions):

1. Baryon number violating processes
2. C and CP Violation
3. Departure from thermal equilibrium

In principle, the SM could satisfy all these three conditions...but in reality, only the first one is fulfilled in a satisfactory way: the CP (CKM) violation is too small!

New physics beyond the Standard Model is required...we need:

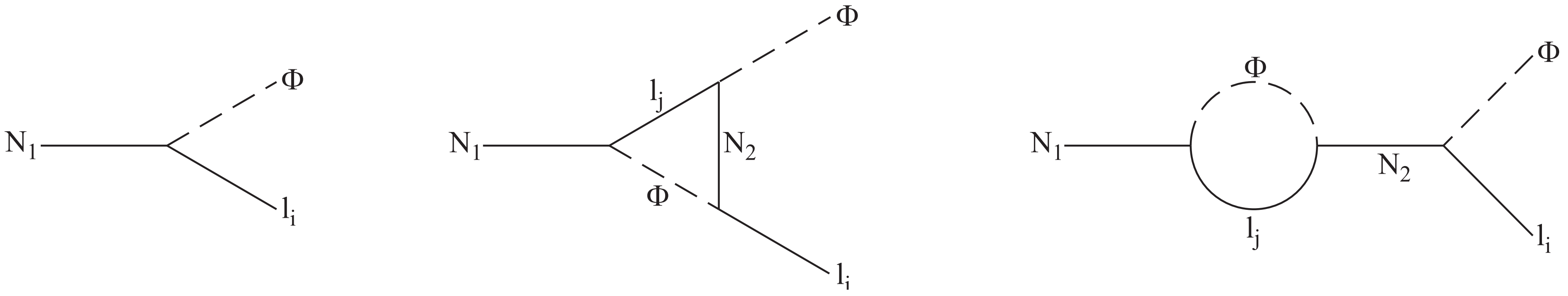
1. New physics could violate L but not B
2. There must be new sources of CP Violation
3. New out-of-equilibrium situations (out-of-equilibrium decays heavy new particles)

Dolci!: Leptogenesis

Is an scenario in which new physics generates a lepton asymmetry in the universe which is partially converted into a baryon asymmetry via sphaleron interactions.
If neutrinos are Majorana particles...the decays of the heavy Majorana neutrinos in the early universe provide the ideal leptogenesis scenario

The heavy Majorana neutrinos can decay into $L\phi$ as well as into $\overline{L}\phi^\dagger$:
if the heavy Majorana fields have L=0, the first mode has L=+1 while the second has L=-1: **Lepton number is violated in these decays!**

The quantum interference between the tree level diagram and the one loop diagram:



If there is more than one heavy Majorana field, there is a relative phase and **CP can be violated in these decays**. To get sufficient baryon asymmetry,~10^(-8)

$$\epsilon_{N_\alpha} = \frac{\Gamma(N_\alpha \to \ell\phi) - \Gamma(N_\alpha \to \bar{\ell}\phi^\dagger)}{\Gamma(N_\alpha \to \ell\phi) + \Gamma(N_\alpha \to \bar{\ell}\phi^\dagger)}.$$

Dolci!: Leptogenesis

Finally, the decay is out-of-equilibrium if the decay rate is slower than the expansion rate of the universe when the temperature of the universe is of the order of the mass of the right handed decaying neutrino

$$\Gamma_\alpha \lesssim H(T \sim M_\alpha)$$

Notice that the CP violating phase in the PMNS matrix is a combination of the CP violating phases relevant for leptogenesis !
However, the experimental discovery of leptonic CP violation plus the Majorana neutrino character would point to baryogenesis via leptogenesis (if accidental cancellations are not present...)

Coffee & Cigarettes, maybe????