Neutrino physics

a few trends

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Outline

ν-mass origin:

- seesaw models, tests and GUT embeddings
- radiative models

leptogenesis, the case of $\sim$ GeV seesaw states

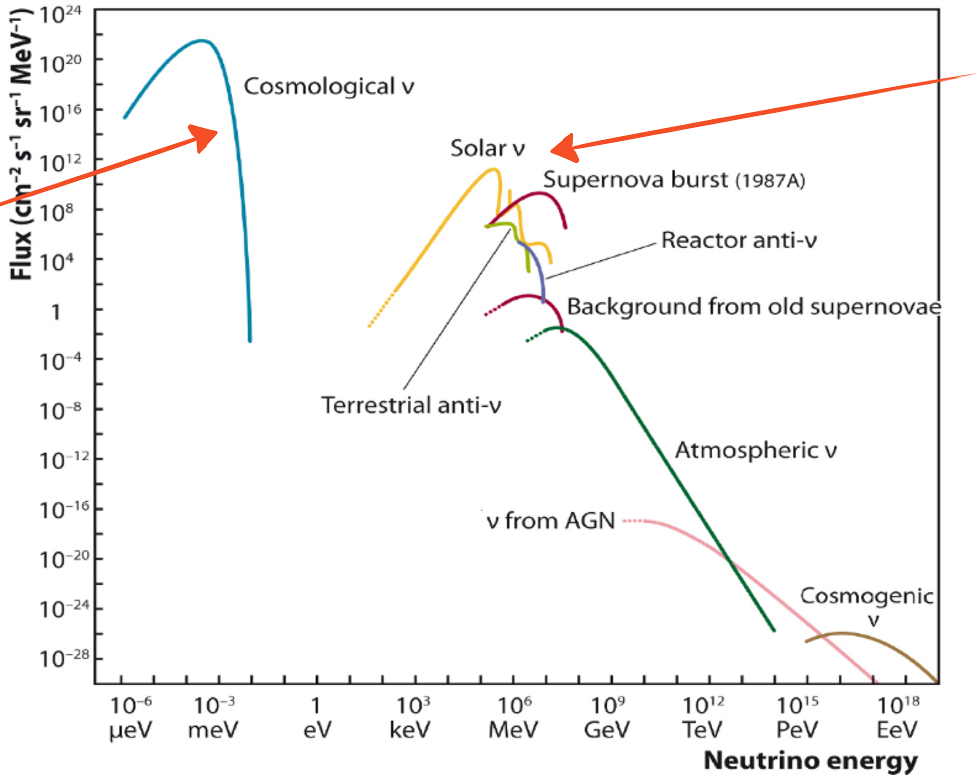
ν-physics and dark matter:

- dark matter experiments for ν Non-Standard Interactions
- ν experiments for boosted DM:
  multi-component DM, DM semi-annihilation, cosmic ray boosted DM, …
- ν lines induced by DM
- ν-mass radiatively induced by DM
- DM medium induced ν-oscillations
- (KeV sterile neutrino DM)

Neutrino sources: fluxes and energies

No man made neutrinos: - sun <~ detected
- atmosphere <~ detected
- supernovae <~ detected (SN1987)
- geo-neutrinos <~ detected
- astrophysical (AGN, cosmogenic, ...) <~ detected
- big-bang relic <~ undetected!

Man-made neutrinos: - reactor <~ detected
- accelerator <~ detected

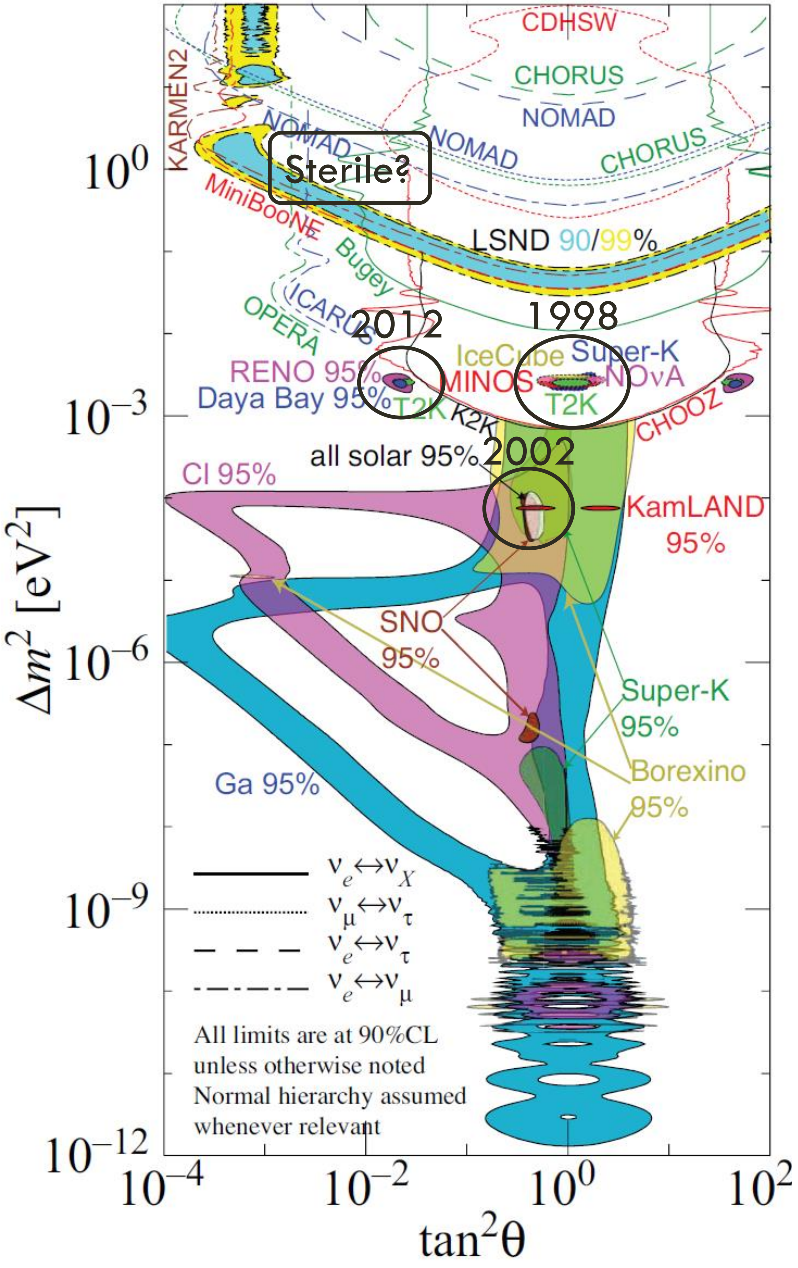


$330\,\text{relic}\,\nu\,/\,\text{cm}^3$

solar neutrinos: most intense detected flux: $10^{11}\,\nu\,/\text{cm}^2/s$

1207.4952

Neutrino oscillations $\Rightarrow$ neutrino masses and mixings



flavor eigenstates $\neq$ mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric } \nu \text{ (1998) + beam } \nu \text{ (2004)}} \cdot \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}}_{\text{reactor } \nu \text{ (2012)}} \cdot$$

$$\cdot \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu \text{ (...-2002)}} \cdot \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \simeq 49°$

$\Delta m^2_{sol} \sim (0.009\,\mathrm{eV})^2$ $\theta_{13} \simeq 8.5°$

$\Delta m^2_{atm} \sim (0.05\,\mathrm{eV})^2$ $\theta_{12} \simeq 34°$

Origin of neutrino masses?????

→ most fundamental question associated to ν-physics!!

Two possible types of neutrino masses: Dirac and Majorana

a mass is an hermitian and Lorentz invariant bilinear interaction which transforms a particle into itself or into another one

$\Downarrow$

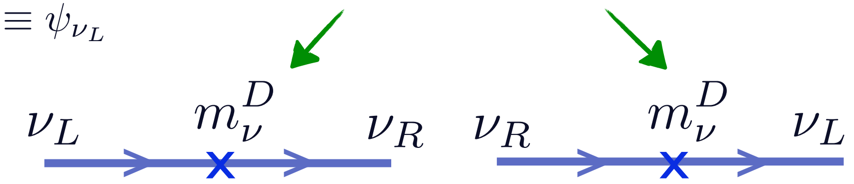
for a fermion there are 2 possible types of masses:

Dirac mass

an interaction of a left-handed fermion ψ_L with a right-handed fermion ψ_R which is not its anti-particle

$$\mathcal{L} \ni -m_\nu^D \left(\overline{\nu_R}\, \nu_L + \overline{\nu_L}\, \nu_R \right)$$

$\nu_L \equiv \psi_{\nu_L}$



$$L \equiv \begin{pmatrix} \nu_L \\ l^- \end{pmatrix} \qquad \mathcal{L} \ni -Y_{\nu_{i\alpha}} \overline{\nu_{R_i}} L_\alpha H + h.c.$$

Not in Standard Model because no ν_R in Standard Model

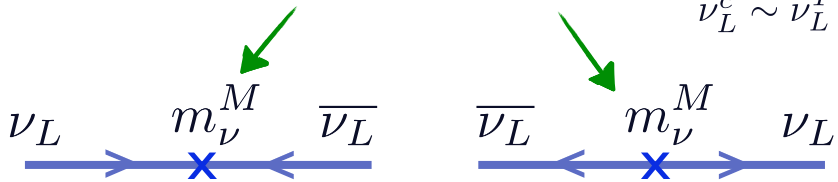
Majorana mass

an interaction of a left-handed fermion ψ_L with a right-handed fermion ψ_R which is its anti-particle $\psi_R = \psi_L^c$

$$\mathcal{L} \ni -\frac{1}{2} m_\nu^M \left(\overline{\nu_L^c}\, \nu_L + \overline{\nu_L}\, \nu_L^c \right)$$

$\nu_L^c \sim \overline{\nu_L}^T$

$\overline{\nu_L^c} \sim \nu_L^T$



$$\mathcal{L} \ni \frac{c_{\alpha\beta}}{\Lambda} L_\alpha^T \cdot L_\beta \, H^T \, H$$

Not in Standard Model because of SM gauge symmetries

$\Rightarrow$ since the ν_L is in the doublet, ν-masses require both $SU(2)_L \times U(1)_Y$ breaking and BSM physics

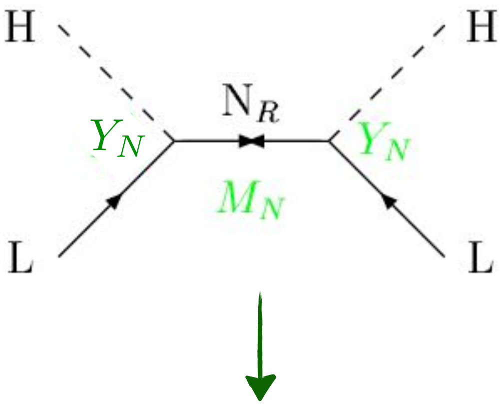
A Dirac mass requires a ν_R but if a ν_R exists, a Majorana mass for this ν_R is not forbidden by SM gauge interactions, in case one expects the ν_L mass to be of Majorana type: seesaw

Tree level origin: the 3 seesaw models

Fermion singlets:
(type-I seesaw)

$$N_{R_i}$$

$$\mathcal{L} \ni \; -Y_{N_{ij}} \bar{N}_i L_j H$$
$$- \frac{m_{N_i}}{2} \overline{N_i^c} N_i + h.c.$$



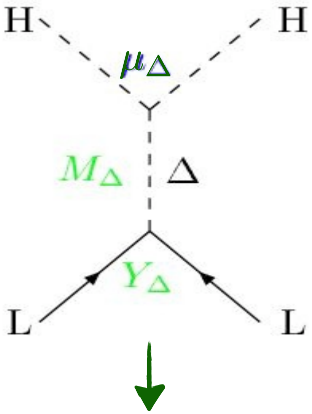
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky;
Yanagida;Glashow; Mohapatra, Senjanovic

Scalar triplet:
(type-II seesaw)

$$\Delta \equiv (\Delta^{++}, \Delta^{+}, \Delta^{0})$$

$$\mathcal{L} \ni \; -Y_\Delta \Delta \, L_i L_j$$
$$-\mu_\Delta \Delta H H + h.c.$$



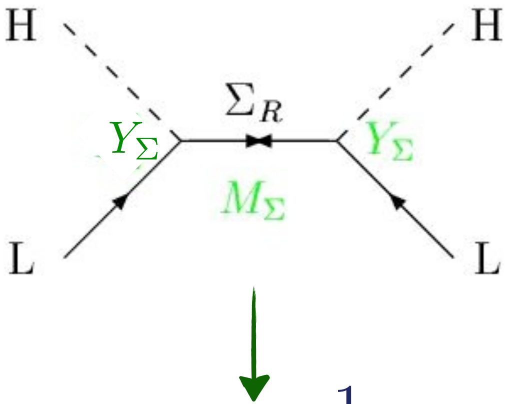
$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi;
Mohapatra, Senjanovic; Schechter, Valle

Fermion triplets:
(type-III seesaw)

$$\Sigma_i \equiv (\Sigma_i^{+}, \Sigma_i^{0}, \Sigma_i^{-})$$

$$\mathcal{L} \ni \; -Y_{\Sigma_{ij}} \bar{\Sigma}_i L_j H$$
$$- \frac{m_{\Sigma_i}}{2} \overline{\Sigma_i^c} \Sigma_i + h.c.$$



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

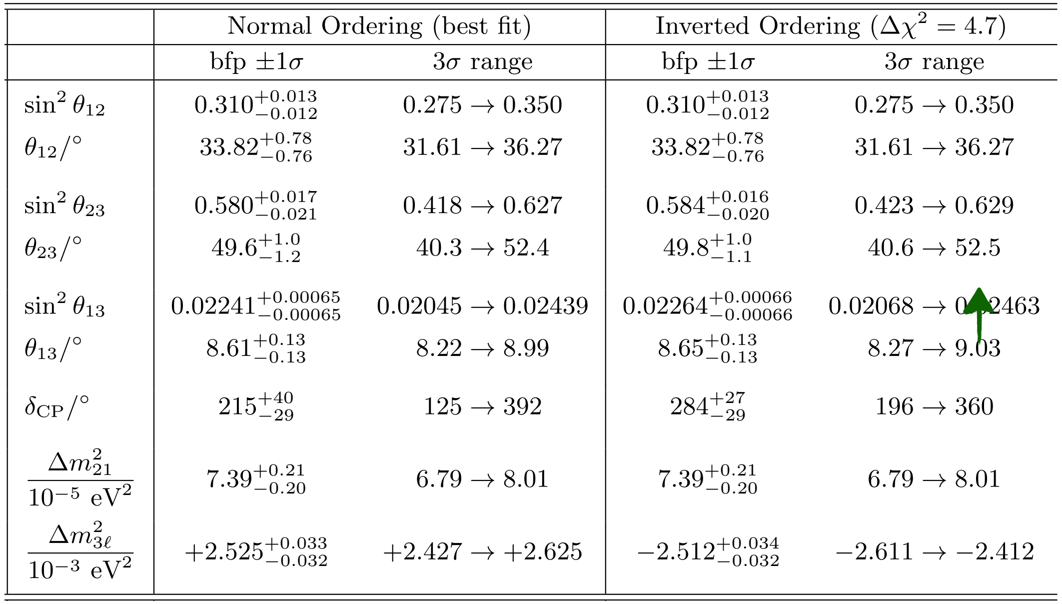
Foot, Lew, He, Joshi; Ma; Ma, Roy;T.H., Lin, Notari,
Papucci, Strumia; Bajc, Nemevsek,
Senjanovic; Dorsner, Fileviez-Perez;....

Seesaw models: neutrino mass data impact

neutrino mass matrix data:

- neutrino oscillations: mass differences and mixings

See talks by K. Scholberg & R. Petti, S. Raut, D. Pramanik



	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
$\delta_{\rm CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

Esteban, Gonzalez-Garcia, Hernandez-Gabezudo, Maltoni, Schwetz, 18'

including recent

$\sim 1.2\sigma$ hint for CP violation (T2K, Nova,...)

$\sim 2\sigma$ hint for normal mass hierarchy (T2K, Nova, SK, ...)

- neutrino absolute mass scale experiments: $m_\nu < 1.1\,\text{eV}\ (90\%\ \text{CL})$ *KATRIN expt. 19'*

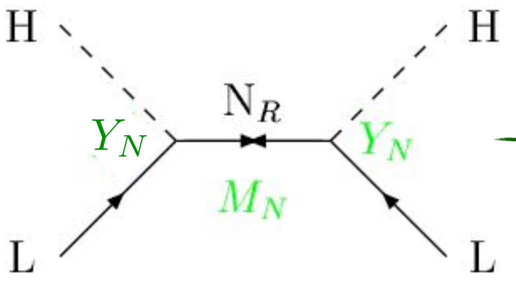
- neutrinoless double beta decay: crucial observable!! $m_{\beta\beta} < 0.16\,\text{eV}\ (90\%\ \text{CL})$ *GERDA expt. 19'*

  would establish that neutrino masses are of Majorana type:

  strong indication in favor of seesaw models!

⟶ very important data but do not allow to discriminate seesaw models alone: any neutrino mass matrix can be accounted for by 3 seesaw models!

Seesaw models: difficult to test in generic models



$$\longrightarrow \quad m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

for example with $Y_N \sim 1,\ m_\nu \sim 0.1\ \mathrm{eV}$ requires $M_N \sim 10^{15}\,\mathrm{GeV}$

very nice explanation of smallness of ν-masses:

GUT scale suppression!! but seesaw states unreachable!!

with $Y_N \sim 10^{-6},\ m_\nu \sim 0.1\,\mathrm{eV}$ requires $M_N \sim \mathrm{TeV}$

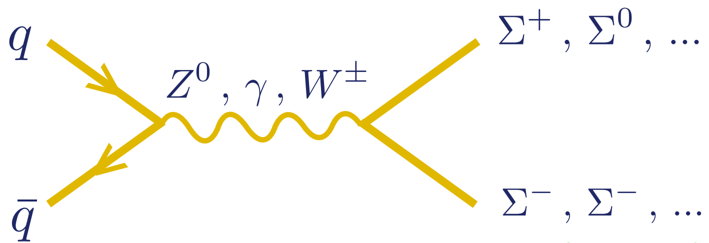
seesaw state low enough but Yukawa are too small to produce them in colliders!!

Seesaw models: type-III at colliders

everything in combination with neutrino mass matrix data!

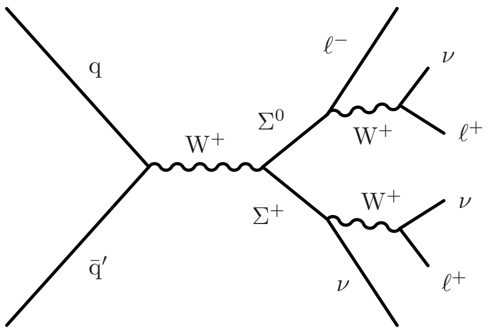
if type-III fermion triplets are around TeV:
can be Drell-Yan pair produced at LHC

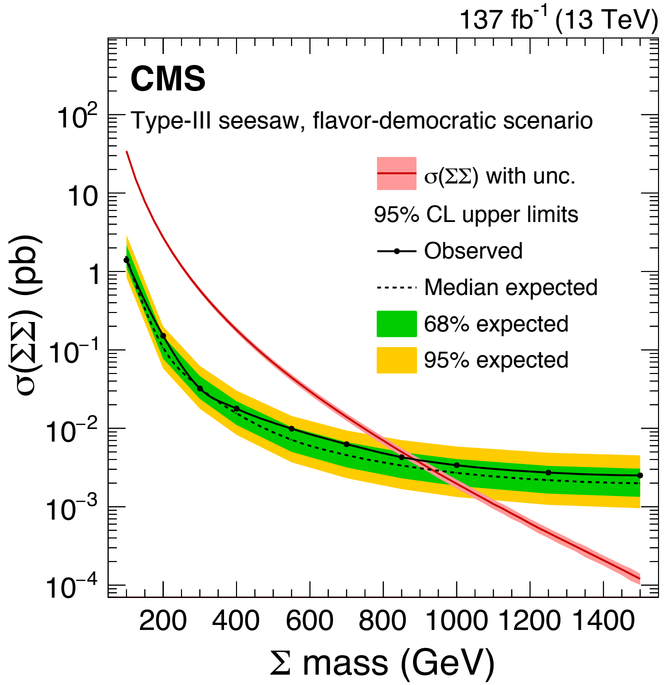
Bajc, Senjanovic 06'; Bajc, Nemvesek, Senjanovic 07'; Franceschini, TH, Strumia 08'; Arhrib et al. 09'; del Aguila et al 09, …., Biggio et al 19, Jana, Okada, Raut 19



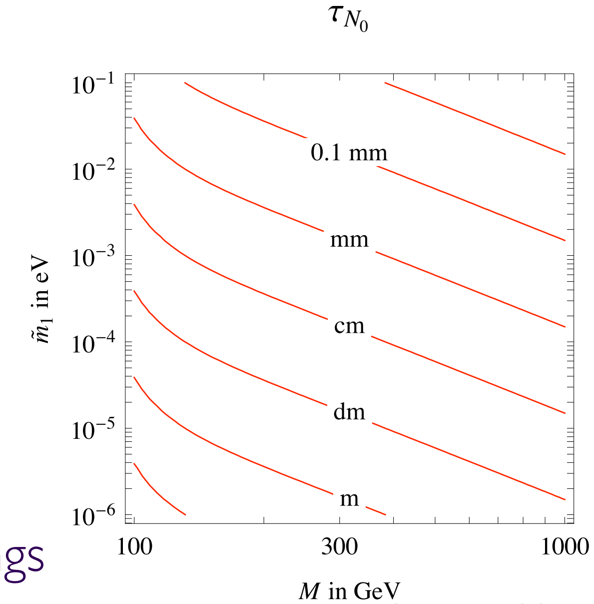
Franceschini, TH, Strumia 08

recent CMS search in multi-lepton channel: $m_\Sigma > 880\,\mathrm{GeV}\ (95\%\mathrm{CL})$





CMS coll. 19'



Franceschini, TH, Strumia 08

given the tiny neutrino masses one e.g. expect couplings sufficiently small to lead to observable displaced vertices

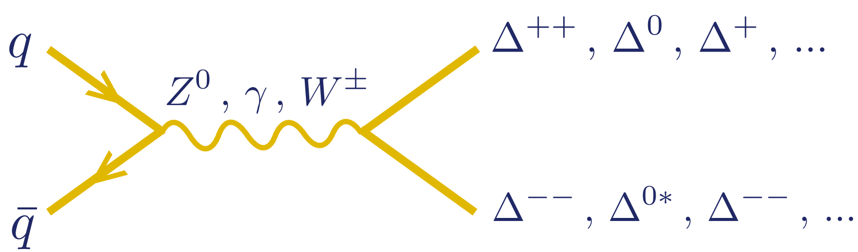
See S. Jana's talk

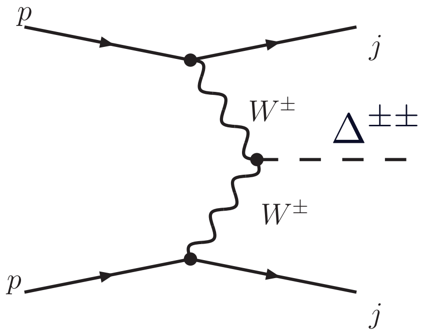
Seesaw models: type-II at colliders

everything in combination with neutrino mass matrix data!

if type-II scalar triplet is around TeV:
can be Drell-Yan pair produced at LHC

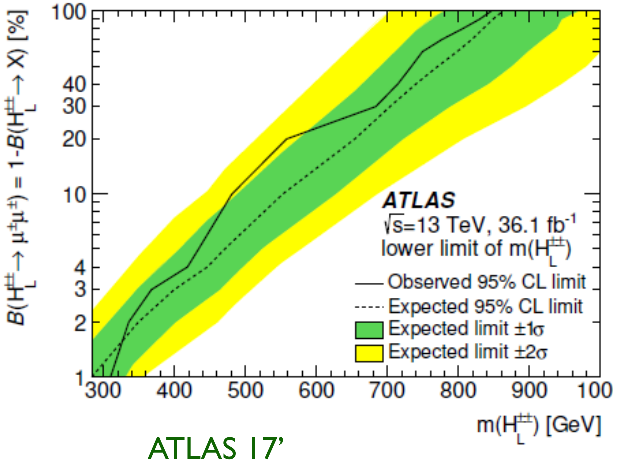
Chun et al. 03'; Akeroyd, Aoki 05'; Hektor et al. 07'; Chun, Lee, Park 07'; Garayoa, Schwetz 08'; Fileviez Perez et al. 08', 09'; del Aguila et al 09'; …..; Chun et al 19,





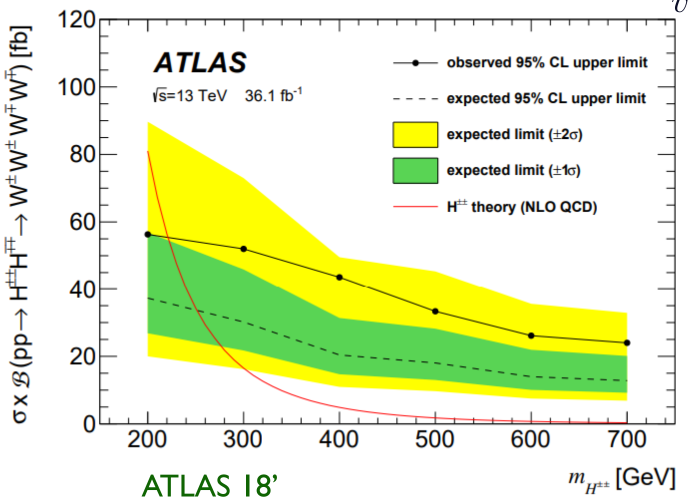
See E. Chun's talk

$pp \to \Delta^{++}\Delta^{--} \to l^+l^-l^+l^-$



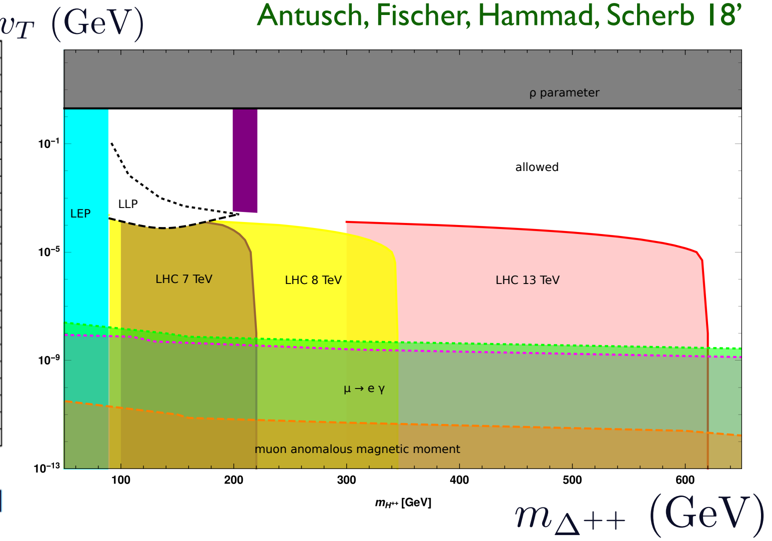
ATLAS 17'

$pp \to H^{++}H^{--} \to W^+W^+W^-W^-$



ATLAS 18'

Antusch, Fischer, Hammad, Scherb 18'



+ here too there are possibilities of displaced vertices but less generic

+ interesting possibilities of tests from rare lepton flavor changing processes

Seesaw models: type-I experimental tests: rare LFV processes

everything in combination with neutrino mass matrix data!

- low scale type-I seesaw models with large Yukawa's cancelling to give small ν-masses

``inverse seesaw models'': - rare lepton flavor changing processes

See M. Mitra's talk

$$\mu \to e\gamma \qquad \tau \to e\gamma \qquad \tau \to \mu\gamma$$
$$\mu \to eee \qquad \tau \to lll$$
$$\mu \to e \text{ conversion in nuclei}$$

huge experimental progresses expected in near future!!

$Br(\mu \to eee) < 10^{-16}\ (Mu3e - future)$

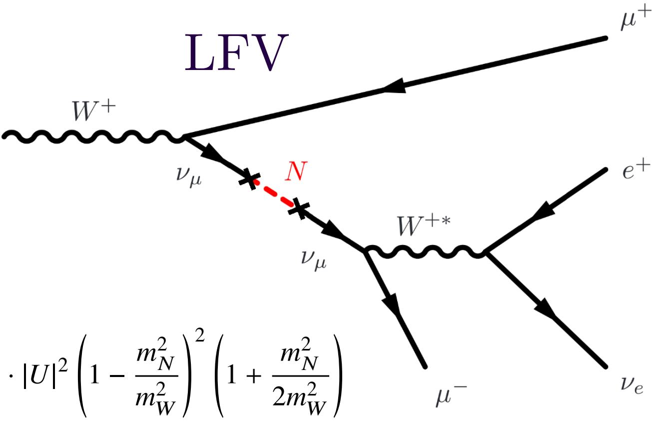
$R^{Ti}_{\mu \to e} < 10^{-18}\ (Comet/Prism, ... - future)$

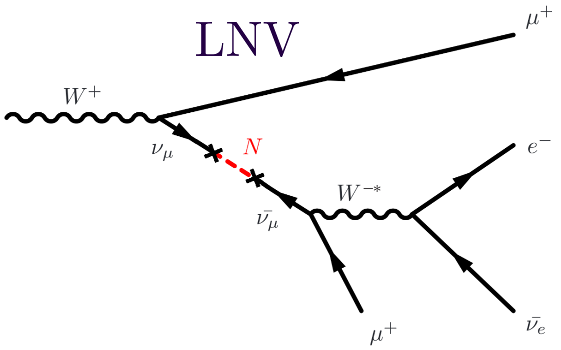
$R^{Al}_{\mu \to e} < 5 \cdot 10^{-17}\ (Mu2e - future)$

- production of $N's$ at LHC

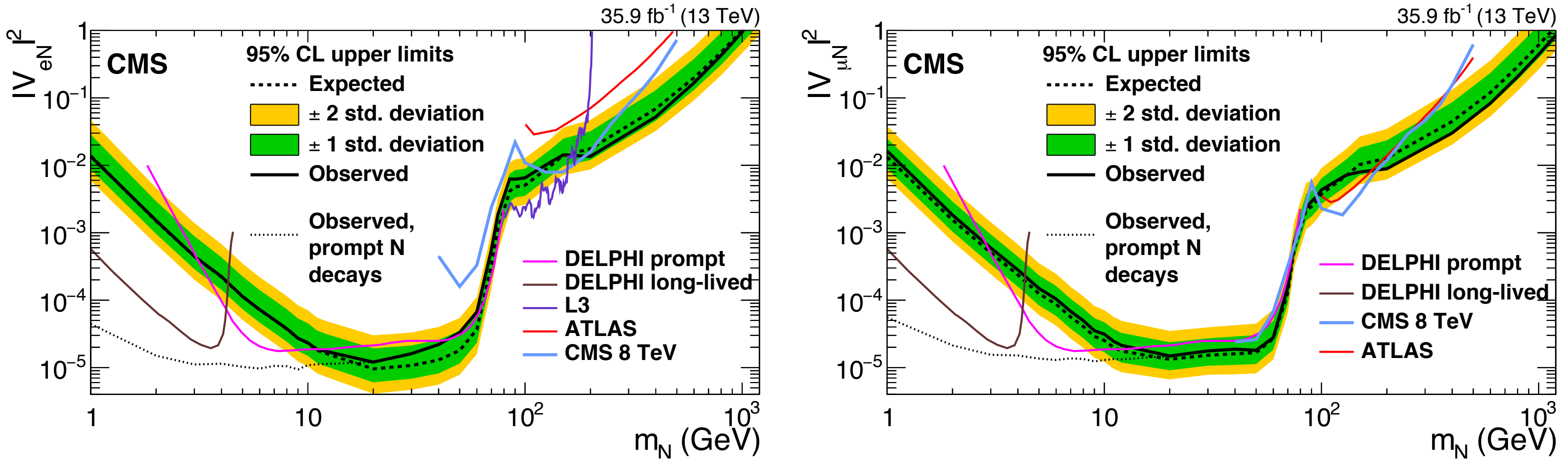
Seesaw models: type-I experimental tests: colliders

$$W^{(*)} \to Nl \to W^{(*)}ll \to lll\nu$$



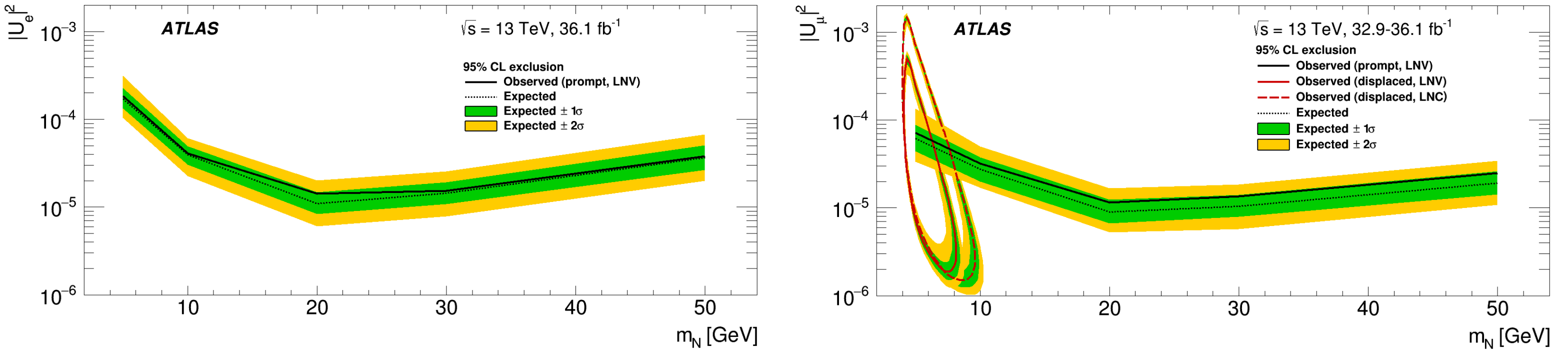


$$\sigma(pp \to W) \cdot \mathcal{B}(W \to \ell N) = \sigma(pp \to W) \cdot \mathcal{B}(W \to \ell \nu) \cdot |U|^2 \left(1 - \frac{m_N^2}{m_W^2}\right)^2 \left(1 + \frac{m_N^2}{2m_W^2}\right)$$



CMS 18'

see talk of Arindam Das



ATLAS 19'

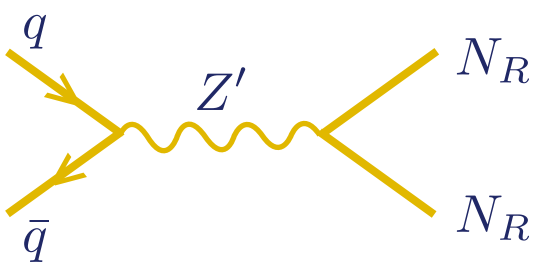
Seesaw models: embedding them in broader frameworks

↪ more possibilities of tests if embedded in more general frameworks

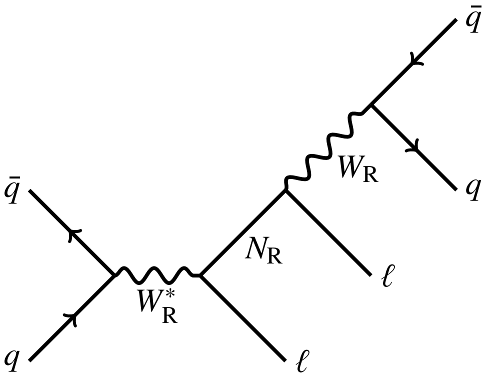
- Supersymmetric seesaw models: effects on rare lepton flavor changing processes, …
  effects of Susy breaking see Sourov Roy talk

- $U(1)_{B-L}$ model: production of low scale $N's$ from Z'_{B-L}

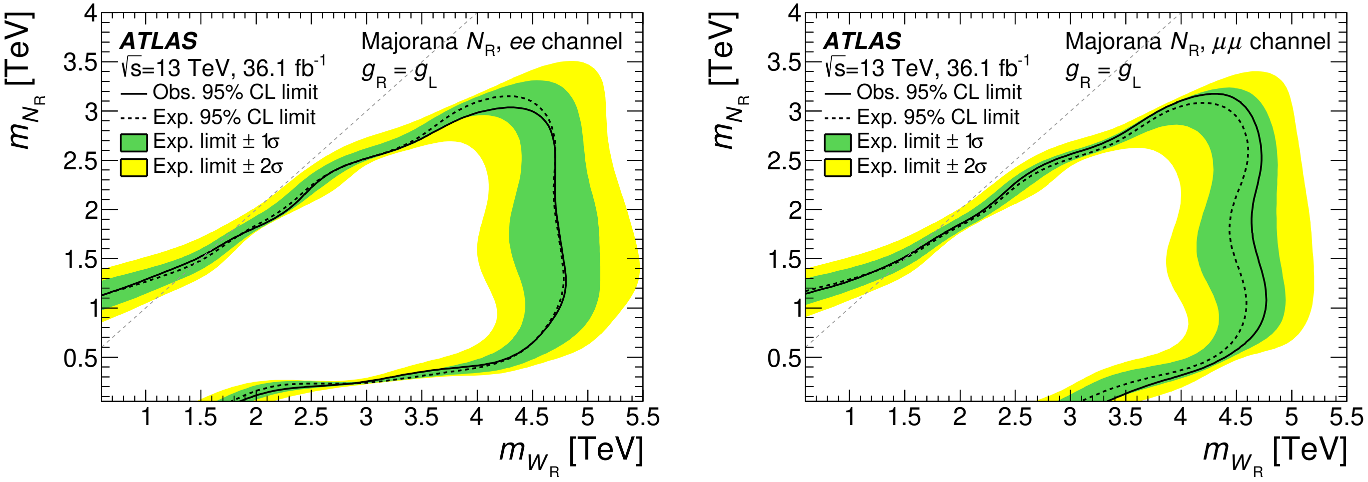
see talk of Arindam Das



- Left-Right models: production of low scale $N's$ from W_R, ...



ATLAS coll. 18'



- …….:

- GUT models: neutrino masses: best probe of GUT scale physics!! (with proton decay)

Seesaw models: embedding them in GUT

neutrino and proton decay data, together with gauge unification and leptogenesis have excluded a number of minimal GUT models

but this remains an extremely well motivated and attractive theory

the models satisfy all constraints, fermion masses and mixings included

as soon as one allows for: - threshold effects see J. Chakrabortty, Maji, King 19'

- and/or masses not all at the same intermediate scale
- and/or one or two more scalar representations

See also T. Bandopadhya talk

Examples of minimal GUT model satisfying all constraints

with a 10_H and a $\overline{126}_H$ scalar representations one can account for all fermion masses and mixings in the SM in Susy $SO(10)$:

$$W = 16^T\,(Y_{10}\,10_H + Y_{126}\overline{126}_H\,)\,16$$

with an extra 210_H and 126_H one gets all needed symmetry breaking

this so called ``minimal Susy $SO(10)$ model'' leads nevertheless to $U(1)_{B-L}$ breaking scale of order $\sim 10^{12-13}\,\mathrm{GeV}$ which is too low to give gauge unification

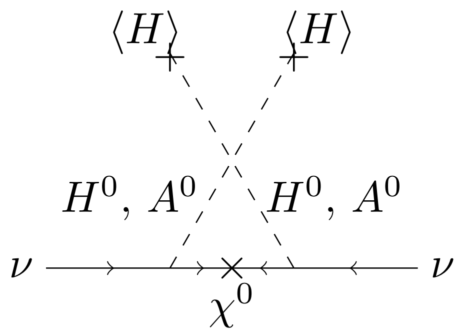
Moreover one gets too fast proton decay $p \to \bar{\nu} K^+$

Babu, Bajc, Saad 18'

These problems can be cured for example adding an extra 54_H with still a single intermediate breaking scale (of $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$)

or adding a 120_H *Diduta, Mimura, Mohapatra 05', Mohapatra, Severson 18', Aulakh, Garg 08'*

Radiative neutrino mass models



……

many possible models at radiative level!!

involve new particles at lower scale than seesaw scale, possibly at TeV

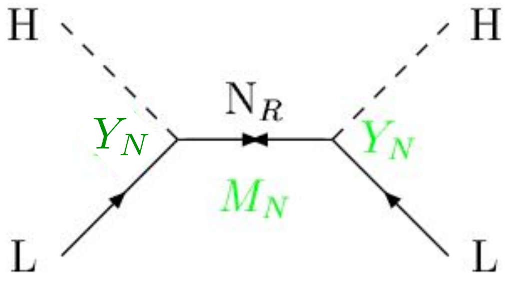
interesting phenomenology

it seems that all possibilities have still not been identified

recent interesting models: radiative Dirac seesaw models

new class of models

beside radiative Majorana mass models and radiative Dirac mass models

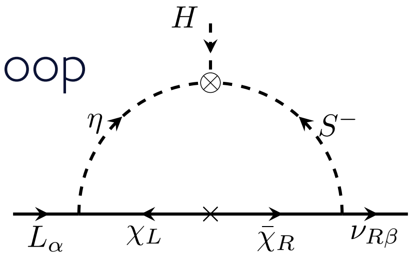


$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Arbelaez, Carcamo, Cepedello, Hirsch, Kovalenko 19'

with Y_N induced at one loop

⇒ 2 loop model !



see also recent systematic determination of neutrino mass models

Jana, Vishnu, Saad 19'
Lindner et al 18', 19'

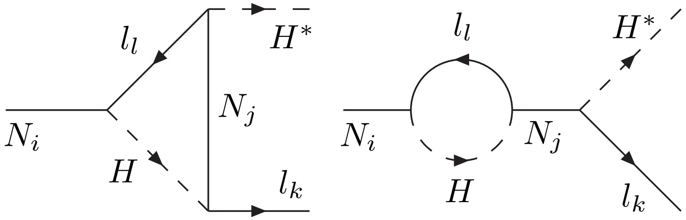
Leptogenesis

Leptogenesis motivation

Two fundamental questions beyond the Standard Model

origin of neutrino masses ⇔ origin of the baryon asymmetry of the Universe

Leptogenesis:
both origins are the same



the Yukawa couplings inducing the neutrino masses also induce decays of seesaw states to leptons and antileptons, which:

- break L
- violate C et CP
- are naturally out of equilibrium in the early Universe

this creates a L asymmetry reprocessed in part to a B asymmetry by SM sphalerons

very natural at high scale: a series of numerical coincidences which makes it particularly effective if seesaw states are at a high scale: $m_N,\, m_\Delta,\, m_\Sigma \gtrsim 10^{9-10}\,\mathrm{GeV}$

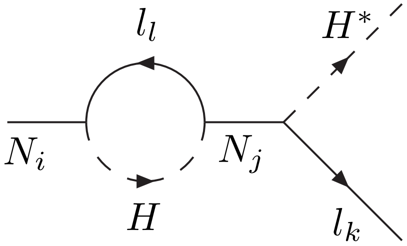
but difficult to test then!

Going down to ~TeV right-handed neutrinos: resonance from quasi degenerate spectrum

Covi, Roulet, Vissani 96'
Flanz, Paschos, Sarkar 96'

for a quasi-degenerate spectrum of N_i : resonance occurs for CP-asymmetry

$$M_{N_1} \sim M_{N_2}$$



M_{N_1} bounded from below only by sphaleron decoupling scale and m_h

leptogenesis with $M_{N_1} \sim \mathrm{TeV}$ perfectly possible

Pilaftsis '97; '99; Pilaftsis, Underwood '05; ...;
Dev, Millington, Pilaftsis, Teresi '14

a precise treatment of the resonant case requires inclusion of a series of extra effects, in particular quantum Boltzmann equations

takes into account memory effects, off-shell effects,
finite density effects, flavor oscillations, decoherence

Buchmüller, Fredenhagen '00
De Simone, Riotto '07
Cirigliano, Isidori, Masina, Riotto, '08
Anisimov, Buchmüller, Drewes, Mendizabal '08
Garny, Hohenegger, Kartavtsev, Lindner '09
Garny, Hohenegger, Kartavtsev, '11
Garbrecht, Herranen '11
Cirigliano, Lee, Ramsey-Musolf, Tulin '13,
Bhupal Dev, Millington, Pilaftsis, Teresi '14, '15
....

Leptogenesis for very light N : $m_N \sim \mathrm{GeV}$

N oscillation frameworks

↪ based on purely flavour asymmetries

Akhmedov, Rubakov, Smirnov 98'
Asaka, Shaposhnikov 05'; Shaposhnikov 08'
Drewes, Garbrecht 11'
Canetti, Drewes, Frossard, Shaposhnikov 13'
Hernandez, Kekic, Lopez-Pavon, Racker, Rius 15'
.....

or new alternative mechanism: leptogenesis from L-violating Higgs decay

T.H., Teresi 16', 17'

$$H \to NL$$

Leptogenesis relevant scales for low m_N

very low m_N leptogenesis: different from $m_N \gtrsim TeV$ leptogenesis in many ways:

$T_{Sphaler.} > m_H >> m_{N,L}$ $T_{Sphaler.} \sim 135\,\mathrm{GeV}$

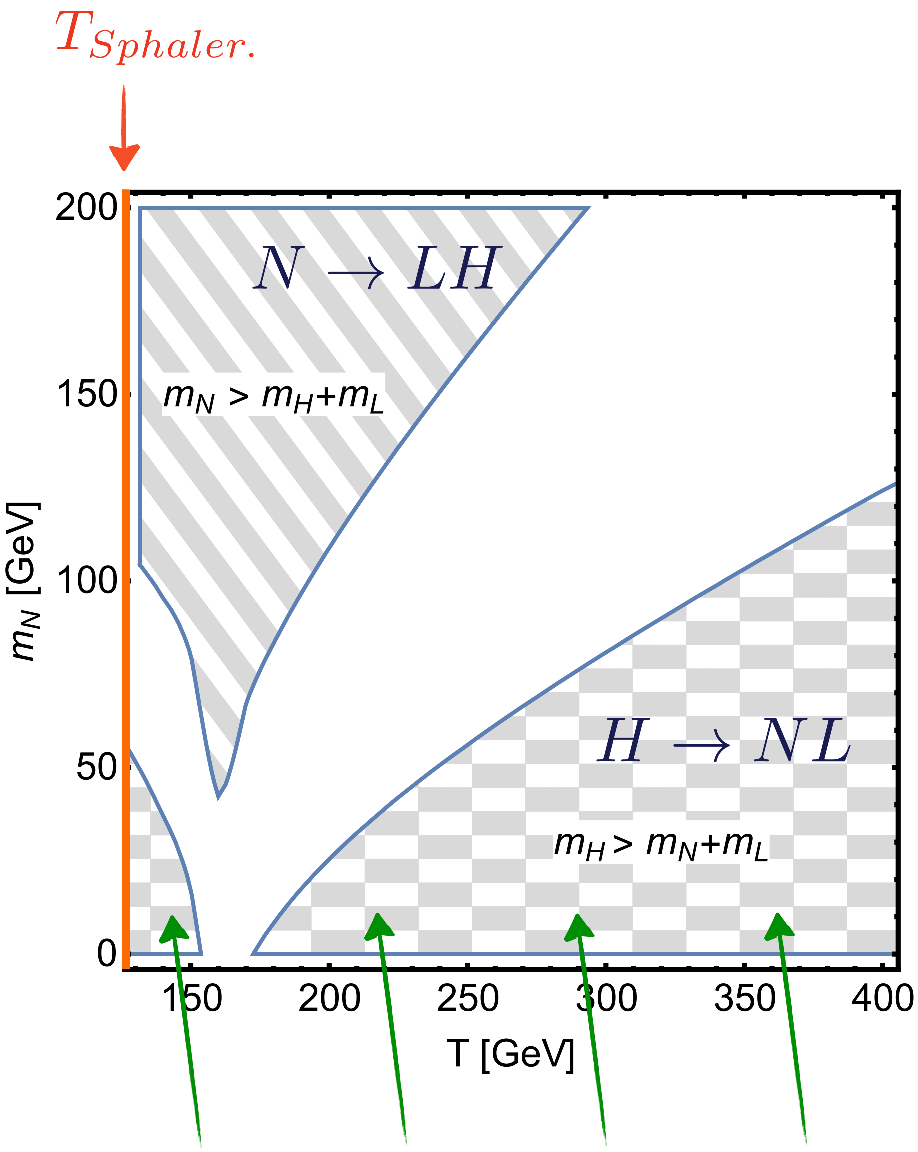
↪ creation of L asymmetry at $T > T_{Sphaler.} >> m_N$ ⇒ $\neq$ regime

↪ thermal effects are fully relevant: $T > T_{Sphaler.} > m_H >> m_{N,L}$

$$m_H^2(T) = m_H^2 + c_H \cdot T^2 \qquad m_L^2(T) = m_L^2 + c_L \cdot T^2 \qquad m_N^2(T) = m_N^2 + c_N \cdot T^2$$

↪ usual leptogenesis $N \rightarrow LH$ decay forbidden but $H \rightarrow NL$ allowed

Temperatures allowing the $N \to LH$ and $H \to NL$ decays



$H \to NL$ leptogenesis from this region?

L asymmetry production from $H \to NL$ decay

↪ 2 issues at first sight:

1) out-of-equilibrium decay? ← 3rd Sakharov condition

↪ H decaying particle is in deep thermal equilibrium at $T > T_{Sphaler.}$

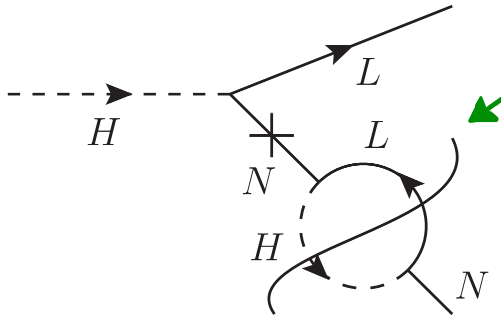
but N in decay product is not necessarily in thermal equilibr.

$$\frac{dn_N}{dt} \propto \Big(\underset{\underset{H \to NL}{\uparrow}}{n_N^{eq}} - \underset{\underset{NL \to H}{\uparrow}}{n_N}\Big) \cdot \Gamma_{H\to NL}$$

L asymmetry production from $H \to NL$ *decay*

T.H., Teresi 16'

2) Absorptive part for CP violation?



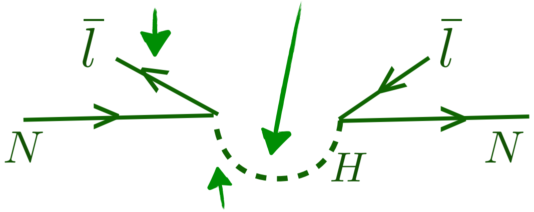
$m_H + m_L > m_N$ $\Rightarrow$ no absorptive part?

↪ but only for $T = 0$!

finite T corrections: thermal cut: if H or L comes from the thermal bath the cut is kinematically allowed

$\propto f_{\bar{l}}^{FD} \propto \underline{1} + f_H^{BE}$

Giudice, Notari, Raidal, Riotto, Strumia 03'
Frossard, Garny, Hohenegger, Kartavtsev, Mitrouskas 12'



$\Rightarrow$ absorptive part $\Gamma_N(T)$ (calculated in Kadanoff Baym formalism)

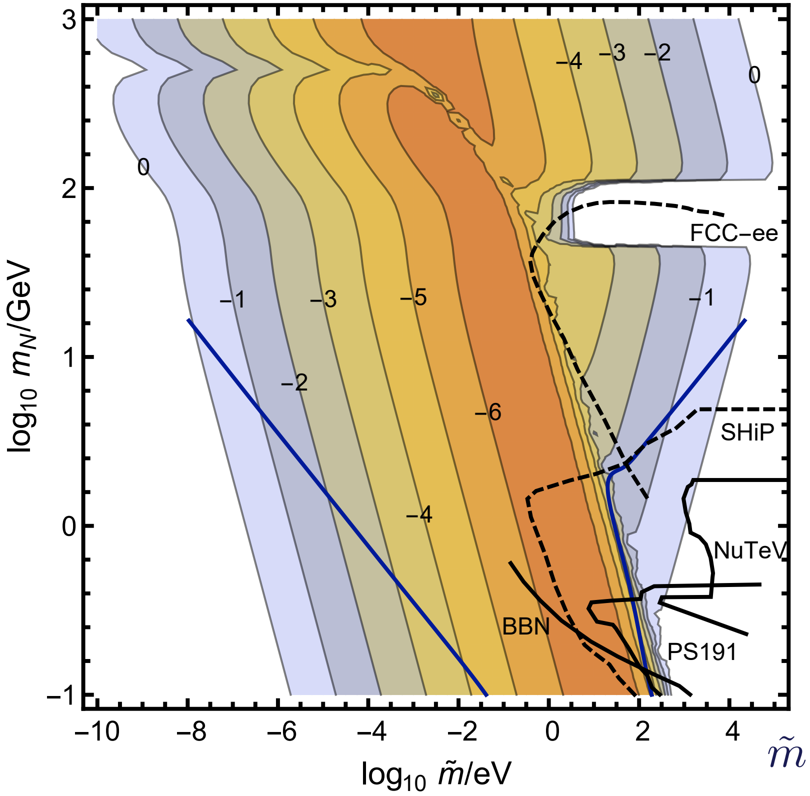
Frossard, Garny, Hohenegger, Kartavtsev, Mitrouskas 12'

$$\varepsilon_{CP} = \frac{\mathrm{Im}[(Y_N Y_N^\dagger)_{12}^2]}{(Y_N Y_N^\dagger)_{11}(Y_N Y_N^\dagger)_{22}} \cdot \frac{2\,\Delta m_N^0\,\Gamma_N(T)}{4\,\Delta m_N(T)^2 + \Gamma_N(T)^2}$$

↪ with thermal mass splitting: $\Delta m_N(T) \simeq \Delta m_N^0 + \frac{\pi T^2}{4\,m_N^2}\Gamma_{22}\sqrt{\left(1 - \frac{\Gamma_{11}}{\Gamma_{22}}\right)^2 + 4\,\frac{|\Gamma_{12}|^2}{\Gamma_{22}^2}}$

$\Gamma_{ij} \equiv m_N (Y_N Y_N^\dagger)_{ij}/(8\pi)$

Results for the CP asymmetry needed for successful leptogenesis



$$\tilde{m} \equiv \frac{Y_N Y_N^\dagger v^2}{2m_N}$$

Boltzmann equations:

$$\frac{n_\gamma H_N}{z}\frac{d\eta_N}{dz} = \left(1 - \frac{\eta^N}{\eta_N^{\rm eq}}\right)\Big[\gamma_D + 2(\gamma_{Hs} + \gamma_{As}) + 4(\gamma_{Ht} + \gamma_{At})\Big]\,,$$

$$\frac{n_\gamma H_N}{z}\frac{d\eta_L}{dz} = \gamma_D\left[\left(\frac{\eta^N}{\eta_N^{\rm eq}} - 1\right)\epsilon_{CP}(z) - \frac{2}{3}\eta_L\right] - \frac{4}{3}\eta_L\left[2(\gamma_{Ht} + \gamma_{At}) + \frac{\eta^N}{\eta_N^{\rm eq}}(\gamma_{Hs} + \gamma_{As})\right]$$

$$\eta_N \equiv n_N/n_\gamma$$

$$z \equiv m_N/T$$

- requires that at least 2 of the N have quasi-degenerate masses

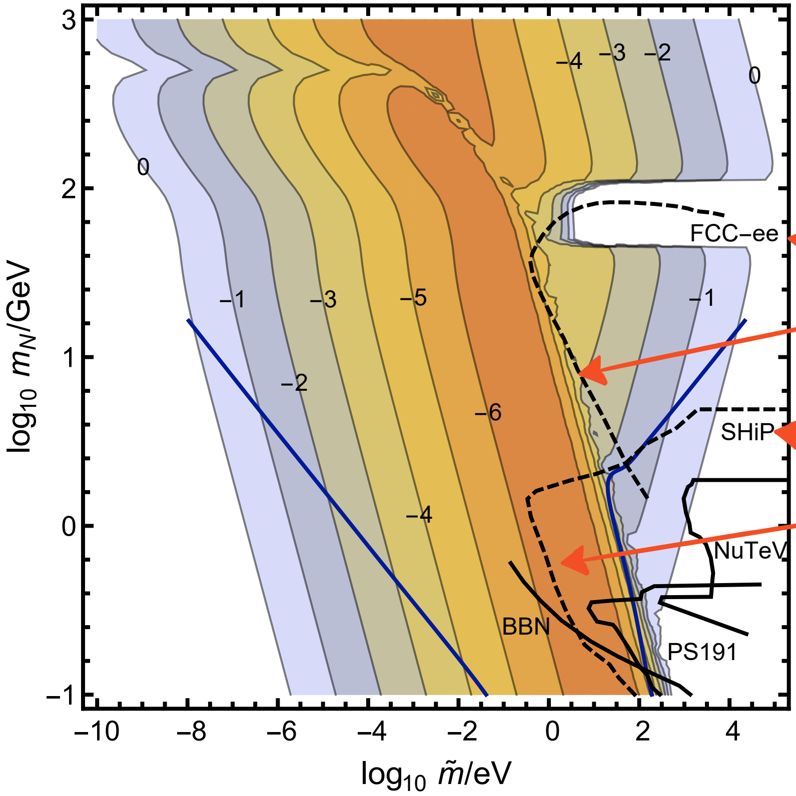
  for example for $m_N \sim 10\,\mathrm{GeV}$ and $\tilde{m} \sim 0.1\,\mathrm{eV}$ one needs $\Delta m_N^0/m_N \lesssim 10^{-5}$

- leptogenesis for m_N as low as $\sim 20\,\mathrm{MeV}$ is possible (BBN concerns below $\sim 200\,\mathrm{MeV}$)

  if only $N \to LH$ decay we need instead: $m_N > 50\,\mathrm{GeV}$

- in all cases: asymmetry production at T just above $T_{Sphaler.}$ $\Rightarrow$ no dependence on UV physics!

Testability!



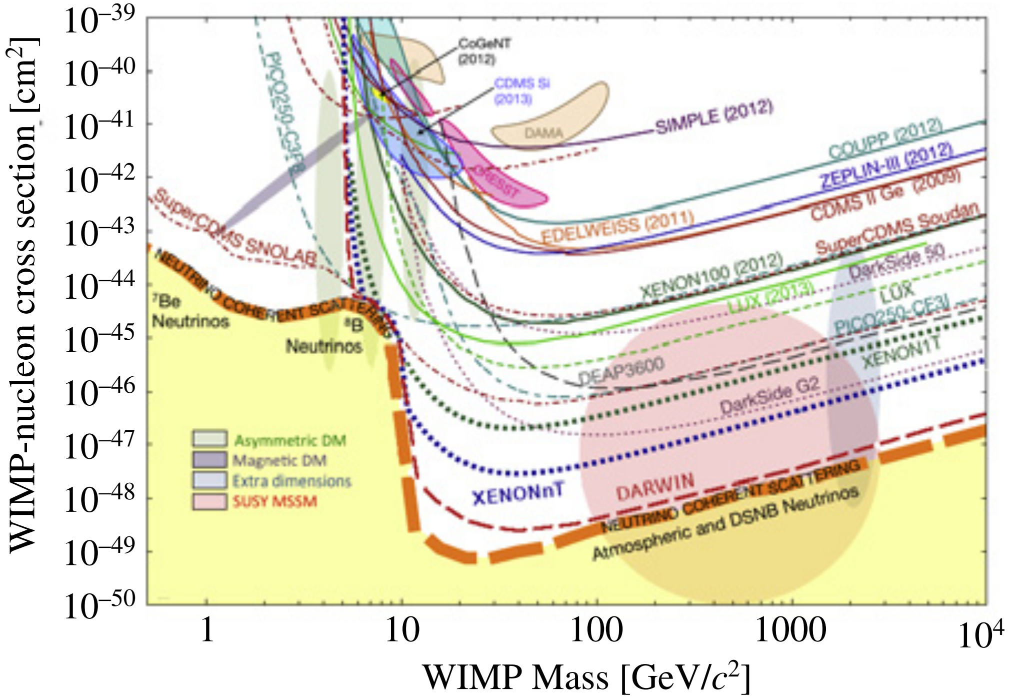
region that FCC should probe if constructed

region that SHIP should probe

Neutrino physics and Dark Matter

Testing ν-physics at DM direct detection expts.

solar and atmospheric neutrinos constitute an irreducible background for DM direct detection experiments



Neutrino Non-Standard Interactions can increase or lower the neutrino floor level by a factor of ~2

$$\mathcal{L}_{NSI} = 2\sqrt{2}G_F\,\bar{\nu}_{\alpha L}\gamma^{\mu}\nu_{\beta L}(\epsilon^{fL}_{\alpha\beta}\bar{f}_L\gamma_{\mu}f_L + \epsilon^{fR}_{\alpha\beta}\bar{f}_R\gamma_{\mu}f_R)$$

see talk by M. Masud

Dutta, Liao, Strigari, Walker 17'
Ariztizabal-Sierra, Rojas, Tytgat 17'
Ariztizabal-Sierra, Dutta, Liao, Strigari 19'

⇒ DM direct detection at the level of neutrino floor will constraint the NSI

The recent COHERENT expt results reporting the first evidence for coherent nu-nuclei scattering are also quite interesting for constraining NSI

COHERENT Coll. 17'

See talk by K. Scholberg

Coloma, Esteban, Gonzalez-Garcia, Maltoni 19'

Boosted DM in neutrino detectors

- halo DM today is highly non relativistic: $v/c \sim 10^{-3}$ ⇒ DM not detectable in neutrino detectors through DM-Nucleon or DM-electron scattering
- but if small proportion of DM was relativistic today they could be observed

D'Eramo, Thaler 10', ….

2 clear possible ways to get boosted DM particles today

multicomponents DM

$$m_{DM_A} > m_{DM_B}$$

$$DM_A DM_A \to DM_B DM_B$$

$$DM_A \to DM_B + X$$

semi-annihilating DM

TH 08'

$$DM + DM \to DM + X$$

Boosted DM in neutrino detectors

first result on boosted DM from Super-Kamiokande for an example model *SK 18'*

$$DM_A DM_A \xrightarrow{\sigma_{thermal}} DM_B DM_B$$

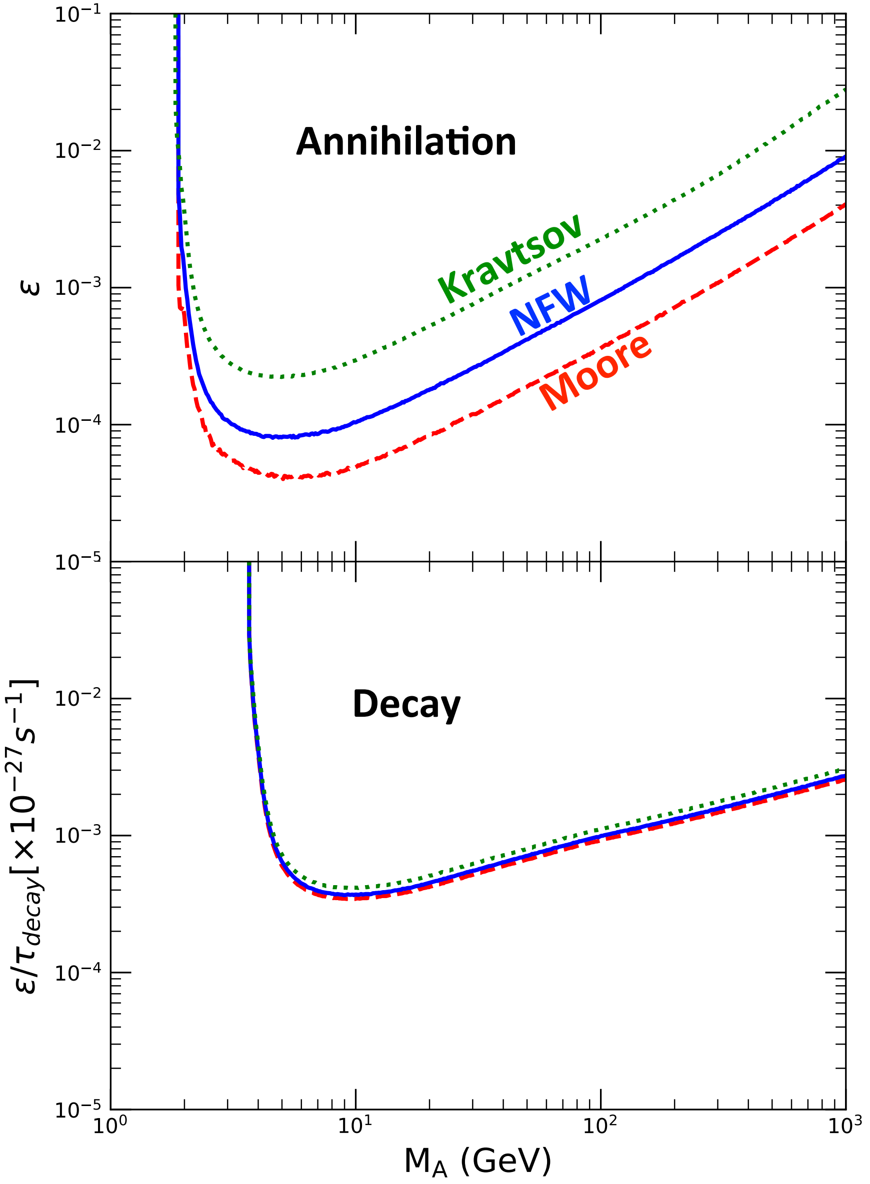
$$DM_B + e^- \xrightarrow{\epsilon} DM_B + e^-$$

$$E_{DM_B} = m_{DM_A}$$

$$DM_A \xrightarrow{\tau_A} DM_B + X$$

$$DM_B + e^- \xrightarrow{\epsilon} DM_B + e^-$$

$$E_{DM_B} = m_{DM_A}/2$$

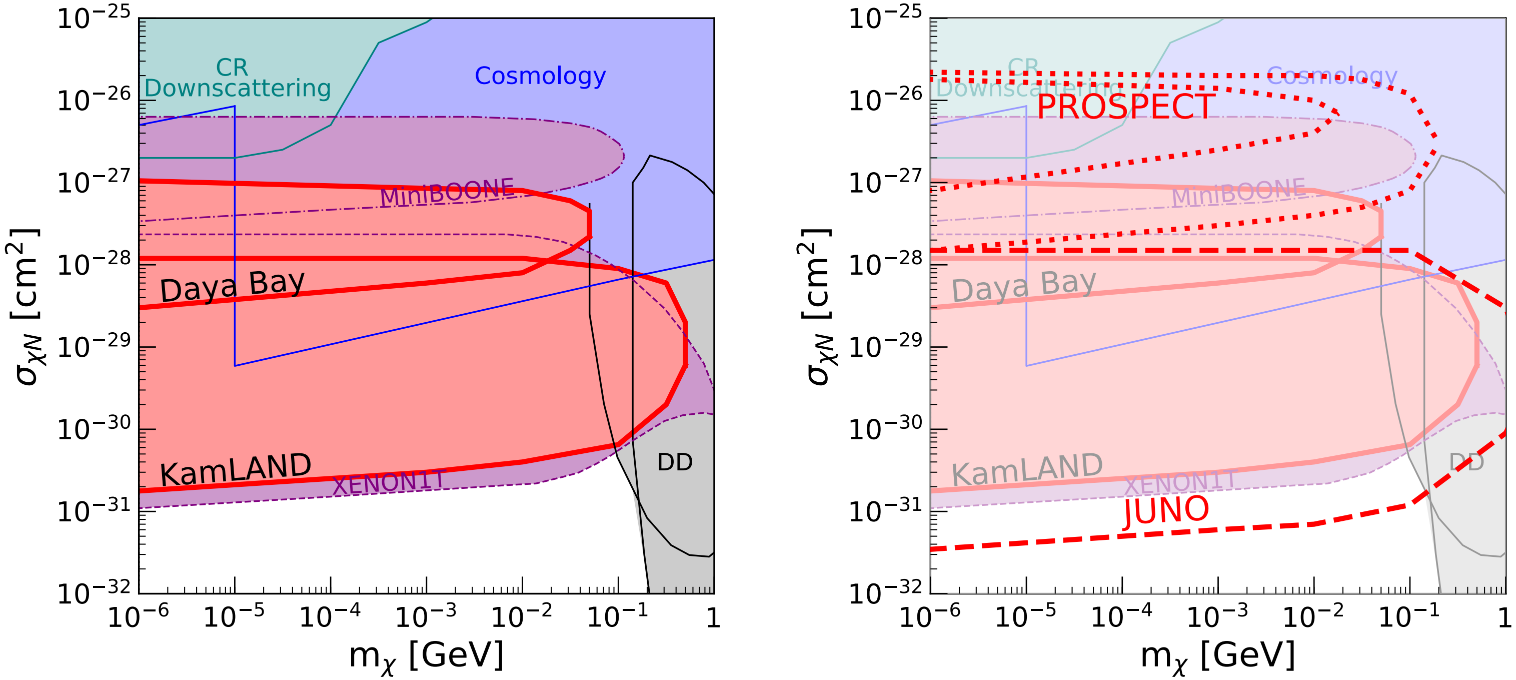


Boosted DM from scatterings with cosmic rays

DM particles from time to time scatters with cosmic rays (mainly p) and get boosted in this way: this gives a low but guaranteed flux of boosted DM!

for low DM mass this gives a very weak upper bound on DM-N cross section but still the best one because no other relevant bounds in this case

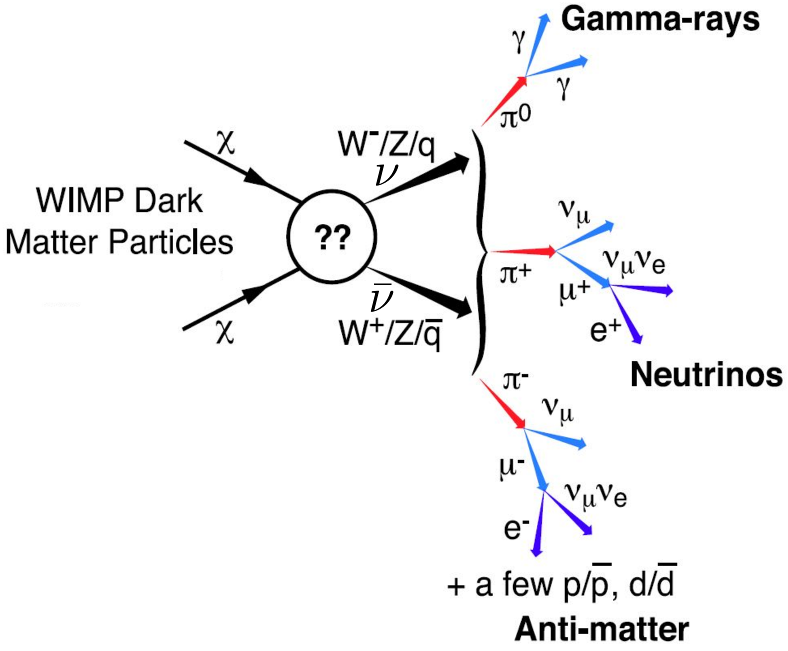
Bringmann, Pospelov 18'
Beacom, Cappiello 19'



probing directly a < GeV DM directly is a just starting but very active task

Probing DM with neutrinos: neutrino telescopes

→ DM annihilation or decay in the galactic center and halo can produce neutrinos



⇒ 2 kinds of signals:

- diffuse ν flux
- monochromatic ν flux

Icecube: see M. Pandey's talk

Motivations for the search of ν-lines

$DM\,DM \rightarrow \nu\,\bar{\nu}$ or $DM \rightarrow \nu + X$: monochromatic flux of ν : "ν-line"

- no astrophysical background: DM smoking gun!

- a ν -line can be produced from a tree level annihilation unlike a γ-line

- for the $DM\,DM \rightarrow \nu\,\bar{\nu}$ channel, neutrino telescopes have the best sensitivity unlike for other channels where γ telescopes are more sensitive

  $DMDM \rightarrow \tau^+\tau^-,\ \mu^+\mu^-,\ e^+e^-,\ W^+W^-,\ q\bar{q},\ ...$

- a line can be very well distinguished from background: in neutrino energy spectrum

well known for γ-rays

from γ telescopes the limit on γ-line channel is 2-3 orders of magnitude better than on channels with secondary photons

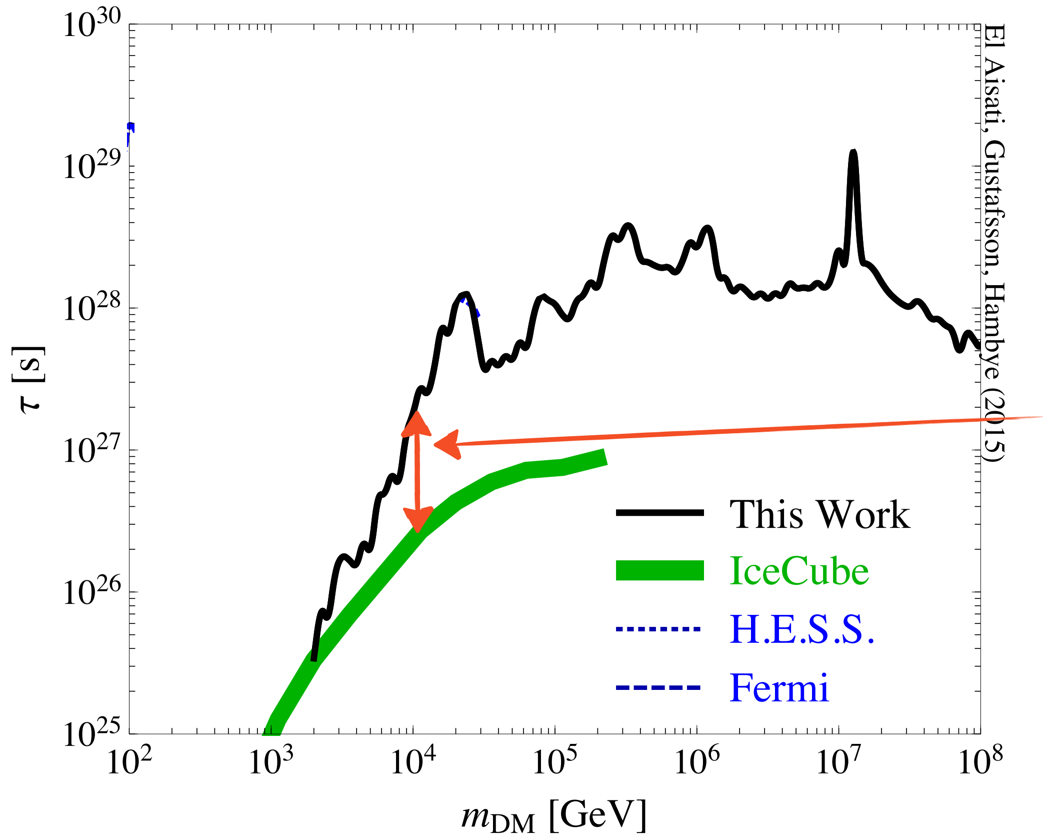
but so far all neutrino telescope limits on ν channel do not look at energy spectrum!!!

First spectrum based search of a 'ν-line' from IceCube data

using a 2010-2012 public IceCube data sample: for DM decay: $\Gamma_{DM\to\nu+X}$

Lifetime lower limit exploiting the sharp spectral feature property:

El Aisati, Gustafsson, TH 15'



~ an order of magnitude improvement from few TeV to 100 TeV

Above 100 TeV there are other limits: Rott, Kohri, Park , 14'
Esmaili, Kang, Serpico 14'

First spectrum based search of a 'ν-line' from IceCube data

using a 2010-2012 public IceCube data sample: for DM decay: $\Gamma_{DM\rightarrow\nu+X}$

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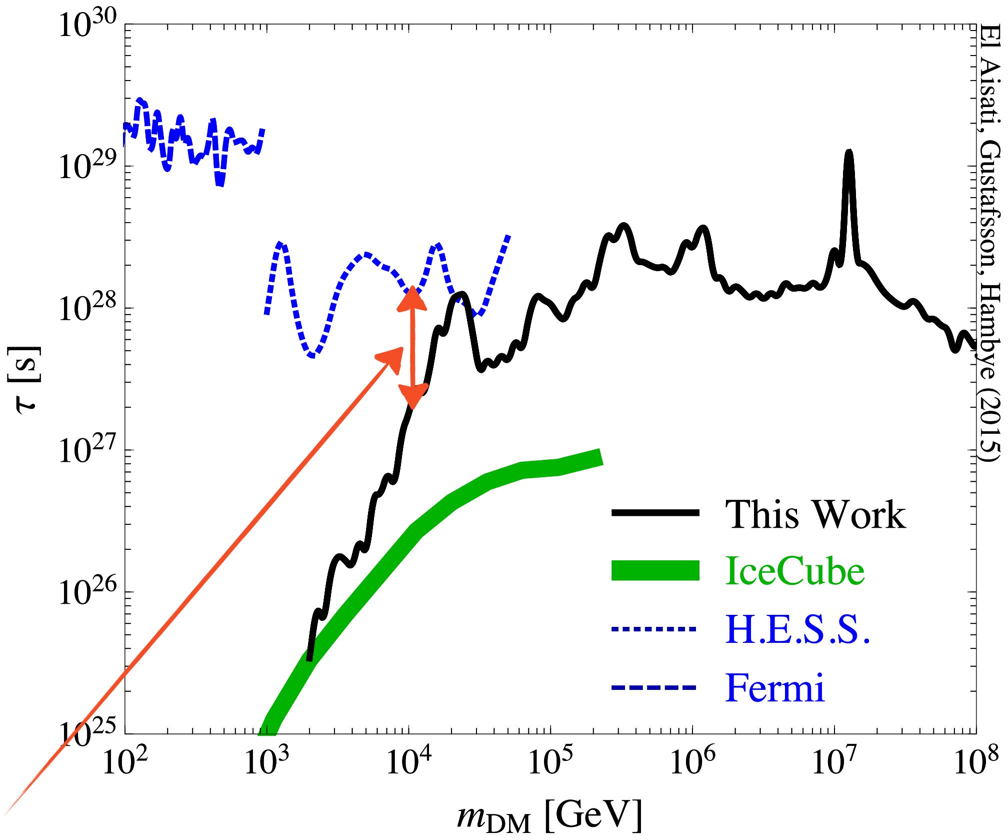
Lifetime lower limit:



between few TeV and 50 TeV, γ and ν line sensitivities are similar! ← within a factor 1 to 20

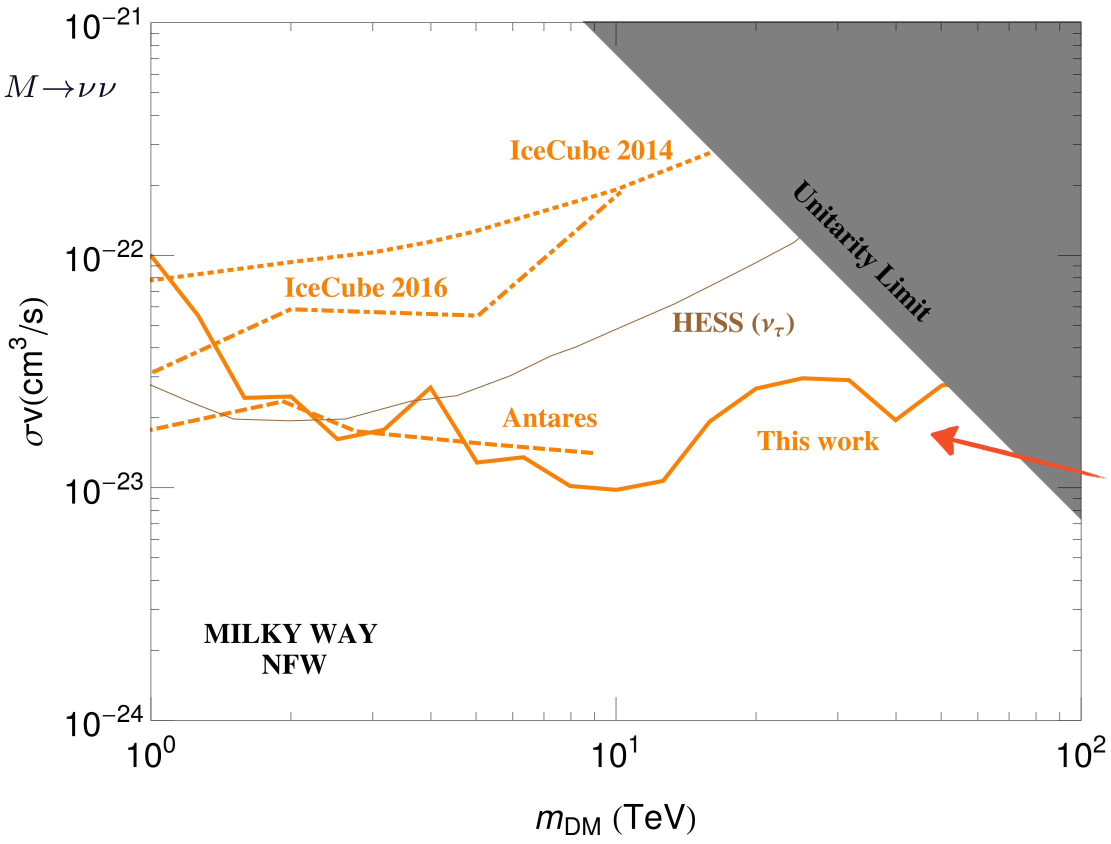
Monochromatic flux of ν from DM annihilation: experimental limits

Observational situation for an annihilation: $\langle\sigma\, v\rangle_{DMDM\to\nu\nu}$

Annihilation cross section upper limit:

El Aisati, Garcia-Cely, T.H., Vanderheyden 17

$\langle\sigma\, v\rangle_{DMDM\to\nu\nu}$



from line dedicated search using same 1-year data sample than for the decay

decay: $n_\nu \propto \rho_{DM}$

only illustrative: based on sample of only one year and with no angular information:

crucial for annihilation: $n_\nu \propto \rho_{DM}^2$

annihilation signal largely peaked on galactic center unlike for a decay

need also to see the galactic center with good angular resolut. : IceCube new results to come soon!

⇒ Given this exciting experimental situation:

could we expect on the theoretical side signals at the level of present and future sensitivities??

What about model-building? ν-line sensitivity reachable?

for the decay case: easy to have an observable flux!

El Aisati, Gustafsson,TH, Scarna '16

for the annihilation case: possibilities to have an observable flux!

future ν-line sensitivity $\langle \sigma v \rangle_{DM\,DM \to \nu\nu} \sim \mathrm{few}\, 10^{-25}$ will not reach the thermal freeze out total cross section value $\langle \sigma v \rangle_{Tot} \sim 3 \cdot 10^{-26}$

this excludes an observable ν-line for most models but not necessarily: need for a boost of the cross section from freeze out epoch to today

astrophysical boost

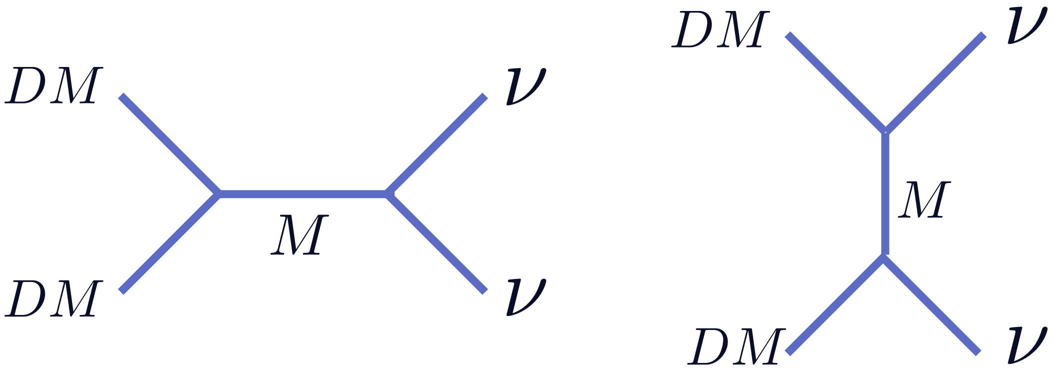
particle physics boost: Sommerfeld effect

non relativistic DM particles today can exchange many lighter mediators before annihilating

Determination of minimal models leading to observable ν-line from DM annihilation

El Aisati, Garcia-Cely, TH, Vanderheyden 17

- for spin 0 or 1/2 DM
- with DM out of single multiplet of $SU(3)_c \times SU(2)_L \times U(1)_Y$
- with $DM\,DM \to \nu\nu$ mediated by single mediator multiplet



⇒ systematic study of these minimal models

⇒ which ones of these models can lead to an observable ν-line from DM annihilation through the Sommerfeld effect????

List of simple candidate models for an observable ν flux

20 models: surviving direct detection, s-wave annihil., …

DM and mediator up to triplets

only Dirac DM for $\nu\bar{\nu}$ channel

$\nu\nu$ channel

Annihilation Channel	DM		Mediator		m_ν OK at 1-loop?	Suppressed by $v_{\text{EW}}/m_{\text{DM}}$?	$\ell^+\ell^-$	Model
$\overline{\text{DM}}\text{DM} \to \bar{\nu}\nu$	Dirac	T_0	s-chann. vector	S	Yes	No	$=$	F_1
		T_0	t-chann. scalar	D				F_2
		S	s-chann. vector	S				F_3
		S	t-chann. scalar	D				F_4
$\text{DMDM} \to \nu\nu$	Real Scalar	D	s-chann. scalar	T_2	$\pm$	No	$/$	S_1^r
		S	t-chann. Majorana	D	No	Yes		S_2^r
		D		S		No		S_3^r
		D		T_0		No		S_4^r
		D		T_2		Yes		S_5^r
		T_0		D		Yes		S_6^r
		T_2		D		Yes		S_7^r
	Majorana	D	s-chann. scalar	T_2	$\pm$	No		F_1^m
		S	t-chann. scalar	D	No	Yes		F_2^m
		D		S		No		F_3^m
		D		T_0		No		F_4^m
		D		T_2		Yes		F_5^m
		T_0		D		Yes		F_6^m
		T_2		D		Yes		F_7^m
	Complex Scalar	S	t-chann. Majorana	D	Yes	Yes		S_1
		T_0		D				S_2
	Dirac	S	t-chann. scalar	D	Yes	Yes		F_4
		T_0		D				F_2

El Aisati, Garcia-Cely, T.H., Vanderheyden '17
See also related table in Lindner, Merle, Niro '10

7 simple models leading to observable ν flux at ν telescopes

surviving neutrino mass constraint, other indirect detection limits, perturbativity….

Annihilation Channel	DM		Mediator		m_ν OK at 1-loop?	Suppressed by $v_{\rm EW}/m_{\rm DM}$?	$\ell^+\ell^-$	Model
$\overline{\rm DM}{\rm DM} \to \bar{\nu}\nu$	Dirac	T_0	s-chann. vector	S	Yes	No	$=$	F_1
		T_0	t-chann. scalar	D				F_2
		S	s-chann. vector	S				F_3
		S	t-chann. scalar	D				F_4
${\rm DMDM} \to \nu\nu$	Real Scalar	D	s-chann. scalar	T_2	±	No	≠	S_1^r
		~~S~~	~~t-chann. Majorana~~	~~D~~	No	~~Yes~~		~~S_2^r~~
		~~D~~		~~S~~		~~No~~		~~S_3^r~~
		~~D~~		~~T_0~~		~~No~~		~~S_4^r~~
		~~D~~		~~T_2~~		~~Yes~~		~~S_5^r~~
		~~T_0~~		~~D~~		~~Yes~~		~~S_6^r~~
		~~T_2~~		~~D~~		~~Yes~~		~~S_7^r~~
	Majorana	D	s-chann. scalar	T_2	±	No		F_1^m
		~~S~~	~~t-chann. scalar~~	~~D~~	No	~~Yes~~		~~F_2^m~~
		~~D~~		~~S~~		~~No~~		~~F_3^m~~
		~~D~~		~~T_0~~		~~No~~		~~F_4^m~~
		~~D~~		~~T_2~~		~~Yes~~		~~F_5^m~~
		~~T_0~~		~~D~~		~~Yes~~		~~F_6^m~~
		~~T_2~~		~~D~~		~~Yes~~		~~F_7^m~~
	Complex Scalar	S	t-chann. Majorana	D	Yes	Yes		S_1
		~~T_0~~		~~D~~				~~S_2~~
	Dirac	S	t-chann. scalar	D	Yes	Yes		F_4
		T_0		D				F_2

possible only for $m_{DM} \gtrsim$ TeV not to induce too large l^+l^- flux because these models predict

$$\Phi_{\nu\bar{\nu}} = \Phi_{l^+l^-}$$

excluded: give too many diffuse W^+W^- or too intense γ-line

possible only for $m_{DM} \lesssim$ TeV due to perturbativity:

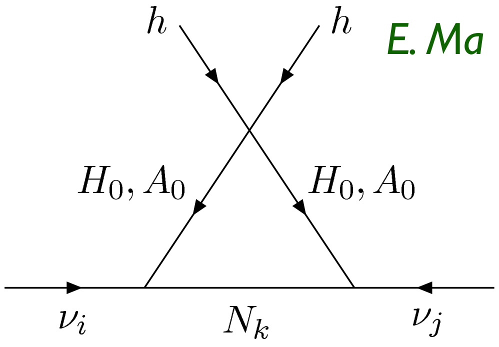
El Aisati, Garcia-Cely, T.H., Vanderheyden '17

there exist simple models leading to observable neutrino flux at neutrino telescopes

Neutrino masses, leptogenesis and Dark Matter common frameworks

an all industry! (India is biggest world producer of these models!)

the most well-known example: scotogenic model



E. Ma

H_2 and N_i are odd under a Z_2 symmetry → the lightest of these states is DM

if the inert doublet is DM: successful leptogenesis at low scale without mass degeneracy

TH, Ling, Lopez-Honorez, Rocher 09'
Hugl, Platscher, Schmitz 18
Borah, Dev, Kumar 18

if N_1 is DM: successful leptogenesis from N_2 decay *Borah, Mahanta 19'*

other recent example of tree level or radiative ν mass + DM (+ leptogenesis):

Biswas, Choubey, Covi, Khan 18', ….+ ~100 papers….,Bhattacharya, Ghosh, Saha, Sil 19', Bhattacharya, Chakrabarty, Roshan, Sil 19'

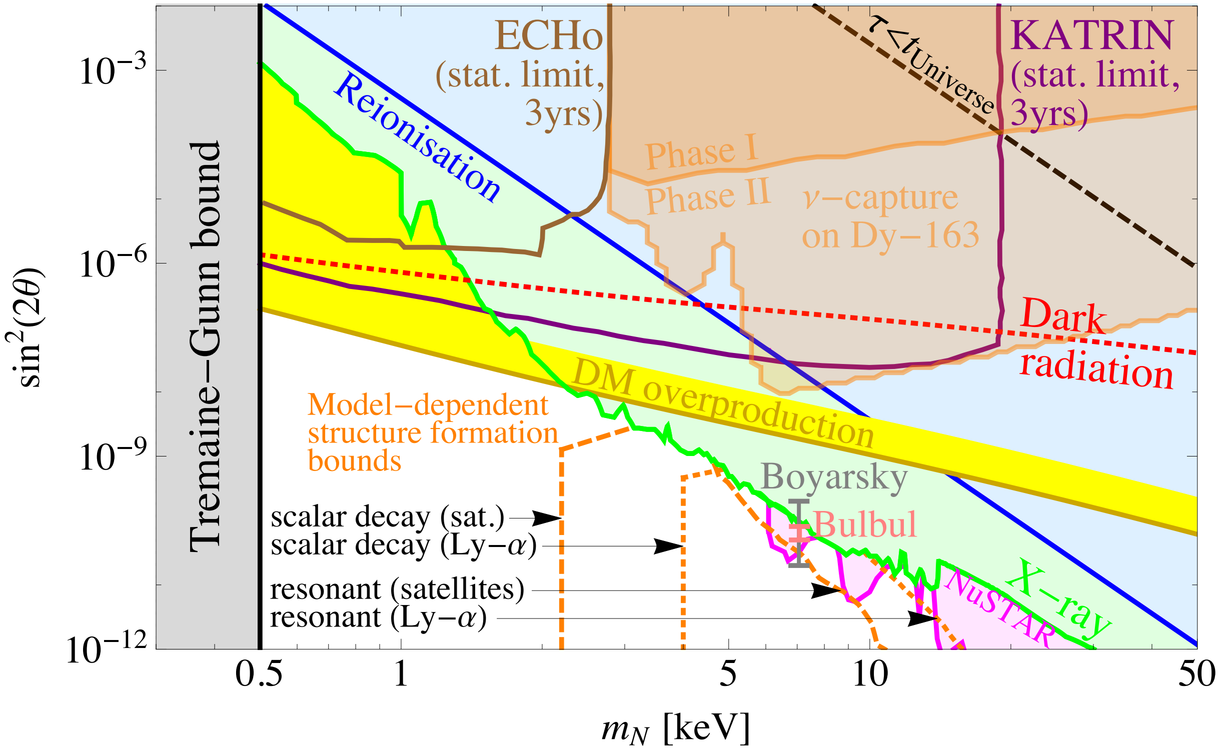
See Anirban Biswas and Subhaditya Bhattacharya' talks

keV sterile neutrino DM

- production through mixing with active neutrinos: very squeezed scenario
- production from decay of BSM scalar particle: more open possibility

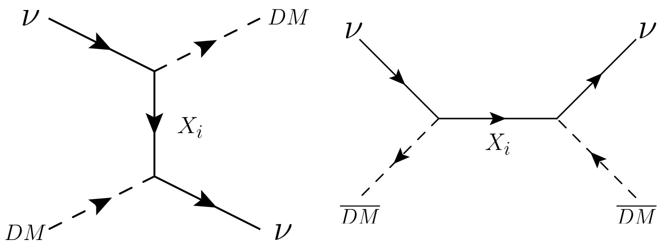
⇓

a talk in itself



Oscillations without ν masses?? ν in a DM medium

ν propagating in a medium of ultralight DM particles



$m_{DM} \sim 10^{-3}\ eV$

$m_X \lesssim 100\ \mathrm{eV}$

$\longrightarrow$ matter effect:

$$\mathcal{H} = \frac{\Delta m^2}{4E_\nu}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} V_{\mu\mu} & V_{\mu\tau} \\ V_{\mu\tau}^* & V_{\tau\tau} \end{pmatrix}$$

$$E_\nu >> \frac{m_X^2}{2m_{DM}} \longrightarrow V_{\alpha\beta} \simeq \frac{g_{\alpha i}^* g_{\beta i}}{4}\,\frac{\rho_{DM}/m_{DM}^2}{2E_\nu}$$

$\uparrow$

same $1/E_\nu$ dependence as
for ν mass contribution

⇒ one can fit ν oscillations without ν masses!

Sawyer 99',Hung 00', Berlin 16', Berlin, Hooper 17',
….., Pandey, Karmakar Rakshit 19',
Gey, Murayama 19', Choi, Chun, Kim 19'

still to be fitted by professional neutrino fitters

issues: UV completion, ….., … ????
implies $\neq$ oscillations for ν and $\bar{\nu}$ if DM asymmetric (to be tested)

Short Summary

ν masses: - best evidence for BSM we have

- origin difficult to probe but clear possibilities exist
- strong indication for GUT: alive and well

Leptogenesis: - works impressively well at GUT scale too

- interesting possibilities at low scale

Many links between DM and ν physics:

- interplay of DM direct detection ν floor and NSI
- observation of boosted DM in ν detectors
- neutrino line smoking gun search fully competitive

further IceCube improvements to be expected in a few months

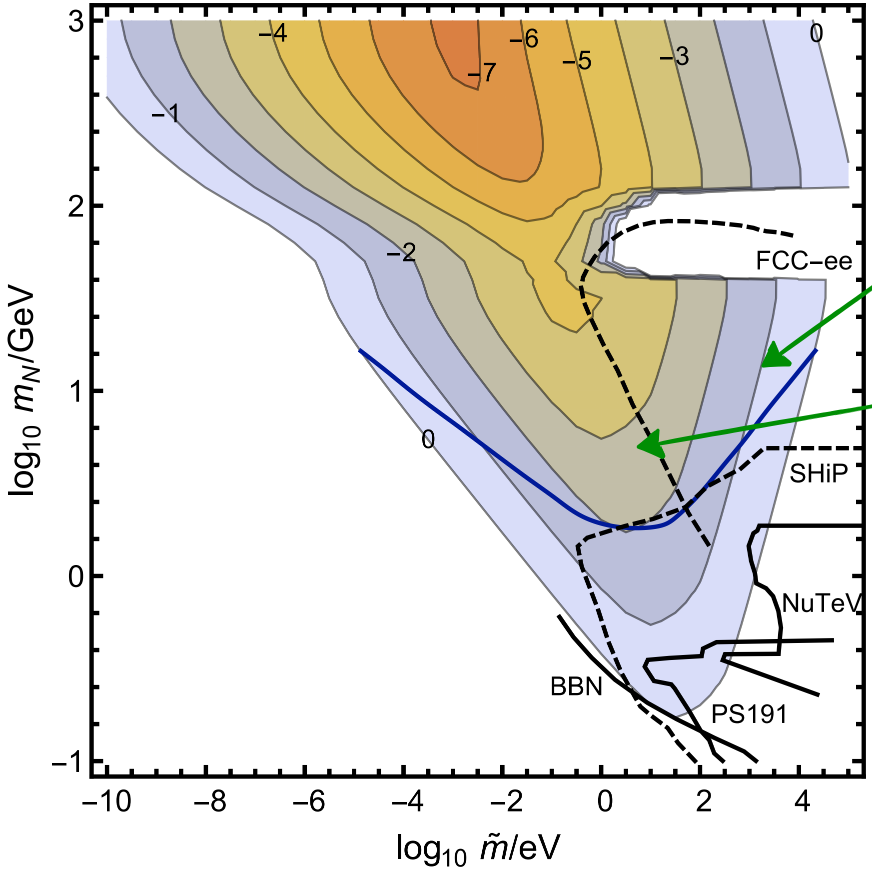
models leading to neutrino line flux sensitivity do exist

- (PeV events: non-thermal DM decay?)
- (keV sterile neutrino DM)
- DM medium induced oscillations

Results for the case where the N have thermalized

if N thermalized by large Y_N Yukawas or other interaction (e.g. a W_R) before an asymmetry is produced

CP-asymmetry needed for successful leptog.



the lower is m_N , the later it goes out-of-equilibrium, the more it will be in equilibr. at $T > T_{Sphaler.}$

$\Downarrow$

lower bound on m_N

$m_N > 2.2\,\mathrm{GeV}$

if only $N \to LH$ decay we get: $m_N > 50\,\mathrm{GeV}$

$$\tilde{m} \equiv \frac{Y_N Y_N^\dagger v^2}{2 m_N}$$

requires that at least 2 of the N have quasi-degenerate masses

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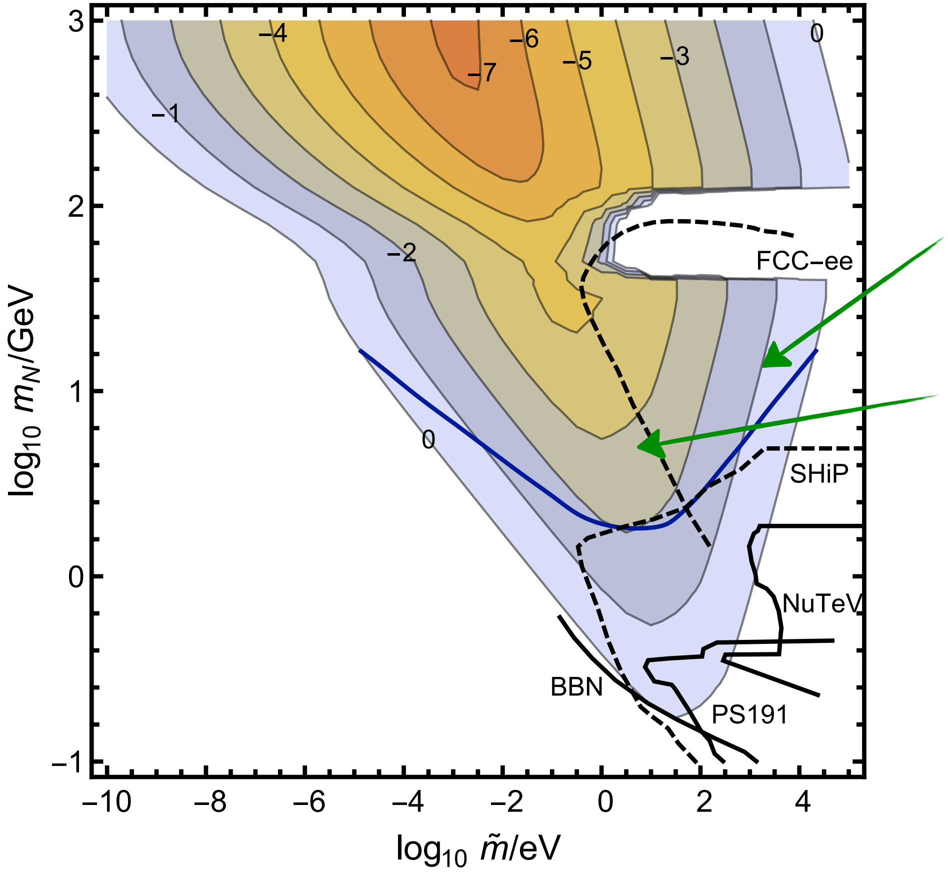

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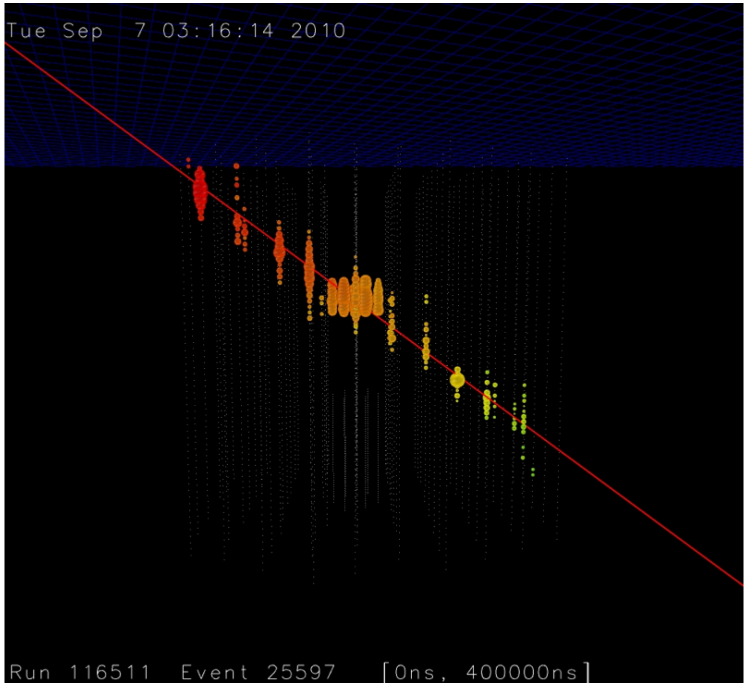
requires that at least 2 of the N have quasi-degenerate masses

More details about minimal models for nu-lines

ν-line search from DM annihilation: need good energy resolution and good angular resolution towards galactic center

muon track:

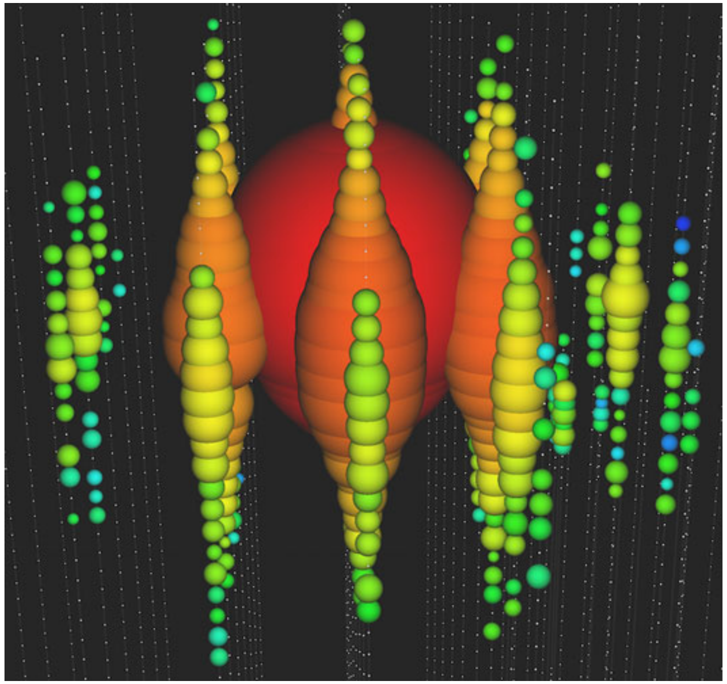


good angular resolut.: $\sim 0.2^\circ - 1^\circ$

poor energy resolut. unless fully contained

OK to see the galactic center for starting inside events

cascade events:



good energy resolut.: $\sim 15\%$

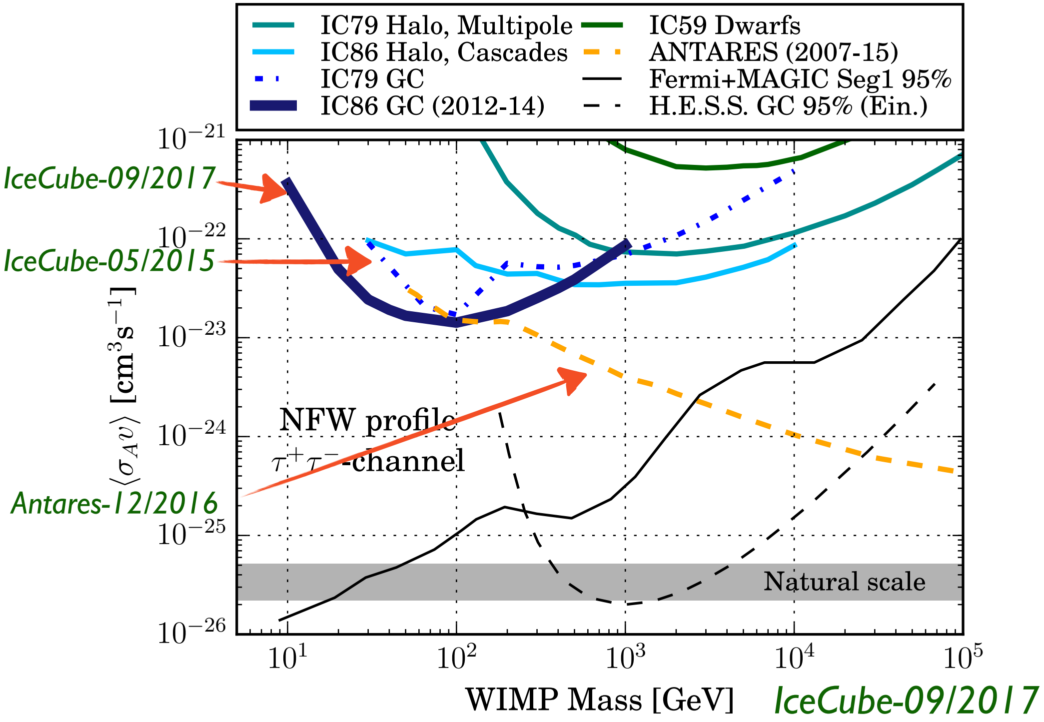
not so good ang. resol.: $\sim 10^\circ - 15^\circ$

good for galactic center events

$\Rightarrow$ very promising even if not as easy as for a decay and as for a γ-line

DM indirect detection with neutrinos

$DM\,DM \rightarrow \tau^+\tau^-$ example:



IceCube-09/2017

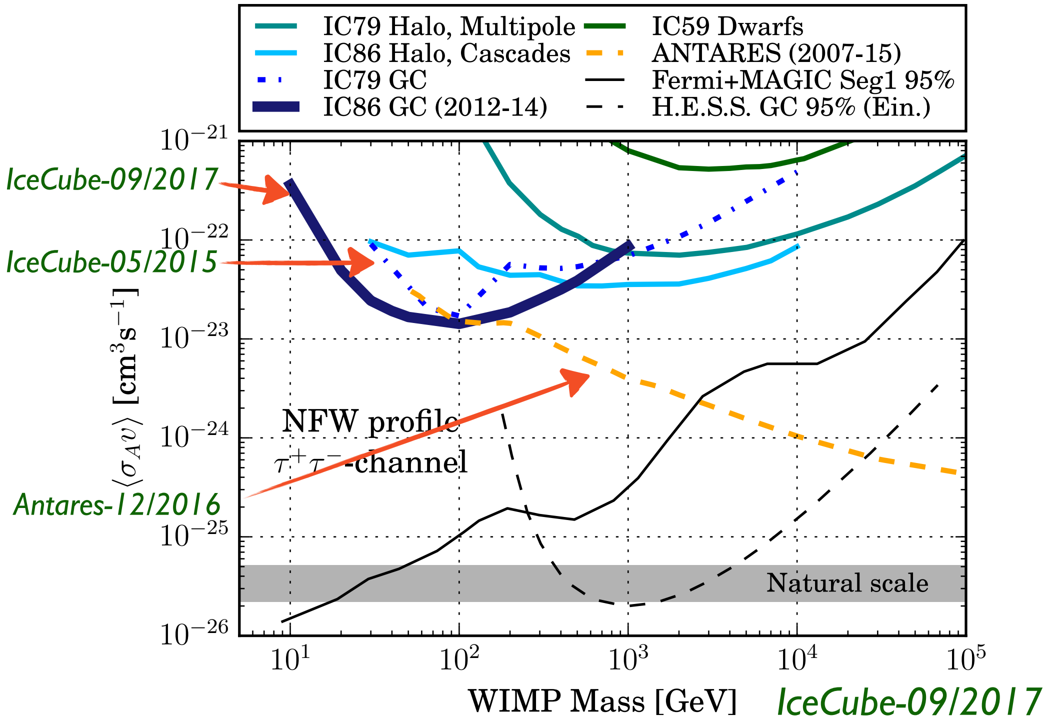
IceCube-05/2015

Antares-12/2016

IceCube-09/2017

DM indirect detection with neutrinos

$DM\ DM \to \tau^+\tau^-$ example:



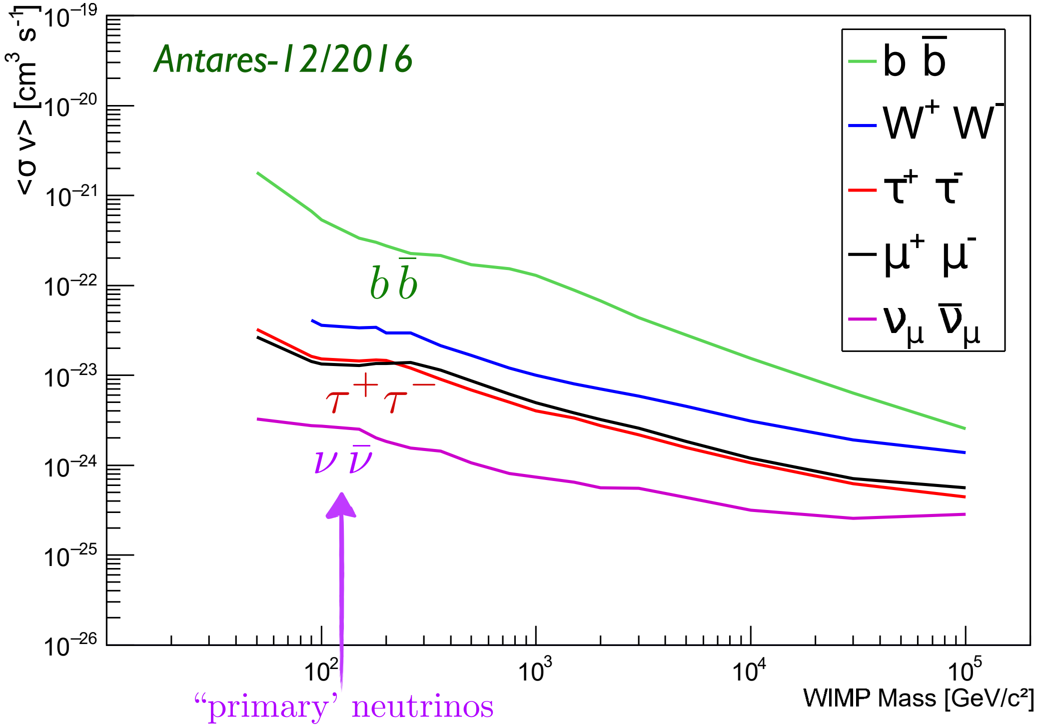
IceCube-09/2017

IceCube-05/2015

Antares-12/2016

IceCube-09/2017

other annihilation channels:

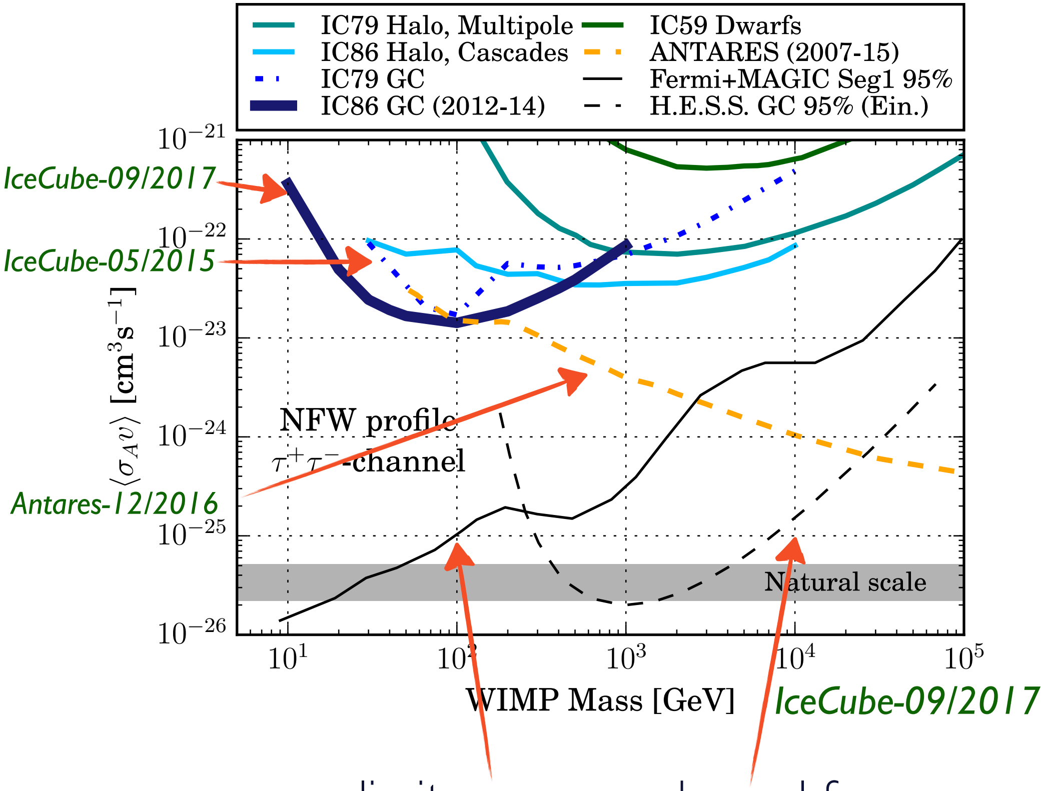


Antares-12/2016

“primary” neutrinos

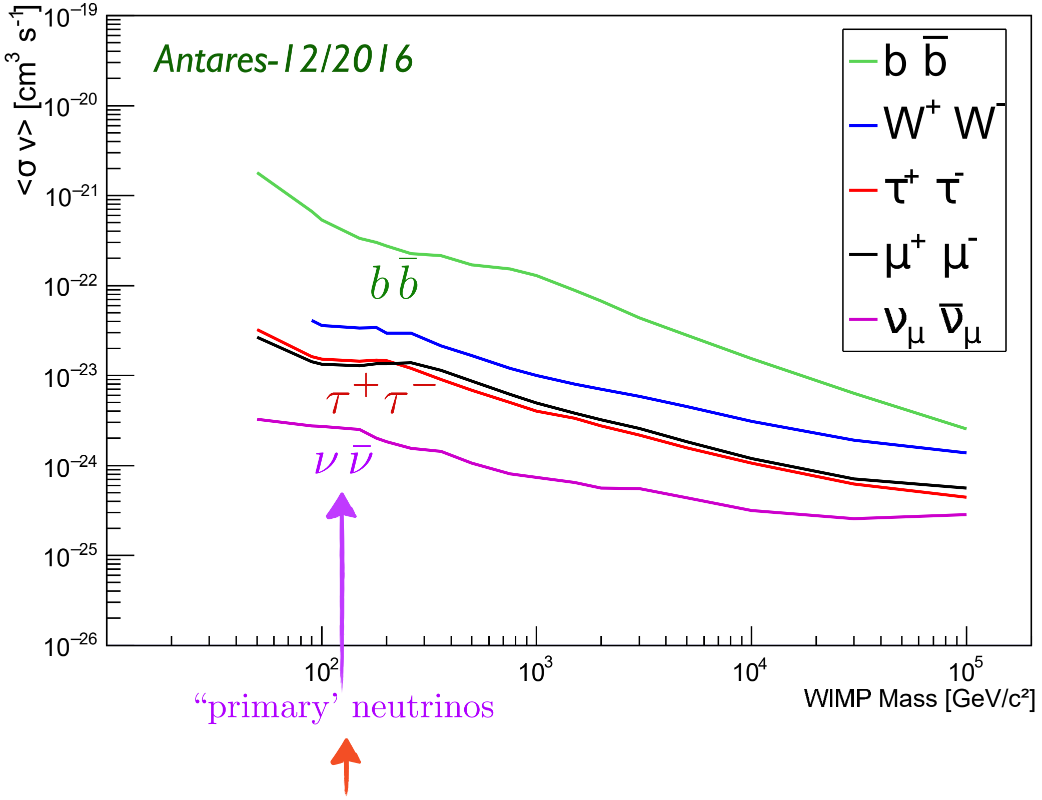
DM indirect detection with neutrinos

$DM\ DM \rightarrow \tau^+\tau^-$ example:



limits on same channel from Fermi and HESS observation of secondary γ-rays better than from observation of secondary ν

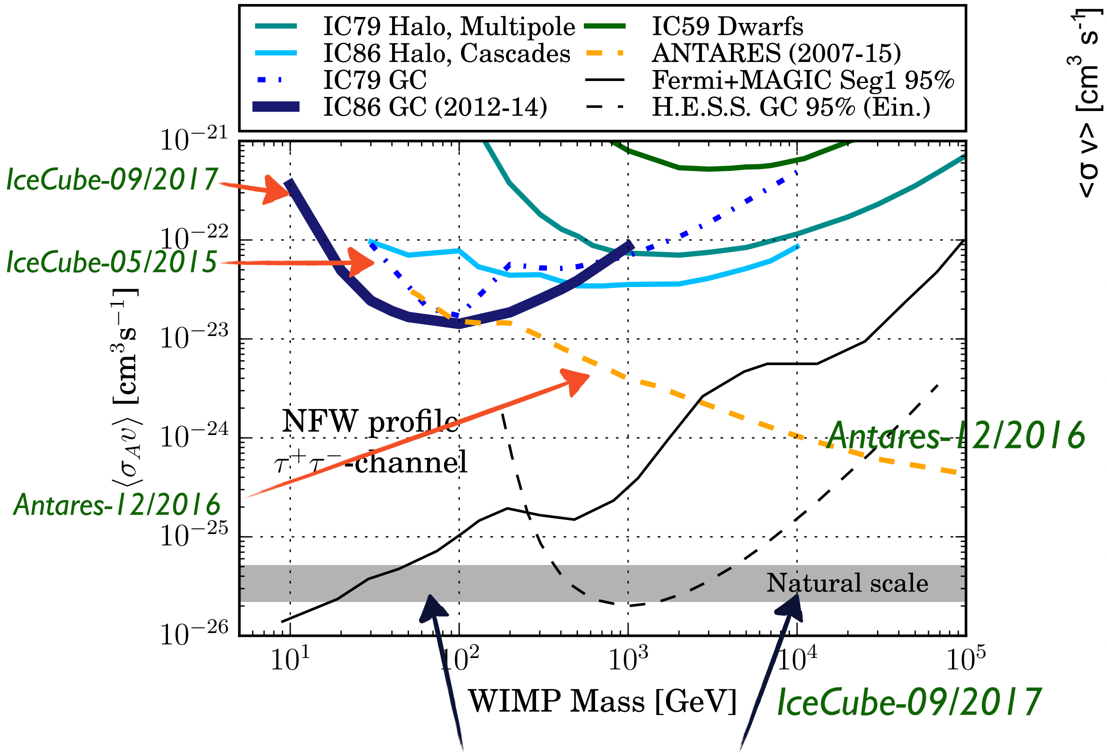
other annihilation channels:



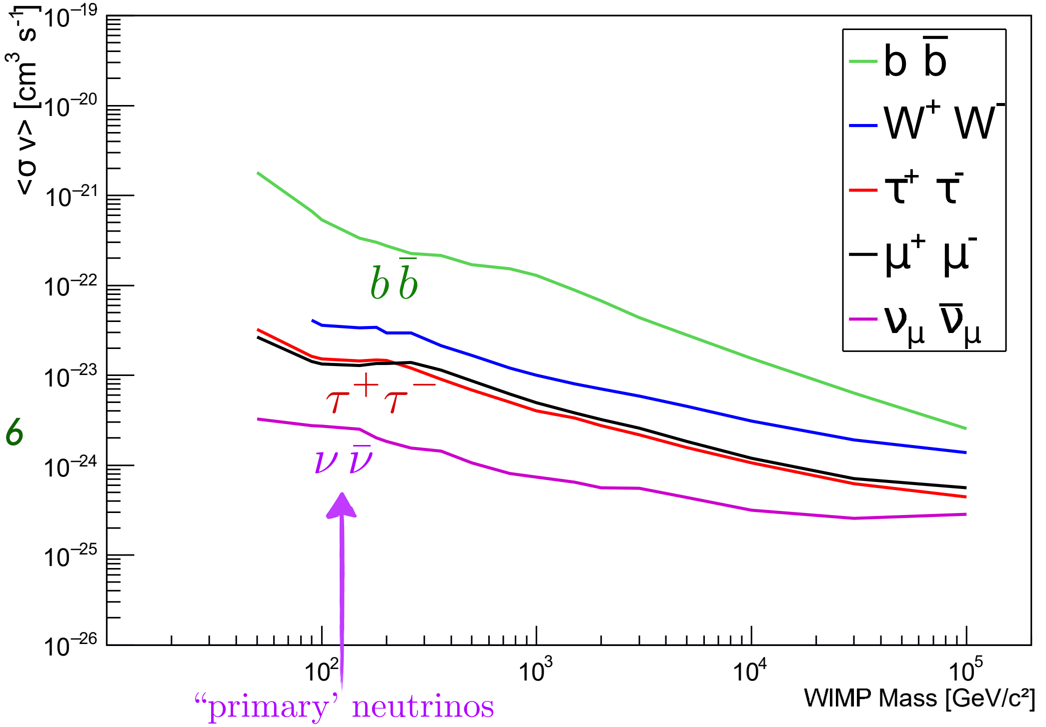
observation of primary neutrinos more competitive

DM indirect detection with neutrinos

$DM\ DM \rightarrow \tau^+\tau^-$ example:



other annihilation channels:



thermal freeze-out value of the cross section smaller than experimental sensitivity

→ at freeze-out early Universe epoch

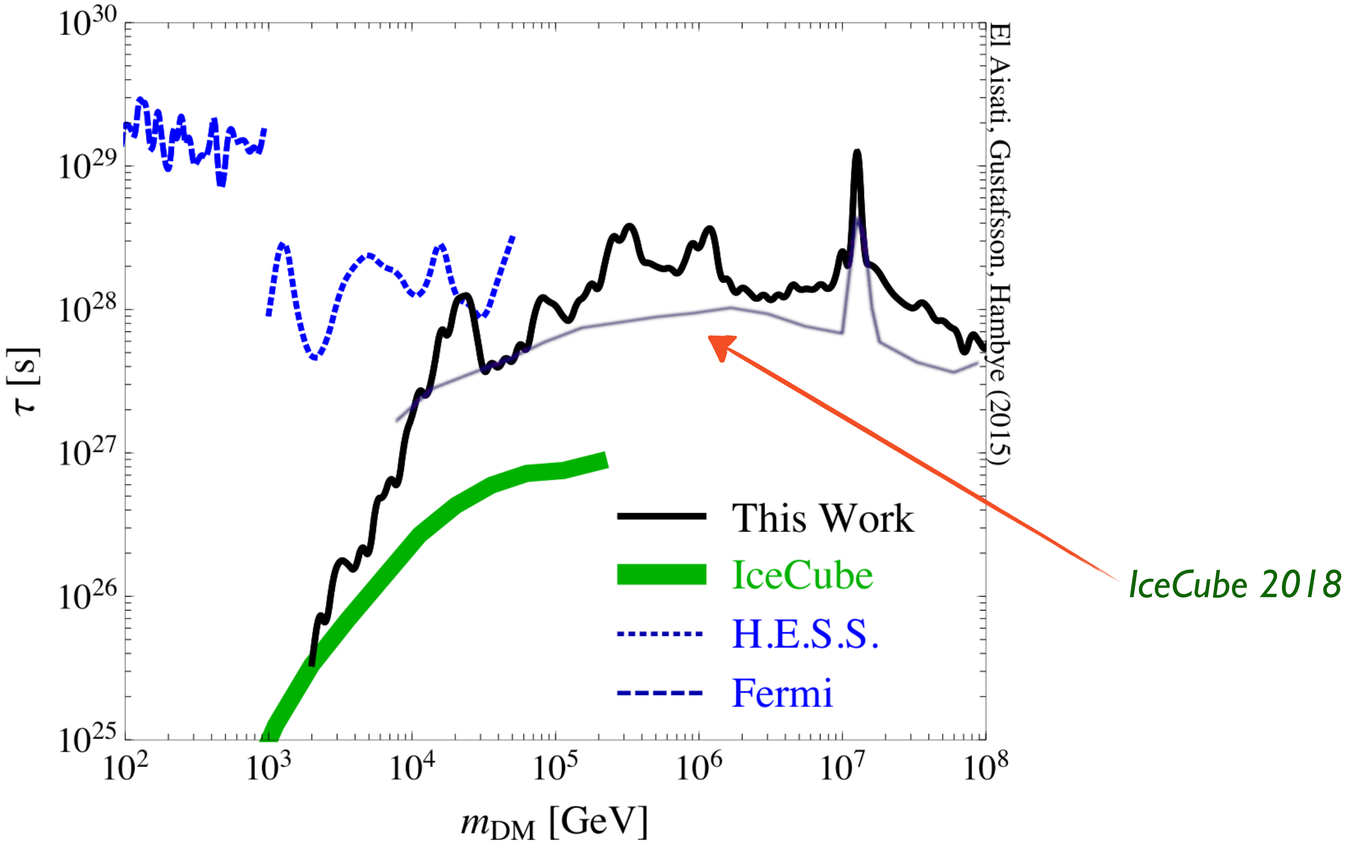
→ today

→ needs for a boost of annih. cross section today with respect to freeze-out epoch

Monochromatic flux of ν from DM decay: experimental limits

→ using a 2010-2012 public IceCube data sample: for DM decay: $\Gamma_{DM\to\nu+X}$

With more statistics but still without exploiting the sharp feature property: Icecube 2018



Probing the DM-Nucleon elastic cross section: ν *from the Sun*

- DM accumulates in the center of the Sun from capture: $DM + N \to DM + N$

- as the amount of captured DM increases, DM annihilates more and more into SM particles leading to a ν flux, until both rates equilibrate each other and the amount of DM in the Sun doesn't change anymore

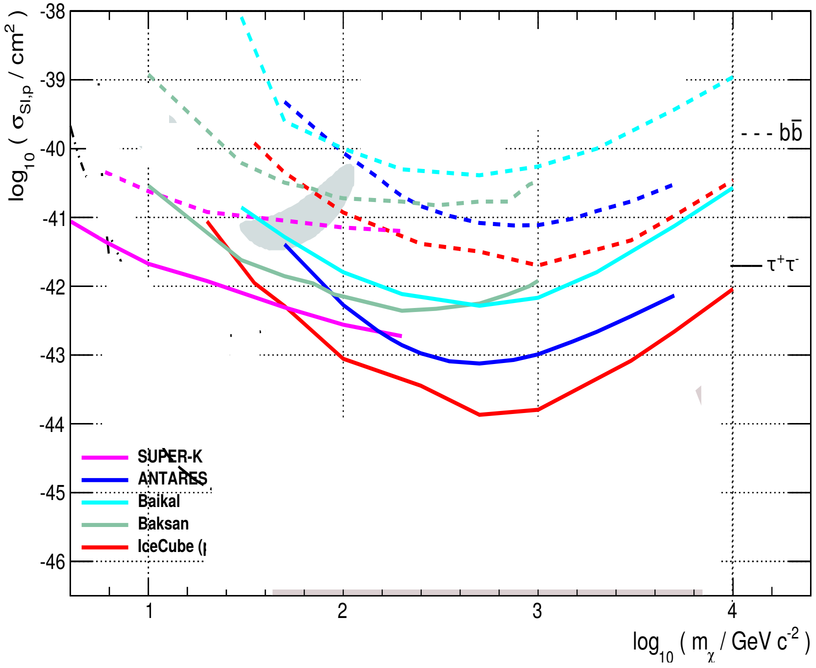
$$\frac{dn_{DM}}{dt} \propto \underset{\substack{\uparrow \\ \text{capture rate}}}{C_{DM+N\to DM+N}} - n_{DM}^2 \underset{\substack{\uparrow \\ \text{annihilation rate}}}{\langle\sigma_{DMDM\to SMSM}v\rangle}$$

⇒ observed ν flux gives constraint on $\sigma_{DM+N\to DM+N}$, not on $\langle\sigma_{DMDM\to SMSM}\, v\rangle$

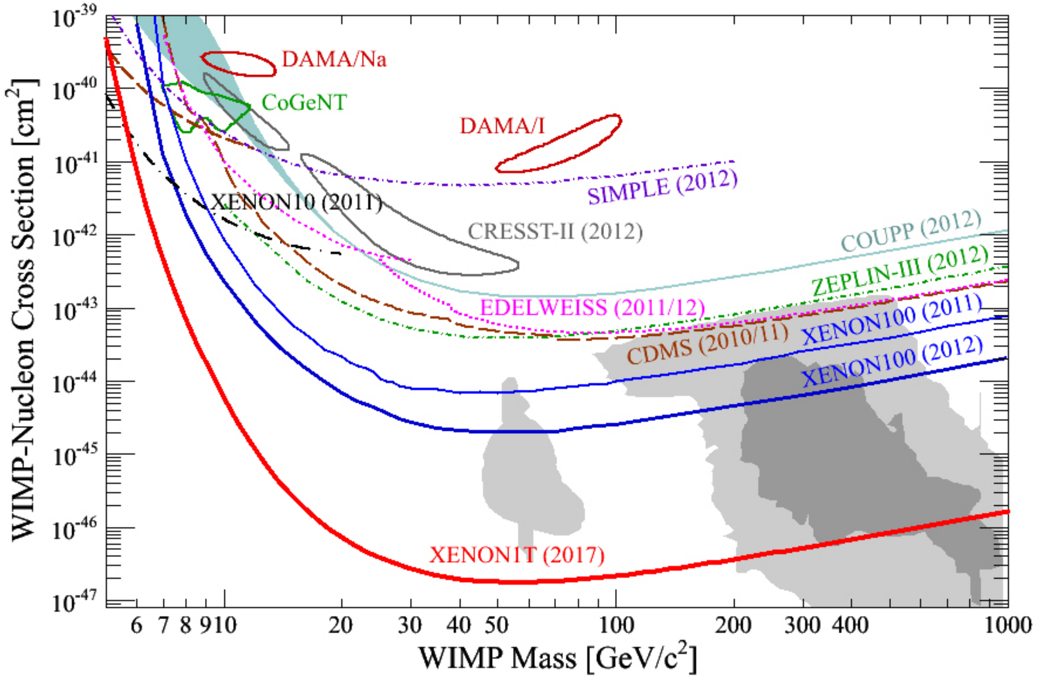
Upper limit on $\sigma_{DM+N\rightarrow DM+N}$ *from Sun neutrino flux*

spin independent elastic cross section case

neutrino detector limits:

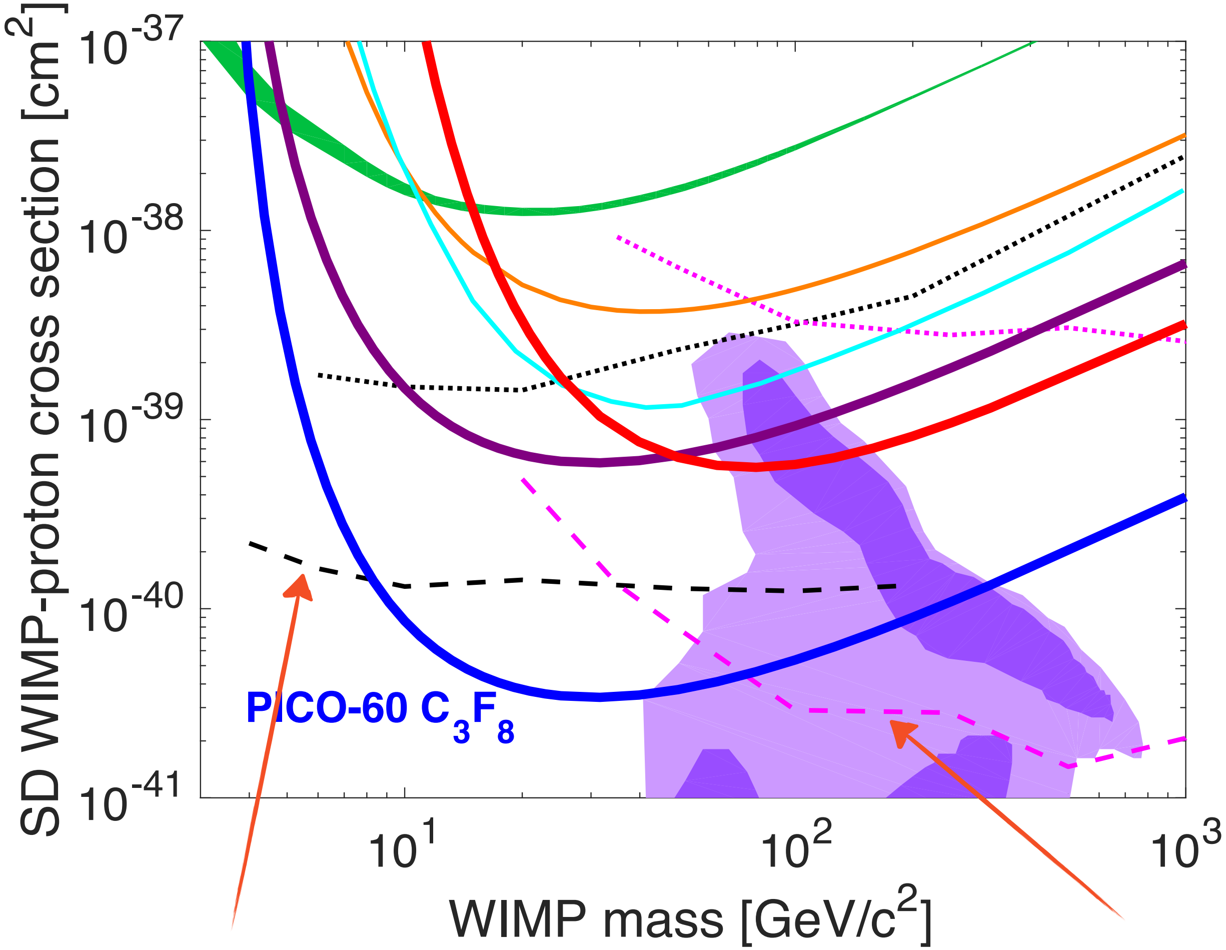


DM direct detection limits:



Upper limit on $\sigma_{DM+N \to DM+N}$ *from Sun neutrino flux*

spin dependent elastic cross section case



SuperKamiokande
$\tau^+\tau^-$

IceCube
$\tau^+\tau^-$

Determination of minimal models leading to observable ν-line from DM annihilation

many constraints:

- constraint 1: annihilation must proceed through s-wave

not to be suppressed by velocity powers today

for the $DM\,DM \to \nu\,\bar{\nu}$ channel this excludes all scalar and Majorana DM models

but leaves open many possibilities in the $DM\,DM \to \nu\,\nu$ channel

Determination of minimal models leading to observable ν-line from DM annihilation

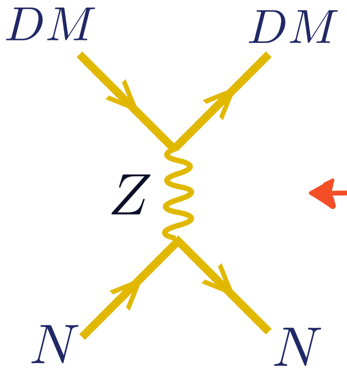
many constraints:

- constraint 2: direct detection constraint:

big issue for DM multiplet with non-zero hypercharge

⇓

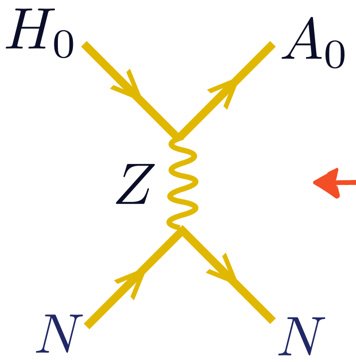
need to split in mass the neutral components of the DM multiplet



far too large

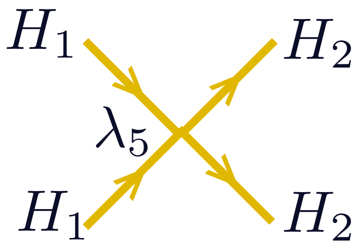
example: DM is neutral component of scalar doublet: ``inert'' doublet

$$H_2 = \begin{pmatrix} H^+ \\ \frac{H_0 + iA_0}{\sqrt{2}} \end{pmatrix}$$



kinematically forbidden
if: $m_{A_0} - m_{H_0} \gtrsim 100\ \mathrm{keV}$

possible from
λ_5 interaction



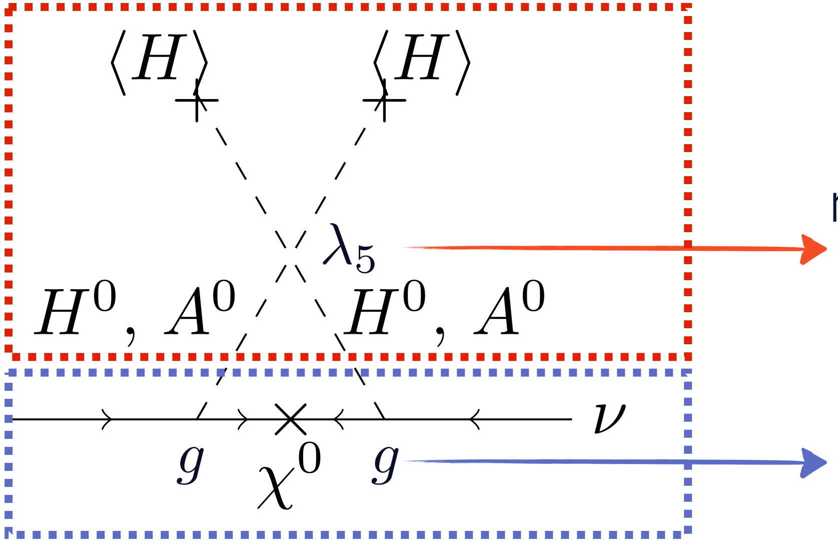
similarly $Y \neq 0$ DM Dirac fermion must be split into Majorana fermions

ν mass constraint: kills many $\nu\nu$ channel possibilities

⇓

constraint 3:

example: inert doublet DM:



minimum value from direct detection constraint

minimum value to get an observable ν-line

⇓

too large neutrino masses! $m_\nu \gtrsim 100\ \mathrm{keV}$

El Aisati, Garcia-Cely, T.H., Vanderheyden '17

ν-line cross section results including Sommerfeld effect

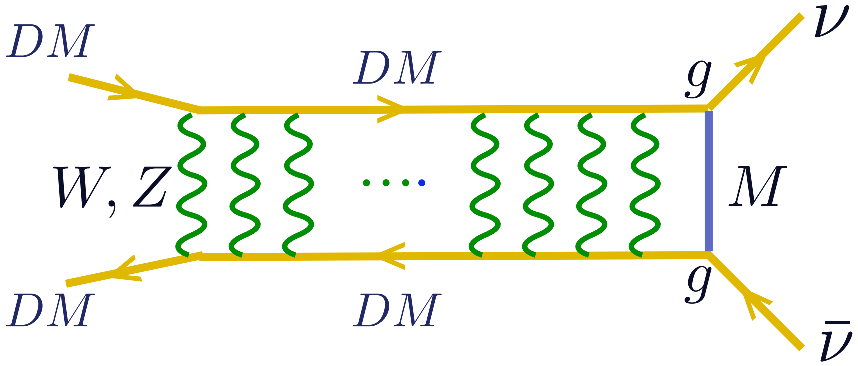
↪ example: model F_2 : a $Y = 0$ fermion DM triplet + a scalar doublet mediator

⇓

Sommerfeld for free and known: E-W interactions

as models
$F_1,\ S_1^r,\ F_1^m$

⇓



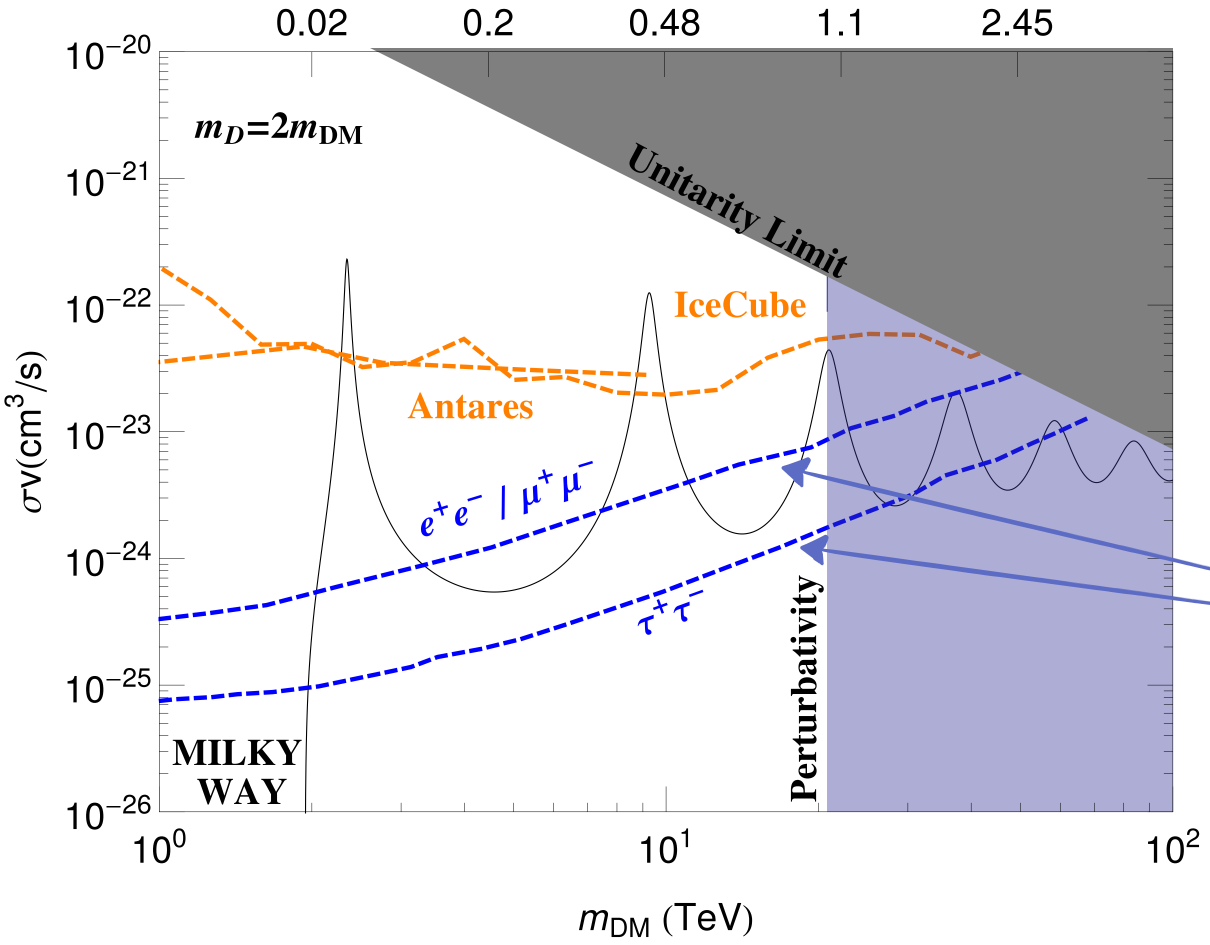
ν-line is predicted as a function of
m_{DM} and $DM - Med - \nu$ coupling g

⇑

can be fixed by
DM relic density

ν-line cross section results including Sommerfeld effect

example: model F_2 : a $Y=0$ fermion DM triplet + a scalar doublet mediator



El Aisati, Garcia-Cely, T.H., Vanderheyden '17

$\Phi_{\nu\bar{\nu}} = \Phi_{l^+l^-}$

charged lepton flux constraint

constraint 4

⇒ all fluxes predicted: ν-line and associated charged lepton flux around the corner

discrimination of the models

ν-line flavor composition

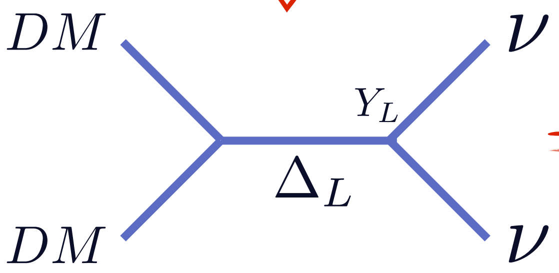
→ further possibility of model discrimination

a type-II seesaw state Δ_L

⇓

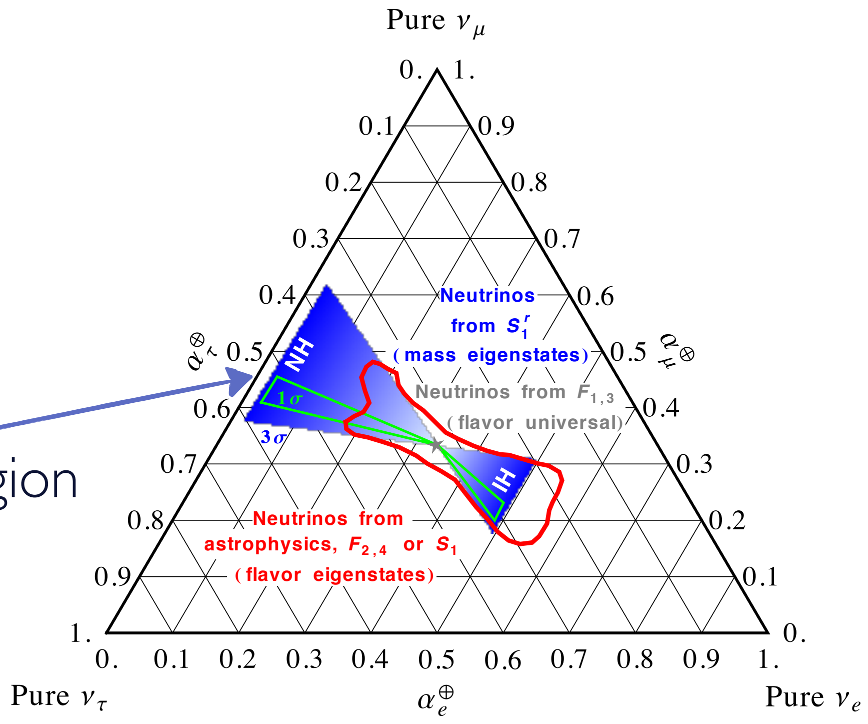
example: model S_1^r : real scalar DM from doublet + scalar $Y = 2$ triplet mediator

⇓



⇒ neutrinos are produced as mass eigenstates

flavour flux composition outside oscillation region



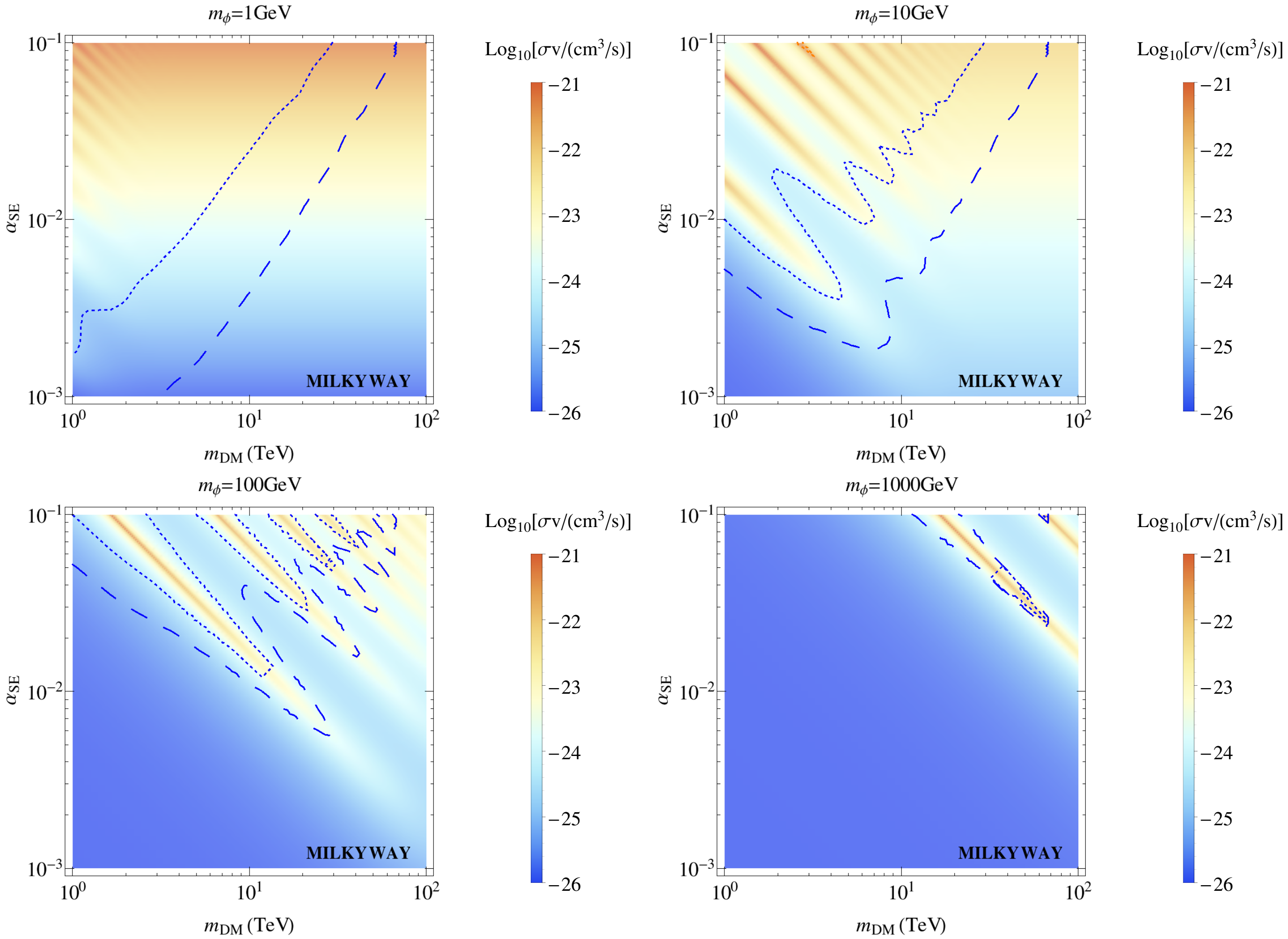
Garcia-Cely, Heeck '16
El Aisati, Garcia-Cely, TH, Vanderheyden '17

ν-line cross section results including Sommerfeld effect

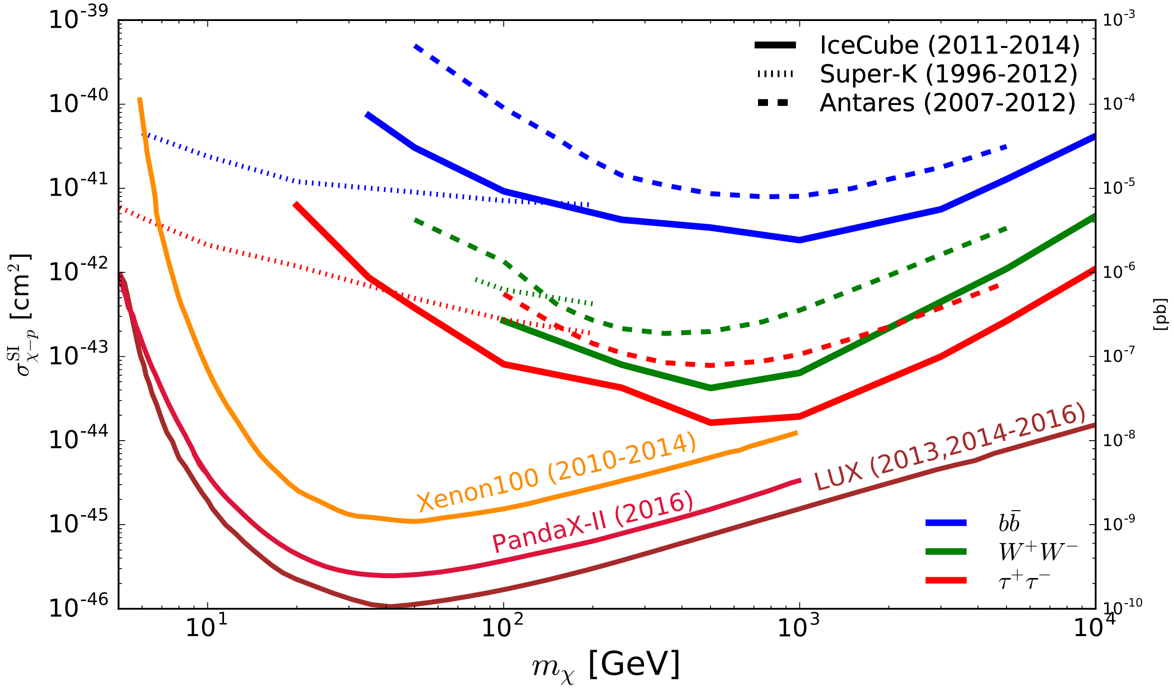
other example: model F_4: a $Y = 0$ fermion DM singlet + a scalar doublet med.

Sommerfeld requires extra light BSM mediator

ν-line is predicted as a function of of m_{DM} and $DM - Med - \nu$ coupling g and Som. mediator mass and coupling



El Aisati, Garcia-Cely, T.H., Vanderheyden '17



IceCube (2011-2014)
Super-K (1996-2012)
Antares (2007-2012)
$b\bar{b}$
W^+W^-
$\tau^+\tau^-$
Xenon100 (2010-2014)
PandaX-II (2016)
LUX (2013,2014-2016)
$\sigma^{\mathrm{SI}}_{\chi-p}$ [cm^2]
m_χ [GeV]
[pb]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{1}
10^{2}
10^{3}
10^{4}
10^{-3}
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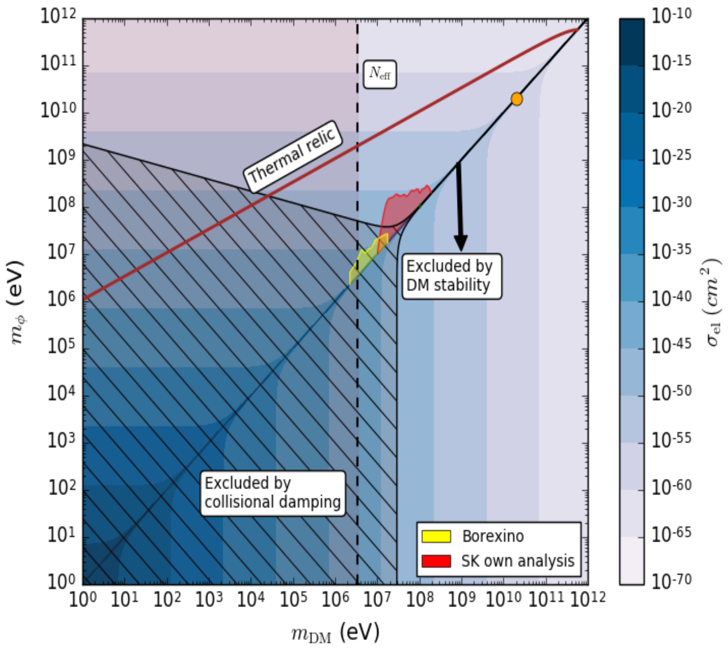
10^{-7}
10^{-8}
10^{-9}
10^{-10}

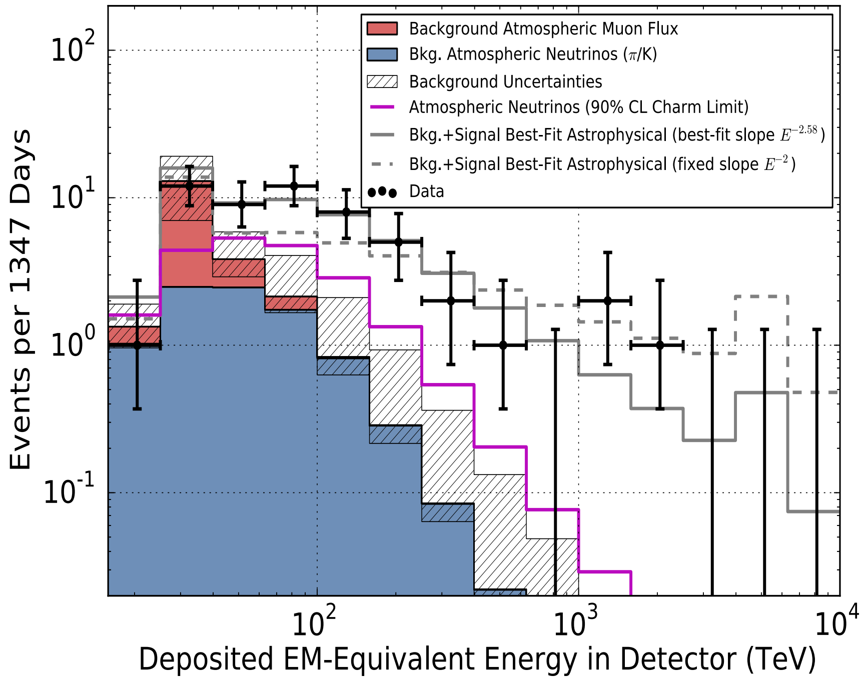


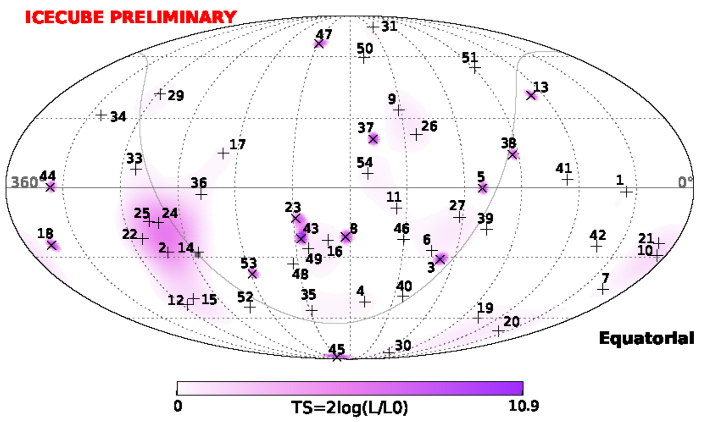
N_{eff}
Thermal relic
Excluded by DM stability
Excluded by collisional damping
Borexino
SK own analysis
m_ϕ (eV)
m_{DM} (eV)
σ_{el} (cm^2)
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
10^{-45}
10^{-50}
10^{-55}
10^{-60}
10^{-65}
10^{-70}

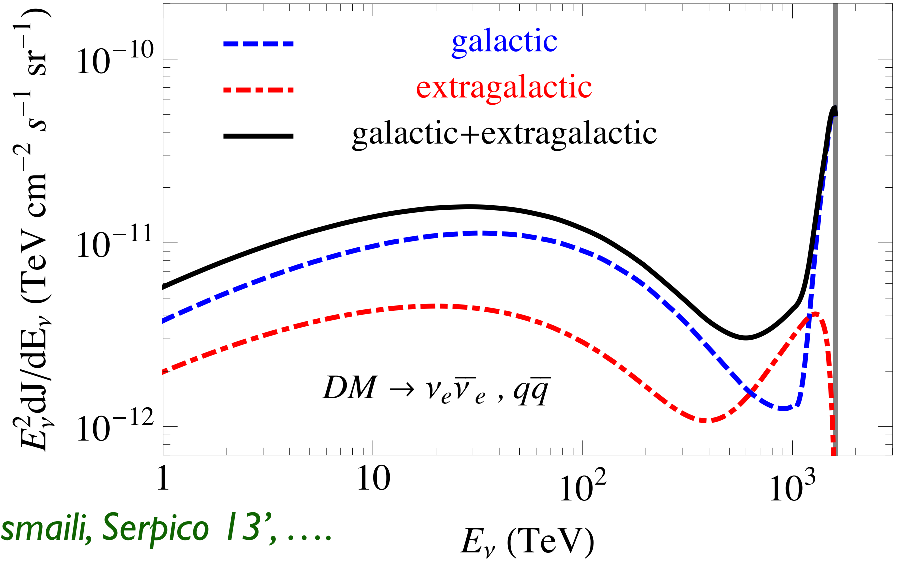
IceCube PeV events: decay of PeV DM particle?

for such a high mass DM is non-thermal

IceCube 4 years



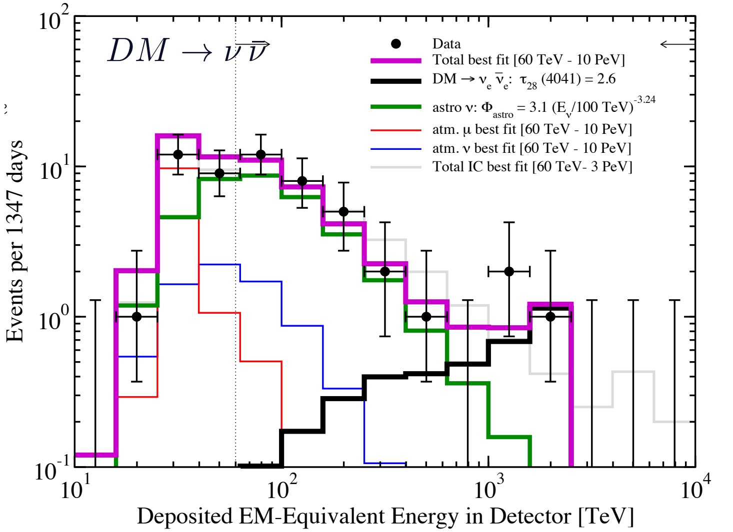




Esmaili, Serpico 13', ….

4 years data set

$m_{\rm DM} = 4041$ TeV



Battacharya, Esmaili, Palomares-Ruiz, Sarcevic 17'

⇒ not much clear: need for more data