Neutrinos: the quest for a new physics scale

27-31 March 2017, CERN

Neutrino Secret Interaction (νSI)

Ninetta Saviano
Mainz University

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

erc European Research Council Established by the European Commission

PRISMA Cluster of Excellence

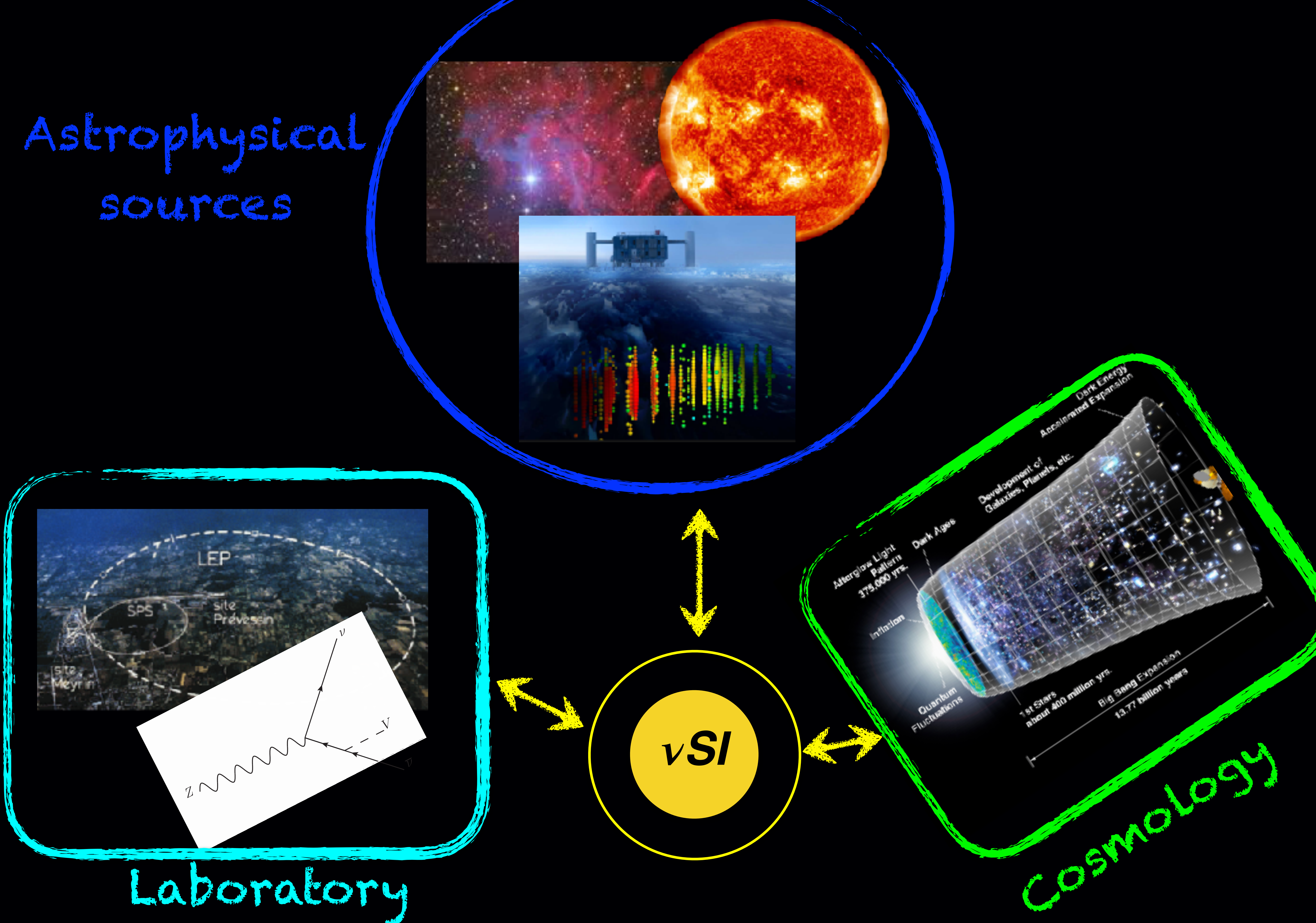
Outline

The term “secret neutrino interactions” (νSI) indicates new physics that couples ν to ν

Several models have been studied (vector, scalar, pseudo-scalar boson) for a large range of the new mediator mass.

Concise overview on:

- νSI constraints in the active sector
- νSI constraints in the sterile sector
- Dark Matter connection

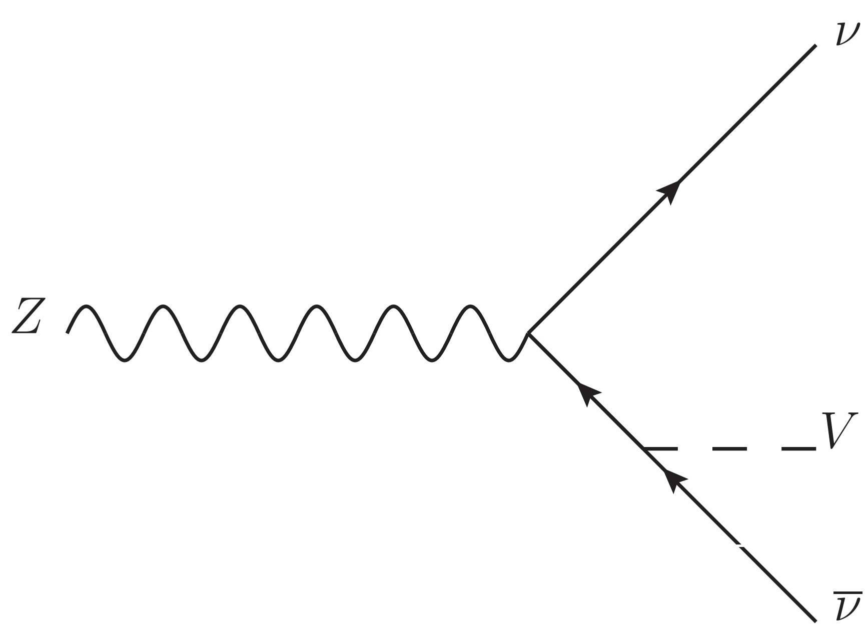


Astrophysical sources
LEP
SPS
site Prévessin
site Meyrin
Laboratory
νSI
Dark Energy Accelerated Expansion
Afterglow Light Pattern 375,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.77 billion years
Cosmology

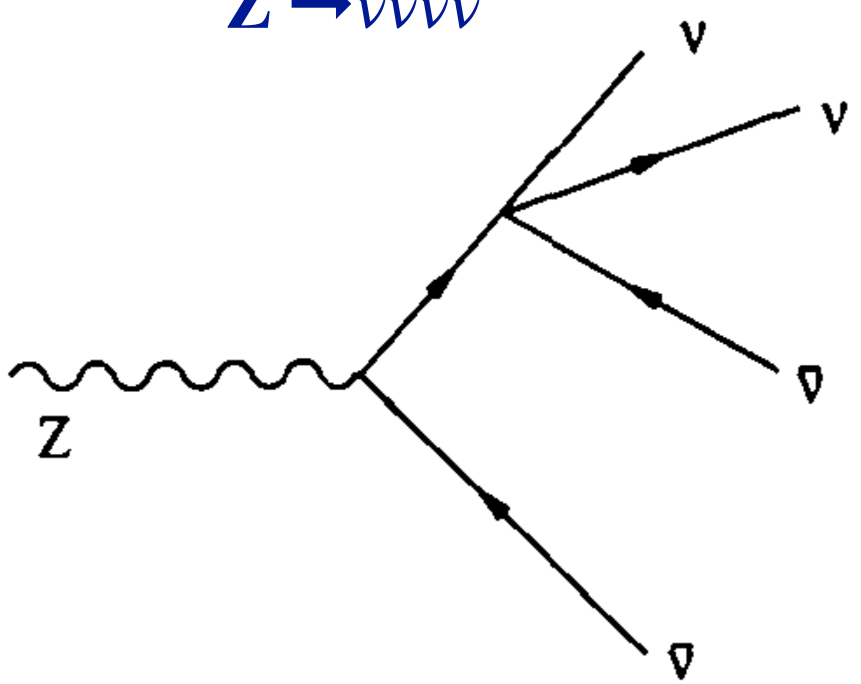
Constraints from laboratory

A light boson V coupling to ν can be constrained by:

The 3- body decay of the Z increases the total decay width of the Z



$Z \rightarrow \nu\nu\nu\nu$



The decays remain consistent with existing measurements

Bilenky & Santamaria, 1992

Laha, Dasgupta and Beacom, 2014

Constraints from astro-sources

SN

PHYSICAL REVIEW D

PARTICLES AND FIELDS

THIRD SERIES, VOLUME 36, NUMBER 10 15 NOVEMBER 1987

Supernova 1987A and the secret interactions of neutrinos

Edward W. Kolb
Osservatorio Astronomico di Roma, via del Parco Mellini 84, 00136 Rome, Italy
and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
and Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637

Michael S. Turner
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
and Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637
and Department of Physics and the Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

(Received 13 July 1987)

By using SN1987A as a "source" of neutrinos with energy ~ 10 MeV we place limits on the couplings of neutrinos with cosmic background particles. Specifically, we find that the Majoron–electron-neutrino coupling must be less than about 10^{-3}; if neutrinos couple to a massless vector particle, its dimensionless coupling must be less than about 10^{-3}; and if neutrinos couple with strength g to a massive boson of mass M, then g/M must be less than 12 MeV^{-1}.

Long list of publication, especially in connection to Majoron models…
… a limited selection:

Kolb and Turner 1987

Fuller, Mayle, Wilson (1988)

Choi and Santamaria, 1990

Kachelrieß, Tomas, Walle 2003

Yasaman Farzan, 2003…

Effects on SN by secret interactions:

- *absorption*: can suppress the spectrum of the observed neutrino flux from a supernova explosion.
- *Energy loss*: reduces the duration of the ν burst
- *Deleptonization:* reduced lepton number of SN core due to Majoron emission

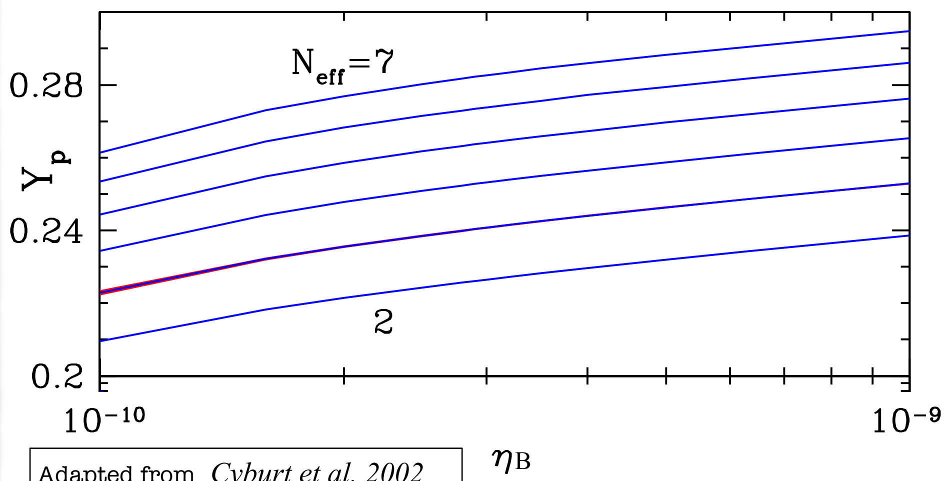
IceCube

IceCube neutrinos have a much longer baseline through the CνB and much higher energies

Constraints from Cosmology

BBN

sensitive to the radiation density of the Universe, parametrised by N_{eff} and to the spectrum of ν_e (especially in the contest of ν flavour evolution).
Both effects can alter the n/p ratio.



Adapted from *Cyburt et al, 2002*

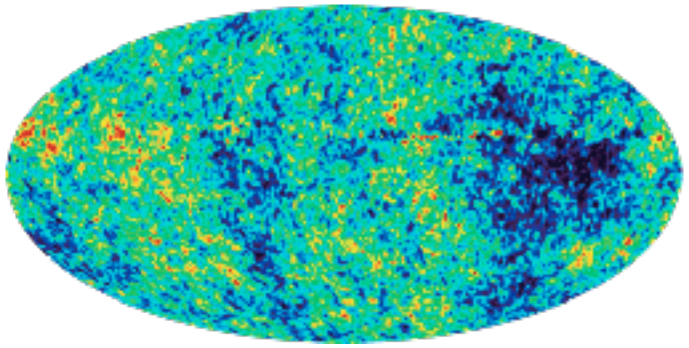
If at the BBN time new particles exist, (i.e new mediators, majorons…), if sufficiently light, they could contribute to N_{eff}, increasing the primordial abundance of light elements.

BBN does not prefer a N_{eff} >3 (ΔN_{eff} < 1)

Mangano and Serpico 2011, R. Cooke et al, 2013

CMB

Collisional processes induced by the new interaction would affect the evolution of perturbations in the cosmological neutrino fluid.



Consequent observational signatures on the CMB spectrum

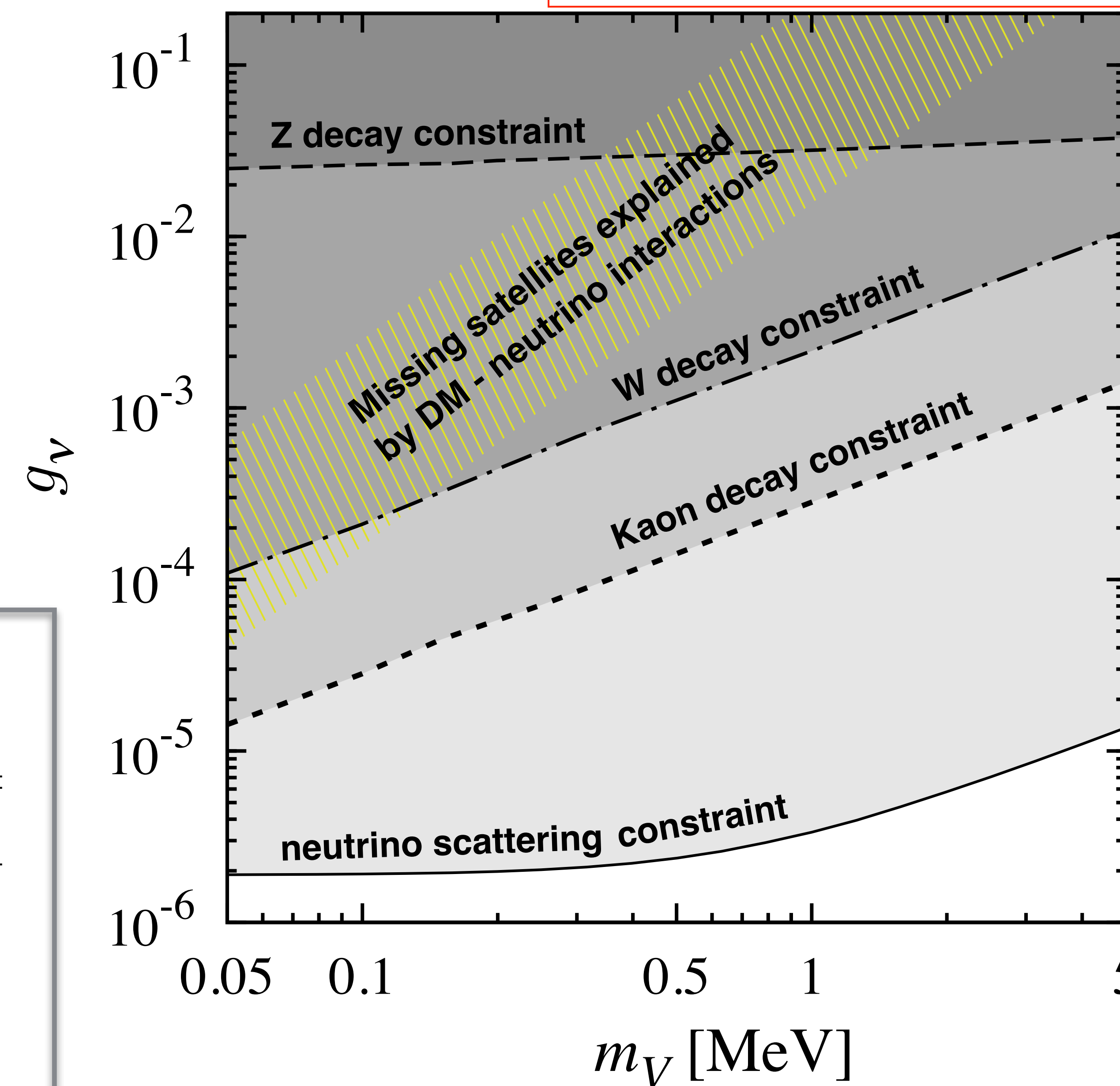
νSI in the active sector

Lab constraints for Vector Boson

Light vector gauge boson V, with mass $\mathcal{O}$ MeV and couples only to SM neutrinos (and charged leptons through their V-A current): $g_\nu \overline{\nu} \not{V} \nu$

$$\Gamma(Z \to \nu\overline{\nu}V) \leq 1.28 \times 0.0023\,\mathrm{GeV} \Rightarrow g_\nu \lesssim 0.03$$

Laha, Dasgupta and Beacom, 2014



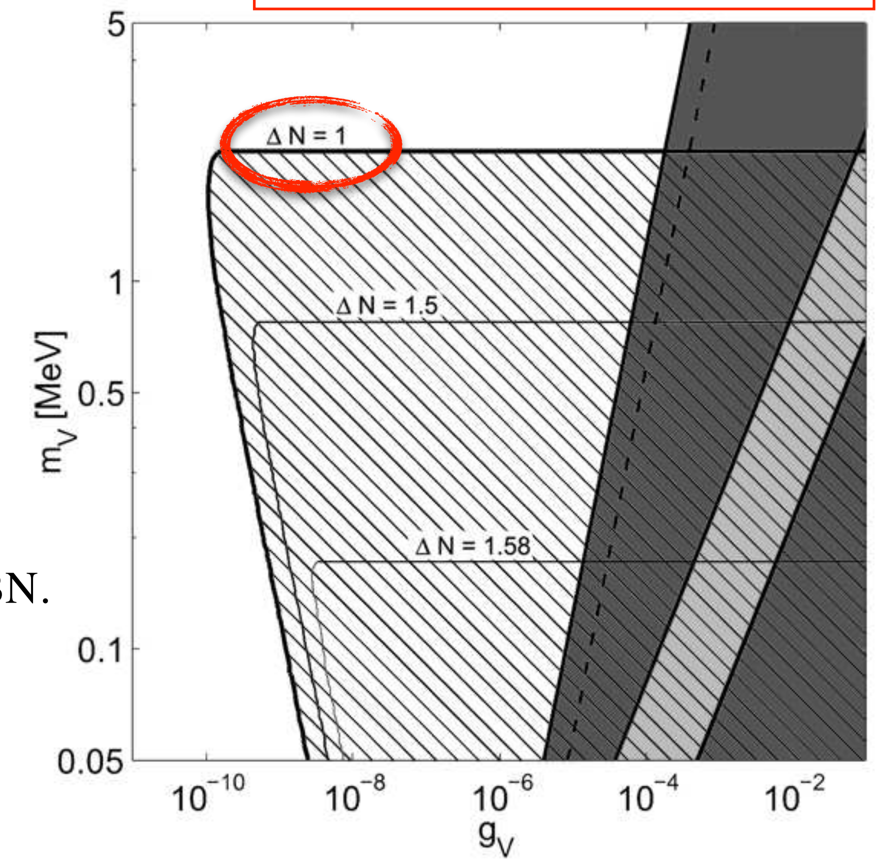
Summary of constraints on new interactions of neutrinos with light vector gauge bosons at mV = 1 MeV

Process	Interaction	Constraint
$Z \to \nu\overline{\nu}V$	$g_\nu \overline{\nu} \not{V} \nu$	$g_\nu \lesssim 3 \times 10^{-2}$
$W \to \tau^- \overline{\nu}_\tau V$	$g_\nu (\overline{\nu} \not{V} \nu + \overline{\ell} \not{V} \ell)$	$g_\nu \lesssim 2 \times 10^{-3}$
$K^- \to \mu^- \overline{\nu}_\mu V$	$g_\nu (\overline{\nu} \not{V} \nu + \overline{\ell} \not{V} \ell)$	$g_\nu \lesssim 3 \times 10^{-4}$
$\nu e \to \nu e$	$g_\nu (\overline{\nu} \not{V} \nu + \overline{\ell} \not{V} \ell)$	$g_\nu \lesssim 3 \times 10^{-6}$

BBN & CMB constraints for Vector Boson

The constraints on g_V and m_V from BBN are very restrictive.

Ahlgren, Ohlsson and Zhou 2013



In the early Universe, V can be thermalized via

- the inverse decay $\nu+\nu \rightarrow V$
- pair annihilation $\nu+\nu \rightarrow V+V$

and contribute to the energy density

Constraints on g_V and m_V from K decays (gray, solid line), W decays (gray, dashed line), and BBN.

The hashed region bounded by the thick solid curve is excluded by $\Delta N_\nu < 1$ at 95% C.L.

CMB

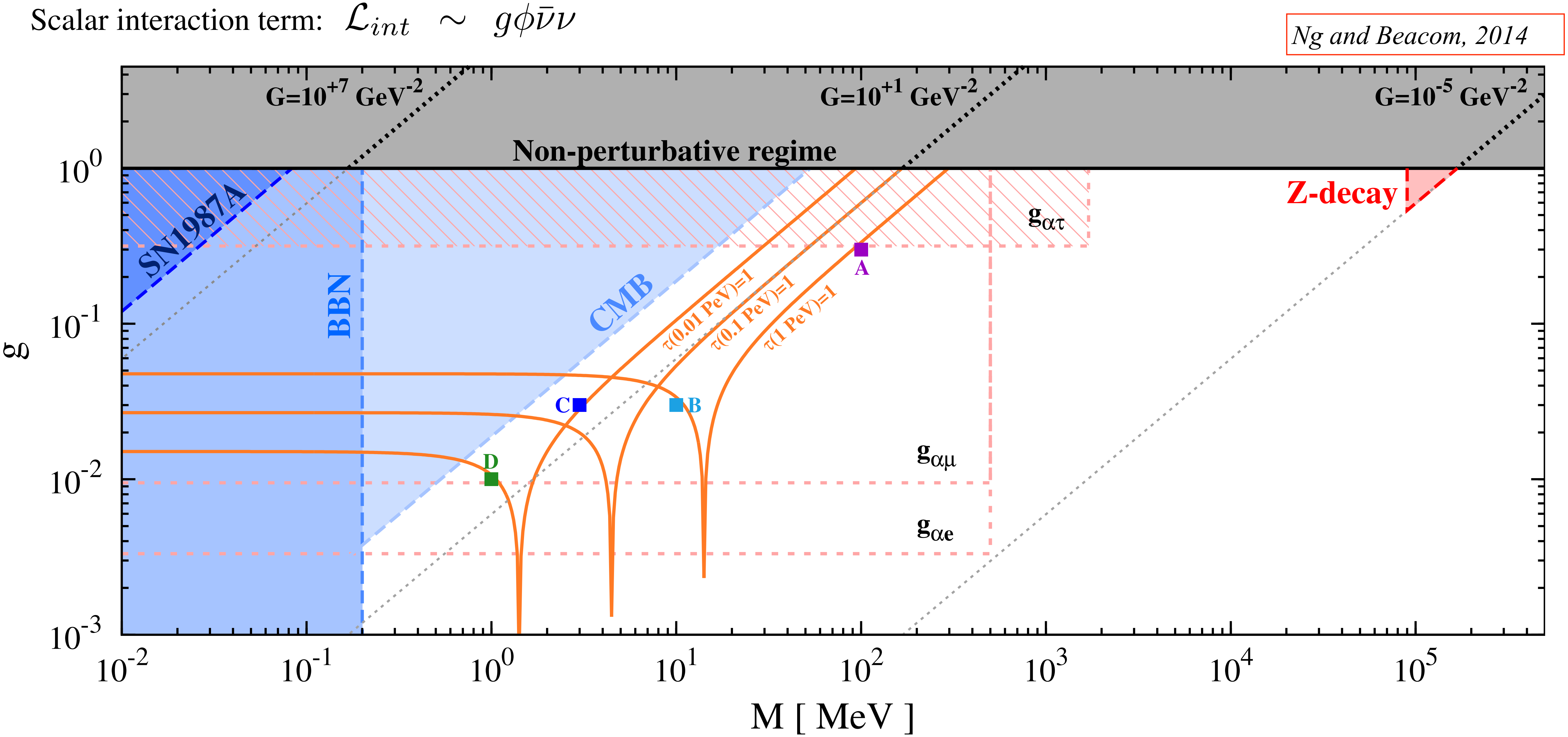
4-fermion point-like interaction model: $G_X = g^2/m_X^2$

Using Planck data (combined with other data): $G_X \leq 2.5 \times 10^7 \, G_F$

Archidiacono &Hannestad 2014

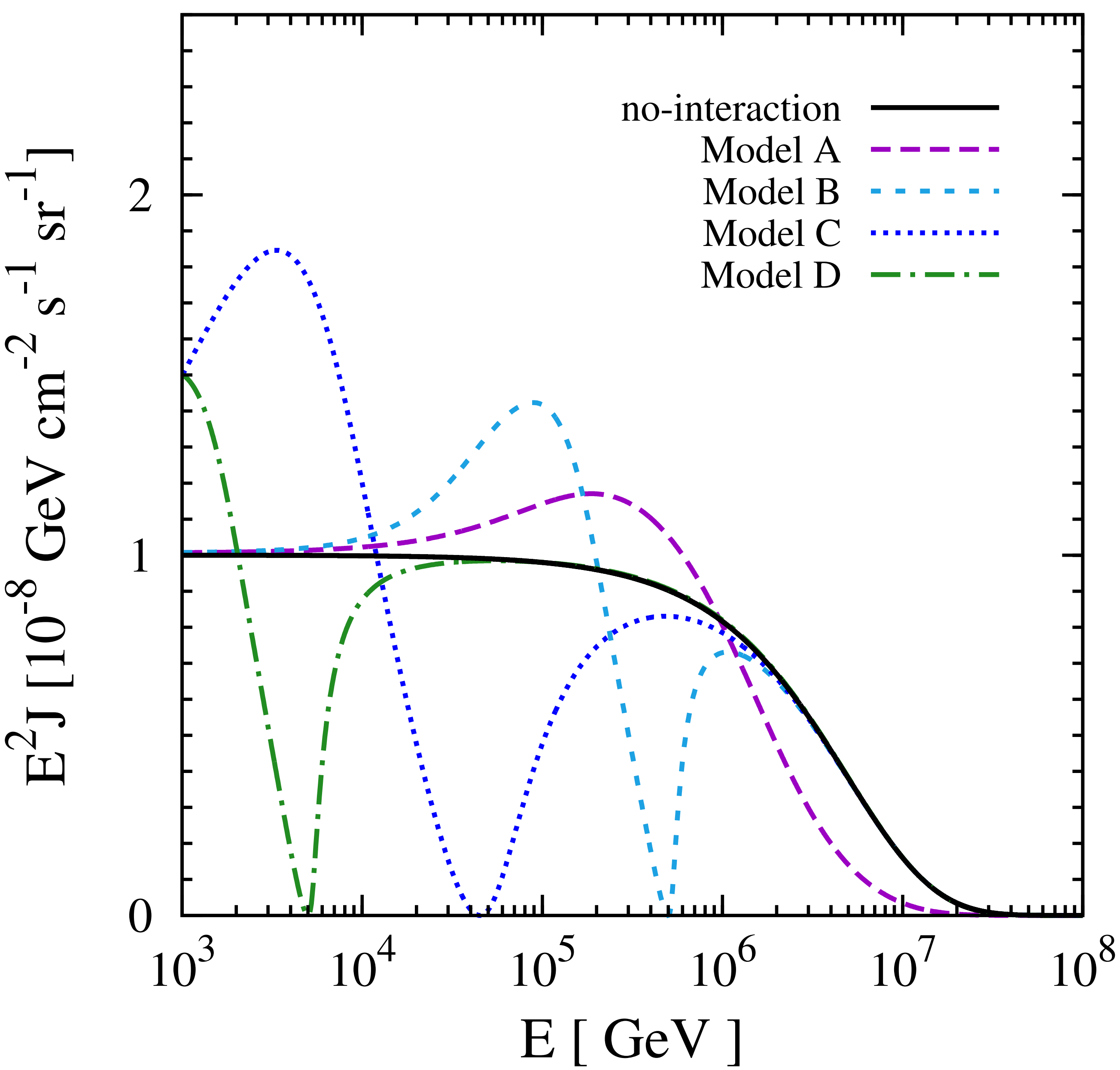
Constraints for Scalar Boson

Scalar interaction term: $\mathcal{L}_{int} \sim g\phi\bar{\nu}\nu$



Blue shaded regions are excluded by astrophysical and cosmological considerations based on SN 1987A [K&T], BBN [A,O,Z], and the CMB [A&H]. Pink dashed lines indicate flavor-dependent limits based on laboratory measurements of meson and lepton decays. Shaded pink: only the weakest limit for ν_τ. Red shaded region is excluded based on measurement of Z-boson decay [B&S]. Grey shaded region indicates the non-perturbative regime. Orange lines are contours of unit optical depth for different initial neutrino energies, indicating the **approximate boundary of the parameter space above which IceCube is sensitive to νSI.**

"scalar" νSI impact on IceCube spectra



$$\mathcal{L}_0(E) \propto E^{-\gamma} e^{-E/E_{\rm cut}}$$

$$\gamma = 2 \text{ and } E_{\rm cut} = 10^7\,\text{GeV}$$

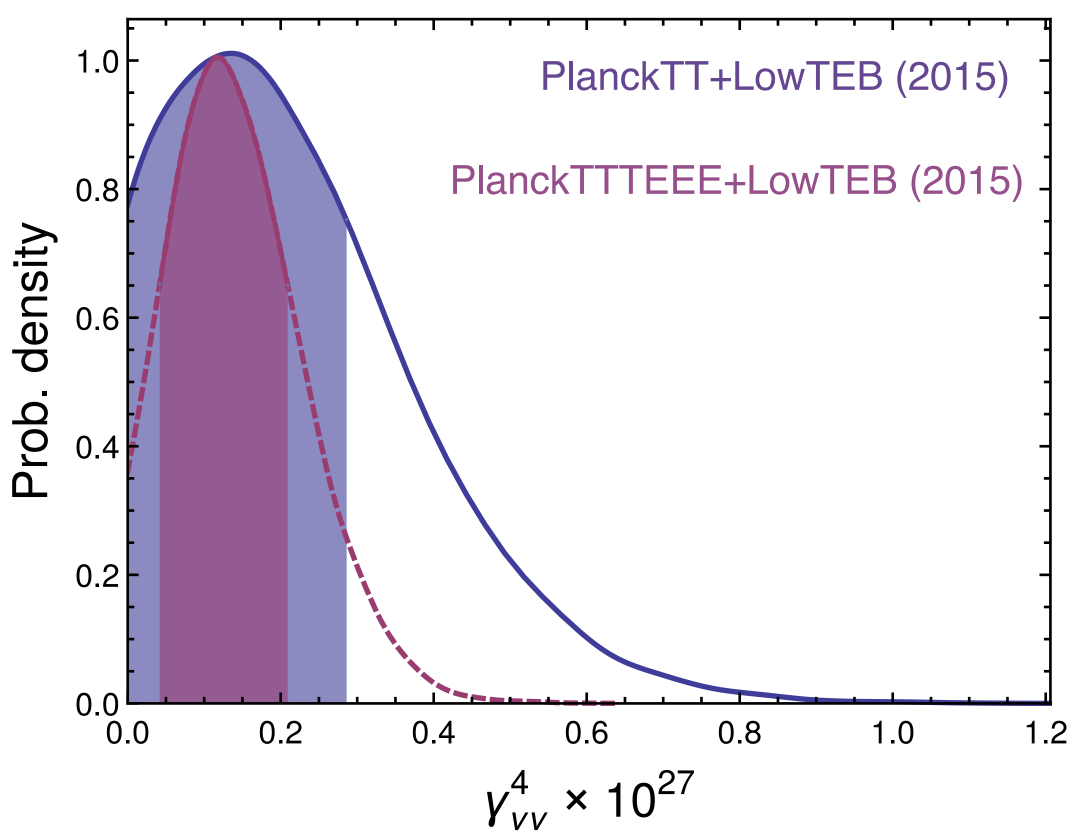
	A	B	C	D
g	0.3	0.03	0.03	0.01
M [MeV]	100	10	3	1
τ (1 PeV)	~ 0.7	~ 0.6	~ 0.2	~ 0.002
$E_{\rm res}$ [PeV]	50	0.5	0.045	0.005

CMB constraints for light (pseudo) scalar Boson

$$\mathcal{L} = h_{ij}\bar{\nu}_i\nu_j\phi + g_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + h.c.$$

Scalar and pseudoscalar neutrino couplings can be relevant for CMB, since collisional processes induced by the new interaction would affect the evolution of perturbations in the cosmological neutrino fluid.

For binary process mediated by a massless boson, $\sigma_{\rm bin} \sim g^4/s \longrightarrow \Gamma_{\rm bin} = \langle \sigma_{\rm bin} v \rangle n_{\rm eq} \propto g^4 T$



Constraint in the Majoron case: $g \lesssim 7.4 \times 10^{-7}$

$g^4 = \gamma^4_{\nu\nu} / (1.8 \times 10^{-3})$

Forastieri, Lattanzi and Natoli 2015

see also Archidiacono &Hannestad 2014

νSI in the (light) sterile sector

eV sterile neutrinos

The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments

Interpretation: ***1*** (or more) ***sterile neutrino*** with $\Delta m^2 \sim O\,(\mathrm{eV}^2)$ and $\theta_s \sim O\,(\theta_{13})$

Giunti et al 2013; J. Kopp et al, 2013

Giunti's Talk

ν_s can be produced in the *EU* by the mixing with the active species in presence of collisions

Are eV ν_s compatible with cosmology?

eV sterile neutrinos

The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments

Interpretation: ***1*** (or more) ***sterile neutrino*** with $\Delta m^2 \sim O\,(\mathrm{eV}^2)$ and $\theta_s \sim O\,(\theta_{13})$

Giunti et al 2013; J. Kopp et al, 2013

Giunti's Talk

ν_s can be produced in the *EU* by the mixing with the active species in presence of collisions

Are eV ν_s compatible with cosmology? **NO** *Too "many" and too heavy*

eV sterile neutrinos

The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments

Interpretation: ***1*** (or more) ***sterile neutrino*** with $\Delta m^2 \sim O\,(\mathrm{eV}^2)$ and $\theta_s \sim O\,(\theta_{13})$

Giunti et al 2013; J. Kopp et al, 2013

Giunti's Talk

ν_s can be produced in the *EU* by the mixing with the active species in presence of collisions

Are eV ν_s compatible with cosmology? **NO** *Too "many" and too heavy*

Possible solutions:

- ***suppress the ν_s abundance***

  Feasible with lepton asymmetry, low-reheating scenario, secret interactions

  *Di Bari et al, 2001, Cirelli et al., 2004, Gelmini, Palomarez-Ruiz, Pascoli, 2004, Chu & Cirelli, 2006, Mirizzi, **N.S.**, Miele, Serpico 2012, Hannestad, Tamborra and Tram 2012, Saviano et al., 2013,*

- ***modification of cosmological model***

  Gariazzo, Giunti, Laveder, 2015

SI for sterile neutrinos

Different authors have assumed the Standard Model (SM) is augmented by one extra species of light (~ eV) neutrinos ν_S, which do not couple to the SM gauge bosons but experiment a new force

Hannestad et al., 2013,, Dasgupta and Kopp 2013, Bringmann et al., 2014

Such a new interaction can have profound effects on active-sterile neutrino conversion in the early Universe, **since sterile ν feel a new potential that can suppresses active-sterile mixing** *(through an effective ν_a-ν_s mixing reduced by a large matter term)*

Caveat: ⚠ they also generate MSW resonance and strong collisional production, increasing their abundance, with non trivial consequences on the cosmological observables

➜ **νSI constraints from cosmological probes**

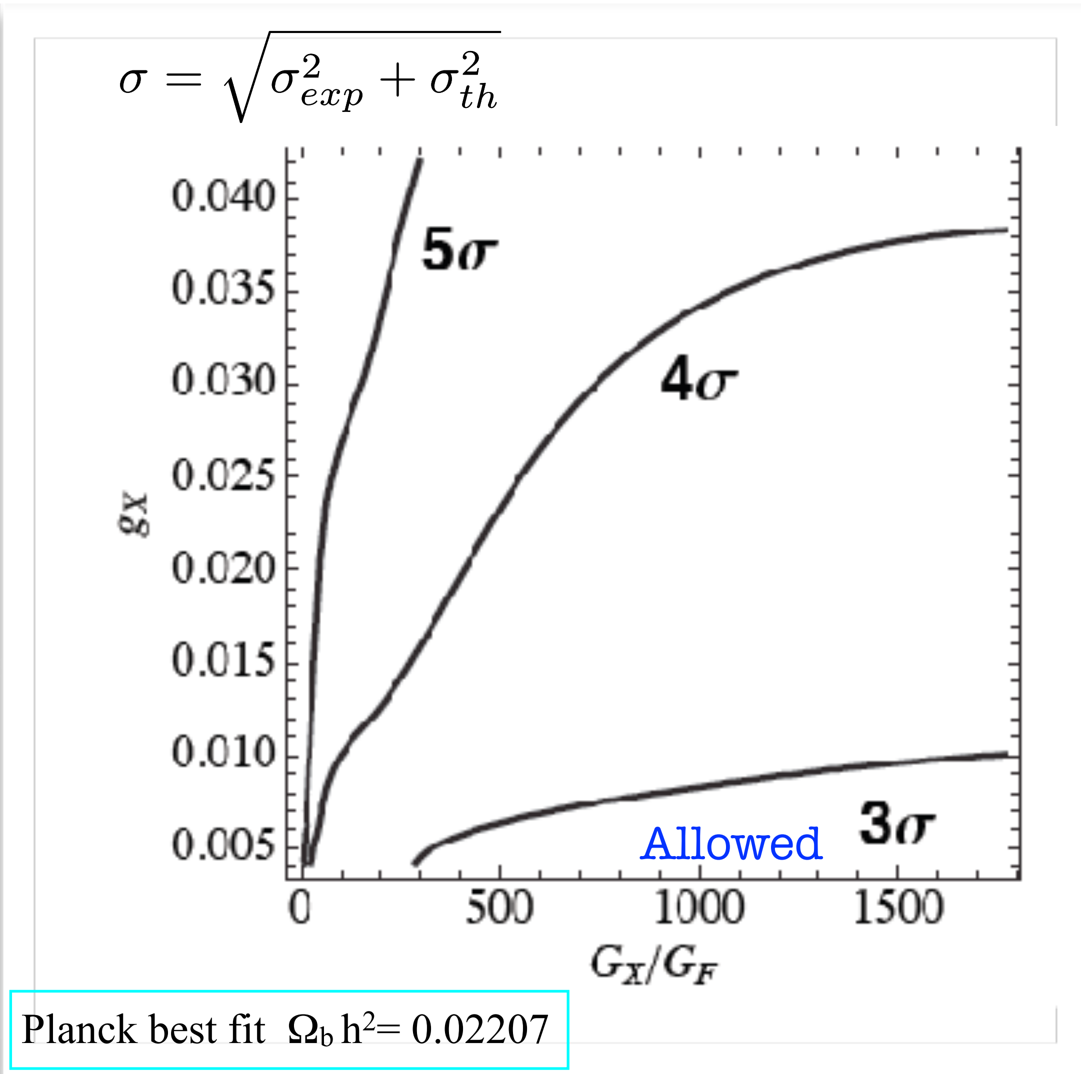
If the new mediator interaction X also couples to Dark Matter possible attenuation of some of the small scale structure problems (“missing satellites” problem...)

BBN constraints for sterile νSI (vector)

Particular model: **4-fermion point-like interaction** $G_X = \frac{\sqrt{2}}{8}\frac{g_X^2}{M_X^2}$ *for* $T << M_X$

After the ν oscillation in the range of g_x and G_X relevant for BBN, we have both :

$\Delta N_{eff} > 0$ and distortions of the active ν_e spectra



Deuterium yield

Experimental reference value:

$^2H/H = (2.53 \pm \underbrace{0.04)}_{\sigma_{exp}} \times 10^{-5}$

R. Cooke et al, 2013

Translating in a bound for the mediator mass:

mass permitted: $M_X \leq 40$ MeV

Saviano, Pisanti, Mangano, Mirizzi 2014

Mass constraints for sterile νSI (vector)

If we want to constraint lower M_X $\leftrightarrow$ very large G_X ($> 10^5\, G_F$)

Very strong secret collisional term leads to a quick flavor equilibrium

Stodolsky, 1987

$$(\rho_{ee},\ \rho_{\mu\mu},\ \rho_{\tau\tau},\ \rho_{ss})_{\text{initial}} \longrightarrow (\rho_{ee},\ \rho_{\mu\mu},\ \rho_{\tau\tau},\ \rho_{ss})_{\text{final}}$$

$$(1,\quad 1,\quad 1,\quad 0) \qquad\qquad (3/4,\ 3/4,\ 3/4,\ 3/4)$$

$\Downarrow$

lower value in the 2σ range from anomalies gives $m^{\text{eff}}_s \sim 0.8$ eV

in tension with the CMB and LSS bounds on sterile mass (< 0.5 eV***)***

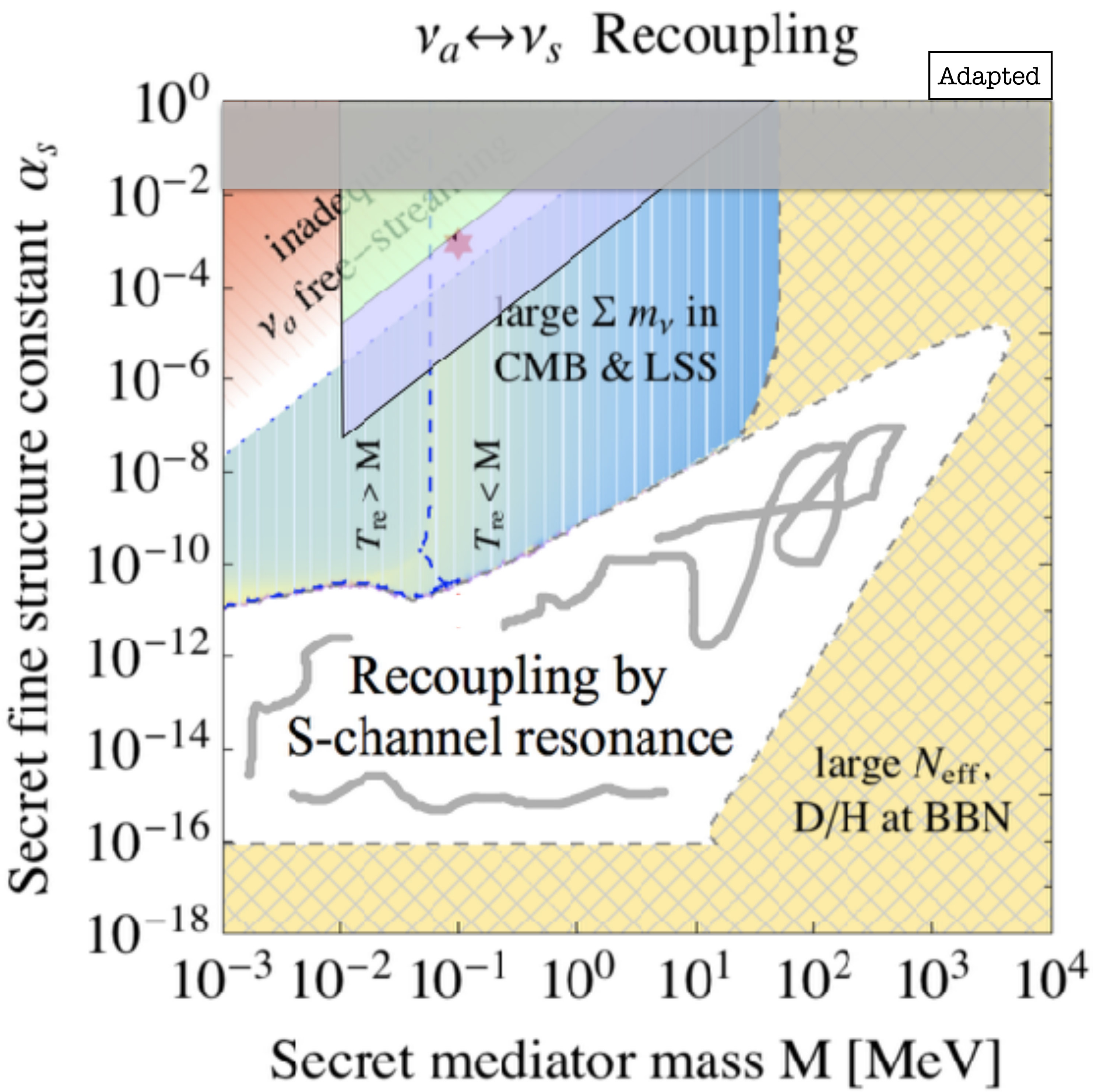
Mirizzi,Mangano, Pisanti Saviano, 2014

Secret interaction scenario: disfavored M_X > 0.1 MeV ($\Leftrightarrow \sim 10^9\, G_F$)

For $M_X \leq 0.1$ MeV ($\geq 10^{10}\, G_F$) $\rightarrow \nu_s$ could be still coupled at CMB and LSS epoch $\rightarrow$ no free-streaming…

…. an appropriated analysis should be performed

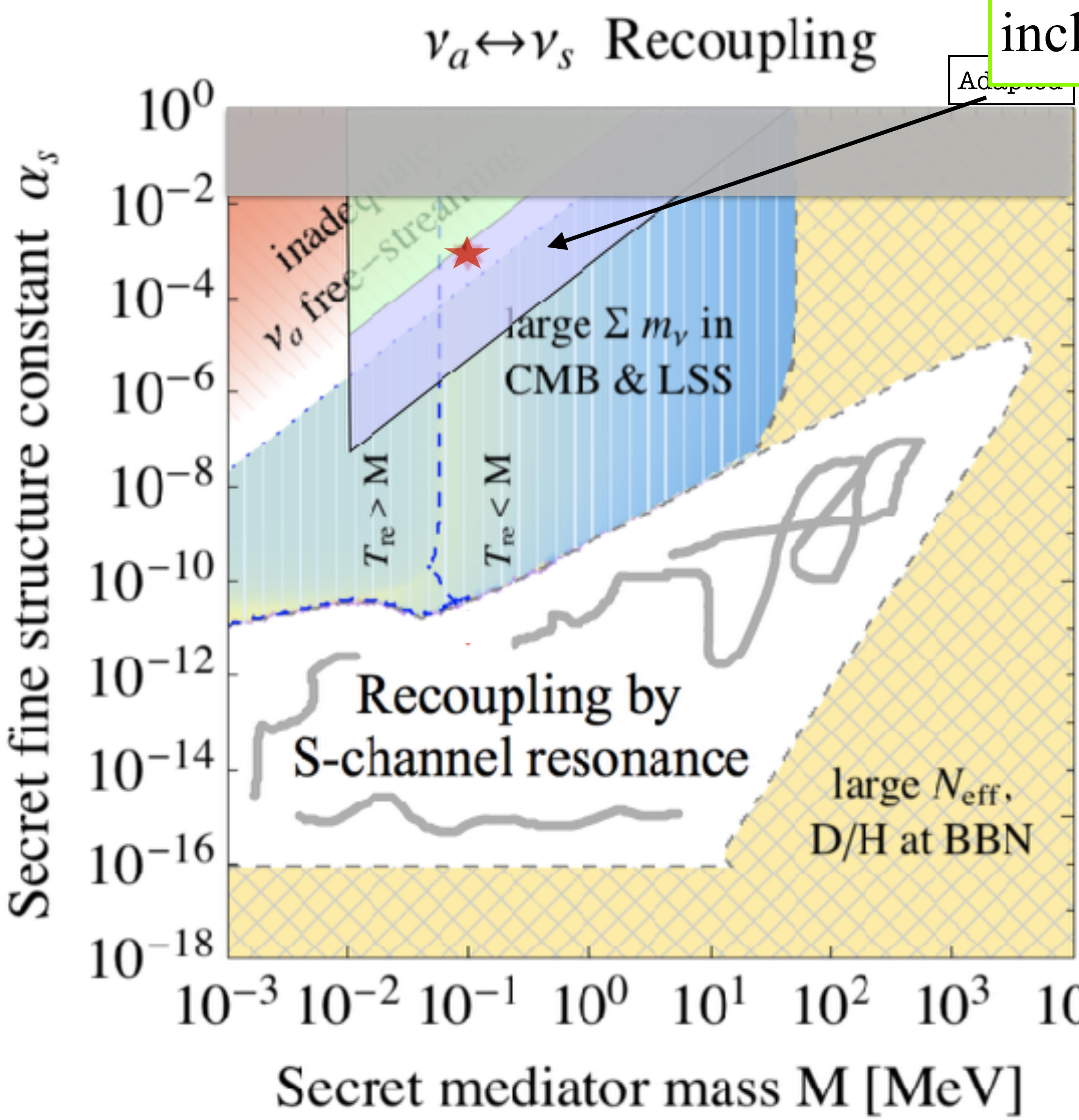
Summary Plot



Chu, Dasgupta and Kopp 2015

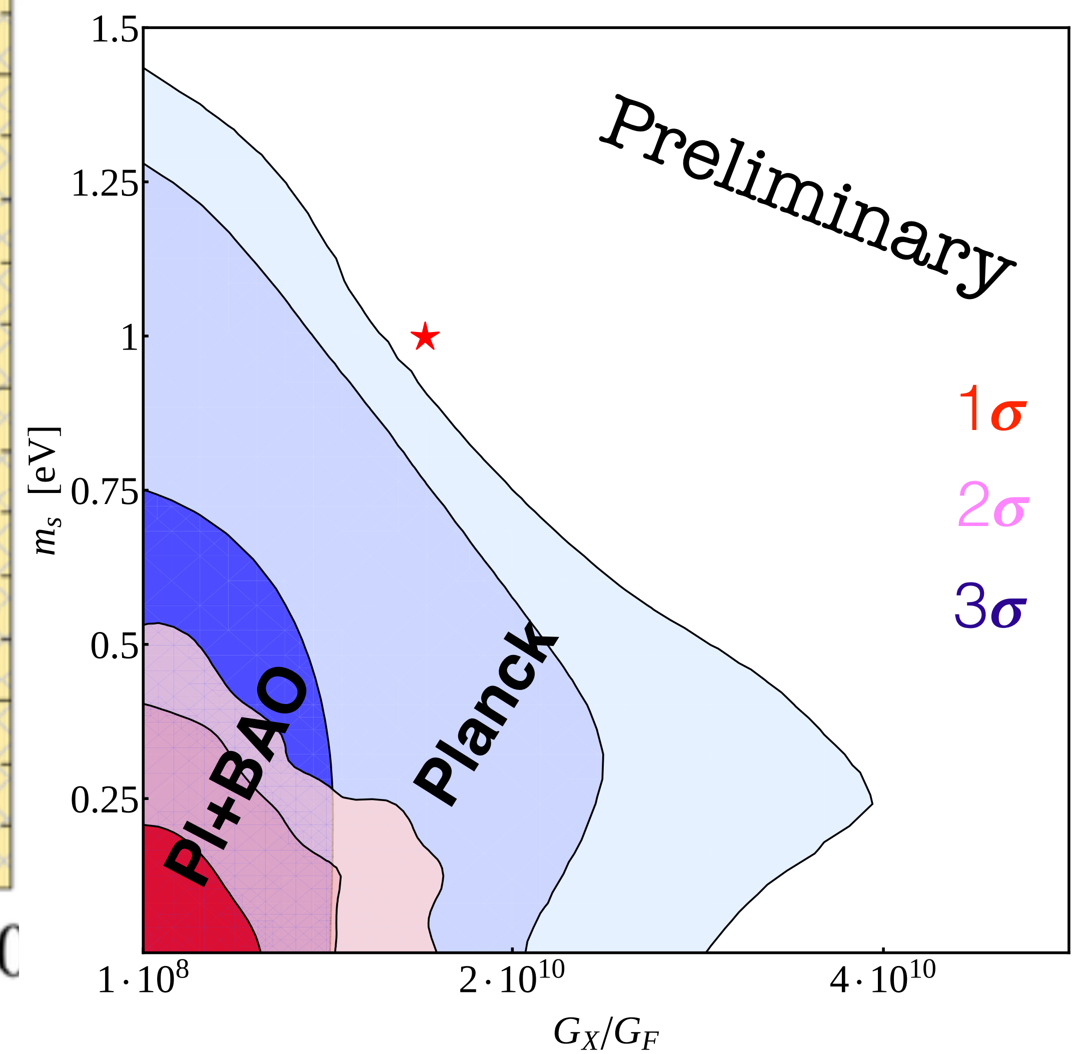
Summary Plot

Preliminary results of CMB analysis including no-free-streaming sterile ν



Forastieri, Lattanzi, Mangano, Mirizzi, Natoli, Saviano, 2017

to appear soon

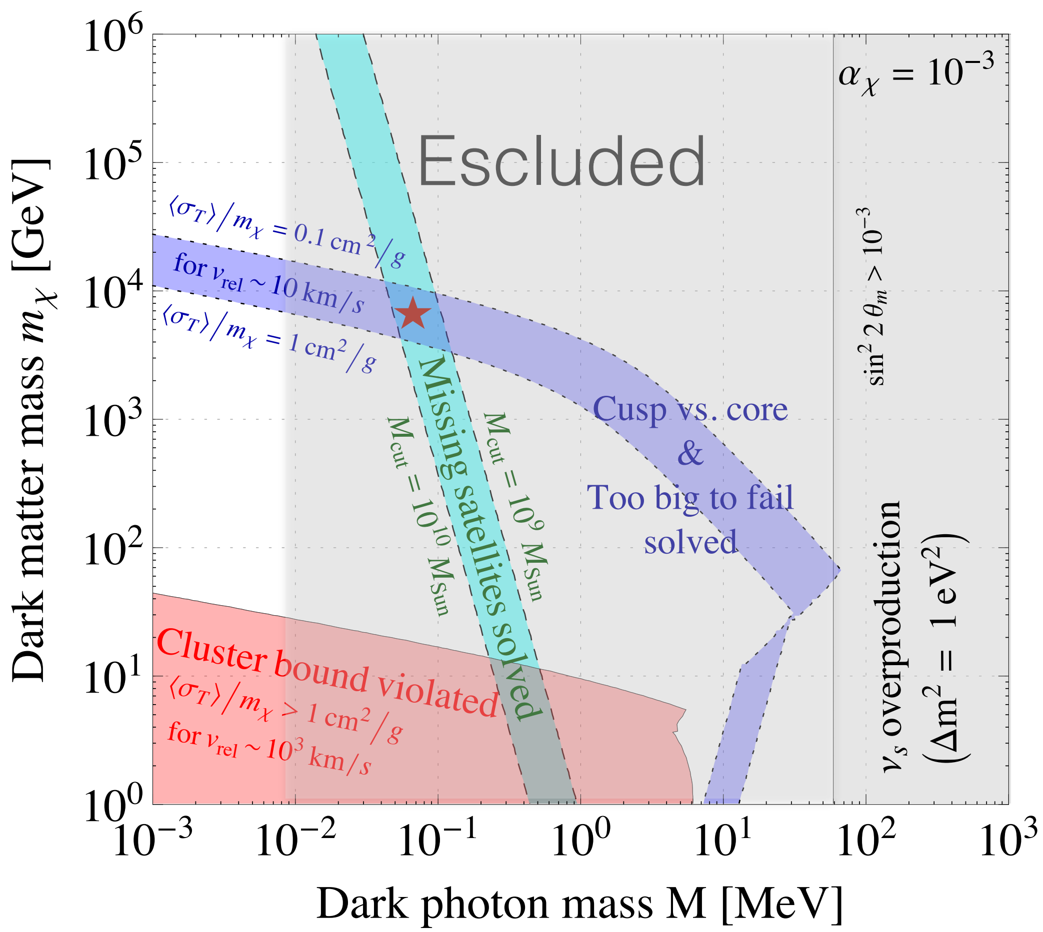


Chu, Dasgupta and Kopp 2015

Connection with the DM

If a new force exists, it is plausible that not only (sterile) neutrinos, but also DM particles couple to it

"***neutrinophilic DM***" $\mathcal{L}_{\rm int} \supset -g_\chi \bar{\chi} \not{V} \chi - g_\nu \bar{\nu} \not{V} \nu$

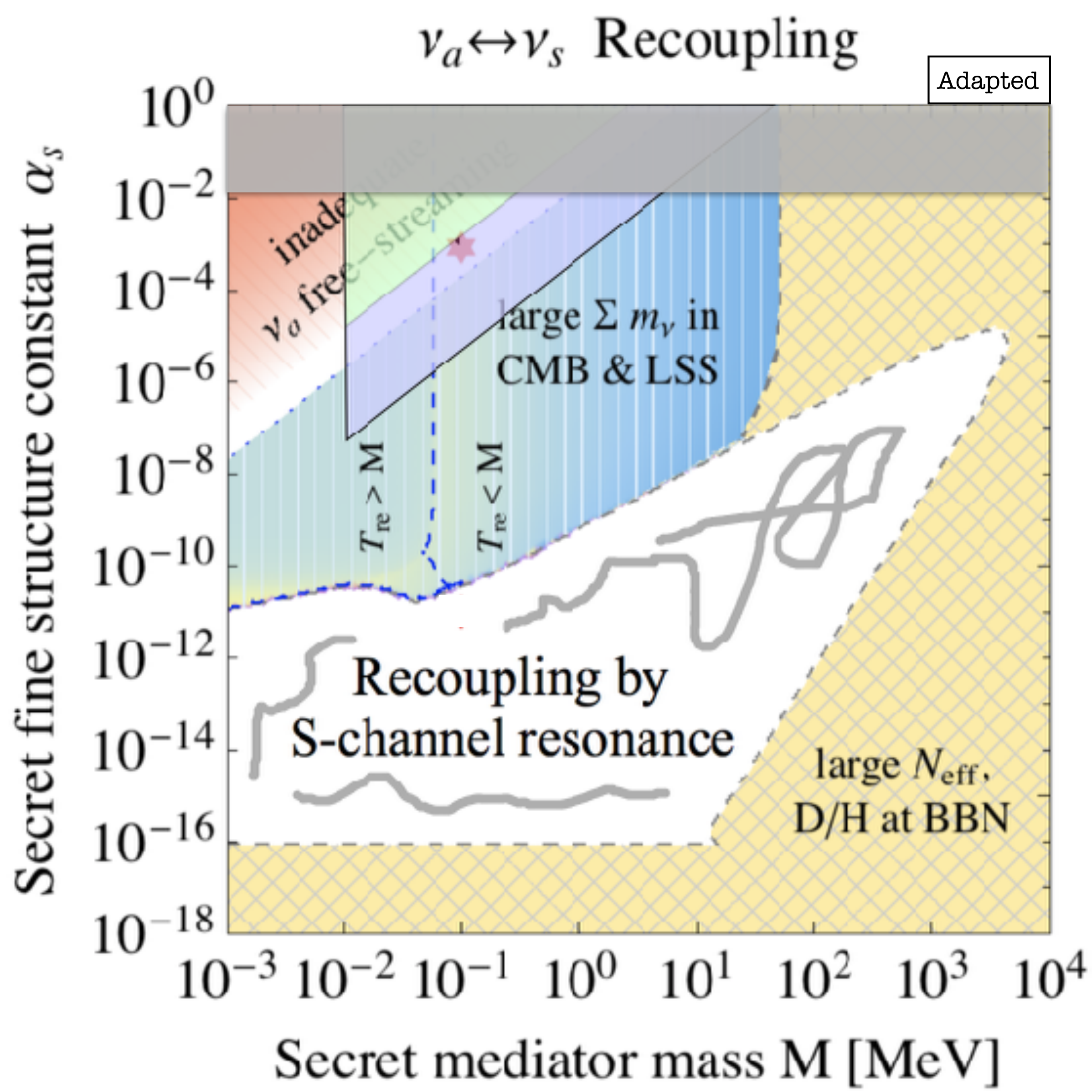


This scenario may solve all of the small-scale structure issues mentioned above. Indeed, the efficient scattering of DM would lead to late kinetic decoupling, delaying the formation of the smallest protohalos.

(Barions?)

van den Aarssen, Bringmann and Pfrommer 2012, Dasgupta and Kopp 2013, Bringmann, Hasenkamp, Kersten 2014, Cherry, Friedland, Shoemaker 2014, Archidiacono et al. 2015….

Summary Plot



Chu, Dasgupta and Kopp 2015

Similar plot obtained by *Cherry, Friedland, Shoemaker 2016* using present data and future sensitivity of IceCube

Possible hint (very dependent on the set of data used): in pseudoscalar model, $10^{-6} \lesssim g_s \lesssim 10^{-5}$ would reconcile eV sterile ν , H_0, ν SI. Also link to the DM small scale problem. *Archidiacono et al. 2015*

Open questions

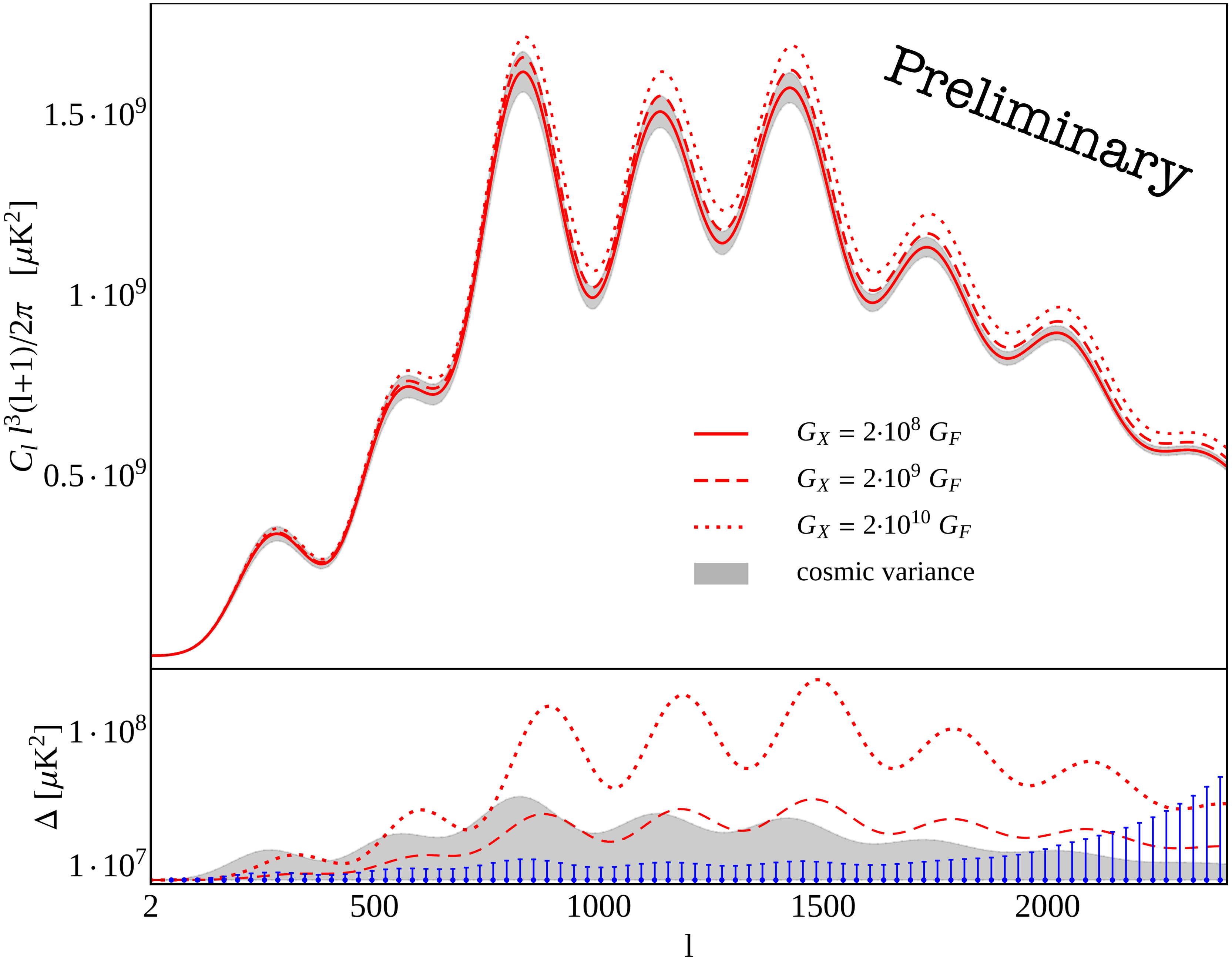
What happens considering sterile ν and νSI in the SN?

Secret interactions can be productive for other sterile ν mass scales?

How many extra exotic ingredients we are willing to introduce in our theory? (sterile ν, dark matter, secret interactions…)

Thank you

Backup slides



Forastieri, Lattanzi, Mangano, Mirizzi, Natoli, Saviano, 2017

to appear soon

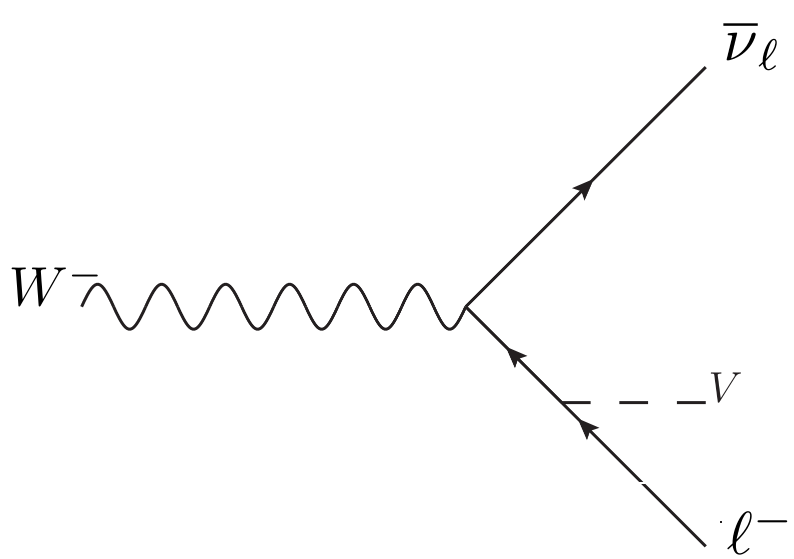
As long as the collision rate is much larger than the expansion rate, interacting neutrinos behave as perfect fluid. This means that shear and higher moments are exponentially suppressed. The net effect is that, at scales that are within the horizon during the interacting regime, density and pressure perturbations are enhanced with respect to the non-interacting case.

This enhancement propagates to the photon fluid, and thus to CMB anisotropies, through the metric perturbations.

Constraints for Vector Boson

Light vector gauge boson V, with mass O MeV and couples only to SM neutrinos and charged leptons through their V-A current:

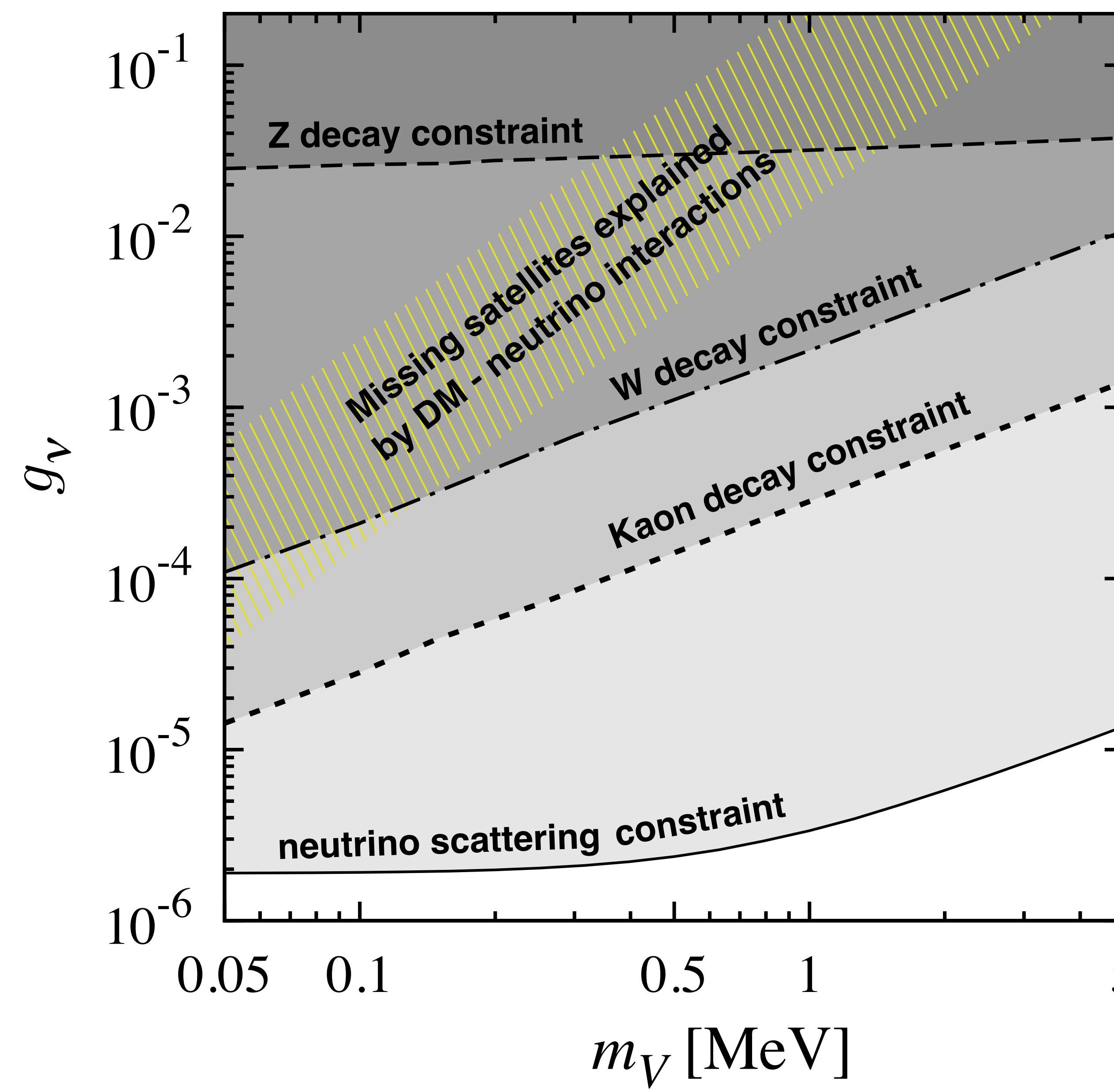
$$-g_\nu \left(\bar{\ell}\not{V} P_L \ell - \bar{\nu}\not{V} P_L \nu\right)$$



The 3-body decay of the W leads to additional events with missing energy, increasing the total decay width of the W

The decay remains consistent with existing measurements

$$\Gamma(W^- \to \ell^- \overline{\nu}_\ell V) \leq 1.28 \times 0.042\,\mathrm{GeV}$$



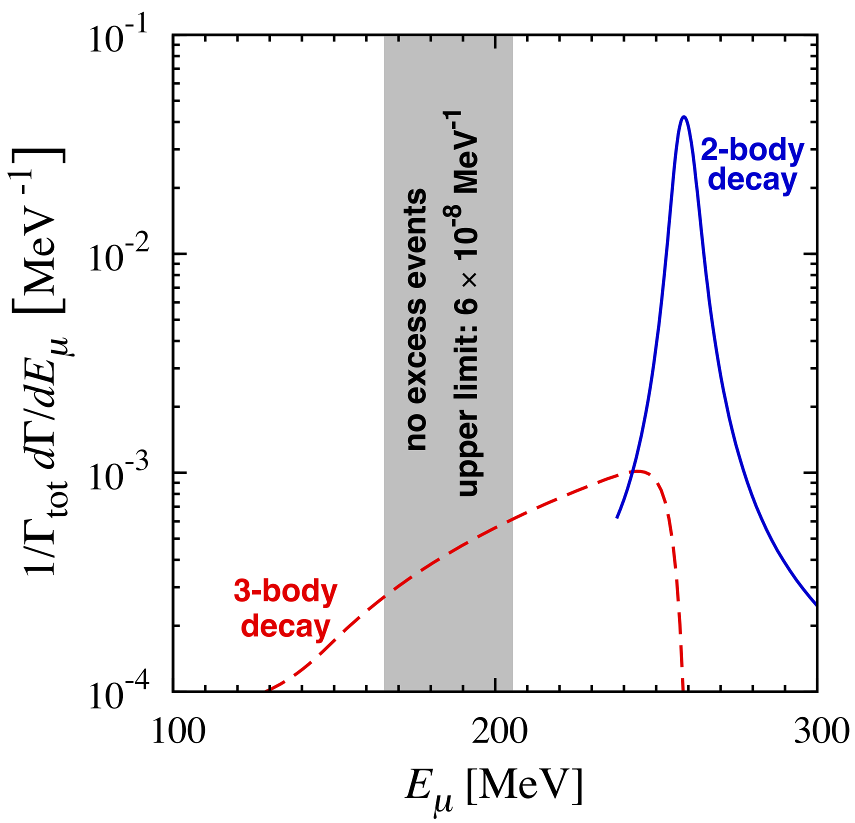
Constraints for Vector Boson

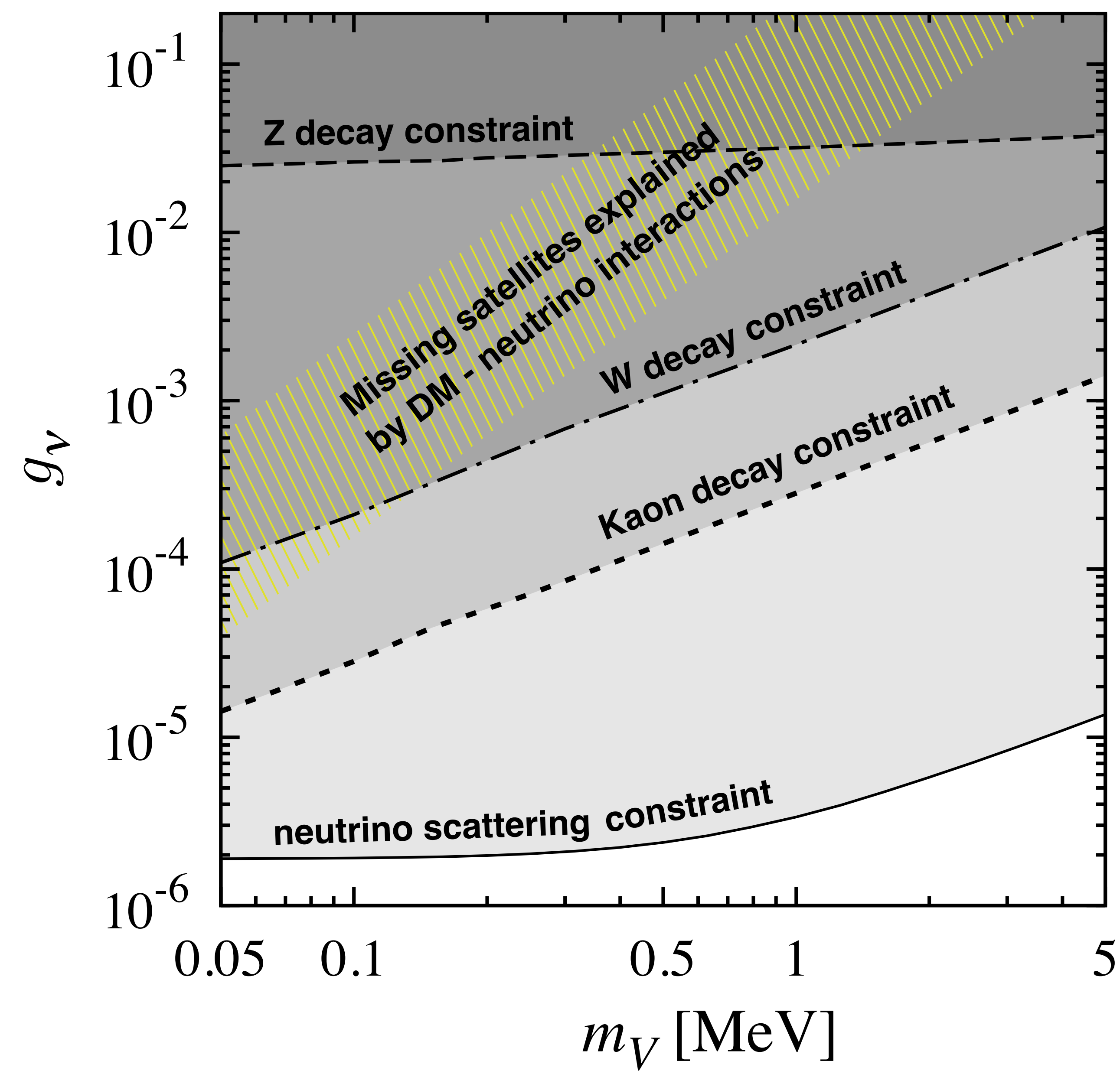
Light vector gauge boson V, with mass $\mathcal{O}$ MeV and couples only to SM neutrinos and charged leptons through their V-A current:

$$-g_\nu \left(\bar{\ell}\not{V} P_L \ell - \bar{\nu}\not{V} P_L \nu\right)$$

Distortion of the charged lepton spectrum due to excess missing energy in kaon decays

$$K^- \to \mu^- \bar{\nu}_\mu V$$





$$\Gamma(K^- \to \mu^- + \text{inv.})/\Gamma(K^- \to \mu^- \, \bar{\nu}_\mu) \leq \, 3.5 \times 10^{-6}$$

Constraints for Vector Boson

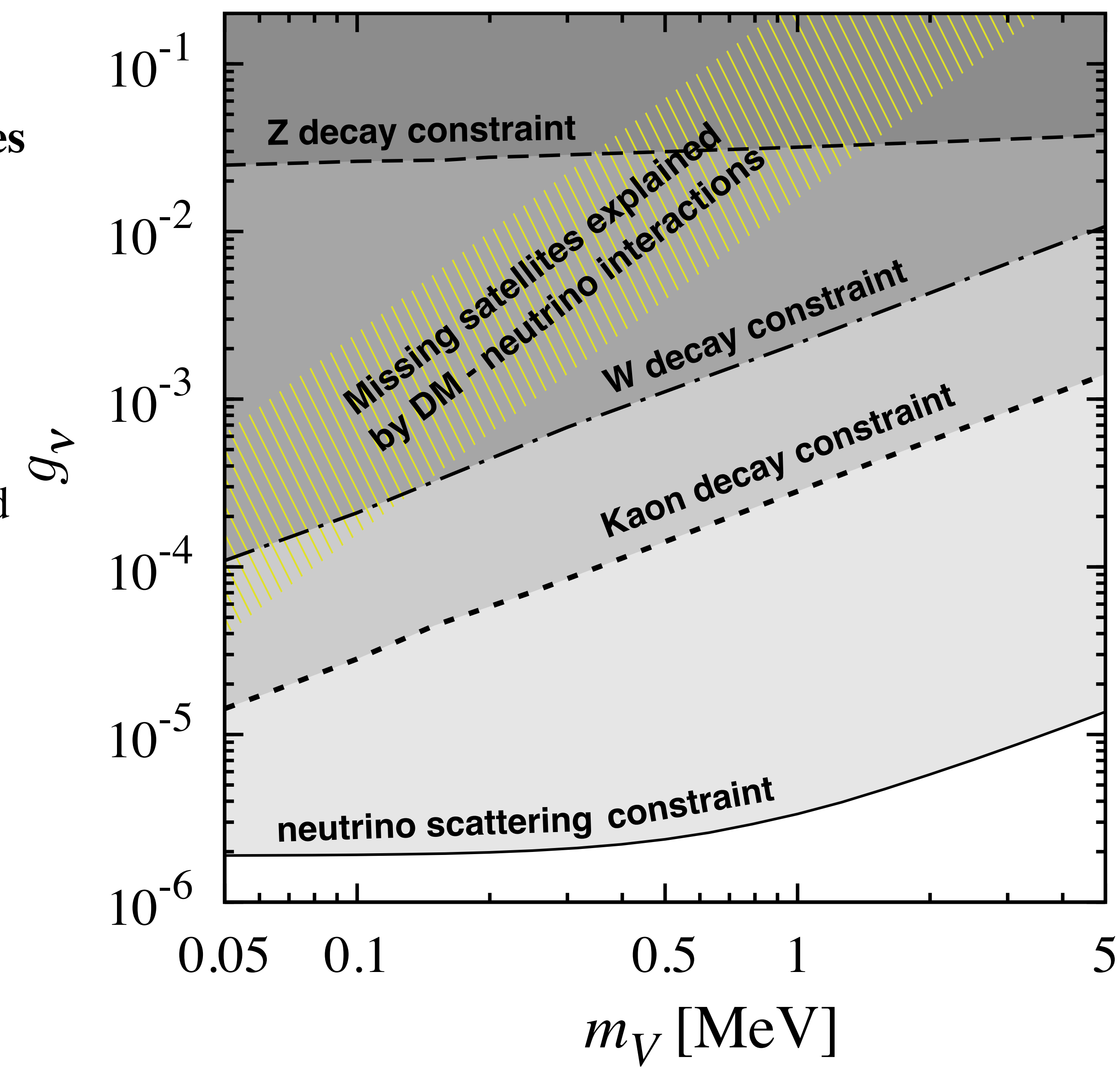
Light vector gauge boson V, with mass O MeV and couples only to SM neutrinos and charged leptons through their V-A current:

$$-g_\nu \left(\bar{\ell} \not{V} P_L \ell - \bar{\nu} \not{V} P_L \nu\right)$$

neutrino-electron scattering at very low neutrino energies (e.g., as in solar neutrino detection)

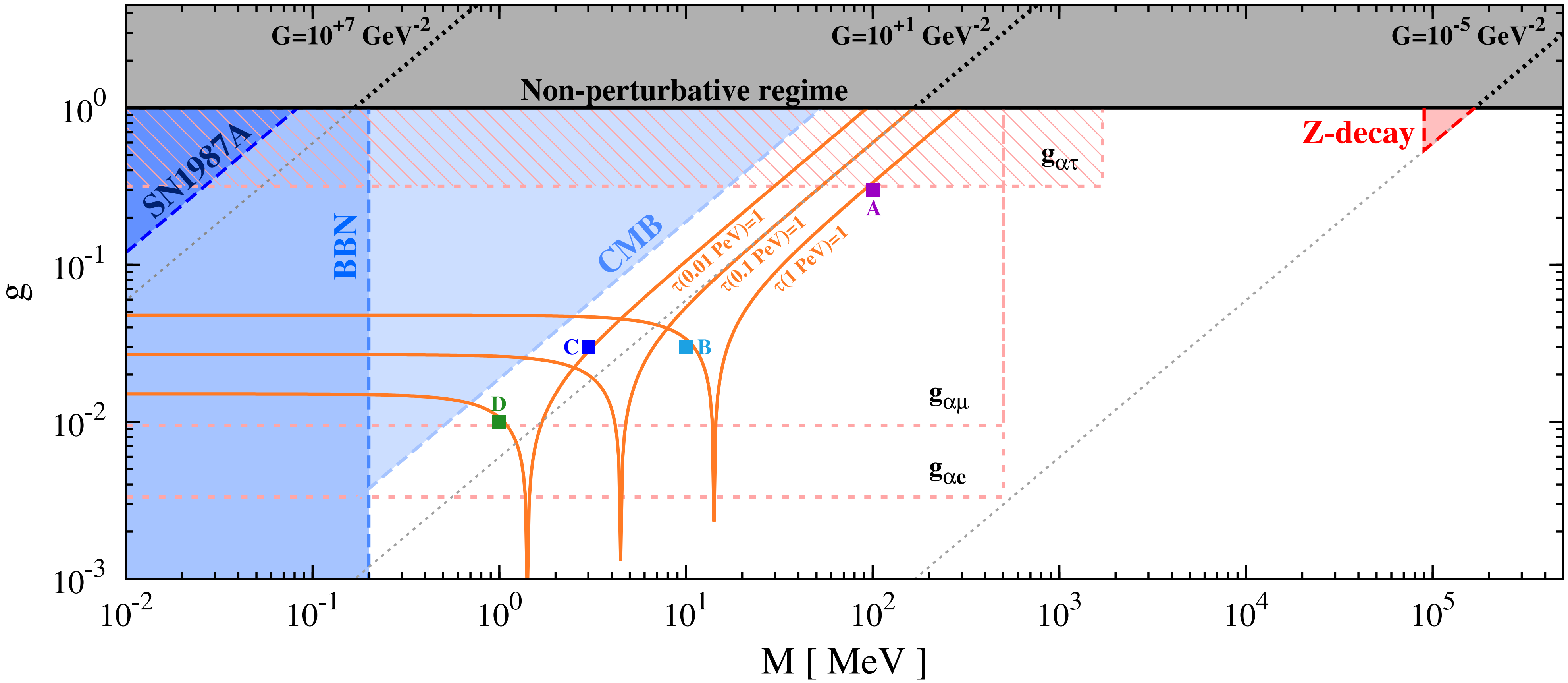
Solar neutrinos, produced as ν_e, change to ν_μ or ν_τ

The presence of the new vector boson would alter the charged current (CC) interaction between solar ν_e neutrinos and target electrons in the detector. It would also alter the ν_μ or ν_τ interaction with electrons via the weak neutral current (NC) interaction



Constraints for Scalar Boson

Scalar interaction term: $\mathcal{L}_{int} \;\sim\; g\phi\bar{\nu}\nu$



νSI: elastic scattering of neutrinos in the s channel $\rightarrow$ $\boxed{\sigma(E) = \frac{g^4}{4\pi}\frac{s}{(s-M^2)^2+M^2\Gamma^2}}$

$$s = 2Em_\nu$$
$$\Gamma = g^2 M/4\pi$$

3 kinematic regimes:

- **mediator mass < √s** (i.e. Majoron with m=0), $\sigma \simeq g^4/(4\pi s)$
- **mediator mass ∼ √s** (resonance) , s= M^2, $\sigma = 4\pi/M^2$
- **mediator mass > √s** (effective theory), $\sigma \simeq g^4 s/(4\pi M^4)$

$$\tau(E|g,M) = c\int_0^1 dz \frac{n_t(0)}{H(z)}(1+z)^2\sigma(E|g,M)$$

	A	B	C	D
g	0.3	0.03	0.03	0.01
M [MeV]	100	10	3	1
τ (1 PeV)	~ 0.7	~ 0.6	~ 0.2	~ 0.002
$E_{\rm res}$ [PeV]	50	0.5	0.045	0.005

Secret interactions for sterile ν_s

4-fermion point-like interaction:
new secret self-interactions among sterile ν mediated by a massive gauge boson X : $M_X << M_W$

➔ *Suppress the thermalization of sterile neutrinos*
(Effective ν_a-ν_s mixing reduced by a large matter term)

ν_s - ν_s *interaction strength* $G_X = \frac{\sqrt{2}}{8}\frac{g_X^2}{M_X^2}$ *for* $T << M_X$

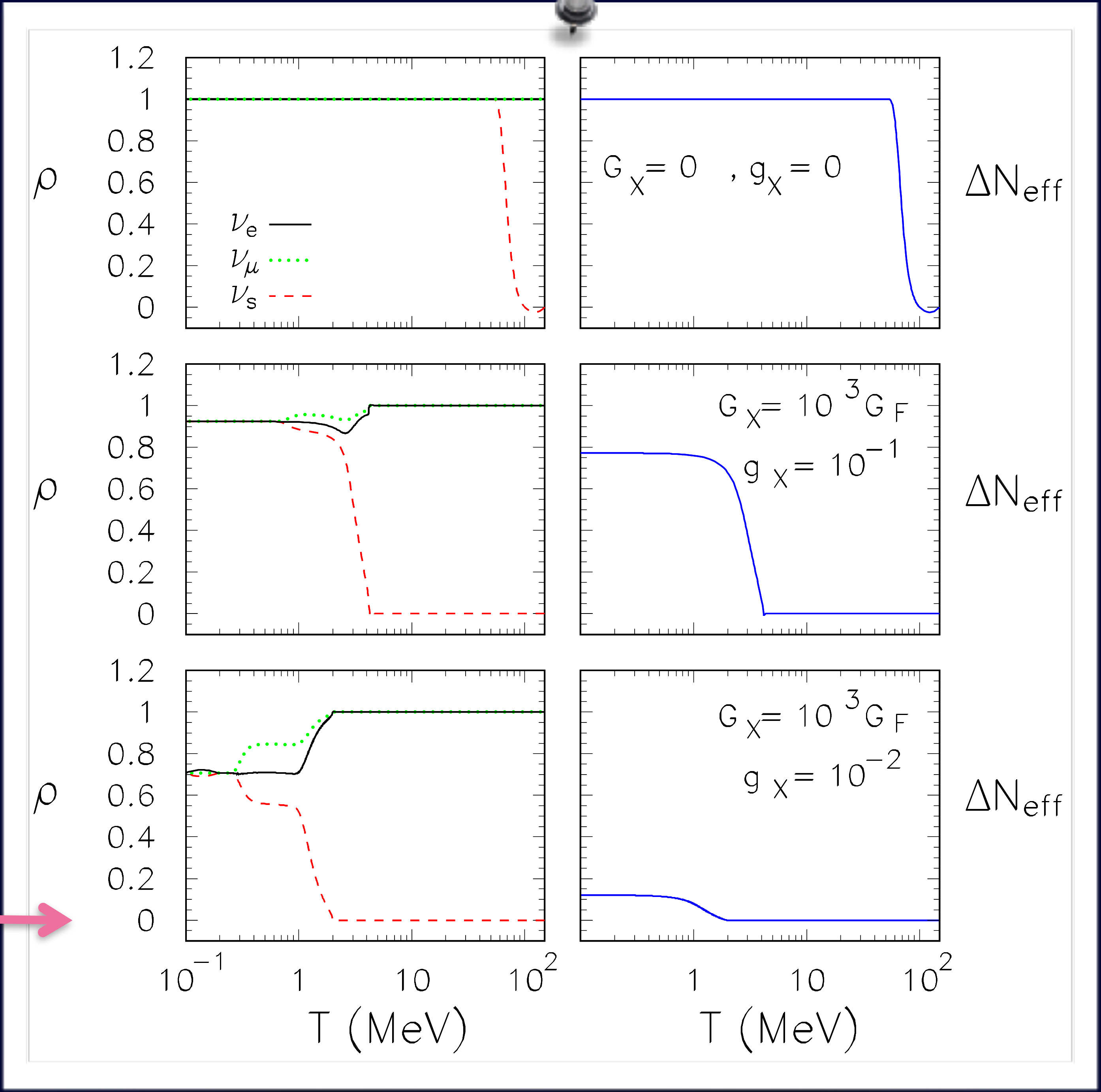
Evolution equation:

$$\mathrm{i}\,\frac{d\rho}{dt} = [\Omega, \rho] + C[\rho]$$

$$\Omega = \Omega_{\rm vac} + \underbrace{\Omega_{\rm mat} + \Omega_{\nu-\nu}}_{\propto G_F} + \underbrace{\Omega^{\rm secr}_{\nu_s-\nu_s}}_{\propto G_X}$$

$$C = \underbrace{C_{\rm SM}}_{\propto G_F^2} + \underbrace{C_{\rm secr}}_{\propto G_X^2}$$

Sterile production by secret interactions



Secret interactions: resonances around 1 MeV,

sterile ν suppressed.

Note that also ν_e and ν_μ the are depleted:

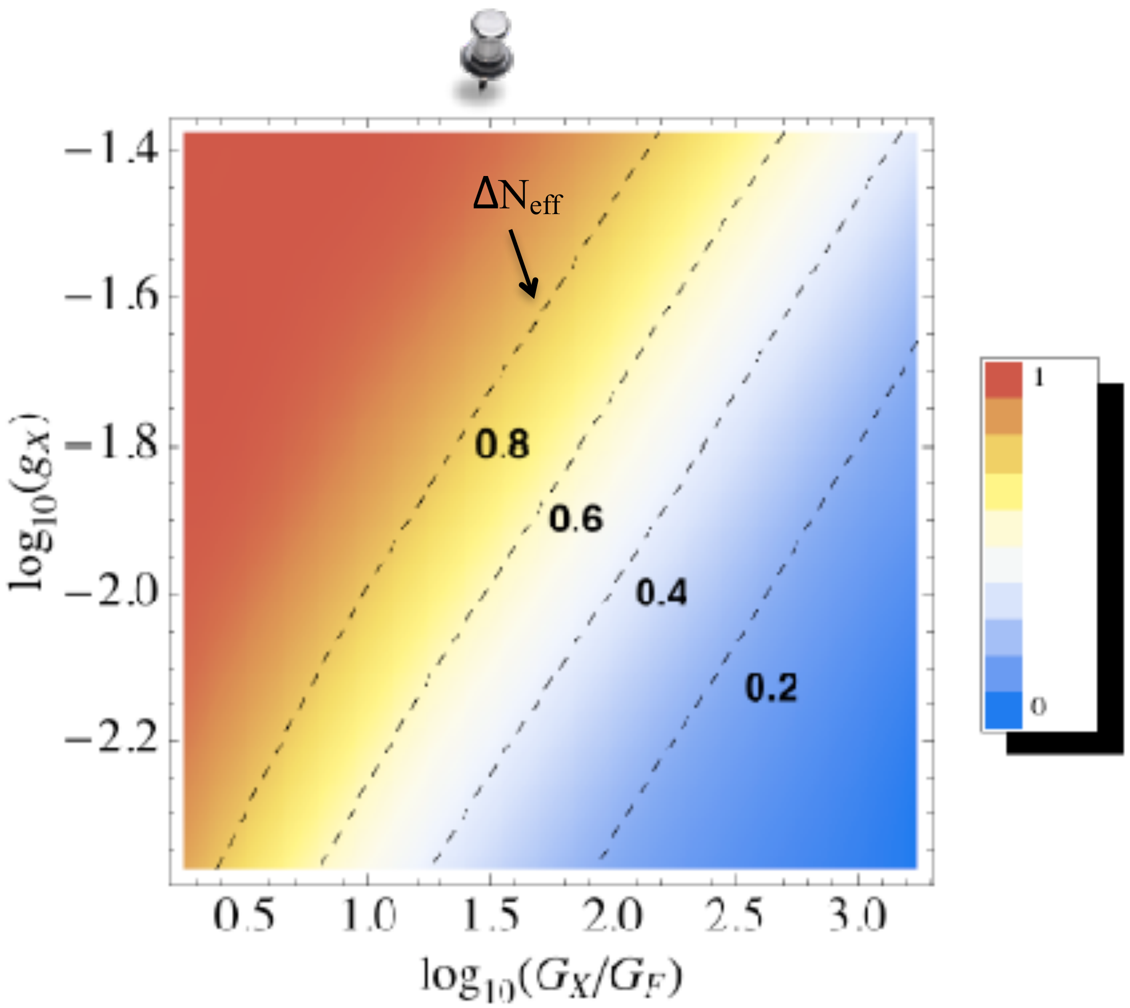
crucial for N_{eff} but also for BBN

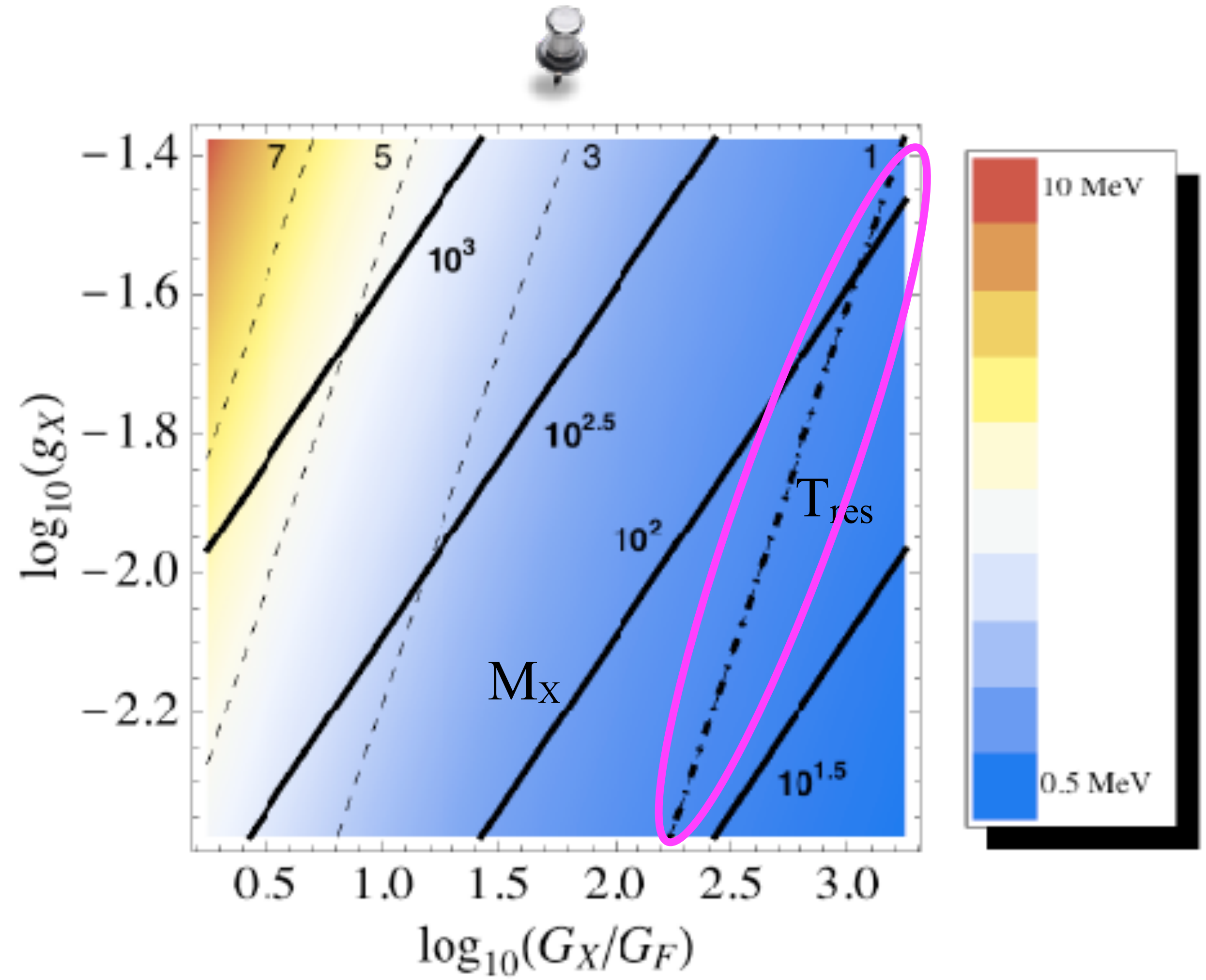
$\rho_{ee} = 0.7$, $N_{eff} = 0.18$

Saviano, Pisanti, Mangano, Mirizzi 2014, ArXiv: *1409.1680*

Secret interactions and BBN

Asymptotic values of ΔN_{eff} versus G_X and g_X





Resonance temperature in the plane (G_X, g_X)

Dashed curves: constant T_{res} contours

Solid curves: constant M_X contours

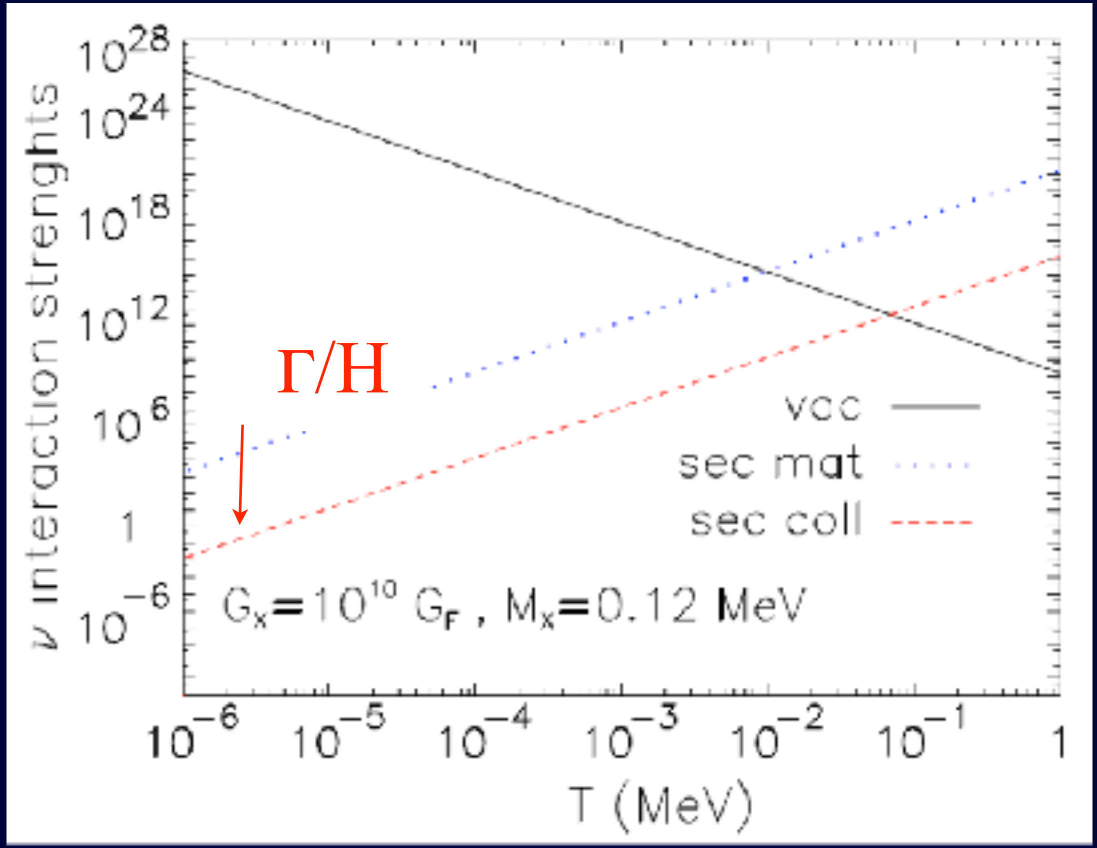
Cosmological constraints on secret interactions

Summarising:

✓ Very large M_X → thermalization of ν_s ↔ secret interactions do not have effect

✓ 400 MeV< M_X < 40 MeV → severely constrained by BBN bounds

✓ 40 MeV < M_X < 0.1 MeV → severely constrained by sterile mass bounds



For M_X < 0.1 MeV → ν_s could be still coupled at CMB and LSS epoch → no free-streaming

Present cosmological mass bound obtained considering free-streaming ν

↓

An appropriated analysis should be performed

A surprising feature on Neff

- After the production, ν_s have a "grey-body" spectrum ($\rho_{ss} = 3/4$)....

.... but the collisions and oscillations are still active pushing all neutrinos to a common FD distribution

Constraint: $n_{\nu\ TOT}$ must be constant

↓

$T\nu$ is reduced by a factor $(3/4)^{1/3}$,
leading to an effect on the radiation density

$$\boxed{\epsilon_{\nu,\text{in}} = 3 \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \epsilon_\gamma}$$

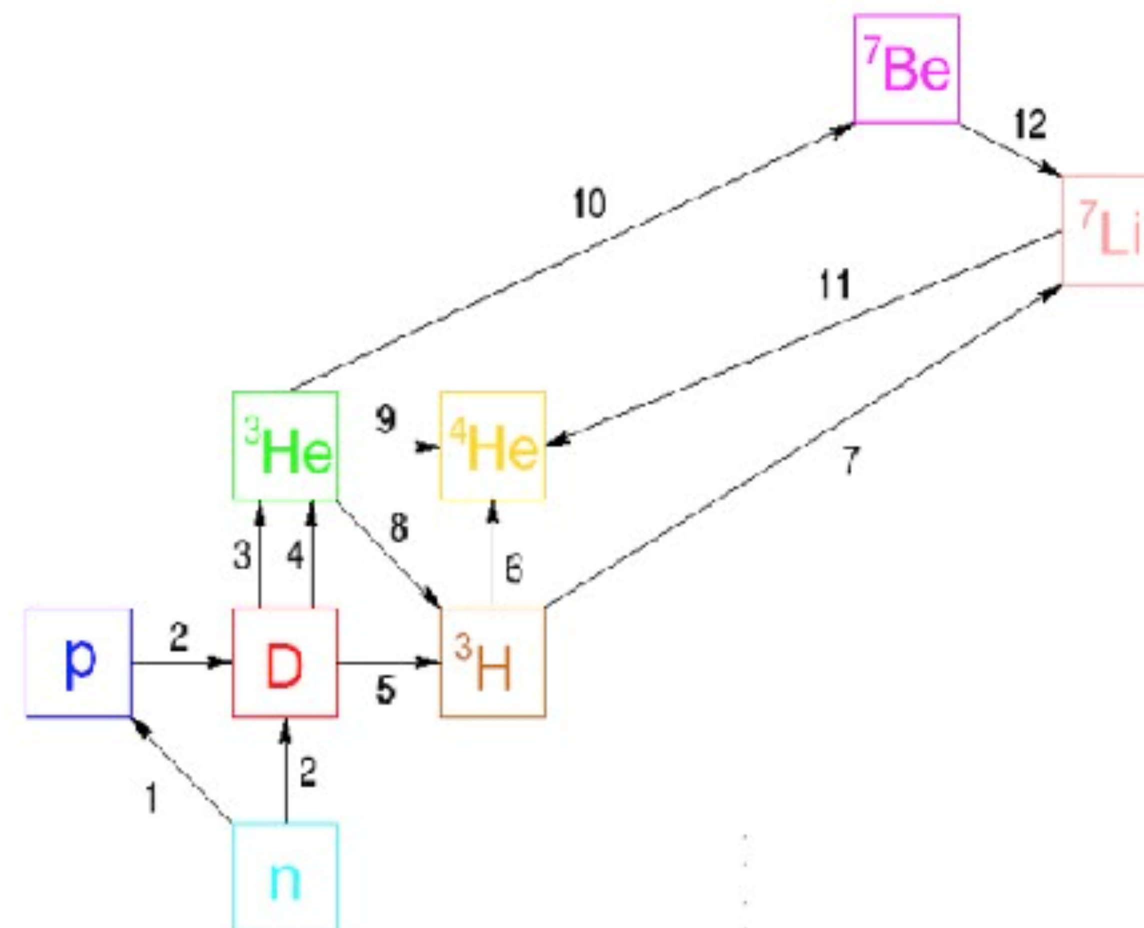
$$\boxed{\epsilon_{\nu,\text{fin}} = 4 \times \left(\frac{3}{4}\right)^{4/3} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \epsilon_\gamma}$$

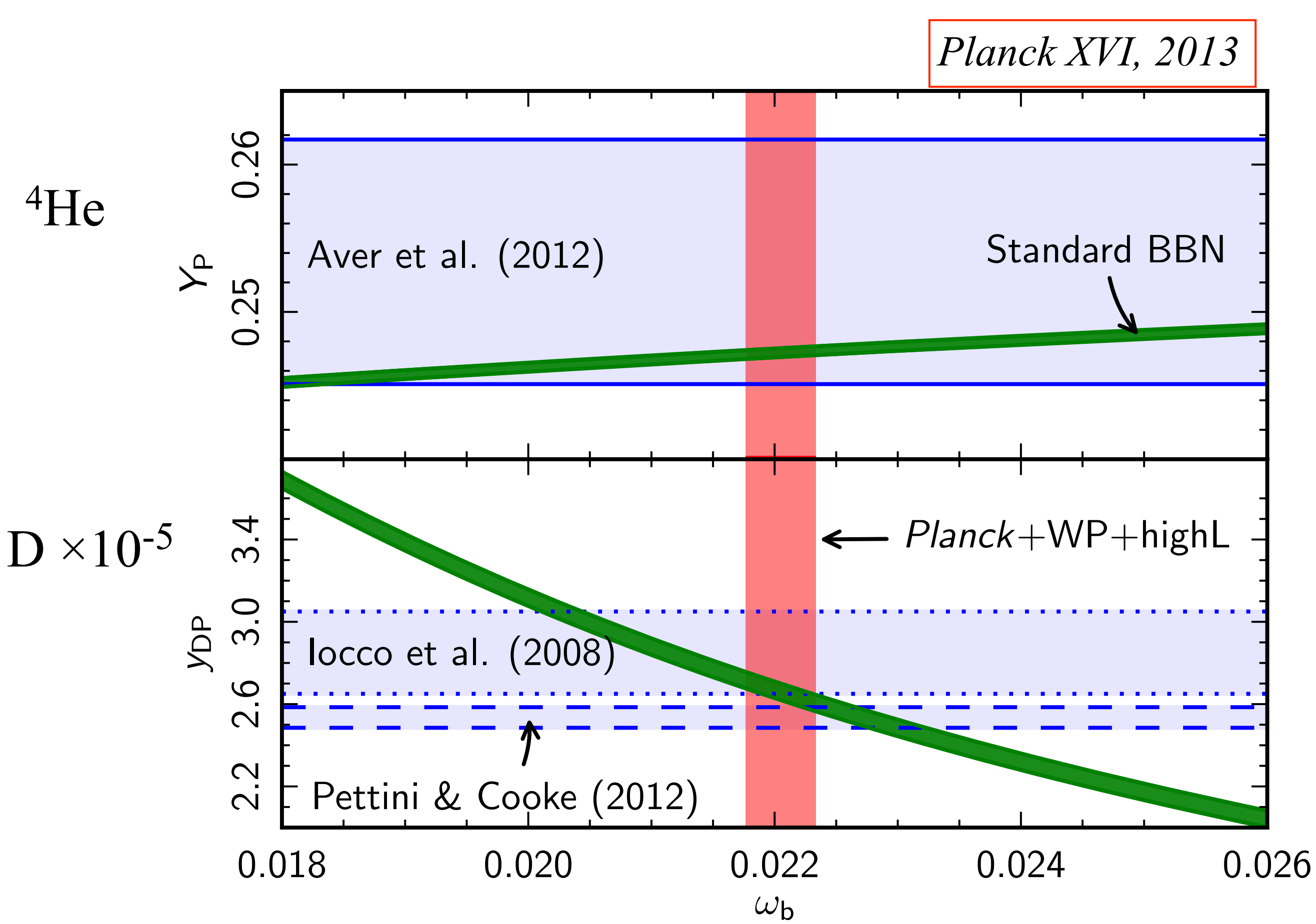
Mirizzi, Mangano, Pisanti Saviano, 2014,
ArXiv:1410.1385

Big Bang Nucleosynthesis

* 0.1-0.01 MeV
Formation of light nuclei starting from D

1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. $p + n \rightarrow D + \gamma$
3. $D + p \rightarrow {}^3He + \gamma$
4. $D + D \rightarrow {}^3He + n$
5. $D + D \rightarrow {}^3H + p$
6. ${}^3H + D \rightarrow {}^4He + n$
7. ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8. ${}^3He + n \rightarrow {}^3H + p$
9. ${}^3He + D \rightarrow {}^4He + p$
10. ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11. ${}^7Li + p \rightarrow {}^4He + {}^4He$
12. ${}^7Be + n \rightarrow {}^7Li + p$





Prediction for ^{4}He and D in a **standard** BBN obtained by Planck collaboration using `PArthENoPE`

Blue regions: primordial yields from measurements performed in different astrophysical environments

$\omega_b = 0.02207 \pm 0.00027$