25th International Workshop on Weak Interactions and Neutrinos (WIN2015)

MPIK Heidelberg, 13th June 2015

Astroparticle Physics Theory Summary

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invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

OUTLINE

- Effective Theory for DM Direct Detection
- DM Indirect Detection and backgrounds
- The LHC and DM connection
- DM and Baryo connection

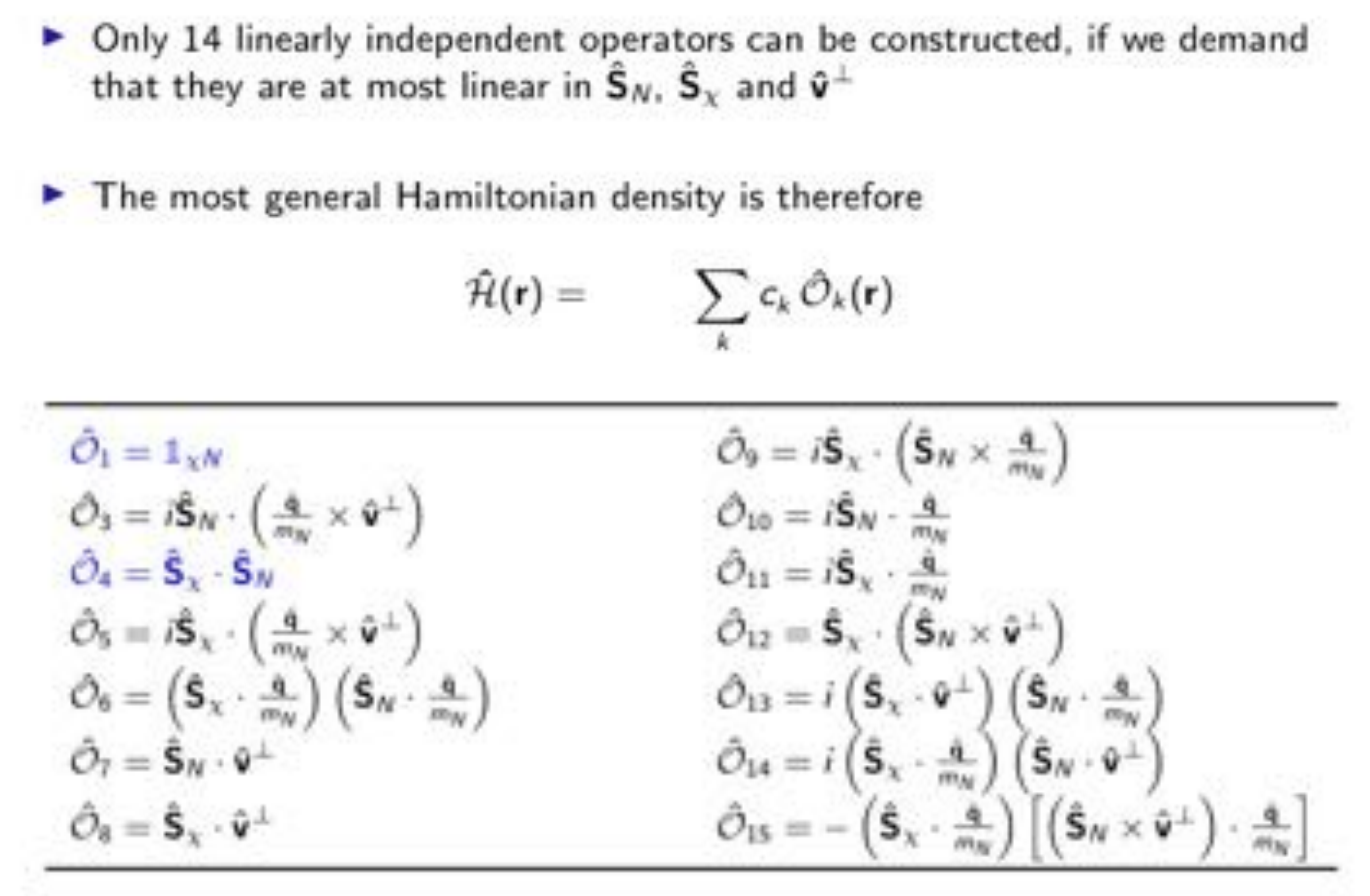
“LEITMOTIVS” OF THEORY

- Power and limitations of effective theories !
- More precise determinations of backgrounds and signals...
- Interdisciplinary approaches
- Connection of DM with Baryons, Neutrinos, Model Building, etc...

Effective Theory for DM DD

EFFECTIVE THEORY FOR DD

[Riccardo Catena Astro-1]



- Only 14 linearly independent operators can be constructed, if we demand that they are at most linear in $\hat{\mathbf{S}}_N$, $\hat{\mathbf{S}}_\chi$ and $\hat{\mathbf{v}}^\perp$
- The most general Hamiltonian density is therefore

$$\hat{\mathcal{H}}(\mathbf{r}) = \sum_k c_k \hat{\mathcal{O}}_k(\mathbf{r})$$

$$\hat{\mathcal{O}}_1 = 1_{\chi N}$$

$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\mathbf{q}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$

$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\mathbf{q}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\mathbf{q}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\mathbf{q}}{m_N}\right)$$

$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\mathbf{q}}{m_N}\right)$$

$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\mathbf{q}}{m_N}$$

$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\mathbf{q}}{m_N}$$

$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\mathbf{q}}{m_N}\right)$$

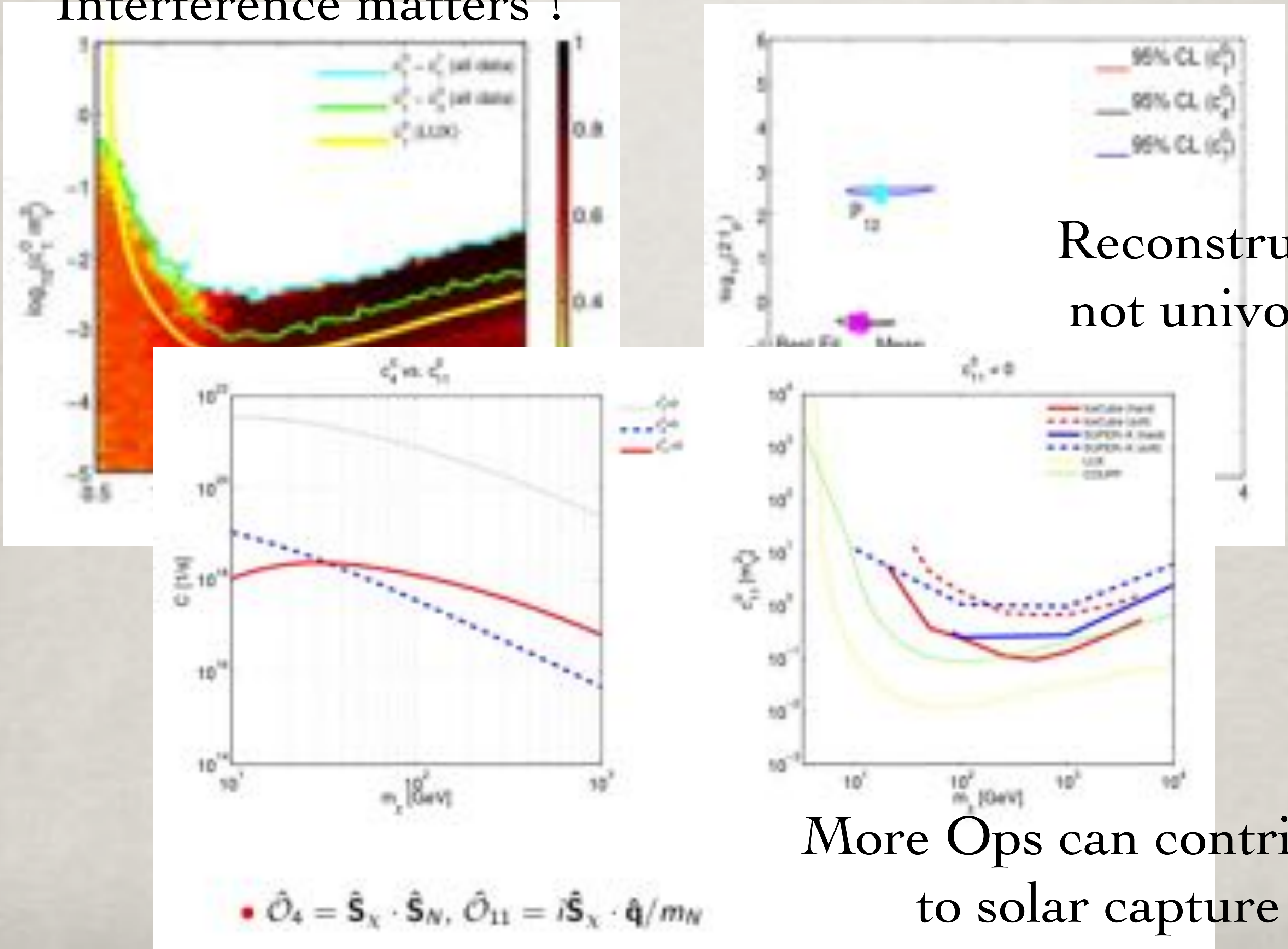
$$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\mathbf{q}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\mathbf{q}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\mathbf{q}}{m_N}\right]$$

EFFECTIVE THEORY FOR DD

[Riccardo Catena Astro-1]

Interference matters !



$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N,\ \hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{q}}/m_N$

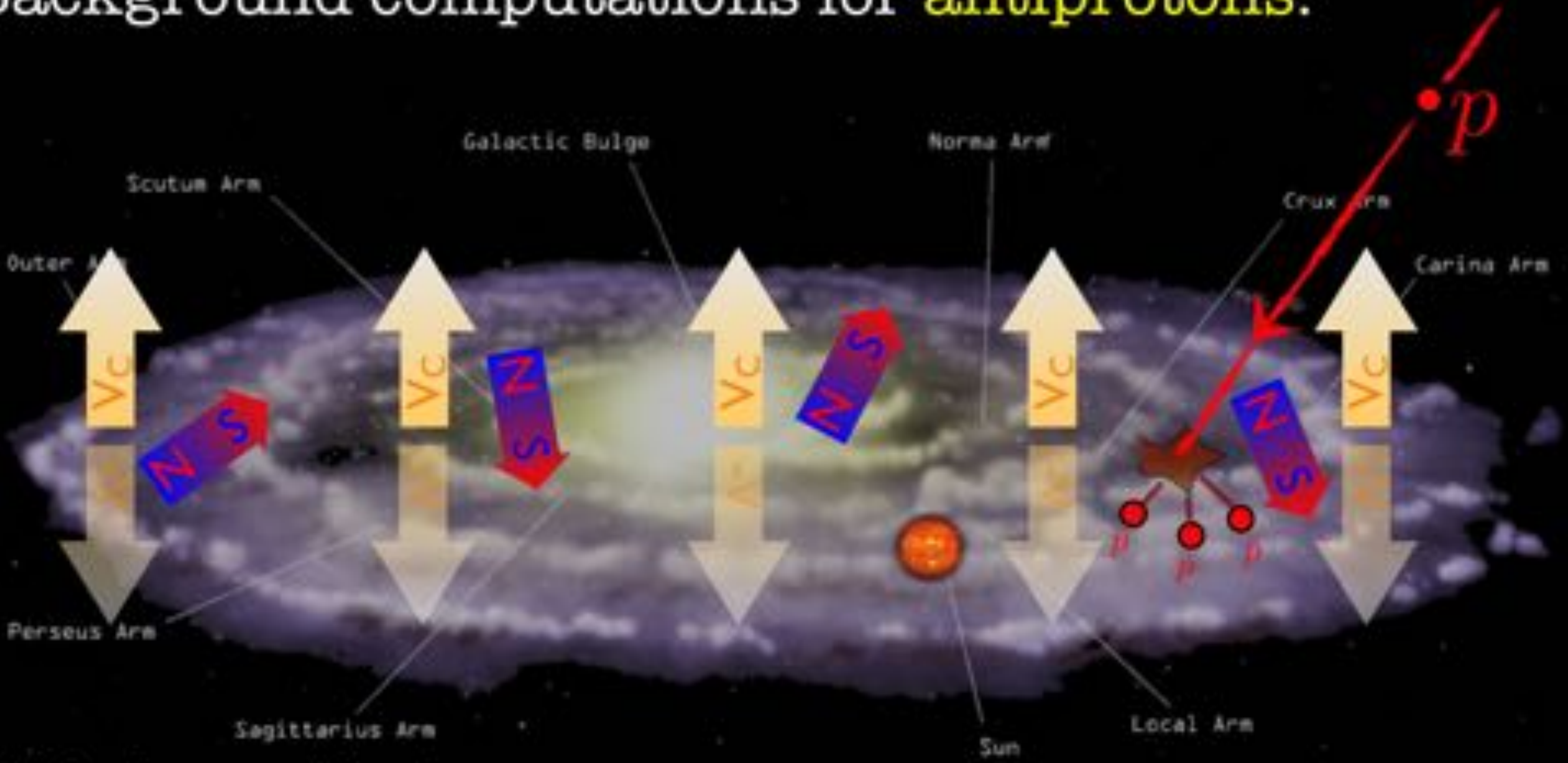
Reconstruction
not univocal...

More Ops can contribute
to solar capture

DM indirect detection & backgrounds

Indirect Detection

Background computations for antiprotons:



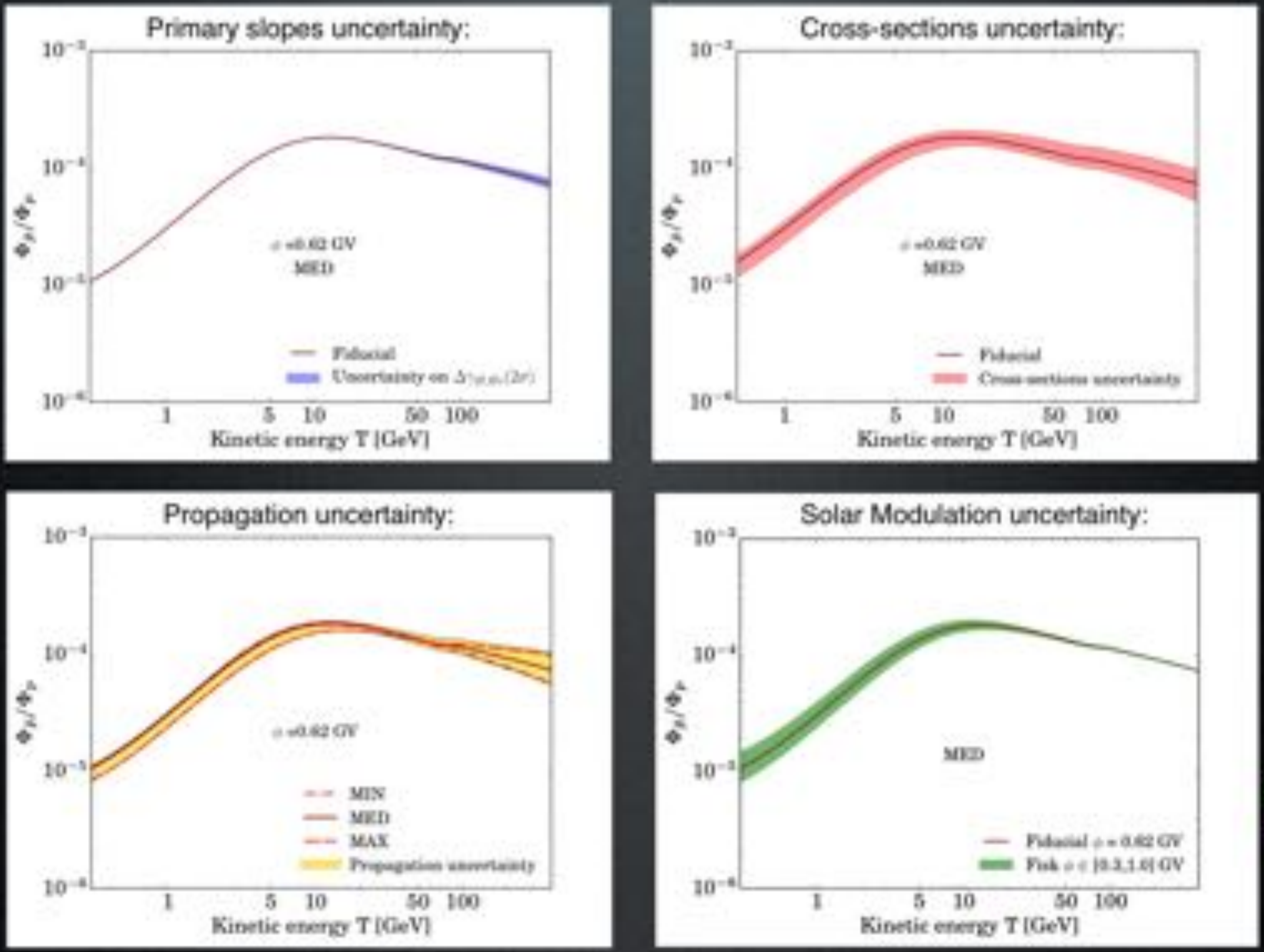
Main ingredients:

- primary p (and He) **New!**
- spallation cross-sections $\sigma_{\rm pH\to\bar pX}, \sigma_{\rm pHe\to\bar pX}, \sigma_{\rm HeH\to\bar pX}, \sigma_{\rm HeHe\to\bar pX}$ **New!**
- propagation
- solar modulation

Indirect Detection

Background computations for antiprotons:

Uncertainties:

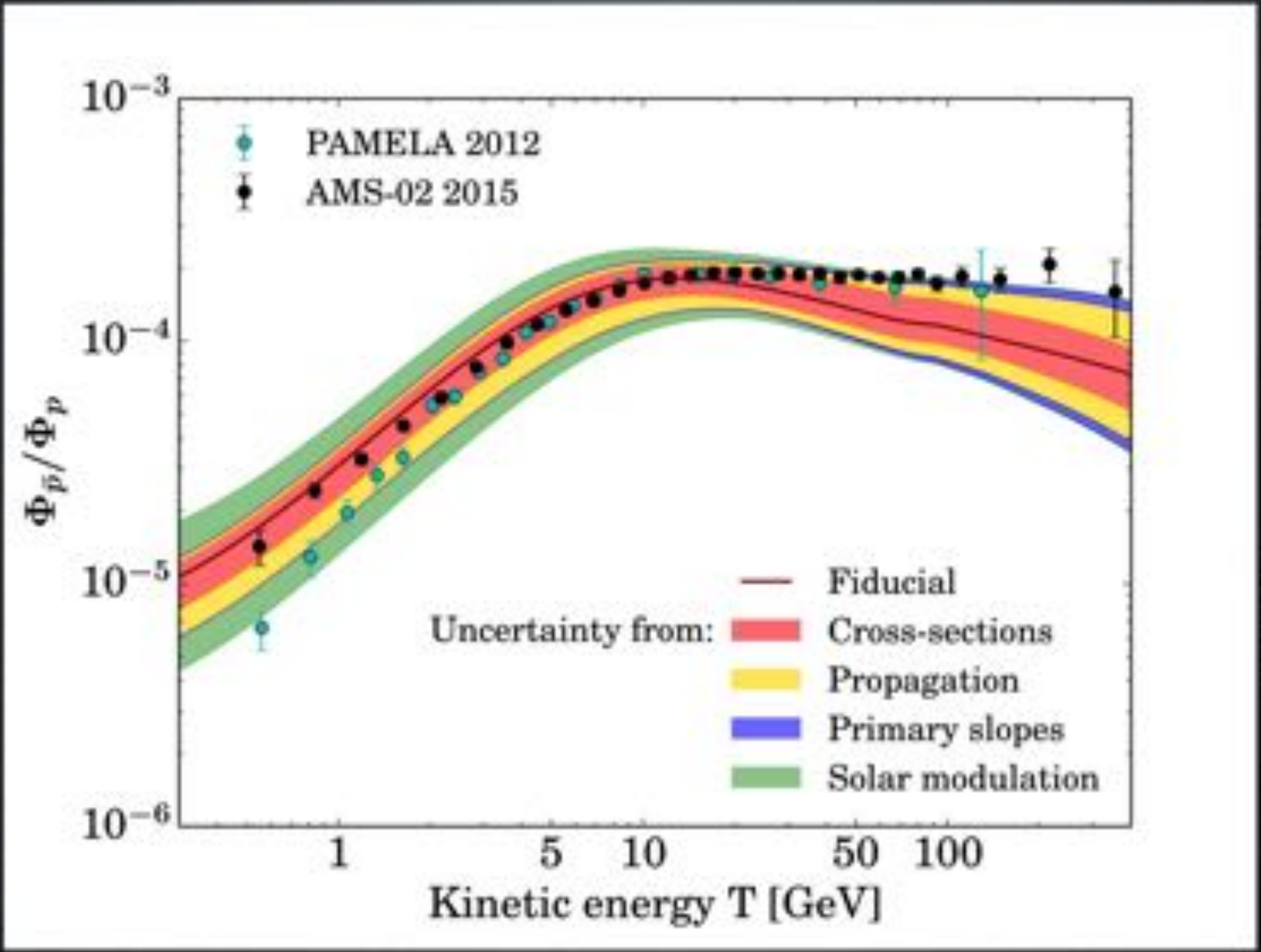


Giesen, Boudaud,
Genolini, Poulin,
Cirelli, Salati,
Serpico
1504.04276

Indirect Detection

Antiproton data vis-à-vis the background:

M. Cirelli - Astro 2



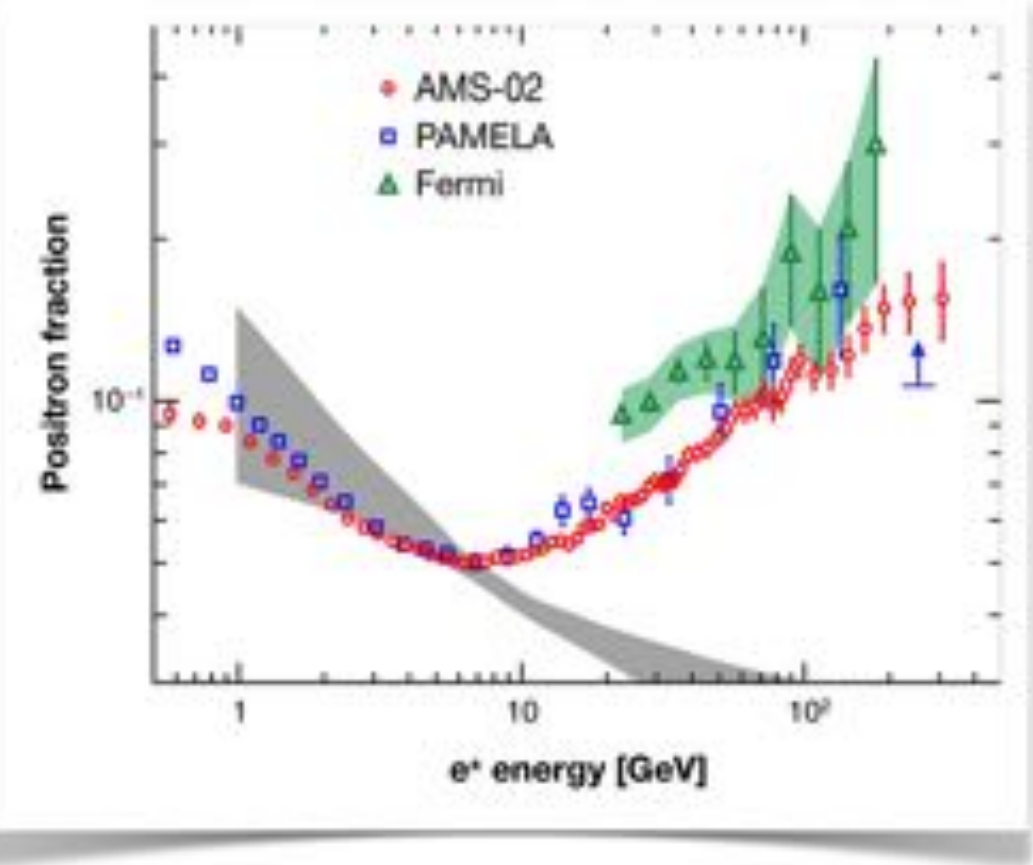
No evident **excess**

Some preference for flatness

Giesen, Boudaud, Genolini, Poulin, Cirelli, Salati, Serpico 1504.04276

E+/E- EXCESS

[Andrea Vittino Astro-2]



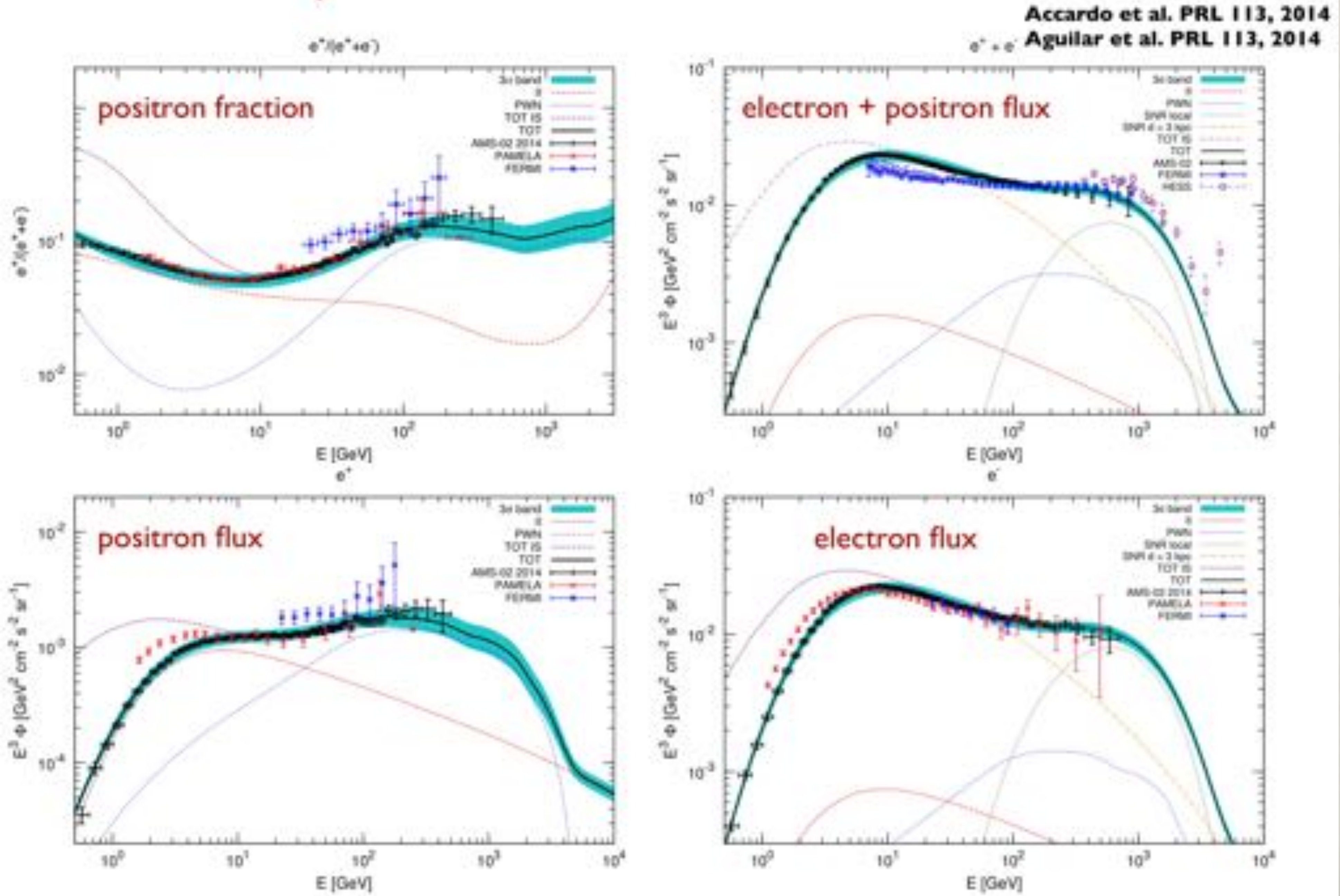
The rise is **not compatible** with the hypothesis that all positrons have a **secondary origin**

It implies the existence of additional **sources of primary e^+**

In principle, these high-energy positrons can be generated by **astrophysical sources** or by the **annihilation/decay of WIMPs**

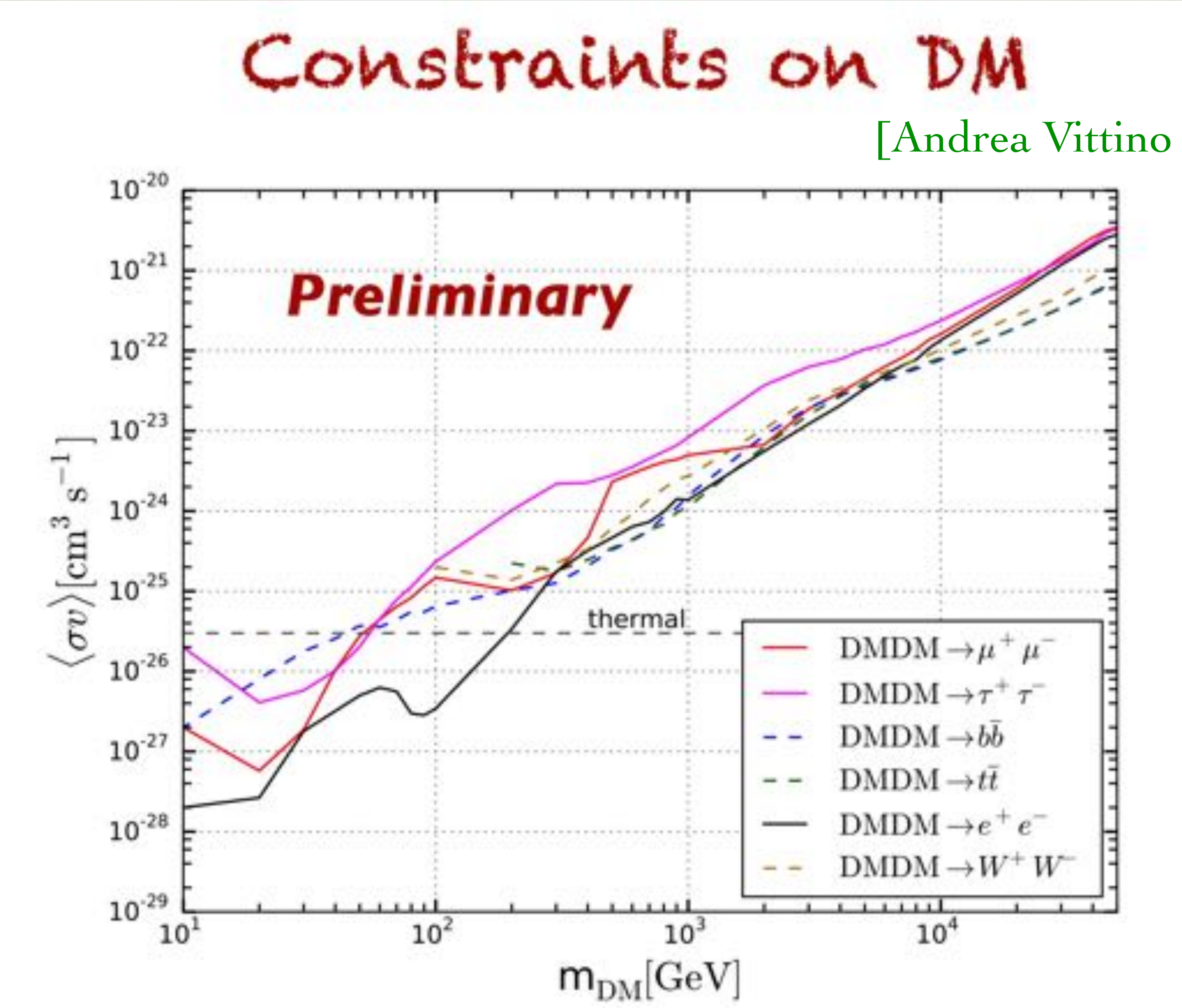
E+/E- EXCESS: NO DM !?!

fit to AMS-02 data [Andrea Vittino Astro-2]



Accardo et al. PRL 113, 2014
Aguilar et al. PRL 113, 2014

E+/E- EXCESS: DM BOUNDS

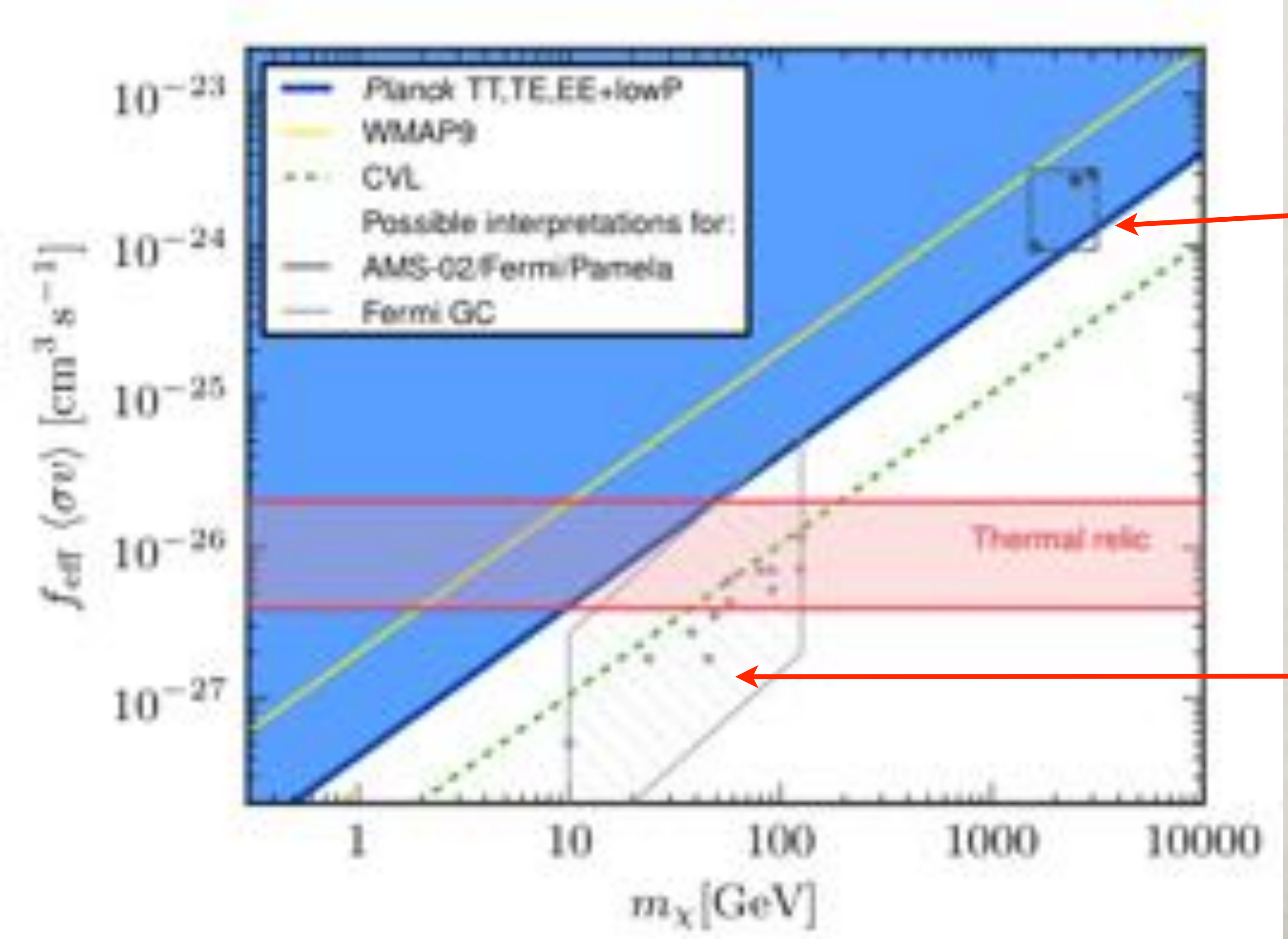


[Andrea Vittino Astro-2]

PLANCK: DM ANNIHILATION

WIMP annihilation also modifies the epoch of recombination due to the release of energy in the primordial plasma and leaves imprints into the CMB ! Planck can now exclude cross-sections as those needed by PAMELA and AMS-02:

[Planck 1502.01589]

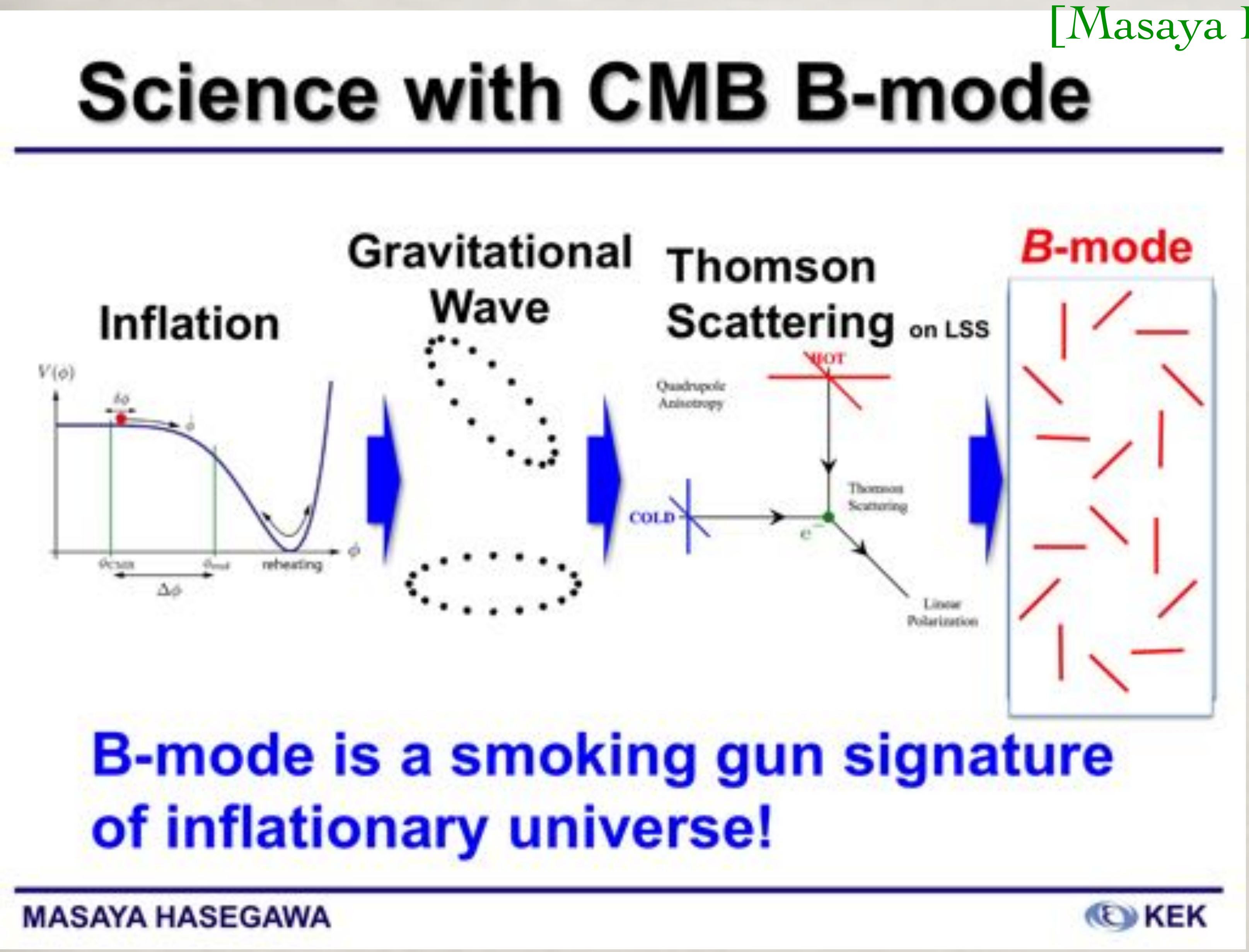


Pamela-inspired DM models

Galactic centre excess

CMB B-MODE POLARIZATION

[Masaya Hasegawa Astro-7]



Science with CMB B-mode

Inflation → **Gravitational Wave** → **Thomson Scattering** on LSS → ***B*-mode**

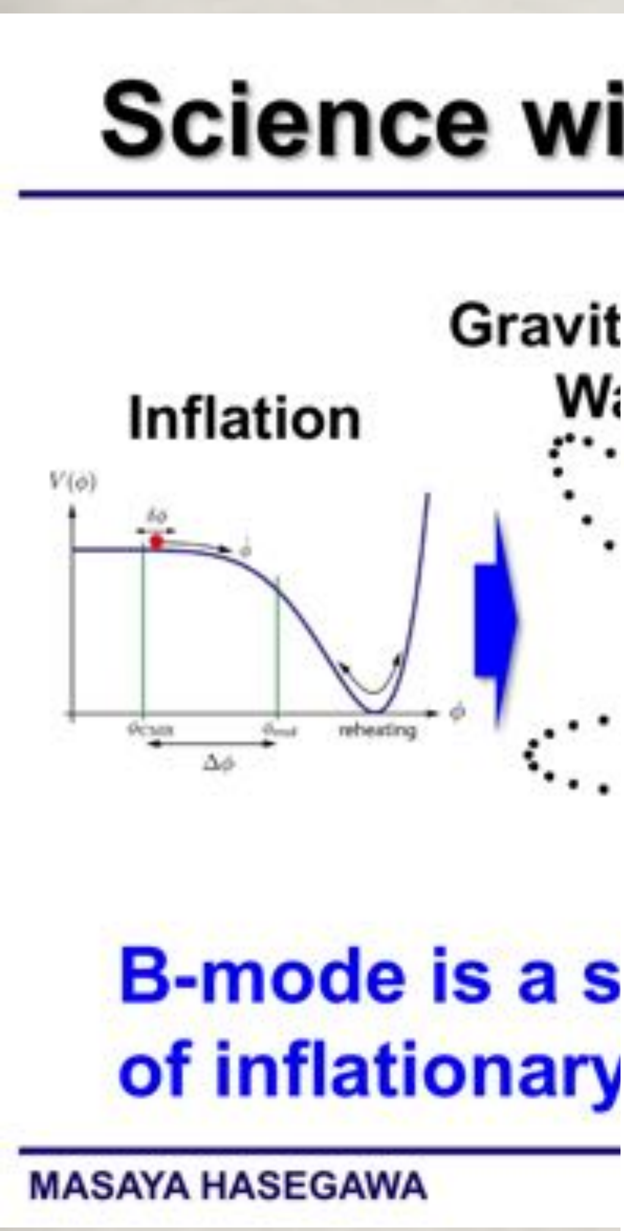
B-mode is a smoking gun signature of inflationary universe!

MASAYA HASEGAWA

KEK

CMB B-MODE POLARIZATION

[Masaya Hasegawa Astro-7]



Science with CMB B-mode

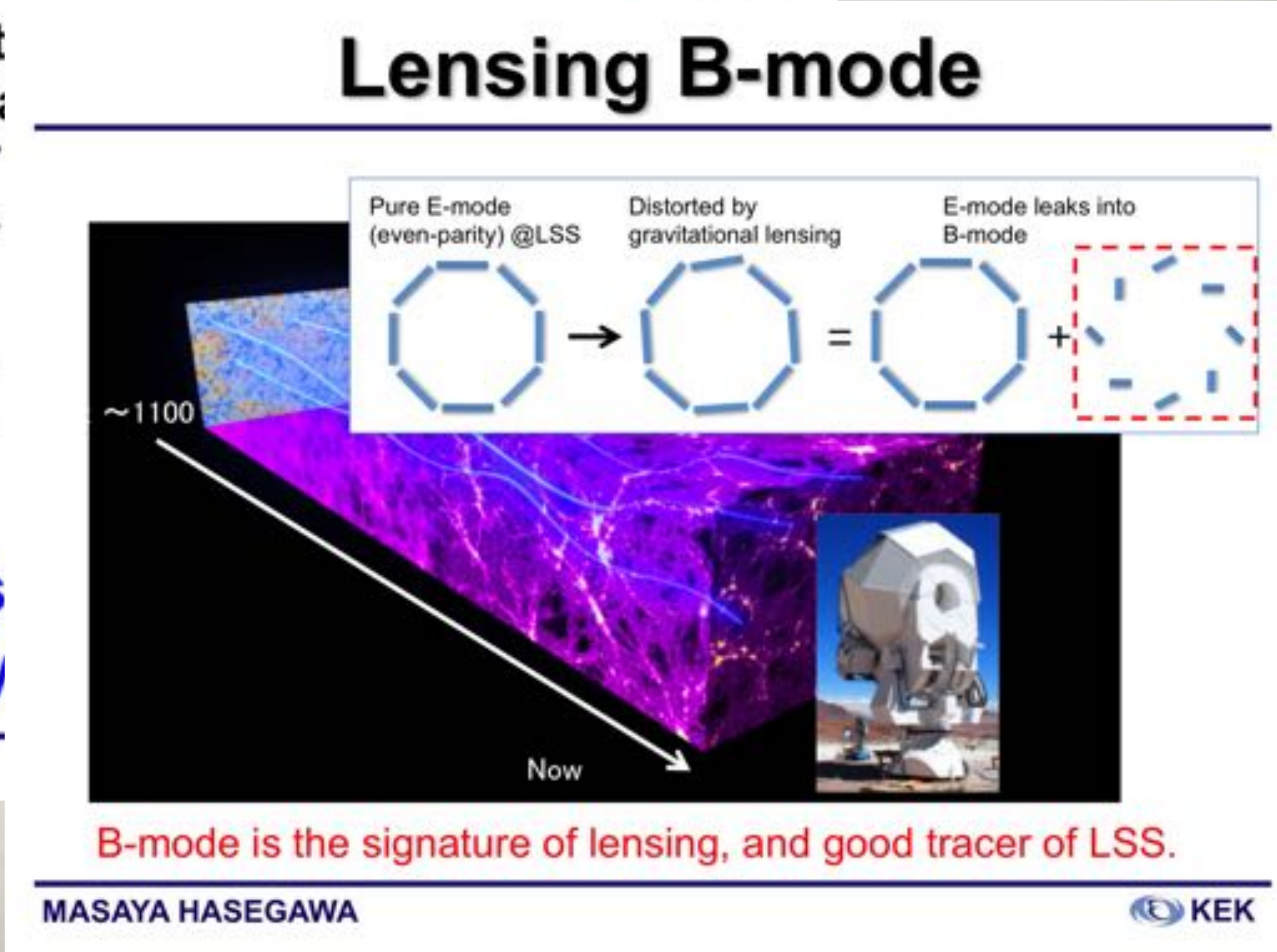
Inflation

Gravit

W

B-mode is a s
of inflationary

MASAYA HASEGAWA



Lensing B-mode

Pure E-mode (even-parity) @LSS → Distorted by gravitational lensing = E-mode leaks into B-mode

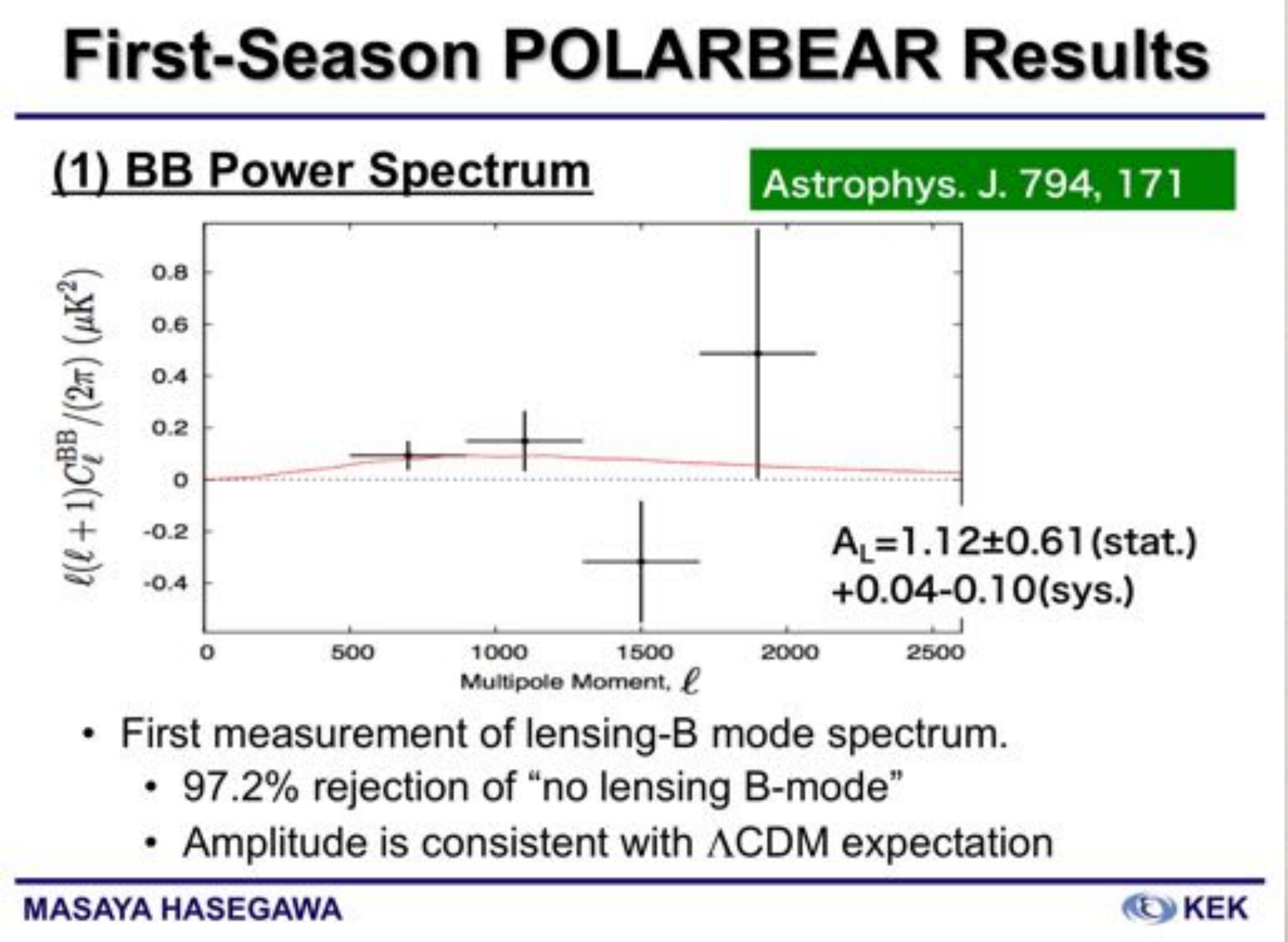
B-mode is the signature of lensing, and good tracer of LSS.

MASAYA HASEGAWA

KEK

CMB B-MODE POLARIZATION

[Masaya Hasegawa Astro-7]



First-Season POLARBEAR Results

(1) BB Power Spectrum

Astrophys. J. 794, 171

A_L=1.12±0.61(stat.) +0.04-0.10(sys.)

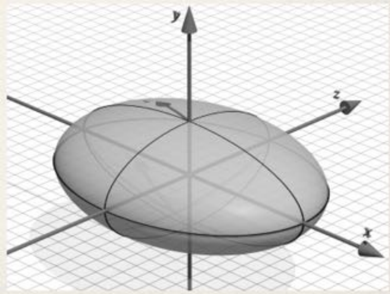
- First measurement of lensing-B mode spectrum.
  - 97.2% rejection of "no lensing B-mode"
  - Amplitude is consistent with ΛCDM expectation

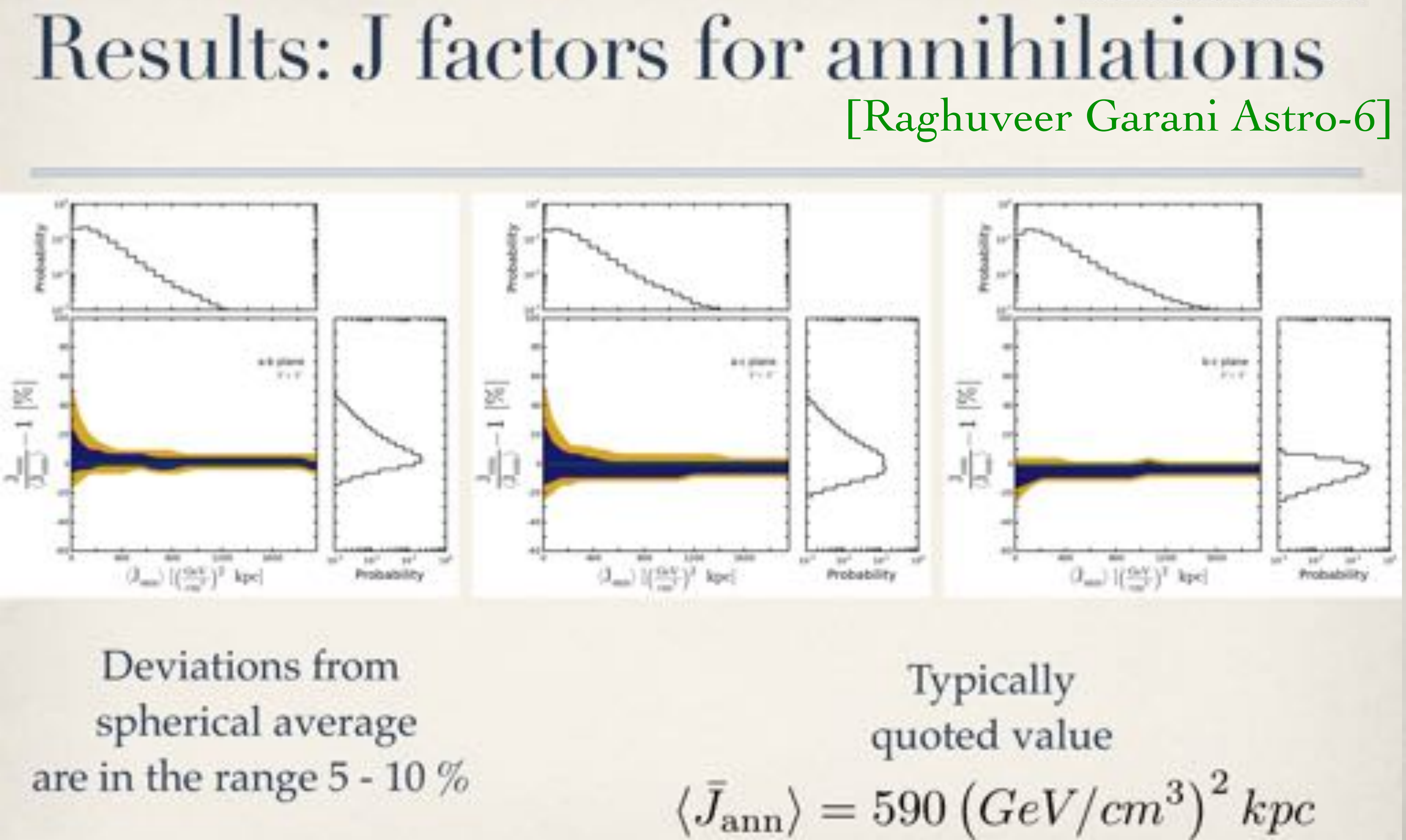
MASAYA HASEGAWA

KEK

J-FACTOR IN TRIAXIAL HALO

DM halos in simulations are not spherical !
Consider the effect of a triaxial structure.





Results: J factors for annihilations

[Raghuveer Garani Astro-6]

Deviations from
spherical average
are in the range 5 - 10 %

Typically
quoted value

$$\langle \bar{J}_{\mathrm{ann}} \rangle = 590\,(GeV/cm^3)^2\,kpc$$

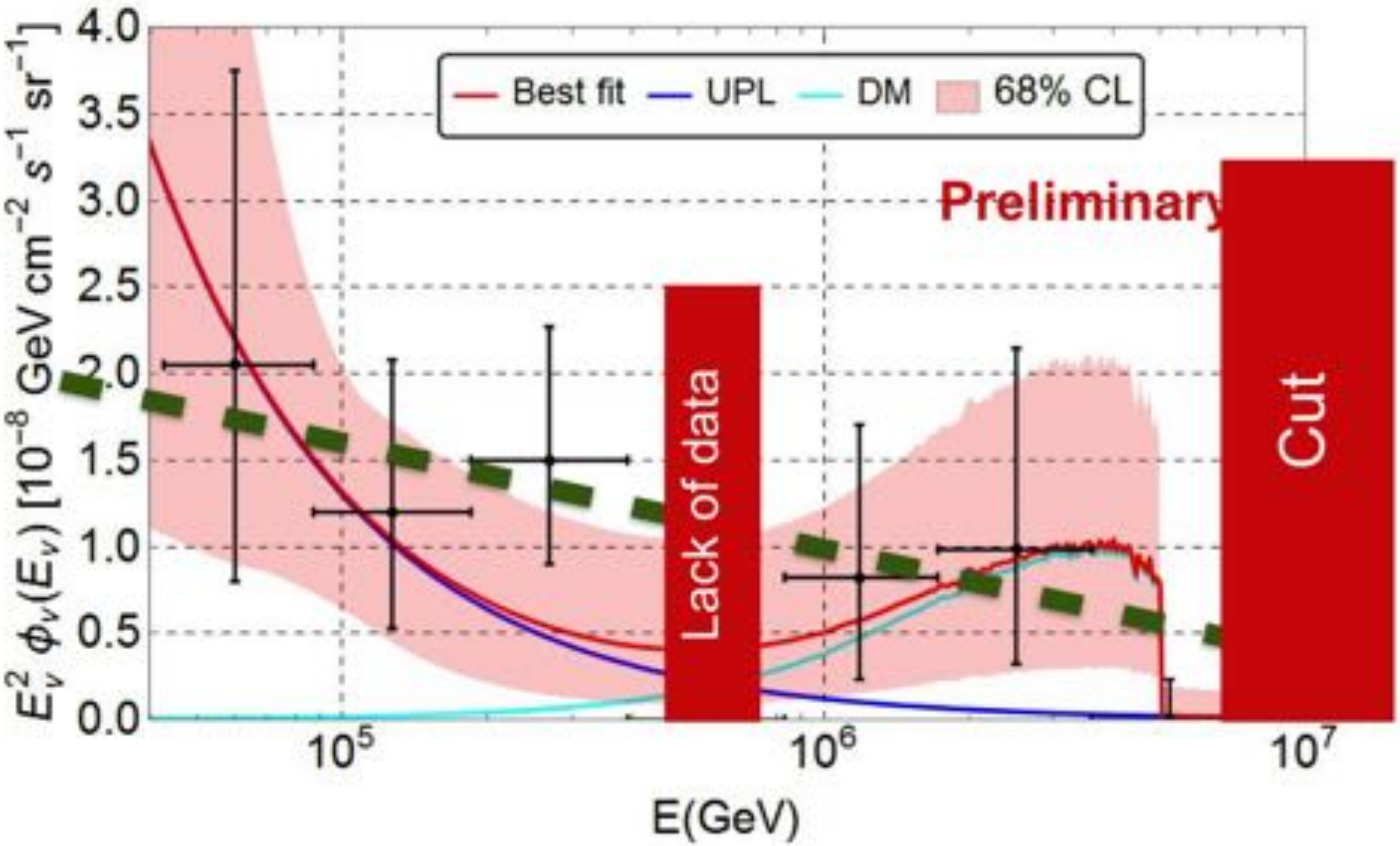
PEV NEUTRINOS

$$\boxed{\frac{y_{\alpha\beta\gamma}}{\Lambda^2}\,\overline{L_\alpha}\,\overline{L_\beta}\,\ell_\gamma\,\chi}$$

[Stefano Morisi Astro-3]

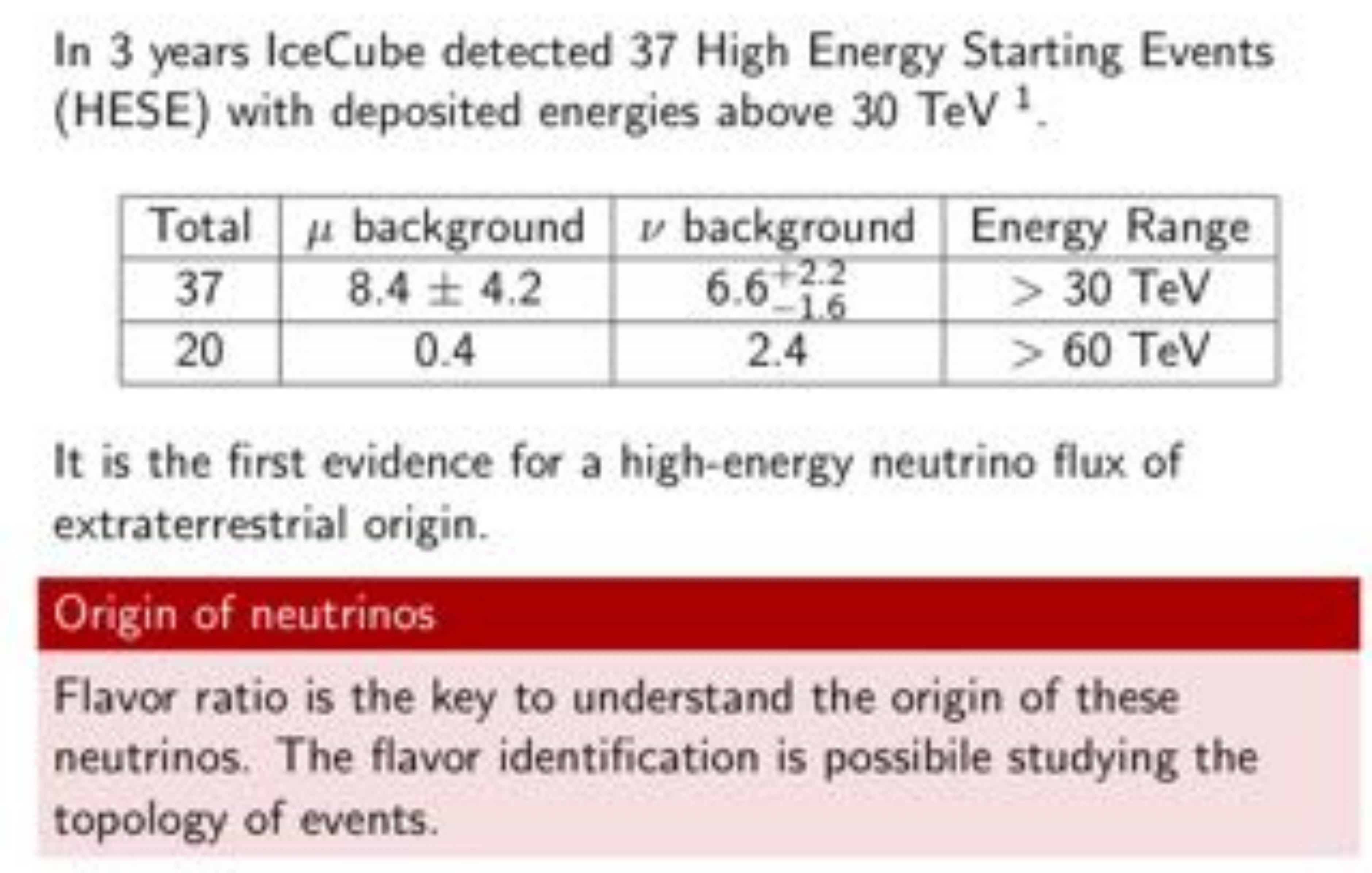
$$\phi = \phi_0\, E^{-\gamma}$$

DM
3-body
decay
+
power-law at
LE



TeV-PeV Neutrinos

[Andrea Palladino Astro-2]



In 3 years IceCube detected 37 High Energy Starting Events (HESE) with deposited energies above 30 TeV [1].

Total	μ background	ν background	Energy Range
37	8.4 ± 4.2	$6.6^{+2.2}_{-1.6}$	> 30 TeV
20	0.4	2.4	> 60 TeV

It is the first evidence for a high-energy neutrino flux of extraterrestrial origin.

Origin of neutrinos

Flavor ratio is the key to understand the origin of these neutrinos. The flavor identification is possibile studying the topology of events.

TeV-PeV Neutrinos

[Andrea Palladino Astro-2]

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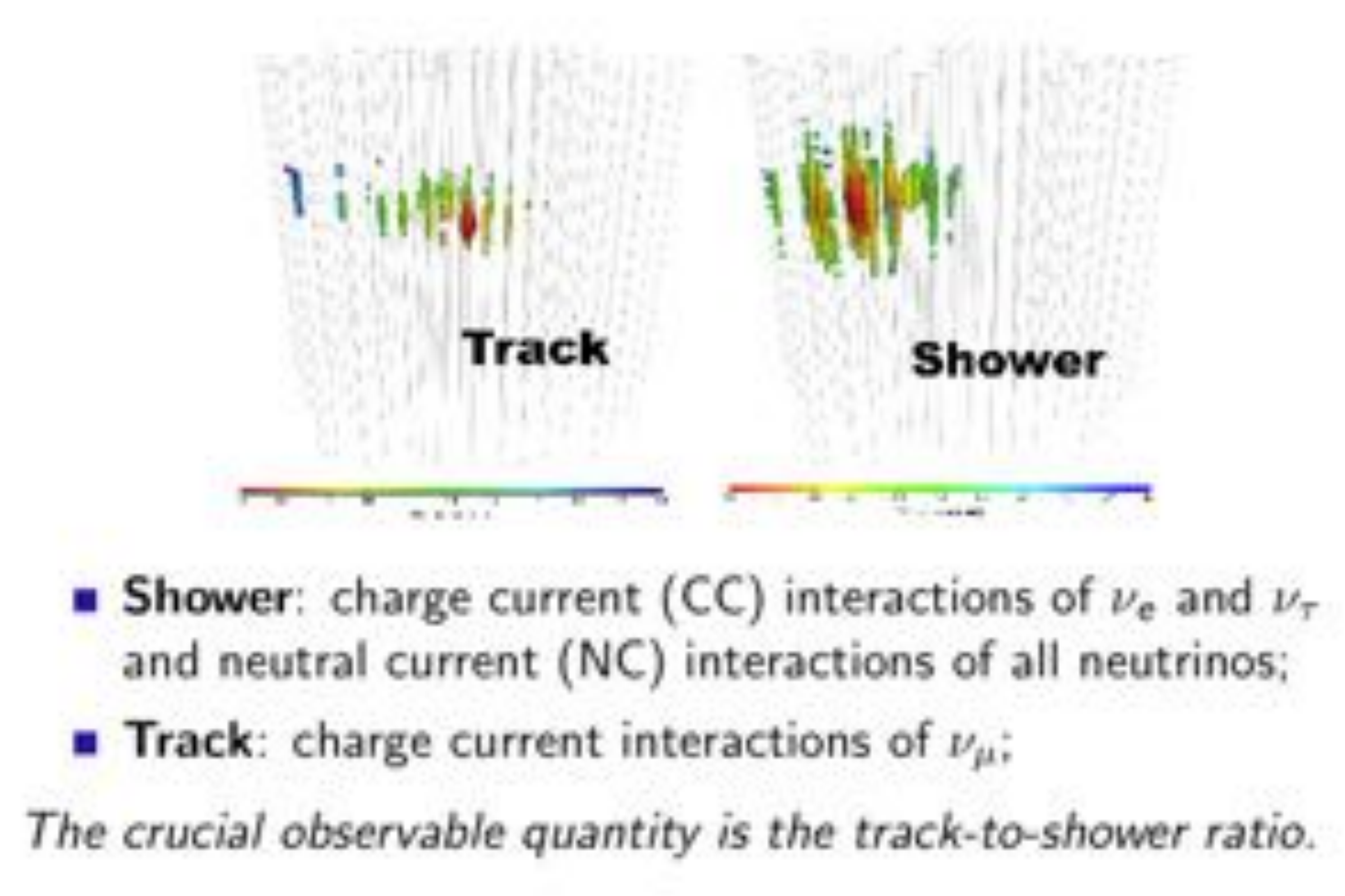
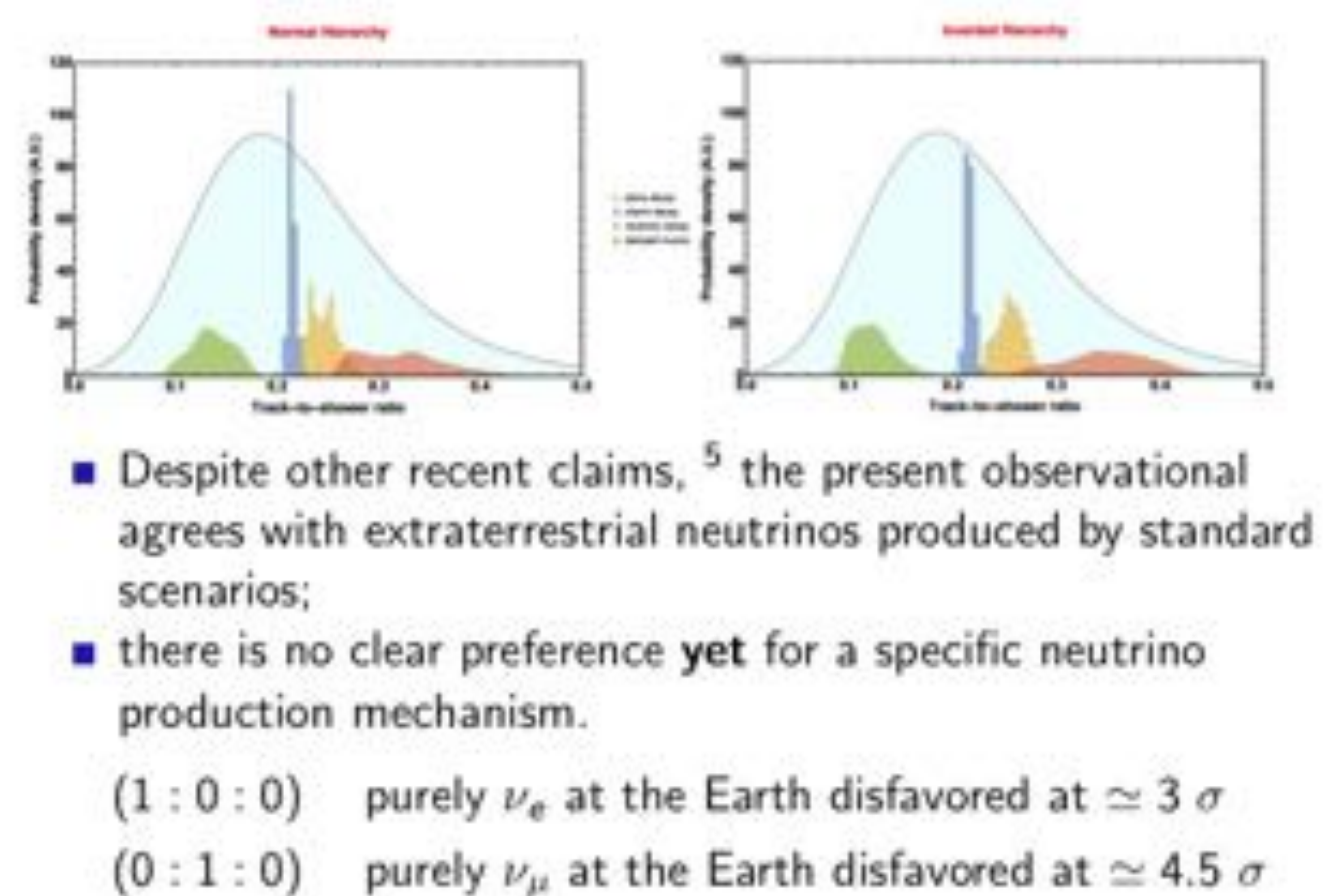


- **Shower**: charge current (CC) interactions of ν_e and ν_τ and neutral current (NC) interactions of all neutrinos;
- **Track**: charge current interactions of ν_μ;

The crucial observable quantity is the track-to-shower ratio.

TeV-PeV Neutrinos

[Andrea Palladino Astro-2]



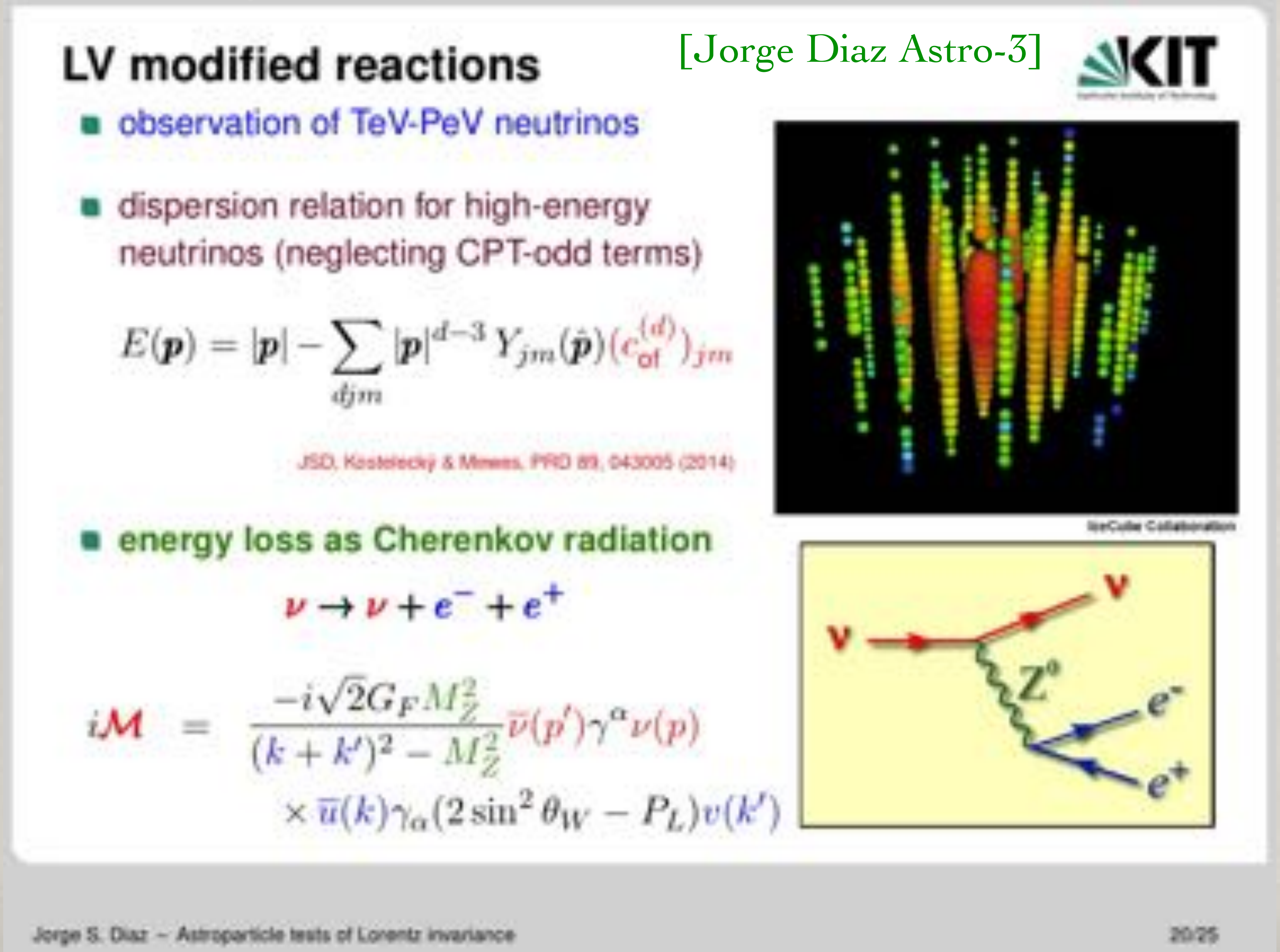
- Despite other recent claims, [5] the present observational agrees with extraterrestrial neutrinos produced by standard scenarios;
- there is no clear preference **yet** for a specific neutrino production mechanism.

(1 : 0 : 0) purely ν_e at the Earth disfavored at $\simeq 3\,\sigma$

(0 : 1 : 0) purely ν_μ at the Earth disfavored at $\simeq 4.5\,\sigma$

LORENTZ VIOLATION

[Jorge Diaz Astro-3]



LV modified reactions

- observation of TeV-PeV neutrinos
- dispersion relation for high-energy neutrinos (neglecting CPT-odd terms)

$$E(\mathbf{p}) = |\mathbf{p}| - \sum_{djm} |\mathbf{p}|^{d-3} Y_{jm}(\hat{\mathbf{p}}) (c_{\text{of}}^{(d)})_{jm}$$

JSD, Kostelecký & Mewes, PRD 89, 043005 (2014)

- energy loss as Cherenkov radiation

$$\nu \to \nu + e^- + e^+$$

$$i\mathcal{M} = \frac{-i\sqrt{2}G_F M_Z^2}{(k+k')^2 - M_Z^2} \overline{\nu}(p')\gamma^\alpha \nu(p)$$
$$\times \overline{u}(k)\gamma_\alpha(2\sin^2\theta_W - P_L)v(k')$$

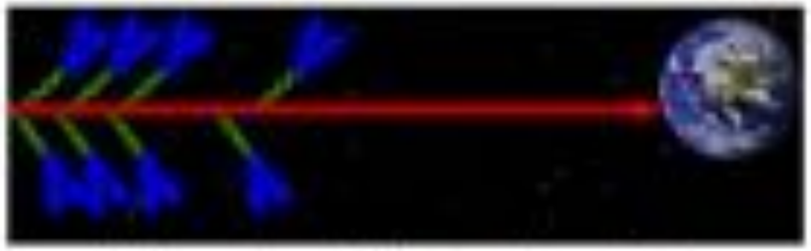
Jorge S. Diaz – Astroparticle tests of Lorentz invariance

20/25

LV modified reactions

[Jorge Diaz Astro-3]

JSD, Kostelecký & Mewes, PRD 89, 043005 (2014)

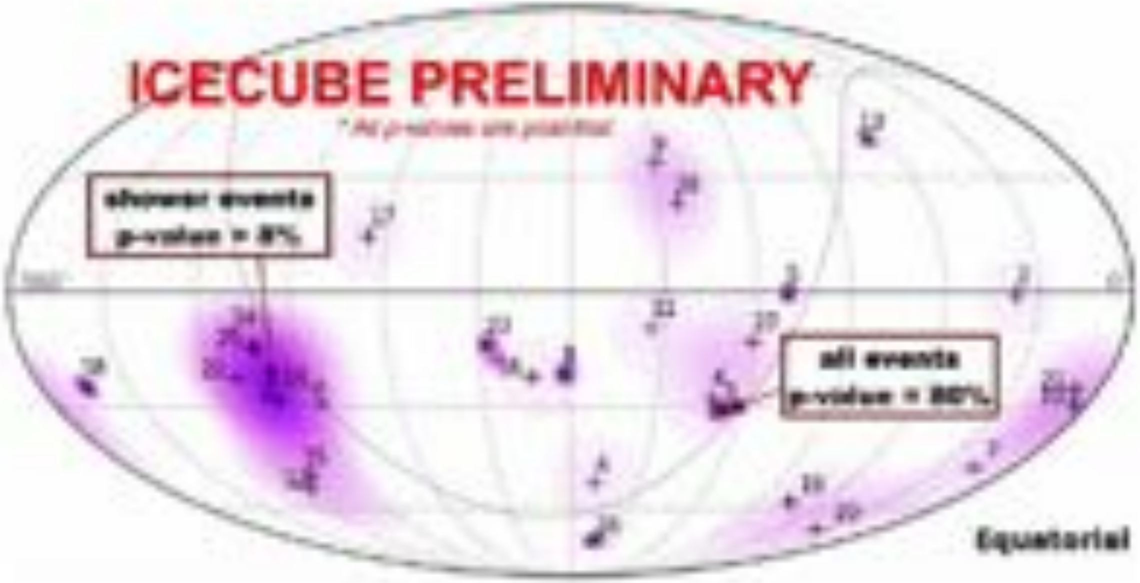


d j	Lower bound	Coefficient	Upper bound
4 0	$-4 \times 10^{[illegible]} <$	$(c^{(4)}_{\rm of})_{00}$	
4 1	$-1 \times 10^{[illegible]} <$	$(c^{(4)}_{\rm of})_{10}$	$< 4 \times 10^{[illegible]}$
	$-3 \times 10^{[illegible]} <$	$\mathrm{Re}(c^{(4)}_{\rm of})_{11}$	$< 3 \times 10^{[illegible]}$
	$-2 \times 10^{[illegible]} <$	$\mathrm{Im}(c^{(4)}_{\rm of})_{11}$	$< 2 \times 10^{[illegible]}$
4 2	$-1 \times 10^{[illegible]} <$	$(c^{(4)}_{\rm of})_{20}$	$< 7 \times 10^{[illegible]}$
	$-2 \times 10^{[illegible]} <$	$\mathrm{Re}(c^{(4)}_{\rm of})_{21}$	$< 3 \times 10^{[illegible]}$
	$-3 \times 10^{[illegible]} <$	$\mathrm{Im}(c^{(4)}_{\rm of})_{21}$	$< 5 \times 10^{[illegible]}$
	$-5 \times 10^{[illegible]} <$	$\mathrm{Re}(c^{(4)}_{\rm of})_{22}$	$< 2 \times 10^{[illegible]}$
	$-5 \times 10^{[illegible]} <$	$\mathrm{Im}(c^{(4)}_{\rm of})_{22}$	$< 4 \times 10^{[illegible]}$
6 0	$-3 \times 10^{[illegible]} <$	$(c^{(6)}_{\rm of})_{00}$	
6 1	$-2 \times 10^{[illegible]} <$	$(c^{(6)}_{\rm of})_{10}$	$< 9 \times 10^{[illegible]}$
	$-6 \times 10^{[illegible]} <$	$\mathrm{Re}(c^{(6)}_{\rm of})_{11}$	$< 5 \times 10^{[illegible]}$
	$-3 \times 10^{[illegible]} <$	$\mathrm{Im}(c^{(6)}_{\rm of})_{11}$	$< 3 \times 10^{[illegible]}$
6 2	$-4 \times 10^{[illegible]} <$	$(c^{(6)}_{\rm of})_{20}$	$< 7 \times 10^{[illegible]}$
	$1 \times 10^{[illegible]} <$	$\mathrm{Re}(c^{(6)}_{\rm of})_{21}$	$< 2 \times 10^{[illegible]}$
	$-1 \times 10^{[illegible]} <$	$\mathrm{Im}(c^{(6)}_{\rm of})_{21}$	$< 5 \times 10^{[illegible]}$
	$-5 \times 10^{[illegible]} <$	$\mathrm{Re}(c^{(6)}_{\rm of})_{22}$	$< 8 \times 10^{[illegible]}$
	$1 \times 10^{[illegible]} <$	$\mathrm{Im}(c^{(6)}_{\rm of})_{22}$	$< 4 \times 10^{[illegible]}$

Astrophysical Cherenkov threshold

$$-\sum_{djm} |\boldsymbol{p}|^{d-2}\, Y_{jm}(\hat{\boldsymbol{p}})\, (c^{(d)}_{\rm of})_{jm} \lesssim 2m_e^2$$

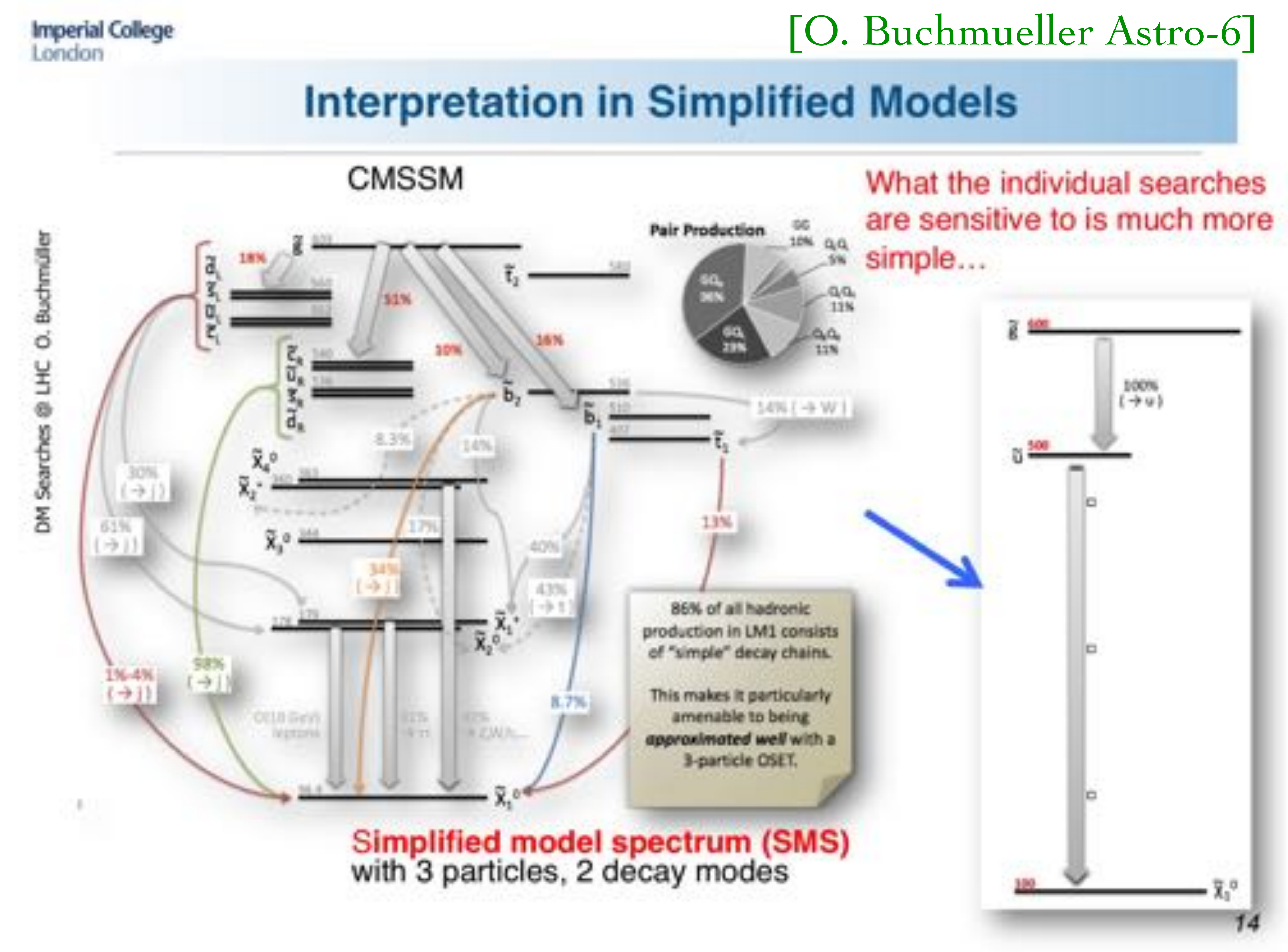
two-sided bounds can be obtained from several events distributed in the sky



LHC & DM CONNECTION

LHC: SIMPLIFIED MODELS

[O. Buchmueller Astro-6]



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Interpretation in Simplified Models

CMSSM

What the individual searches are sensitive to is much more simple…

86% of all hadronic production in LM1 consists of "simple" decay chains.

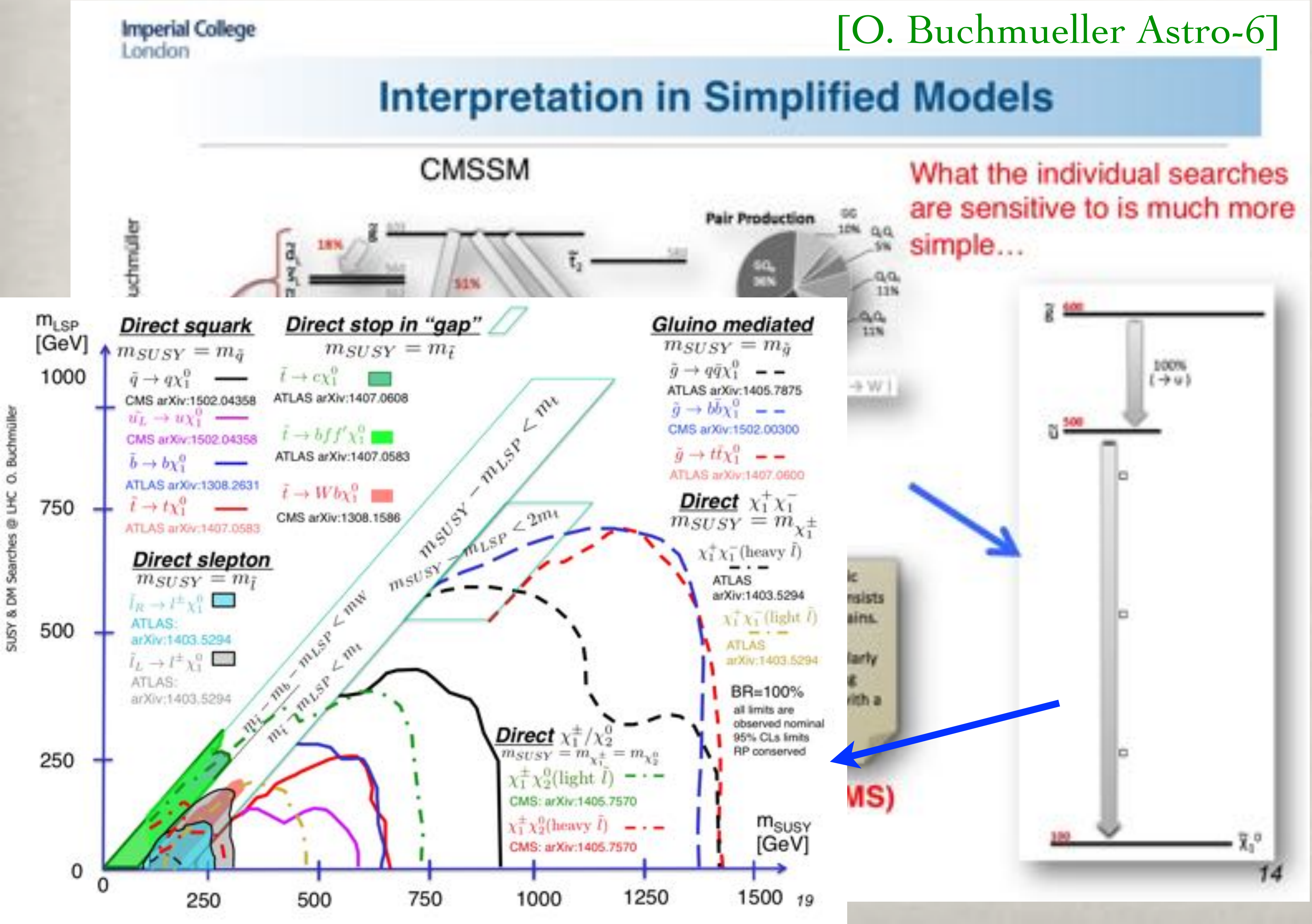
This makes it particularly amenable to being *approximated well* with a 3-particle OSET.

Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

DM Searches @ LHC O. Buchmüller

LHC: SIMPLIFIED MODELS

[O. Buchmueller Astro-6]



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Interpretation in Simplified Models

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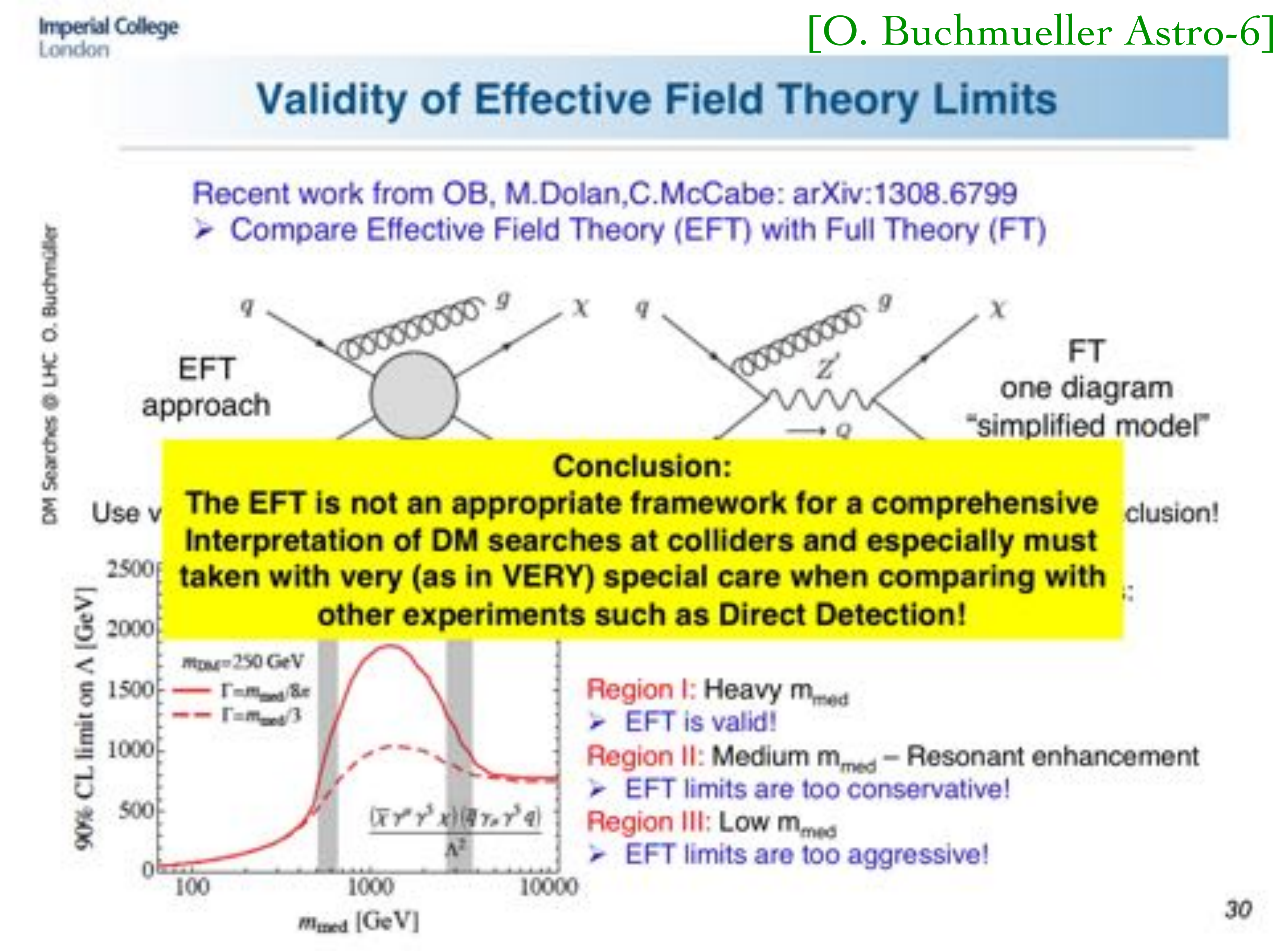
14

LHC:EFT BREAKDOWN !

[O. Buchmueller Astro-6]



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Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799
- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach

FT one diagram "simplified model"

Use v … clusion!

Conclusion:
The EFT is not an appropriate framework for a comprehensive Interpretation of DM searches at colliders and especially must taken with very (as in VERY) special care when comparing with other experiments such as Direct Detection!

Region I: Heavy $m_{\rm med}$
- EFT is valid!

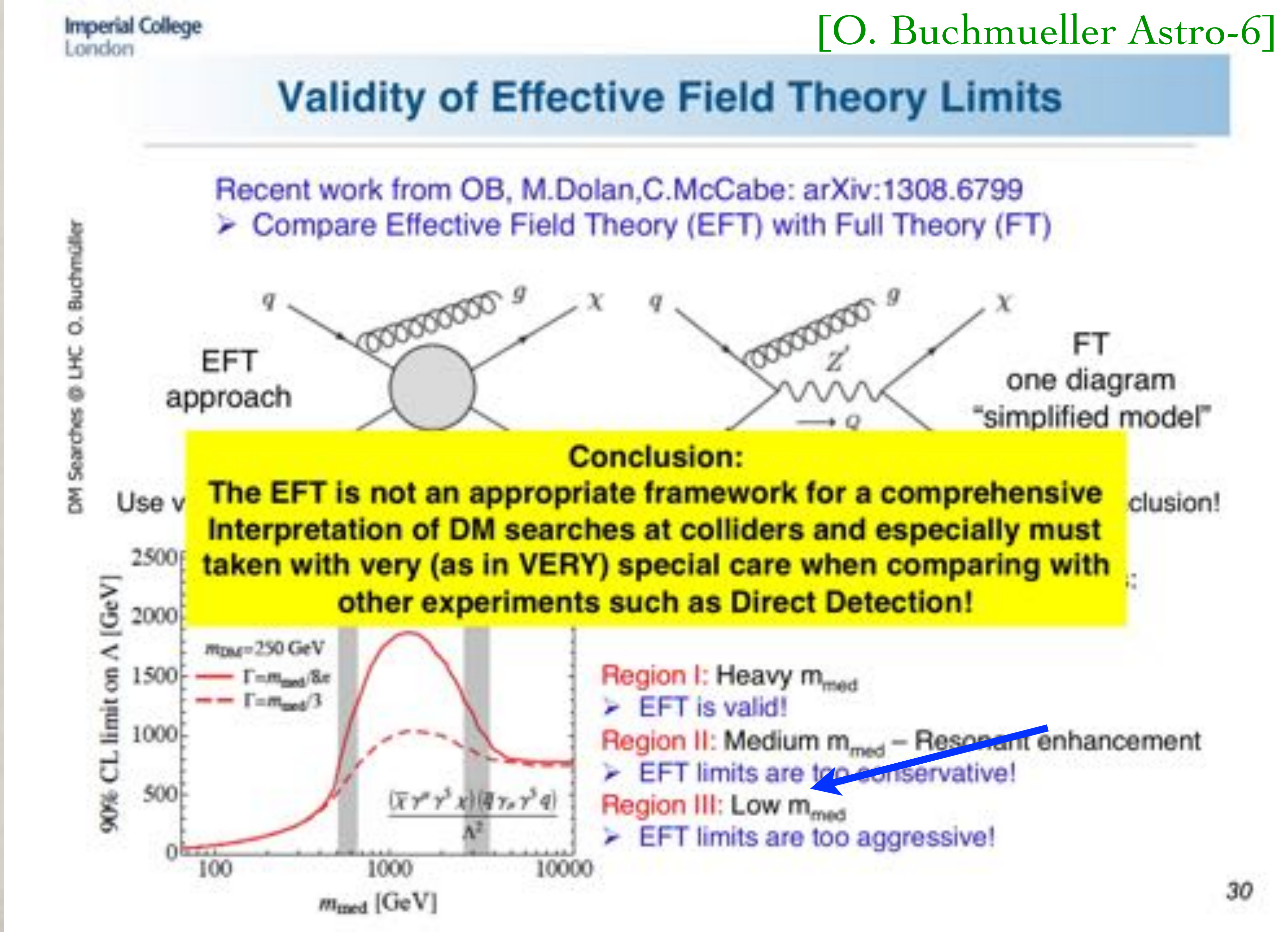
Region II: Medium $m_{\rm med}$ – Resonant enhancement
- EFT limits are too conservative!

Region III: Low $m_{\rm med}$
- EFT limits are too aggressive!

DM Searches @ LHC O. Buchmüller

LHC:EFT BREAKDOWN !

[O. Buchmueller Astro-6]



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EFT
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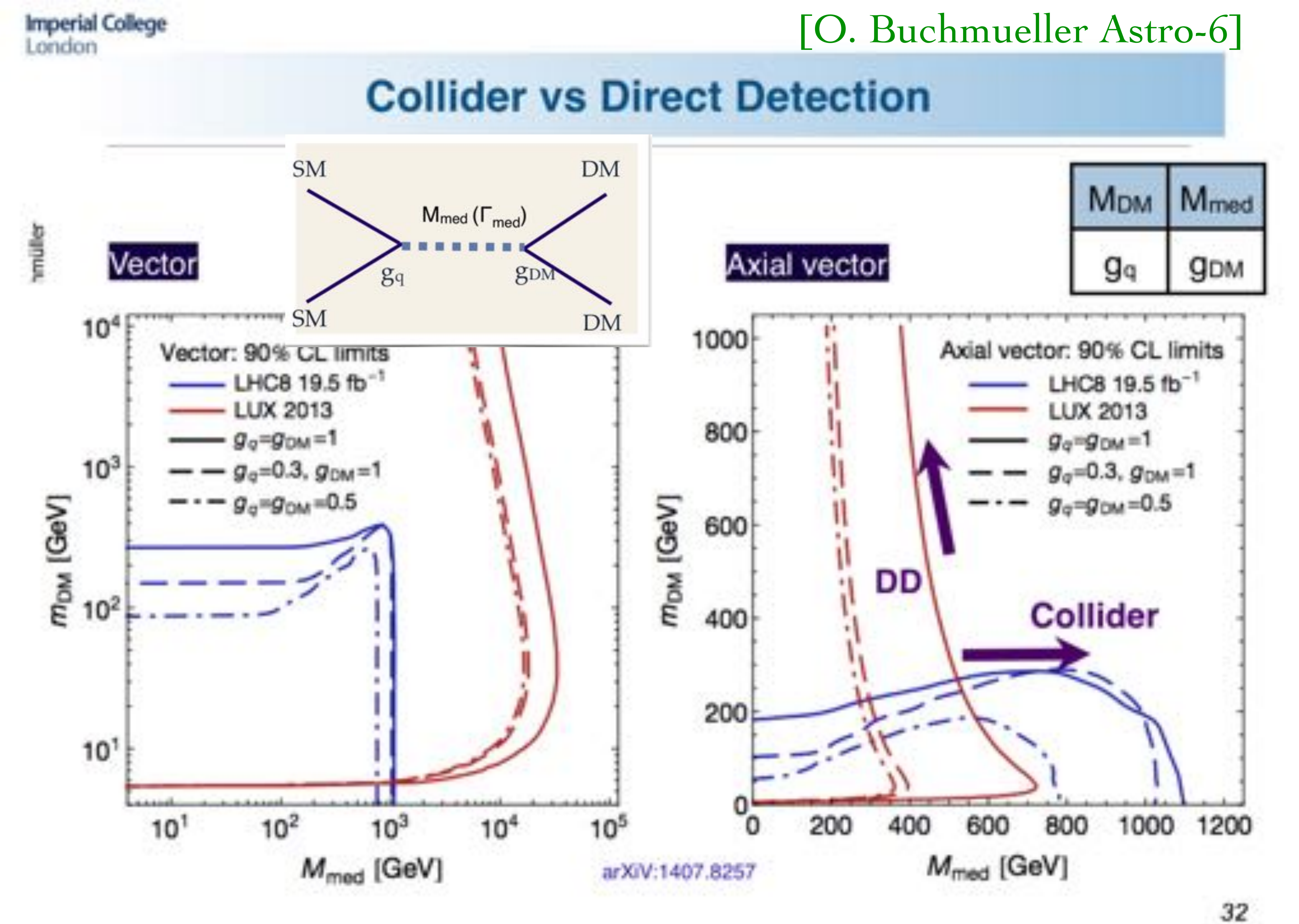
LHC:EFT BREAKDOWN !

[O. Buchmueller Astro-6]



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Collider vs Direct Detection

M_{DM}	M_{med}
g_q	g_{DM}

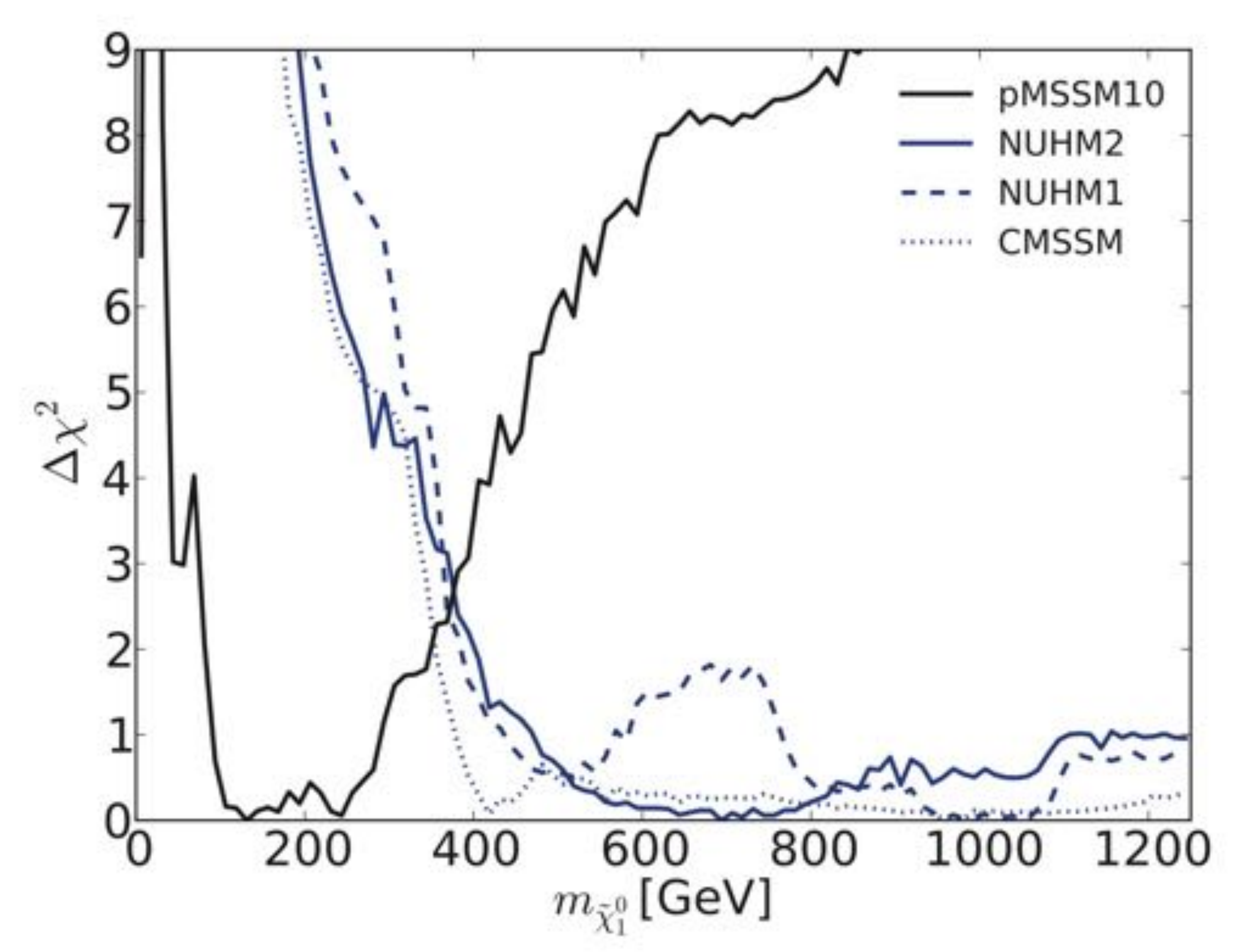
arXiV:1407.8257

MODELS AT LHC

- SUSY [Sven Heinemeyer Astro-2]
- Z' models [Farinaldo Queiroz Astro-6]
- Baryon Number -DM models [Sebastian Ohmer Astro-5, Michael Duerr Astro-6]
- ...

SUSY NEUTRALINO DM

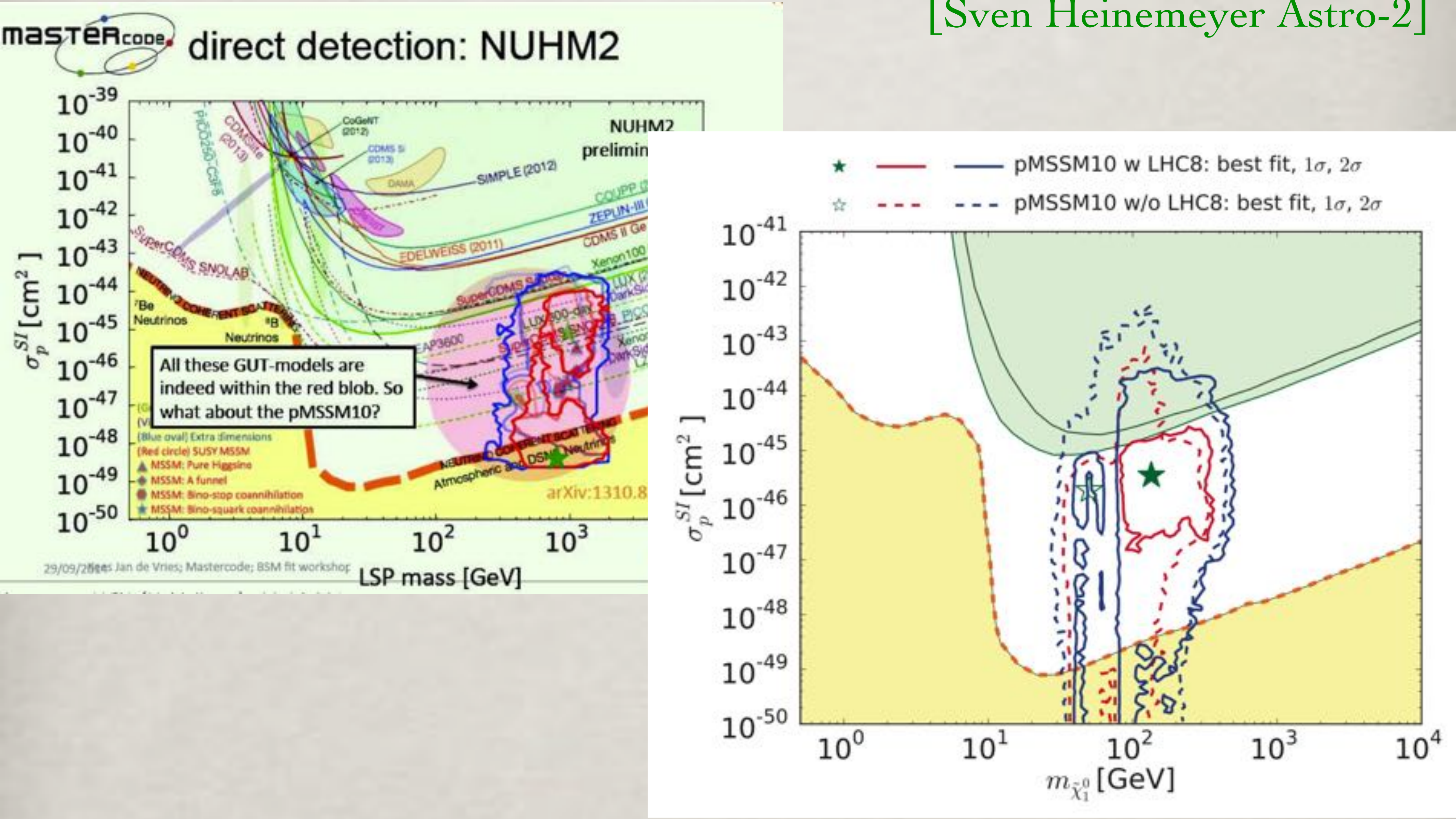
[Sven Heinemeyer Astro-2]



GUT-based models prefer large mass scales above 400 GeV, while phenomenological models point to 100-300 GeV DM !

SUSY NEUTRALINO DM

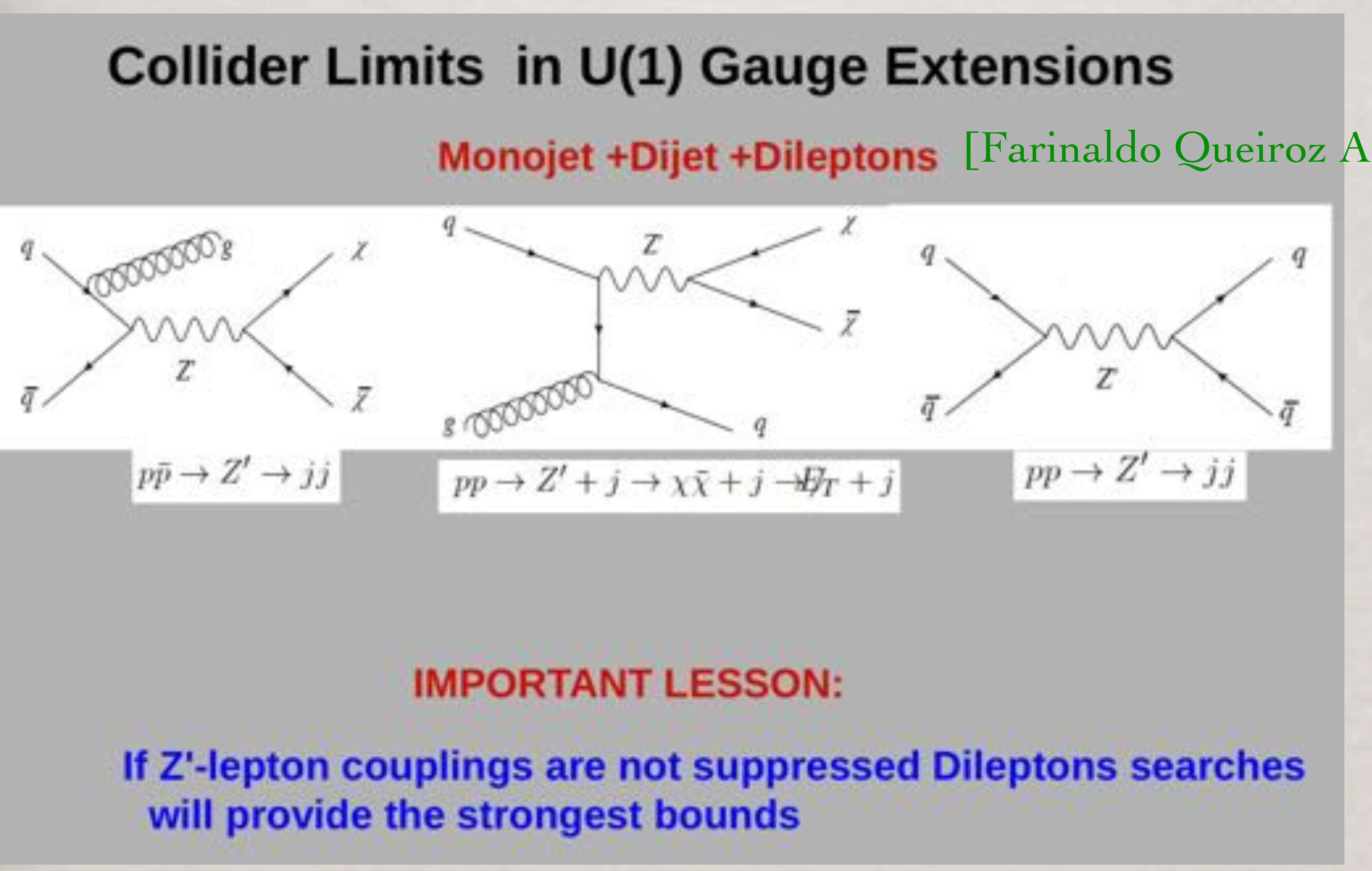
[Sven Heinemeyer Astro-2]



All these GUT-models are indeed within the red blob. So what about the pMSSM10?

For GUT models DD signal could be lower than neutrino floor, in the pMSSM more favorable prospects for DD !

Z' MODELS AT LHC



Collider Limits in U(1) Gauge Extensions

Monojet +Dijet +Dileptons

$p\bar{p} \to Z' \to jj$

$pp \to Z' + j \to \chi\bar{\chi} + j \to \not{E}_T + j$

$pp \to Z' \to jj$

IMPORTANT LESSON:

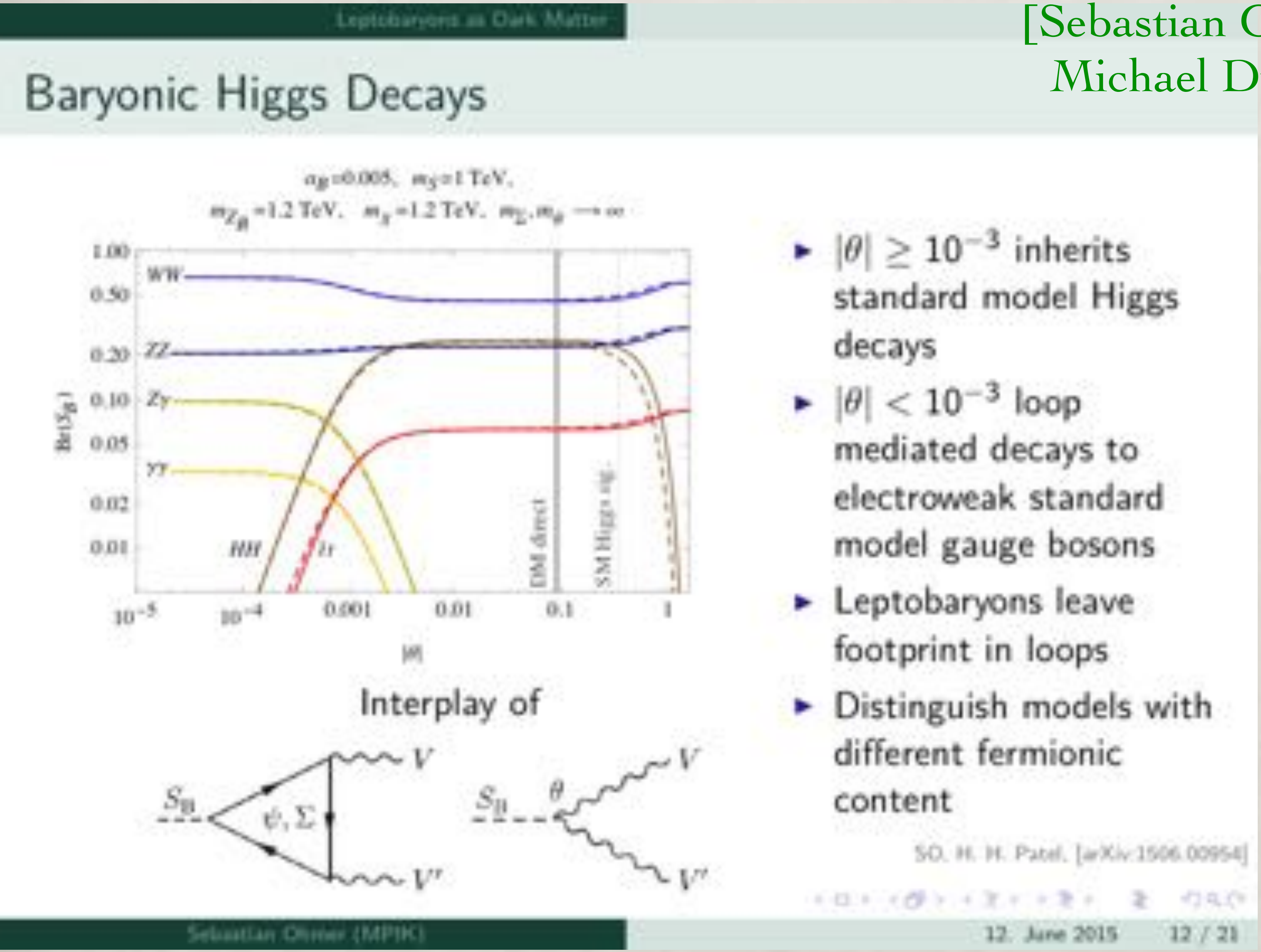
If Z'-lepton couplings are not suppressed Dileptons searches will provide the strongest bounds

[Farinaldo Queiroz Astro-6]

Large mass for the mediator implies DM masses above 1 TeV !

BARYON-DM MODELS

[Sebastian Ohmer Astro-5,
Michael Duerr Astro-6]



Baryonic Higgs Decays

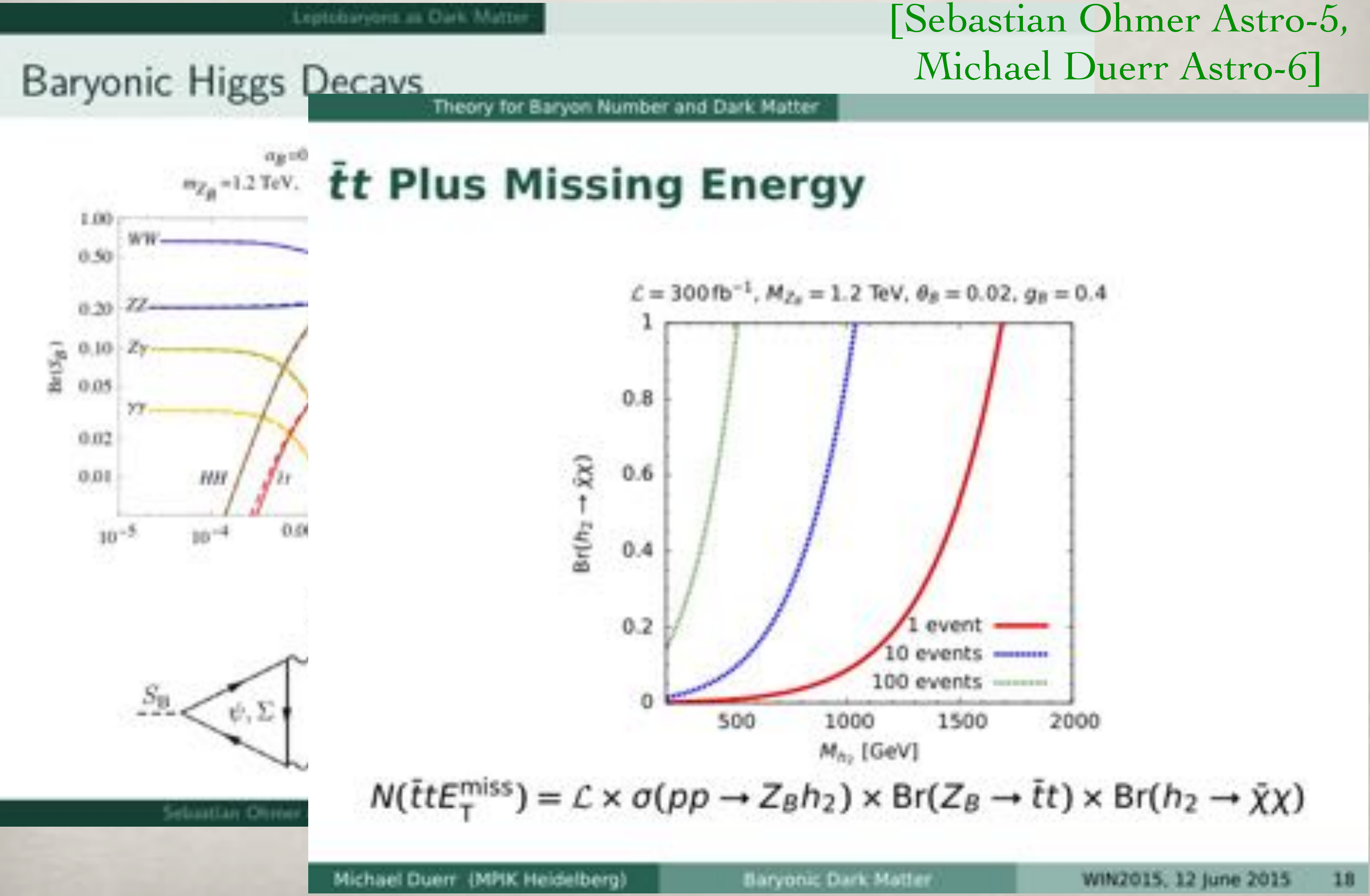
Interplay of

- $|\theta| \geq 10^{-3}$ inherits standard model Higgs decays
- $|\theta| < 10^{-3}$ loop mediated decays to electroweak standard model gauge bosons
- Leptobaryons leave footprint in loops
- Distinguish models with different fermionic content

SO, H. H. Patel, [arXiv:1506.00954]

BARYON-DM MODELS

[Sebastian Ohmer Astro-5,
Michael Duerr Astro-6]



Leptobaryons as Dark Matter

Baryonic Higgs Decays

Sebastian Ohmer

Theory for Baryon Number and Dark Matter

$\bar{t}t$ Plus Missing Energy

$$N(\bar{t}tE_T^{\text{miss}}) = \mathcal{L} \times \sigma(pp \to Z_B h_2) \times \text{Br}(Z_B \to \bar{t}t) \times \text{Br}(h_2 \to \bar{\chi}\chi)$$

Michael Duerr (MPIK Heidelberg) Baryonic Dark Matter WIN2015, 12 June 2015 18

DM & BARYON CONNECTION

What if $\Omega_\chi = 5\Omega_B$ is not just a coincidence?

[Sofiane Boucenna Astro-5]

In a nutshell, ADM theories set DM abundance via its chemical potential; they relate number densitites.

$$M_\chi n_\chi \sim 5 M_p n_p$$

E.g. sphalerons or transfer operators

DM asymmetry is protected thanks to extra charge → no annihilation signal. Also, DM mass is a free parameter.

[Sofiane Boucenna Astro-5]

Minimal ADM

MADM is a framework based on an extension of SM by hypercharged SU(2)$_L$ multiplets and an effective interaction playing two roles:

$$\frac{1}{\Lambda^{4y+2(\underset{\uparrow \atop \text{Spin}}{s}-1)}}\chi\chi\underset{\uparrow \atop \text{Higgs (y=-1/2)}}{\phi}^{4y}$$

At hight T, it transfers asymmetries between SM & DM (ADM)

After EWSB, it splits the d.o.f. of the neutral state, and regenerates the symmetry (WIMP)

[Sofiane Boucenna Astro-5]

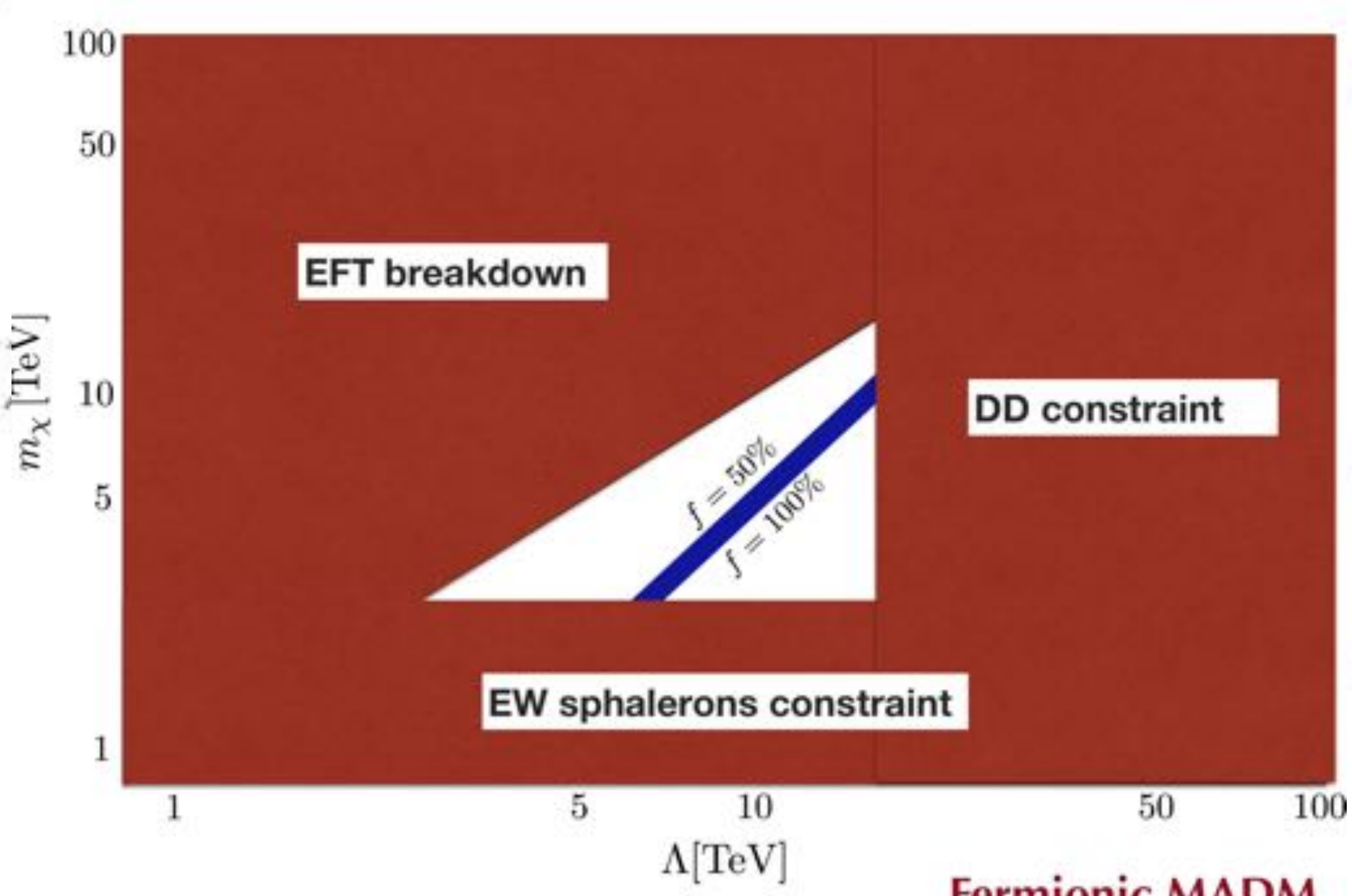
Minimal ADM

MADM is a framework based on an extension of SM by hypercharged SU(2)$_L$ multiplets and an effective interaction playing two roles:

$$\frac{1}{\Lambda^{4y+2(s-1)}}\chi$$

Spin

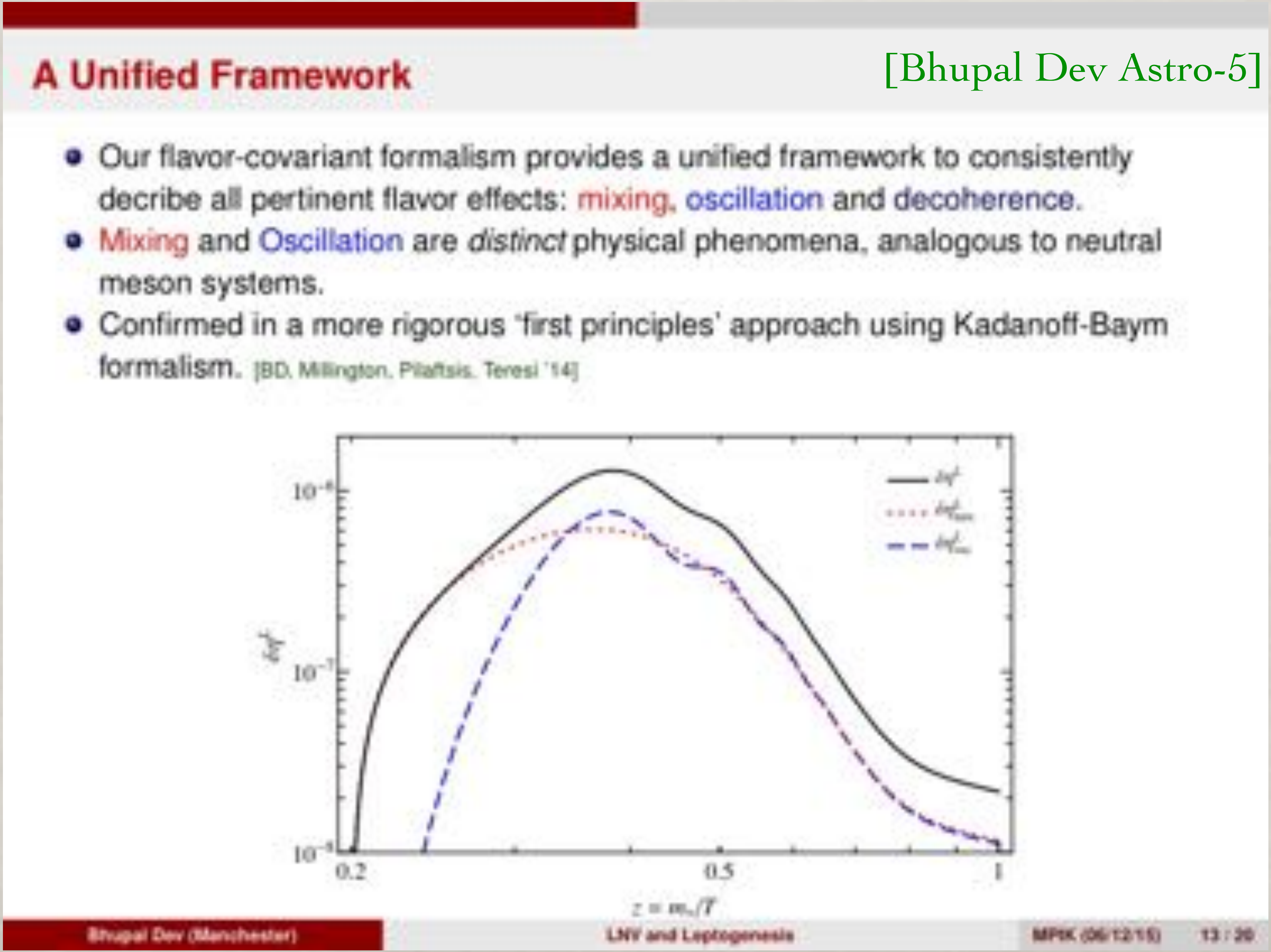
y=1



Fermionic MADM

Resonant Leptogenesis

[Bhupal Dev Astro-5]



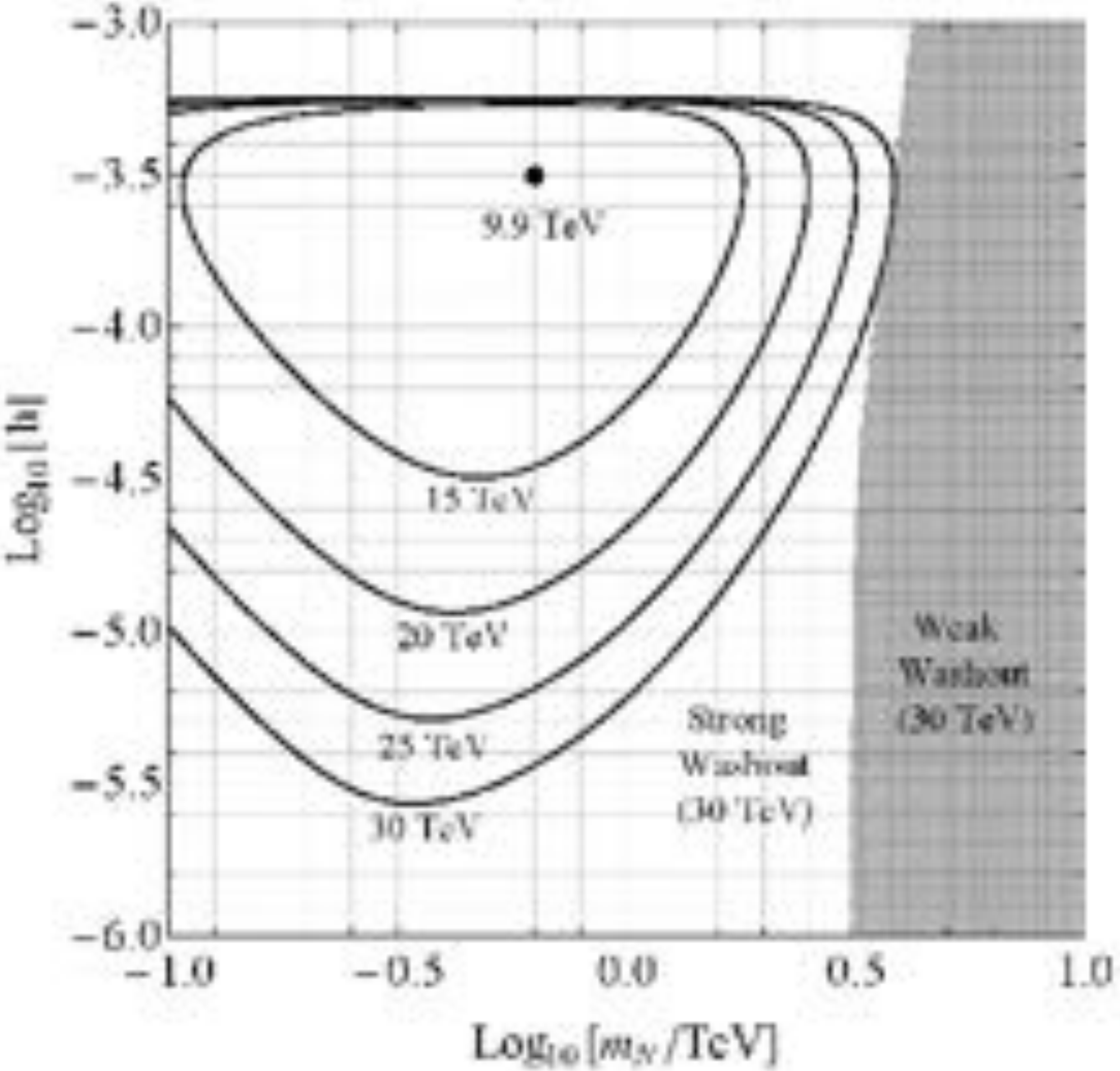
A Unified Framework

- Our flavor-covariant formalism provides a unified framework to consistently decribe all pertinent flavor effects: mixing, oscillation and decoherence.
- Mixing and Oscillation are *distinct* physical phenomena, analogous to neutral meson systems.
- Confirmed in a more rigorous 'first principles' approach using Kadanoff-Baym formalism. [BD, Millington, Pilaftsis, Teresi '14]

Lower Bound on M_{W_R} from Leptogenesis

[Bhupal Dev Astro-5]

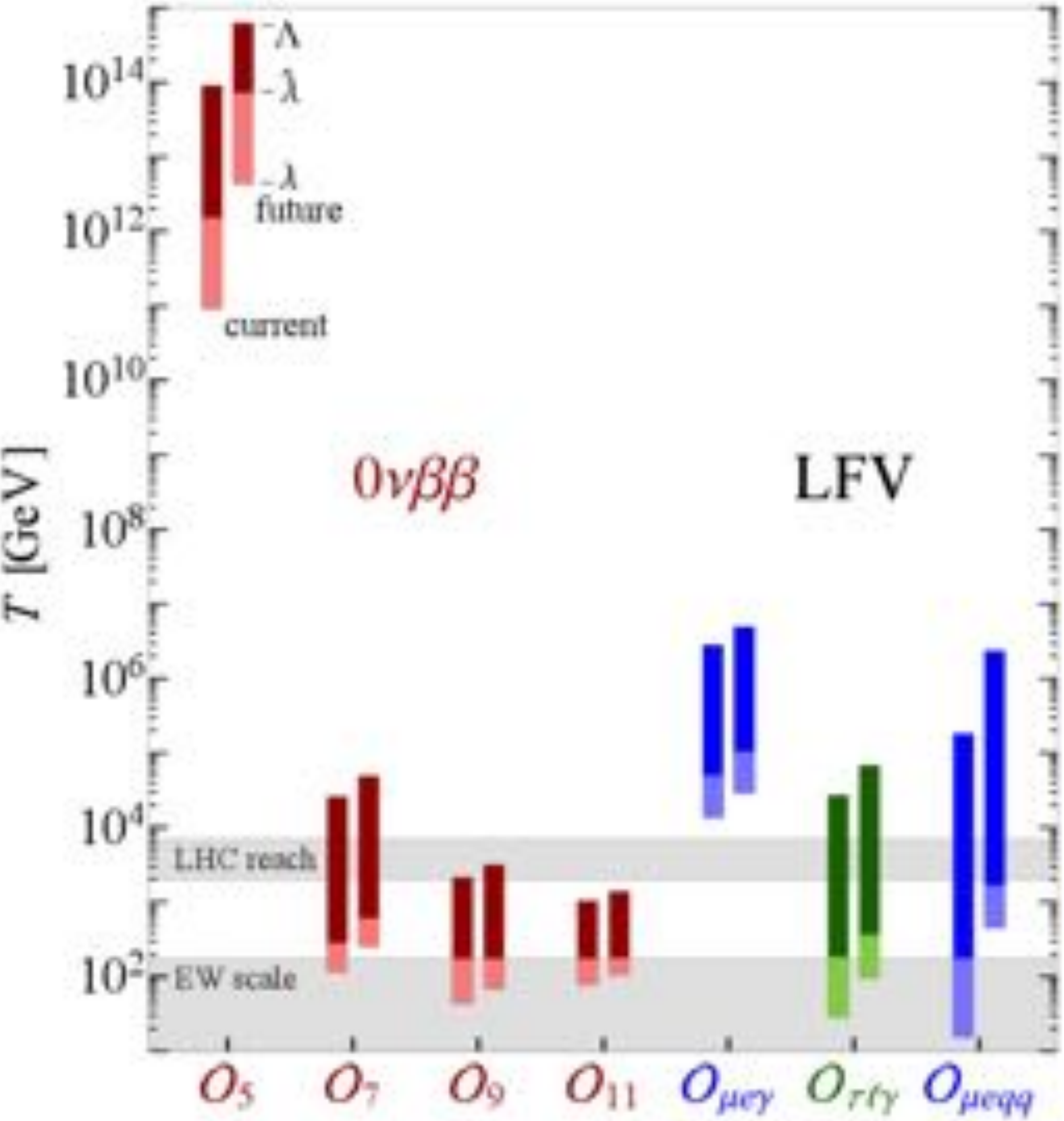
Left-Right Model



[BD, Lee, Mohapatra '15]

Lepton Flavour Violation - Results

[Julia Harz Astro-5]



- Most stringent limits on LFV set by 6-dim $\Delta L = 0$ operators

$$\mathcal{O}_{\ell\ell\gamma} = \mathcal{C}_{\ell\ell\gamma} \bar{L}_\ell \sigma^{\mu\nu} \bar{\ell}^c H F_{\mu\nu}$$

$$\mathcal{O}_{\ell\ell qq} = \mathcal{C}_{\ell\ell qq}(\bar{\ell}\,\Pi_1 \ell)(\bar{q}\,\Pi_2 q)$$

$$\mathcal{C}_{\ell\ell qq} = \frac{g^2}{\Lambda^2_{\ell\ell qq}} \qquad \mathcal{C}_{\ell\ell\gamma} = \frac{eg^3}{16\pi^2\Lambda^2_{\ell\ell\gamma}}$$

- Current & future limits:

$\mathrm{Br}_{\mu\to e\gamma} < 5.7 \times 10^{-13} \quad (6.0 \times 10^{-14})$

$\mathrm{Br}_{\tau\to\ell\gamma} < 4.0 \times 10^{-8} \quad (1.0 \times 10^{-9}),\ \ell = e, \mu$

$\mathrm{R}^{\mathrm{Au}}_{\mu\to e} < 7.0 \times 10^{-13} \quad (2.7 \times 10^{-17})$

- determine temperature interval in which LFV process equilibrate pre-existing flavour asymmetry

- IF LFV processes are observed as well, loophole of asymmetry being stored in another flavour sector is ruled out

F. Deppisch, JH, W. Huang, M. Hirsch, H. Päs, arXiv:1503.07632 [hep-ph]

Lepton Number Violation at the LHC

[Julia Harz Astro-5]

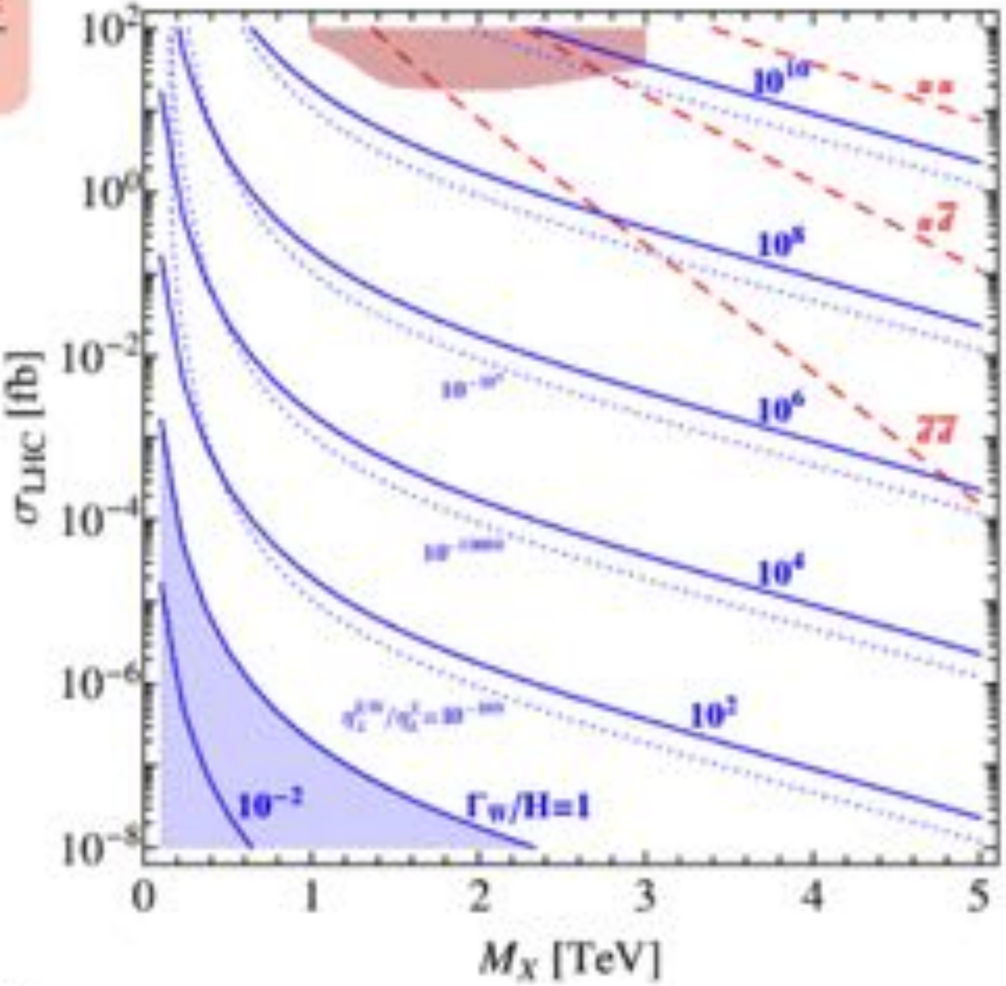
$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\text{TeV}} - 1\right) + \log_{10}\frac{\sigma_{\text{LHC}}}{\text{fb}}$$

- For any realistic cross section at LHC with $\sigma_{\text{LHC}} > 10^{-2}$ fb washout highly effective

$$\frac{\Gamma_W}{H} >> 1$$

- enormous washout of any pre-existing lepton asymmetry

$$\eta_L^{\text{EW}}/\eta_L^X \approx \exp(-\Gamma_W/H)$$



- LHC starts to exclude top of parameter plane

⇨
- observation of LNV processes sets serious bounds on washout
- excludes LG models which generate asymmetry above

F. Deppisch, JH, M. Hirsch, PRL 112 (2014) 221601, arXiv:1312.4447 [hep-ph]

CONCLUSIONS

- Improvement in the model-independent parametrization of DM-matter NR interactions
- Better understanding of propagation and background uncertainties in DM ID
- Connection LHC-DM more intensively exploited, in SUSY but not only !
- Tests of leptogenesis/baryogenesis possible !
- Very lively session and very active theory astroparticle community

… stay tuned for more results !

THANKS TO

- All the speakers for the wonderful talks and providing the slides for this summary.
- All the session participants for the lively disussions and questions

- Manfred Lindner and the WIN-2015 OrgaTeam for the wonderful atmosphere and the smooth working during all the conference !!!