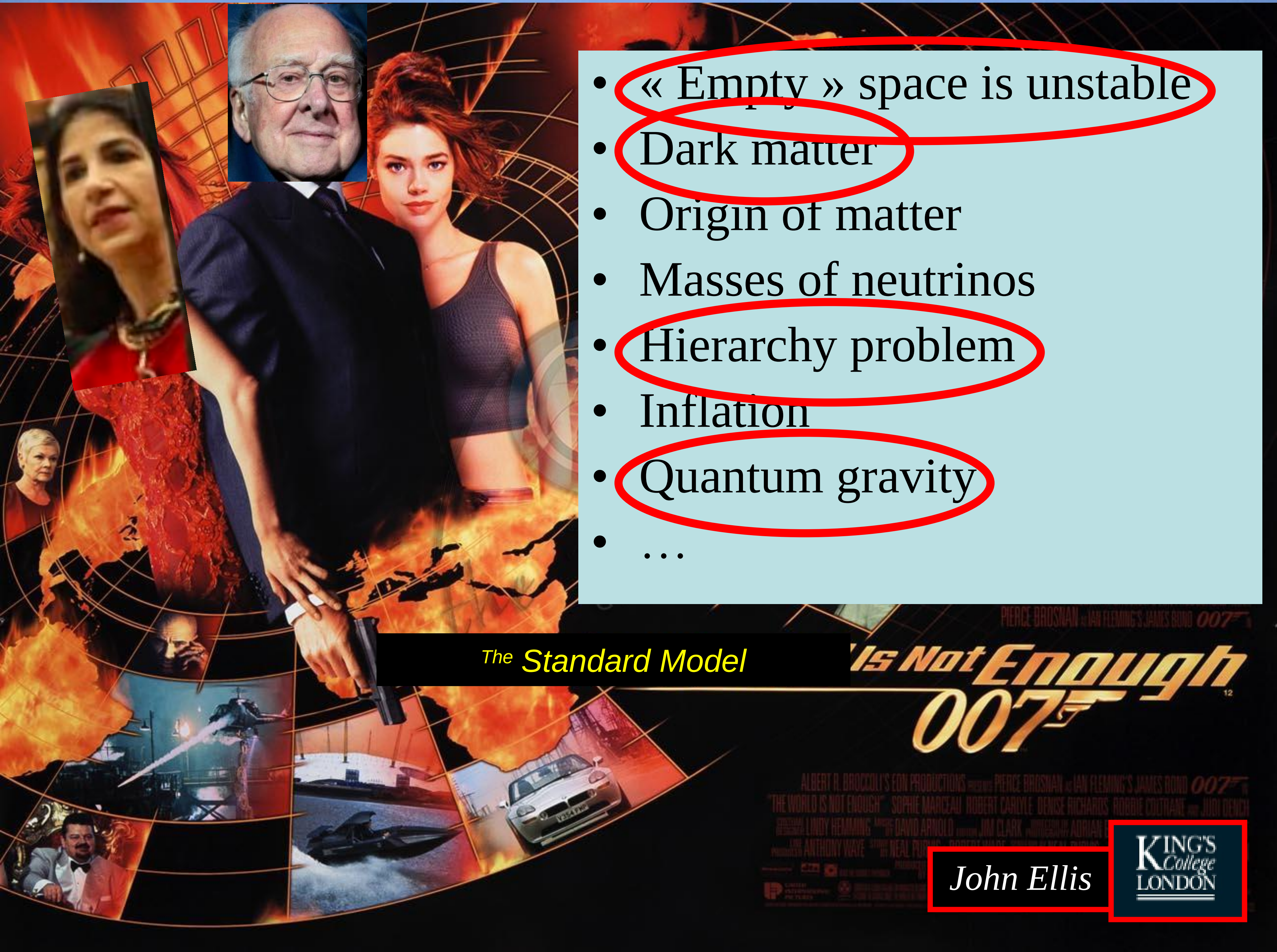
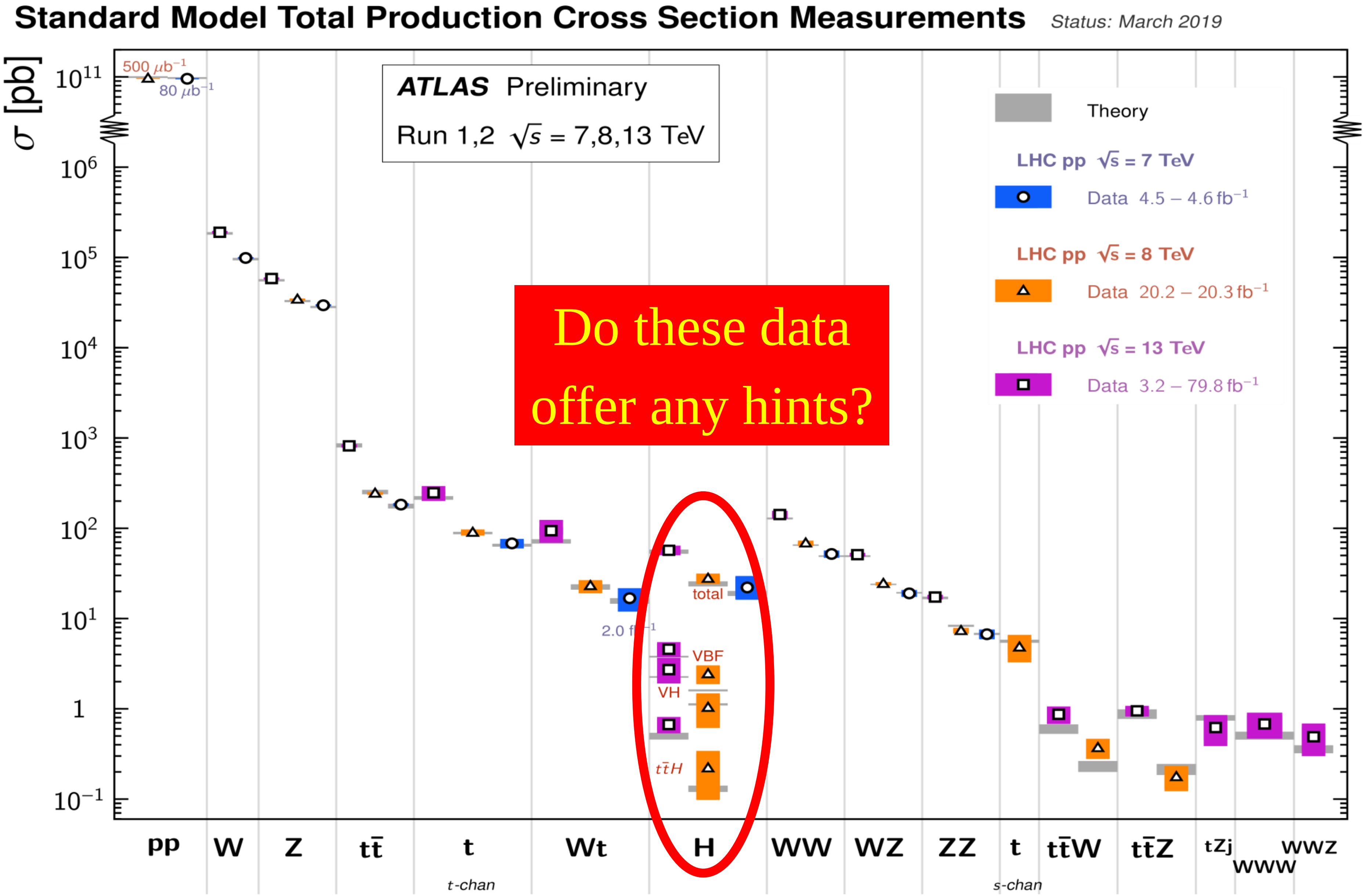


- « Empty » space is unstable
- Dark matter
- Origin of matter
- Masses of neutrinos
- Hierarchy problem
- Inflation
- Quantum gravity
- …

The Standard Model

John Ellis

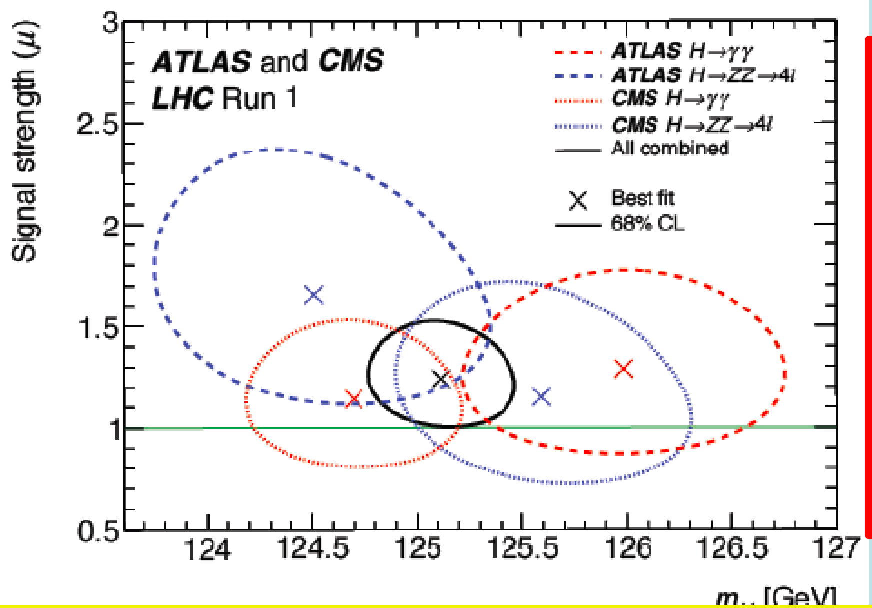
Standard Model Measurements @ LHC



Do these data offer any hints?

Higgs Mass Measurements

- ATLAS + CMS ZZ^* and γγ final states



Crucial for stability of Electroweak vacuum

- Run 1: $125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$
- CMS Run 2: $125.26 \pm 0.20(\text{stat.}) \pm 0.08(\text{sys.})$ GeV
- ATLAS Run 2: 124.98 ± 0.28 GeV

Naïve combination 125.13 ± 0.14 GeV

Theoretical Constraints on Higgs Mass

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

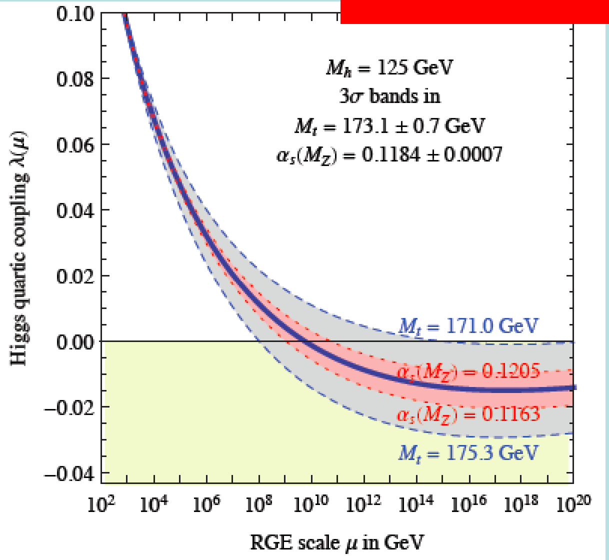
- Large M_h → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$

$$\lambda(Q) =$$

Instability @ $10^{11.4\pm0.8}$ GeV

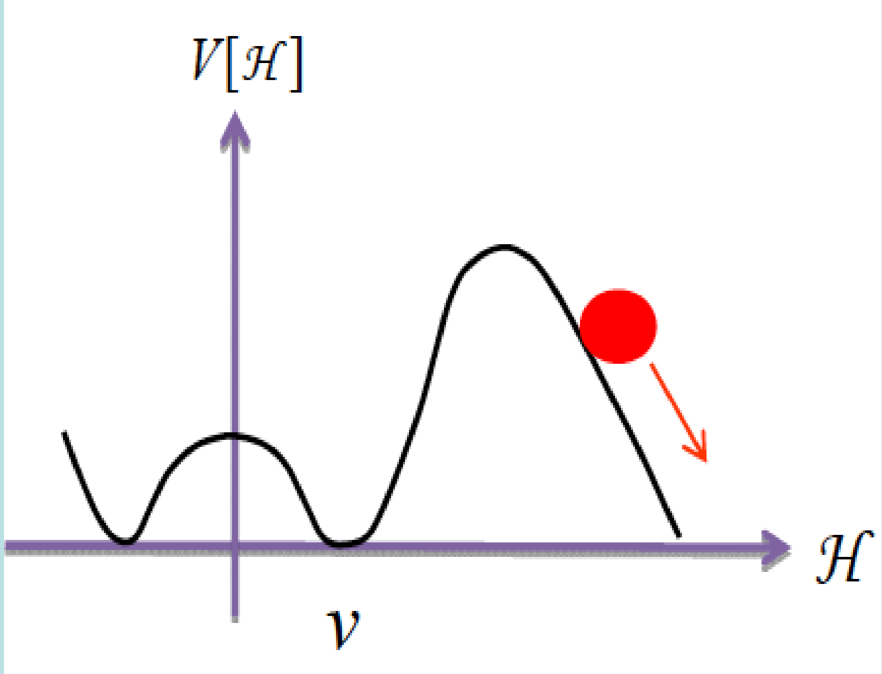
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable

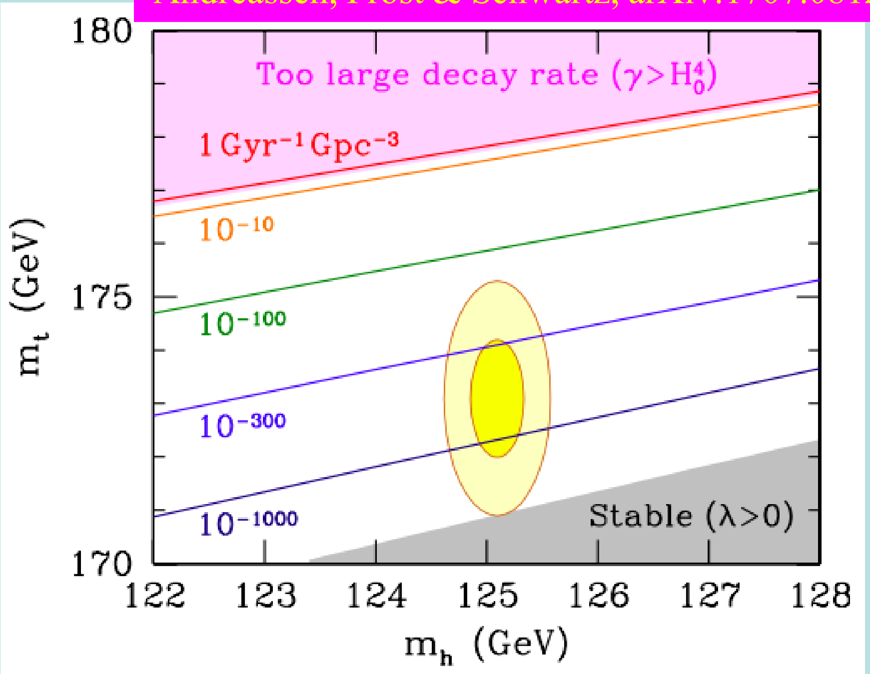


- Vacuum could be stabilized by **Supersymmetry**

Vacuum Instability in the Standard Model

Andreassen, Frost & Schwartz, arXiv:1707.08124





- Sensitive to α_s as well as m_t and M_H
- Instability scale:

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

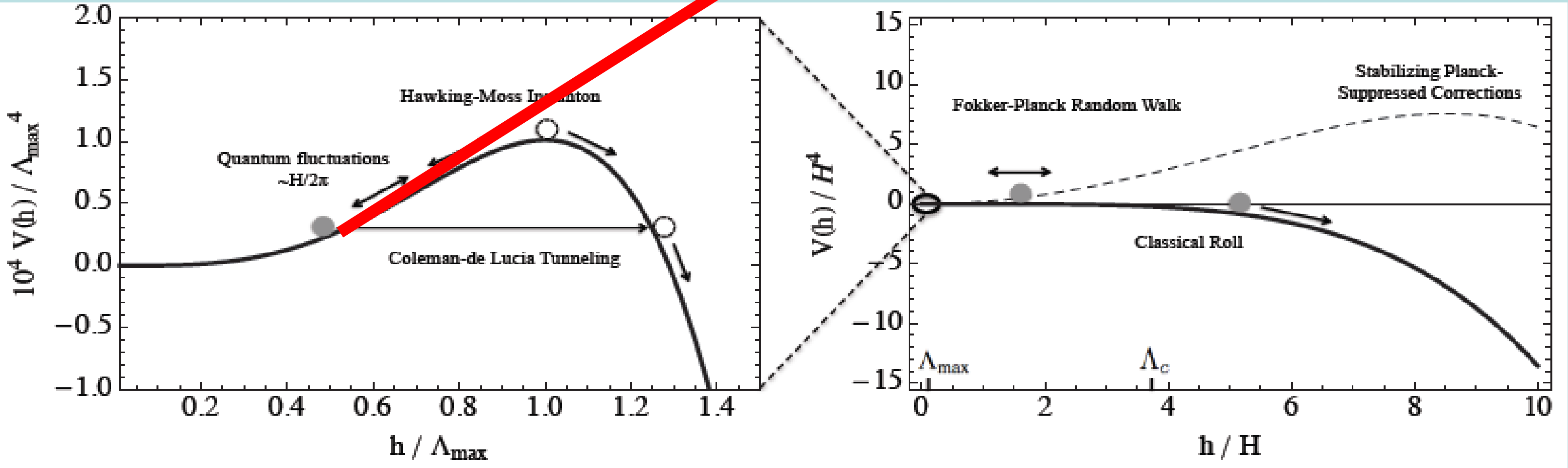
$$\log_{10}\frac{\Lambda_I}{\mathrm{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\mathrm{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\mathrm{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

m_t = 172.47±0.35 GeV → $\log_{10}(\Lambda/\mathrm{GeV})$ = 11.4±0.8

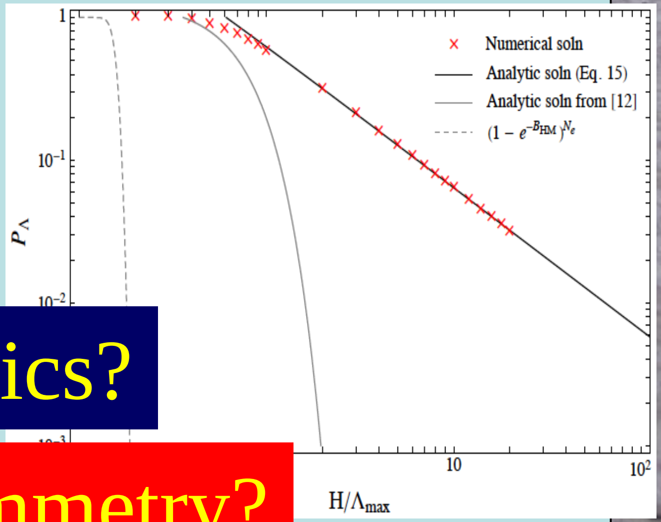
Instability during Inflation?

Hook, Kearney, Shakya & Zurek: arXiv:1404.5953

- Do inflation fluctuations drive us over the hill?



- Then Fokker-Planck evolution
- Do AdS regions eat us?
  - Disaster if so



Stabilize vacuum with BSM physics?

“Build a wall” with supersymmetry?

Standard Model as an Effective Field Theory

- Supplement Standard Model with higher-dimensional interactions generated by new physics at scale Λ

Buchmueller & Wyler, 1986

- Leading dimension-6 operators:

$$\mathcal{L}_{\rm SMEFT} \supset \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda_i^2} \mathcal{O}_i$$

- Use data to constrain operator coefficients
- Look for indirect effects of physics beyond the Standard Model

Dimension-6 Operators in Warsaw Basis

- Involved in precision electroweak, diboson data

$$\begin{aligned}\mathcal{L}^{\text{Warsaw}}_{\text{SMEFT}} \supset\ & \frac{\bar{C}^{(3)}_{Hl}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l) + \frac{\bar{C}^{(1)}_{Hl}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l) + \frac{\bar{C}_{ll}}{v^2}(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)\\ &+ \frac{\bar{C}_{HD}}{v^2}\left|H^\dagger D_\mu H\right|^2 + \frac{\bar{C}_{HWB}}{v^2}H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}\\ &+ \frac{\bar{C}_{He}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e) + \frac{\bar{C}_{Hu}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u) + \frac{\bar{C}_{Hd}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)\\ &+ \frac{\bar{C}^{(3)}_{Hq}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q) + \frac{\bar{C}^{(1)}_{Hq}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q) + \frac{\bar{C}_W}{v^2}\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho\end{aligned}$$

$$\bar{C} \equiv \frac{v^2}{\Lambda^2}C$$

- Operators affecting Higgs observables

$$\begin{aligned}\mathcal{L}^{\text{Warsaw}}_{\text{SMEFT}} \supset\ & \frac{\bar{C}_{eH}}{v^2}(H^\dagger H)(\bar{l}eH) + \frac{\bar{C}_{dH}}{v^2}(H^\dagger H)(\bar{q}dH) + \frac{\bar{C}_{uH}}{v^2}(H^\dagger H)(\bar{q}u\widetilde{H})\\ &+ \frac{\bar{C}_G}{v^2}f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{\bar{C}_{H\Box}}{v^2}(H^\dagger H)\Box(H^\dagger H) + \frac{\bar{C}_{uG}}{v^2}(\bar{q}\sigma^{\mu\nu}T^A u)\widetilde{H}\,G^A_{\mu\nu}\\ &+ \frac{\bar{C}_{HW}}{v^2}H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu} + \frac{\bar{C}_{HB}}{v^2}H^\dagger H\, B_{\mu\nu}B^{\mu\nu} + \frac{\bar{C}_{HG}}{v^2}H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}\,.\end{aligned}$$

Updated Global SMEFT Fit
to Higgs, Diboson and Electroweak Data

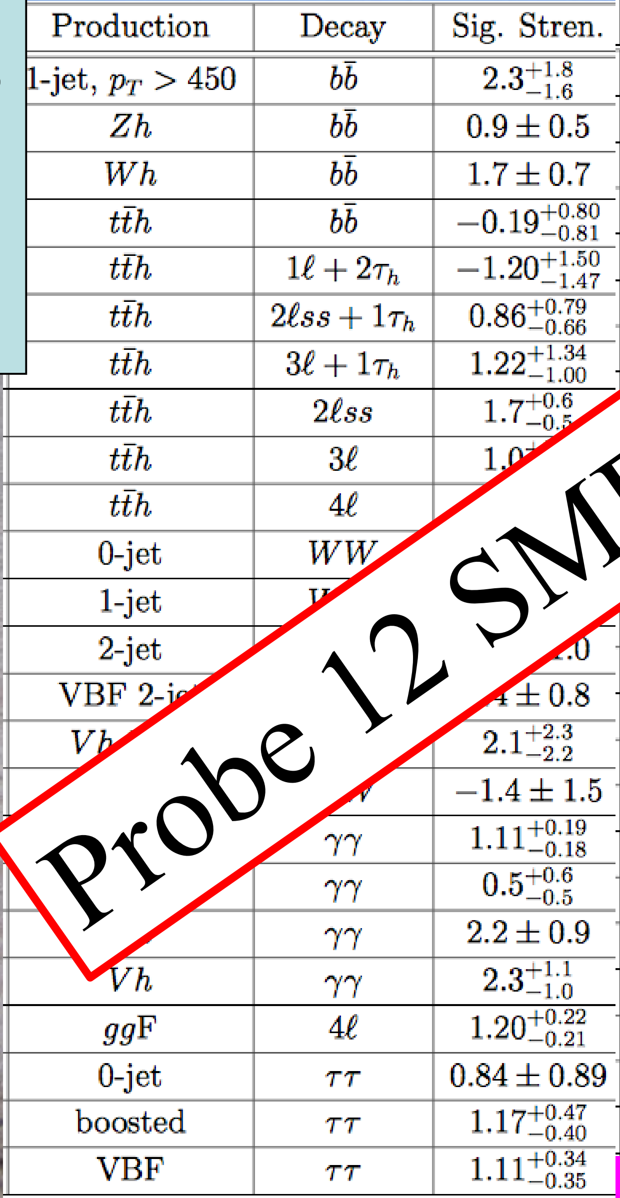
- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, Higgs and diboson data from LHC Runs 1 and 2
- Improvements in the constraints from Run 2
- Constraints on BSM models
  - Some contribute to operators at tree level
  - Stops that contribute at loop level

JE, Murphy, Sanz & You, arXiv:1803.03252

Run 2 Higgs Measurements used in SMEFT Fit

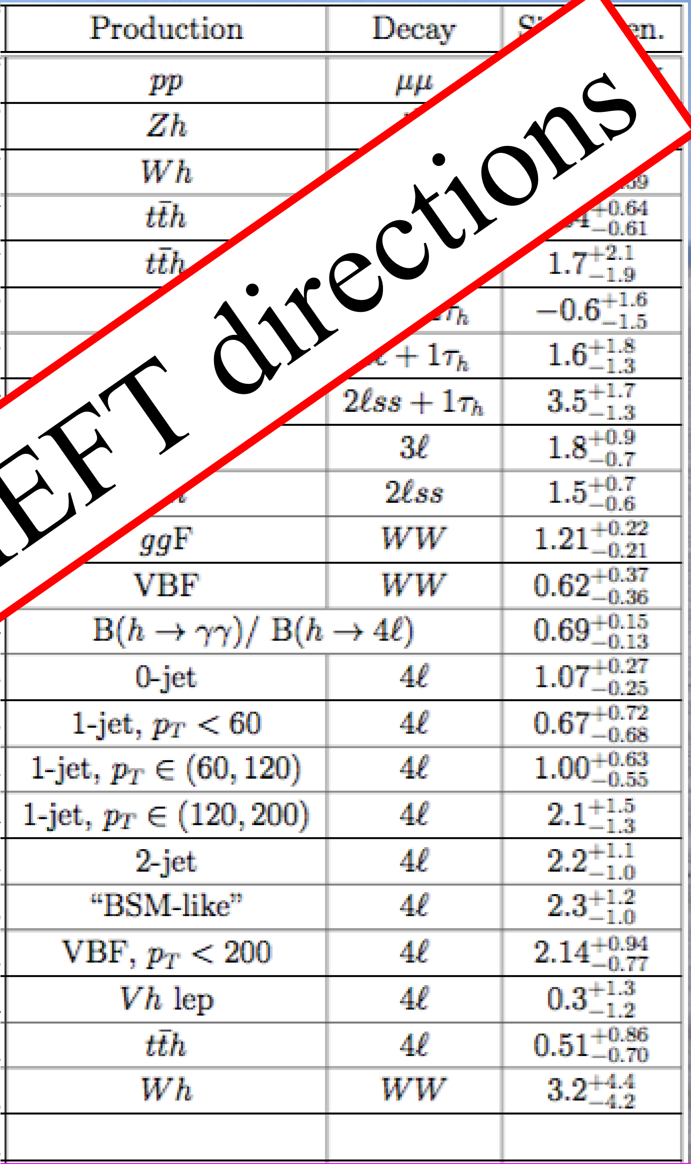
Include all available kinematical information + W^+W^- measurement at high p_T

CMS



Production	Decay	Sig. Stren.
1-jet, $p_T > 450$	$b\bar{b}$	$2.3^{+1.8}_{-1.6}$
Zh	$b\bar{b}$	0.9 ± 0.5
Wh	$b\bar{b}$	1.7 ± 0.7
$t\bar{t}h$	$b\bar{b}$	$-0.19^{+0.80}_{-0.81}$
$t\bar{t}h$	$1\ell + 2\tau_h$	$-1.20^{+1.50}_{-1.47}$
$t\bar{t}h$	$2\ell ss + 1\tau_h$	$0.86^{+0.79}_{-0.66}$
$t\bar{t}h$	$3\ell + 1\tau_h$	$1.22^{+1.34}_{-1.00}$
$t\bar{t}h$	$2\ell ss$	$1.7^{+0.6}_{-0.5}$
$t\bar{t}h$	3ℓ	[illegible]
$t\bar{t}h$	4ℓ	[illegible]
0-jet	WW	[illegible]
1-jet	[illegible]	[illegible]
2-jet	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
Vh	[illegible]	$2.1^{+2.3}_{-2.2}$
[illegible]	[illegible]	-1.4 ± 1.5
[illegible]	$\gamma\gamma$	$1.11^{+0.19}_{-0.18}$
[illegible]	$\gamma\gamma$	$0.5^{+0.6}_{-0.5}$
[illegible]	$\gamma\gamma$	2.2 ± 0.9
Vh	$\gamma\gamma$	$2.3^{+1.1}_{-1.0}$
ggF	4ℓ	$1.20^{+0.22}_{-0.21}$
0-jet	$\tau\tau$	0.84 ± 0.89
boosted	$\tau\tau$	$1.17^{+0.47}_{-0.40}$
VBF	$\tau\tau$	$1.11^{+0.34}_{-0.35}$

ATLAS



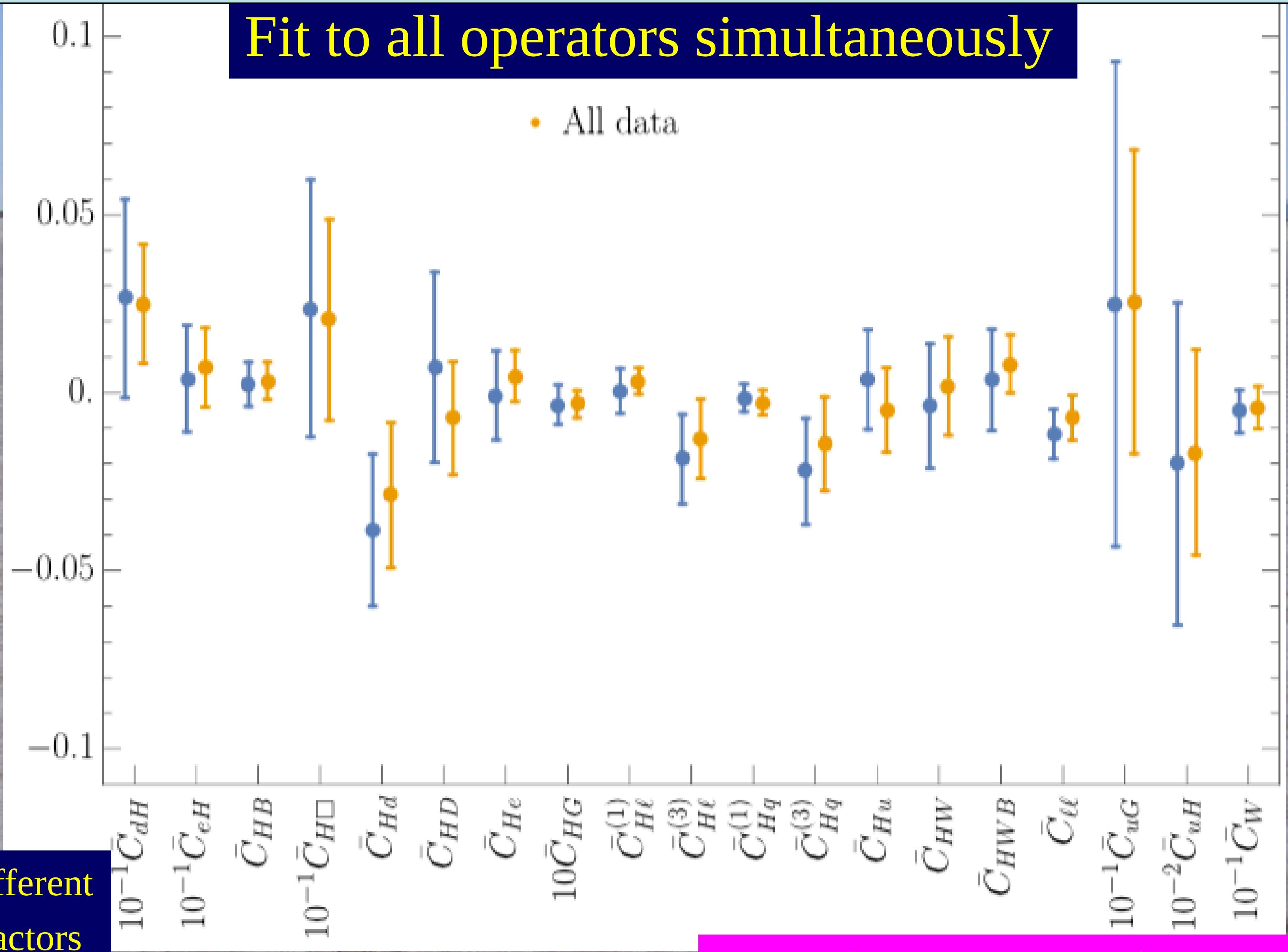
Production	Decay	[illegible]
pp	$\mu\mu$	[illegible]
Zh	[illegible]	[illegible]
Wh	[illegible]	[illegible]
$t\bar{t}h$	[illegible]	[illegible]
$t\bar{t}h$	[illegible]	$1.7^{+2.1}_{-1.9}$
[illegible]	[illegible]	$-0.6^{+1.6}_{-1.5}$
[illegible]	[illegible]	$1.6^{+1.8}_{-1.3}$
[illegible]	$2\ell ss + 1\tau_h$	$3.5^{+1.7}_{-1.3}$
[illegible]	3ℓ	$1.8^{+0.9}_{-0.7}$
[illegible]	$2\ell ss$	$1.5^{+0.7}_{-0.6}$
ggF	WW	$1.21^{+0.22}_{-0.21}$
VBF	WW	$0.62^{+0.37}_{-0.36}$
$B(h \to \gamma\gamma)/\ B(h \to 4\ell)$		$0.69^{+0.15}_{-0.13}$
0-jet	4ℓ	$1.07^{+0.27}_{-0.25}$
1-jet, $p_T < 60$	4ℓ	$0.67^{+0.72}_{-0.68}$
1-jet, $p_T \in (60, 120)$	4ℓ	$1.00^{+0.63}_{-0.55}$
1-jet, $p_T \in (120, 200)$	4ℓ	$2.1^{+1.5}_{-1.3}$
2-jet	4ℓ	$2.2^{+1.1}_{-1.0}$
"BSM-like"	4ℓ	$2.3^{+1.2}_{-1.0}$
VBF, $p_T < 200$	4ℓ	$2.14^{+0.94}_{-0.77}$
Vh lep	4ℓ	$0.3^{+1.3}_{-1.2}$
$t\bar{t}h$	4ℓ	$0.51^{+0.86}_{-0.70}$
Wh	WW	$3.2^{+4.4}_{-4.2}$

Probe 12 SMEFT directions

JE, Murphy, Sanz & You, arXiv:1803.03252

Results of Global Fit in Warsaw Basis

Fit to all operators simultaneously

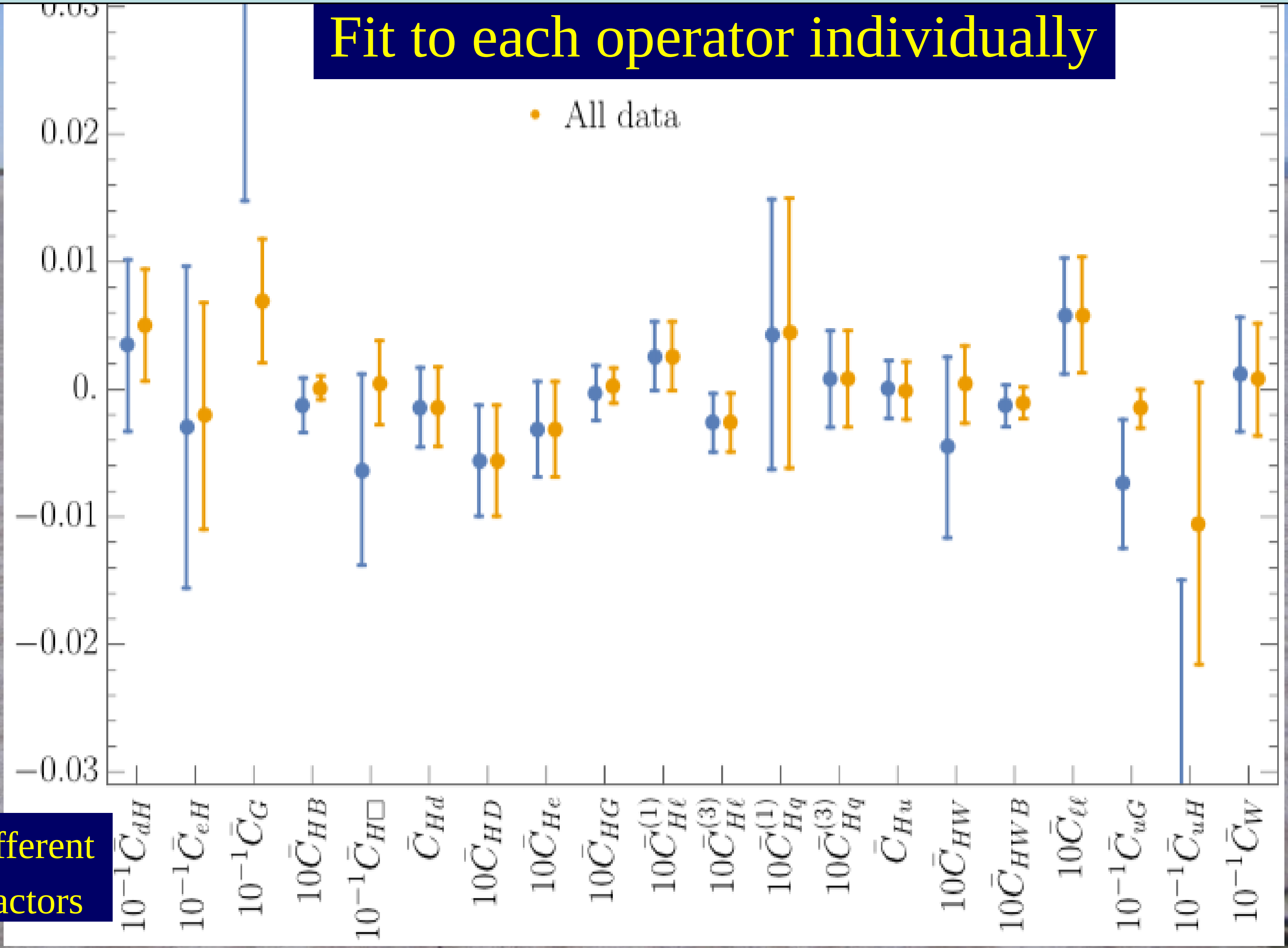


NB: Different scale factors

JE, Murphy, Sanz & You, arXiv:1803.03252

JE, Murphy, Sanz & You, arXiv:1803.03252

Results of Global Fit in Warsaw Basis



Fit to each operator individually

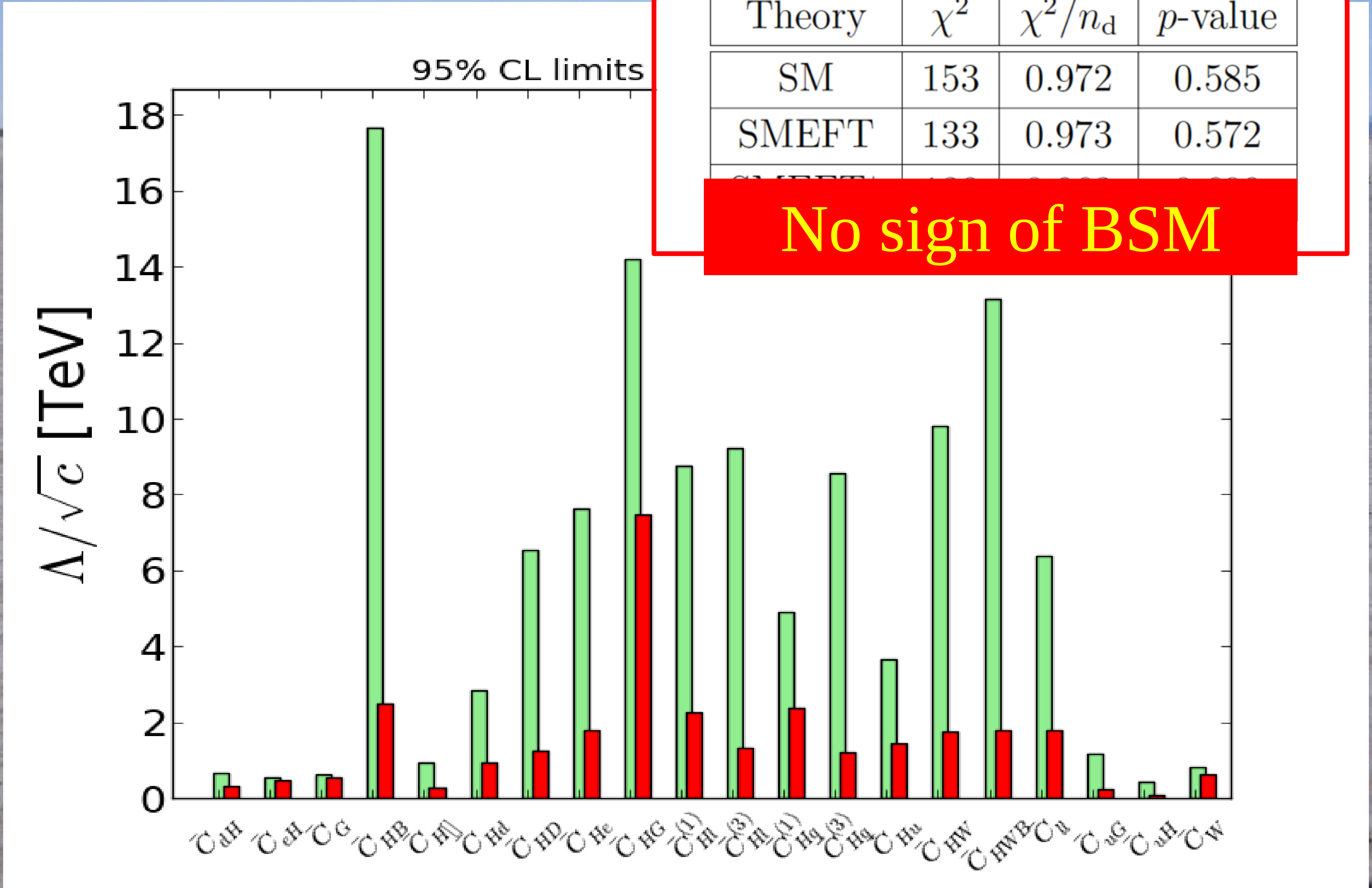
NB: Different scale factors

JE, Murphy, Sanz & You, arXiv:1803.03252

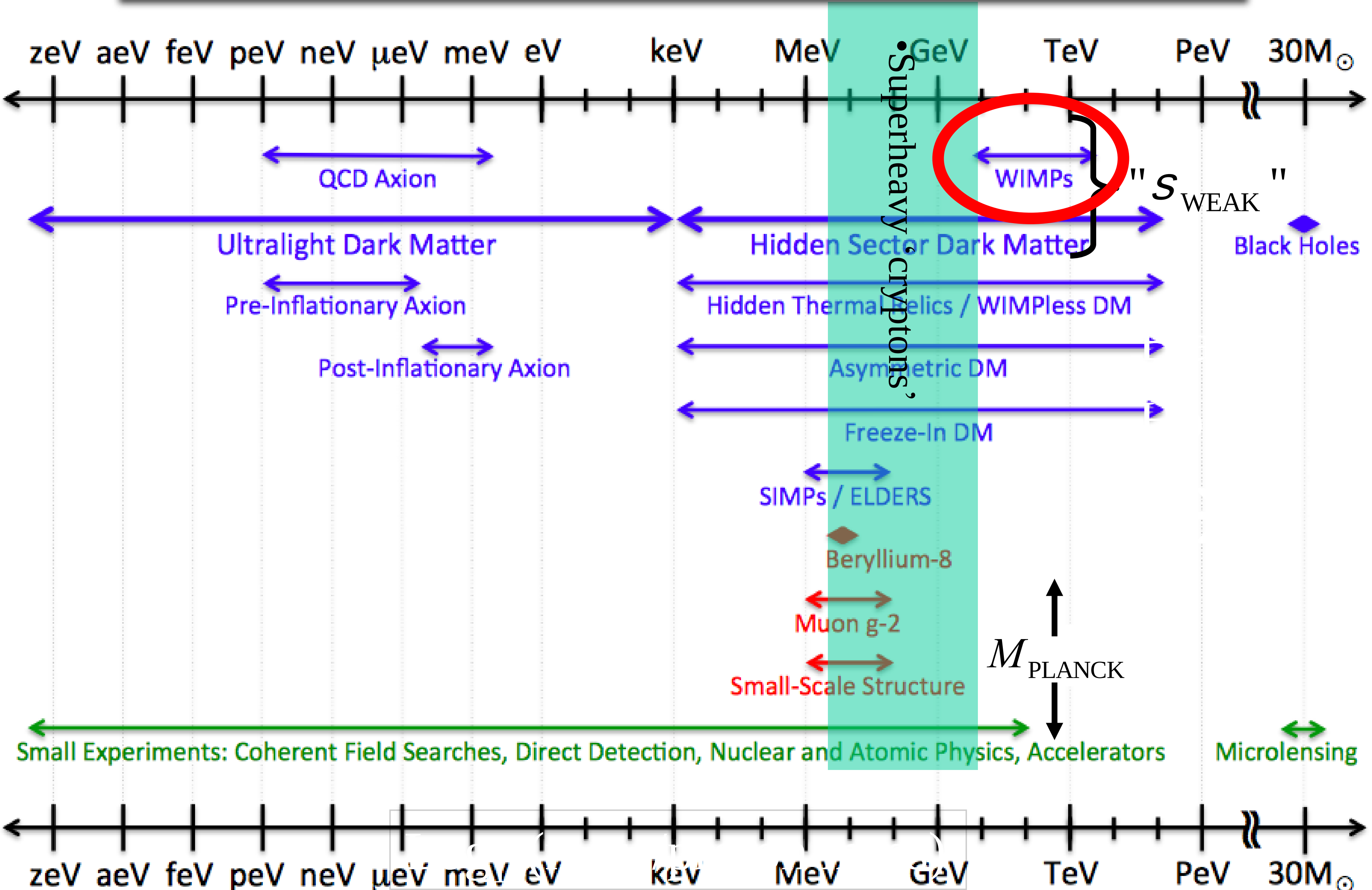
Summary

Theory	χ^2	$\chi^2/n_{\rm d}$	p-value
SM	153	0.972	0.585
SMEFT	133	0.973	0.572

No sign of BSM



Dark Matter Candidates



WIMP Candidates

- Could have right density if weigh 100 to 1000 GeV (accessible to LHC experiments?)
- Present in many extensions of Standard Model
- Particularly in attempts to understand strength of weak interactions, mass of Higgs boson
- Examples:
  - Extra dimensions of space
  - **Supersymmetry** ♥

We still believe in supersymmetry

You must be joking

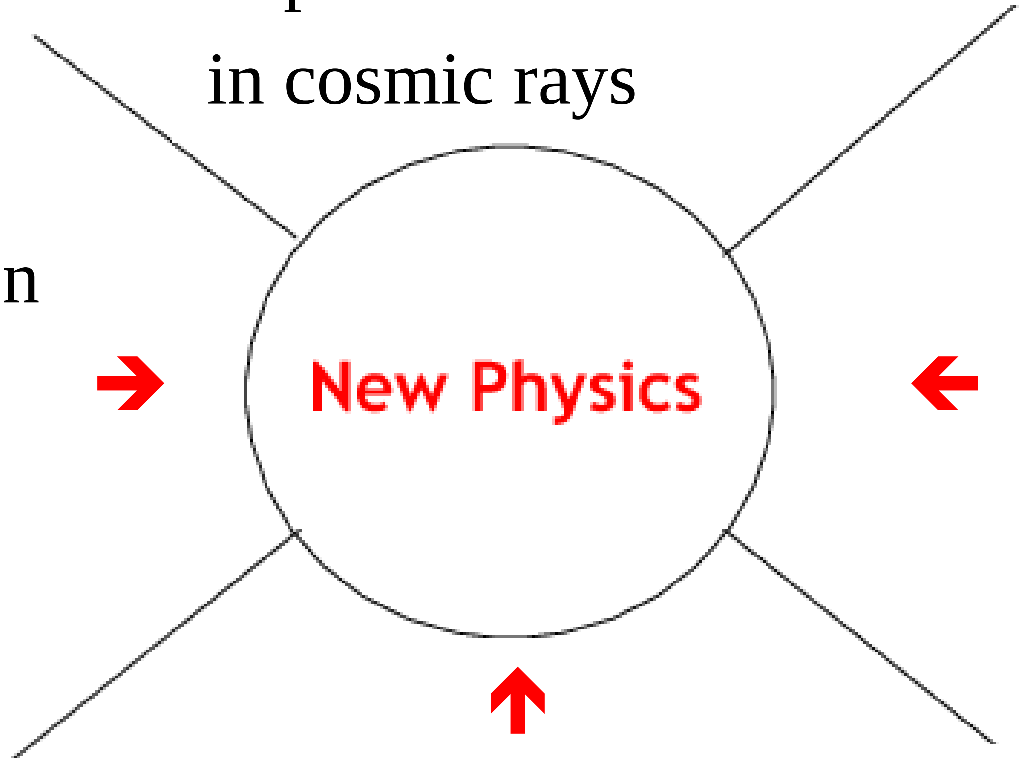
What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

Searches for WIMP Dark Matter



Dark Matter

Annihilation
to particles
in cosmic rays →

Standard Model

Annihilation
in the early
Universe →

New Physics

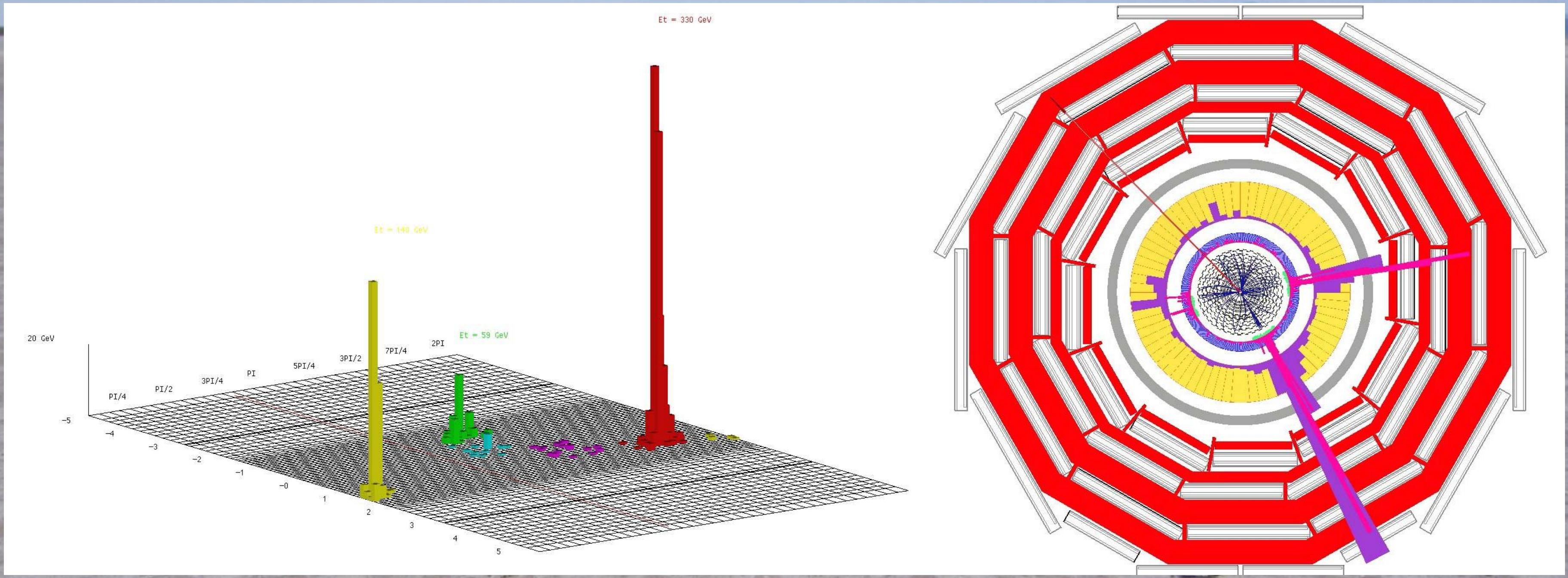
← Production
at particle
colliders

↑
Direct dark matter
detection

Dark Matter

Standard Model

Classic LHC Dark Matter Signature

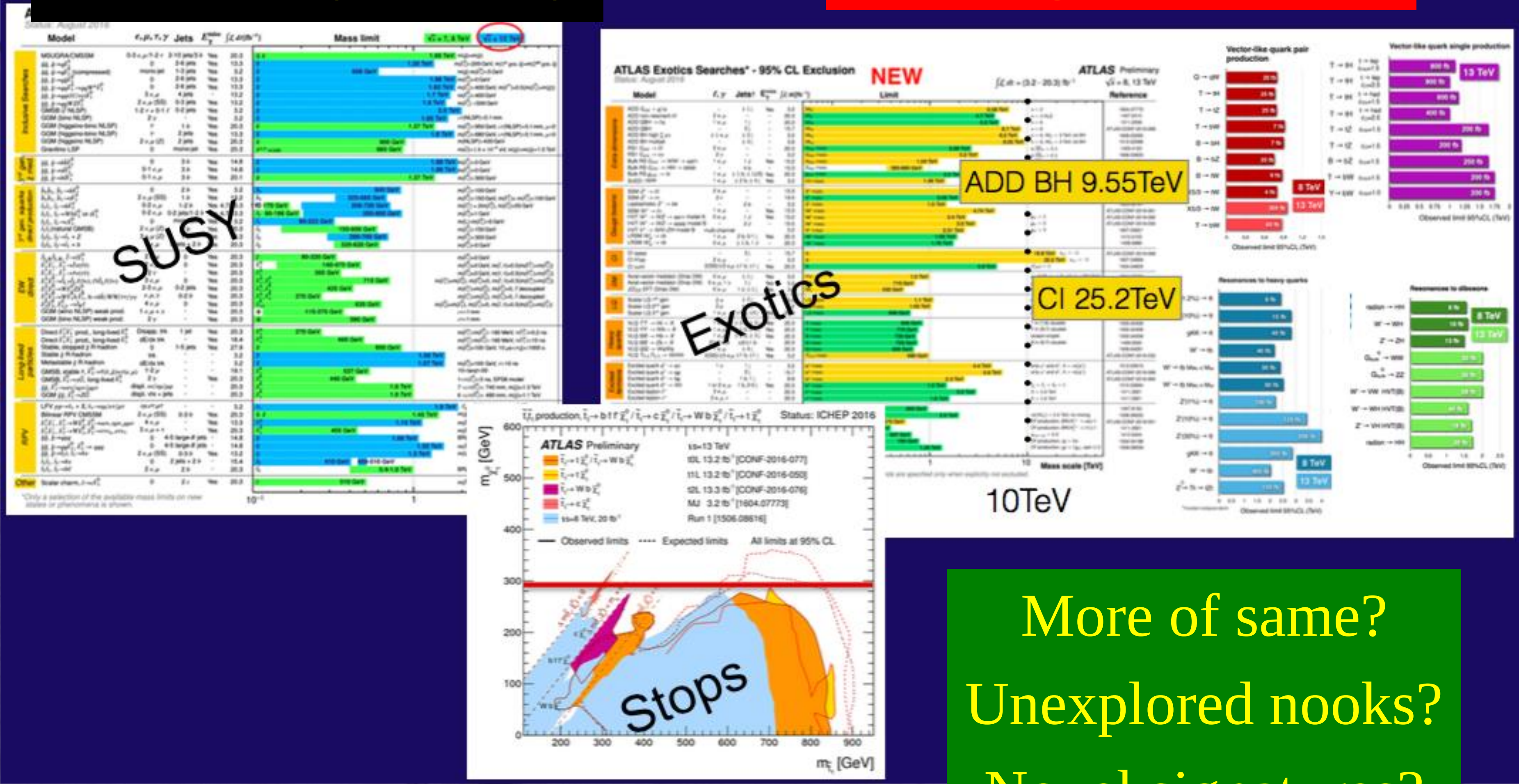


Missing transverse energy
carried away by dark matter particles

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either

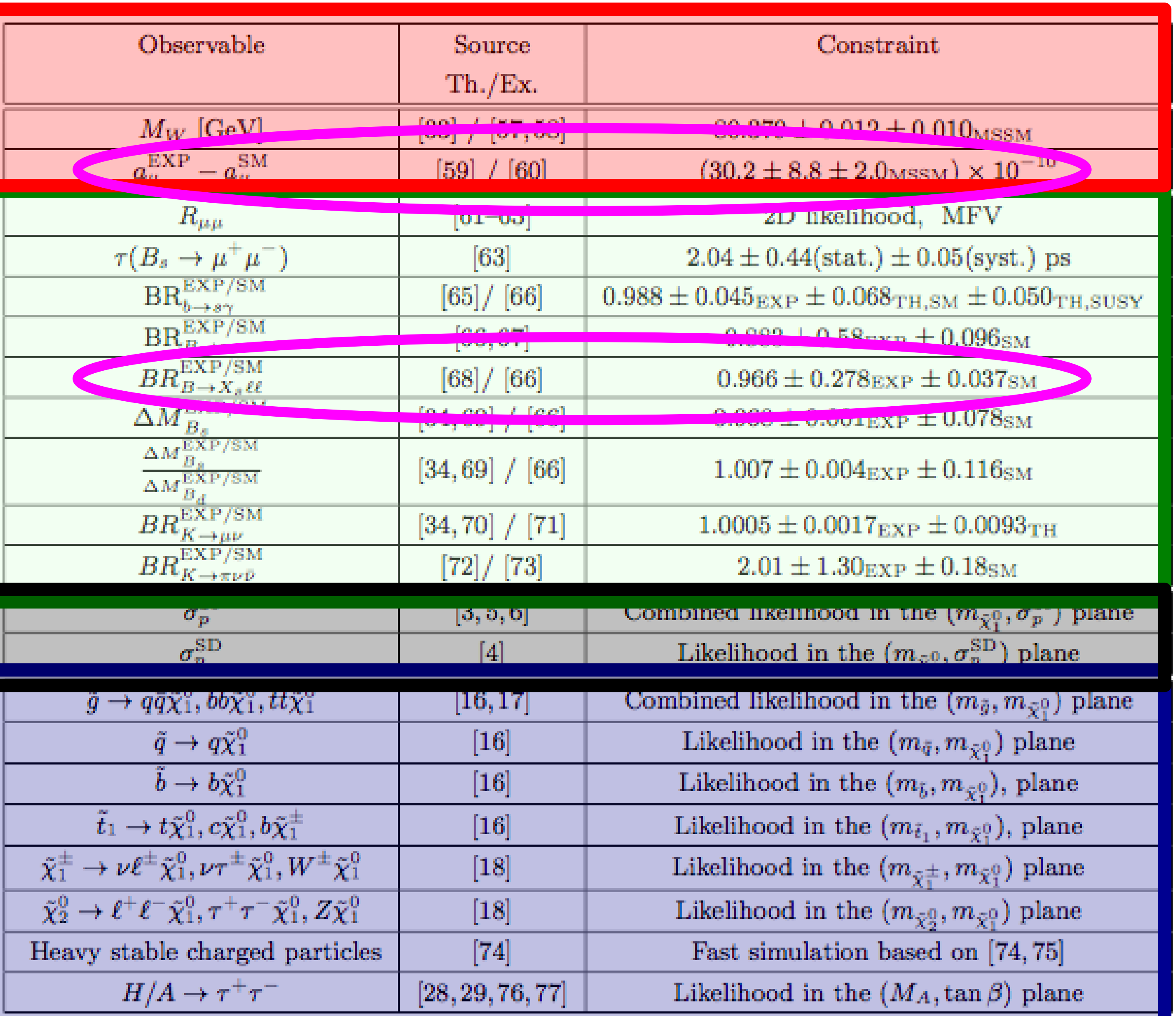


More of same?

Unexplored nooks?

Novel signatures?

Inputs to Global Fits for New Physics



Electroweak observables

Flavour observables: Interpretation requires lattice inputs

Dark Matter

LHC observables

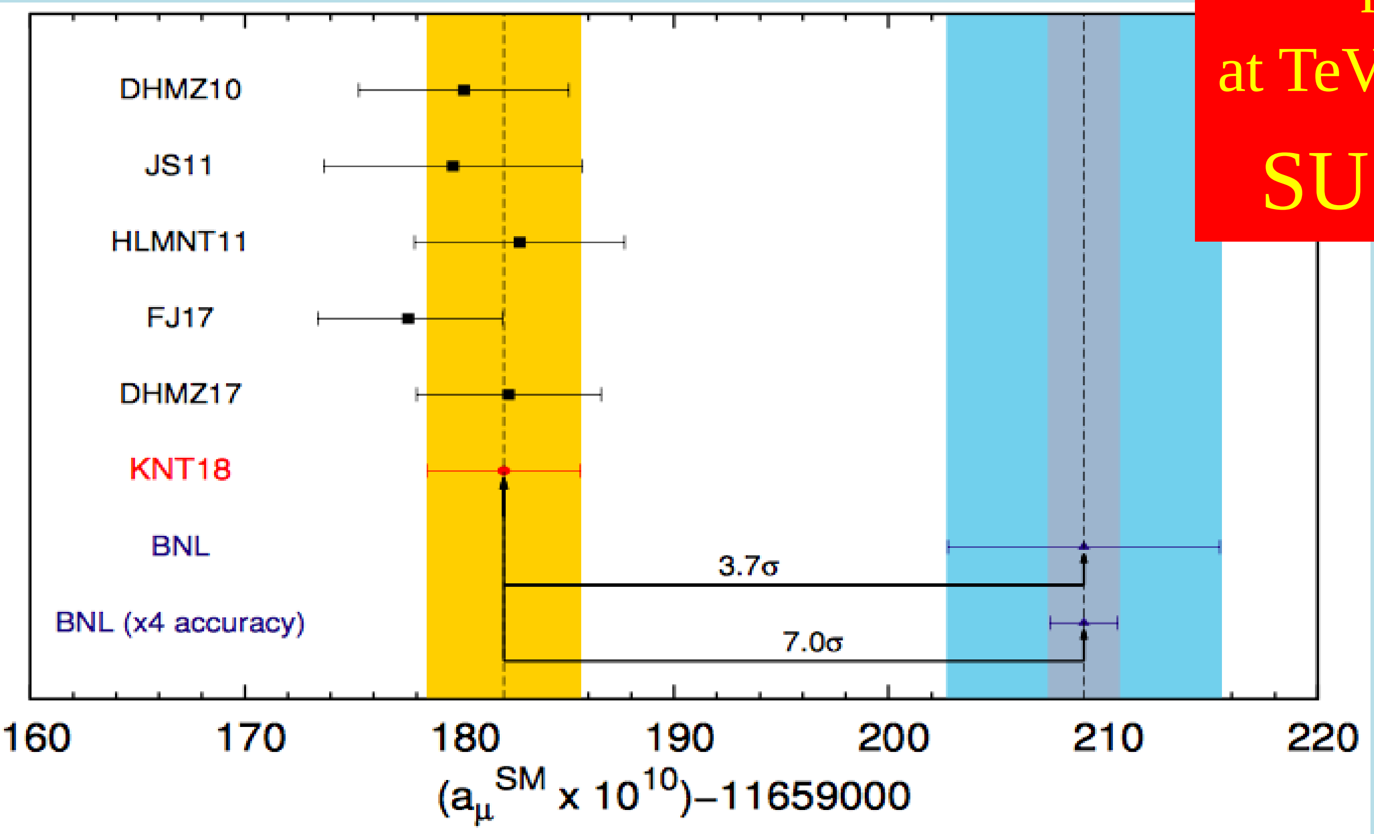
Observable	Source Th./Ex.	Constraint
M_W [GeV]	[56] / [57, 58]	$80.379 \pm 0.012 \pm 0.010_{\rm MSSM}$
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[59] / [60]	$(30.2 \pm 8.8 \pm 2.0_{\rm MSSM}) \times 10^{-10}$
$R_{\mu\mu}$	[61–63]	2D likelihood, MFV
$\tau(B_s \to \mu^+\mu^-)$	[63]	$2.04 \pm 0.44({\rm stat.}) \pm 0.05({\rm syst.})$ ps
${\rm BR}^{\rm EXP/SM}_{b\to s\gamma}$	[65]/ [66]	$0.988 \pm 0.045_{\rm EXP} \pm 0.068_{\rm TH,SM} \pm 0.050_{\rm TH,SUSY}$
${\rm BR}^{\rm EXP/SM}_{B_u\to\tau\nu}$	[66, 67]	$0.883 \pm 0.58_{\rm EXP} \pm 0.096_{\rm SM}$
$BR^{\rm EXP/SM}_{B\to X_s\ell\ell}$	[68]/ [66]	$0.966 \pm 0.278_{\rm EXP} \pm 0.037_{\rm SM}$
$\Delta M^{\rm EXP/SM}_{B_s}$	[34, 69] / [66]	$0.968 \pm 0.001_{\rm EXP} \pm 0.078_{\rm SM}$
$\frac{\Delta M^{\rm EXP/SM}_{B_s}}{\Delta M^{\rm EXP/SM}_{B_d}}$	[34, 69] / [66]	$1.007 \pm 0.004_{\rm EXP} \pm 0.116_{\rm SM}$
$BR^{\rm EXP/SM}_{K\to\mu\nu}$	[34, 70] / [71]	$1.0005 \pm 0.0017_{\rm EXP} \pm 0.0093_{\rm TH}$
$BR^{\rm EXP/SM}_{K\to\pi\nu\bar\nu}$	[72]/ [73]	$2.01 \pm 1.30_{\rm EXP} \pm 0.18_{\rm SM}$
$\sigma_p^{\rm SI}$	[3, 5, 6]	Combined likelihood in the $(m_{\tilde\chi^0_1}, \sigma_p^{\rm SI})$ plane
$\sigma_p^{\rm SD}$	[4]	Likelihood in the $(m_{\tilde\chi^0_1}, \sigma_p^{\rm SD})$ plane
$\tilde g \to q\bar q\tilde\chi^0_1, b\bar b\tilde\chi^0_1, t\bar t\tilde\chi^0_1$	[16, 17]	Combined likelihood in the $(m_{\tilde g}, m_{\tilde\chi^0_1})$ plane
$\tilde q \to q\tilde\chi^0_1$	[16]	Likelihood in the $(m_{\tilde q}, m_{\tilde\chi^0_1})$ plane
$\tilde b \to b\tilde\chi^0_1$	[16]	Likelihood in the $(m_{\tilde b}, m_{\tilde\chi^0_1})$, plane
$\tilde t_1 \to t\tilde\chi^0_1, c\tilde\chi^0_1, b\tilde\chi^\pm_1$	[16]	Likelihood in the $(m_{\tilde t_1}, m_{\tilde\chi^0_1})$, plane
$\tilde\chi^\pm_1 \to \nu\ell^\pm\tilde\chi^0_1, \nu\tau^\pm\tilde\chi^0_1, W^\pm\tilde\chi^0_1$	[18]	Likelihood in the $(m_{\tilde\chi^\pm_1}, m_{\tilde\chi^0_1})$ plane
$\tilde\chi^0_2 \to \ell^+\ell^-\tilde\chi^0_1, \tau^+\tau^-\tilde\chi^0_1, Z\tilde\chi^0_1$	[18]	Likelihood in the $(m_{\tilde\chi^0_2}, m_{\tilde\chi^0_1})$ plane
Heavy stable charged particles	[74]	Fast simulation based on [74, 75]
$H/A \to \tau^+\tau^-$	[28, 29, 76, 77]	Likelihood in the $(M_A, \tan\beta)$ plane

Quo Vadis g_μ - 2?

- Strong discrepancy between BNL experiment and e^+e^- data now ~ 3.7 σ

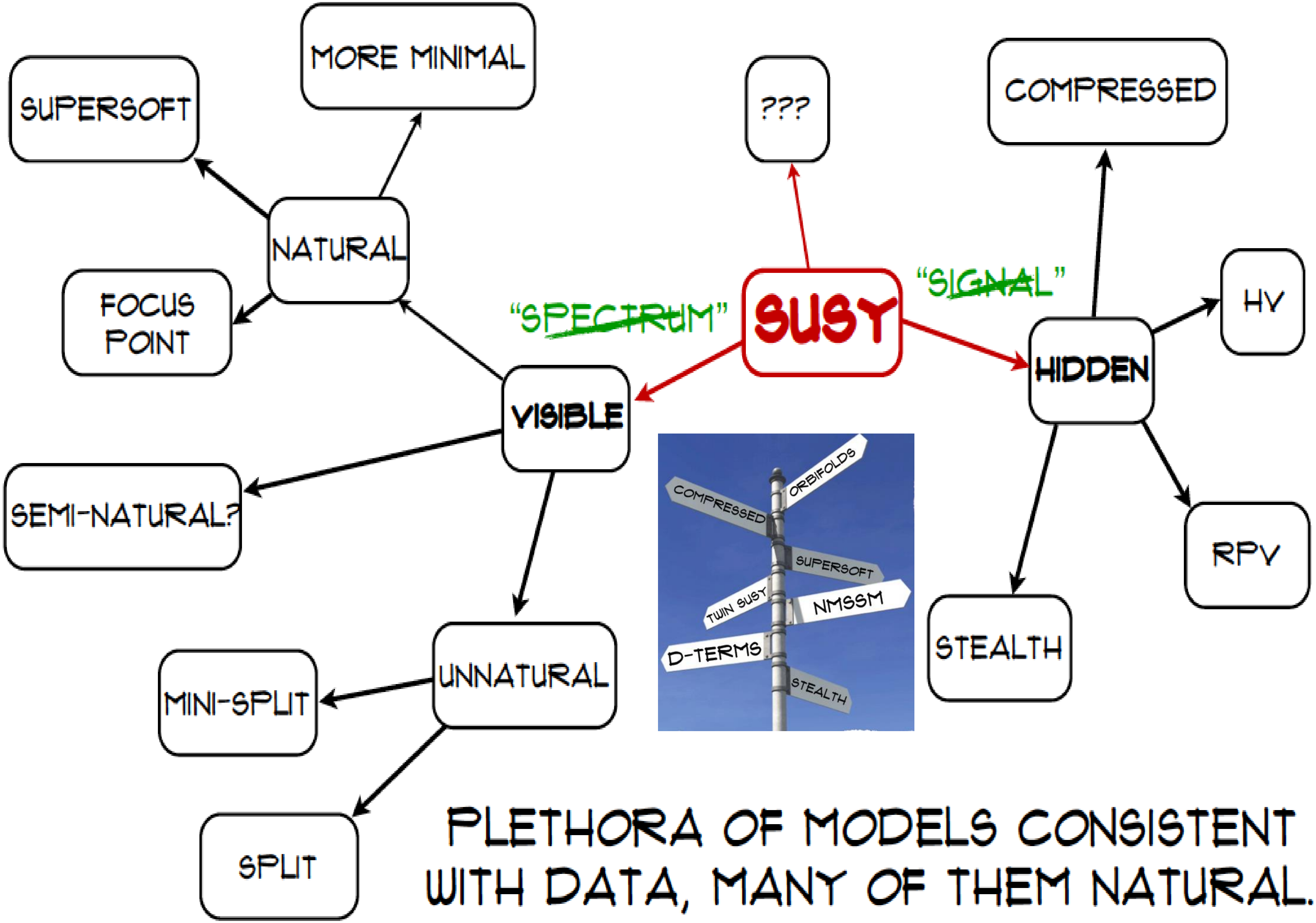
$$\Delta a_\mu = (27.05 \pm 7.26) \times 10^{-10}$$

New physics
at TeV scale?
SUSY?



- **New experiment at FNAL (J-PARC)**

Keshavarrzi, Nomura & Teubner, arXiv:1802.02995



SUSY

“~~SPECTRUM~~”

“~~SIGNAL~~”

???

VISIBLE

NATURAL

MORE MINIMAL

SUPERSOFT

FOCUS POINT

SEMI-NATURAL?

UNNATURAL

MINI-SPLIT

SPLIT

HIDDEN

COMPRESSED

HV

RPV

STEALTH

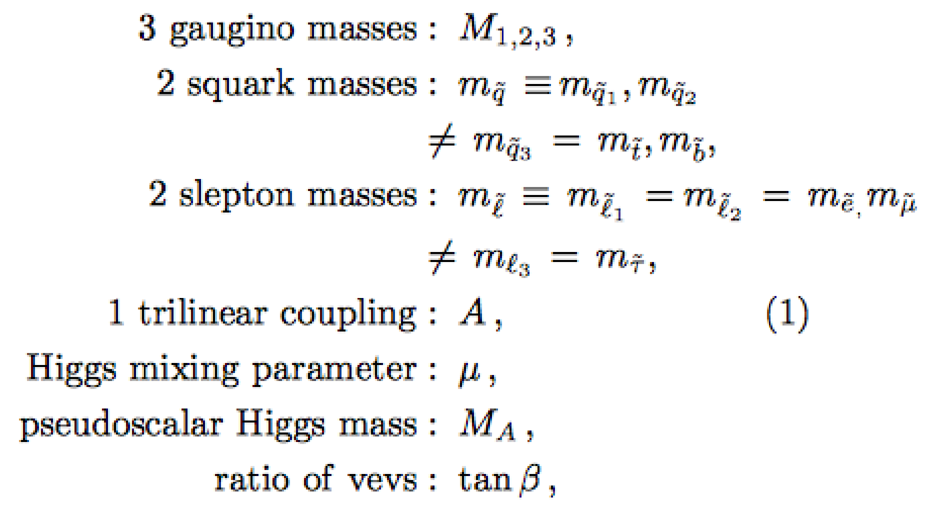
PLETHORA OF MODELS CONSISTENT WITH DATA, MANY OF THEM NATURAL. WHERE DOES THE DATA POINT US?

Craig@LHCP

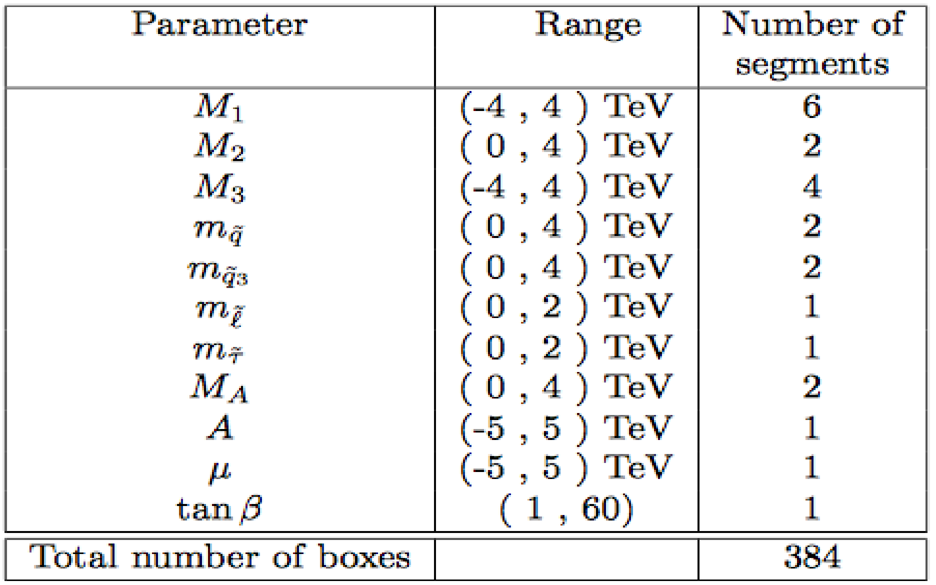
Analysis of pMSSM11

- Phenomenological MSSM with 11 parameters
- Sample parameter space using Multinest technique
- Sampling with/without g-2
- Dedicated sampling of Dark Matter regions
- Sample 2 × 10^9 points

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091



$$\begin{aligned}
\text{3 gaugino masses}: &\quad M_{1,2,3}\,,\\
\text{2 squark masses}: &\quad m_{\tilde q} \equiv m_{\tilde q_1}, m_{\tilde q_2}\\
&\quad \neq m_{\tilde q_3} = m_{\tilde t}, m_{\tilde b},\\
\text{2 slepton masses}: &\quad m_{\tilde \ell} \equiv m_{\tilde \ell_1} = m_{\tilde \ell_2} = m_{\tilde e}, m_{\tilde \mu}\\
&\quad \neq m_{\ell_3} = m_{\tilde \tau},\\
\text{1 trilinear coupling}: &\quad A\,, \qquad\qquad (1)\\
\text{Higgs mixing parameter}: &\quad \mu\,,\\
\text{pseudoscalar Higgs mass}: &\quad M_A\,,\\
\text{ratio of vevs}: &\quad \tan\beta\,,
\end{aligned}$$

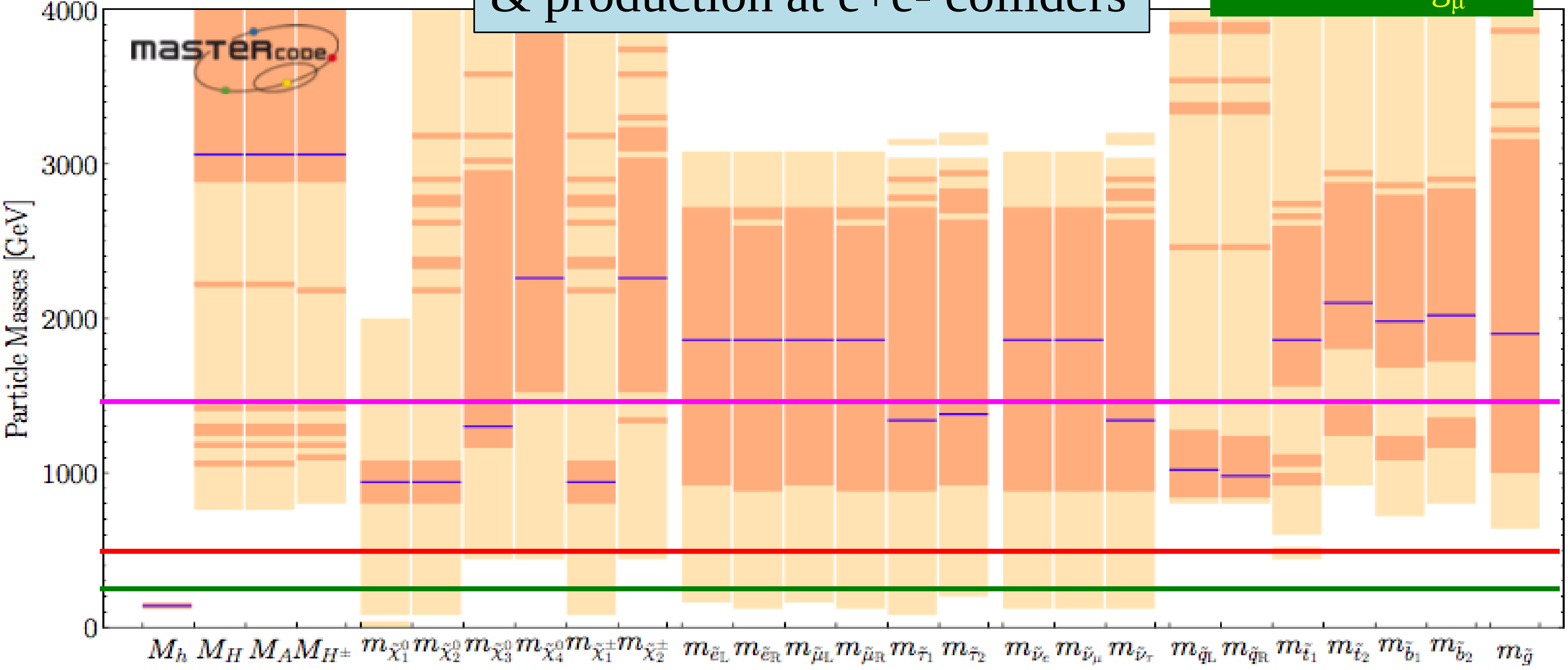


Parameter	Range	Number of segments
M_1	(-4 , 4) TeV	6
M_2	(0 , 4) TeV	2
M_3	(-4 , 4) TeV	4
$m_{\tilde q}$	(0 , 4) TeV	2
$m_{\tilde q_3}$	(0 , 4) TeV	2
$m_{\tilde \ell}$	(0 , 2) TeV	1
$m_{\tilde \tau}$	(0 , 2) TeV	1
M_A	(0 , 4) TeV	2
A	(-5 , 5) TeV	1
μ	(-5 , 5) TeV	1
$\tan\beta$	(1 , 60)	1
Total number of boxes		384

Sparticle Masses in the pMSSM

& production at e+e- colliders

Fit without g_μ-2



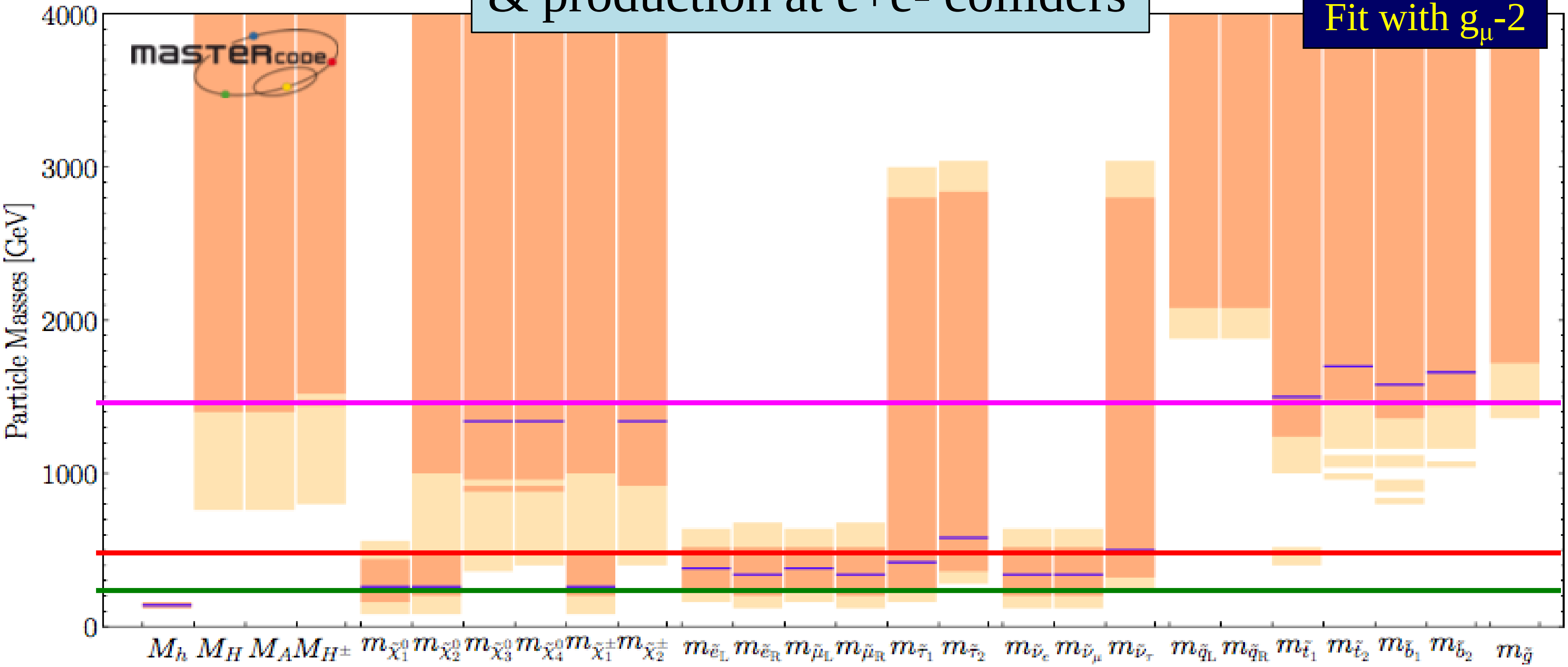
- **68 & 95% CL ranges**
- **Best-fit values**
- **Accessible in pair production at ILC500, ILC1000, CLIC**

Bagnaschi, Sakurai, JE et al,

Sparticle Masses in the pMSSM

& production at e+e- colliders

Fit with g_μ-2



- 68 & 95% CL ranges
- Best-fit values
- Accessible in pair production at ((ILC500)), (ILC1000), CLIC

Bagnaschi, Sakurai, JE et al,

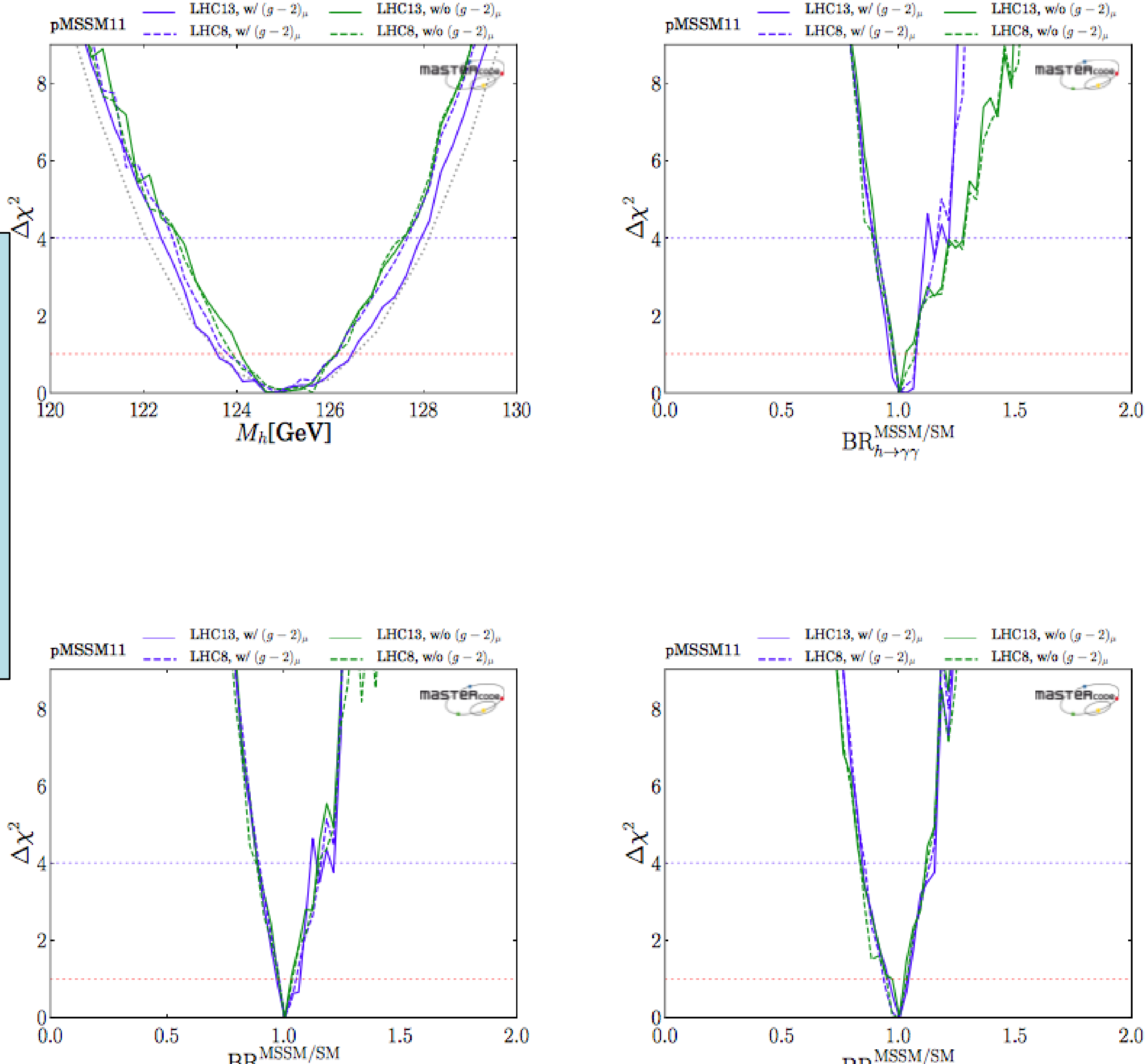
Higgs properties in the pMSSM

Fit with g_μ-2

Fit without g_μ-2

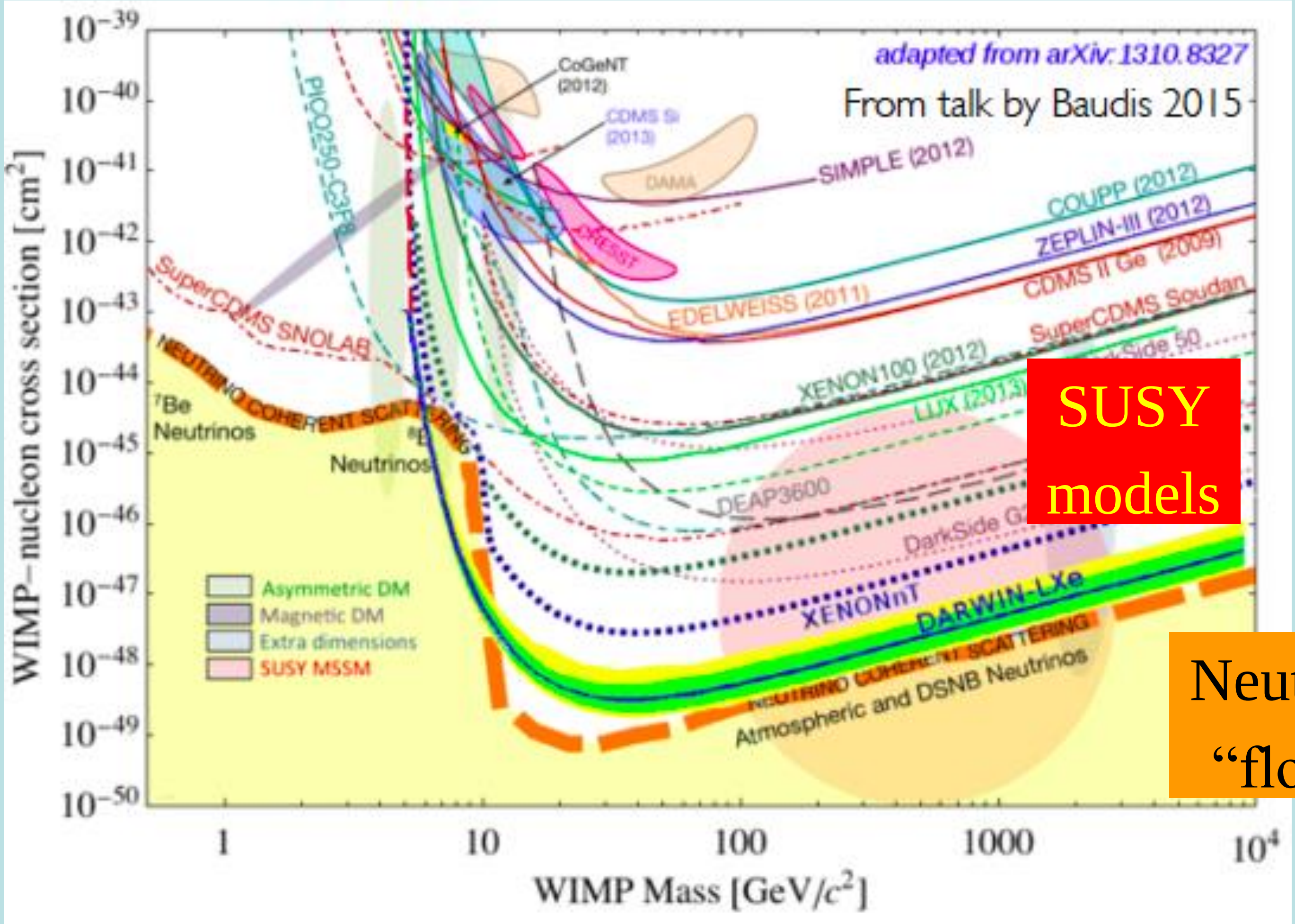
- No issue with measured Higgs mass
- Central values of decay BRs similar to SM
- Substantial deviations possible

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091



Direct Dark Matter Searches

- Compilation of present and future sensitivities



SUSY models

Neutrino “floor”

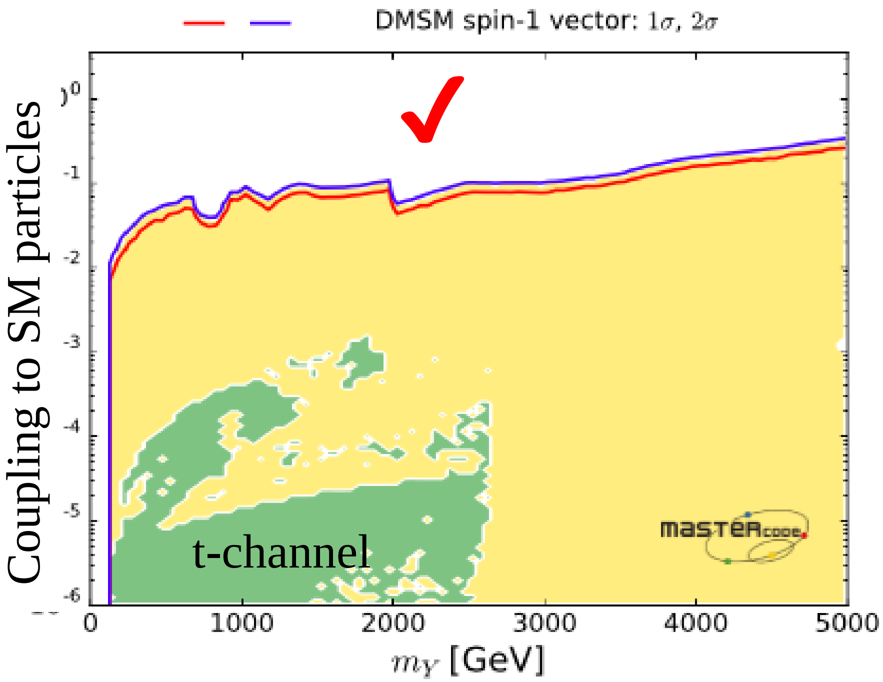
Simplified Dark Matter Models

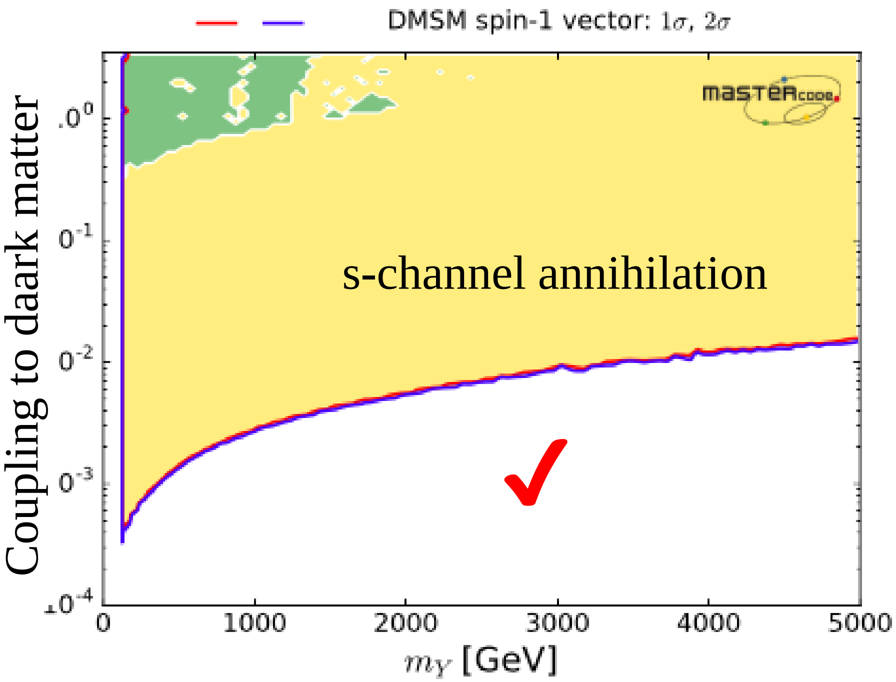
- Dark matter χ + mediator particle of spin 0 or 1
- Assume leptophobic gauge boson Y of some U(1)’ with vector and/or axial-vector couplings
- Model parameters:
  - Coupling of mediator Y to dark matter: g_{DM}
  - Coupling of Y to quarks (assumed universal): g_{SM}
  - Mediator mass: m_Y
  - Dark matter particle mass: m_χ
- Global analysis using MasterCode

Bagnaschi, …, JE et al, arXiv:1905.00892

Dark Matter Simplified Models

Leptophobic vector mediator



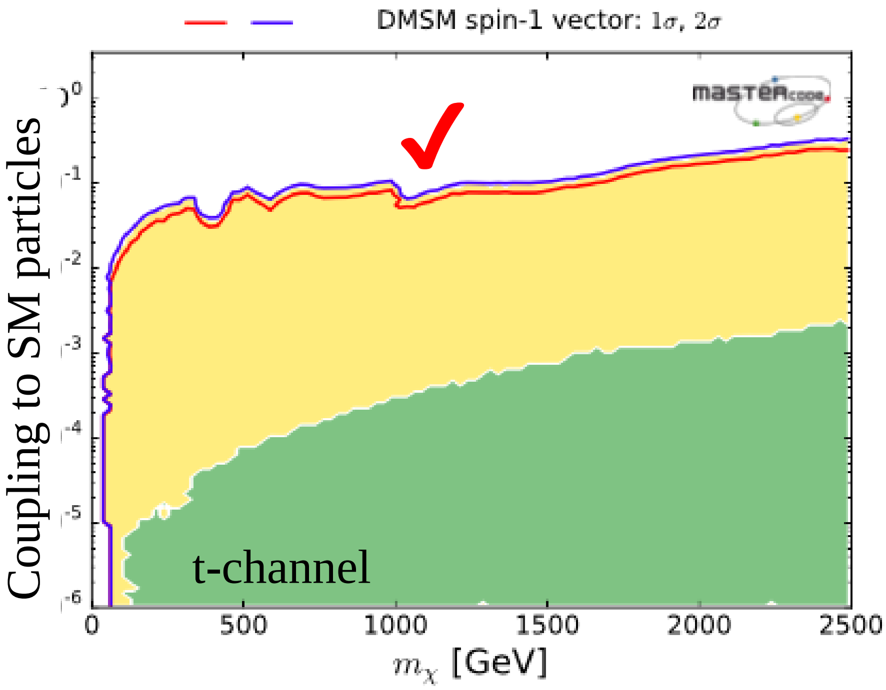


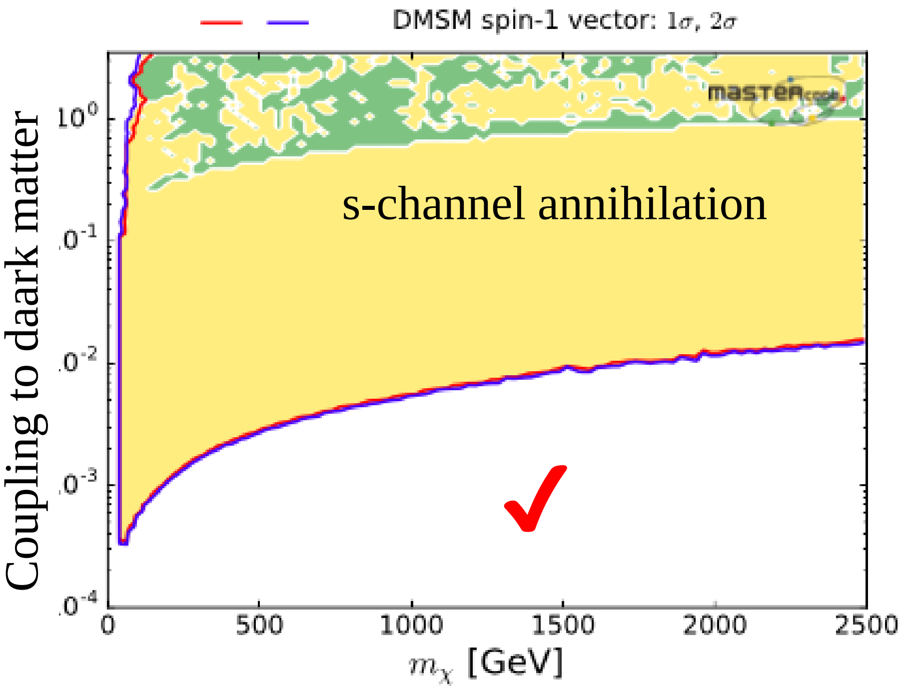
Mediator masses between 100 GeV and > 5 TeV allowed

Bagnaschi, …, JE et al, arXiv:1905.00892

Dark Matter Simplified Models

Leptophobic vector mediator





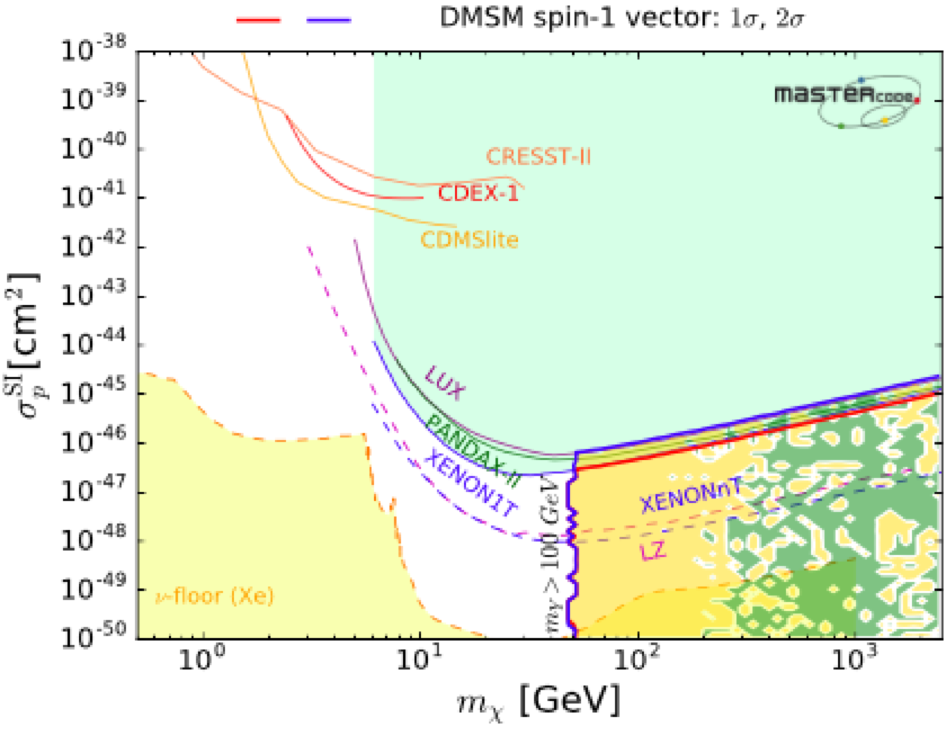
DM particle masses between 50 GeV and > 2.5 TeV allowed

Bagnaschi, …, JE et al, arXiv:1905.00892

Dark Matter Simplified Models

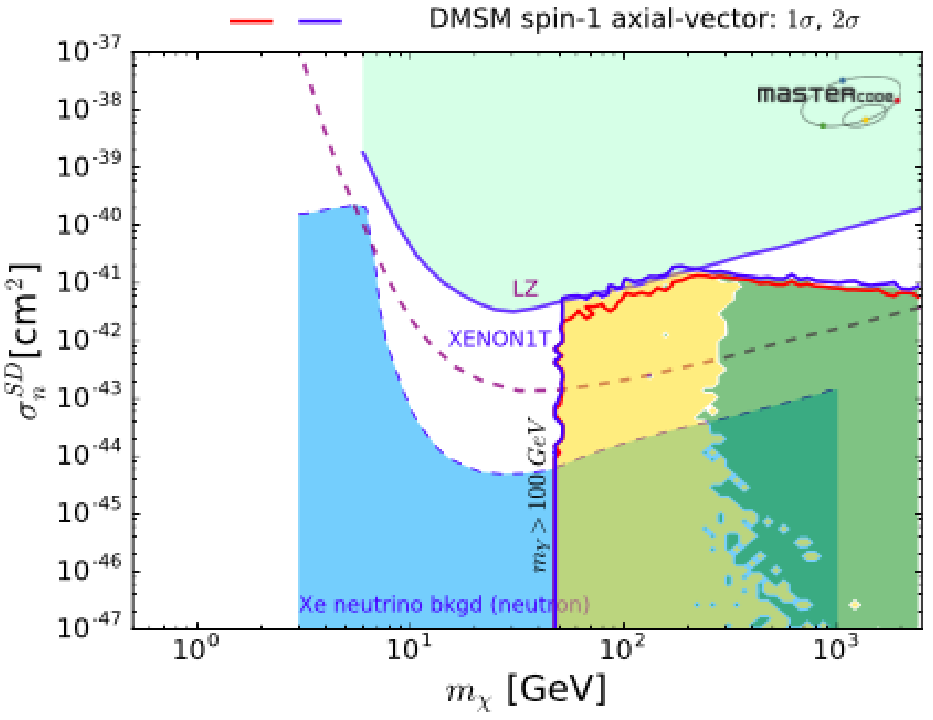
Leptophobic vector mediator

Spin-independent scattering



Leptophobic axial mediator

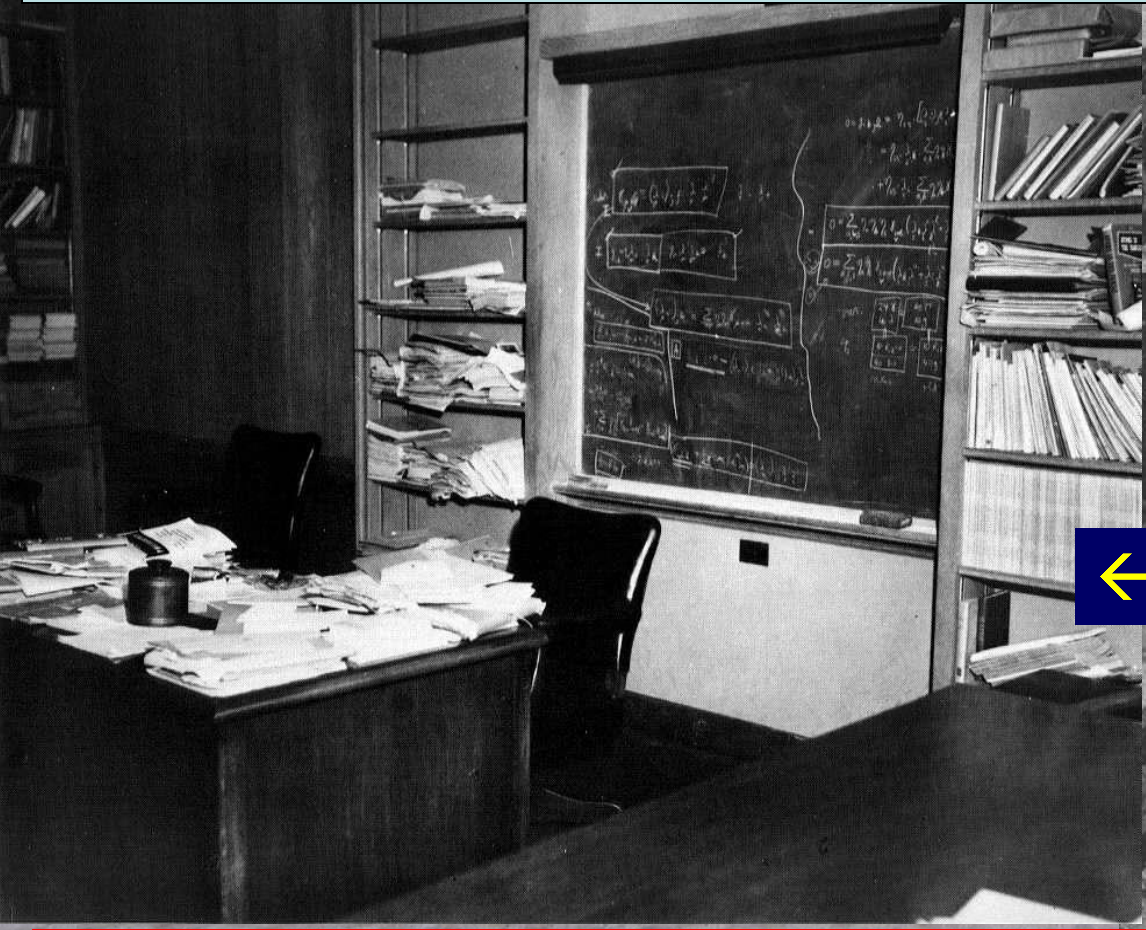
Spin-dependent scattering

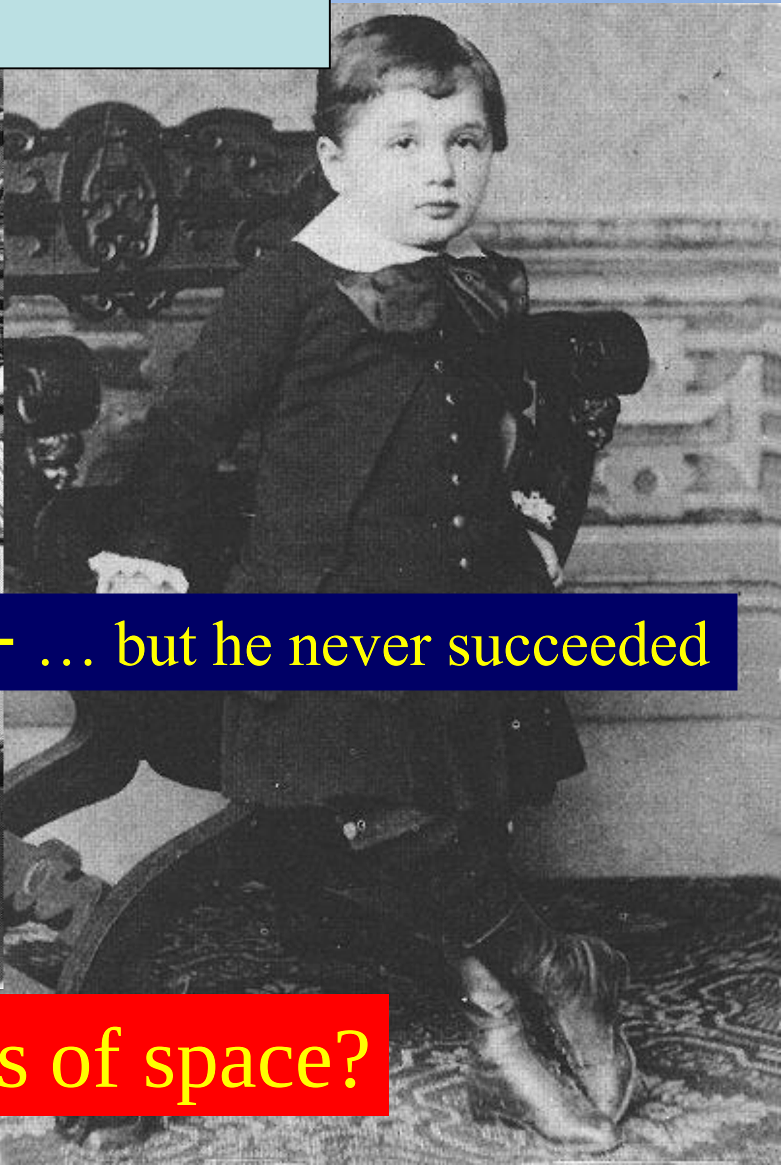


Scattering could be close to experimental limits

Bagnaschi, …, JE et al, arXiv:1905.00892

Unify the Fundamental Interactions:
Einstein’s Dream …

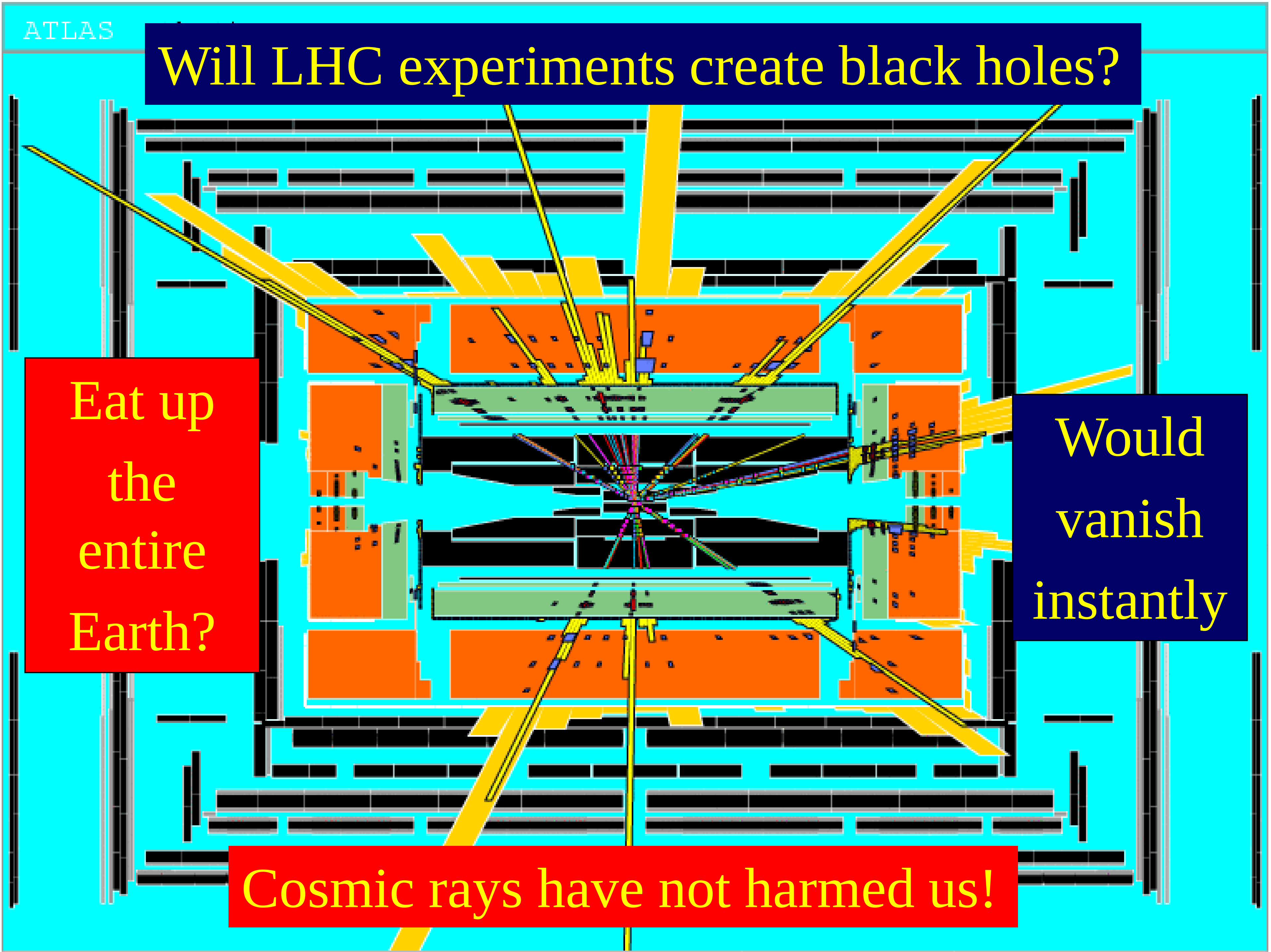




← … but he never succeeded

Unification via extra dimensions of space?

Will LHC experiments create black holes?



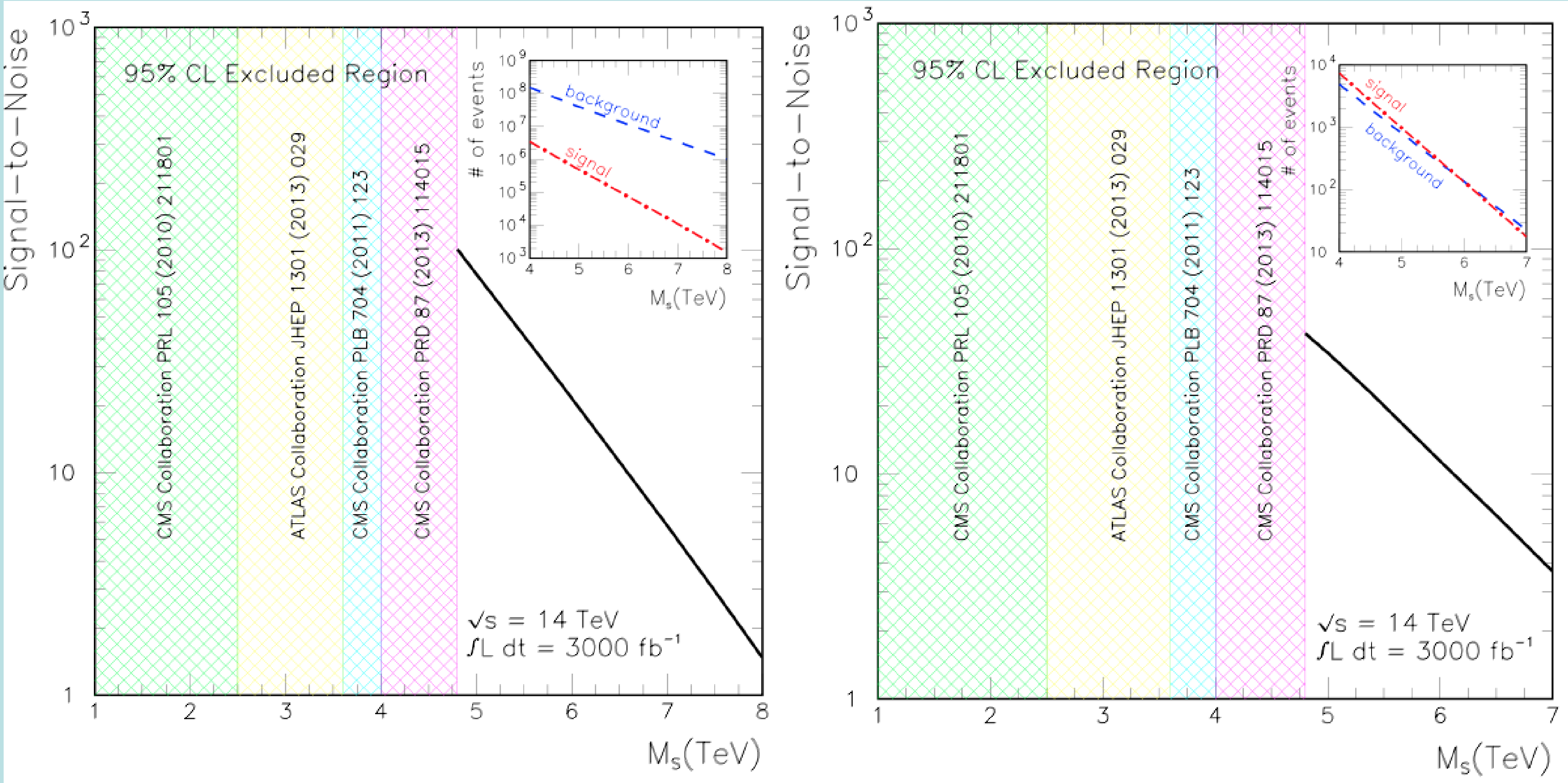
Eat up the entire Earth?

Would vanish instantly

Cosmic rays have not harmed us!

String Bump Hunting @ LHC

- Look for string recurrences in jets, γ + jets



Anchordoqui, Antoniadis, Dai, Feng, Goldberg,Huang, Lust, Stojkovic, Taylor, arXiv:1407.8120

How to get there from here?

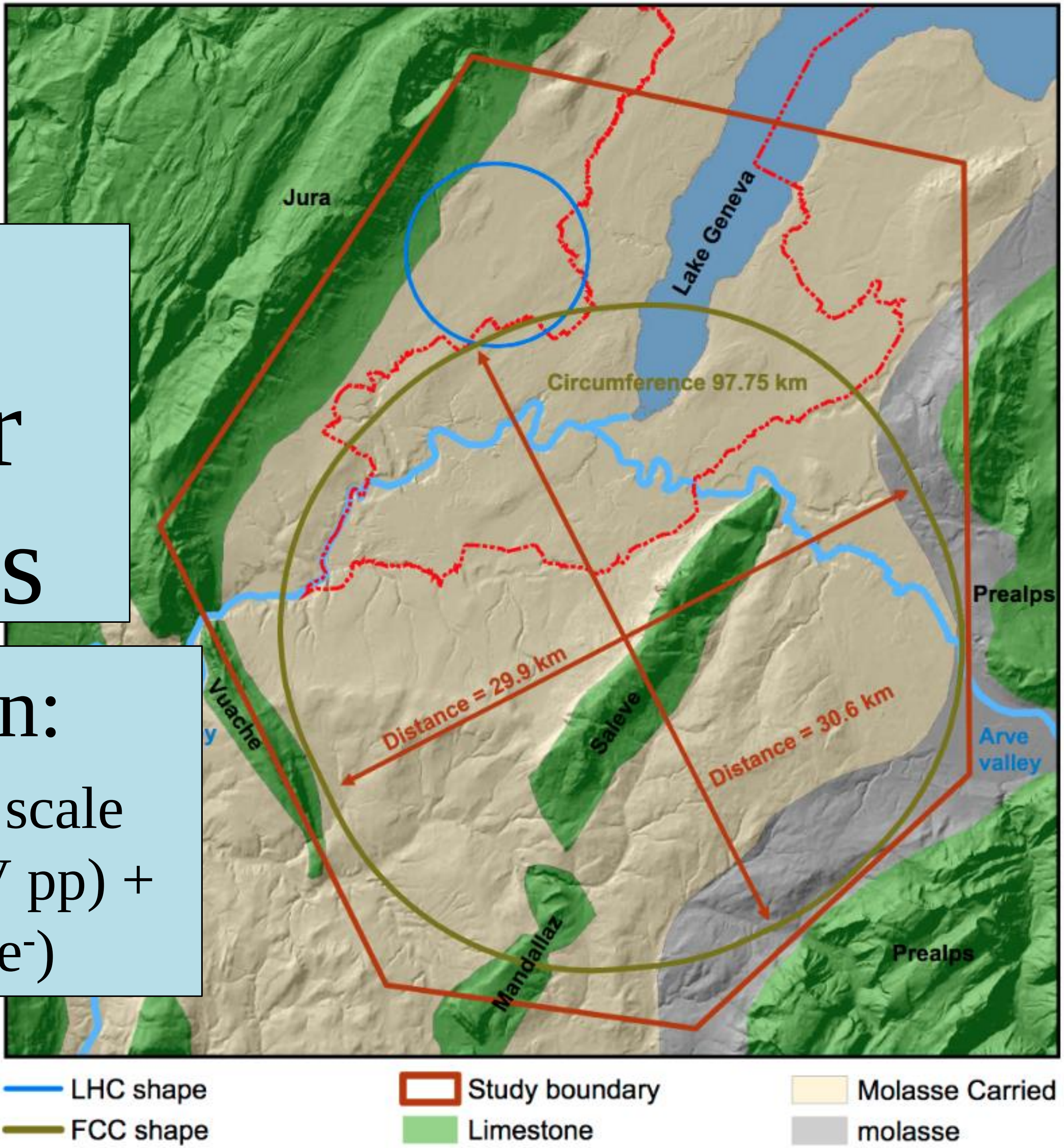
Future Circular Colliders

The vision:

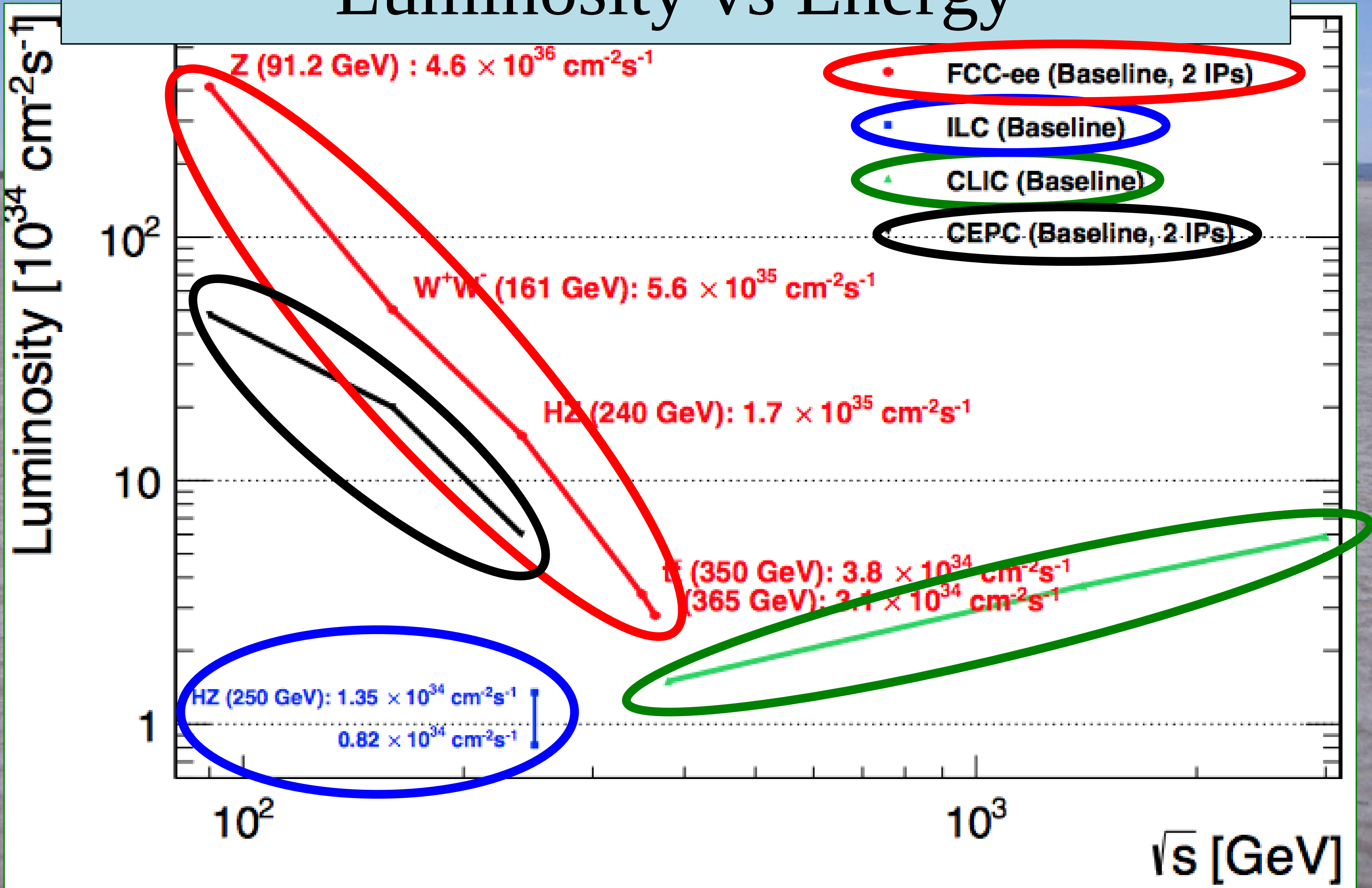
explore 10 TeV scale directly (100 TeV pp) + indirectly (e^+e^-)

CEPC-SPPC

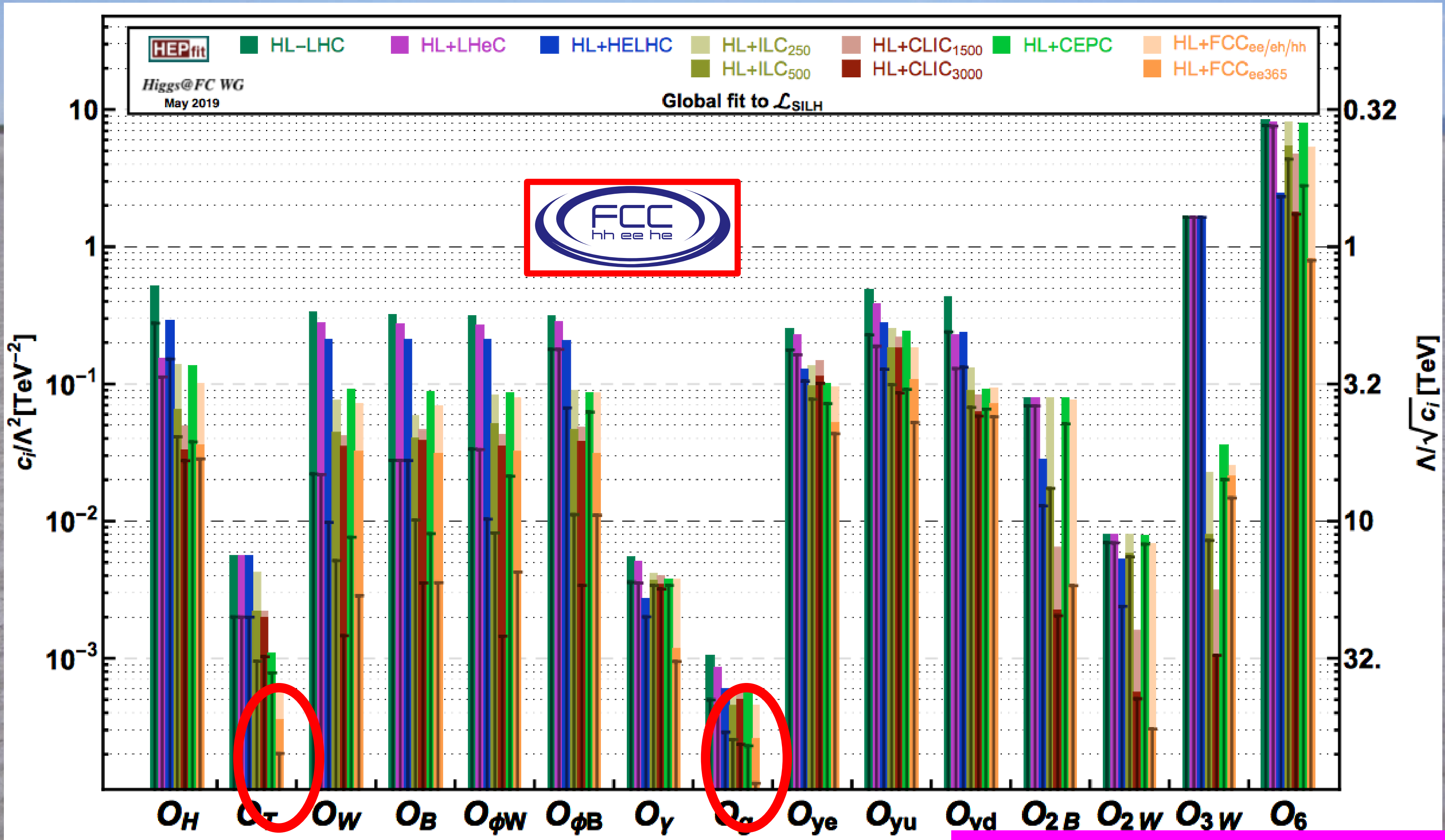
Preliminary Conceptual Design Report



Projected e^+e^- Colliders: Luminosity vs Energy



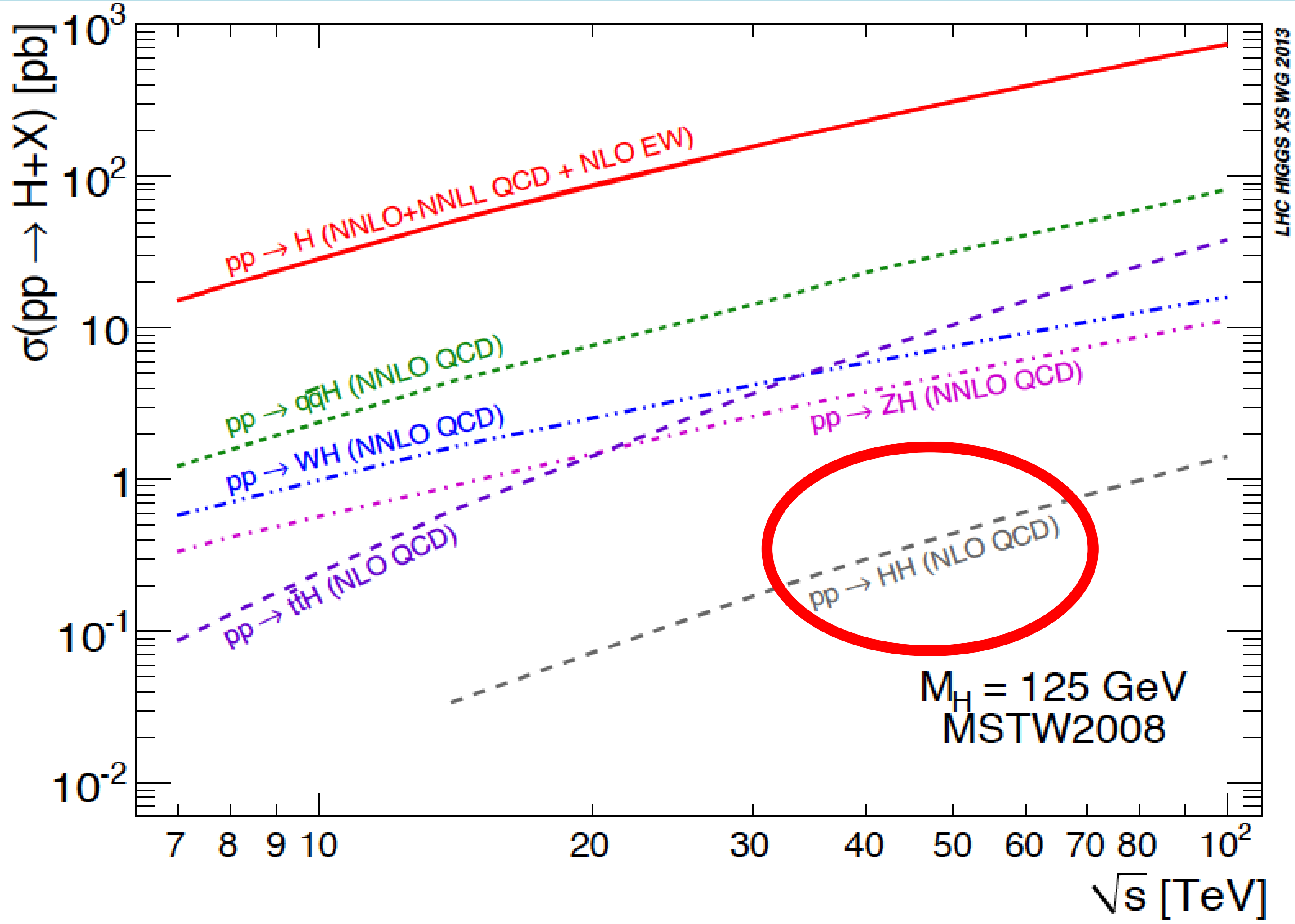
SMEFT Analysis



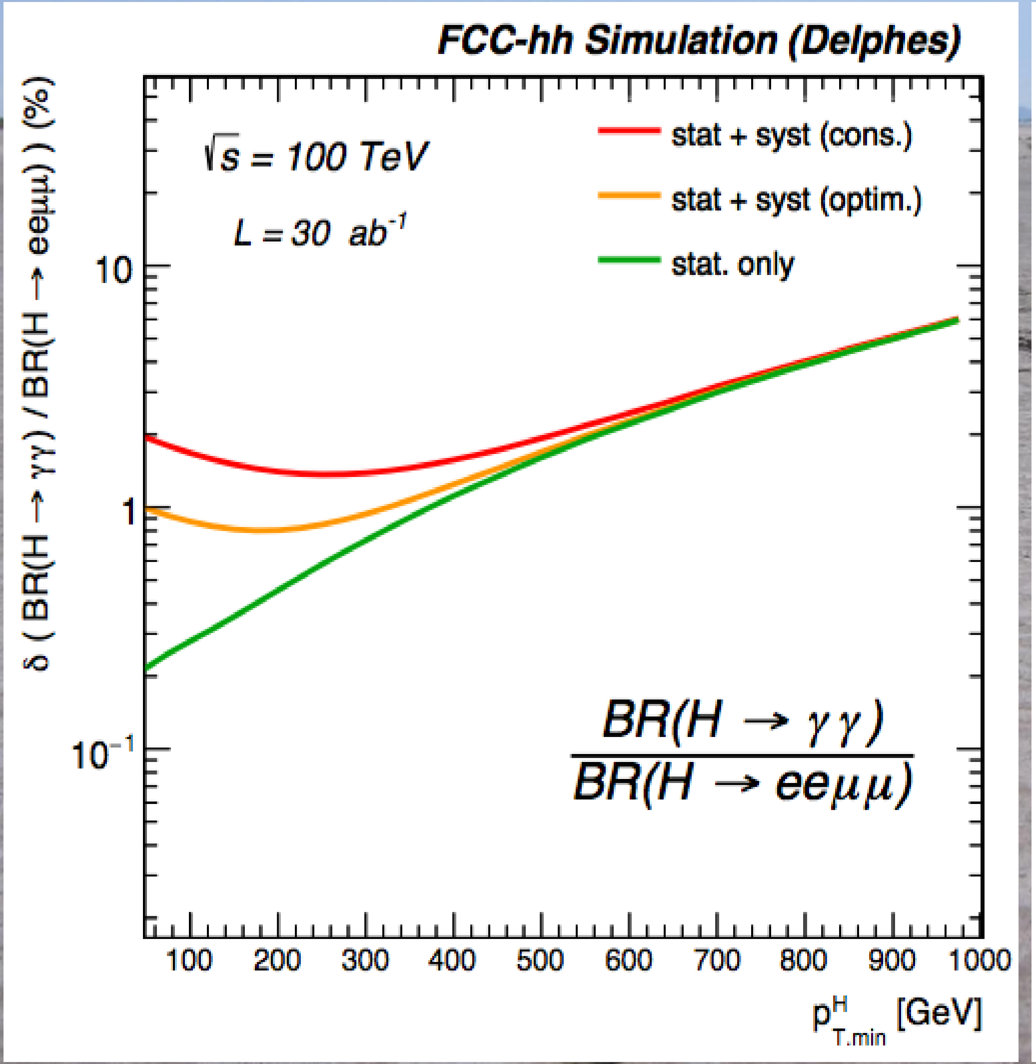
De Blas et al, arXiv:1905.03764

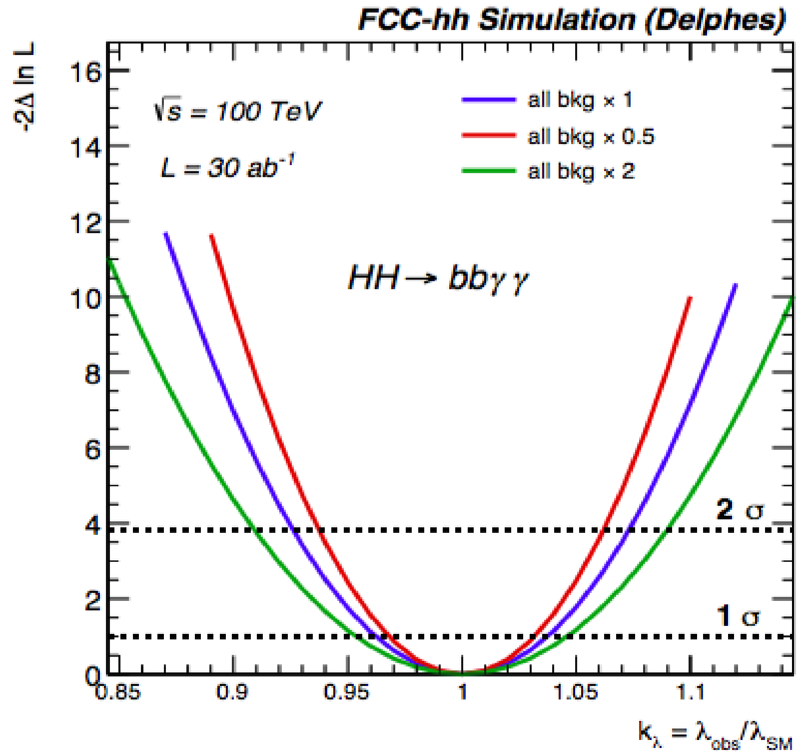
Higgs Cross Sections

- At the LHC and beyond:



Examples of Higgs Measurements

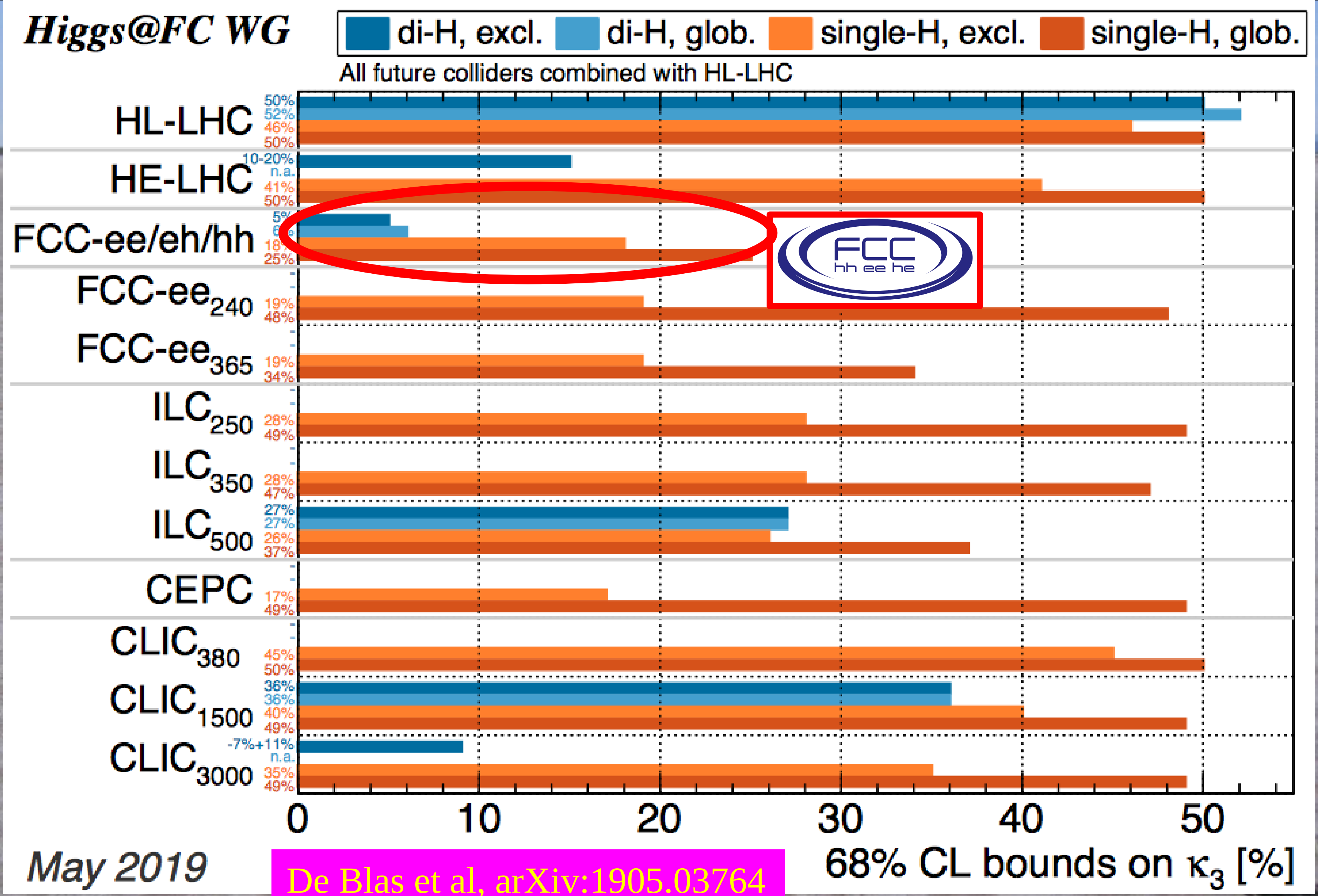




varying (0.5x-2x) background yields:

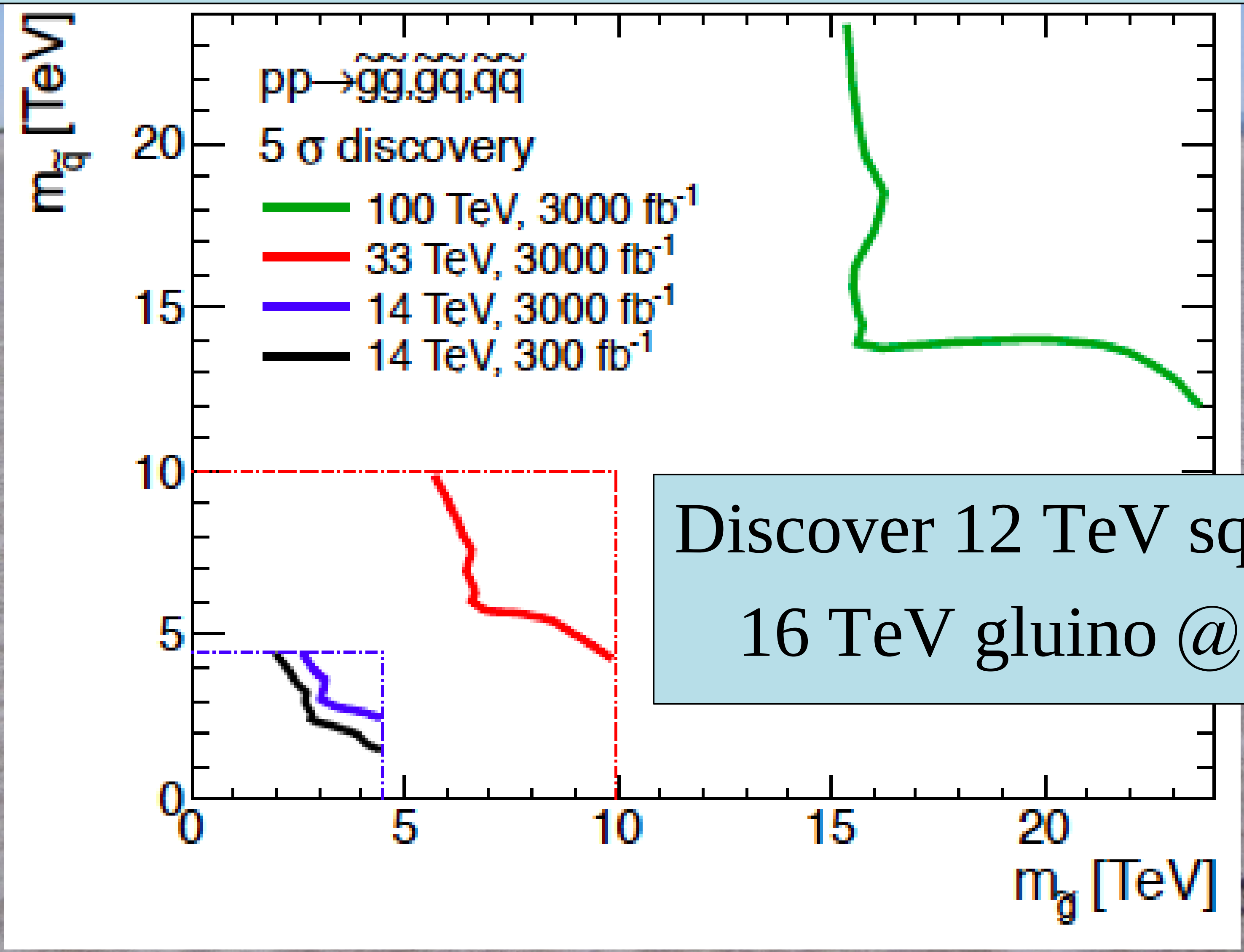
$\delta\kappa_\lambda$(stat) ≈ 3 - 5 %
δr(stat) ≈ 2 - 3%

Triple-Higgs Coupling Analysis



De Blas et al, arXiv:1905.03764

Squark-Gluino Plane



Discover 12 TeV squark,

16 TeV gluino @ 5σ

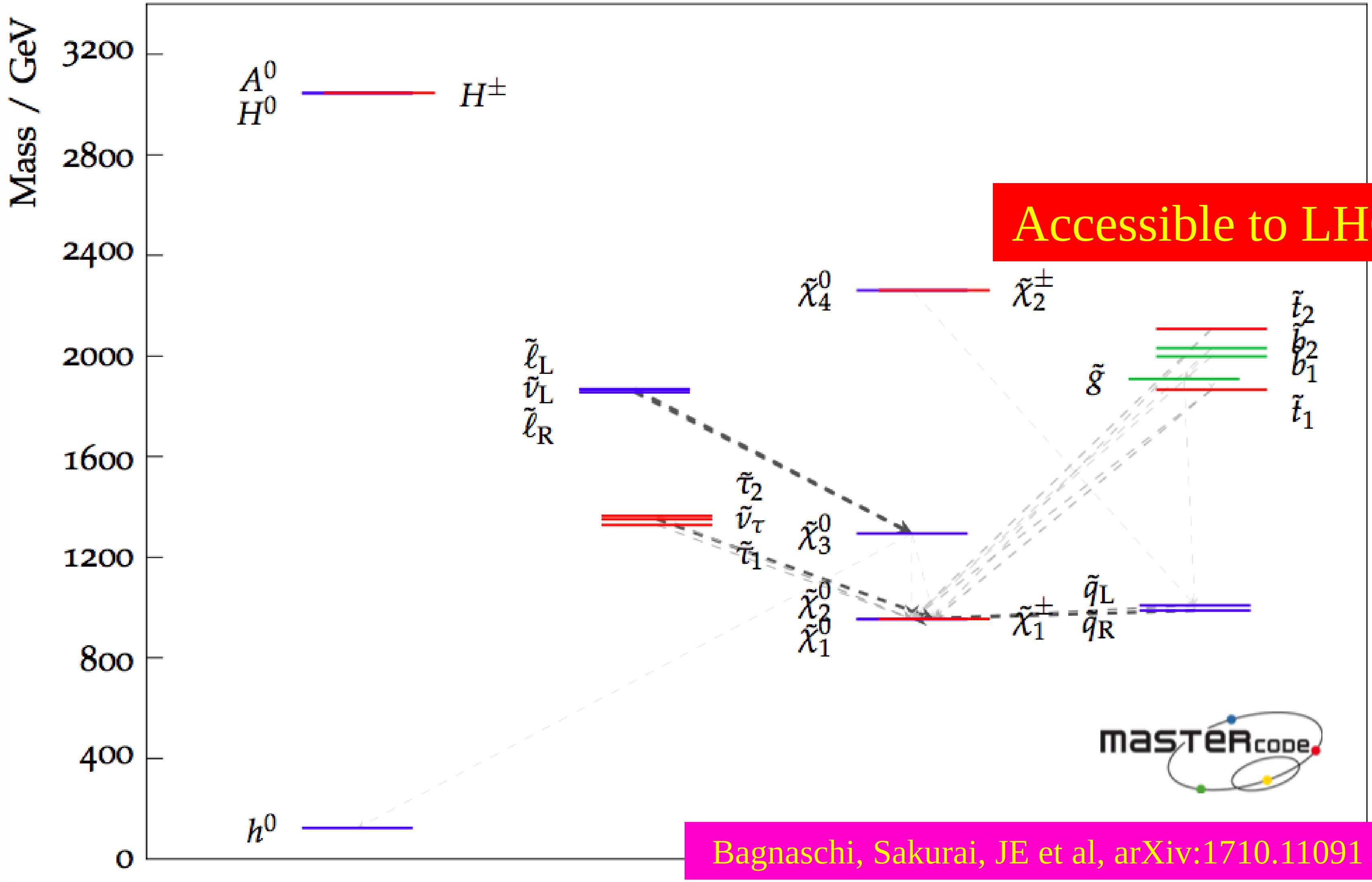
How to get there from here?

Go around in circles!

Best-Fit Sparticle Spectrum

Phenomenological MSSM

Fit excluding g_μ-2



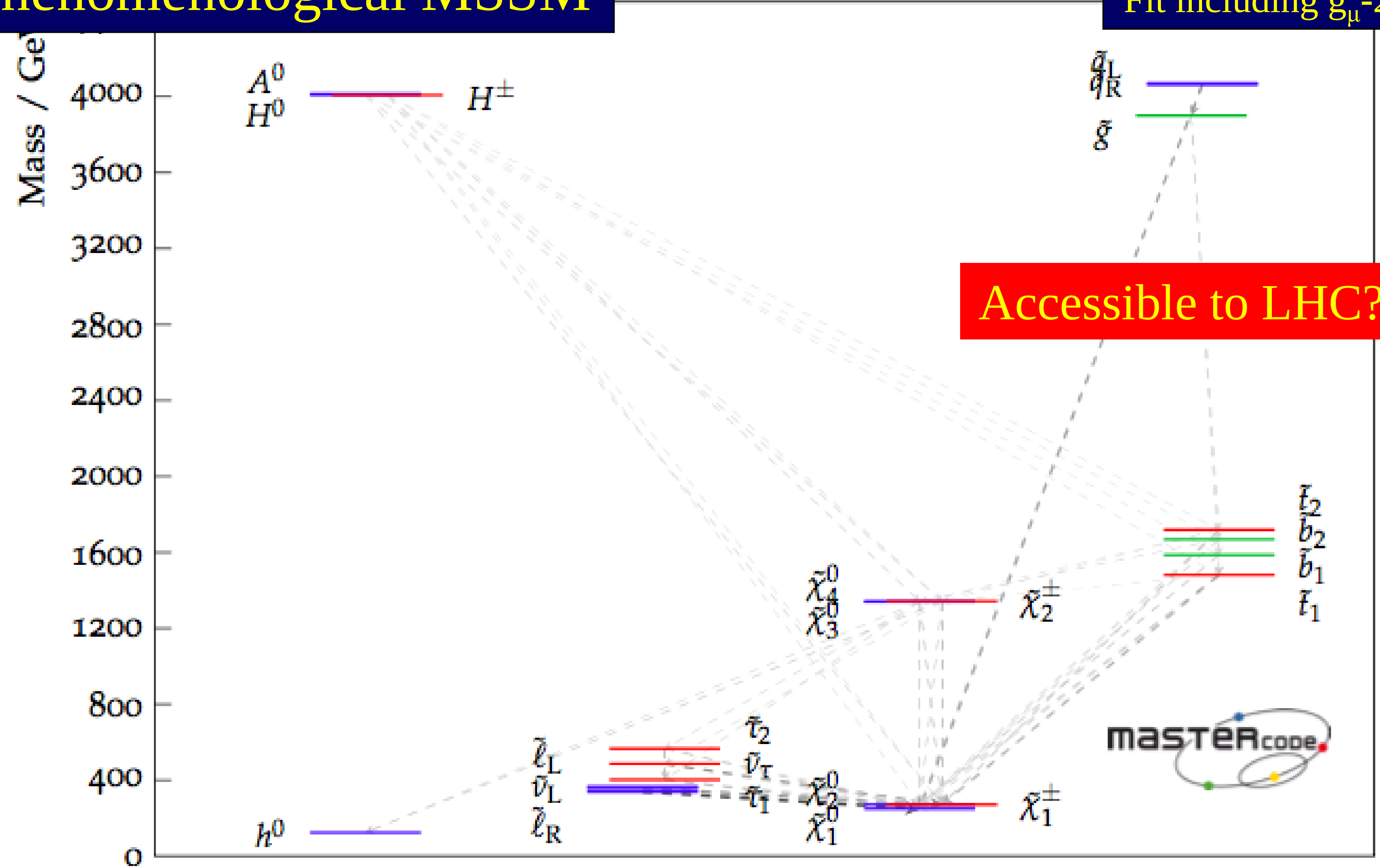
Accessible to LHC?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Best-Fit Sparticle Spectrum

Phenomenological MSSM

Fit including g_μ-2

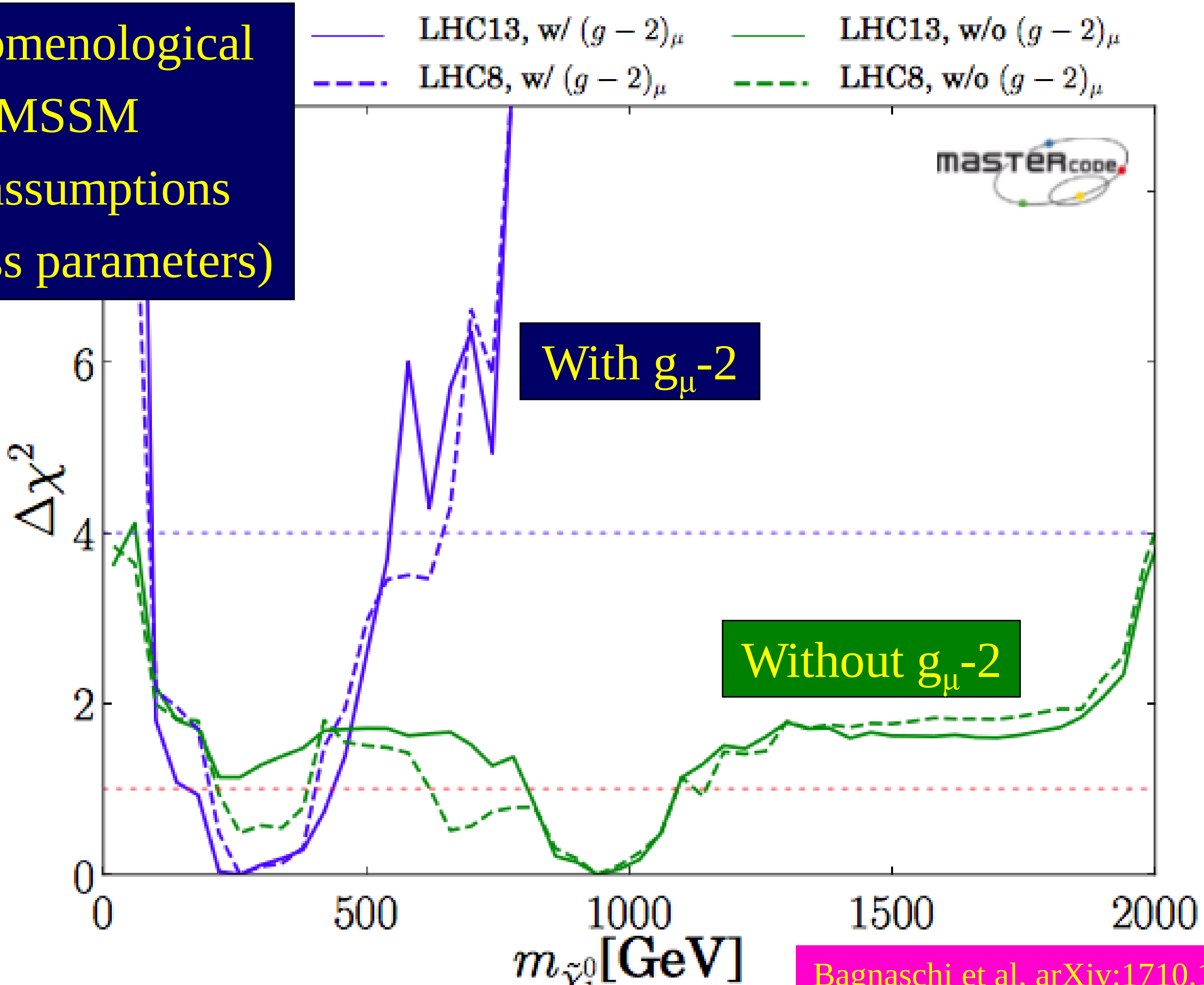


Accessible to LHC?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Likelihood for LSP Mass

Phenomenological MSSM
(no assumptions
on mass parameters)



With g_μ-2

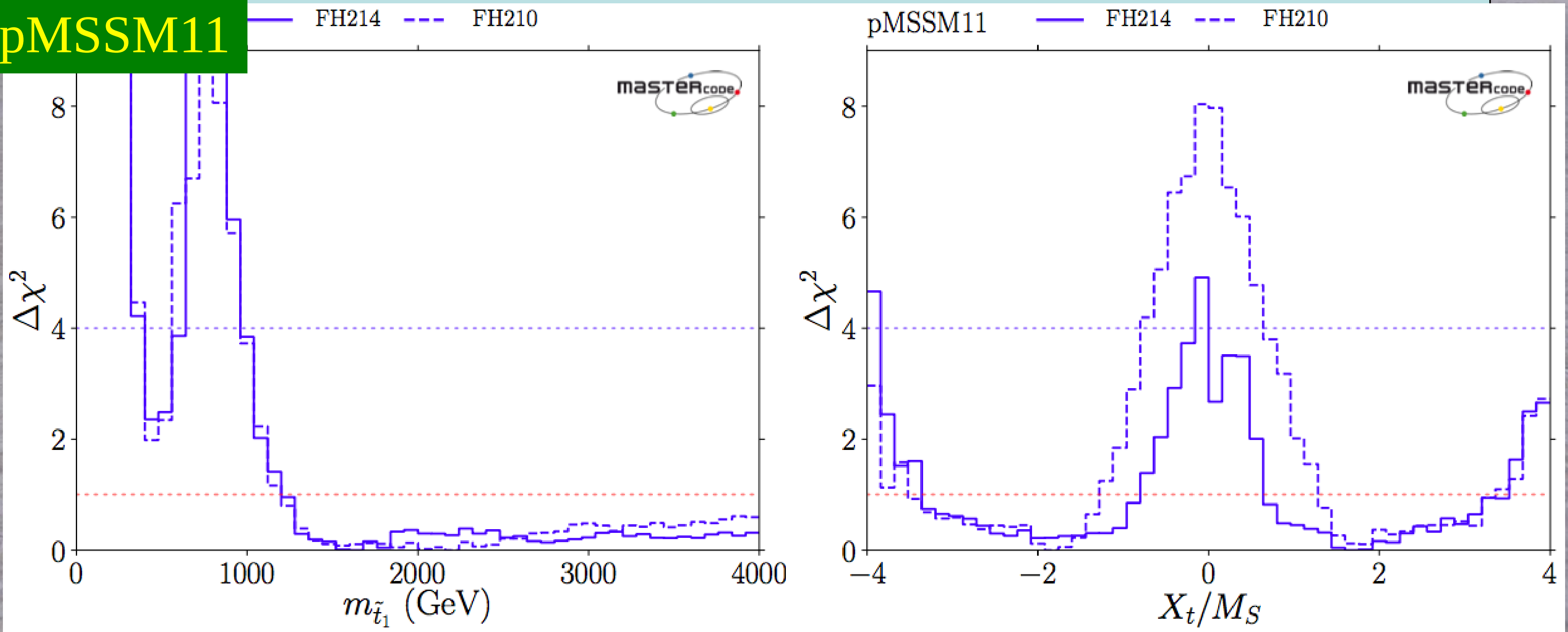
Without g_μ-2

Bagnaschi et al. arXiv:1710.11091

The Lighter Stop may be Light

- χ^2 likelihood functions for m_{stop}, stop mixing

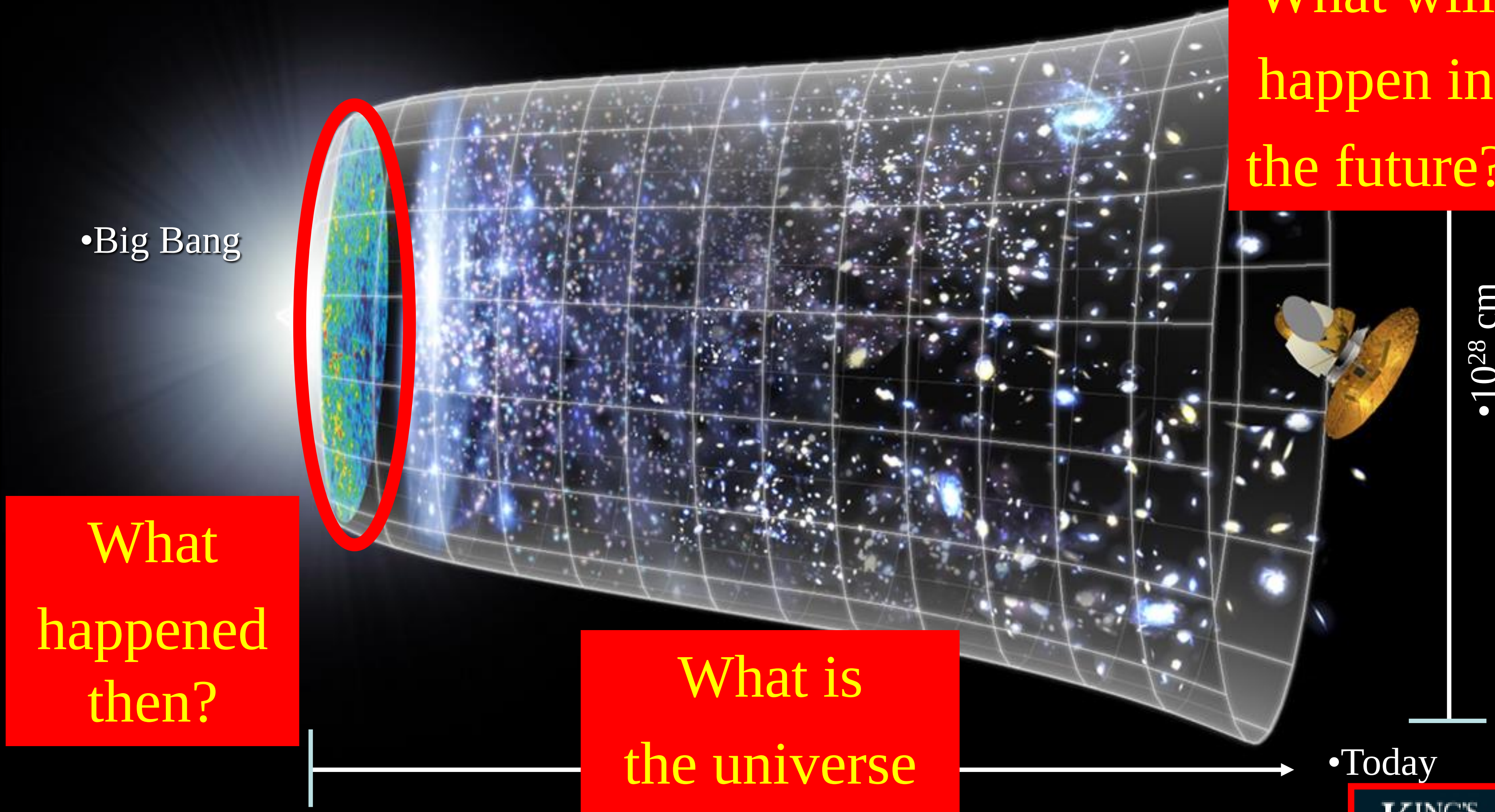
pMSSM11



- **$M_{stop} < 500$ GeV allowed with $\Delta\chi^2 \sim 2$**

Bagnaschi, Bahl, JE et al, arXiv:1810.10905

From Little Bangs to the Big Bang



- Big Bang

What will happen in the future?

- 10^{28} cm

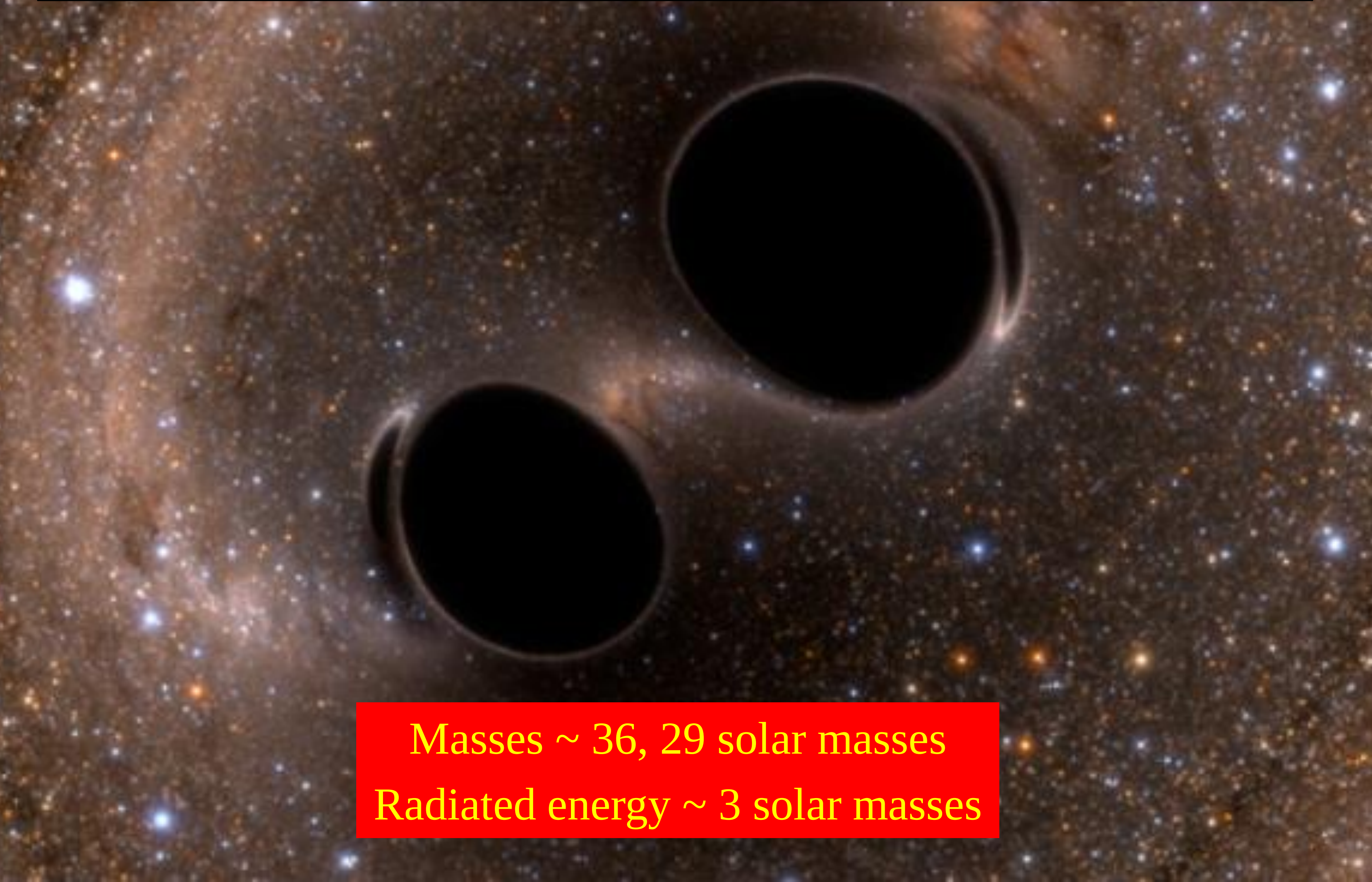
What happened then?

What is the universe made of?

- Today

John Ellis

Fusion of two massive black holes



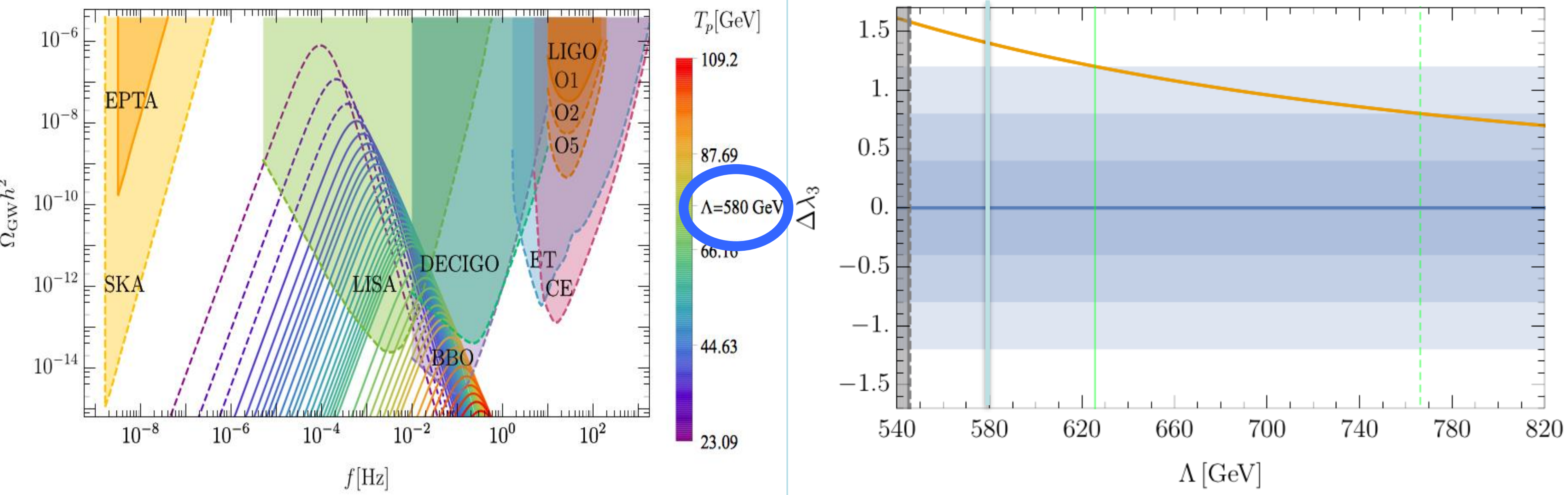
Masses ~ 36, 29 solar masses

Radiated energy ~ 3 solar masses

Remark on Primordial Gravitational Waves

Generated by first-order electroweak phase transition

Observable if $|\Phi|^6/\Lambda^2$, Λ small, also at HL-LHC



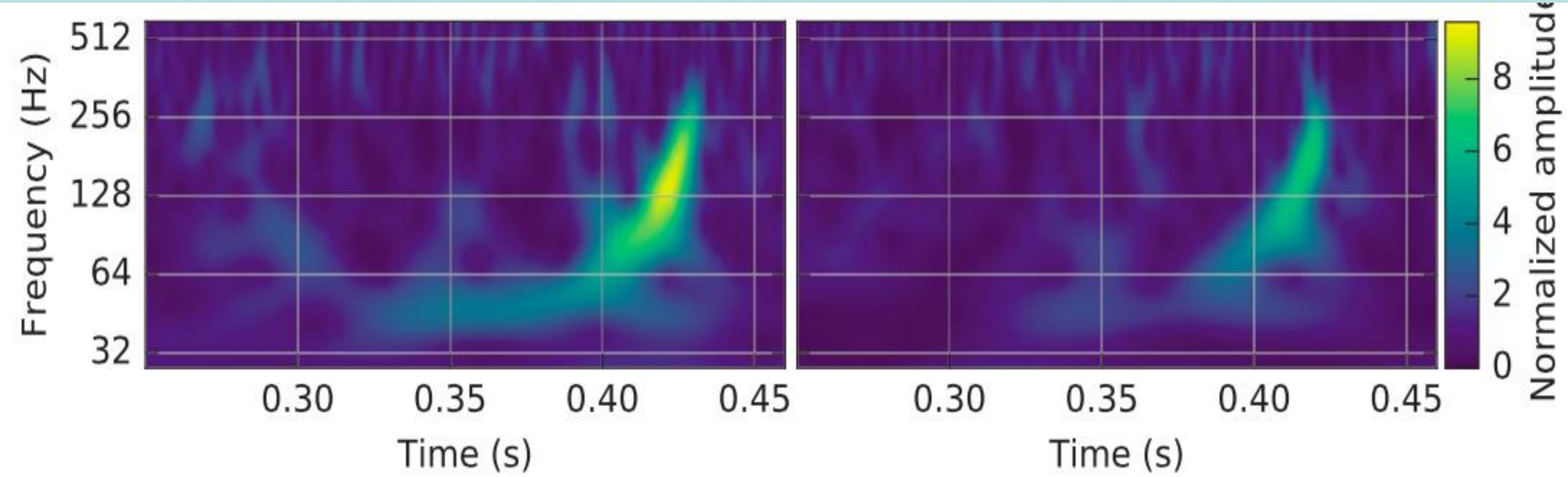
Reach of HL-LHC: **625 GeV @ 3σ, 766 GeV 2σ**

Reach of LISA: **580 GeV**

JE, Lewicki & No, arXiv:1809.08242

The Gravitational Chirp …

- … heard around the world

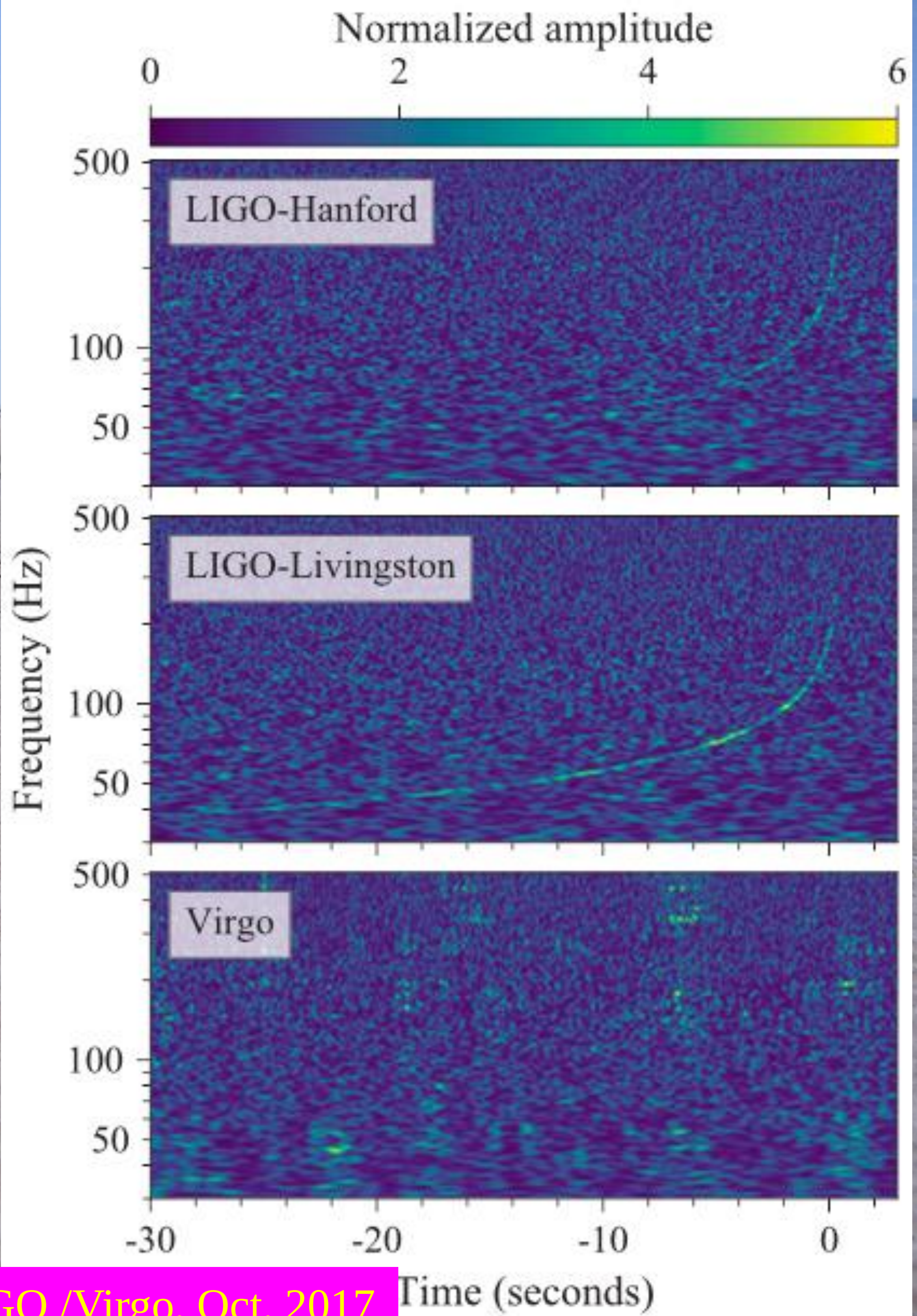


- Frequency increases with time during inspiral
- Followed by ringdown of combined black hole
- Graviton mass < 10^{-27} × mass of electron LIGO
- GWs of different frequencies have same speed

JE, Mavromatos & Nanopoulos, arXiv:1602.04764

Neutron Star Merger GW170817

- Longer chirp, extending to higher frequencies
- Masses < 2 solar masses
- 2 neutron stars!
- Constraints on properties
- Weak signal in Virgo helps localization
- Electromagnetic counterpart seen in detail



LIGO /Virgo, Oct. 2017

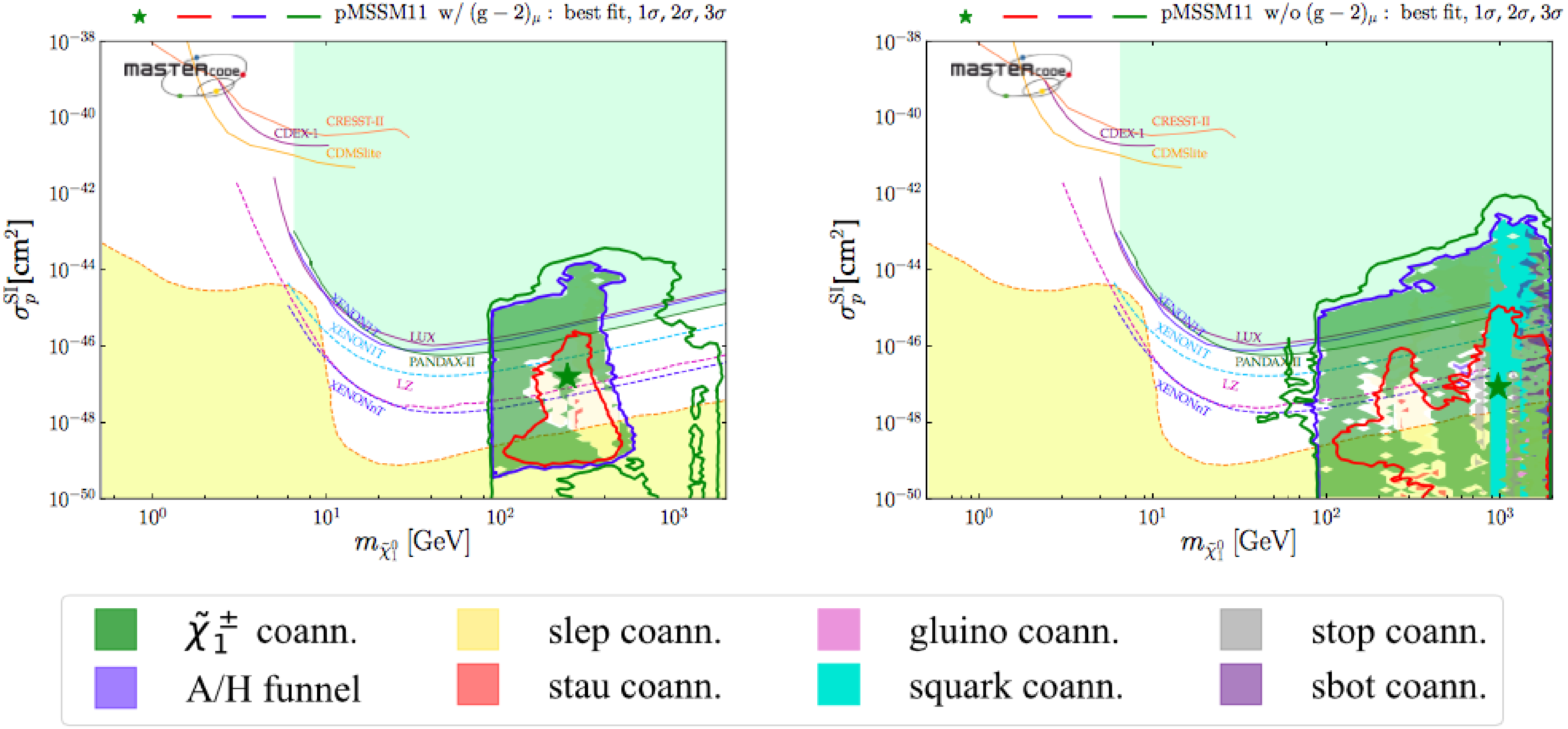
Direct Dark Matter Searches

Phenomenological MSSM

Spin-Independent Scattering

With g_μ-2

Without g_μ-2



Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

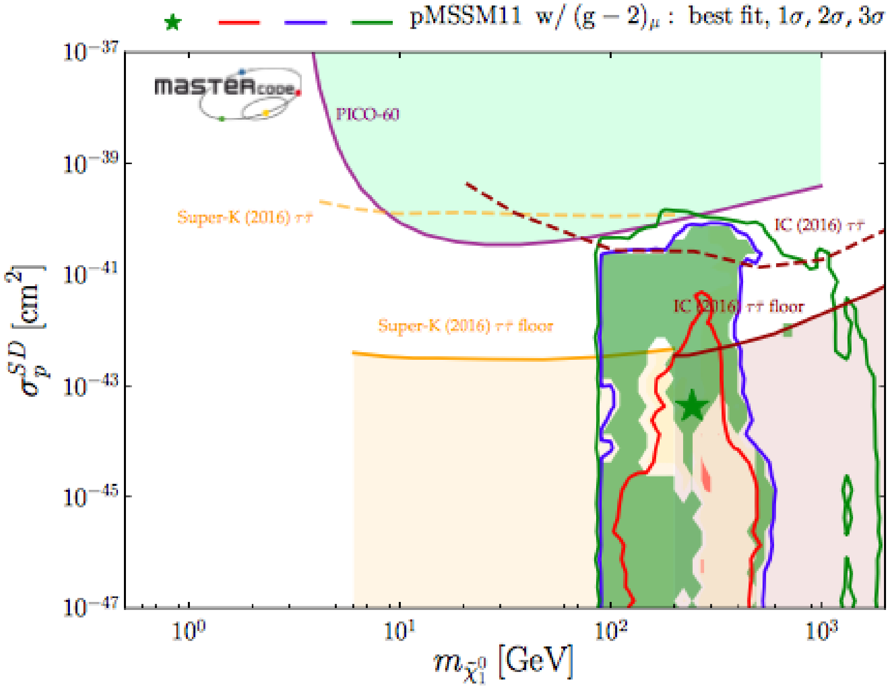
Direct Dark Matter Searches

Phenomenological MSSM

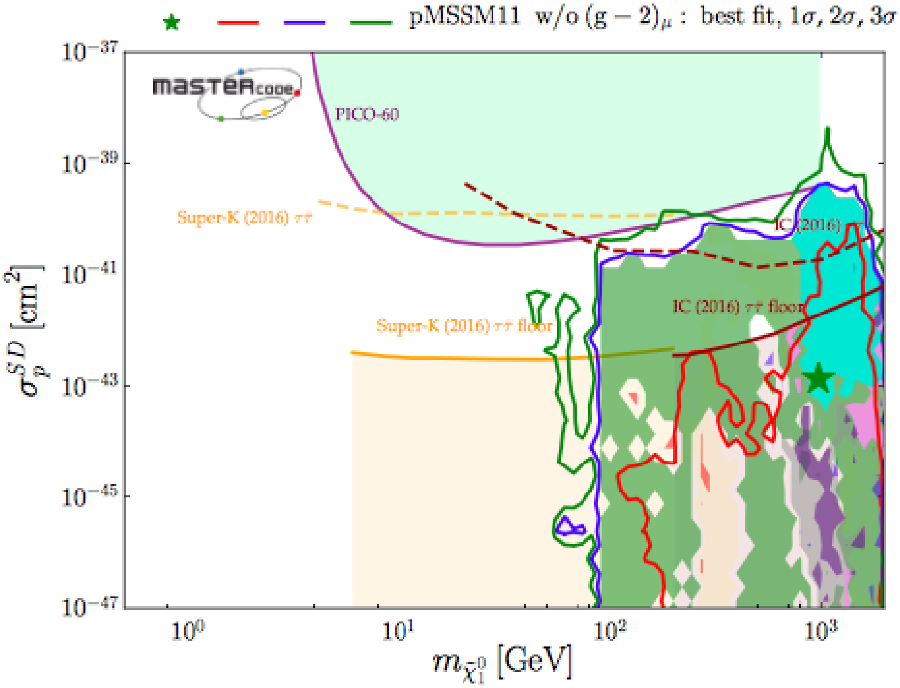
Spin-Dependent Scattering

sensitive to quark contributions to nucleon spin

With g_μ-2



Without g_μ-2



🟩	$\tilde{\chi}_1^\pm$ coann.	🟨	slep coann.	🟪	gluino coann.	⬜	stop coann.
🟪	A/H funnel	🟥	stau coann.	🟦	squark coann.	🟪	sbot coann.

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

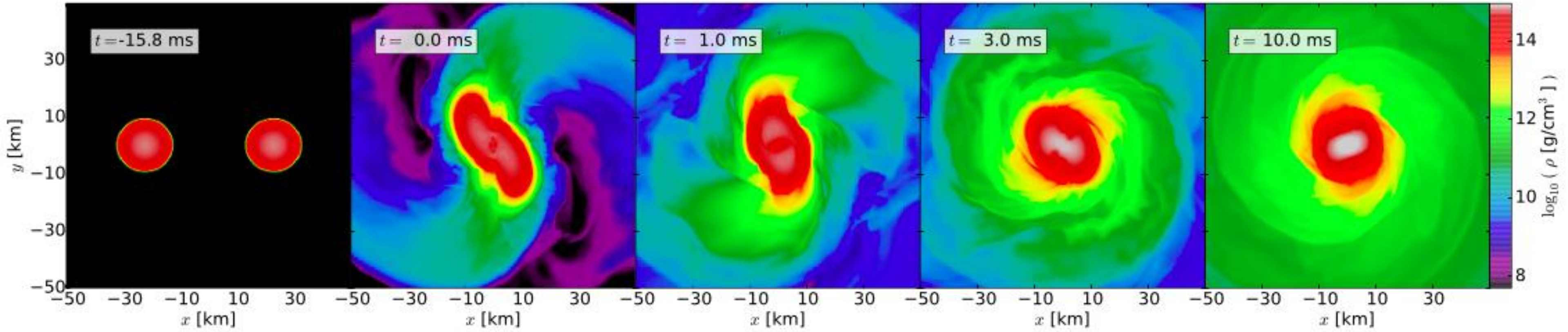
Search for Dark Matter in NS-NS Mergers?

Crazy ideas for dark matter signatures

JE, Hektor, Hütsi, Kannike, Marzola, Raidal & Vaskonen, arXiv:1710.05540

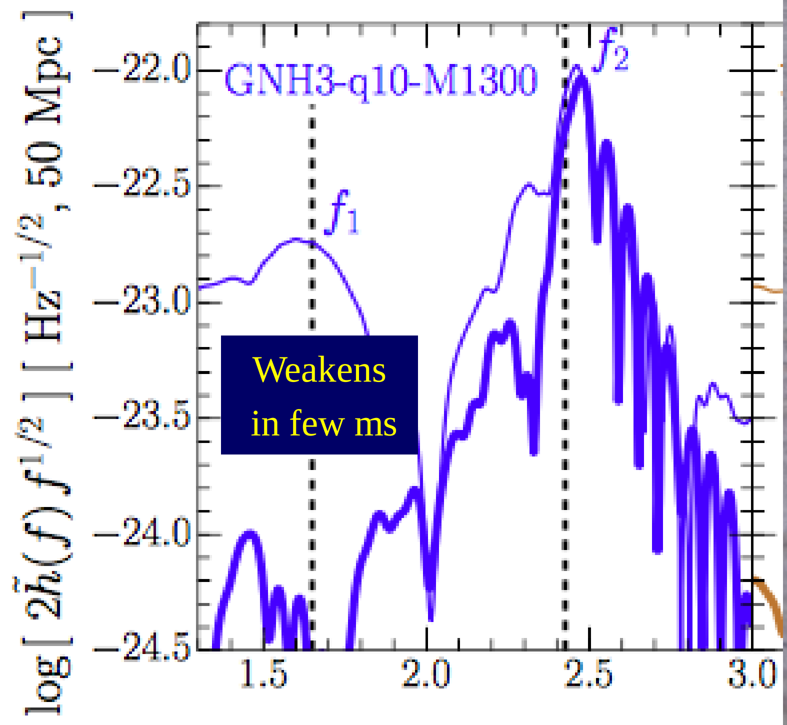
JE, Hütsi, Kannike, Marzola, Raidal & Vaskonen, arXiv:1804.01418

What Happens after the Merger?

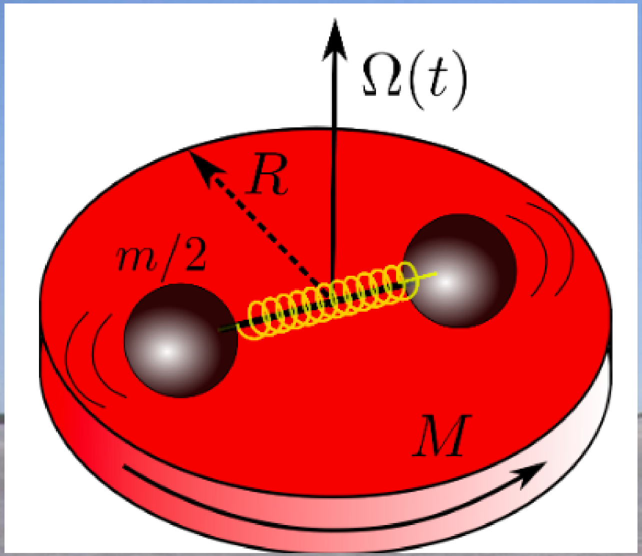


- NS cores orbit and oscillate radially during ringdown
- Characteristic spectrum of frequencies in GW emissions
- Frequency peaks at stationary points in oscillations

Takami, Rezzolla & Baiotti, arXiv:1403.56720, 1412.3240

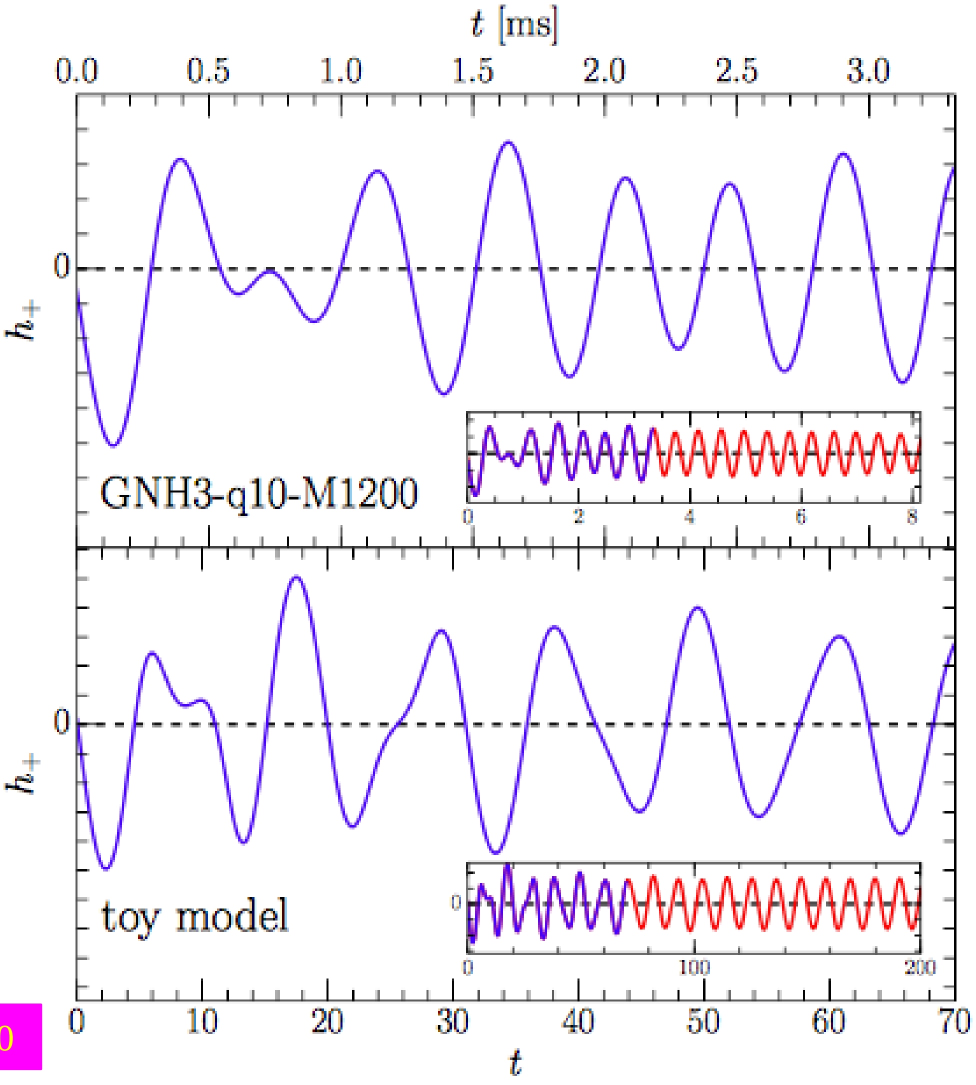


Weakens in few ms

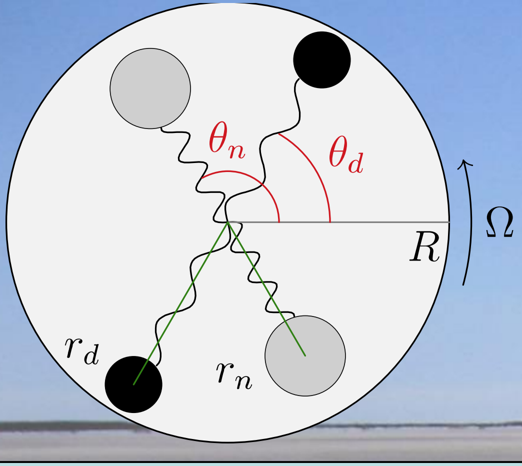


Toy Mechanical Model

- Neutron cores oscillate and rotate inside disc
- Captures surprisingly well major features of strain fluctuations



Takami, Rezzolla & Baiotti, arXiv:1403.56720, 1412.3240

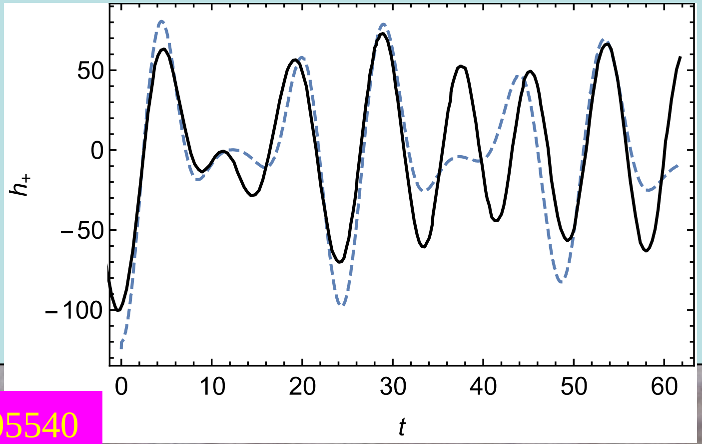


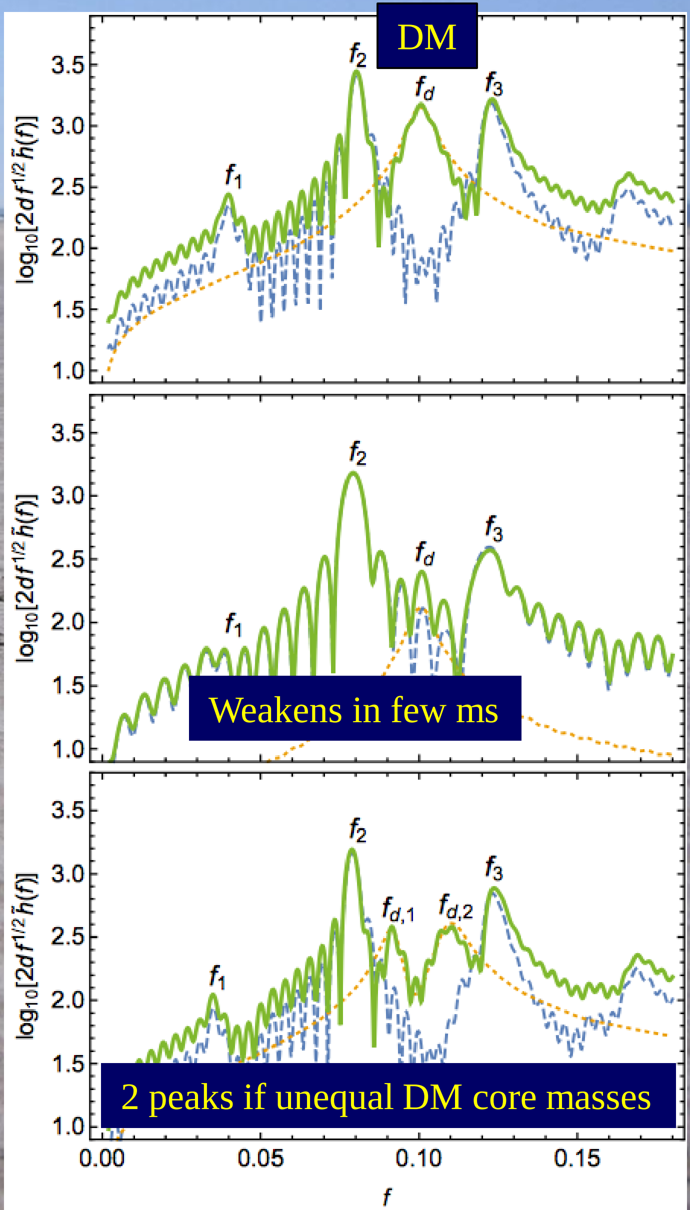
Including Dark Matter

- Two pairs of oscillating cores

$$L = \frac{m_n}{2}\left(\dot{r}_n^2 + \left(r_n\dot{\theta}_n\right)^2\right) + \frac{m_d}{2}\left(\dot{r}_d^2 + \left(r_d\dot{\theta}_d\right)^2\right) + \frac{MR^2\dot{\theta}_n^2}{4} + 2k_n(r_n - a_n)^2 + 2k_d(r_d - a_d)^2 ,$$

- Reproduce results when no DM





DM

Weakens in few ms

2 peaks if unequal DM core masses

EHHKMRV, arXiv:1710.05540

Models for Massive DM Cores

- Conversion of neutron to heavier DM particle inside NS: n on Fermi surface ➔ χ
- Bremsstrahlung of lighter DM particle:

$$n + n \rightarrow n + n + \chi$$

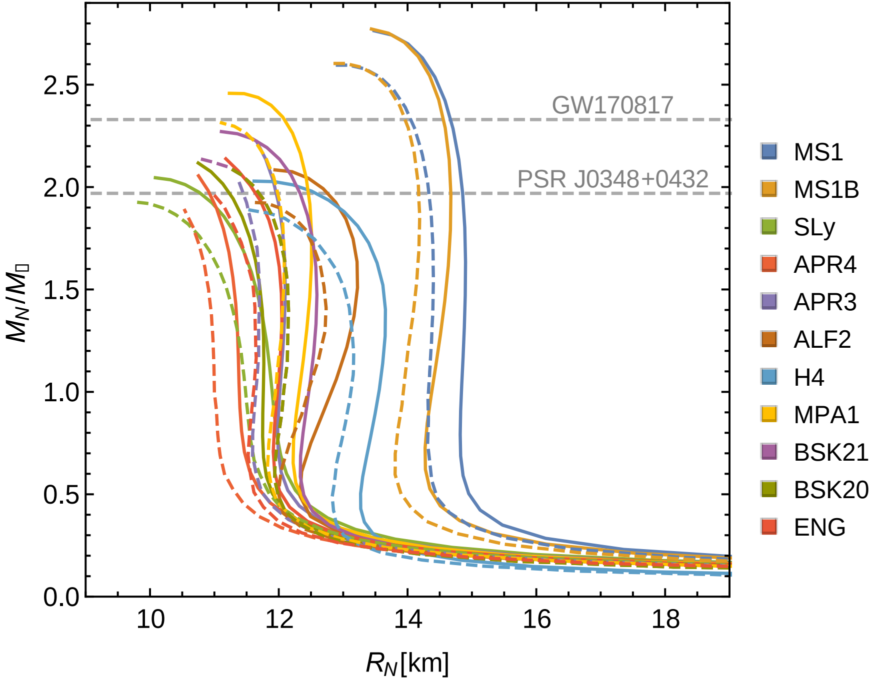
- DM mass fraction ~ 5% possible
- Merger of DM star with conventional star before/after becoming NS
- DM fraction may depend on age, environment

JE, Hütsi, Kannike, Marzola, Raidal & Vaskonen, arXiv:1804.01418

DM Effects on NS Properties

for various nuclear equations of state (EOS)

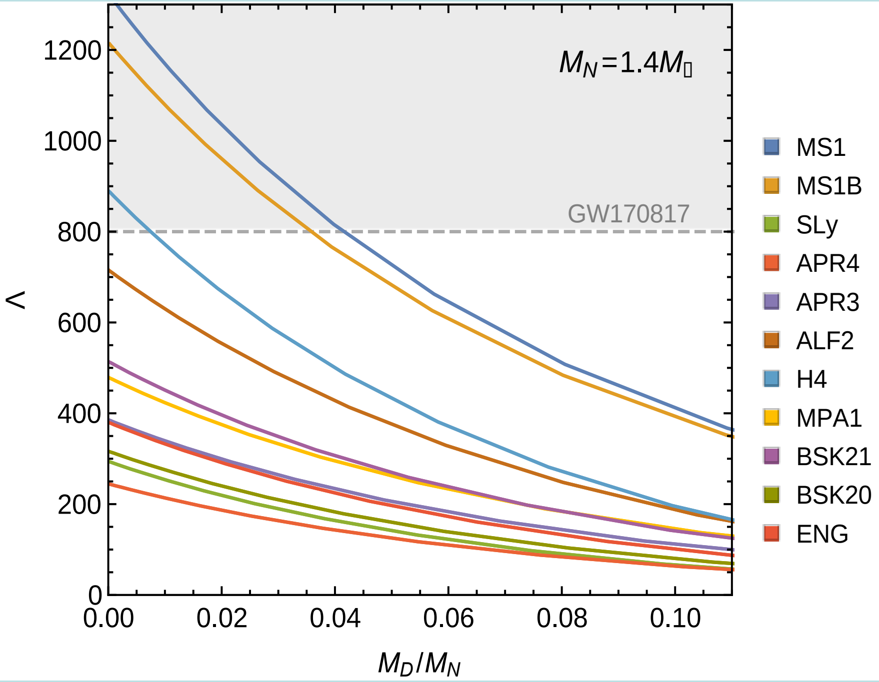
Effects on mass and radius



Maximum mass, radius decrease

Potential issue for some EOS

Effect on tidal deformability



Decrease in tidal deformability

Potential constraint on EOS

JE, Hütsi, Kannike, Marzola, Raidal & Vaskonen, arXiv:1804.01418

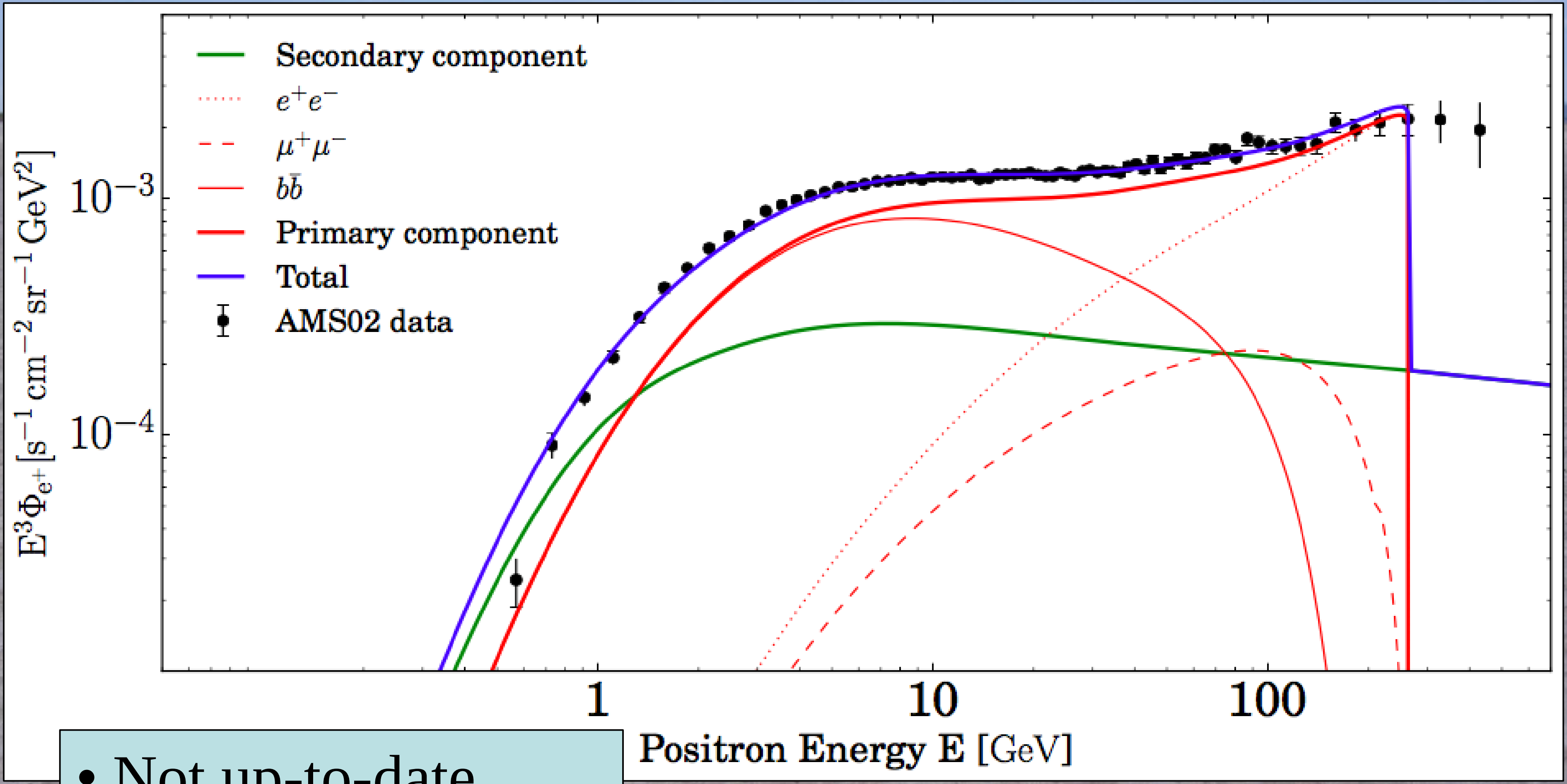
Summary

- The Big Bang raises many problems needing physics beyond the Standard Model
- Address them in smaller bangs:

– LHC	TeV
– Direct dark matter searches	keV
– Indirect dark matter searches	GeV
– CMB	10^{15} GeV ?
– Black hole and neutron star mergers	M_{Planck} ?

- ***"Per ardua ad astra" - By struggles to the stars***

Dark Matter Models for e^+ Spectrum

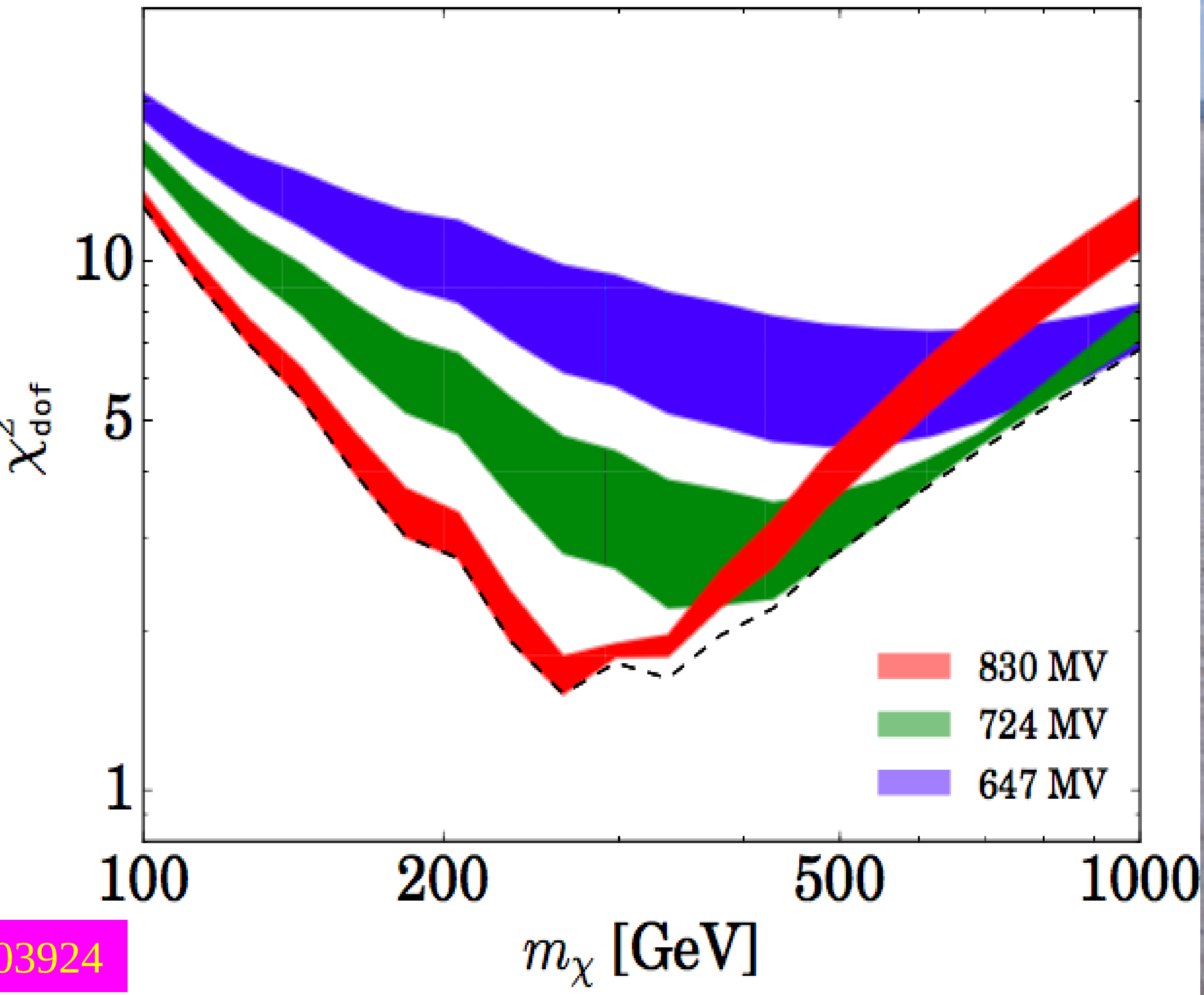


- Not up-to-date
- Illustrates problems

Boudeaud et al., arXiv:1612.03924

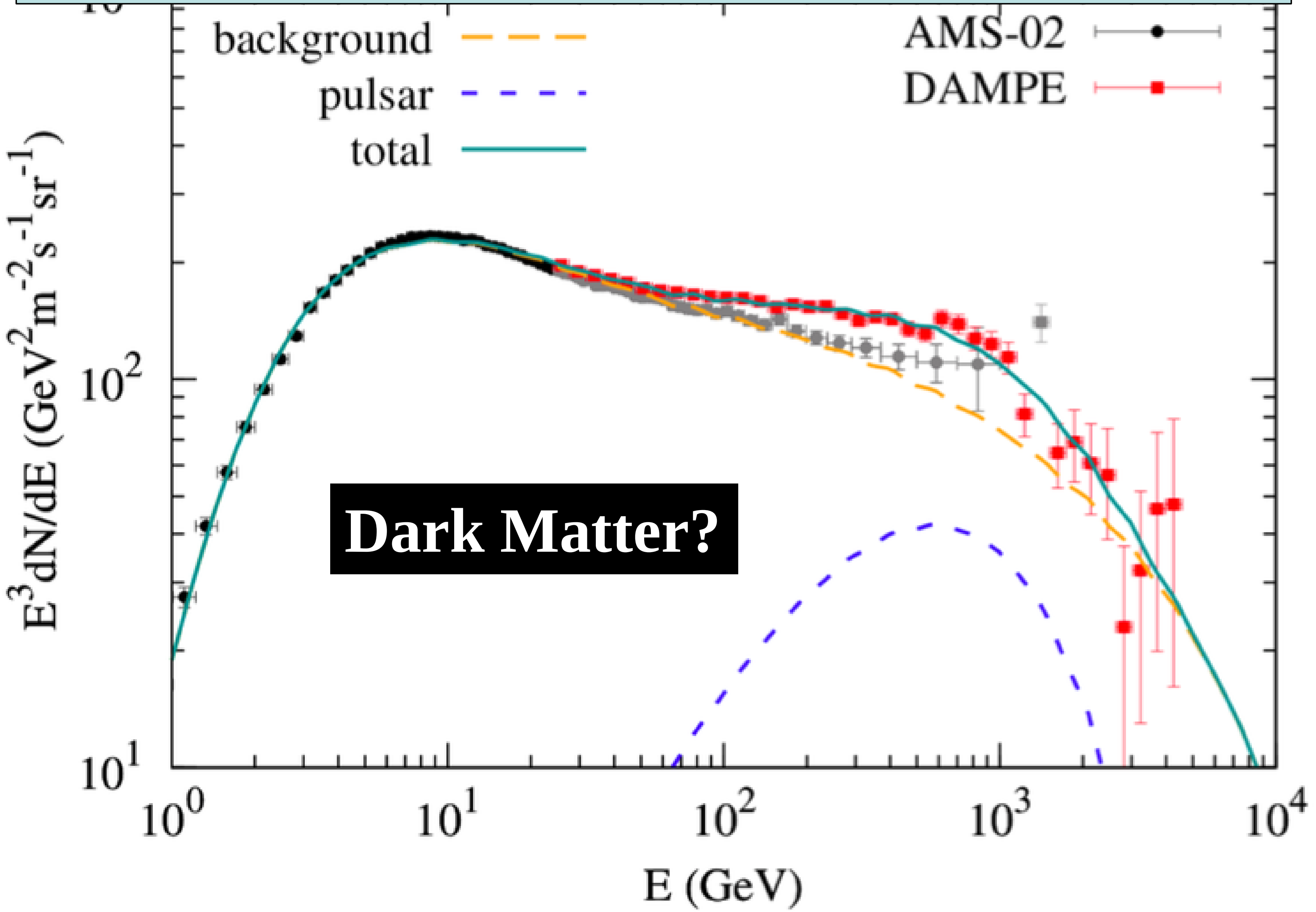
Fits to DM Annihilations

- Annihilation mainly into $b\bar{b}$, some admixture of e^+e^-, $\mu^+\mu^-$
- Different cosmic ray models
- Different solar potentials
- **Annihilation σ = 272 ✕ thermal**



Boudeaud et al., arXiv:1612.03924

Cosmic-Ray Positrons

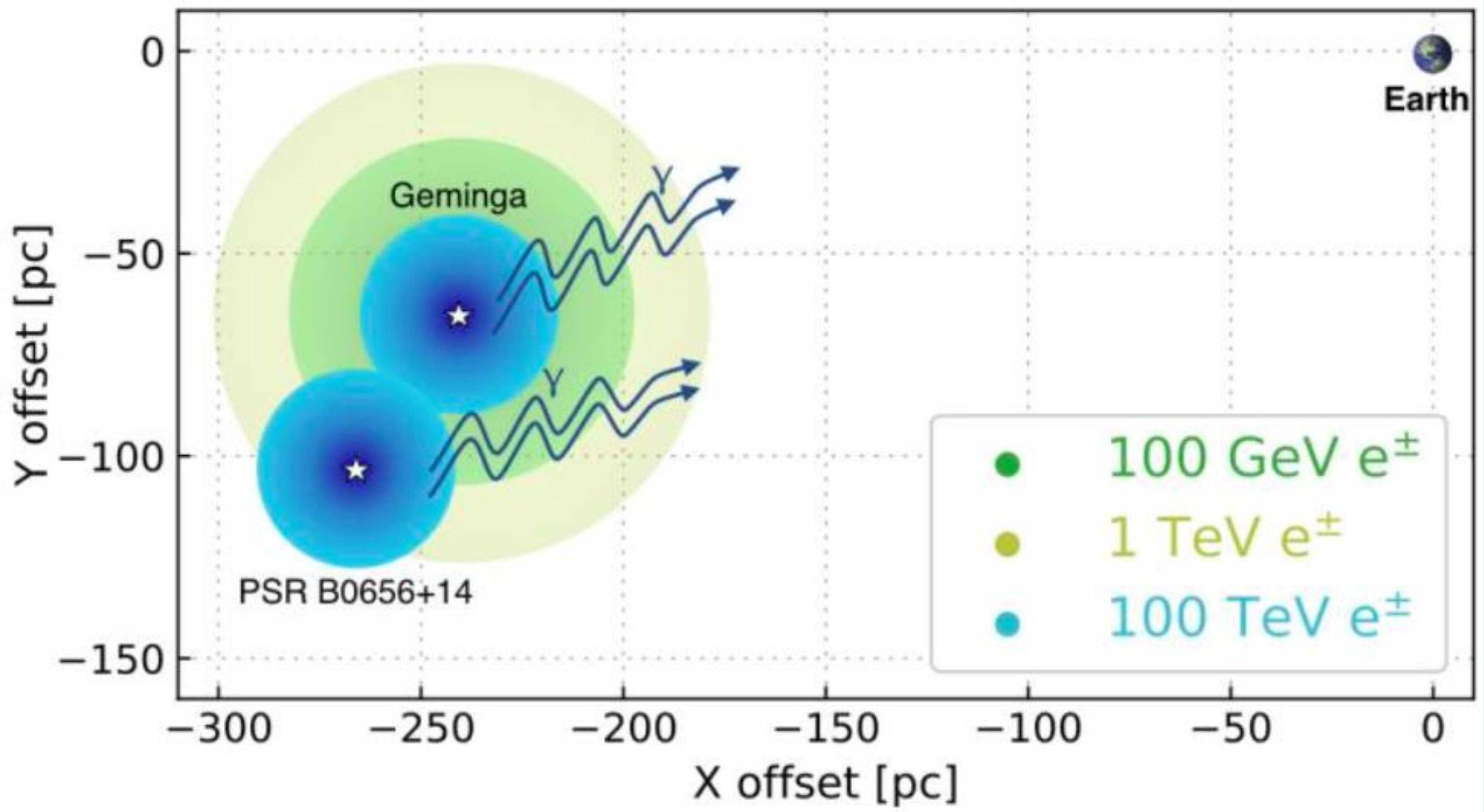


Dark Matter?

HAWC Collaboration, DOI:10.1126/science.aan4880

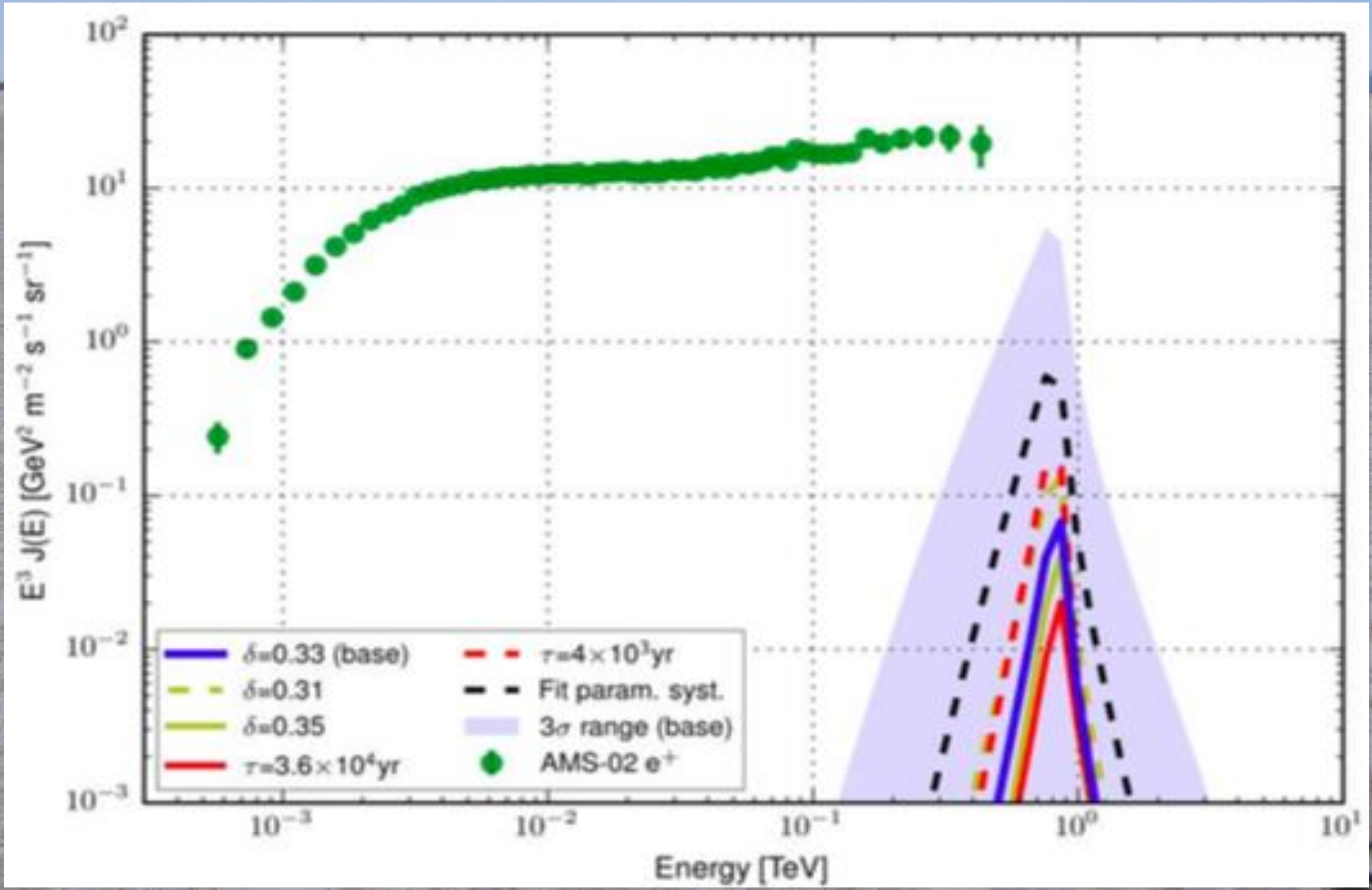
Diffuse γ Emission near Pulsars

- Absrorption of lower-energy γ



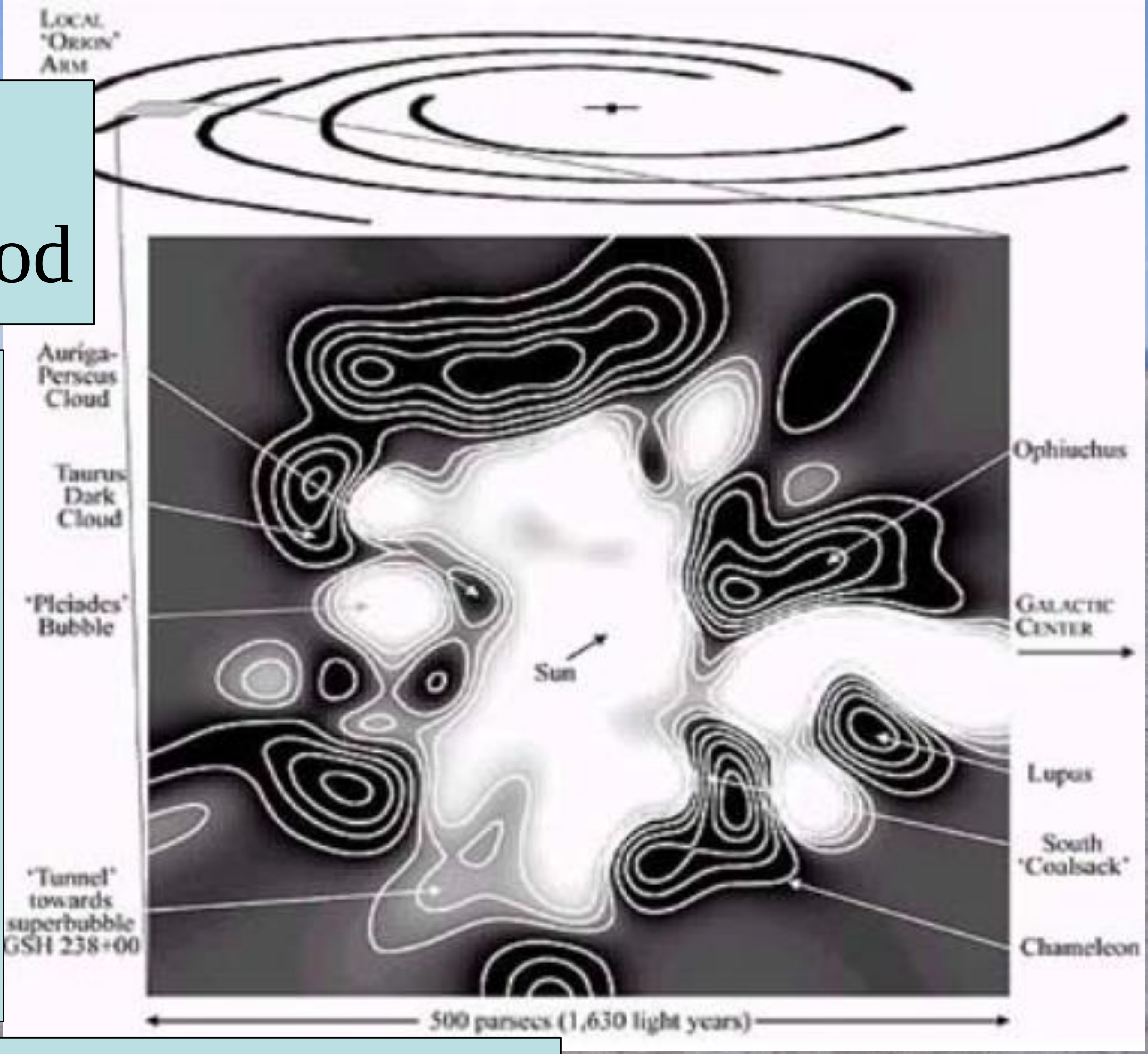
HAWC Collaboration, DOI:10.1126/science.aan4880

Effect on Pulsar Positron Spectrum



A Tough Neighbourhood

- We live in a local bubble
- Excavated by many supernovae in ‘recent’ past
- **Opportunity for AMS?**

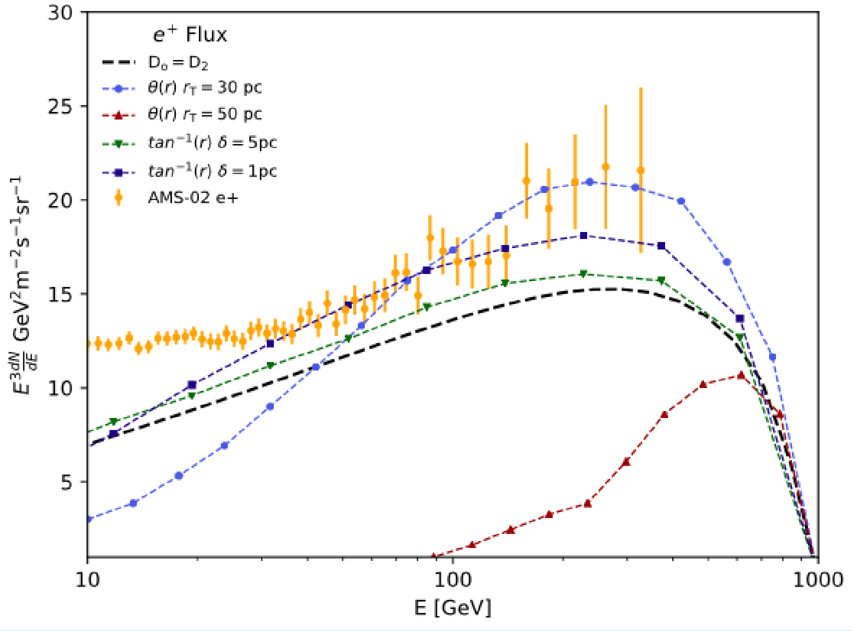


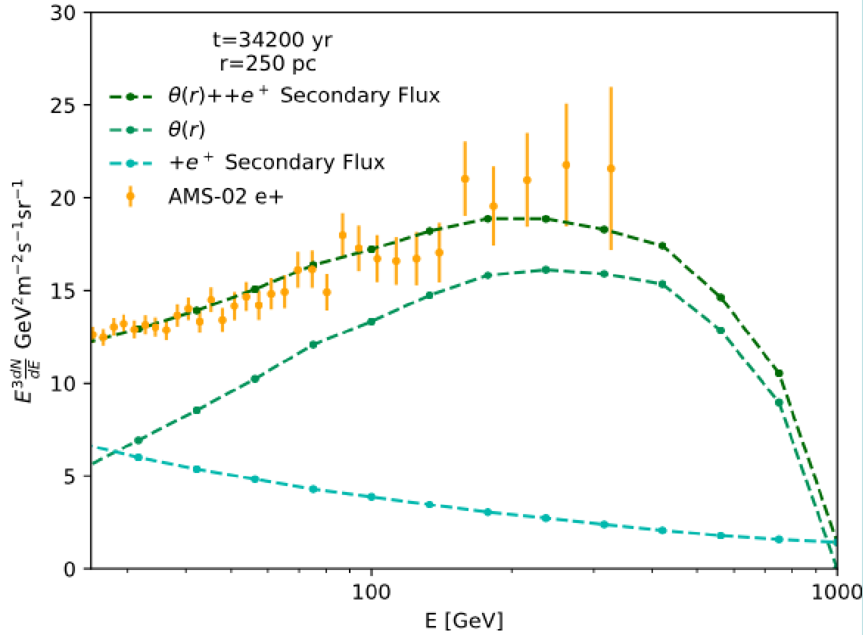
“16 supernovae have exploded during the past 13 million years within the boundaries of the Local Bubble.”

Breitschwerdt et al, Nature 532, 73 (2016)

Inhomogeneous Diffusion Coefficient?

- More similar to AMS-02 spectrum with spatial dependence of diffusion coefficient

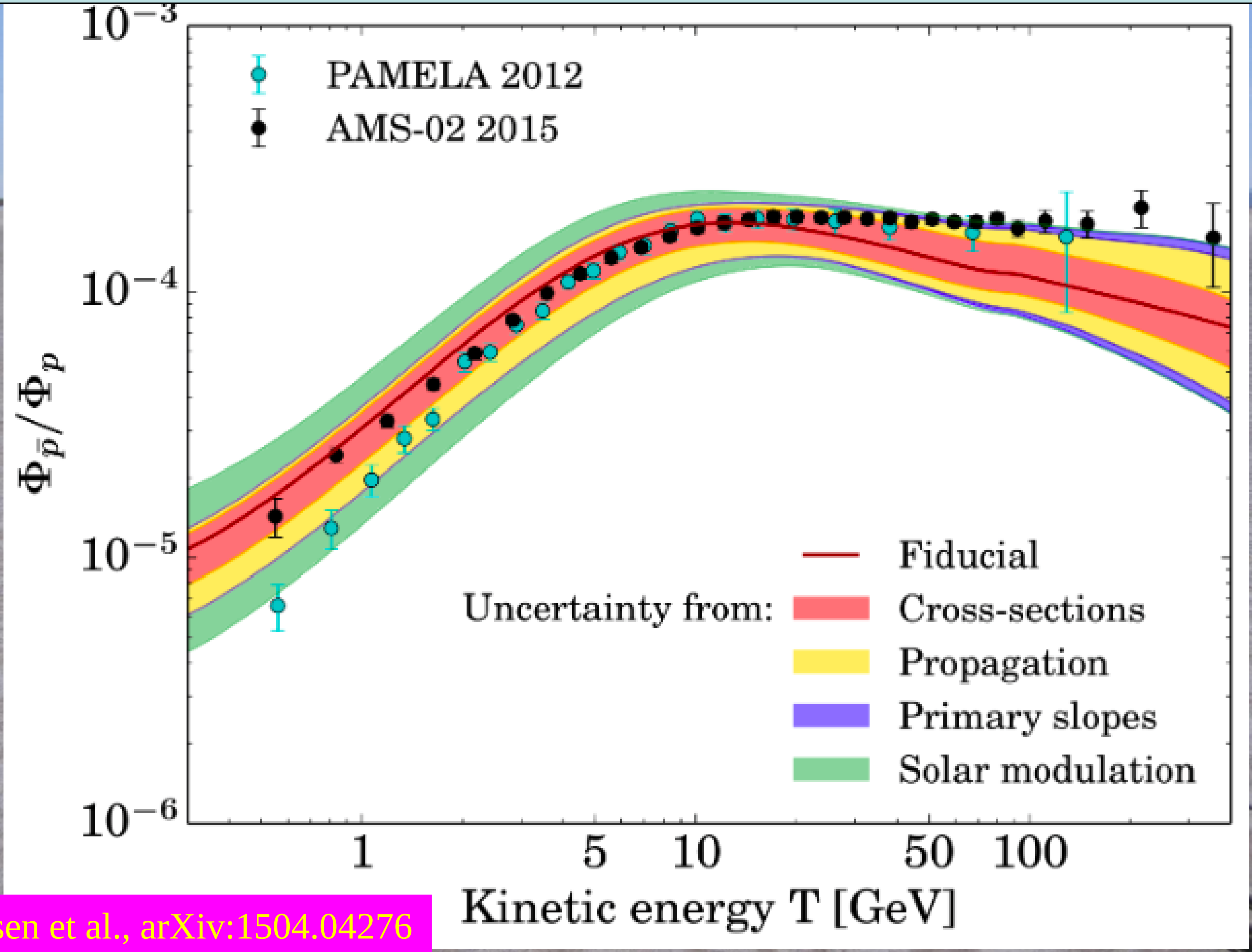




- Better fit including secondary production

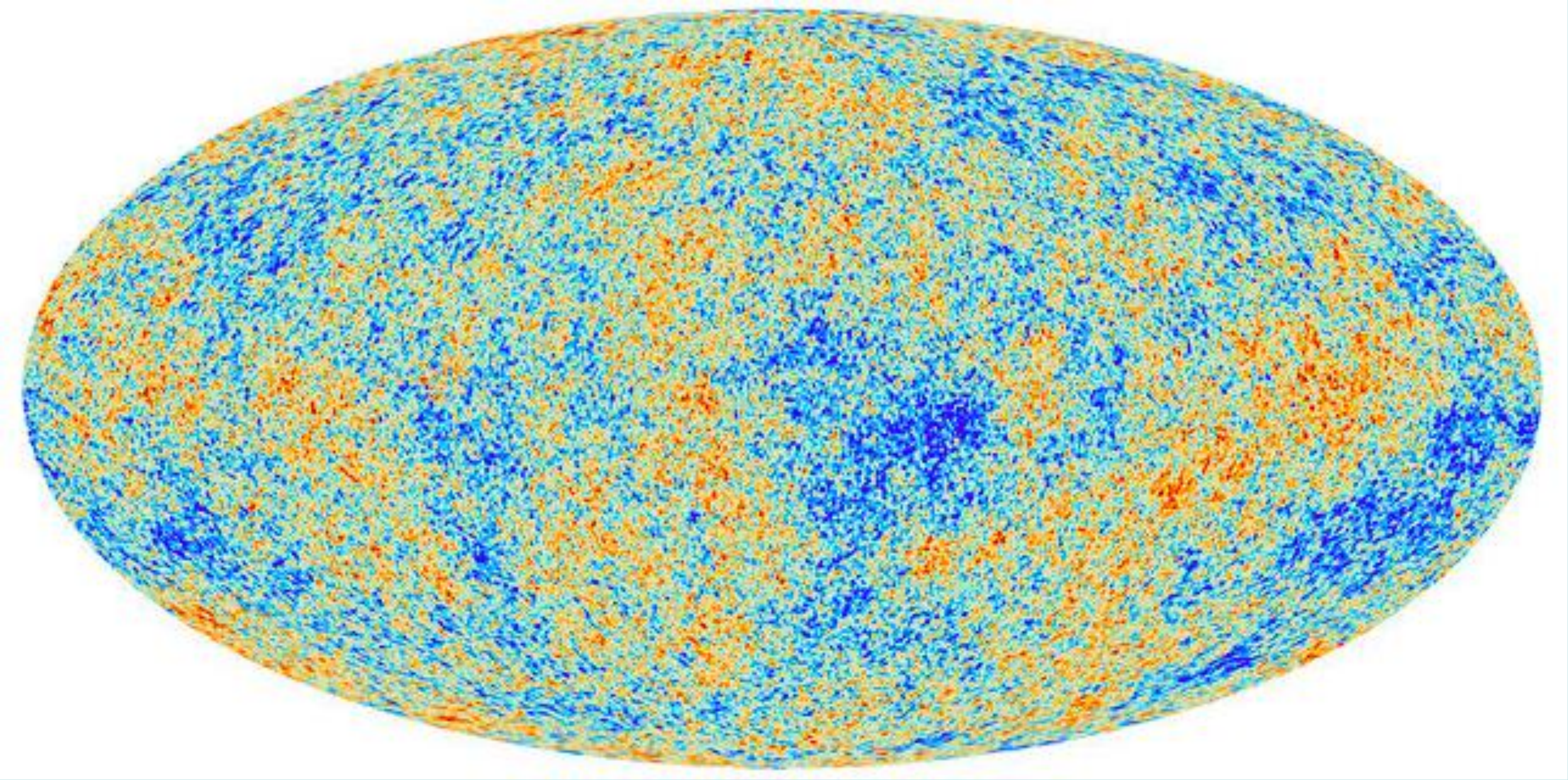
Profumo, ReynosCordova, Kaaz & Silverman, arXiv:1803.09731

Antiprotons Compatible with Cosmic Rays



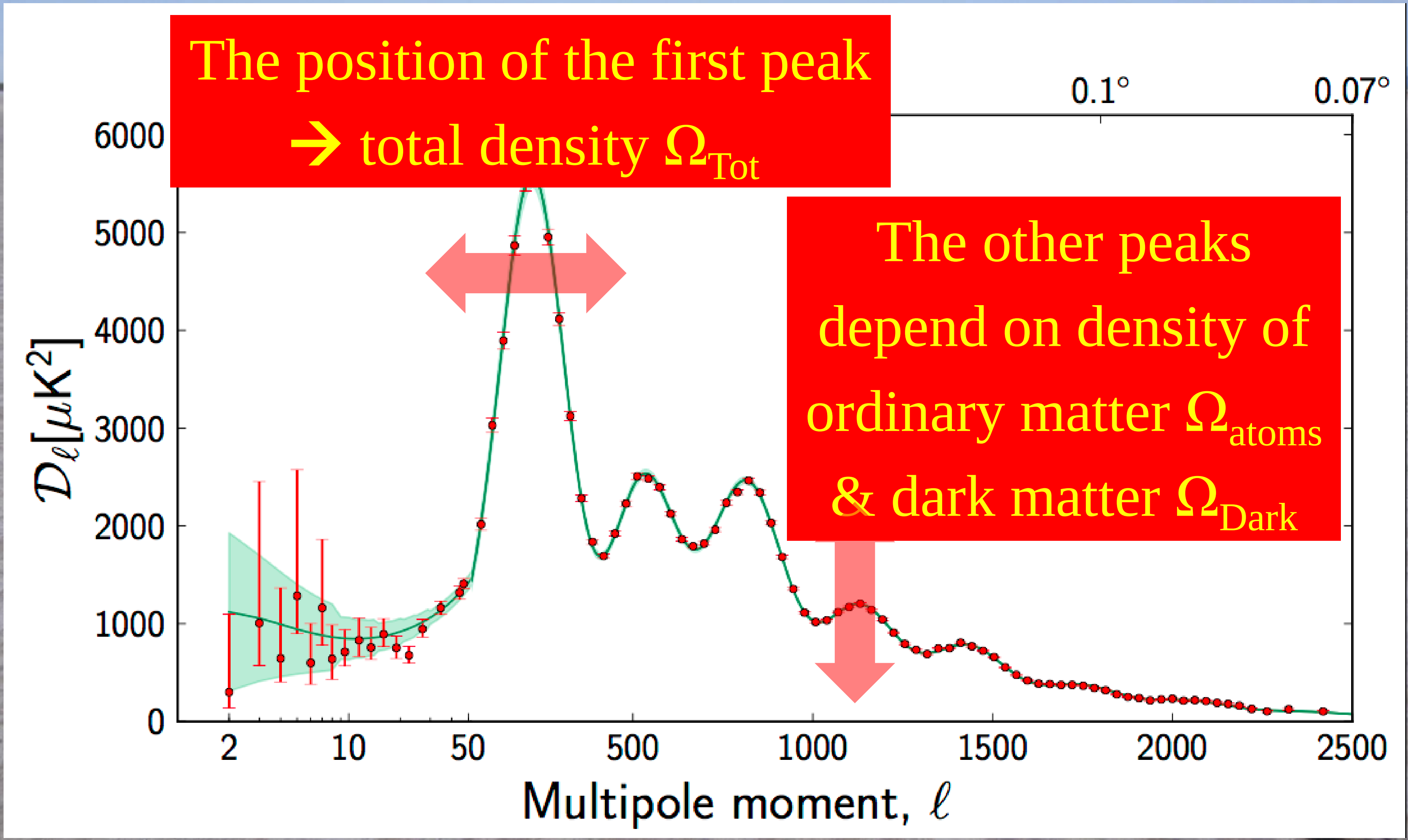
Giesen et al., arXiv:1504.04276

Cosmological Inflation in Light of Planck



A scalar in the sky? Supersymmetry/supergravity?

The Spectrum of Fluctuations in the Cosmic Microwave Background

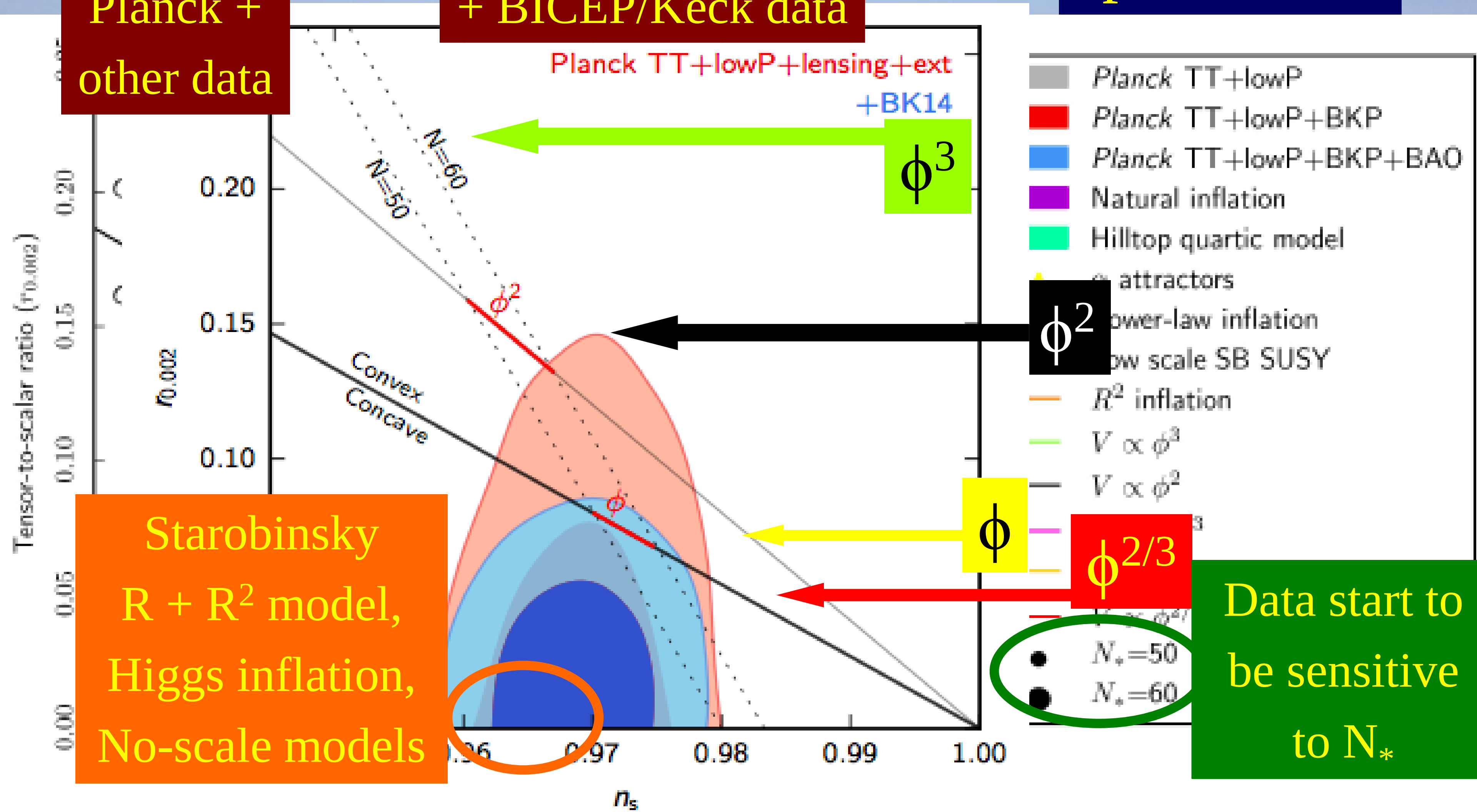


The position of the first peak
→ total density Ω_{Tot}

The other peaks depend on density of ordinary matter Ω_{atoms} & dark matter Ω_{Dark}

Inflationary Landscape

Monomial Single-field potentials



Planck + other data

+ BICEP/Keck data

ϕ^3

ϕ^2

ϕ

$\phi^{2/3}$

Starobinsky
$R + R^2$ model,
Higgs inflation,
No-scale models

Data start to be sensitive to N_*

Challenges for Inflationary Models

- Links to low-energy physics?
  - – Only SM candidate for inflaton is Higgs
    - **BUT** negative potential ….
- Link to other physics?
  - – SUSY partner of RH (singlet) neutrino?
  - – Some sort of axion?
- Links to Planck-scale physics?
  - – Inflaton candidates in string theory?
  - – Inflaton candidates in compactified string models?

Starobinsky Model

- Non-minimal general relativity (singularity-free cosmology):

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)$$

Starobinsky, 1980

- **No scalar!?**
- **Conformally equivalent to scalar field model:**

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2\right]$$

Stelle; Whitt, 1984

- Inflationary interpretation, calculation of perturbations:

Mukhanov & Chibisov, 1981

$$\delta S_b = \frac{1}{2}\int d^4x\left[\phi'^2 - \nabla_a\phi\nabla^a\phi + \left(\frac{a''}{a} + M^2a^2\right)\phi^2\right]$$

Higgs Inflation: a Single Scalar?

Bezrukov & Shaposhnikov, arXiv:0710.3755

- Standard Model with non-minimal coupling to gravity:

$$S_J = \int d^4x\sqrt{-g}\left\{ -\frac{M^2 + \boxed{\xi h^2}}{2}R + \frac{\partial_\mu h \partial^\mu h}{2} - \frac{\lambda}{4}\left(h^2 - v^2\right)^2 \right\}$$

- Consider case $1 \ll \sqrt{\xi} \lll 10^{17}$: in Einstein frame

$$S_E = \int d^4x\sqrt{-\hat{g}}\left\{ -\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - U(\chi)\right\}$$

- With potential: $U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 + \exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$

  Similar to Starobinsky, but not identical

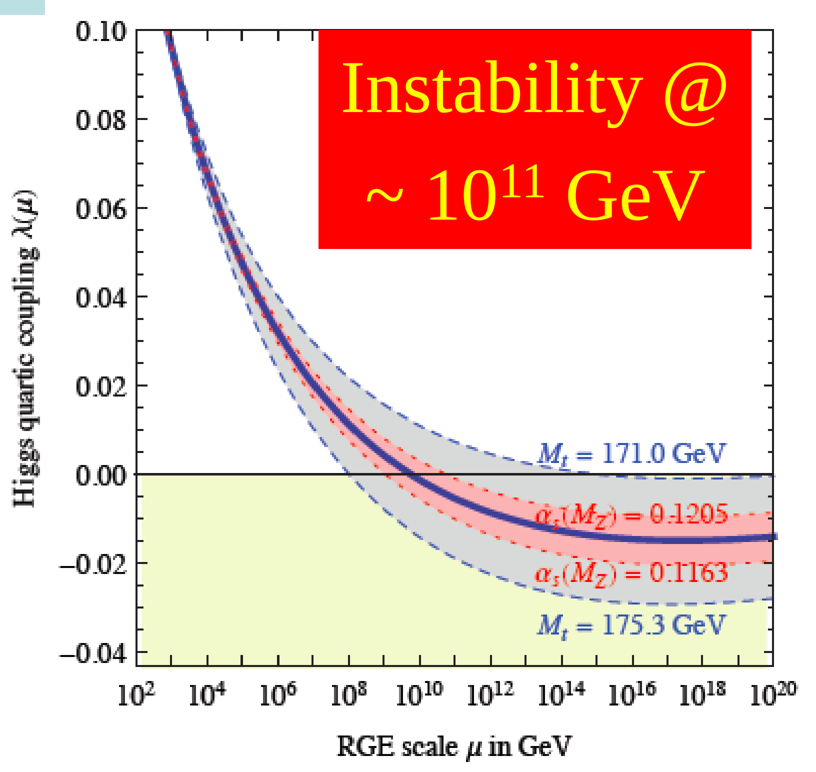
- Successful inflationary potential at $\chi \gg M_P$

Problem for Higgs Inflation

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

- Large M_h → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$



Instability @ ~ 10^{11} GeV

- Small M_h: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- **Negative potential not suitable for inflation**
- **Problem avoided with supersymmetry**

Inflation Cries out for Supersymmetry

- Want “elementary” scalar field

  (at least looks elementary at energies << M_P)
- To get right magnitude of perturbations

  prefer mass << M_P

  (~ 10^{13} GeV in simple φ^2 models)
- And/or prefer small self-coupling λ << 1
- **Both technically natural with supersymmetry**

JE, Nanopoulos, Olive & Tamvakis 1983

Inflation cries out for Supergravity

- Stabilize ‘elementary’ scalar inflaton
  (needs mass << m_P and/or small coupling)
- **Supersymmetry**
- The only good symmetry is a local symmetry
  (cf, gauge symmetry in Standard Model)
- **Local supersymmetry = supergravity**
- Early Universe cosmology needs gravity
- **Supersymmetry + gravity = supergravity**

No-Scale Supergravity Inflation

- **Supersymmetry + gravity = Supergravity**
- Include conventional matter?
- Potentials in generic supergravity models have ‘holes’ with depths ~ – M_P^4
- Exception: **no-scale supergravity**

Cremmer, Ferrara, Kounnas & Nanopoulos, 1983

- **Appears in compactifications of string**

Witten, 1985

- Flat directions, scalar potential ~ global model + controlled corrections

JE, Enqvist, Nanopoulos, Olive & Srednicki, 1984

JE, Nanopoulos & Olive, arXiv:1305.1247, 1307.3537, …

No-Scale Supergravity Inflation Revived

JE, Nanopoulos & Olive, arXiv:1305.1247

- Simplest SU(2,1)/U(1) example:
- Kähler potential: $K = -3\ln(T + T^* - |\phi|^2/3)$
- Wess-Zumino superpotential: $W = \frac{\mu}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$
- Assume modulus $T = c/2$ fixed by ‘string dynamics’
- Ef

$$\mathcal{L}_{eff} = \frac{c}{(c - |\phi|^2/3)^2}|\partial_\mu \phi|^2 - \frac{\hat{V}}{(c - |\phi|^2/3)^2}$$

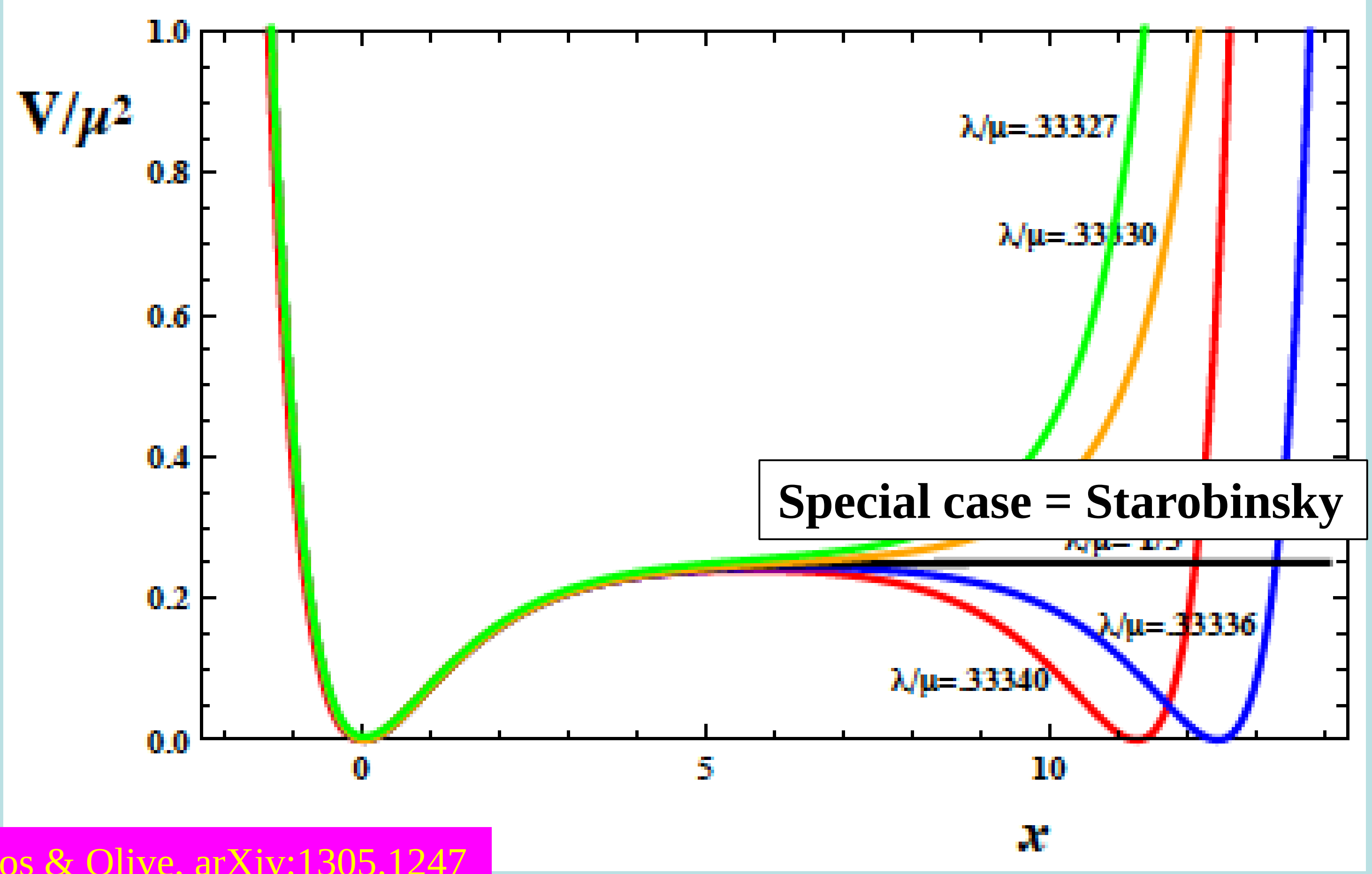
$$\hat{V} \equiv \left|\frac{\partial W}{\partial \phi}\right|^2$$

:

- Modifications to globally supersymmetric case
- Good inflation possible …

No-Scale Supergravity Inflation

- Inflationary potential for $\lambda \simeq \mu/3$



Special case = Starobinsky

JE, Nanopoulos & Olive, arXiv:1305.1247

Is there more profound connection?

- Starobinsky model:

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)$$

- After conformal transformation:

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2\right]$$

- Effective potential: $V = \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2$
- Identical with the no-scale Wess-Zumino model for the case $\lambda = \mu/3$

… it actually IS Starobinsky

Cecotti, 1987

JE, Nanopoulos & Olive, arXiv:1305.1247

How many e-Folds of Inflation?

- General expression:

JE, García, Nanopoulos & Olive, arXiv:1505.06986

$$N_* = 67 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_*^2}{M_P^4 \rho_{\rm end}}\right) + \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\ln\left(\frac{\rho_{\rm reh}}{\rho_{\rm end}}\right) - \frac{1}{12}\ln g_{\rm th}$$

Amplitude of perturbations

- In no-scale supergravity models:

$$N_* = 68.659 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(A_{S*}\right) - \frac{1}{4}\ln\left(N_* - \sqrt{\frac{3}{8}}\frac{\phi_{\rm end}}{M_P} + \frac{3}{4}e^{\sqrt{\frac{2}{3}}\frac{\phi_{\rm end}}{M_P}}\right)$$
$$+ \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\left(2.030 + 2\ln\left(\Gamma_\phi/m\right) - 2\ln(1+w_{\rm eff}) - 2\ln(0.81 - 1.10\ln\delta)\right)$$
$$- \frac{1}{12}\ln g_{\rm th},$$

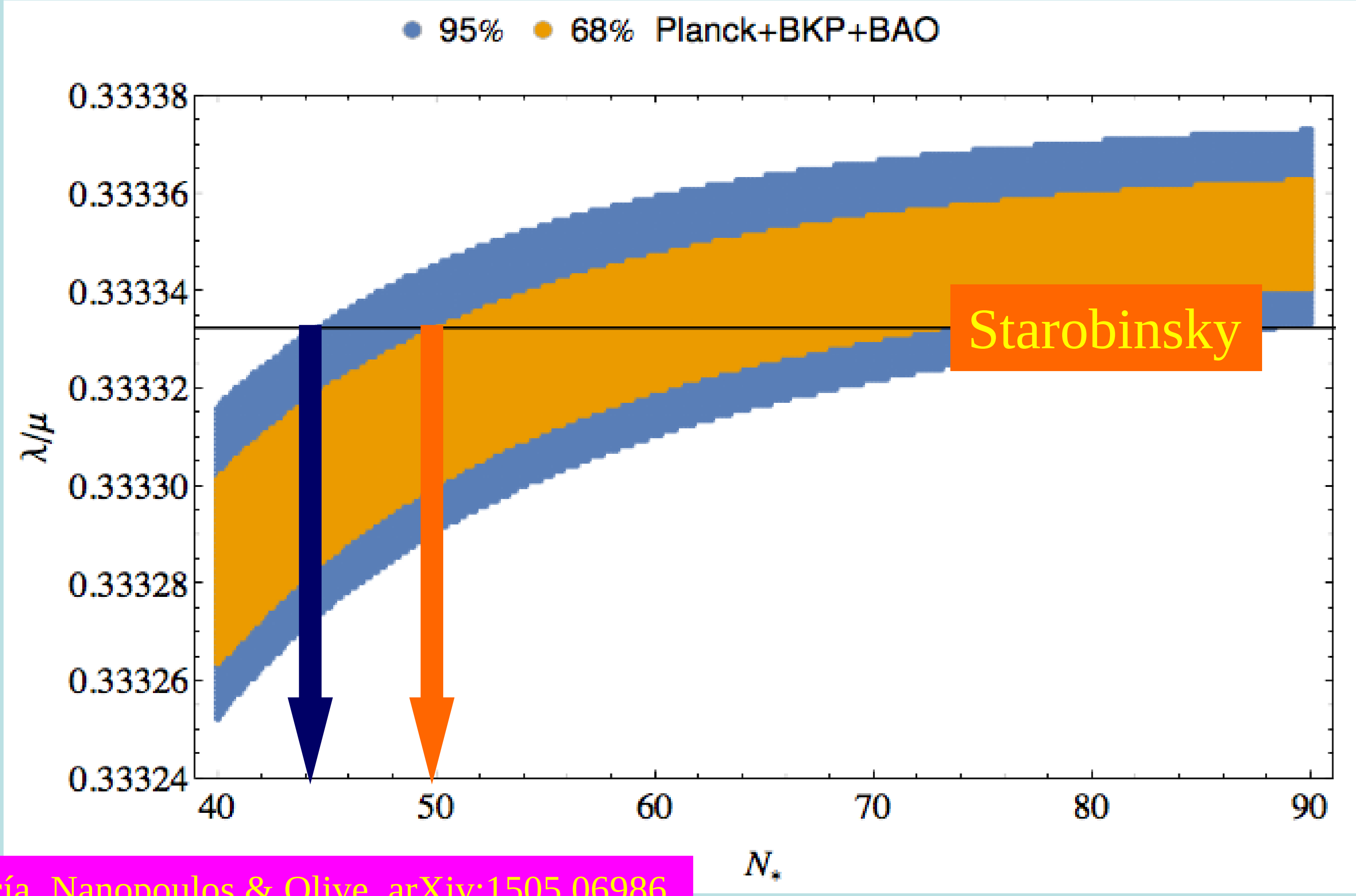
Equation of state during inflaton decay

Inflaton decay rate

- **Prospective constraint on inflaton models?**

Planck Constraints on # of e-Folds

- Starobinsky-like no-scale models



JE, García, Nanopoulos & Olive, arXiv:1505.06986