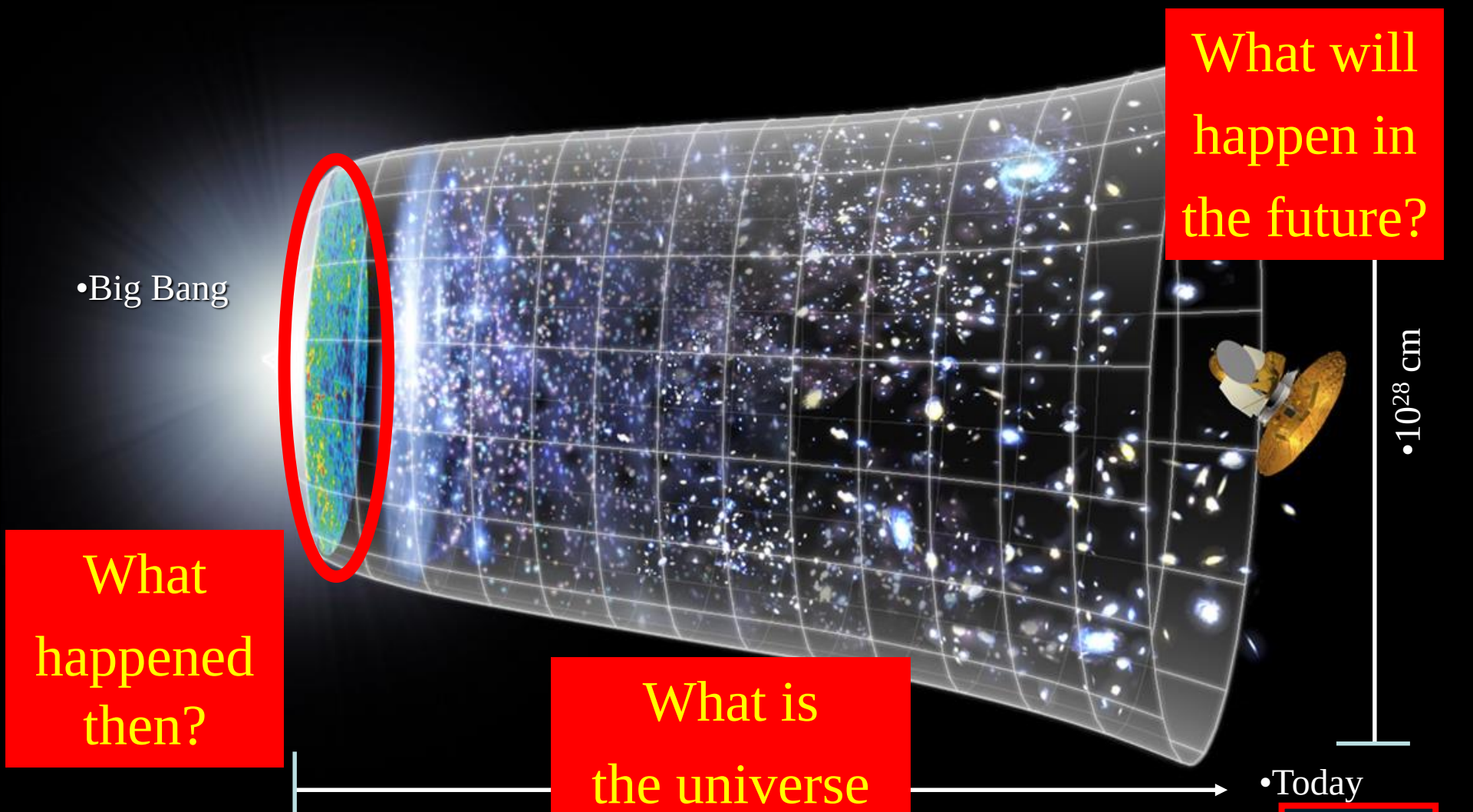
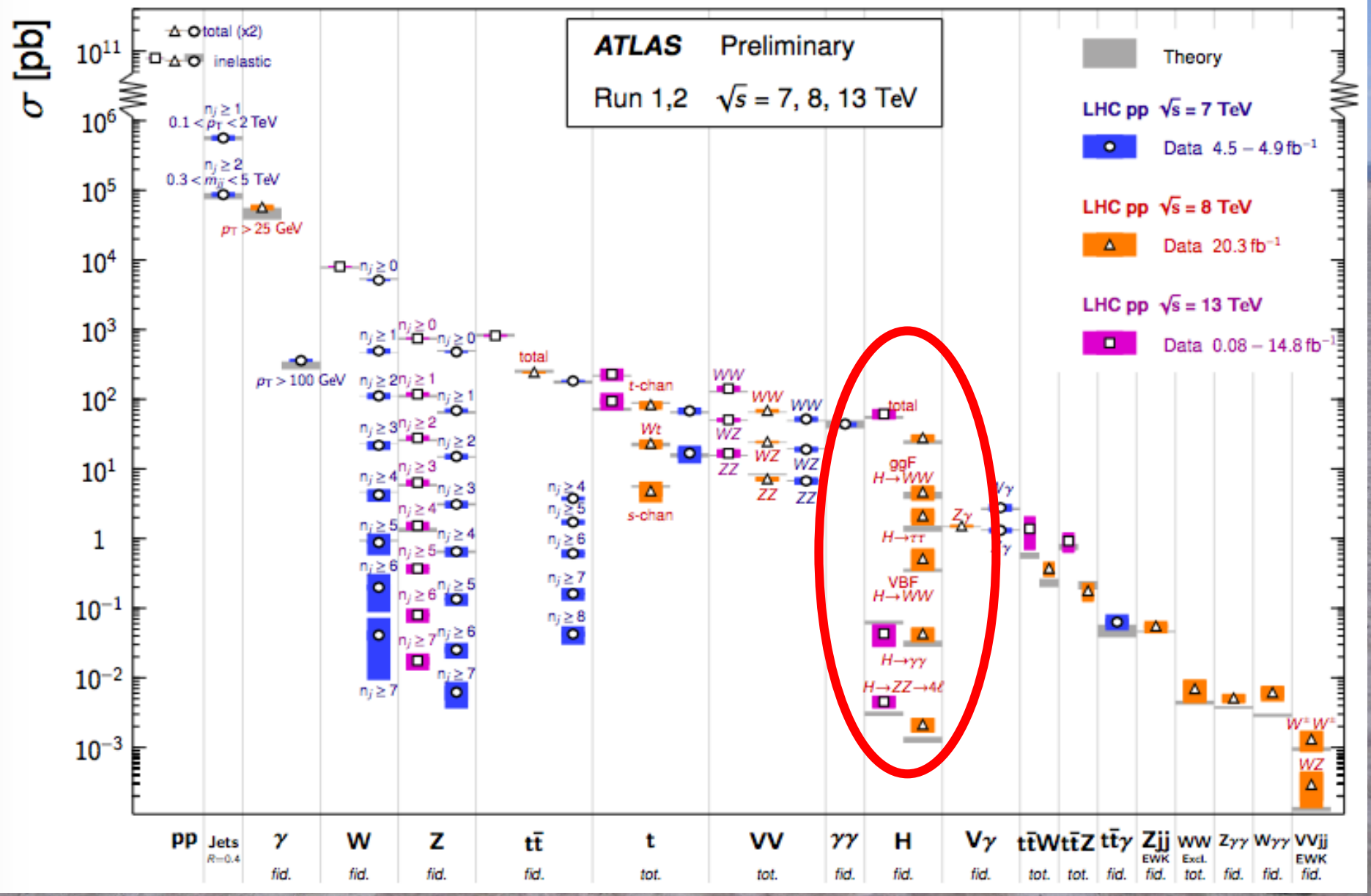
From Little Bangs to the Big Bang



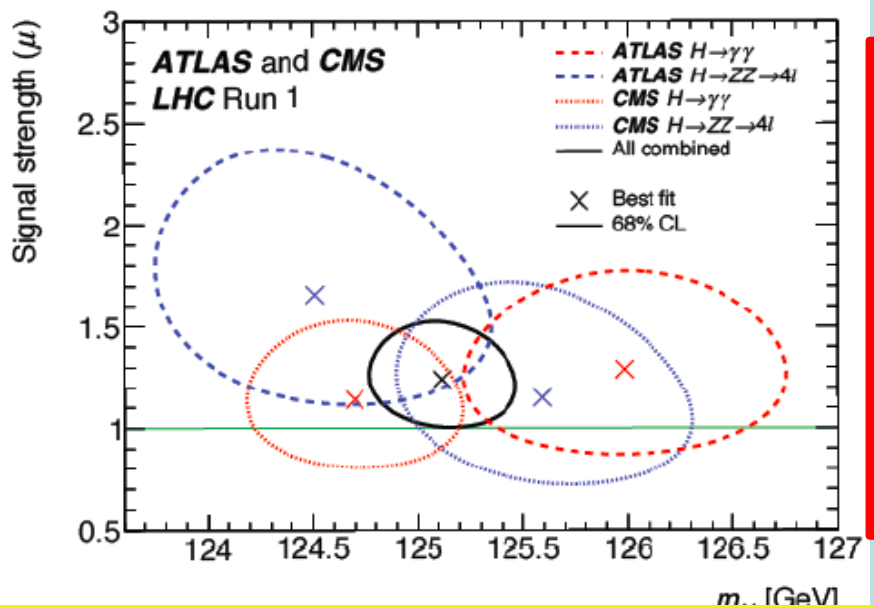
John Ellis
KING'S College LONDON

Physics Measurements @ LHC



Higgs Mass Measurements

- ATLAS + CMS ZZ^* and $\gamma\gamma$ 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

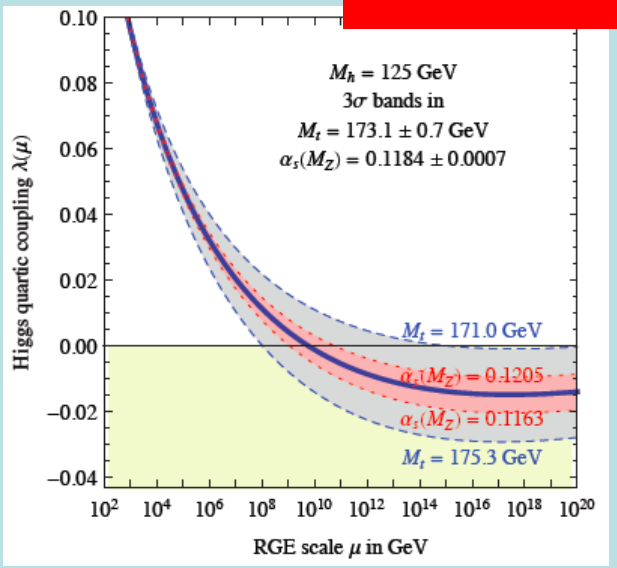
- Large M_h → large self-coupling → blow up at

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

$$\lambda(Q) = \frac{\lambda(v)}{1 - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q^2}{v^2}}$$

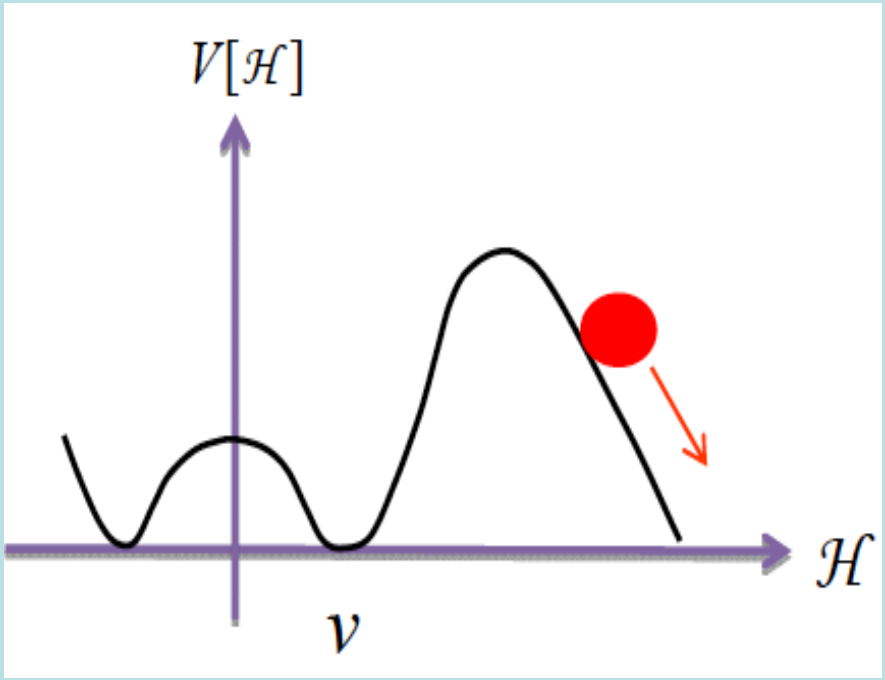
Instability @ $10^{11.4 \pm 0.8}$ GeV

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

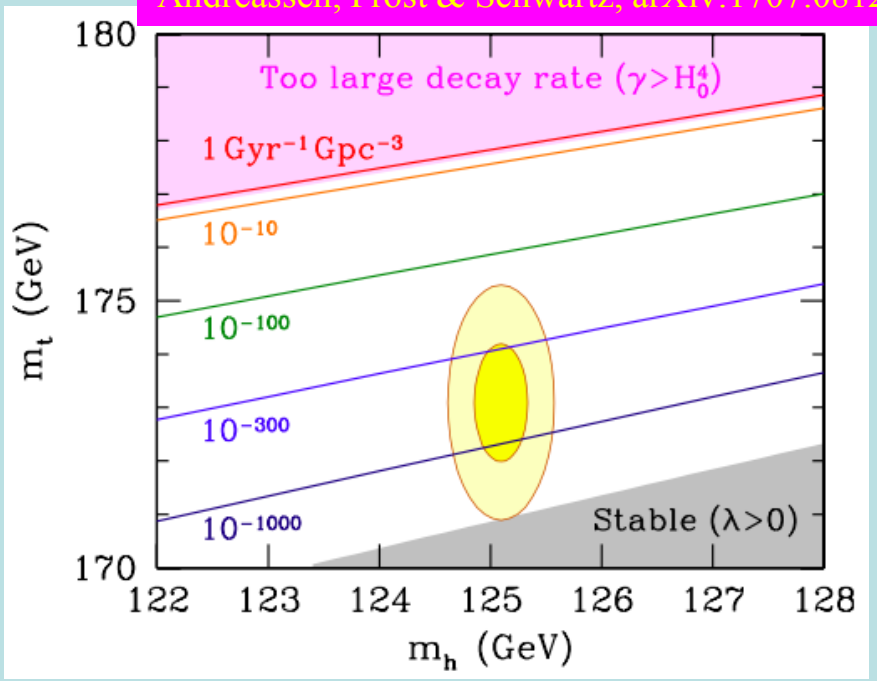


- Vacuum could be stabilized by **Supersymmetry**

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

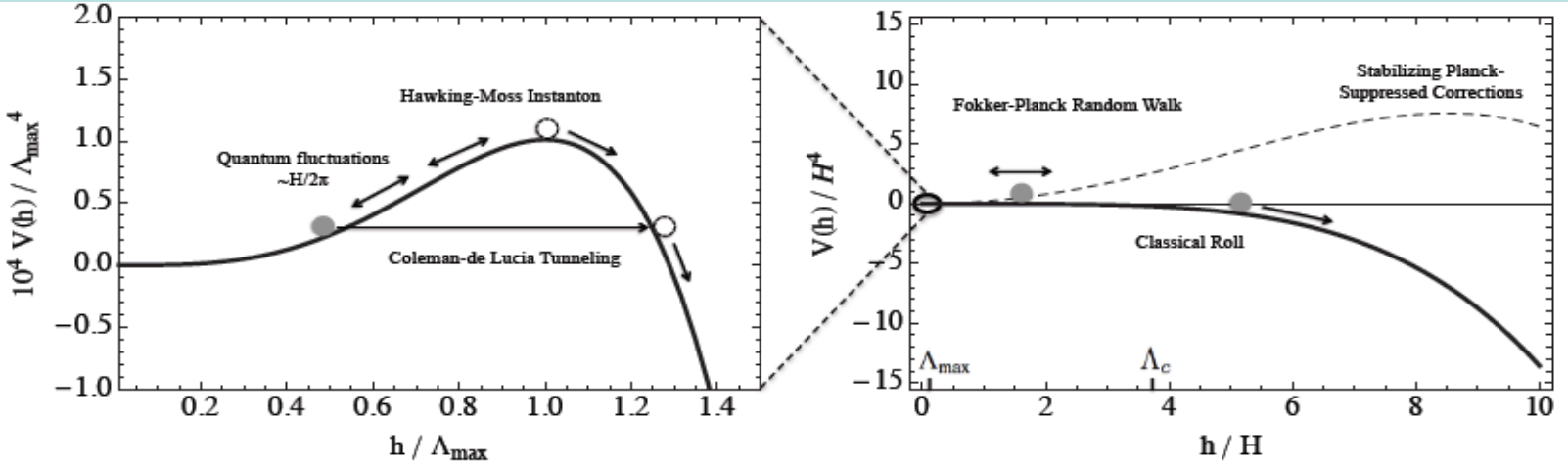
$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

$m_t = 172.47 \pm 0.35$ GeV ➔ $\log_{10}(\Lambda/\text{GeV}) = 11.4 \pm 0.8$

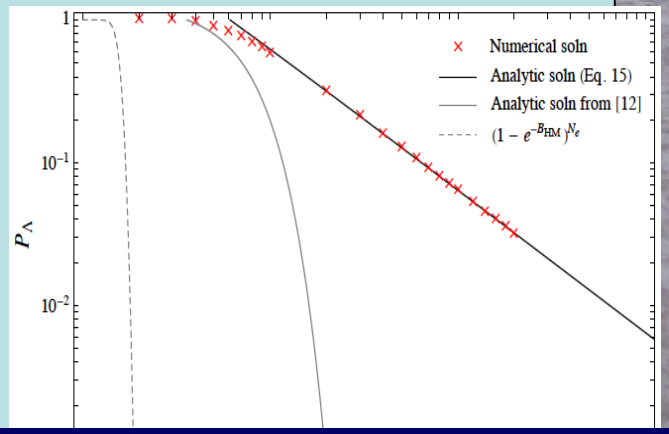
Instability during Inflation?

Hook, Kearns, 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
  - Mitigate with more inflation?



Stabilize vacuum with some physics beyond the SM?

Standard Model as an Effective Field Theory

- Supplement Standard Model with higher-dimensional interactions generated by new physics at scale Λ
- Leading dimension-6 operators:

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

- 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

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

- Operators affecting Higgs observables

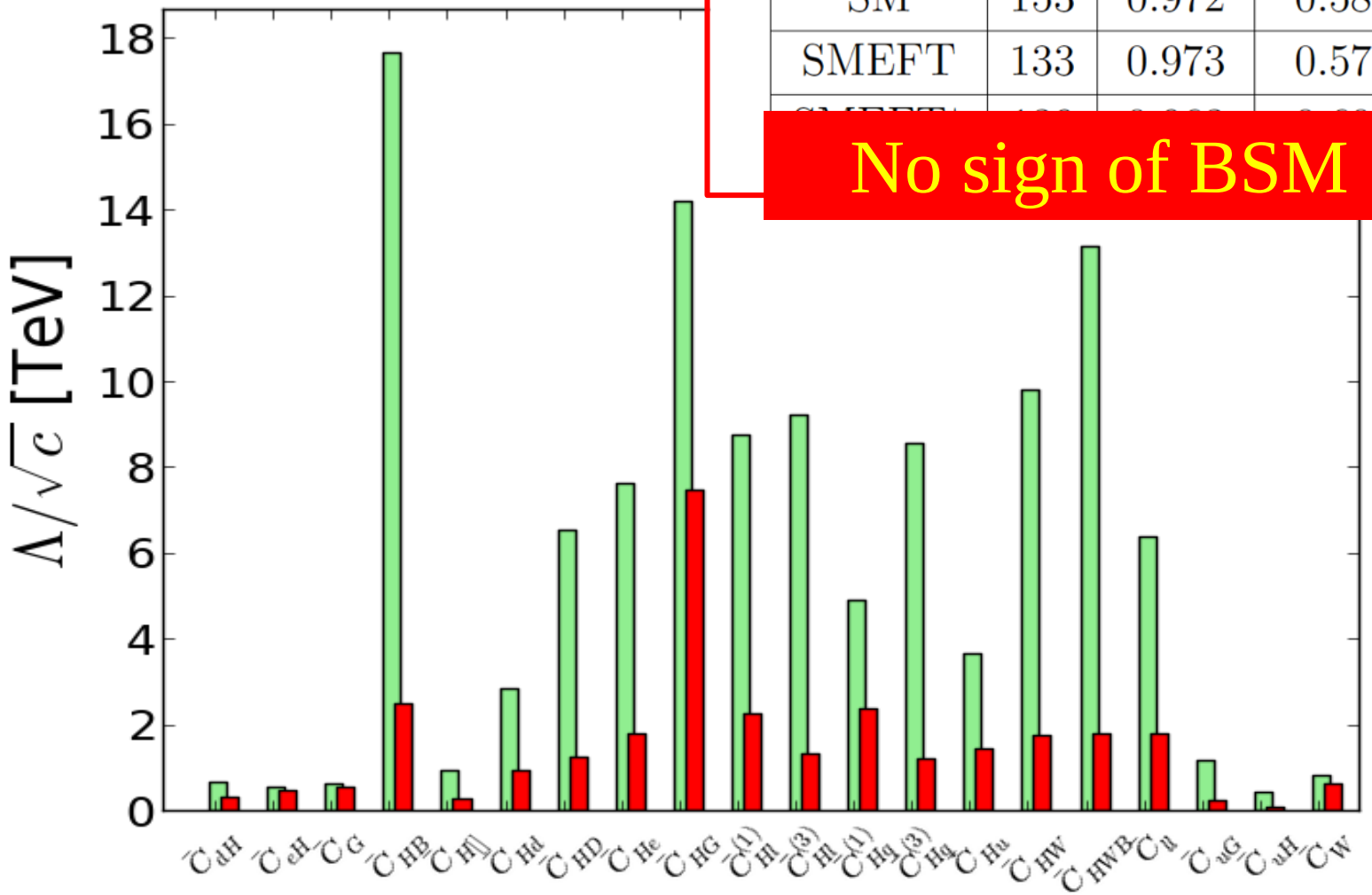
$$\mathcal{L}^{\text{Warsaw}}_{\text{SMEFT}} \supset \frac{\bar{C}_{eH}}{v^2}(H^\dagger H)(\bar{l}eH) + \frac{\bar{C}_{dH}}{v^2}(H^\dagger H)(\bar{q}dH) + \frac{\bar{C}_{uH}}{v^2}(H^\dagger H)(\bar{q}u\widetilde{H})$$
$$+ \frac{\bar{C}_G}{v^2}f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{\bar{C}_{H\Box}}{v^2}(H^\dagger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

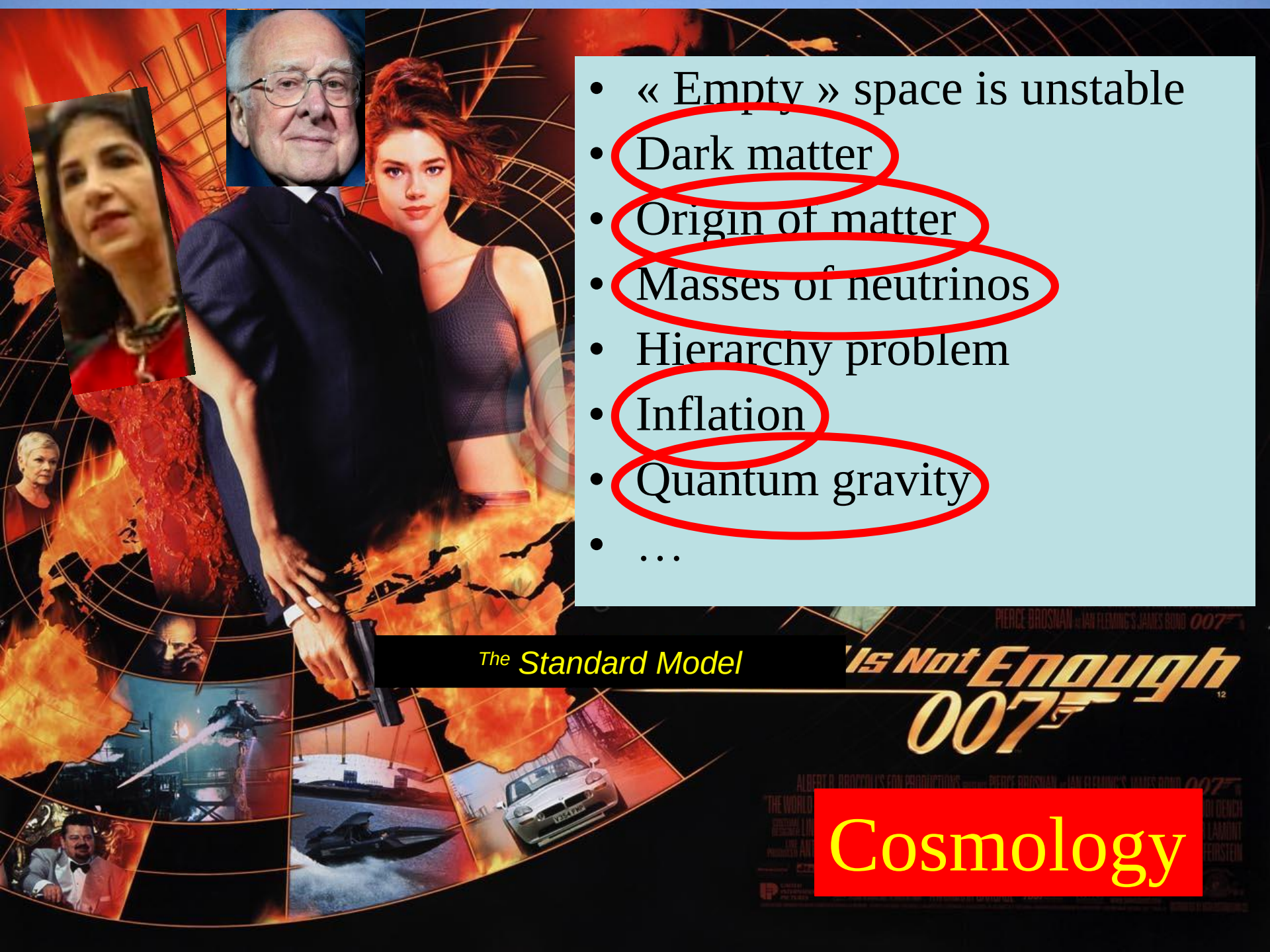
JE, Murphy, Sanz & You, arXiv:1803.03252

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



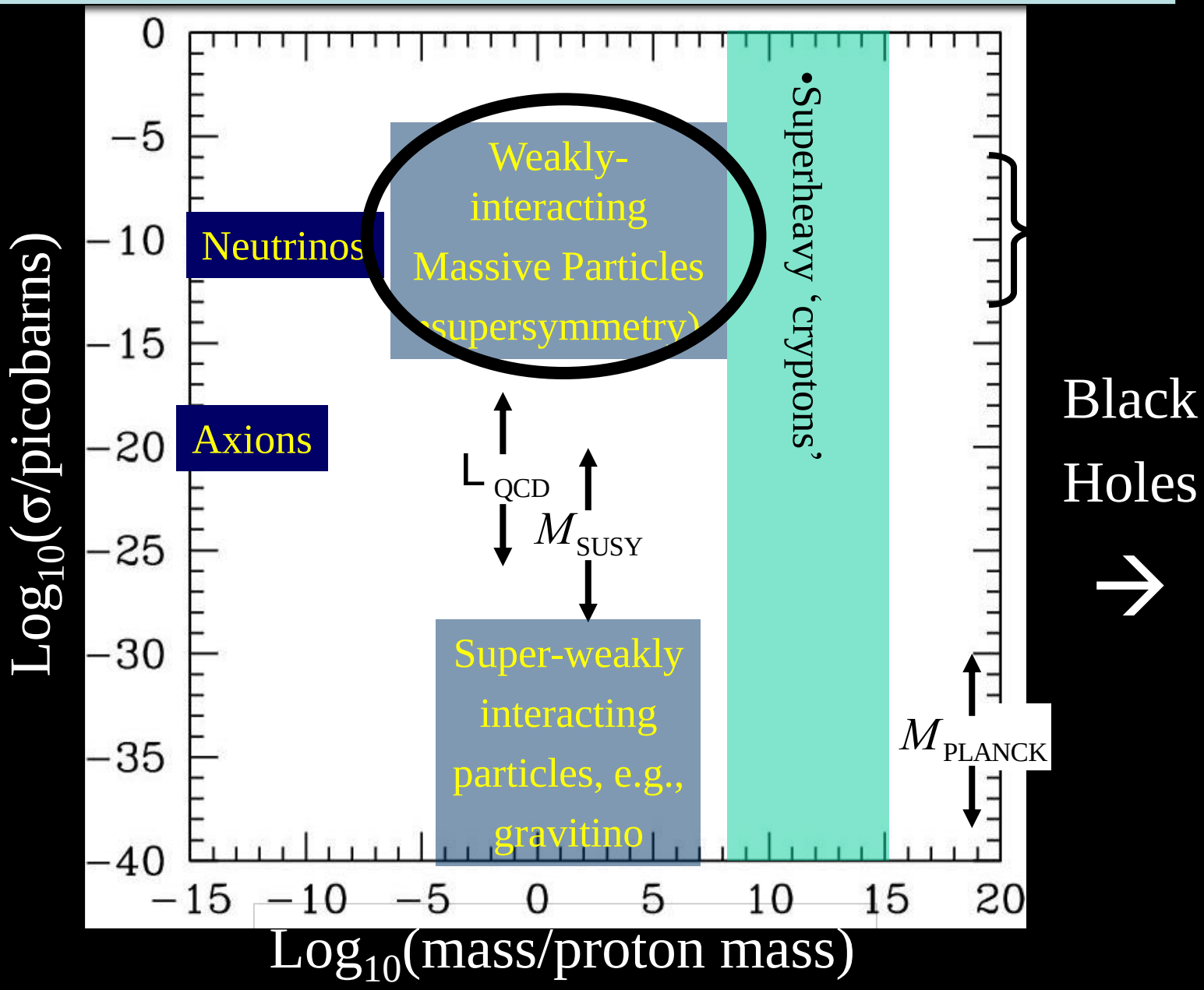


- « Empty » space is unstable
- Dark matter
- Origin of matter
- Masses of neutrinos
- Hierarchy problem
- Inflation
- Quantum gravity
- …

The Standard Model

Cosmology

Particle 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**

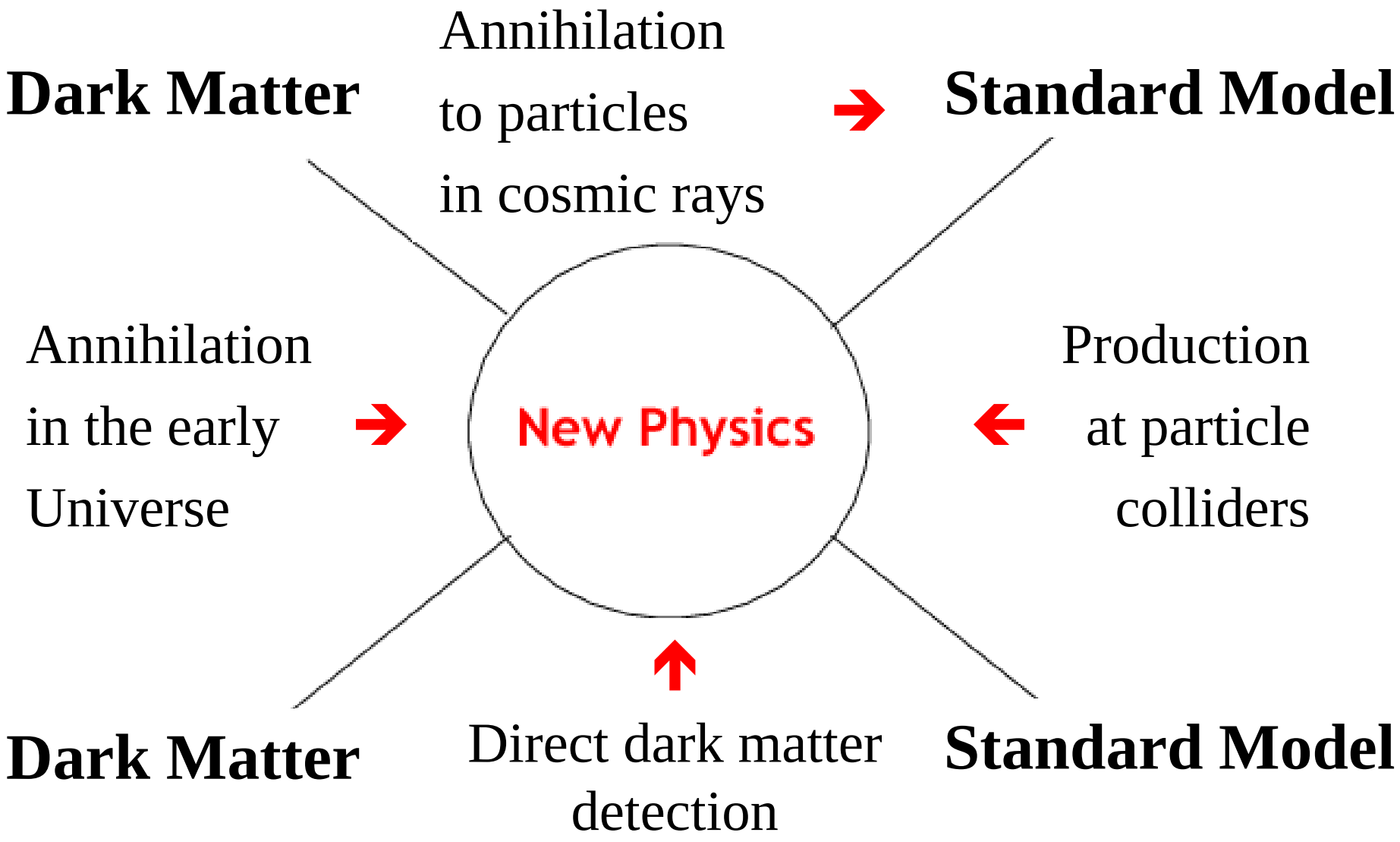
What lies beyond the Standard Model?

Supersymmetry

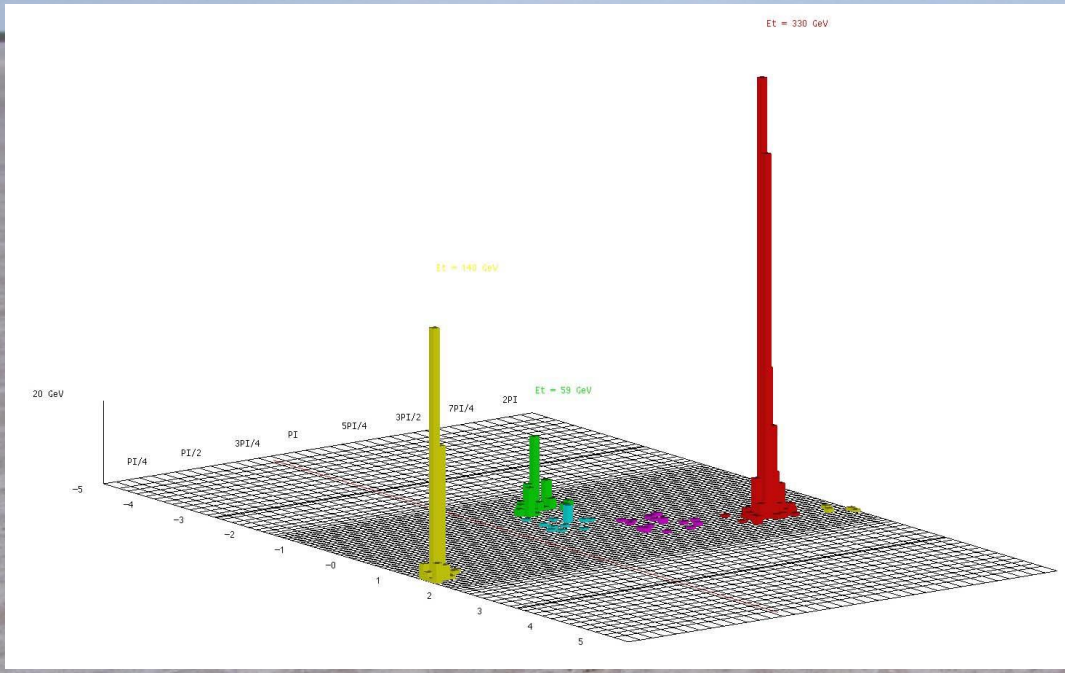
New motivations
From LHC Run 1

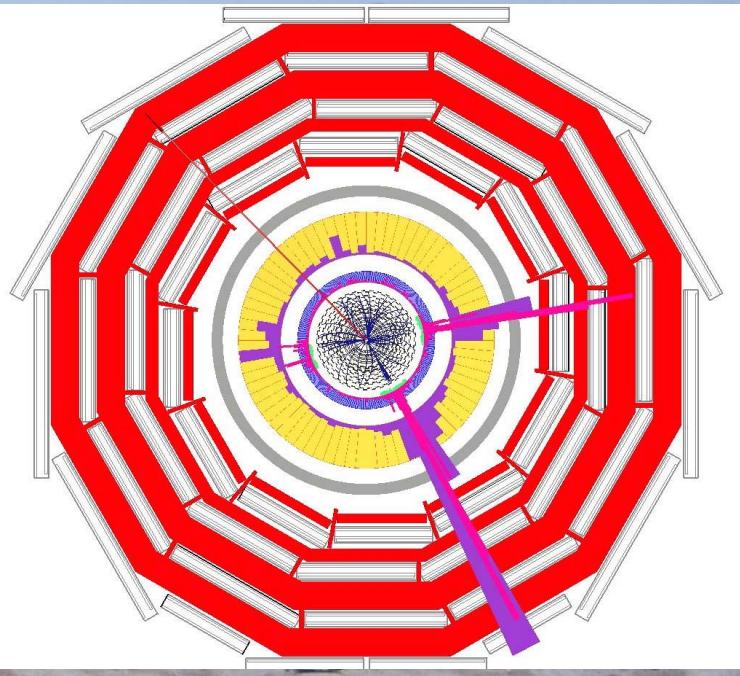
- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

Searches for WIMP Dark Matter



Classic LHC Dark Matter Signature



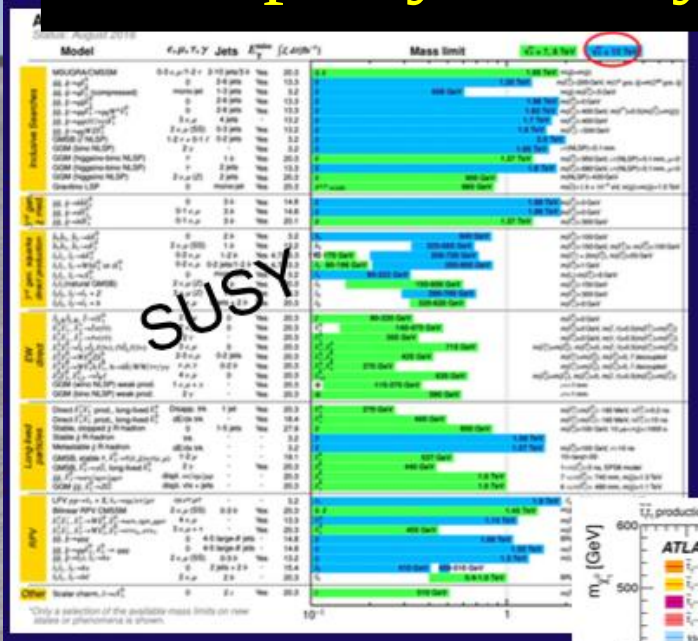


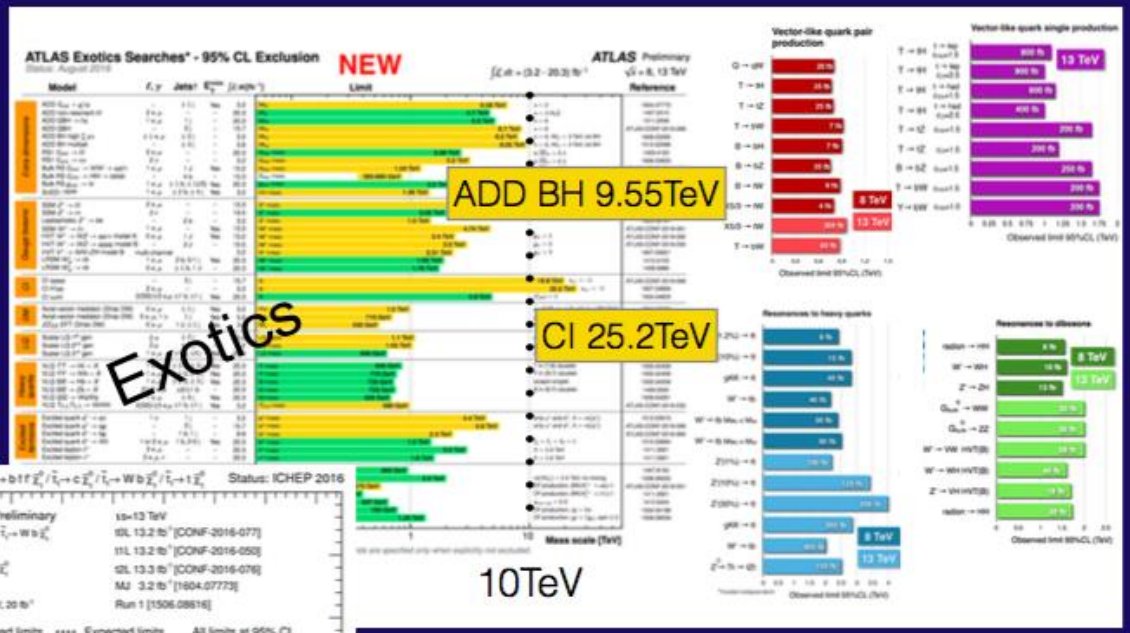
Missing transverse energy
carried away by dark matter particles

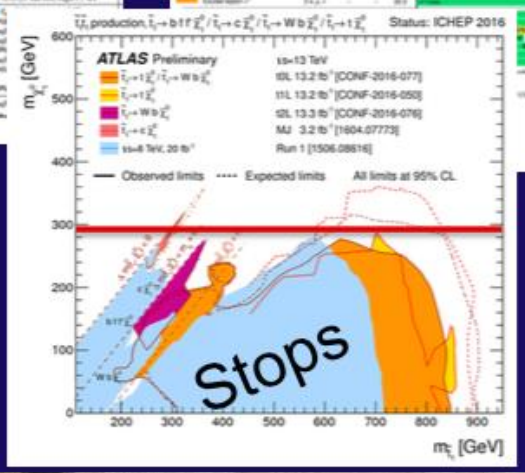
Nothing (yet) at the LHC

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

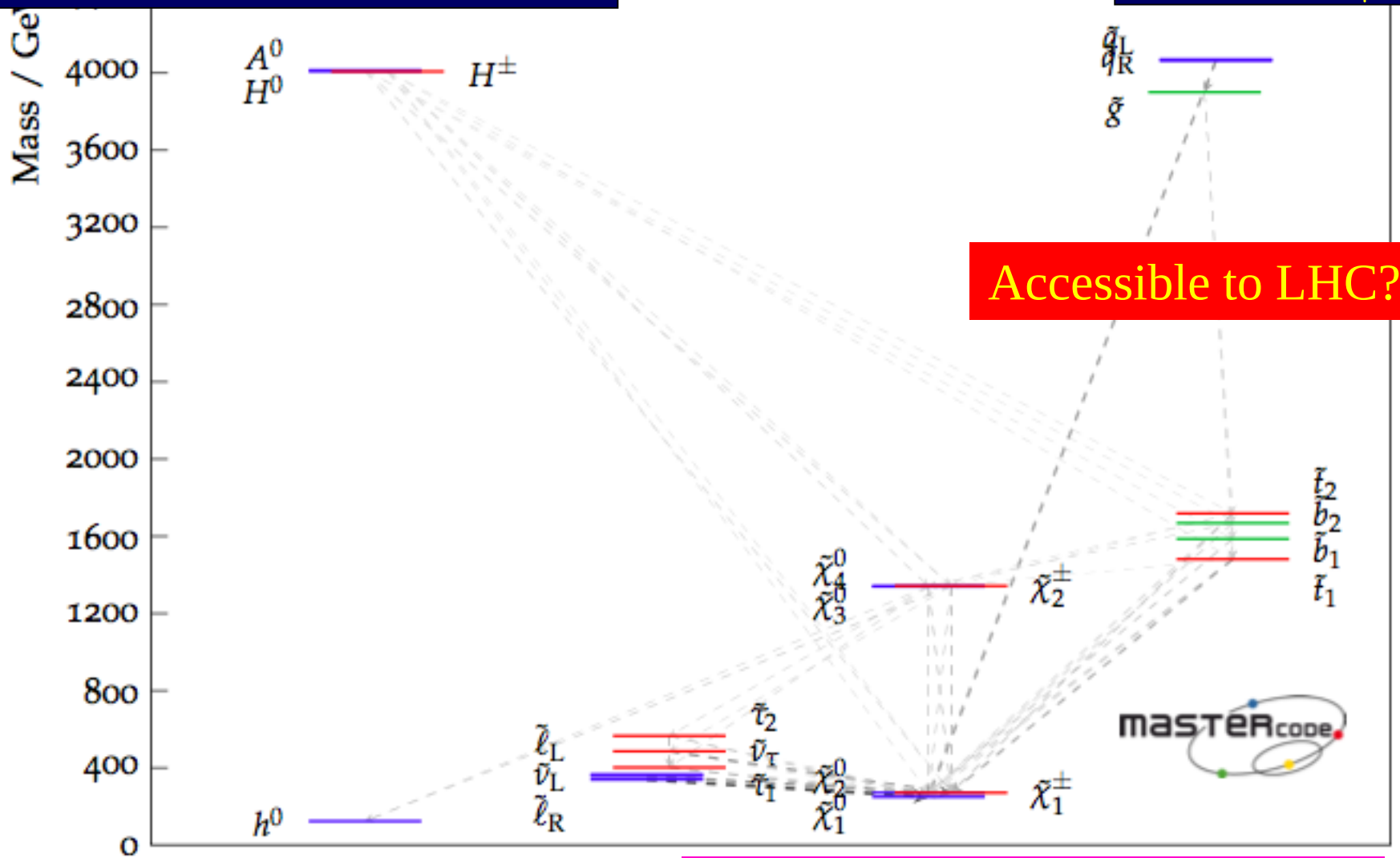
LHC observables

Observable	Source Th./Ex.	Constraint
M_W [GeV]	[58] / [57,58]	$80.370 \pm 0.012 \pm 0.010_{\rm MSSM}$
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[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
$\mathrm{BR}_{b\to s\gamma}^{\rm EXP/SM}$	[65]/ [66]	$0.988 \pm 0.045_{\rm EXP} \pm 0.068_{\rm TH,SM} \pm 0.050_{\rm TH,SUSY}$
$\mathrm{BR}_{B\to\tau\nu}^{\rm EXP/SM}$	[66,67]	$0.880 \pm 0.258_{\rm EXP} \pm 0.096_{\rm SM}$
$BR_{B\to X_s\ell\ell}^{\rm EXP/SM}$	[68]/ [66]	$0.966 \pm 0.278_{\rm EXP} \pm 0.037_{\rm SM}$
$\Delta M_{B_s}^{\rm EXP/SM}$	[34,69] / [66]	$0.933 \pm 0.061_{\rm EXP} \pm 0.078_{\rm SM}$
$\frac{\Delta M_{B_s}^{\rm EXP/SM}}{\Delta M_{B_d}^{\rm EXP/SM}}$	[34,69] / [66]	$1.007 \pm 0.004_{\rm EXP} \pm 0.116_{\rm SM}$
$BR_{K\to\mu\nu}^{\rm EXP/SM}$	[34,70] / [71]	$1.0005 \pm 0.0017_{\rm EXP} \pm 0.0093_{\rm TH}$
$BR_{K\to\pi\nu\bar{\nu}}^{\rm EXP/SM}$	[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 $(m_{\tilde\chi_1^0}, \sigma_p^{\rm SI})$ plane
$\sigma_p^{\rm SD}$	[4]	Likelihood in the $(m_{\tilde\chi^0}, \sigma_p^{\rm SD})$ plane
$\tilde g \to q\bar q\tilde\chi_1^0, b\bar b\tilde\chi_1^0, t\bar t\tilde\chi_1^0$	[16,17]	Combined likelihood in the $(m_{\tilde g}, m_{\tilde\chi_1^0})$ plane
$\tilde q \to q\tilde\chi_1^0$	[16]	Likelihood in the $(m_{\tilde q}, m_{\tilde\chi_1^0})$ plane
$\tilde b \to b\tilde\chi_1^0$	[16]	Likelihood in the $(m_{\tilde b}, m_{\tilde\chi_1^0})$, plane
$\tilde t_1 \to t\tilde\chi_1^0, c\tilde\chi_1^0, b\tilde\chi_1^\pm$	[16]	Likelihood in the $(m_{\tilde t_1}, m_{\tilde\chi_1^0})$, plane
$\tilde\chi_1^\pm \to \nu\ell^\pm\tilde\chi_1^0, \nu\tau^\pm\tilde\chi_1^0, W^\pm\tilde\chi_1^0$	[18]	Likelihood in the $(m_{\tilde\chi_1^\pm}, m_{\tilde\chi_1^0})$ plane
$\tilde\chi_2^0 \to \ell^+\ell^-\tilde\chi_1^0, \tau^+\tau^-\tilde\chi_1^0, Z\tilde\chi_1^0$	[18]	Likelihood in the $(m_{\tilde\chi_2^0}, m_{\tilde\chi_1^0})$ 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

Best-Fit Sparticle Spectrum

Phenomenological MSSM

Fit including g_μ-2



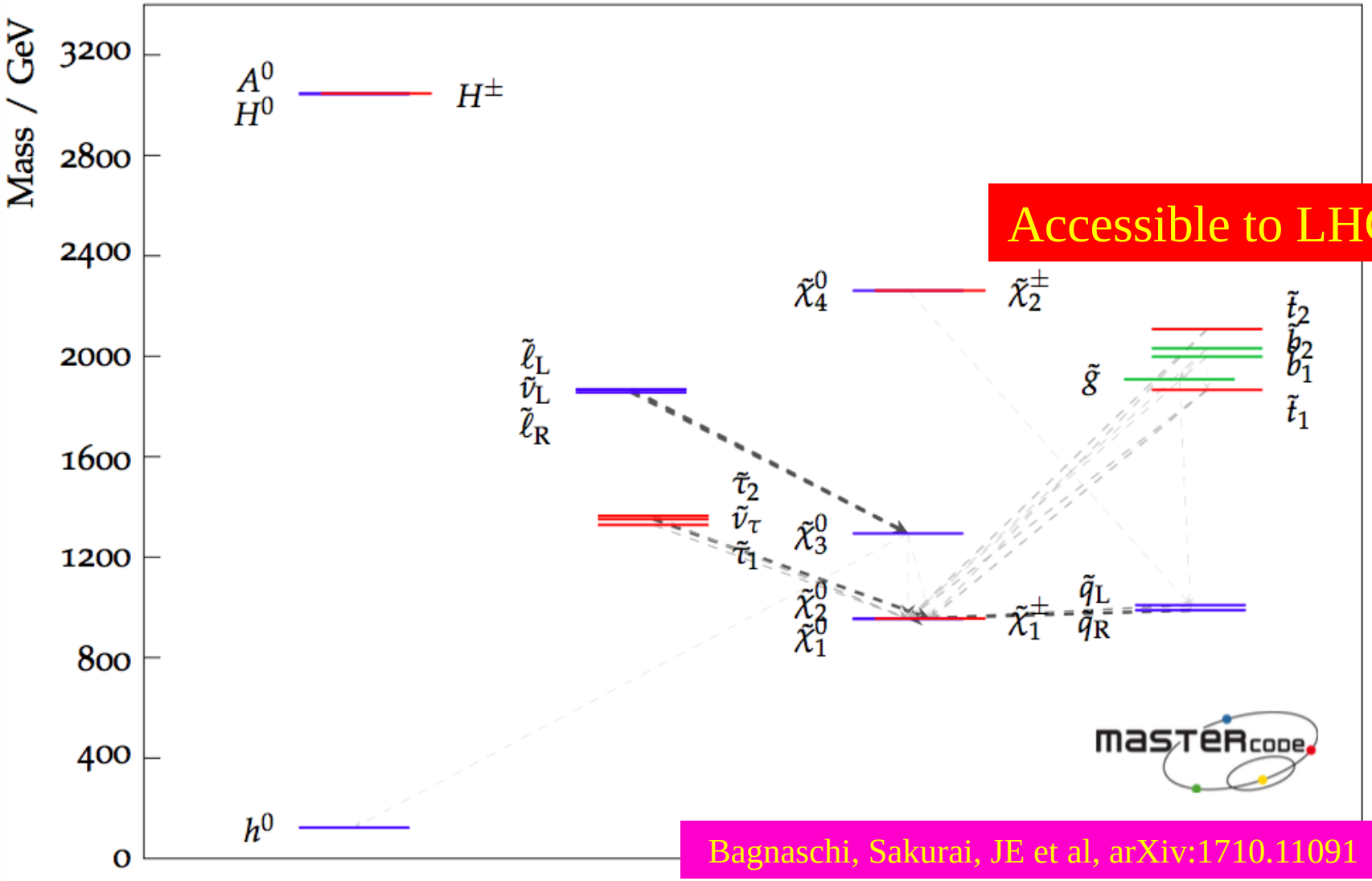
Accessible to LHC?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Best-Fit Sparticle Spectrum

Phenomenological MSSM

Fit excluding g_μ-2

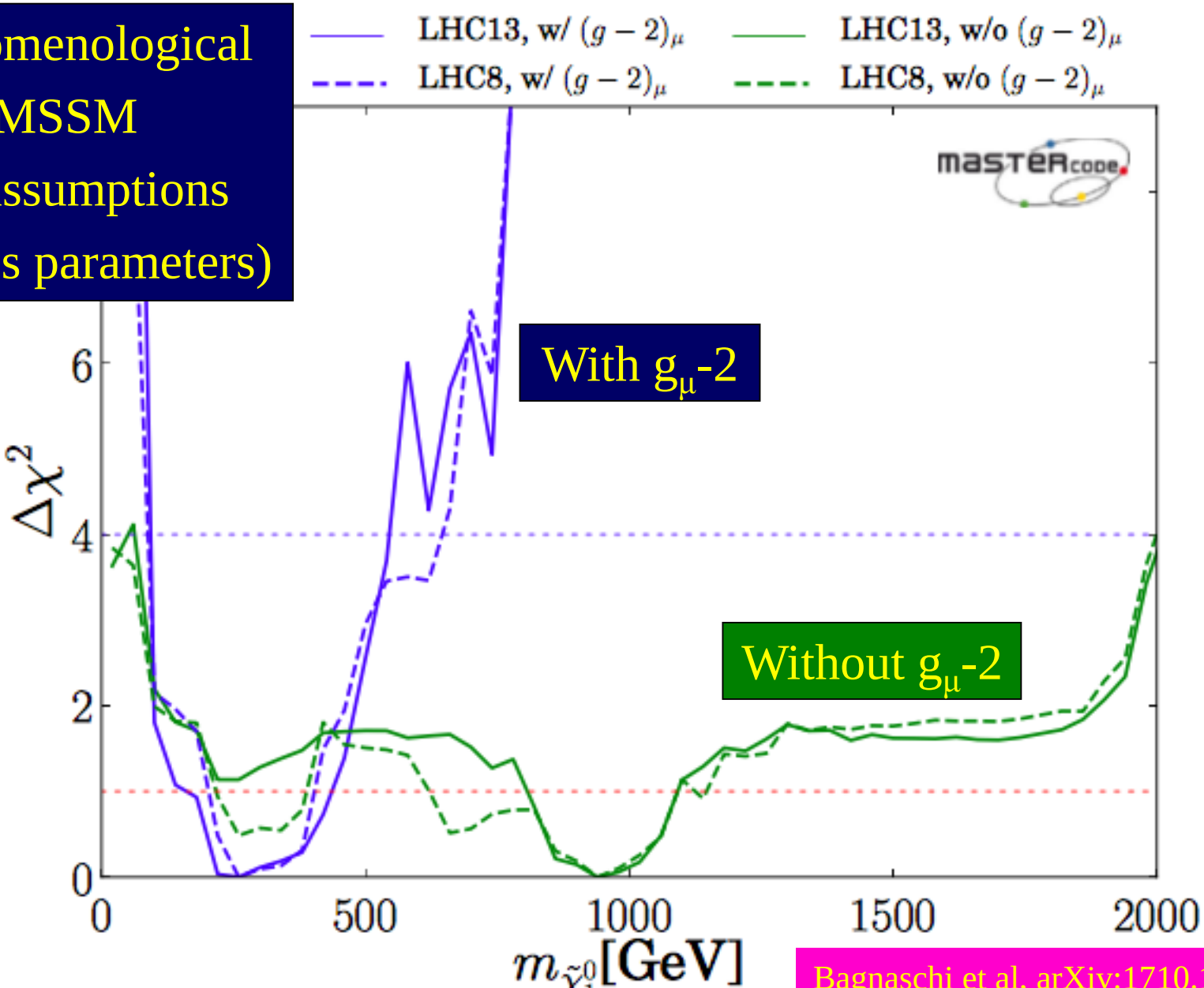


Accessible to LHC?

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Likelihood for LSP Mass

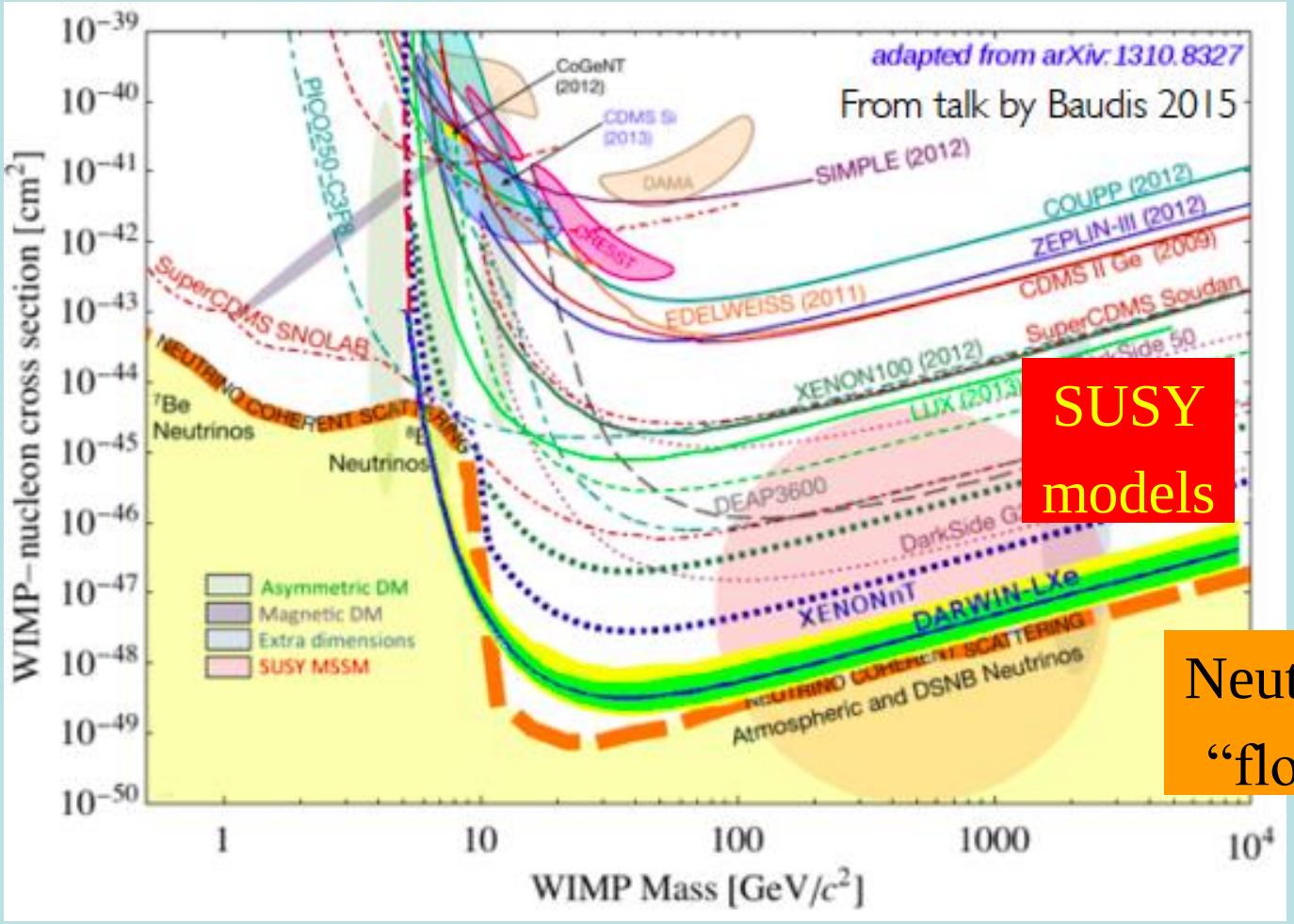
Phenomenological MSSM (no assumptions on mass parameters)



Bagnaschi et al. arXiv:1710.11091

Direct Dark Matter Searches

- Compilation of present and future sensitivities

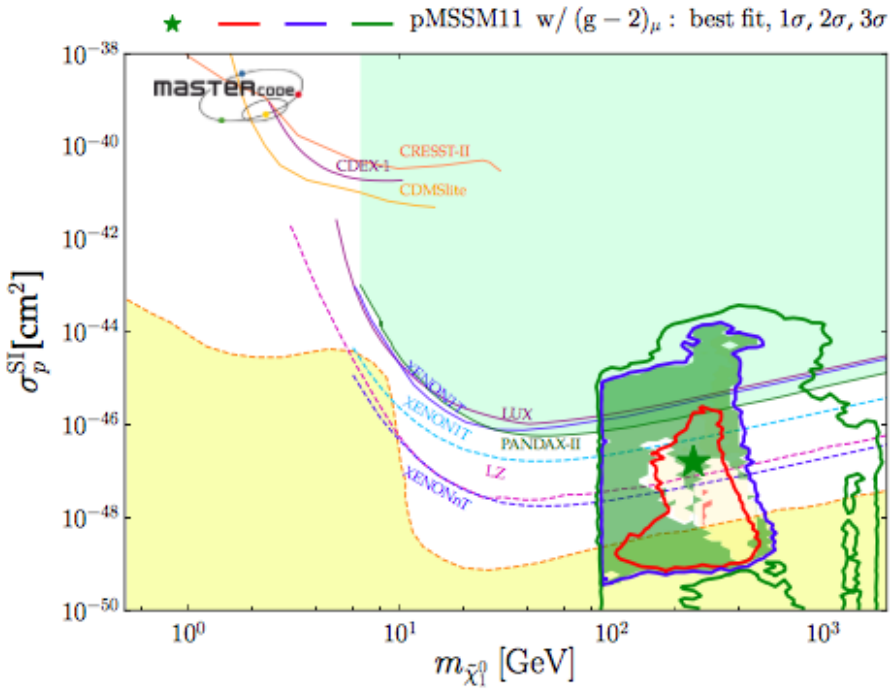


Direct Dark Matter Searches

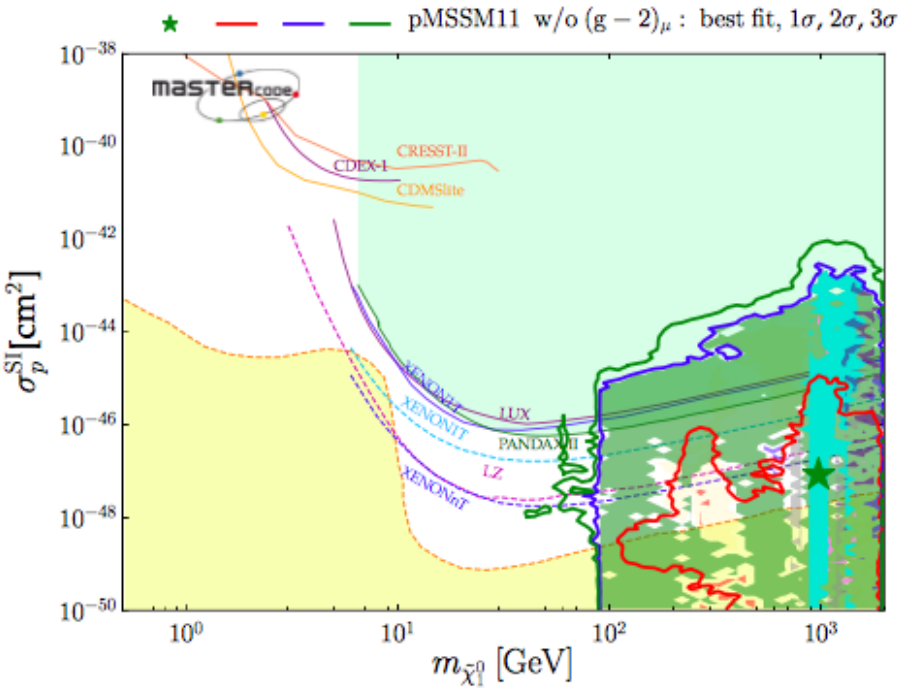
Phenomenological MSSM

Spin-Independent Scattering

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

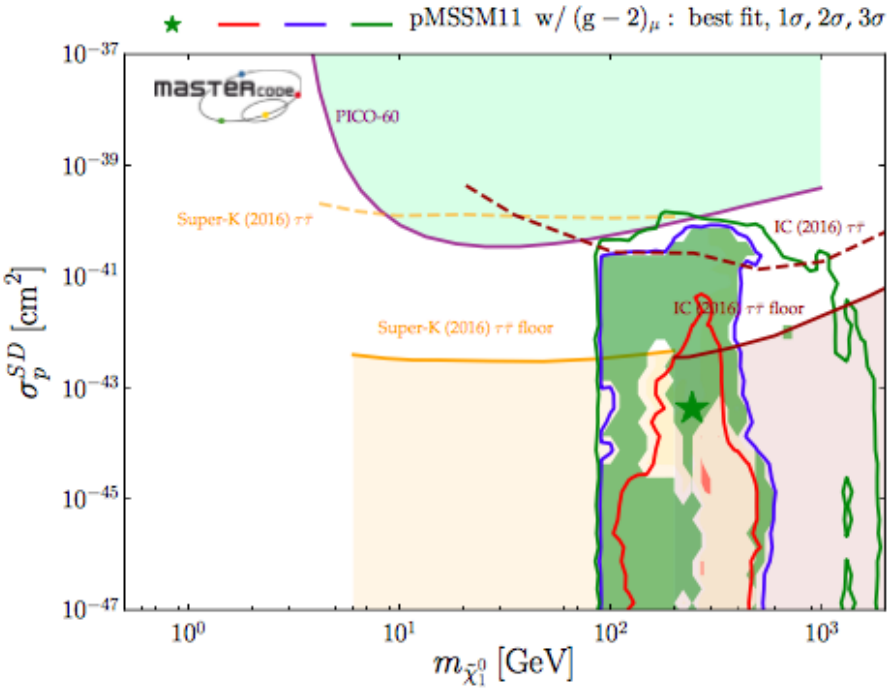
Direct Dark Matter Searches

Phenomenological MSSM

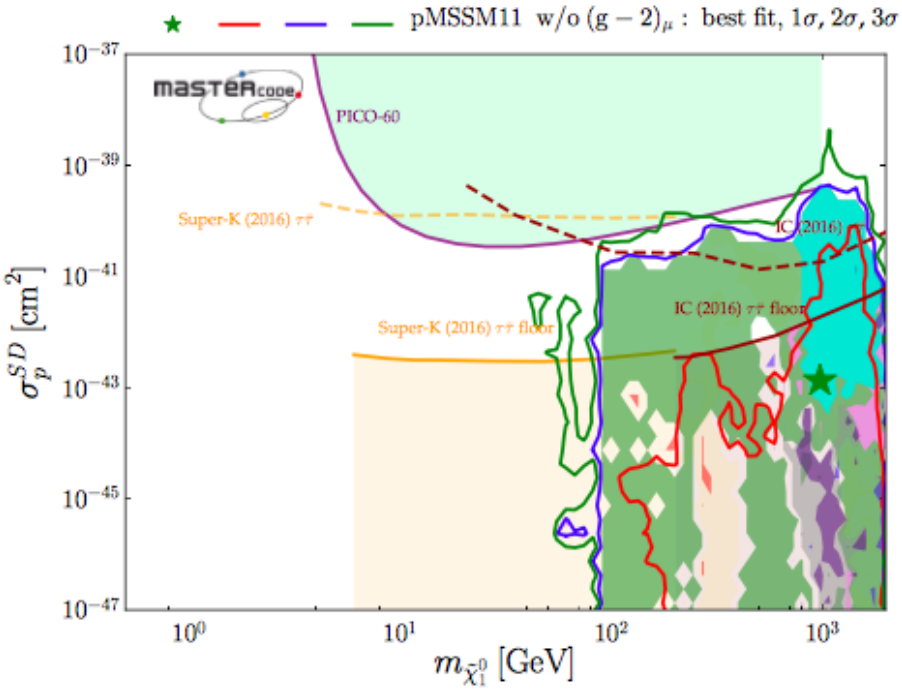
Spin-Dependent Scattering

sensitive to quark contributions to nucleon spin

With g_μ-2



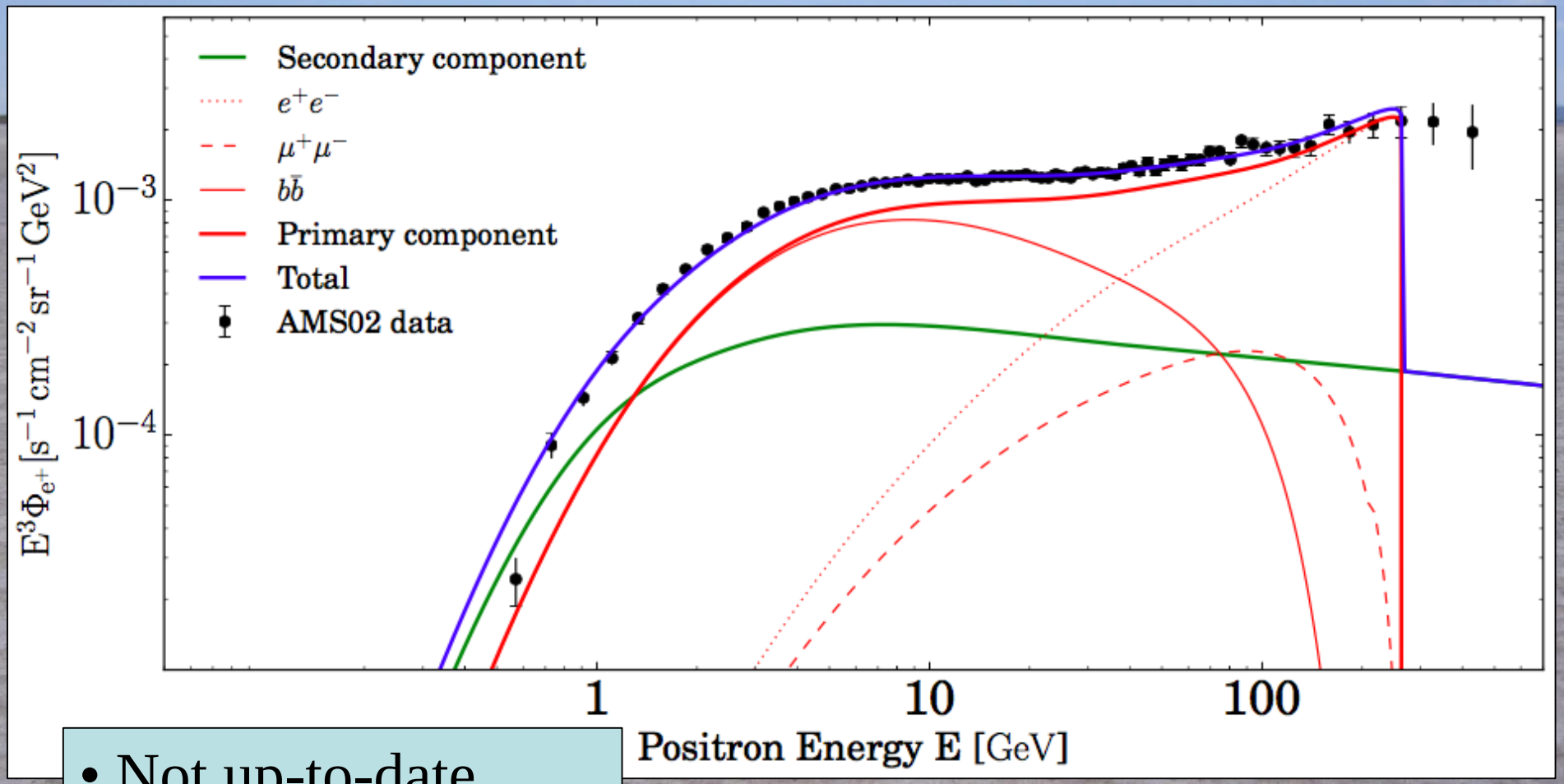
Without g_μ-2



$\tilde{\chi}_1^\pm$ coann.	slep coann.	gluino coann.	stop coann.
A/H funnel	stau coann.	squark coann.	sbot coann.

Bagnaschi, Sakurai, JE et al, arXiv:1710.11091

Dark Matter Models for e^+ Spectrum

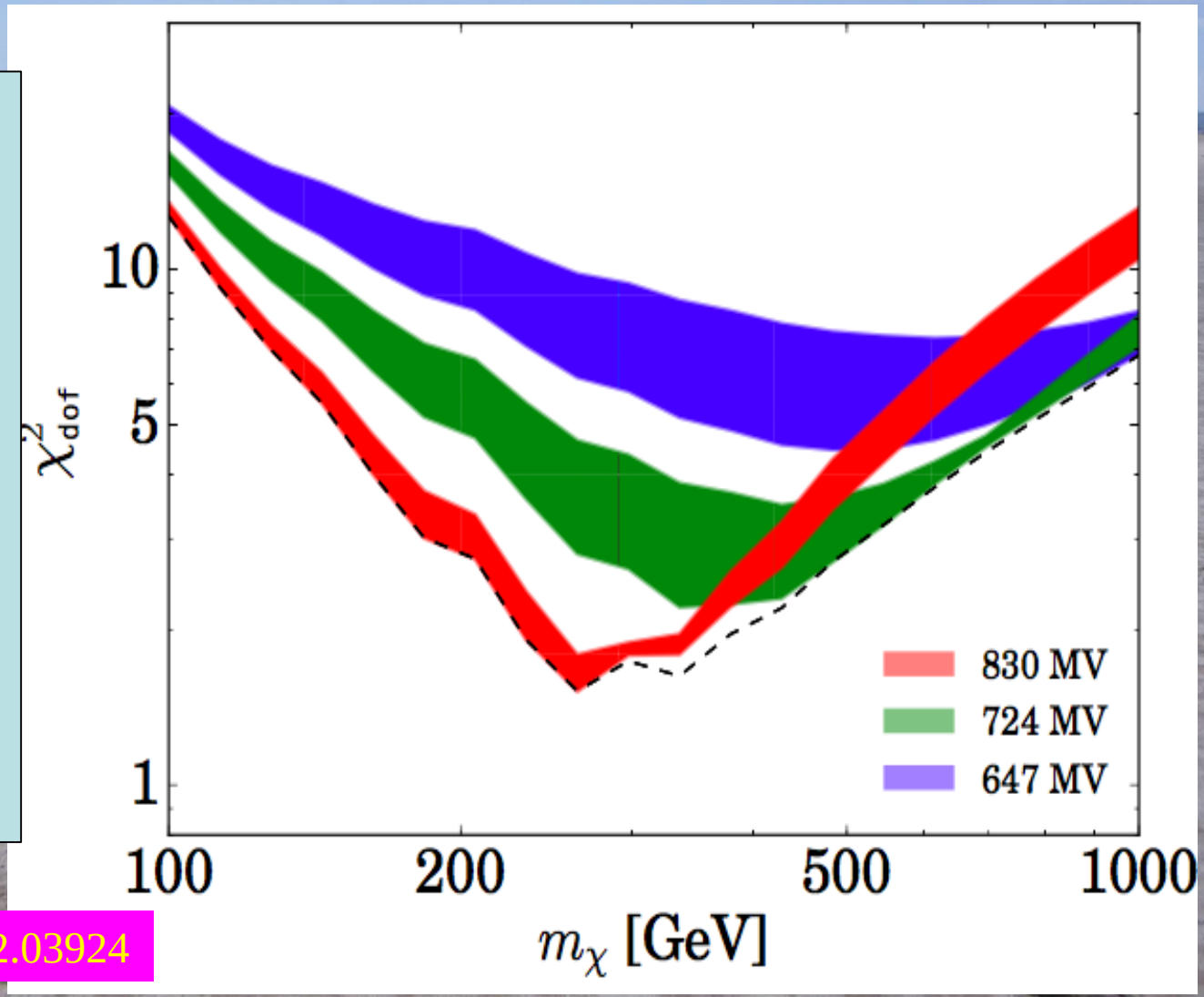


- Not up-to-date
- Illustrates problems

Boudeaud et al., arXiv:1612.03924

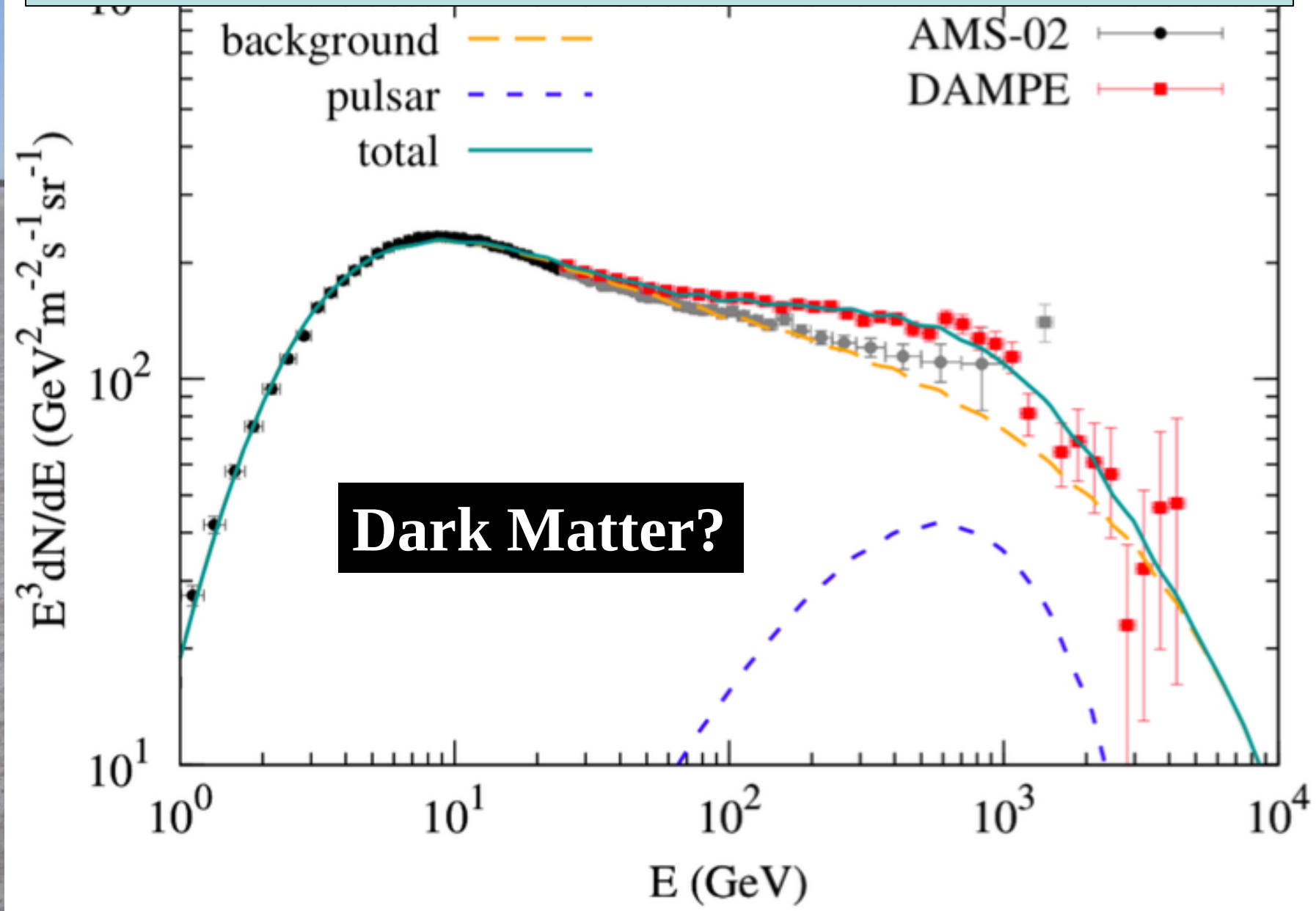
Fits to DM Annihilations

- 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

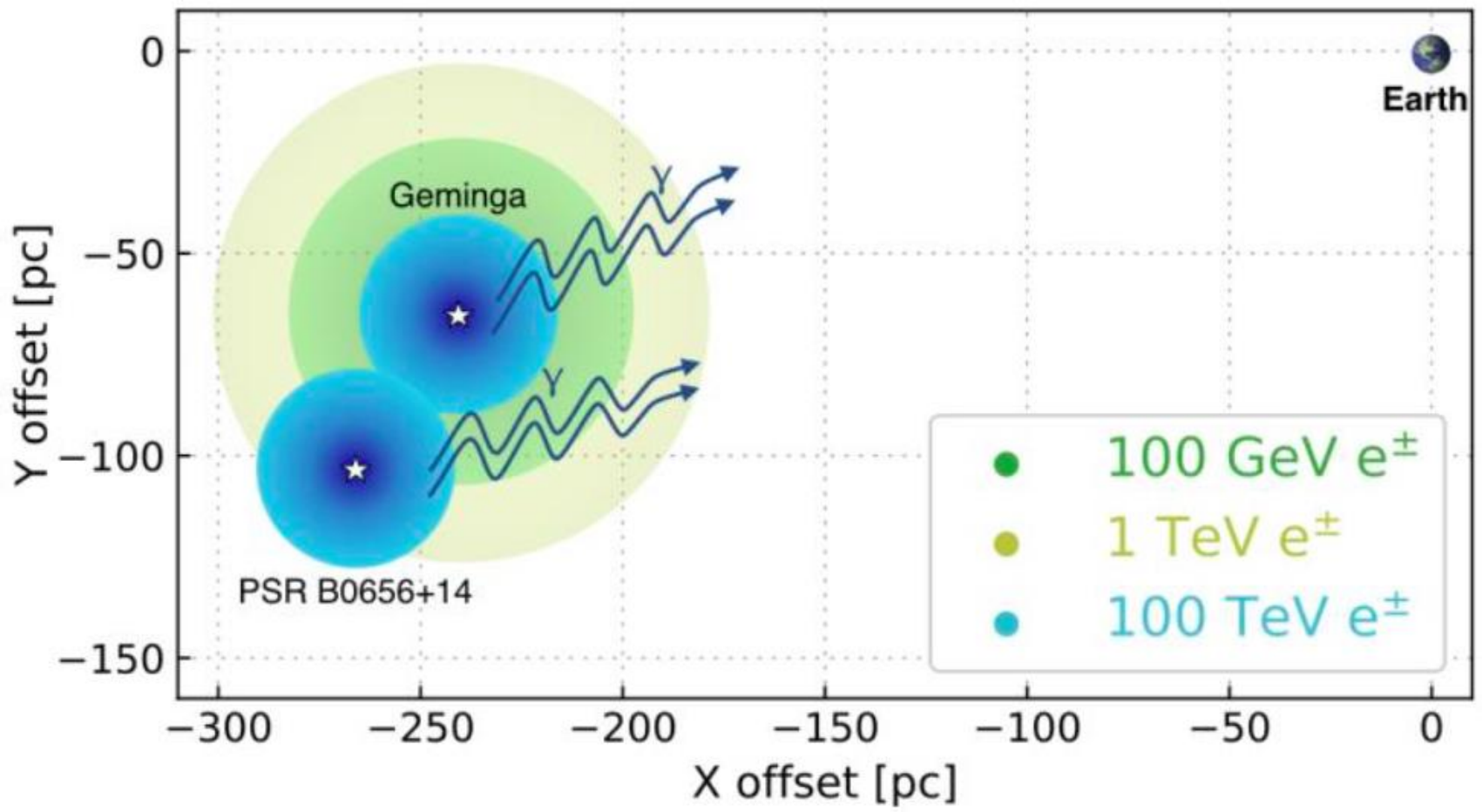
Cosmic-Ray Positrons



HAWC Collaboration, DOI:10.1126/science.aan4880

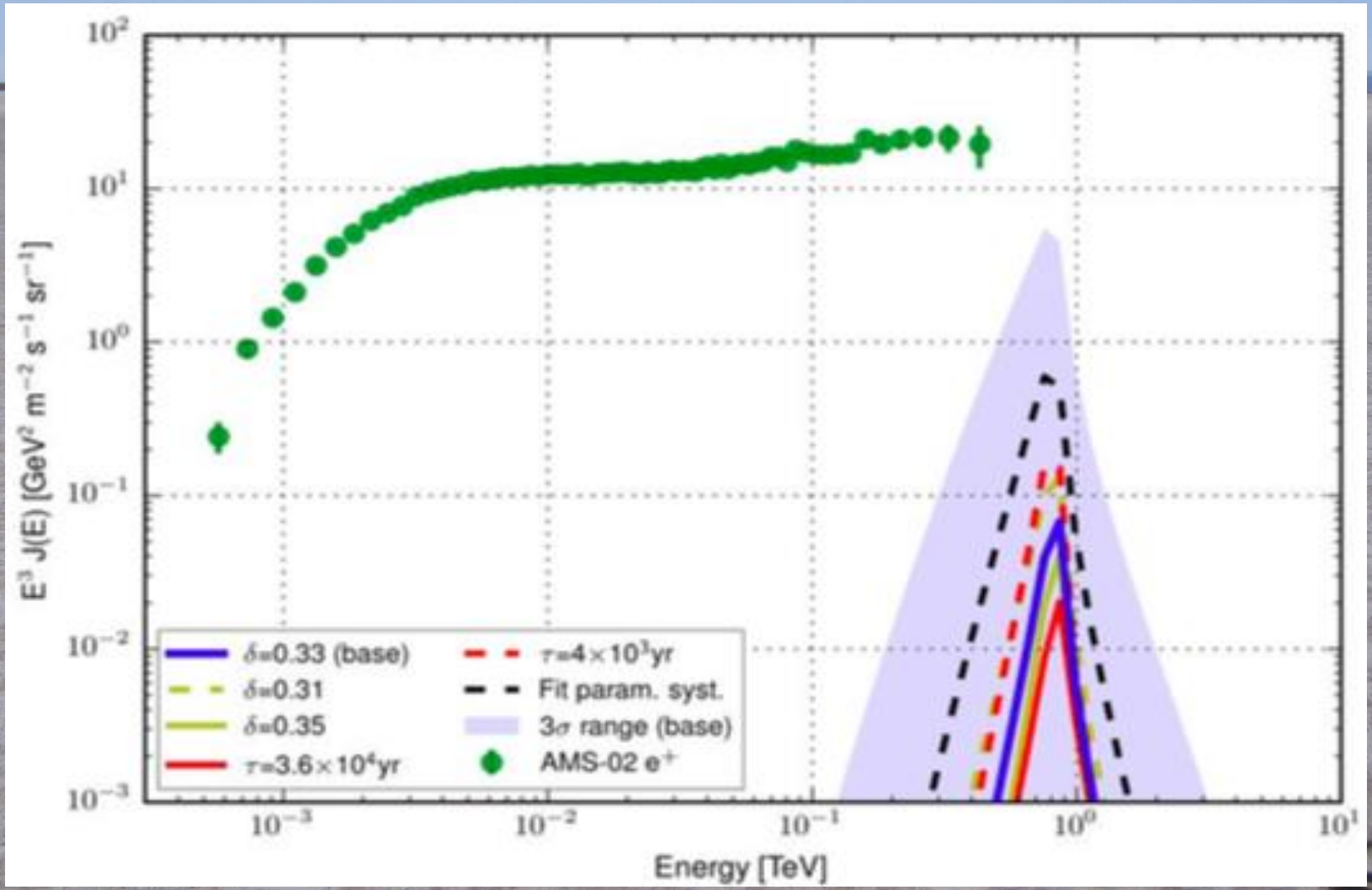
Diffuse γ Emission near Pulsars

- Absrorption of lower-energy γ



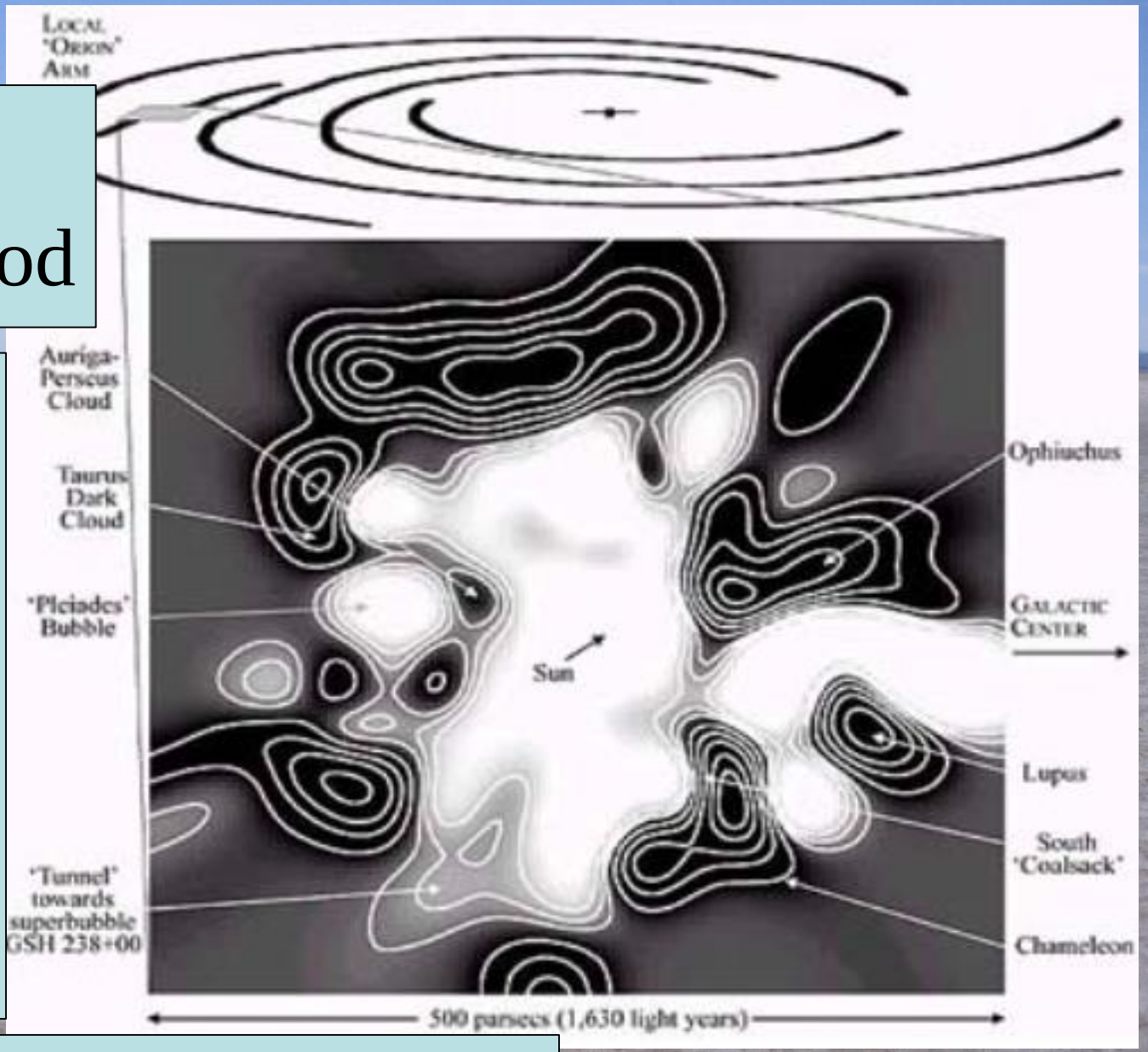
HAWC Collaboration, DOI:10.1126/science.aan4880

Effect on Pulsar Positron Spectrum



A Tough Neighbourhood

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

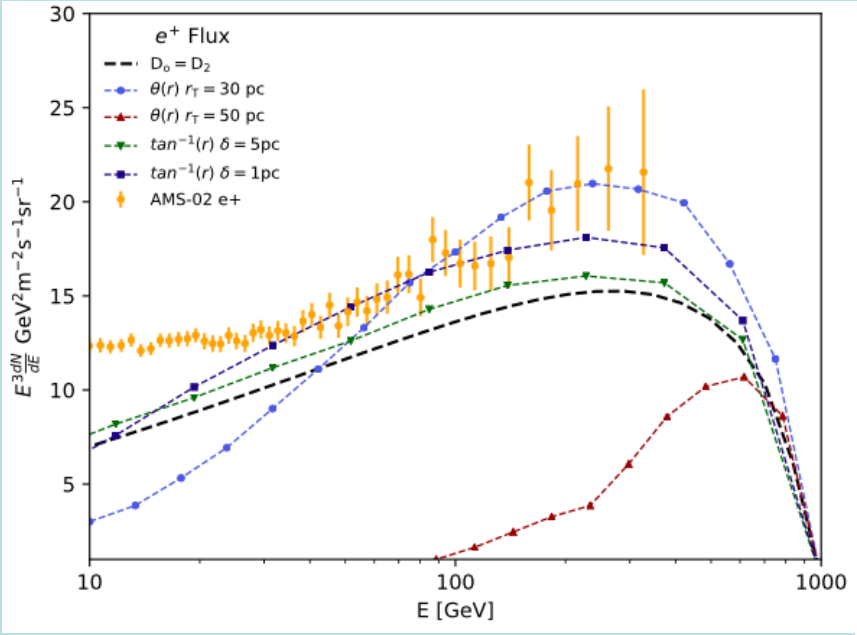


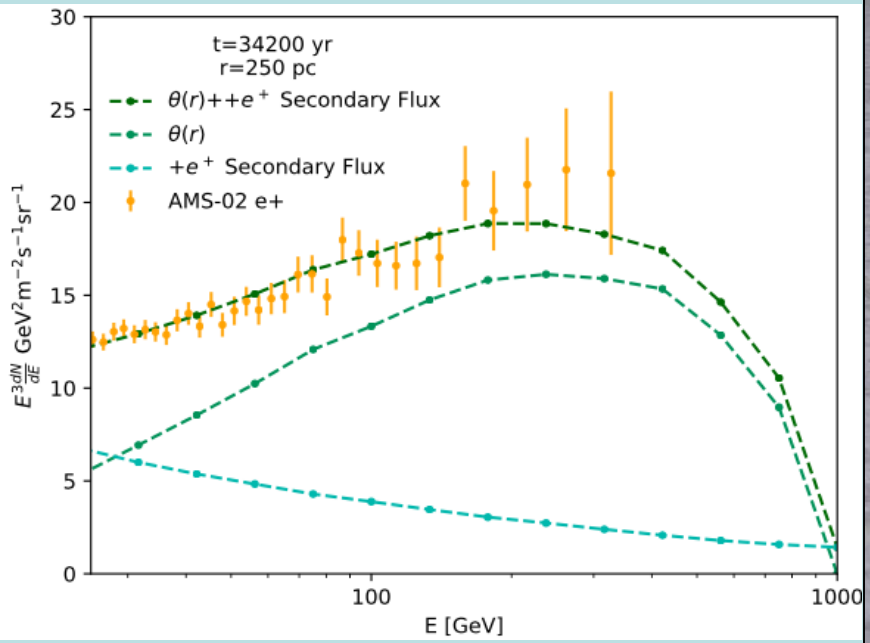
“16 supernovae have exploded during the past 13 million years within the boundaries of the Local Bubble.”

Breitschwerdt et al, Nature 532, 73 (2016)

Inhomogeneous Diffusion Coefficient?

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

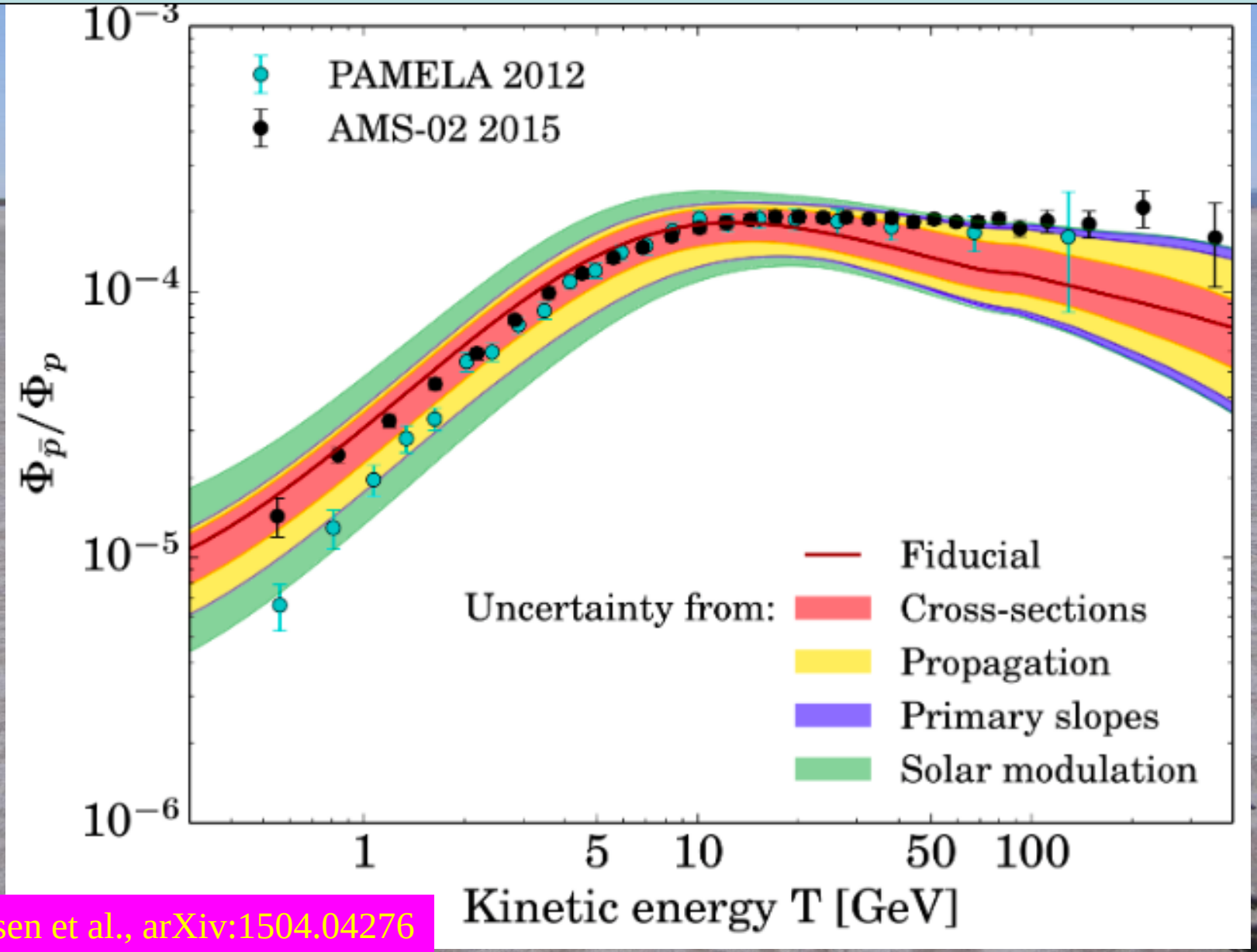




- Better fit including secondary production

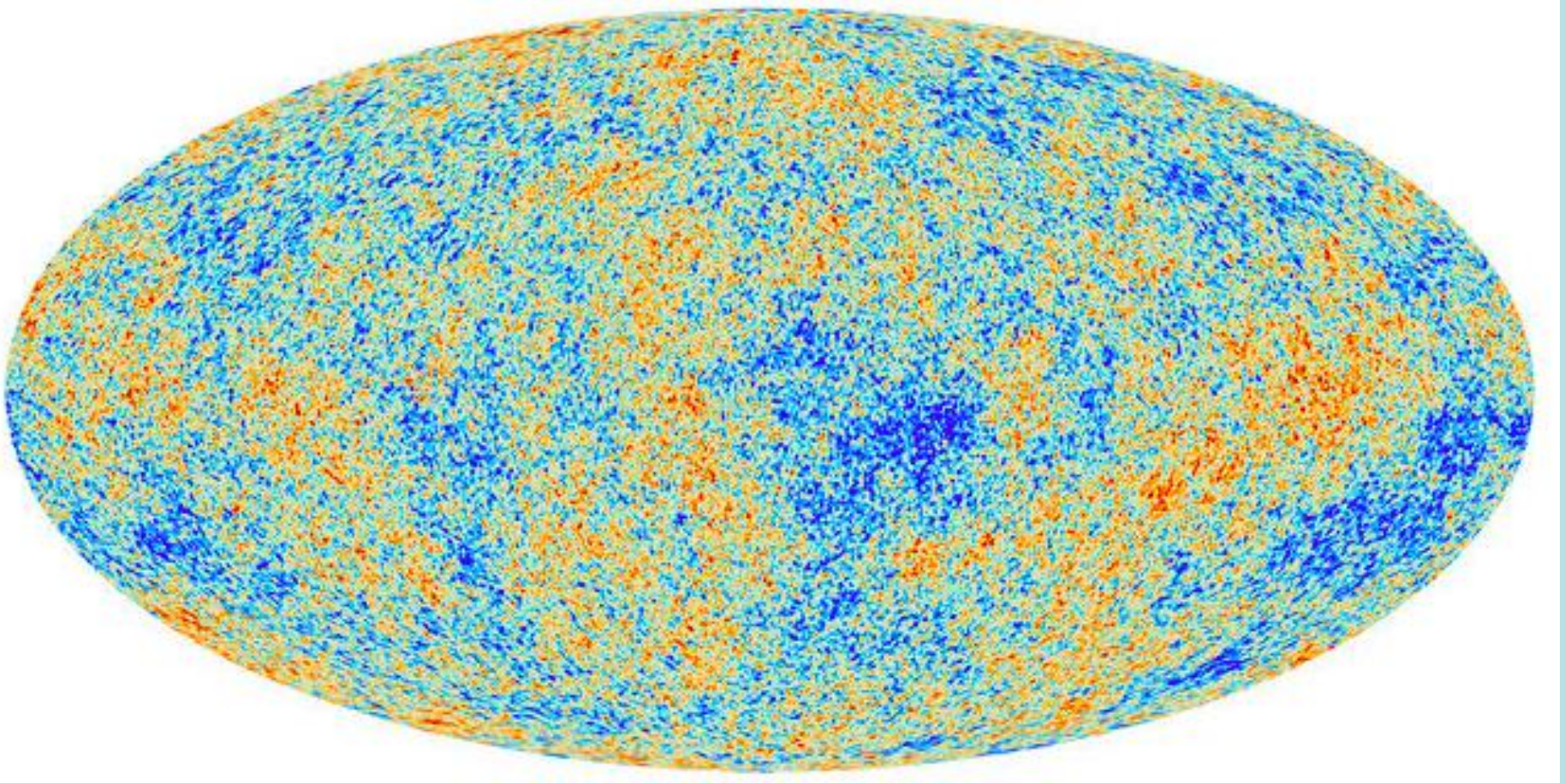
Profumo, ReynosCordova, Kaaz & Silverman, arXiv:1803.09731

Antiprotons Compatible with Cosmic Rays



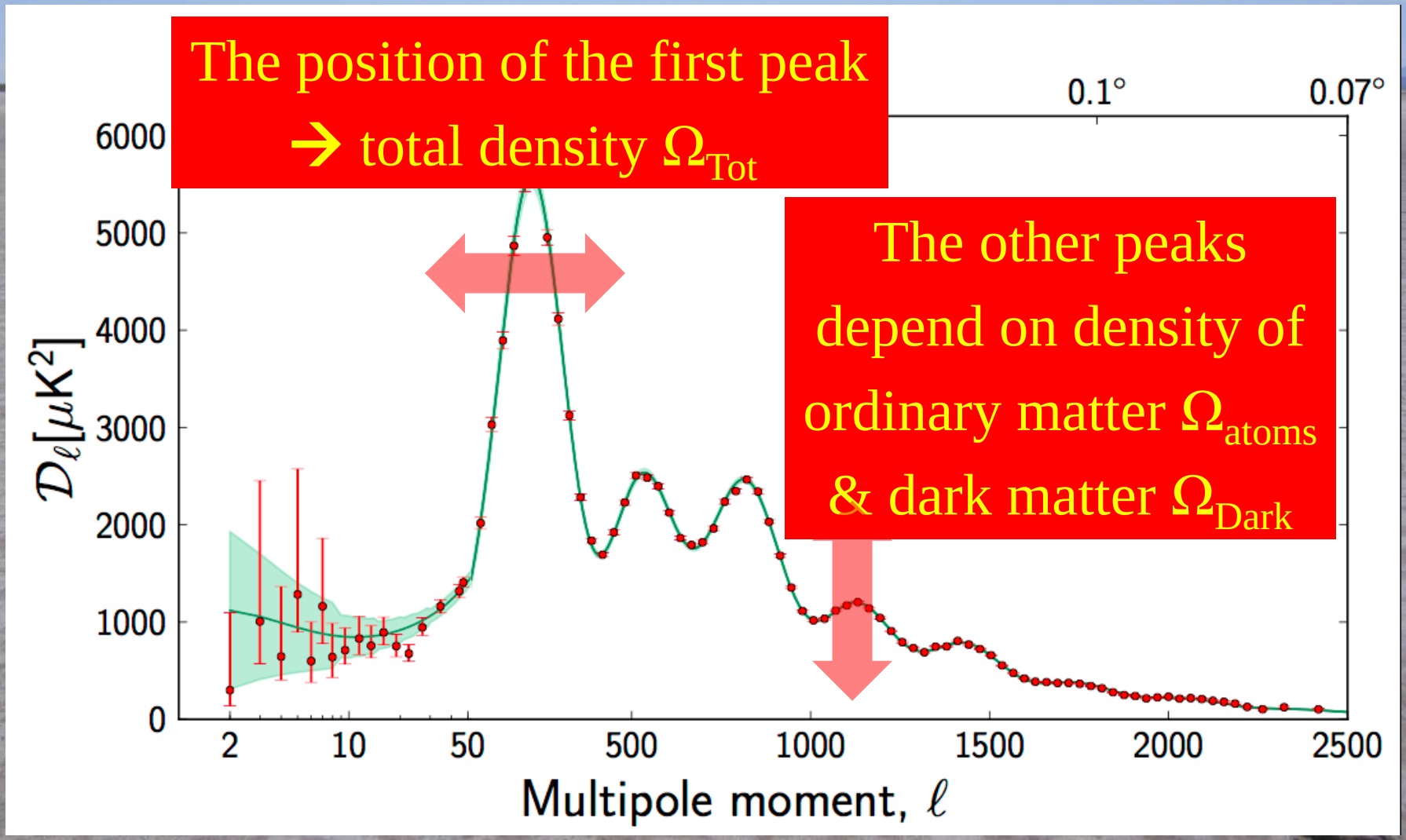
Giesen et al., arXiv:1504.04276

Cosmological Inflation in Light of Planck



A scalar in the sky? Supersymmetry/supergravity?

The Spectrum of Fluctuations in the Cosmic Microwave Background

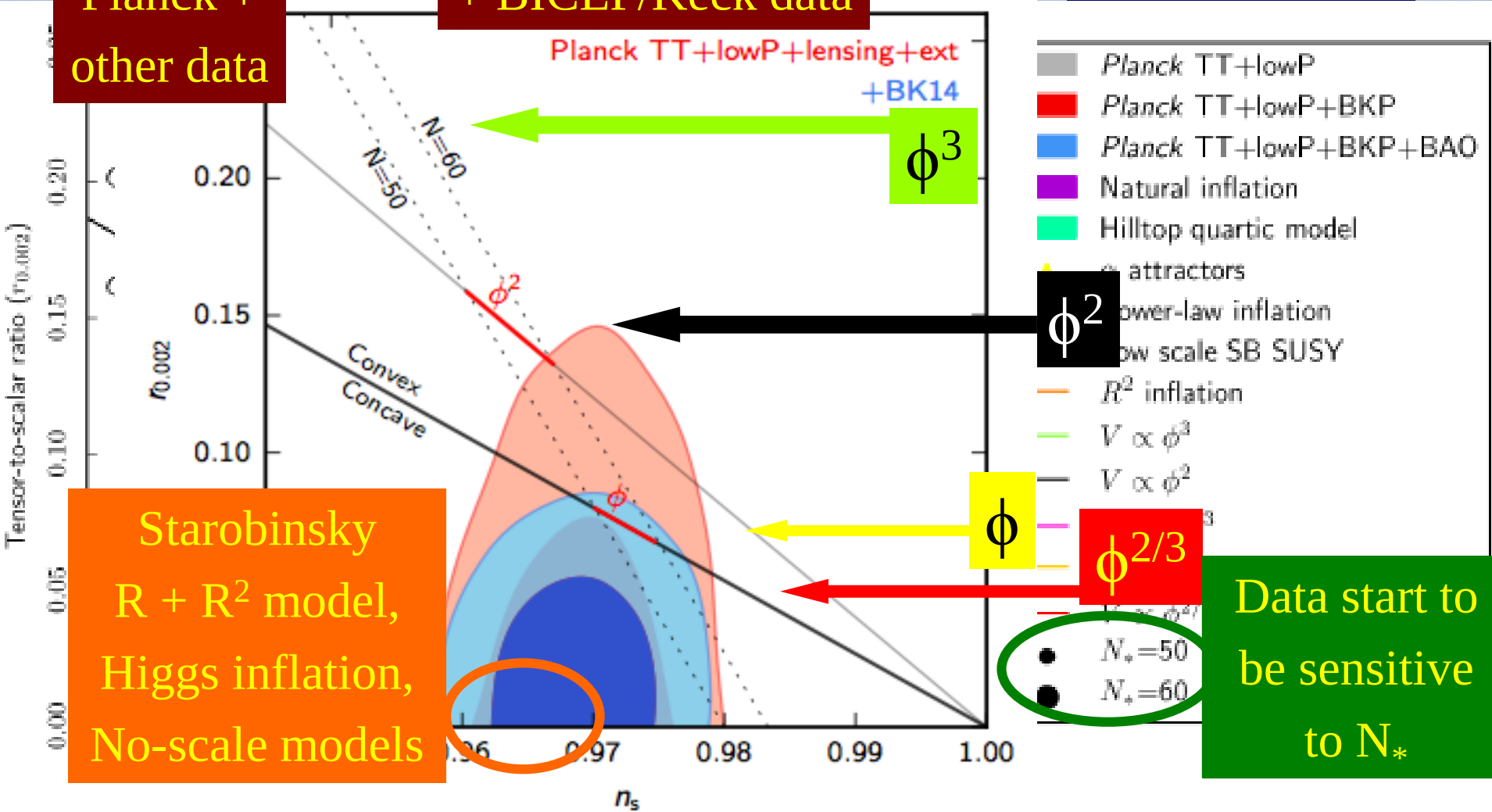


Inflationary Landscape

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:

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

- Consider case $1 \ll \sqrt{\xi} \ll 10^{17}$: 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 $\chi \gg M_P$

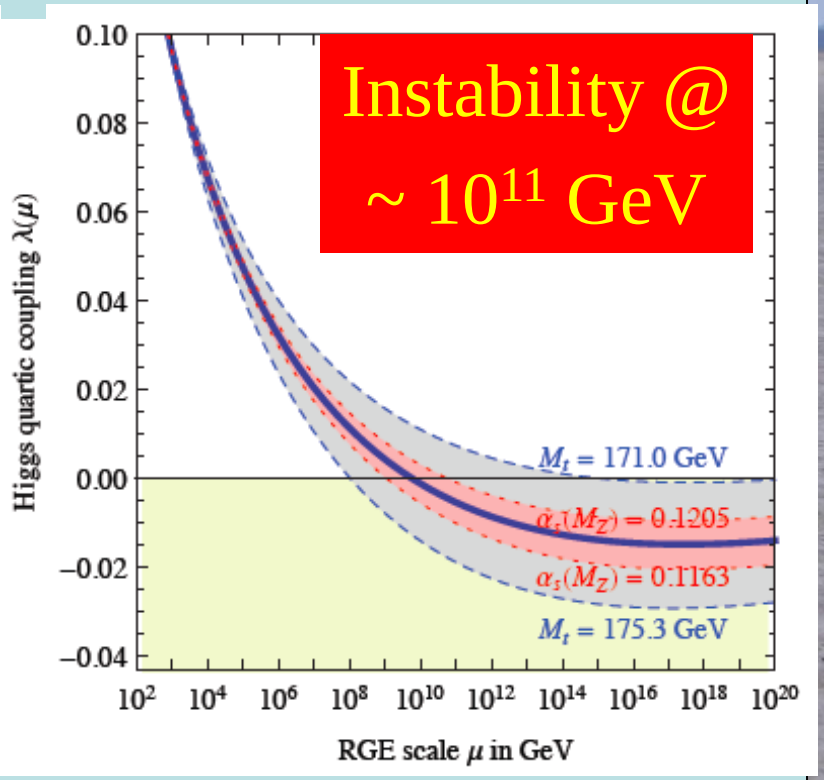
Problem for Higgs Inflation

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

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

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

- 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

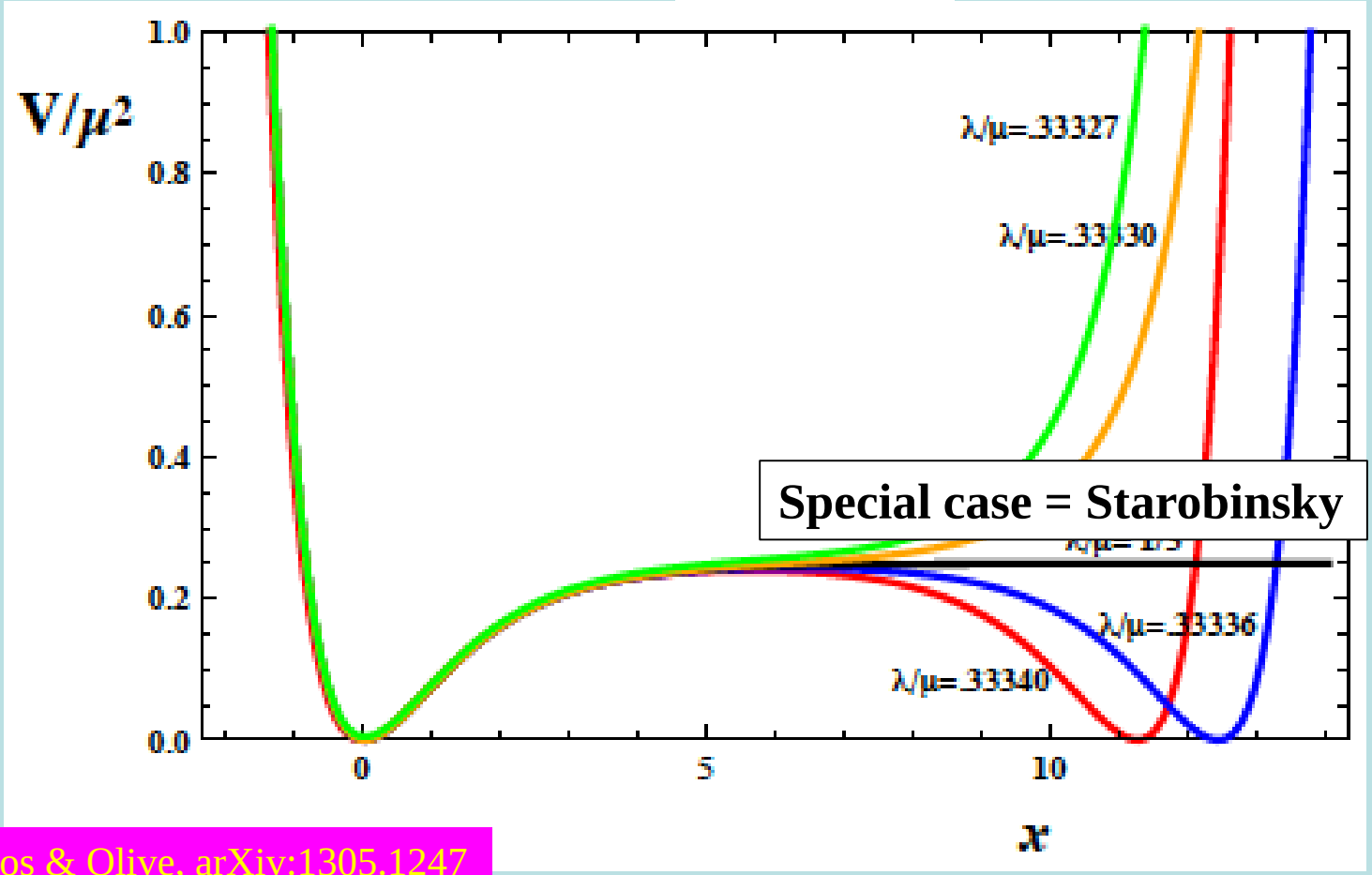
$$\mathcal{L}_{eff} = \frac{c}{(c - |\phi|^2/3)^2}|\partial_\mu \phi|^2 - \frac{\hat{V}}{(c - |\phi|^2/3)^2} \qquad \hat{V} \equiv \left|\frac{\partial W}{\partial \phi}\right|^2$$

:

- Modifications to globally supersymmetric case
- Good inflation possible …

No-Scale Supergravity Inflation

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



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

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

- In no-scale supergravity models:

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

Amplitude of perturbations

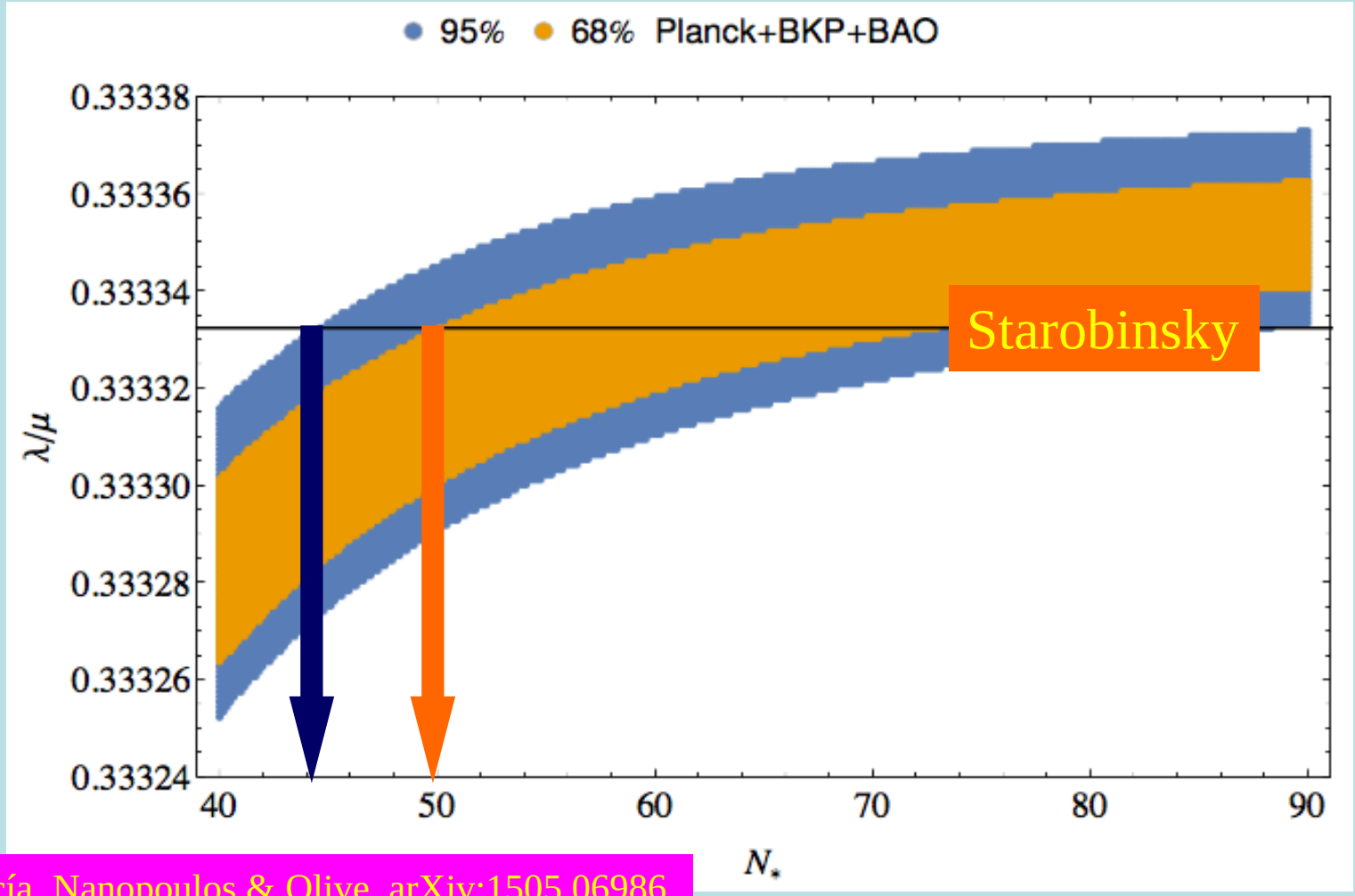
Equation of state during inflaton decay

Inflaton decay rate

- **Prospective constraint on inflaton models?**

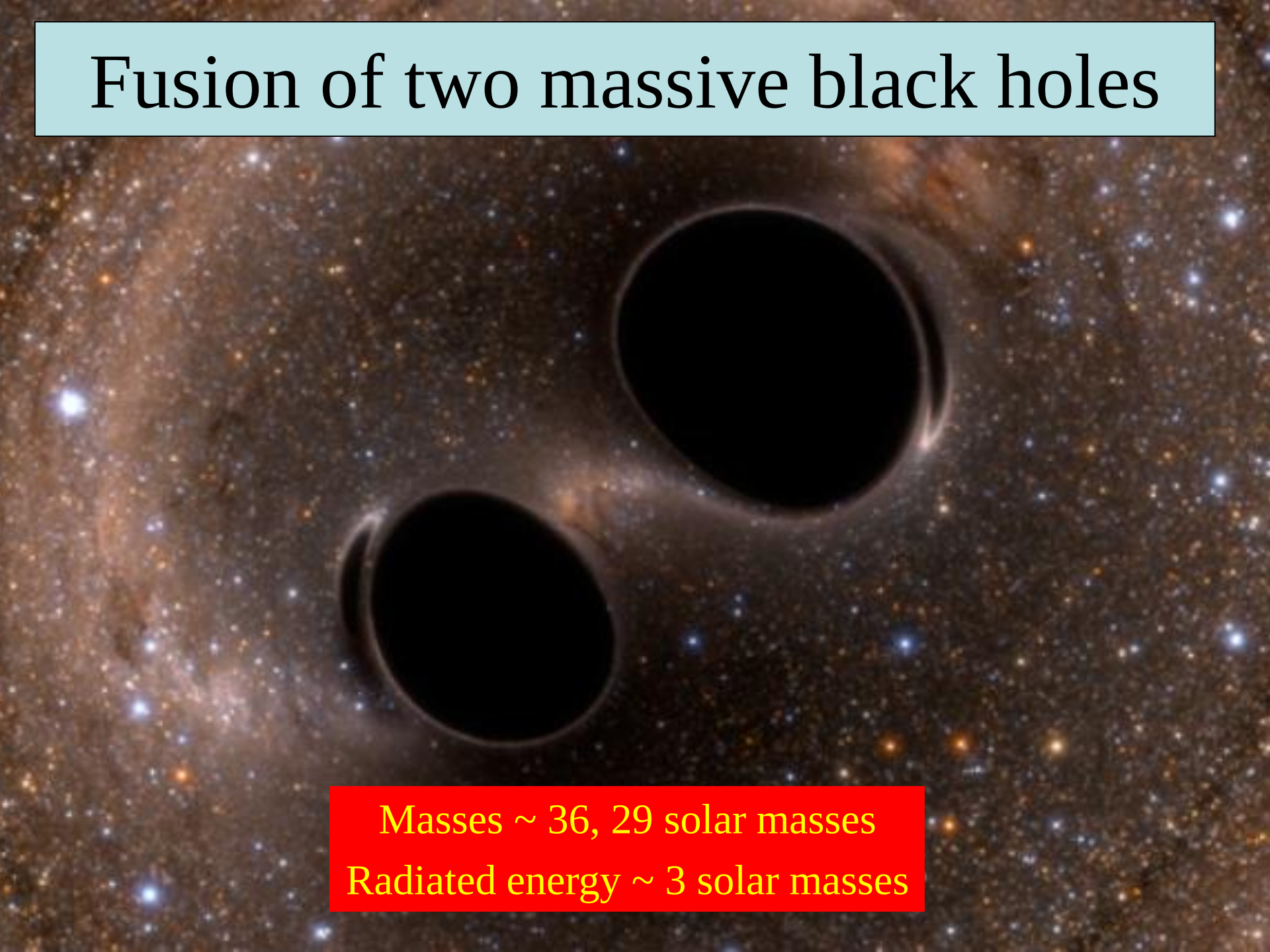
Planck Constraints on # of e-Folds

- Starobinsky-like no-scale models



JE, García, Nanopoulos & Olive, arXiv:1505.06986

Fusion of two massive black holes

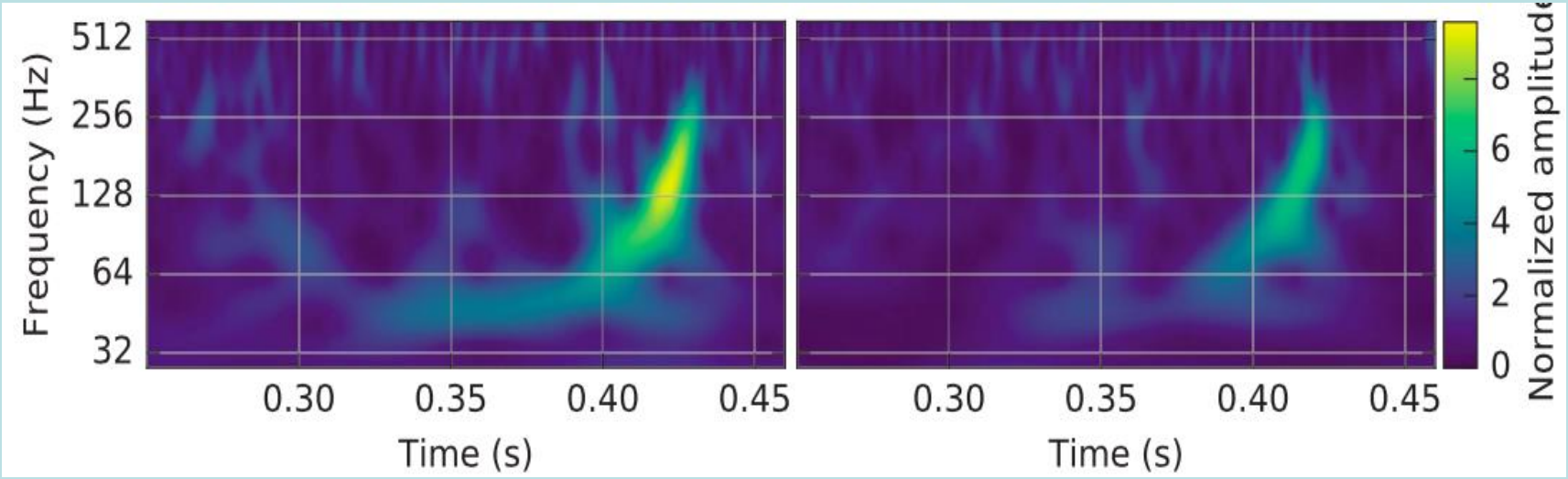


Masses ~ 36, 29 solar masses

Radiated energy ~ 3 solar masses

The Gravitational Chirp …

- … heard around the world

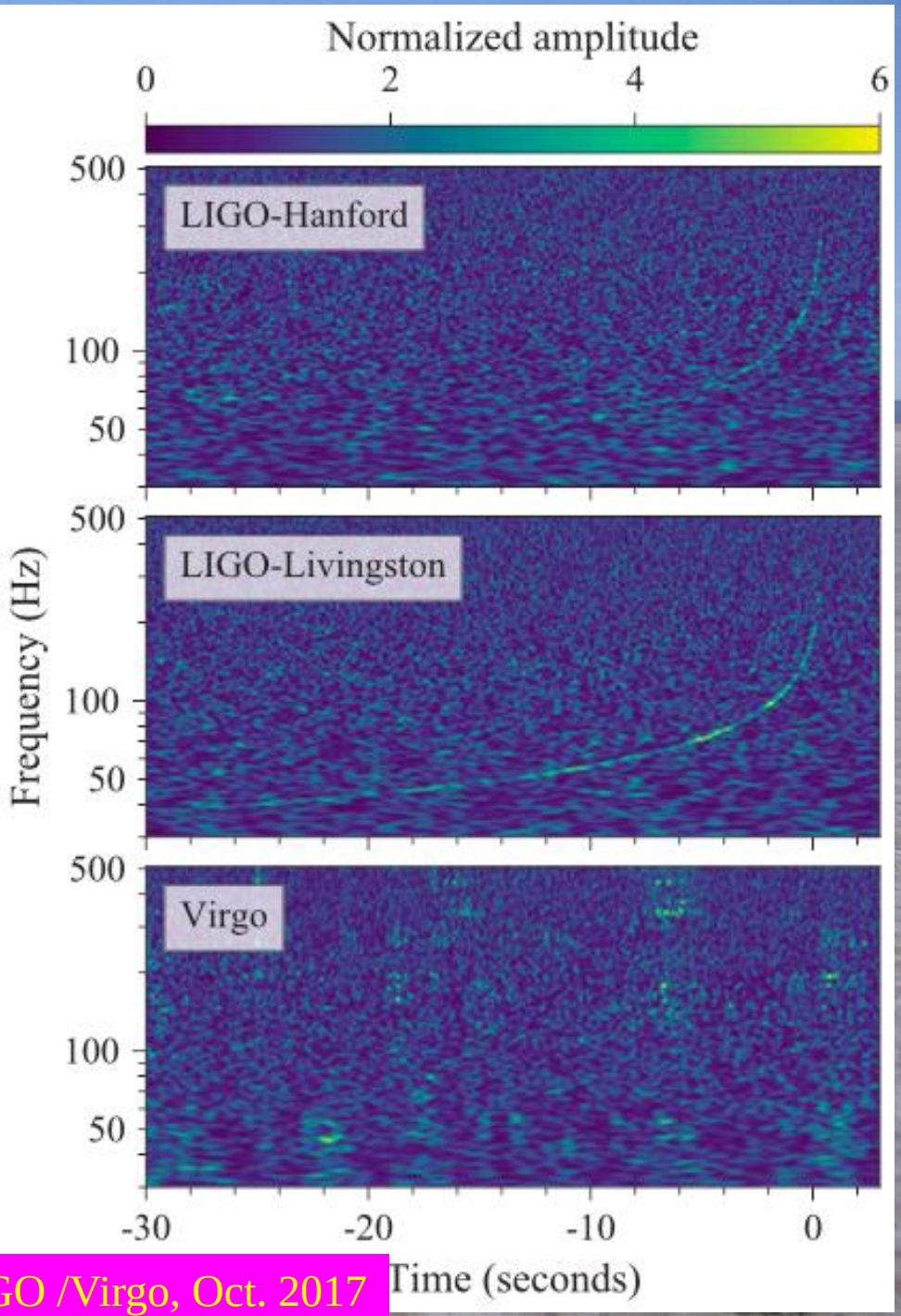


- Frequency increases with time during inspiral
- Followed by ringdown of combined black hole
- Graviton mass < 10^{-27} × mass of electron LIGO
- GWs of different frequencies have same speed

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

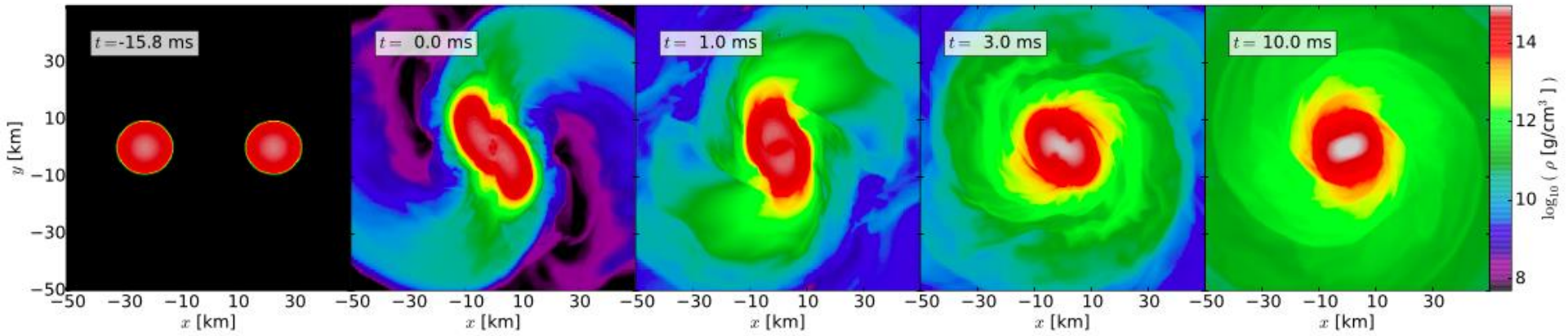
Search for Dark Matter in NS-NS Mergers?

Crazy ideas for dark matter signatures

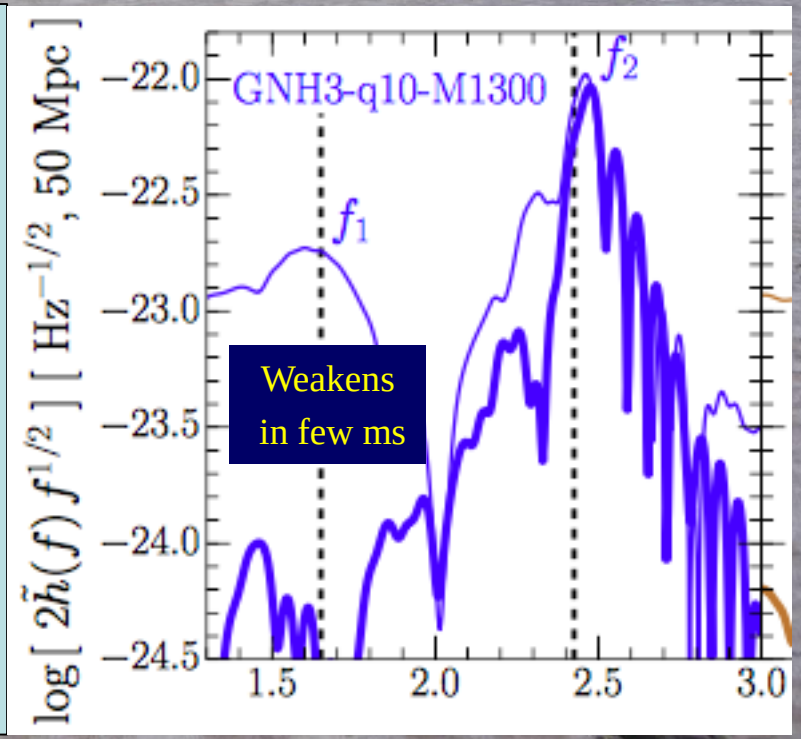
JE, Hektor, Hütsi, Kannike, Marzola, Raidal & Vaskonen, arXiv:1710.05540

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

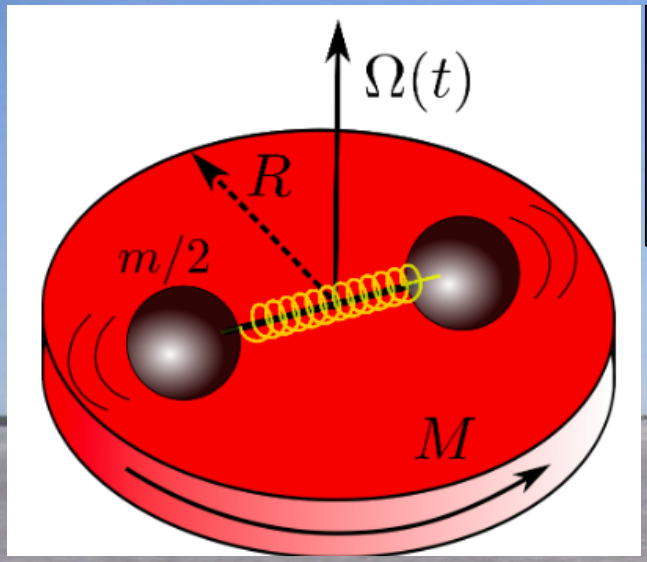
What Happens after the Merger?



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

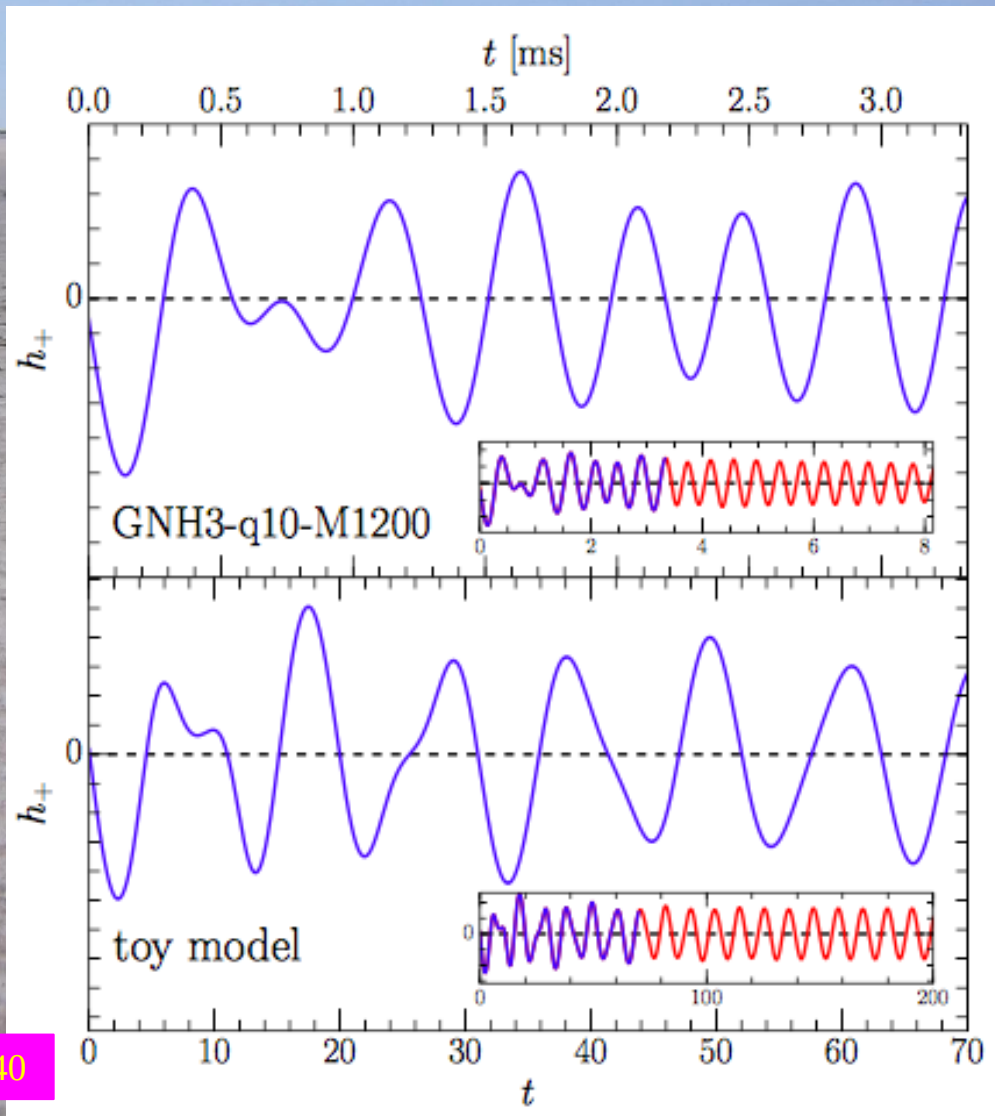


Takami, Rezzolla & Baiotti, arXiv:1403.56720, 1412.3240

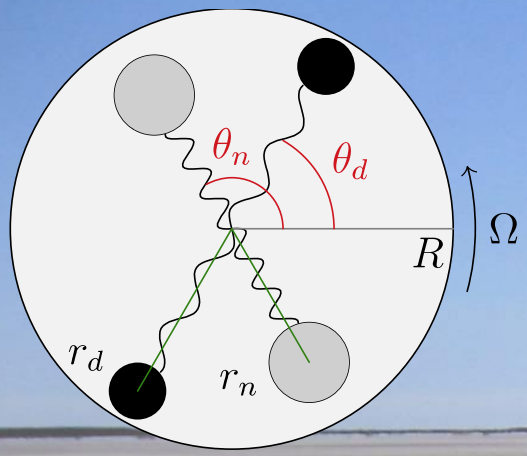


Toy Mechanical Model

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



Takami, Rezzolla & Baiotti, arXiv:1403.56720, 1412.3240

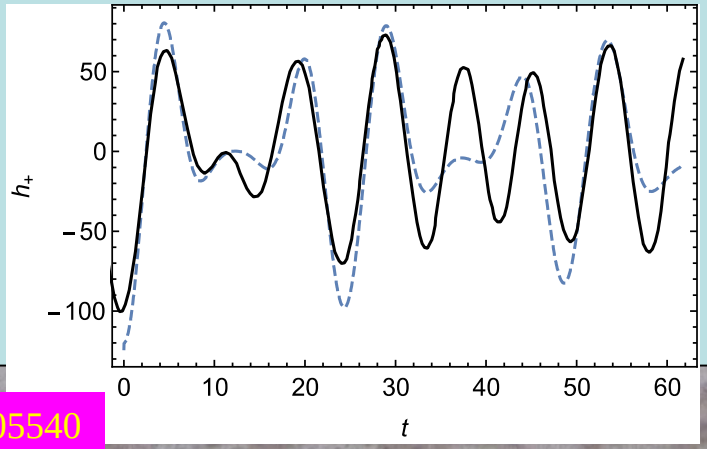


Including Dark Matter

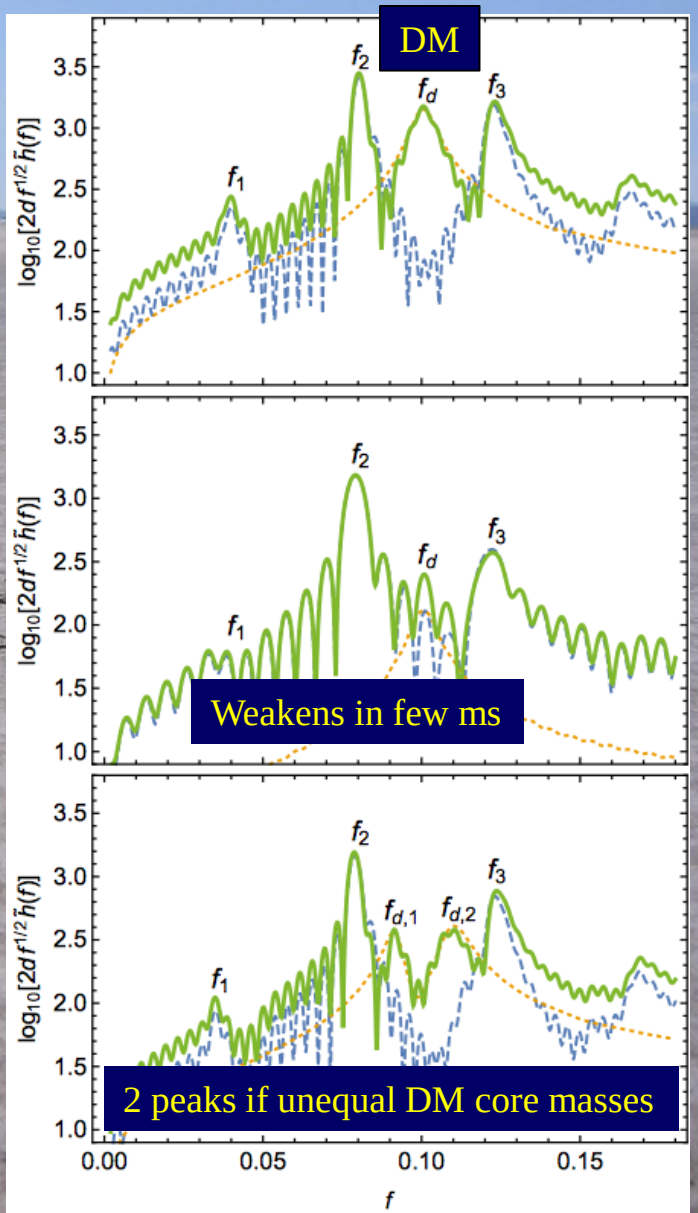
- Two pairs of oscillating cores

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

- Reproduce results when no DM



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:

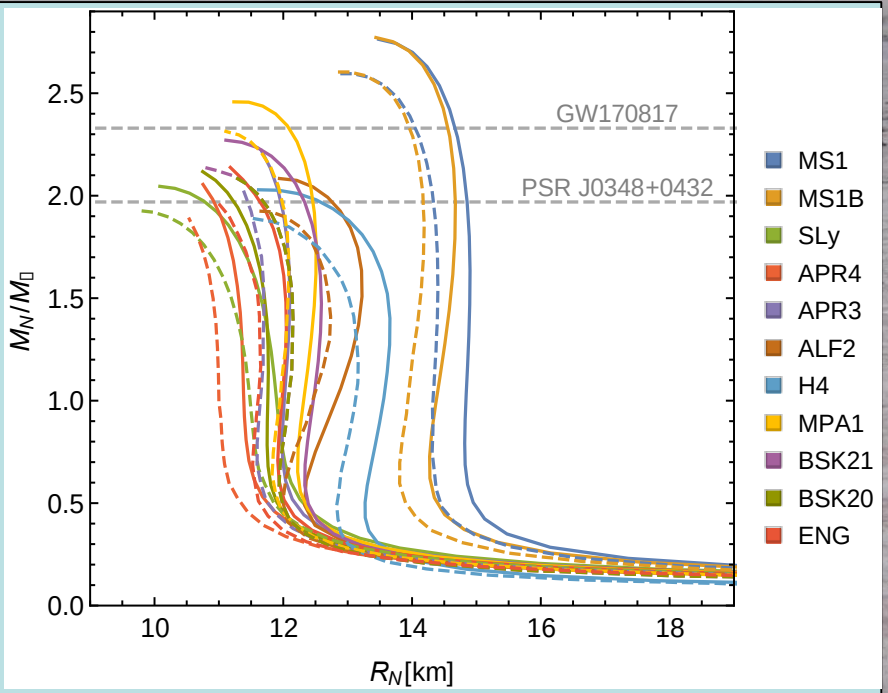
  $n + n \rightarrow n + n + \chi$
- DM mass fraction ~ 5% possible
- Merger of DM star with conventional star before/after becoming NS
- DM fraction may depend on age, environment

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

DM Effects on NS Properties

for various nuclear equations of state (EOS)

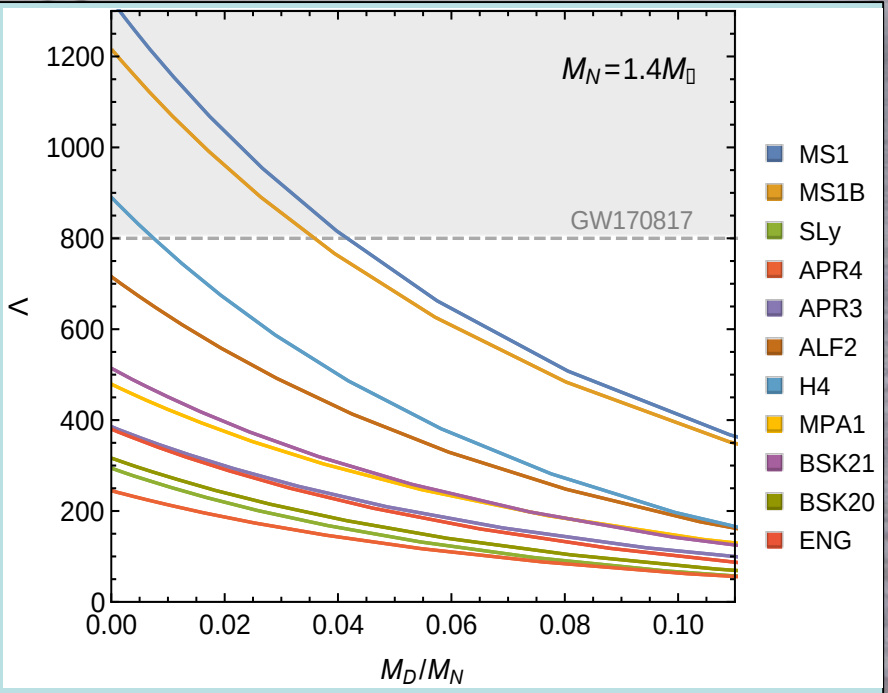
Effects on mass and radius



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***