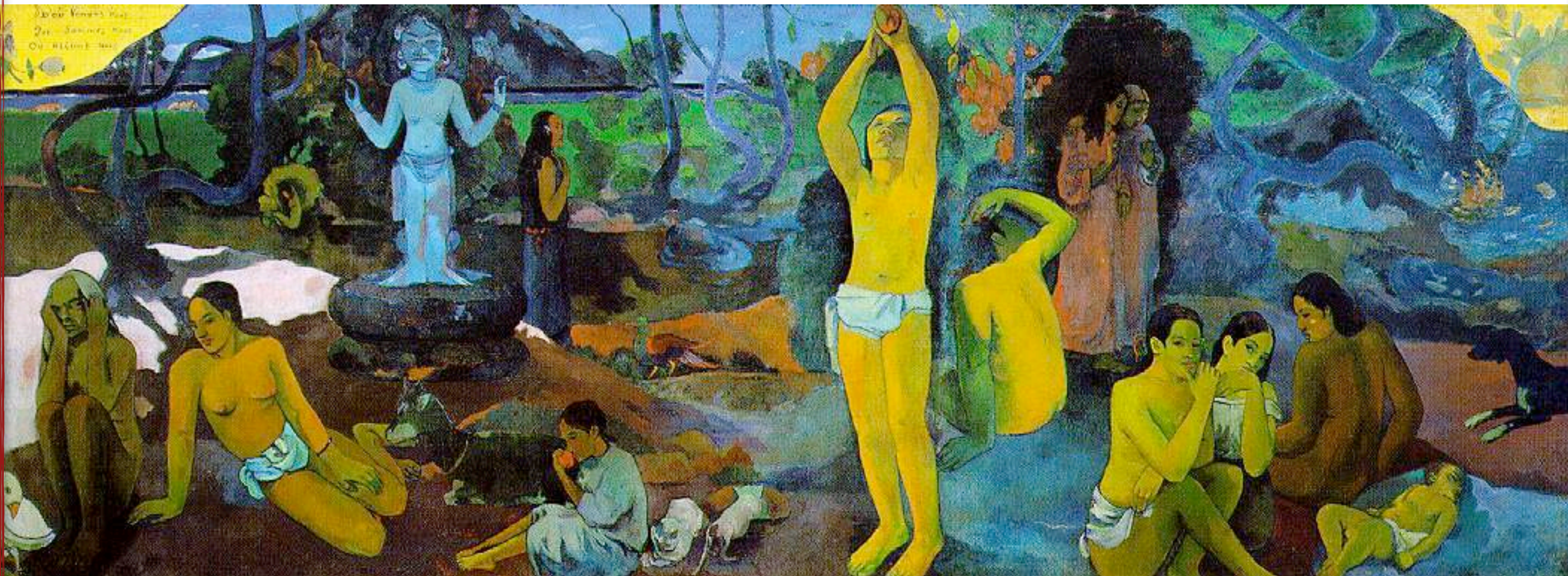
Prospettive in fisica teorica

Alfredo Urbano
Sapienza University of Rome

Retreat della sezione INFN di Roma
June 13-15, 2022



Where Do We Come From? What Are We? Where Are We Going?

ECFA-CERN Workshop, Summary Report
Lausanne and Geneva, March 1984

"…we now have to face deeper questions such as:

what is the origin of mass?
what kind of unification may exist beyond the standard model?
what is the origin of flavour?
is there a deeper reason for gauge symmetry?

[…] Experimentation in the TeV range at the constituent level
is bound to provide most essential clues…"

INFN Retreat, Assisi 2022

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what is the nature of dark energy?
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what is the nature of dark matter?
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One word in common: Naturalness

Naturalness: Very practical definition

For any observable $\mathcal{O}$ which consists of a sum of n independent contributions

$$\mathcal{O} = a_1 + a_2 + \ldots + a_n$$

all *independent* contributions to $\mathcal{O}$ should be comparable in size to or less than $\mathcal{O}$.

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Otherwise, if one contribution, say $a_1 \gg \mathcal{O}$, then some other independent contribution would have to be fine-tuned to a large opposite-sign value such as to maintain $\mathcal{O}$ at its measured value.

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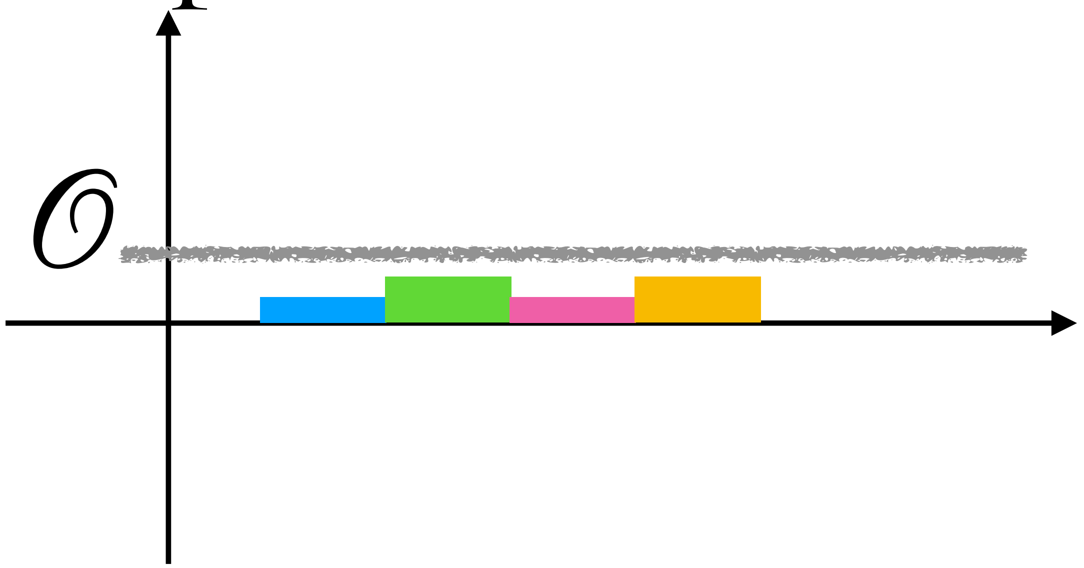

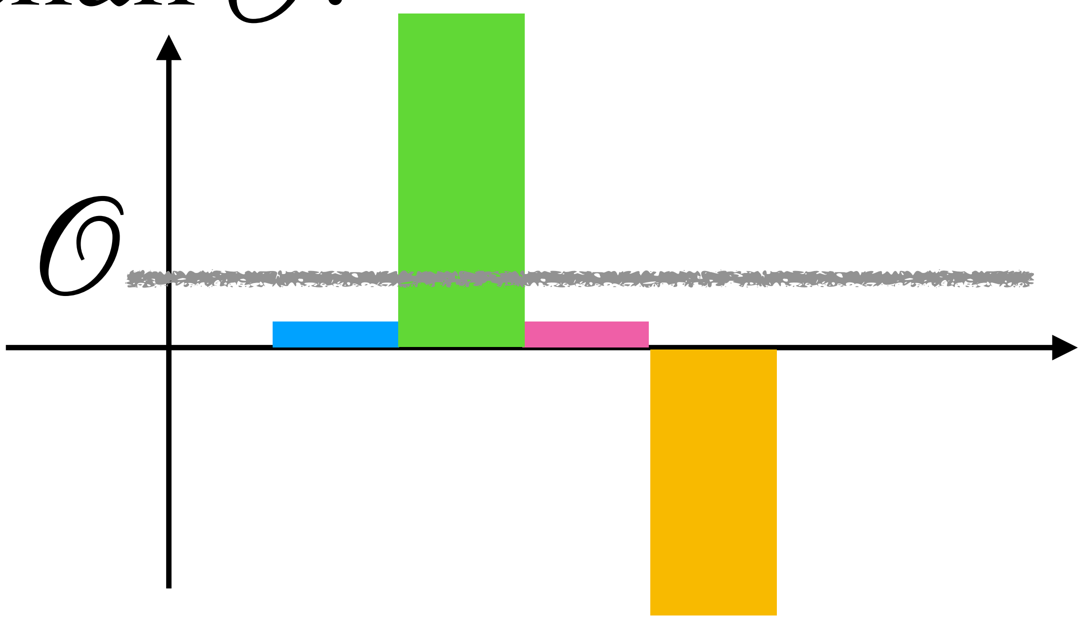

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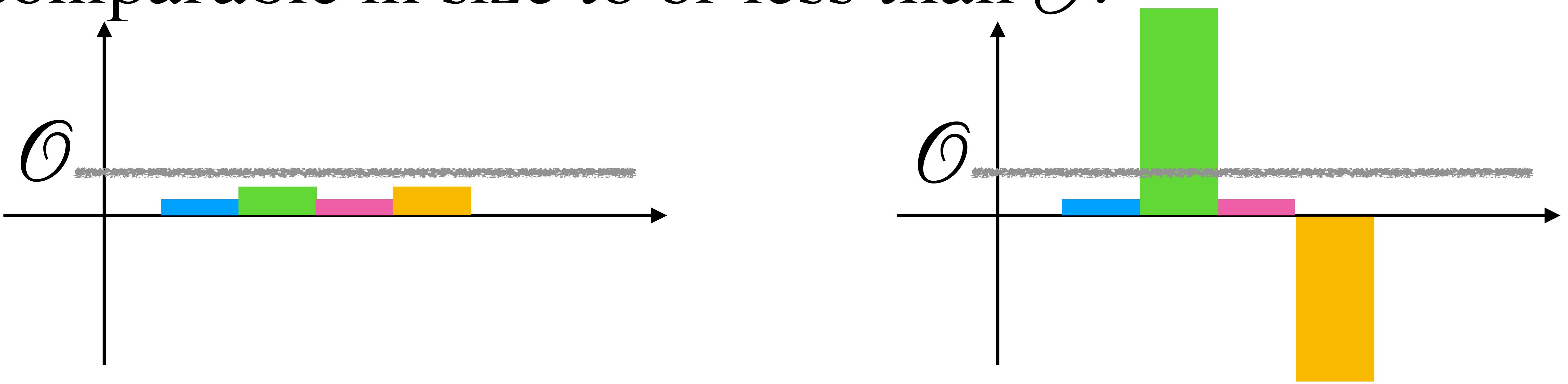

Such fine-tuning is regarded as unnatural and indicative of some missing ingredient in the theory.

Naturalness: the Higgs mass

$$\mathcal{O} = a_1 + a_2 + \ldots + a_n$$

[tree level]

$$(125\,\mathrm{GeV})^2 = (m_h^2)_{\mathrm{obs}} = 2\lambda v^2$$

$$v = \frac{m}{\sqrt{2\lambda}} \approx 246.2\,\mathrm{GeV}$$

$$V = -\frac{m^2}{2}|H|^2 + \lambda |H|^4$$

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[1 loop]

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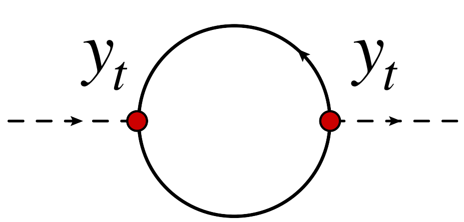

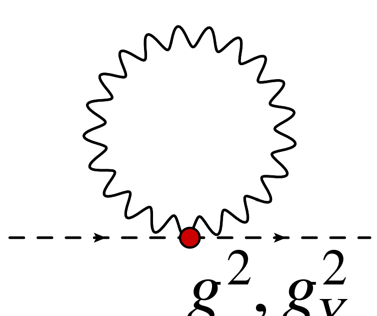

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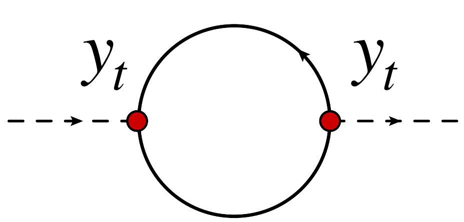

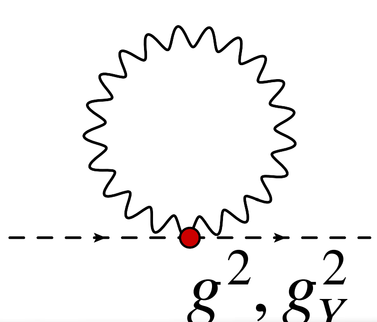

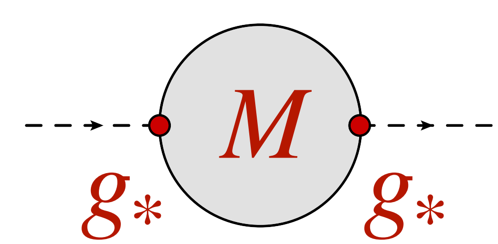

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$$\frac{g_*^2}{16\pi^2} M^2 \lesssim (m_h^2)_{\text{obs}} \longmapsto M < 1\,\text{TeV}$$

Naturalness: the cosmological constant

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$$\mathcal{O} = (\rho_\Lambda)_{\rm obs} = (2.26 \times 10^{-3}\ {\rm eV})^4$$

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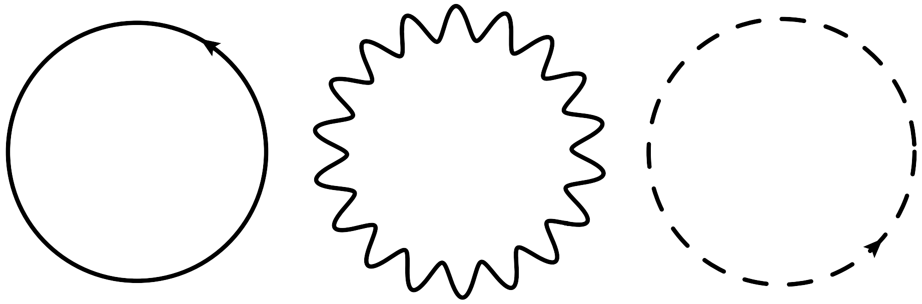
[SM]



[new mass scale M]

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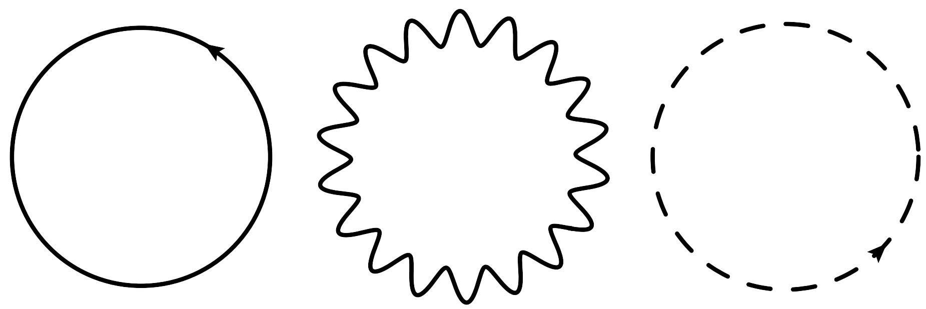

Even if we consider the SM and nothing else, we still have a huge problem of naturalness for the CC.

Naturalness: the strong CP problem

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$$\mathcal{O} = (d_n)_{\rm obs} < 1.8 \times 10^{-26}\, e\,{\rm cm}$$

$$(d_n)_{\rm obs} = 5 \times 10^{-16}\, [\,\theta + \arg\det(\mathcal{M}_q)]\; e\,{\rm cm}$$

Originates from the phases of the quark masses

$$\mathcal{L}_{\rm mass} = -\,\overline{q}_{R,i}(\mathcal{M}_q)_{ij}q_{L,j}$$

$$\mathcal{L}_{\rm QCD} \supset \theta\, \tilde{G}^a_{\mu\nu}G^{a,\mu\nu}$$

Naturalness: strategies

Higgs mass

New degrees of freedom coupled to the EW sector with TeV mass.

SUSY
Composite Higgs
Little Higgs
Twin Higgs
…

CC

Anthropic

Strong CP

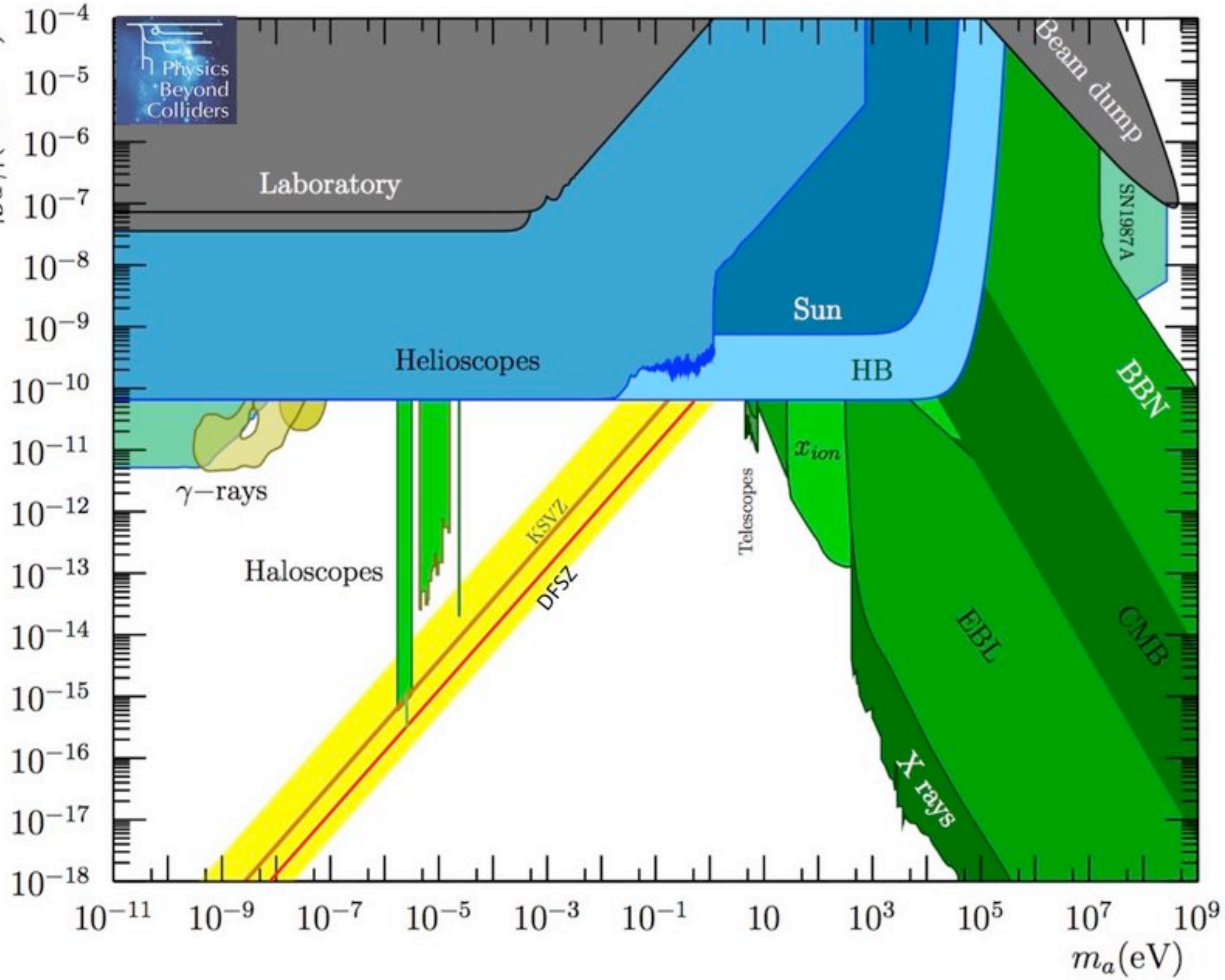
New light degree of freedom that naturally realizes

$\bar{\theta} \approx 0$

the Axion

Goldstone boson of a spontaneously broken U(1) global symmetry that is anomalous, at the quantum level, under QCD (Peccei-Quinn symmetry).

Naturalness: strategies



J.Beacham et al.
"Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report," [arXiv:1901.09966 [hep-ex]].

Strong CP

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Naturalness: strategies

In most of the axion models studied in the literature, the global PQ symmetry is imposed by hand, leaving its origin unspecified.

However, we believe that **gravity breaks explicitly global symmetries**.
The **axion solution** is, therefore, extremely **fragile**, and needs to be protected from these explicit breaking terms: this is the so-called "axion quality problem."

R.Contino, A.Podo and F.Revello,
"Chiral models of composite axions and accidental Peccei-Quinn symmetry"
JHEP **04** (2022), 180
[arXiv:2112.09635 [hep-ph]].

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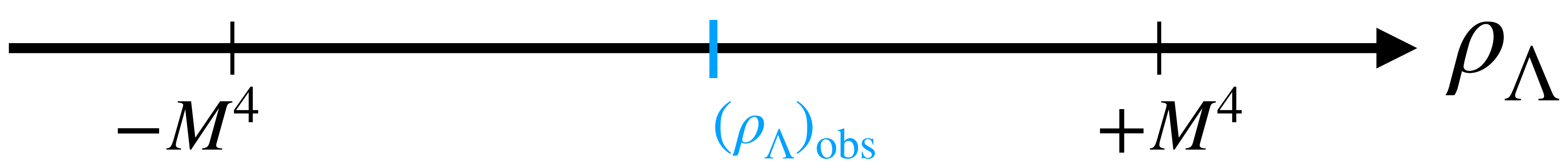

Naturalness: strategies

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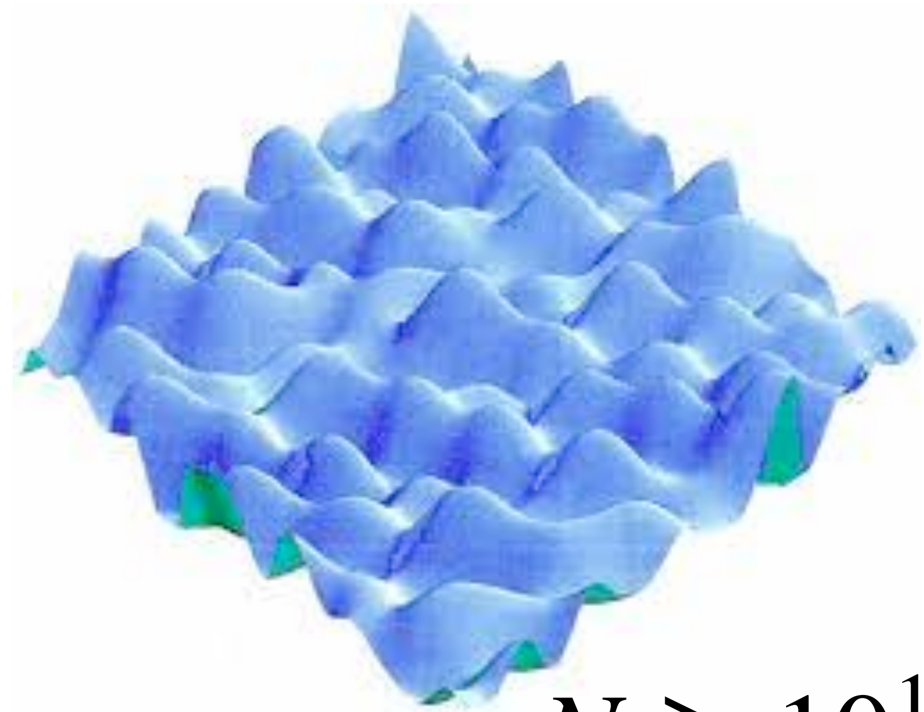
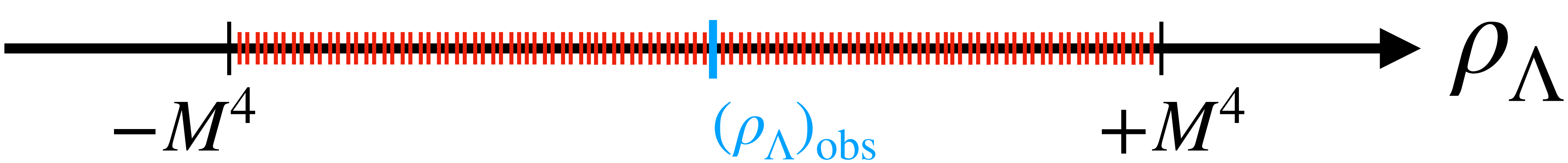


$N \gtrsim 10^{120}$

N vacua each of which with its own value of the CC; assume they are distributed in the range $[-M^4, +M^4]$ with spacing M^4/N.



Naturalness: strategies

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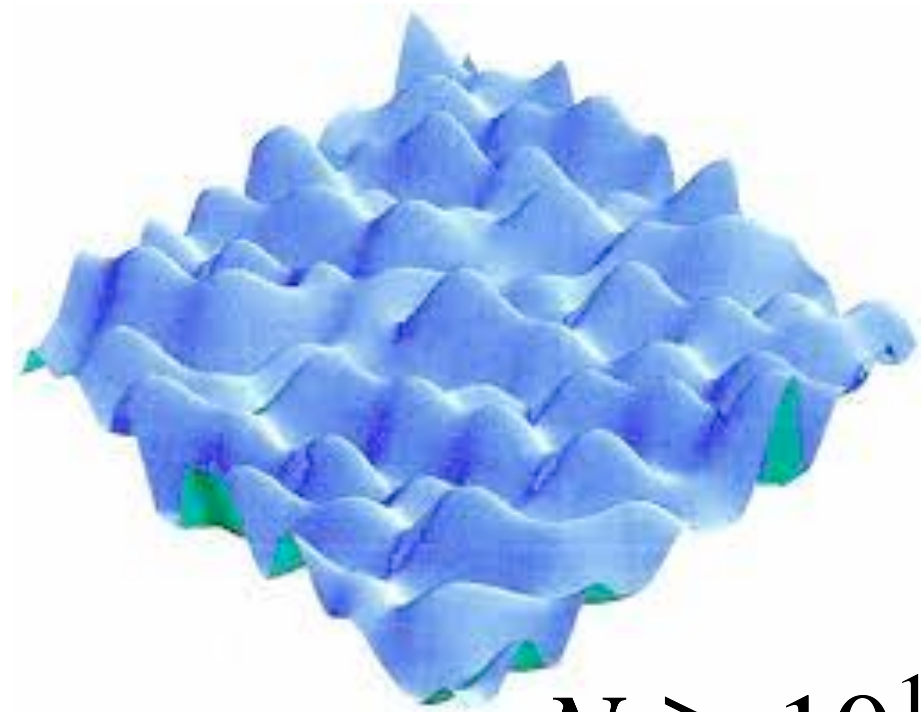

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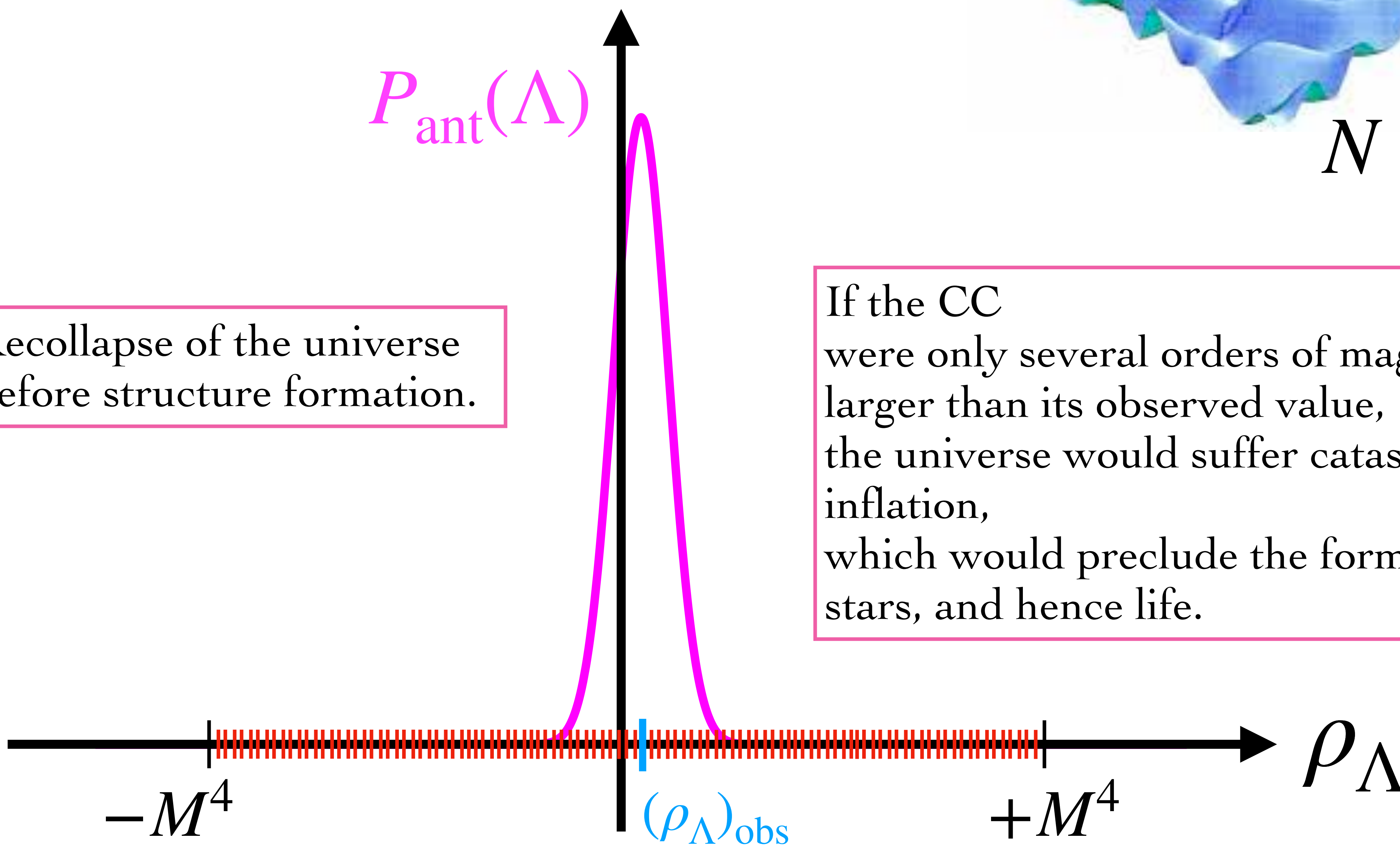

Recollapse of the universe before structure formation.

If the CC
were only several orders of magnitude larger than its observed value,
the universe would suffer catastrophic inflation,
which would preclude the formation of stars, and hence life.

Naturalness: strategies

Higgs mass

New degrees of freedom coupled to the EW sector with TeV mass.

SUSY
Composite Higgs
Little Higgs
Twin Higgs
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Experiments at LEP and at the LHC
have neither discovered
the symmetries that we expected
nor those that initially we did not expect,
leaving the value of the Higgs mass as puzzling as ever.

Naturalness: strategies

Higgs mass:

There is no mass scale beyond the Standard Model sufficiently strongly coupled to the Higgs to generate a fine-tuning problem.

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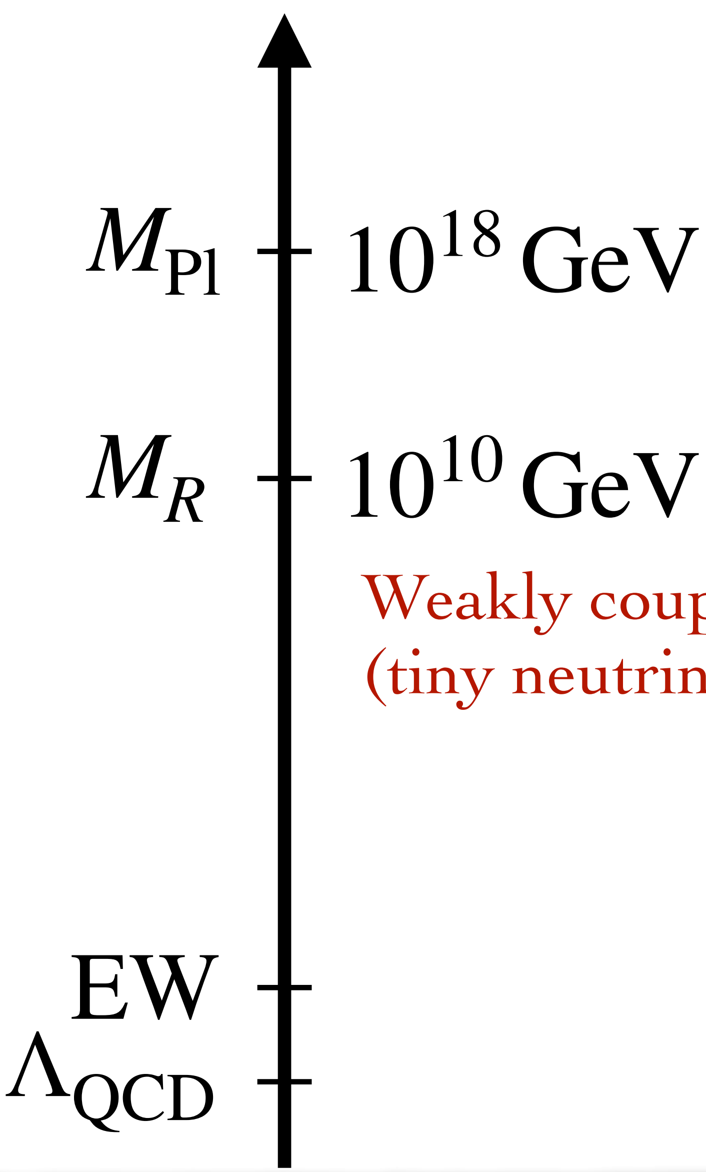


Theories of gravity with no new mass scales? Are they consistent?

A.Salvio and A.Strumia, "Agravity"
JHEP **06** (2014), 080
[arXiv:1403.4226 [hep-ph]].

Weakly coupled to the Higgs
(tiny neutrino masses)

Naturalness: strategies

Higgs mass:

> Significant deviations from the Standard Model are observed in semi-leptonic charged and neutral-current B-decays and the muon magnetic moment.

M.Ciuchini, A.M.Coutinho, M.Fedele, E.Franco, A.Paul, **L.Silvestrini** and M.Valli,
"New Physics in $b \to s\ell^+\ell^-$ confronts new data on Lepton Universality"
Eur.Phys.J.C **79** (2019) no.8, 719
[arXiv:1903.09632 [hep-ph]].

L.Allwicher, L.Di Luzio, M.Fedele, F.Mescia and **M.Nardecchia**,
"What is the scale of new physics behind the muon g-2?"
Phys.Rev.D **104** (2021) no.5, 055035
[arXiv:2105.13981 [hep-ph]].

L.Di Luzio, A.Greljo and **M.Nardecchia**,
"Gauge leptoquark as the origin of B-physics anomalies"
Phys.Rev.D **96** (2017) no.11, 115011
[arXiv:1708.08450 [hep-ph]].

few TeV — combined explanation to the above-mentioned anomalies while being consistent with all other phenomenological constraints?

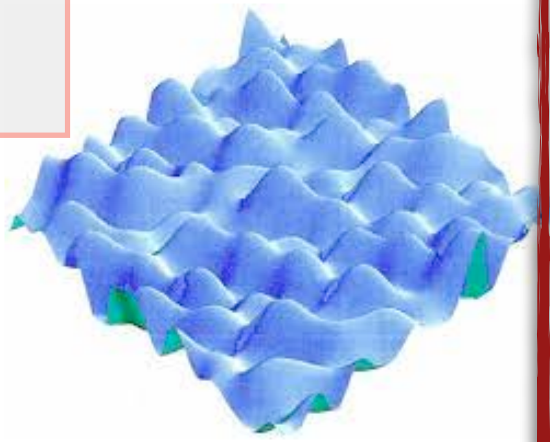
EW

Λ_{QCD}

Naturalness: strategies

Higgs mass:

New formulation of the idea:
"cosmological naturalness"?



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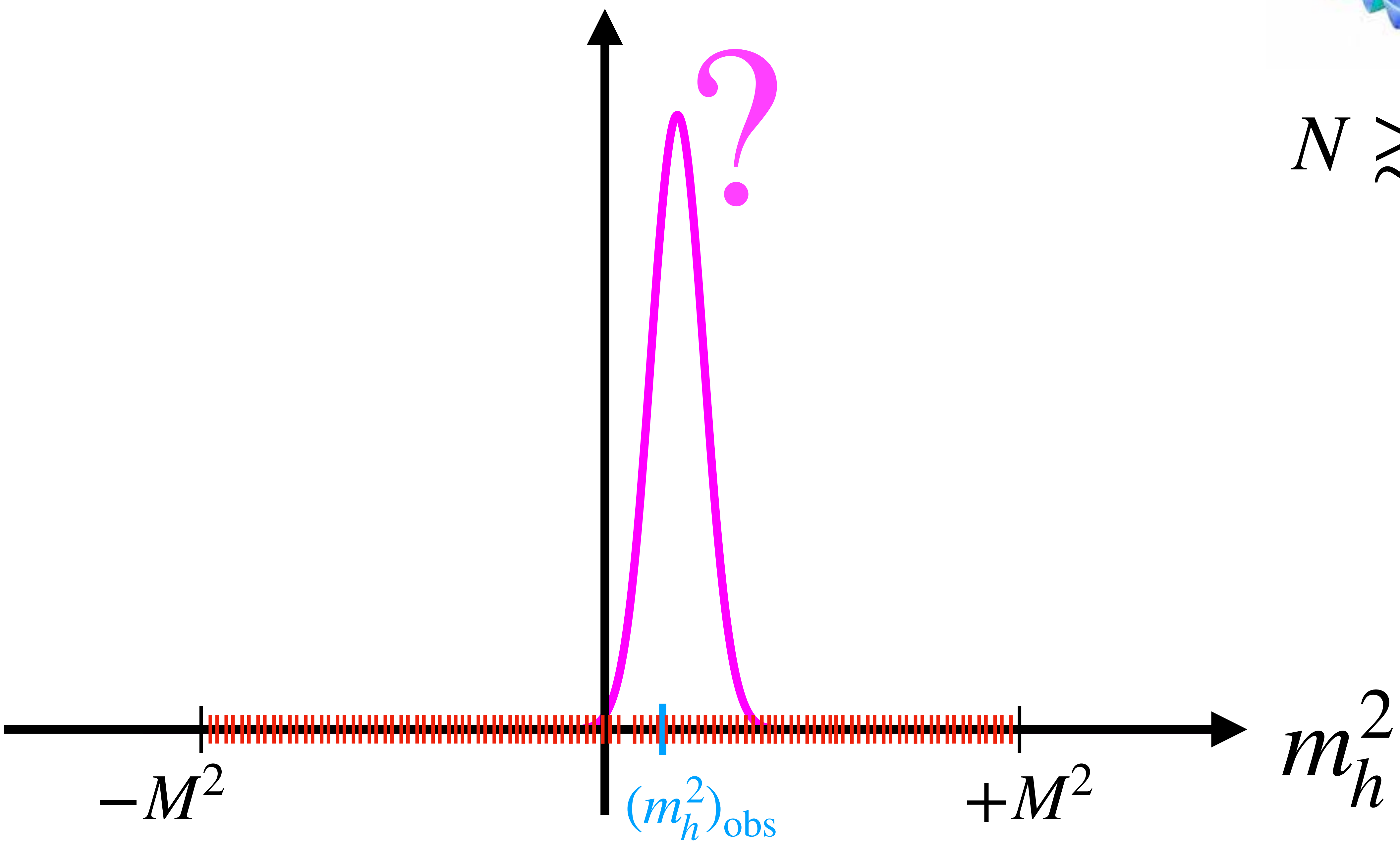

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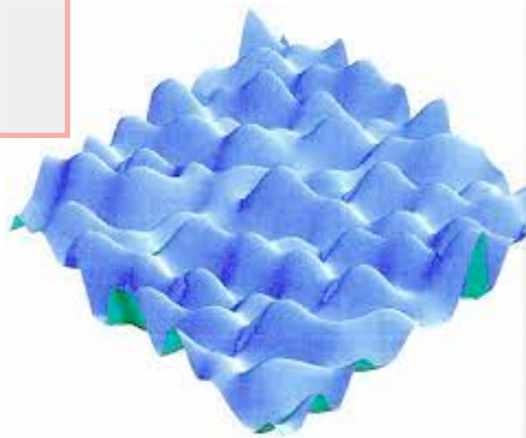
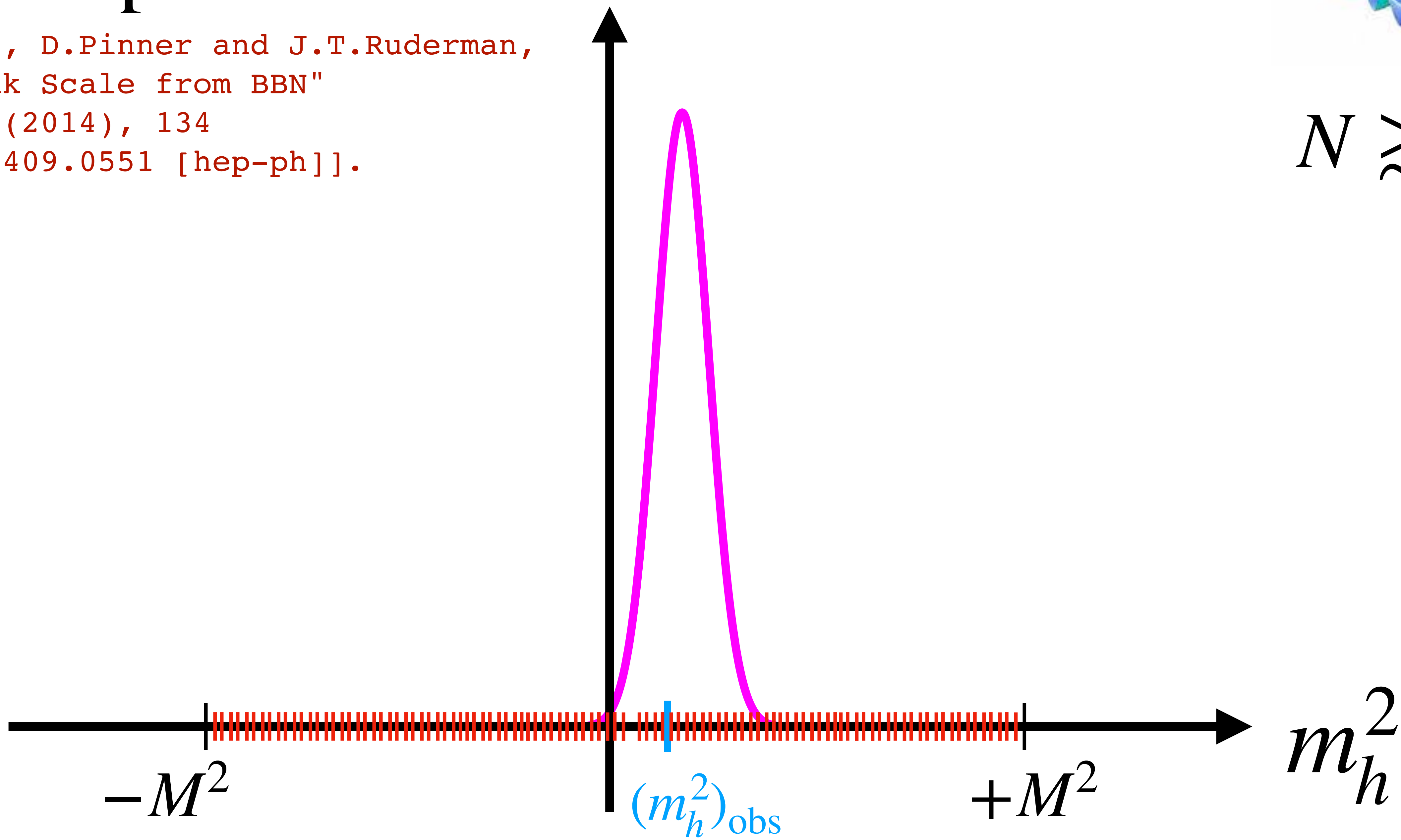


$N \gtrsim 10^{???}$

1) Anthropic Selection?

L.J.Hall, D.Pinner and J.T.Ruderman,
"The Weak Scale from BBN"
JHEP **12** (2014), 134
[arXiv:1409.0551 [hep-ph]].



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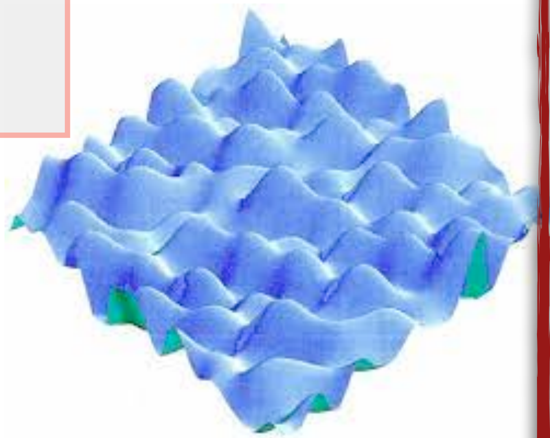


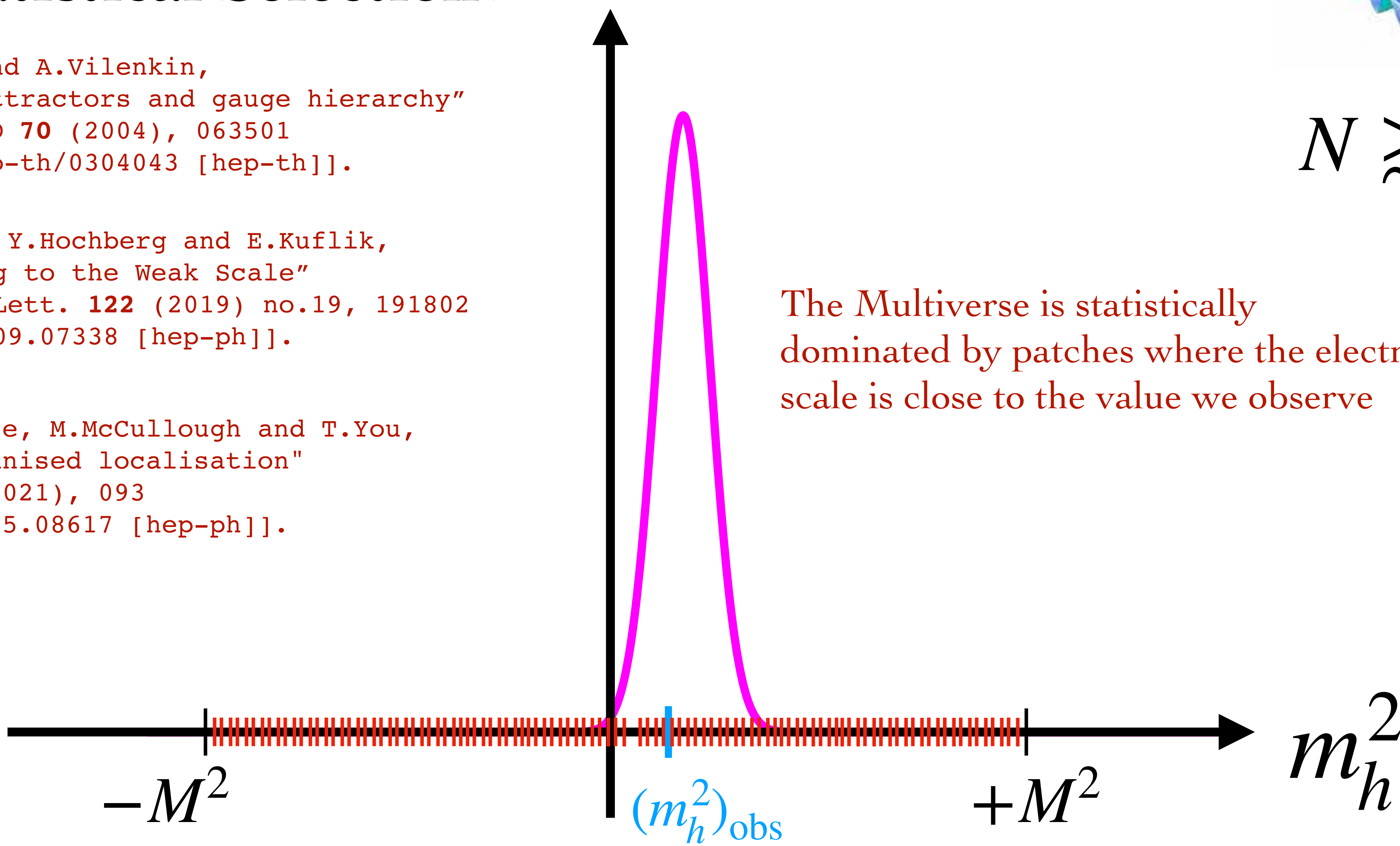
$N \gtrsim 10^{???}$

2) Statistical Selection?

G.Dvali and A.Vilenkin,
“Cosmic attractors and gauge hierarchy”
Phys.Rev.D **70** (2004), 063501
[arXiv:hep-th/0304043 [hep-th]].

M.Geller, Y.Hochberg and E.Kuflik,
“Inflating to the Weak Scale”
Phys.Rev.Lett. **122** (2019) no.19, 191802
[arXiv:1809.07338 [hep-ph]].

G.F.Giudice, M.McCullough and T.You,
“Self-organised localisation"
JHEP **10** (2021), 093
[arXiv:2105.08617 [hep-ph]].

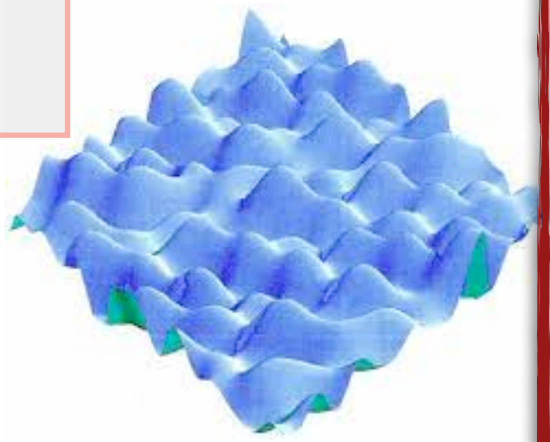


The Multiverse is statistically dominated by patches where the electroweak scale is close to the value we observe

Naturalness: strategies

Higgs mass:

New formulation of the idea: "cosmological naturalness"?



3) Dynamical Selection?

P.W.Graham, D.E.Kaplan and S.Rajendran, "Cosmological Relaxation of the Electroweak Scale" Phys.Rev.Lett. **115** (2015) no.22, 221801 [arXiv:1504.07551 [hep-ph]].

N.Arkani-Hamed, T.Cohen, R.T.D'Agnolo, A.Hook, H.D.Kim and D.Pinner, "Solving the Hierarchy Problem at Reheating with a Large Number of Degrees of Freedom" Phys.Rev.Lett. **117** (2016) no.25, 251801 [arXiv:1607.06821 [hep-ph]].

R.Tito D'Agnolo and D.Teresi, "Sliding Naturalness: New Solution to the Strong-CP and Electroweak-Hierarchy Problems" Phys.Rev.Lett. **128** (2022) no.2, 021803 [arXiv:2106.04591 [hep-ph]].

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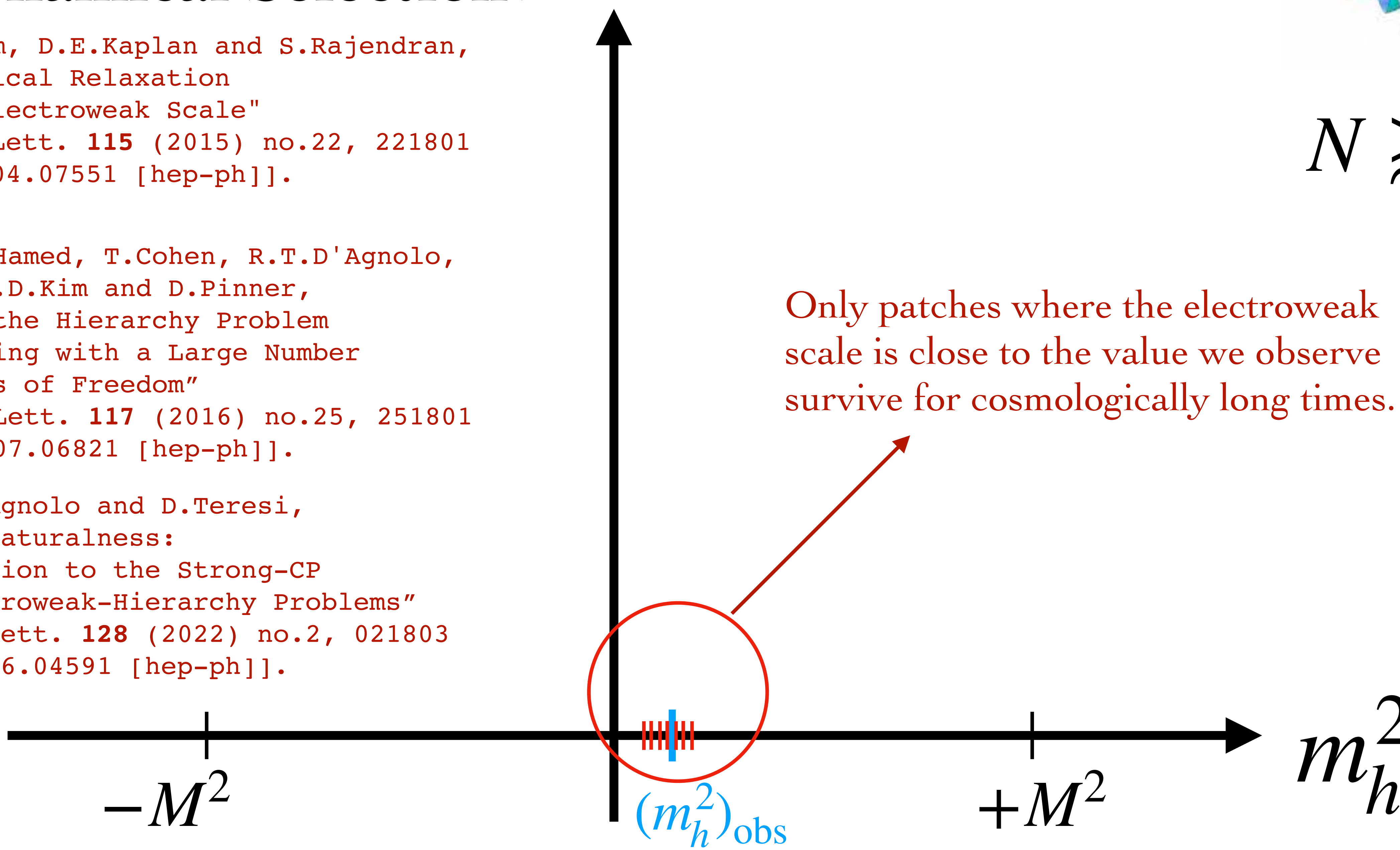

Naturalness: strategies

Higgs mass:

New formulation of the idea:
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Solution of the naturalness problem based on a very interesting interplay with cosmology.

Is it possible to address all three naturalness problems in the same theoretical construction?

What are the phenomenological implications?

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What could dark matter be?

Classify models according to their thermal history

89 orders of magnitude of possibilities…

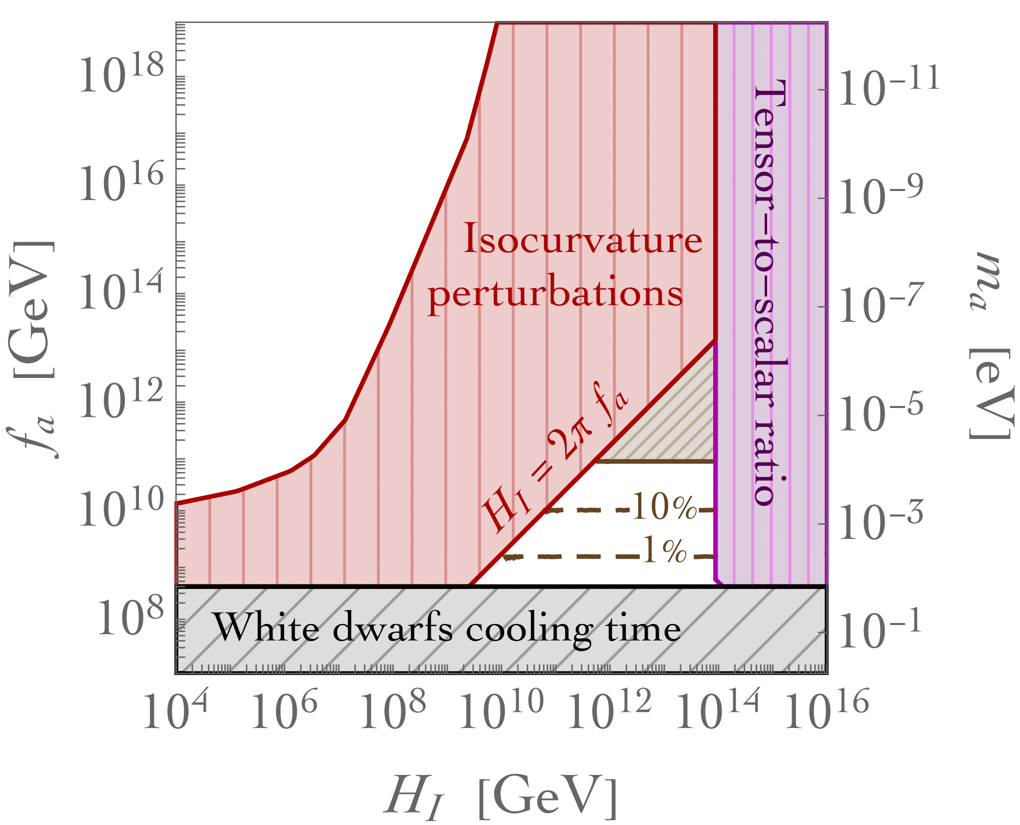
What could dark matter be?

Classify models according to their thermal history

Non-thermal **Thermal** **Non-thermal**

$10^{-22}\,\mathrm{eV}$ keV MeV GeV 100 TeV M_{Pl} $30\,M_{\odot}$

Axion dark matter



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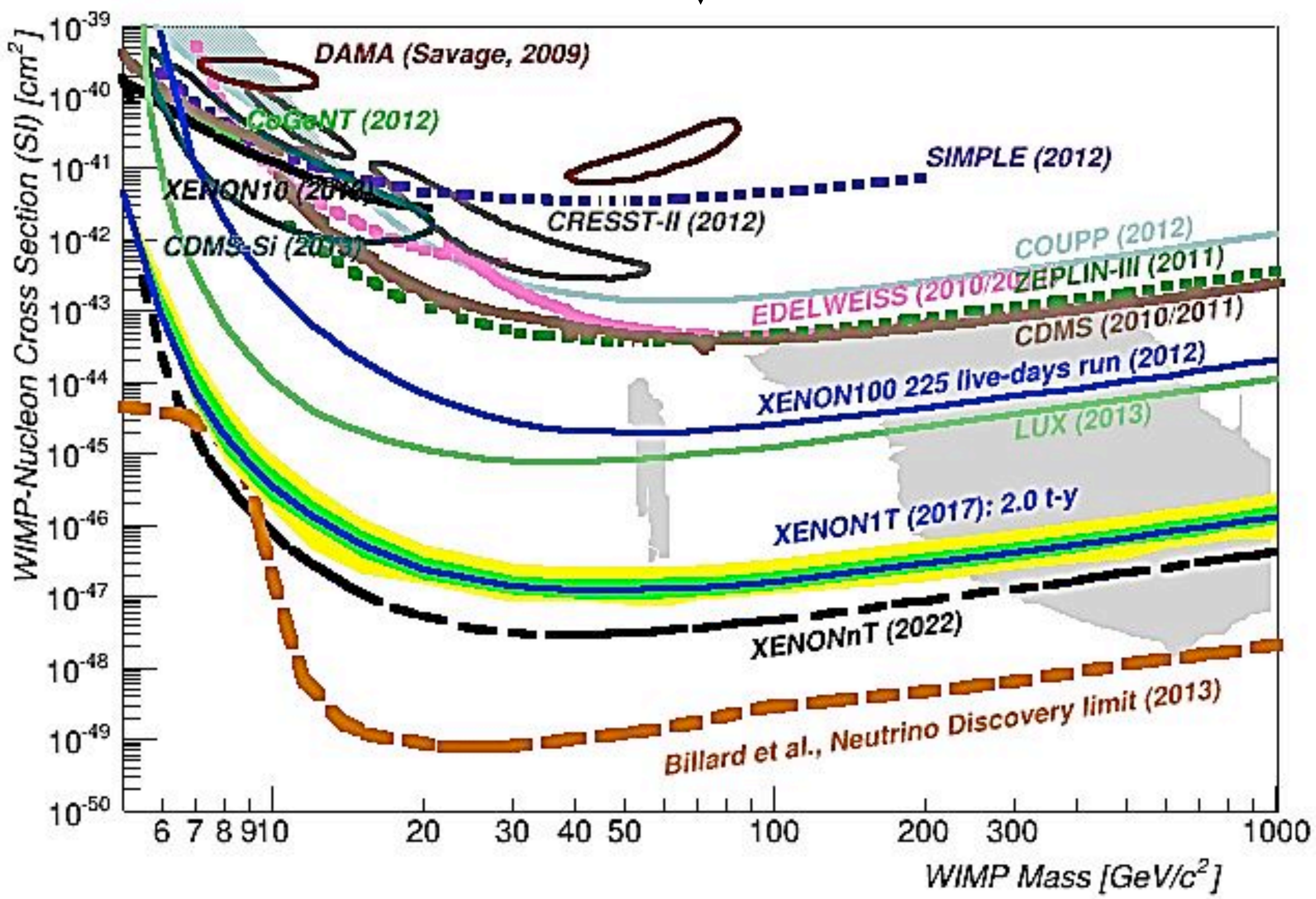
WIMP?



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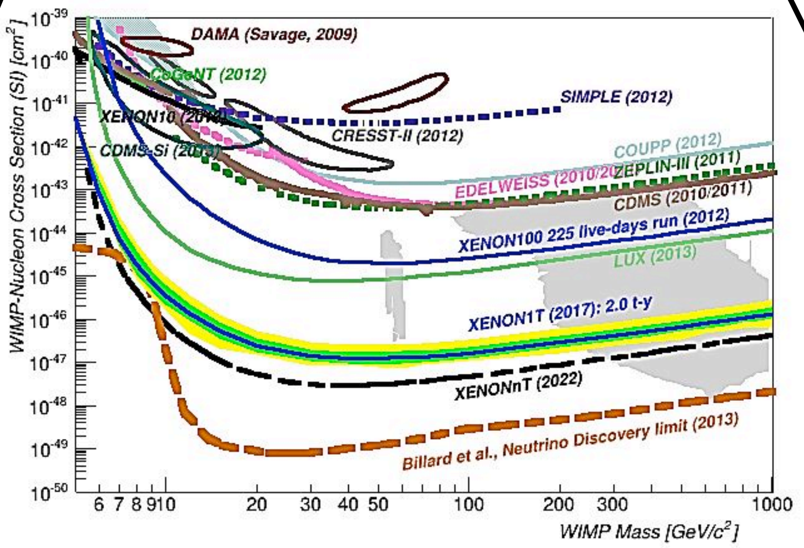
Non-thermal | **Thermal** | **Non-thermal**

$10^{-22}\,\mathrm{eV}$ keV MeV GeV 100 TeV $M_{\rm Pl}$ $30\,M_\odot$



sub-GeV models

10-TeV models

F.Acanfora, **A.Esposito** and **A.D.Polosa**, "Sub-GeV Dark Matter in Superfluid He-4: an Effective Theory Approach" Eur.Phys.J.C **79** (2019) no.7, 549 [arXiv:1902.02361 [hep-ph]].

S.Bottaro, D.Buttazzo, M.Costa, R.Franceschini, P.Panci, D.Redigolo and L.Vittorio, "Closing the window on WIMP Dark Matter" Eur.Phys.J.C **82** (2022) no.1, 31 [arXiv:2107.09688 [hep-ph]].

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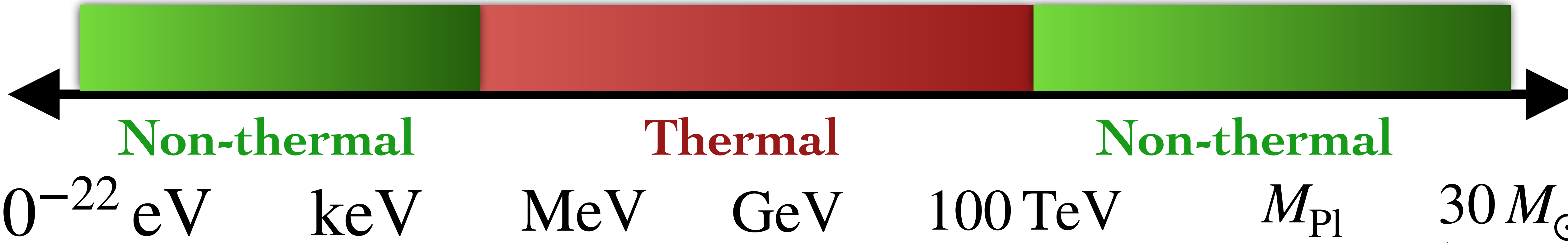
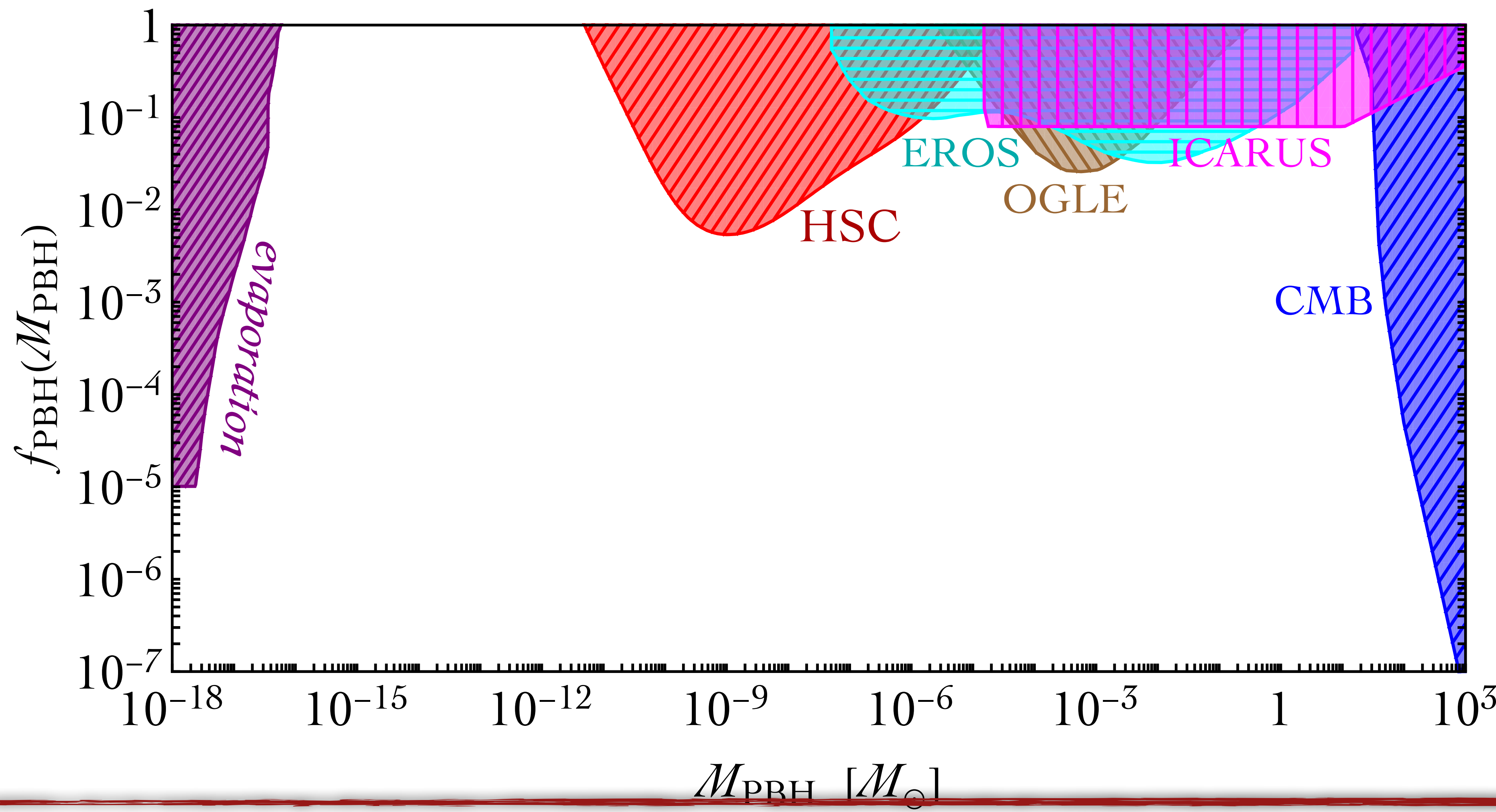


Dark matter in the form of primordial black holes



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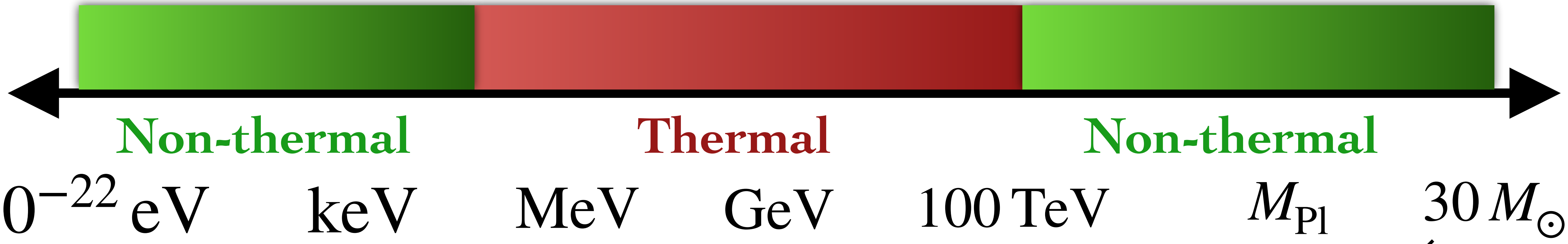

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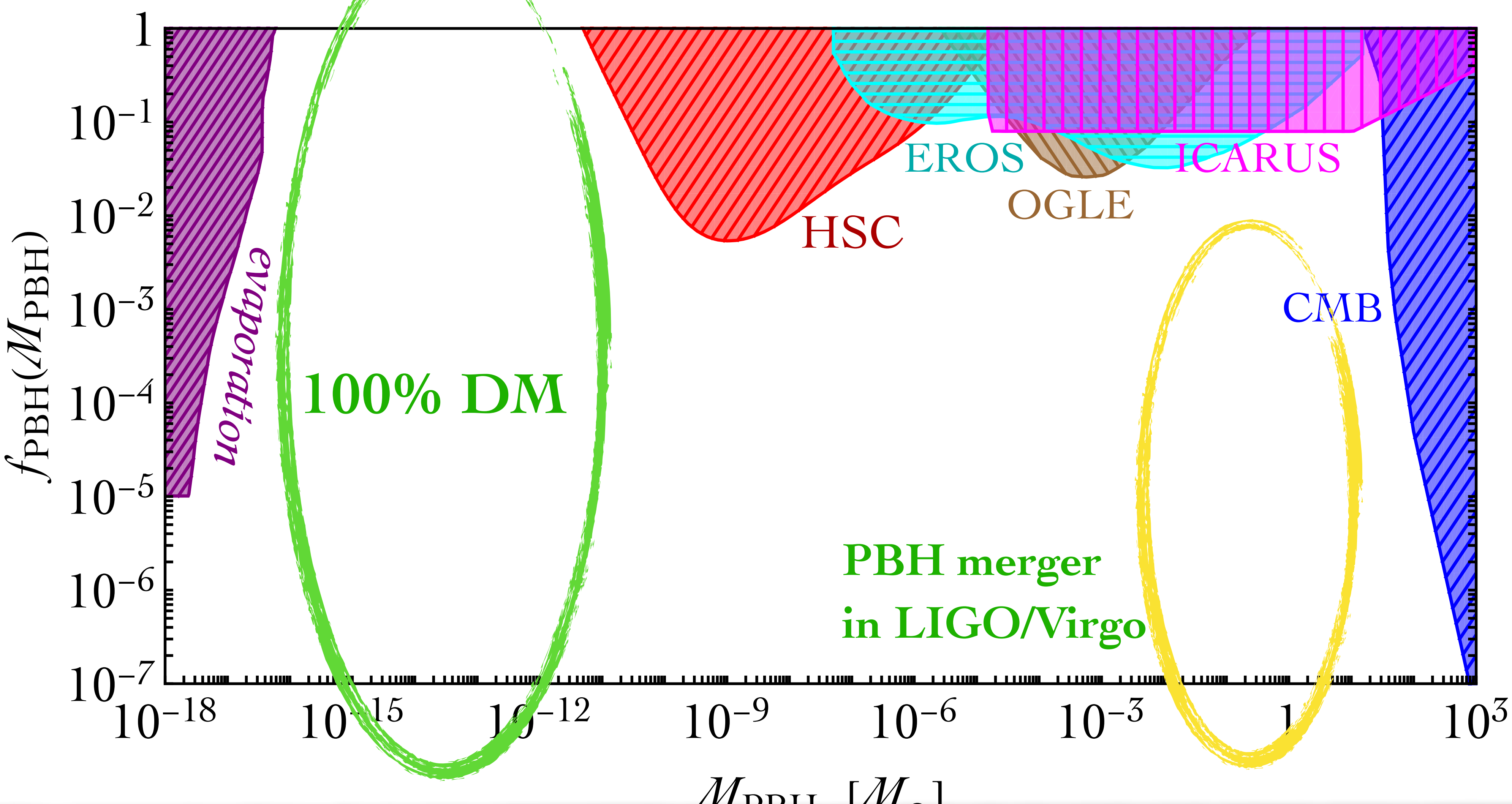


$a(t) \propto e^{Ht}$ $a(t) \propto t^{1/2}$ $a(t) \propto t^{3/2}$ $a(t) \propto e^{H_\Lambda t}$

Inflation

Radiation epoch

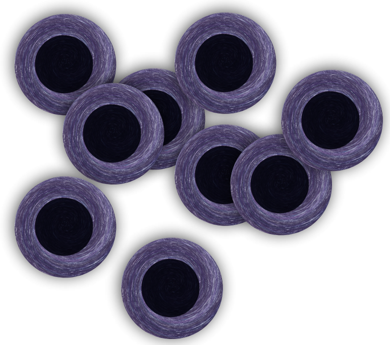
Matter epoch

Present-day Universe

$a(t) \propto e^{Ht}$ | $a(t) \propto t^{1/2}$ | $a(t) \propto t^{3/2}$ | $a(t) \propto e^{H_\Lambda t}$

Inflation | Radiation epoch | Matter epoch | Present-day Universe

- How did they form?



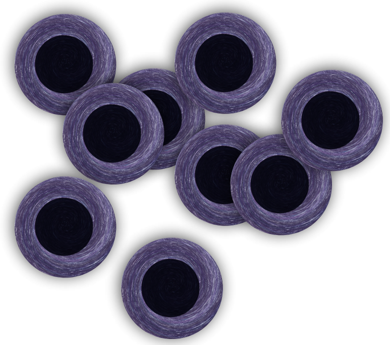
- What is the abundance at formation?

- How do they evolve?

$a(t) \propto e^{Ht}$ $a(t) \propto t^{1/2}$ $a(t) \propto t^{3/2}$ $a(t) \propto e^{H_\Lambda t}$

Inflation | Radiation epoch | Matter epoch | Present-day Universe

- How did they form?



PBHs form if the cosmological perturbation amplitude $\delta > \delta_c$

- What is the abundance at formation?

The formation mechanism is a non-linear process, and requires dedicated relativistic numerical simulations.

The abundance of PBHs is exponentially sensitive to the value of the threshold δ_c, $\propto \exp(-\delta_c/2\sigma^2)$

Threshold and variance depend on the power spectrum of curvature perturbations (i.e. they depend on the inflationary model).

- How do they evolve?

Clustering? Mass accretion?

$a(t) \propto e^{Ht}$ $a(t) \propto t^{1/2}$ $a(t) \propto t^{3/2}$ $a(t) \propto e^{H_\Lambda t}$

Inflation | Radiation epoch | Matter epoch | Present-day Universe

- How did they form?

For a review:
A.M.Green and B.J.Kavanagh,
"Primordial Black Holes as a dark matter candidate"
J.Phys.G **48** (2021) no.4, 043001
[arXiv:2007.10722 [astro-ph.CO]].

- What is the abundance at formation?

C.Germani and **I.Musco**,
"Abundance of Primordial Black Holes Depends on the Shape of the Inflationary Power Spectrum"
Phys.Rev.Lett. **122** (2019) no.14, 141302
[arXiv:1805.04087 [astro-ph.CO]].

I.Musco,
"Threshold for primordial black holes: Dependence on the shape of the cosmological perturbations"
Phys.Rev.D **100** (2019) no.12, 123524
[arXiv:1809.02127 [gr-qc]].

S.Young, **I.Musco** and C.T.Byrnes,
"Primordial black hole formation and abundance: contribution from the non-linear relation between the density and curvature perturbation"
JCAP **11** (2019), 012 [arXiv:1904.00984].

I.Musco, V.De Luca, **G.Franciolini** and A.Riotto,
"Threshold for primordial black holes. II. A simple analytic prescription"
Phys.Rev.D **103** (2021) no.6, 063538
[arXiv:2011.03014 [astro-ph.CO]].

- How do they evolve?

V.De Luca, **G.Franciolini**, A.Kehagias, **P.Pani** and A.Riotto,
"Primordial Black Holes in Matter-Dominated Eras: the Role of Accretion"
[arXiv:2112.02534 [astro-ph.CO]].

- What detection strategies?

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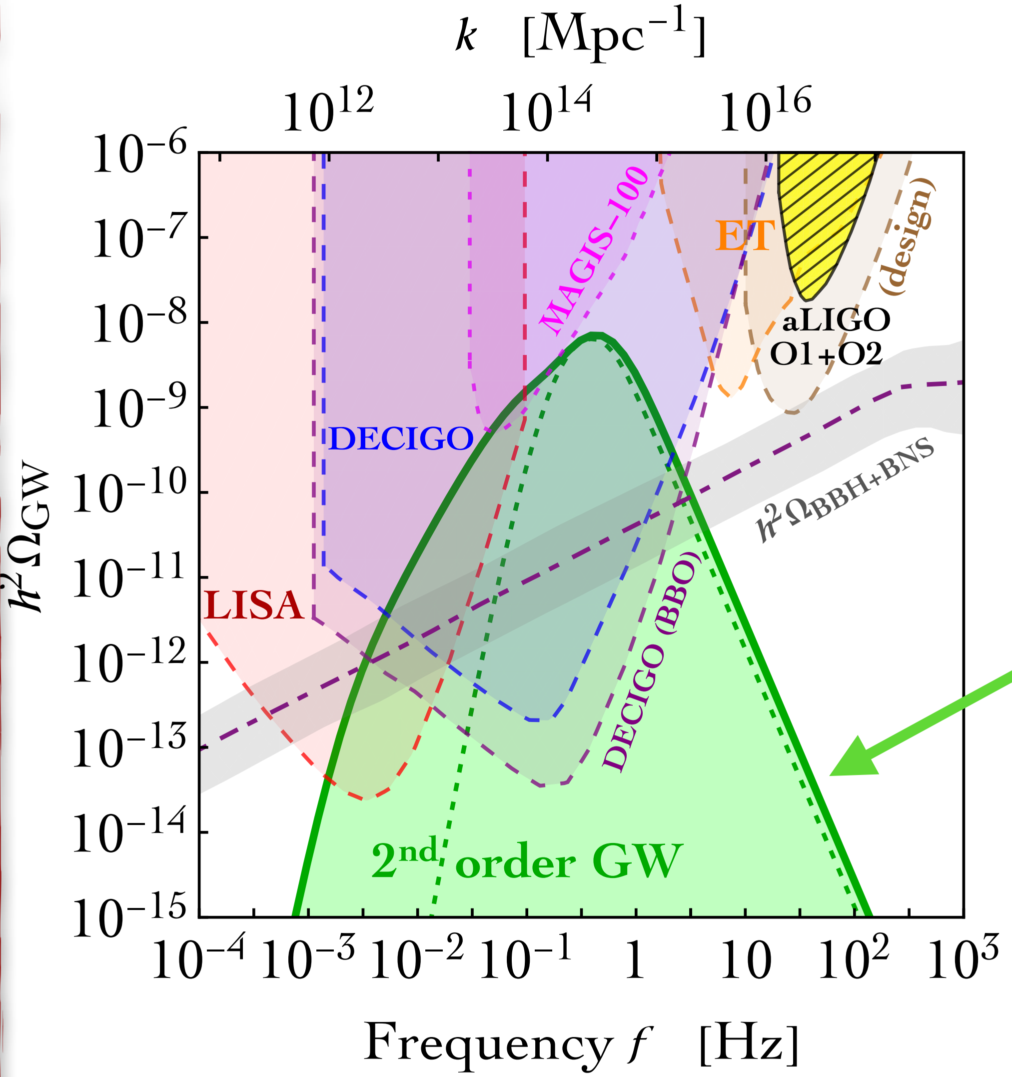
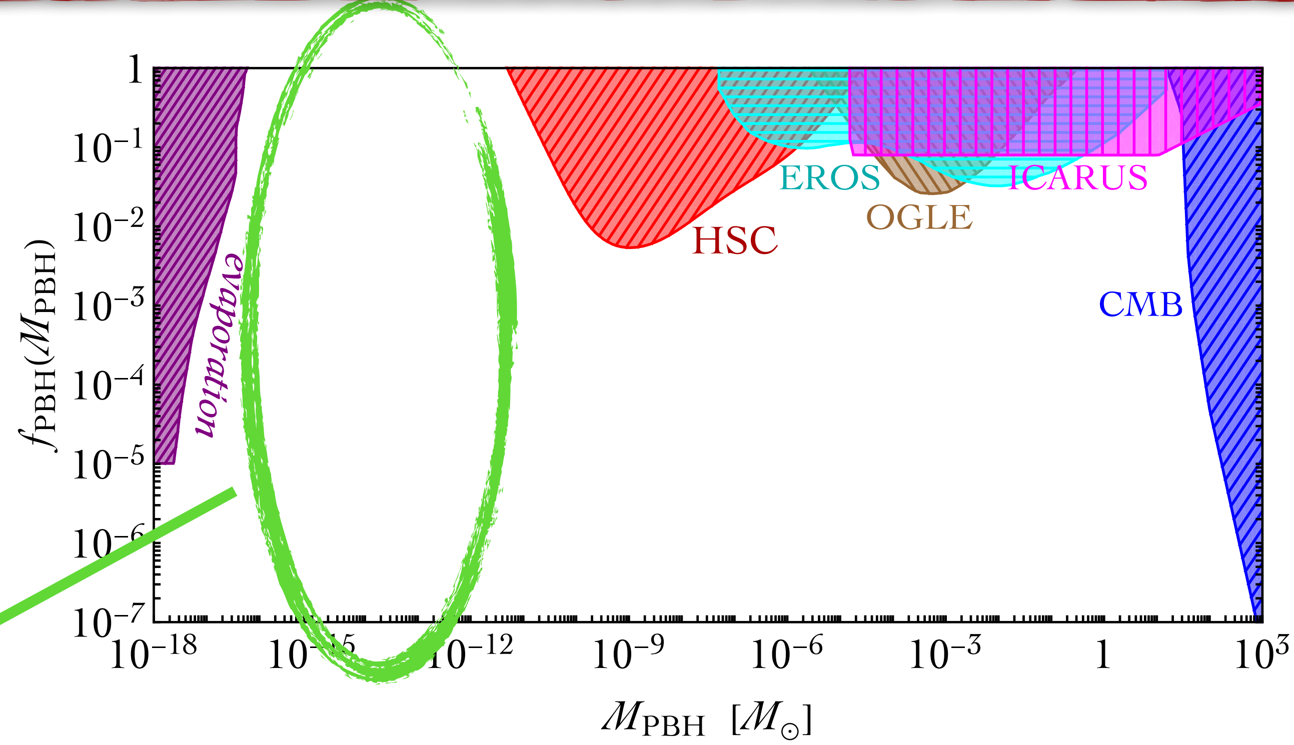
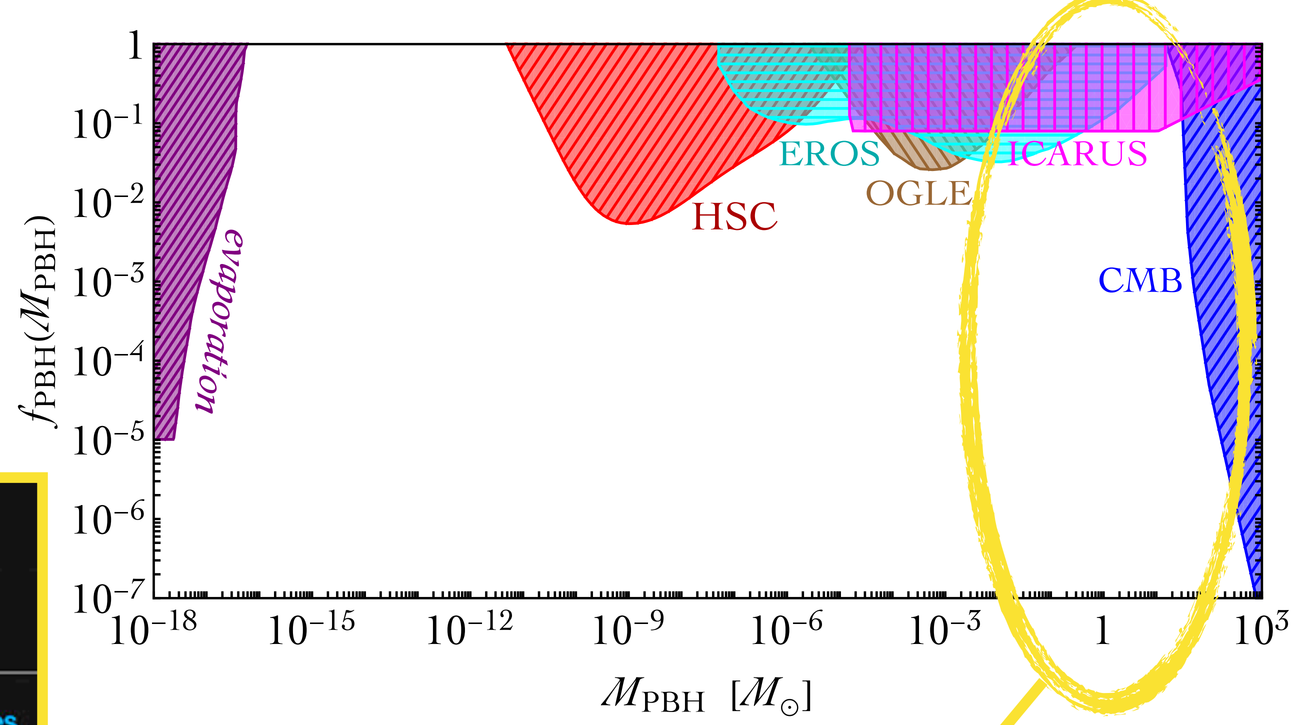


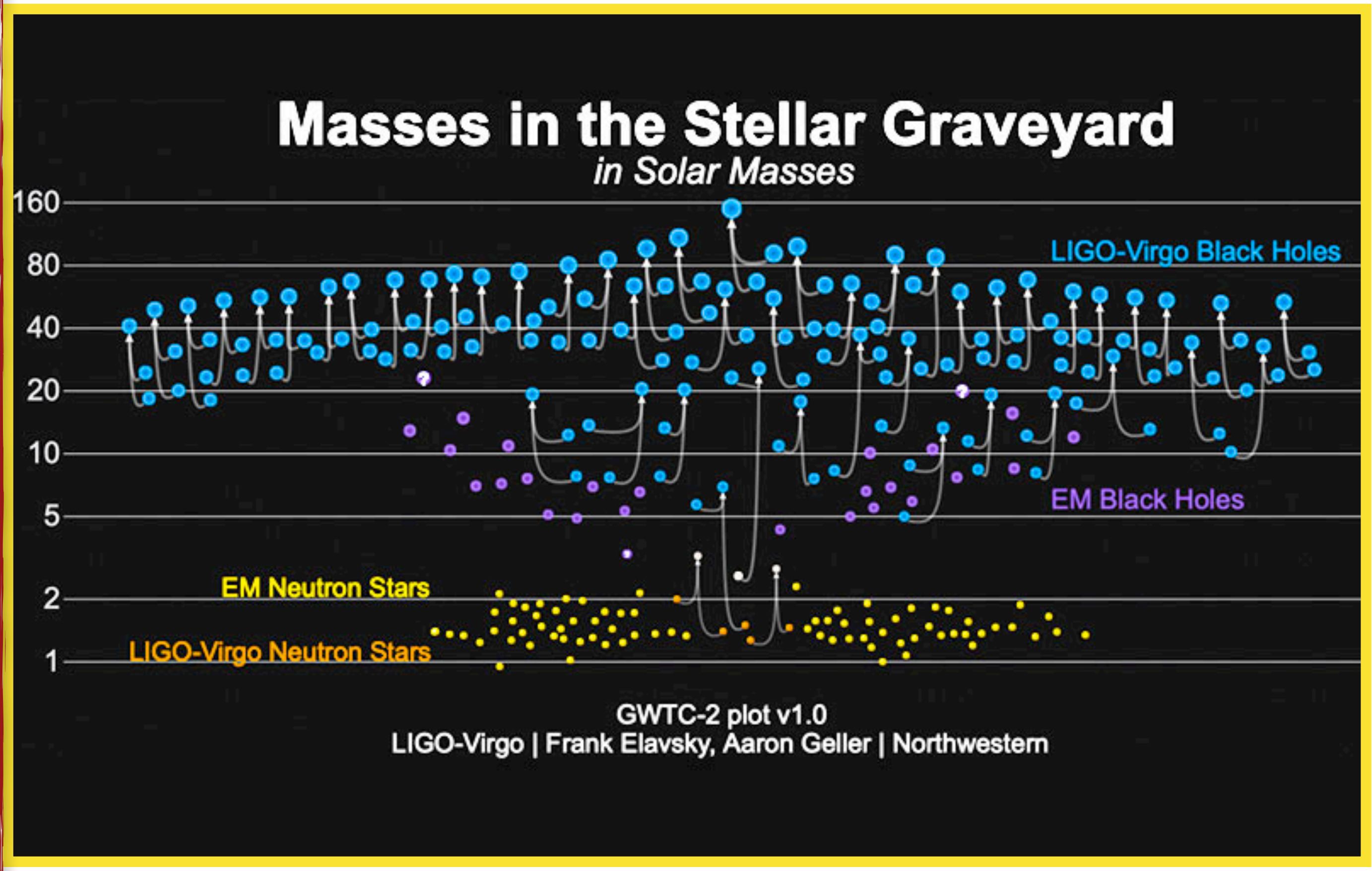


2^{nd}-order GW

For a review:
G.Domenech,
"Scalar Induced Gravitational Waves Review"
Universe **7** (2021) no.11, 398
[arXiv:2109.01398 [gr-qc]].

- What detection strategies?





Merger of PBHs in the LIGO/Virgo dataset?

Accurate statistical analysis based on the presence of different populations (astro-BH, NS, PBHs).
Accurate modeling of the quark-hadron phase transition (**softening of the equation of state, lower value of the threshold for formation**).

I.Musco, K.Jedamzik, S.Young, in progress

G.Franciolini, **I.Musco**, **P.Pani**, in progress

Conclusions

Conclusions

- New discoveries around the corner?

- Is naturalness still a "guiding principle"?

  Yes but maybe in a modified new way, in particular as far as the Higgs mass is concerned.
  Interplay with cosmology?
  Definitely worth investigating.

- Dark matter beyond the WIMP paradigm.

  Many natural possibilities,
  from light axions (and perhaps ultra-light bosons) **to primordial black holes.**