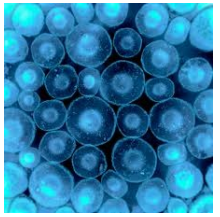
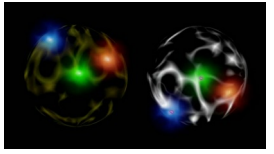
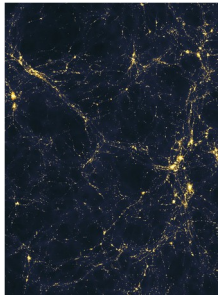
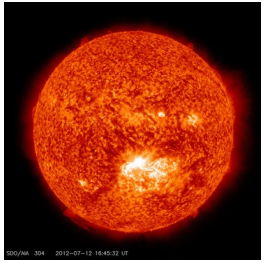
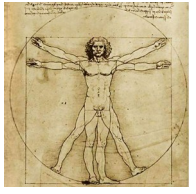
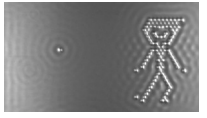
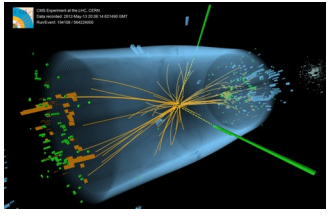
Scientific Motivation Overview

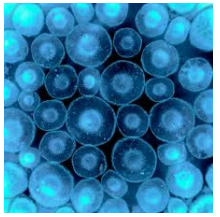
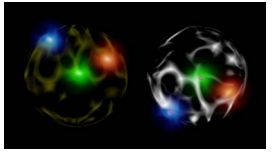
Giovanni Villadoro

The Abdus Salam International Centre for Theoretical Physics

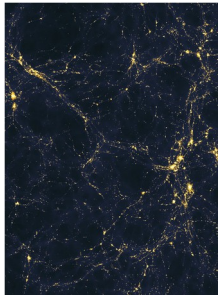
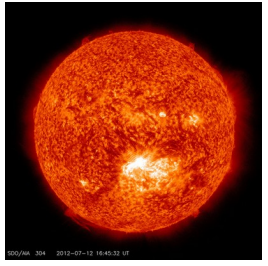
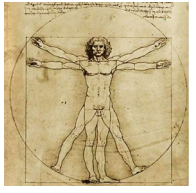
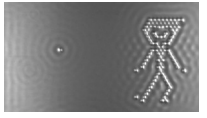
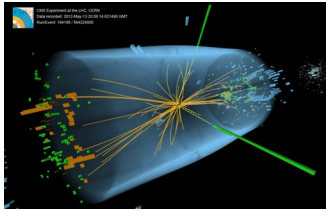
H 10^{-30} 10^{-20} 10^{-10} $1\ eV$ 10^{10} 10^{20} M_{Pl}

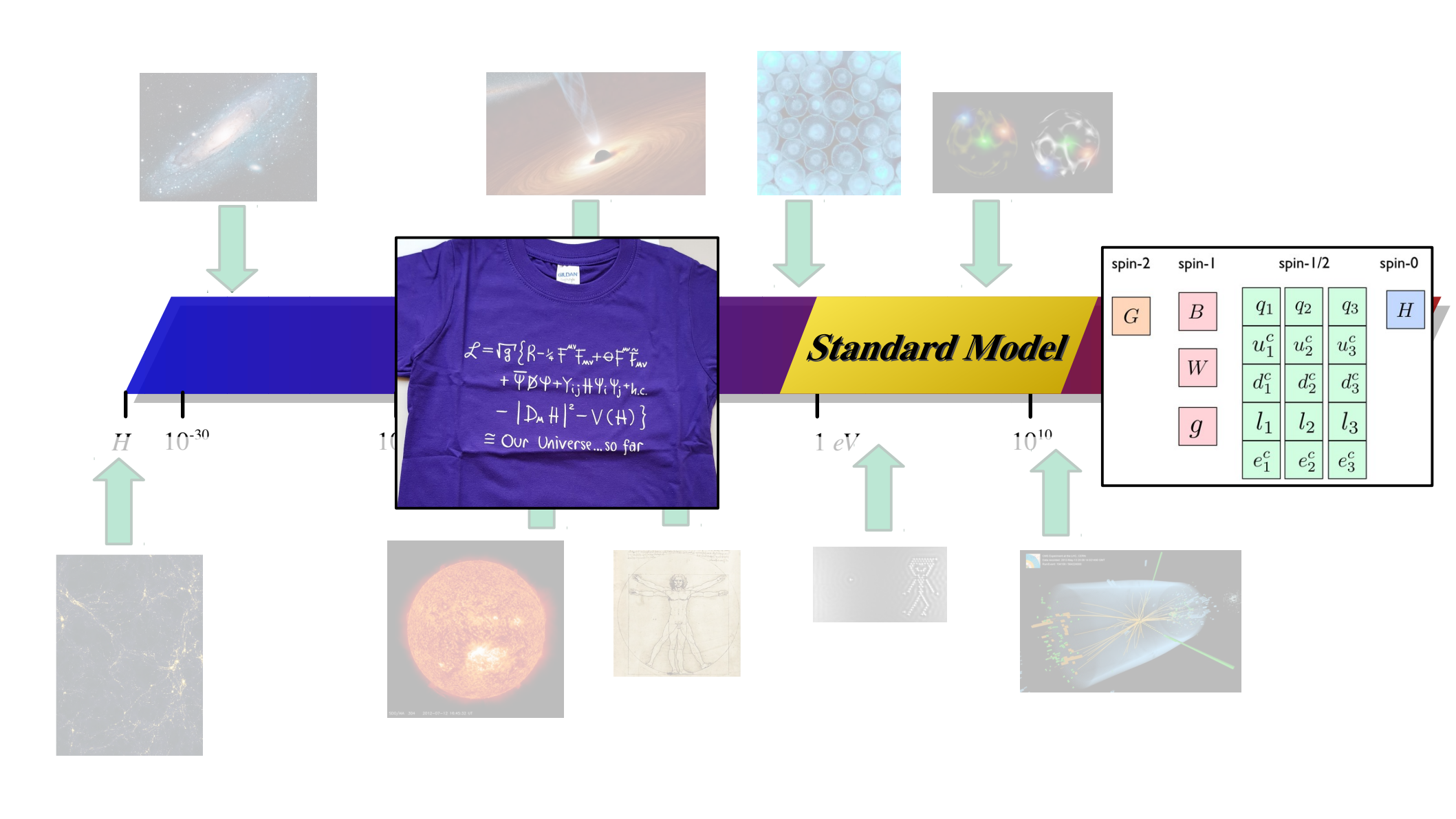






Standard Model

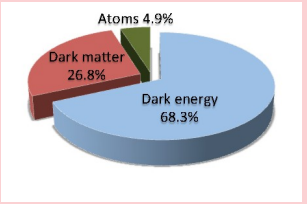
H 10^{-30} 10^{-20} 10^{-10} $1\ eV$ 10^{10} 10^{20} M_{Pl}


$\mathcal{L} = \sqrt{g}\{R - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \Theta F^{\mu\nu} \tilde{F}_{\mu\nu}$
$+ \bar{\Psi} \not{D} \Psi + Y_{ij} H \Psi_i \Psi_j + h.c.$
$- |D_\mu H|^2 - V(H)\}$
≅ Our Universe... so far
Standard Model
H
10^{-30}
1 eV
10^{10}
spin-2
spin-1
spin-1/2
spin-0
G
B
W
g
q_1 q_2 q_3
u_1^c u_2^c u_3^c
d_1^c d_2^c d_3^c
l_1 l_2 l_3
e_1^c e_2^c e_3^c
H

Still So Much to be Explained

- Dark Matter
- Neutrino Masses
- Quantum Gravity



(WIMPS?, axions?, etc...)

(RH neutrinos?, extra scalars?, etc...)

(String Theory?)

Still So Much to be Explained

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- Neutrino Masses
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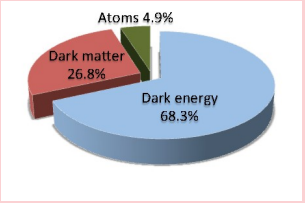
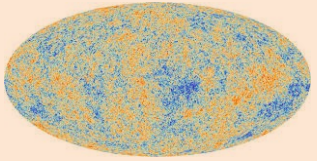


(WIMPS?, axions?, etc...)

(RH neutrinos?, extra scalars?, etc...)

(String Theory?)

- Baryogenesis
- CMB (homogeneity/flatness)

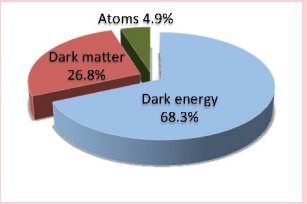


(Leptogenesis? extra EW scalar? etc...)

(Inflaton?)

Still So Much to be Explained

- Dark Matter
- Neutrino Masses
- Quantum Gravity

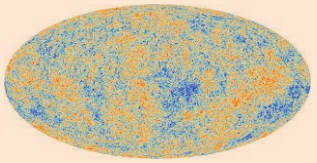


(WIMPS?, axions?, etc...)

(RH neutrinos?, extra scalars?, etc...)

(String Theory?)

- Baryogenesis
- CMB (homogeneity/flatness)

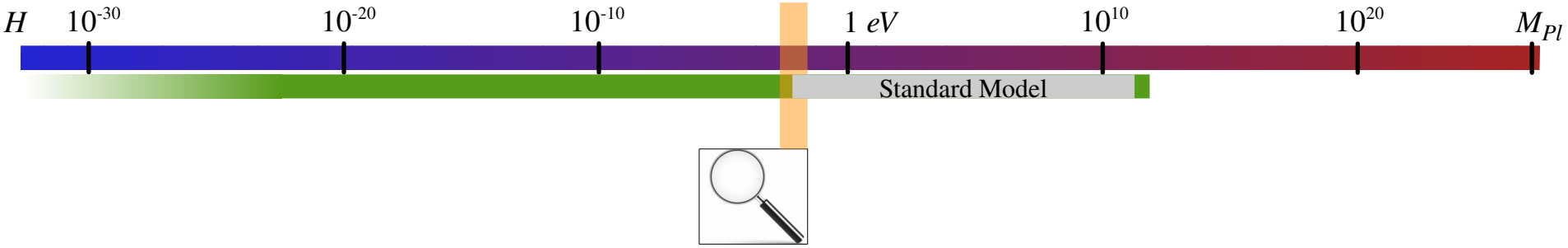


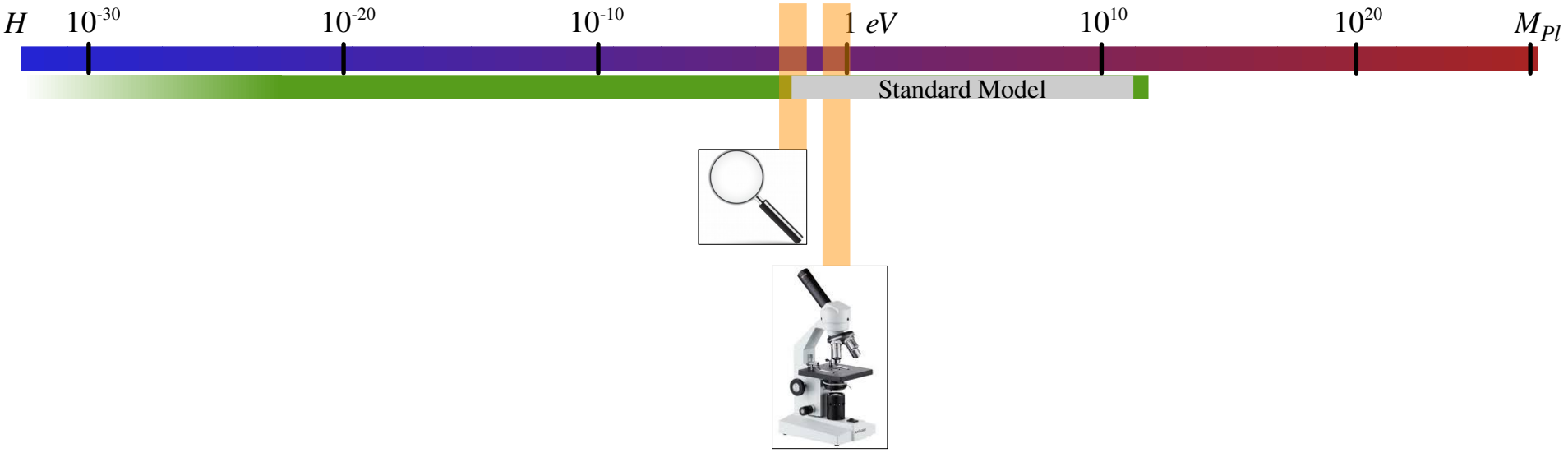
(Leptogenesis? extra EW scalar? etc...)

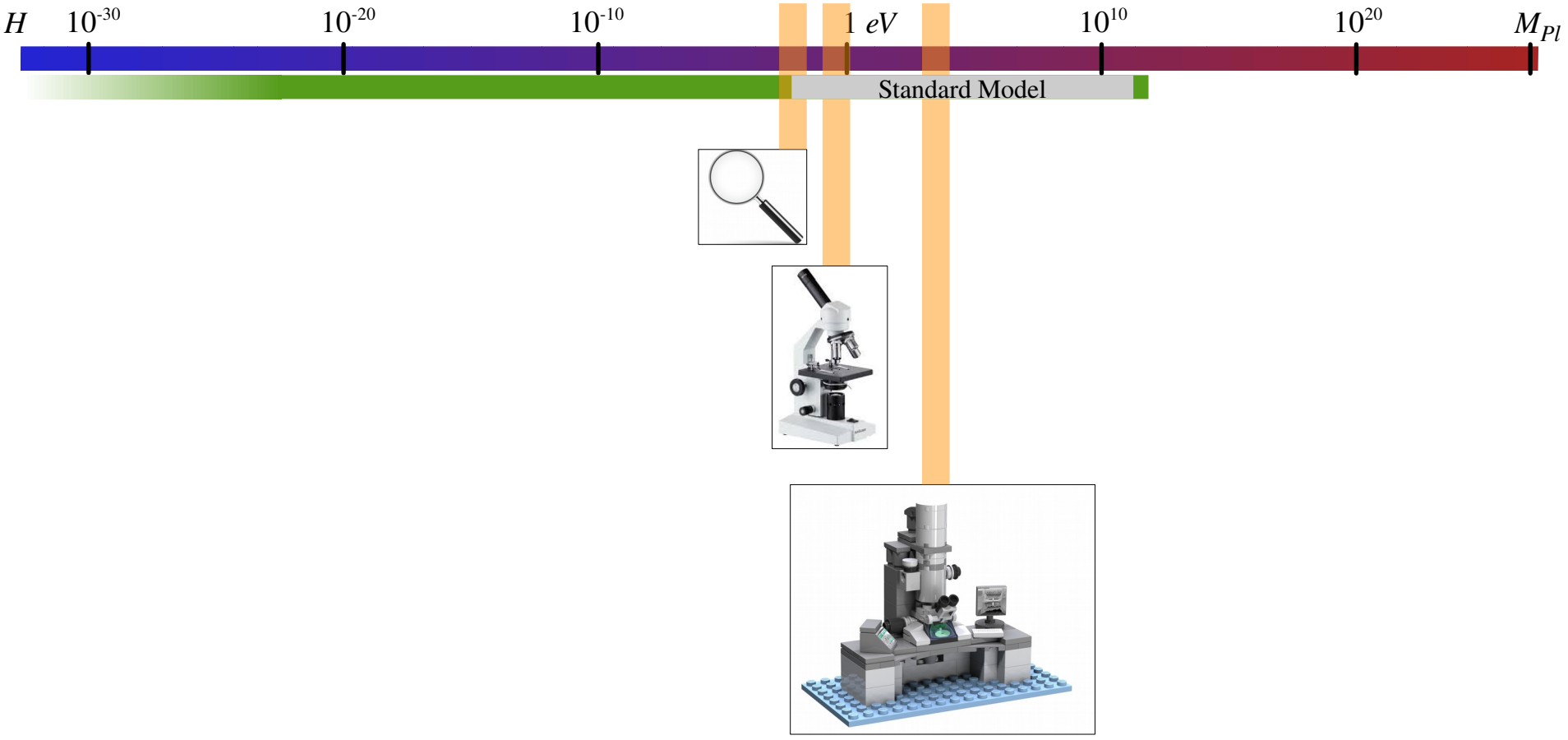
(Inflaton?)

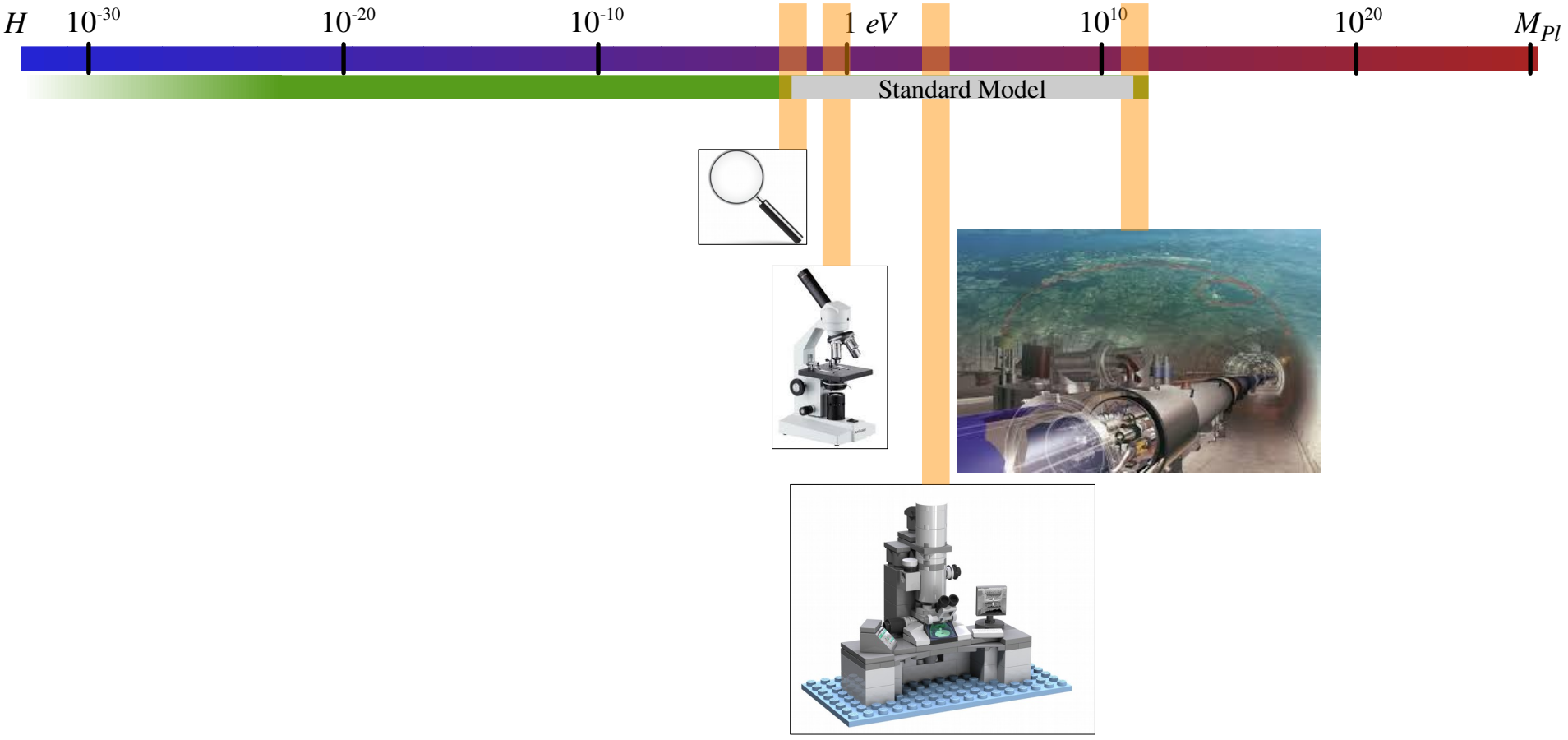
- Strong CP Problem: $\theta \lesssim 10^{-10}$ (QCD Axion?)
- Hierarchy Problems: $\Lambda_{CC}^{1/4} \ll m_h \ll M_{Pl}$ (SUSY?, compositeness?, ...)
- Flavour Problem: $m_e \sim 10^{-6} m_t$ (flavons? extra-dim?)

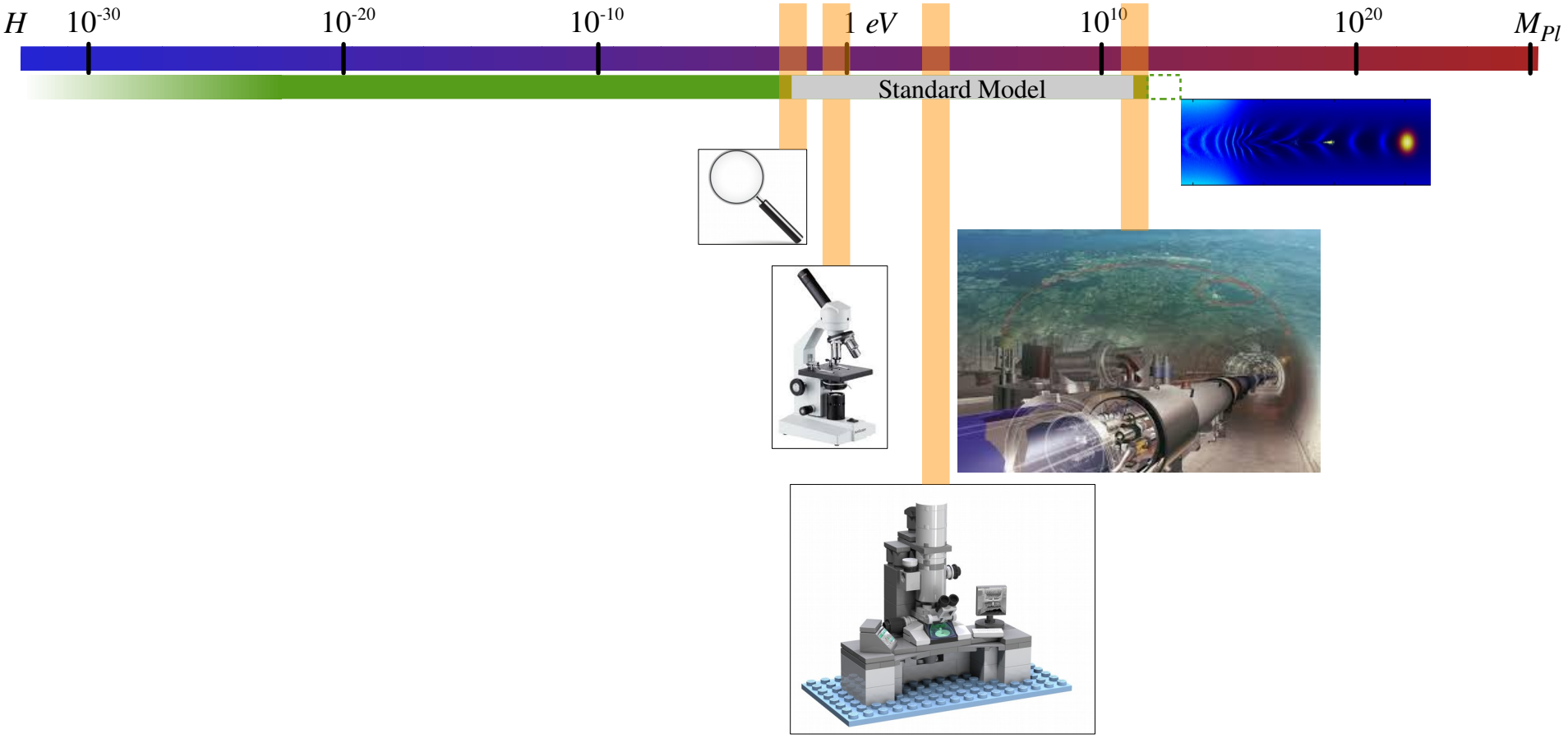
H
10^{-30}
10^{-20}
10^{-10}
$1\ eV$
10^{10}
10^{20}
M_{Pl}
Standard Model


H
10^{-30}
10^{-20}
10^{-10}
1 eV
10^{10}
10^{20}
M_{Pl}
Standard Model

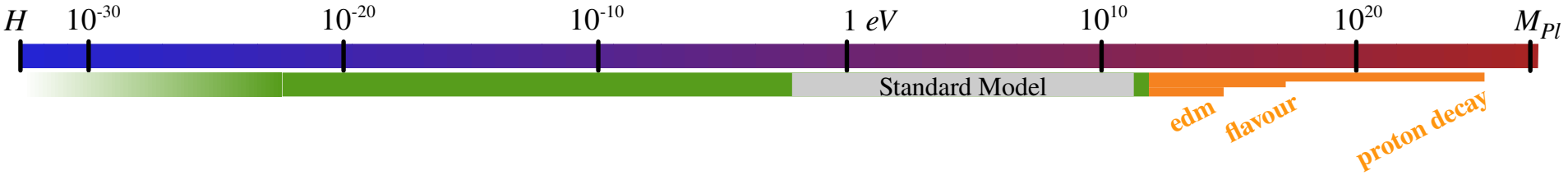

H
10-30
10-20
10-10
1 eV
1010
1020
MPl
Standard Model


H
10^{-30}
10^{-20}
10^{-10}
1 eV
10^{10}
10^{20}
M_{Pl}
Standard Model


H
10^-30
10^-20
10^-10
1 eV
10^10
10^20
M_Pl
Standard Model

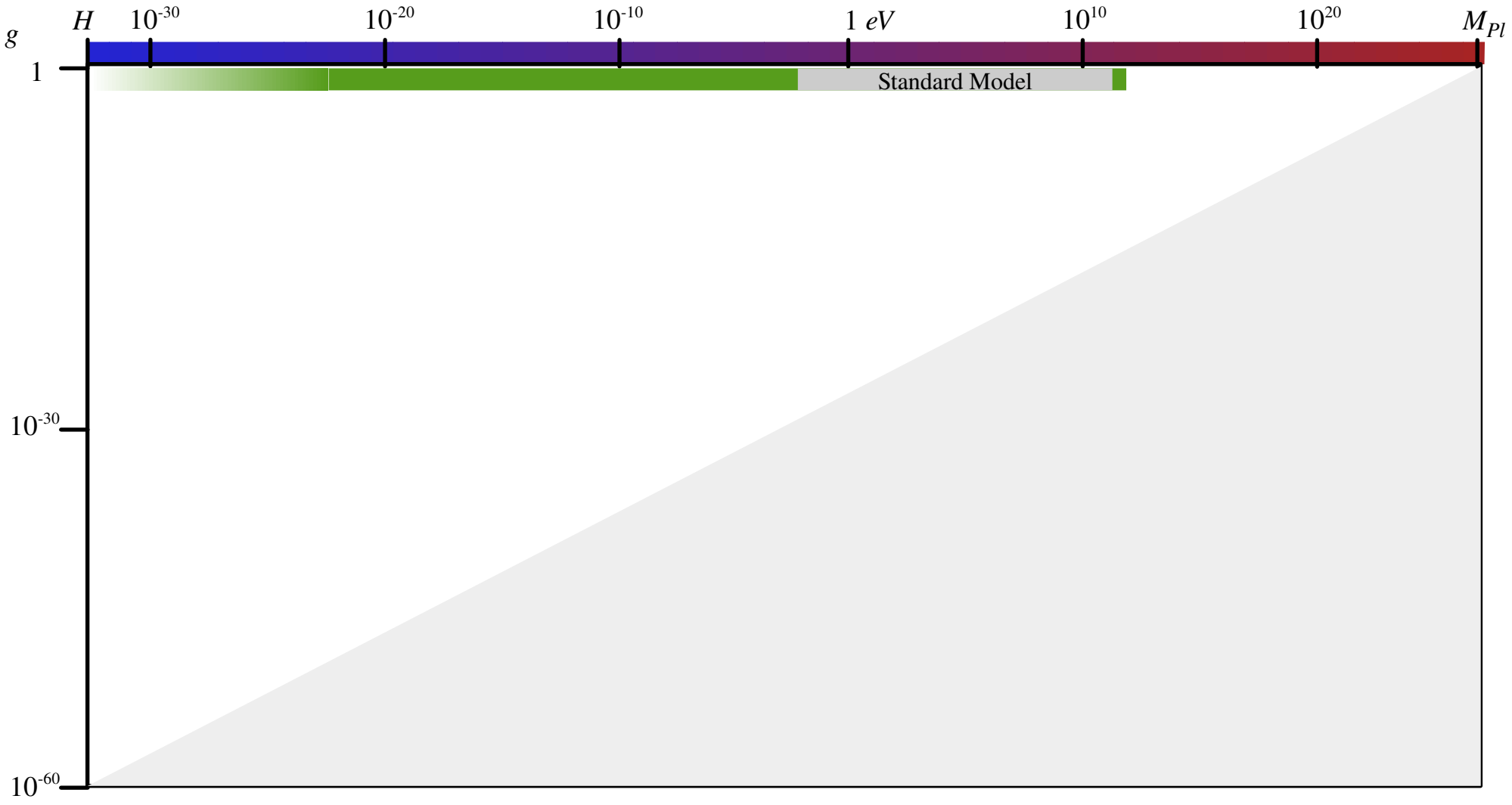

H
10^-30
10^-20
10^-10
1 eV
10^10
10^20
M_Pl
Standard Model

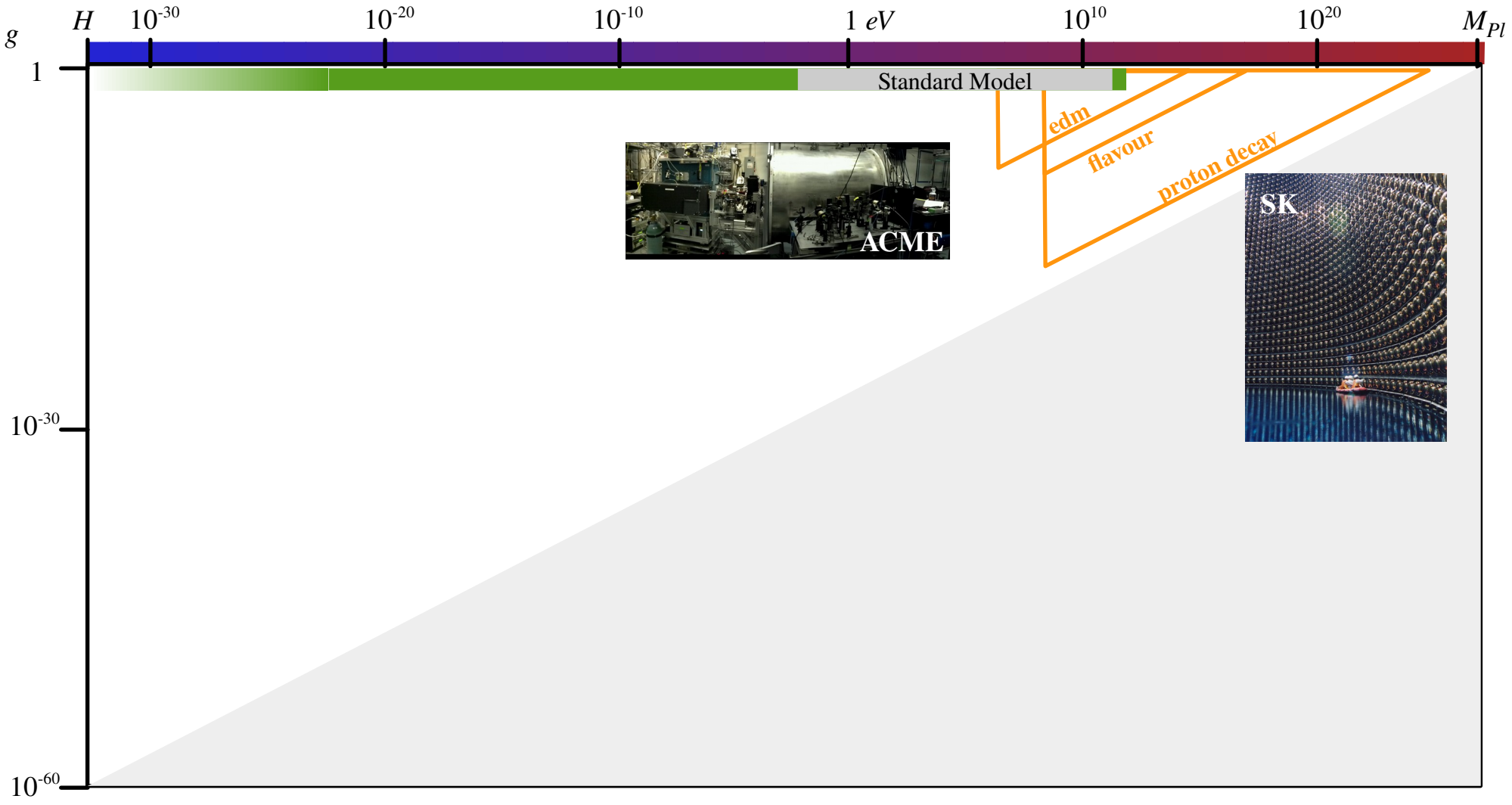
Precision Physics $\mathcal{O} = \mathcal{O}_{SM} + \sum_n c_n \frac{E^n}{M^n}$

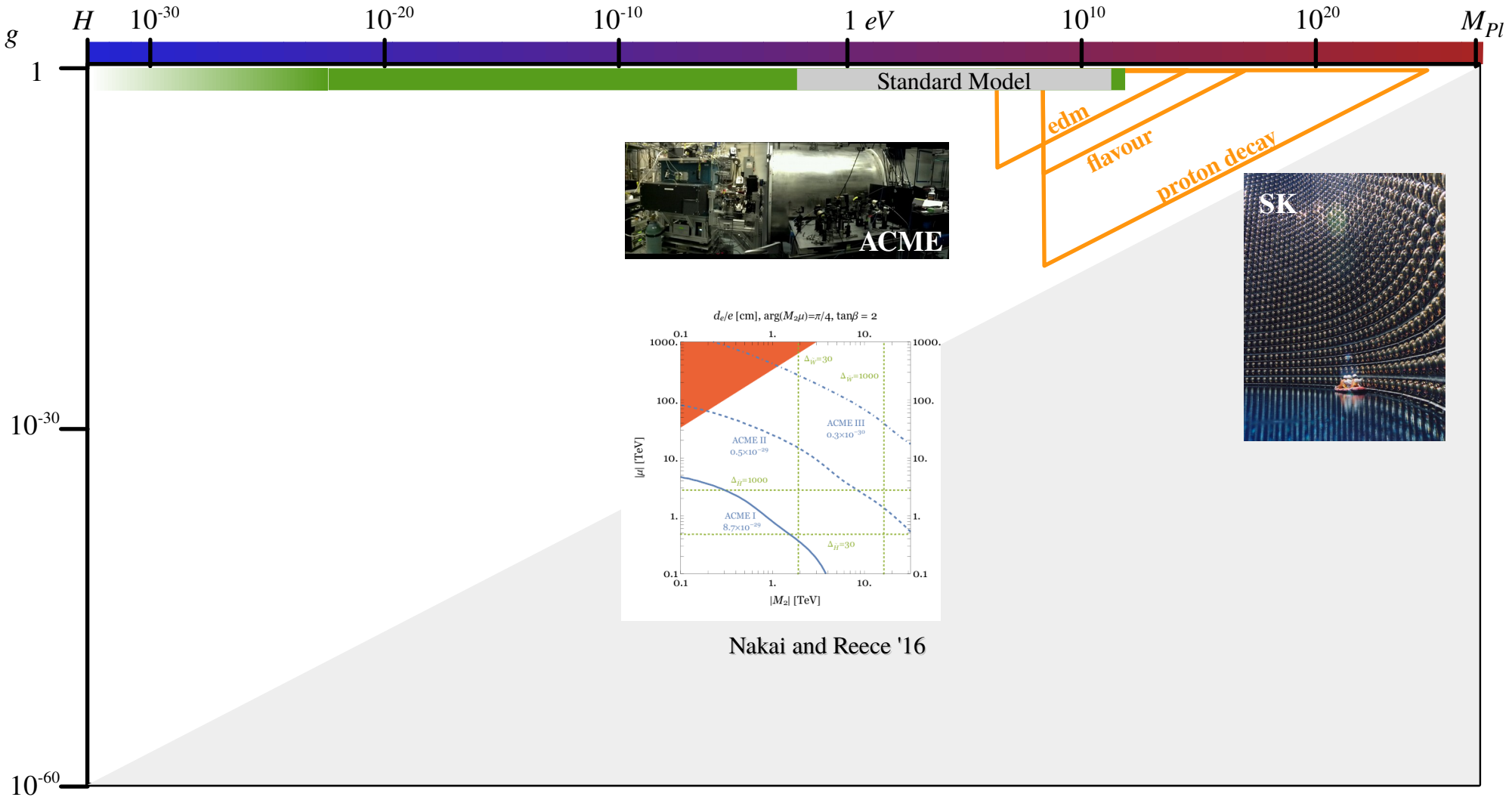


Precision Physics $\mathcal{O} = \mathcal{O}_{SM} + \sum_n c_n \frac{E^n}{M^n}$

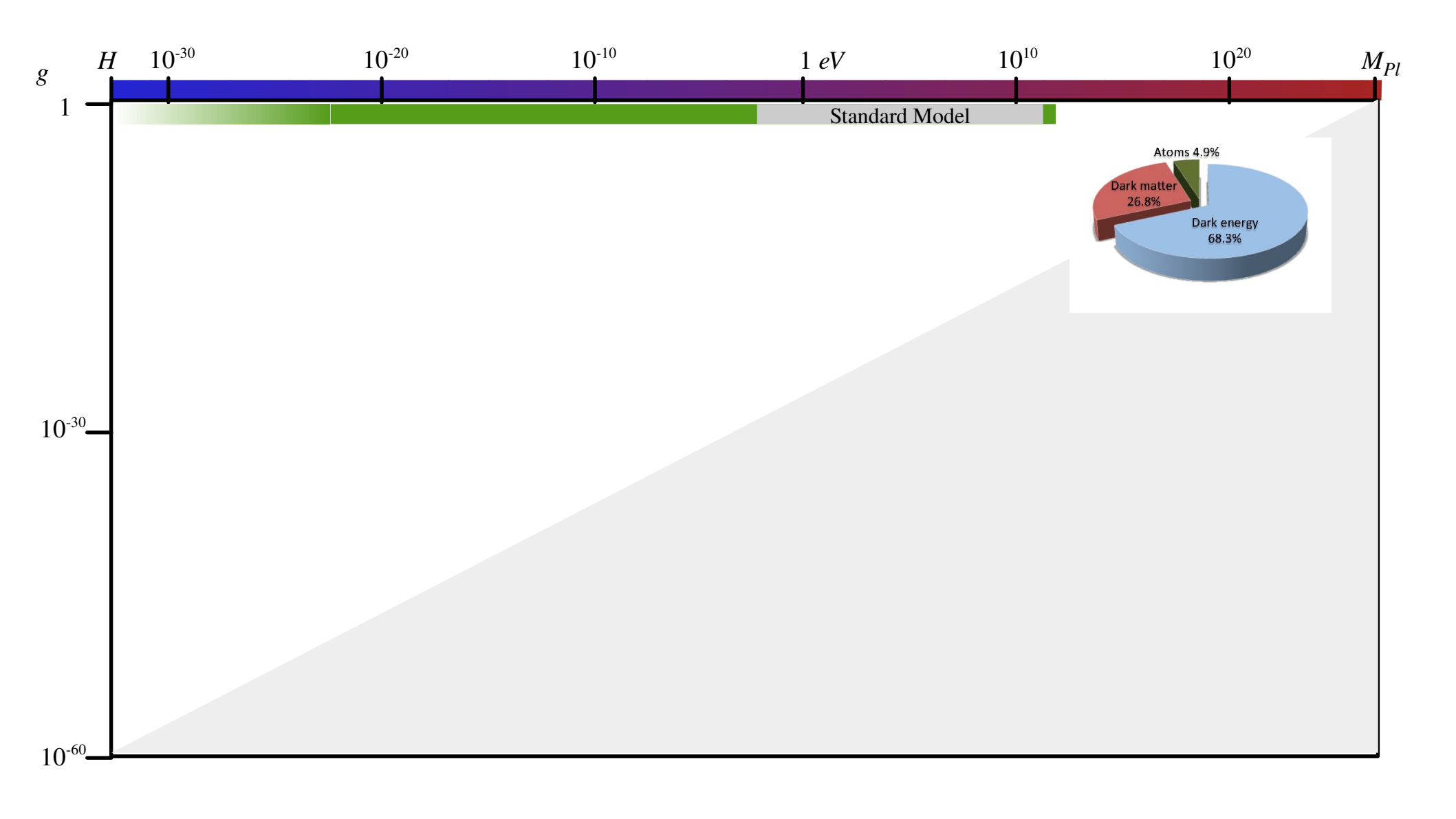
Many SM particles discovered in this way

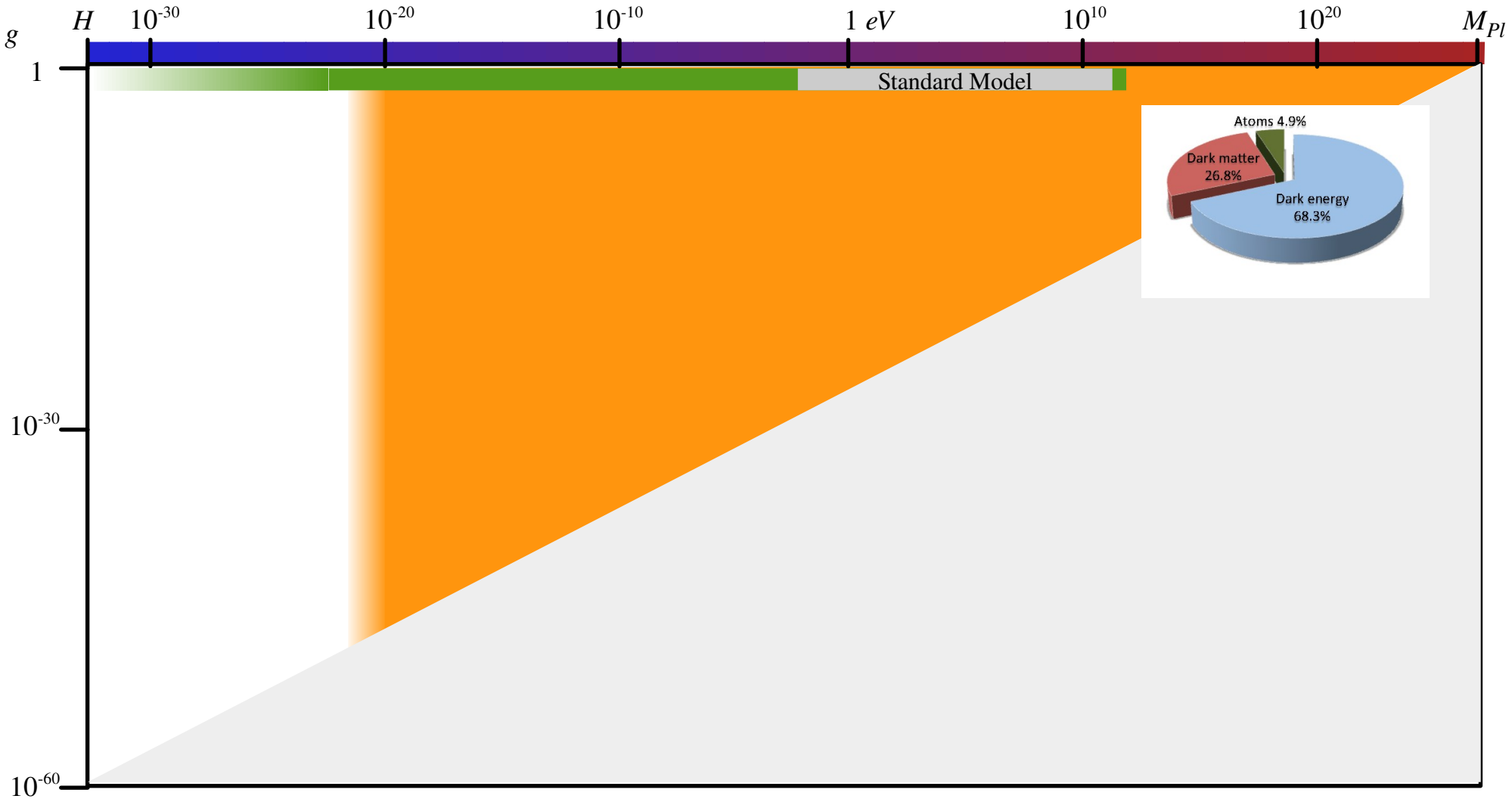

g
H
10-30
10-20
10-10
1 eV
1010
1020
MPl
1
Standard Model
10-30
10-60

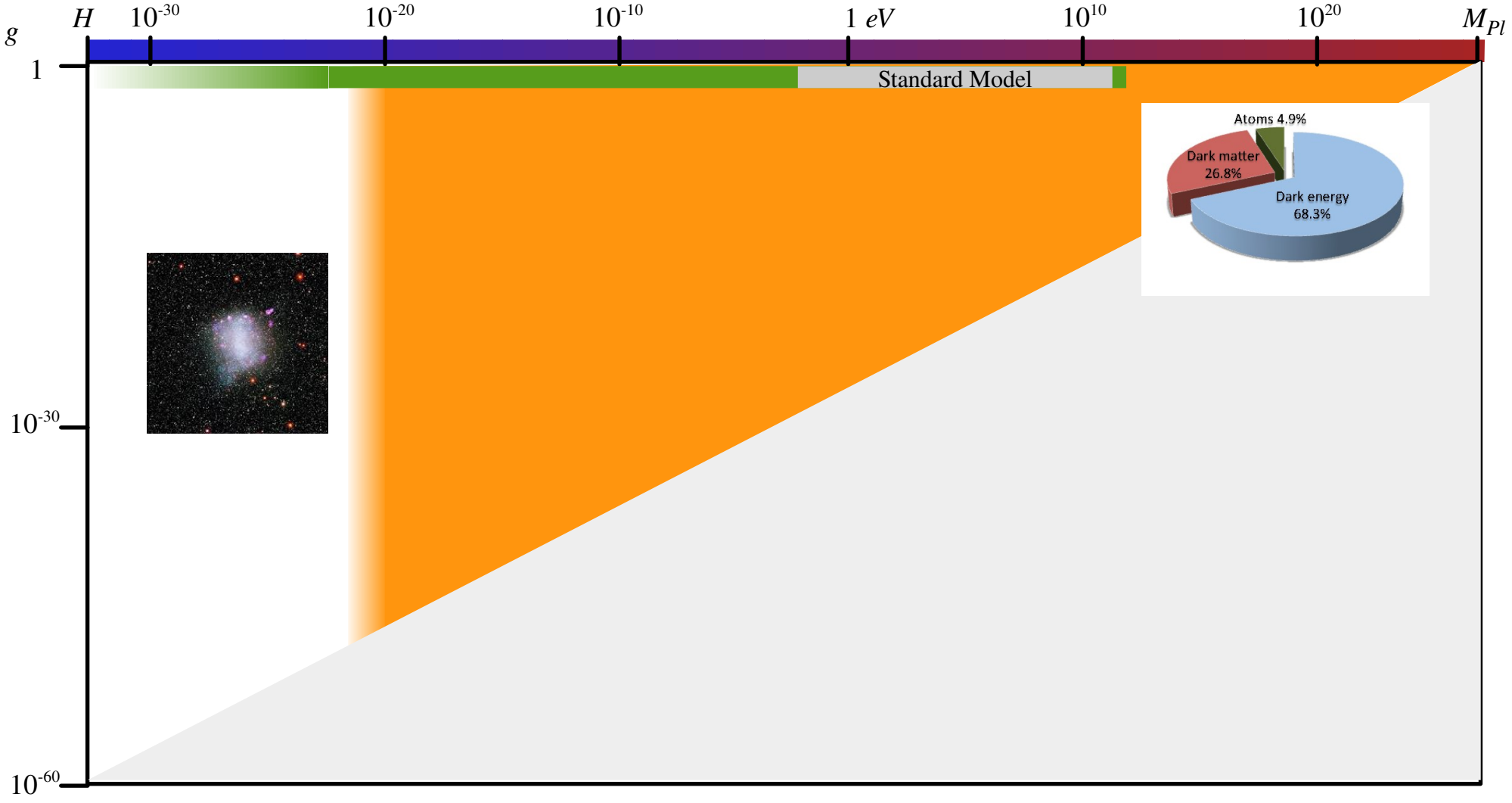

g
H
10^-30
10^-20
10^-10
1 eV
10^10
10^20
M_Pl
1
Standard Model
edm
flavour
proton decay
ACME
SK
10^-30
10^-60

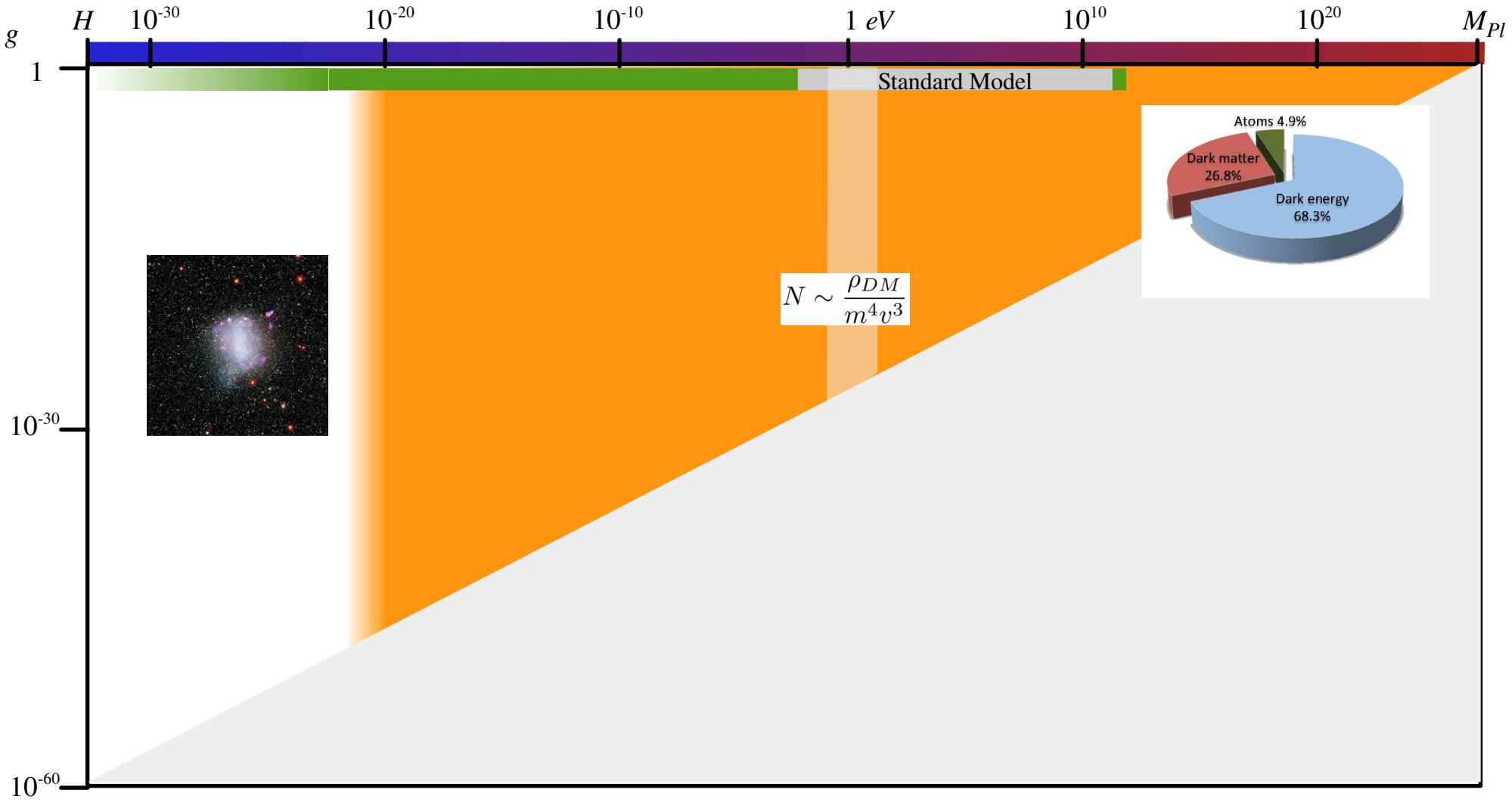


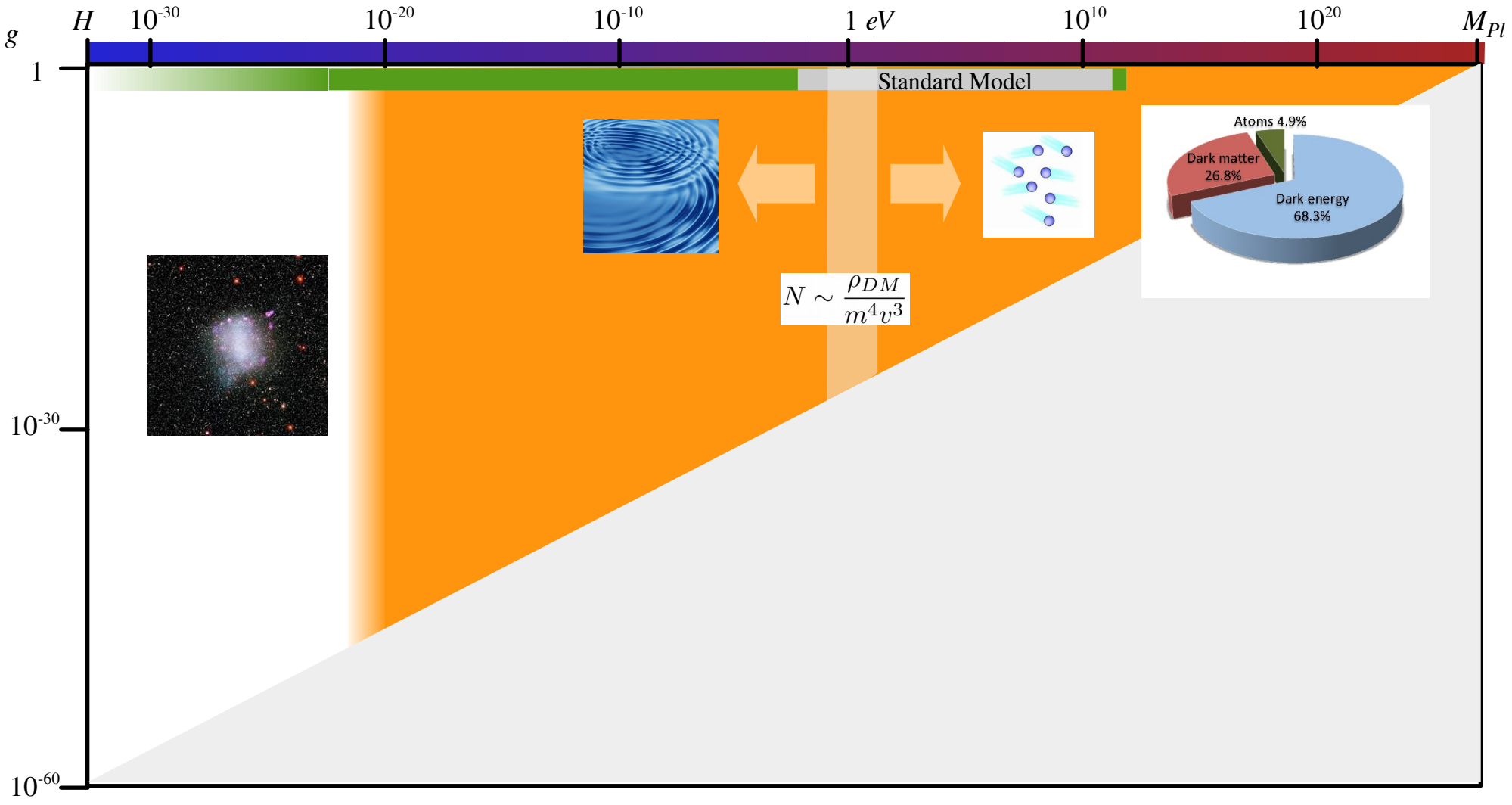
Nakai and Reece '16

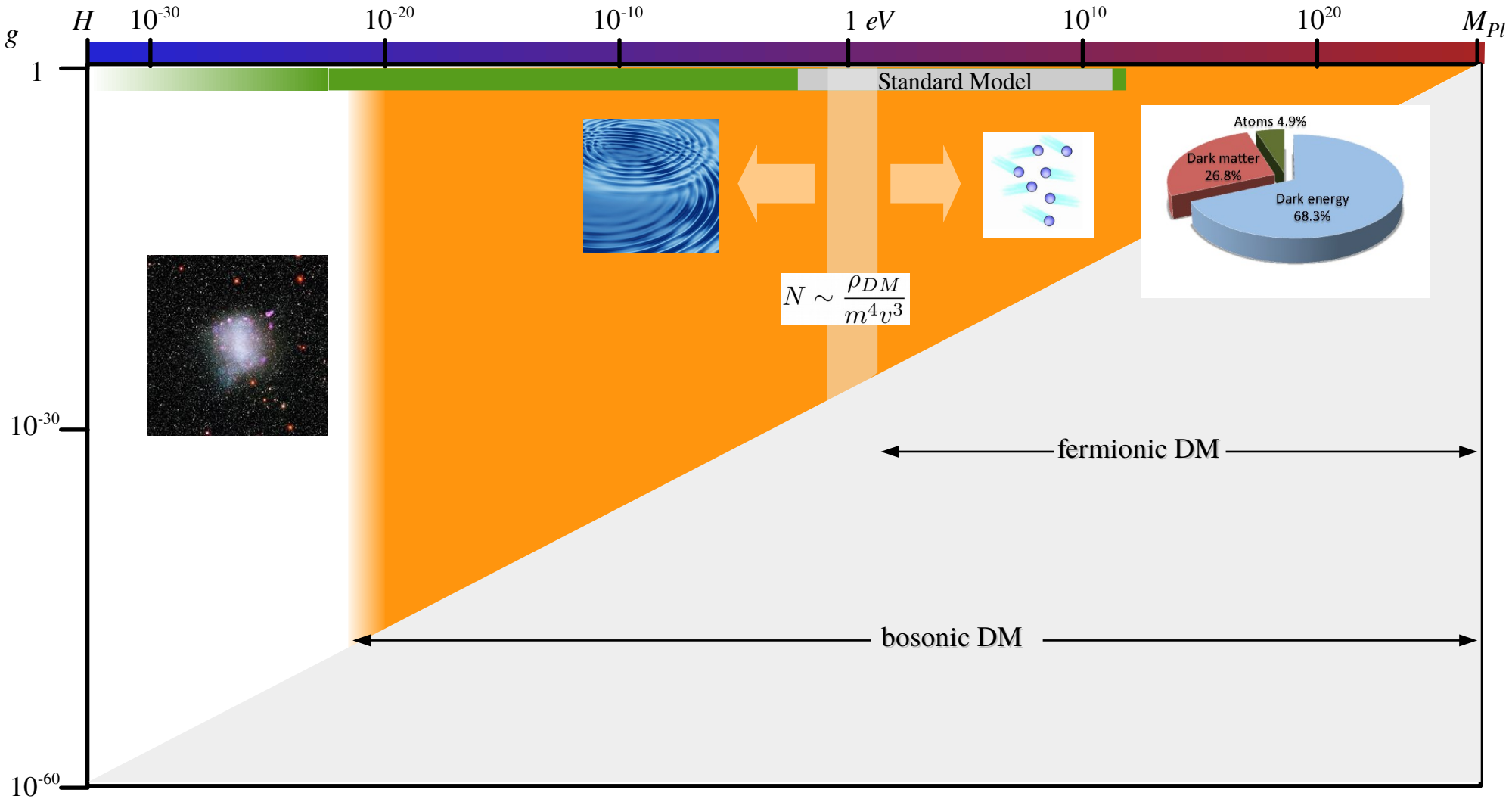

g
H
10-30
10-20
10-10
1 eV
1010
1020
MPl
1
Standard Model
Atoms 4.9%
Dark matter 26.8%
Dark energy 68.3%
10-30
10-60

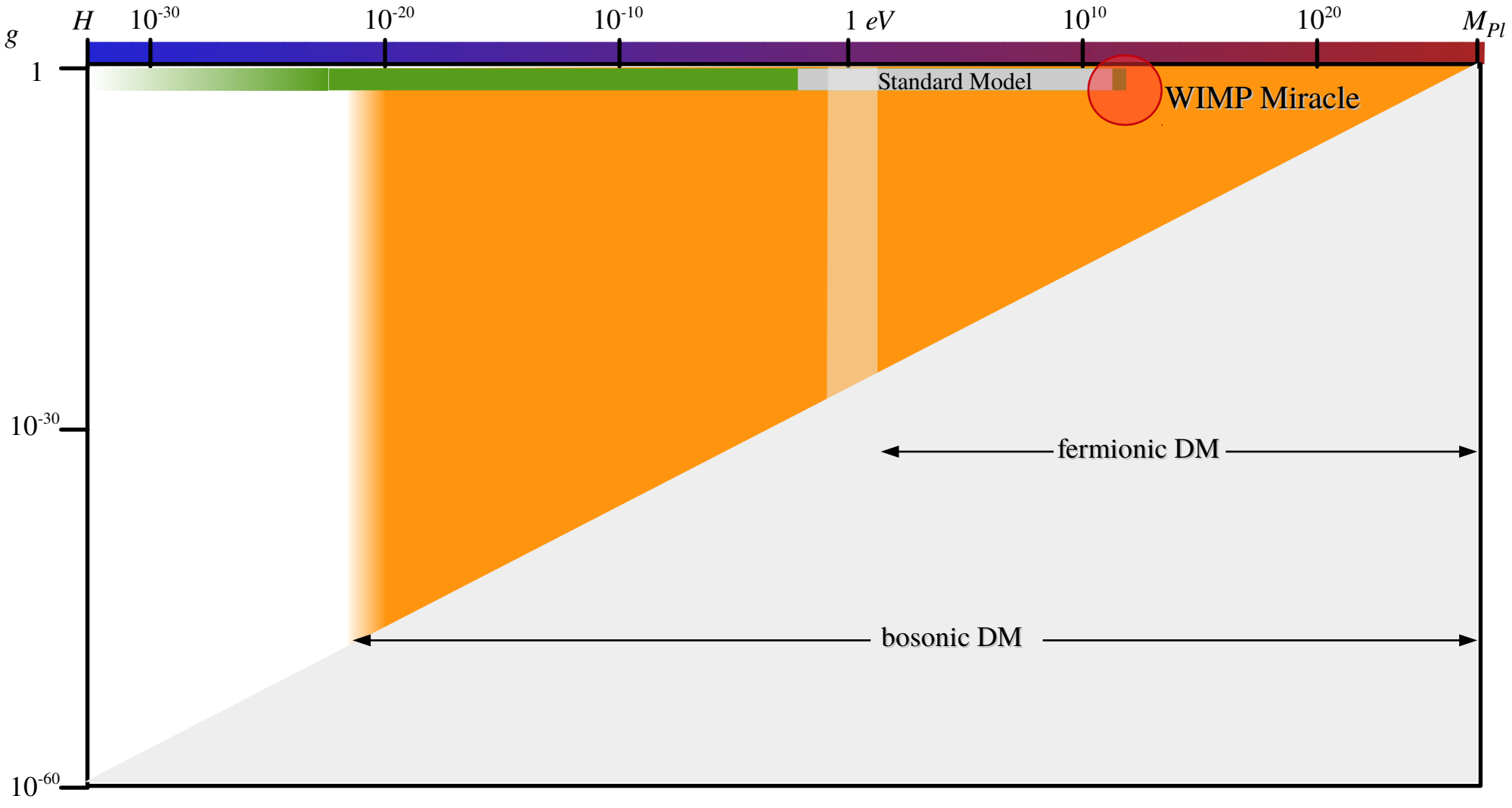

g
H
10-30
10-20
10-10
1 eV
1010
1020
MPl
1
Standard Model
Atoms 4.9%
Dark matter
26.8%
Dark energy
68.3%
10-30
10-60

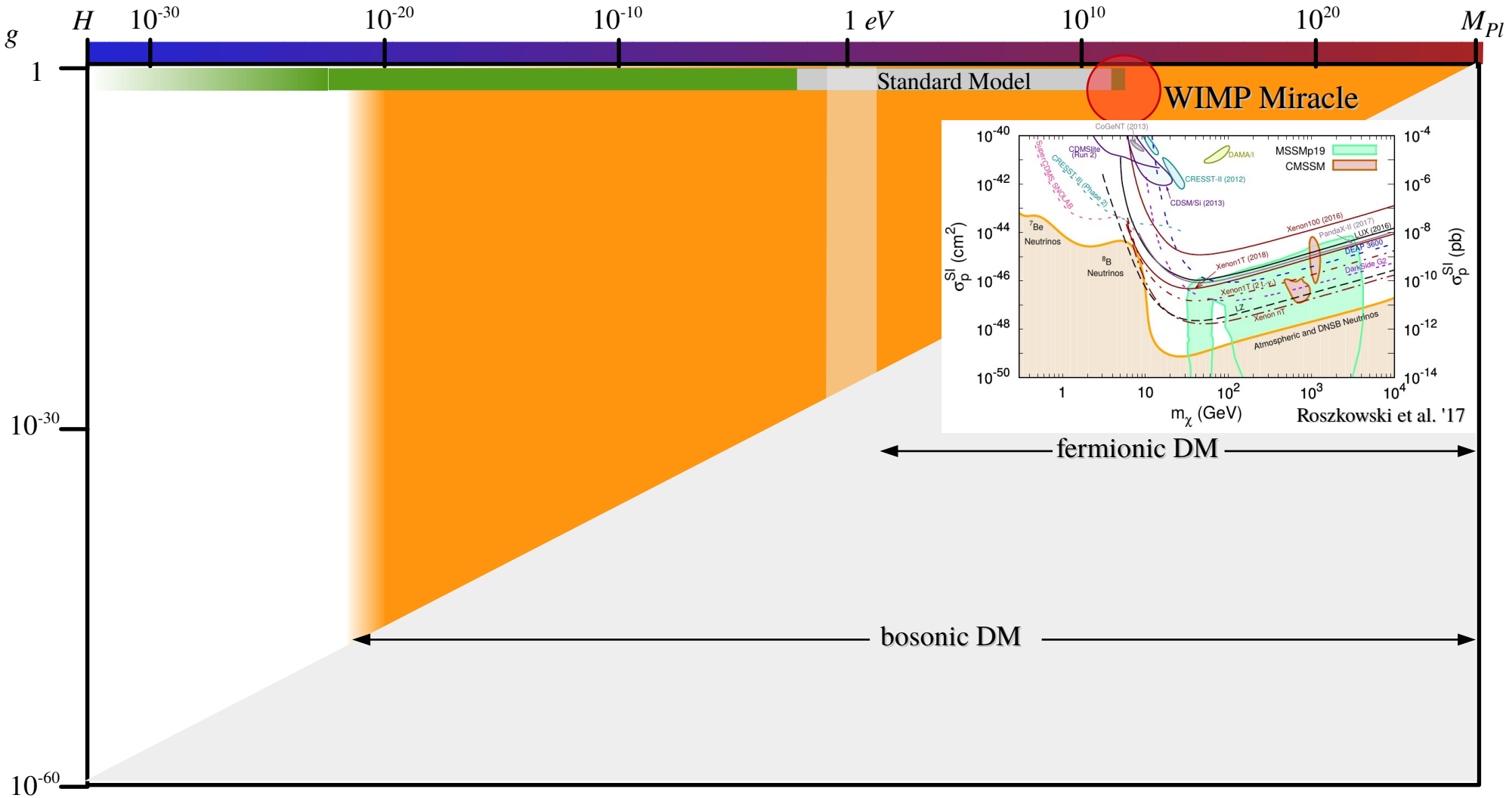

g
H
10^{-30}
10^{-20}
10^{-10}
1 eV
10^{10}
10^{20}
M_{Pl}
1
Standard Model
10^{-30}
10^{-60}
Atoms 4.9%
Dark matter 26.8%
Dark energy 68.3%

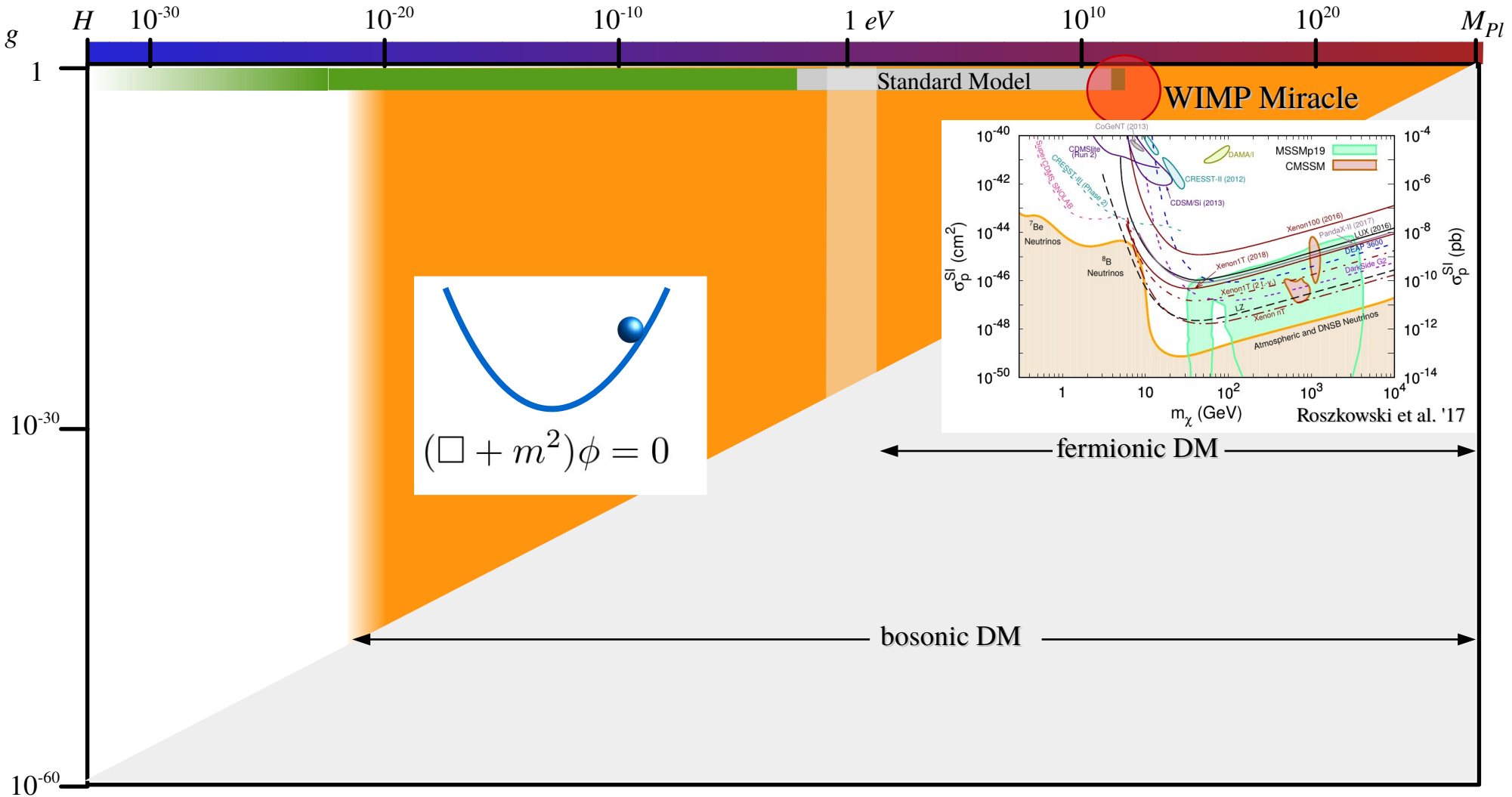

g
H
10-30
10-20
10-10
1 eV
1010
1020
MPl
1
Standard Model
10-30
10-60
Atoms 4.9%
Dark matter 26.8%
Dark energy 68.3%
$N \sim \frac{\rho_{DM}}{m^4 v^3}$


g
H
10-30
10-20
10-10
1 eV
1010
1020
MPl
1
Standard Model
10-30
10-60
Atoms 4.9%
Dark matter 26.8%
Dark energy 68.3%
$N \sim \frac{\rho_{DM}}{m^4 v^3}$


g
H
10-30
10-20
10-10
1 eV
1010
1020
MPl
1
Standard Model
Atoms 4.9%
Dark matter 26.8%
Dark energy 68.3%
$N \sim \frac{\rho_{DM}}{m^4 v^3}$
10-30
fermionic DM
bosonic DM
10-60


g
H
10^-30
10^-20
10^-10
1 eV
10^10
10^20
M_Pl
1
Standard Model
WIMP Miracle
10^-30
fermionic DM
bosonic DM
10^-60


g
H
10^-30
10^-20
10^-10
1 eV
10^10
10^20
M_Pl
1
10^-30
10^-60
Standard Model
WIMP Miracle
fermionic DM
bosonic DM
CoGeNT (2013)
CDMSlite (Run 2)
SuperCDMS-SNOLAB
CRESST-III (Phase 2)
DAMA/I
CRESST-II (2012)
CDSM/Si (2013)
MSSMp19
CMSSM
Xenon100 (2016)
PandaX-II (2017)
LUX (2016)
DEAP 3600
Xenon1T (2018)
DarkSide G2
Xenon1T (2 t-y)
LZ
Xenon nT
Atmospheric and DNSB Neutrinos
7Be Neutrinos
8B Neutrinos
σ_p^SI (cm^2)
σ_p^SI (pb)
m_χ (GeV)
Roszkowski et al. '17


g
H
10^-30
10^-20
10^-10
1 eV
10^10
10^20
M_Pl
1
Standard Model
WIMP Miracle
10^-30
10^-60
$(\Box + m^2)\phi = 0$
fermionic DM
bosonic DM
CoGeNT (2013)
CDMSlite (Run 2)
SuperCDMS-SNOLAB
CRESST-III (Phase 2)
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Atmospheric and DNSB Neutrinos
^{7}Be Neutrinos
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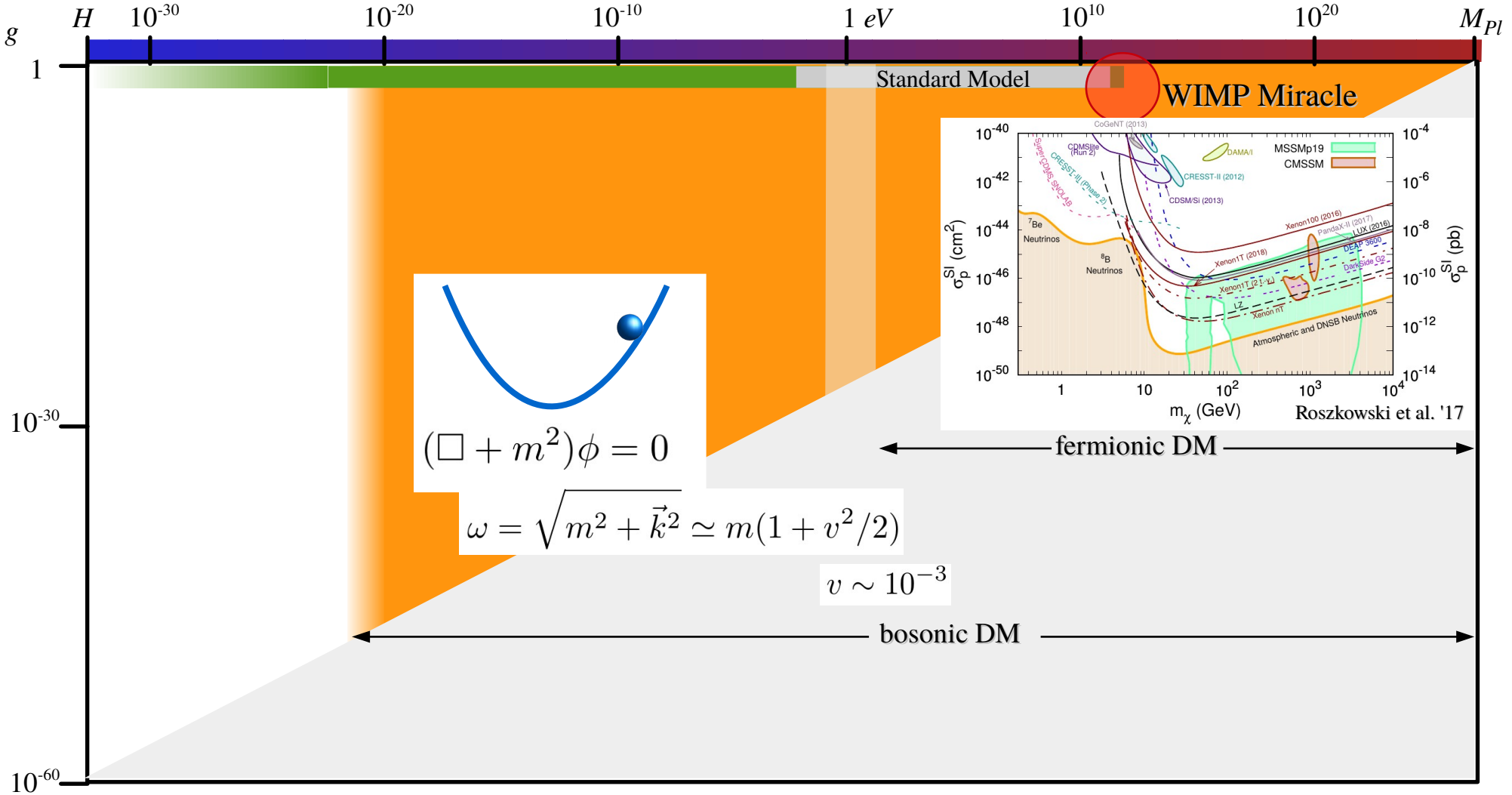
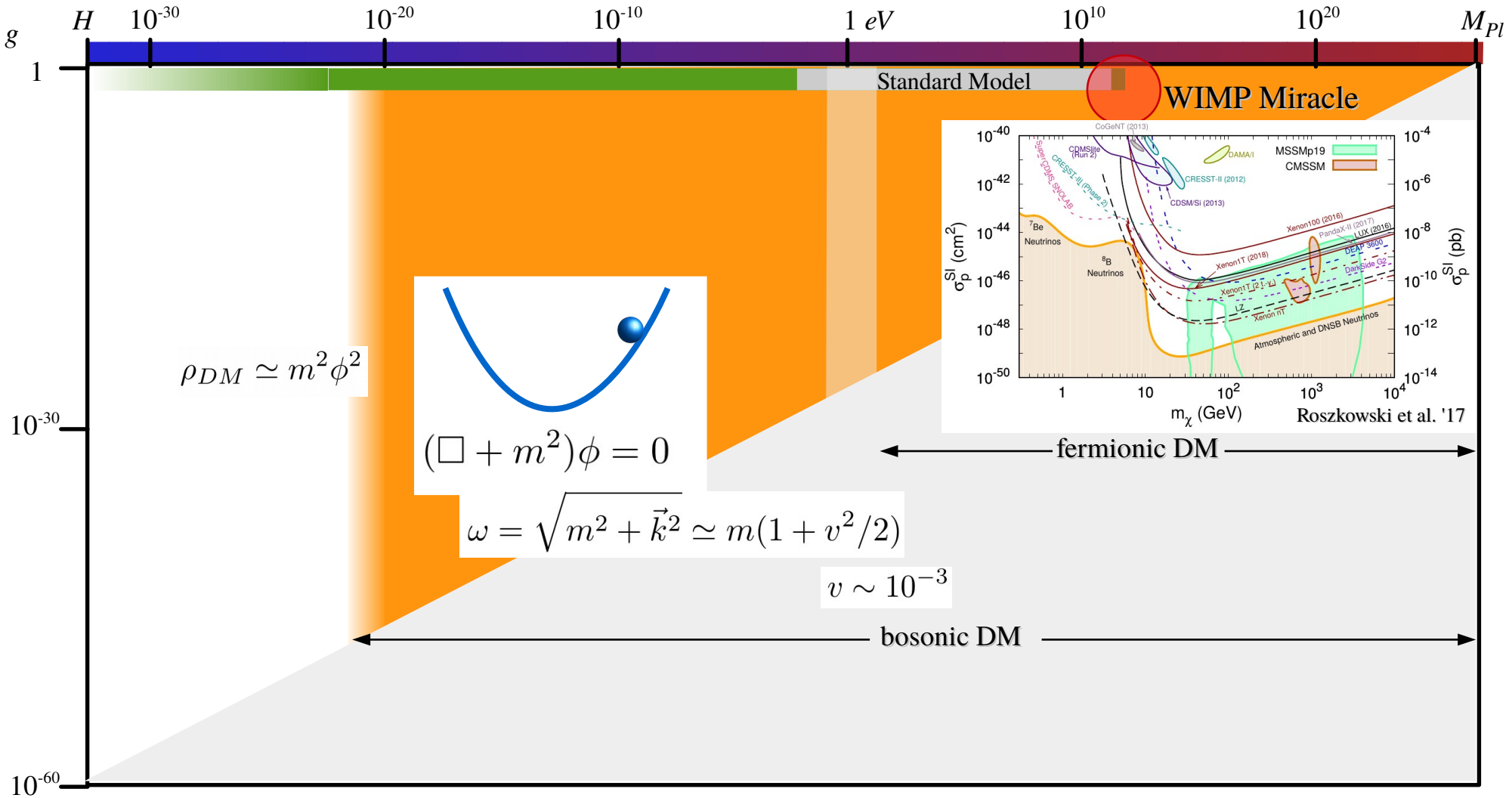
σ_p^{SI} (cm^2)
σ_p^{SI} (pb)
m$_\chi$ (GeV)
Roszkowski et al. '17


g
H
10^-30
10^-20
10^-10
1 eV
10^10
10^20
M_Pl
1
Standard Model
WIMP Miracle
10^-30
10^-60
(□ + m^2)φ = 0
ω = √(m^2 + k^2) ≃ m(1 + v^2/2)
v ~ 10^-3
fermionic DM
bosonic DM
CoGeNT (2013)
CDMSlite (Run 2)
SuperCDMS_SNOLAB
CRESST-III (Phase 2)
DAMA/I
CRESST-II (2012)
CDSM/Si (2013)
MSSMp19
CMSSM
Xenon100 (2016)
PandaX-II (2017)
LUX (2016)
DEAP 3600
Xenon1T (2018)
DarkSide G2
Xenon1T (2 t-y)
LZ
Xenon nT
Atmospheric and DNSB Neutrinos
7Be Neutrinos
8B Neutrinos
σ_p^SI (cm^2)
σ_p^SI (pb)
m_χ (GeV)
Roszkowski et al. '17


g
H
10^{-30}
10^{-20}
10^{-10}
1 eV
10^{10}
10^{20}
M_{Pl}
1
10^{-30}
10^{-60}
Standard Model
WIMP Miracle
$\rho_{DM} \simeq m^2\phi^2$
$(\Box + m^2)\phi = 0$
$\omega = \sqrt{m^2 + \vec{k}^2} \simeq m(1 + v^2/2)$
$v \sim 10^{-3}$
fermionic DM
bosonic DM
CoGeNT (2013)
CDMSlite (Run 2)
SuperCDMS_SNOLAB
CRESST-III (Phase 2)
DAMA/I
CRESST-II (2012)
CDSM/Si (2013)
MSSMp19
CMSSM
Xenon100 (2016)
PandaX-II (2017)
LUX (2016)
DEAP 3600
Xenon1T (2018)
DarkSide G2
Xenon1T (2 t-y)
LZ
Xenon nT
Atmospheric and DNSB Neutrinos
^{7}Be Neutrinos
^{8}B Neutrinos
σ_p^{SI} (cm^2)
σ_p^{SI} (pb)
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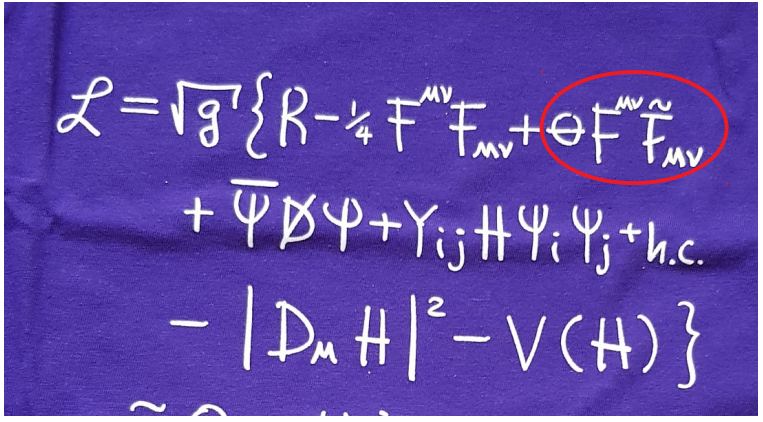
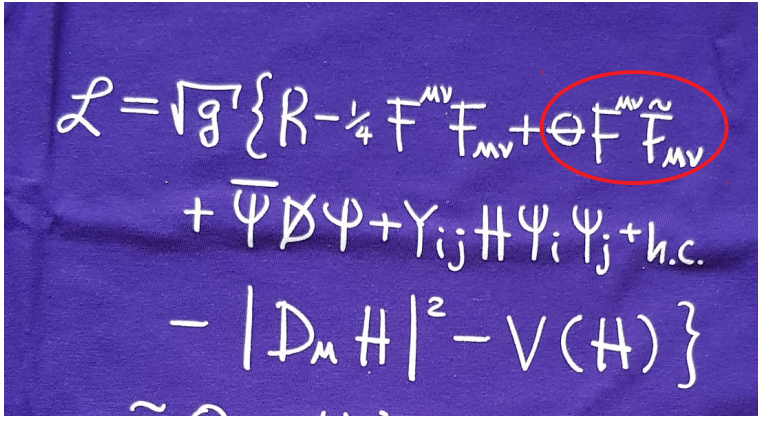


$$\theta \lesssim 10^{-10}$$



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Axion

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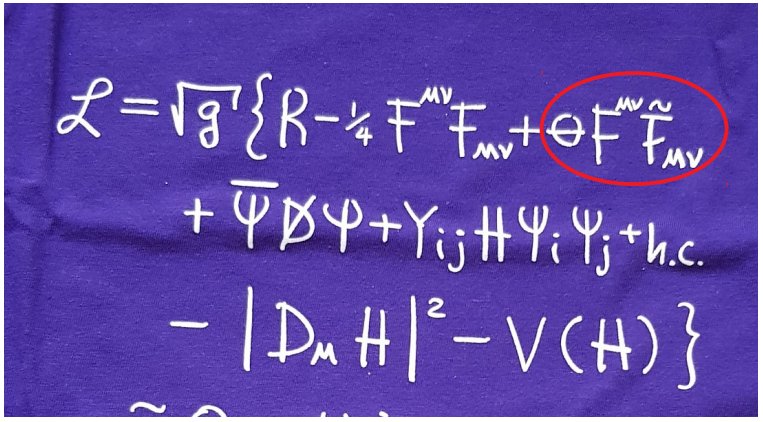

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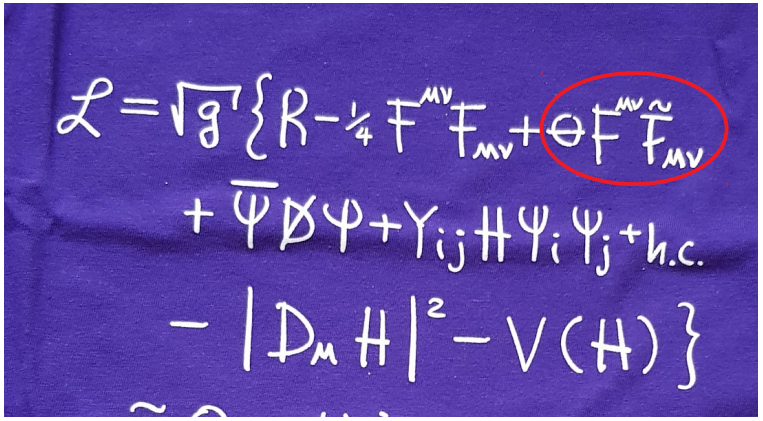


$\theta \lesssim 10^{-10}$

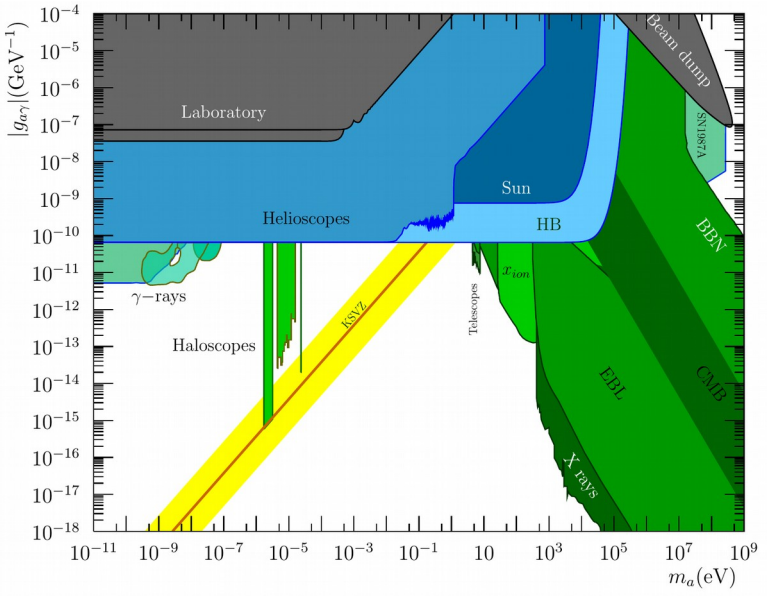
Axion

$$\theta \to \frac{\phi(x)}{M}$$

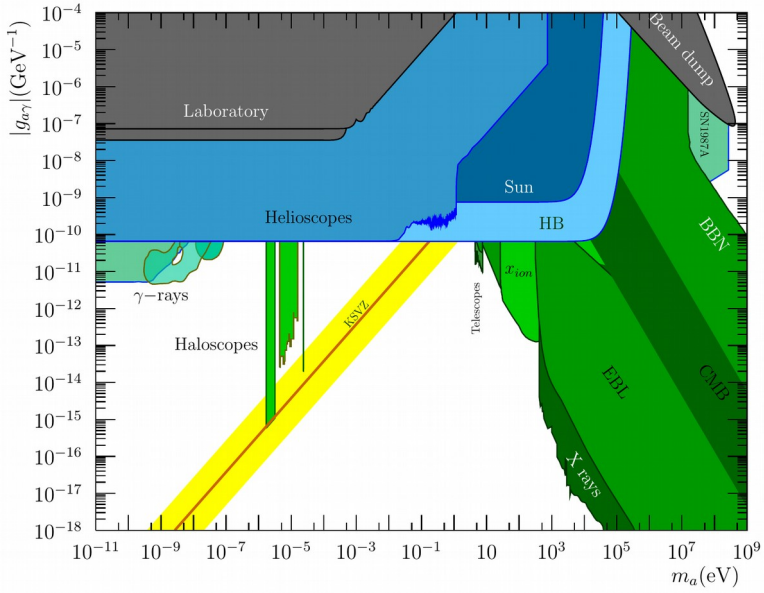
$$m_\phi \simeq \frac{(75\ \mathrm{MeV})^2}{M} \sim (10^{-11} \div 10^{-1})\ \mathrm{eV}$$

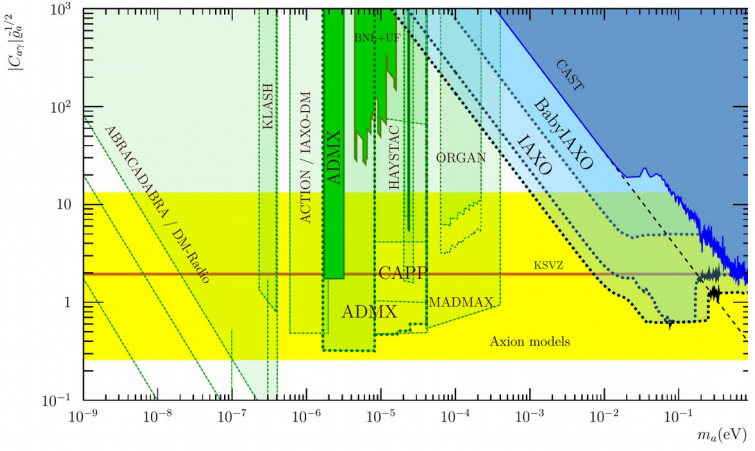
$$\sim (10^{8} \div 10^{17})\ \mathrm{GeV}$$

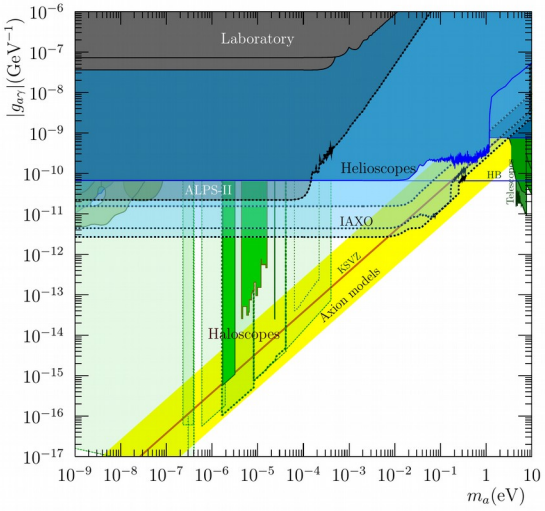
$$g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$



Irastorza Redondo '18







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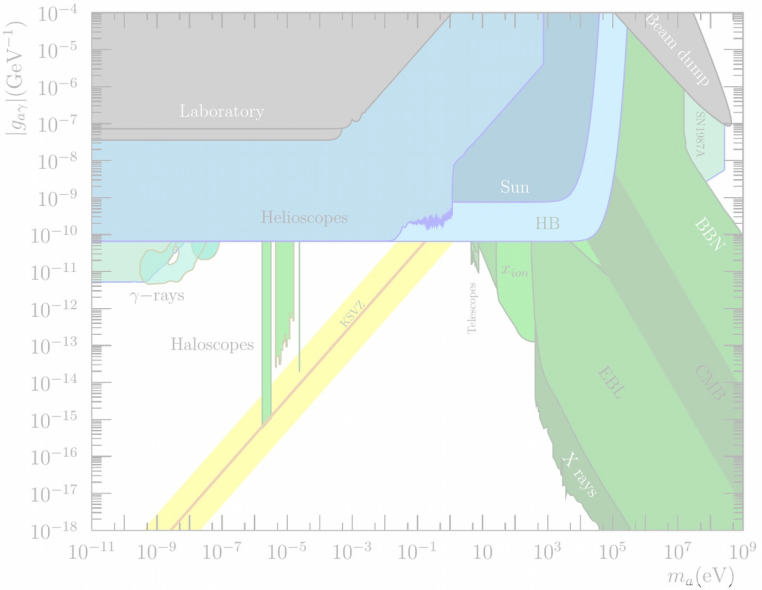
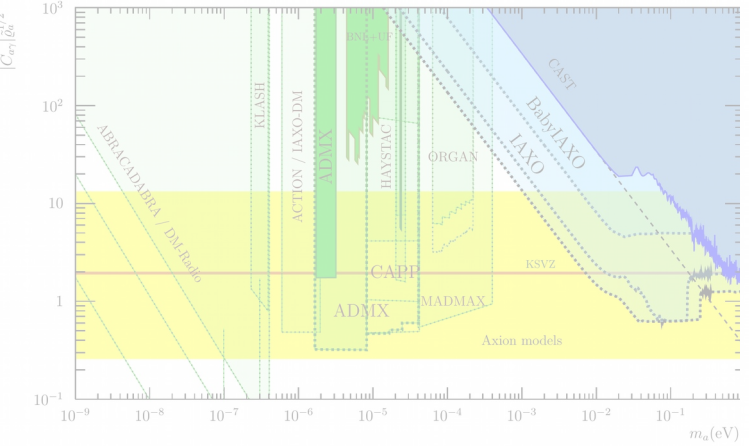
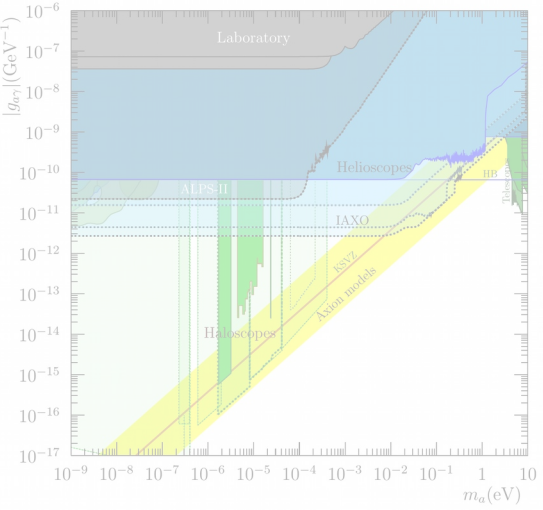
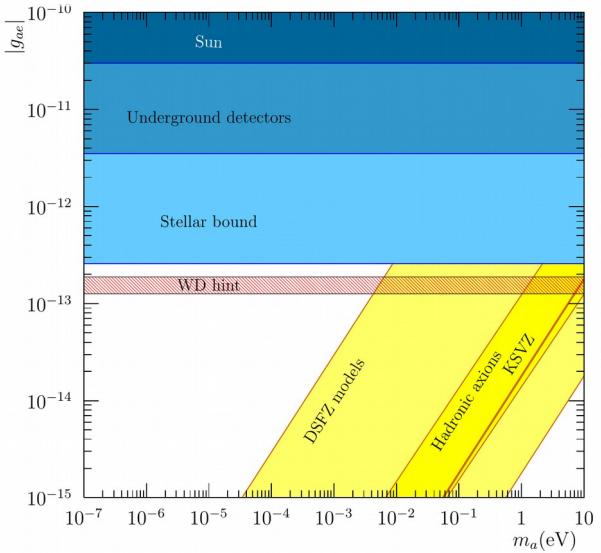






$$g_{a\psi}\frac{\partial_\mu a}{2m_\psi}\bar{\psi}\gamma^\mu\gamma_5\psi$$



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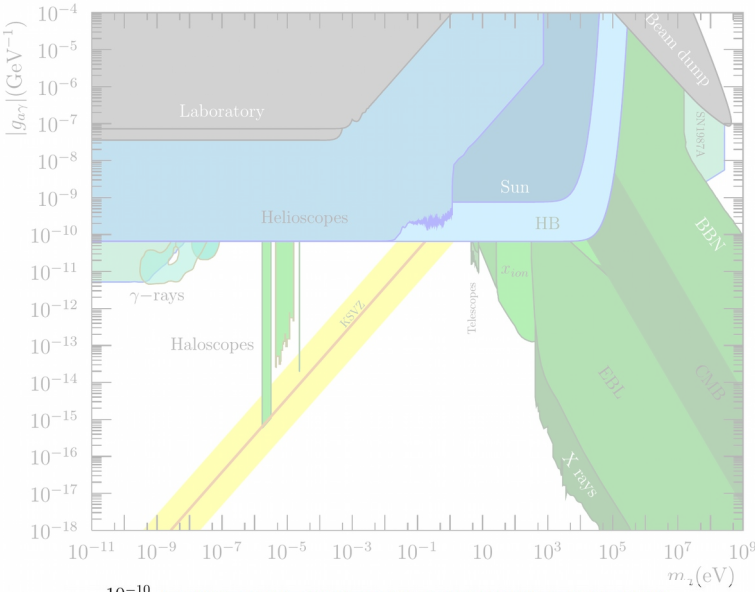

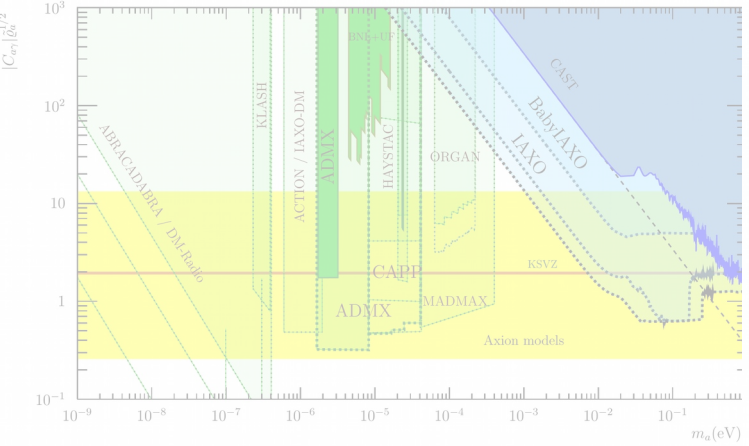

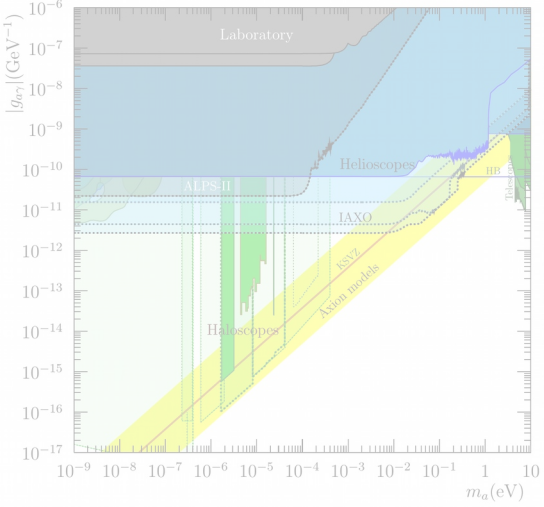

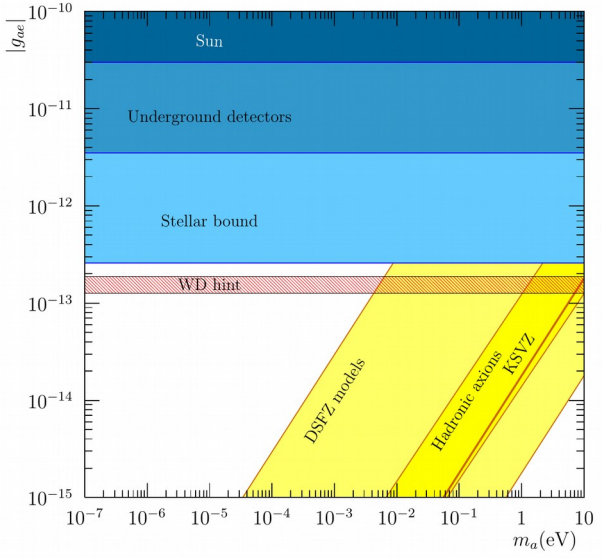

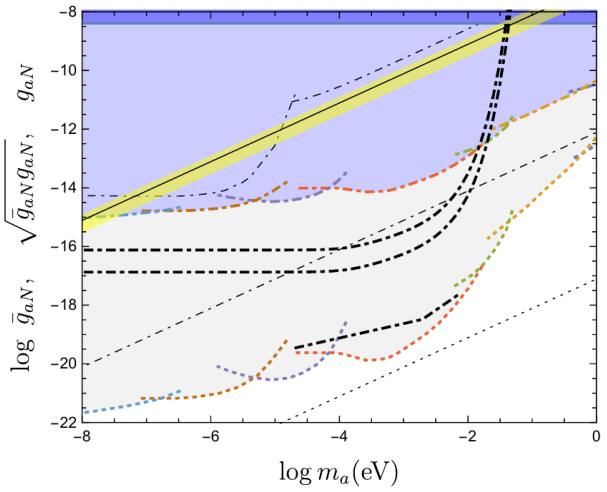

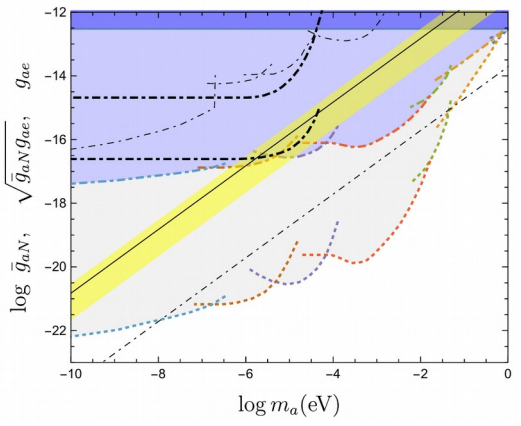

Irastorza Redondo '18

Axion-Like Particles (ALPs) [pseudo-Nambu Goldstone bosons]

derivative couplings: $\partial_\mu \phi \, j^\mu_{\rm SM}$ $\phi \, F \tilde{F}$ $\cdots$

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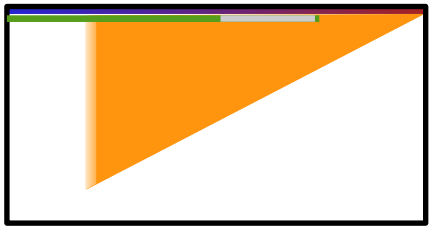

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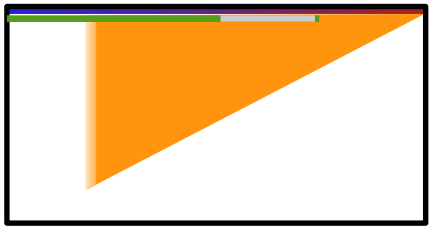

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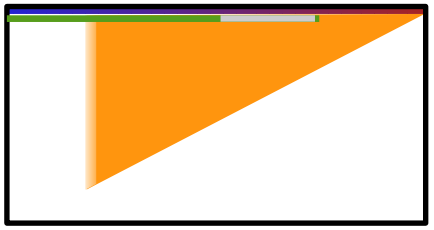

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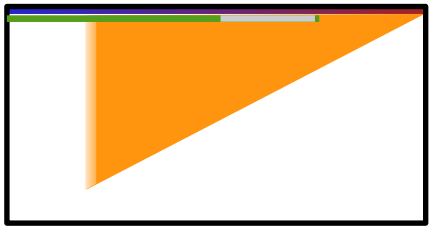

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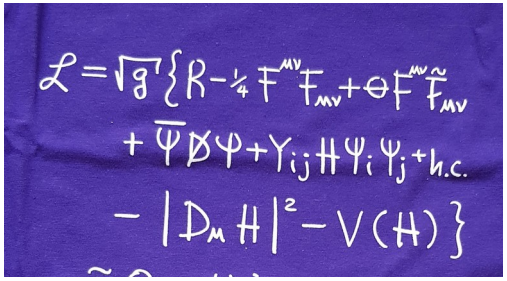
Dark Photons [massive spin-1 fields]

$m^2 A'^2_\mu$ $A'_\mu \, j^\mu_{\rm SM}$

Fundamental Theory?



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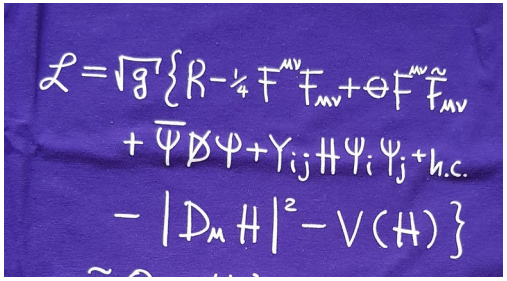

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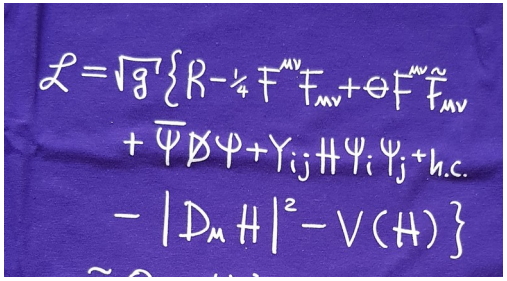

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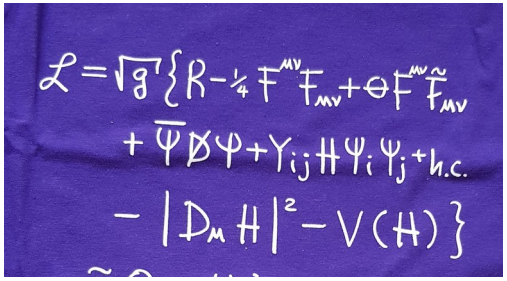

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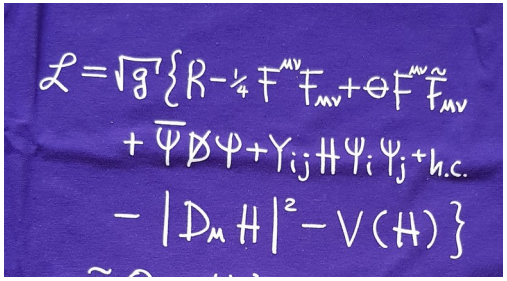

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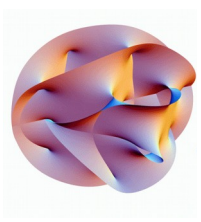
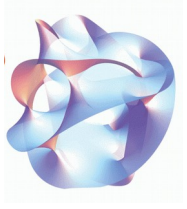


→ String Theory



$$g_i \rightarrow \phi_i(x) \qquad \langle \phi_i(x) \rangle = g_i$$

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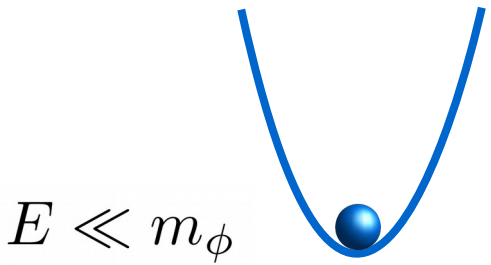

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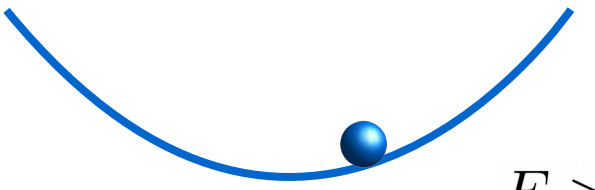

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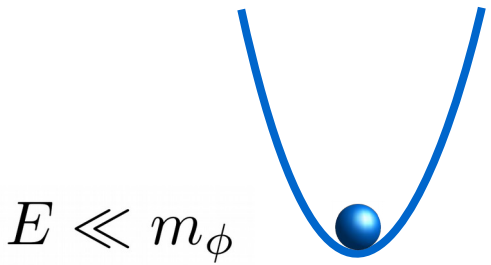

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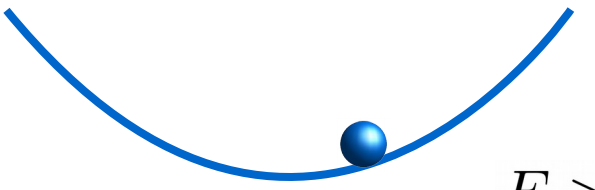

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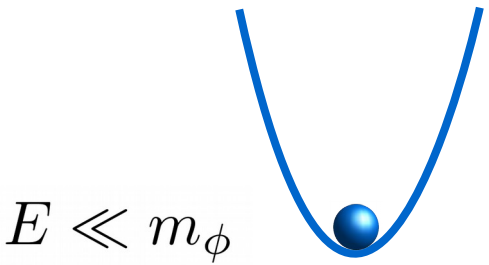

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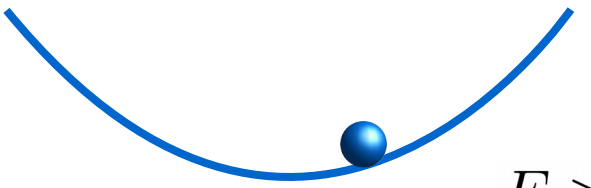

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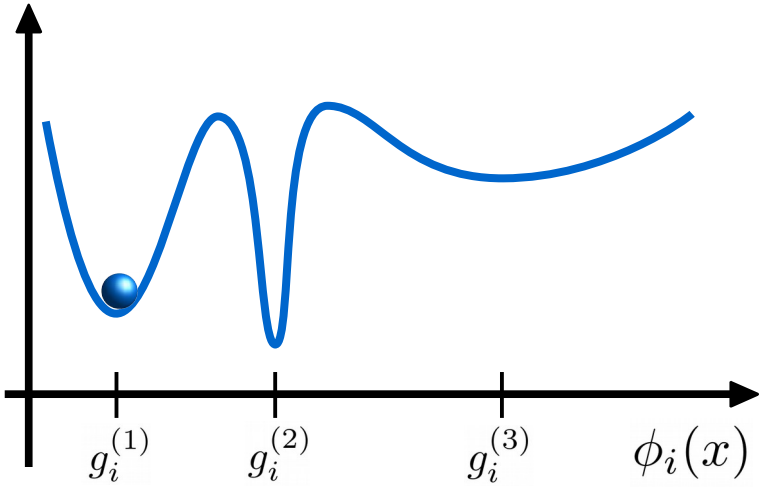
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$g_i^{(2)}$
$g_i^{(3)}$
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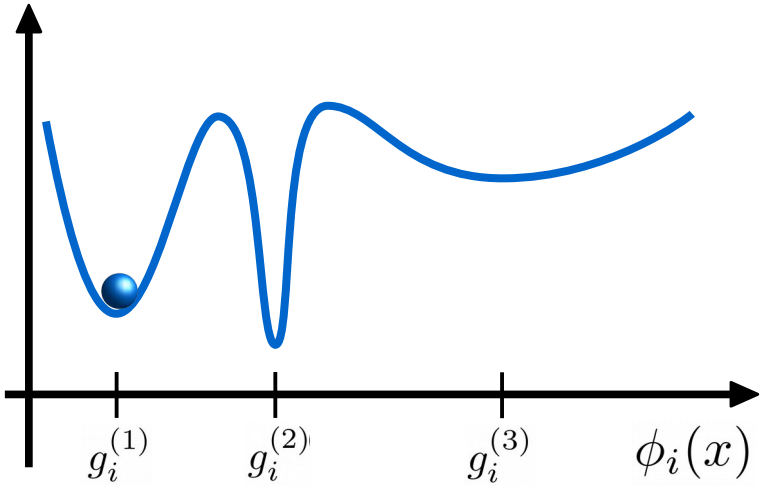
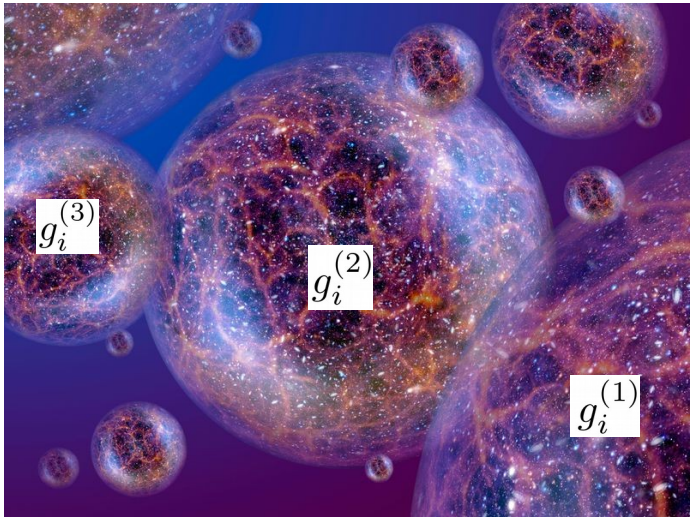
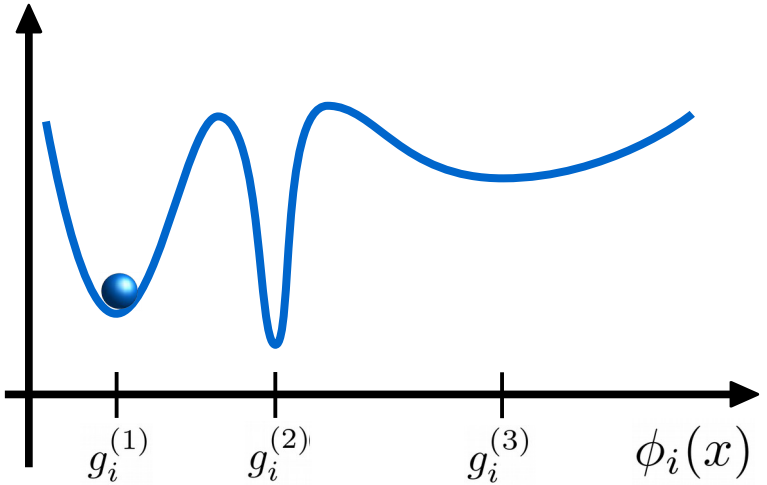
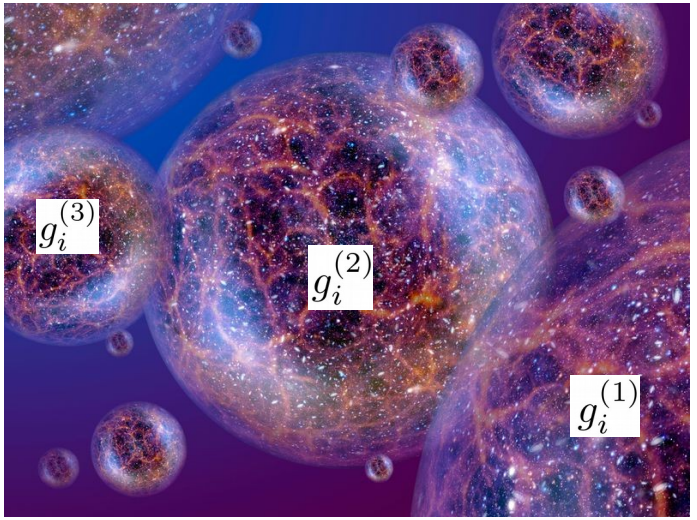




Multiverse





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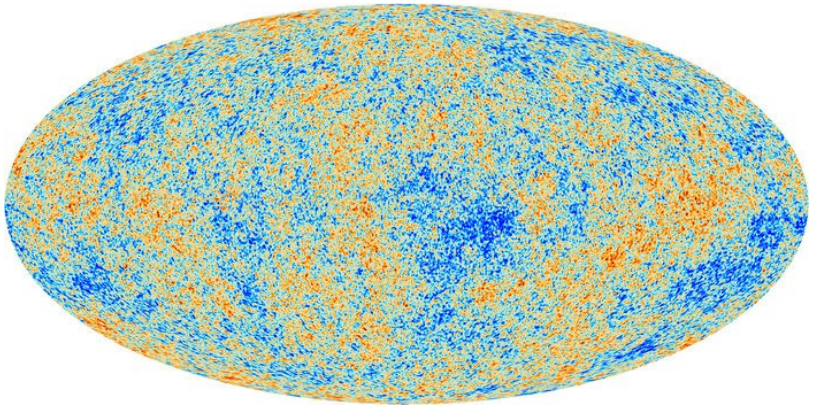

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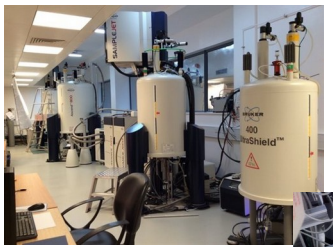
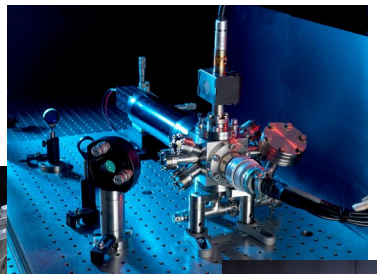
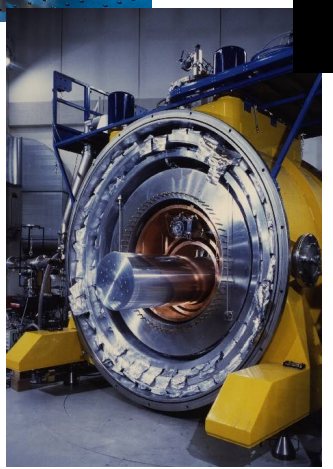
$$\langle \phi_i(x) \rangle = g_i$$

A new Copernican revolution?

How can we tell?