

# Open Questions in Fundamental Physics

Filippo Sala

DESY Hamburg

[filippo.sala@desy.de](mailto:filippo.sala@desy.de)



**Open Questions: 1900 to Today**

**Open Questions from Data**

**Open Questions from Theory**

# Open Questions from Data

Dark Matter

Are we answering the wrong question?



# Uranus or Mercury?



Urbain le Verrier

**1845** his computations of **Uranus** orbit revealed an anomaly  
predicted existence of Neptune

**1846** Neptune discovered!

**1859** his computations of **Mercury** orbit revealed an anomaly  
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**1916** General Relativity!

(another important lesson: the power of computing the n-th digit)

# Uranus or Mercury?



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## Modified Newtonian Dynamics (MOND)

**1983** Mordehai Milgrom: from  $F = m a$  to 
$$\begin{cases} F = m a & a \gtrsim a_0 \approx 10^{-10} \text{ m/s}^2 \\ F = m a^2 / a_0 & a \ll a_0 \end{cases}$$

Just a phenomenological relation, but allowed to fit motion of stars&gas in galaxies!

Important: back then, neither Bullet Cluster nor CMB spectrum observed yet

# Challenges to Modifying Gravity

**Theory** should be consistent and reproduce confirmed predictions of General Relativity (energy and angular momentum conservation, relativity, gravitational lensing,...)

**2004** “Tensor-Vector-Scalar gravity” [Bekenstein astro-ph/0403694](#)

SM + GR + 2 fields, 3 free parameters, 1 arbitrary function

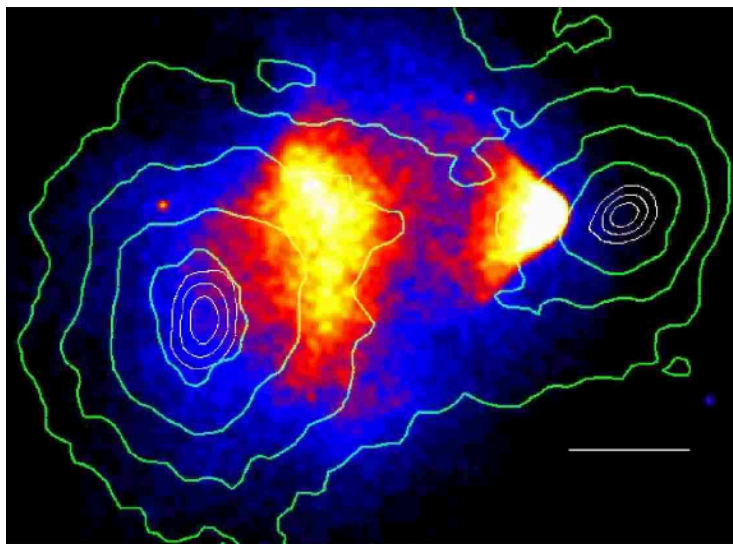
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## Clusters



### A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER \*

DOUGLAS CLOWE<sup>1</sup>, MARUŠA BRADAČ<sup>2</sup>, ANTHONY H. GONZALEZ<sup>3</sup>, MAXIM MARKEVITCH<sup>4,5</sup>, SCOTT W. RANDALL<sup>4</sup>,  
CHRISTINE JONES<sup>4</sup>, AND DENNIS ZARITSKY<sup>1</sup>

*ApJ Letters in press*

#### ABSTRACT

We present new weak lensing observations of 1E0657–558 ( $z = 0.296$ ), a unique cluster merger, that enable a direct detection of dark matter, independent of assumptions regarding the nature of the gravitational force law. Due to the collision of two clusters, the dissipationless stellar component and the fluid-like X-ray emitting plasma are spatially segregated. By using both wide-field ground based images and HST/ACS images of the cluster cores, we create gravitational lensing maps which show that the gravitational potential does not trace the plasma distribution, the dominant baryonic mass component, but rather approximately traces the distribution of galaxies. An  $8\sigma$  significance spatial offset of the center of the total mass from the center of the baryonic mass peaks cannot be explained with an alteration of the gravitational force law, and thus proves that the majority of the matter in the system is unseen.

**CMB** Substituting DM with Modified Gravity fails to explain CMB [see [Skordis 0903.3602](#) for a review]

Only way-out found so far: add matter, that we do not see today (Dark Matter is back!)

No “no-go theorems” here, but explanation why most people work within GR + Dark Matter

# Back to General Relativity + Dark Matter

# Cooking a DM model: ingredients

“**Particle**” properties

- feels **Gravity**
- CMB (& not spoil BBN,...) = **non-baryonic**
- Invisible now = almost **electrically neutral**
- **stable** enough

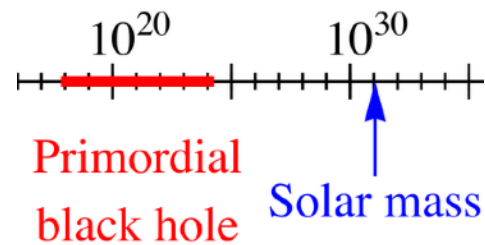
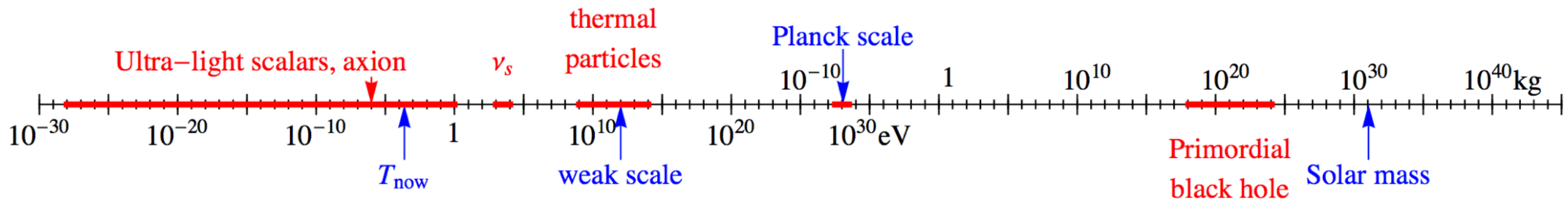
“**Historical**” properties

How much?  $\Omega_{\text{DM}} \simeq 0.26$  (Planck satellite)

Since when? enough **before CMB**

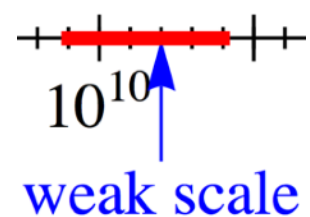
How fast? **Non-relativistic**

# Rules of the game + creativity =



Possibly the “least conventional” candidate

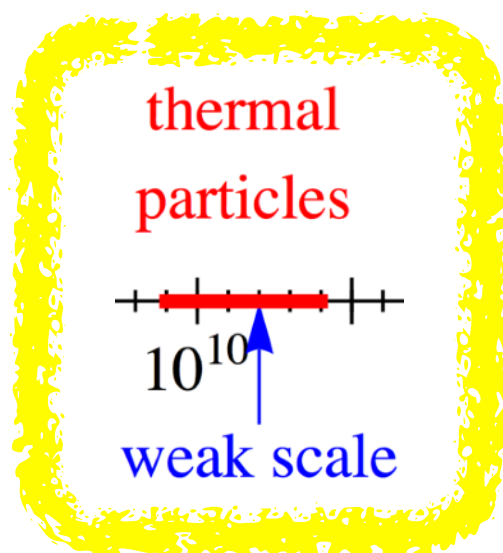
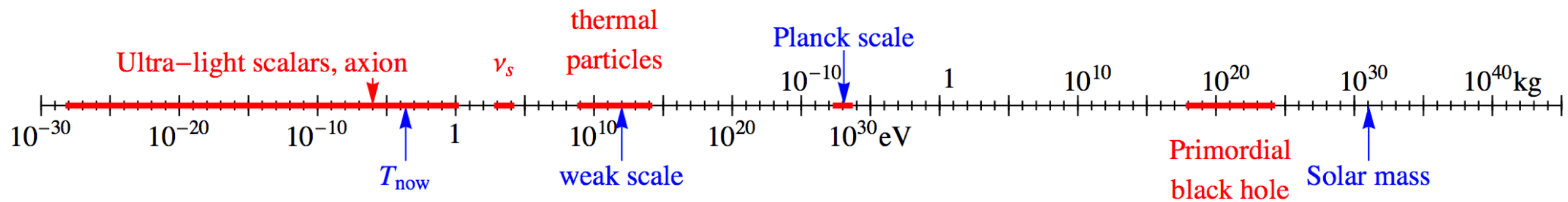
thermal  
particles



Possibly the “most conventional” candidate

Apologies for not explaining all the rest...

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# Weakly Interacting Massive Particles

Weak = SM weak force, DM charged under  $SU(2)_w \times U(1)_Y$   
(or = whatever interaction with the SM, provided  $\alpha = 10^{-3} - 10^{-1}$ )

**Particle** properties:    **massive**     $U(1)_{\text{em}}$  **neutral**    **stable**    **not a baryon**

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## A possible **Cosmological History**

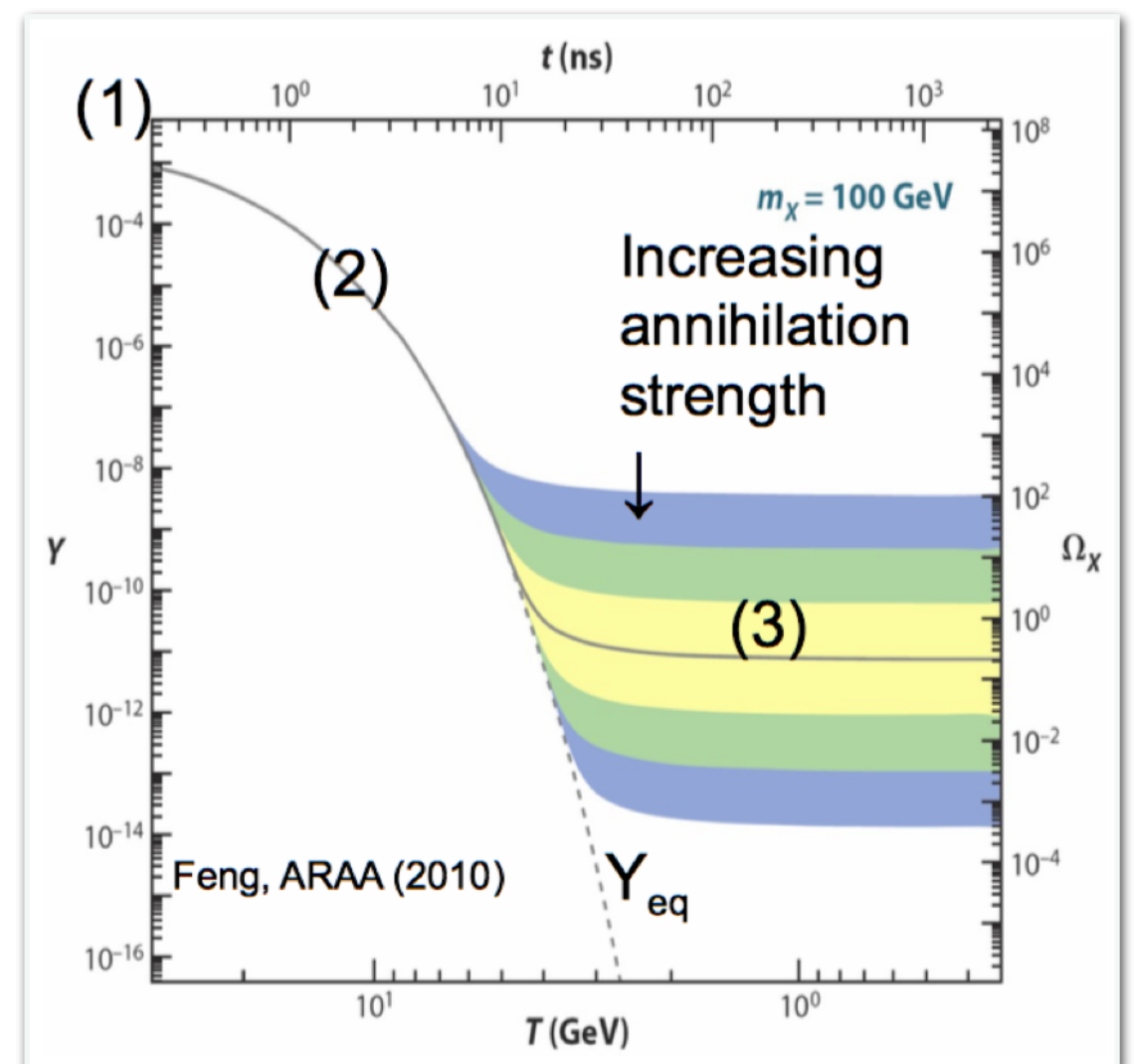
(1) Thermal equilibrium DM DM  $\longleftrightarrow$  SM SM

(2) Universe cools DM DM  $\longrightarrow$  SM SM

(3) Universe expands DM DM SM SM

$\Omega_{\text{DM}} \simeq 0.26$  from annihilation cross section!

$$n_{\text{DM}} \langle \sigma v \rangle \simeq H \Rightarrow \sigma v \sim 3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}}$$



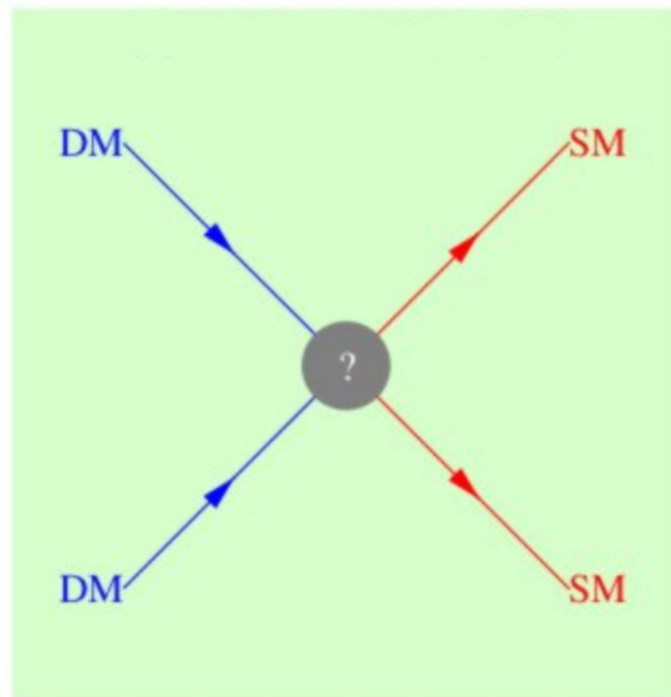
# How to see WIMPs?

“WIMP miracle”

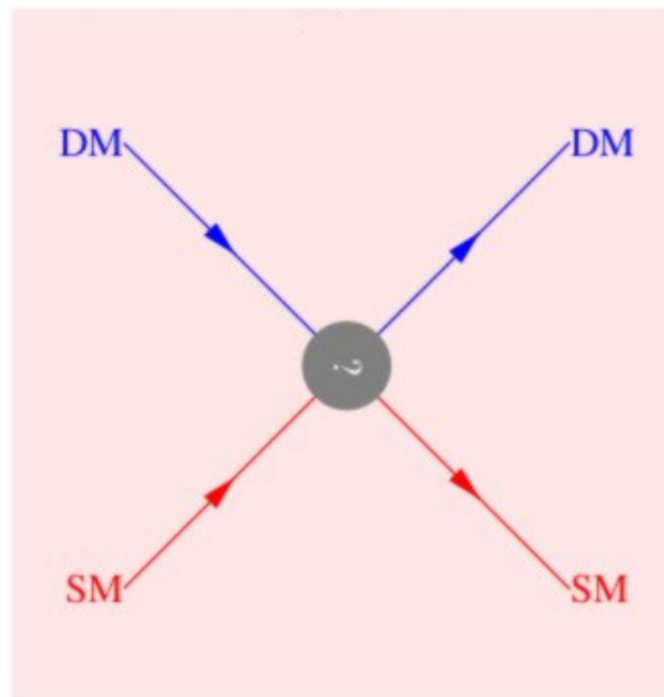
$$\alpha = 10^{-3} - 10^{-1} + M_{\text{DM}} \sim 10 - 10^3 \text{ GeV} = \sigma v \sim 3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}}$$

WIMP miracle motivates BSM at the current experiments!

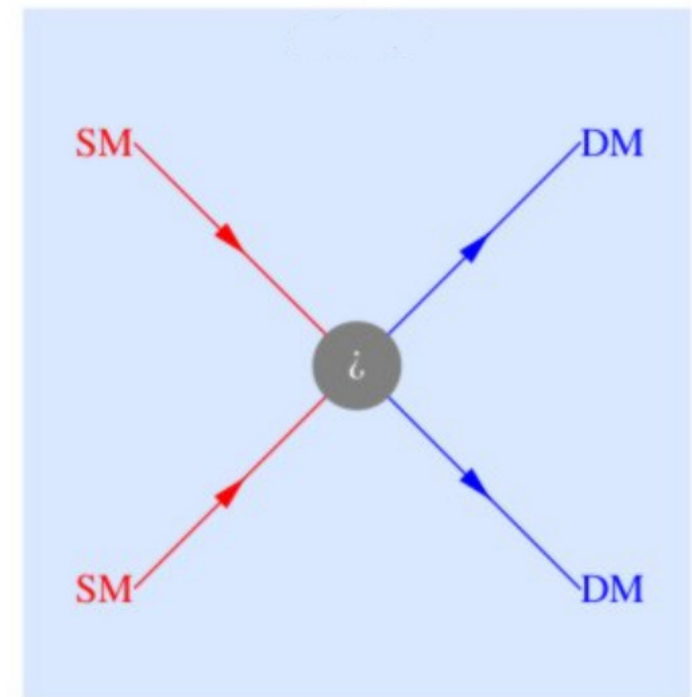
Indirect Detection



Direct Detection



Particle Colliders



# Indirect Detection

Annihilations of DM in the Universe produce  $\gamma$ ,  $e^+$ ,  $\bar{p}$ ,  $\nu$ ,  $\dots$  to be seen with telescopes!



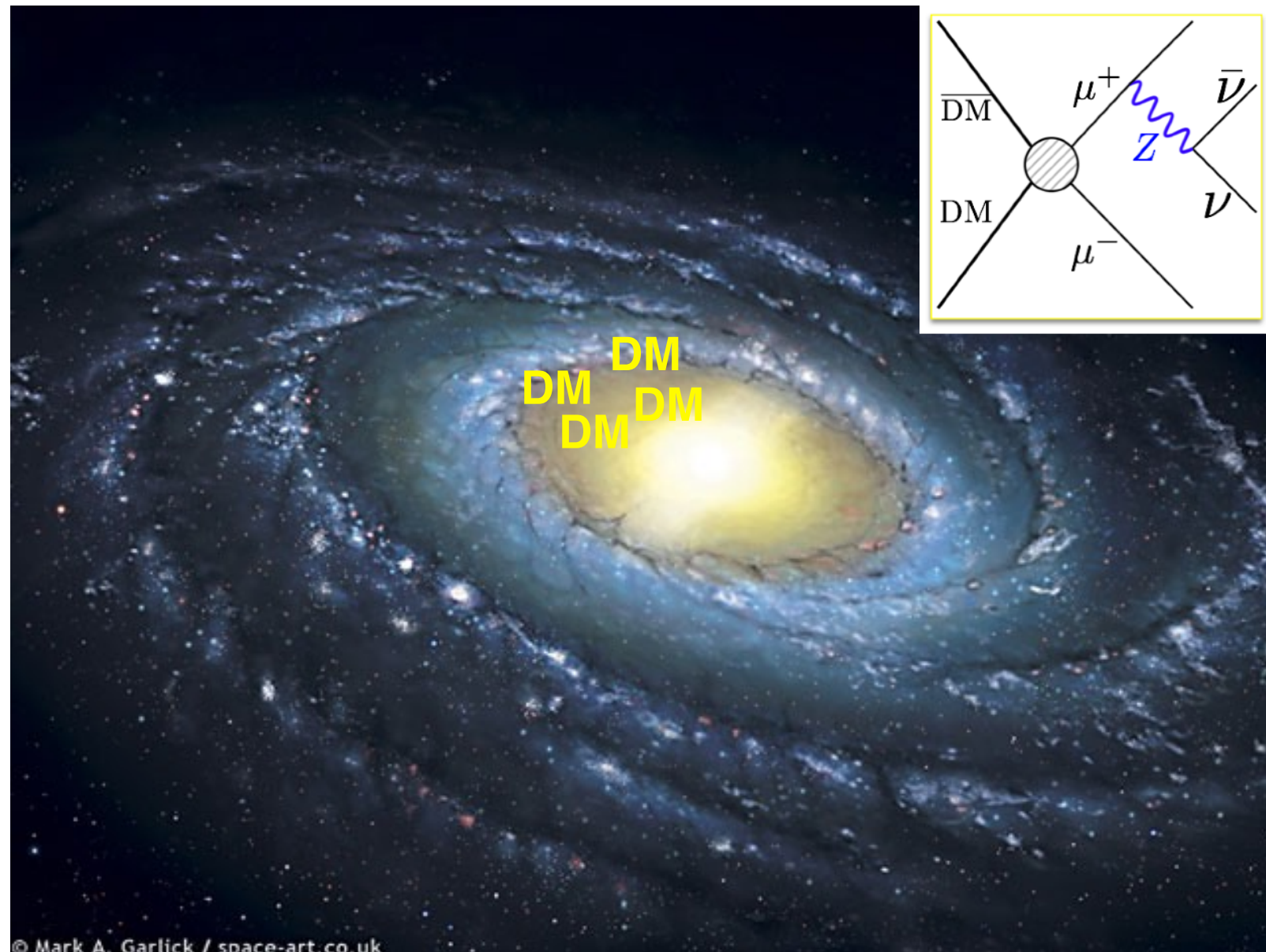
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Gives tools to compute signals given a DM model, you can try playing with it!



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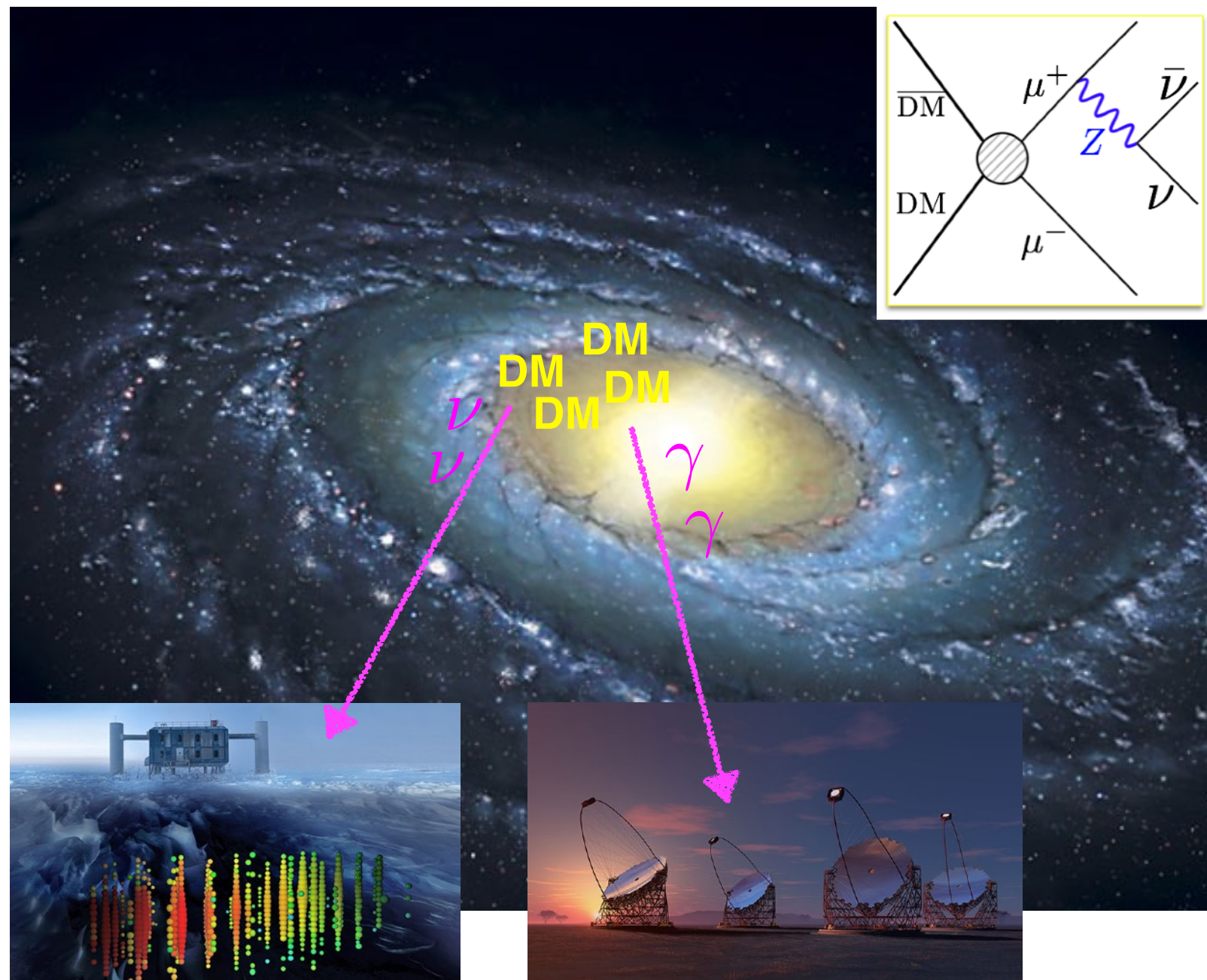
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Astro



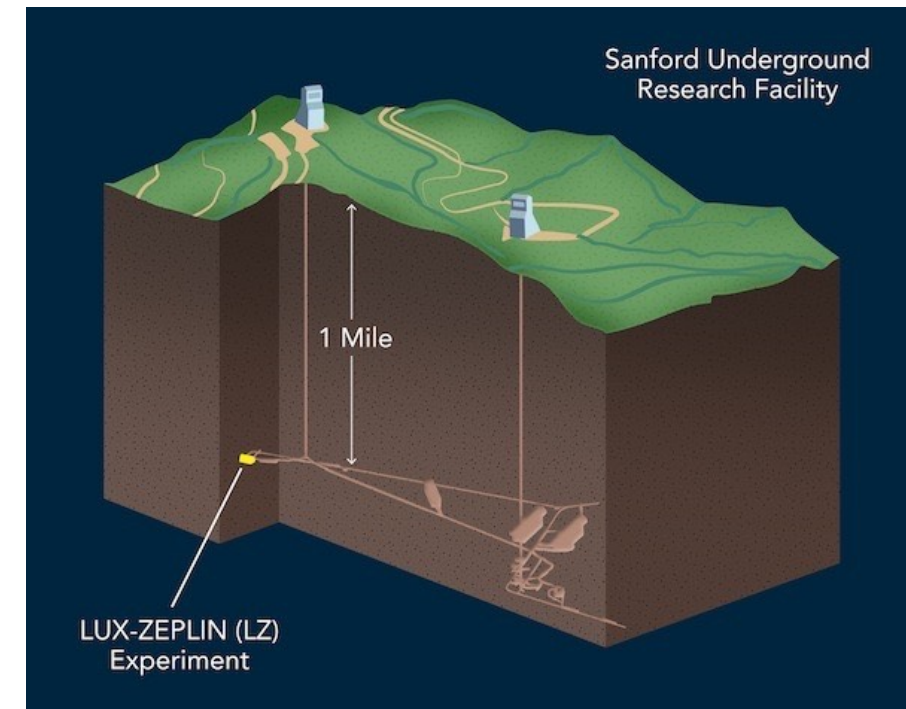
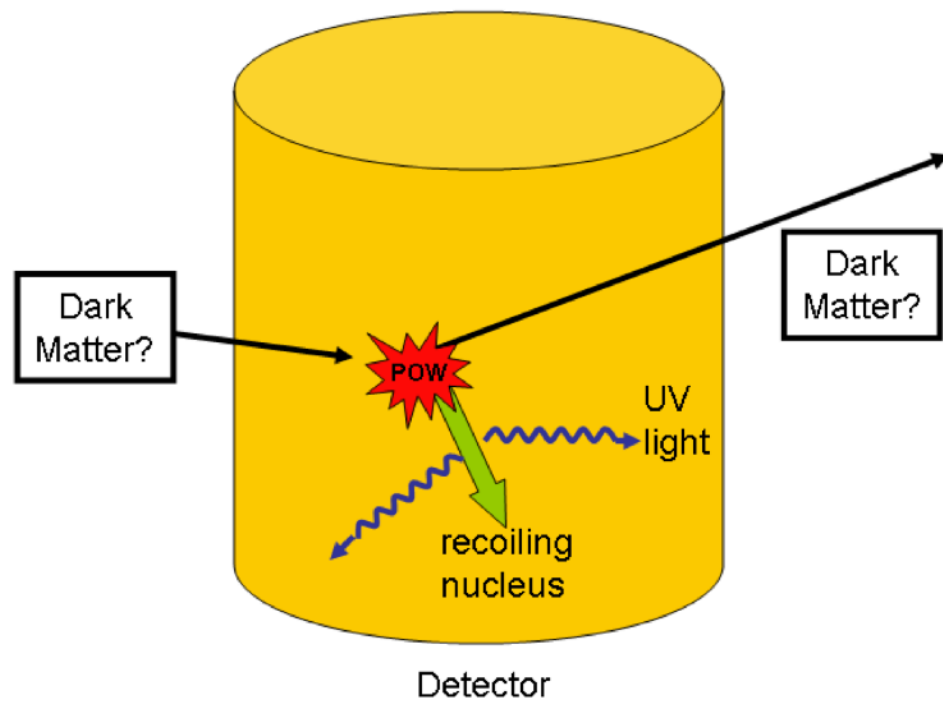
Particle

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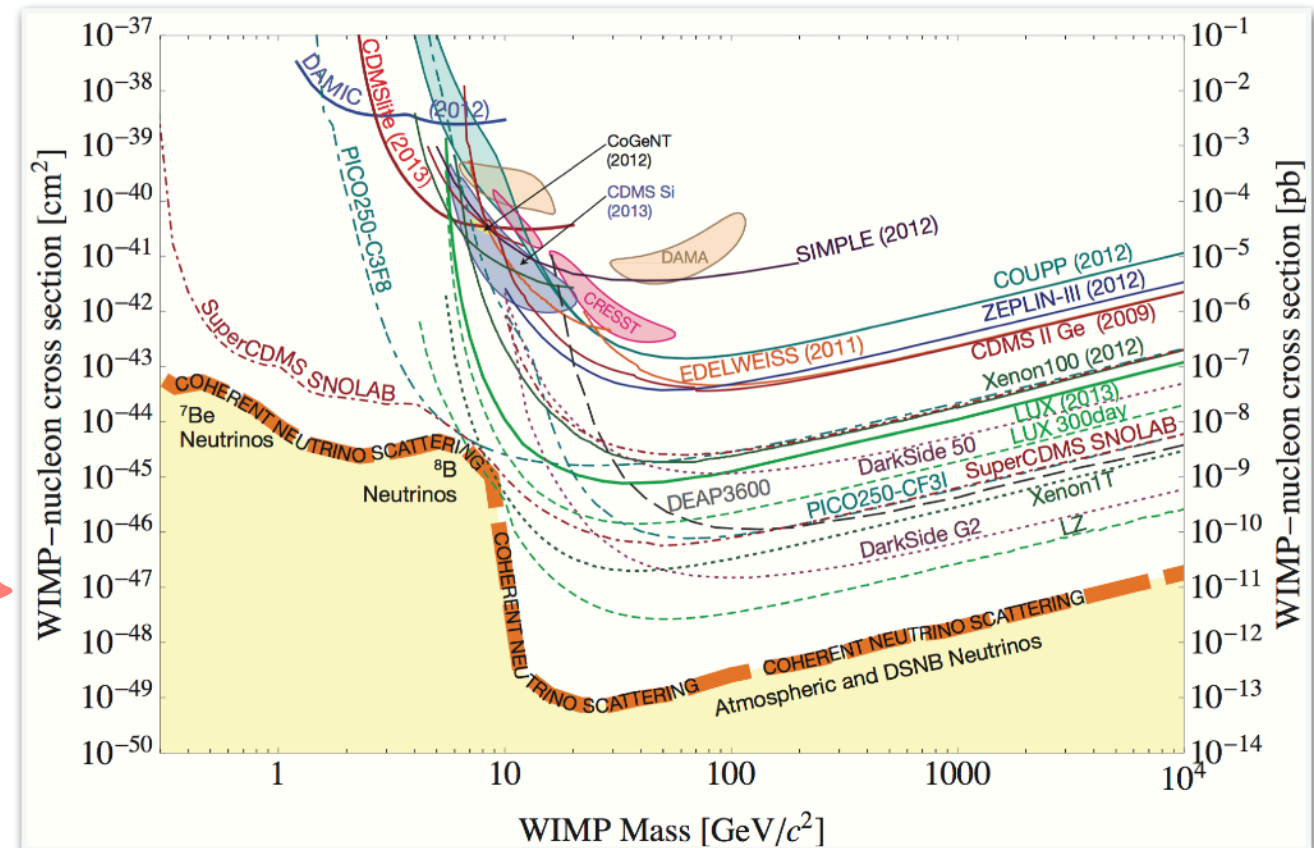
# Direct Detection



Astro: density and velocity of DM in solar system

Particle: interaction of DM with nuclei

For the moment only constraints



# WIMPs at Colliders

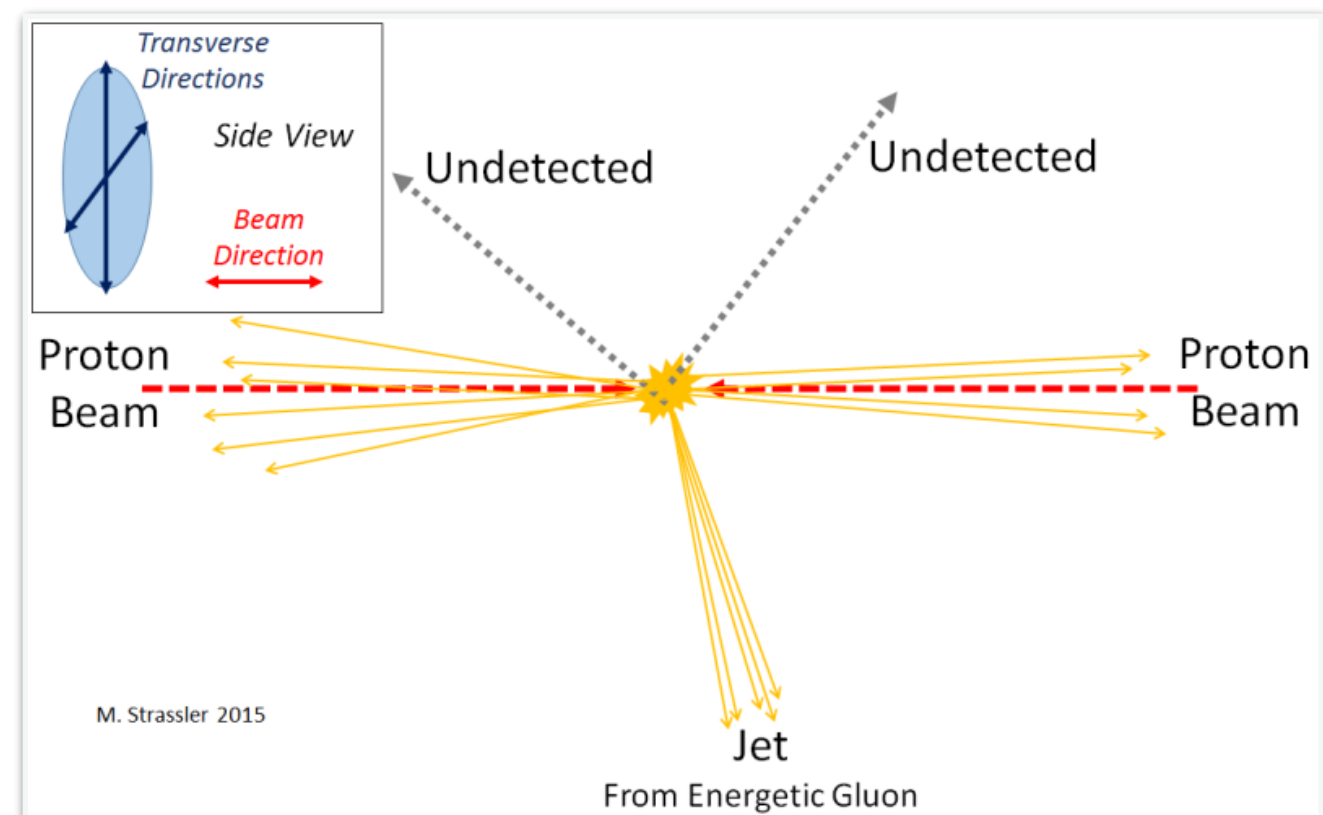
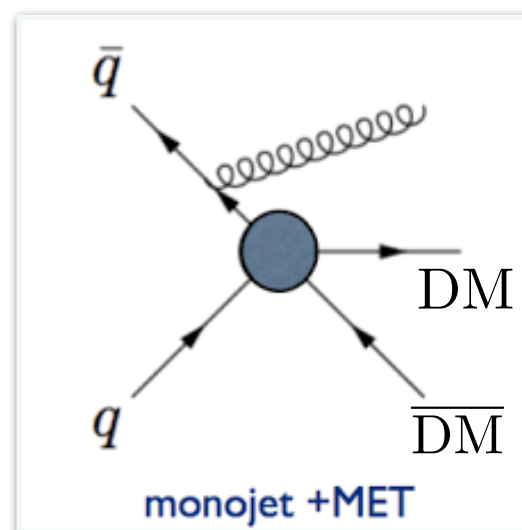
DM (weakly) coupled to the SM  $\longrightarrow$  It is produced in particle collisions!

DM stable or almost  $\longrightarrow$  It flies outside detectors, so you do not see it

So: look for SM objects (photon, gluon, W, Z, ...) recoiling against “nothing”

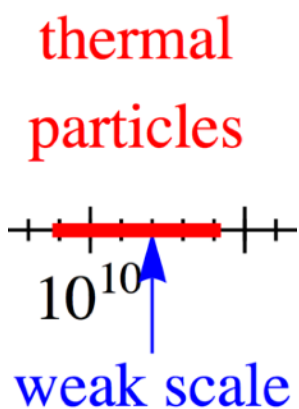
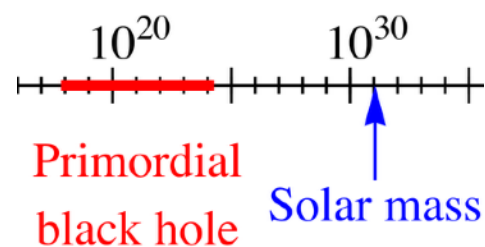
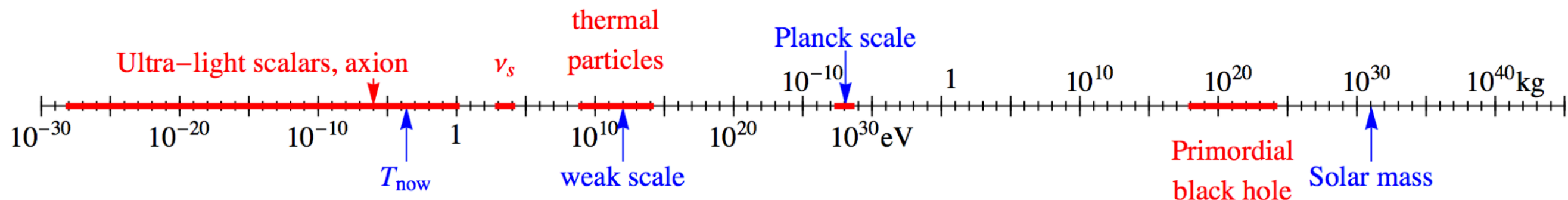
aka mono-SM+ **Missing Transverse Energy** (MET)

@ the **LHC**





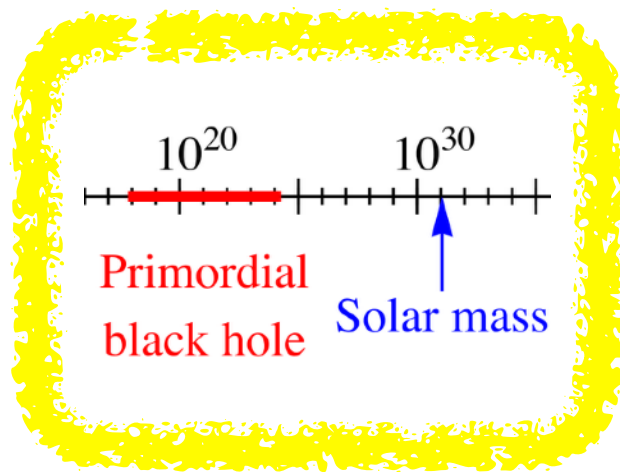
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WIMPs not discovered so far

(though some “hints” in direct and indirect detection exist, you can ask offline)

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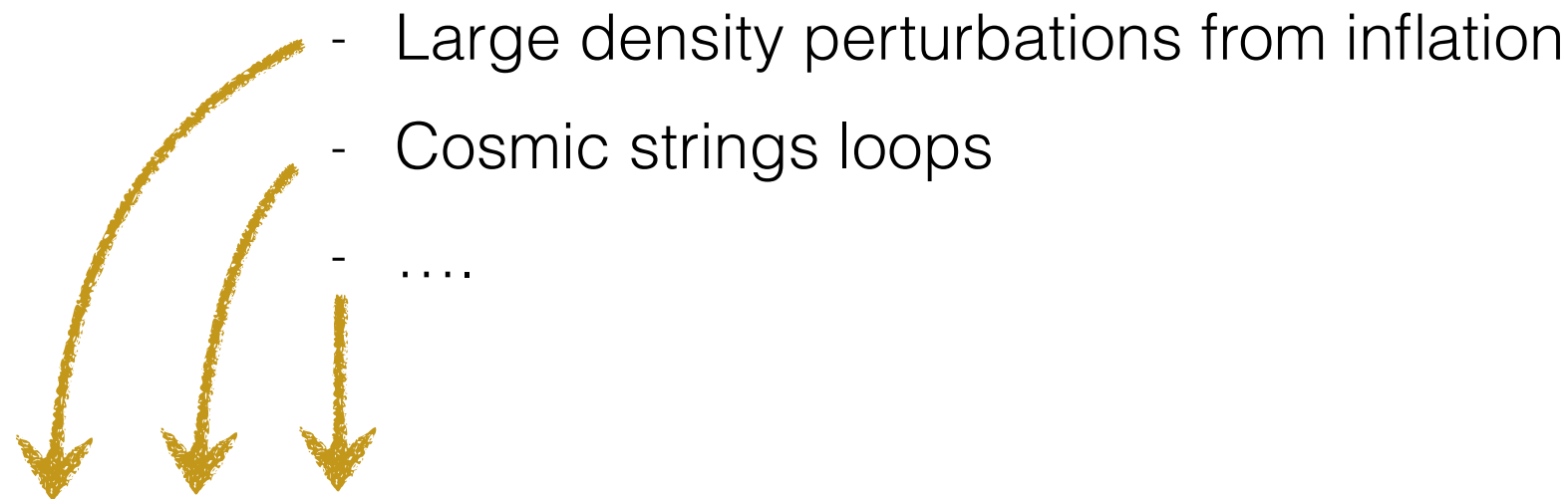


# Primordial Black Holes (?)

- ☑ Gravity (and nothing else: non baryonic + electrically neutral)
- ☑ Stable enough (provided they did not evaporate)
- ☑ How to have them? How to have them at CMB??? See e.g. Anne Green 1403.1198
  - Large density perturbations from inflation
  - Cosmic strings loops
  - ....

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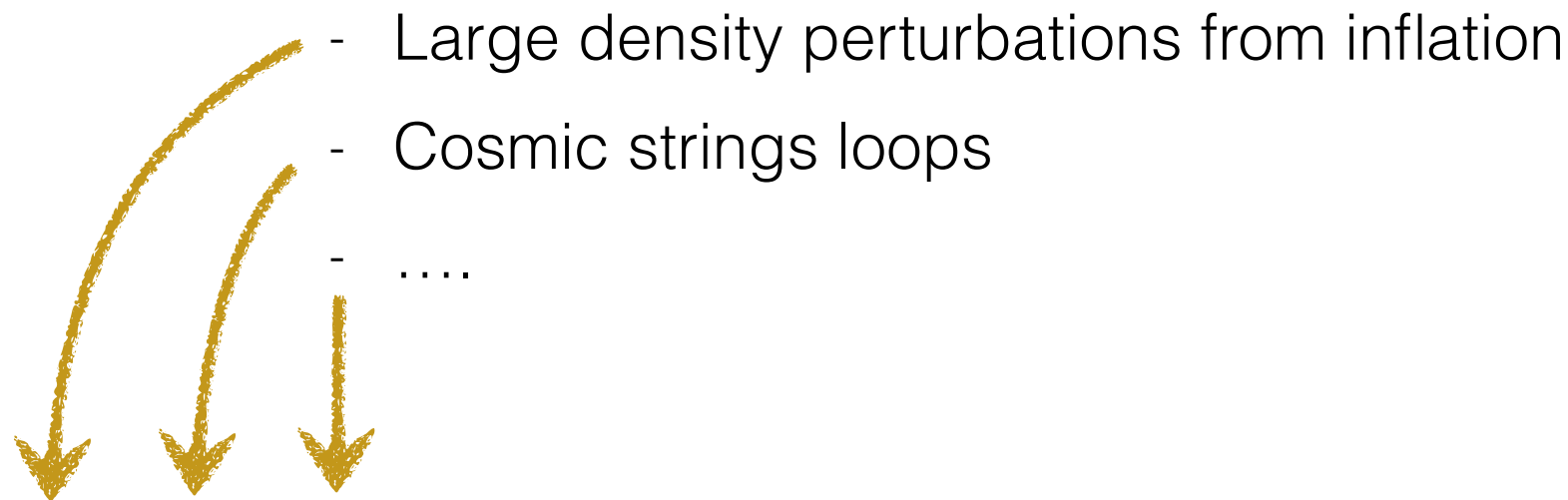


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What masses can those mechanisms produce? ~ anything (as far as I understand)

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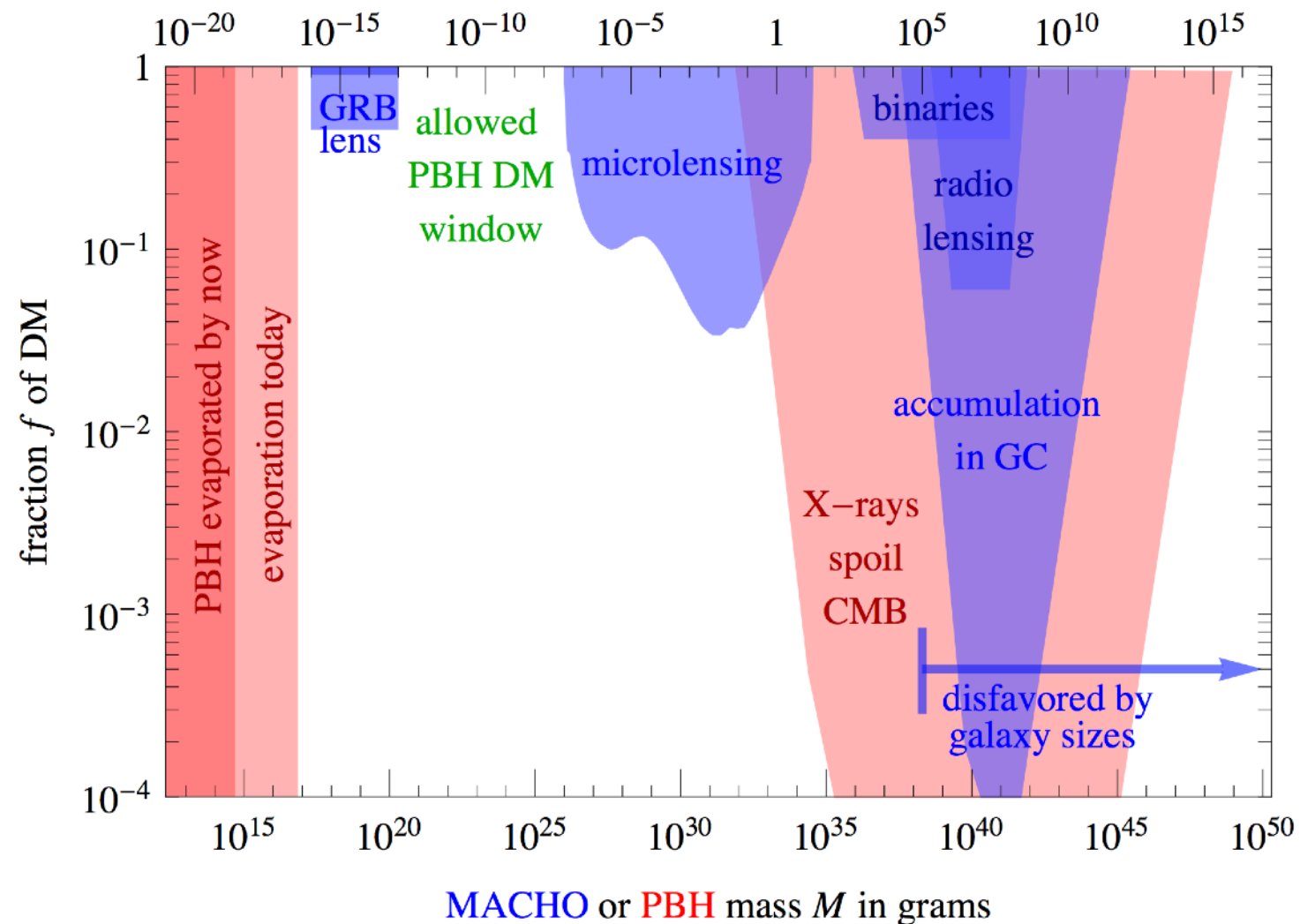
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Still we have gravity to probe them!

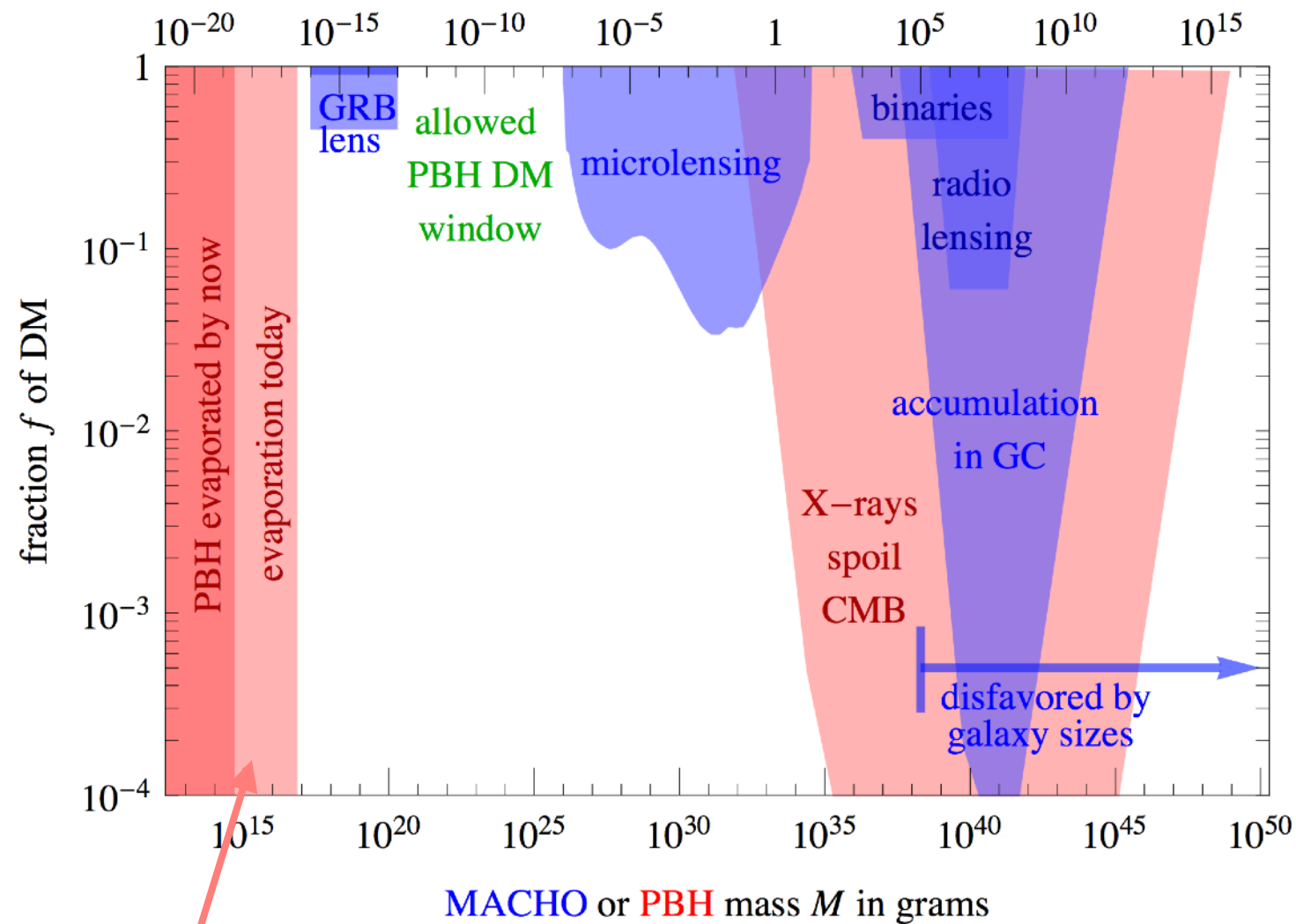
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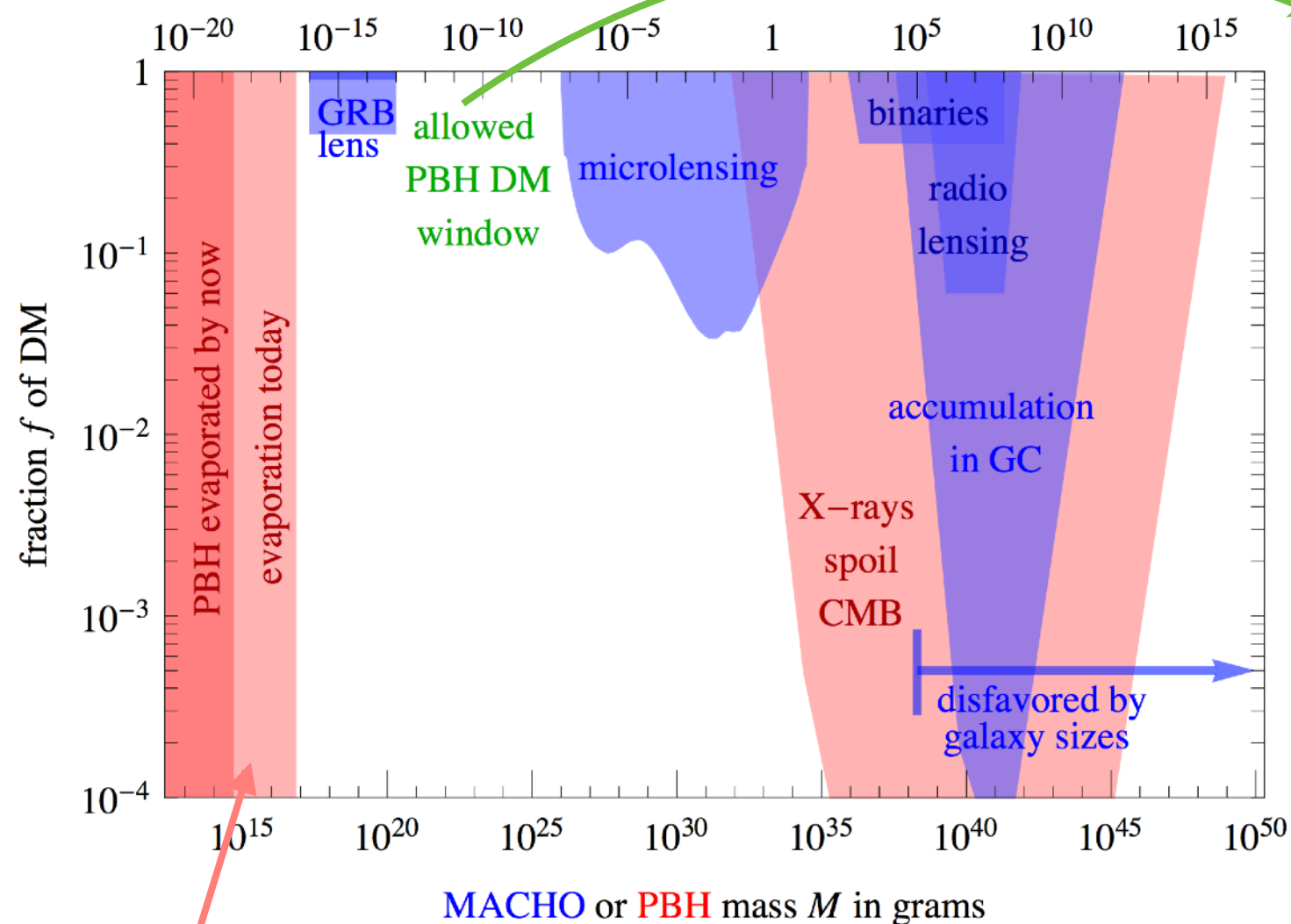


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NB: Evaporation peculiar of BH

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**Allowed window:** mass < Moon  
size < 1 mm

Pani Loeb 1401.3025

Strong claim of exclusions via capture in  
(and disruption of) neutron stars

Claim eventually confuted

Capela et al. 1402.4671,...

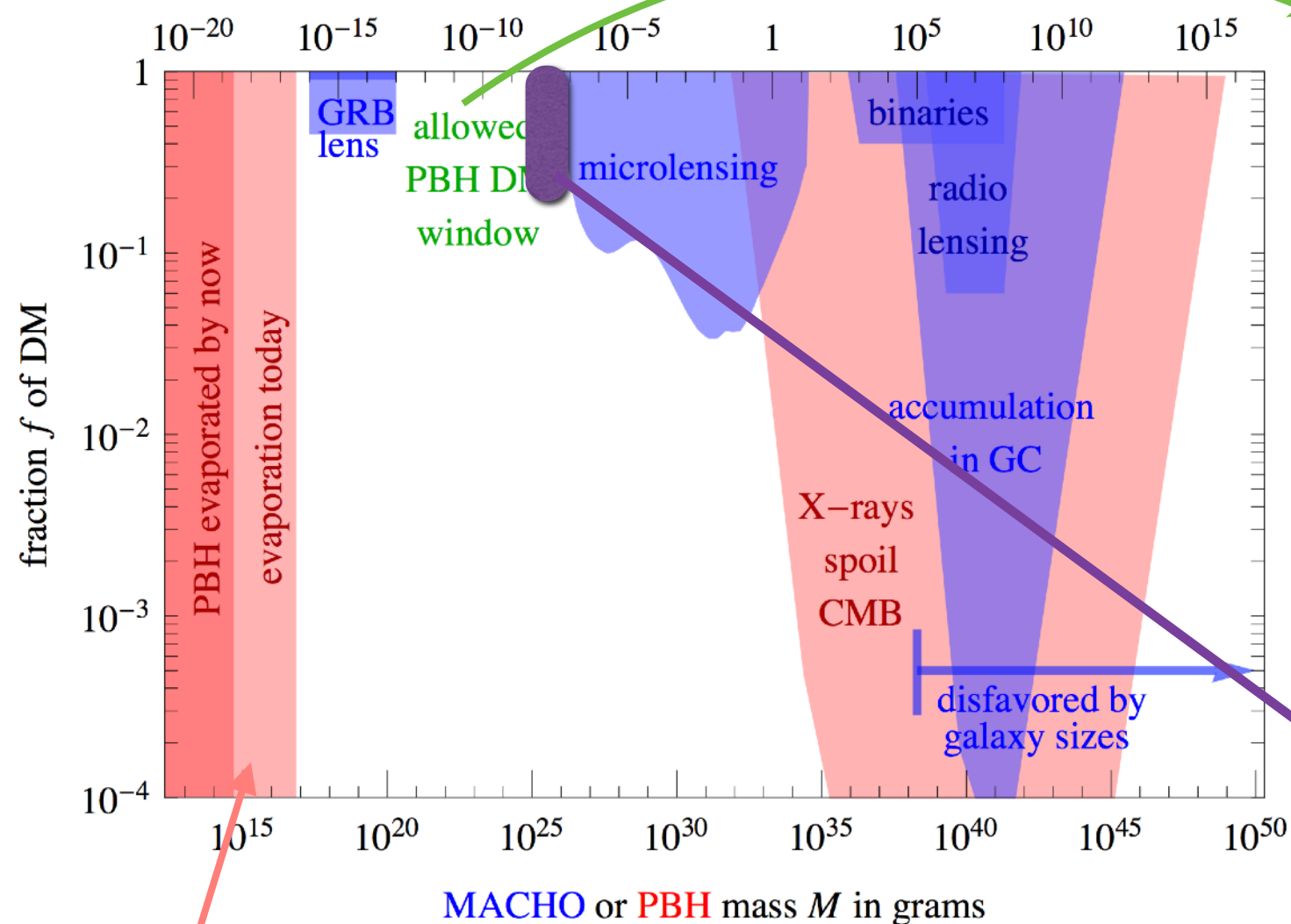
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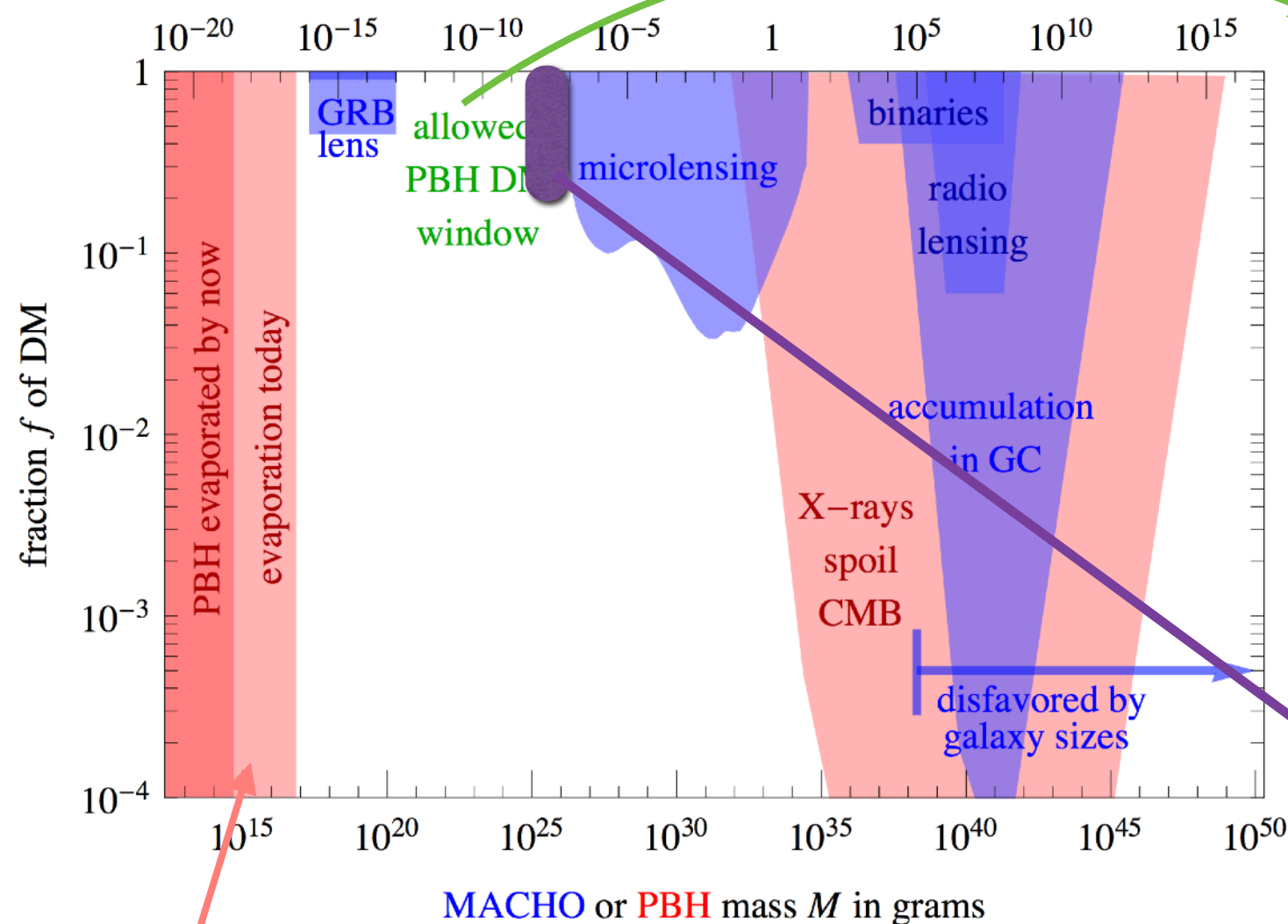
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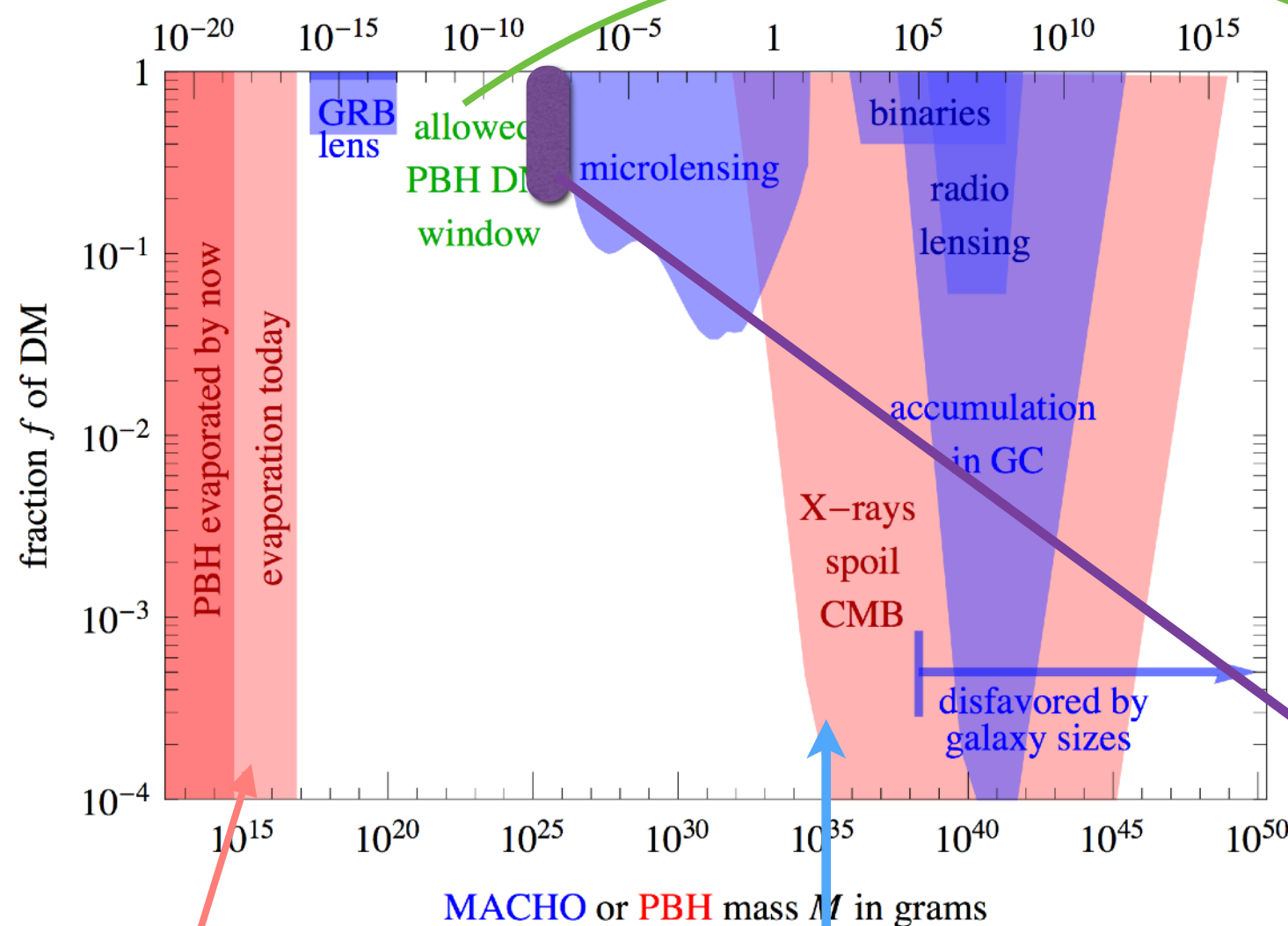
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PBH seed explosion of white dwarves  
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LIGO observed **gravitational waves** from merging  
of Black Hole pairs. Could they be Dark Matter?

YES Bird+7 et al. 1603.00464

NO Sasaki et al. 1603.08338, + many more...

NB: Dark Energy can be explained by SM vacuum energy  
(this would pose an enormous theoretical problem, see later)

# Open Questions from Data

Dark Matter

Baryon Asymmetry

Neutrino Oscillations

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Baryon Asymmetry

# Baryon Asymmetry

**Baryon** Particle that is charged under  $U(1)_{\text{baryon}}$  (NB not same meaning of cosmo baryons)

SM particles (and their Baryon charge): quarks (1/3), proton (1), leptons (0), ...

**Baryon number** Counts the difference between baryons and anti baryons

Conserved in the SM Lagrangian (*accidental* symmetry, was not imposed)

But: not conserved in the SM, at non-perturbative level

**Baryon Asymmetry**  $n_B, n_{\bar{B}}, n_\gamma$  number densities of baryons, antibaryons, photons

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

measured independently from CMB and BBN (so it is a check of theory)

**“Thermal” Populations** Thermal freeze-out of SM baryon interactions  $n_{B,\bar{B}} \langle \sigma v \rangle \simeq H$

$$\longrightarrow n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 10^{-21}$$

# Baryon Asymmetry implies BSM

## Sakharov Conditions (1967)

**Baryon Number Violation** otherwise no-way to have  $n_B \neq n_{\bar{B}}$   
starting from  $n_B = n_{\bar{B}}$

**CP Violation** otherwise conjugate processes generate  
the same asymmetry, but with opposite sign

**Out-of-Equilibrium** otherwise expectation value would remain  
the initial one  $n_B = n_{\bar{B}}$

## Standard Model

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## The Baryon Asymmetry implies physics Beyond the SM

Yes non-perturbative phenomena (“sphalerons”)  
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**No** The SM thermal evolution does not go out enough of thermal equilibrium  
(e.g. ElectroWeak phase transition is second-order)

# Models for the Baryon Asymmetry

## Decays of Heavy Particles

- New particle  $X$  that decays **out-of-equilibrium**:  $\Gamma_X/H \ll 1$  at  $T \sim M_X$   
decay rate is much slower than expansion (Hubble) rate
- with two decay channels with **different baryon (or lepton) number**  $X \rightarrow a$   $X \rightarrow b$
- and where **antiparticles** have **different Branching Ratio**  $r = \text{BR}(X \rightarrow a) \neq \text{BR}(\bar{X} \rightarrow \bar{a}) = \bar{r}$   
 $\Rightarrow$  generates net baryon number  $\Delta B = (r - \bar{r})(B_a - B_b)$

## Electroweak Baryogenesis

SM already **breaks baryon number**

Let us rely on that, and modify EW phase transition so that it is sufficiently **out-of-equilibrium**  
(i.e. strong first-order)  
and add BSM source of **CP violation**

can give baryon asymmetry, predicts **New Physics at  $\sim \text{TeV}$**  and **gravitational waves!**

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- $X$  could have any mass, also very heavy

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Like DM, the Baryon Asymmetry does not tell us the energy scale of New Physics

# Open Questions from Data

Neutrino Oscillations

# Neutrino Oscillations



In the SM, neutrinos do not change flavour while they propagate (= “oscillate”)

**1960's-2000's**   **Solar** Neutrinos   Deficit of  $\nu_e$  from the Sun wrt to prediction w/ massless neutrinos

**1990's**   **Atmospheric** Neutrinos    $\nu_\mu \rightarrow \nu_e$    deficit of muon neutrinos wrt to electron ones

**2012**   **Reactor** Neutrino   yet another oscillation angle

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## Neutrino Masses imply Neutrino Oscillations

Degree of freedom that propagates = by def. eigenstate of  $p^2$ , so of mass

In the flavor basis  $\nu_e, \nu_\mu, \nu_\tau$  the mass matrix is non-diagonal    $|\nu_e\rangle = \sum_{i=1}^3 U_{ei} |\nu_i\rangle$

And SM (e.g. in the Sun) produces flavor eigenstates

(where mass basis =  $\nu_1, \nu_2, \nu_3$ )

$$P_{\alpha \rightarrow \beta} = |\langle \nu_\beta(t) | \nu_\alpha \rangle|^2 = \left| \sum_i U_{\alpha i}^* U_{\beta i} e^{-im_i^2 L/2E} \right|^2$$

# Neutrino Masses beyond the SM

Measured oscillations  $\Rightarrow$  we know two mass differences, we do not know mass scale

$\Rightarrow$  at least one neutrino should have mass  $m_\nu \gtrsim 0.05 \text{ eV}$

$$\Omega_\nu \simeq \frac{\sum m_\nu}{50 \text{ eV}} + \text{CMB} + \text{other cosmology} \Rightarrow \sum m_\nu \lesssim 0.2 \text{ eV}$$



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Only operator of dimension 5 that you can write in the SM, others start at dimension 6

$$\frac{1}{\Lambda_{\text{NP}}} L^2 H^2$$

$$L = \begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix} \quad H = \begin{pmatrix} G^+ \\ \frac{v + h + iG_0}{\sqrt{2}} \end{pmatrix}$$

$$m_\nu \simeq \frac{v^2}{\Lambda_{\text{NP}}}$$

$$\Rightarrow \Lambda_{\text{NP}} \simeq 10^{15} \text{ GeV}$$



# Neutrino Masses beyond the SM

Measured oscillations  $\Rightarrow$  we know two mass differences, we do not know mass scale

$\Rightarrow$  at least one neutrino should have mass  $m_\nu \gtrsim 0.05 \text{ eV}$

$$\Omega_\nu \simeq \frac{\sum m_\nu}{50 \text{ eV}} + \text{CMB} + \text{other cosmology} \Rightarrow \sum m_\nu \lesssim 0.2 \text{ eV}$$

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Dimension 5 violates our recipe (non-renormalizable): needs “UV completion”

$$\Lambda_{\text{NP}} = \frac{M_N}{y_\nu^2} \quad \begin{array}{ll} y_\nu \approx 1 & M_N \approx 10^{15} \text{ GeV} \\ y_\nu \ll 1 & M_N \ll 10^{15} \text{ GeV} \end{array}$$

Again, not an indication of a New Physics scale!

**Open Questions: 1900 to Today**

**Open Questions from Data**

**Open Questions from Theory**

SM + GR = ?

EW vacuum stable?

Why  $Q_e = -Q_p$ ??

Unification of Interactions

Unification of Matter and Interactions (Supersymmetry)

Hierarchy Problems

---

Not here: Why 3 generations?

Why hierarchical flavour couplings?

Why Universe flat? (Cosmic Inflation)

...

# Open Questions from Theory

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# Open Questions from Theory

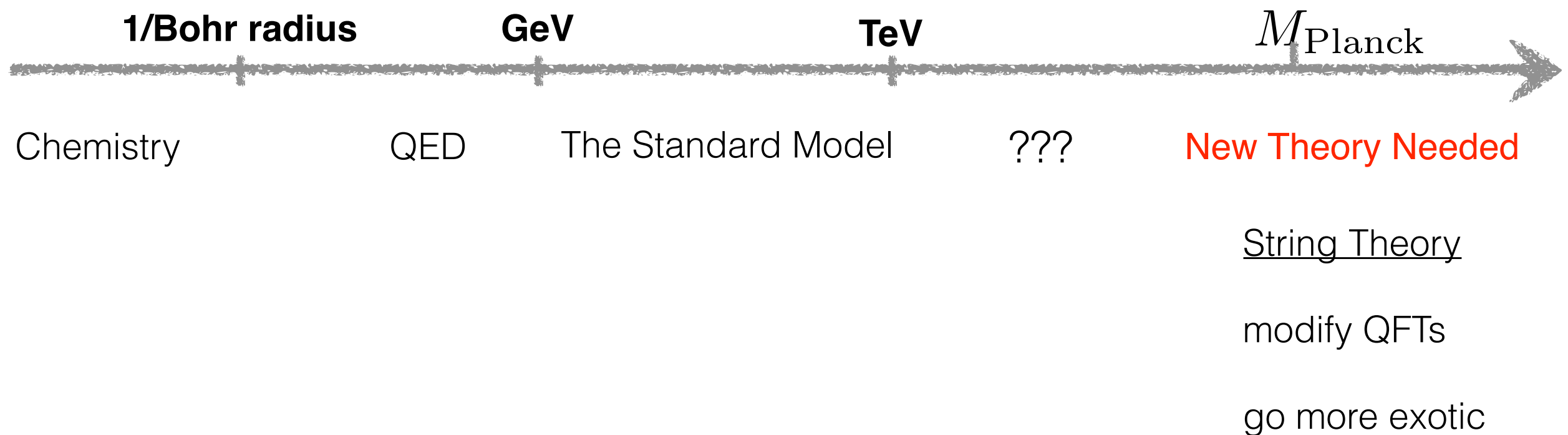
# NP scale from consistency of the theory

Gravitational Interaction contains a new fundamental scale

$$M_{\text{Planck}} \equiv 1/G_{\text{Newton}} \simeq 10^{19} \text{ GeV}$$

At those scales one needs to go beyond either **SM + GR** or **QFT** , possibly **both**  
(GR is non-renormalizable)

Domains of validity



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## Domains of validity



Will we ever have access to such high energy scales?  
No way with colliders, cosmo looks hard,...

String Theory

modify QFTs

go more exotic

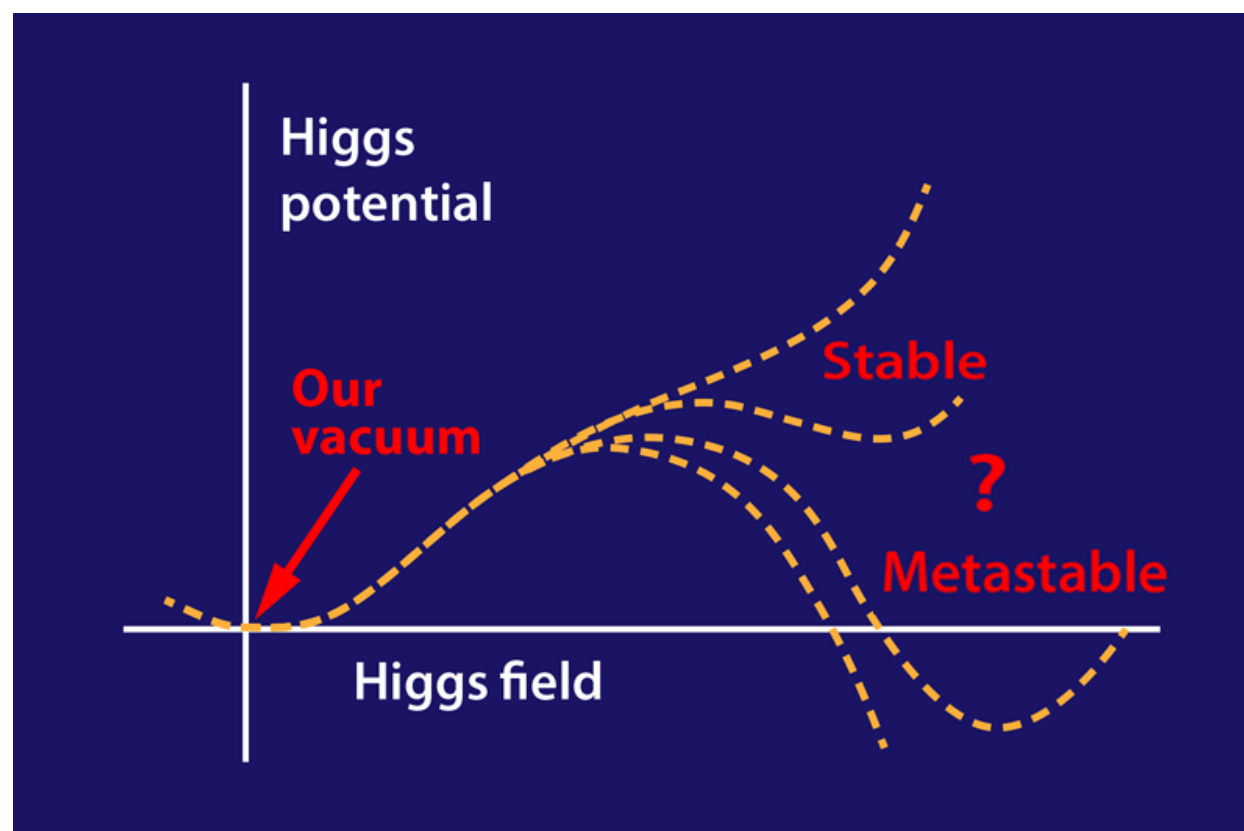
Could the SM become inconsistent for other reasons, before  $M_{\text{Planck}}$  ?

# Is the EW vacuum stable?

If not, then need NP at the scale where unstable, because we are still here!

$$V(h) = -m^2 h^2 + \frac{\lambda(\mu)}{4} h^4$$

$\lambda(\mu = m_h) \simeq 0.13$  and SM + QFT predicts its running at higher energies

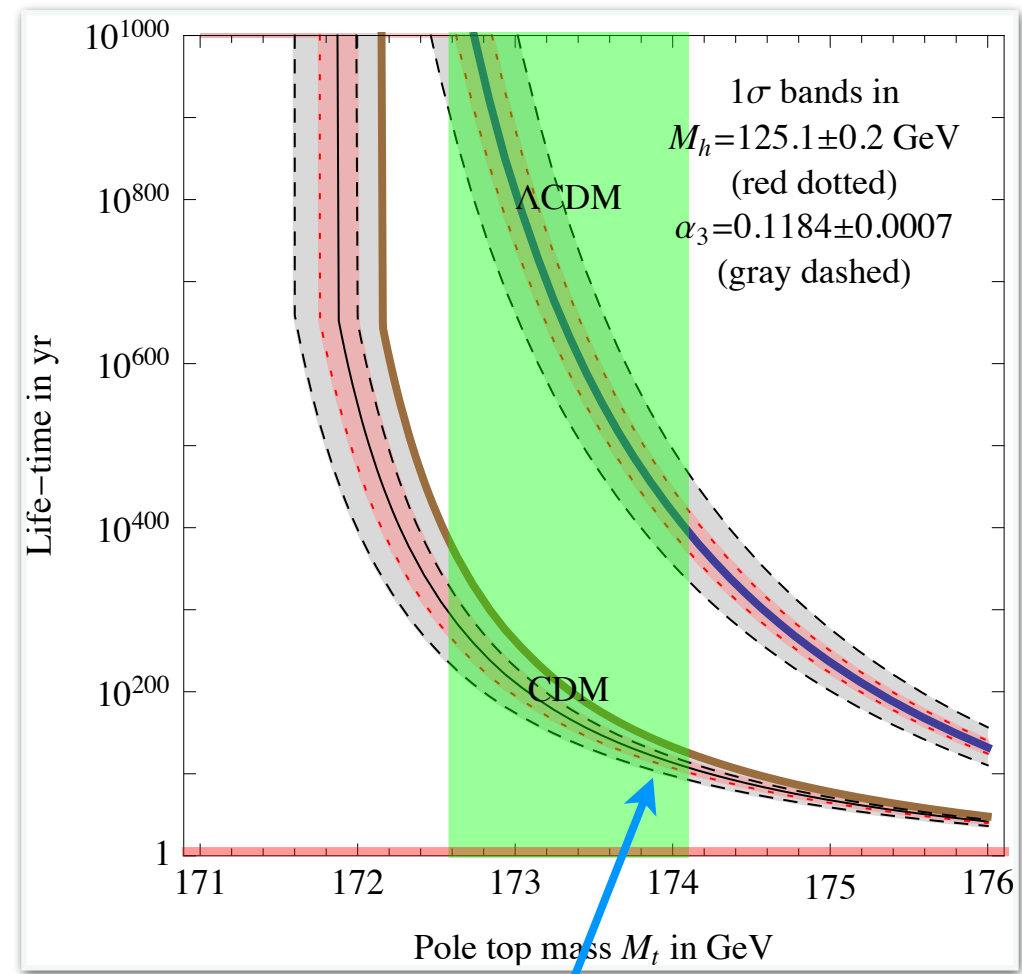
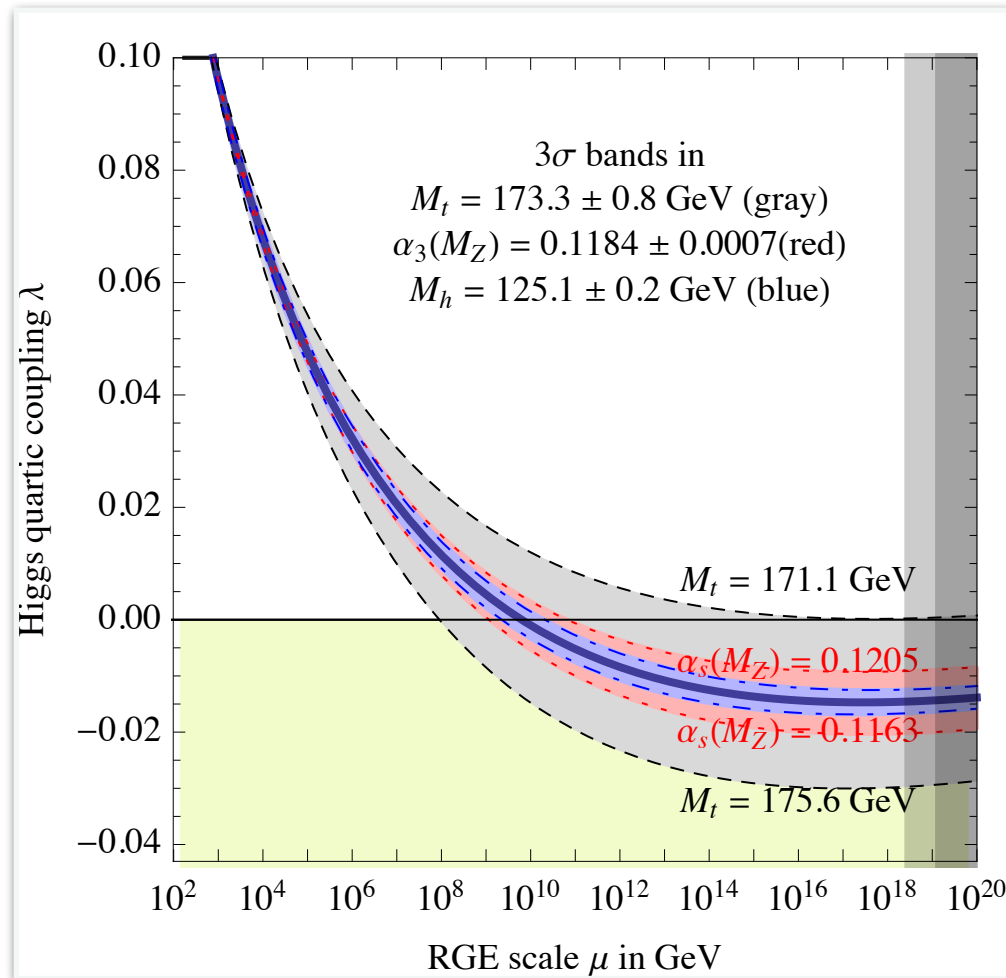


If  $\lambda(\mu) < 0$  then our **vacuum unstable** & decays via quantum tunneling to the true vacuum



# Our Fate (according to the SM)

Most precise computation to date [Buttazzo+ 1307.3536](#)



**SM is not inconsistent up to the Planck scale!**

Domains of validity



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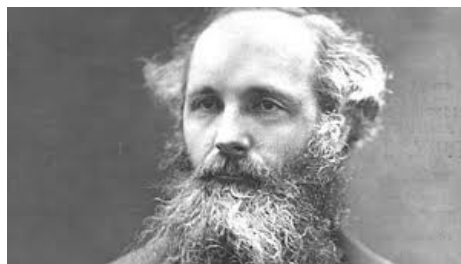
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# Open Questions from Theory

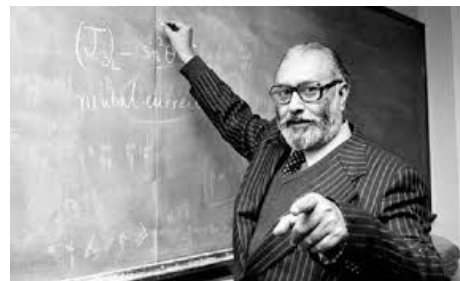
# Unifying Interactions - the past



Unified celestial bodies and apples



Unified Electricity and Magnetism



Related Electromagnetism and Weak force

Why should Nature stop unifying?

Why should Nature keep unifying?

# Unifying Interactions - the present

**Algebraic unification** of **fermion charges** is already a fact of Nature! Explains  $Q_e = -Q_p$ !

$SU(5)$

Georgi Glashow  
PRL **32**, 438 1974

$$5 = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e^- \\ -\nu_e \end{pmatrix} \quad 10 = \begin{pmatrix} 0 & u_3^c & -u_2^c & -u^1 & -d^1 \\ & 0 & u_1^c & -u^2 & -d^2 \\ & & 0 & -u^3 & -d^3 \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}$$

The group might be another one, but this is intriguing - to say the least

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How the rest fits

**gauge bosons**

$$SU(5) \supset SU(3) \times SU(2) \times U(1)$$

$$Y \propto \left( \begin{array}{c|c} \mathbf{1}_{3 \times 3} & \\ \hline & -\frac{3}{2} \mathbf{1}_{2 \times 2} \end{array} \right) \quad \left( \begin{array}{c|c} \frac{1}{2} \lambda_{3 \times 3}^i & \\ \hline X_{3 \times 2} & \frac{1}{2} \sigma_{2 \times 2}^a \end{array} \right) \quad \text{Predicts extra stuff!}$$

Price to pay: Ugliness of **Higgs sector**

See later for other problems

# Unifying Interactions - the present

**Dynamical unification** of **gauge couplings** is to be checked - can be computed!

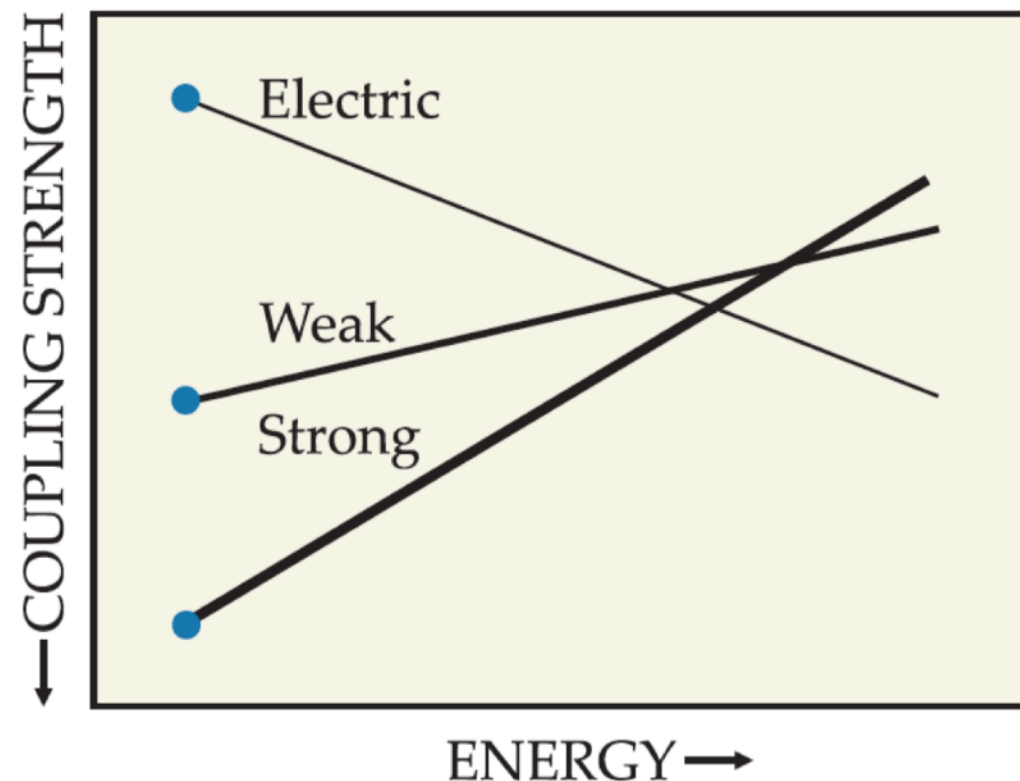
3 input parameters: electromagnetic, weak and strong coupling

2 output parameters: “the” coupling, the scale of unification

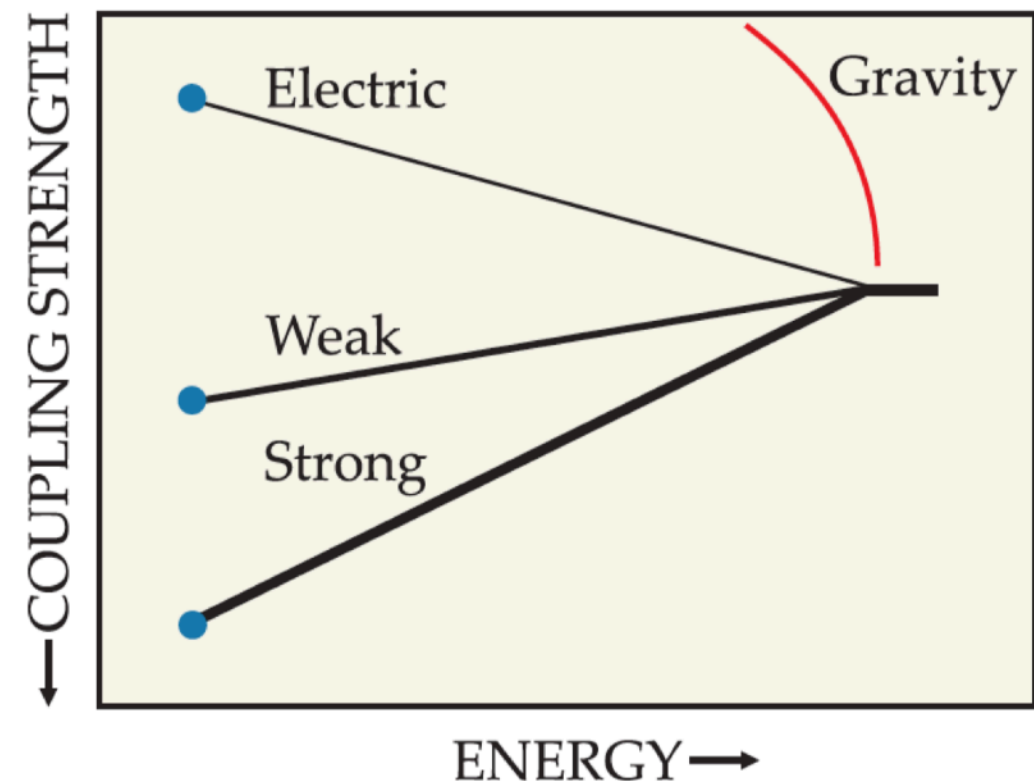
1 highly non-trivial consistency condition!



Standard Model



Supersymmetry



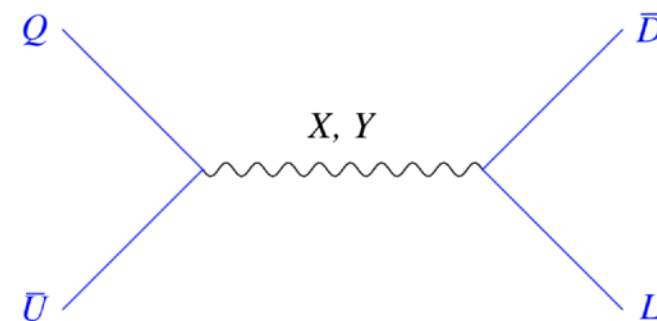


# Coupling Unification - Predictions

Algebraic unification “predicts” quarks talk to leptons

for example via the new gauge bosons that live here

$$\left( \begin{array}{c|c} \frac{1}{2} \lambda_{3 \times 3}^i & \\ \hline X_{3 \times 2} & \frac{1}{2} \sigma_{2 \times 2}^a \end{array} \right)$$



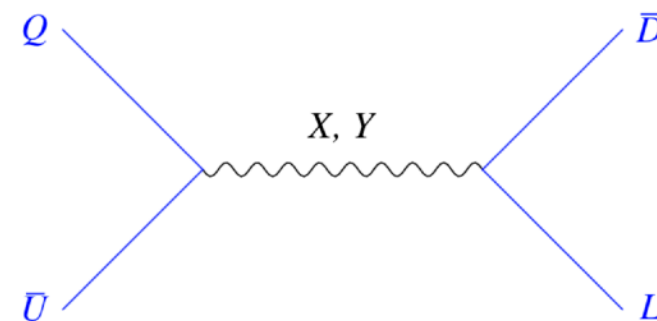
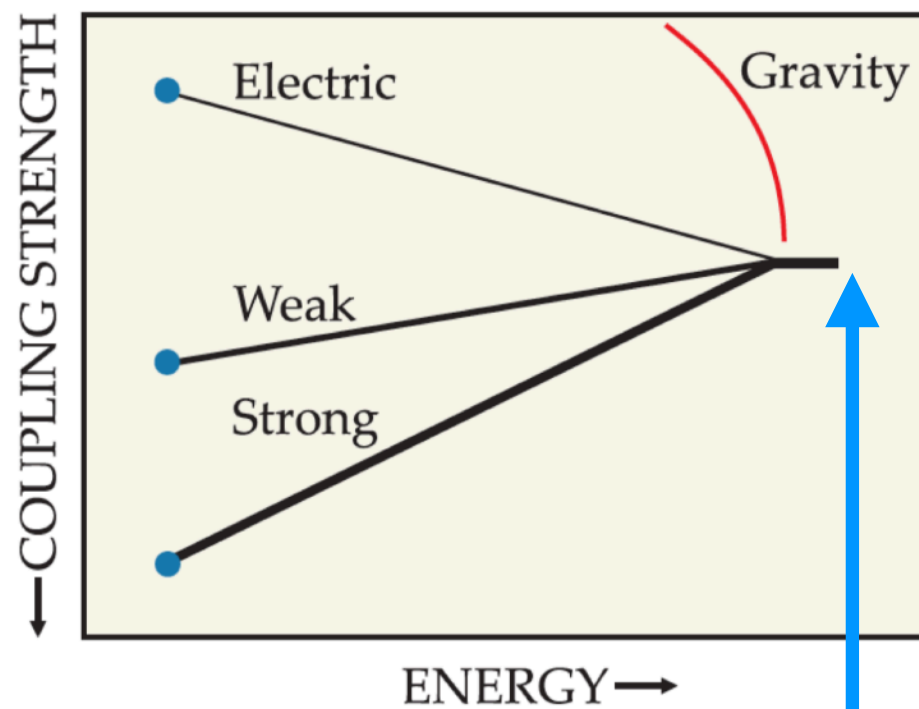
$$\approx \frac{g^2}{M_X^2} [\bar{D} \gamma_\mu L] [\bar{U} \gamma_\mu Q]$$

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$$\approx \frac{g^2}{M_X^2} [\bar{D} \gamma_\mu L] [\bar{U} \gamma_\mu Q]$$

Unification scale  $M_{\text{GUT}} \simeq 10^{15} \text{ GeV}$

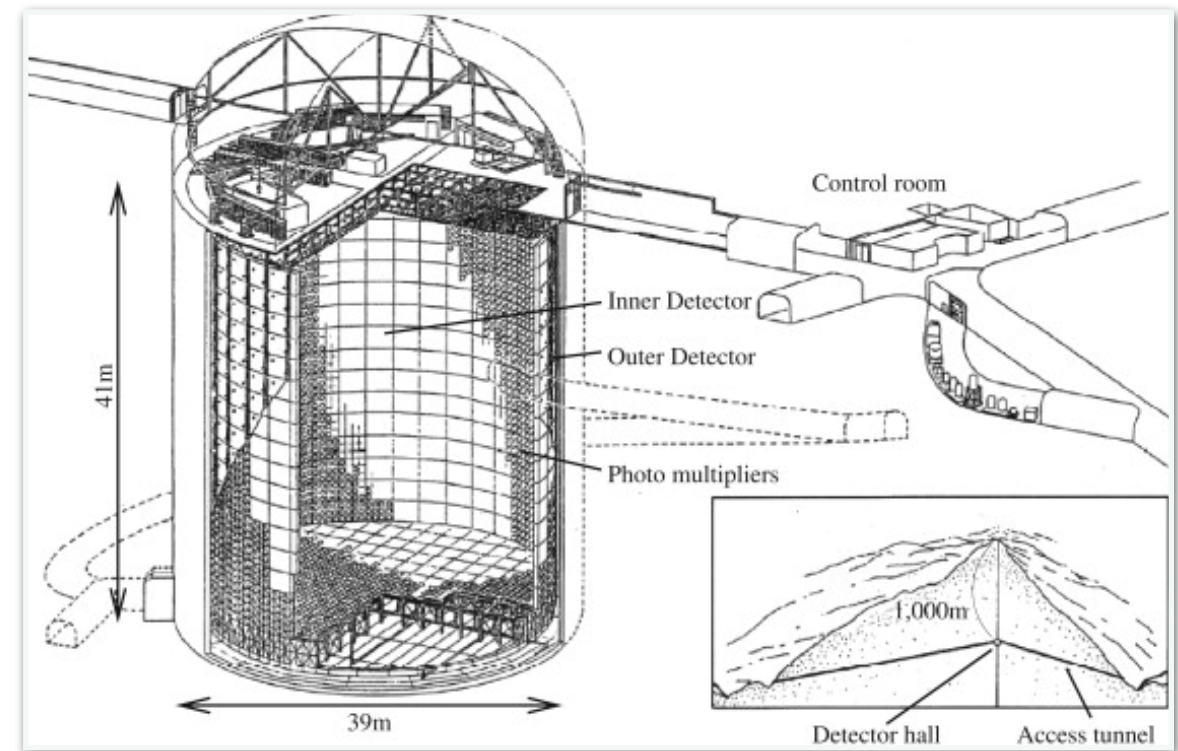
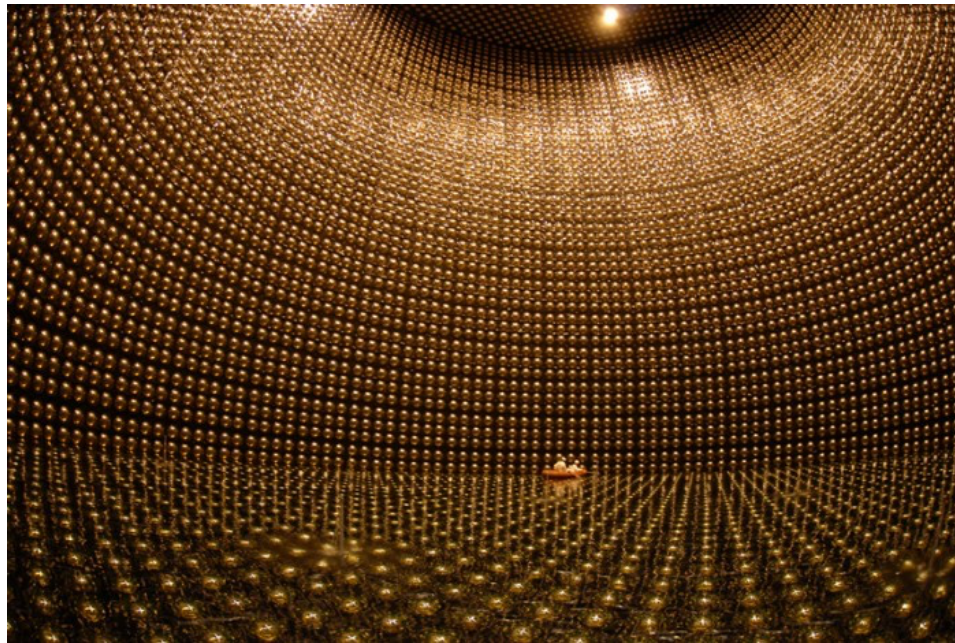
## Protons decay!

$$p \rightarrow \pi^0 e^+, \pi^+ \bar{\nu}$$

$$\tau(p) \sim m_p \left( \frac{M_{\text{GUT}}}{m_p} \right)^4 \sim 10^{32} \text{ yr} \left( \frac{M_{\text{GUT}}}{10^{15} \text{ GeV}} \right)^4$$

# Coupling Unification - experimental tests

## SuperKamiokande

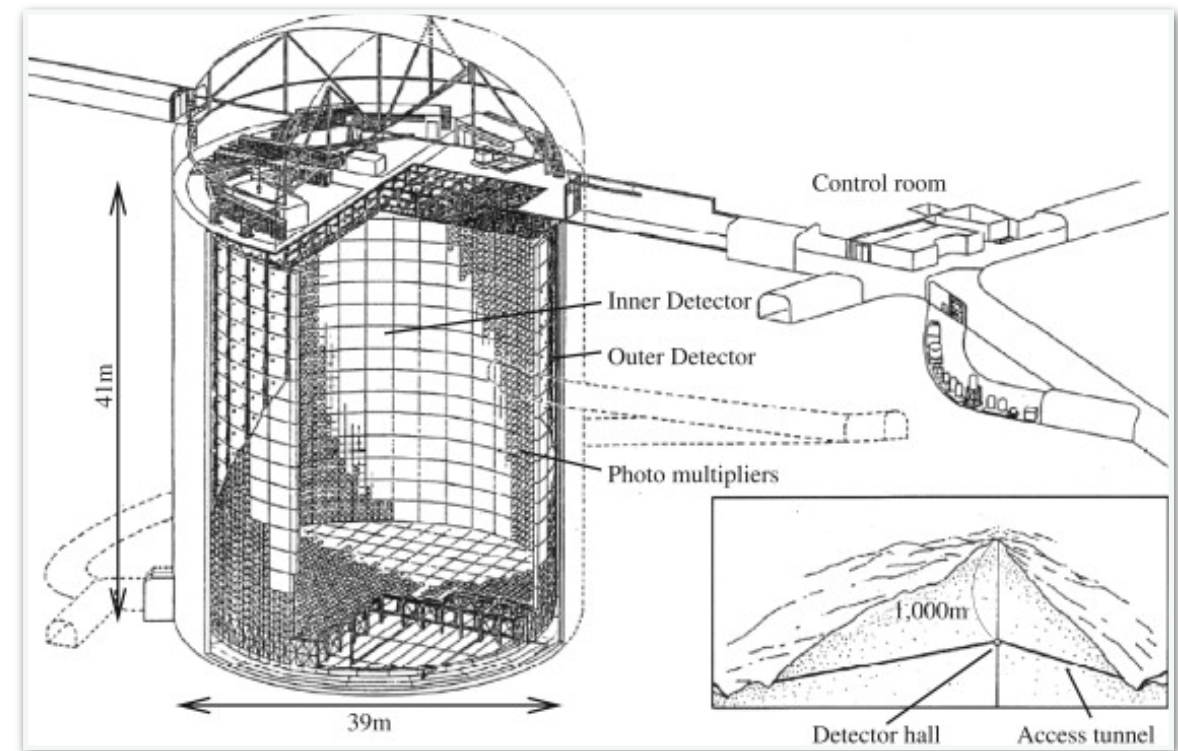
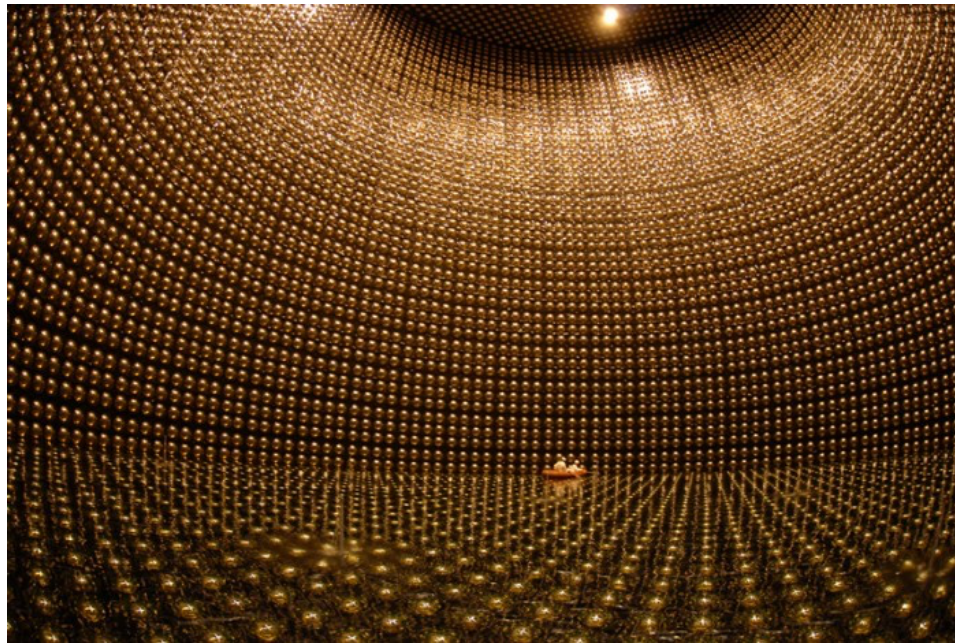


$\approx 20 \times 10^3$  tons of water, surrounded by detectors



# Coupling Unification - experimental tests

## SuperKamiokande



$\approx 20 \times 10^3$  tons of water, surrounded by detectors

$\approx 10^{10}$  moles of protons

Observe for some years:

$$\tau(p) > 10^{10} N_A \text{yr} \sim 10^{33} \text{yr} \quad M_{\text{GUT}} \gtrsim 10^{15 \div 16} \text{GeV}$$

Limit “touches” current predictions, but not enough to disproof unification

Another lesson: precision measurements can tell us about extremely large scales!

# Deeper Unification: Supersymmetry

Unifies **Matter** with **Interactions**

SUSY does so by relating fermions and bosons

$$Q |\text{fermion}\rangle = \text{boson}$$

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Roots: **1967** Coleman & Mandula

Most general **symmetry** structure of QFT can be Poincaré x internal symmetries

Assumptions: causality, locality, ..., bosonic symmetry generators

What's the physical motivation?

Drop this assumption  $\longrightarrow$  **Supersymmetry!**

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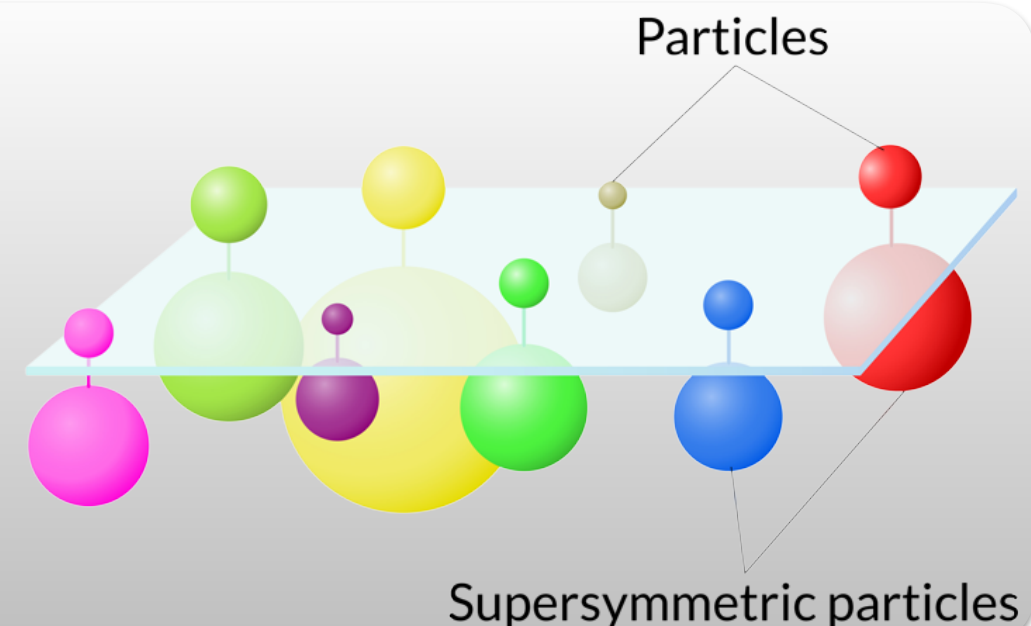
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What's the physical motivation?

Drop this assumption  $\longrightarrow$  **Supersymmetry!**

Every particle has a partner with  
spin differing by 1/2  
same mass  
same quantum numbers

Partners of SM particles not seen  $\longrightarrow$  **Break SUSY!**





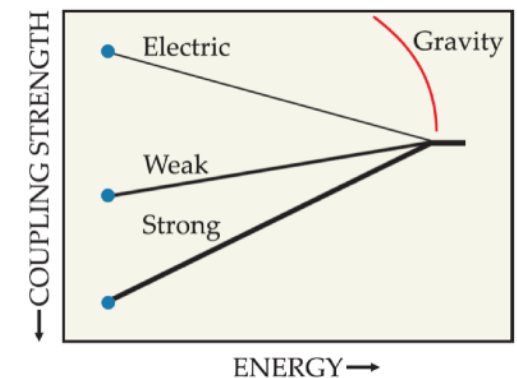
# SUSY: Many Virtues and one Vice



By itself a deeper Unification of Laws of Nature (**matter and interactions**)



Predicts New Particles  
that automatically induce **gauge couplings unification**



Necessary ingredient of **String Theory** (“leading” candidate for quantum gravity)



Accidental Symmetries provide many **Dark Matter** candidates (WIMP, Gravitino...)



Solves the **Hierarchy Problem** of the Fermi Scale (see next slides)

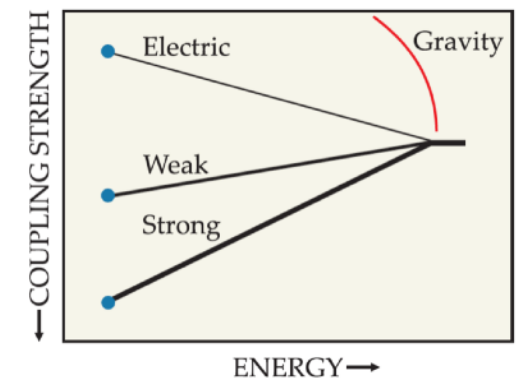
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Not here: Why 3 generations?

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# Open Questions from Theory

Hierarchy Problems

# Open Questions from Theory

# Beauty and Ugliness in the SM



credit to Maldacena 1410.6753

Gauge sector

Scalar sector

- Higgs **mass** and **couplings**
- **Cosmological constant**

**2 hierarchy problems**

**flavour problem**

# The Hierarchy (or Naturalness) Problems

Physical system (SM + GR) with 3 fundamental scales They should be of the same order

$$\text{Why } \frac{\Lambda}{M_{\text{Planck}}^4} \approx 10^{-120}, \quad \frac{m_h^2}{M_{\text{Planck}}^2} \approx 10^{-34} \quad ???$$

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In particular: dimensionful parameters receive contributions from any scale the SM couples to

E.g. **NP energy scale** responsible for: DM, Neutrino Masses, Quantum Gravity, GUT,...

$$\text{So why not } m_h^2 \approx M_{\text{DM}}^2 + M_{\text{GUT}}^2 + M_N^2 + \dots \quad ?$$

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Needs huge **fine-tuning** of coefficients of each contribution

SM depends on detail of much larger scales: a challenge to reductionism?





# Hierarchy Problem and New Physics

In the past, naturalness problems signaled new physics:

Problem	Natural solution?	New physics
$\delta m_e = \alpha \Lambda$	Yes: chiral <b>symmetry</b>	positron
$\delta(m_{\pi^+}^2 - m_{\pi^0}^2) = \alpha \Lambda^2$	Yes: $\pi$ are <b>composite</b>	QCD

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## Supersymmetry

What are **natural solutions** for the Higgs mass? **Compositeness** of the Higgs boson  
(Higgs boson ~ as the pion of new strong interaction)

...

“Natural Solutions” by definition predict New Physics close to the Higgs mass

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But LEP and LHC found no BSM!

Also, they do not work at all for the cosmological constant!

# Other Solutions?

## Warning: my opinion

Current experimental exclusions not enough to discard Naturalness \*\*

However, they definitely motivate to explore alternatives (+ we still have to explain  $\Lambda$  )

\*\*Quantitatively, they imply tuning at % level and we observe similar tunings in Nature (e.g. Solar Eclipses!)

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## **Anthropic** Selection on a Multiverse

Some parameters, if slightly different, would not allow for life to develop

But: how to test?



Weinberg obtained this way an upper bound on  $\Lambda$ , very close to value measured much later!

Same reasoning can work for Higgs mass (and also light Yukawa couplings)...

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## **Cosmological Relaxation** of the EW scale Graham Kaplan Rajendran 1504.07551

Evolution of a BSM field during Universe Expansion sets Higgs mass

kind of “Self-organised criticality”, for the moment does not explain  $\Lambda$

Idea in early stages, needs further studies...

**Open Questions: 1900 to Today**

**Open Questions from Data**

**Open Questions from Theory**



# What Next?

Like in 1900: we understand almost everything, but for some “clouds”

Like in 1900: paradigms that worked in the past century are suffering!

Unlike 1900: current model passed loads of experiment and theory tests

The optimist    Dream-like situation!    On the verge of a revolution!

The pessimist    The needed NP could not, and so will not, show up at experiments  
corollary: go to math/finance/agriculture/...

The pragmatic    Let's make more tests    **Good News** is that data are coming!