Looking into the Universe: Higgs and Gravitational Wave

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Physics of the Universe

10^19 GeV
10^-34m

nm A0 fm

nuclear physics

atomic physics

biology chemistry

Planck scale

(universe might be born from O(1) quantum fluctuations?)

Among many features characterizing each physics system and its effective theory,,,

Energy frontier of our understanding of the Universe

100 GeV
10^-17m

10^19 GeV
10^-34m

nm A0 fm

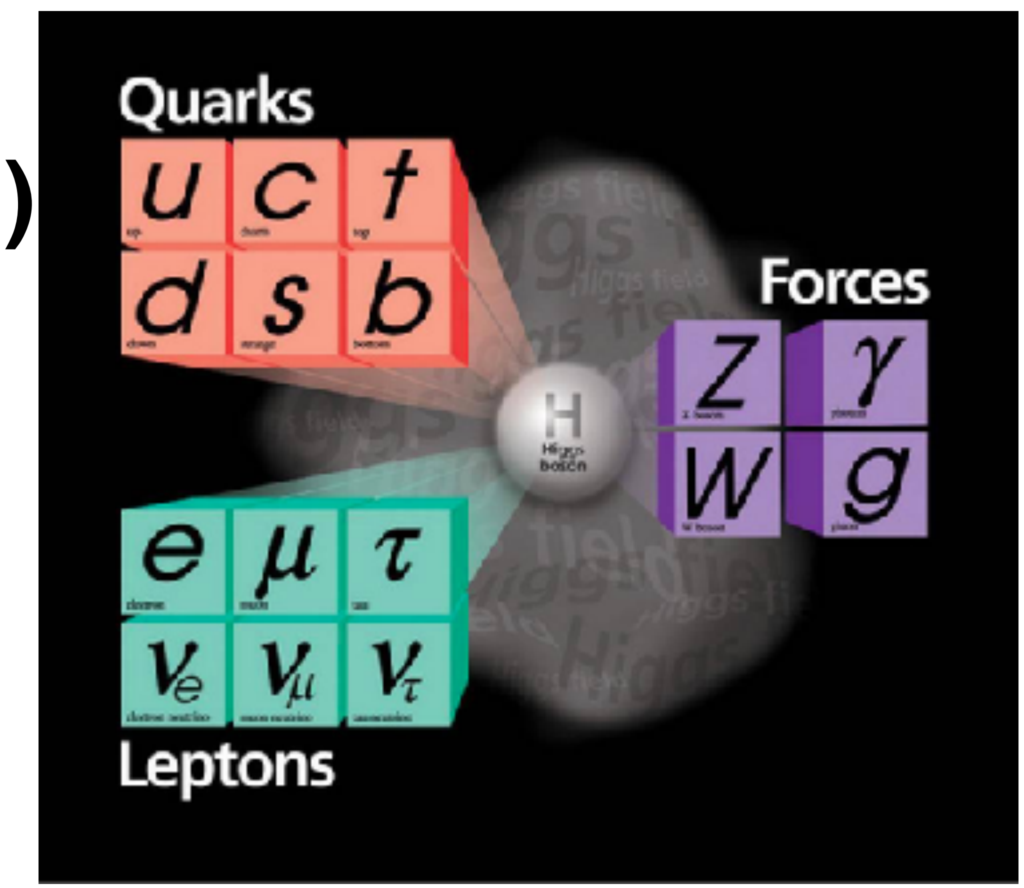
nuclear physics

Standard Model (SM)

quarks, leptons, forces, Higgs

atomic physics

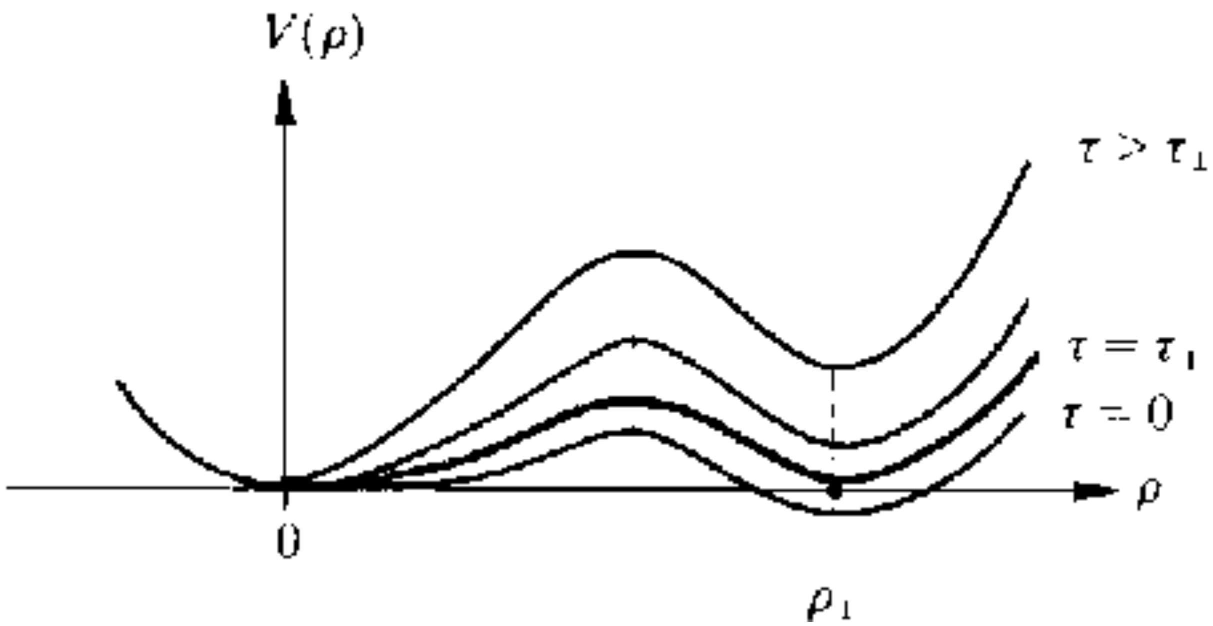
biology
chemistry

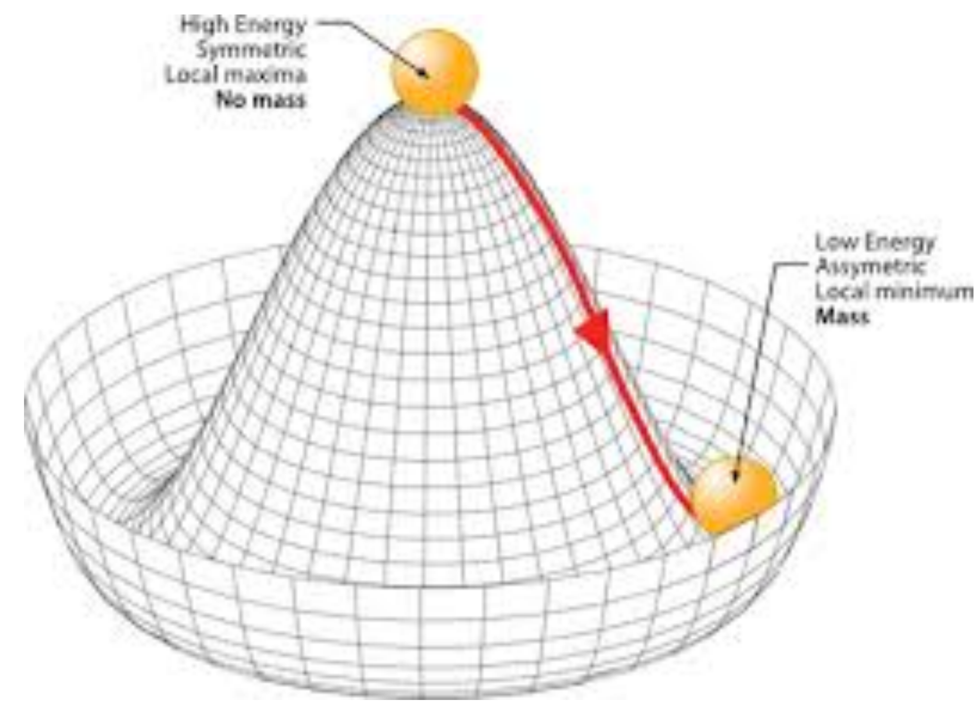


Planck scale

(universe might be born from O(1) quantum fluctuations?)

Higgs: uniquely shaping our daily life

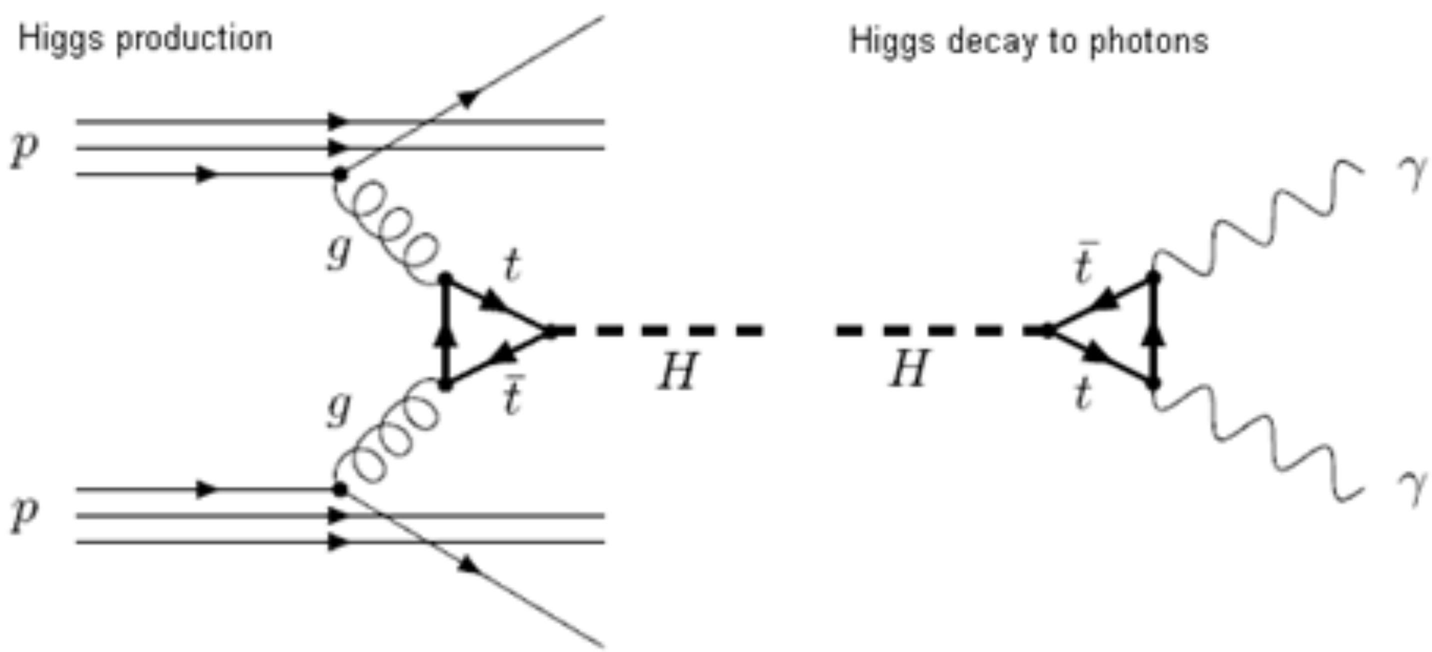


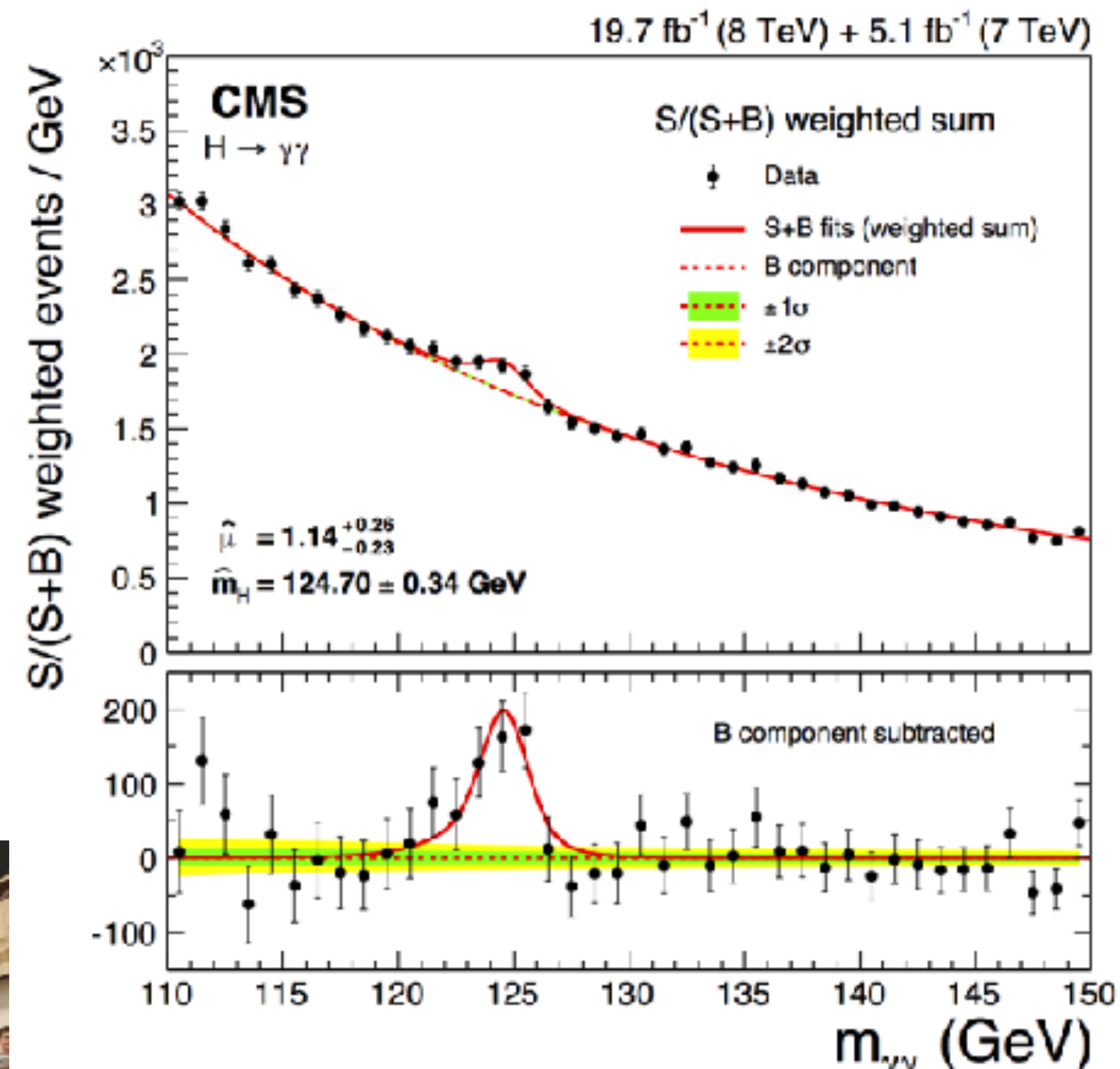


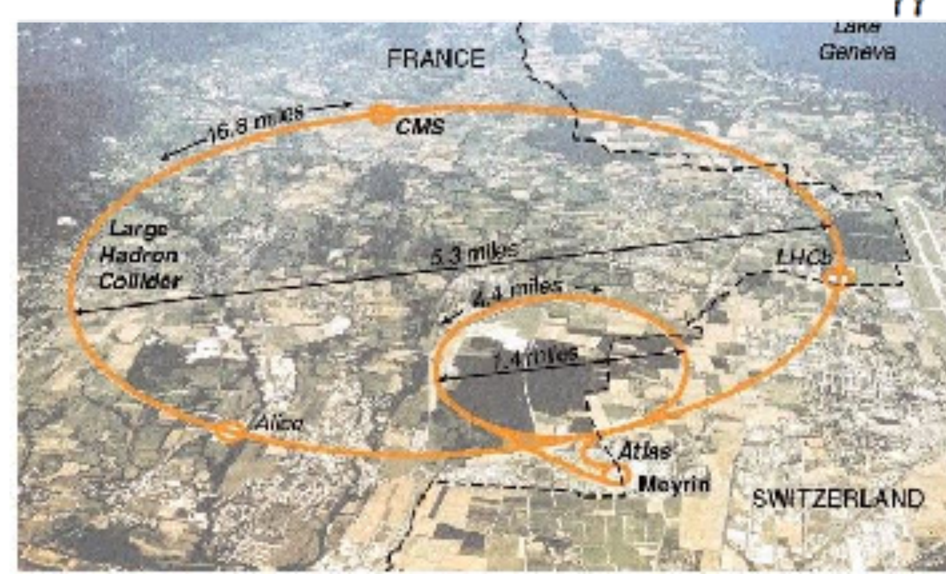
Phase transition & vacuum condensation as universe cools freeze its interactions with elem particles — mass.

If Higgs were slightly different, our life would have been totally different (may not even exist).

SM and Higgs are confirmed







SM is not a complete theory

Many questions beyond the SM

- Why does **Higgs** (and daily life) look like today?
- What is **Dark Matter**?
- What is **Dark Energy**?
- Why is matter much more than anti-matter?
- neutrino mass, strong CP, inflation, cosmological constant, CPV sources, etc.

Unexplored Beyond the SM

100 GeV
10^-17m

10^19 GeV
10^-34m

nm A0 fm

nuclear
physics

atomic
physics

biology
chemistry

Standard
Model (SM)

quarks,
leptons,
forces,
Higgs

Planck
scale

In particular,
Higgs (and DM) calculation
imply that new physics should
exist just beyond the SM.

GW can perhaps provide new
ways to probe new physics
and Dark Energy.

Some history analogies

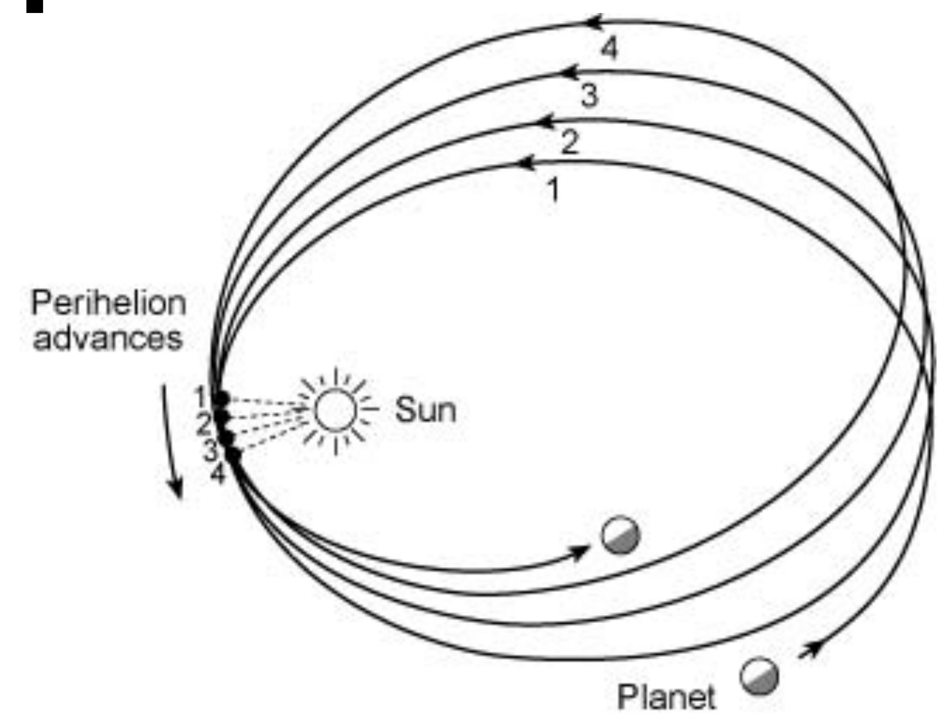
Uranus orbit

$$F = \frac{GMm}{r^2}$$

$$V = \frac{GMm}{r}$$

- Uranus orbit was not exactly the Keplerian/Newtonian. It was a big puzzle in 1840's.
- Le Verrier postulated it is due to nearby planet's perturbation, and predicted its location. (1846)
- Neptune was discovered on the same night at the exact location (within 1-degree)!

Mercury perihelion precession



- A few years later, Le Verrier also found anomalous Mercury's perihelion precession.

- He predicted yet another planet, Vulcan, in between Mercury and the Sun. (1859)

- But, No planet was found.

- All other efforts to explain it failed; including non-standard medium in between Mercury and the Sun.

This time, special relativity

- This time,,,
  the solution was found from a totally different approach: special relativity — the more fundamental theory of gravitation.

- Mercury is closest to the Sun’s gravity and moves fastest, in which relativistic effects are largest.

Could have been expected…

- Newton wrote in *Principia*:

  “1/r^2 law is proved with the greatest exactness from the fact that the aphelia are at rest… The slightest departure from it would necessarily result in noticeable motion of the apsides.”

- But there was no principles to retain only 1/r^2…

- Indeed, higher-power terms exist in the Relativity.

Newton's gravity is only an effective theory (ET)

- In fact, Newton's theory was only an ET of the Relativity valid for low velocity and weak gravity.

- In fact, every theory we use is an ET valid/suited for certain physics systems!
  Core of our science and *reductionism*.

- *We couldn't have done any physics if Mercury's motion is important in baseball trajectories.*

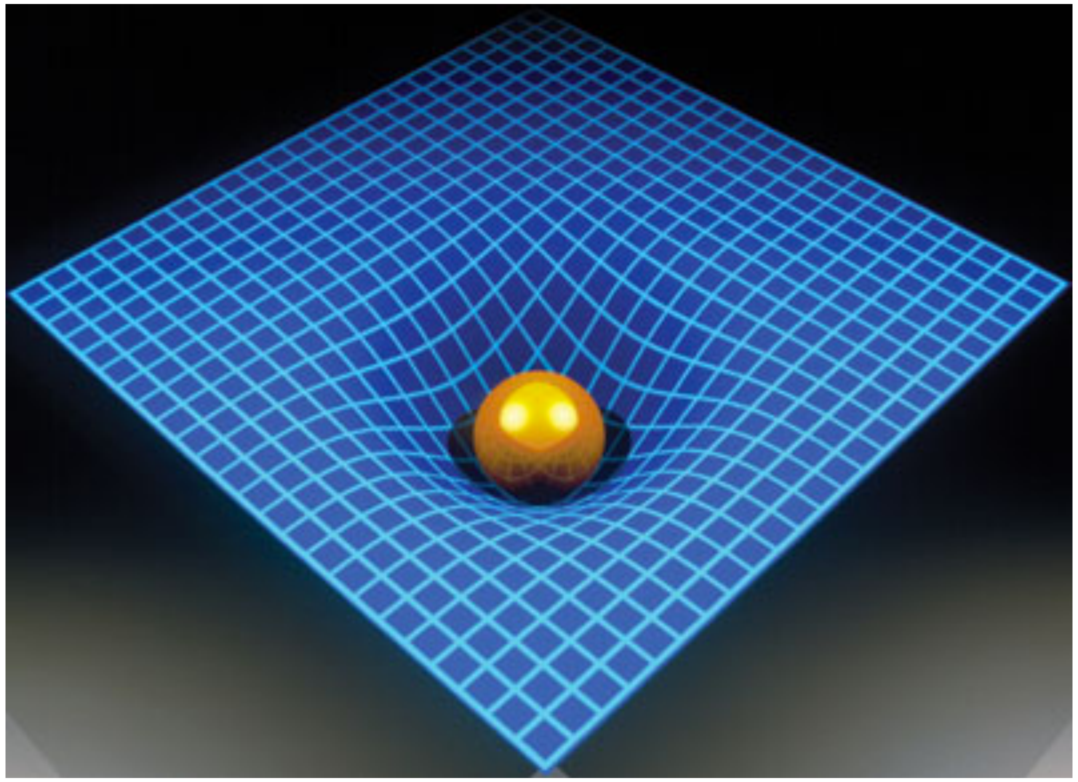
Newton’s gravity is only an effective theory (ET)

- In fact, Newton’s theory was only an ET of the Relativity valid for low velocity and weak gravity.

- As an ET, all such power corrections not prohibited by symmetries shall be considered.

- Richard Feynman:
  “Anything that are not prohibited is allowed.”

What are symmetries of Newton's gravitation law?



- Rotational invariance of gravity.
- $V \ni 1/r$ is rotation-invariant.
- But higher-order terms $1/r^2$, $1/r^3$ are also invariant.
- They did exist and Newton's law was not absolute. The anomalous precession could have been expected.

Natural size of precession

- ET even allows us to predict a natural size of precession!

$$V \ni \frac{1}{r} \qquad \text{vs.} \qquad \frac{R_0}{r^2} \qquad \frac{R_1^2}{r^3} \qquad\qquad \frac{R}{r} \ll 1$$

- R is the length scale in which gravity becomes very strong and Newton’s ET breaks down.

- What is R value?

Natural size of precession

- In a gravity system with M and m orbiting at v, the only length scale present is

$$R \sim \frac{GM}{v^2}?$$

- Well, wrong v-behavior and v is not independent…

- The most global and inherent velocity scale was unknown at the Newton's and Le Verrier's era.

c: Next fundamental scale

- By the early 1900's, there were plenty of experimental evidences that c is a constant for all inertial observers.

- Einstein bravely assumed/discovered that c is the next fundamental and inherent constant velocity scale.

$$R \sim \frac{GM}{c^2}$$

$$2\frac{GM}{c^2}$$

cf) Schwarzschild radius

- Adding *natural-sized* R/r^2 and R^2/r^3 terms to Newton's law does explain the Mercury observation!

c: Next fundamental scale

- By the early 1900's, there were plenty of experimental evide… …s.

- Einst… …xt funda…

$\dots 2\frac{GM}{c^2}$

…arzschild radius

If Le Verrier knew about ET,
he could have deduced the value of c
well before Michelson-Morley and
Einstein!

- Adding *natural-sized* R/r^2 and R^2/r^3 terms to Newton's law does explain the Mercury observation!

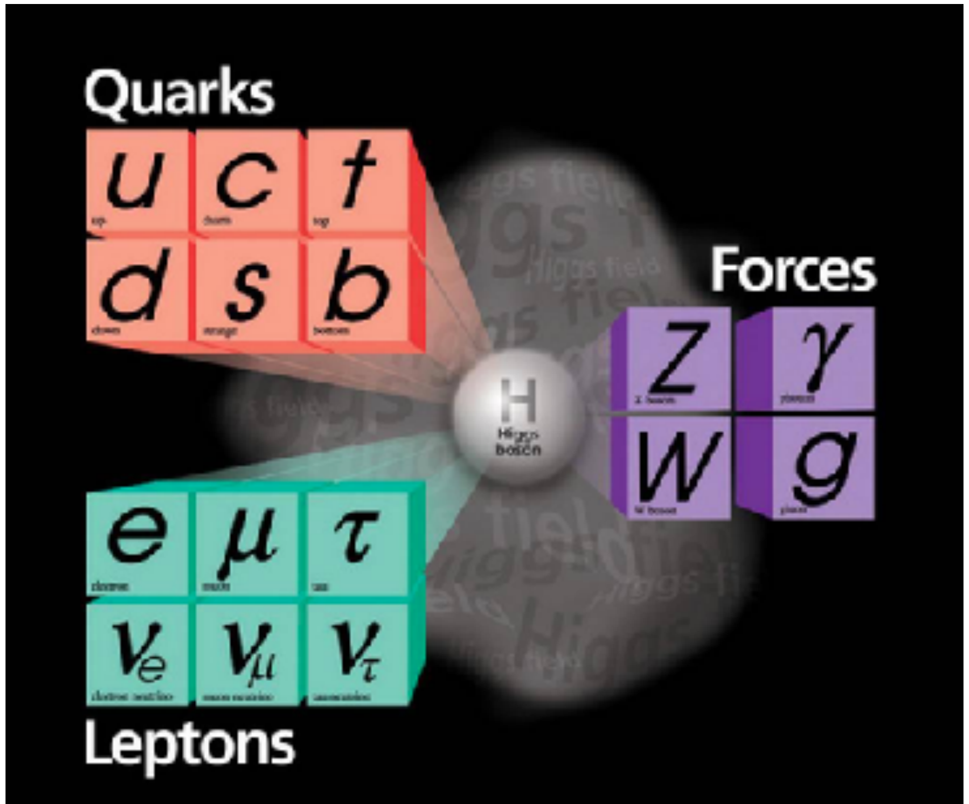
Ben Lee's prediction

- Such power of ET is not accidental.
- Benjamin W. Lee could predict the 4th quark (charm) mass (and its existence) in this way (1974)!

  (to explain very small Kaon mass difference that couldn't be explained with u-d-s three quarks.)

- 'ET + naturalness'

  Many such examples in physics history…



Particle physics prediction!

- SM is only an ET of a more fundamental theory.
- Based on the Higgs boson (and Dark Matter) data,

  (in a way similar to Ben Lee's prediction)

  the next energy cutoff scale of the SM ET, or new physics energy scale, was predicted !
- That is just beyond the SM!

Unbearable lightness of the Higgs boson

- Almost whatever you do in QFT, you end up concluding that our life depends on this fine cancellation.

  (Higgs mass)^2 = (100)^2 =
  1000000000000000000000000000000000010000 -
  1000000000000000000000000000000000000000

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- Thinking the SM as an ET, we could convert it to a more comfortable one:
  (Higgs mass)^2 = (100)^2 = 1010000 - 1000000

- (only) if a new physics exists *just* beyond the SM!

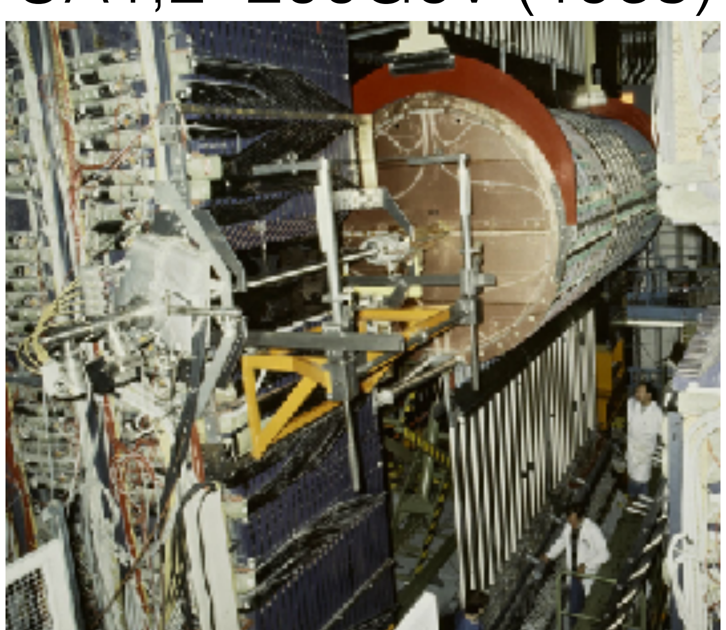
Probing SM @ Particle Collider

charm, tau @
SLAC 3GeV (1970's)

gluon @
PETRA 40GeV(1972)

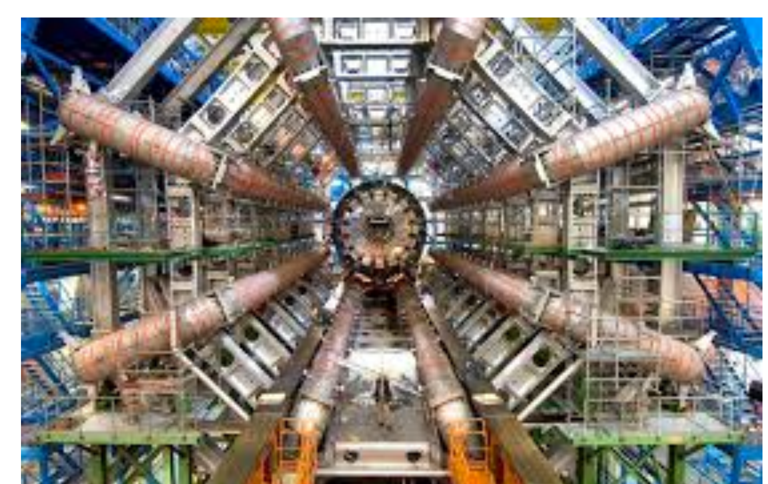
electroweak precision test @
SLAC SLC 90GeV (2000's)

W,Z bosons @
UA1,2 200GeV (1983)



top quark @
Tevatron 2TeV (1995)

Higgs @
LHC 8 TeV (2012)

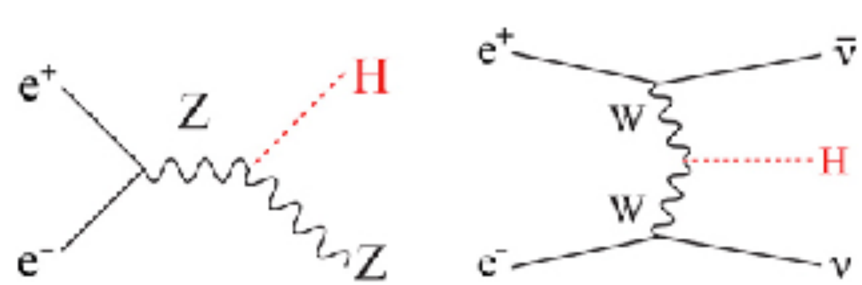


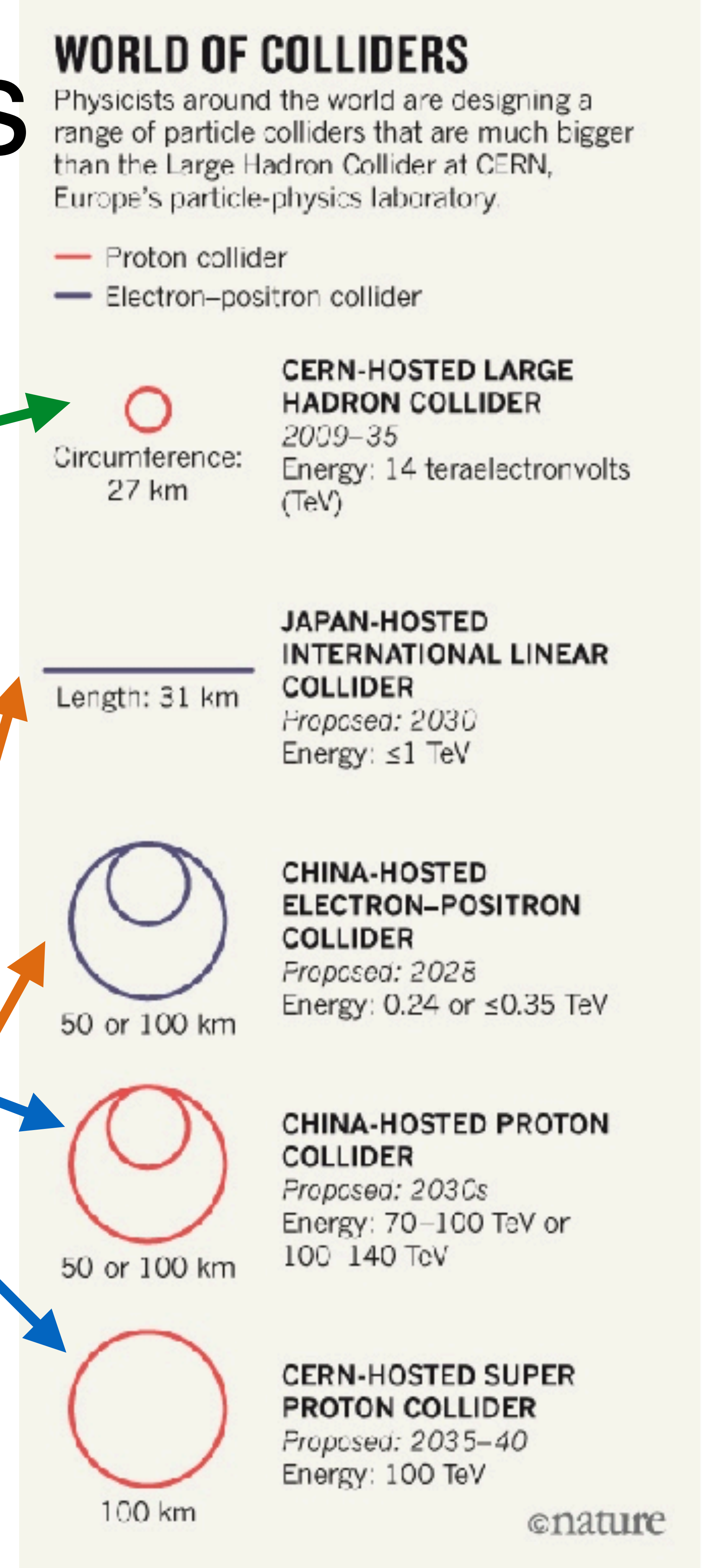
Probing Higgs origins @ Particle Collider

- LHC with the highest collision energy ever (13TeV) produced 1M Higgs so far and currently probing highest energy scale directly.

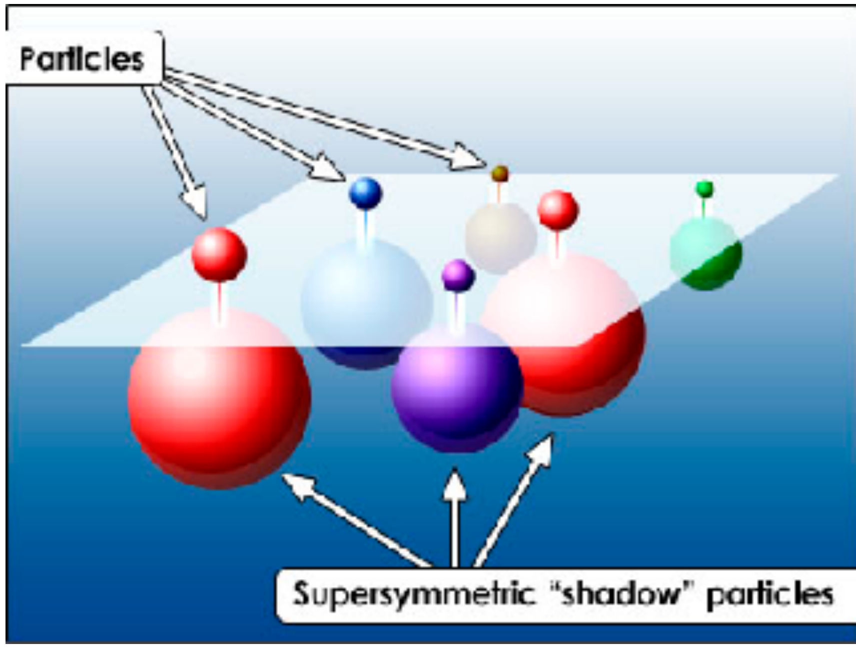
- Future 1: A bigger collider with a higher collision energy

- Future 2: A more precise collider

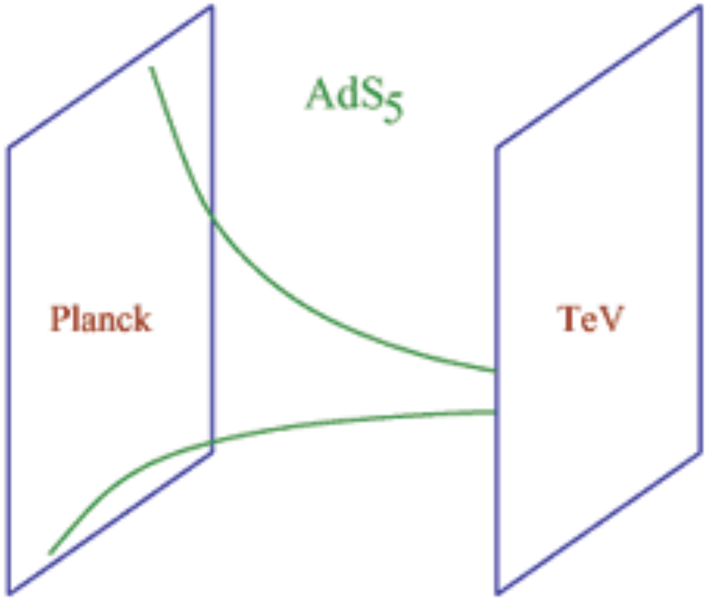




Higgs origin candidate



- Supersymmetry
  - the symmetry btwn bosons and fermions
  - Fermion statistics is opposite to bosons'
  - cancelling any such dangerous effects
- Warped Extra dimension
  - 5th dimension is exponentially warped.
  - Plack scale in 4d projection is exponentially small.
- Many others… but all predict new particles beyond the SM.



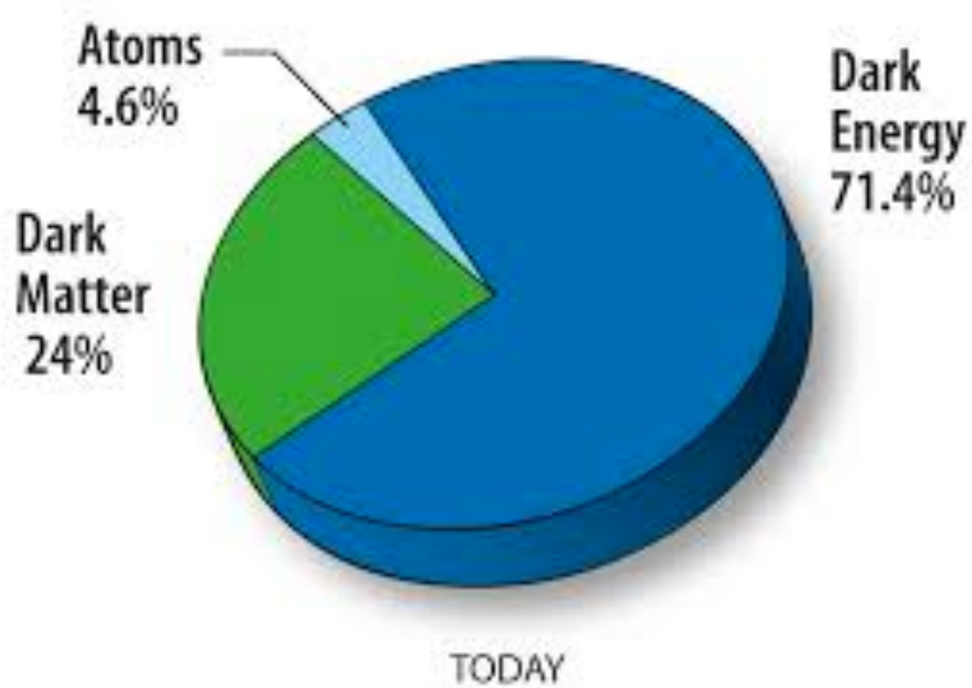
Higgs Effective Theory

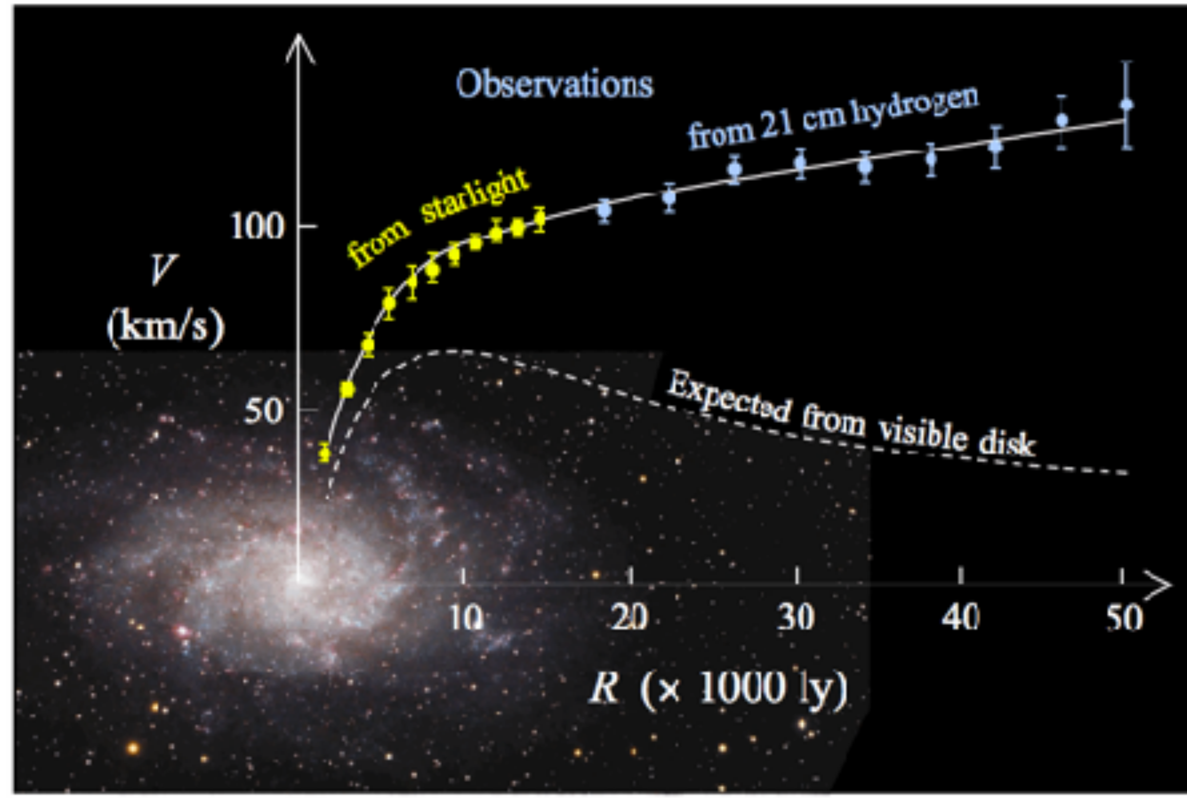
- All these theories should have common elements to explain the origin of the Higgs.
- ET can (model independently) capture them.
- Efforts to measure power corrections to the SM Higgs and to deduce new physics.
  Various idea and interdisciplinary approaches…

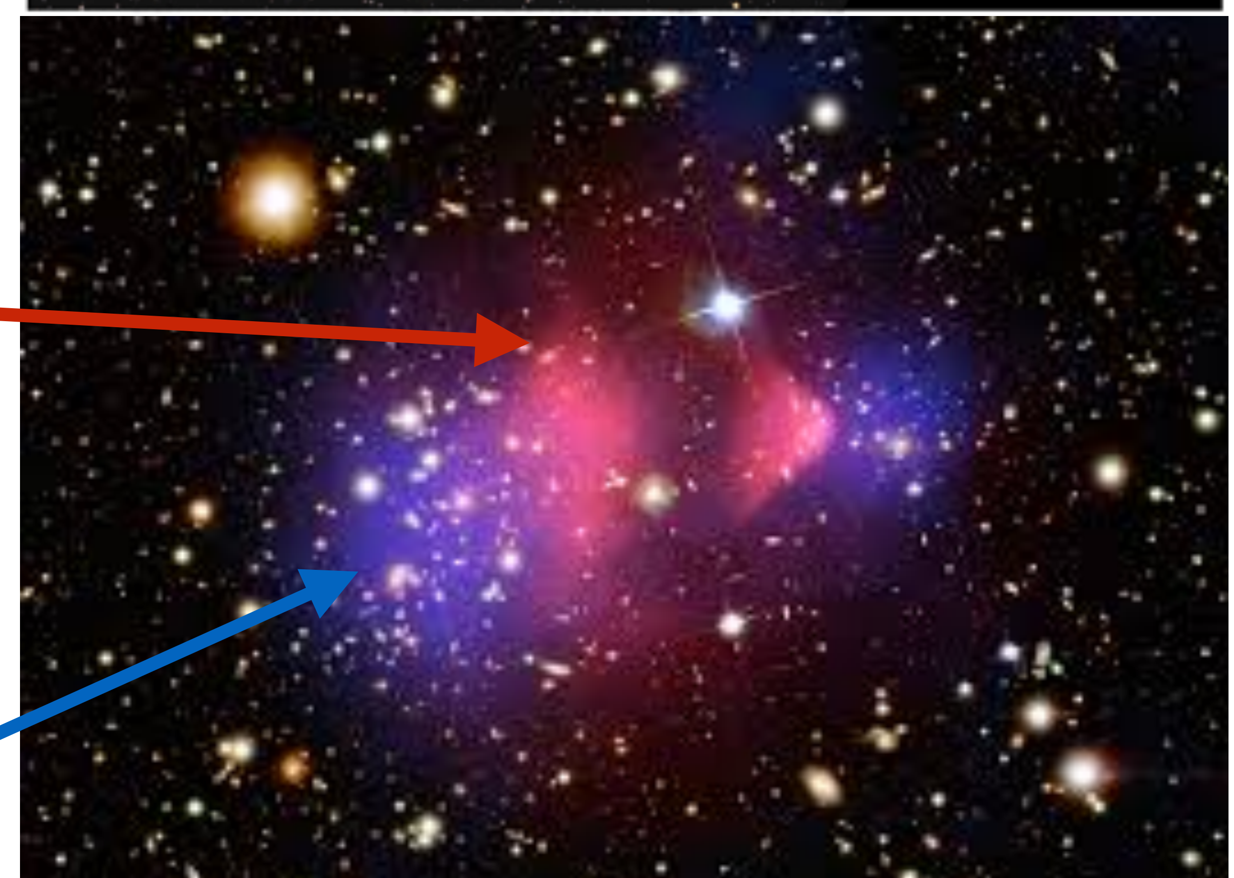
$$\frac{m^2_{\rm Higgs}}{m^2_{\rm NewPhysics}}$$

Dark Matter

- It should abundantly exist.
- But what is it? How to discover them?



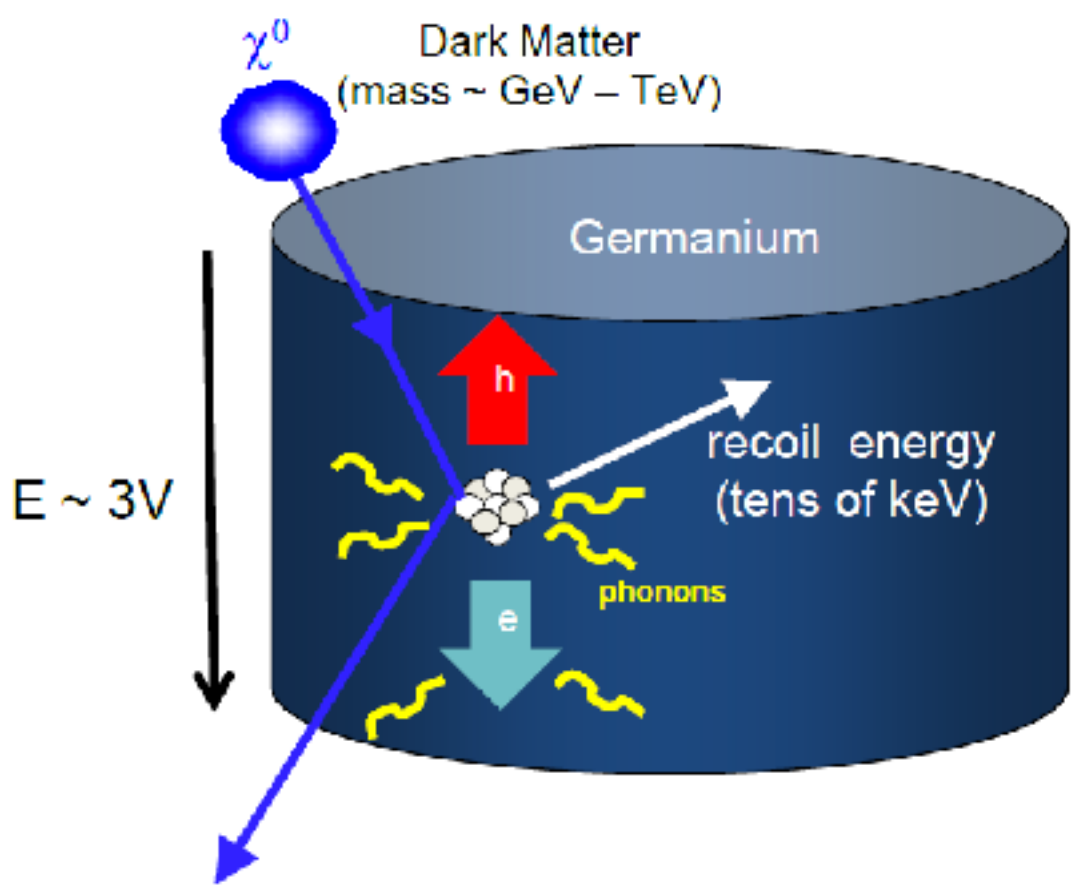


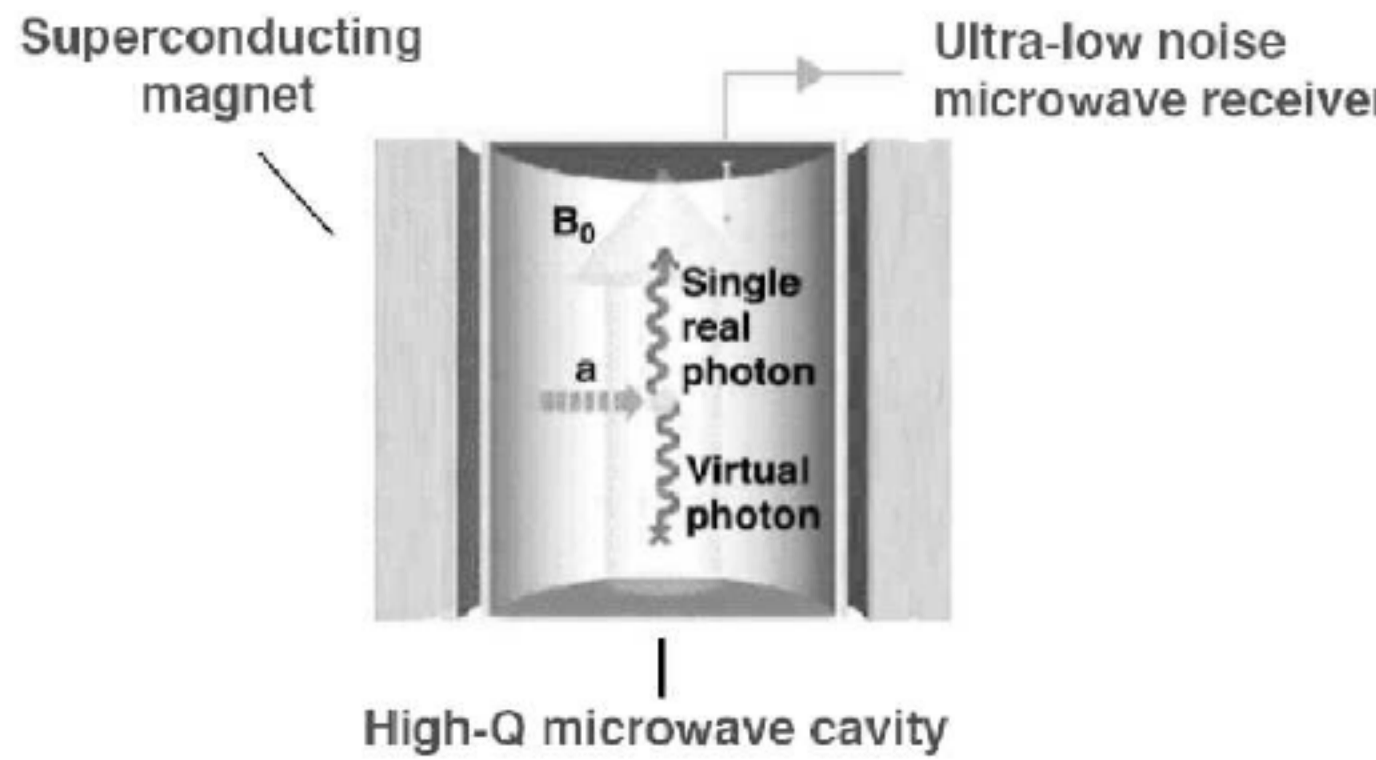


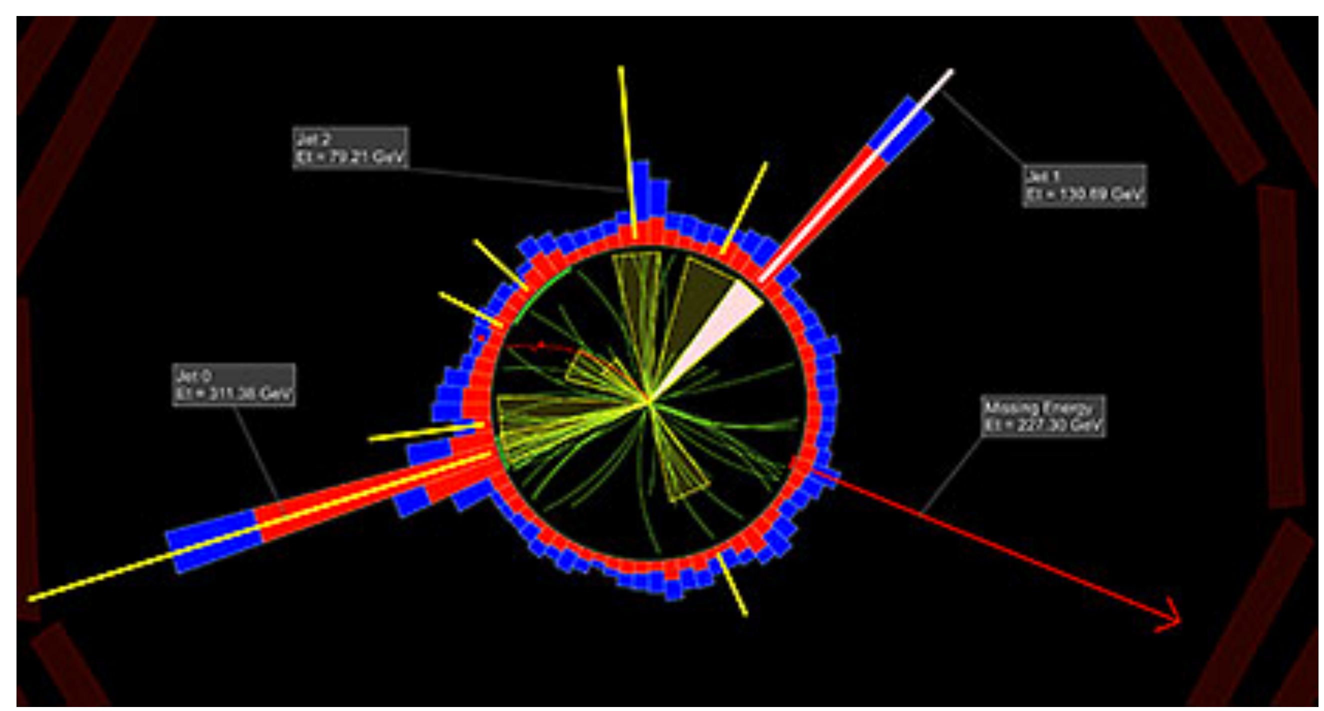
X-ray

gravitational lensing

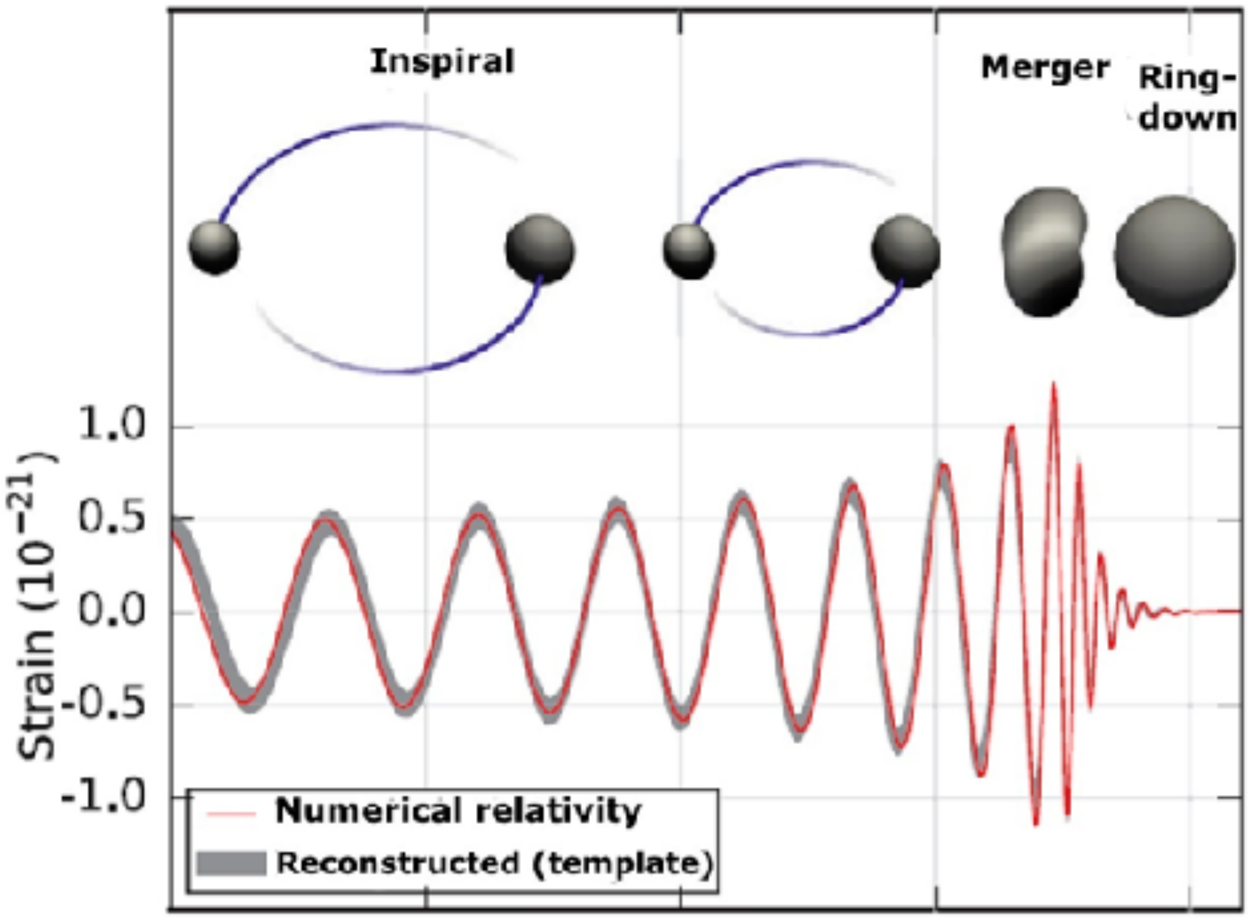
Dark Matter detectors

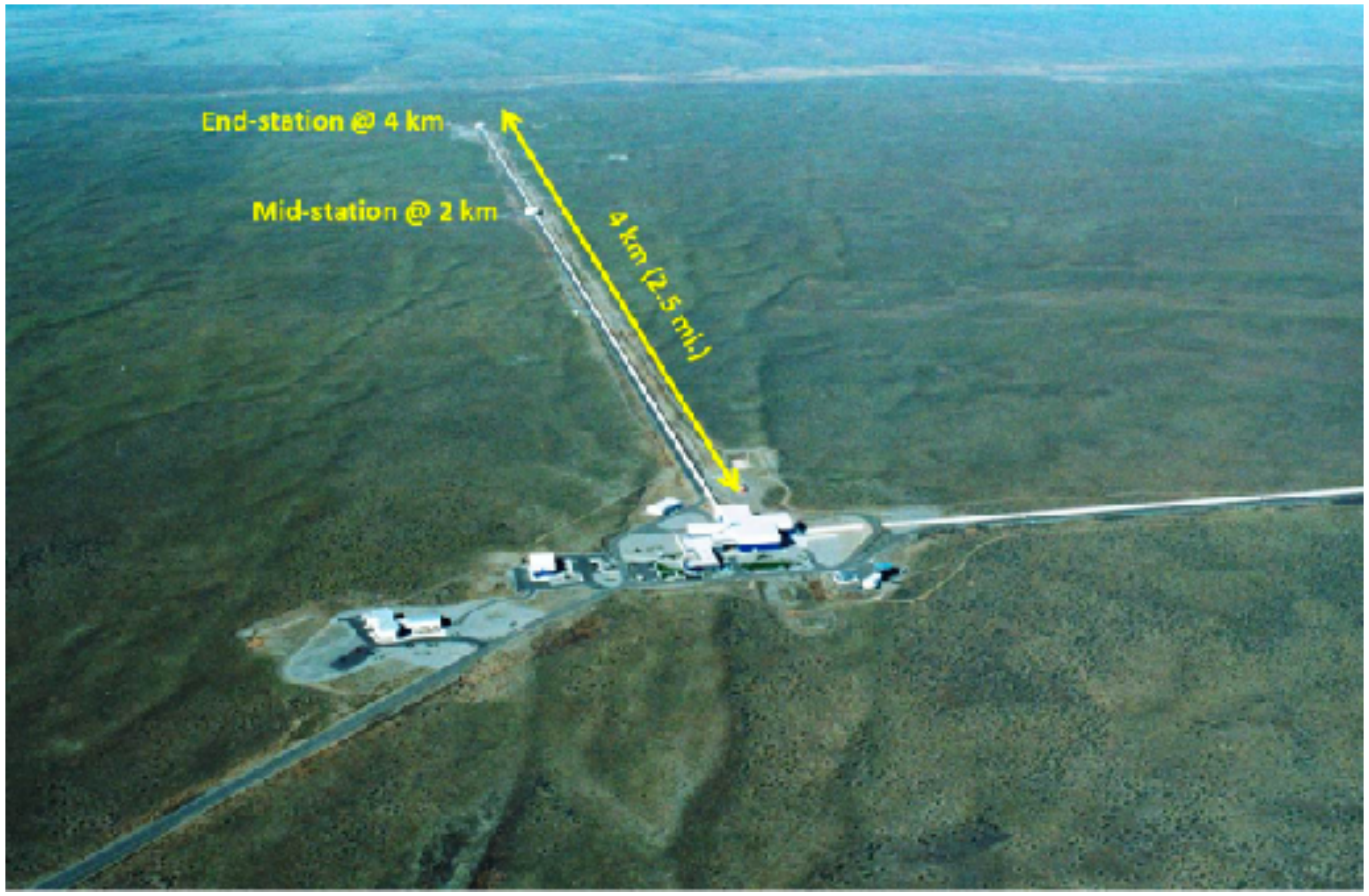






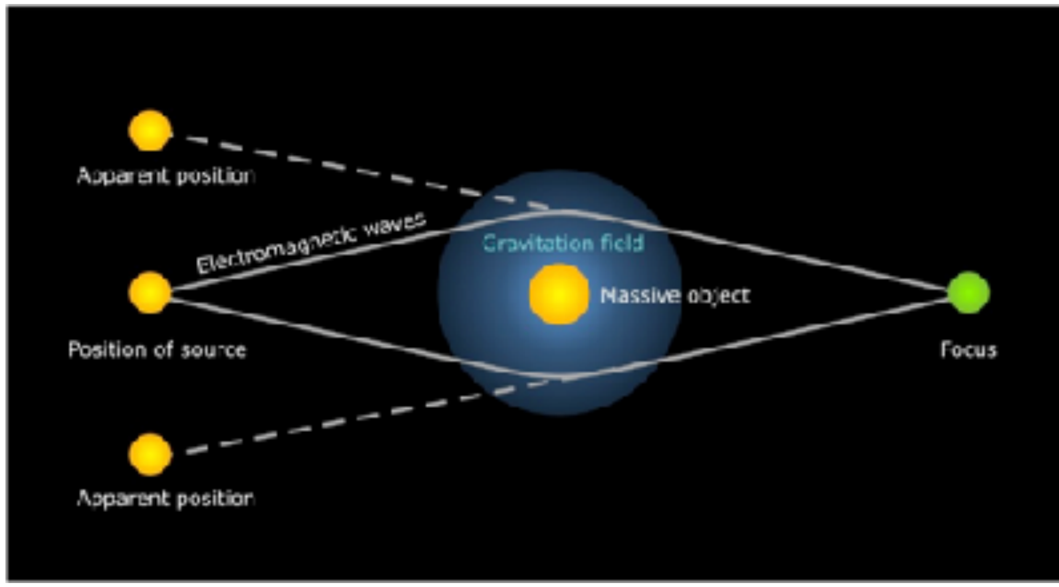
Gravitational Wave





- Orbiting binary black holes or neutron stars can bremsstrahlung GW while merging.
- Finally discovered at LIGO last year. (maybe 2017 Nobel?)

GW and particle physics

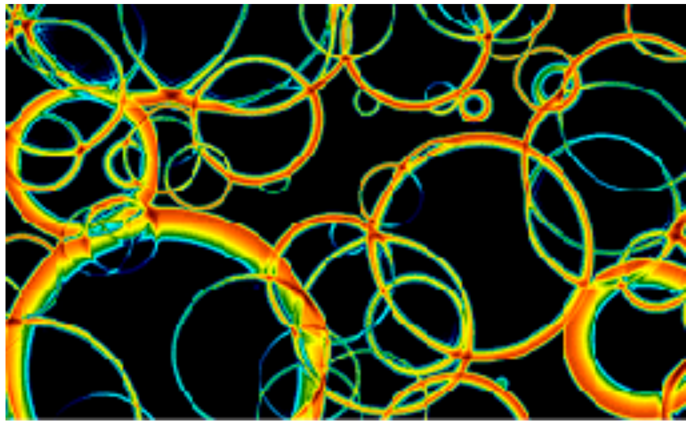


- As it travels farther than photons without being much perturbed,

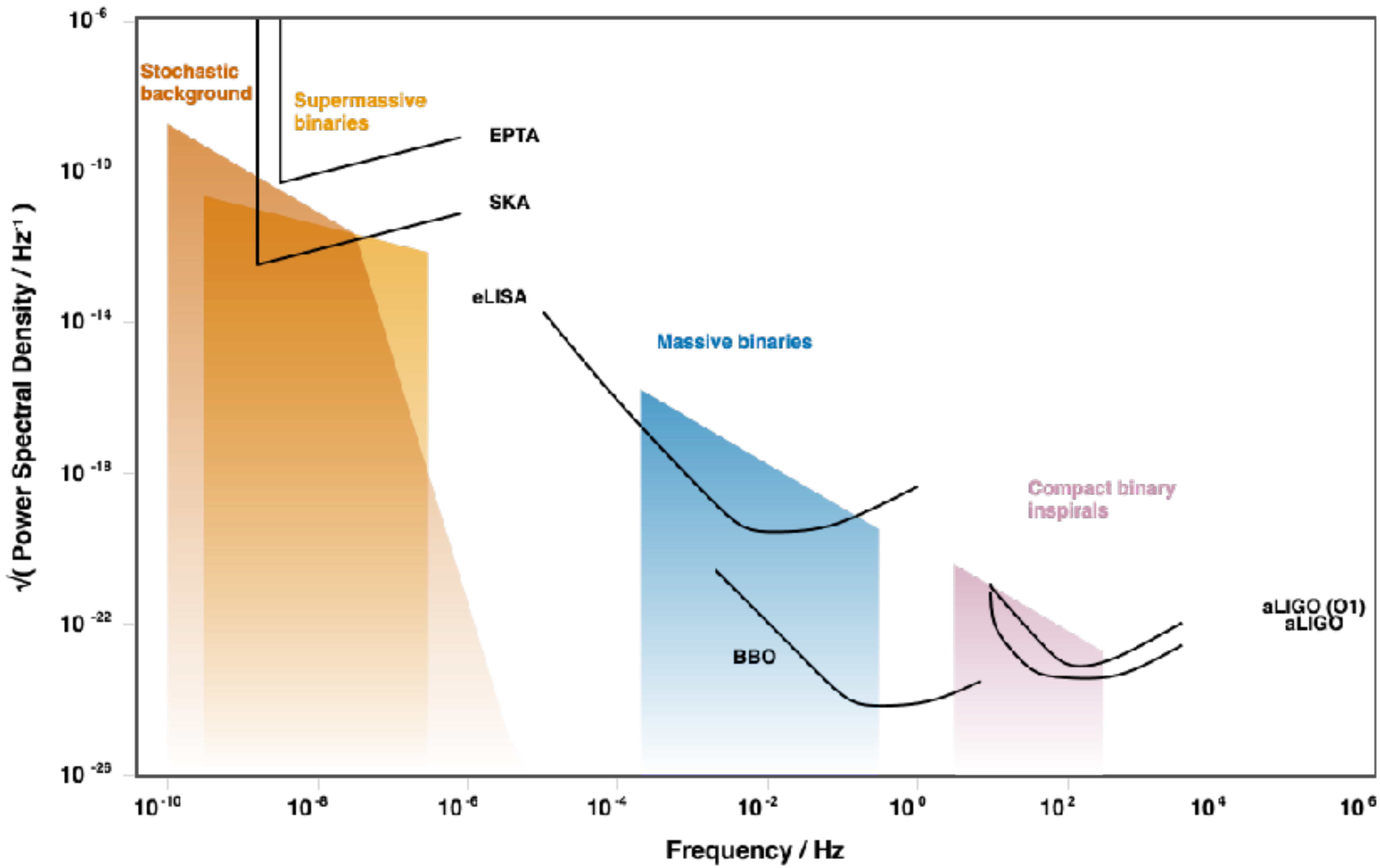
  (1) farther and earlier universe with **Dark Energy (standard siren;** GW amplitude tells us its distance**)**,

  (2) **DM** present everywhere in which GW propagates, or super-light DM whose wave properties can mimic GW.

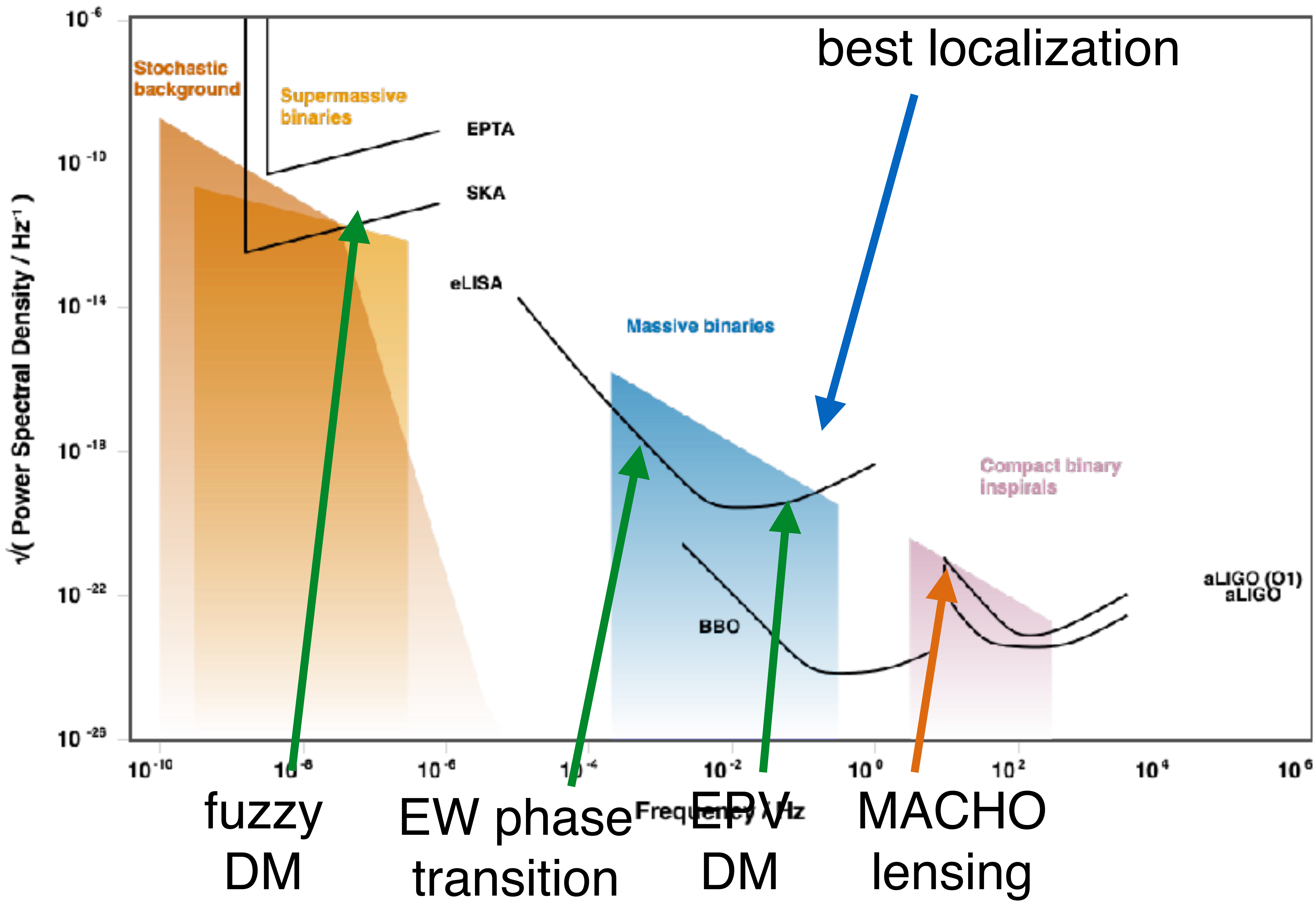
- **1st order electroweak phase transition** for the Higgs mechanism can produce GW.



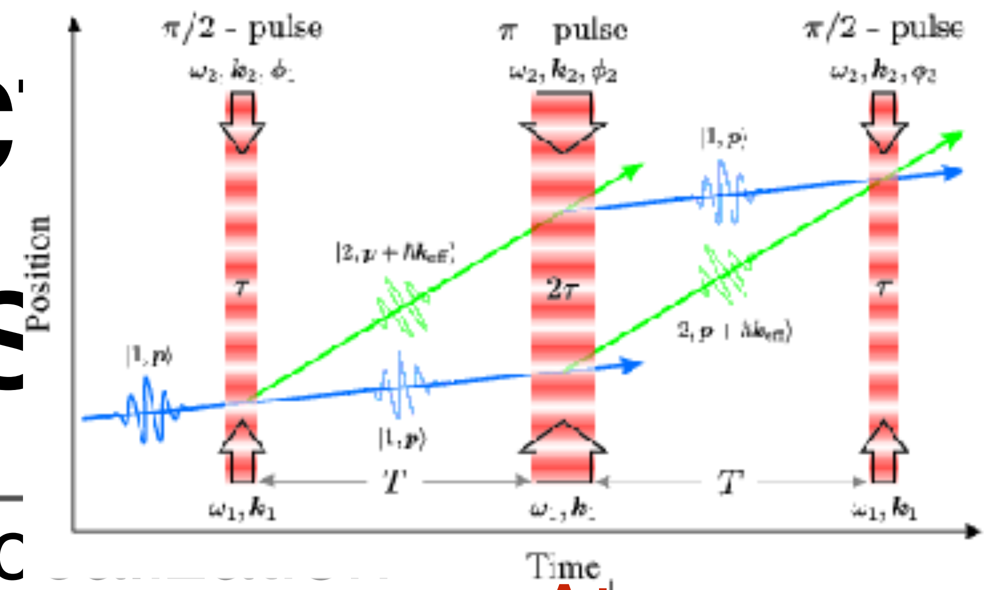
Future GW detectors and particle physics

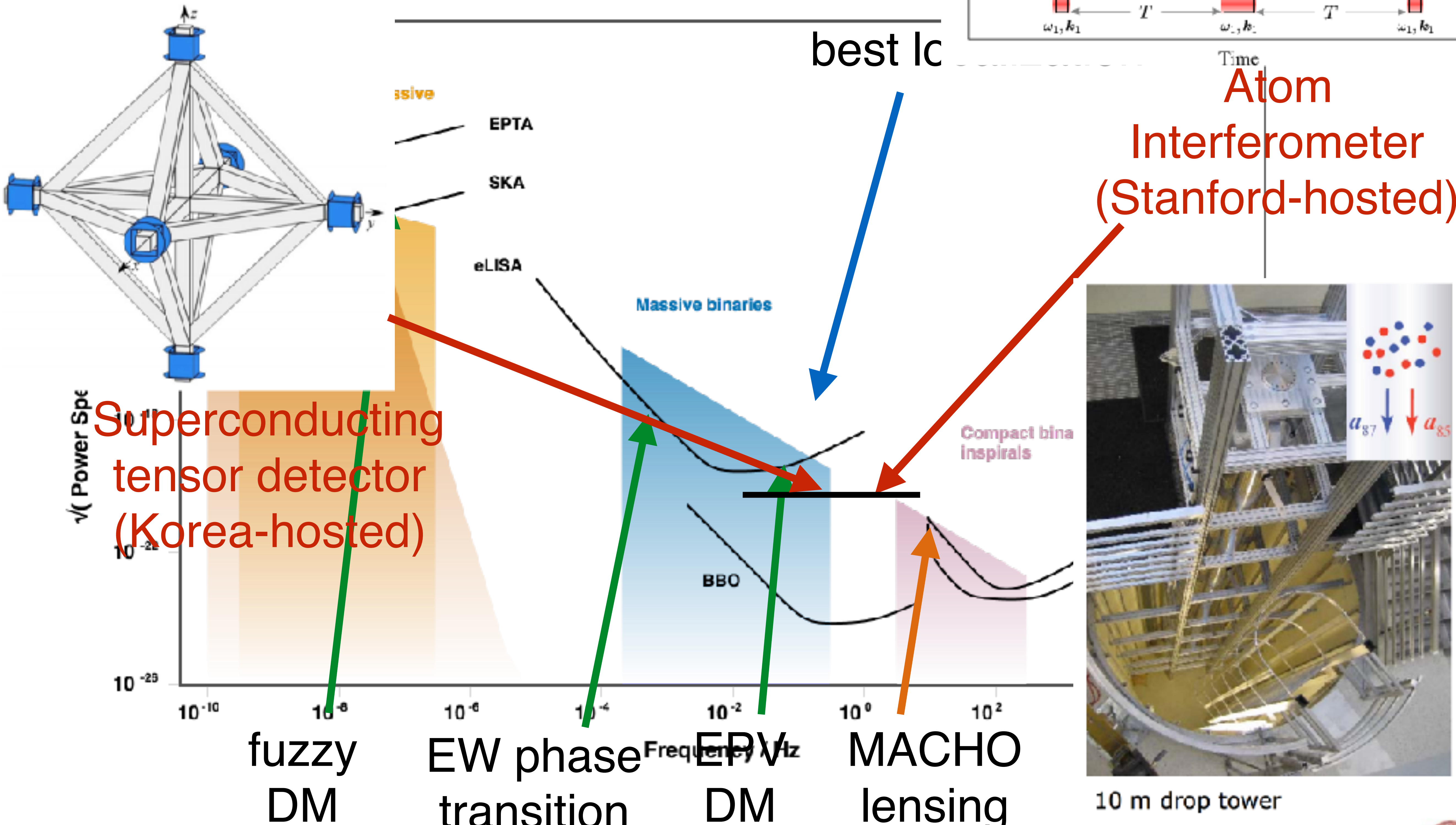


Future GW detectors and particle physics



Future GW detec particle phys





Various probes and ideas will lead us to early universe

- We are probing the new energy scale that the ET+naturalness of the Higgs boson (and DM) predict. Nothing so far yet. Becoming mysterious.

- Various probes are ongoing (often seemingly unrelated). They will somehow but surely merge onto unveil the next layer of the Universe soon!
  (Tomorrow can be another discovery day!)

Subjective measure

- The problem is that

  ET+naturalness can give **somewhat** quantitative prediction.

- “How natural should it be?” is a subjective question.

ET + naturalness

- ET is at the core of our science and reductionism.
- Nature does seem to respect ET.
- Nature does seem to have an inherent notion of naturalness.
- Thus, ET can give powerful qualitative predictions, and also has somewhat quantitative power too.

Naturalness implies a new physics beyond the SM

- SM is only an ET of a more fundamental theory of the universe.
- Why is Higgs boson mass (and the SM energy scale) so muuuuuch 10^17 smaller than the Planck scale?
- To explain this, Naturalness predicts that the Planck scale is NOT the next cutoff scale of the SM ET.

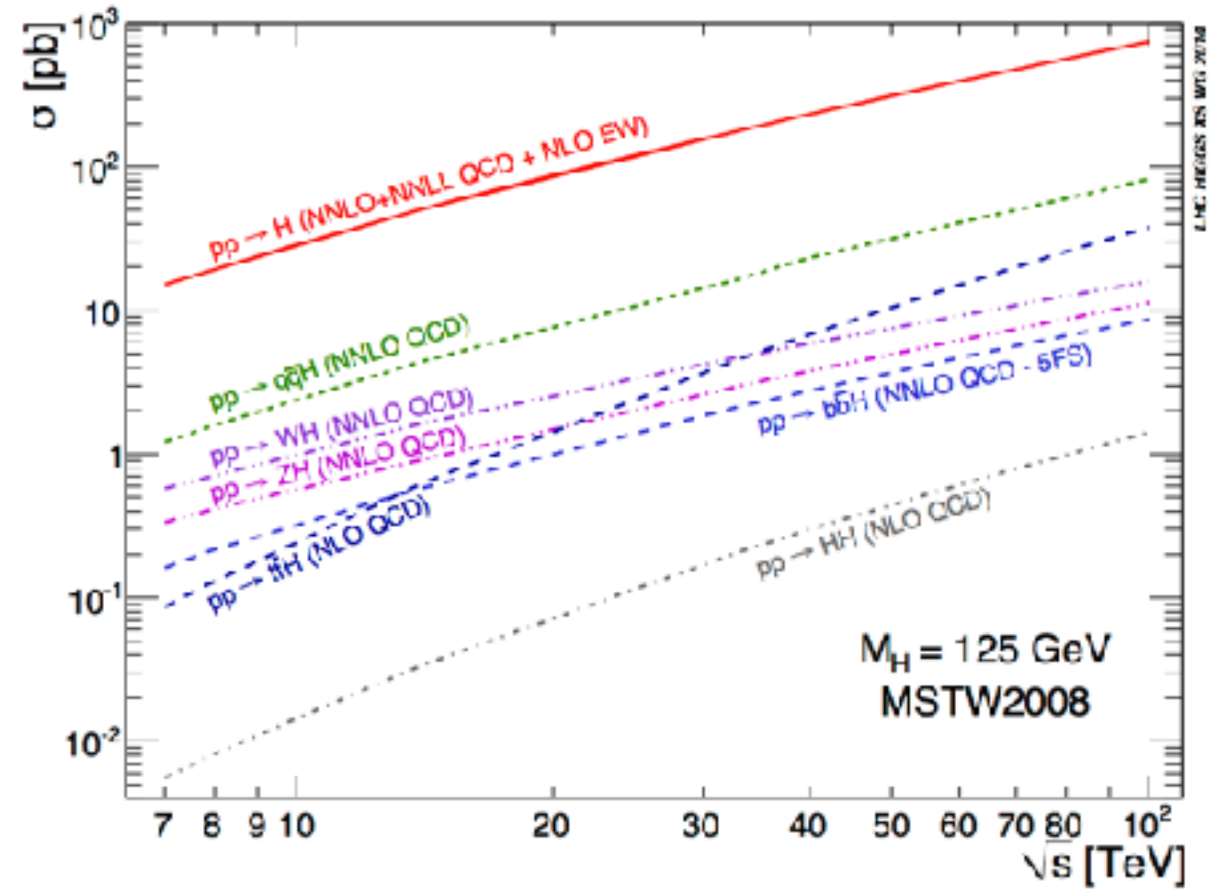
  There must be a new physics in between! Not far above!!

Bigger with higher energy

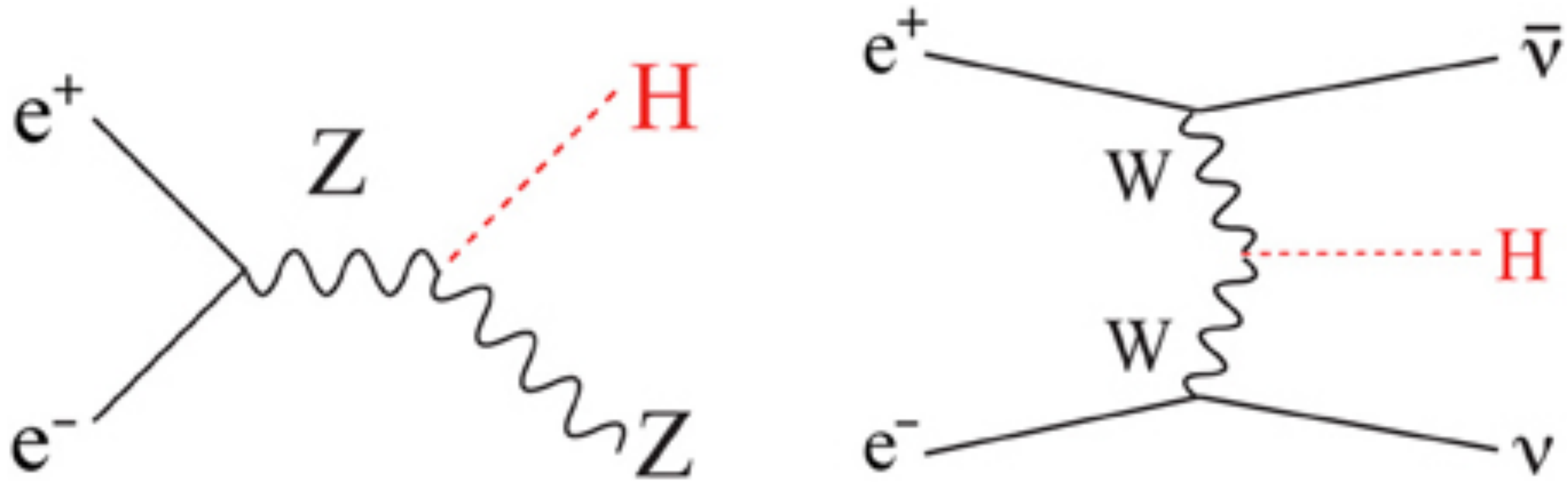
- Future 1: A bigger collider with a higher collision energy (probing new physics energy scales directly)

- Looking for new particles by directly producing them.

- More (single) Higgs data, rare Higgs phenomena.



Higher precision



- Future 2: A more precise electron-positron collider (probing new physics effects indirectly)

- Much more clean Higgs data

- Looking for deviations from SM predictions