OUTLOOK AND PERSPECTIVES

Warning/disclaimer : this is NOT a summary talk.

E. Dudas – CNRS and E. Polytechnique

35th Rencontres de Blois
oct. 25, 2024

Outline

- Energy (colliders) and Intensity (axions, dark sectors) Frontiers

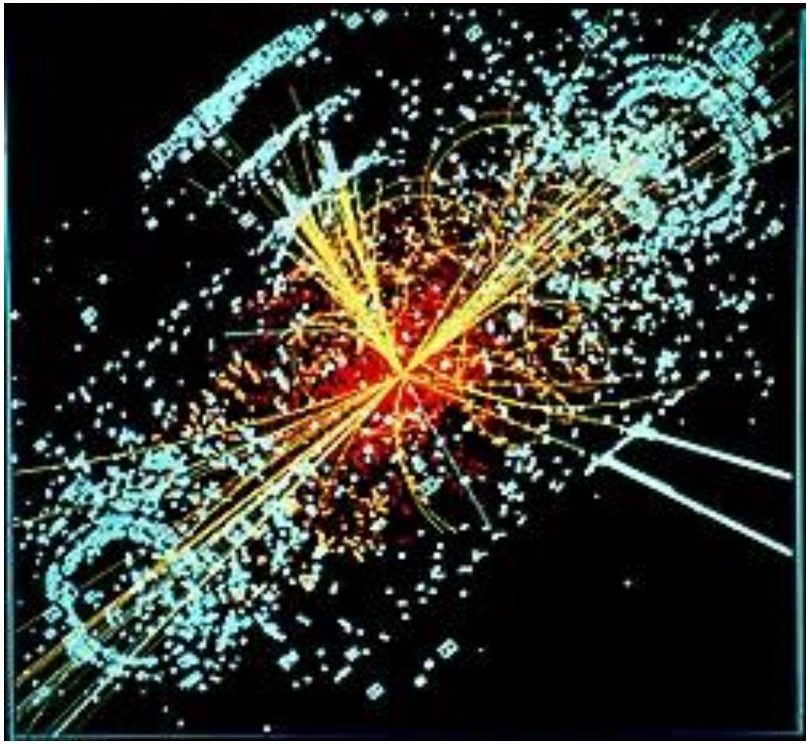
- amplitudes

- Astroparticles, Cosmology, Neutrinos: window into UV physics ?
- Quantum Gravity: UV predictions for low-energy ?

ENERGY and INTENSITY FRONTIERS

SM is an amazingly successful theory. LHC and other collider tests of SM and new physics searches are impressive

EW+new physics: Armadillo, Arnold, Azzuri,Bruschini, Cherepanova, Farmer, Gravili, Hermann, Hindrichs, Hirschbuehl, Hooberman, Hodkinson, Javaid, Jimenez, Perez, Ramirez-Berend, Tancredi, Villalba, Xie,Wang, Zabinski



QCD: Biello, Bonino, Fontana, Karwowska, Menke,Rescia

LHC Upgrades: Brandt, Oppedisano, Radogna

- B-factories: Belle II (Leo,Martellini,Rout)
- BESSIII (Ke,Rosini), NA61 (Zimmermann), NA62 (Brizioli,Peruzzo)

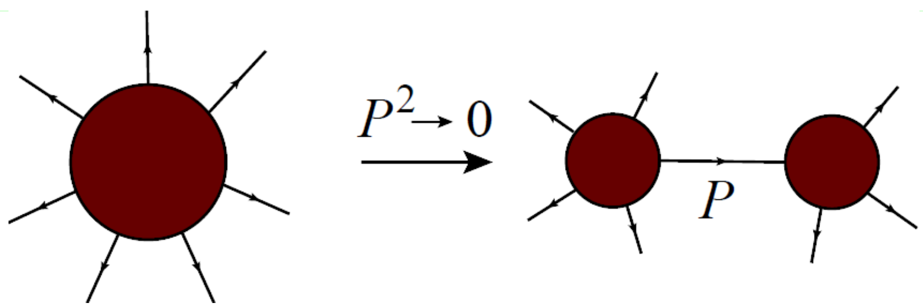
→ Triumph of perturbative QFT and SM, significant progress in Nonperturbative methods

Multi-loop and multi-particle processes with Feynman diagrams techniques get exponentially complicated.
One of the important recent developments is use of modern amplitude methods to deal with multi-loops and multiparticle processes (Tancredi)

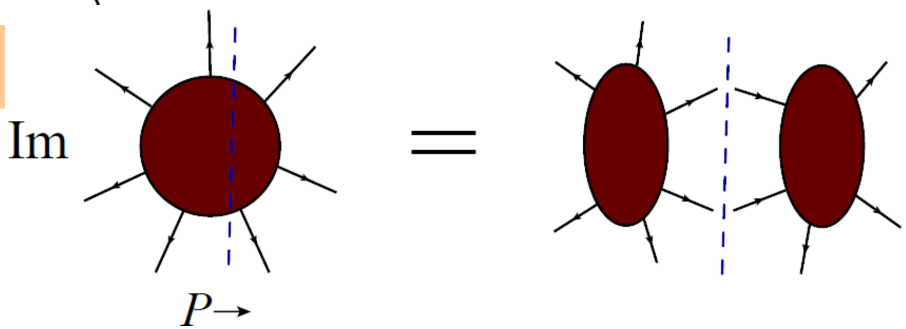
- on-shell methods : analyticity, recursion relations, spin-helicity formalism

- unitarity (ex. Optical theorem)

• Poles



• Branch cuts

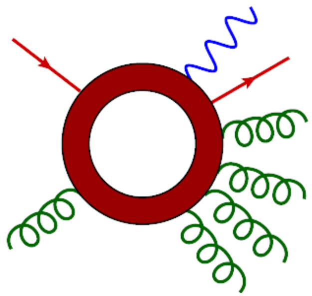


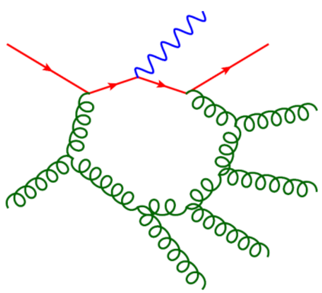
NLO needs 1 loop

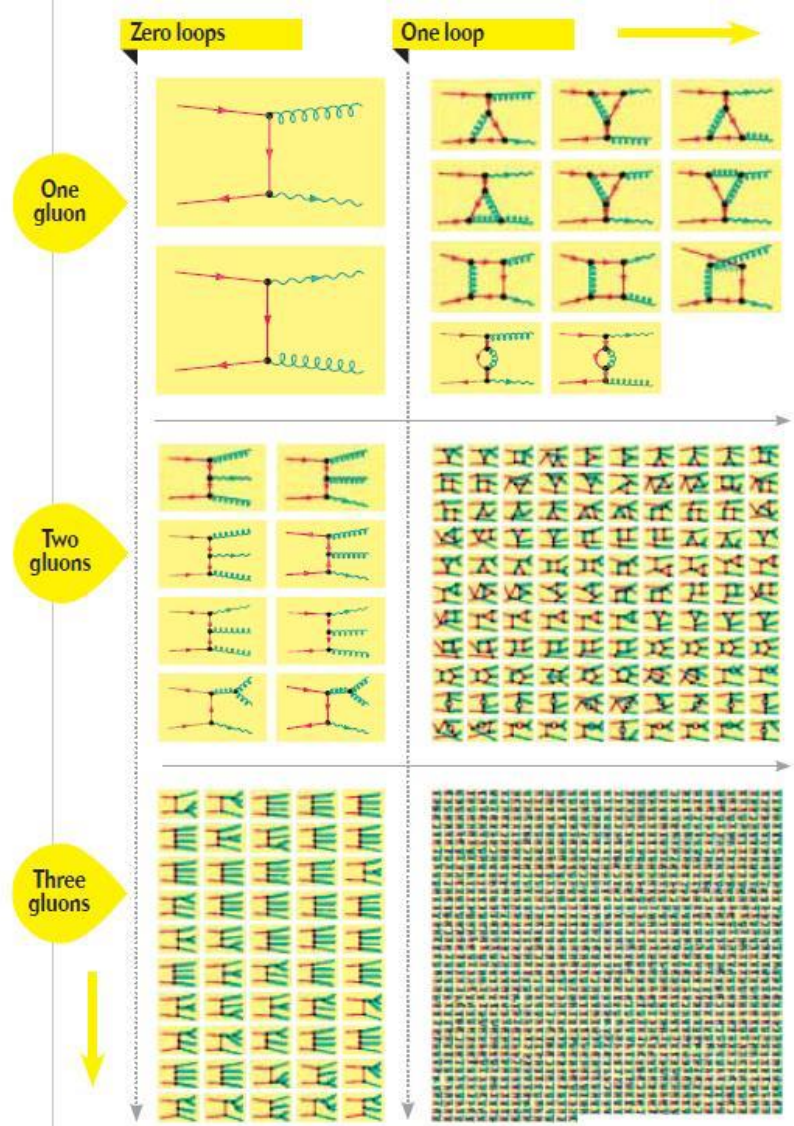
first quantum corrections

Challenging in QCD if many legs – depends on many variables

$q\bar{q} \to W + n$ gluons



=  + 256,264 more



(Lance Dixon, “Higgs Hunting 2024”)

However, main reason to build LHC is finding new physics.
Not many BSM theory talks…. Davighi, Pesut

Intense (and desperate) search for anomalies/deviations from SM :

- W boson mass CDF (Azzuri) , Muon g-2 (Lellouch), Rare decays (Brizioli,Schune)

→ virtual effects heavy particles

- Hope for discovery new physics: SUSY (S. Bein), extra Higgses, DM , extra-dims, quantum gravity, etc

- SMEFT: a very useful tool in parametrizing virtual effects of heavy new physics.

Amplitude techniques useful in SMEFT (on-shell approach, associate independent operators with independent on-shell amplitudes, which are independent polynomials in momentum invariants).

- FCNC processes particularly sensitive to heavy new physics:

(Brizioli, Peruzzo , Schune, Venditti)

$K^0 - \overline{K^0}$ $\mu \to e\gamma$ Higgs couplings (Davighi)

rare decays, ex. $B \to K\ \bar{l}\ l$

- Sensitive to $\geq 10^3\ TeV$ new particles masses with flavor-dependent couplings

- CKM matrix, CP violation: Okubo, Suljik

More sources of CP violation needed for matter-antimatter asymmetry.

- Quantum sensors for particle detection (Ellis,Latina), quantum entanglement Colliders (Aguilar-Saavedra)

- The high-energy frontier is still the main priority for the high-energy community: understanding the electroweak scale, DM, neutrino sector, etc

- But what if no new fundamental particles are discovered at LHC ?

Obs: LHC did not discover only the Higgs: exotic hadrons, tetraquarks,pentaquarks,etc (M.Karliner)

- Future colliders (Pellecchia) are needed for :

- Precision tests of the Higgs couplings (FCC-ee, muon collider)
- Discovering new particles in the multi-TEV mass range (FCC-hh,muon collider)

- But the timescales for FCC-ee, FCC-hh are scary, funding also...

Important to look for alternatives to going at higher and higher energies

DM, DARK SECTORS

On the other hand, there is the intensity frontier:
dark sectors (axions/ALP's, dark photons, light DM…).

- Colliders can be used to search for them (MET, invisible Higgs decays, displayed jets, displayed leptons, fractionally charged particles)

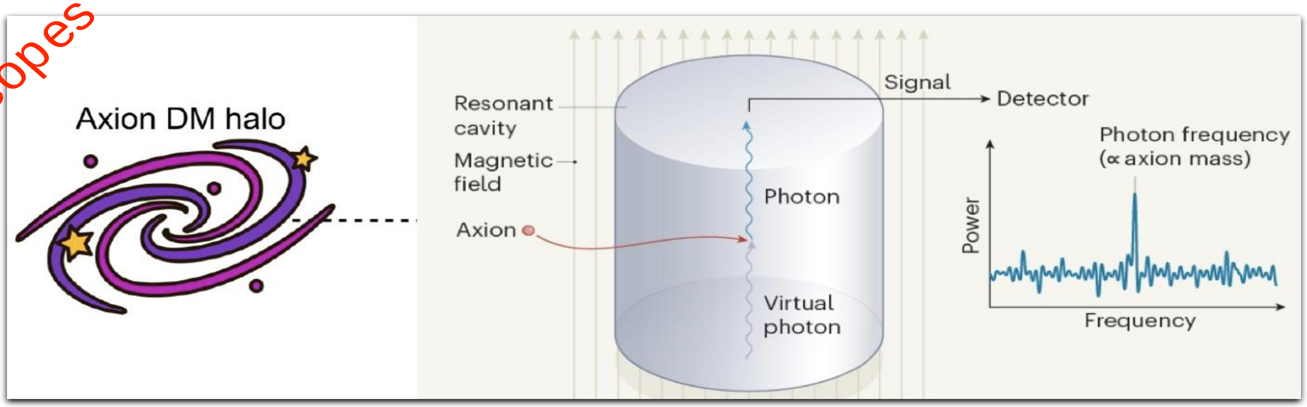
- but also cheaper experiments

PQ axion is well-motivated (strong CP problem); others we don't know "who ordered them" , although they are generic in UV constructions

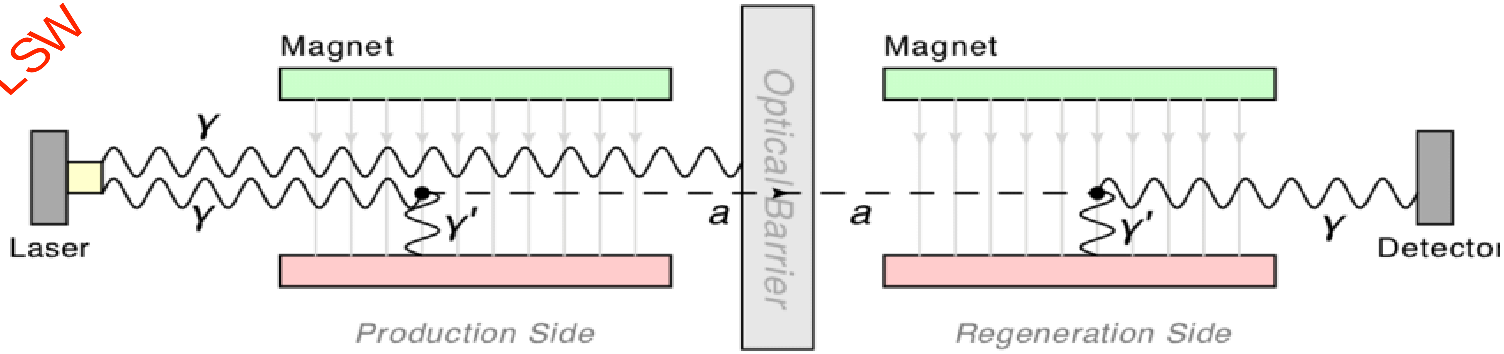
- Light DM searches are to a large extent similar:

Baker, Benato, Chau, Franchini, Grigat, Kemp, Ovchynnikov , Ruderman, Pierre, Santone, Troncino

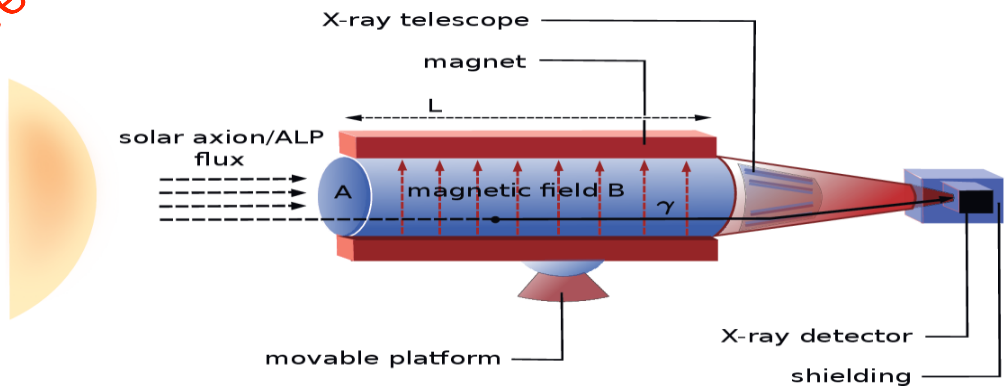
Haloscopes



LSW



Helioscopes



(A. Kemp)

Rare decays into light dark particles are highly sensitive to large mass scales : ex. $K \to \pi\, a$

Observable	Mass range [MeV]	ALP decay mode	Constrained coupling c_{ij}	Limit (95% CL) on $c_{ij} \cdot \left(\frac{\text{TeV}}{f}\right) \cdot \sqrt{\mathcal{B}}$	Limit (95% CL) on $c_{ij}/\lvert V_{ti}^* V_{tj}\rvert \cdot \left(\frac{\text{TeV}}{f}\right) \cdot \sqrt{\mathcal{B}}$	Figure
$\text{Br}(K^- \to \pi^- a(\text{inv}))$	$0 < m_a < 261\,^{(*)}$	long-lived	$\lvert k_D + k_d\rvert_{12}$	1.2×10^{-9}	3.9×10^{-6}	7a)
$\text{Br}(K_L \to \pi^0 a(\text{inv}))$	$0 < m_a < 261$	long-lived	$\lvert\text{Im}[[k_D + k_d]_{12}\rvert$	8.1×10^{-9}	7.0×10^{-5}	7b)
$\text{Br}(K^- \to \pi^- \gamma\gamma)$	$m_a < 108$	$\gamma\gamma$	$\lvert k_D + k_d\rvert_{12}$	2.1×10^{-8}	6.9×10^{-5}	7c)
$\text{Br}(K^- \to \pi^- \gamma\gamma)$	$220 < m_a < 354$	$\gamma\gamma$	$\lvert k_D + k_d\rvert_{12}$	2.0×10^{-7}	6.5×10^{-4}	7d)
$\text{Br}(K_L \to \pi^0 \gamma\gamma)$	$m_a < 110$	$\gamma\gamma$	$\lvert\text{Im}[[k_D + k_d]_{12}]\rvert$	1.3×10^{-8}	1.1×10^{-4}	7e)
$\text{Br}(K_L \to \pi^0 \gamma\gamma)$	$m_a < 363^{(✠✠)}$	$\gamma\gamma$	$\lvert\text{Im}[[k_D + k_d]_{12}]\rvert$	1.3×10^{-7}	1.1×10^{-3}	7f)
$\text{Br}(K^+ \to \pi^+ a(e^+e^-))$	$1 < m_a < 100$	e^+e^-	$\lvert k_D + k_d\rvert_{12}$	3.4×10^{-7}	1.1×10^{-3}	7g)
$\text{Br}(K_L \to \pi^0 e^+e^-)$	$140 < m_a < 362$	e^+e^-	$\lvert\text{Im}[[k_D + k_d]_{12}]\rvert$	3.1×10^{-9}	2.6×10^{-5}	7h)
$\text{Br}(K_L \to \pi^0 \mu^+\mu^-)$	$210 < m_a < 350$	$\mu^+\mu^-$	$\lvert\text{Im}[[k_D + k_d]_{12}]\rvert$	4.0×10^{-9}	3.4×10^{-5}	7i)
$\text{Br}(B^+ \to \pi^+ e^+e^-)$	$140 < m_a < 5140$	e^+e^-	$\lvert k_D + k_d\rvert_{13}$	7.0×10^{-7}	8.7×10^{-5}	8a)
$\text{Br}(B^+ \to \pi^+ \mu^+\mu^-)$	$211 < m_a < 5140\,^{(‡‡)}$	$\mu^+\mu^-$	$\lvert k_D + k_d\rvert_{13}$	1.2×10^{-7}	1.4×10^{-5}	8b)
$\text{Br}(B^- \to K^- \nu\bar{\nu})$	$0 < m_a < 4785$	long-lived	$\lvert k_D + k_d\rvert_{23}$	6.2×10^{-6}	1.6×10^{-4}	9a)
$\text{Br}(B \to K^* \nu\bar{\nu})$	$0 < m_a < 4387$	long-lived	$\lvert k_D - k_d\rvert_{23}$	4.1×10^{-6}	1.1×10^{-4}	9b)
$d\text{Br}/dq^2(B^0 \to K^{*0} e^+e^-)_{[0.0,0.05]}$	$1 < m_a < 224$	e^+e^-	$\lvert k_D - k_d\rvert_{23}$	6.4×10^{-7}	1.6×10^{-5}	9c)
$d\text{Br}/dq^2(B^0 \to K^{*0} e^+e^-)_{[0.05,0.15]}$	$224 < m_a < 387$	e^+e^-	$\lvert k_D - k_d\rvert_{23}$	9.3×10^{-7}	2.4×10^{-5}	9d)
$\text{Br}(B^- \to K^- a(\mu^+\mu^-))$	$250 < m_a < 4700\,^{(\dagger)}$	$\mu^+\mu^-$	$\lvert k_D + k_d\rvert_{23}$	4.4×10^{-8}	1.1×10^{-6}	9e)
$\text{Br}(B^0 \to K^{*0} a(\mu^+\mu^-))$	$214 < m_a < 4350\,^{(\dagger)}$	$\mu^+\mu^-$	$\lvert k_D - k_d\rvert_{23}$	5.1×10^{-8}	1.3×10^{-6}	9f)
$\text{Br}(B^- \to K^- \tau^+\tau^-)$	$3552 < m_a < 4785$	$\tau^+\tau^-$	$\lvert k_D + k_d\rvert_{23}$	8.2×10^{-5}	2.1×10^{-3}	9g)
$\text{Br}(D^0 \to \pi^0 e^+e^-)$	$1 < m_a < 1730^{(\ddagger)}$	e^+e^-	$\lvert k_U + k_u\rvert_{12}$	2.8×10^{-5}	–	10a)
$\text{Br}(D^+ \to \pi^+ e^+e^-)$	$200 < m_a < 1730^{(\dagger\dagger)}$	e^+e^-	$\lvert k_U + k_u\rvert_{12}$	8.4×10^{-6}	–	10b)
$\text{Br}(D_s^+ \to K^+ e^+e^-)$	$200 < m_a < 1475^{(✠)}$	e^+e^-	$\lvert k_U + k_u\rvert_{12}$	2.4×10^{-5}	–	10c)
$\text{Br}(D^+ \to \pi^+ \mu^+\mu^-)$	$250 < m_a < 1730^{(**)}$	$\mu^+\mu^-$	$\lvert k_U + k_u\rvert_{12}$	2.1×10^{-6}	–	10d)
$\text{Br}(D_s^+ \to K^+ \mu^+\mu^-)$	$200 < m_a < 1475^{(***)}$	$\mu^+\mu^-$	$\lvert k_U + k_u\rvert_{12}$	5.7×10^{-5}	–	10e)

(Bauer et al, 2021)

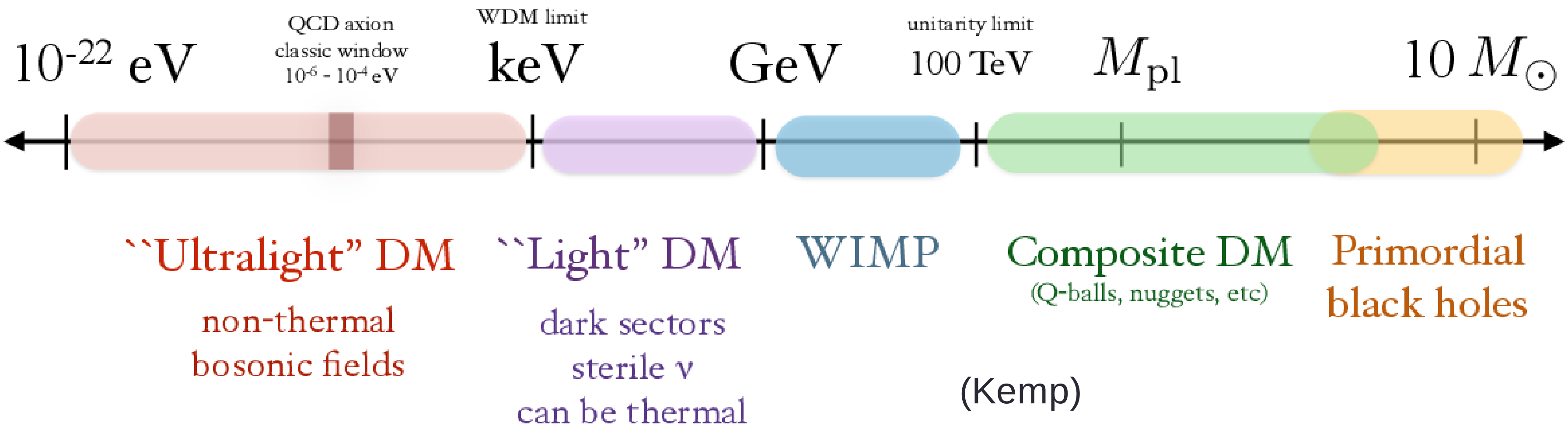
- Plenty of DM candidates :

- WIMP SUSY DM not yet dead : pure higgsino, pure wino still OK (Ruderman):

- over 80 orders of magnitude : $10^{-22}\ eV\ -\ 10\ M_{\odot}$ (A. Kemp, J. Jochum)

- Primordial BH of mass $M > 10^{11}\ kg$ live longer than the Universe's age

⟹ they can constitute part or all of DM (Ballesteros)



(Kemp)

COSMOLOGY

- lots of new experiments

- Primordial BH (Martinez) , DESI-BAO (Yeche), PTA (Babak), Large Scale Structure Cosmo (Casas,Senatore)
LiteBIRD and Simons Obs. (Beringue): LSST (Moniez)

New methods to compute vacuum decay (Espinosa)

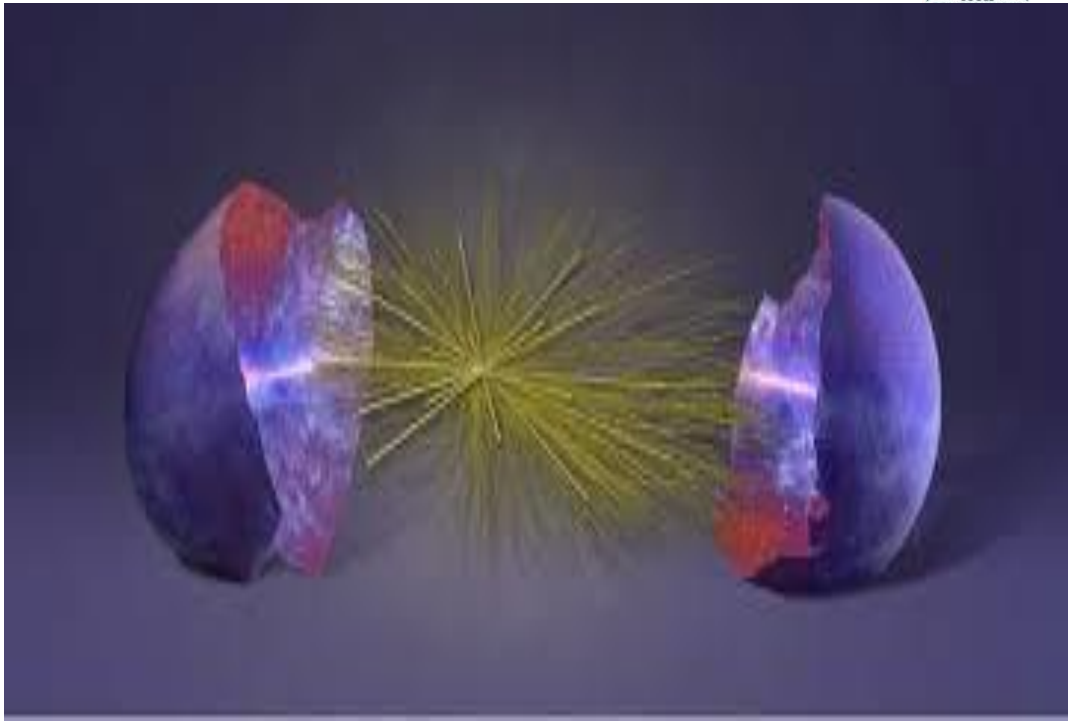
- Impressive use of EFT for inflation and for large scale structure (Senatore)
- Various QFT calculations applied to cosmology require renormalization and counterterms: experimental verification/interpretation ?

More and more Important applications of QFT techniques :

- Cosmological collider:
Non-gaussianities produced by heavy particles

3-point corr. $\sim e^{-\frac{m}{H}}$

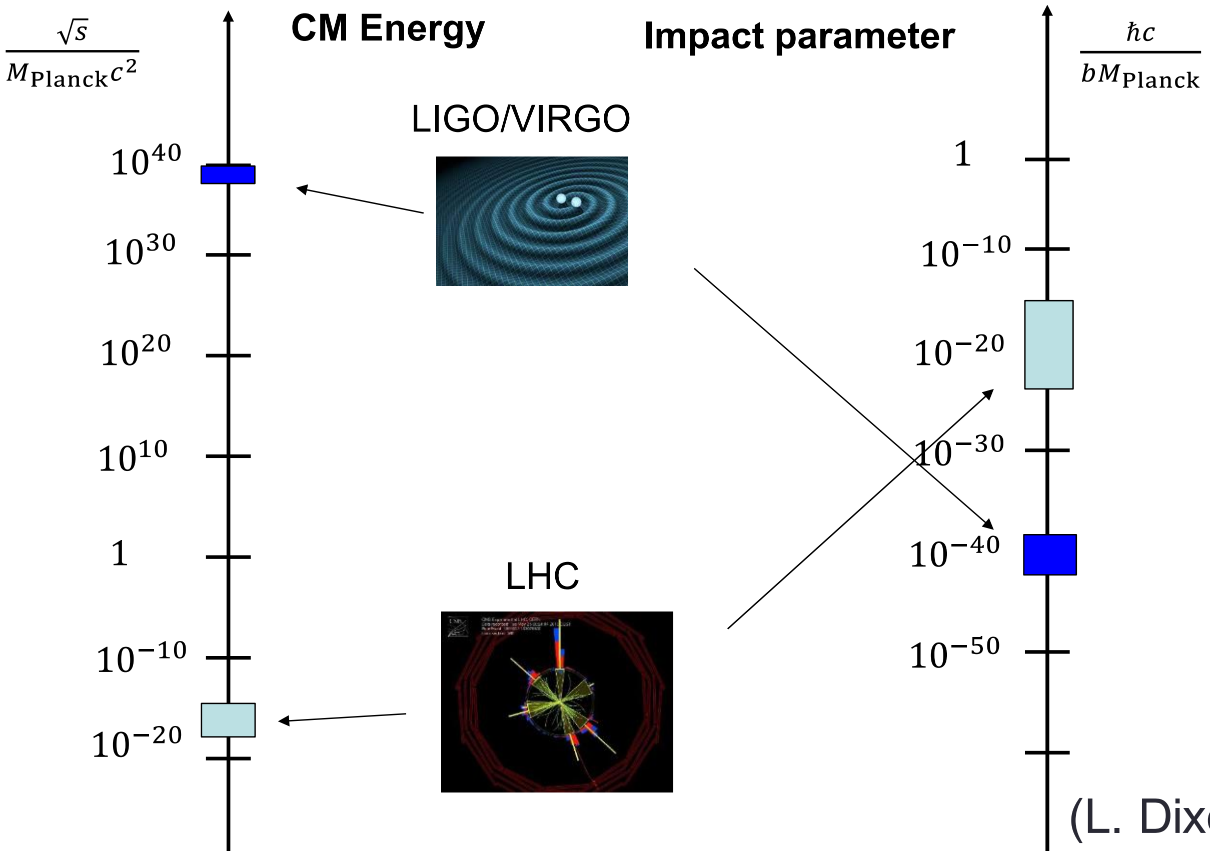
$$H \leq 5 \times 10^{-13}\ GeV$$



- Potentially observable signatures for particle of masses $m \sim H$ and their spin

- Window into UV physics: GUT, right-handed neutrinos, extra-dims, heavy SUSY partners, etc.

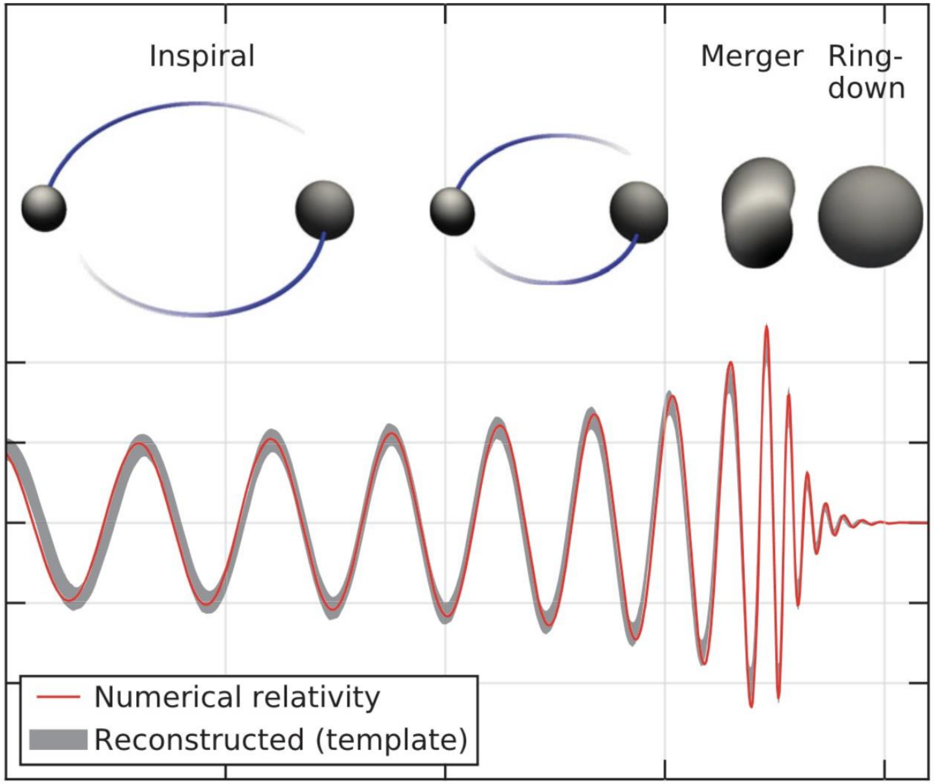
- On-shell amplitude techniques for BH/neutron stars classical scattering
- Higher perturbative orders in $G_N m_1 m_2$ for the GW emission of BH inspirals (bound orbits) for LIGO



(L. Dixon, “Higgs Hunting” 2024)

ASTROPHYSICS/PARTICLES

- GW (Christensen): remarkable confirmation of GR (Nobel prize 2017)



- Impressive data and computations of GW from BH mergers.

- Already severe constrains from NS mergers on modified gravity models

- IPTA and LISA lower the frequency range detection.

The high-energy community is mostly interested in primordial origin of GW and BSM signatures.

- IPTA has signature compatible with stochastic GW. Are they of primordial origin ? Frequency range sensitive to inflation, 1st order phase transitions, cosmic strings, GUT physics…

High-energy cosmic neutrinos (ANITA, ICECUBE: Biteau,Maltoni), cosmic rays (LHAASO, Semikoz) :

⟹ a window into high-energy physics : heavy RH neutrinos, decaying DM (gravitinos,etc)

- BSM constraints: (Gora)

- Pulsar/neutron stars probing DM (Barausse)

NEUTRINOS

Caden,Calgaro, Campani, Habib,Lecocq,Macmahon, Maltoni,Mcelwee, Santos, Oldengott, Tretin,Vockerodt,Volpe,Xia,Xu

- Neutrino masses and oscillations: arguably the first “evidence” for new physics, new mass scale

- Explaining neutrino masses and mixings a major theoretical challenge

- Many questions: Dirac vs Majorana, CP violation, light sterile neutrinos (DM, small mixing with active neutrinos)

If large (seesaw) scale Important for matter-antimatter asymmetry (leptogenesis), SM vacuum (in)stability…

- Many new experiments…

Quantum gravity implications for low-energy ?

Are all consistent Quantum Field Theories obtainable from String Theory ?

Probably NO

Swampland = the set of consistent QFT not obtainable from String Theory

There are various swampland conjectures: (Vafa+Ooguri, review E.Palti)

- **No exact global symmetries**, completeness conjecture

- de Sitter: impossibility of constructing a vacuum with positive cosmological constant →

- quintessence-like dark energy models are the only viable possibility ?

- Weak Gravity Conjecture (WGC) ↔
  Gravity is the weakest force (Arkani-Hamed,Motl,Nicolis,Vafa,2006)

- The distance conjecture: : not possible to have super-Planckian field excursions

WGC: For a theory with a massless photon coupled to gravity, it implies that there should exist one charged particle with

$$|q| M_P \geq m$$

Some implications:

- Axion decay constants are bounded $f S_i < M_P$,

Where S_i is the instanton action coupled to the axion. This excludes Super-Planckian decay constants.

There are potential intriguing connections between WGC and

- The hierarchy problem (Cheung-Remmen) : quadratically div. contributions to a charged scalar could violate WGC

$$|q| M_P \geq m$$

log divergent

quadratically div. (Higgs scalar)

$$\delta q \sim \log(\Lambda / m)$$

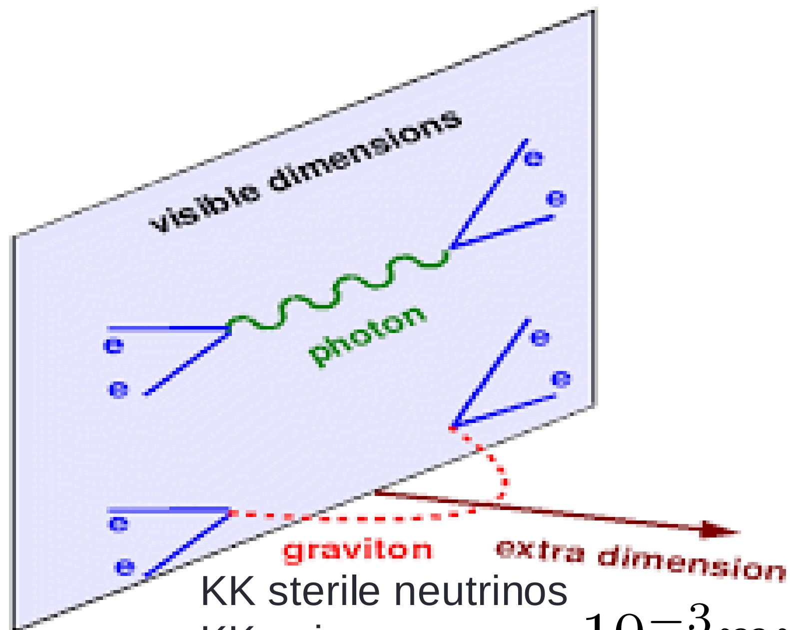
$$\delta m_h^2 \sim \Lambda^2$$

⇒ the UV cutoff Λ cannot be too high ?

- Cosmic censorship (Horowitz et al.) : bad singularities in geometries violating CC are forbidden by WGC

One outcome of the Swampand program: the dark dimension

(Montero,Vafa,Valenzuela, 2022)



KK sterile neutrinos
KK axions

$$10^{-3} mm \sim (1 eV)^{-1}$$

OUTLOOK

- Still hopes for new physics at LHC. New colliders needed for discovering new particles and interactions

- Virtual effects in FCNC and rare decay processes a window into heavy particles or light feebly-coupled "dark" particles

- On-shell amplitude methods became increasingly important. QFT and amplitude methods became very useful in cosmology, inflation and LSS.

- One has to use astrophysics and cosmology to test high-energy models:

- High-energy neutrinos and cosmic rays: Intermediate-scale models: heavy RH neutrinos, axions
- GW waves: inflation, phase transitions, cosmic strings
- Non-gaussianities in primordial cosmological fluctuations : GUT-scale physics, high-scale SUSY, RH neutrinos…

- One could hope to get predictions from quantum gravity arguments

THANK YOU !

EXTRA SLIDES

NOvA (Fermilab -> Minnesota, 800 km; Macmahon): theta_23, delta_23.
Strong preference fort normal ordering.
ICARUS (Fermilab) : Campani
JUNO (Jiangmen, China, 52.5km, reactor detector): Lecocq

- Astrophysical probes of DM (E. Barausse):

Ultralight (bosonic) DM : oscillations detectable by PTAs, Nanograv, pulsar probes, binary pulsars (< 10^-22 eV)
Superradiance spinning BH instabilities -> BH –BE condensates constraints utralight DM masses (BD-type couplings) (< 10^-12 eV) , monochromatic GW emission
Some constraints on PBH DM

High-energy cosmic neutrinos (ANITA, ICECUBE: Biteau,Maltoni), cosmic rays (LHAASO, Semikoz) a window into high-energy physics : heavy RH neutrinos, decaying DM (gravitinos,etc)

BSM constraints: (Gora)