AXIONS FOREVER

H. P. Nilles

München, October 2008

AXIONS COULD BE USEFUL FOR

* STRONG CP-PROBLEM
* DARK MATTER
* DARK ENERGY
* INFLATION

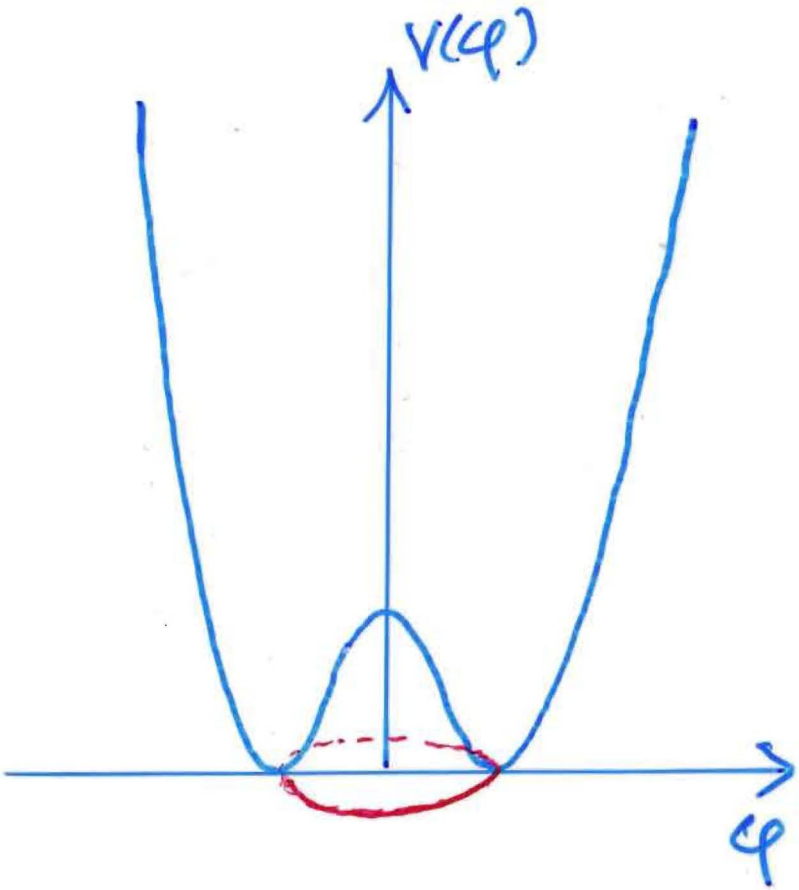
WHAT IS AN AXION ?

* PSEUDO SCALAR PARTICLE

* PROTECTED BY SYMMETRY

* (PSEUDO) - GOLDSTONE BOSON OF SPONTANEOUSLY BROKEN $U(1)_{PQ}$

GOLDSTONE BOSON



SPONTANEOUSLY BROKEN U(1)

→ DEGENERATE VACUUM

→ MASSLESS PARTICLE

ONLY "DERIVATIVE" COUPLINGS

$$\varphi = \exp(ia)\,\eta$$

AXION MASS COULD COME FROM EXPLICIT BREAKDOWN OF SYMMETRY

EXAMPLE: PIONS π^+, π^-, π^0

AS GOLDSTONE BOSONS OF

$$SU(2)_L \times SU(2)_R \longrightarrow SU(2)_V$$

$m_\pi = 0$ IF $m_{QUARK} = 0$

SYMMETRY COULD BE BROKEN BY

ANOMALIES AND/OR NONPERTUBATIVE EFFECTS

THAT PROVIDES A MASS FOR THE GOLDSTONE BOSON

→ PSEUDOGOLDSTONE BOSON OR

AXION

STRONG CP-PROBLEM

QCD IS SU(3) GAUGE THEORY

FIELD STRENGTH $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + \dots$

ACTION $S = \int d^4x \left(\frac{1}{g^2} F_{\mu\nu} F^{\mu\nu} + \theta F_{\mu\nu} \tilde{F}^{\mu\nu} + \dots \right.$

$\theta\, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$ CANNOT BE TRANSFORMED IN A TOTAL DERIVATIVE BECAUSE OF NONPERTURBATIVE EFFECTS: INSTANTONS

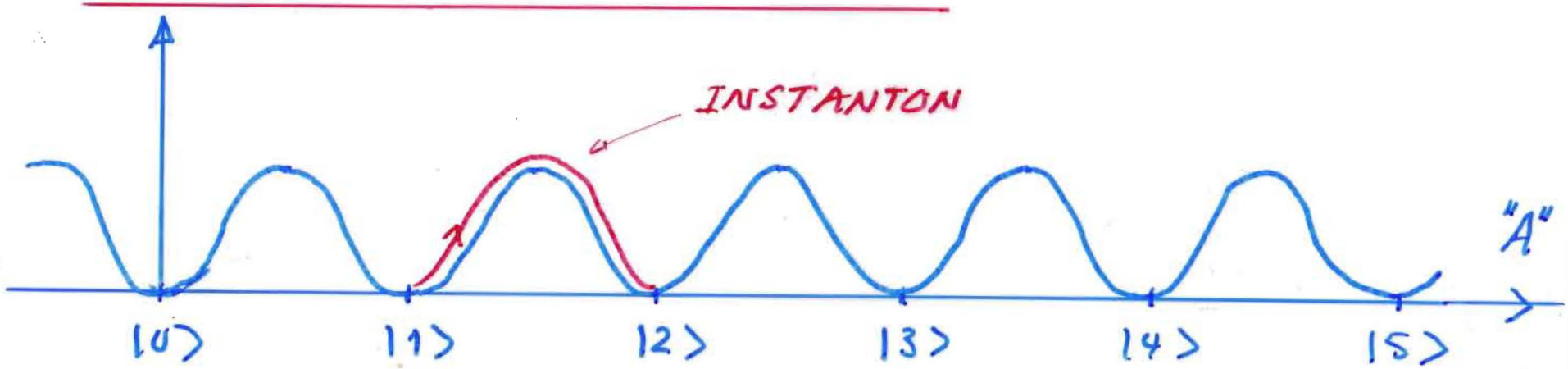
$\theta \epsilon^{\mu\nu\sigma\tau} F_{\mu\nu} F_{\sigma\tau}$ VIOLATES CP!

PROVIDES E.G. ELECTRIC DIPOLE MOMENT FOR NEUTRON .....

EXPERIMENTAL LIMITS REQUIRE

$\theta < 10^{-9}$

θ VACUUM OF QCD



PONTRYAGIN INDEX $n \in \mathbb{N}$

θ-VACUUM: $\quad |\theta\rangle = \sum_{n=-\infty}^{+\infty} \exp(in\theta)\,|n\rangle$

$\mathcal{L}_\theta = \frac{\theta}{32\pi^2}\,\epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$ AND $\underline{0 \leq \theta \leq 2\pi}$

WHY SHOULD WE HAVE $\theta < 10^{-9}$?

THE SOLUTION OF PECCEI AND QUINN

ADD COMPLEX SCALAR FIELD AND $U(1)_{PQ}$

WITH NONTRIVIAL (ANOMALOUS) COUPLING

TO $SU(3)$ OF STRONG INTERACTIONS

$\varphi = \exp(ia)\,\eta$ AND $\dfrac{a}{32\pi^2 F_a} F_{\mu\nu} F_{\delta\sigma} \epsilon^{\mu\nu\delta\sigma}$

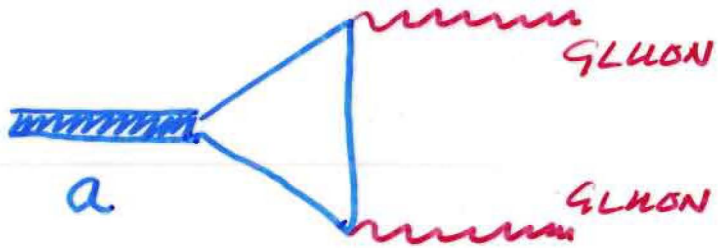
EFFECTIVE θ-ANGLE NOW $\theta' = \theta - \dfrac{a}{F_a}$

BECOMES DYNAMICAL QUANTITY

MINIMUM OF POTENTIAL AT $\theta' = 0$!

WHAT IS THE MASS OF a ?

ANOMALOUS COUPLING



GIVES MASS TO GOLDSTONE BOSON

(WEINBERG, WILCZEK)

$$m_a \sim \frac{\Lambda_{QCD}^2}{F_a}$$

$F_a \sim 100\,GeV \longrightarrow m_a \sim keV$

PQWW-AXION RULED OUT EXPERIMENTALLY

THE INVISIBLE AXION

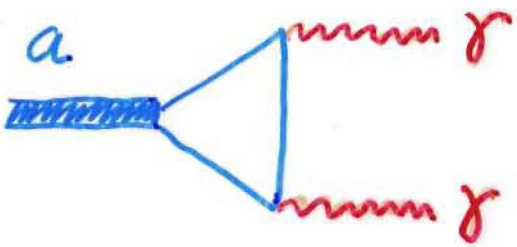
(KIM; DINE, FISCHLER, SREDNICKI ....)

INCREASE F_a ⟶ COUPLING DECREASES

AND ALSO MASS DECREASES

$$M_{axion} \sim 10^6 \left[\frac{GeV}{F_a}\right] [eV]$$

ASTROPHYSICAL CONSTRAINT ON F_a FROM



STABILITY OF "SUN"

REQUIRES $F_a \geq 10^9 GeV$

AXIONIC COLD DARK MATTER

IF WE INCREASE F_a TOO MUCH, THE AXIONS WILL BECOME SO WEAKLY COUPLED THAT A GIVEN COSMIC ABUNDANCE MIGHT NOT DECAY

$$\rho_a \sim \rho_{CRITICAL} \left[\frac{F_a}{10^{12}\,GeV} \right]$$

AXION WINDOW (FOR QCD-AXION)

$$10^9\,GeV \leq F_a \leq 10^{12}\,GeV$$

THEORETICAL EXPECTATIONS

MANY AXION CANDIDATES IN MODELS OF PARTICLE PHYSICS LIKE STRINGS, EXTRA DIM. THROUGH ANTISYMMETRIC TENSOR FIELDS

BUT f_a MIGHT BE AS LARGE AS

$$M_{STRING} \sim 10^{17} - 10^{18}\ GeV$$

OR EVEN M_{PLANCK}.

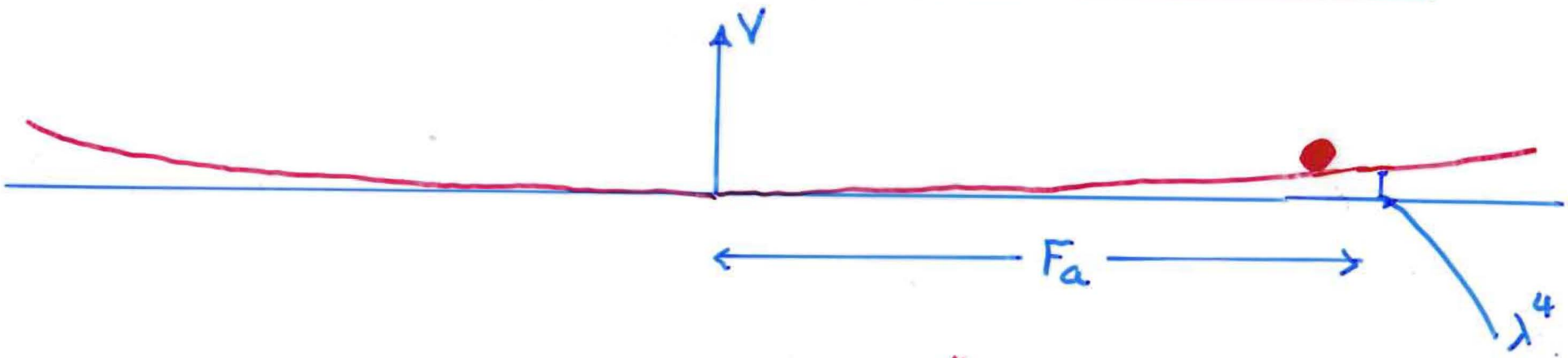
IN SUPERSYMMETRY WE HAVE PARTNERS

AXINO DARK MATTER .....

$F_a \sim M_{PLANK}$ PROBLEMATIC FOR COLD DARK MATTER

(IN CONNECTION WITH QCD AXION)

LARGE F_a → EXTREMELY FLAT POTENTIAL



POTENTIAL ENERGY $V \sim \lambda^4$

IF $\lambda \sim 10^{-3}$ eV AND $F_a \sim M_{PLANCK}$

FIELD WILL BE STUCK !

QUINTESSENTIAL AXION

(KIM, NILLES)

DARK ENERGY FROM AXION FIELD

$E_{VACUUM} \sim (10^{-3}\,eV)^4 \longrightarrow m_{axion} \sim 10^{-33}\,eV$

AXION PSEUDOSCALAR

→ NO DEVIATION FROM NEWTON'S LAW

ONLY DERIVATIVE COUPLINGS:

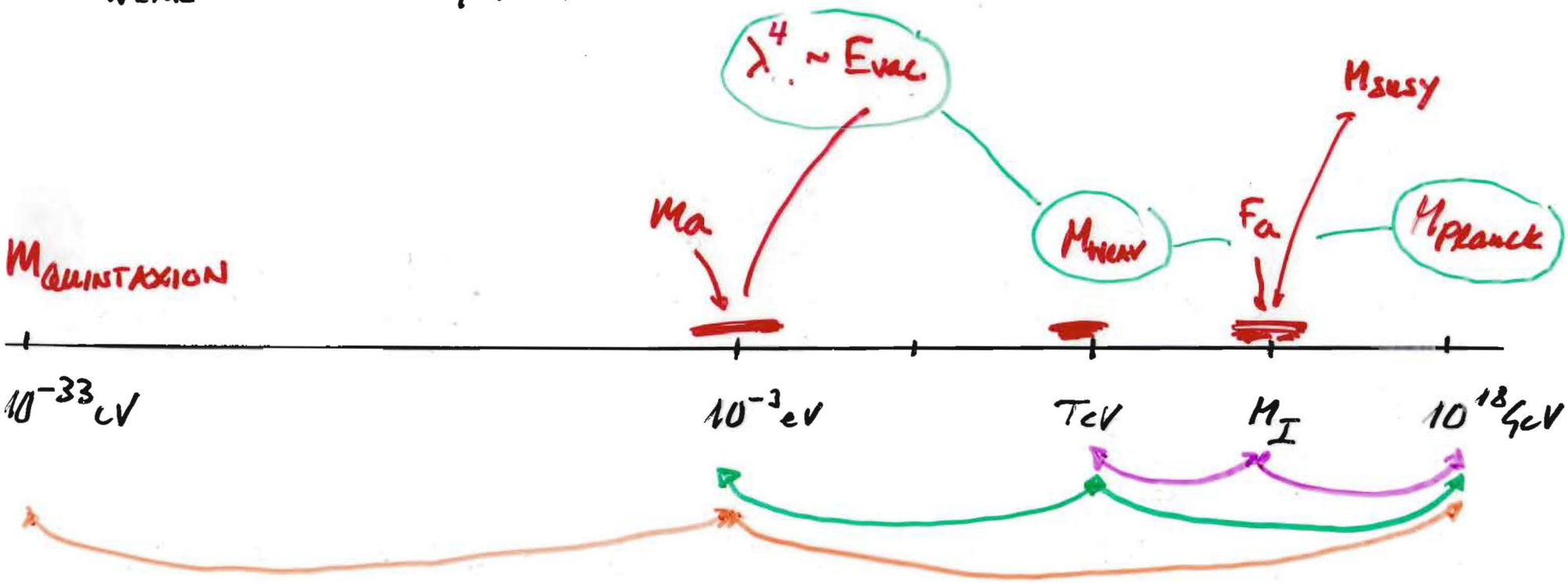
COSMOLOGICAL MAGNETIC FIELDS TO DETECT AXION LIKE FIELDS...

RELATIONS OF SCALES: AXIONIC SEE-SAW

$M_I \sim 10^{10} - 10^{12}$ GeV

$M_{axion} \sim 10^{-5} - 10^{-3}$ eV

$M_{WEAK} \sim 10^{2} - 10^{3}$ GeV



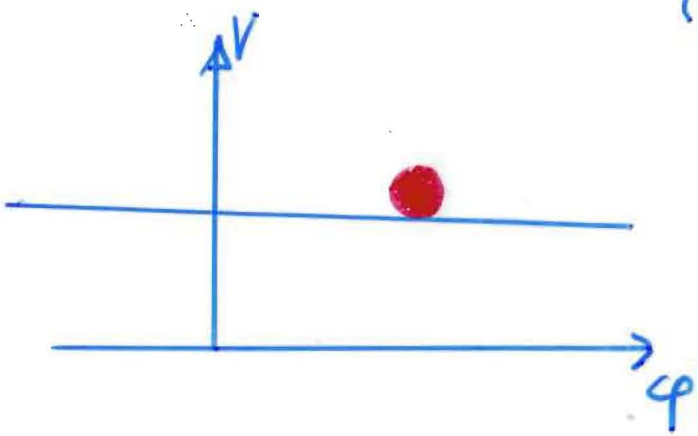
$$m_{3/2} = \frac{M_I^2}{M_{Planck}}$$

$$m_a = \frac{M_{WEAK}^2}{M_{Planck}}$$

$$m_{QUINTAXION} = \frac{\lambda^2}{M_{Planck}}$$

NATURAL INFLATION

(ADAMS, BOND, FREESE, FRIEMAN, OLINTO)



SLOW ROLL INFLATION NEEDS A FLAT POTENTIAL

BUT FLATNESS COULD BE SPOILED .....

PROTECT FLATNESS BY A SYMMETRY

$V(\varphi, \varphi^*) = V(\varphi + \varphi^*)$ SHIFT SYMMETRY

$Im(\varphi)$ IS AXION-LIKE PARTICLE

LARGE $F_a \geq M_{PLANCK}$ NEEDED

(KIM, NILLES, PELOSO)

AXIONS MIGHT SOLVE THE

STRONG CP-PROBLEM

AND PROVIDE CANDIDATES FOR

COLD DARK MATTER AND

DARK ENERGY

MULTI-AXION MODELS CONNECTED VIA A SEQUENCE OF SEE-SAW MECHANISMS COULD LEAD TO A

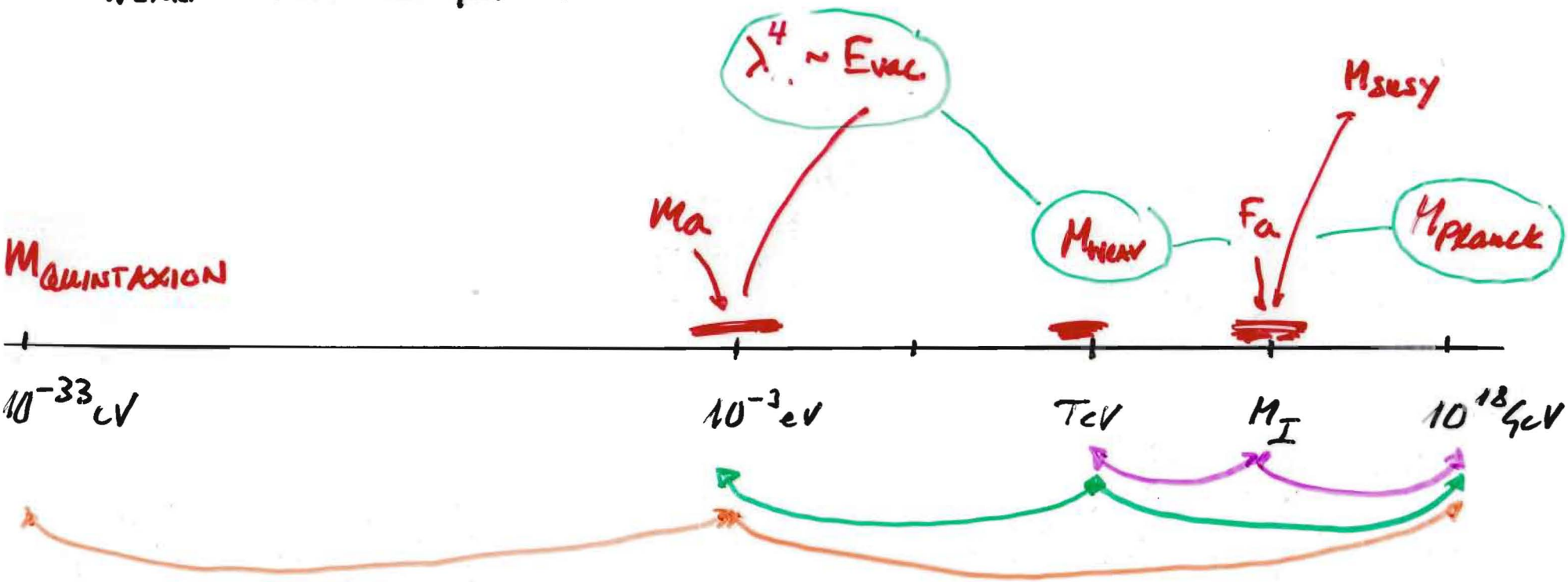
UNIFIED DESCRIPTION OF

DARK MATTER AND DARK ENERGY

$M_I \sim 10^{10} - 10^{12}$ GeV

$M_{axion} \sim 10^{-5} - 10^{-3}$ eV

$M_{WEAK} \sim 10^{2} - 10^{3}$ GeV



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