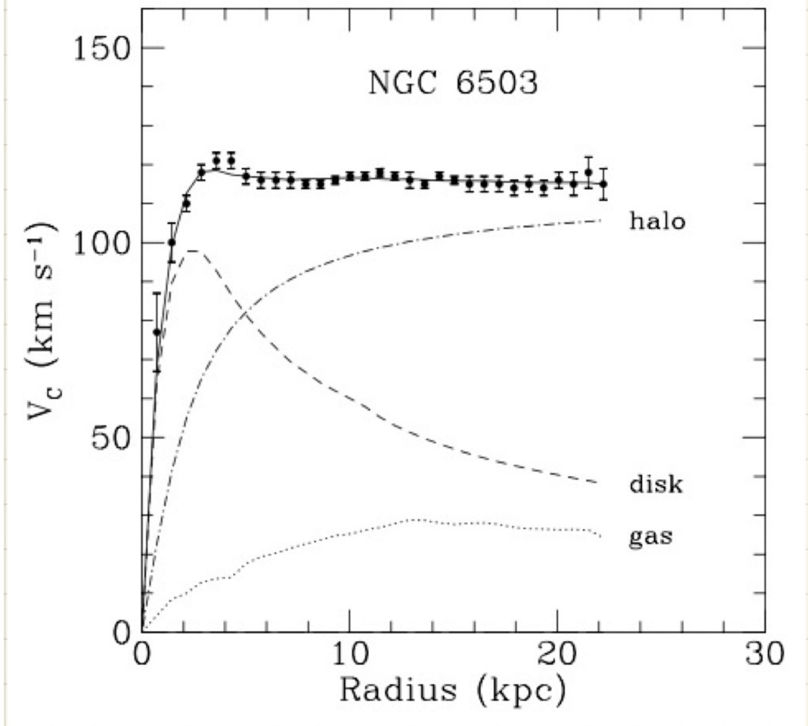
Dark Matter

Data and Candidates

Mads Toudal Frandsen

Recap



- Particle physics candidates for DM particle
  - sterile neutrino
  - axion
  - WIMP

$\rho(r) \sim \frac{1}{r^2}$ at large r

M. Shaposhnikovs lecture

Recap

$\rho(r) \sim \frac{1}{r^2}$ at large r

Is this inferred DM density consistent with particle DM?

Isothermal sphere

Self-gravitating isothermal sphere of ideal gas:

$$\frac{\mathrm{d}p}{\mathrm{d}r} = \frac{k_{\mathrm{B}}T}{m}\frac{\mathrm{d}\rho}{\mathrm{d}r} = -\rho\frac{\mathrm{d}\Phi}{\mathrm{d}r} = -\rho\frac{GM(r)}{r^2},$$

Solution for density

$$\rho(r) = \frac{\sigma^2}{2\pi G r^2}.$$

This solution describes the **singular isothermal sphere**. The mass interior to radius r, the circular speed and the gravitational potential are (eqs. 2.60, 2.61, and 2.62)

$$M(r) = \frac{2\sigma^2 r}{G} \quad ; \quad v_c(r) = \sqrt{2}\sigma \quad ; \quad \Phi(r) = 2\sigma^2 \ln(r) + \text{constant}, \quad (4.104)$$

(Binney & Tremaine; Galactic Dynamics)

Simple(st) particle model of DM halo yields

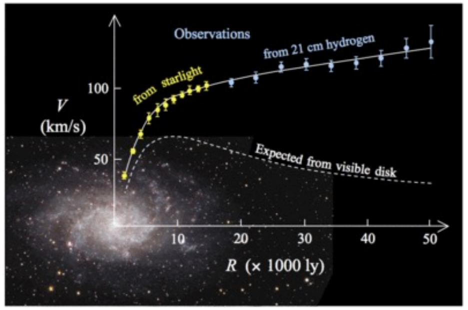
$\rho(r) \sim \frac{1}{r^2}$ at large r

CP³ Origins
Cosmology & Particle Physics

SDU

Missing mass problem

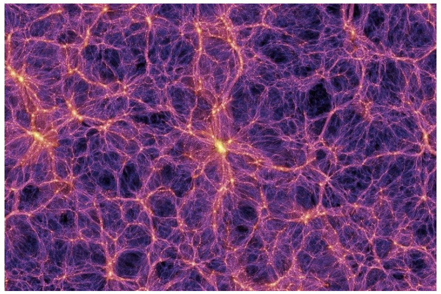
Galactic scales
Rotation curves of stars and gas
(Freeman ’70, Bosma ’78, Rubin et al ’78)

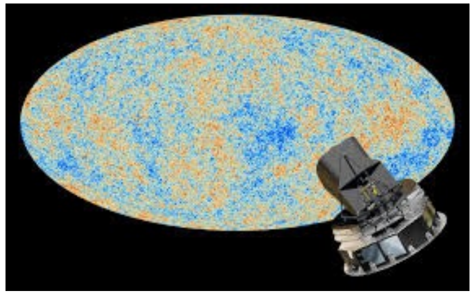


Gravitational evidence from kpc to Gpc scales

Cluster Scales
Galaxy velocity dispersions,
Cluster mergers
(Zwicky ’33, Clowe et al ’06)

Cosmological scales
CMB and LSS
(Davis et al ’82, Peebles ’82)





Missing *gravity* problem

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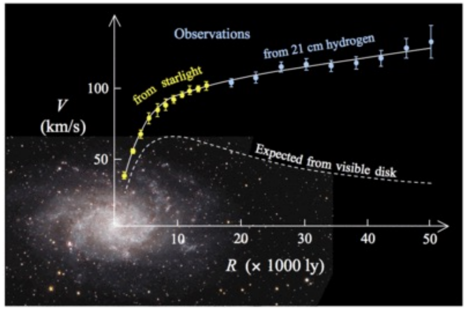

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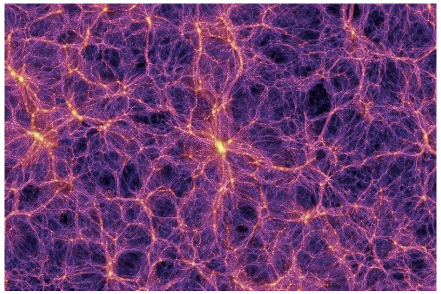
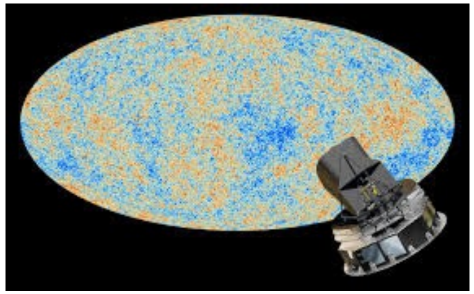
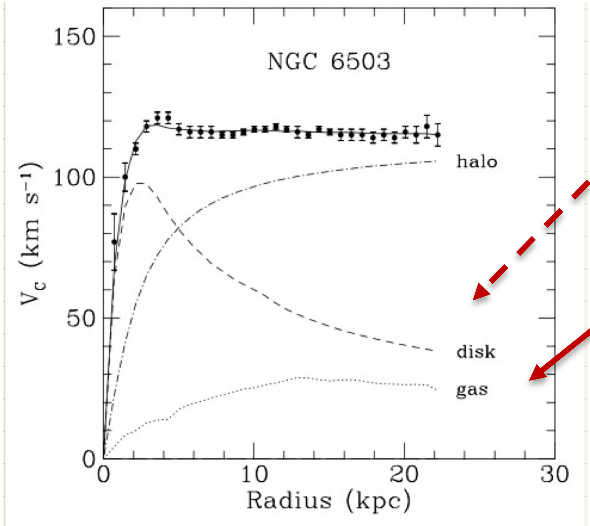


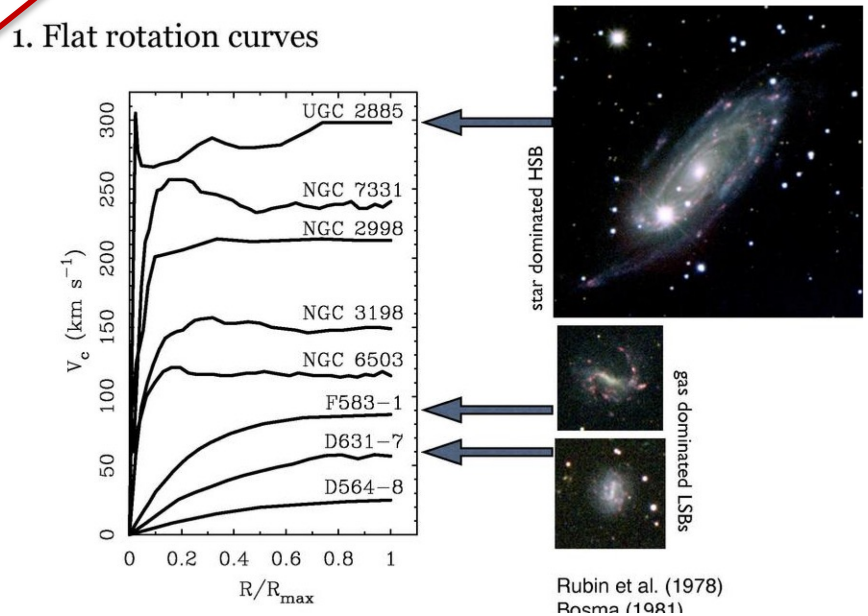


Many types of observational techniques and systems at each scale
E.g. for rotation curves

Spitzer Photometry & Accurate Rotation Curves

175 late-type spirals and irregulars.
Stellar mass range 5 dex, surface brightnesses 4 dex, range of gas fractions





(From McGaugh, KITP DM workshop ’18)

Radial Acceleration Relation

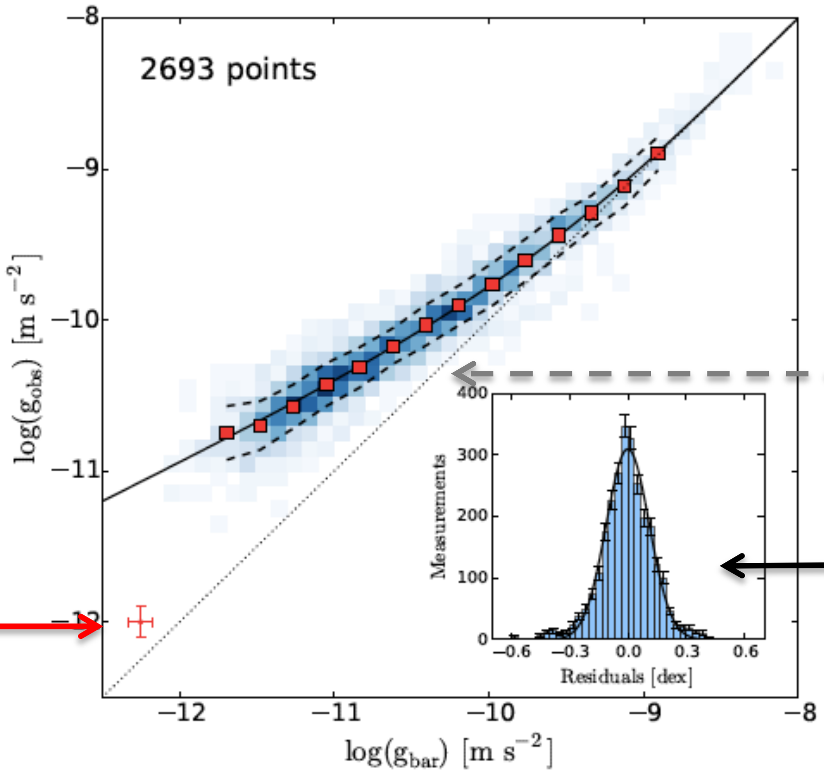
Correlation found between baryonic acceleration and total acceleration in ~ 2700 data points from 175 galaxies from the SPARC database

(McGaugh, Lelli & Schombert ’16)

$$g_{\rm obs} = \frac{v_{\rm obs}^2}{r}$$

$$g_{\rm bar} = \left|\frac{\partial \Phi_{\rm bar}}{\partial r}\right|$$

g2-space curve



g_0

Newtonian, no missing mass $g_{\rm obs} \sim g_{\rm bar}$

Fit residuals

Typical error

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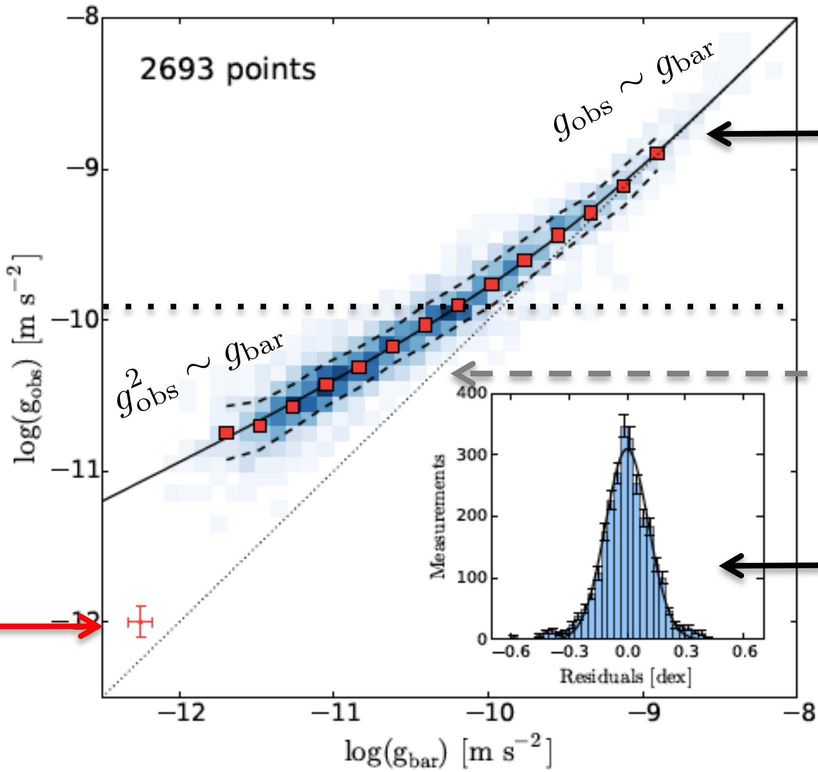

MOND (modified inertia) model curve

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Newtonian, no missing mass

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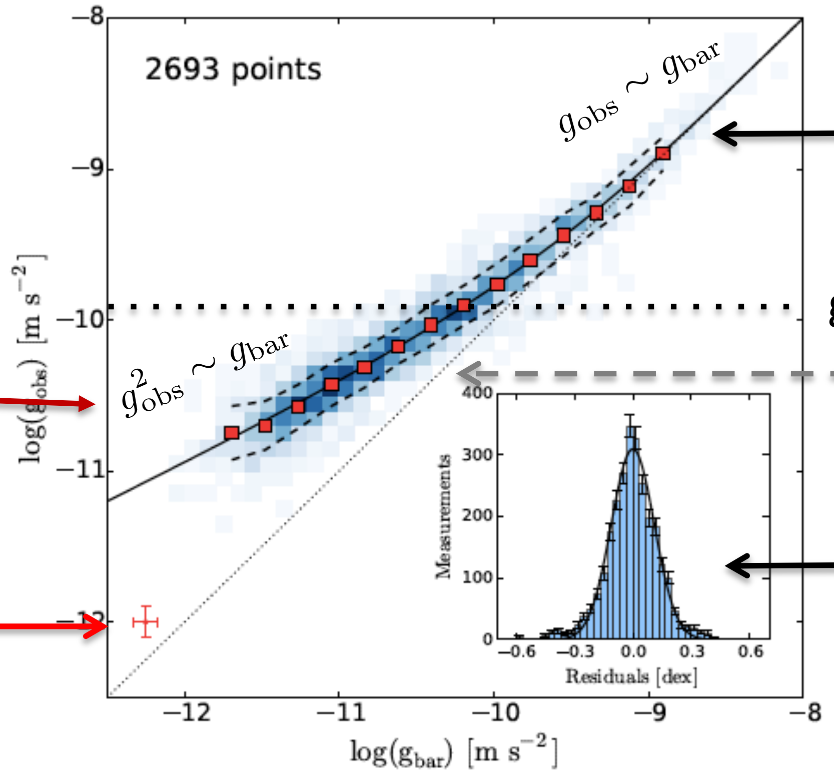

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Fit residuals

Typical error

Indicates new *acceleration* scale g_0?

Modified Newtonian Dynamics

Newtonian acceleration modified below $g_0 \sim 1.2 \times 10^{-10}$ m/s^2 to account for flat rotation curves

(Milgrom '83
Bekenstein & Milgrom '85)

Bekenstein-Milgrom MOND

Newtonian Poisson Equation

$$\vec{\nabla}\cdot\left(\mu\left(\frac{g_M}{g_0}\right)\vec{g}_M\right) = 4\pi G\rho_{\mathrm{bar}} = \vec{\nabla}\cdot\vec{g}_{\mathrm{bar}}$$

MOND acceleration

Baryonic matter distribution ρ_{bar}

Newtonian acceleration

MOND interpolation function

$$\mu(x) = \begin{cases} \mu(x) \simeq 1 & x \gg 1 \\ \mu(x) \simeq x & x \ll 1 \end{cases}$$

Newtonian regime ($x \gg 1$)
Mondian regime ($x \ll 1$)

Radial Acceleration Relation

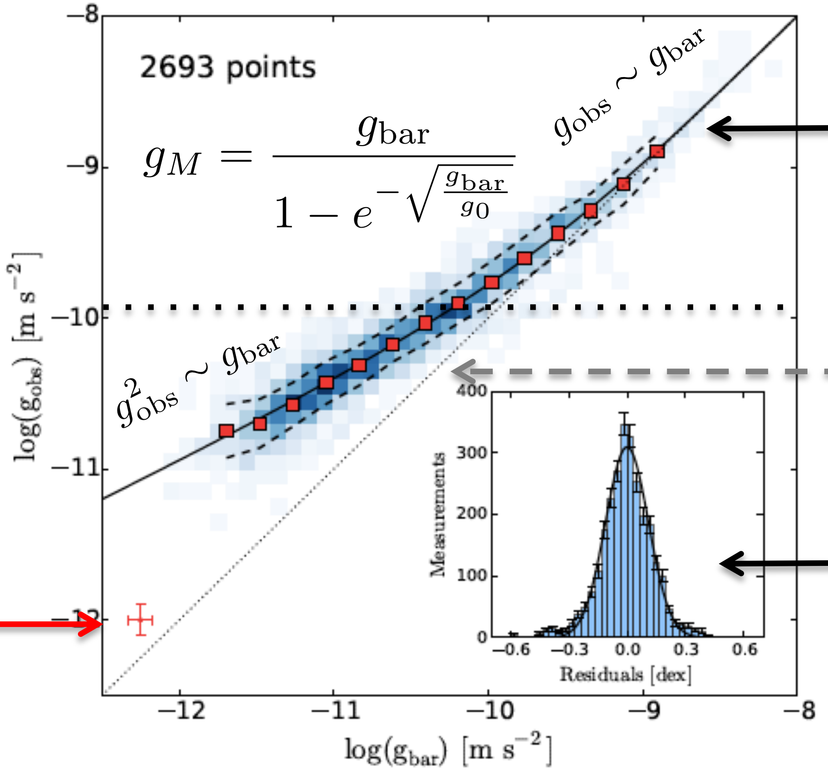
g2-space cuve shows

1) Correlation between baryonic acceleration and total acceleration
2) MOND modified inertia fit.
3) (Simplest) approximation to MOND modified gravity fit.

$$g_{\rm obs} = \frac{v_{\rm obs}^2}{r}$$

$$g_{\rm bar} = \left|\frac{\partial \Phi_{\rm bar}}{\partial r}\right|$$

g2-space curve



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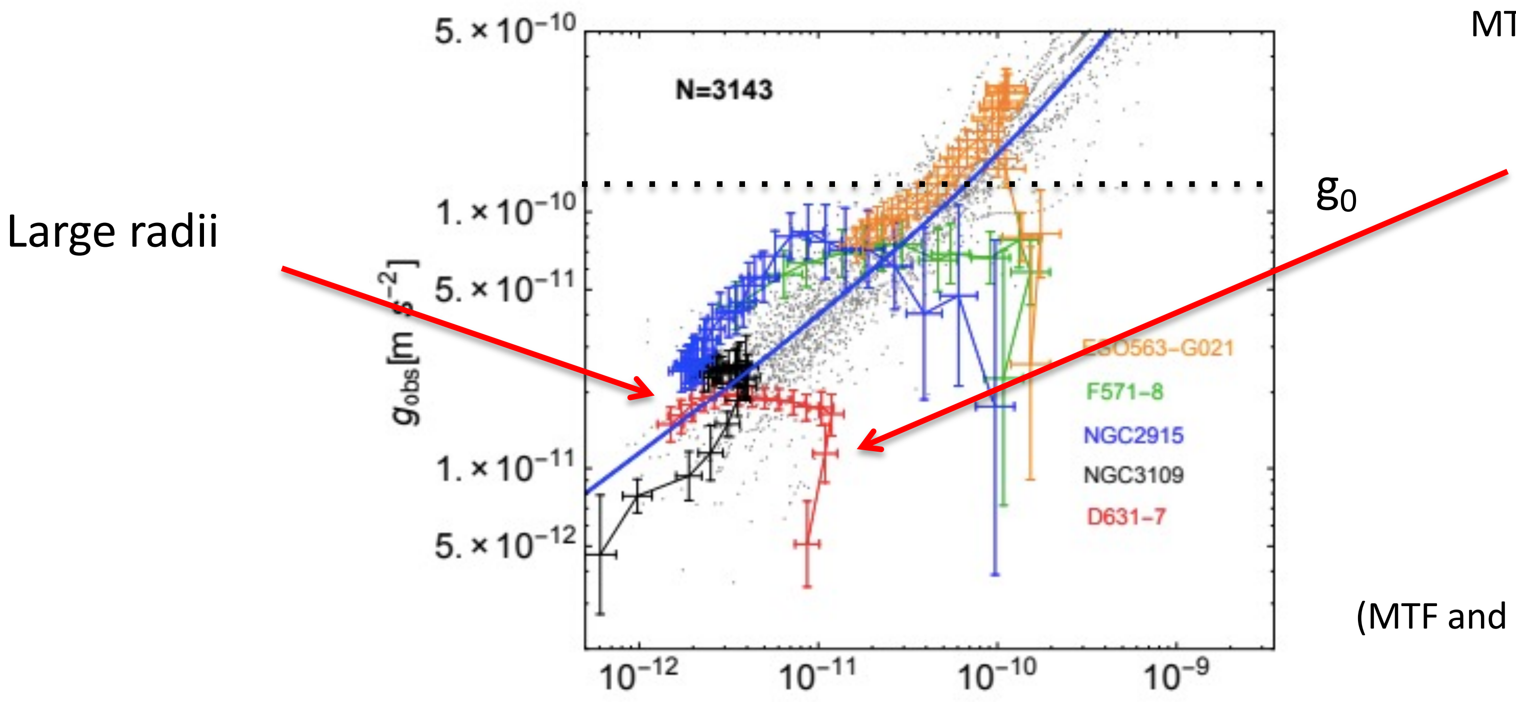
SPARC Individual galaxies

(J. Petersen and MTF '17
MTF and J. Petersen '18)



(MTF and J. Petersen '18)

Highlighted galaxies don't follow Radial Acceleration Relation at smallest radii

Result of baryonic complexities at small radii?

Universality vs Diversity

NFW scaling of radial DM density profiles from dwarf galaxies to galaxy clusters
DM only cosmological N-body simulations. No baryons

$$\rho_{\rm NFW}(r) = \frac{\rho_{0,\rm NFW}}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$$

(Navarro, Frenk & White '95)

MOND/RAR: Total acceleration in circular motion correlates with that from baryons
At galactic scales

(Tully & Fisher '77; McGaugh '11)

Cusp/Core
Flat or cored DM profiles in dwarf and Low Surface Brightness galaxies

$$\rho_{\rm ISO}(r) = \frac{\rho_{0,\rm ISO}}{1+(\frac{r}{r_c})^2}$$

(Moore '94; Flores & Primack '94)

Missing Sattelites & Too-big-to-fail
Too many sattelites that are too dense and massive are predicted

(Moore, Quinn, Governato, Stadel & Lake '99; Klypin, Kravtsov, Valenzuela & Prada '99; Boylan-Kolchin, Bullock, Kaplinghat '11)

Universality vs Diversity

Baryonic physics
Discrepancies arise from comparing to DM-only simulations

(J. Read talk ZPW19)

Adiabatic contraction

Supernova feedback

AGN

DM (self-) interactions
Small scales are high DM density and DM interaction rates

Velocity dependence

Long rage, short range

Gravity

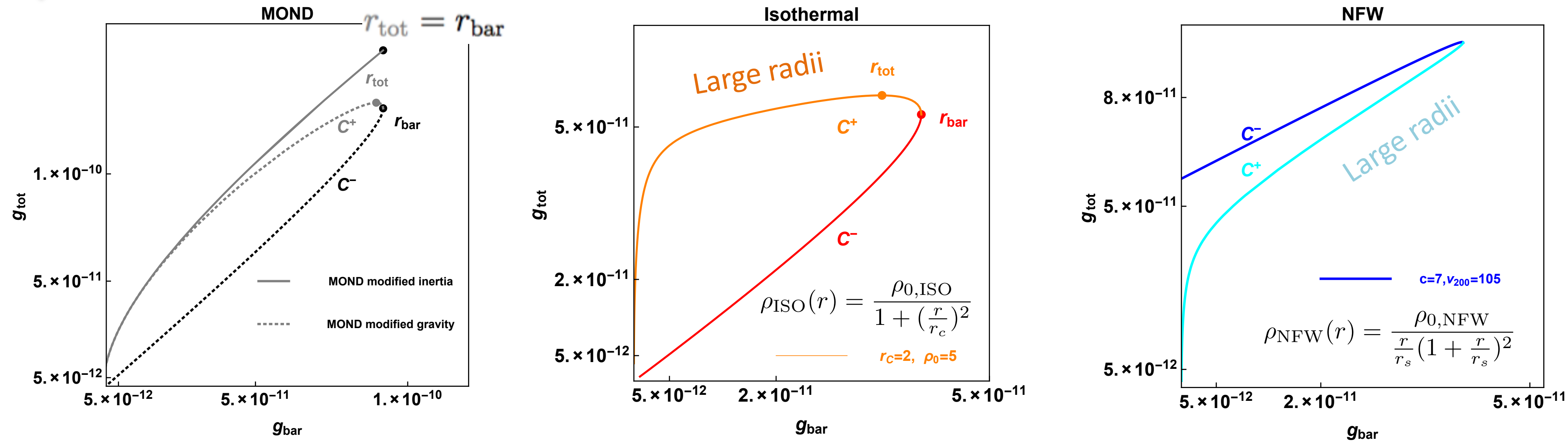
Discrepancies arise assuming Newtonian gravity

With or without DM

Modified NewtonianDynamics

Modified Gravity

MOND and DM geometry in g2-space



Geometric Classification

Mond Modified Inertia

MOND Modified Gravity

DM Pseudo-Isothermal

DM Navarro-Frenk-White

Models	Reference radii	Curve segments	Curve Area[a]
MOND-MI	$r_{tot} = r_{bar}$	$\mathcal{C}^+ = \mathcal{C}^-$	$\mathcal{A}(\mathcal{C}) = 0$
MOND-MG	$r_{tot} > r_{bar}$	$\mathcal{C}^+ > \mathcal{C}^-$	$\mathcal{A}(\mathcal{C}) > 0$
DM-ISO	$r_{tot} > r_{bar}$	$\mathcal{C}^+ > \mathcal{C}^-$	$\mathcal{A}(\mathcal{C}) > 0$
DM-NFW	$r_{tot} < r_{bar}$	$\mathcal{C}^+ < \mathcal{C}^-$	Curves open

THE ASTROPHYSICAL JOURNAL

OPEN ACCESS

Breakdown of the Newton–Einstein Standard Gravity at Low Acceleration in Internal Dynamics of Wide Binary Stars

Kyu-Hyun Chae[1]

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The Astrophysical Journal, Volume 952, Number 2

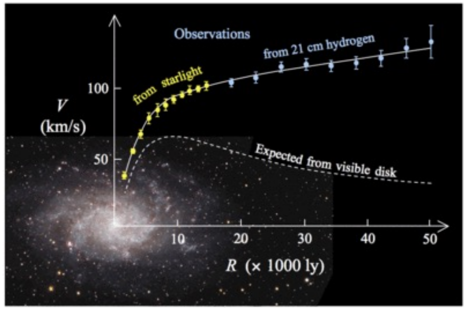
Citation Kyu-Hyun Chae 2023 *ApJ* **952** 128

DOI 10.3847/1538-4357/ace101

MOND keeps sparking some interest
but hard to reconcile MOND with
observations on all scales

Missing mass problem

Galactic scales
Rotation curves of stars and gas
(Freeman ’70, Bosma ’78, Rubin et al ’78)



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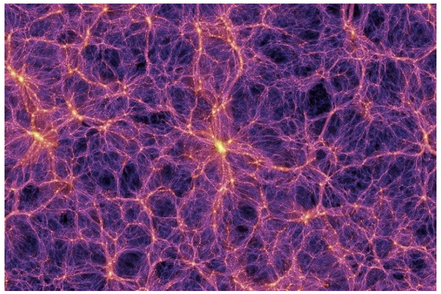
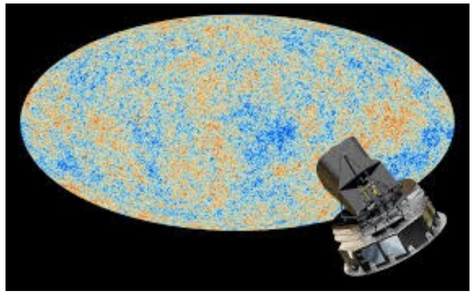




Back to particle DM

To summarise, what we know about DM particles

- lifetime $\tau > \tau_{univers}$
- Relatively light particles must be neutral and very weakly interacting
- DM should be sufficiently cold
- fermions should be heavier than $\sim 500\ eV$
- bosons should be heavier than $\sim 10^{-22}\ eV$

M. Shaposhnikovs lecture

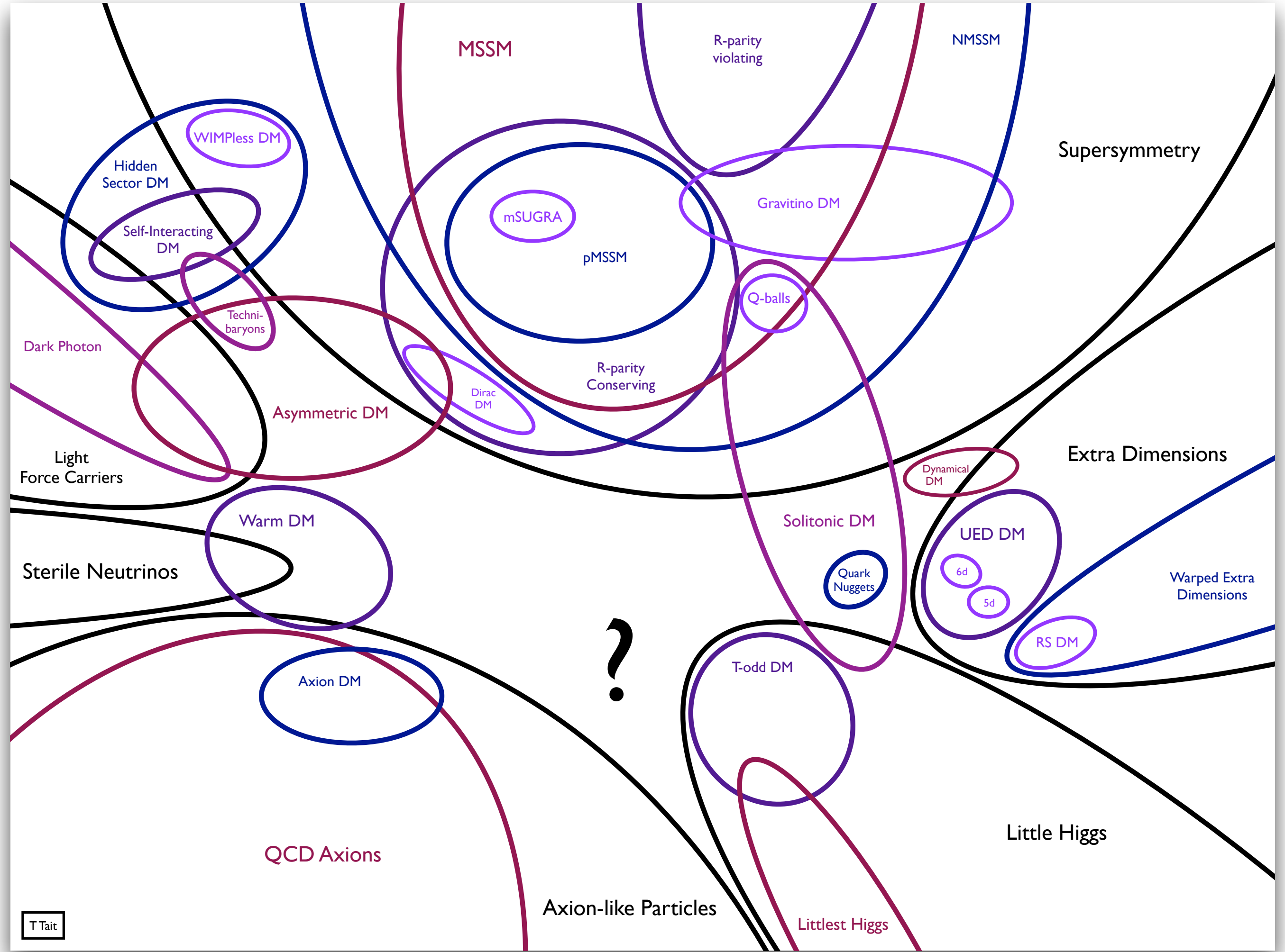
Need theory input!

Particle DM

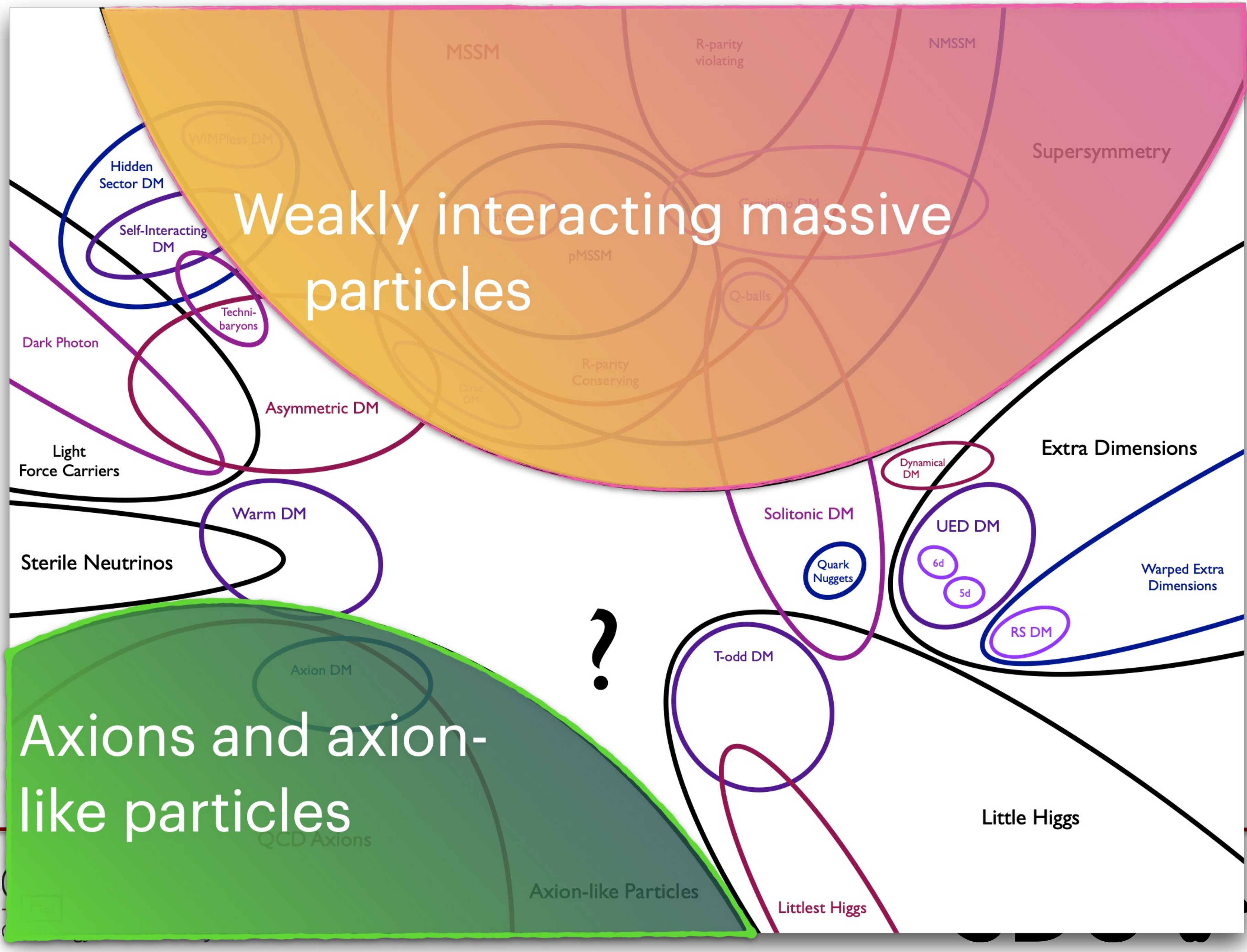
- Particle physics candidates for DM particle
  - sterile neutrino
  - axion
  - WIMP

M. Shaposhnikovs lecture

Particle DM



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Asymmetric DM
Dirac DM
R-parity Conserving
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
?
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait


Weakly interacting massive particles
Axions and axion-like particles
MSSM
R-parity violating
NMSSM
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WIMPless DM
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Particle DM strategies/classifications

- Generalize SM `DM candidates`:
- Generalize the SM neutrino relic – see Shaposhnikovs lecture
- **Generalize the SM baryonic relic (neutron) – Composite DM**

- Clasify by the origin of the DM relic density:
- SM neutrino relic – thermal freeze-out (WIMP)
- **SM baryonic relic (neutron) – asymmetry (Composite DM)**

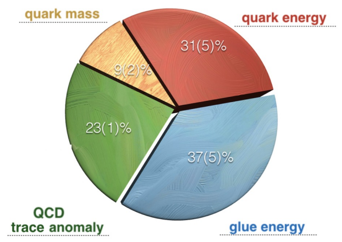
Baryonic relic density

2 flavor massless QCD

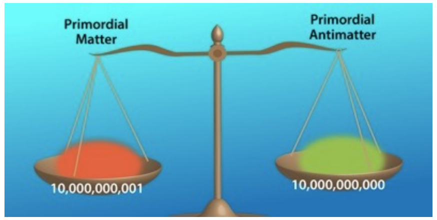
$$SU(2)_L \times SU(2)_R \times U(1)_B$$
$$\to SU(2)_V \times U(1)_B$$

- Proton stability (longevity) due to a **U(1) symmetry**

- Proton mass from **strong dynamics** (and Higgs)



- Proton relic density from some **asymmetry**



- **Neutron** lightest table baryon for zero current quark masses.
  Self-interactions from strong dynamics

Particle DM strategies/classifications

- DM as byproduct(?) from solving other SM problems…

- Particle physics candidates for DM particle
  - sterile neutrino ← Neutrino masses
  - axion ← Strong CP problem
  - WIMP ← Naturalness, relic density

- Composite DM ← Naturalness, relic density

CP³ Origins
Cosmology & Particle Physics

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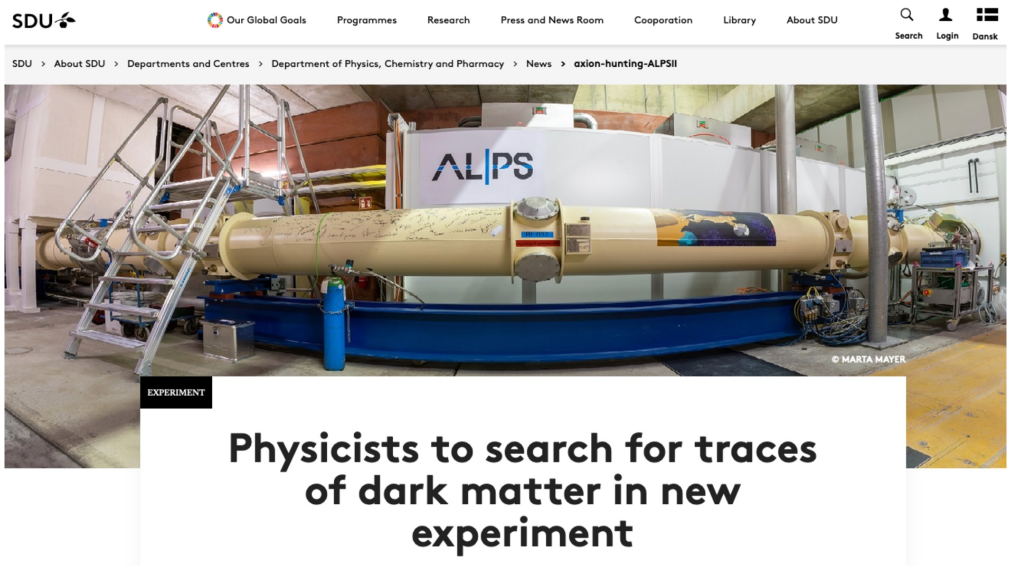
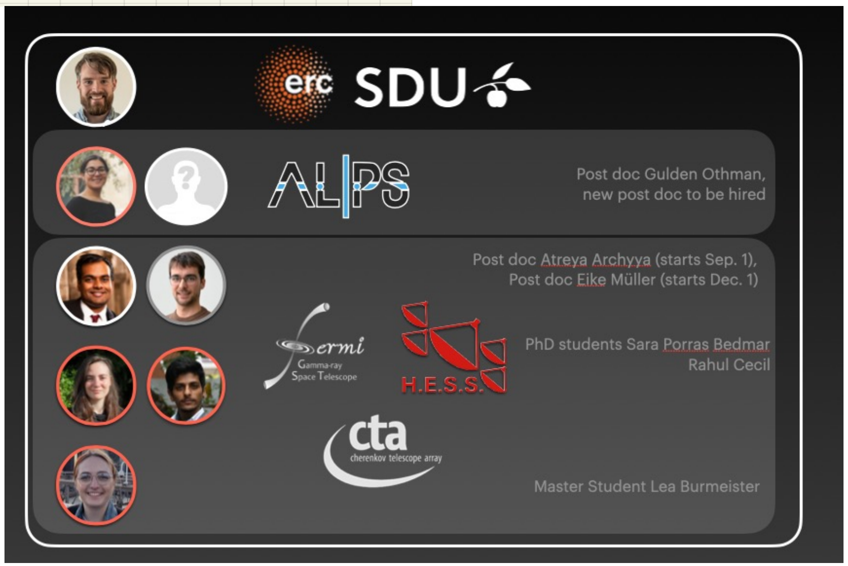
Axions

- Particle physics candidates for DM particle
  - sterile neutrino $\longleftarrow$ Shaposhnikov lecture
  - axion $\longleftarrow$ Strong CP problem





Axions

QCD:

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \sum_{\text{quarks}} \bar{q}\, i \not{D}\, q$$

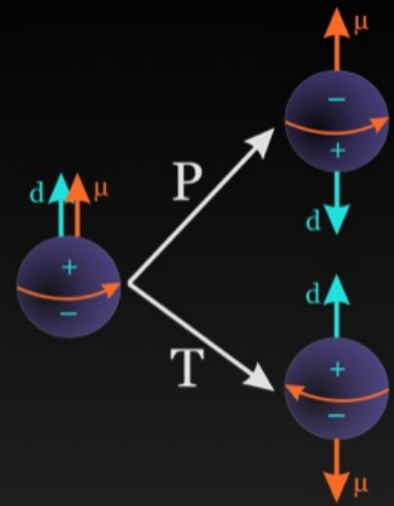
$$\sum_{ij} m_{ij}\, \bar{q}_{iL}\, q_{jR} + h.c. + \frac{\alpha_s}{8\pi} \theta F^a_{\mu\nu} \tilde{F}^a_{\mu\nu}$$

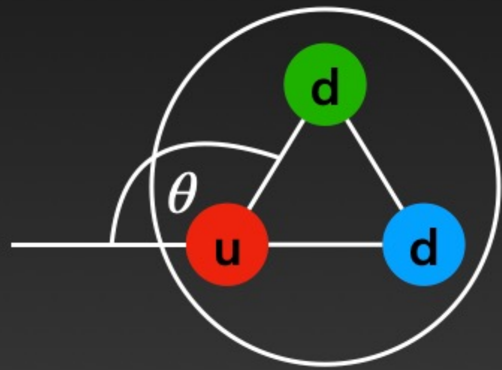
$$\tilde{F}^a_{\mu\nu} = \frac{1}{2} \varepsilon_{\mu\nu\rho\sigma} F^a_{\rho\sigma}$$

From M. Shaposhnikovs lecture
See this for further details

The strong CP problem

- Theory of strong force (QCD) predicts electric dipole moment of the neutron with strength $\theta \in [-\pi,\pi]$
- Violates **P** and **T** symmetry
- Calculation: $|d_n| \approx 2.4 \times 10^{-16}\,\theta\, e$ cm
- Measurement [Abel et al. 2020]: $|d_n| < 1.8 \times 10^{-26} e$ cm
- $\Rightarrow |\theta| < 0.8 \times 10^{-10}$





[Peccei & Quinn 1977;
Weinberg 1978; Wilczek 1978]
Slide credit: Ben Safdi & Axel Lindner

[Hook 2018]

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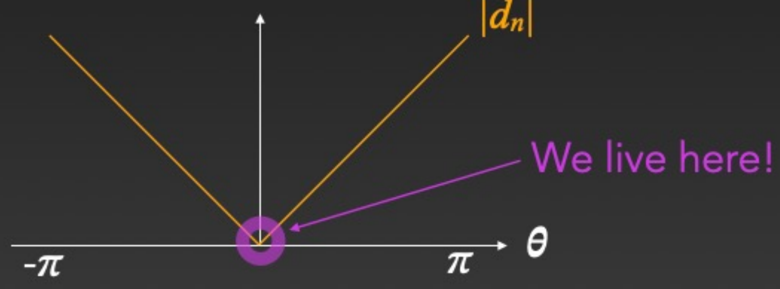

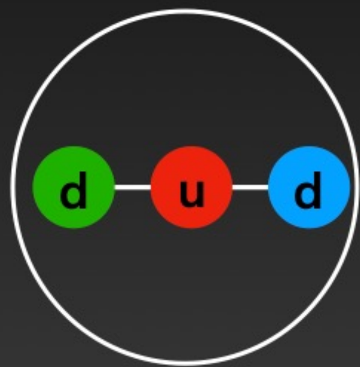

[Peccei & Quinn 1977;
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Slide credit: Ben Safdi & Axel Lindner

[Hook 2018]

CP³ Origins
Cosmology & Particle Physics

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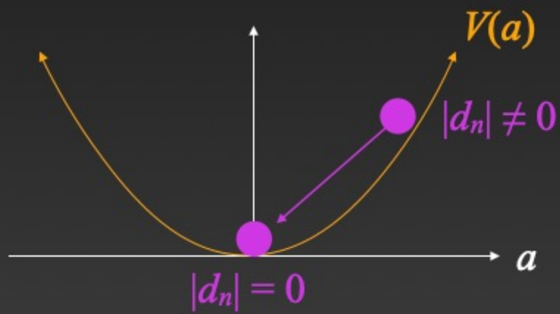
Axion solves the strong CP problem

- $\theta \longrightarrow a\,/\,f_a$ with scalar field a and scale f_a
- Potential $V(a)$ generated by QCD, axion acquires mass

$$m_a \approx 10^{-9}\,\mathrm{eV}\left(\frac{10^{16}\mathrm{GeV}}{f_a}\right)$$



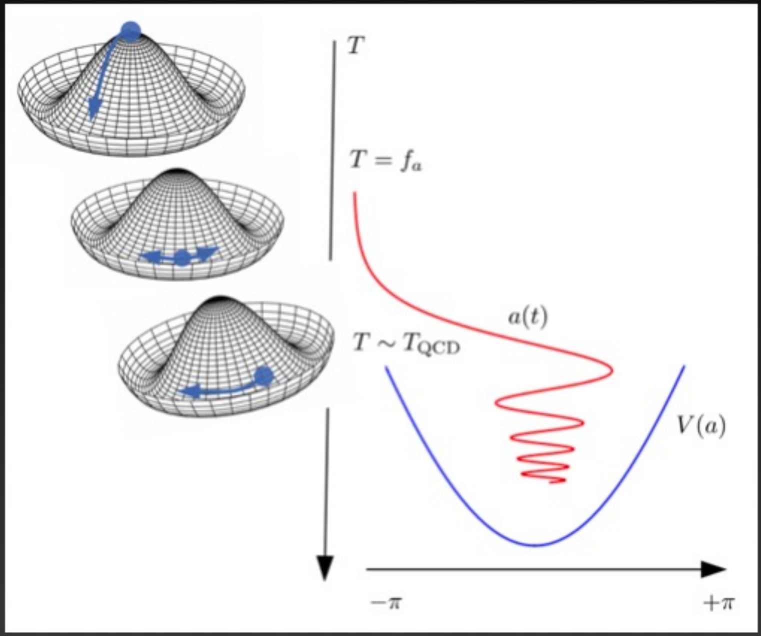
[Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978]

Axions as cold dark matter

Through misalignment mechanism

$$\ddot{a} + 3H(t)\dot{a} + m_a^2(t)a = 0$$

- Overdamped in early Universe as long as $3H \gg m_a$, field frozen at its initial value a_I
- Once $3H \sim m_a$ field will start to oscillate; happens at $t = t_{\text{osc}}$ or equivalently $T = T_{\text{osc}}$
- Oscillations have properties of cold dark matter



[See e.g. this PhD thesis, Marsh 1510.07633, Arias et al. 1201.5902]

Particle DM strategies/classifications

- DM as byproduct(?) from solving other SM problems…

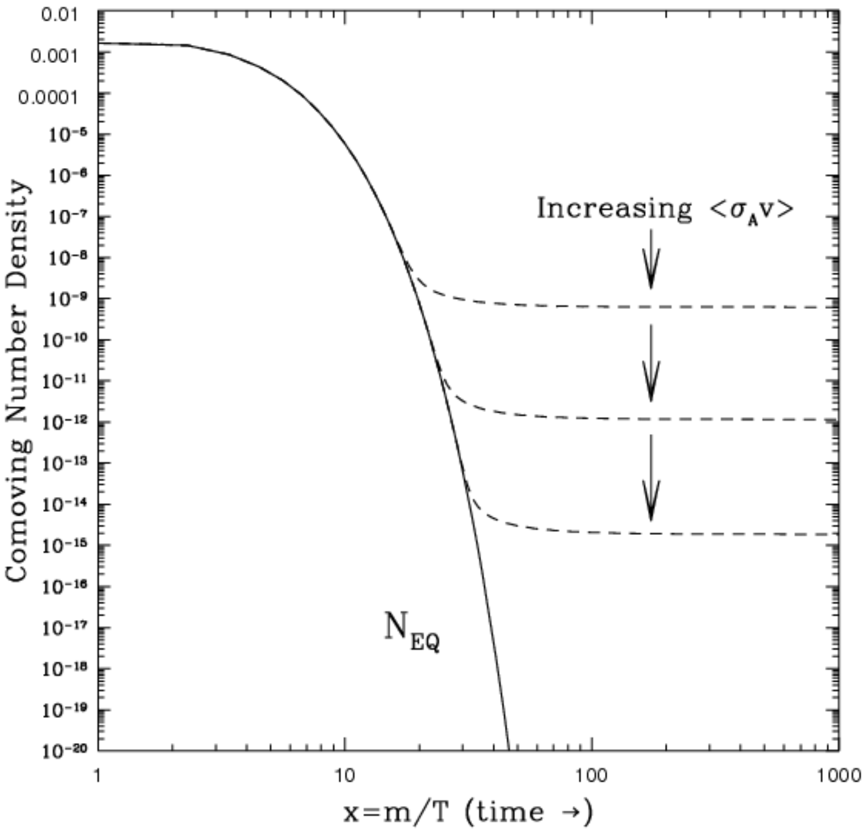
- Particle physics candidates for DM particle
  - sterile neutrino
  - axion
  - WIMP

Neutrino masses

Strong CP problem

Naturalness, relic density

WIMP DM



Computation of abundance

$XX \leftrightarrow$ particles of the SM,

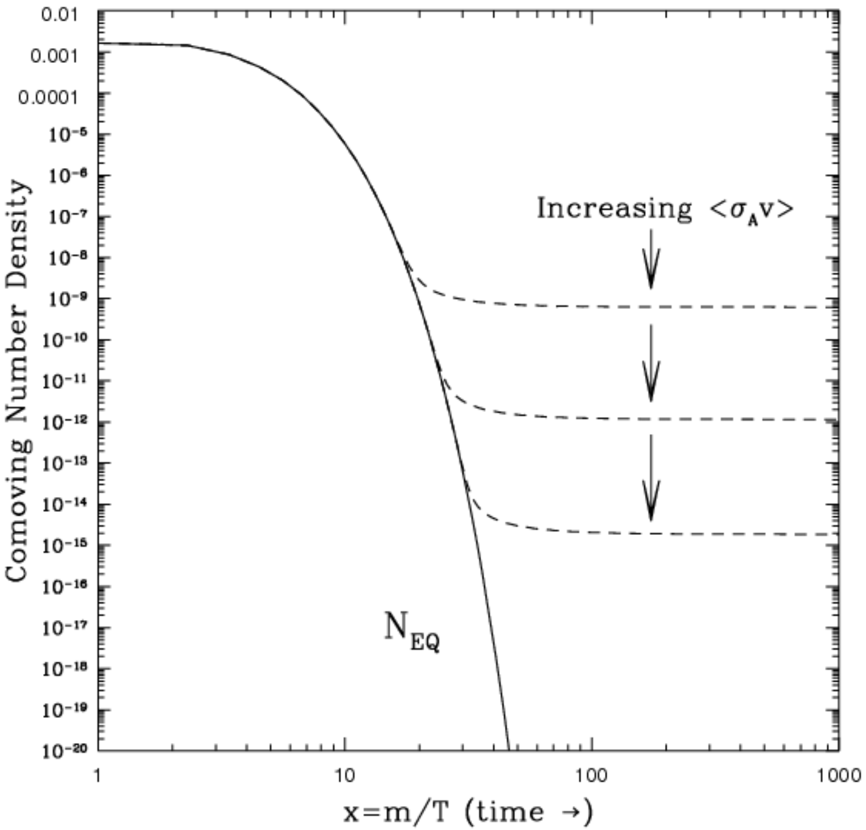
$\sigma_{ann} = \frac{\sigma_0}{v} \leftarrow$ velocity.

Concentration of X:

$$n_X = g_X \left(\frac{MT}{2\pi}\right)^{3/2} e^{-M/T}$$

spin factor

WIMP DM



Freeze-out temperature

$$\langle \sigma n v \rangle = H = \frac{T^2}{M_0}$$

rate of reactions

rate of expansion

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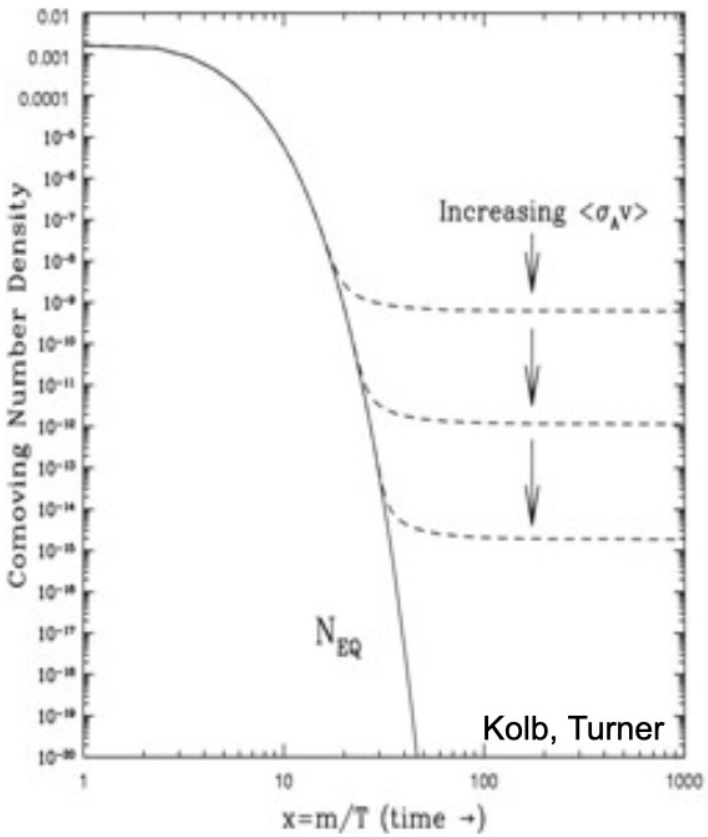
THE WIMP MIRACLE



- Assume a new (heavy) particle X is initially in thermal equilibrium
- Its relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

$$\left. \begin{array}{l} \bullet\, m_X \sim m_{\mathrm{weak}} \sim 100\ \mathrm{GeV} \\ \quad g_X \sim g_{\mathrm{weak}} \sim 0.6 \end{array} \right\} \Omega_X \sim 0.1$$

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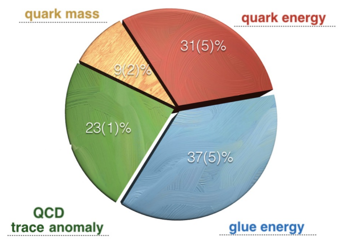
  - axion ← Strong CP problem
  - WIMP ← Naturalness, relic density
  - Composite DM ← Naturalness, relic density

Baryonic relic density

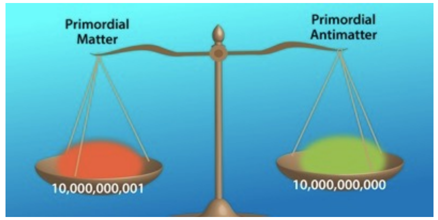
2 flavor massless QCD

$$SU(2)_L \times SU(2)_R \times {\color{red}U(1)_B}$$
$$\to SU(2)_V \times {\color{red}U(1)_B}$$

- Proton stability (longevity) due to a **U(1) symmetry**



- Proton mass from **strong dynamics** (and Higgs)



- Proton relic density from some **asymmetry**

- **Neutron** lightest table baryon for zero current quark masses.
  Self-interactions from strong dynamics

$$\Omega_{\mathrm{DM}}/\Omega_{\mathrm{B}} \sim 5$$

New Composite Dynamics

- 4d Gauge-Yukawa model with fermions and strong interactions
- May also (partially) break EW symmetry $\langle Q^I Q^J \rangle \sim f^3 E_Q^{IJ}$

$$\mathcal{L} = \mathcal{L}_{\rm SD} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SD+SM}$$

CD breaks EW:
e.g TC, CH

$$\mathcal{O}_{\rm CD} \sim QQ$$

$$\mathcal{L} = \mathcal{L}_{\rm SD} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SD+SM}$$

CD induces EW breaking:
e.g. PCH,

$$\mathcal{O}_{\rm CD+SM} \sim QHQ$$

$$\mathcal{O}_{\rm CD+SM} \sim QQH^\dagger H$$

$$\mathcal{L} = \mathcal{L}_{\rm SD} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SD+SM}$$

SM breaks EW:
e.g. SIDM

(Spergel & Steinhardt)

$$\mathcal{O}_{\rm SM} \sim H^\dagger H$$

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$$\mathcal{O}_{\rm SM} \sim H^\dagger H$$

(Spergel & Steinhardt)

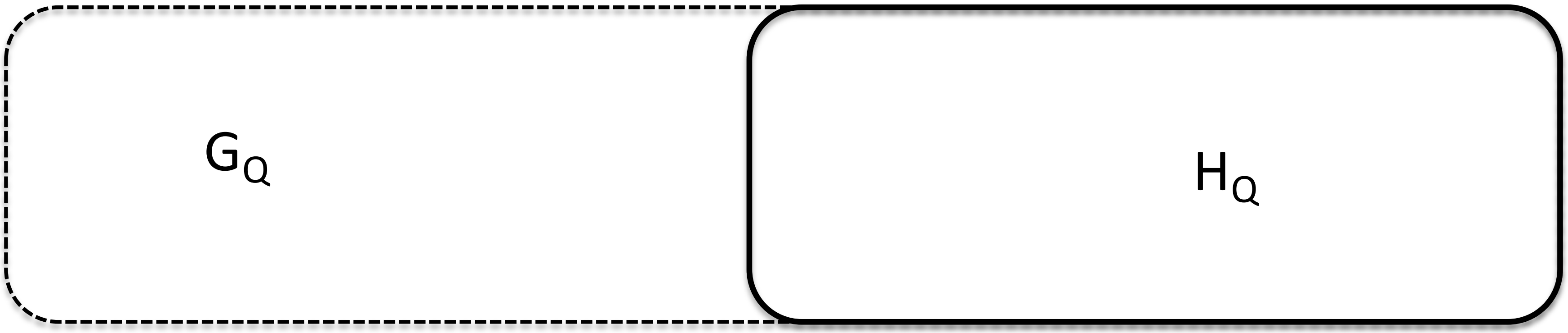
New Composite Dynamics

UV: $\mathcal{L}_{UV} = \bar{Q}\gamma^{\mu} D_{\mu} Q + \mathcal{L}_{SM-Higgs} + \delta\mathcal{L}$

IR: $\langle Q^I Q^J \rangle \sim f^3 E_Q^{IJ}$

$$G_Q \supset SU(2) \times SU(2) \times U(1) \quad \rightarrow \quad H_Q \supset SU(2) \times U(1)$$

SM custodial symmetry   DM symmetry



Framework: Composite Dynamics

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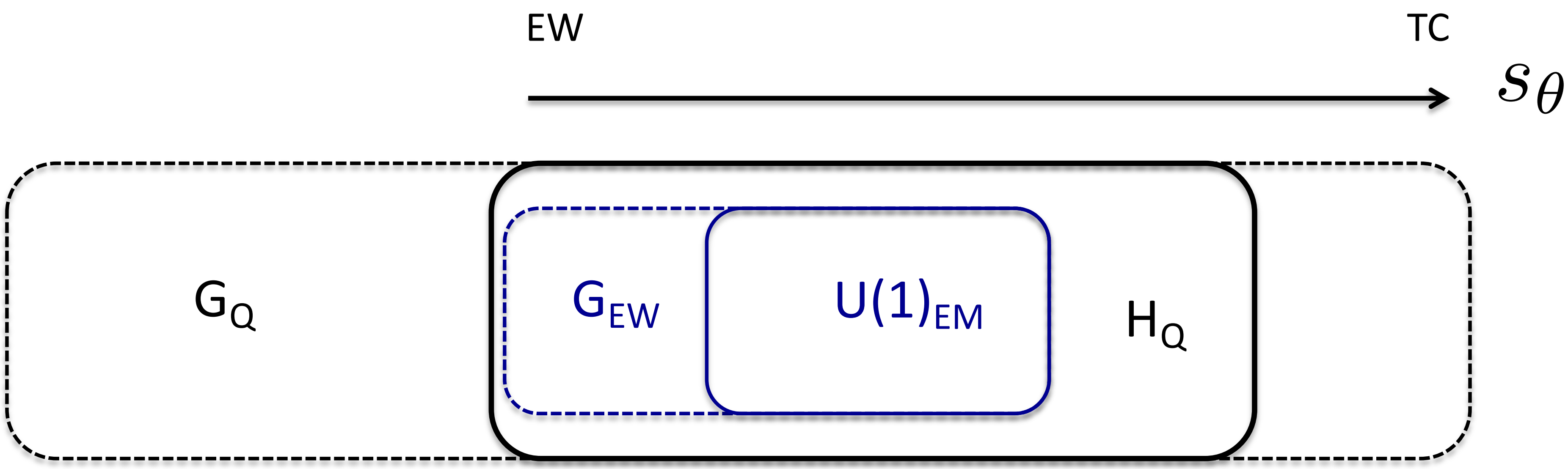

New Composite Dynamics

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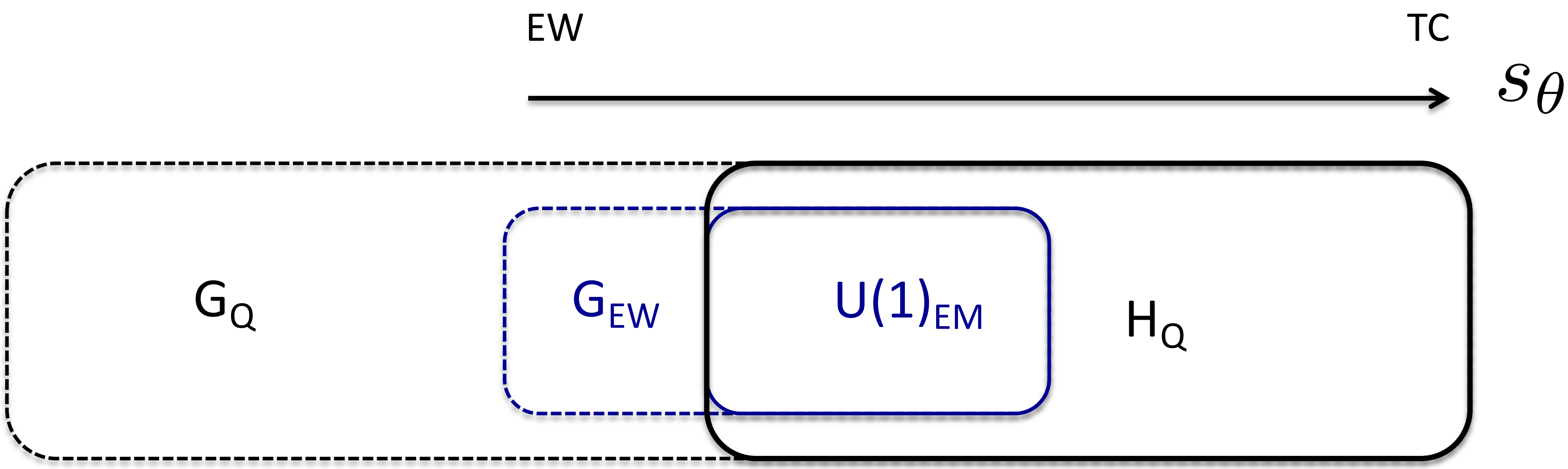

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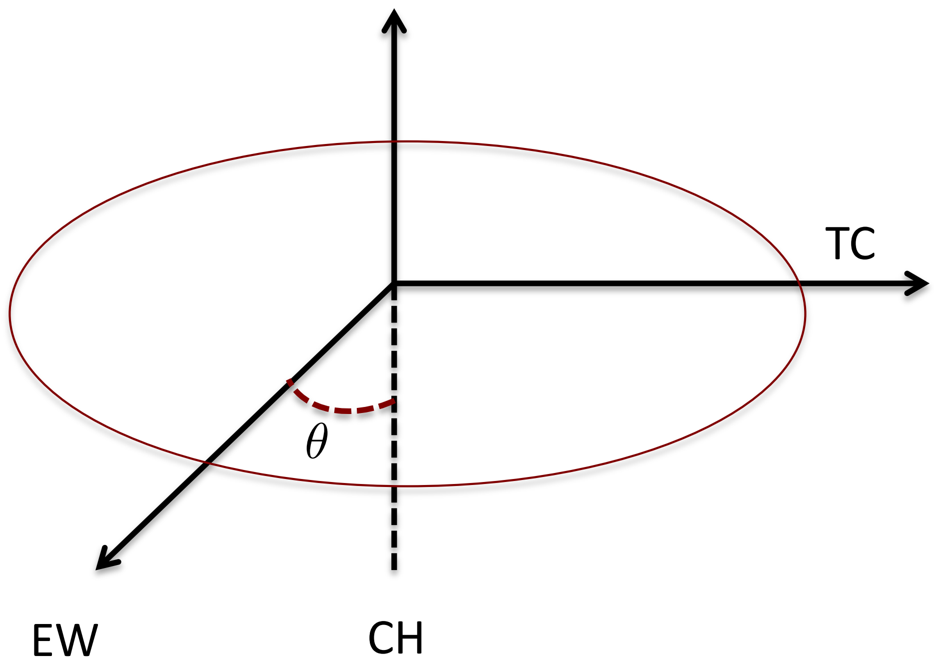
SU(2) Composite Dynamics with 2 flavors



Framework: Composite Dynamics

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$$G_Q \supset SU(2) \times SU(2) \times U(1) \quad \rightarrow \quad H_Q \supset SU(2) \times U(1)$$

SM custodial symmetry — DM symmetry

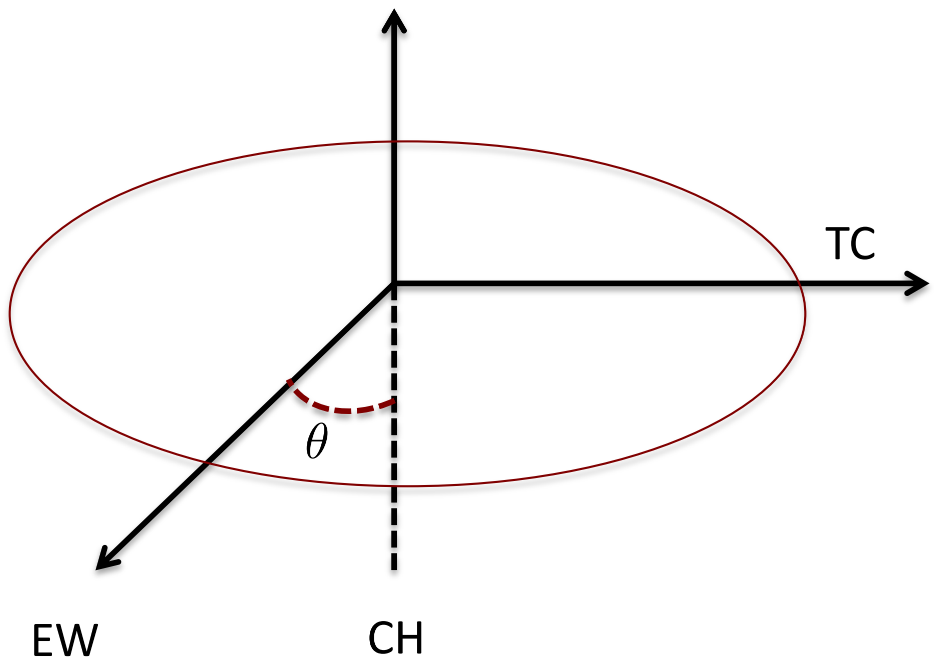
Example: $G_Q = SU(4) \quad \rightarrow \quad H_Q = Sp(4)$

	$\mathrm{SU(2)_{TC}}$	$\mathrm{SU(2)_W}$	$\mathrm{U(1)_Y}$
(U_L, D_L)	$\square$	$\square$	0
$\widetilde{U}_\mathrm{L}$	$\square$	1	$-1/2$
$\widetilde{D}_\mathrm{L}$	$\square$	1	$+1/2$

$$Q = \begin{pmatrix} U_\mathrm{L} \\ D_\mathrm{L} \\ \widetilde{U}_\mathrm{L} \\ \widetilde{D}_\mathrm{L} \end{pmatrix}$$

Which condensate
Preserves/breaks EW

SU(2) Composite Dynamics with 2 flavors



$\langle U_L \tilde{U}_L + D_L \tilde{D}_L \rangle$

Θ=π/2:
EW broken
TC Higgs radial excitation

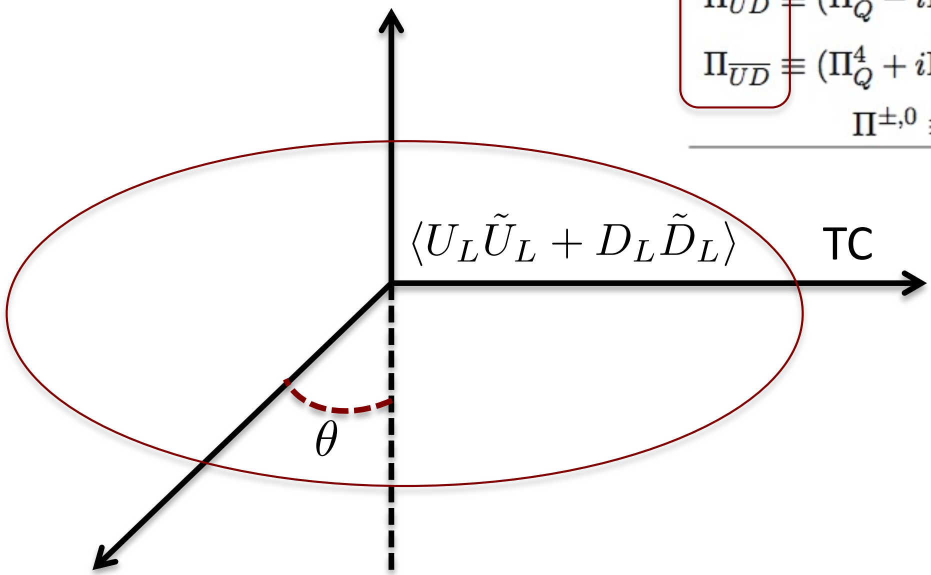
U(1) TB broken only by EW anomaly

$$\partial_\mu J^\mu \sim W^{\mu\nu} \widetilde{W}_{\mu\nu}$$

Technicolor limit

Compelling, apparently wrong limit

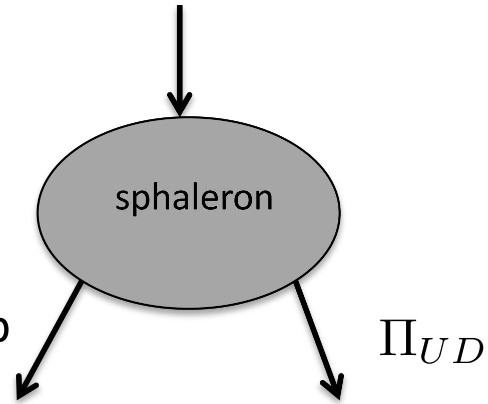
Composites	$U(1)_{TB}$	$U(1)_{EM}$	Θ
$\Pi_{UD} \equiv (\Pi_Q^4 - i\Pi_Q^5)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi_{\overline{UD}} \equiv (\Pi_Q^4 + i\Pi_Q^5)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi^{\pm,0} \equiv \Pi^{1,2,3}$	0	$\pm 1, 0$	$\pi/2$



$$\mathcal{L}_{\rm kin} \supset -\frac{g^2}{2} s_\theta^2 W_\mu^+ W^{-\nu} \Pi_{UD} \bar{\Pi}_{UD}$$

Some initial asymmetry

$$\partial_\mu J^\mu \sim W^{\mu\nu} \widetilde{W}_{\mu\nu}$$



Baryon asymmetry

Technibaryon asymmetry

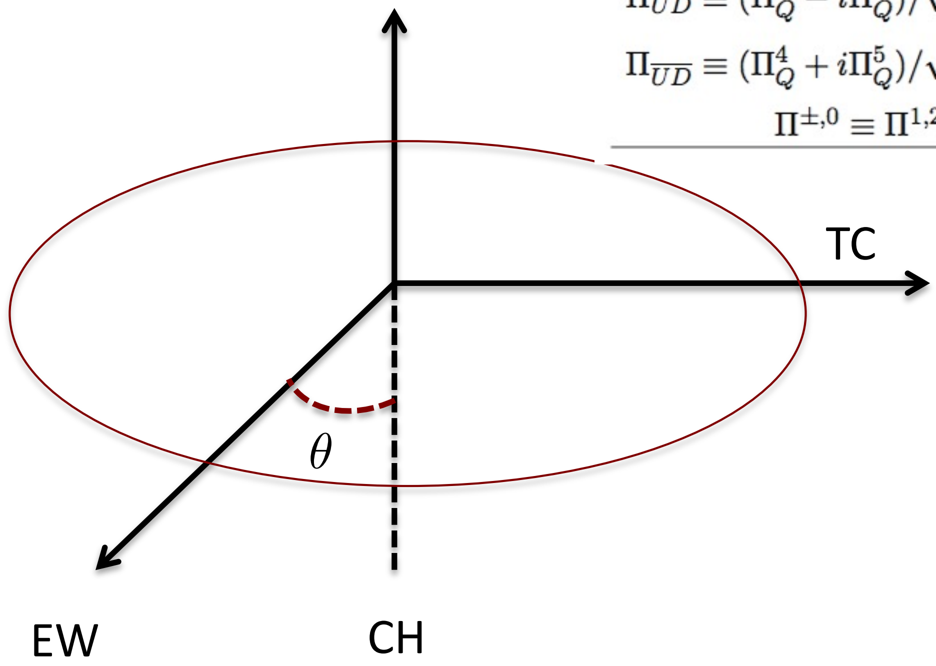
Technicolor

- Technibaryon stability (longevity) due to a U(1) symmetry
- Technibaryon mass from new strong dynamics (and Higgs)
- Technibaryon relic density from baryon asymmetry
- Self-interactions from new strong dynamics
  (though not necessarily big enough to address cusp-core)

Observed Higgs physics not obviously consistent with TC!

Framework: Composite Higgs

Composites	$\mathrm{U}(1)_{\mathrm{TB}}$	$\mathrm{U}(1)_{\mathrm{EM}}$	Θ
$\Pi_{UD} \equiv (\Pi_Q^4 - i\Pi_Q^5)/\sqrt{2} \sim U^T C D$	$\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi_{\overline{UD}} \equiv (\Pi_Q^4 + i\Pi_Q^5)/\sqrt{2} \sim \bar{U} C \bar{D}^T$	$-\frac{1}{\sqrt{2}}$	0	$\pi/2$
$\Pi^{\pm,0} \equiv \Pi^{1,2,3}$	0	$\pm 1, 0$	$\pi/2$



Composites	$\mathrm{U}(1)_{\mathrm{TB}}$	$\mathrm{U}(1)_{\mathrm{EM}}$	Θ
$h \equiv \Pi_Q^4 \sim \bar{U}U + \bar{D}D$	–	0	0
$\eta \equiv \Pi_Q^5 \sim \mathrm{Im}\, U^T C D$	–	0	0
$\Pi^{\pm,0} \equiv \Pi^{1,2,3}$	0	$\pm 1, 0$	0

No underlying stabilizing symmetry
for the CH range of parameters

(Galloway, Evans, Luty & Tacchi ’10; Ferretti & Karateev ‘13; Cacciapaglia & Sannino’14; Alanne, Buarque Franzosi & MTF ‘17)

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Summary

- Composite Dynamics compelling framework for DM and EW

U(1) stabilizing symmetries, dynamical symmetry breaking, naturalness, non-triviality, predictability (lattice)

- Vast space of models from 4d gauge-fermion-Yukawa theories

CH limit yields pNGB Higgs with properties tunably close to the SM Higgs. Correlated with DM turning WIMPy (in studied model)

- Lattice and diverse experiments test underlying models