Title: PSI 2015/2016 Standard Model - Lecture 15

Date: Jan 22, 2016 10:15 AM

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Abstract:

Problems with the SM

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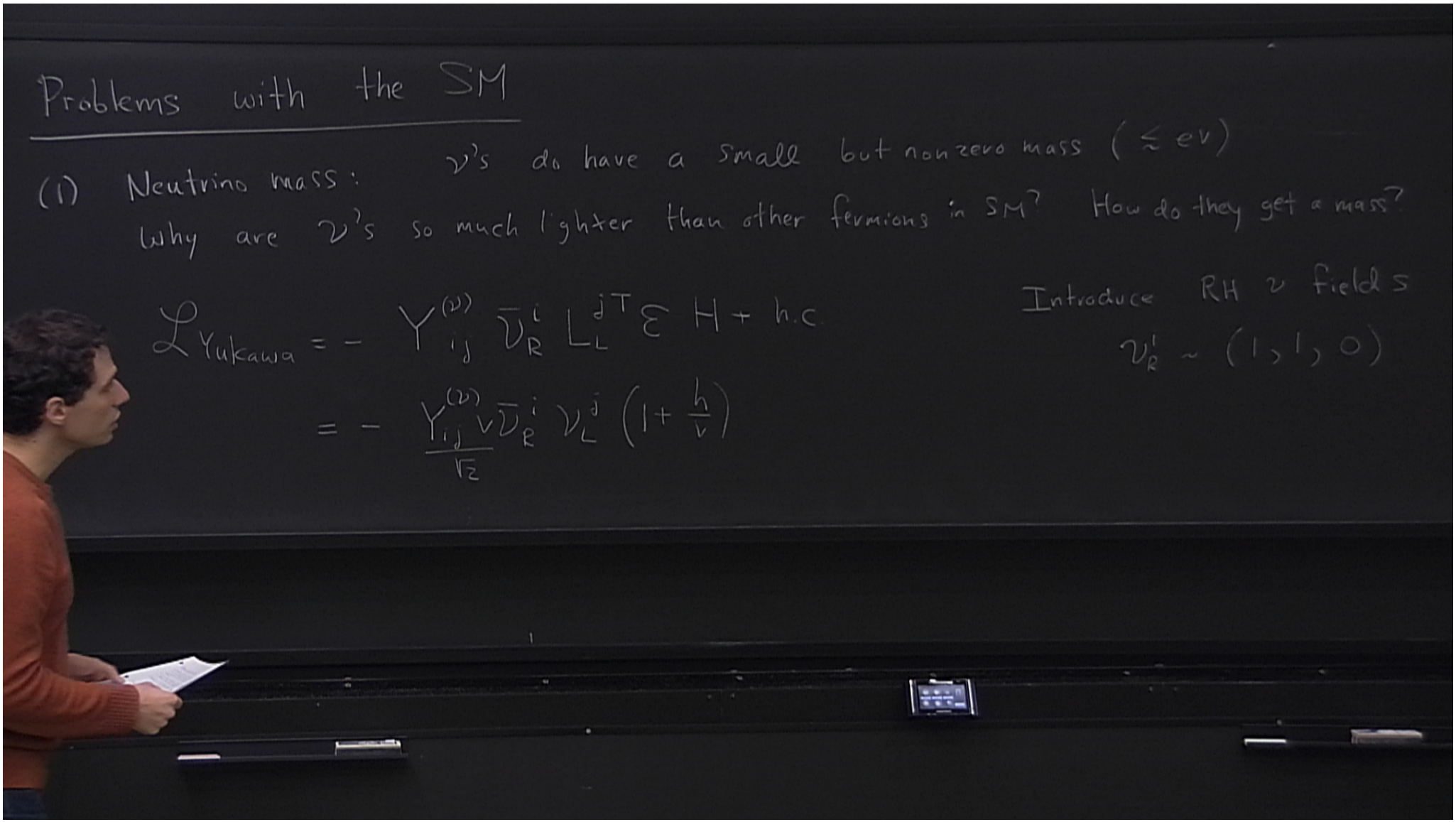
(1) Neutrino mass: ν's do have a small but nonzero mass ($\lesssim$ eV)

Why are ν's so much lighter than other fermions in SM? How do they get a mass?

$$\mathcal{L}_{\text{Yukawa}} = - Y^{(\nu)}_{ij} \bar{\nu}^i_R L^{jT}_L \varepsilon H + h.c$$


Problems with the SM
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$\mathcal{L}_{Yukawa} = - Y^{(\nu)}_{ij} \bar{\nu}^i_R L^{jT}_L \varepsilon H + h.c.$
$= - \frac{Y^{(\nu)}_{ij} v}{\sqrt{2}} \bar{\nu}^i_R \nu^j_L \left(1 + \frac{h}{v}\right)$
Introduce RH ν fields
$\nu^i_R \sim (1, 1, 0)$

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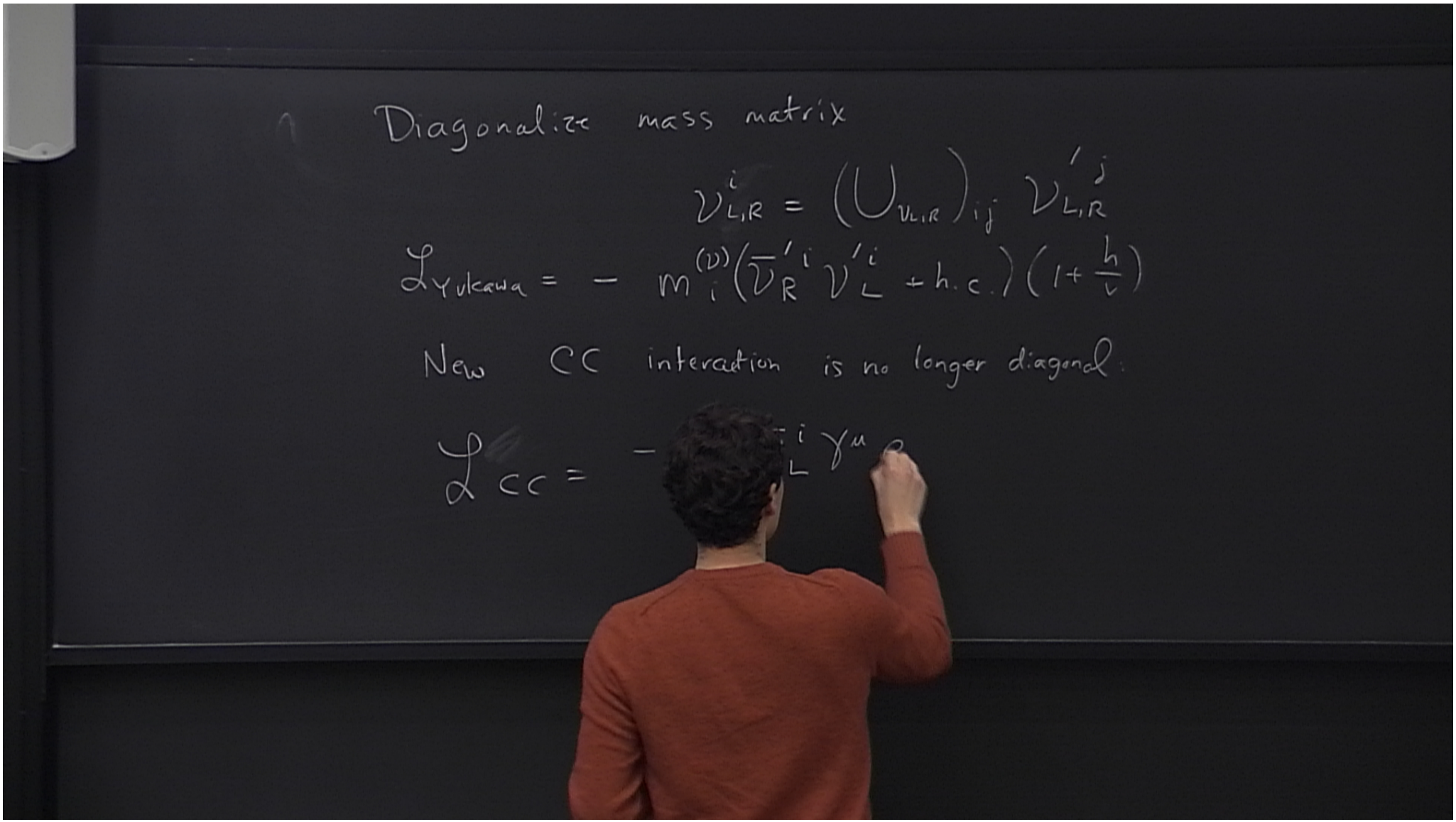
Diagonalize mass matrix

$$\nu^{i}_{L,R} = \left(U_{\nu_{L,R}}\right)_{ij} \nu'^{j}_{L,R}$$


Diagonalize mass matrix
$\nu^i_{L,R} = (U_{\nu_{L,R}})_{ij} \nu'^j_{L,R}$
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Diagonalize mass matrix

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matrix

$$_{L,R} = \left(U_{\nu_{L,R}}\right)_{ij} \nu'^{j}_{L,R}$$

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$$\bar{\nu}^{i}_{L} W^{+} e^{i}_{L} + h.c. = -\frac{g}{\sqrt{2}} \bar{\nu}'^{i}_{L} \left(U^{*}_{\nu_L}\right)_{ij} \left(U_{e_L}\right)_{jk} W^{+} e'^{k}_{L} + h.c.$$

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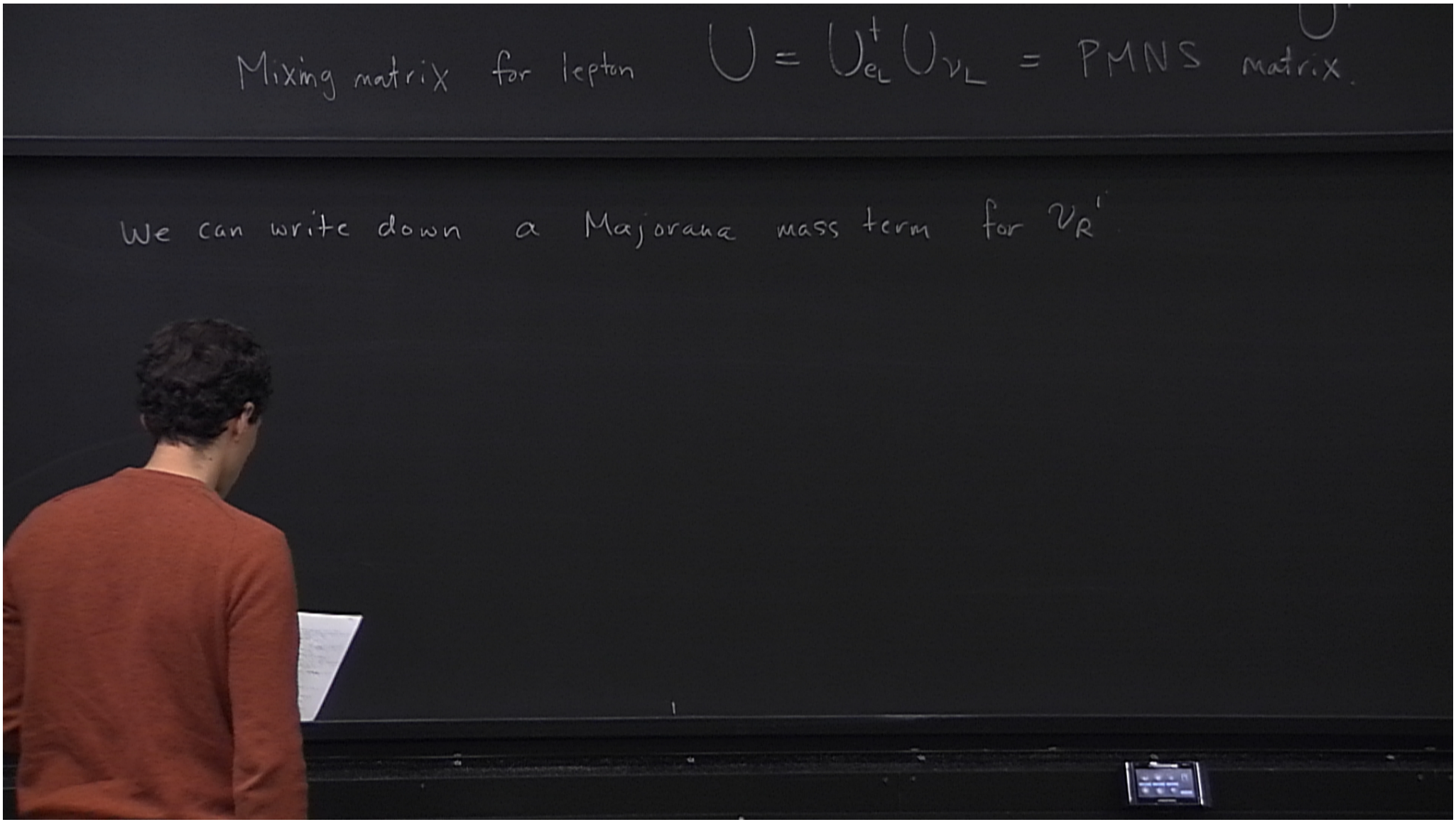
Mixing matrix for lepton $U = U^\dagger_{e_L} U_{\nu_L}$ = PMNS matrix.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We can write down a Majorana mass term for ν_R^i

$$\mathcal{L}_{Majorana} = -\frac{1}{2} M_{ij} \left(\bar{\nu}_R^i \nu_R^{c\,j} + \bar{\nu}_R^{i\,c} \nu_R^j \right)$$

C = charge conjugation

$$\nu_R^c = (\nu_R)^c = (P_R \nu)^c$$

$$\mathcal{L}_{\nu\,\text{mass}} = -m\left(\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R\right) - \frac{1}{2} M \left(\bar{\nu}_R \nu_R^c + \bar{\nu}_R^c \nu_R\right)$$

$m =$ Dirac mass $= \dfrac{y v}{\sqrt{2}}$

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$$\mathcal{L}_{\nu\,\text{mass}} = -\left(\bar{\nu}_L^c, \bar{\nu}_R\right) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + \text{h.c.}$$

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$$\psi = \begin{pmatrix} \xi \\ \eta^\dagger \end{pmatrix} \qquad \psi^c = \begin{pmatrix} \eta \\ \xi^\dagger \end{pmatrix}$$

$$\psi_R = \begin{pmatrix} 0 \\ \eta^\dagger \end{pmatrix} \qquad \psi_R^c = (\psi_R)^c = \begin{pmatrix} \eta \\ 0 \end{pmatrix}$$

Compute eigenvalue & eigenvectors (mass eigen states)

Assume $M \gg m$.

$$\nu \approx \nu_L$$
$$N \approx \nu_R$$

$$\mathcal{L}_{\nu mass} = -\frac{1}{2} m_\nu \bar{\nu}^c \nu - \frac{1}{2} m_N \bar{N}^c N$$

$$\mathcal{L}_{\nu\,\text{mass}} = -m\left(\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R\right) - \frac{1}{2} M \left(\bar{\nu}_R \nu_R^c + \bar{\nu}_R^c \nu_R\right)$$

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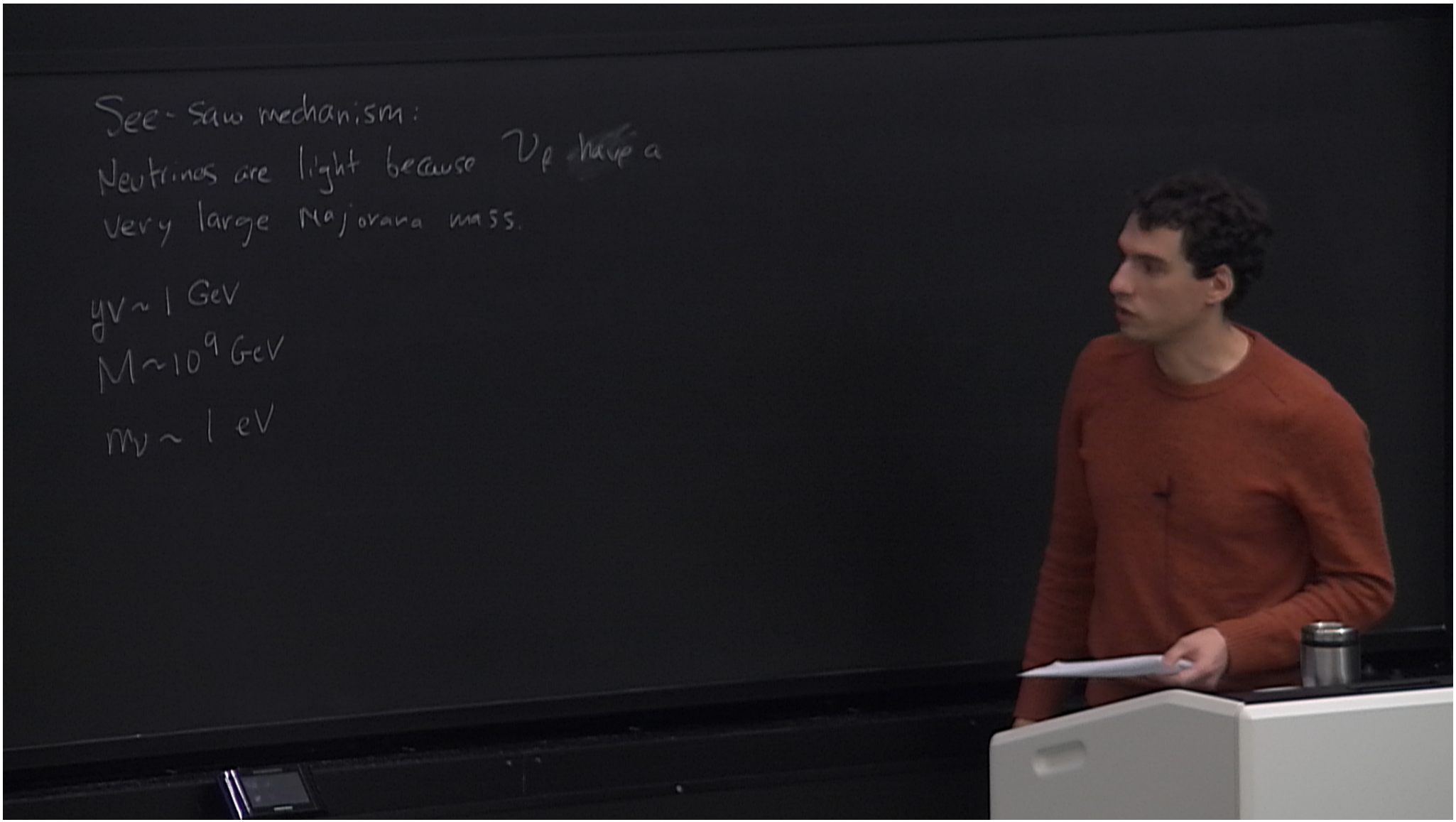
See-saw mechanism:
Neutrinos are light because ν_R have a
very large Majorana mass.
$yv \sim 1$ GeV
$M \sim 10^9$ GeV
$m_\nu \sim 1$ eV

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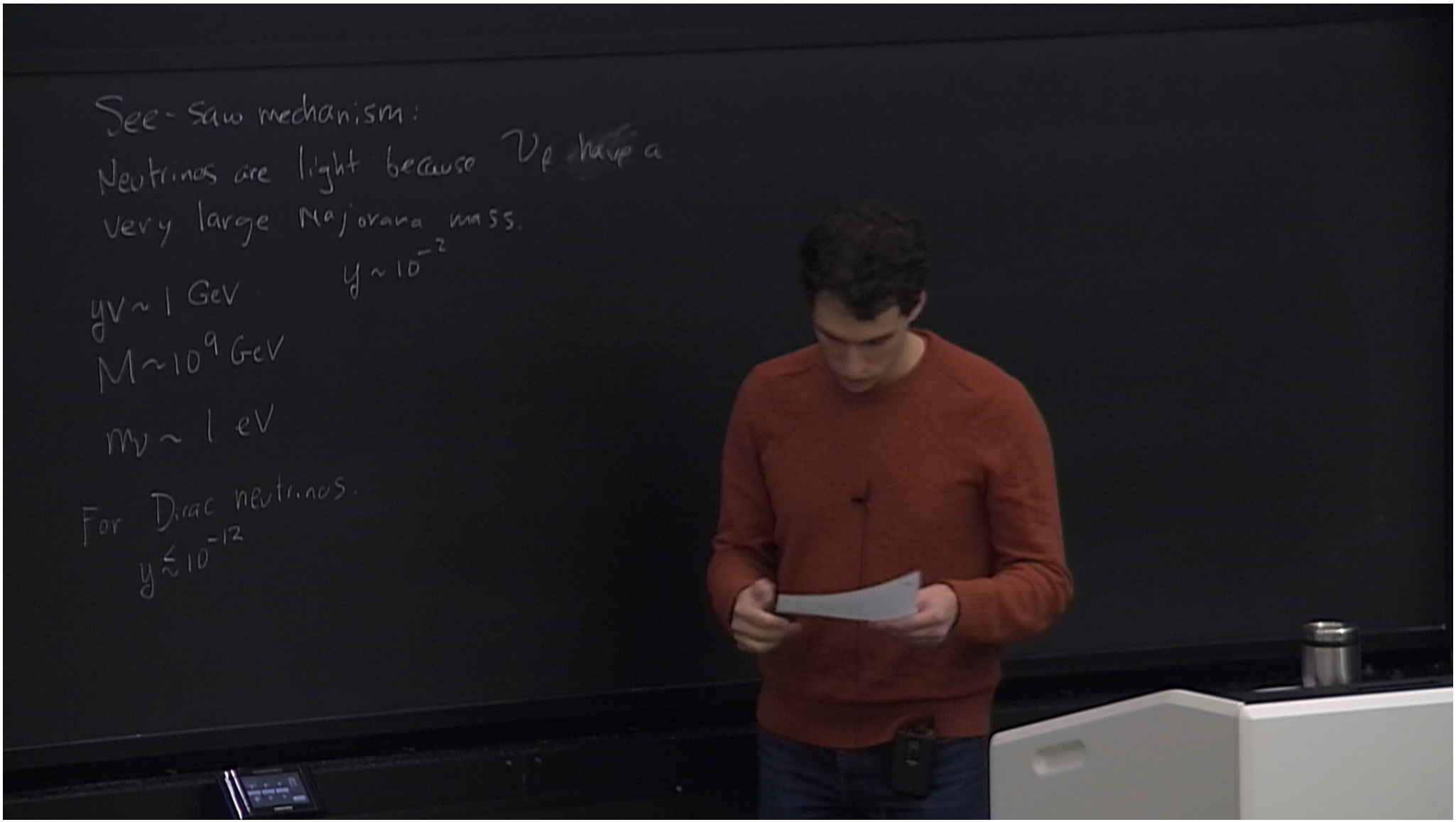
See-saw mechanism:
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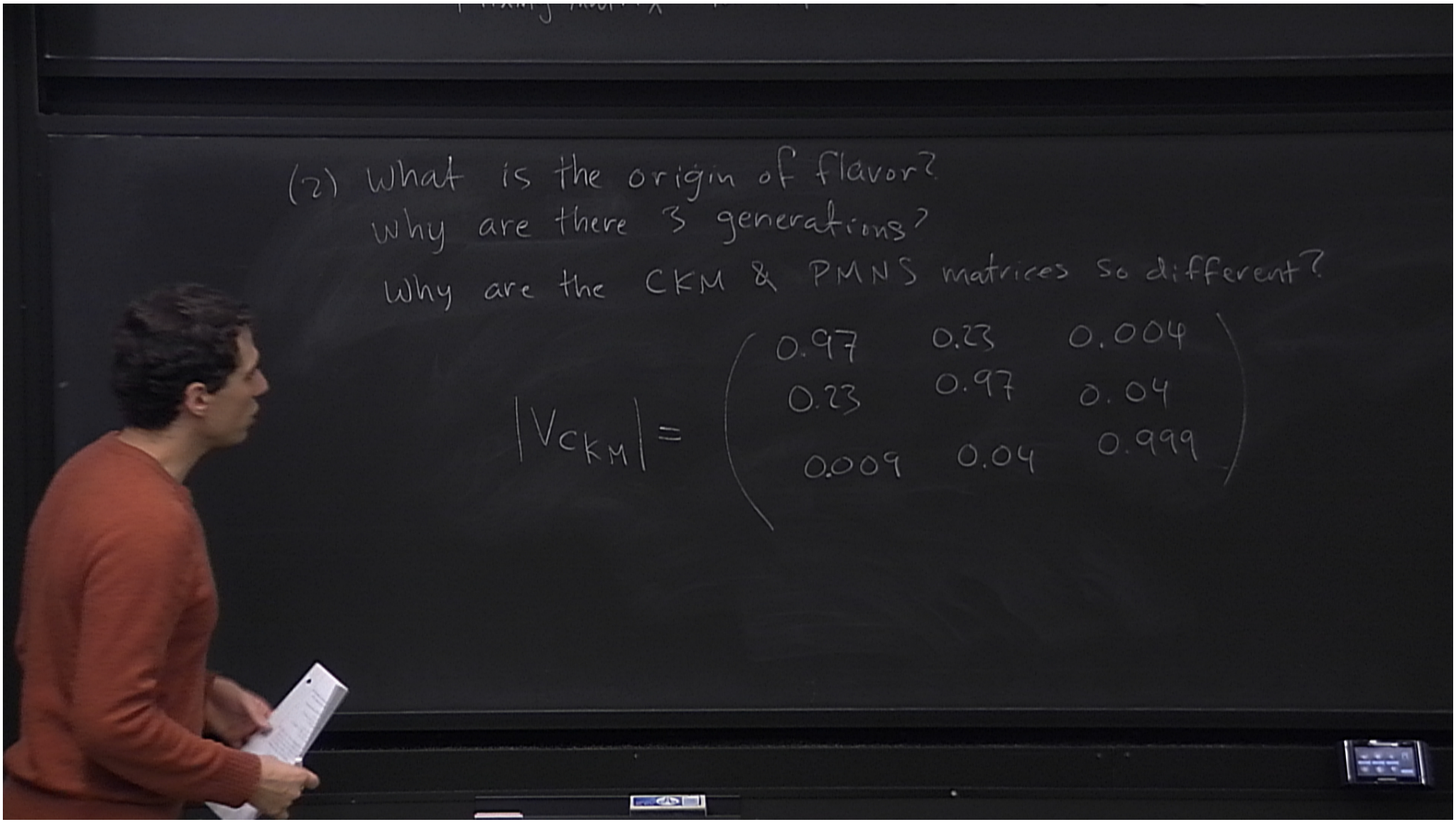
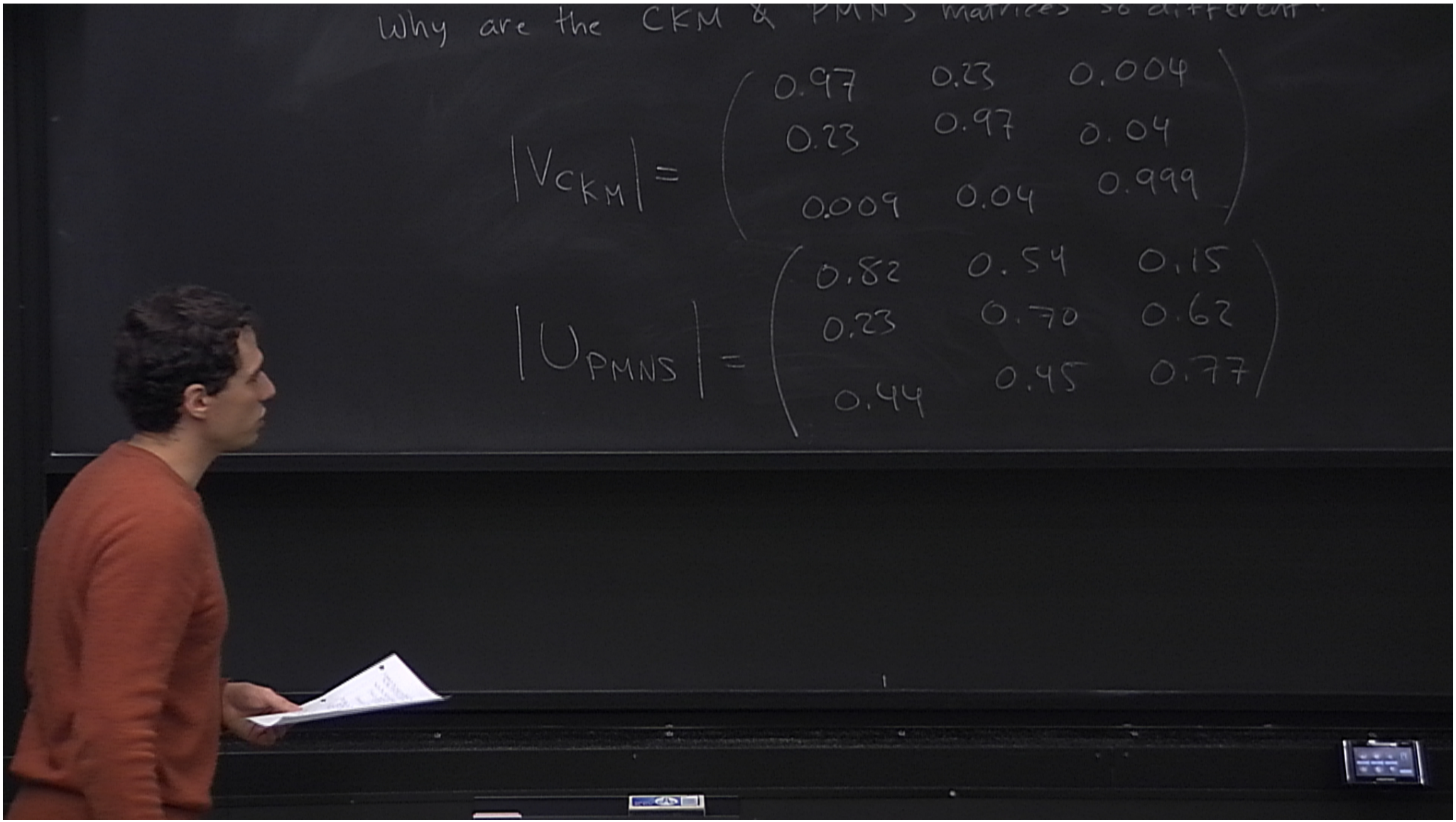
For Dirac neutrinos.
$y \lesssim 10^{-12}$


(2) What is the origin of flavor?
Why are there 3 generations?
Why are the CKM & PMNS matrices so different?
$|V_{CKM}| = \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.009 & 0.04 & 0.999 \end{pmatrix}$

ent?

closely aligned with $\mathbb{1}$.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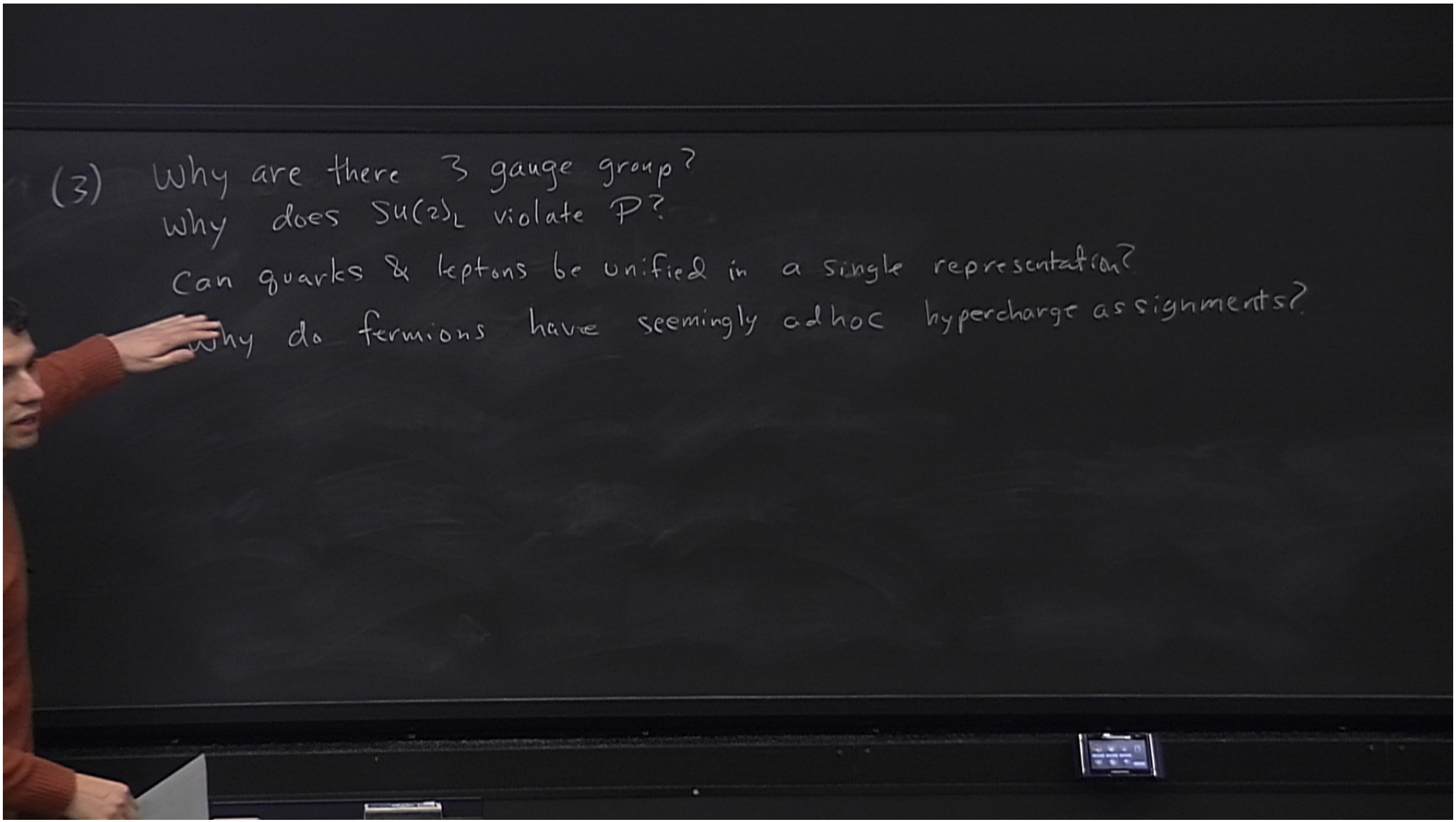
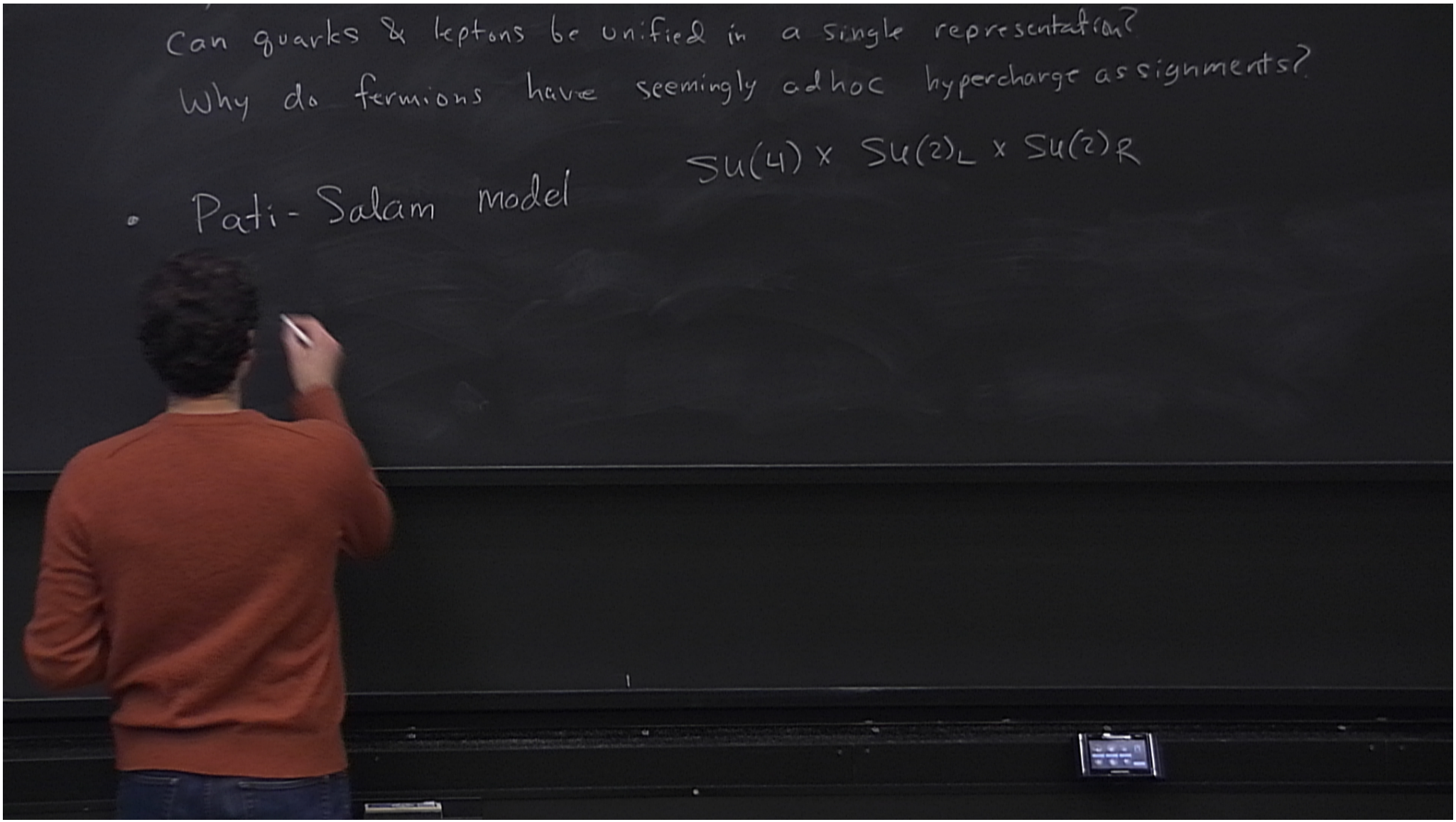
"anarchy"


(3) Why are there 3 gauge group?
Why does $SU(2)_L$ violate P?
Can quarks & leptons be unified in a single representation?
Why do fermions have seemingly ad hoc hypercharge assignments?


Can quarks & leptons be unified in a single representation?
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• Pati-Salam model
$SU(4) \times SU(2)_L \times SU(2)_R$

Can quarks & leptons be unified in a single representation?

Why do fermions have seemingly adhoc hypercharge assignments?

- Pati-Salam model $\quad SU(4) \times SU(2)_L \times SU(2)_R$

  Restores parity.

  Quarks & lepton are unified. $\quad \psi_L \sim (4, 2, 1)$

$$= \begin{pmatrix} u_L^r & d_L^r \\ u_L^g & d_L^g \\ u_L^b & d_L^b \\ \nu_L & e_L \end{pmatrix}$$

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ati-Salam model

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Explains hypercharge.

(combination of $SU(4) \times SU(2)_R$ generators)

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$$\psi_R \sim (4, 1, 2)$$

(combination of SU(4) × SU(2)R generators) $\begin{pmatrix} \nu_L & e_L \end{pmatrix}$

- Georgi-Glashow SU(5) model. (Grand Unified theory (GUT))

  $SU(5) \to SU(3) \times SU(2) \times U(1)_Y$

  SM fermions fit into two representations.

  $\bar{5} = \begin{array}{|c|}\hline \\ \hline \\ \hline \\ \hline \\ \hline \end{array}$

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$$10 = \begin{array}{|c|c|}\hline \\ \hline \\ \hline \\ \hline \end{array}$$

$u_L \quad e_L$

...fied theory (GUT))

3 colors

Lepton doublet

Georgi SO(10)

Fit all SM fermions + ν_R in a single rep. of SO(10).

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Fit all SM fermions + ν_R in a single rep. of SO(10). 16 dim rep.

2 quarks $(u,d) \times 2$ chiralities $\times$ 3 colors

$+$ 2 leptons $(e,\nu) \times 2$ chiralities $= 16$.

$u_L \quad e_L$

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} Lepton doublet

Georgi $SO(10) \nearrow SU(5) \longrightarrow SU(3) \times SU(2) \times U(1)$

$\searrow P.S. \nearrow$

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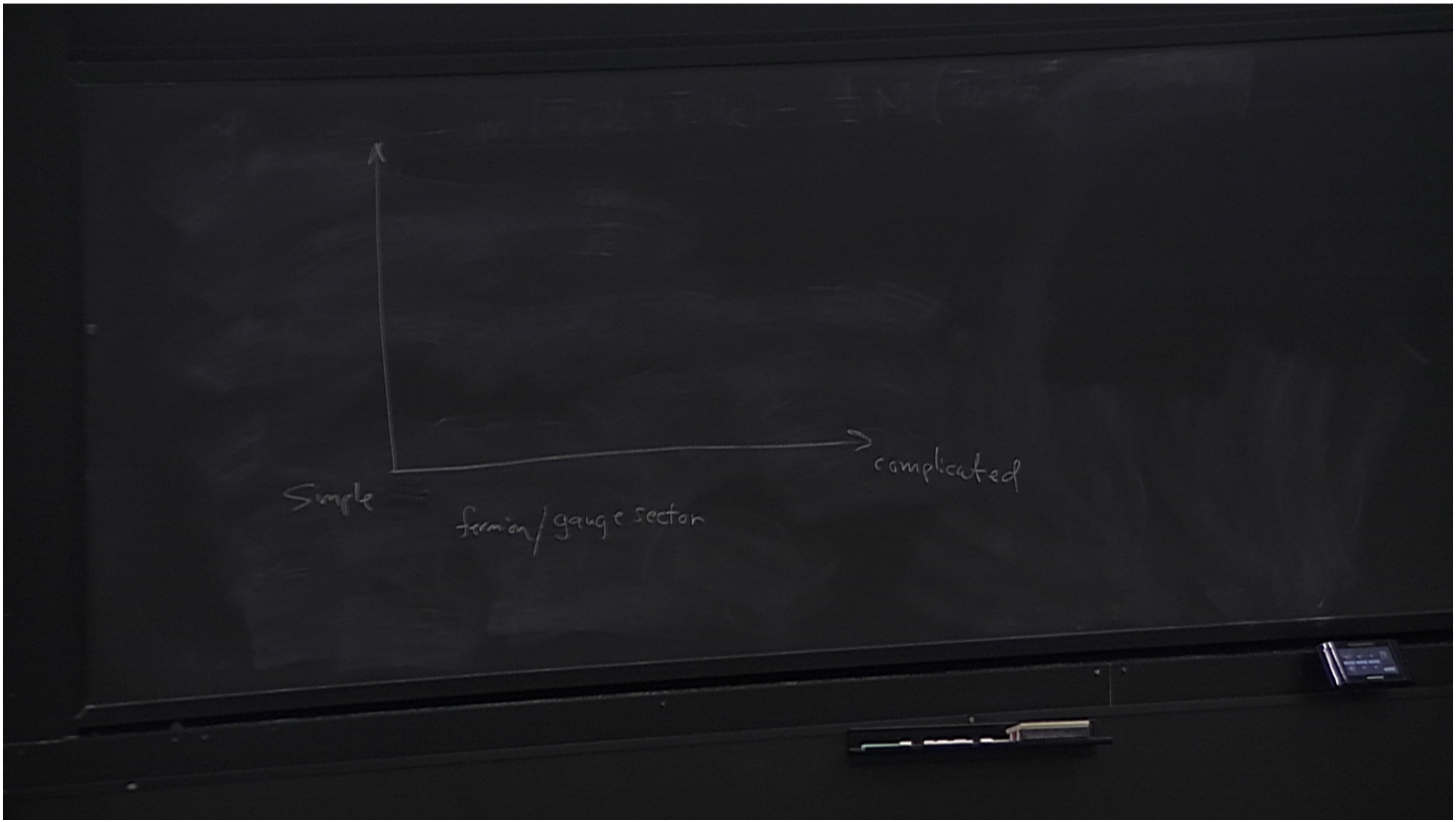
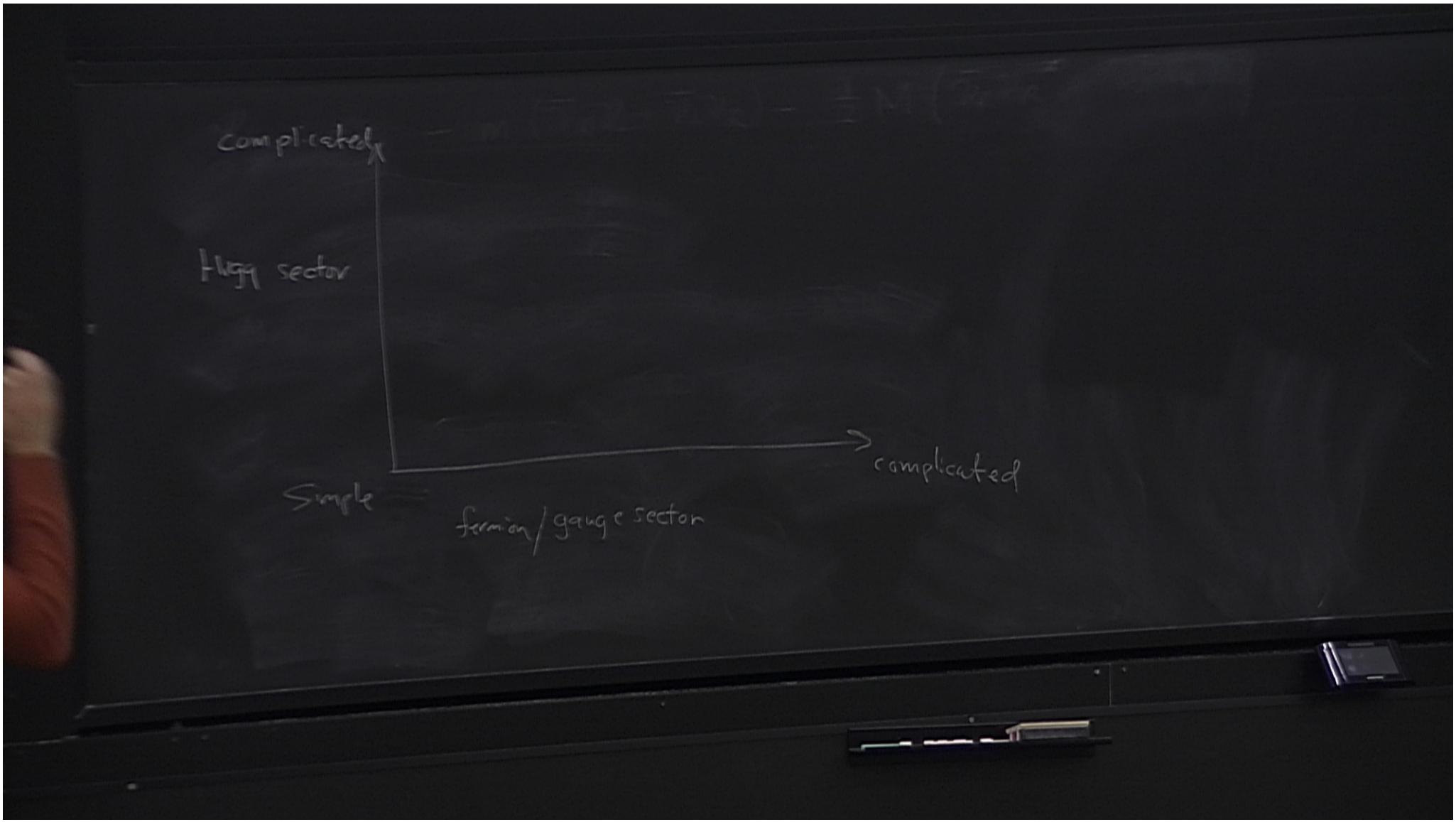

complicated
Simple
fermion/gauge sector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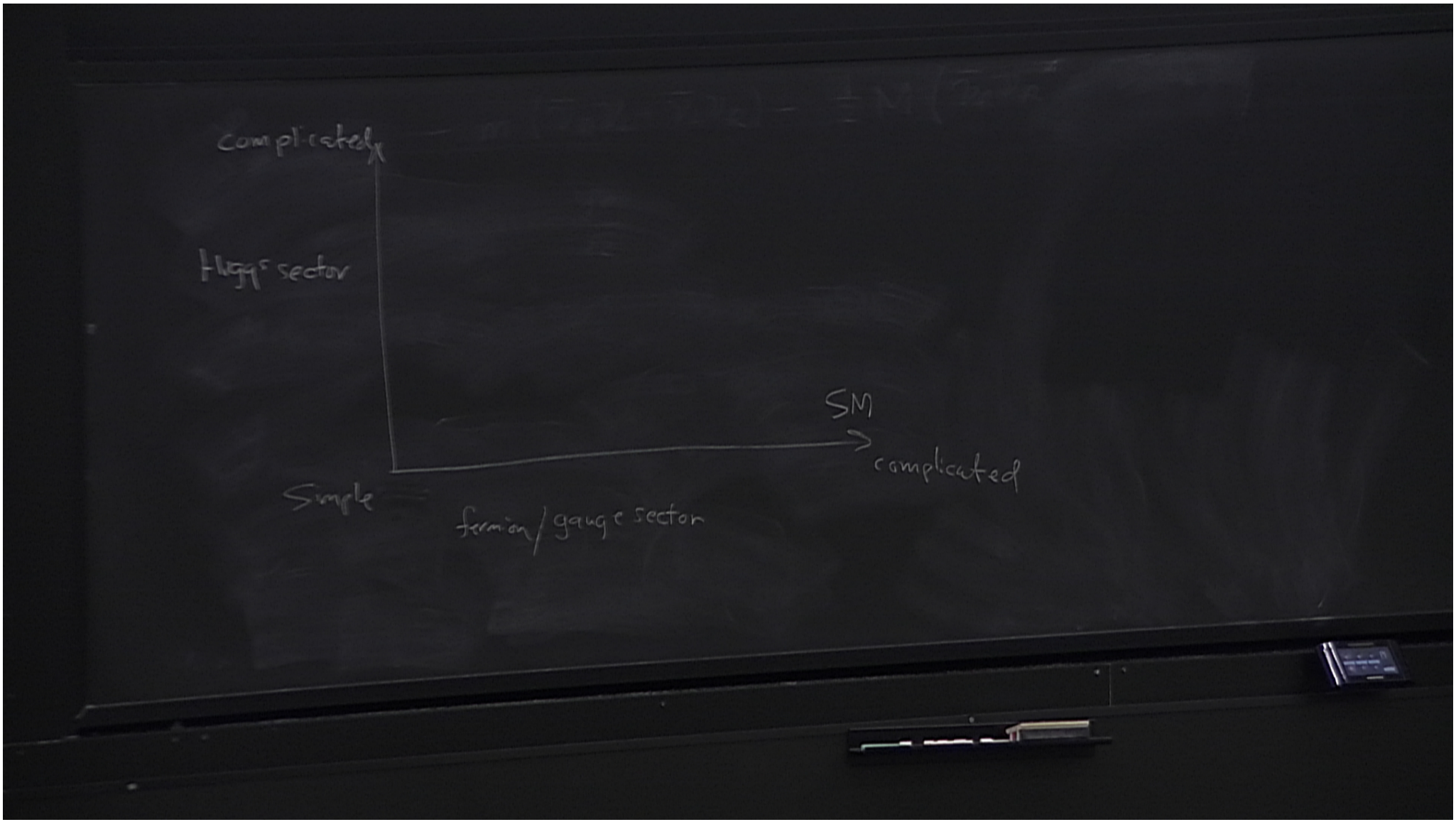
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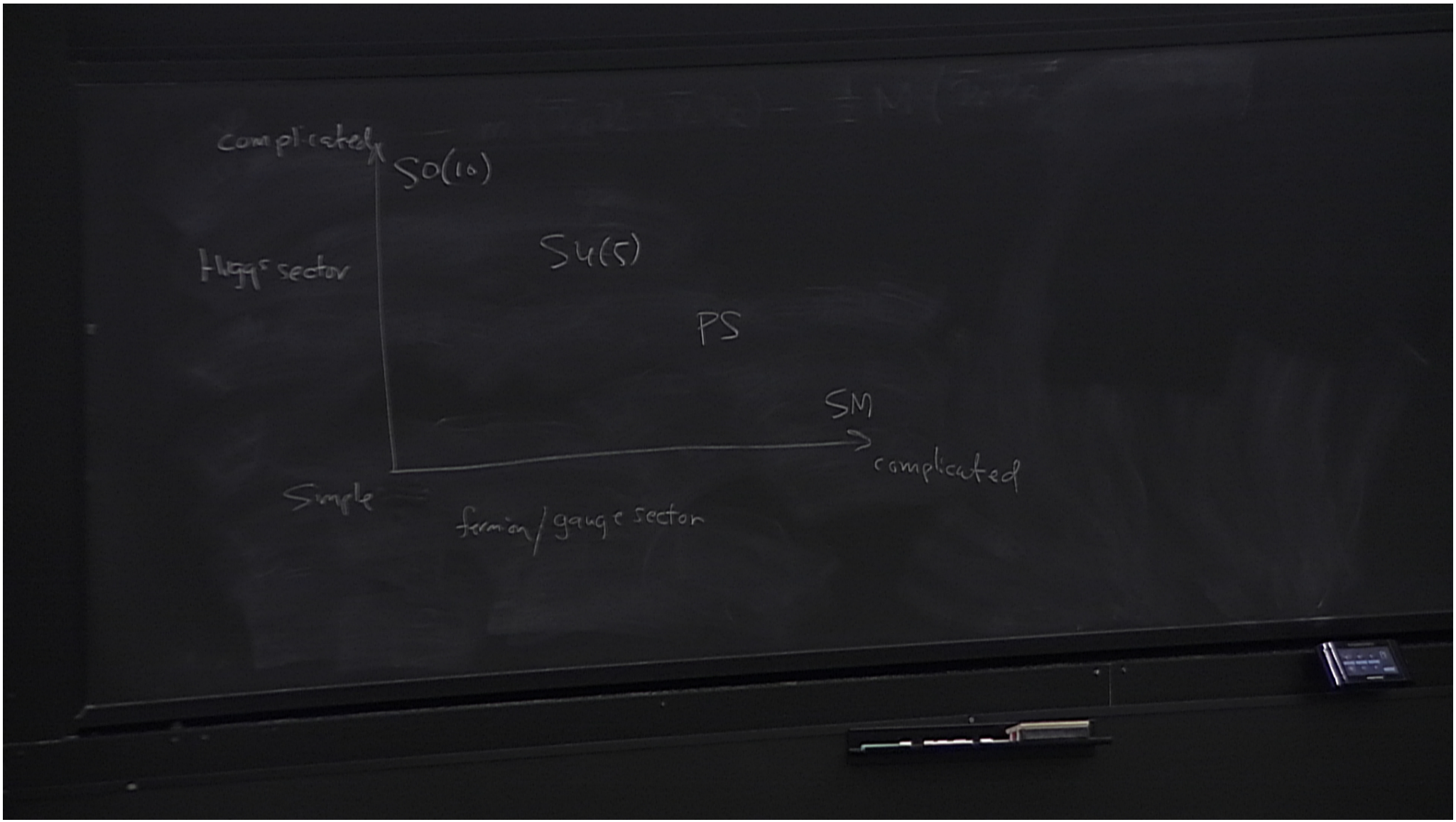
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$$10 = \begin{array}{c} \square \\ \square \\ \square \\ \square \end{array}$$

$$1 = \nu_R$$

(combination of SU(4) × SU(2)R generat...

String theory (2) What is the origin of flavor?

Why are there 3 generations?

Why are the CKM & PMNS matrices so different?

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$| = \nu_R$

Standard Model Problems: The Dark Matter Puzzle

Sean Tulin

PSI lecture Fri Jan 22

YORK UNIVERSITÉ UNIVERSITY

Luminous mass ≠ Gravitational mass

Total mass of what we see (observed stars and gas)

Total mass inferred by how stars and galaxies move under gravity

Dark matter proposed by Fritz Zwicky in 1933, but not taken seriously.

Zwicky

The dark matter issue became a convincing problem after work by Vera Rubin in 1970s.

Rubin

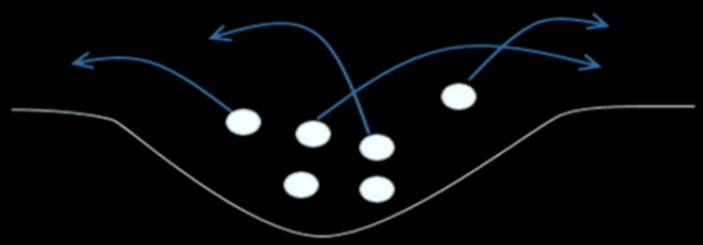
Zwicky's argument for dark matter

Coma cluster (*Sloan Digital Sky Survey*)

Zwicky's argument for dark matter

Galaxies are moving too fast and not enough mass to bind them together

The galaxies should just fly apart!



Coma cluster (*Sloan Digital Sky Survey*)

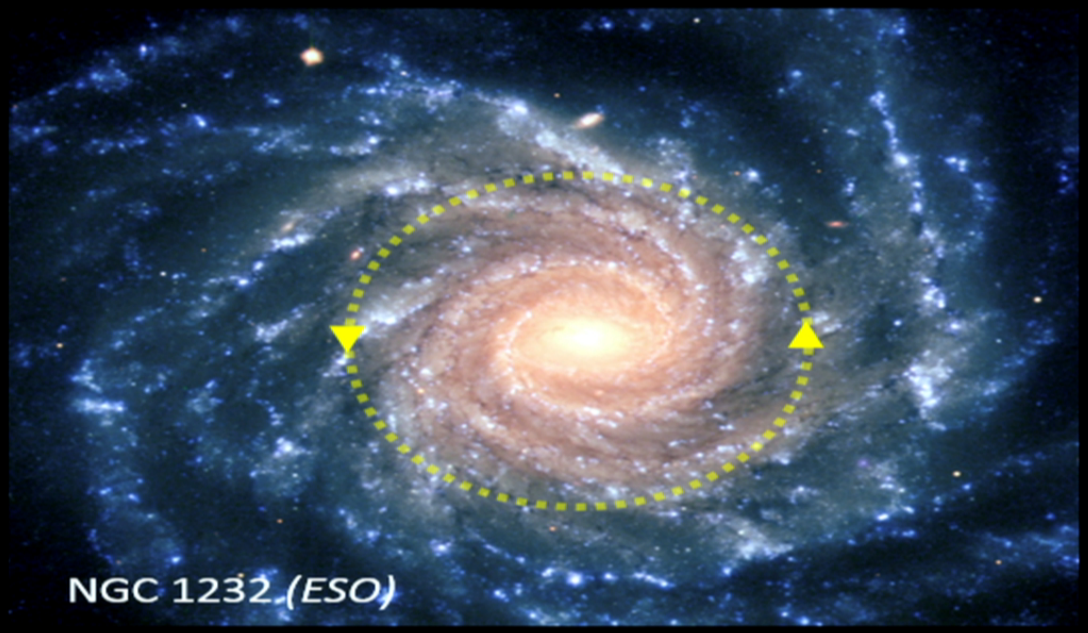
Zwicky's argument for dark matter

There is extra matter: **gas**
X-ray emission from gas

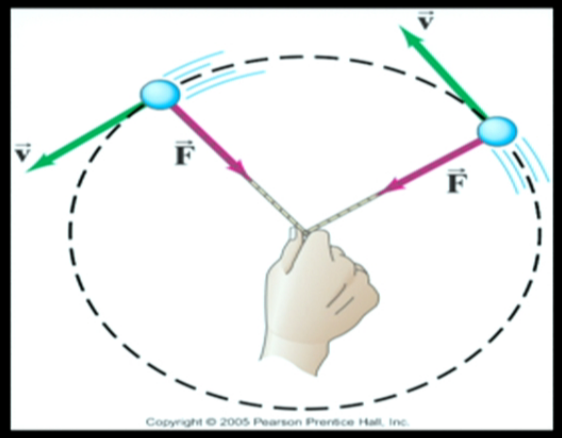
But *still* too little matter

<u>Mass budget for Coma cluster</u>
Stars and gas = 15% of total mass
85% of total mass = unseen mass
(dark matter)

Rubin's argument for dark matter

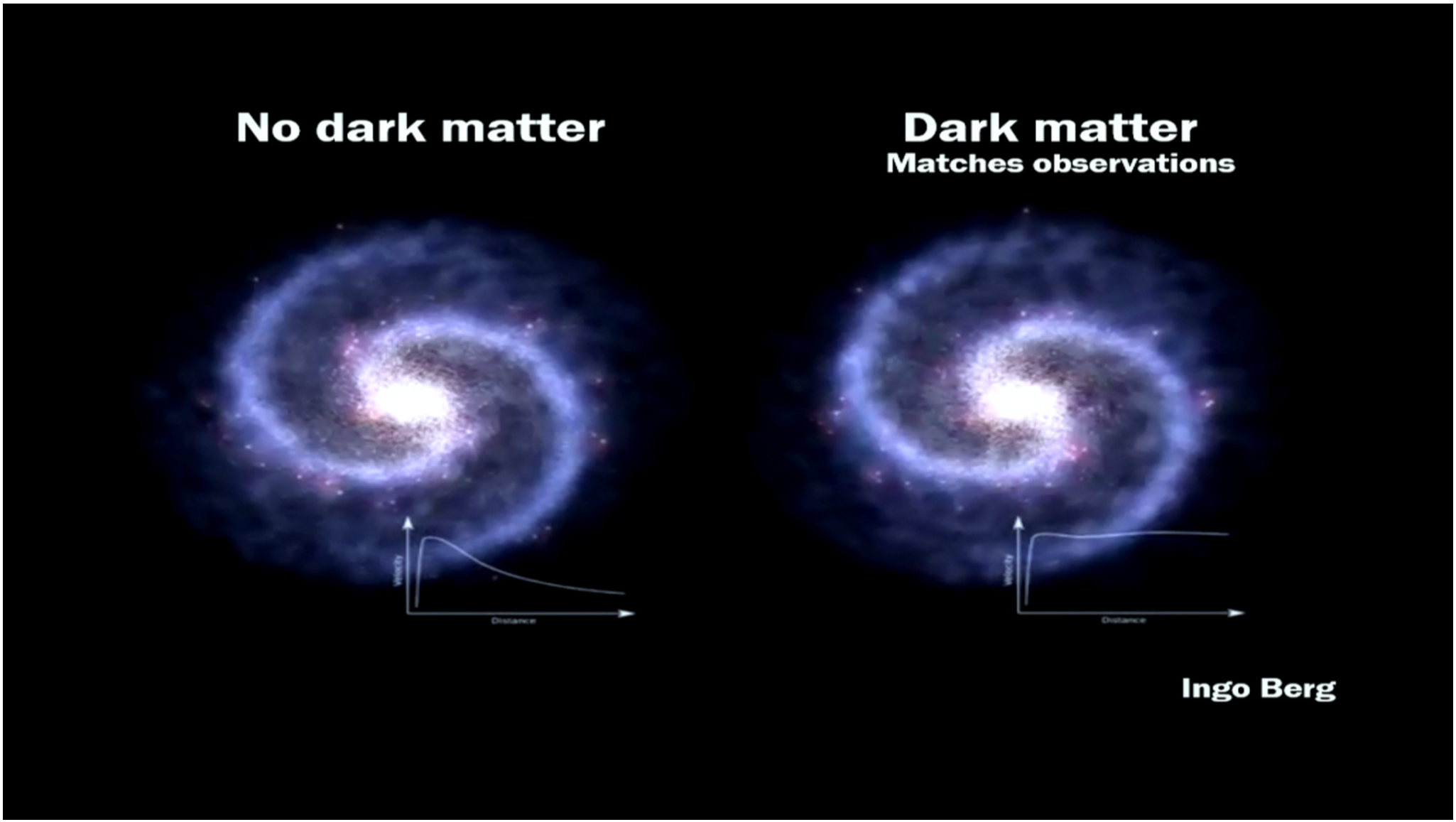


Stars are rotating too fast in galaxies

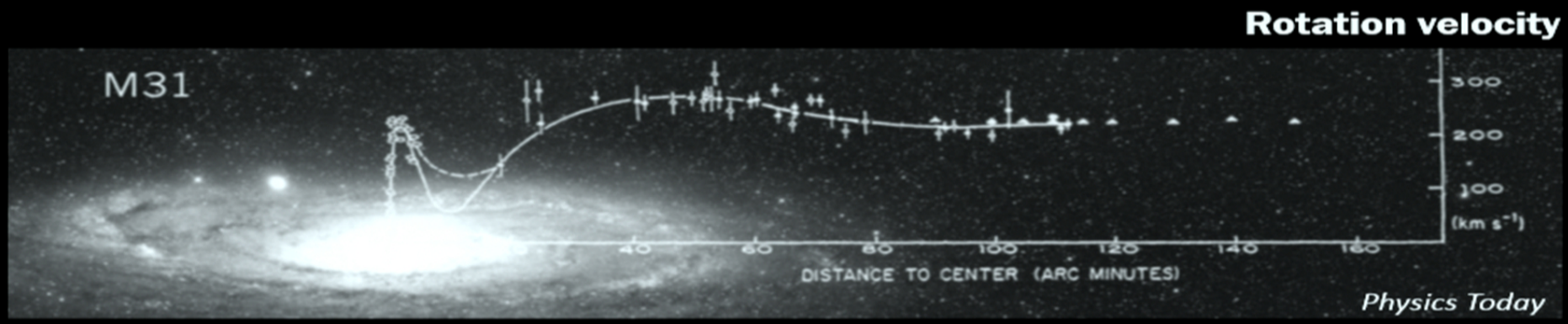


$$v(r)^2 = GM(r)/r$$

v = circular velocity
G = Newton's constant
M = total mass enclosed within radius r


No dark matter
Dark matter
Matches observations
Ingo Berg

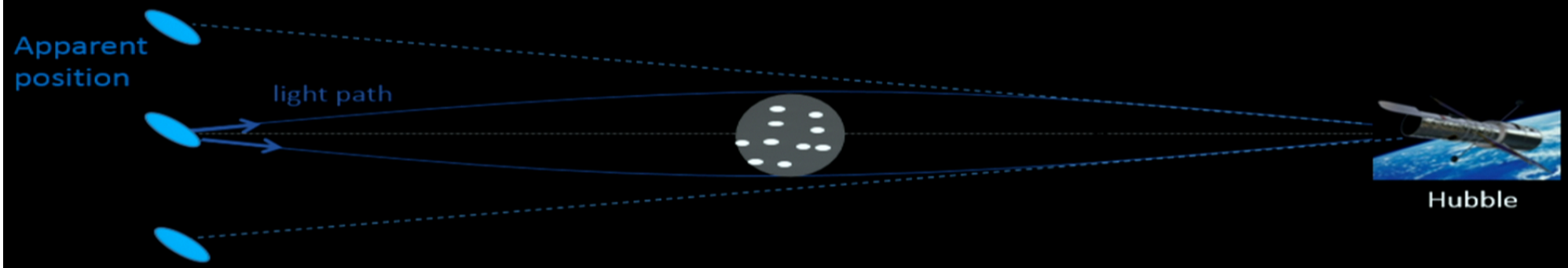
Andromeda galaxy

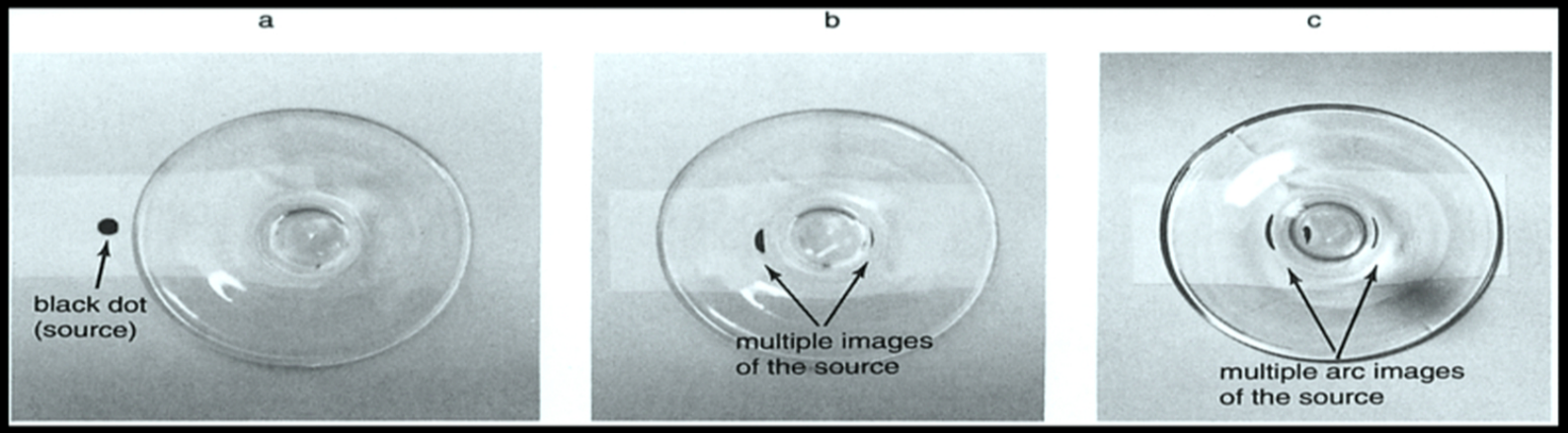


Constant velocity implies dM/dr = constant.

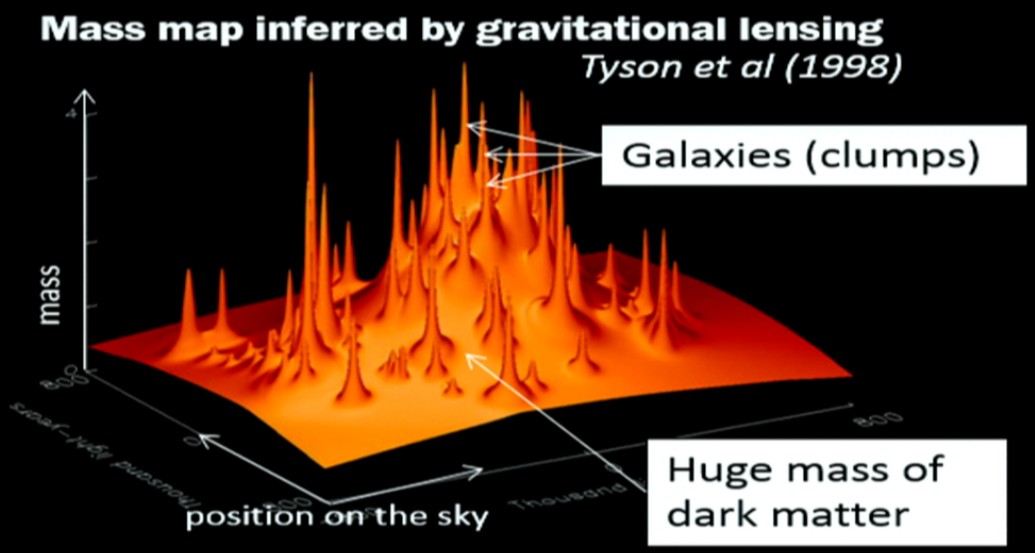
Much more mass in outer halo than the inner halo.

Seeing dark matter through its gravity

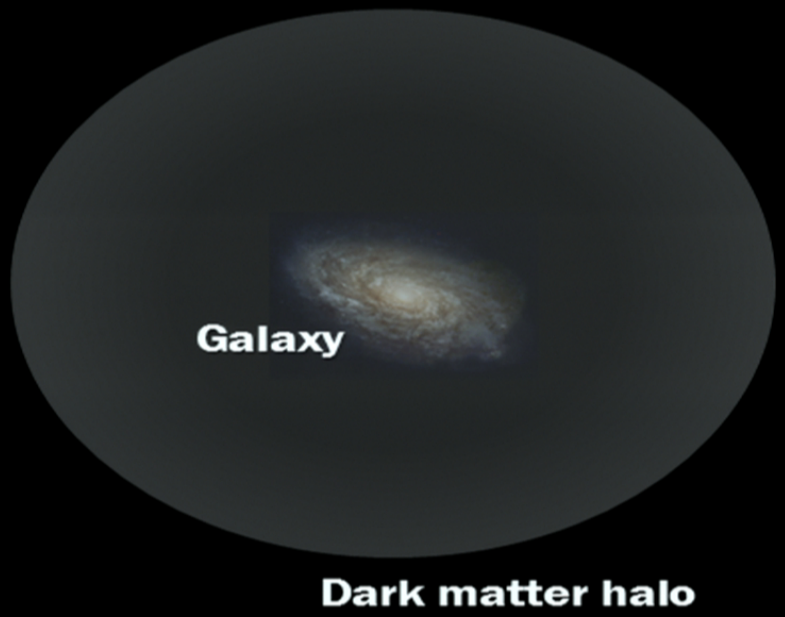




Seeing dark matter through its gravity



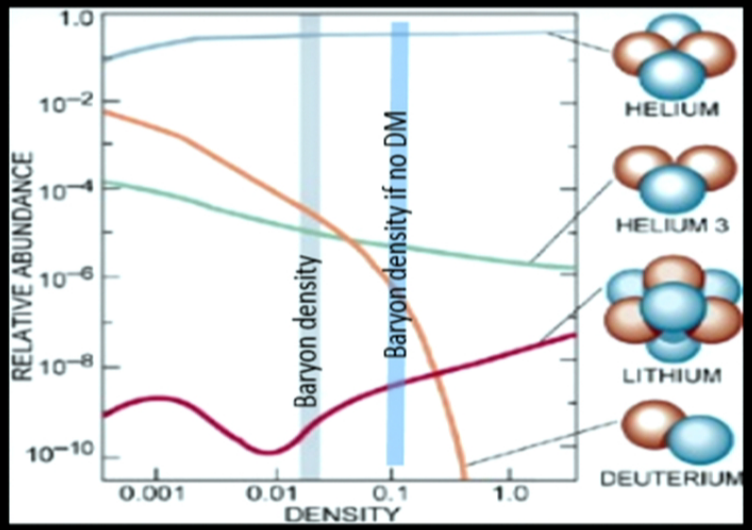
All visible galaxies are tiny objects inside of much bigger, more massive halos of dark matter



Dark matter governs the structure of visible matter

Halo stabilizes thin disk galaxies we observe
Otherwise they are unstable to perturbations

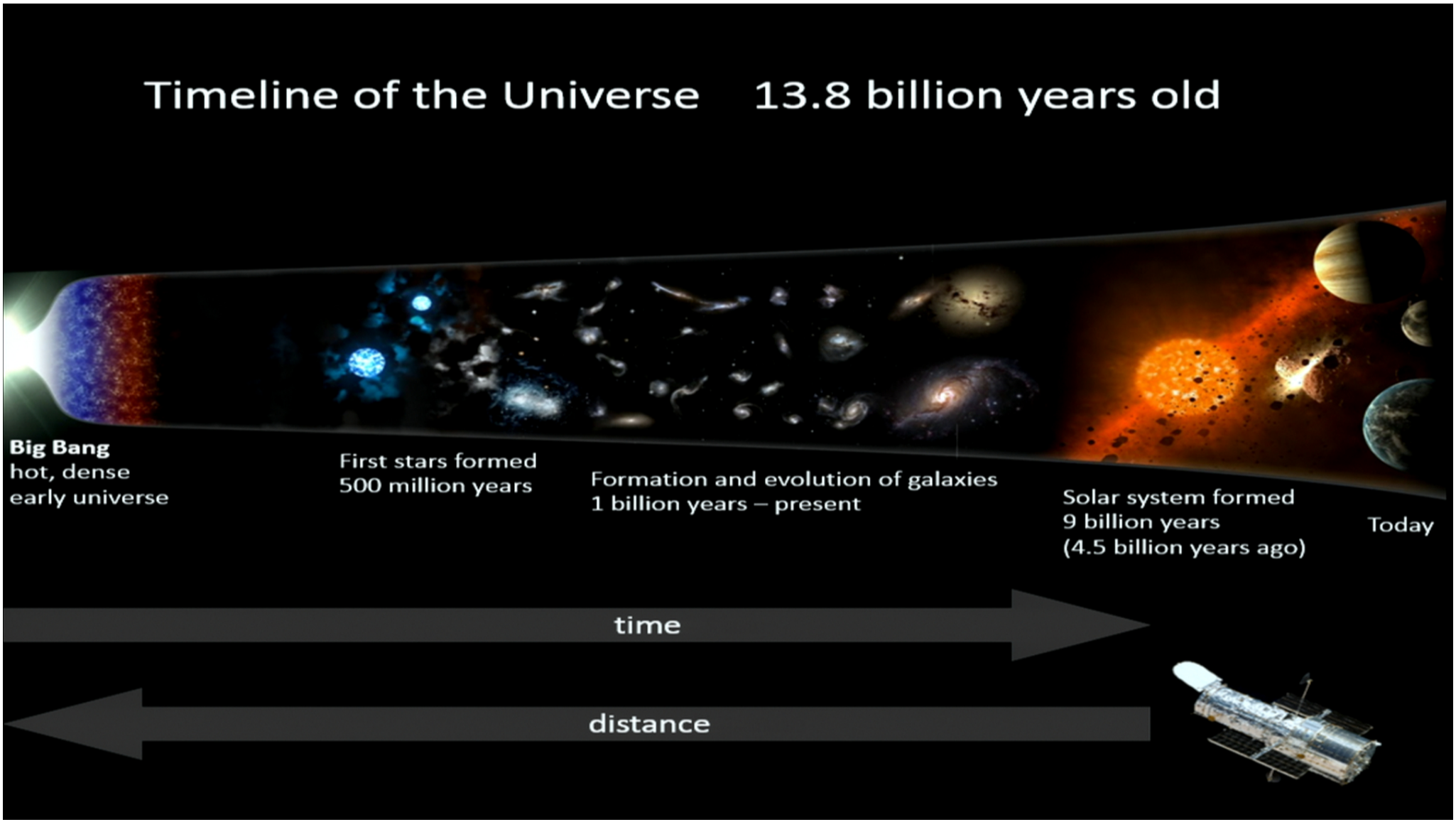
Is dark matter made from baryons?



Very faint stars, gas, or planets that we cannot detect?

Light isotope abundances depend on the baryon density at t ~ 1 min (way before any stars have formed).

Having baryons be all the dark matter is excluded by measured abundance of deuterium
No Standard Model particle can be dark matter


Timeline of the Universe 13.8 billion years old
Big Bang
hot, dense
early universe
First stars formed
500 million years
Formation and evolution of galaxies
1 billion years – present
Solar system formed
9 billion years
(4.5 billion years ago)
Today
time
distance

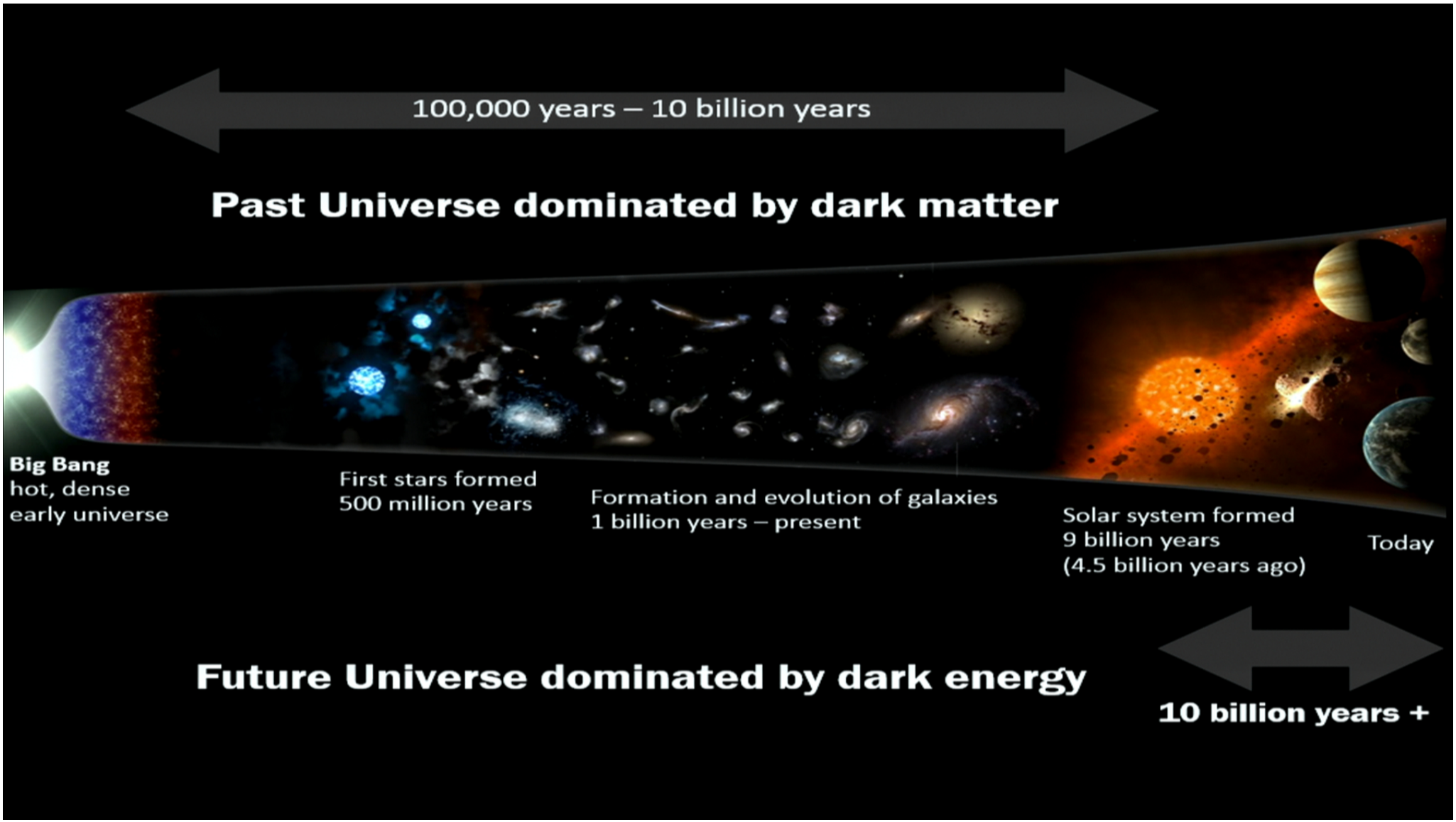
What is the Universe made of?

Energy/mass budget (using $E=mc^2$):

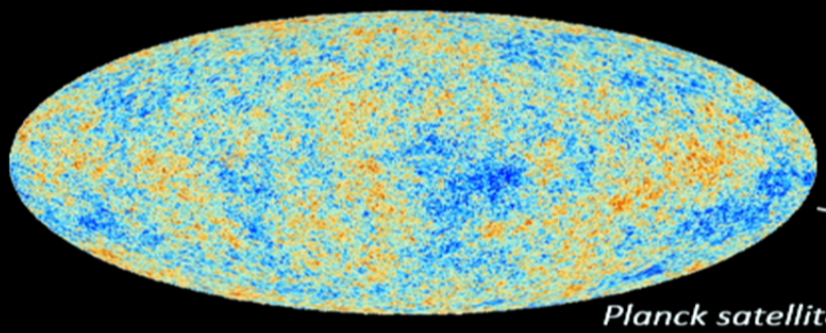
SM
- 0.005% light
- ~ 0.005% neutrinos
- 5% atoms (stars, planets, interstellar gas and dust)

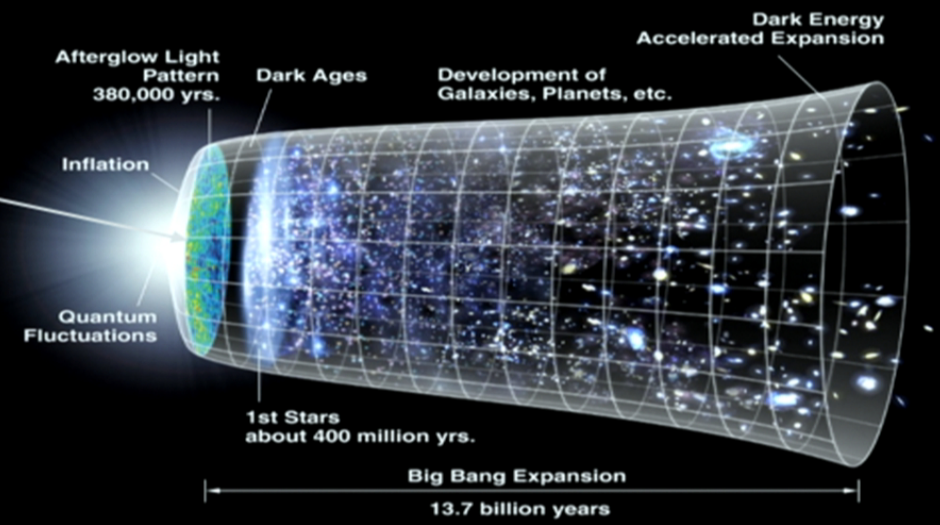
?
- 25% dark matter
- 70% dark energy

Dark Universe is 95% of the Universe.
Its nature is unknown.

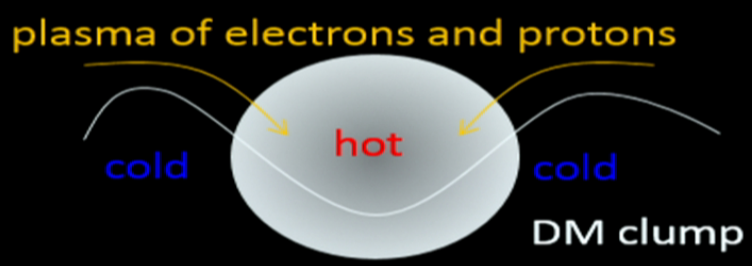

100,000 years – 10 billion years
Past Universe dominated by dark matter
Big Bang
hot, dense
early universe
First stars formed
500 million years
Formation and evolution of galaxies
1 billion years – present
Solar system formed
9 billion years
(4.5 billion years ago)
Today
Future Universe dominated by dark energy
10 billion years +

How does dark matter form the structure of the Universe?



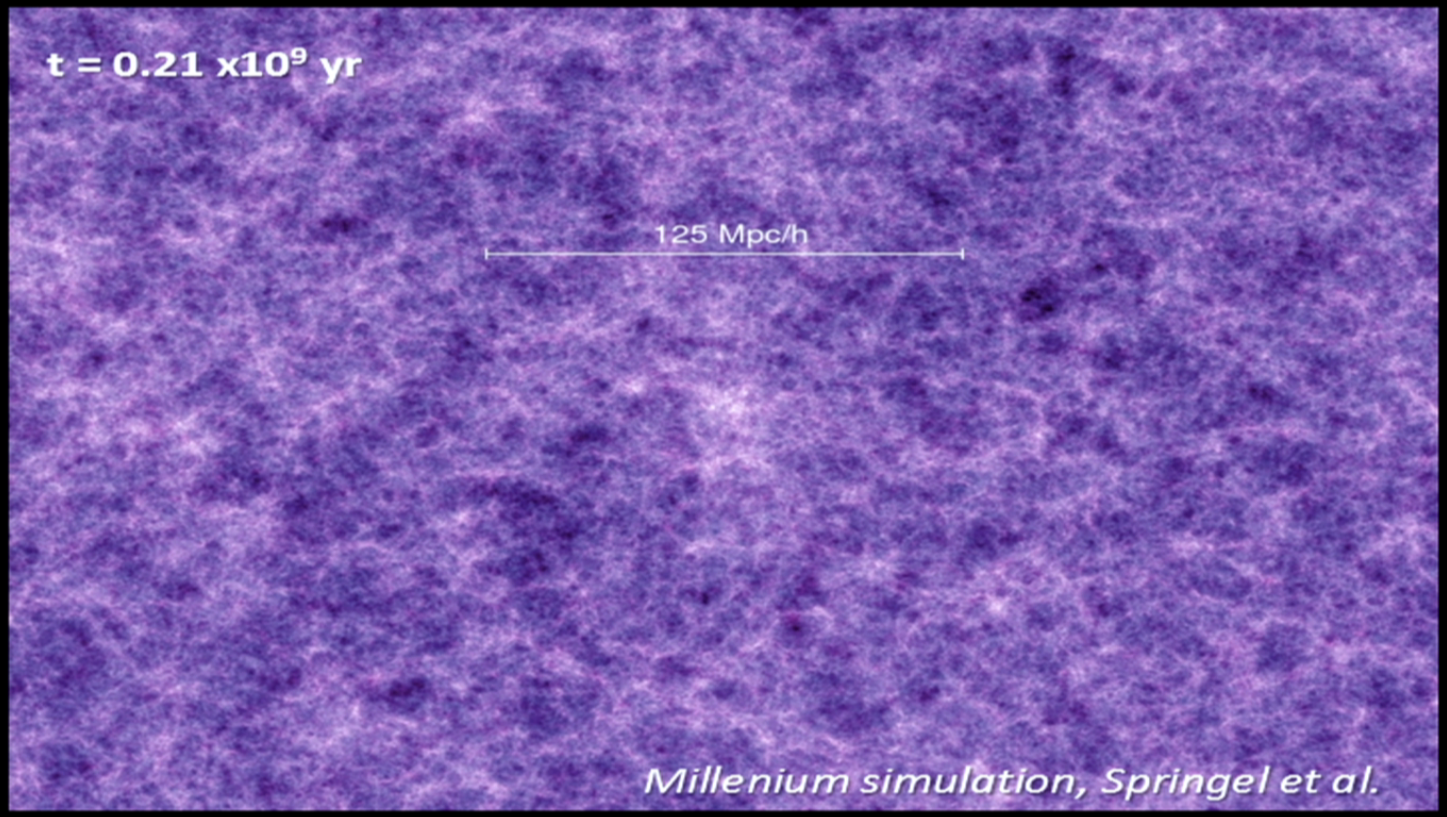


Cosmic microwave background shows the initial fluctuations of dark matter before structure formed ($\delta\rho/\rho \sim 10^{-5}$)

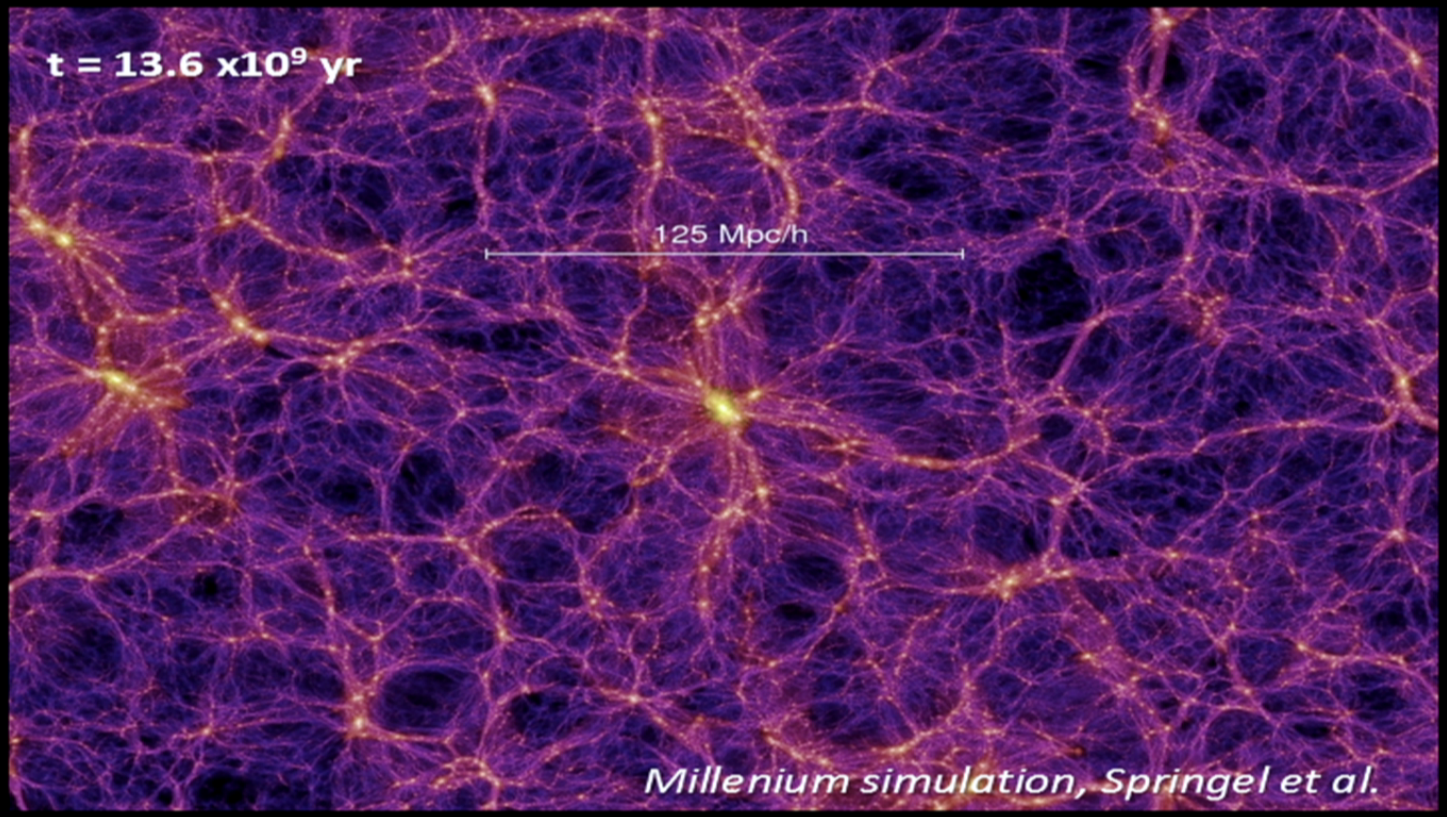


Evolve the Universe in time

Dark matter N-body simulations



Dark matter N-body simulations



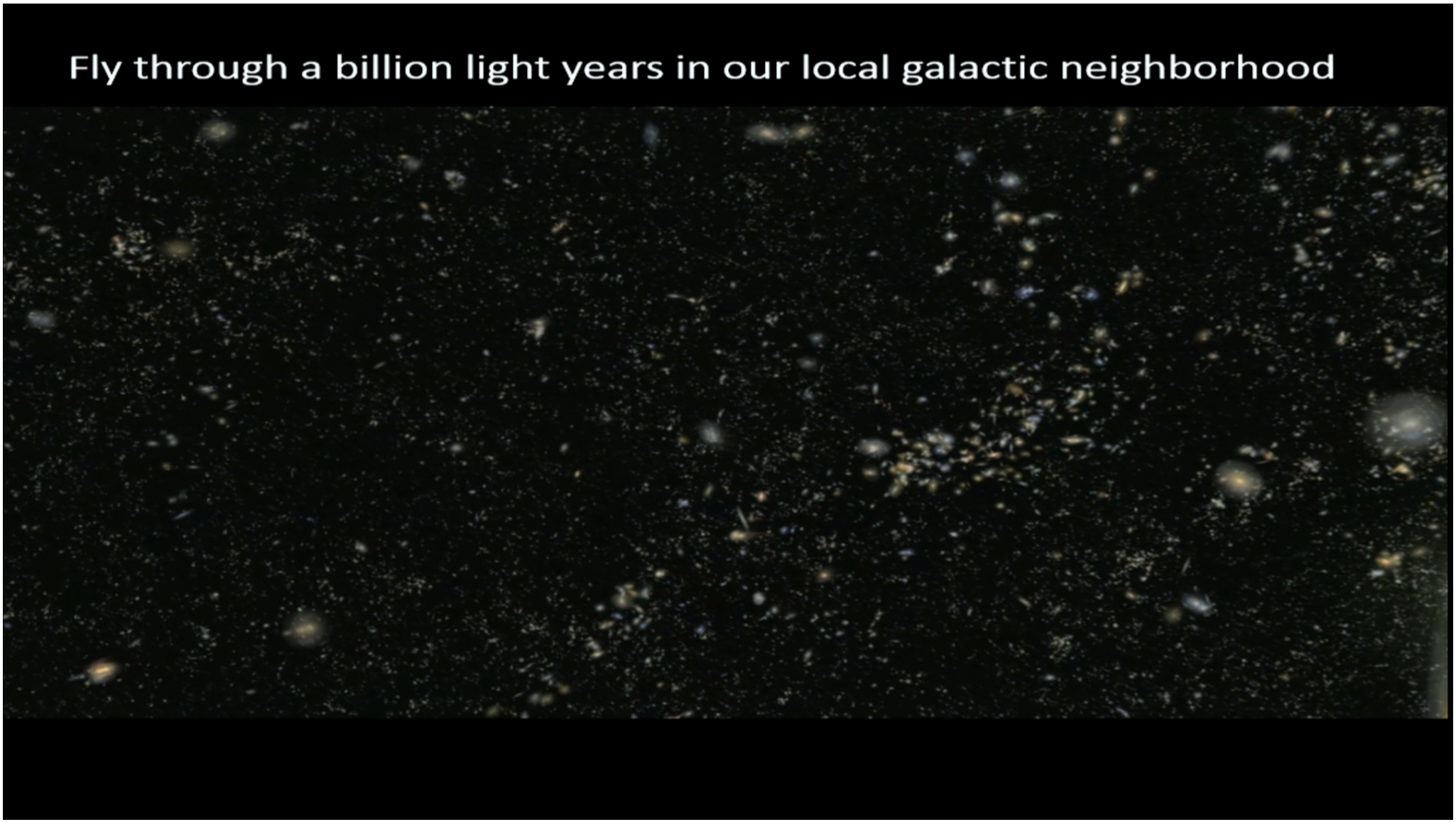
The pattern of visible matter (galaxies) traces the pattern of dark matter

Dark matter has 5x more mass. Visible matter is attracted to where the dark matter is.

The pattern of visible matter (galaxies) traces the pattern of dark matter

Dark matter has 5x more mass. Visible matter is attracted to where the dark matter is.

Dark matter predictions:	Observed Universe:
"Tiny" dark matter clumps	Individual galaxies with DM halos
Dark matter filaments	Galaxies in filaments
Giant dark matter nodes	Clusters of many galaxies
Voids with little dark matter	Voids with few galaxies


Fly through a billion light years in our local galactic neighborhood

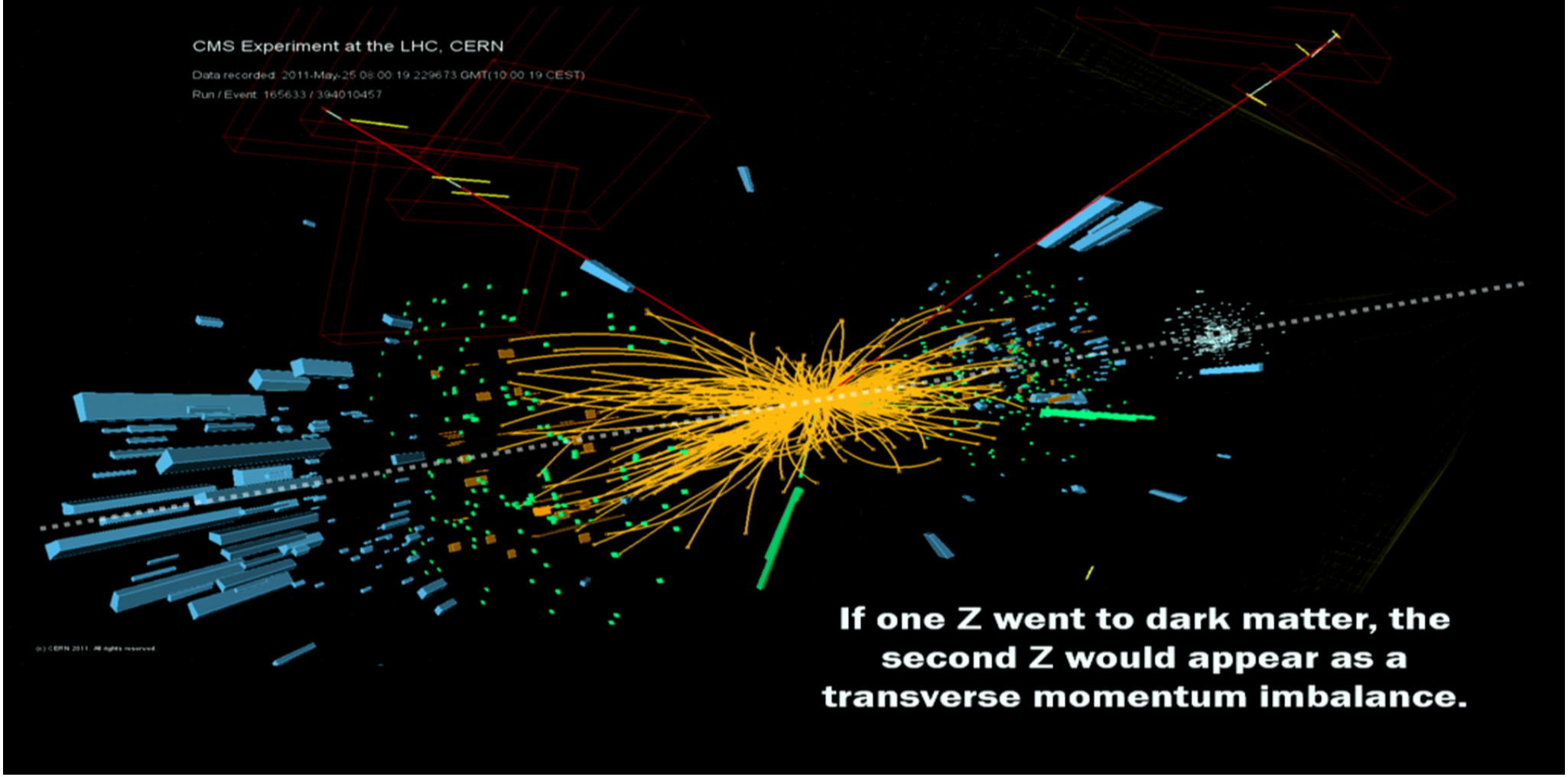
Dark matter is a particle physics problem

Everything we know about dark matter comes from its gravitational influence in the Universe

To discover its particle physics properties, we need to know its non-gravitational interactions.

What is the Lagrangian?
What are the symmetries/forces?

LHC event: pp → ZZ + hadrons



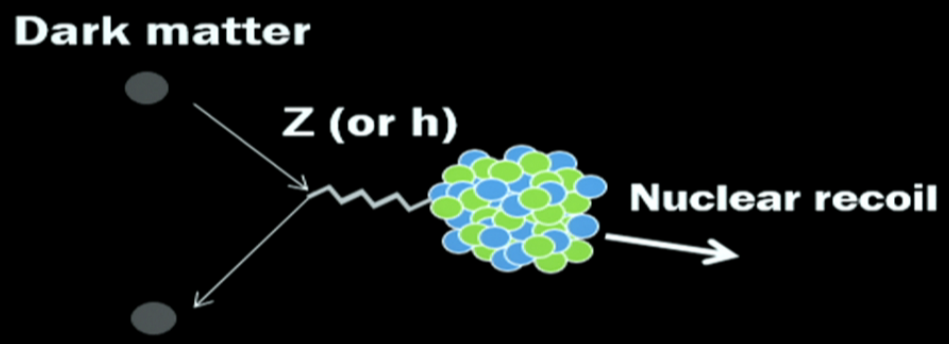
If one Z went to dark matter, the second Z would appear as a transverse momentum imbalance.

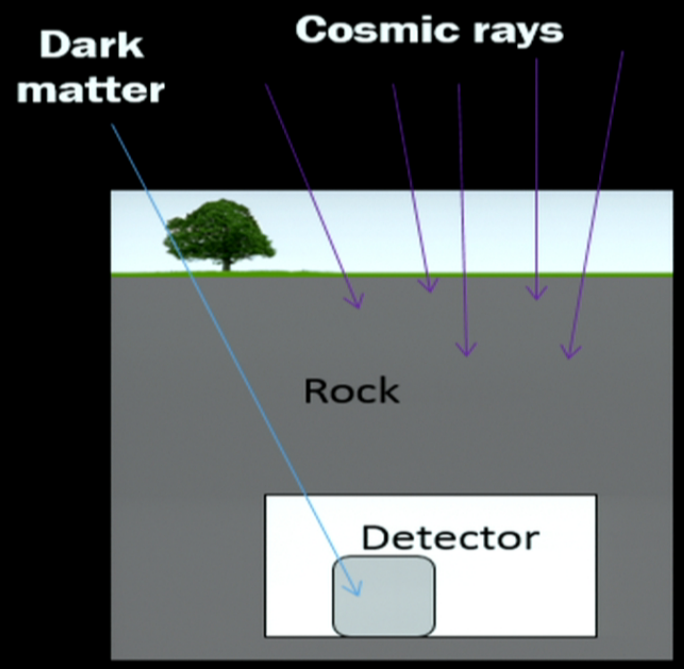
Dark matter at the LHC

For example: Dark matter might be a new very heavy neutrino (m ~ 1000 GeV).

It can be produced in high energy collisions via the weak force.

Direct detection



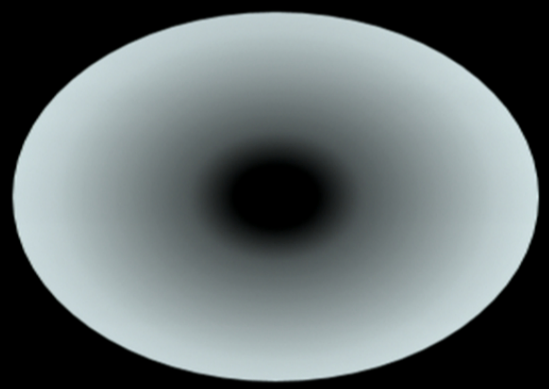


If dark matter is heavier than few GeV, it leaves enough recoil energy to be detected.

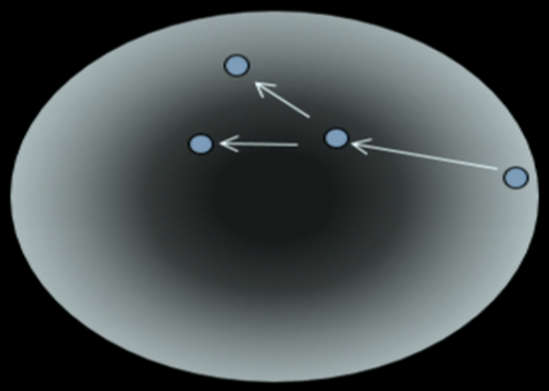
Dark matter and dark forces

SM interactions with dark matter could be very suppressed.
But dark matter could have its own forces.

Feynman diagram for dark matter particles interacting via a dark force

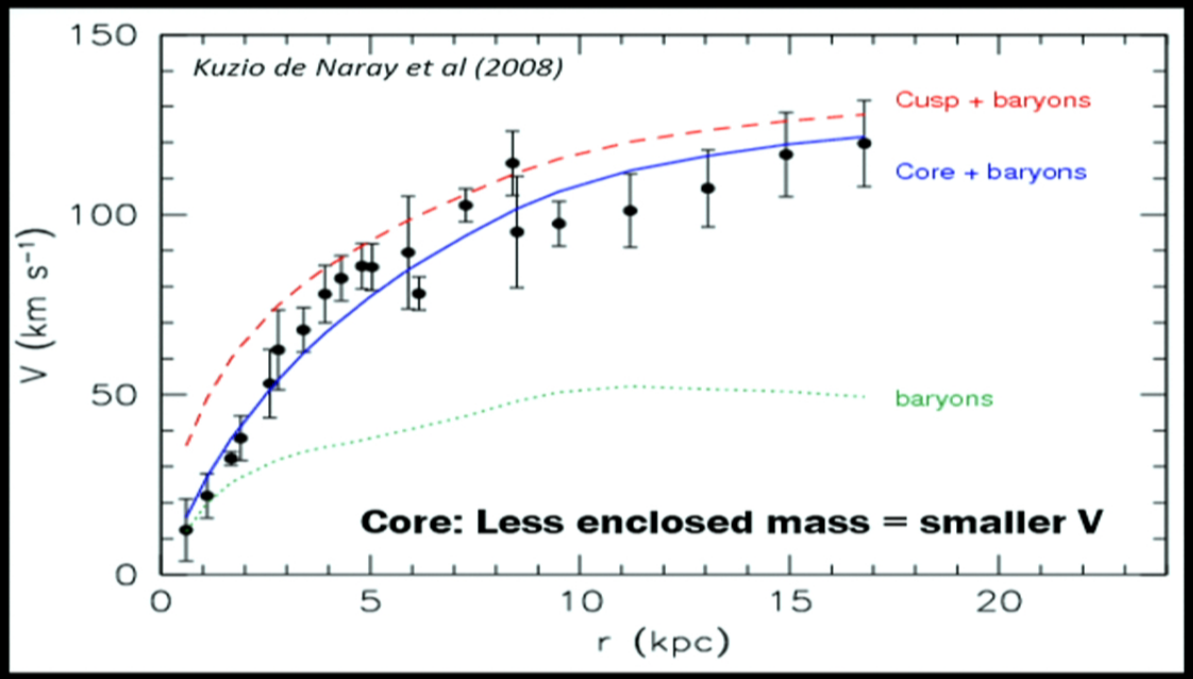


Cuspy halo with no interactions



Halo with interactions ("core")

Cored halos leave their imprint on rotation curves



Most dark matter dominated galaxies have cores.
One possible explanation: Interactions among dark matter particles.

Conclusions (?)