



JULY 2022

= DARK SIDE OF = THE UNIVERSE =

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JOHN S. TOLL RESEARCH PROGRAM (SUMMER 2022)

EARLY EVIDENCE ~1933

NASA / JPL-Caltech / L. Jenkins (GSFC)

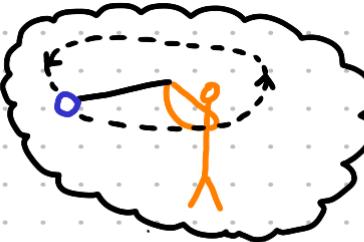


COMA CLUSTER

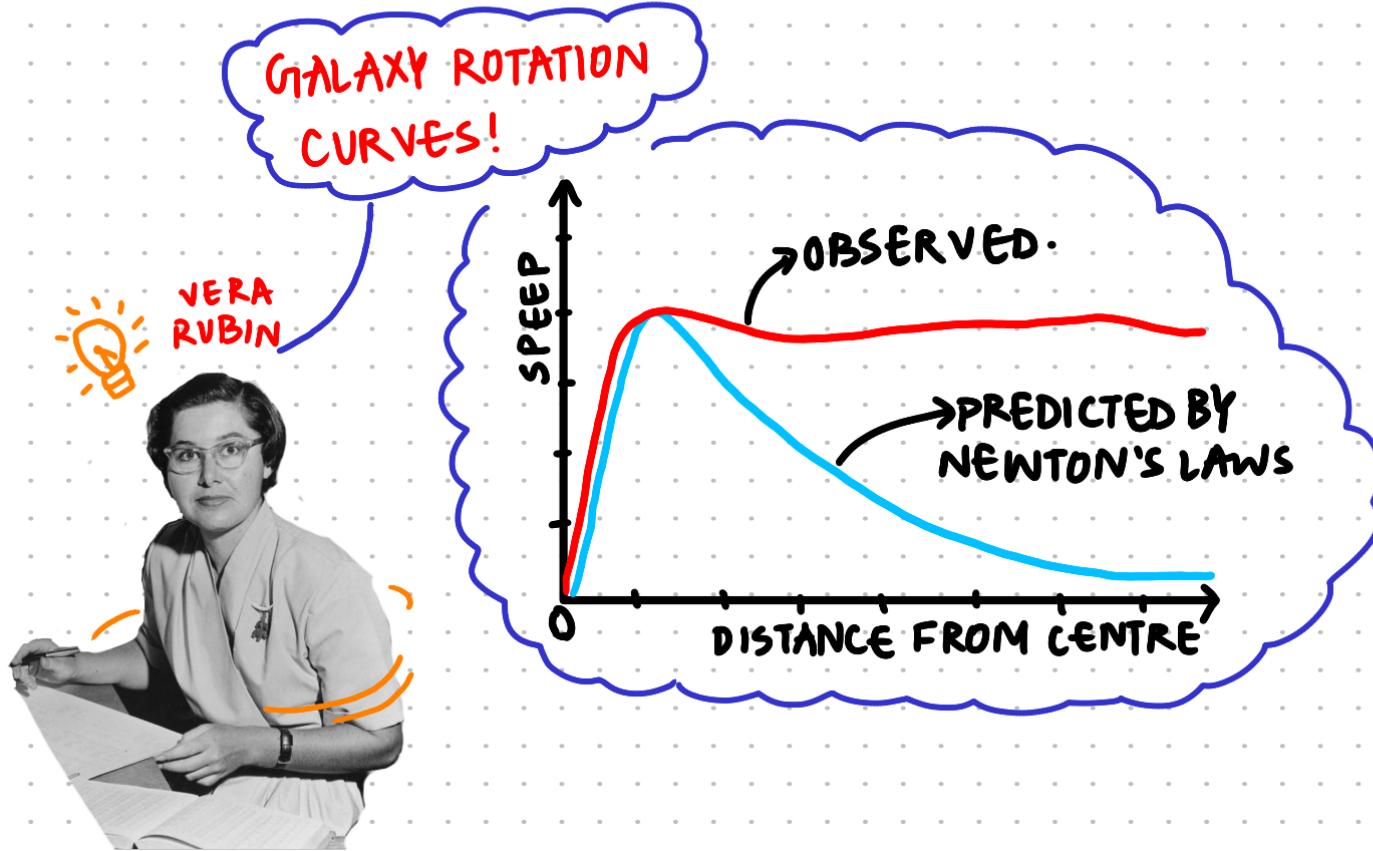
Hm these galaxies on the edge are moving much faster than I predicted

By Newton's law, $F = G \frac{Mm}{r^2}$

FRITZ ZWICKY



MORE EXPERIMENTAL EVIDENCE ~1968



EVERYTHING
WE CAN SEE
IN THE UNIVERSE

VERY WEAK INTERACTION
WITH REGULAR MATTER/
STANDARD MODEL PARTICLES

85%
**DARK
MATTER**



15% ↗

HARD TO DETECT DUE TO
WEAK INTERACTION

= DISTRIBUTION OF ALL MATTER IN THE UNIVERSE =

WHAT IS REGULAR MATTER MADE OF?

UNIVERSE = ENERGY/MASS that interact via **FORCES**

everything
is a particle.

MATTER PARTICLES — STANDARD MODEL — FORCE PARTICLES

?

GRAVITY

QUARKS

u	s	t
d	c	b

e	μ	τ
ν_e	ν_μ	ν_τ

g Z GAUGE BOSONS

Y W

H SCALAR FIELD

— DARK MATTER —

not in
standard
model!

Possible scenario:
WIMP (weakly
interacting
massive particle)

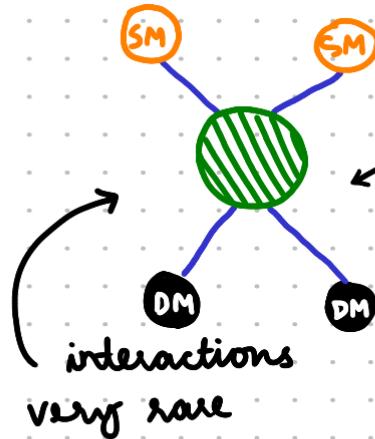
?

LEPTONS

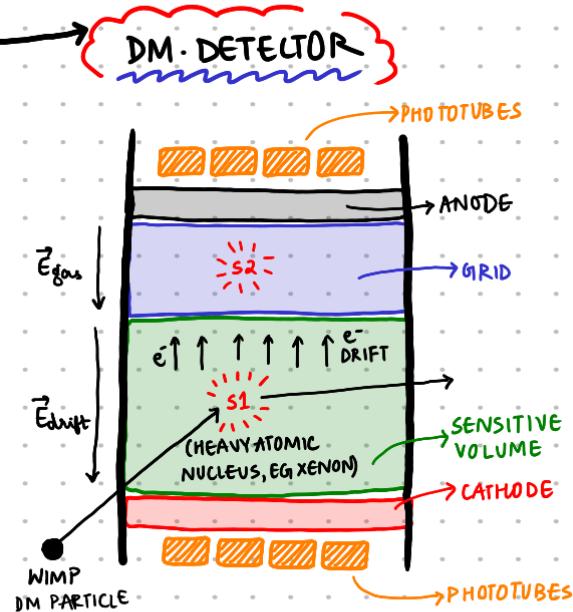
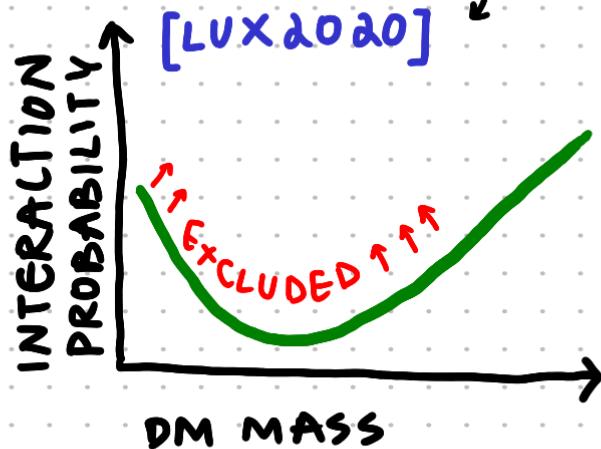
NEW PHYSICS

~~~~ BEYOND STANDARD MODEL ~~~~

DARK ENERGY



WHAT WE KNOW FROM  
EXPERIMENTS



# THE BOLTZMANN EQUATION

SOLUTION tells us

how DM abundance  
changes with time

$$\frac{dY(x)}{dx} = -\int \frac{1}{H(x)} (Y(x)^2 - Y_{eq}^2)$$

interaction strength of DM particles.

abundance of dark matter

abundance of particles in thermal equilibrium

larger  $x =$  later time

Hubble Parameter

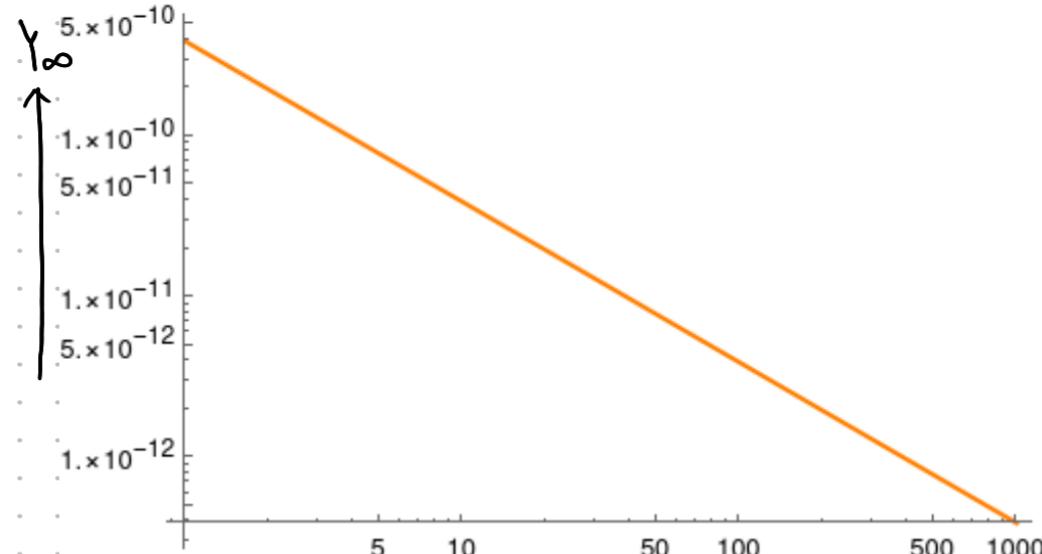
# THE BOLTZMANN EQUATION

[PLANCK 2018]

RELIC ABUNDANCE =  $1.58 \times 10^8 \times m_{Y_0} = 0.11$

[arxiv.org/abs/1807.06209](https://arxiv.org/abs/1807.06209)

$$\left\{ \frac{dY}{dx} = -\frac{\Gamma}{H}(Y^2 - Y_{eq}^2) \right.$$



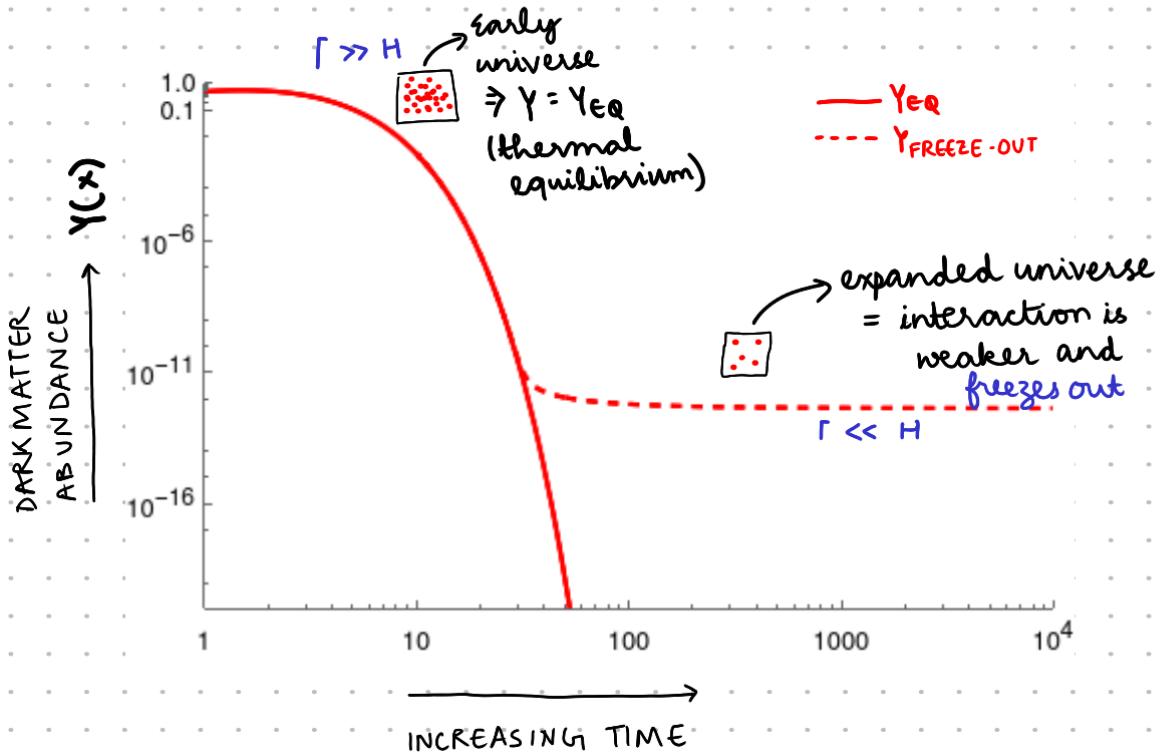
(1 GeV  $\sim 1.79 \times 10^{-29}$  kg)

MASS (GeV)

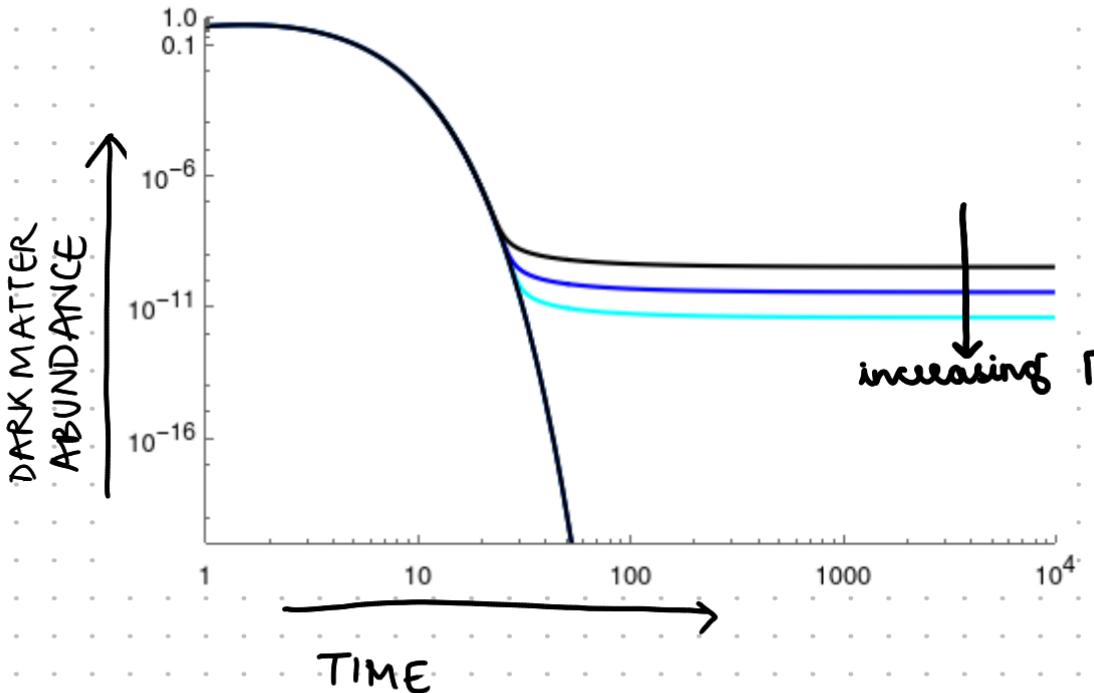
## PROGRESS SO FAR

worked on simplified solution to Boltzmann eqn. using Mathematica.

$$\left\{ \frac{dY}{dx} = -\frac{\Gamma}{H}(Y^2 - Y_{eq}^2) \right.$$



PROGRESS SO FAR



$$\frac{dY}{dx} = -\frac{\Gamma}{M} (Y^2 - Y_{eq}^2)$$

WIMP CASE

2 free parameters

$$\Gamma \propto \frac{g^2}{m^2}$$

( $g \propto$  Interaction strength)

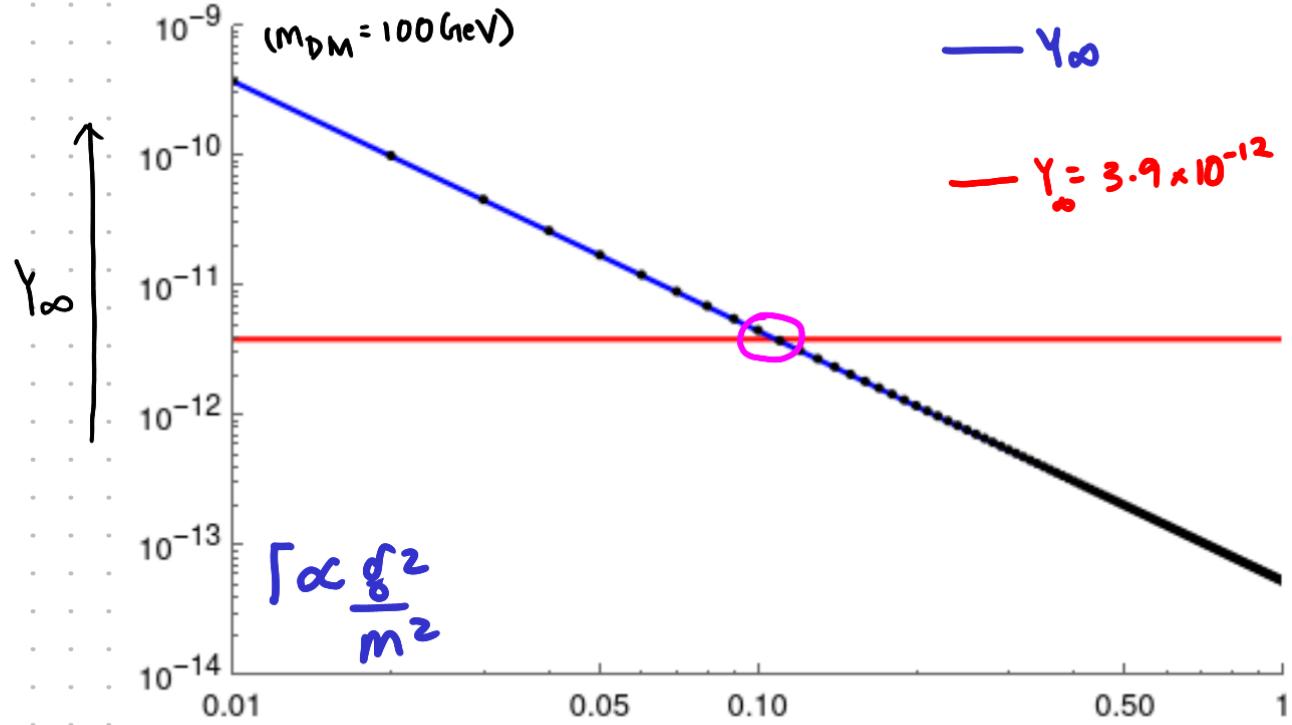
increasing  $\Gamma$

$\equiv g \uparrow$  or  $m \downarrow$

$\Gamma \uparrow = \text{abundance} \downarrow$

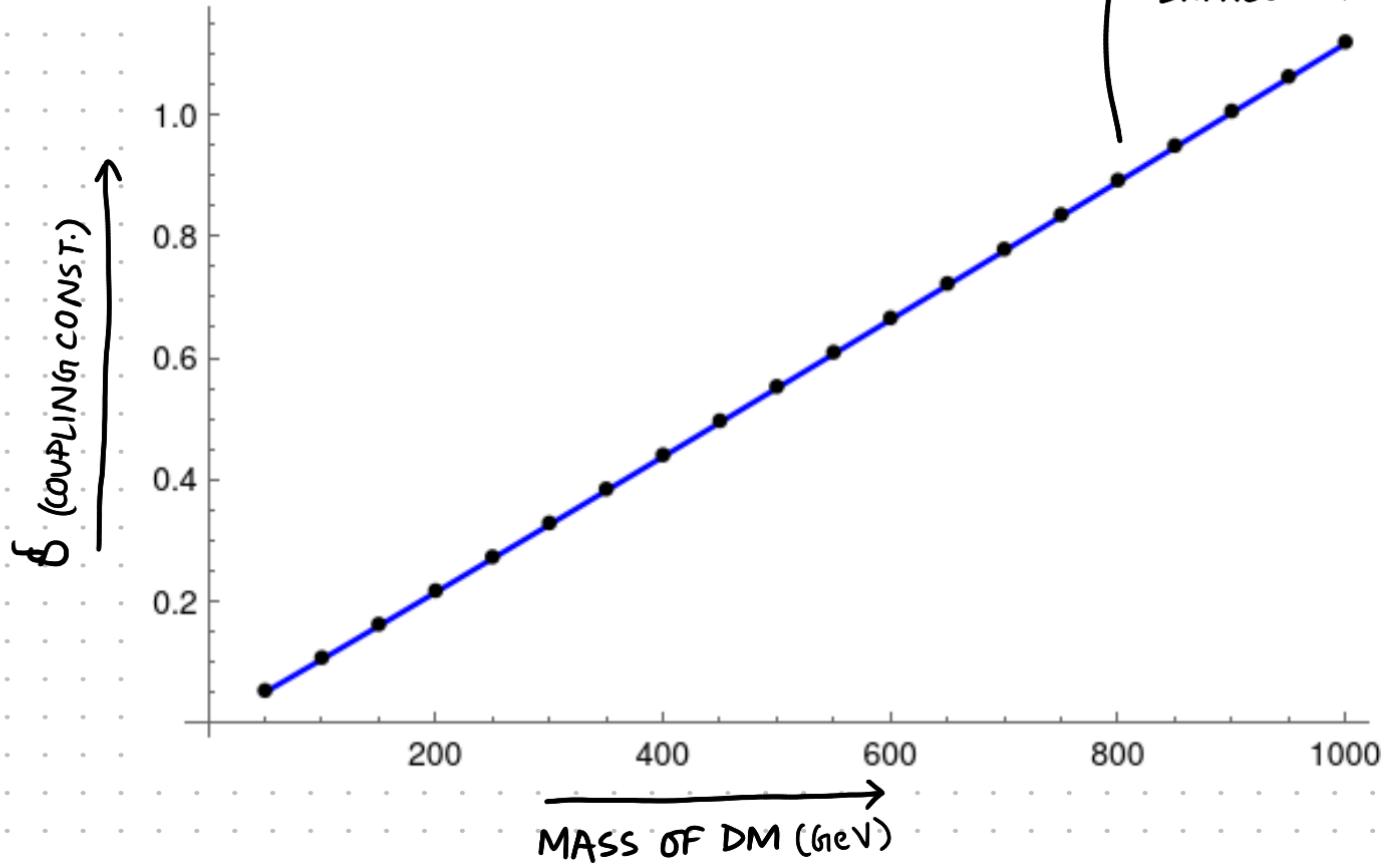
PROGRESS SO FAR

$$\left\{ \frac{dY}{dx} = -\frac{\Gamma}{M} (Y^2 - Y_{eq}^2) \right.$$



$$(1 \text{ GeV} \sim 1.79 \times 10^{-29} \text{ kg})$$

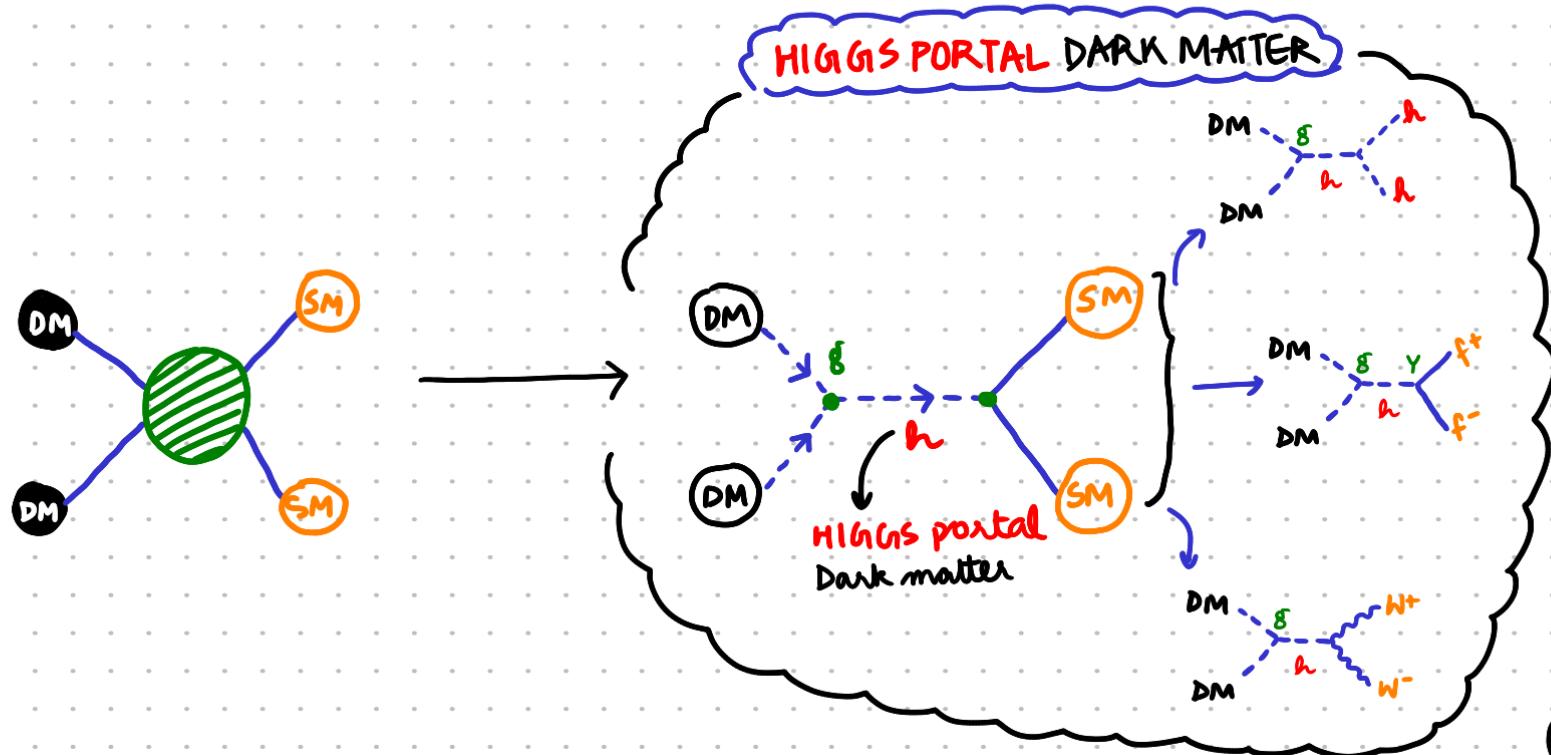
PROGRESS SO FAR



SET OF  $\{m_{DM}, g\}$  VALUES THAT  
REPLICATE PRESENT VALUE OF  
DM ABUNDANCE

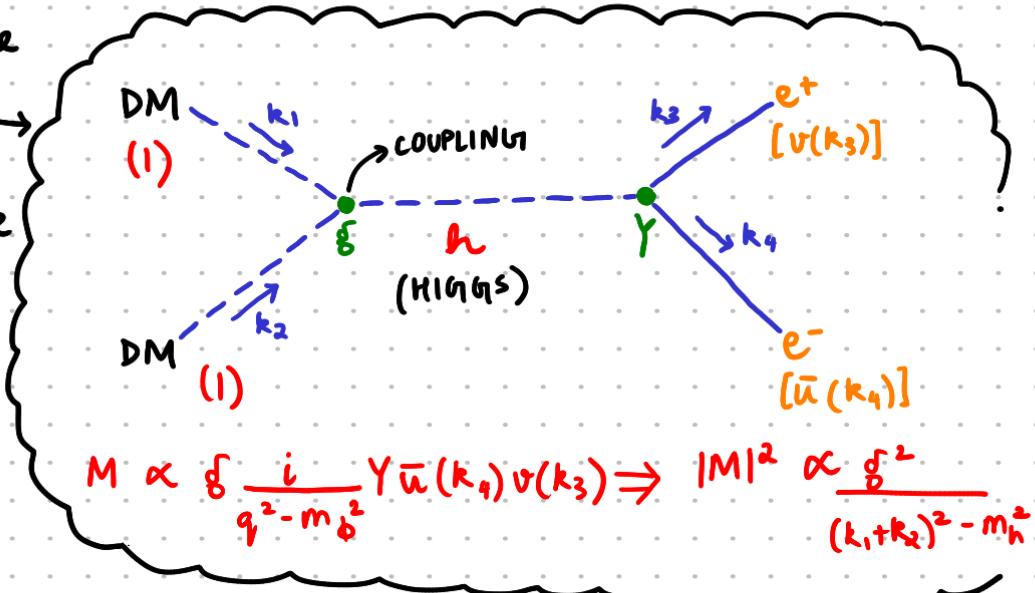
# FUTURE PLANS

understand quantum mechanics in interaction



# FUTURE PLANS

- 1  $\propto \frac{g^2}{m^2}$  calculate more precisely.
- use Mathematica package FeynCalc to precisely calculate processes + reproduce plots
- calculate WIMP DM relic density using MicrOMEGAs.



## REFERENCES

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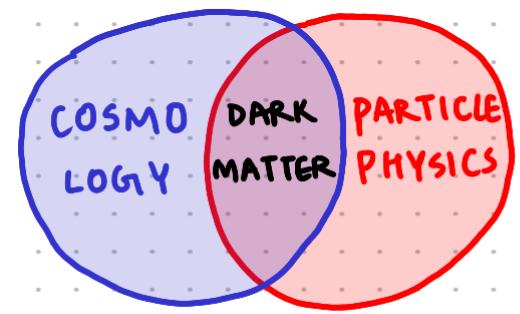
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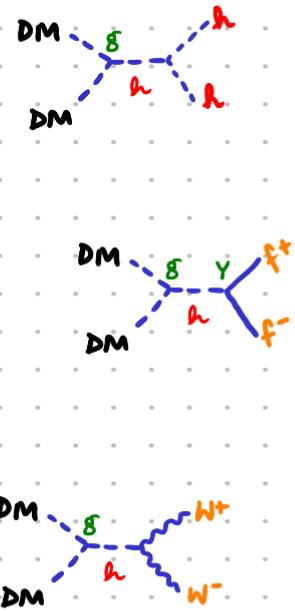
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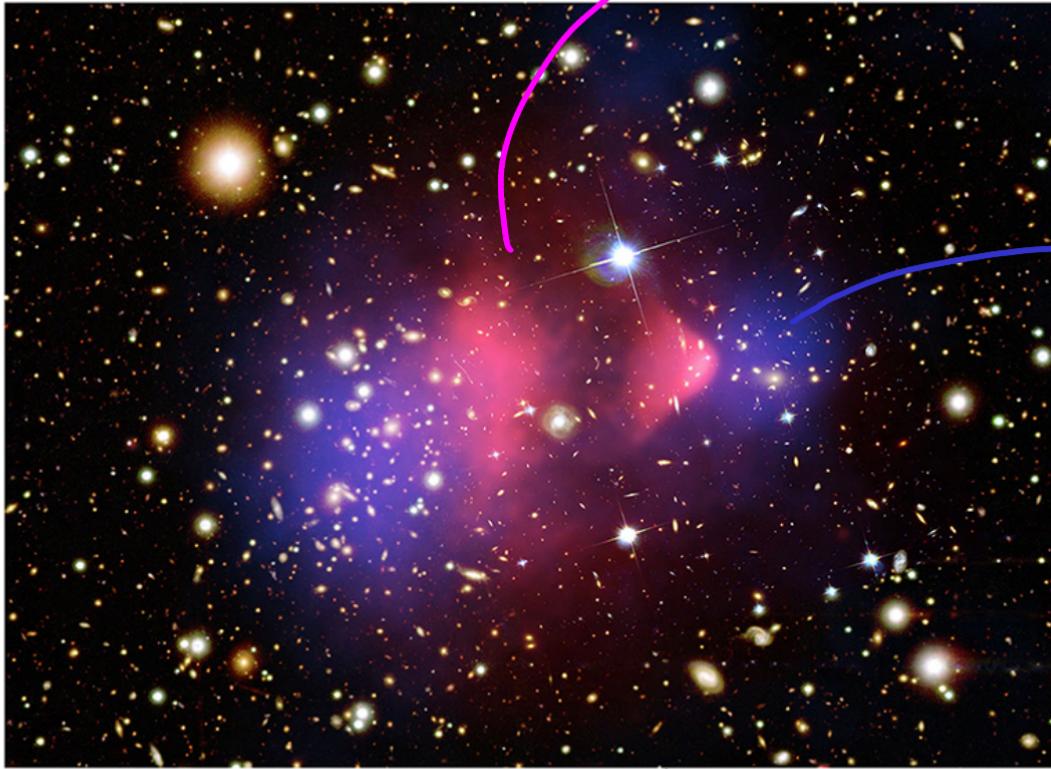
THANK YOU Ü  
+ QUESTIONS?



# GRAVITATIONAL LENSING

(massive bodies acting like lenses)

↓  
lets us see mass distributions

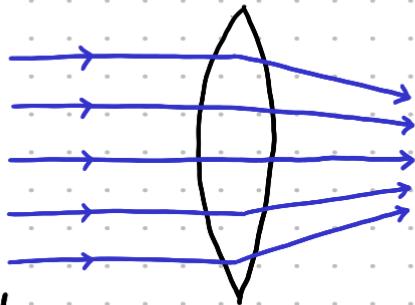


BULLET CLUSTER! (collision of galaxies)

PINK = regular matter.

→ BLUE = DARK MATTER (invisible w/ regular telescope)  
→ (mapped by gravitational lensing.)

# GRAVITATIONAL LENSING



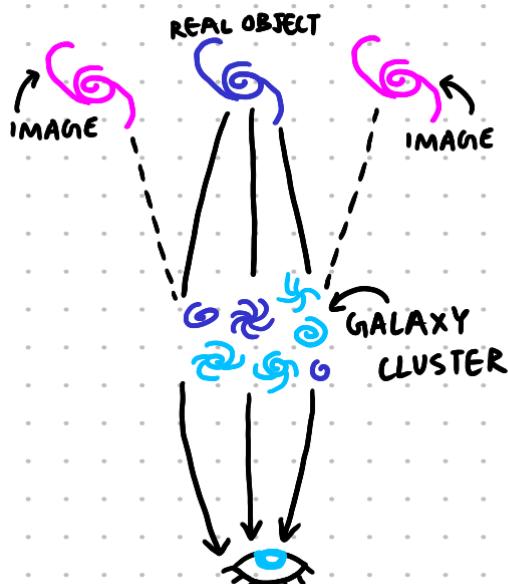
lenses  
bend light

light  $\equiv$  energy

$$E = mc^2$$

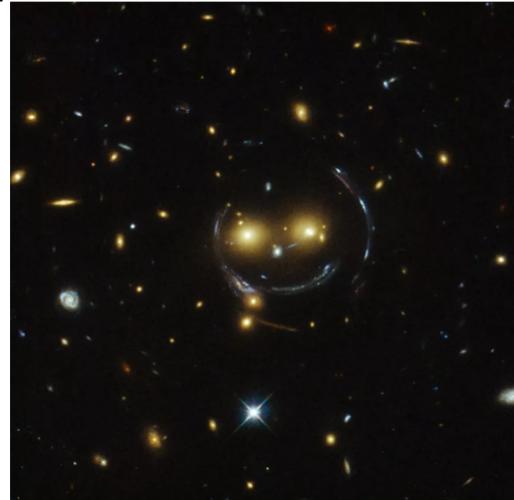
Gravity affects mass

$\Rightarrow$  GRAVITY AFFECTS LIGHT



LENSING BY A CLUSTER  
(SDSS J1038+4849)

NASA/ESA : [http://www.nasa.gov/sites/default/files/thumbnails/image/15861603283\\_3579db3fc6\\_o.jpg](http://www.nasa.gov/sites/default/files/thumbnails/image/15861603283_3579db3fc6_o.jpg)



$\Rightarrow$  'COSMIC SMILEY'.  
'CHESHIRE CAT'.