



Oltre il Modello Standard



Problemi aperti in Fisica delle Particelle

- il *pattern* delle masse e le proprietà dell'higgs



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Problemi aperti in Fisica delle Particelle

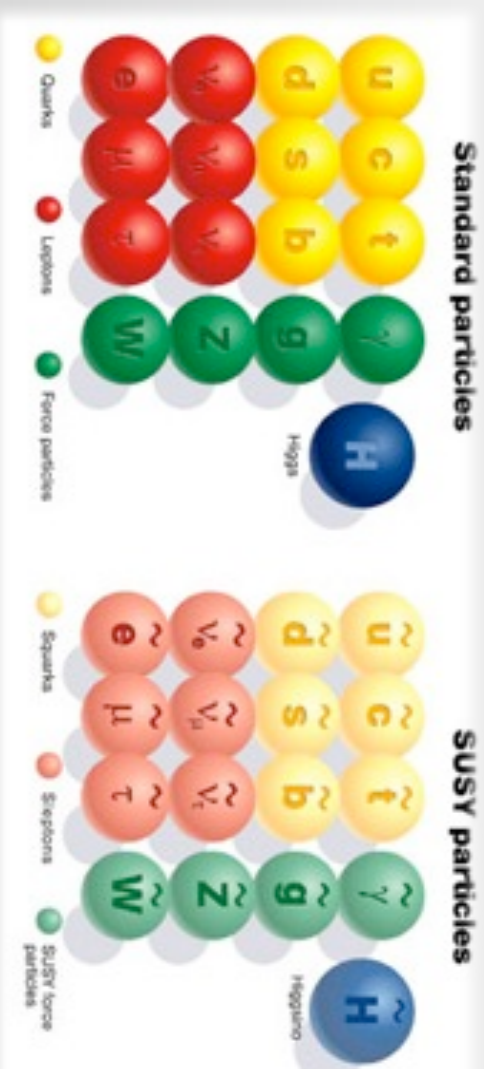
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(forse c'è un partner supersimmetrico per ogni tipo di particella nota!)





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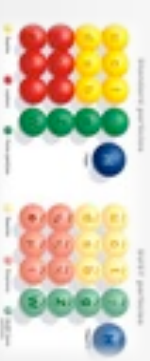
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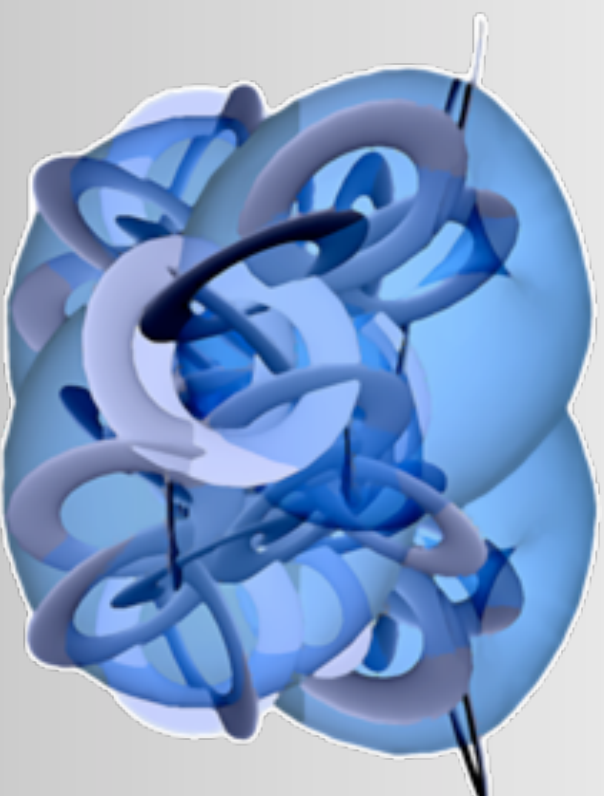
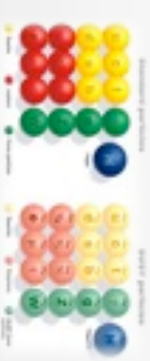
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(forse ci sono più di 3 dimensioni spaziali!)





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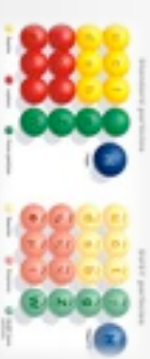
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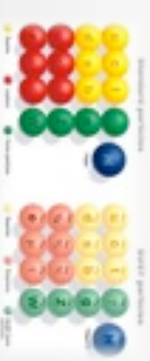
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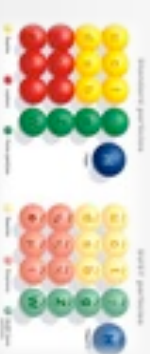
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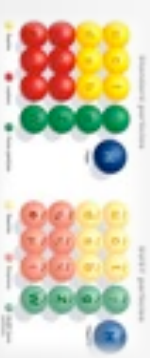
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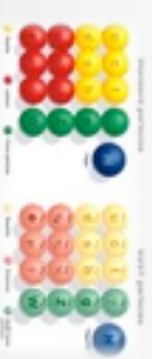
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- l'asimmetria tra materia e antimateria
(dove è finita tutta l'antimateria dell'Universo?)
- il plasma di quarks e gluoni
(come diventa la materia nucleare a energie e densità elevatissime?)

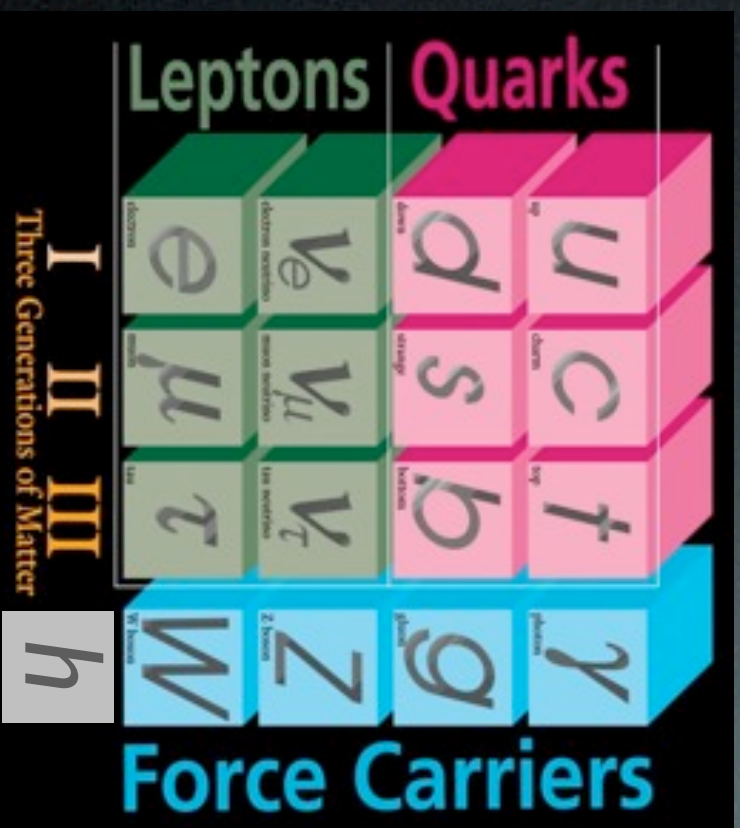


• ...

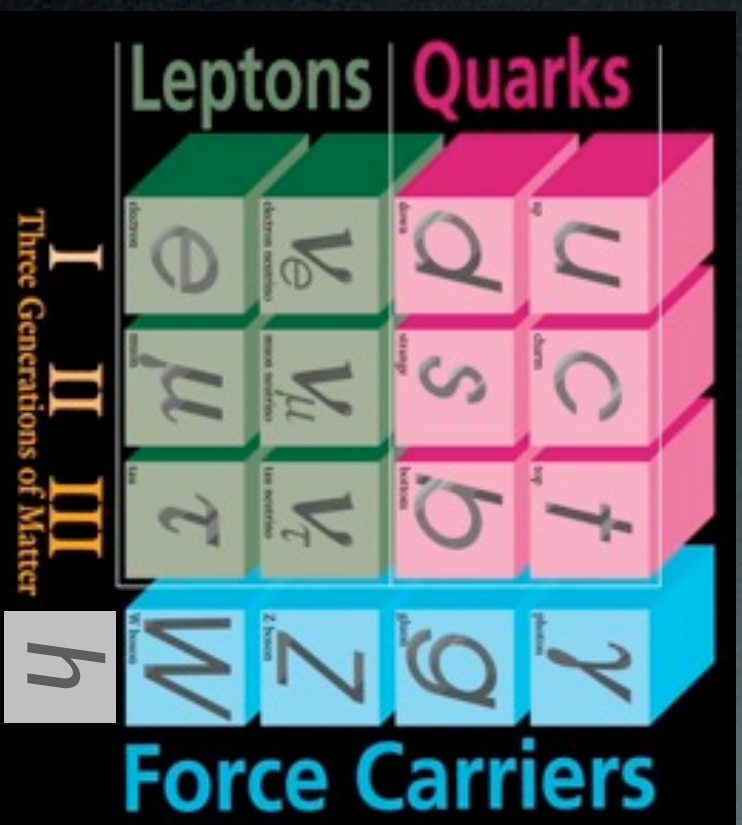


Supersymmetry (Susy)

SuSy in 2 minutes

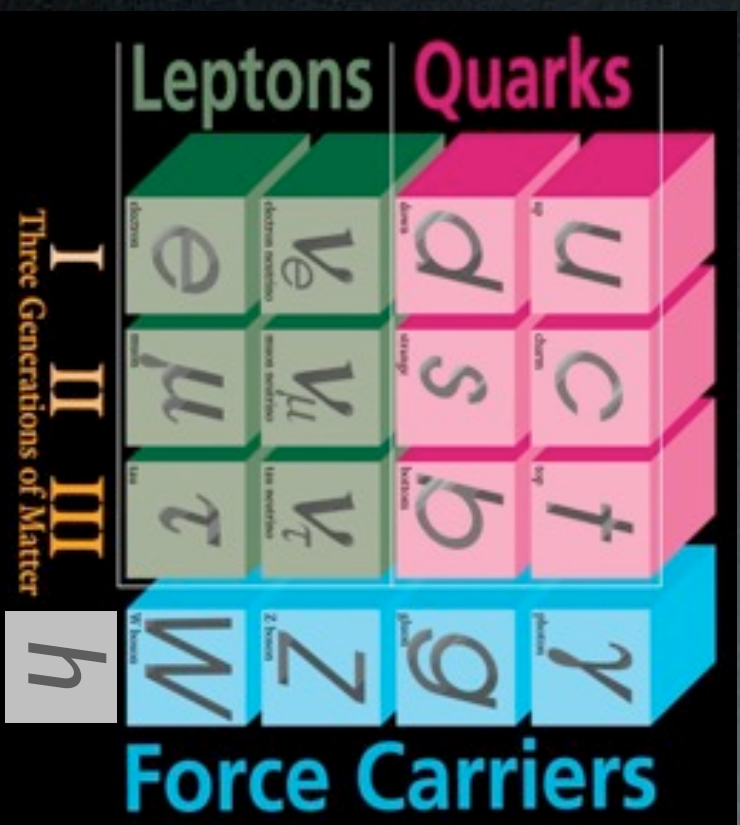


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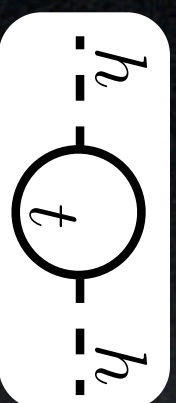


$$m_h \simeq 126 \text{ GeV}$$

Susy in 2 minutes

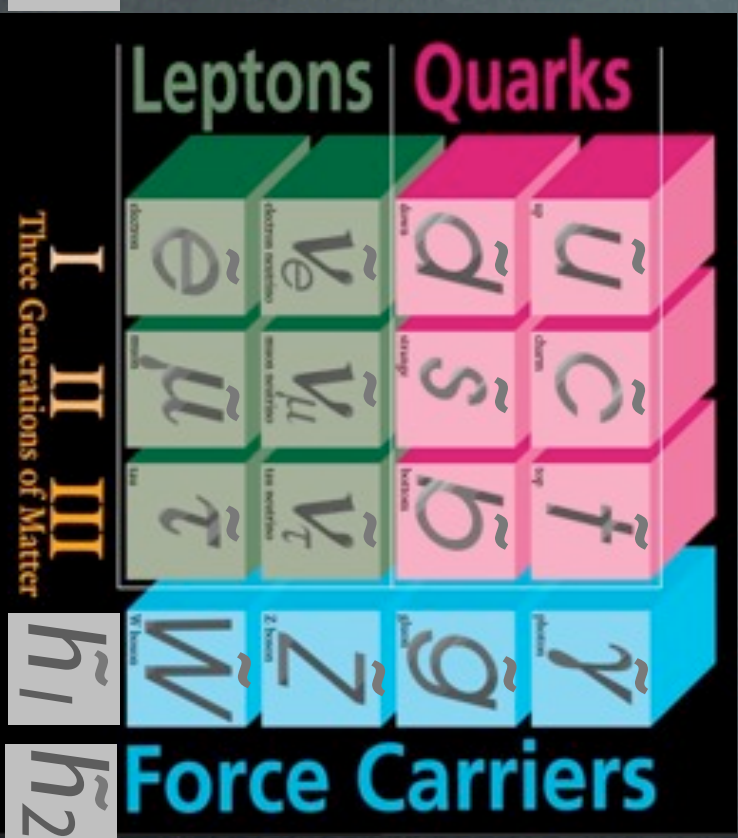
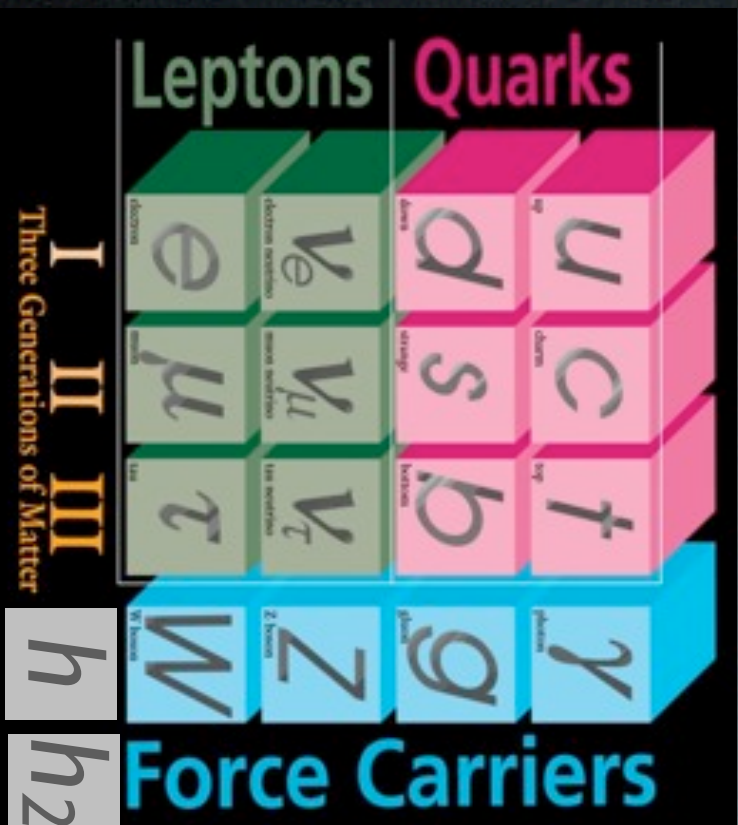


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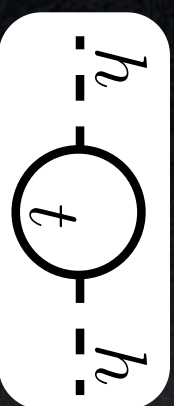


$$\Delta m_h \propto 10^{19} \text{ GeV}$$

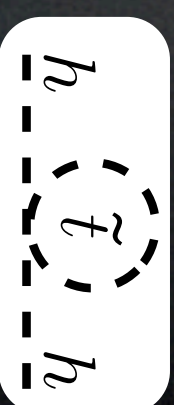
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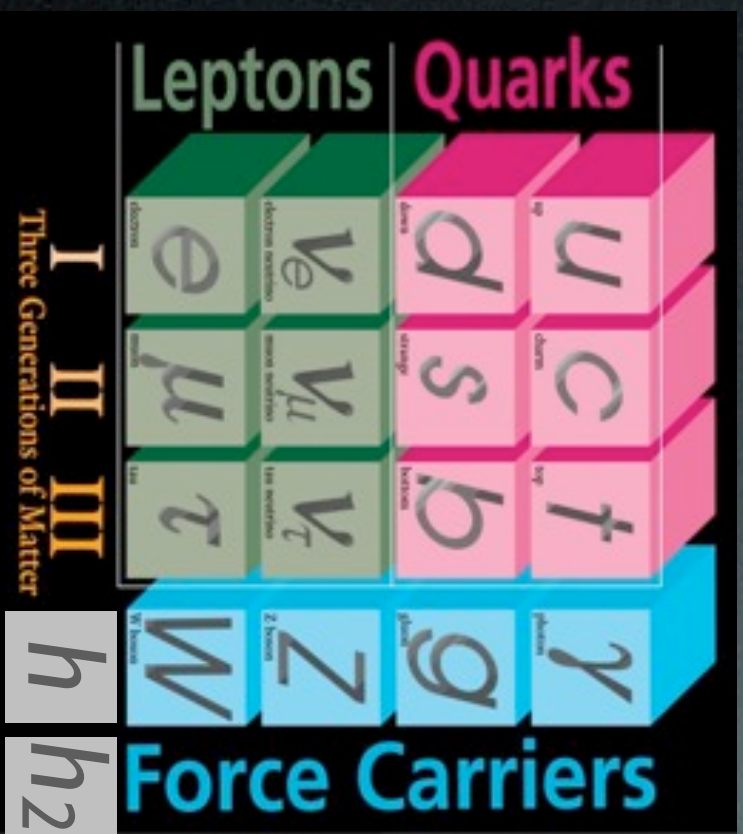


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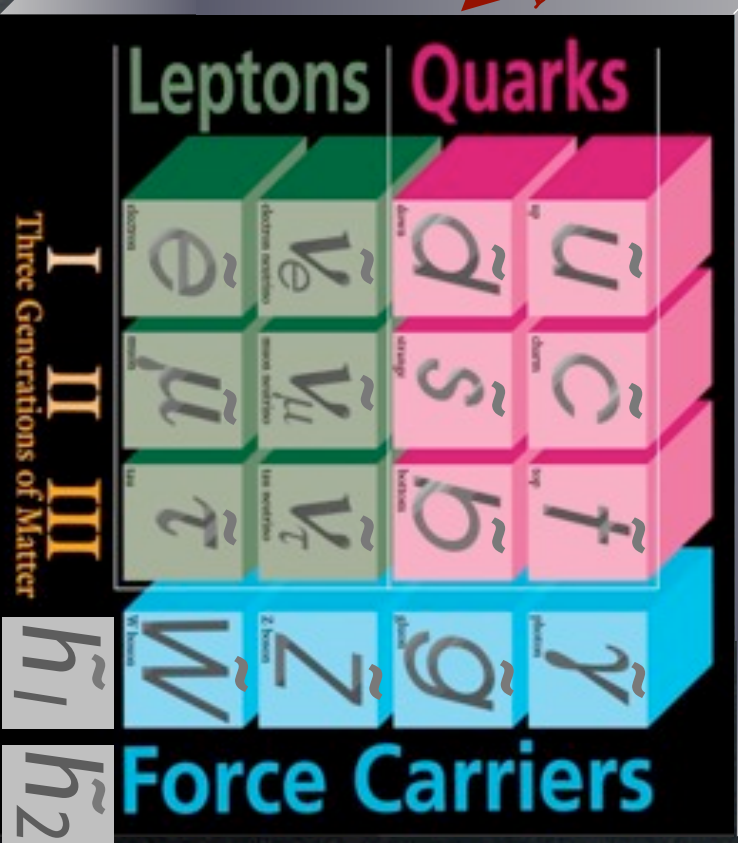


$$\Delta m_h \propto -10^{19} \text{ GeV}$$

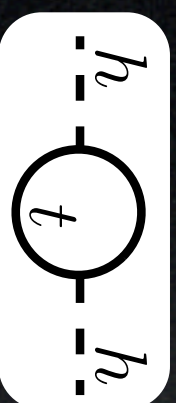
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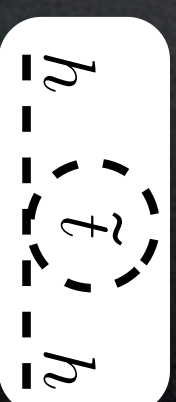
125 GeV



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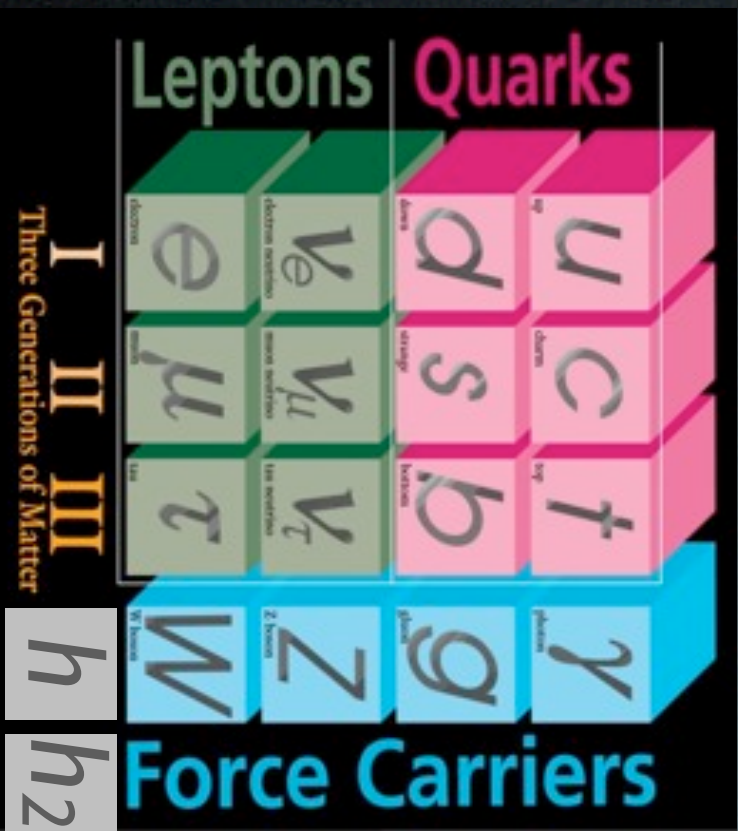


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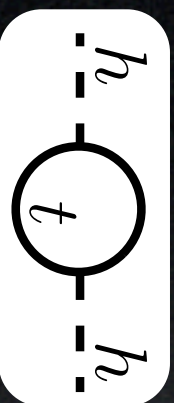
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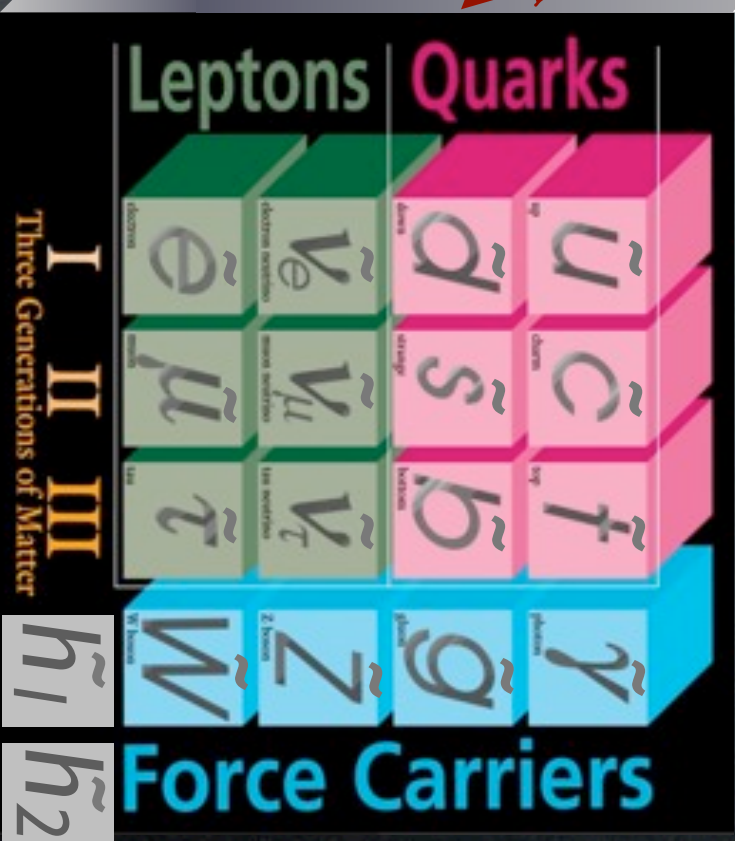
$$R = +1$$

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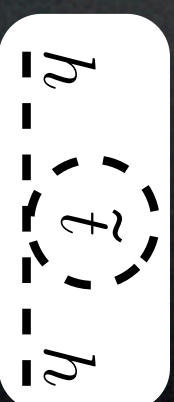


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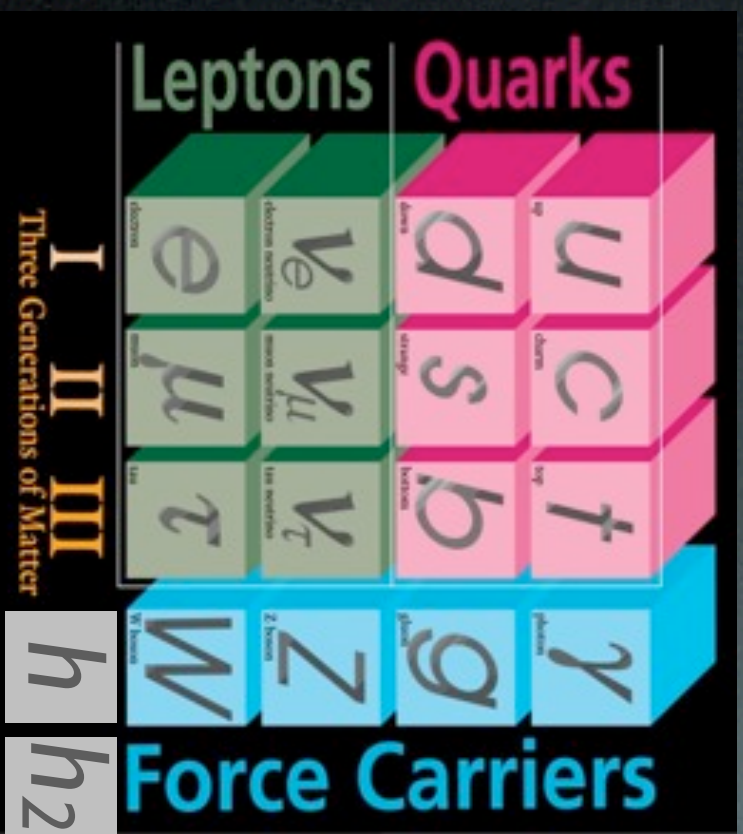


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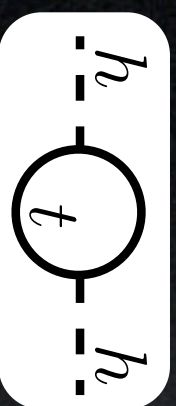
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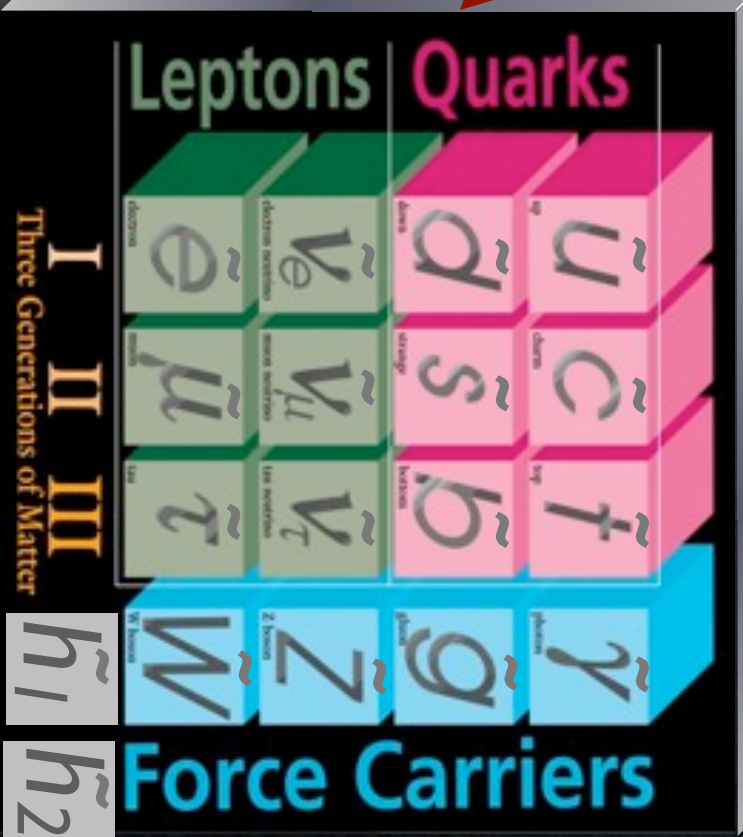
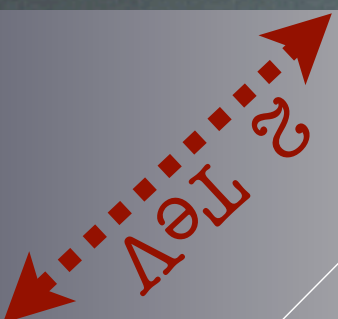


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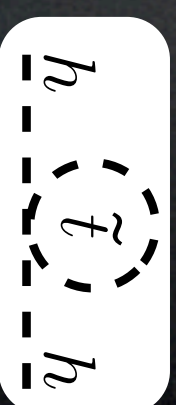
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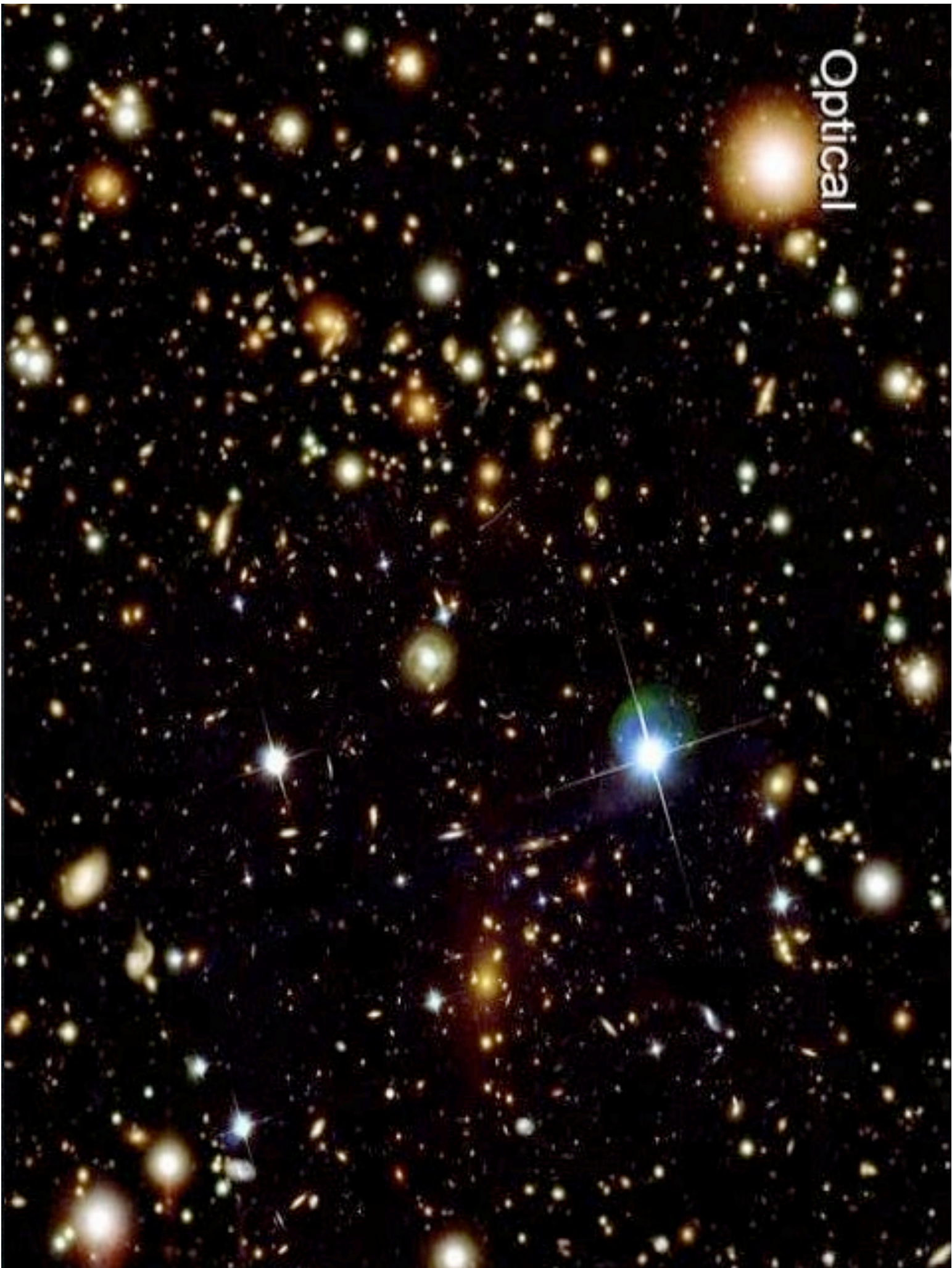
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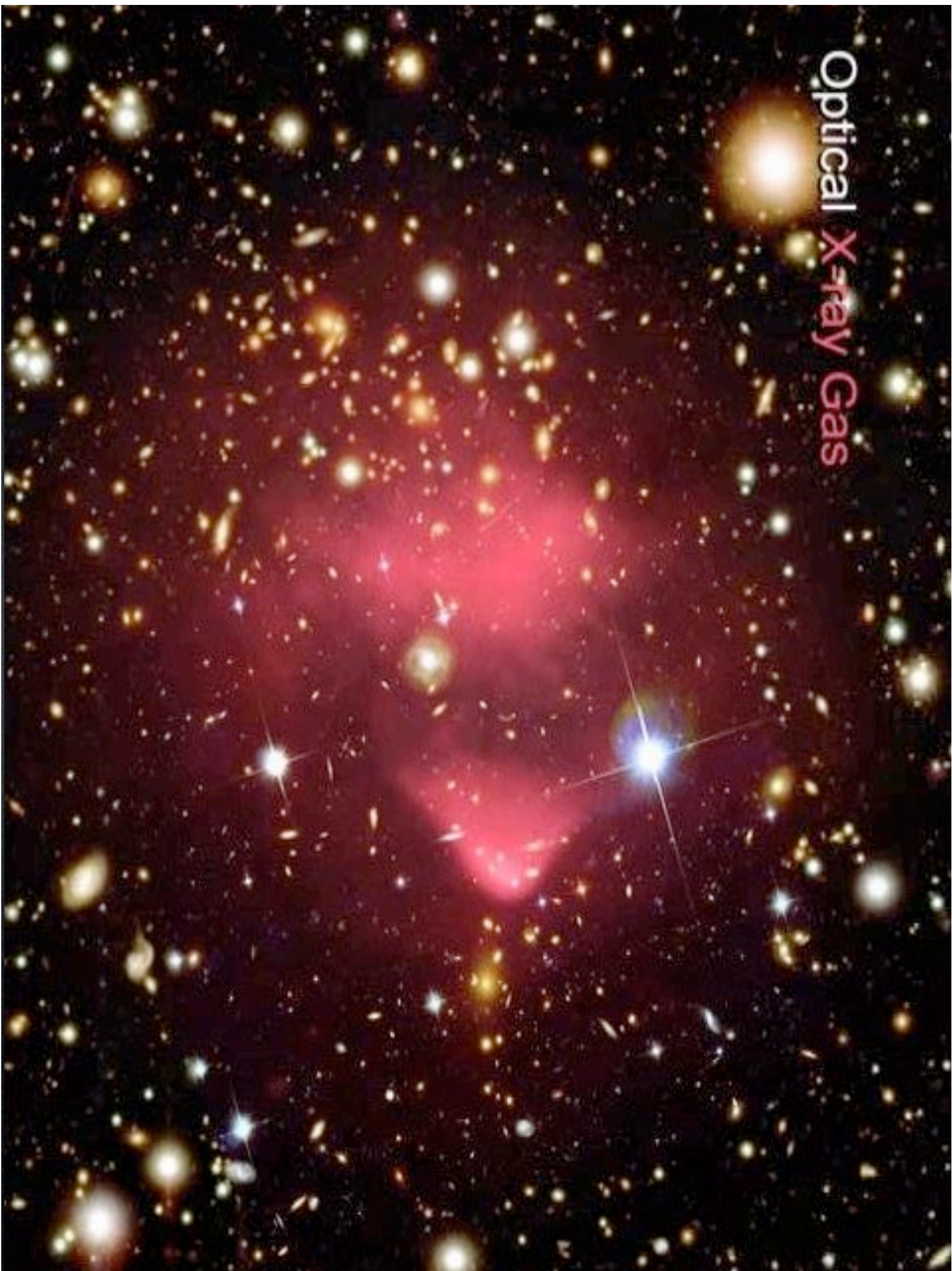
Materia Oscura *(Dark Matter)*

What is the Universe
made of?

Optical



Optical X-ray Gas

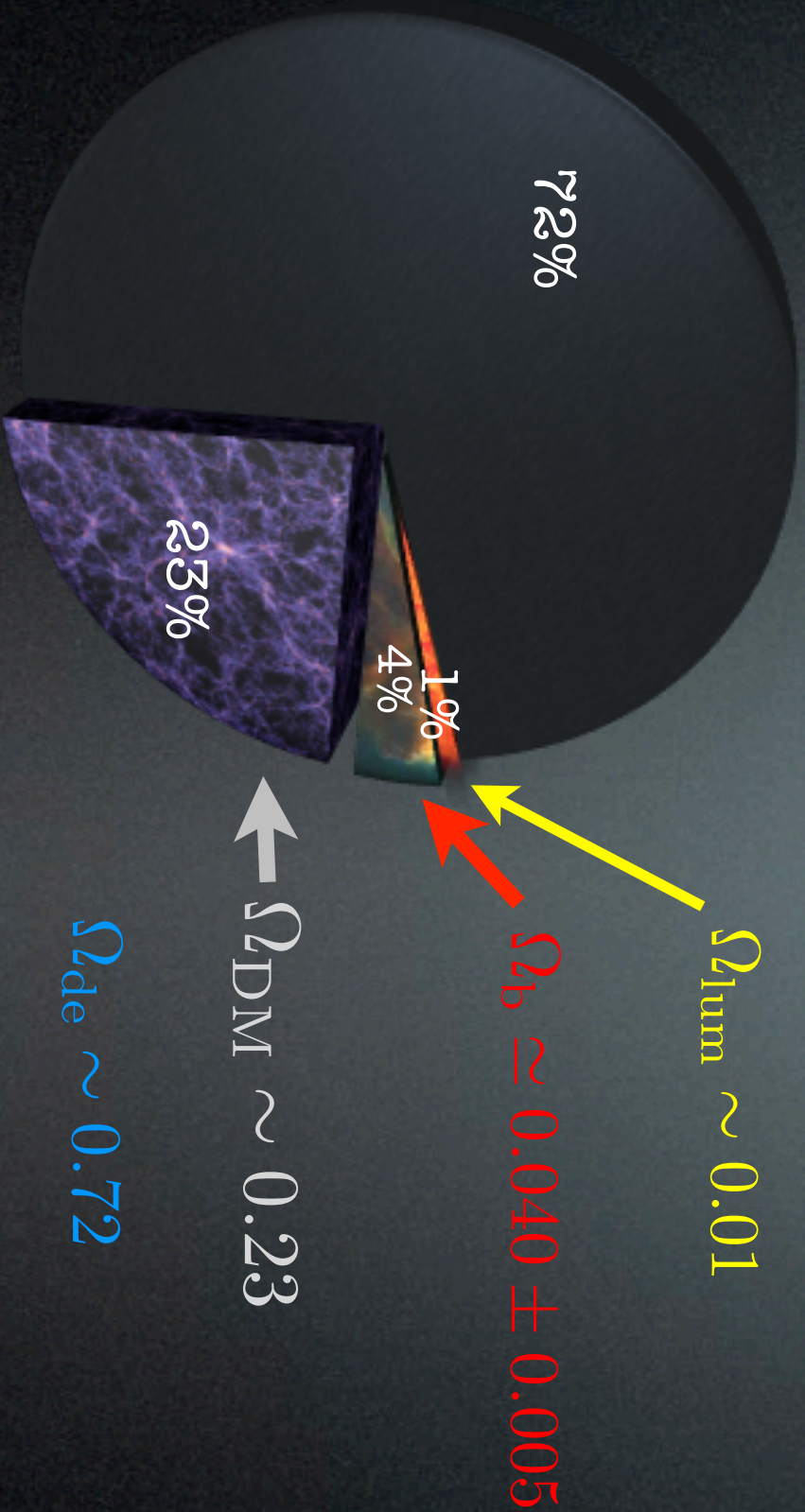


Optical Dark Matter X-ray Gas



The cosmic inventory

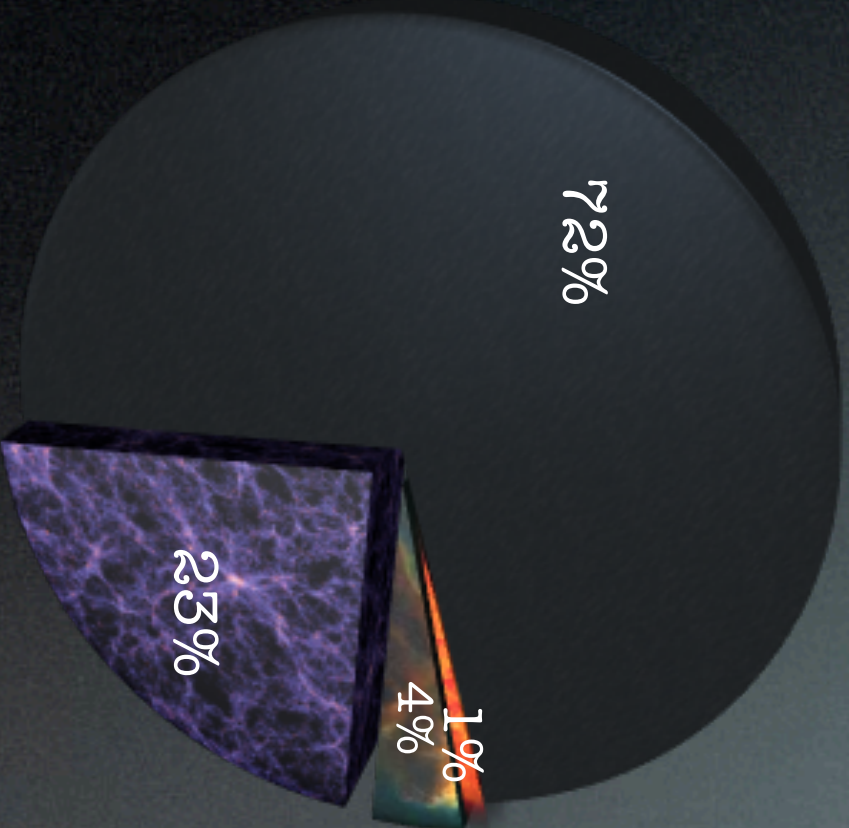
Most of the Universe is Dark



$$\left(\Omega_x = \frac{\rho_x}{\rho_c}; \text{CMB first peak} \Rightarrow \Omega_{\text{tot}} = 1 \text{ (flat)}; \text{HST } h = 0.71 \pm 0.07 \right)$$

The cosmic inventory

Most of the Universe is Dark



FAQ: what's the difference between DM and DE?

DM behaves like matter

- overall it **dilutes** as volume expands
 - **clusters** gravitationally on small scales
 - $w = P/\rho = 0$ (NR matter)
- (radiation has $w = 1/3$)

DE behaves like a constant

- it does not dilute
 - does not cluster, it is prob homogeneous
 - $w = P/\rho \simeq -1$
 - pulls the acceleration, FRW eq.
- $$\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3} (1 - 3w)\rho$$

How do we know that
Dark Matter is out there?

The Evidence for DM

1) galaxy rotation curves

$$m \frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

‘centrifugal’

‘centripetal’

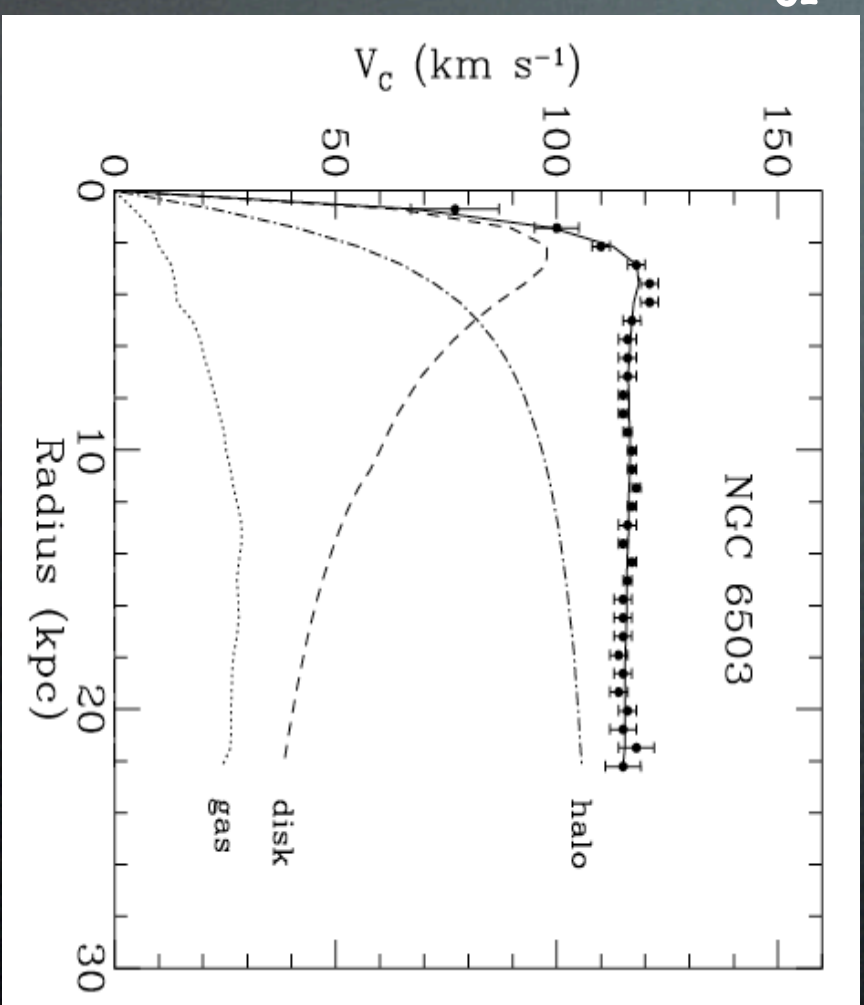
$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

$$\text{with } M(r) = 4\pi \int \rho(r) r^2 dr$$

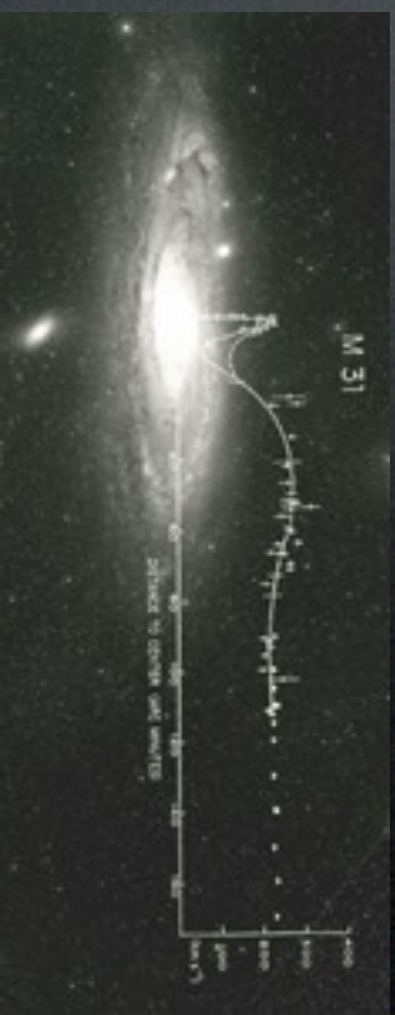
$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$



$$\Omega_M \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)



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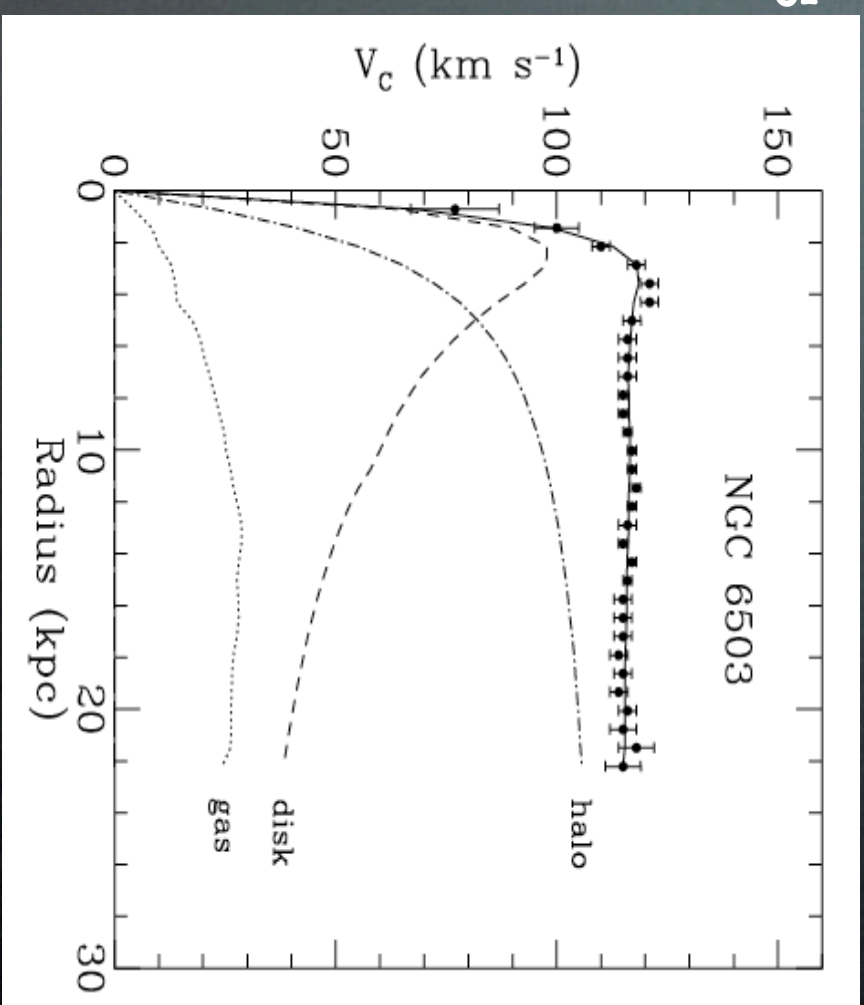
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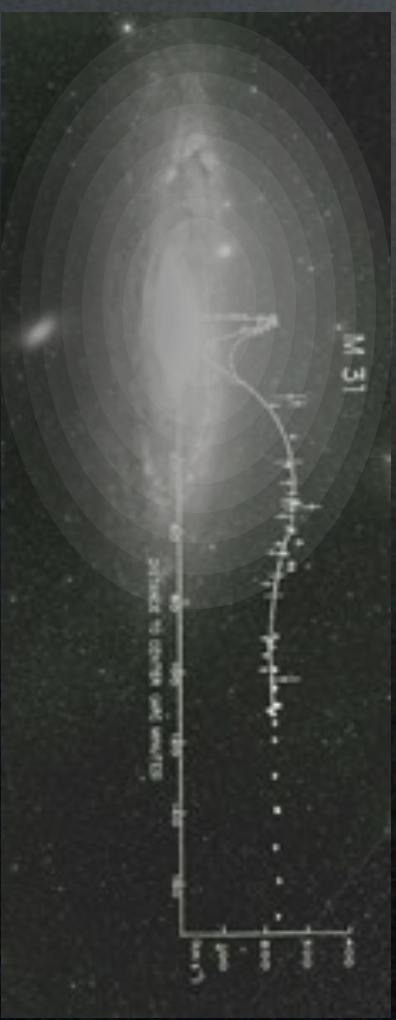
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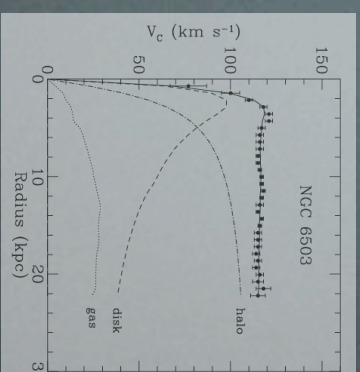
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2) clusters of galaxies

- “rotation curves”
- gravitation lensing



$$\Omega_M \sim 0.2 \div 0.4$$



“bullet cluster” - NASA

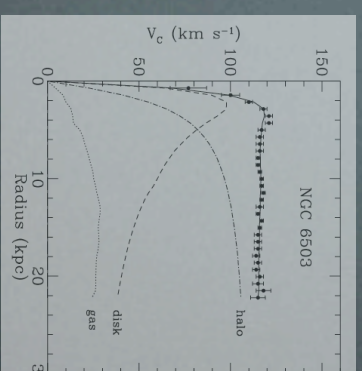
astro-ph/0608247

[further developments]

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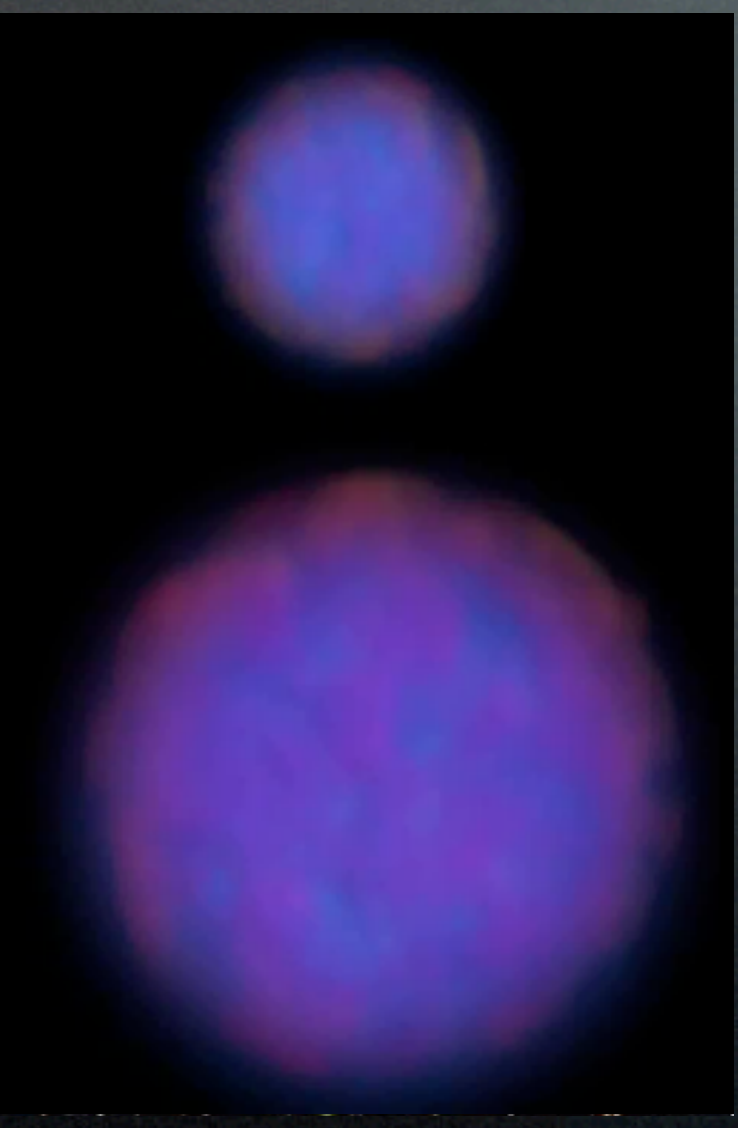


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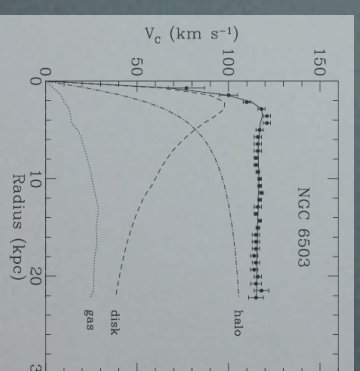
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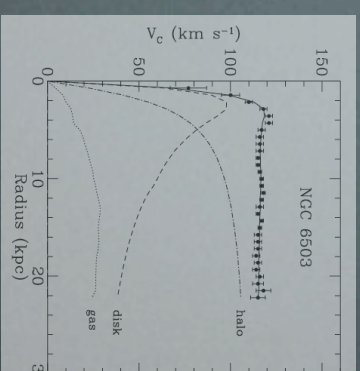
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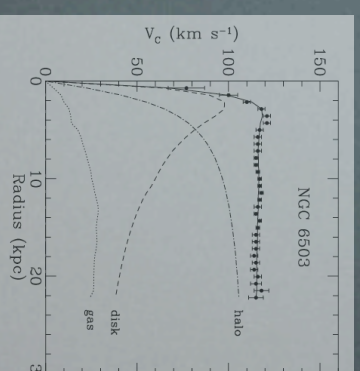
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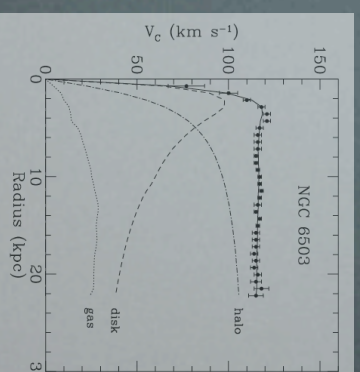
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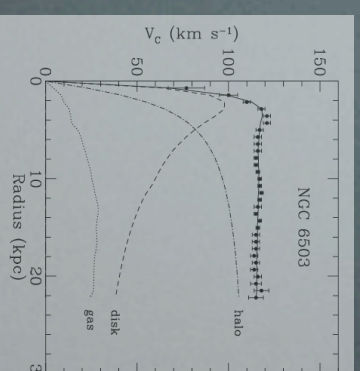
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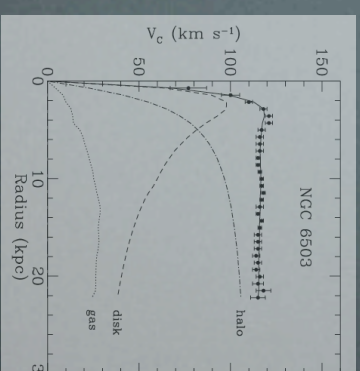
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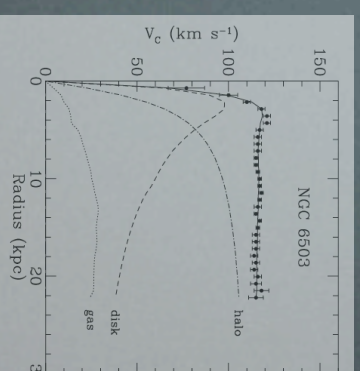
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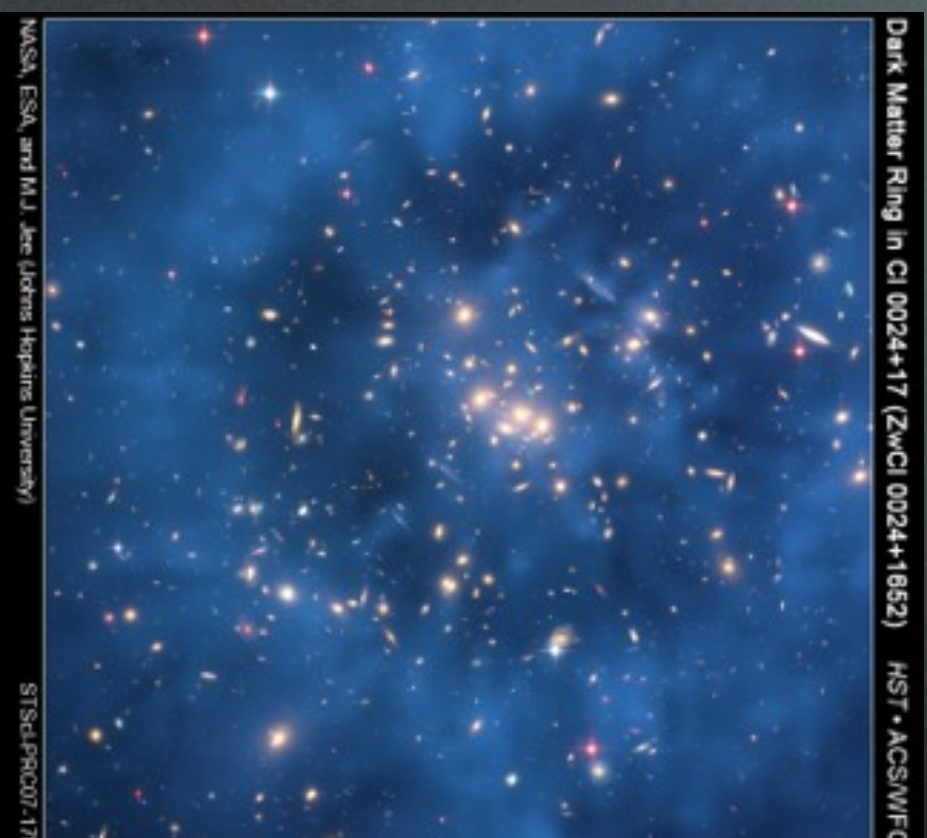


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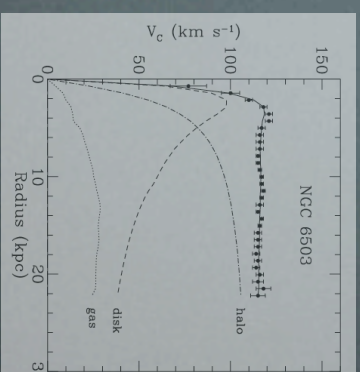


ring of Dark Matter (2007)

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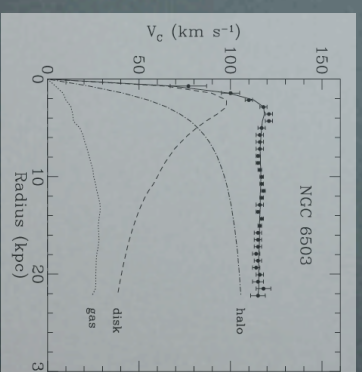


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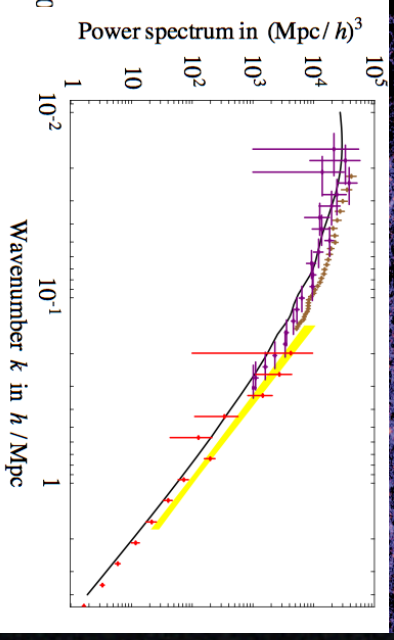
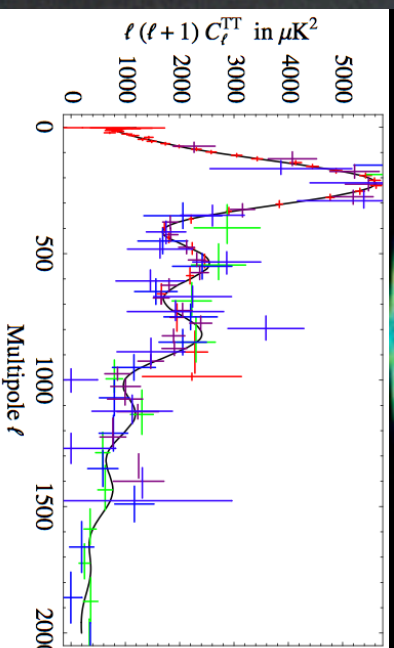
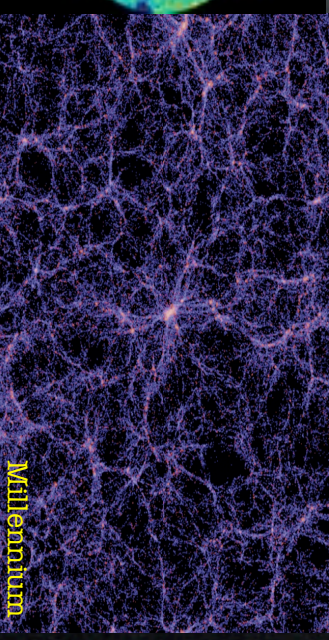
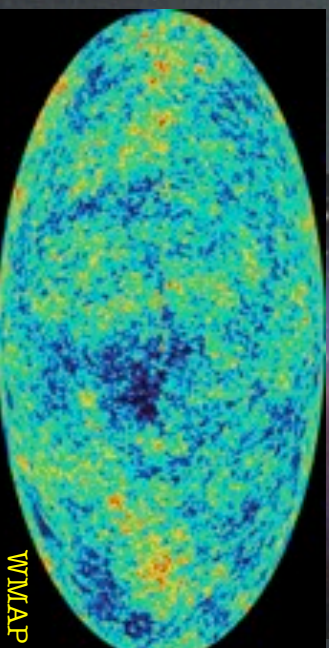


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3) CMB+LSS (+SNIa:)

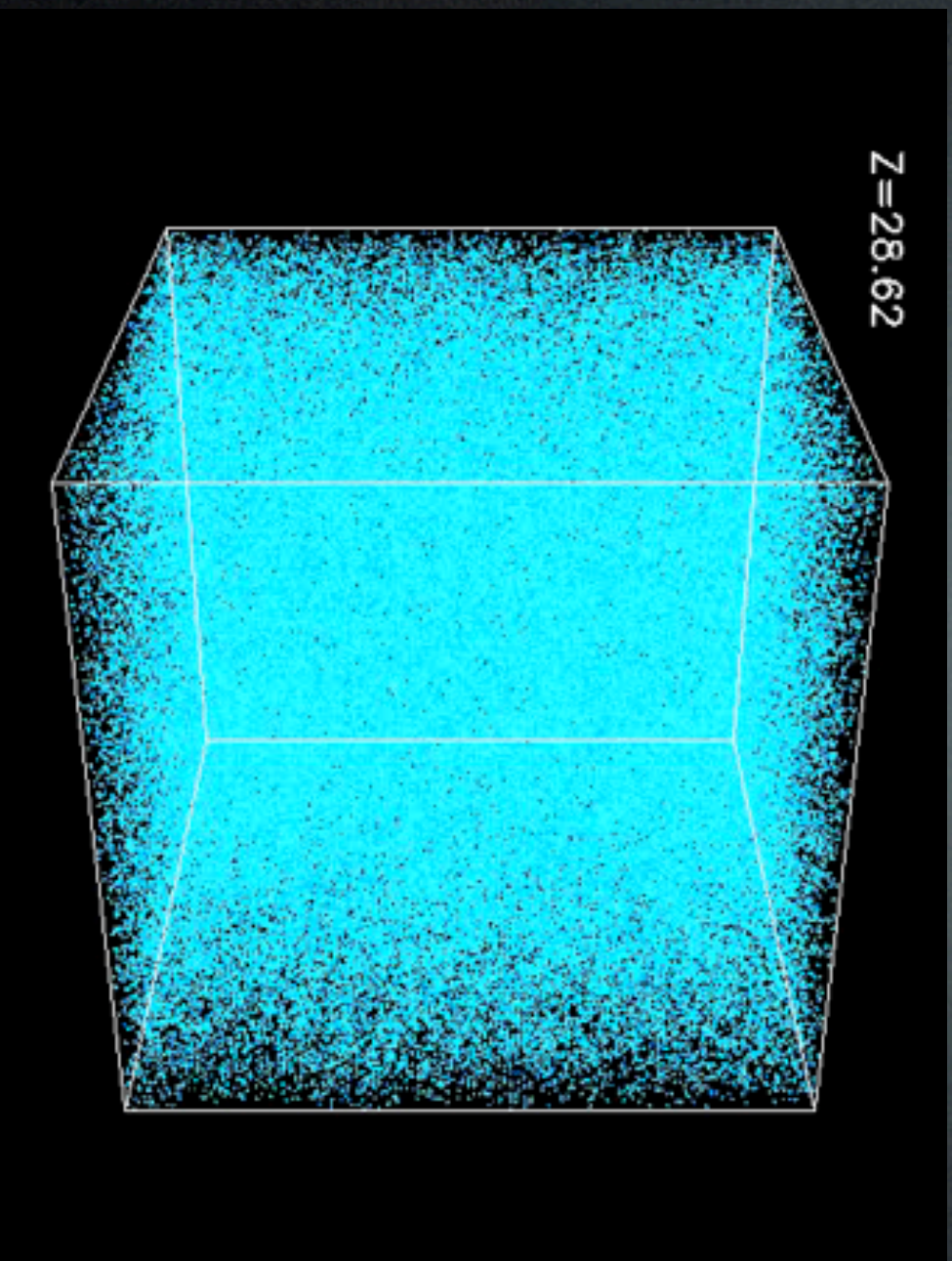


DM *N*-body simulations

2×10^6 CDM particles, 43 Mpc cubic box

DM N-body simulations

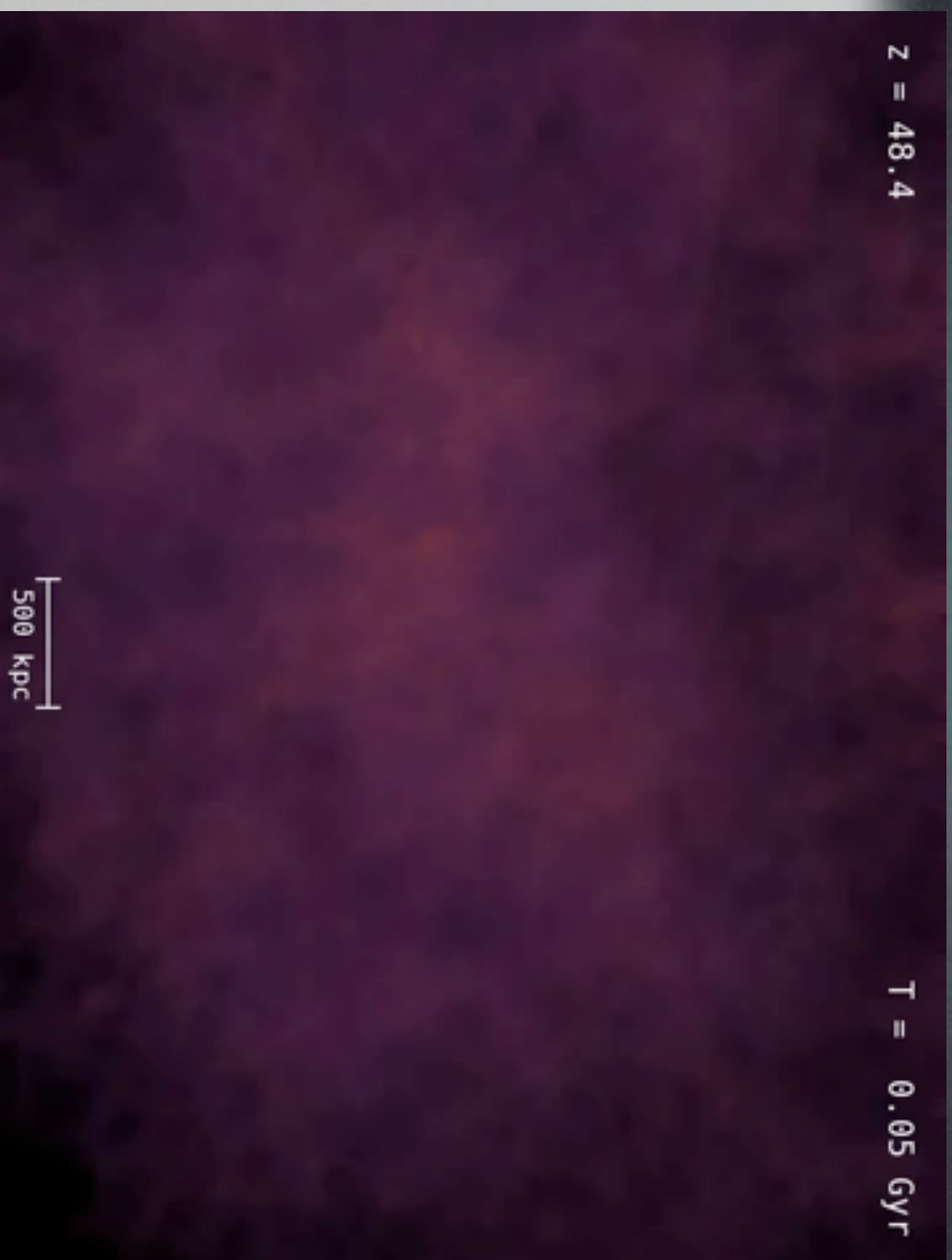
$\approx 10^6$ CDM particles, 43 Mpc cubic box



DM N-body simulations

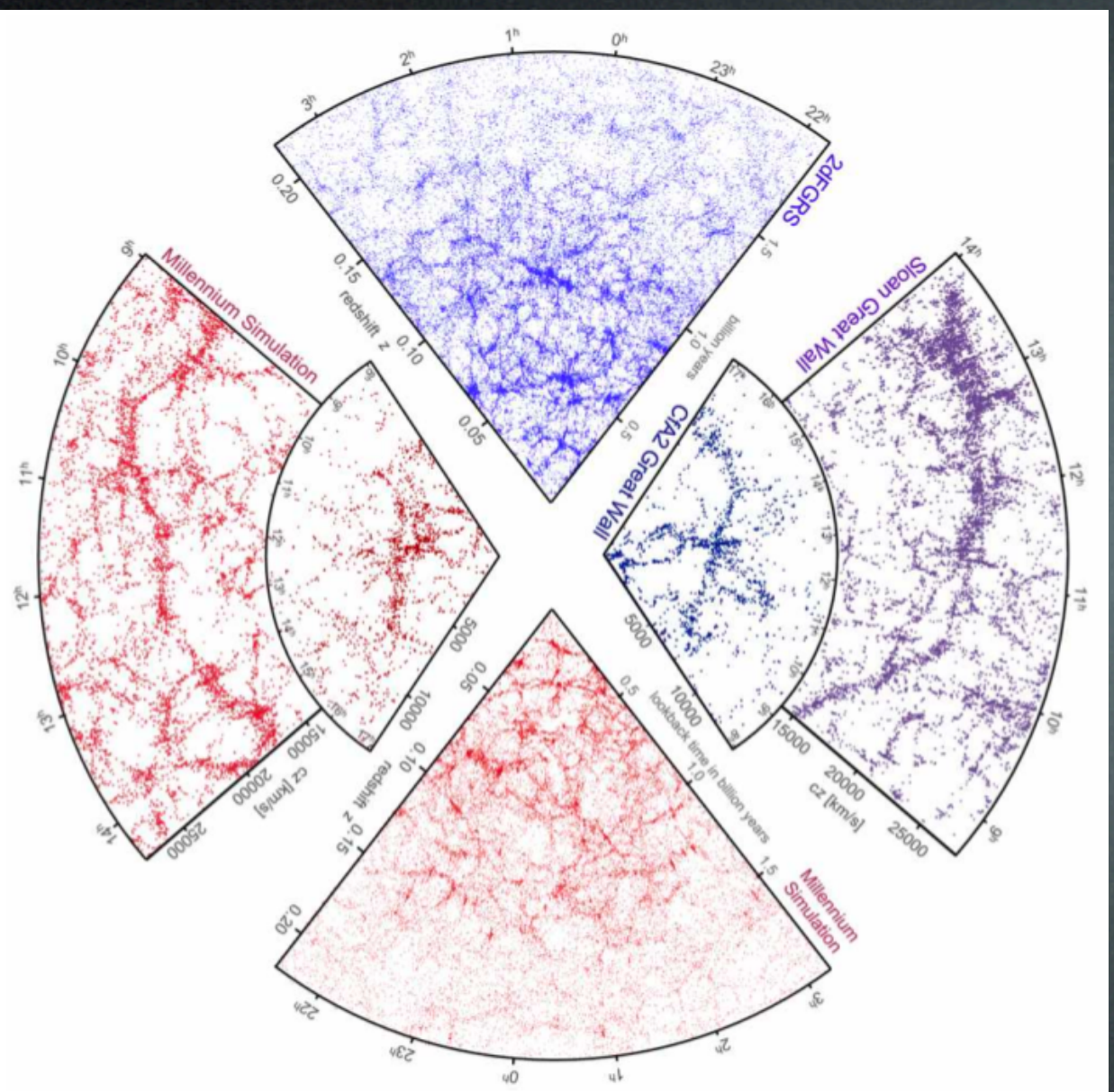
Aquarius project of the VIRGO coll.:

$1.5 \cdot 10^9$ CDM particles, single galactic halo



DM N-body simulations

2dF: 2.2×10^5 galaxies
SDSS: 10^6 galaxies,
 \approx billion lyr



Of course, you have to
infer galaxies within the
DM simulation

Springel, Frenk, White, Nature 440 (2006)

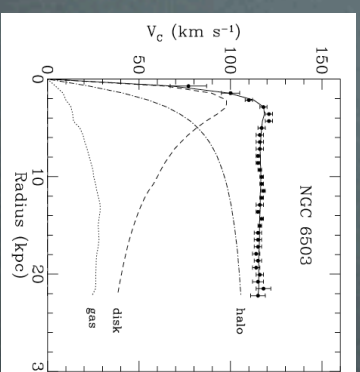
Millennium:
 10^{10} particles,
 $500 h^{-1} \text{ Mpc}$

[back]

The Evidence for DM

1) galaxy rotation curves

$$\Omega_M \gtrsim 0.1$$



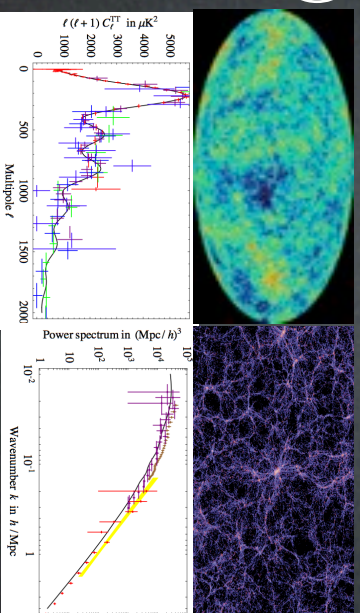
2) clusters of galaxies

$$\Omega_M \sim 0.2 \div 0.4$$



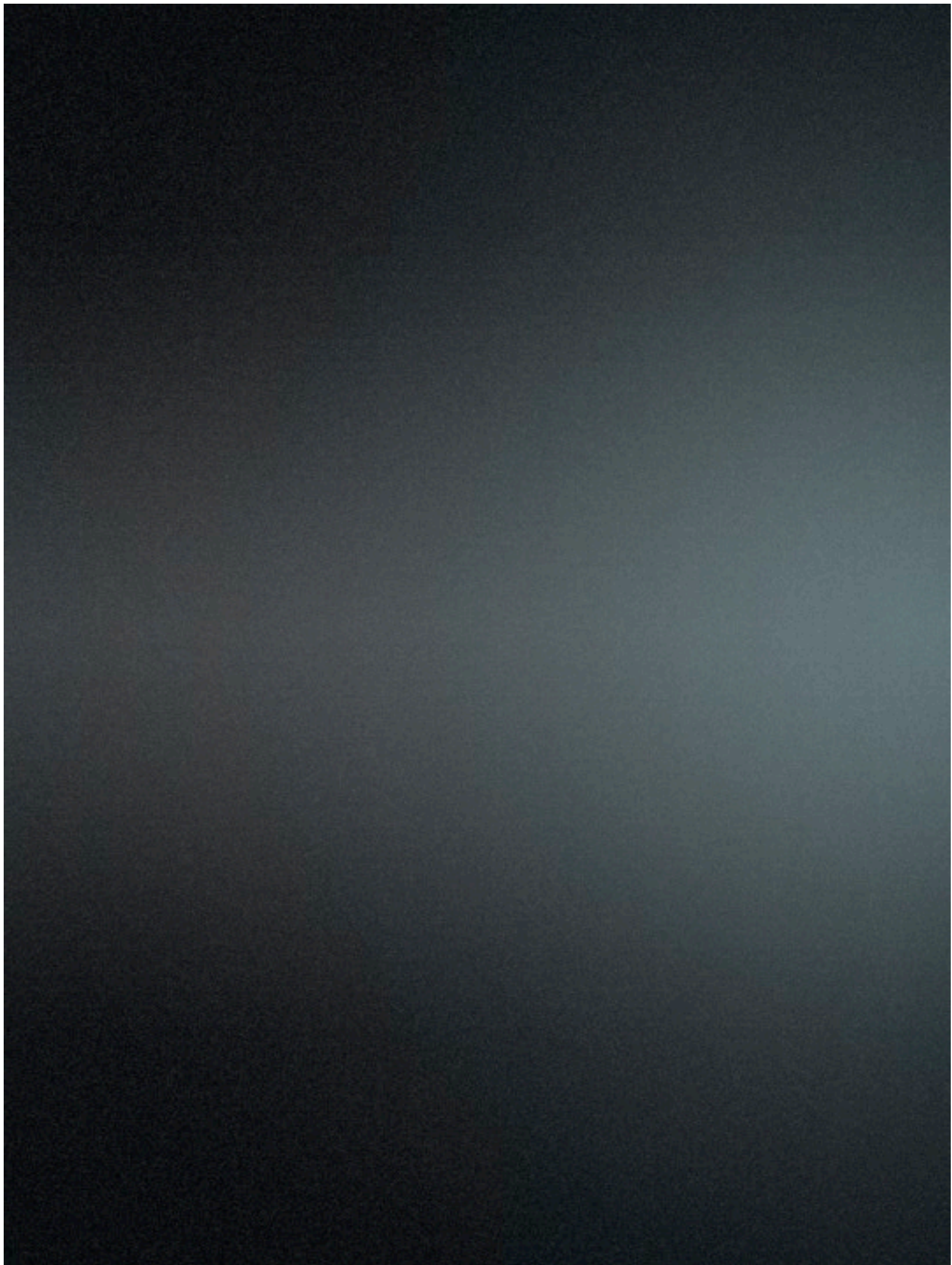
3) CMB+LSS(+SNIa:)

$$\Omega_M \approx 0.26 \pm 0.05$$



What is DM?

What do we know of the
particle physics properties of
Dark Matter?



DM can **NOT** be:

DM can **NOT** be:

an astro *je ne sais pas* quoi:

DM can NOT be:

an astro *je ne sais pas quoi*:

- neutrons
- gas
- Black Holes
- brown dwarves

DM can **NOT** be:

an astro *je ne sais pas* quoi:

- ~~neutrons~~
- gas
- Black Holes
- brown dwarves

DM can **NOT** be:

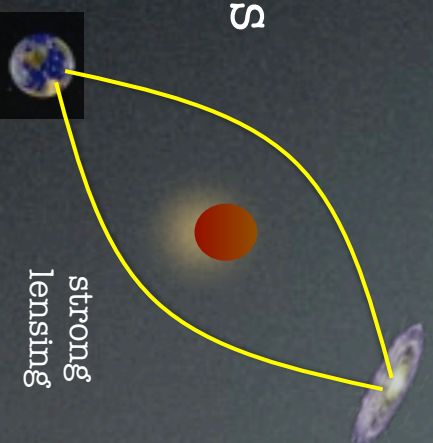
an astro *je ne sais pas* quoi:

- ~~neutrons~~
- ~~gas~~
- Black Holes
- brown dwarves

DM can **NOT** be:

an astro *je ne sais pas* quoi:

- ~~neutrons~~
- ~~gas~~
- ~~Black Holes~~
- ~~brown dwarves~~

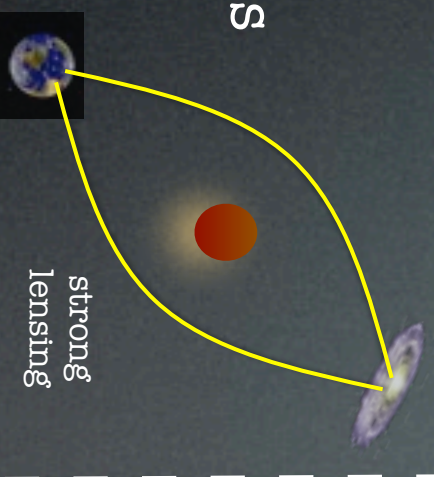


DM can **NOT** be:

an astro *je ne sais pas* quoi:

- ~~neutrinos~~
- ~~gas~~
- ~~Black Holes~~
- ~~brown dwarves~~

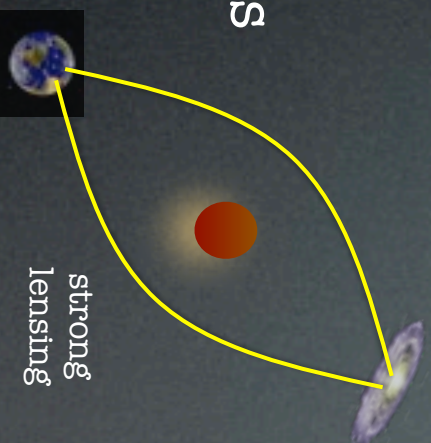
a baryon of the SM:



DM can **NOT** be:

an astro *je ne sais pas* quoi:

- ~~neutrinos~~
- ~~axions~~
- ~~Black Holes~~
- ~~brown dwarves~~



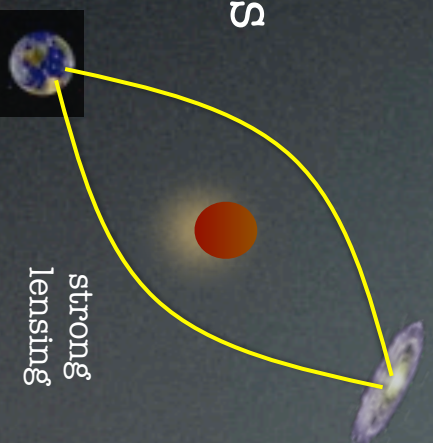
~~a baryon of the SM:~~

- BBN computes the abundance of He in terms of primordial baryons: too much baryons => Universe full of Helium
- CMB says baryons are 4% max

DM can **NOT** be:

an astro *je ne sais pas* quoi:

- ~~neutrinos~~
- ~~gas~~
- ~~Black Holes~~
- ~~brown dwarves~~



~~a baryon of the SM:~~

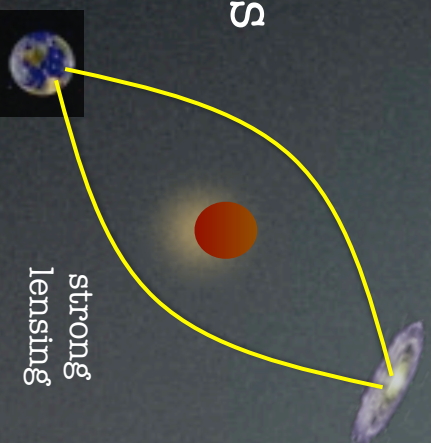
- BBN computes the abundance of He in terms of primordial baryons: too much baryons => Universe full of Helium
- CMB says baryons are 4% max

neutrinos:

DM can **NOT** be:

an astro *je ne sais pas* quoi:

- ~~neutrinos~~
- ~~gas~~
- ~~Black Holes~~
- ~~brown dwarves~~



~~a baryon of the SM:~~

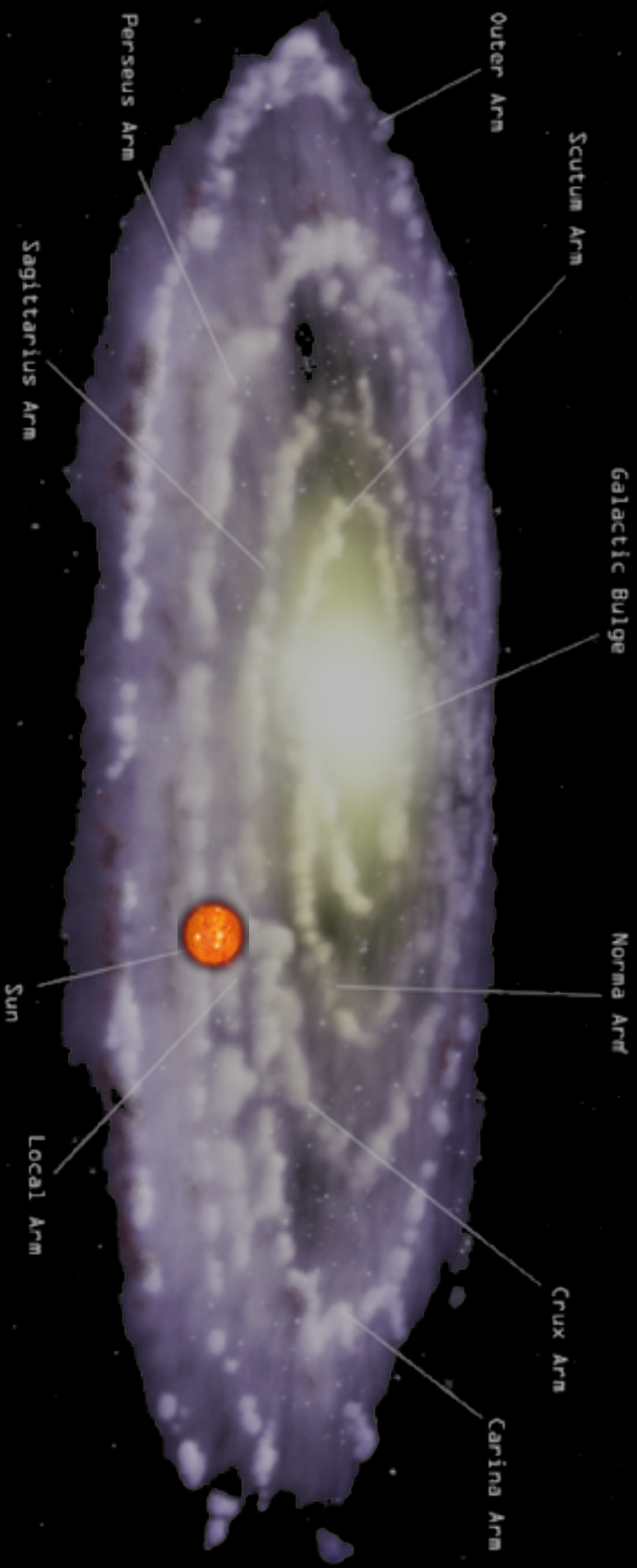
- BBN computes the abundance of He in terms of primordial baryons: too much baryons => Universe full of Helium
- CMB says baryons are 4% max

~~neutrinos:~~

too light! $m_\nu \lesssim 1 \text{ eV}$

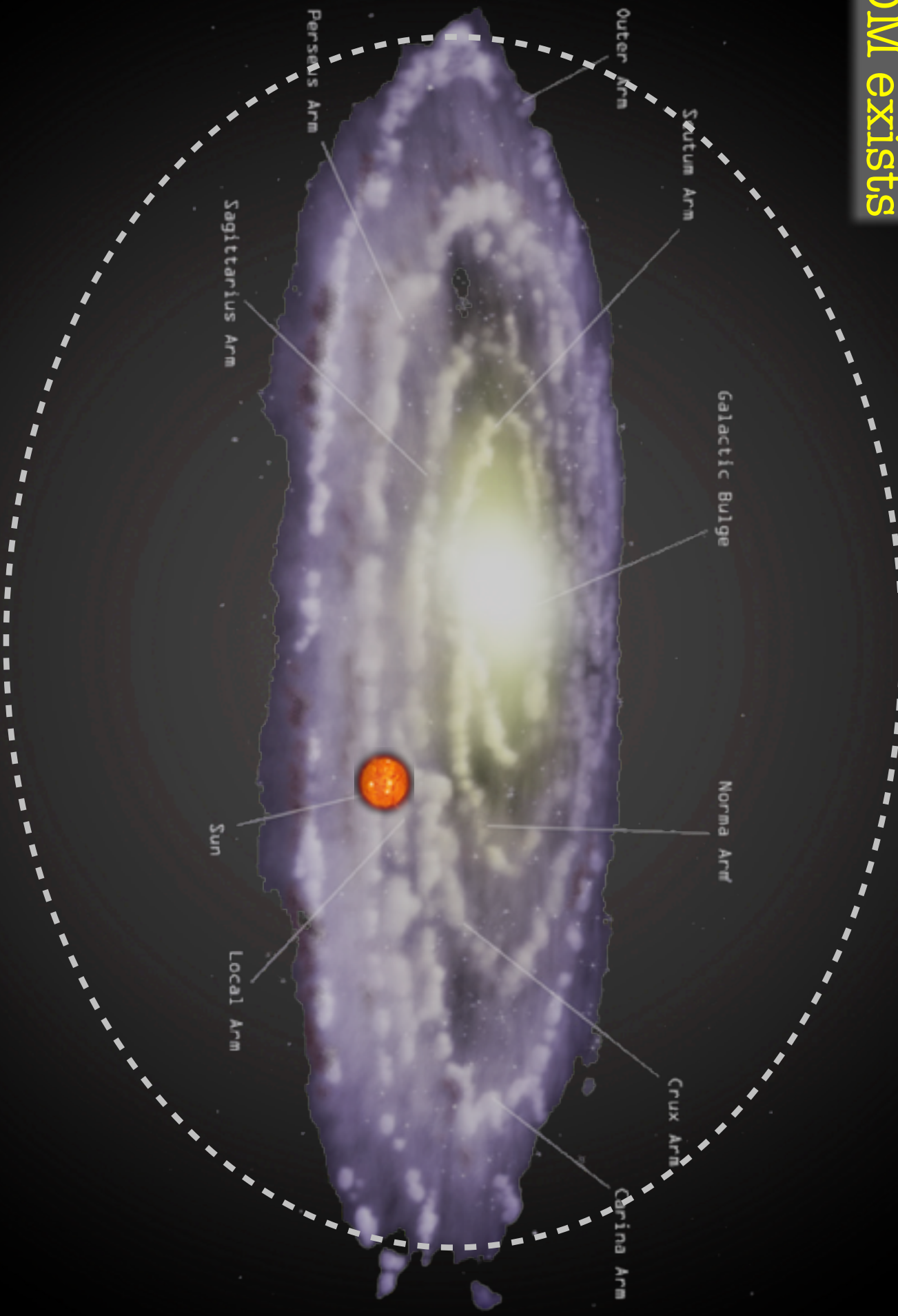
do not have enough mass to act as gravitational attractors in galaxy collapse

Recap: DM factsheet



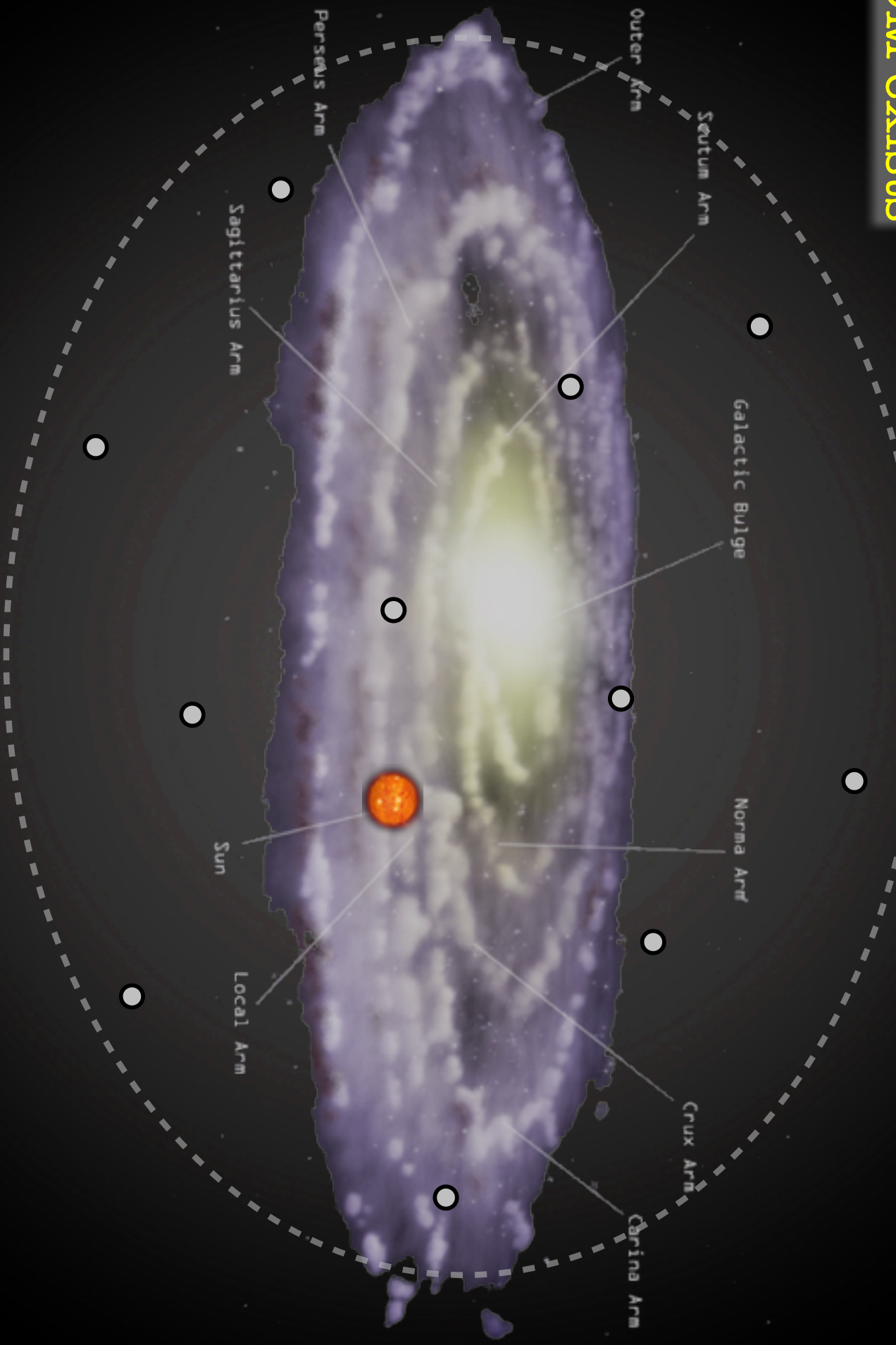
Recap: DM factsheet

DM exists



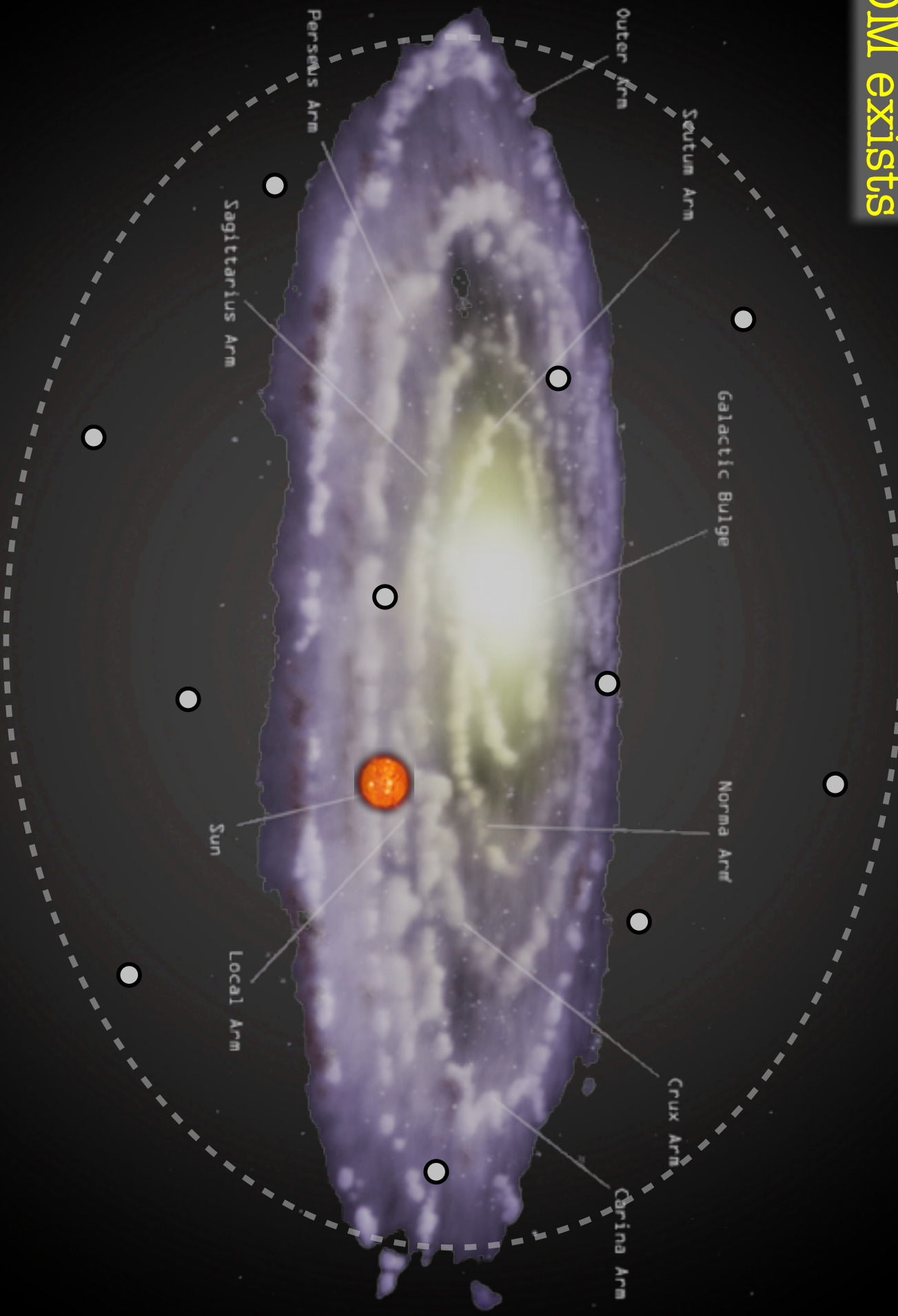
Recap: DM factsheet

DM exists



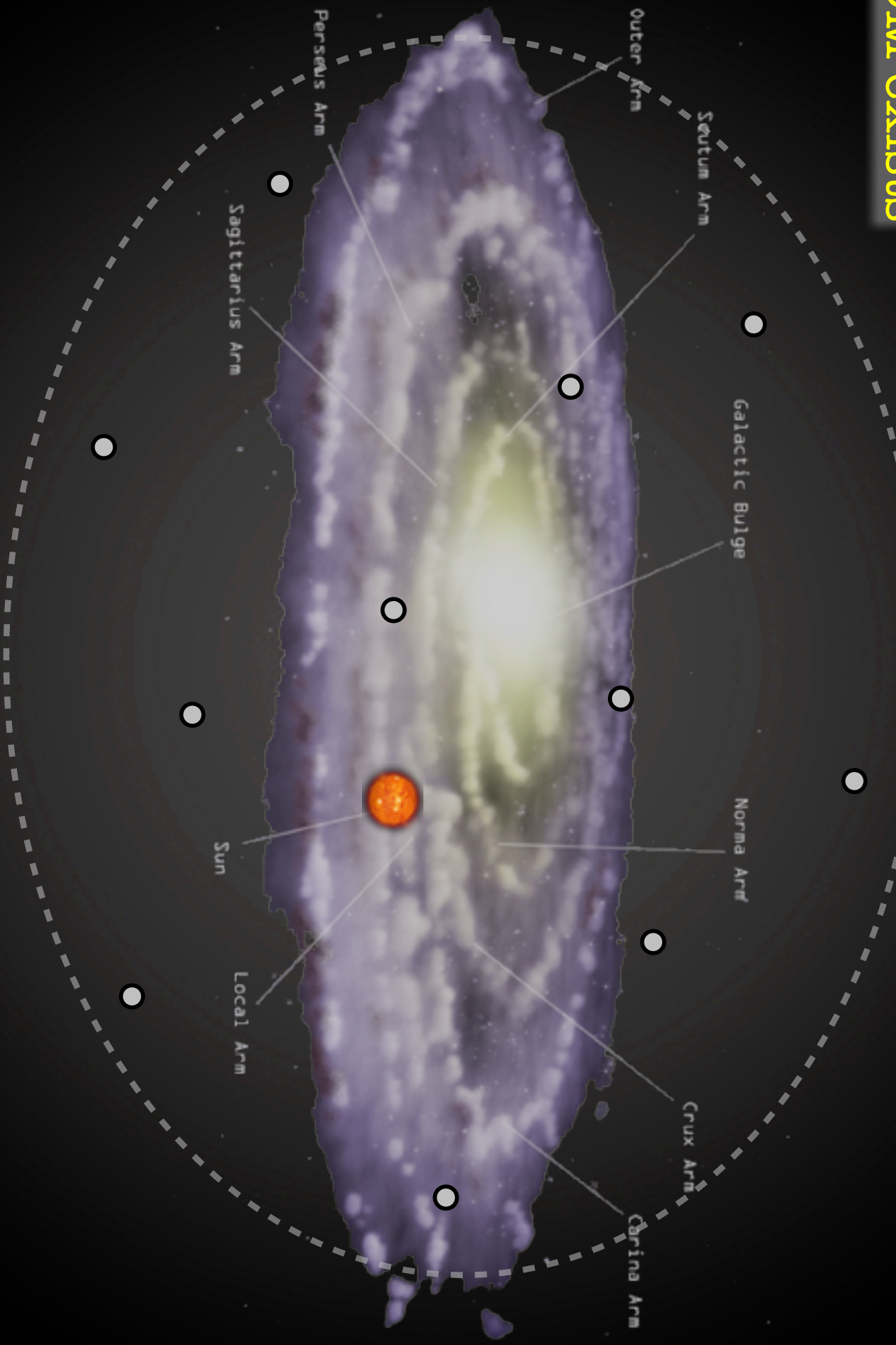
Recap: DM factsheet

DM exists



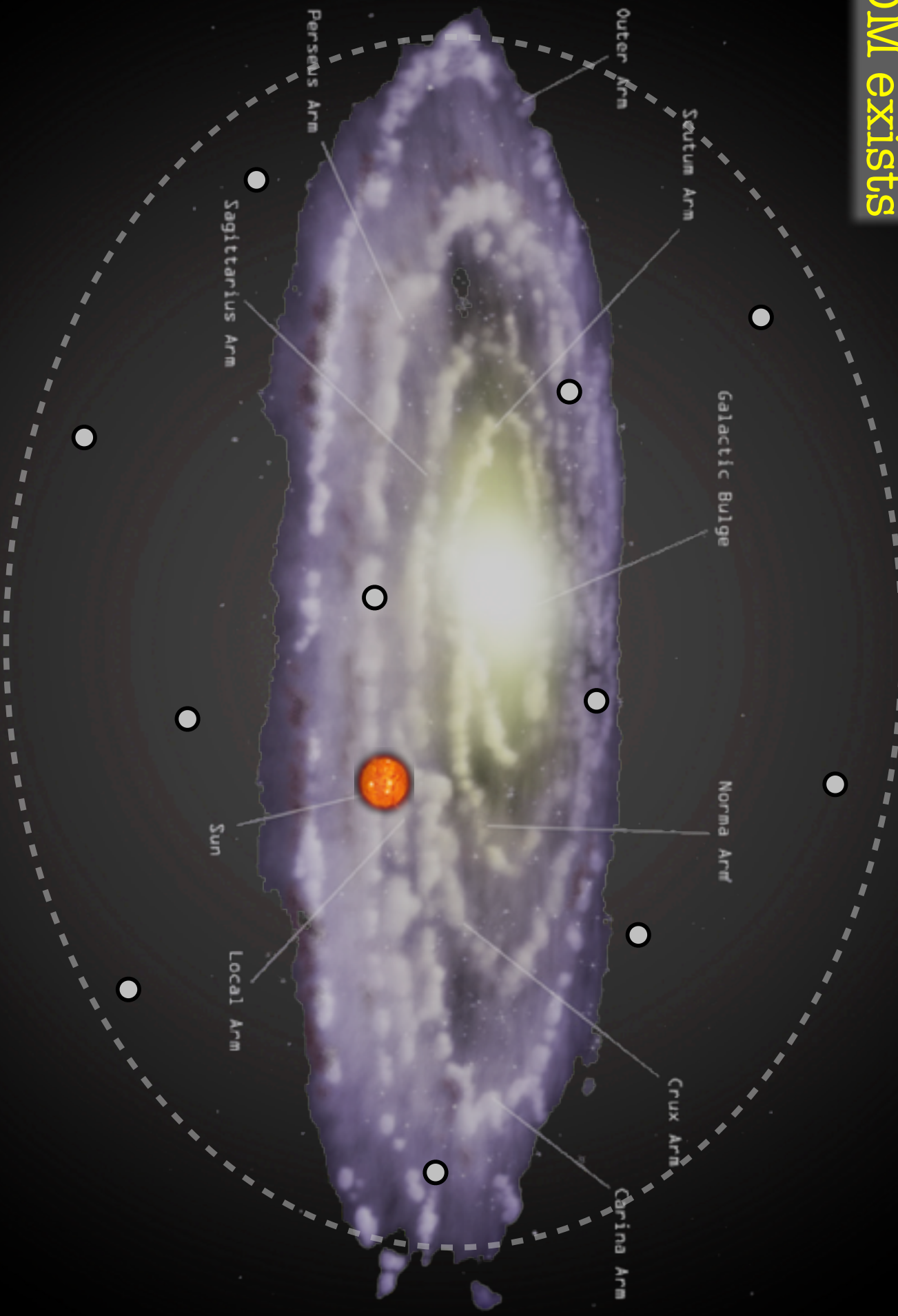
Recap: DM factsheet

DM exists



Recap: DM factsheet

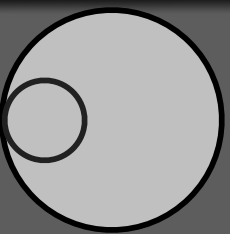
DM exists



Recap: DM factsheet

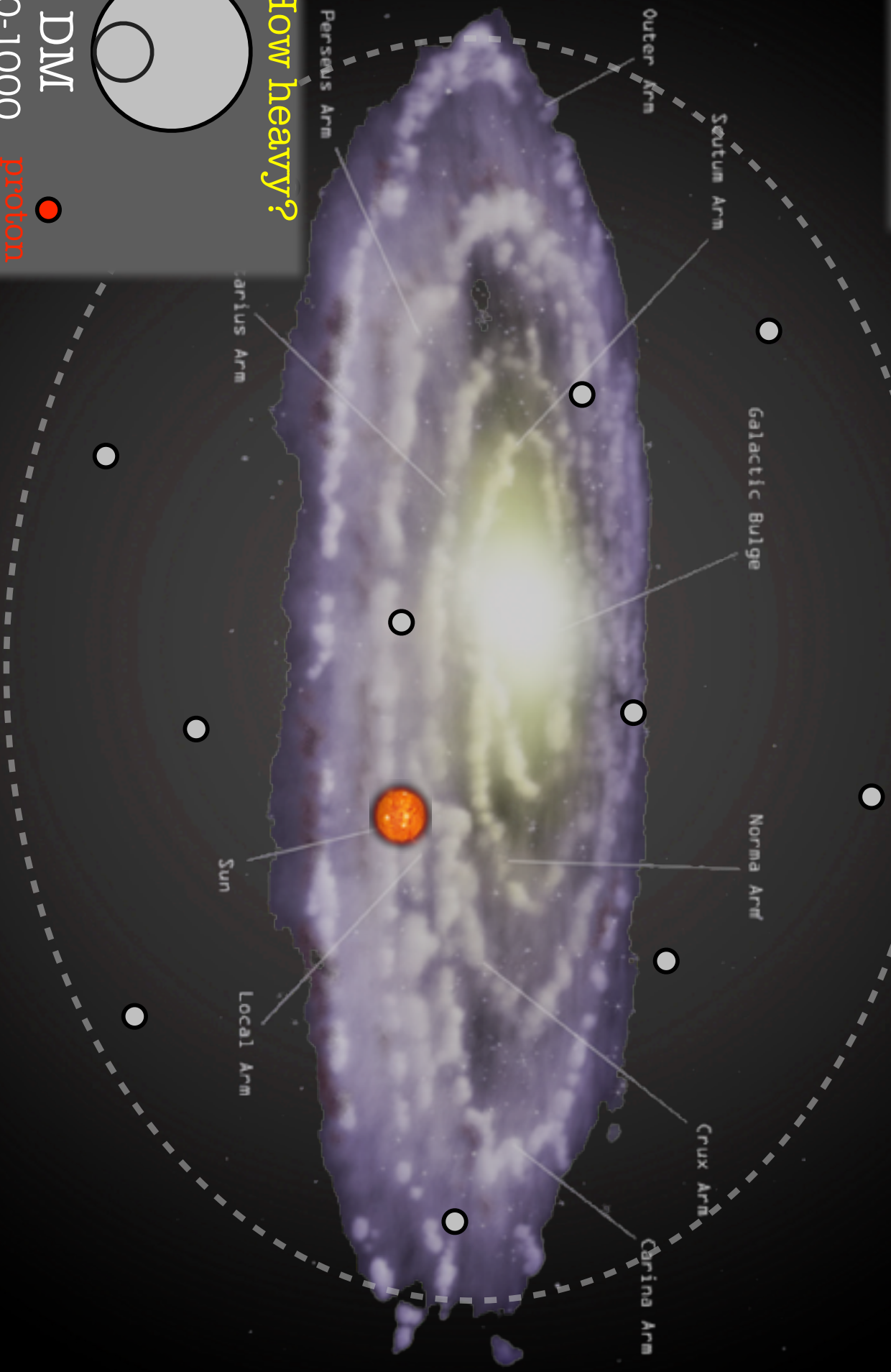
DM exists

How heavy?



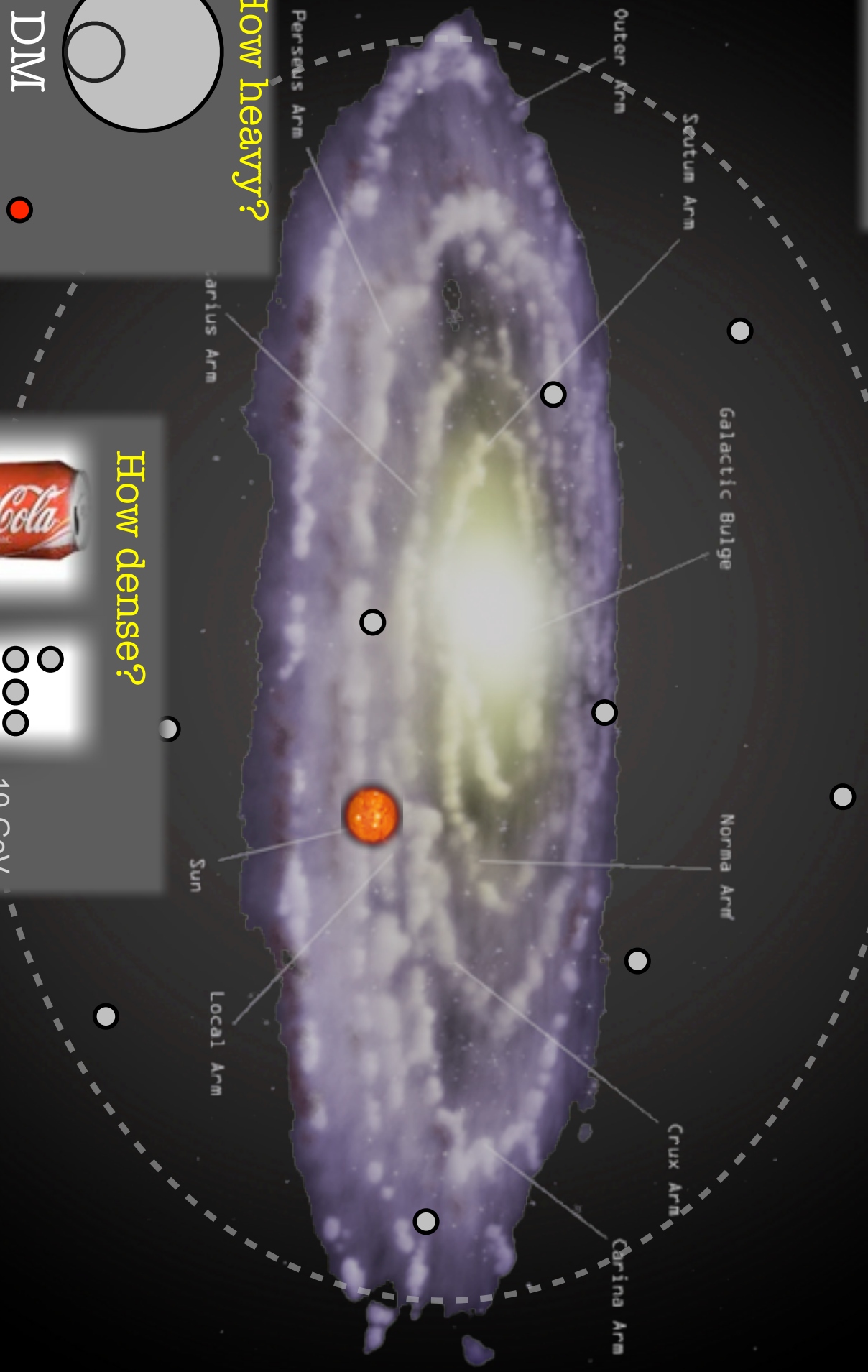
DM
10-1000
GeV

proton
1 GeV

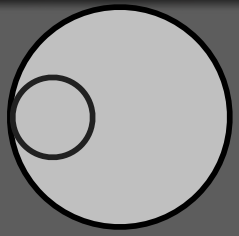


Recap: DM factsheet

DM exists



How heavy?



DM
10-1000 GeV
proton
1 GeV

How dense?

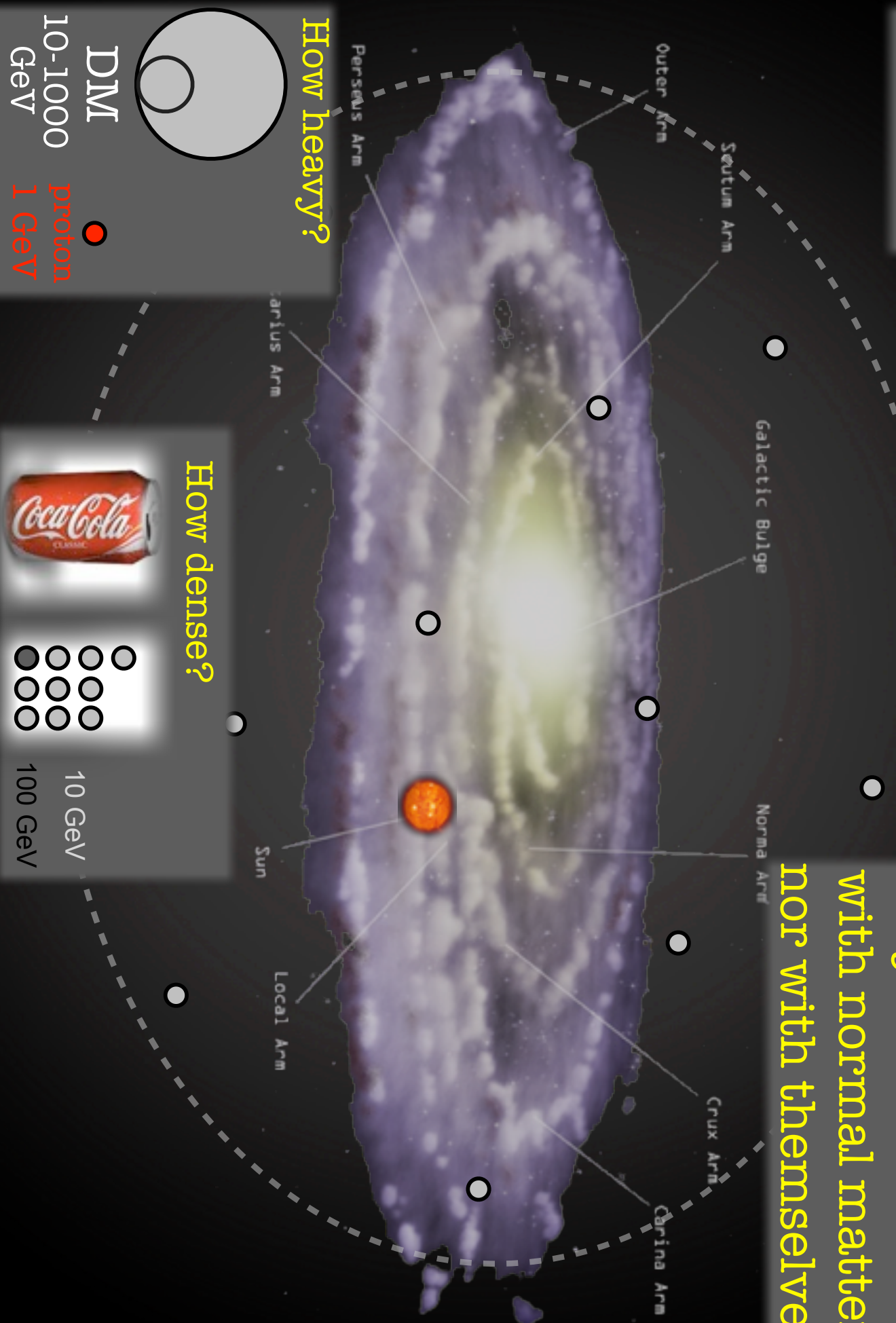


10 GeV
100 GeV

Recap: DM factsheet

DM exists

They do not interact with normal matter nor with themselves



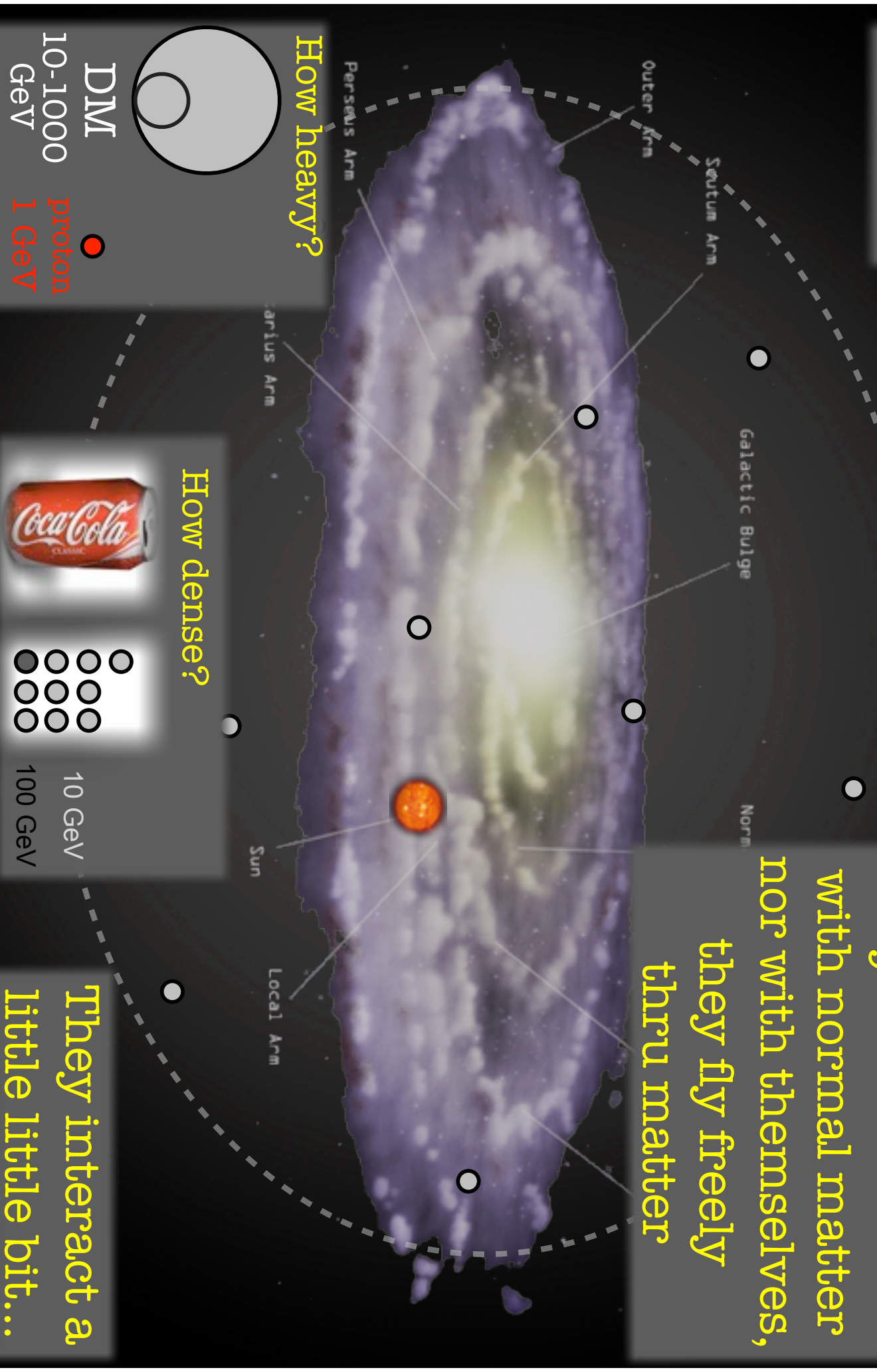
How heavy?

How dense?

Recap: DM factsheet

DM exists

They do not interact with normal matter, nor with themselves, they fly freely thru matter



How heavy?

DM
10-1000 GeV

proton
1 GeV

How dense?

10 GeV
100 GeV

They interact a little little bit...

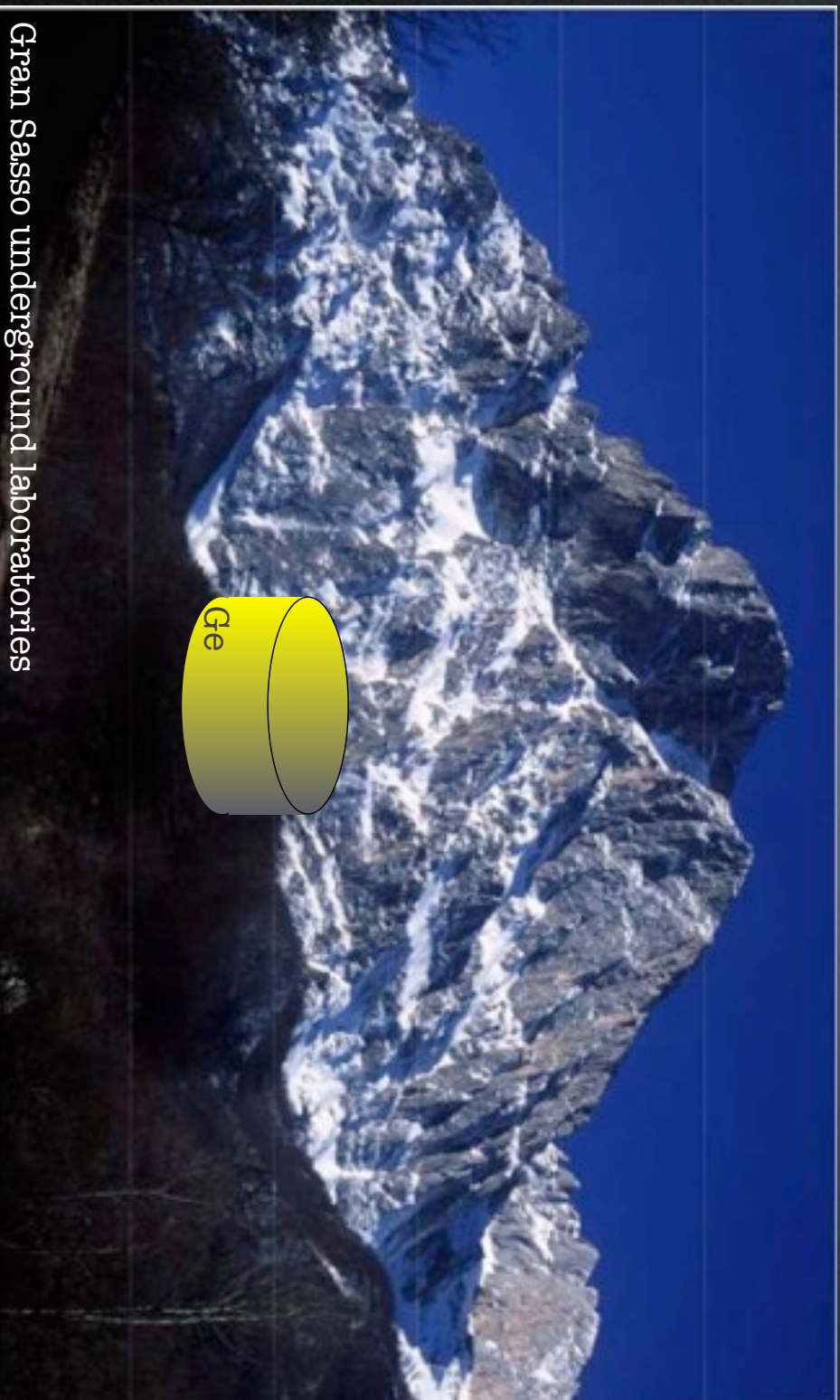
Detecting Dark Matter

1. Direct Detection: **basics**



Gran Sasso underground laboratories

Direct Detection: basics



Gran Sasso underground laboratories

Direct Detection: basics



Gran Sasso underground laboratories

Direct Detection

Strategy #1: silence the Universe

Direct Detection

Strategy #1: **silence the Universe**

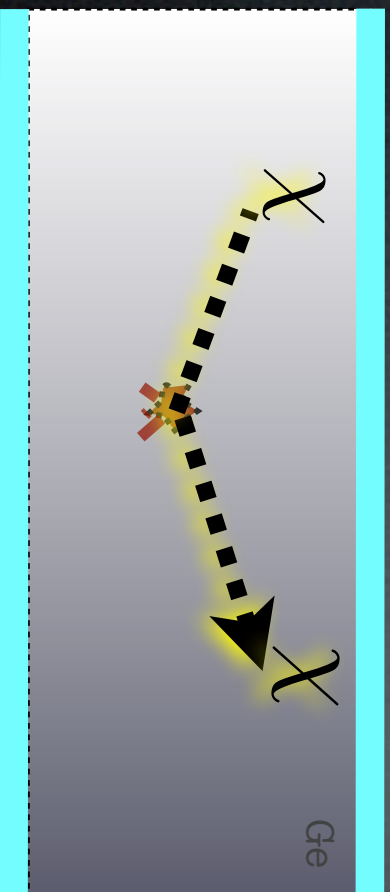
measure two quantities to discriminate Sign & Bkgd,
on event-by-event basis

Direct Detection

Strategy #1: **silence the Universe**

measure two quantities to discriminate Sign & Bkgd,
on event-by-event basis

E.g. **Edelweiss**:



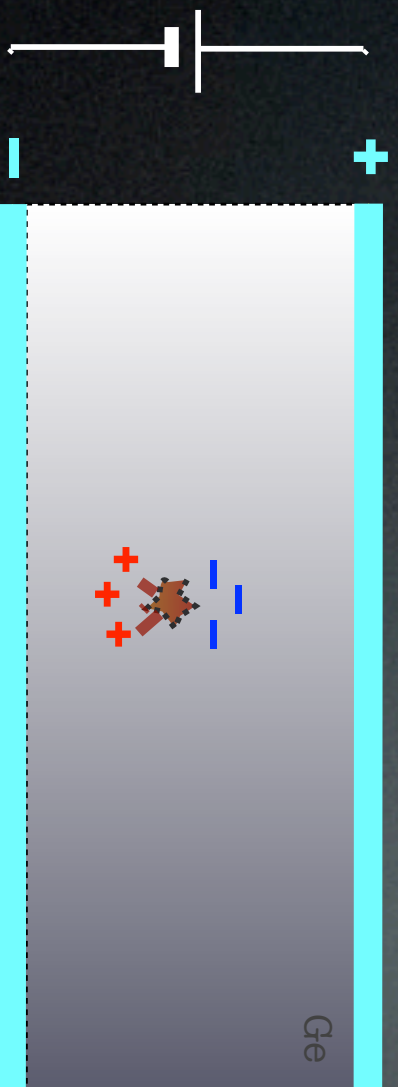
Direct Detection

Strategy #1: **silence the Universe**

measure two quantities to discriminate Sign & Bkgd,
on event-by-event basis

E.g. **Edelweiss**:

ionization



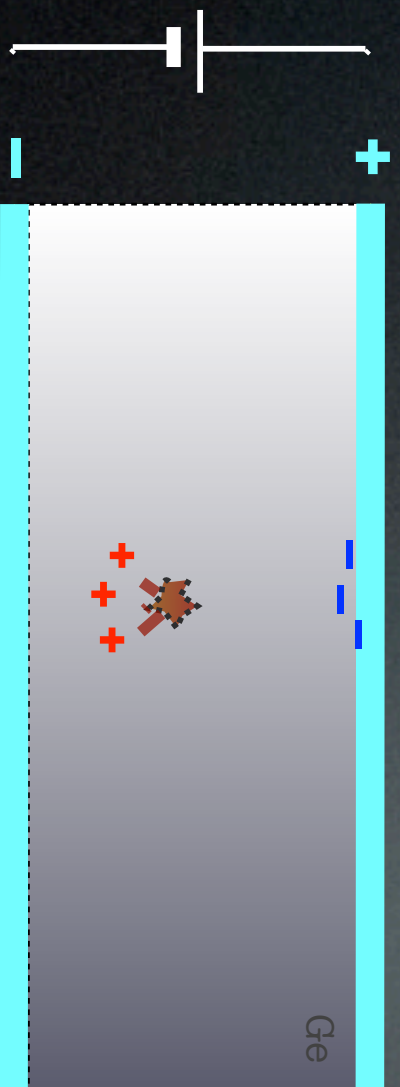
Direct Detection

Strategy #1: **silence the Universe**

measure two quantities to discriminate Sign & Bkgd,
on event-by-event basis

E.g. **Edelweiss**:

ionization

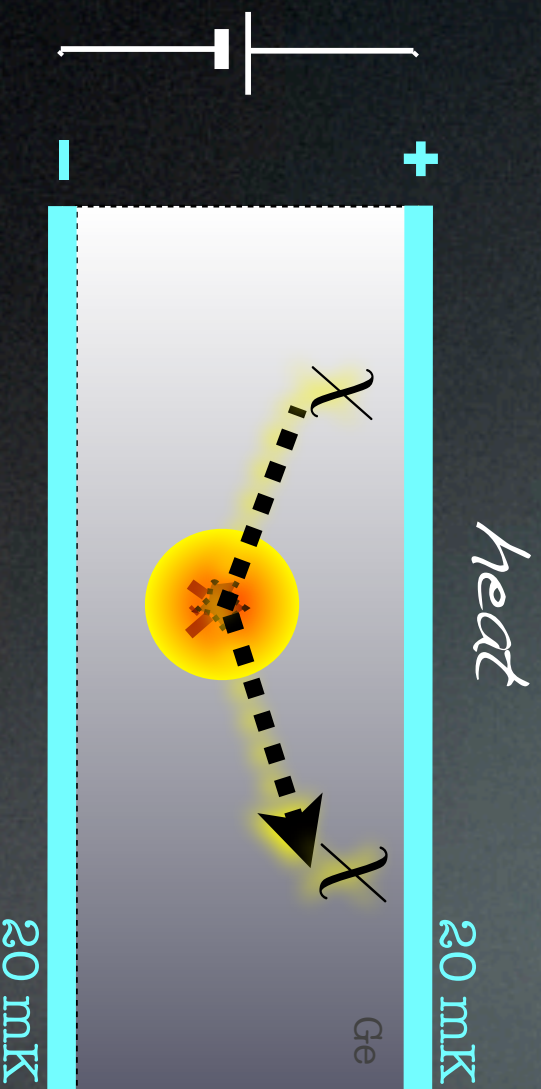


Direct Detection

Strategy #1: silence the Universe

measure two quantities to discriminate Sign & Bkgd, on event-by-event basis

E.g. Edelweiss:

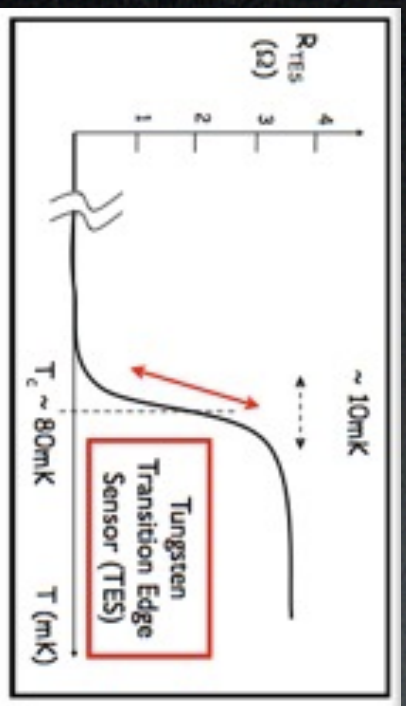
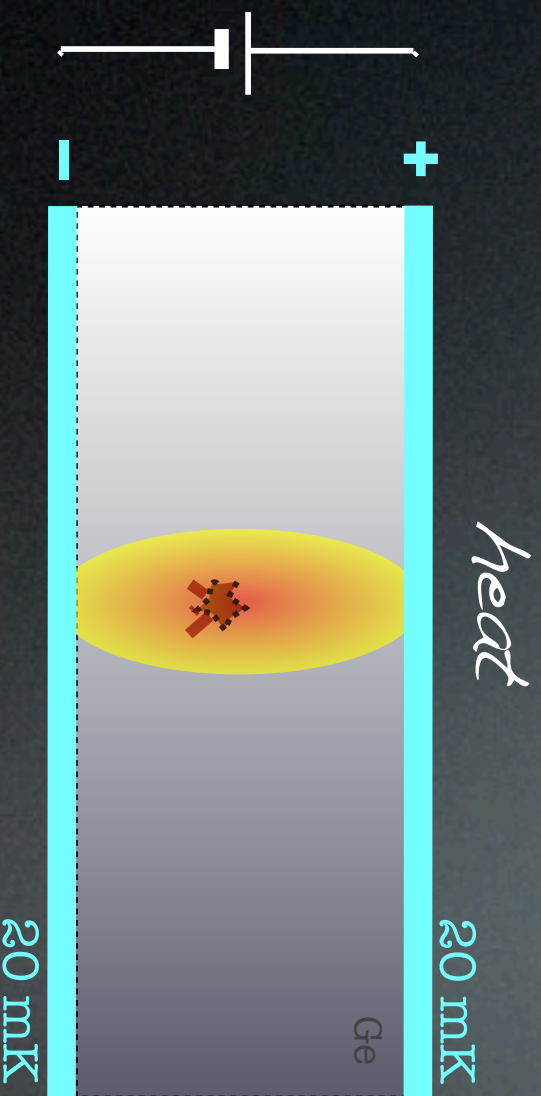


Direct Detection

Strategy #1: **silence the Universe**

measure two quantities to discriminate Sign & Bkgd, on event-by-event basis

E.g. **Edelweiss**:

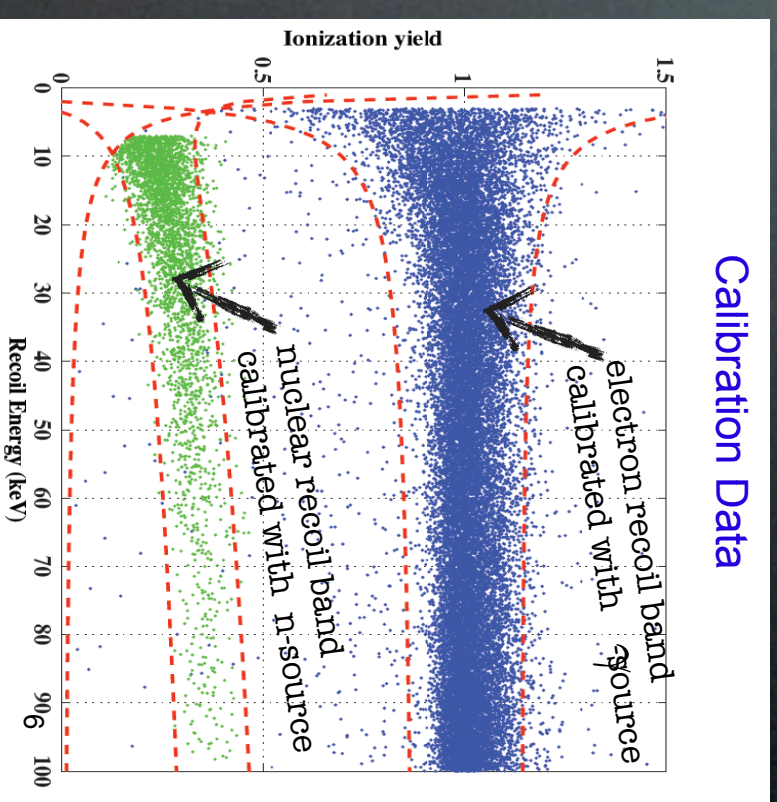
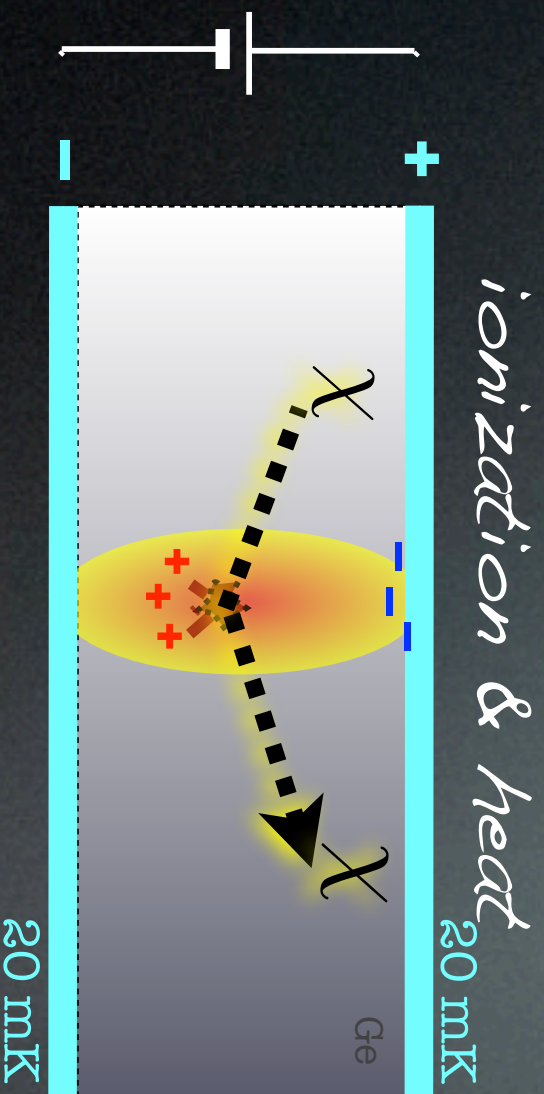


Direct Detection

Strategy #1: silence the Universe

measure two quantities to discriminate Sign & Bkgd, on event-by-event basis

E.g. **Edelweiss**:



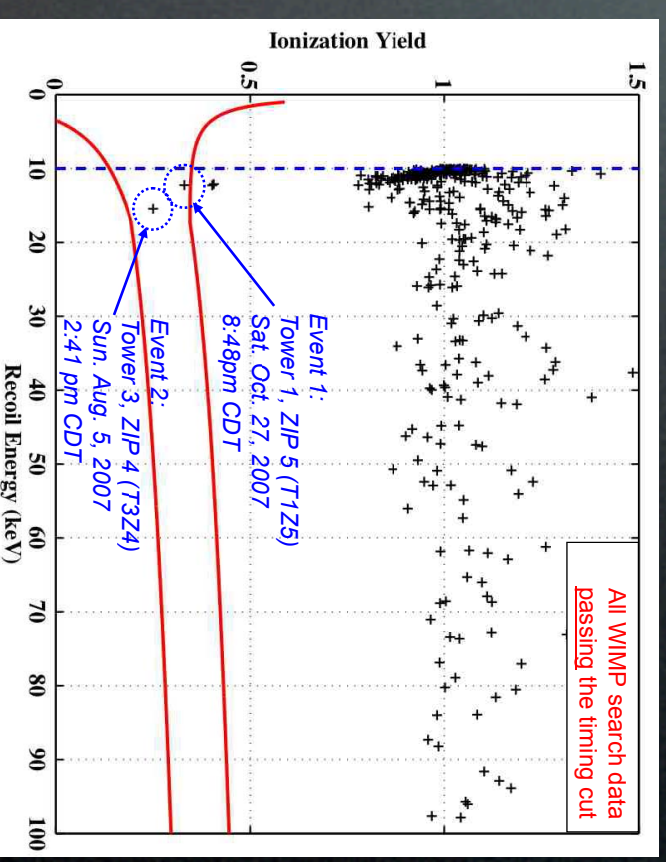
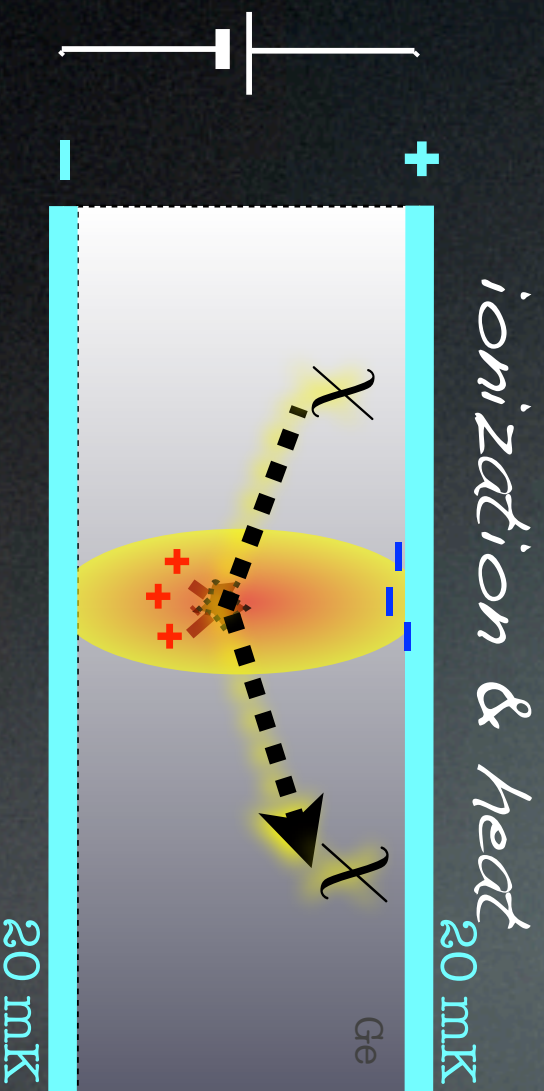
CDMS coll.

Direct Detection

Strategy #1: silence the Universe

measure two quantities to discriminate Sign & Bkgd,
on event-by-event basis

E.g. **Edelweiss**:



CDMS coll., Science 327 (2010), 0912.3592

Direct Detection

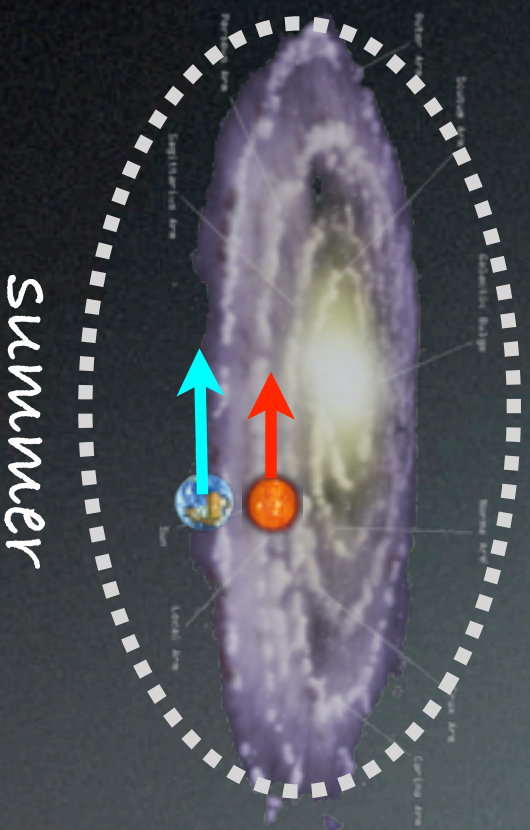
Strategy #2: ride the dark wave

collect all events, and detect an annual modulation

Direct Detection

Strategy #2: ride the dark wave

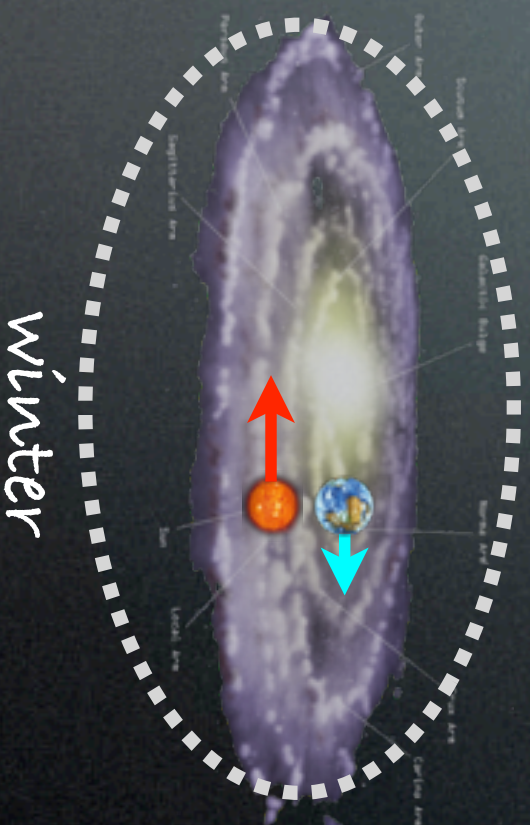
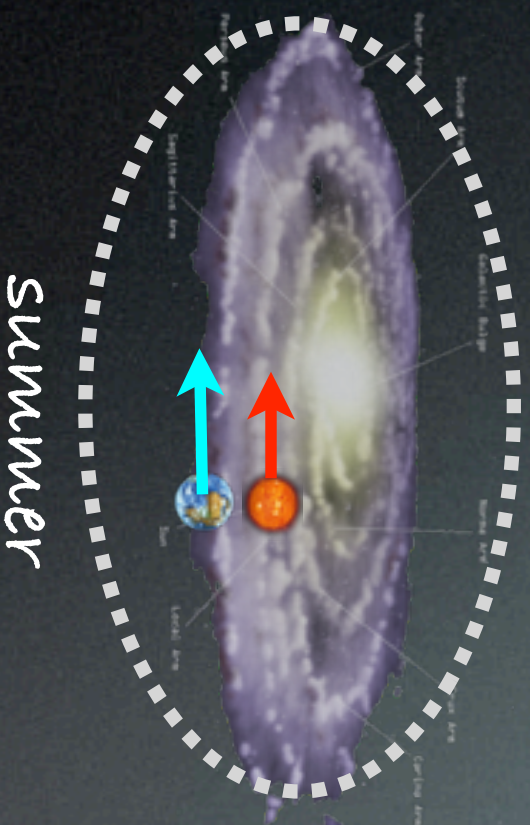
collect all events, and detect an annual modulation



Direct Detection

Strategy #2: ride the dark wave

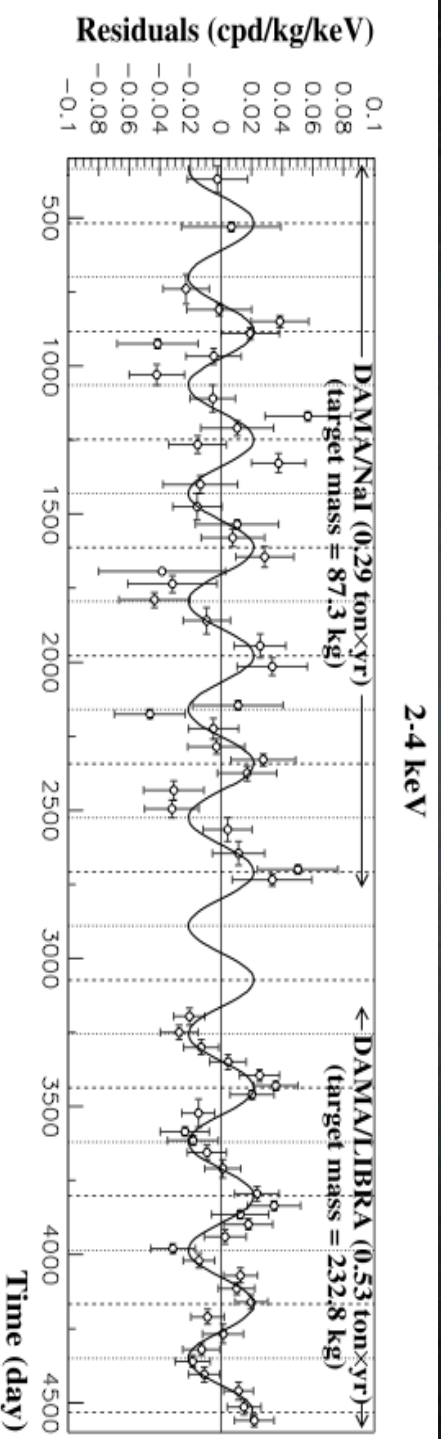
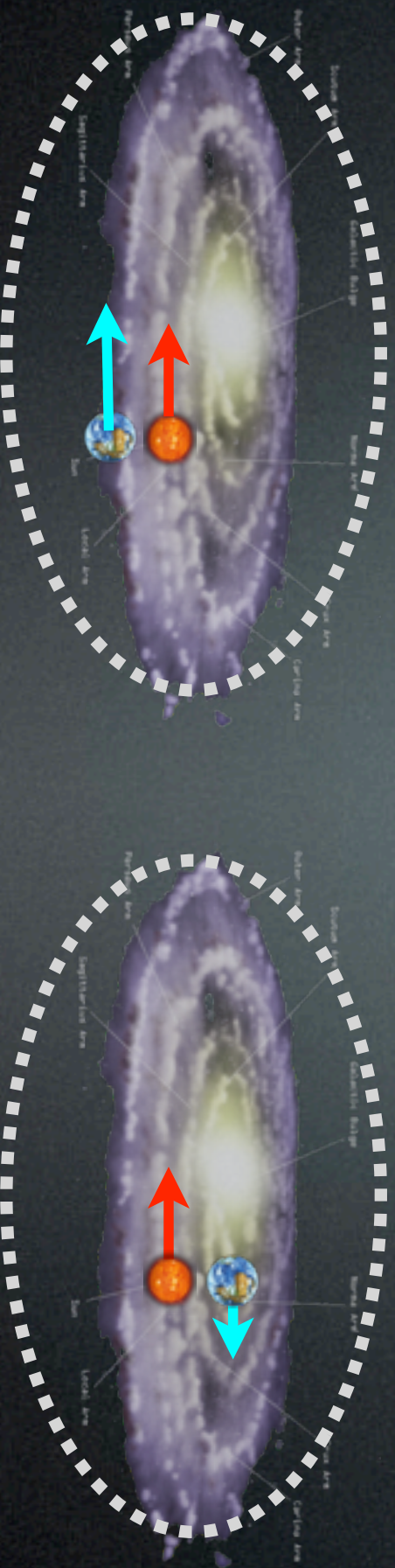
collect all events, and detect an annual modulation



Direct Detection

Strategy #2: ride the dark wave

collect all events, and detect an annual modulation



Direct Detection: status

Direct Detection: status

DAMA/Libra
(1998-2011)



GoGeNT
(2010-2011)



CRISST
(2011)



Dark Matter!

Dark Matter! DARK MATTER!

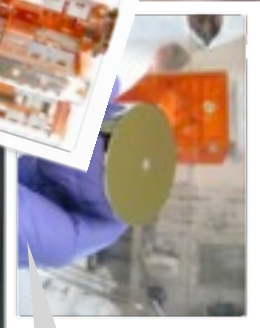
Seen an **excess** of events and/or annual **modulation**.
Light (few GeV) DM with large scattering.

Direct Detection: status

DAMA/Libra
(1998-2011)



GoGeNT
(2010-2011)



CRISST
(2011)



Dark Matter!
Dark Matter! DARK MATTER!

Seen an **excess** of events and/or annual **modulation**.
Light (few GeV) DM with large scattering.

No way.

Absolute **cosmic silence** recorded,
limits are stronger than signal.

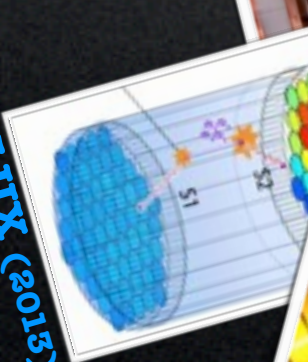
XENON100
(2009-2011)



CDMS (2009)



LUX (2015)

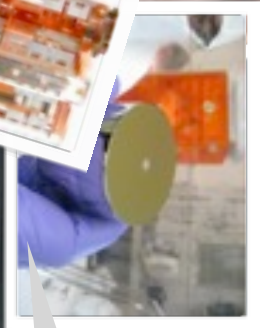


Direct Detection: status

DAMA/Libra
(1998-2011)



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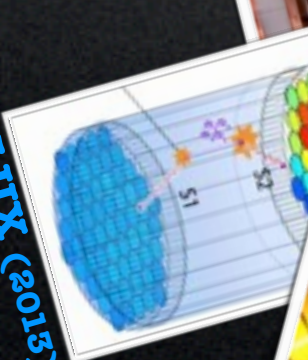
XENON100
(2009-2011)



CDMS (2009)



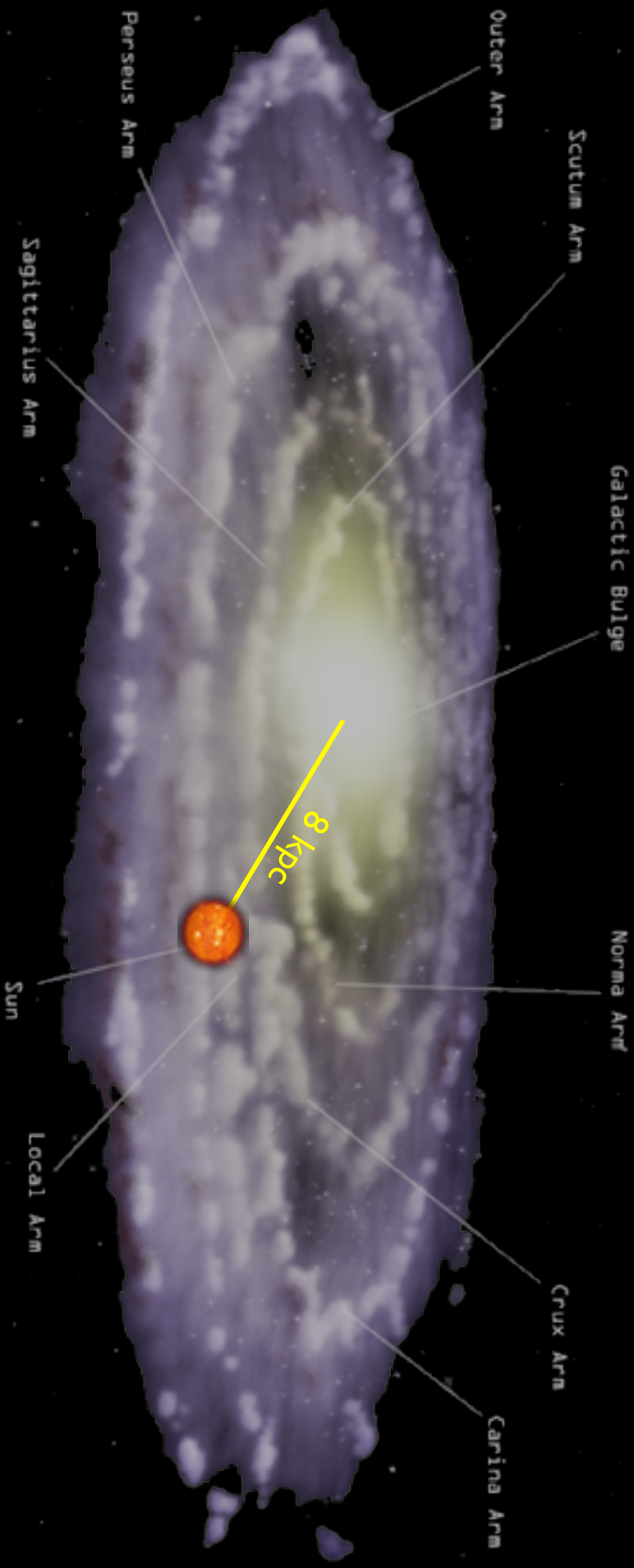
LUX (2015)



Average theorist

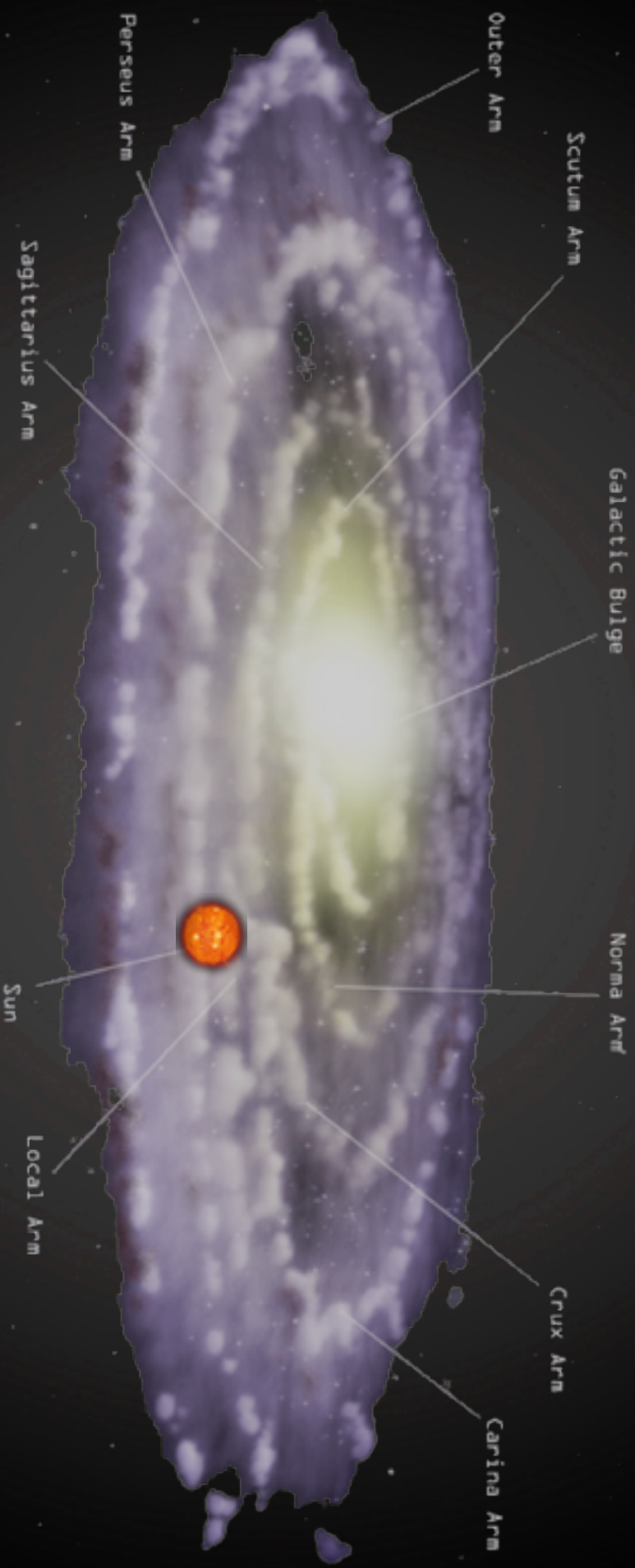
2. Indirect Detection: **basics**

\bar{p} and e^+ from DM annihilations in halo



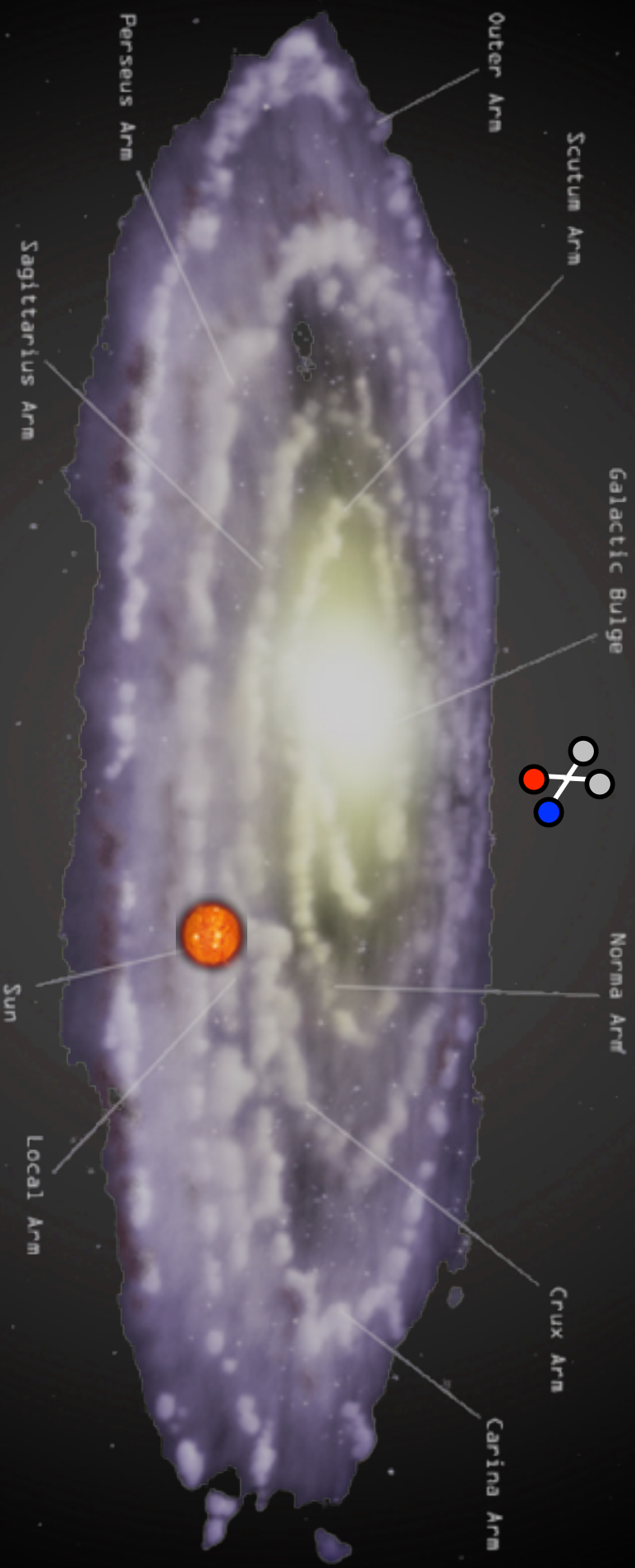
Indirect Detection: basics

\bar{p} and e^+ from DM annihilations in halo



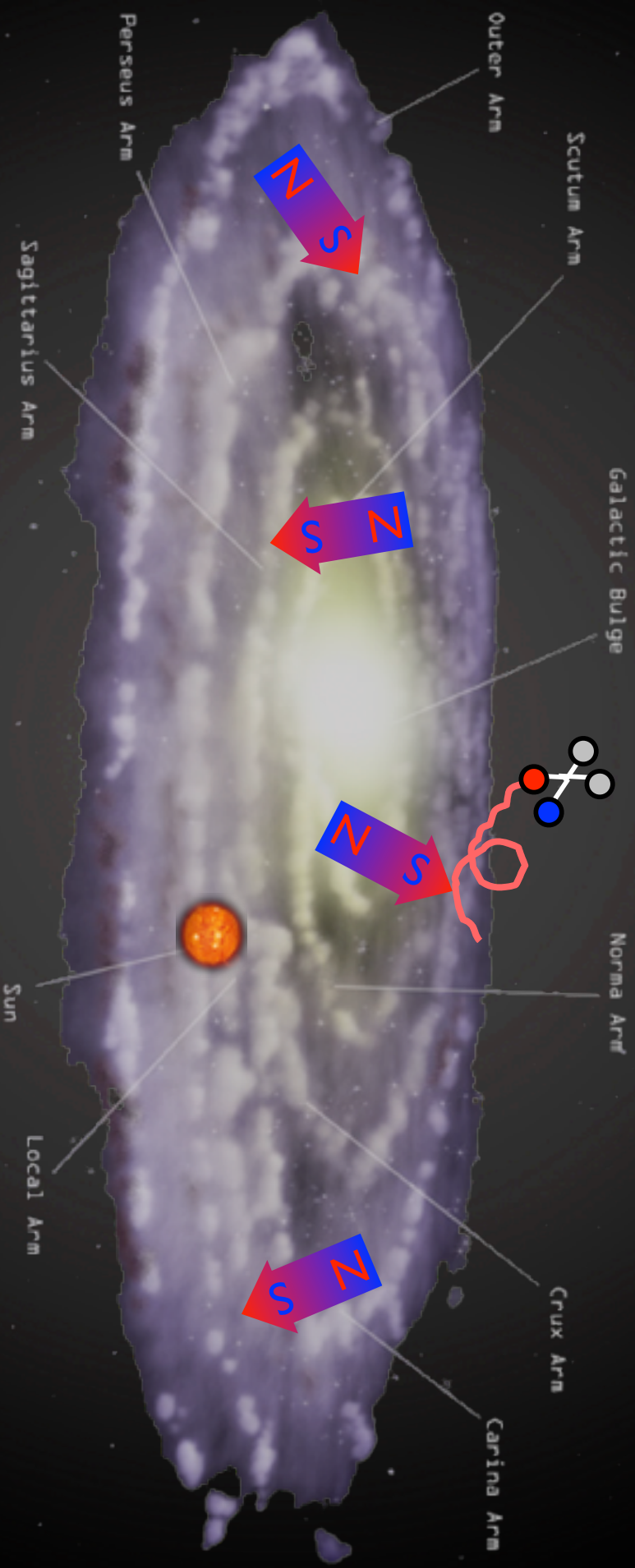
Indirect Detection: basics

\bar{p} and e^+ from DM annihilations in halo



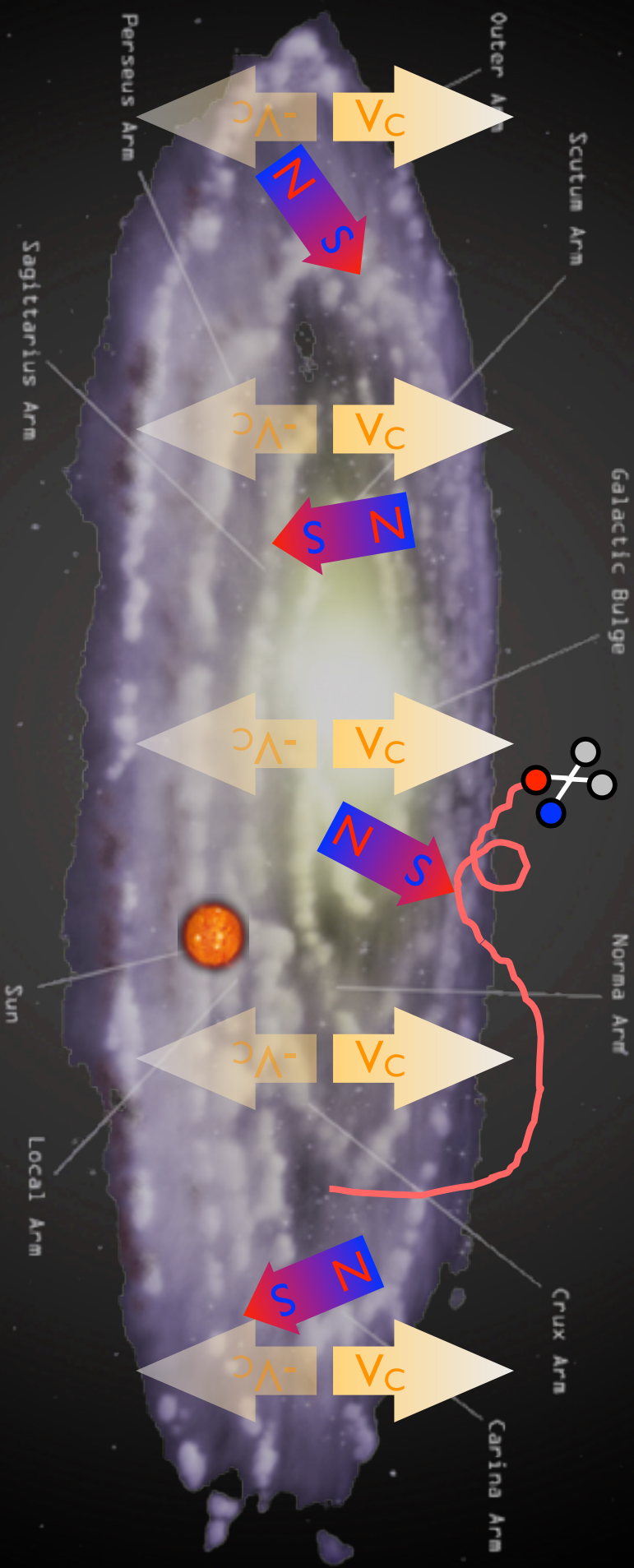
Indirect Detection: basics

\bar{p} and e^+ from DM annihilations in halo



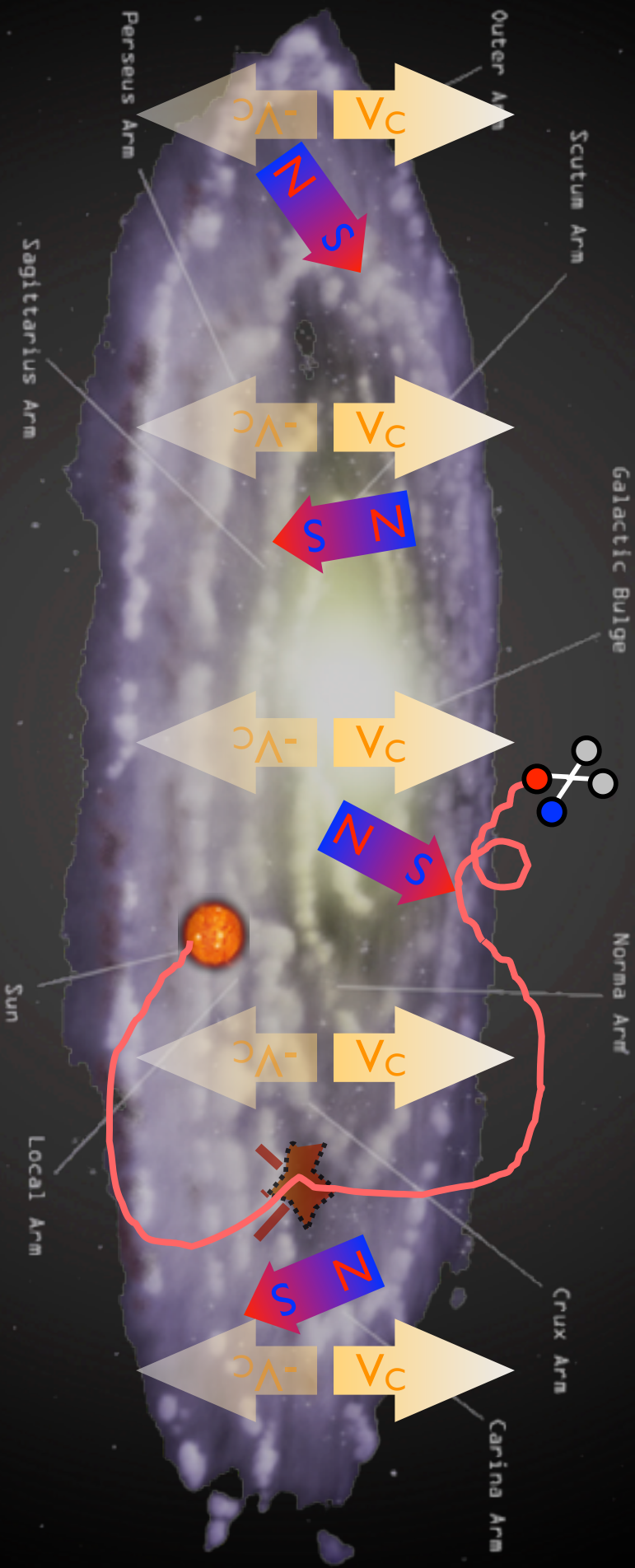
Indirect Detection: basics

\bar{p} and e^+ from DM annihilations in halo

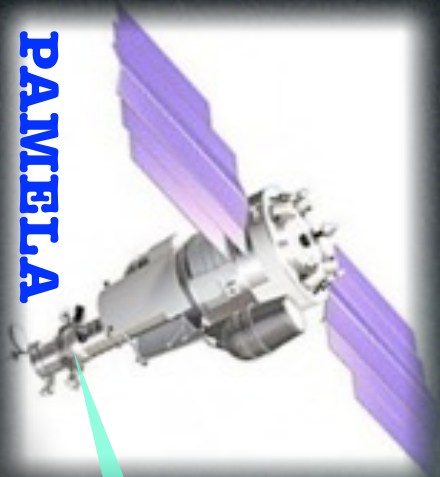


Indirect Detection: basics

\bar{p} and e^+ from DM annihilations in halo



Indirect Detection: **status**



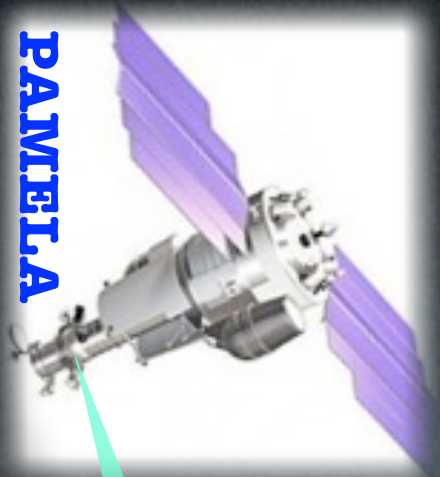
PAMELA

Dark Matter! Dark Matter!

Seen a huge excess in **positrons**

2008

Indirect Detection: status



PAMELA

Dark Matter! Dark Matter!

Seen a huge excess in **positrons**

2008

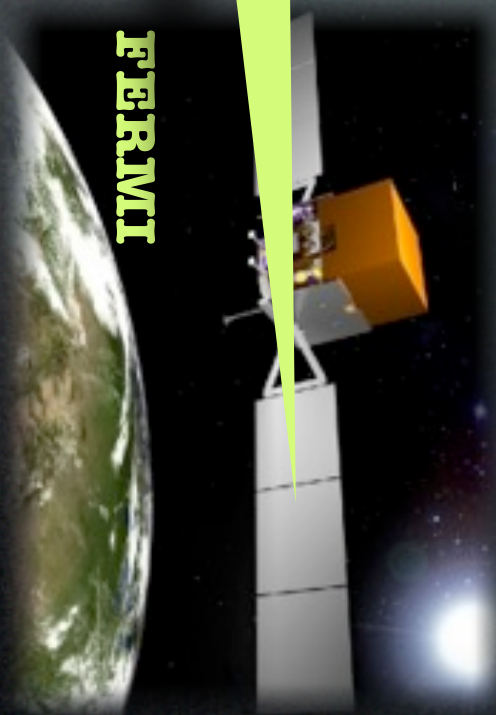
Mmmm, not so sure...

Yes, there's a huge excess in **positrons**,
and there's maybe something in **electrons** too.

But see nothing in **gamma rays**.

Or maybe yes?...

2009-2013



FERMI

Indirect Detection: status



PAMELA

Dark Matter! Dark Matter!

Seen a huge excess in **positrons**

2008

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2009-2013



FERMI

OK, let's go out there and check.

2013-2014...



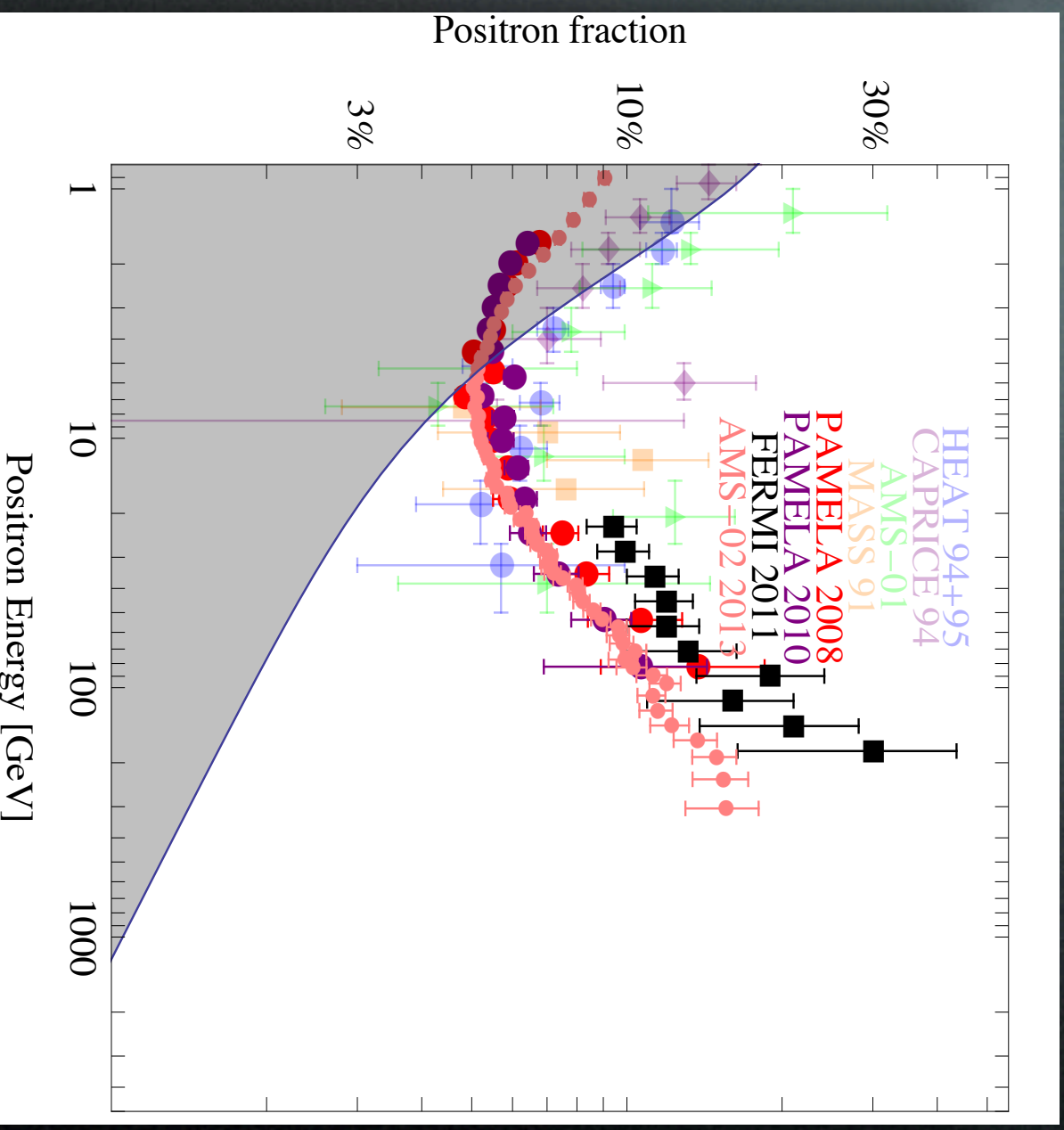
AMS-02

Positrons & Electrons

Positrons from PAMELA and FERMI and AMS-02:

- steep e^+ excess above 10 GeV!
- very large flux!

$$\text{positron fraction: } \frac{e^+}{e^+ + e^-}$$



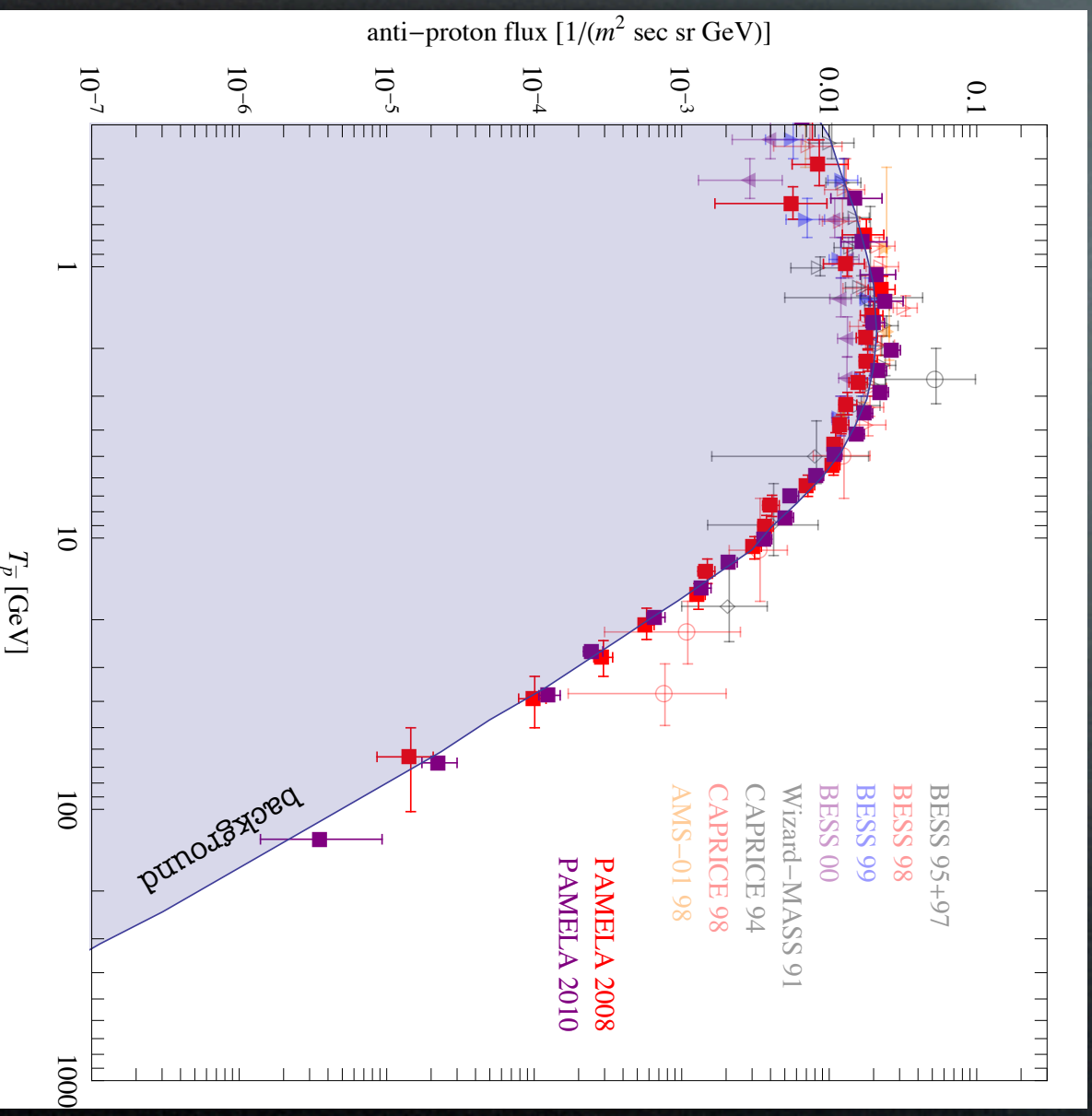
Adriani et al., Nature 458 (2009) 607, *ApJ* 74 (2010) 1

Fermi coll., 1109.0521

AMS-02 coll., *PRL* 110, 141102 (2013)

Indirect Detection: hints Antiprotons from PAMELA:

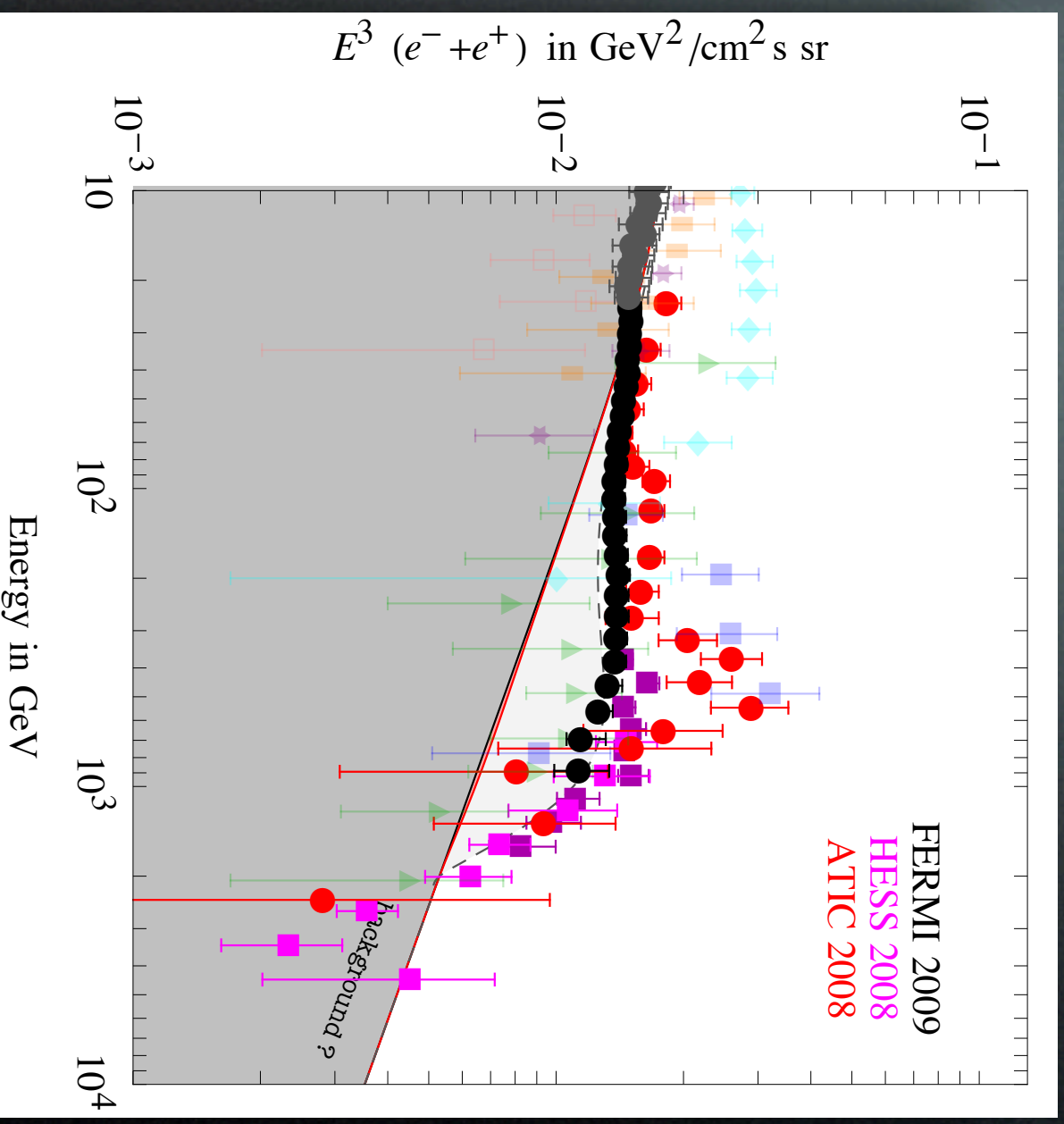
- consistent with
the background



(about 1000 \bar{p} collected
initially)

Indirect Detection: hints Electrons + positrons adding FERMI and HESS:

- $n_{e^+} + e^-$ excess
- spectrum $\sim E^{-3.04}$
- a (smooth) cutoff?



Indirect Detection: status



PAMELA

Dark Matter! Dark Matter!

Seen a huge excess in **positrons**

2008

Mmmm, not so sure...

Yes, there's a huge excess in **positrons**, and there's maybe something in **electrons** too.

But see nothing in **gamma rays**. Or maybe yes?...

2009-2013



FERMI



OK, let's go out there and check.

2013-2014...



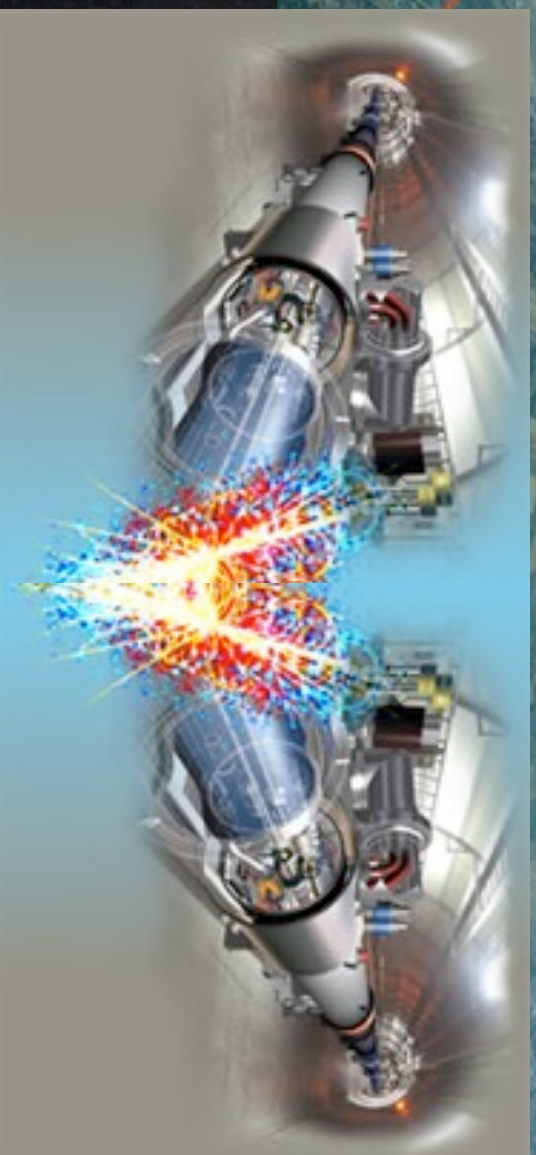
AMS-02

3. Production at colliders

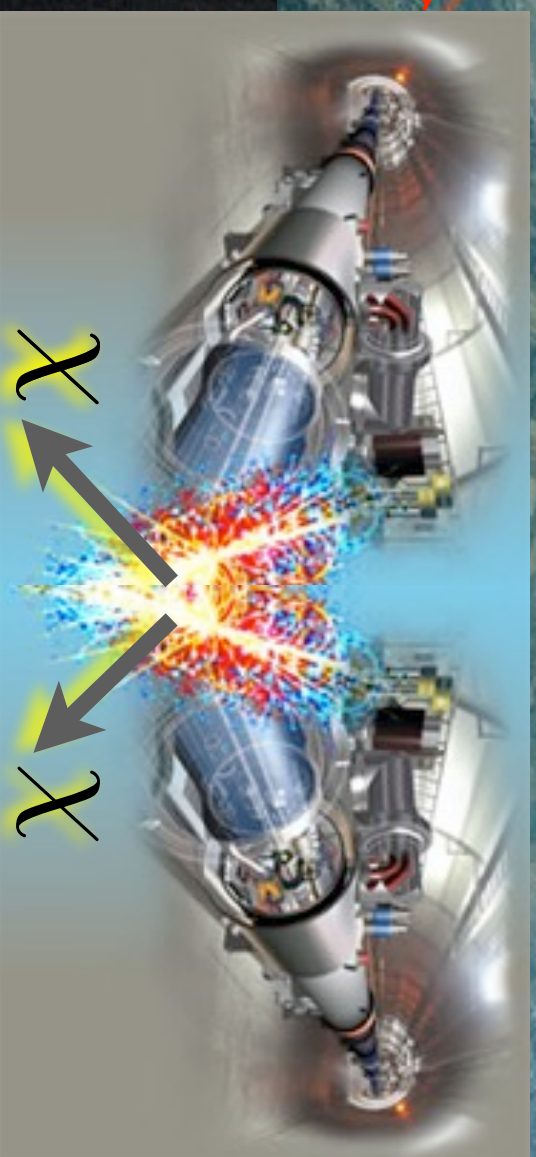
LHC

Monte Bianco

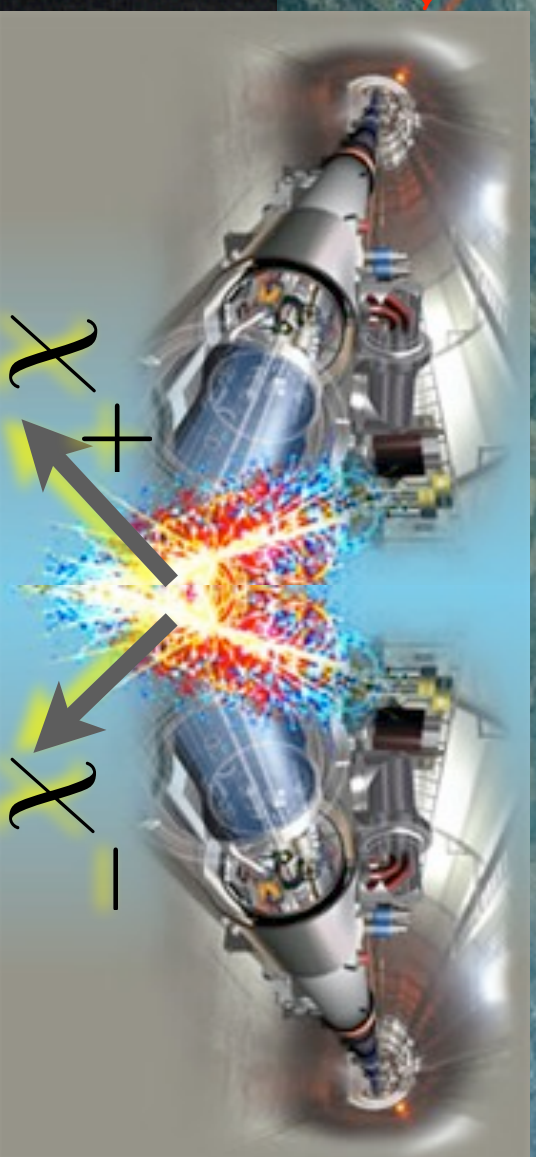
Geneva



Production at colliders



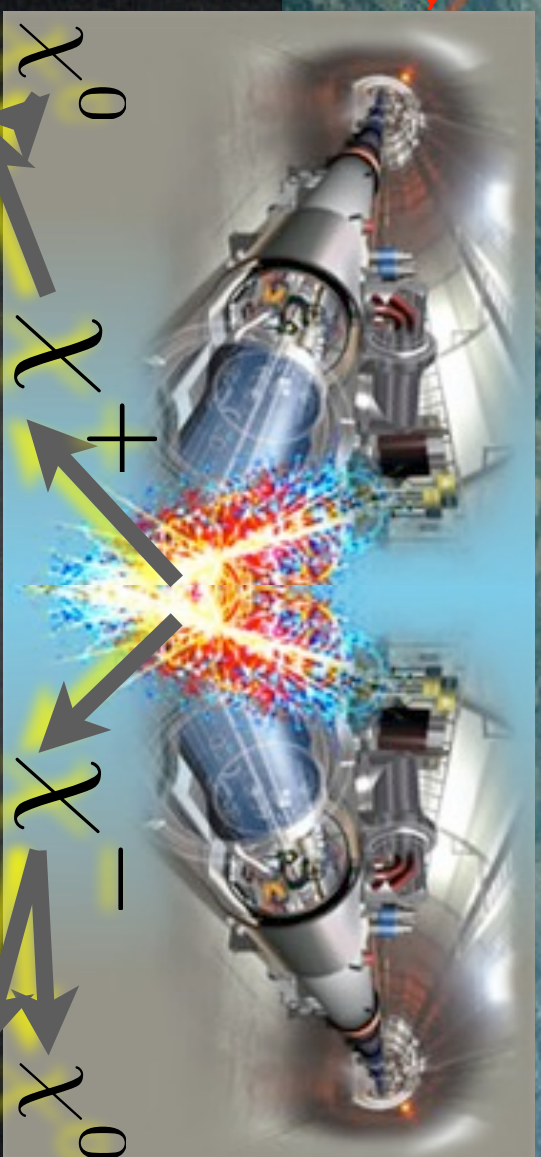
Production at colliders



Production at colliders

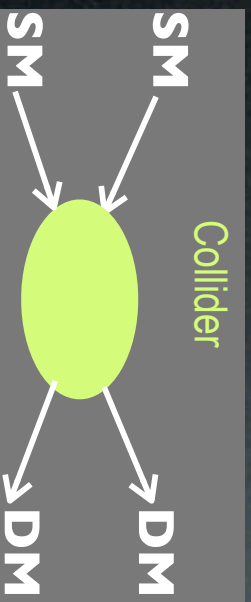


missing
energy

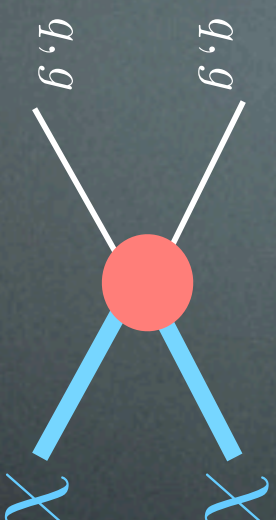


missing
energy

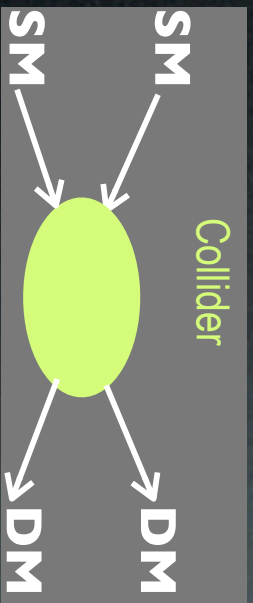
Production at colliders



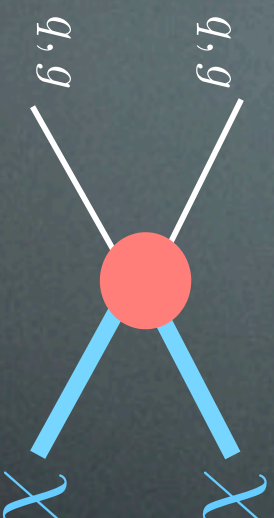
At LHC:



Production at colliders

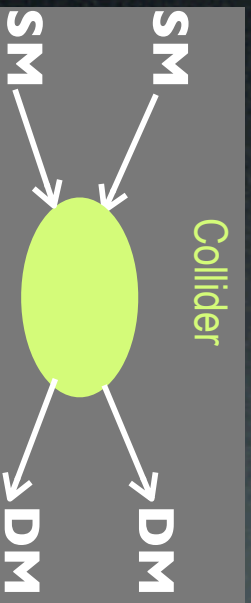


At LHC:

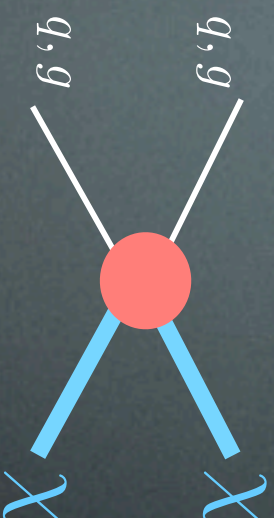


'Problem' is: DM flies away

Production at colliders



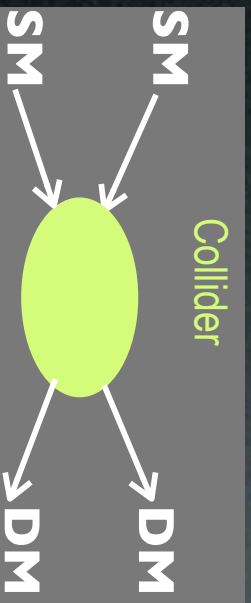
At LHC:



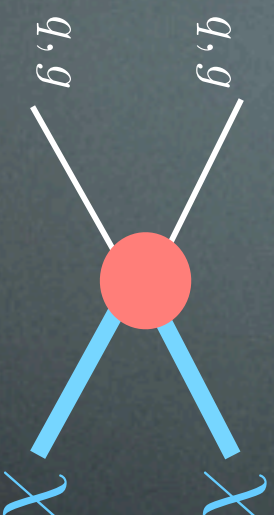
'Problem' is: DM flies away

Signature is: **missing energy**

Production at colliders



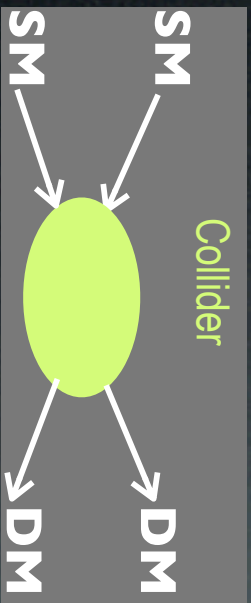
At LHC:



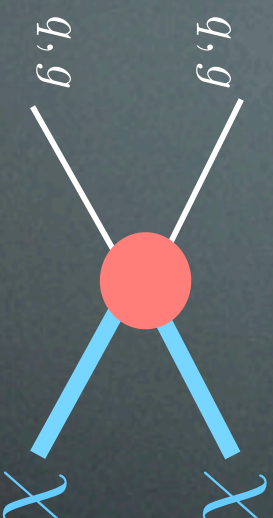
'Problem' is: DM flies away

Signature is: **missing energy**
transverse

Production at colliders

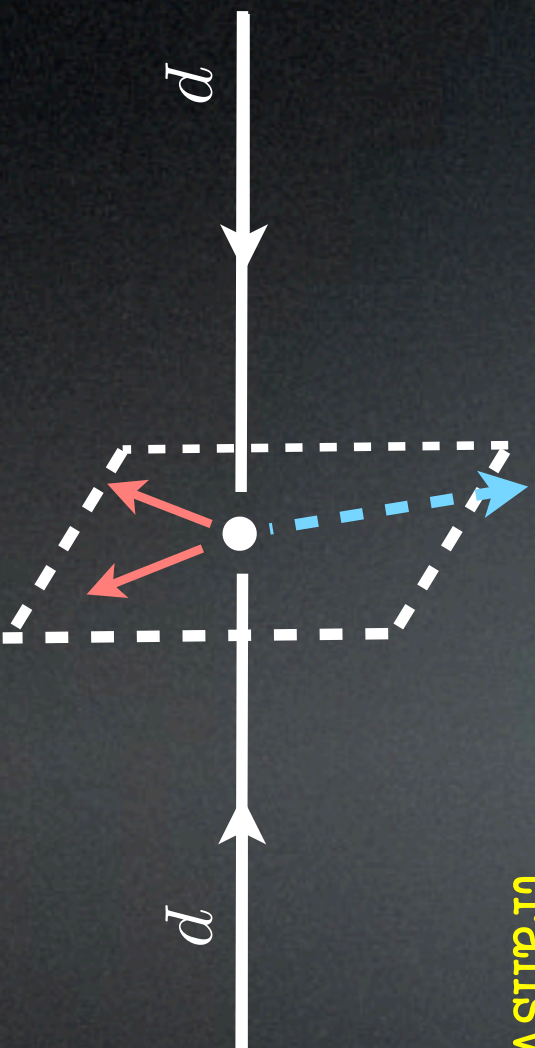


At LHC:



'Problem' is: DM flies away

Signature is: **missing energy**
transverse



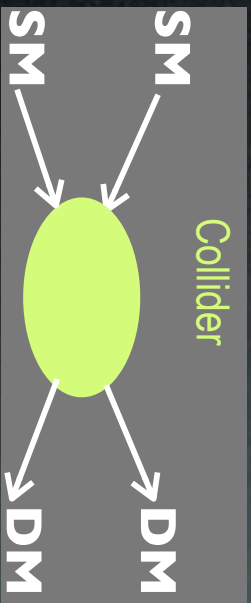
Before collision: $\vec{P}_T^{\text{tot}} \equiv 0$

(NB: $\vec{P}_L^{\text{tot}} \neq 0$ in general)

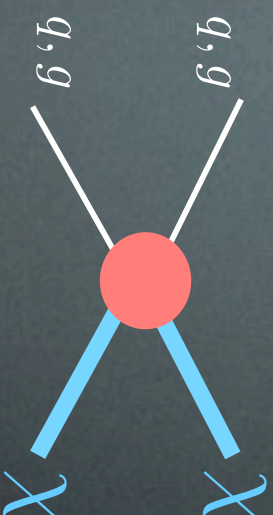
After collision: $\vec{P}_T^{\text{vis}} \stackrel{?}{=} 0$

If \neq , then 'MET'

Production at colliders

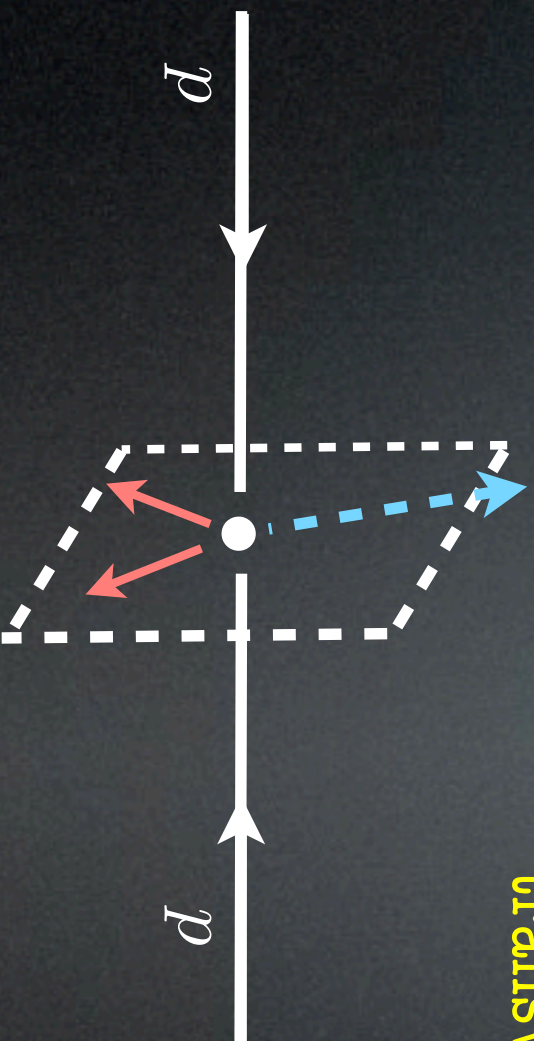


At LHC:



‘Problem’ is: DM flies away

Signature is: **missing energy**
transverse



Before collision: $\vec{P}_T^{\text{tot}} \equiv 0$

(NB: $\vec{P}_L^{\text{tot}} \neq 0$ in general)

After collision: $\vec{P}_T^{\text{vis}} \stackrel{?}{=} 0$

If \neq , then ‘**MET**’

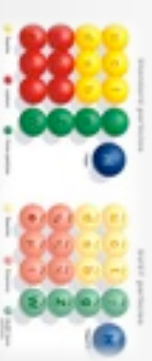
Background: neutrinos (e.g. $W \rightarrow e\nu$)

- model your background and look for anomalies
- construct kinematic variables sensitive to χ mass



Problemi aperti in Fisica delle Particelle

- il *pattern* delle masse e le proprietà dell'higgs
- la supersimmetria
(forse c'è un partner supersimmetrico per ogni tipo di particella nota!)
- le dimensioni dello spazio-tempo
(forse ci sono più di 3 dimensioni spaziali!)
- la Materia Oscura
(una particella sconosciuta che costituisce l'80% della materia dell'Universo!)
- l'asimmetria tra materia e antimateria
(dove è finita tutta l'antimateria dell'Universo?)
- il plasma di quarks e gluoni
(come diventa la materia nucleare a energie e densità elevatissime?)



• ...

