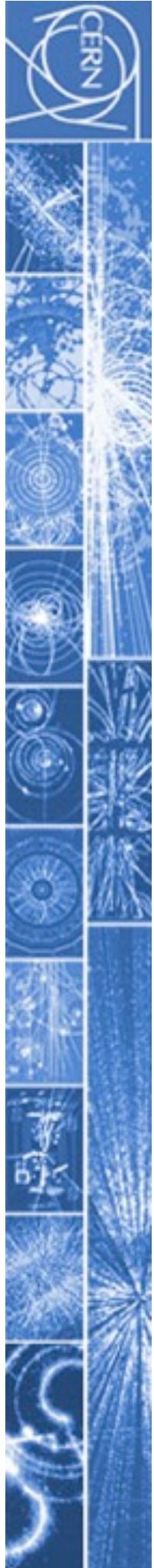




Oltre il Modello Standard

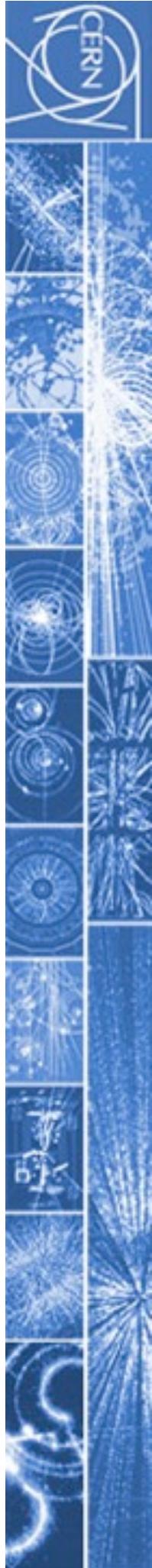


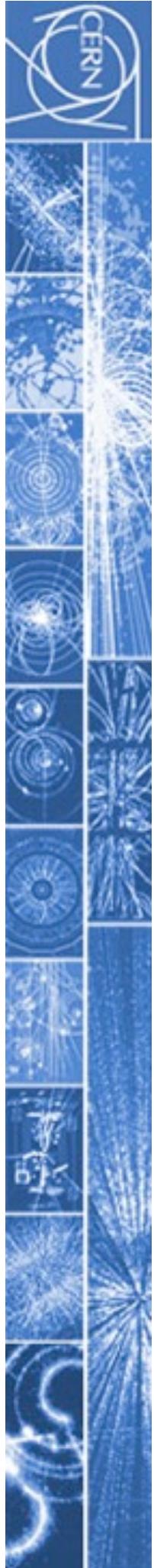
Problemi aperti in Fisica delle Particelle

- il pattern delle masse e le proprietà dell'higgs

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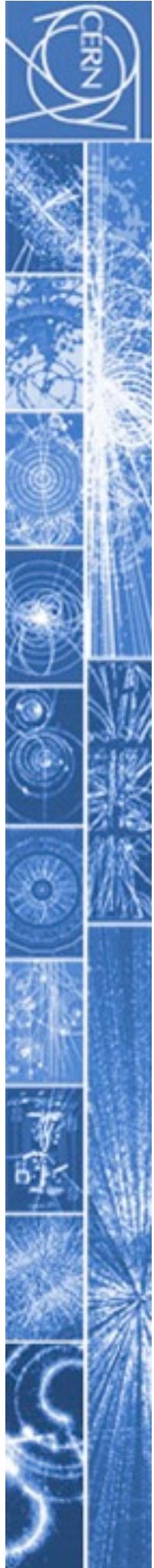




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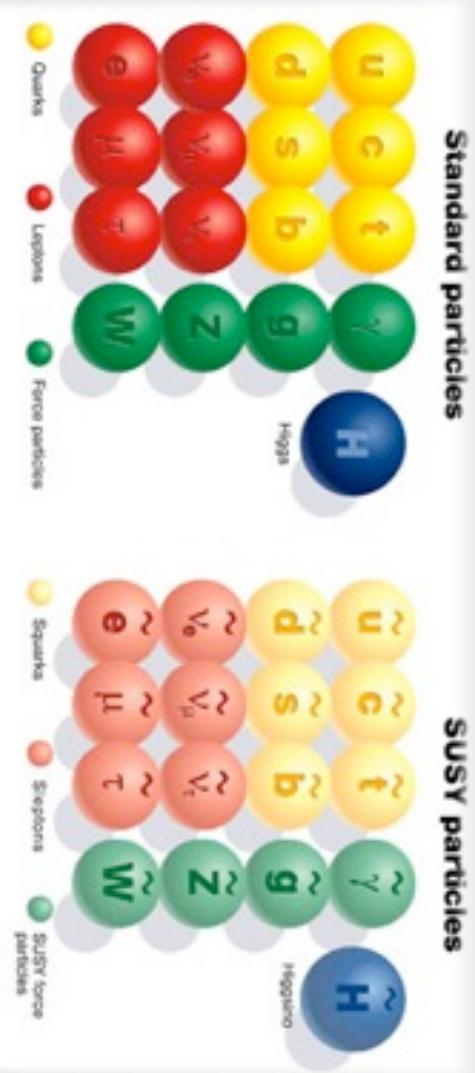
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(forse ci sono più di 3 dimensioni spaziali!)





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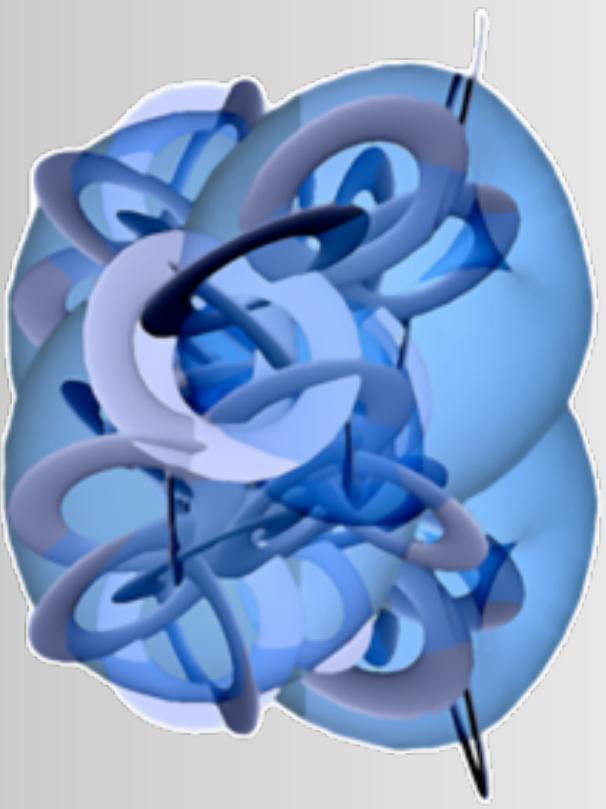
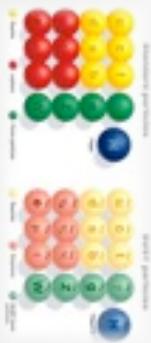
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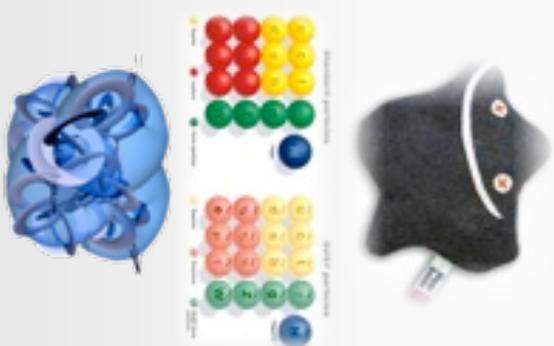
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(una particella sconosciuta che costituisce l'80% della materia dell'Universo!)





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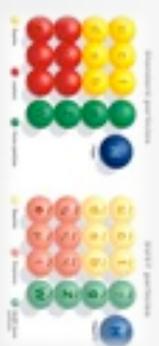
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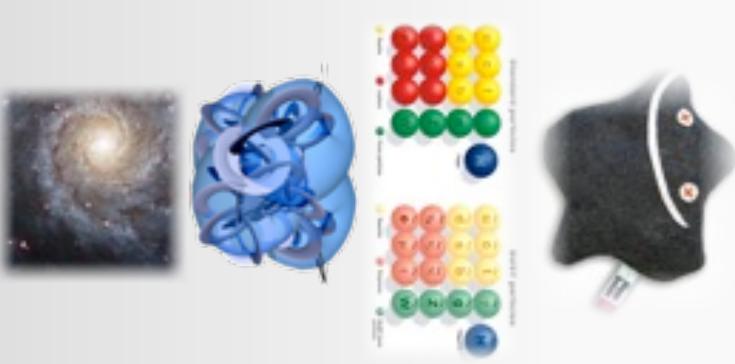
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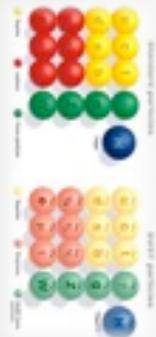
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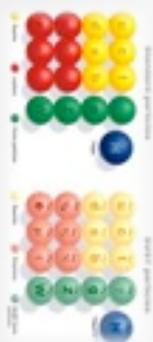
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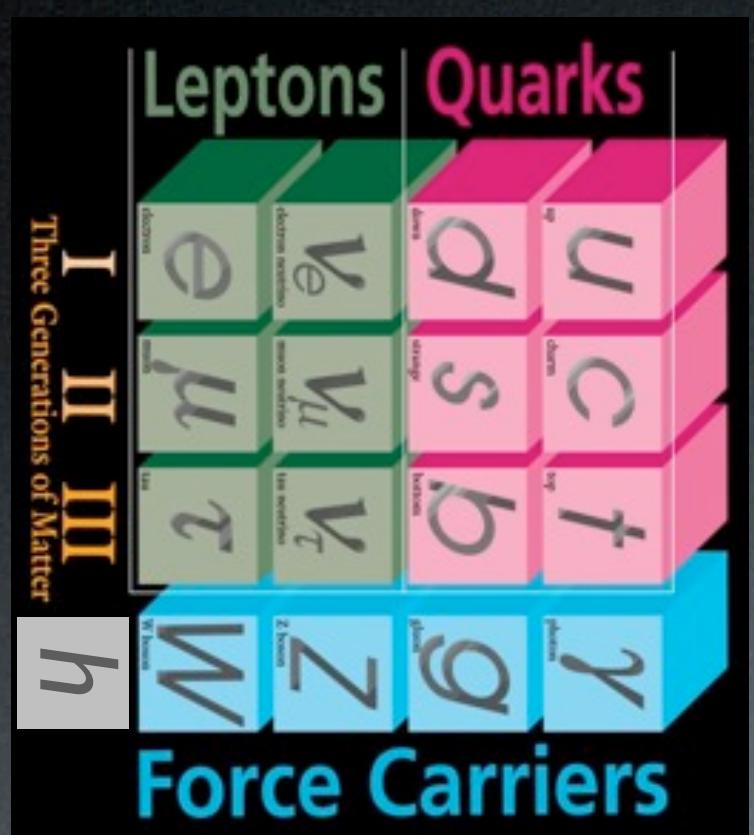
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- l'asimmetria tra materia e antimateria
(dove è finita tutta l'antimateria dell'Universo?)
- il plasma di quarks e gluoni
(come diventa la materia nucleare a energie e densità elevatissime?)
- ...



SuperSymmetry (SuSy)

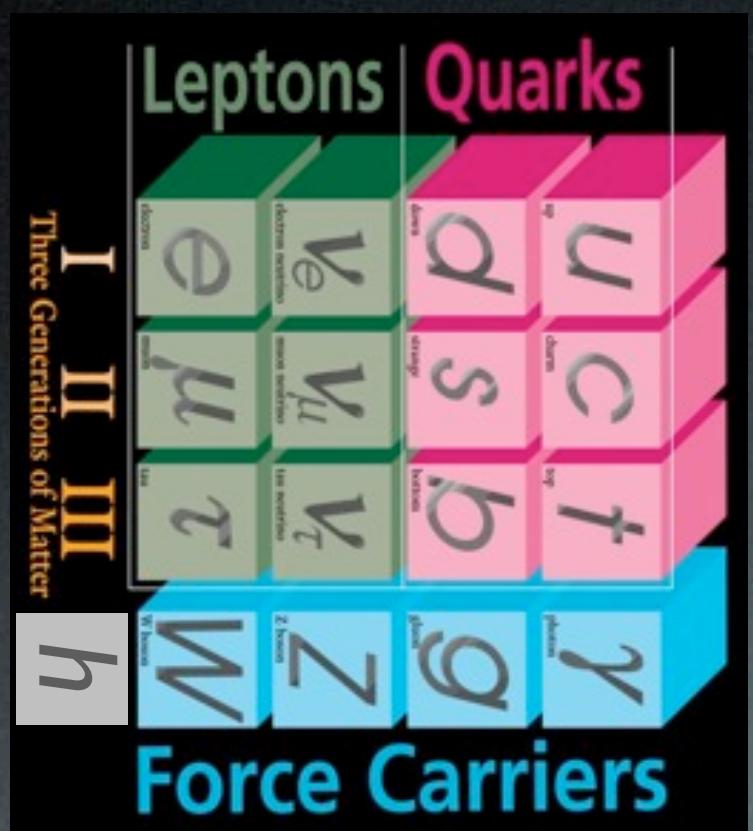


SuSy in 2 minutes



SuSy in 2 minutes

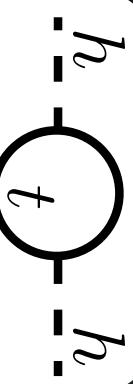
$m_h \simeq 126$ GeV



SuSy in 2 minutes

		Leptons	Quarks	
		Electrons	Up	Down
I II III Three Generations of Matter	Electron neutrino	ν_e	d	u
	Muon neutrino	ν_μ	s	c
	Tau neutrino	ν_τ	b	t
		W	Z	γ
		Vibrons	Gluons	Photinos
			Force Carriers	

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



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

SuSy in 2 minutes

Leptons			Quarks		
I	II	III	I	II	III
e^- electron electron neutrino	ν_e electron neutrino	d down	u up	c charm	t top
μ^- muon muon neutrino	ν_μ muon neutrino	s strange	g gluon	g gluon	γ photon
τ^- tau neutrino	ν_τ tau neutrino	b bottom	W W boson	Z Z boson	
			h Higgs	h_2	h_2
Force Carriers			Force Carriers		

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

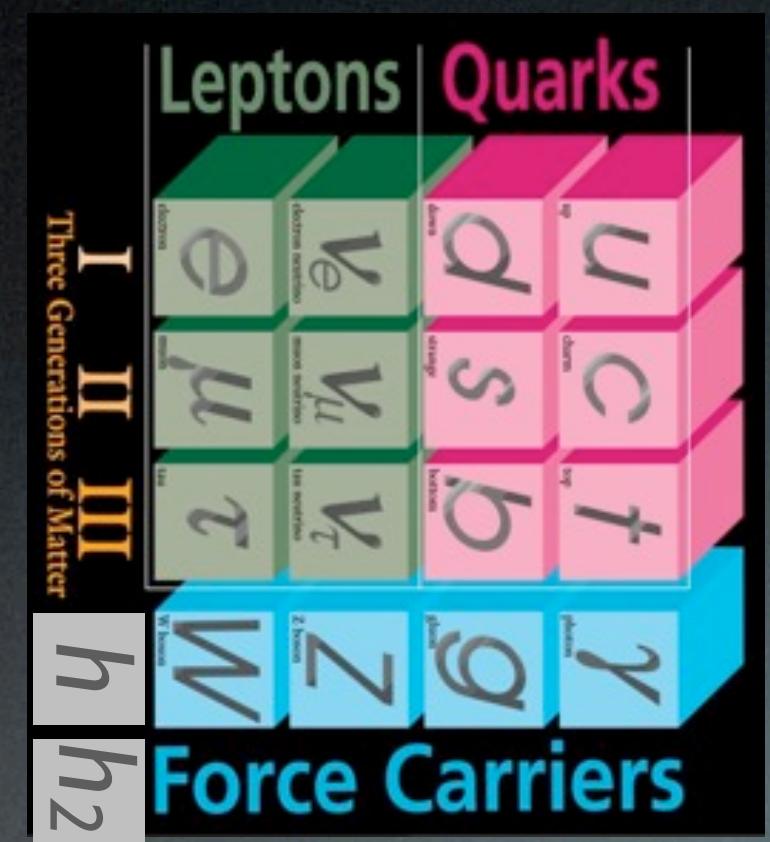


$$\Delta m_h \propto 10^{19} \text{ GeV}$$



$$\Delta m_{\tilde{h}} \propto -10^{19} \text{ GeV}$$

SuSy in 2 minutes

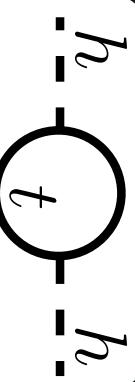


125 GeV



125 GeV

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

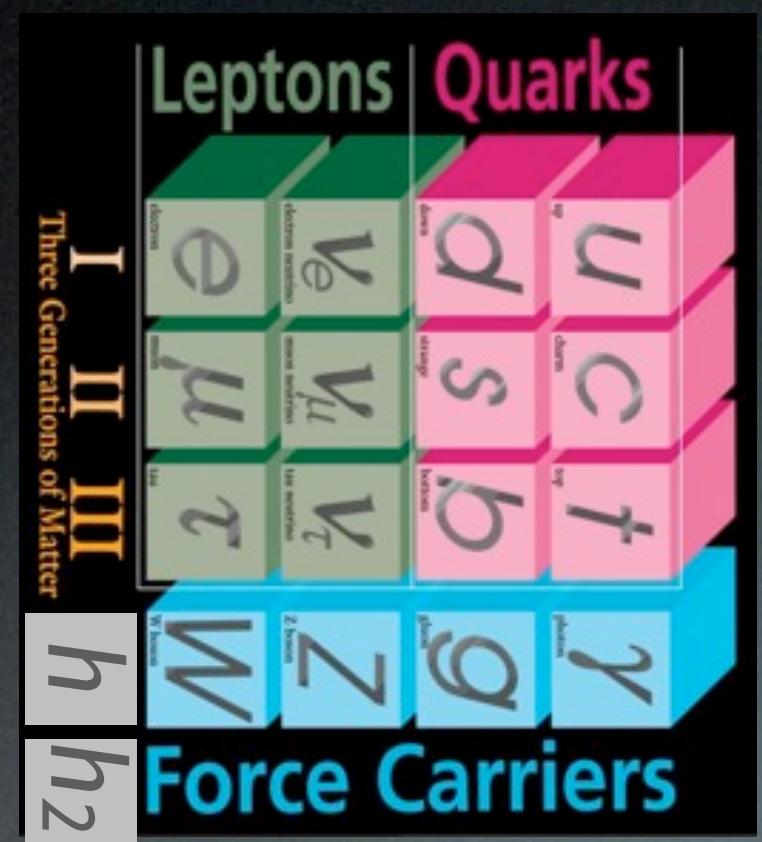


$$\Delta m_h \propto 10^{19} \text{ GeV}$$



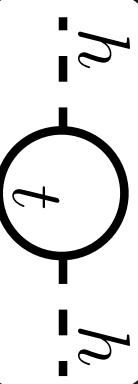
$$\Delta m_h \propto -10^{19} \text{ GeV}$$

SuSy in 2 minutes

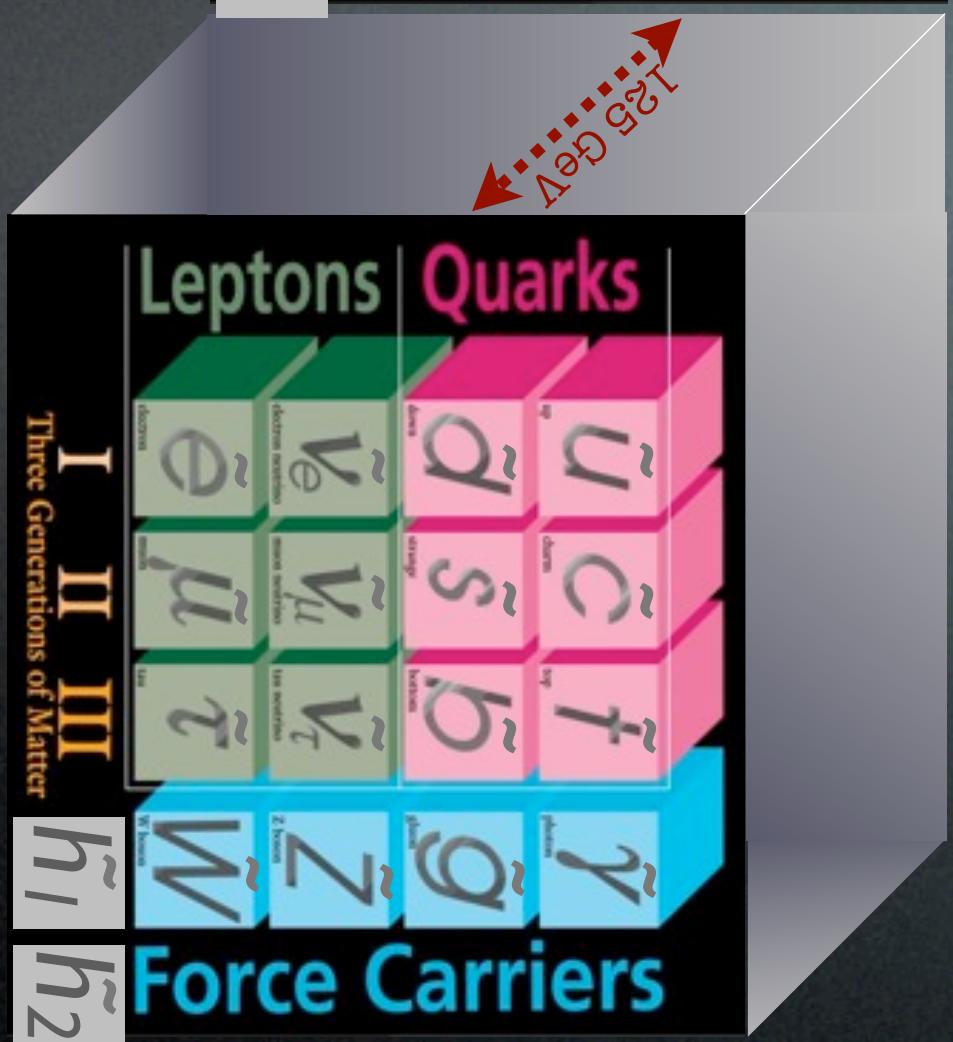


$$R = +1$$

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



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



$$R = -1$$

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

SuSy in 2 minutes

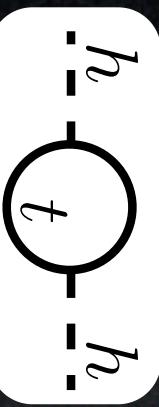
Leptons		Quarks	
I	II	III	
e^- electron neutrino 1st generation	ν_e electron neutrino 1st generation	d down	u up
μ^- muon neutrino 2nd generation	ν_μ muon neutrino 2nd generation	s strange	c charm
τ^- tau neutrino 3rd generation	ν_τ tau neutrino 3rd generation	b bottom	t top
		W gluon 1st boson	Z photon 2nd boson
		h	h_2
Force Carriers			

$$R = +1$$

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

$$R = -1$$

Leptons		Quarks	
I	II	III	
e^- electron neutrino 1st generation	$\tilde{\nu}_e$ electron neutrino 1st generation	\tilde{d} down	\tilde{u} up
$\tilde{\mu}^-$ muon neutrino 2nd generation	$\tilde{\nu}_\mu$ muon neutrino 2nd generation	\tilde{s} strange	\tilde{c} charm
$\tilde{\tau}^-$ tau neutrino 3rd generation	$\tilde{\nu}_\tau$ tau neutrino 3rd generation	\tilde{b} bottom	\tilde{t} top
		\tilde{W} gluon 1st boson	\tilde{Z} photon 2nd boson
		\tilde{h}_1	\tilde{h}_2
Force Carriers			

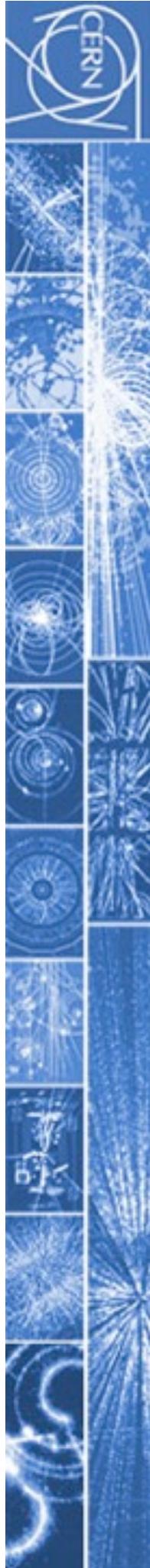


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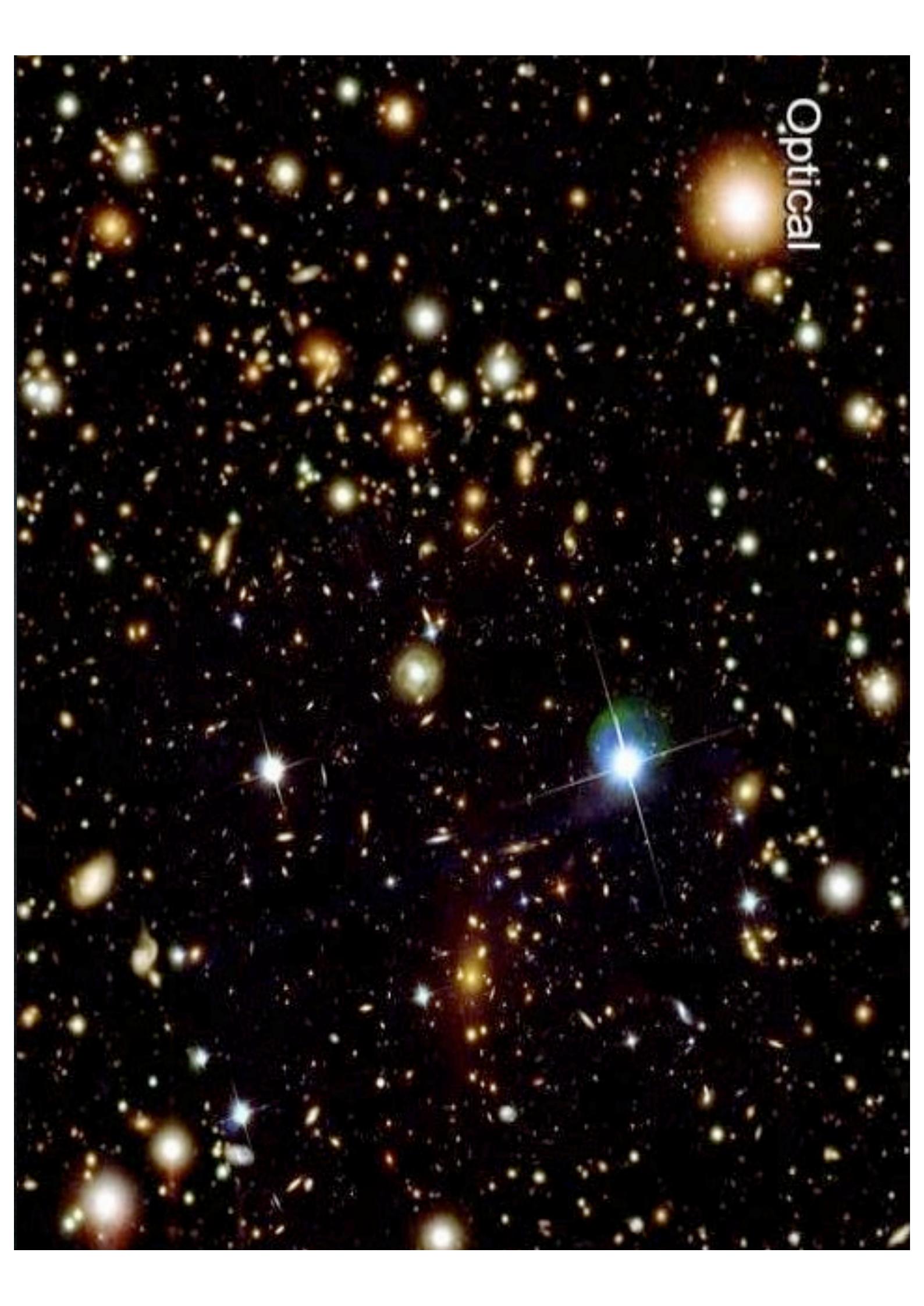
ΔV_{cb}

Materia Oscura *(Dark Matter)*

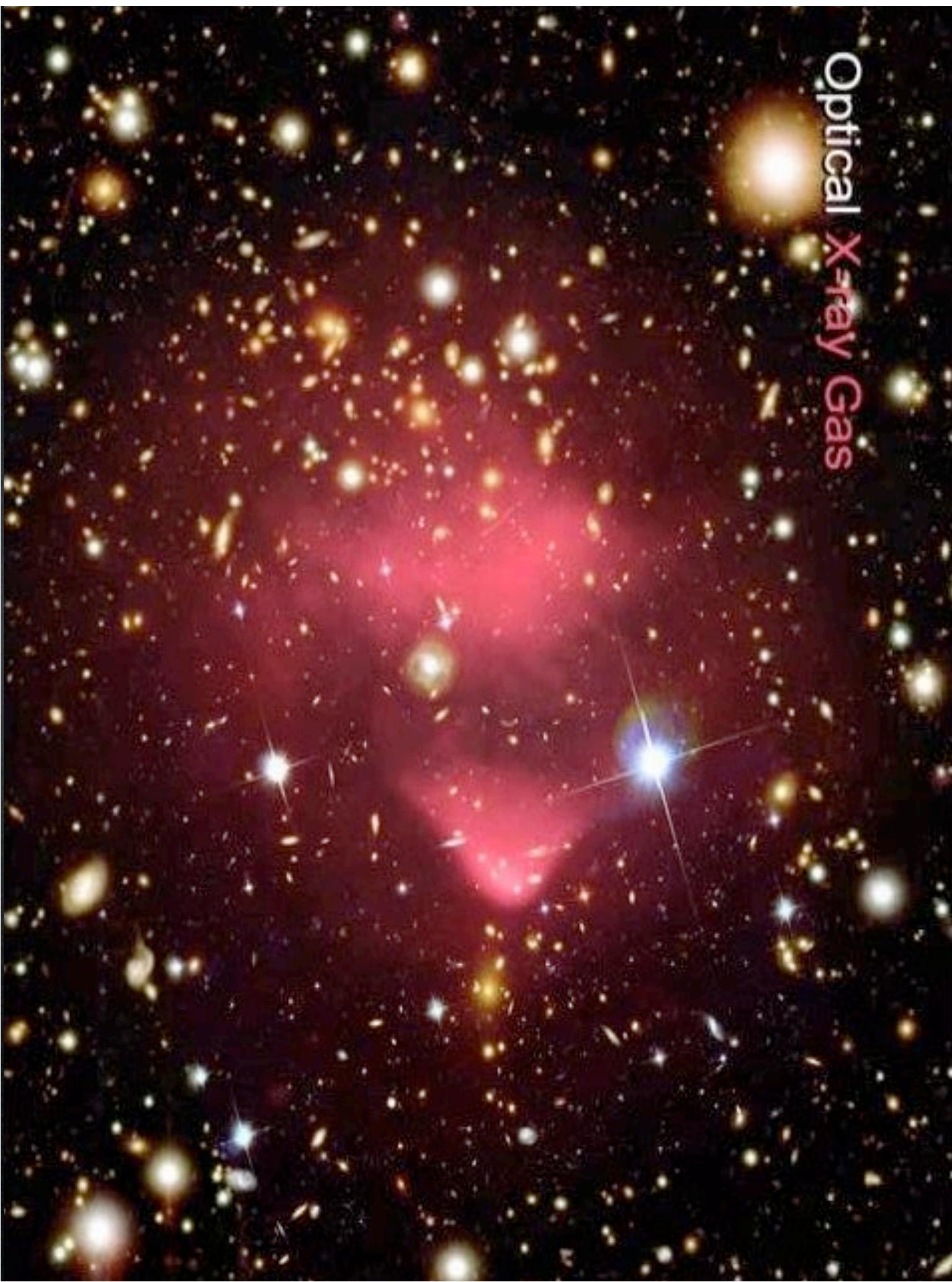


What is the Universe
made of?

Optical



Optical X-ray Gas



A composite image of a galaxy cluster. The background is a deep space view with numerous small, yellow and white galaxies. In the center, there is a large, diffuse red glow representing X-ray gas. Superimposed on this are two sets of concentric ellipses: a blue one representing optical light and a darker blue one representing dark matter. Two bright, white radio sources are visible, each with a long, thin, multi-colored beam extending towards the bottom right. The overall image has a dark, star-filled background.

Optical Dark Matter X-ray Gas

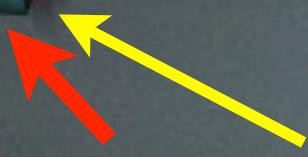
The cosmic inventory

Most of the Universe is Dark

$$\Omega_{\text{lum}} \sim 0.01$$

~2%

4%
1%

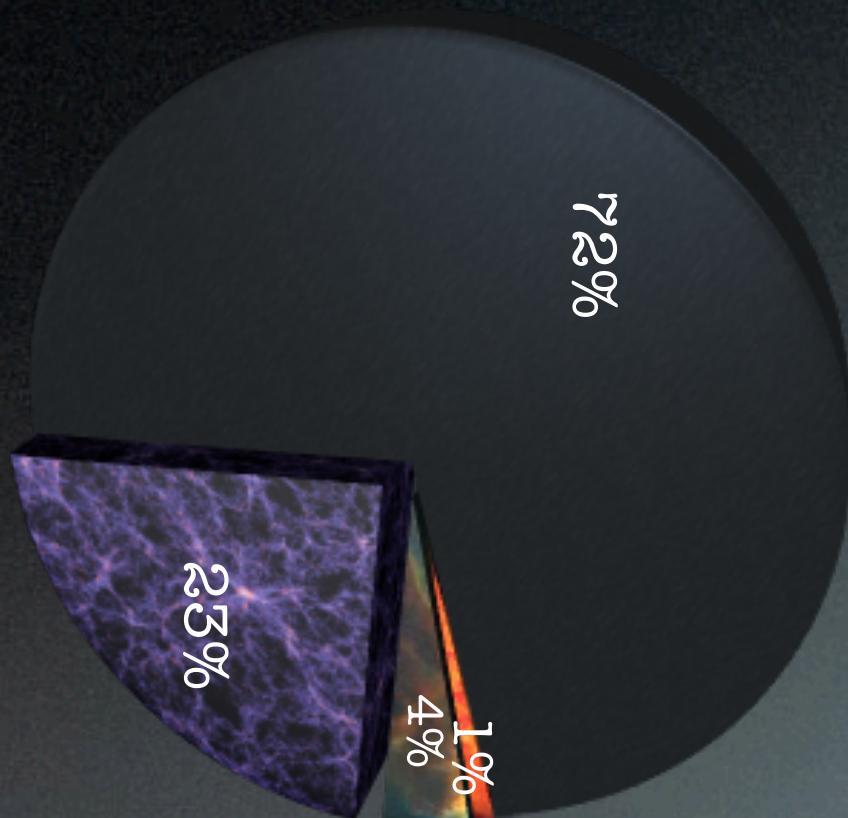


$$\Omega_b \simeq 0.040 \pm 0.005$$

$$\Omega_{\text{DM}} \sim 0.23$$

~23%

$$\Omega_{\text{de}} \sim 0.72$$



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

The cosmic inventory

Most of the Universe is Dark

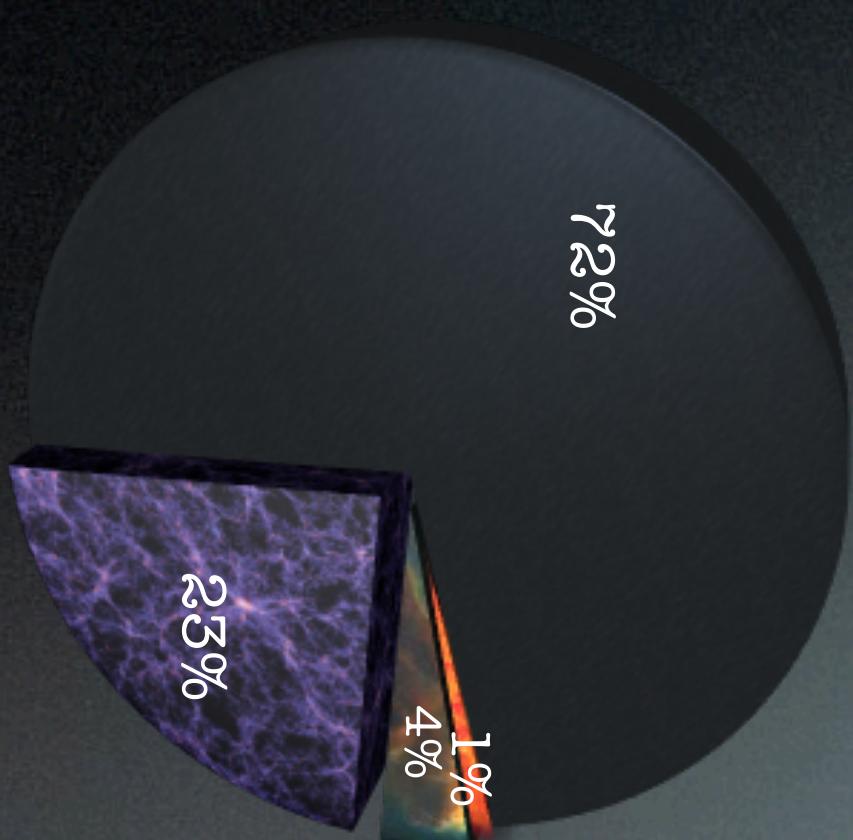
*FAvgQ: What's the difference
between DM and DE?*

DM behaves like matter

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

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

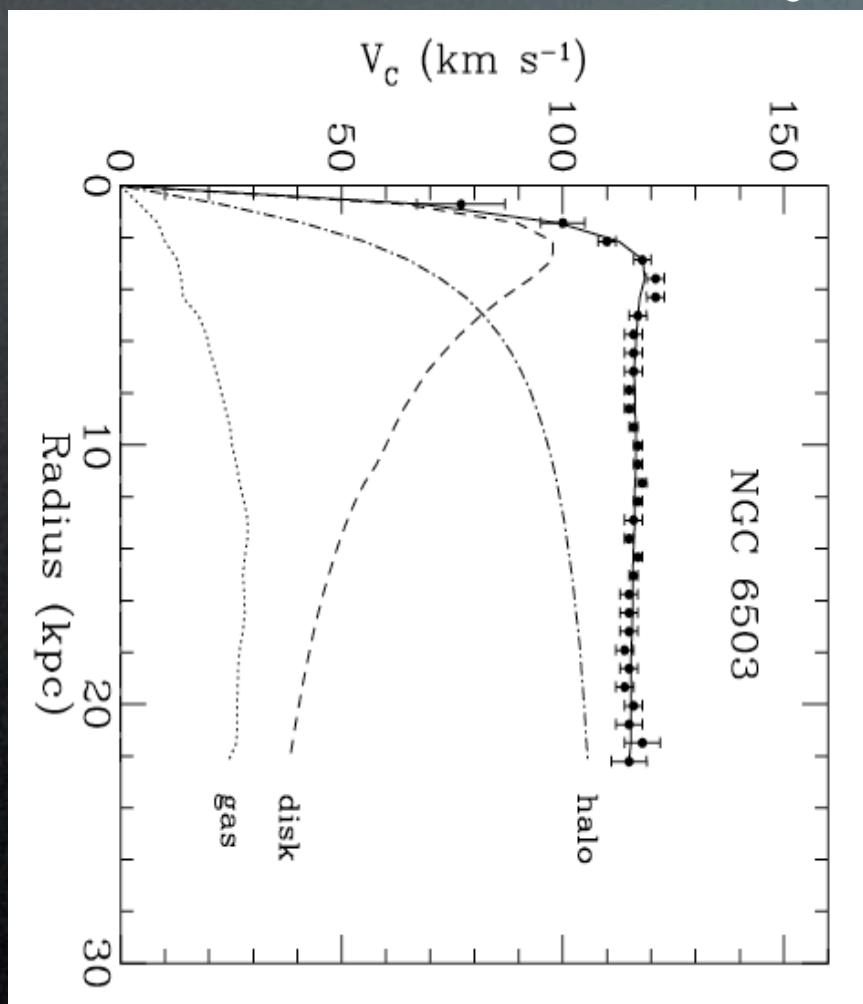
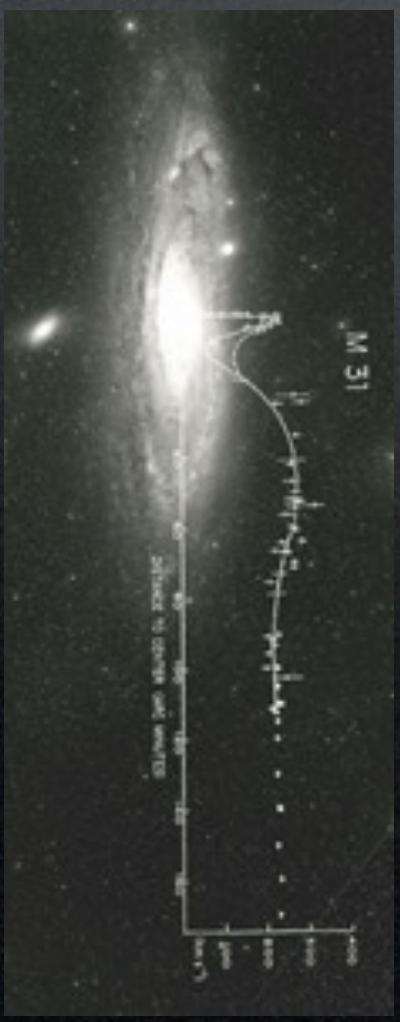
'centrifugal' 'centripetal'

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

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

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

$$\Omega_M \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)

The Evidence for DM

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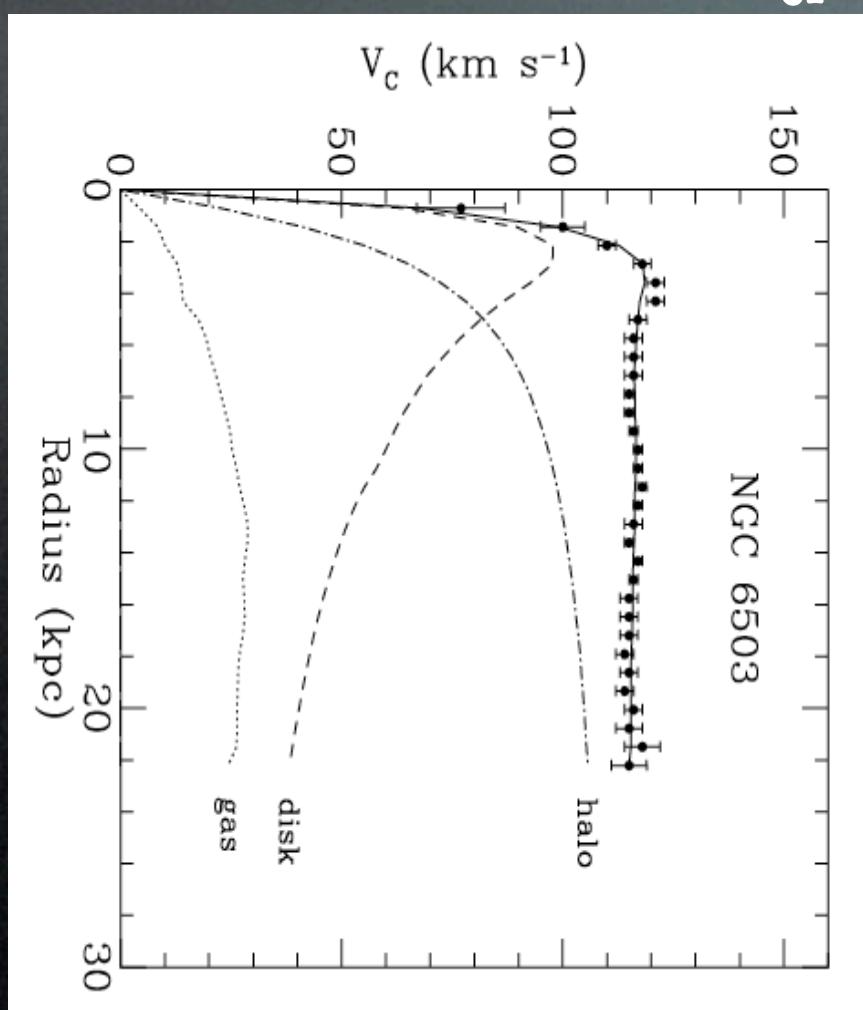
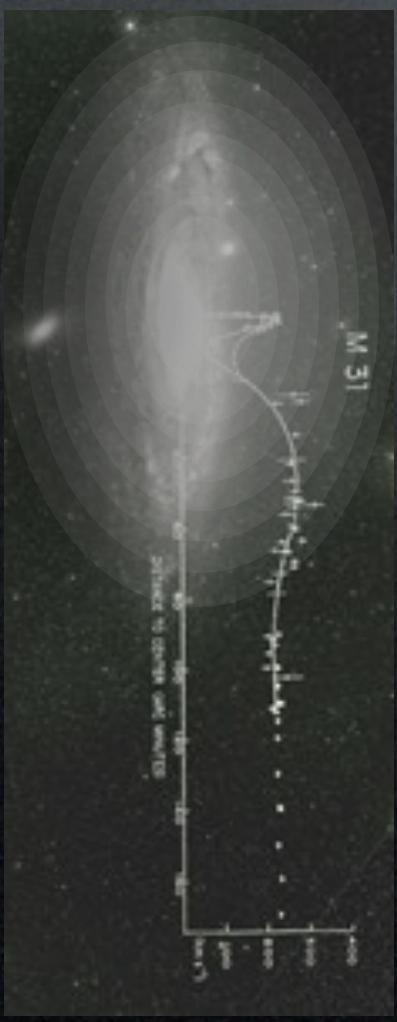
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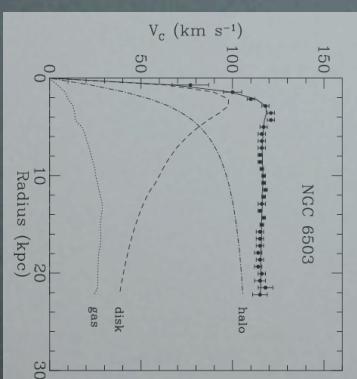
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The Evidence for DM

1) galaxy rotation curves

$$\Omega_M \gtrsim 0.1$$



2) clusters of galaxies

- “rotation curves”
- gravitation lensing



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

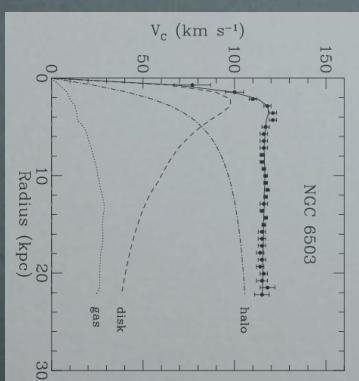


“bullet cluster” - NASA
astro-ph/0608247

[further developments]

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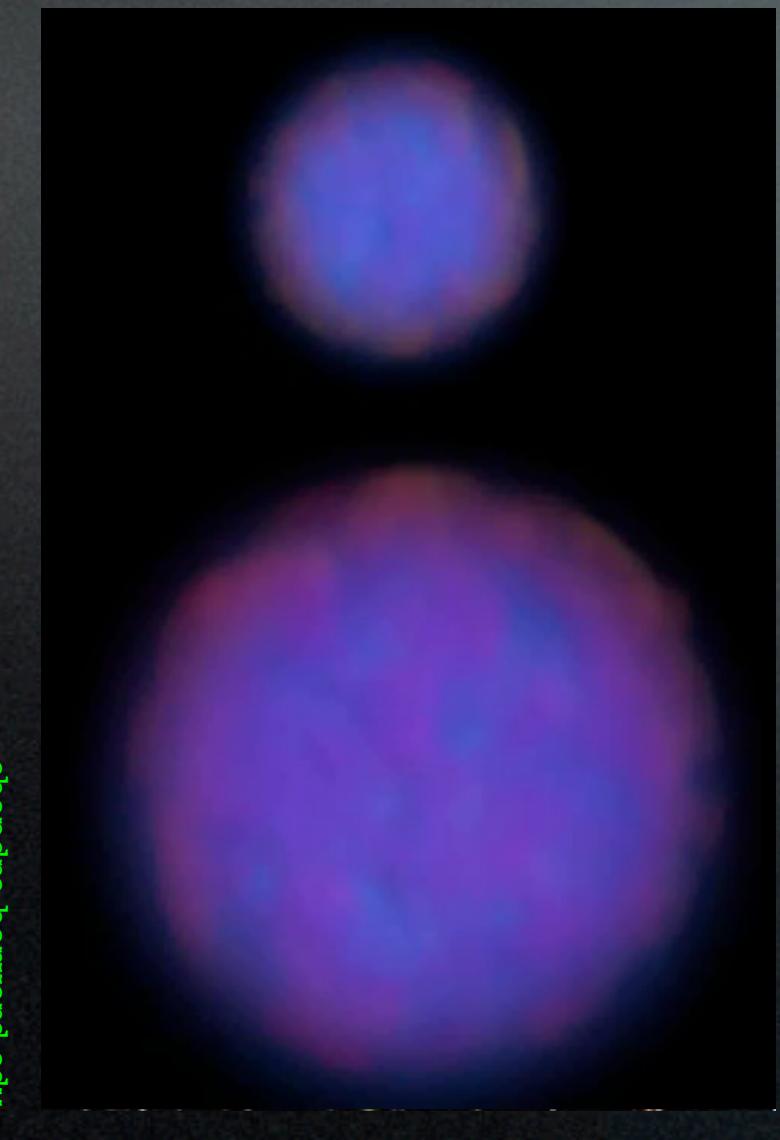


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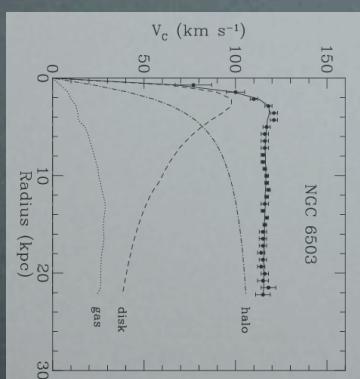
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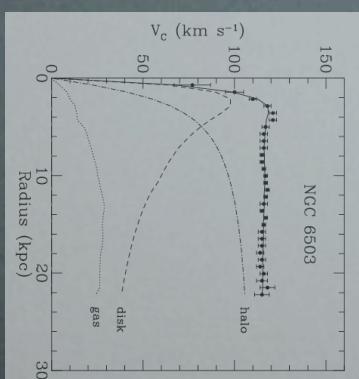
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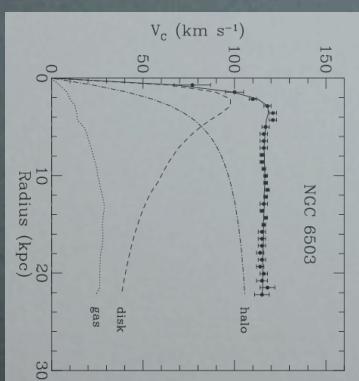
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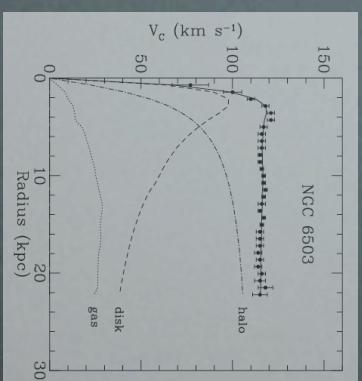
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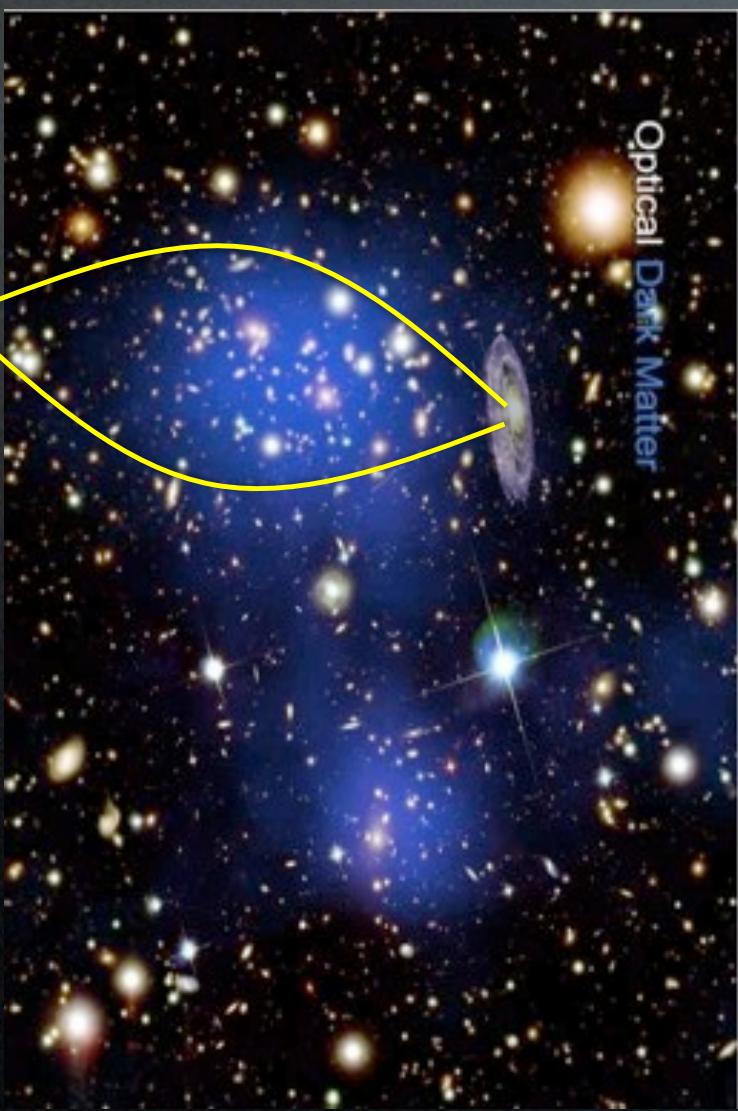


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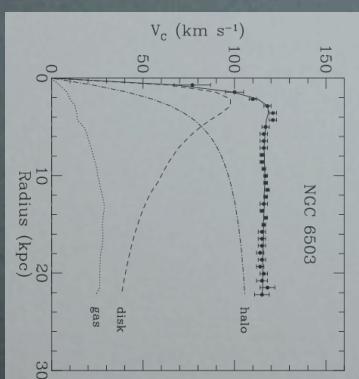
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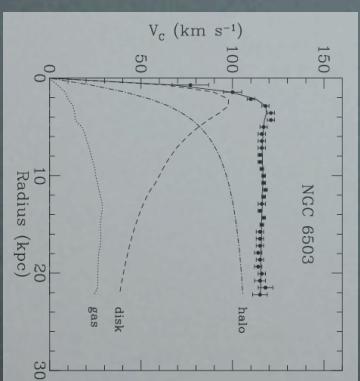
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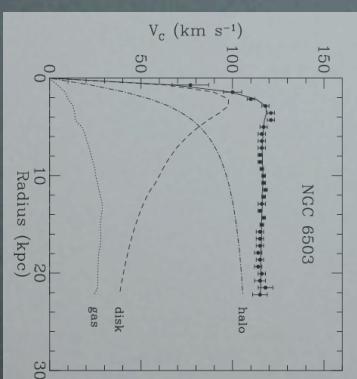
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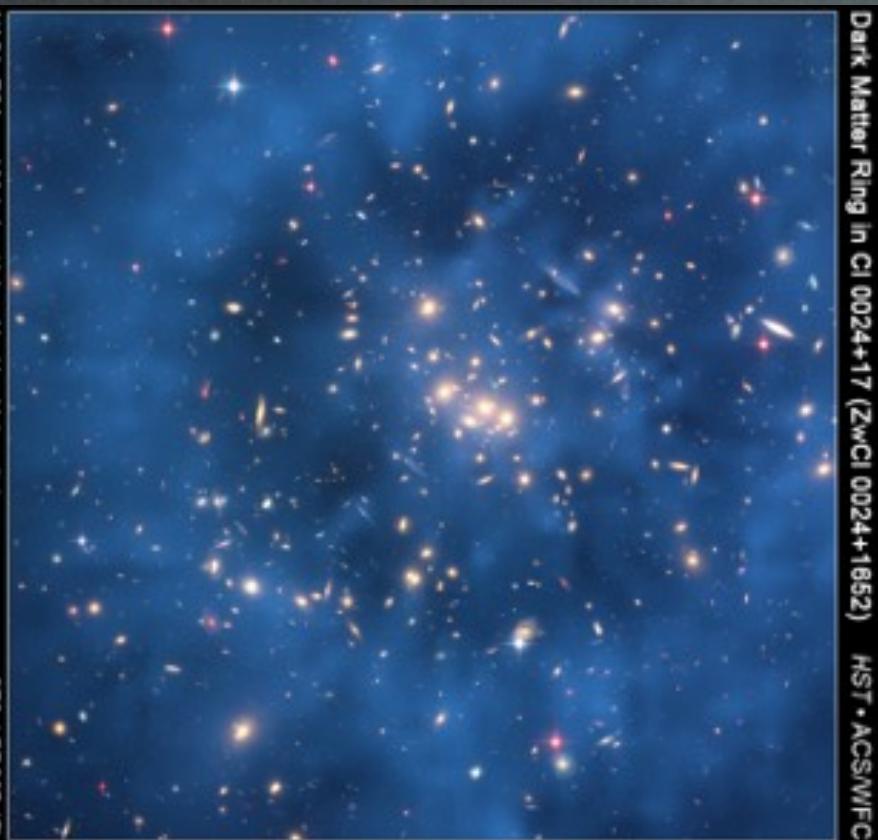
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NASA, ESA, and M.J. Lee (Johns Hopkins University)

STScI-PRC07-17b

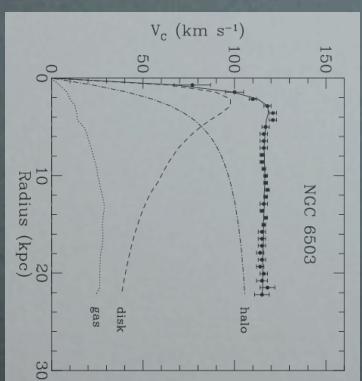
ring of Dark Matter (2007)

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The Evidence for DM

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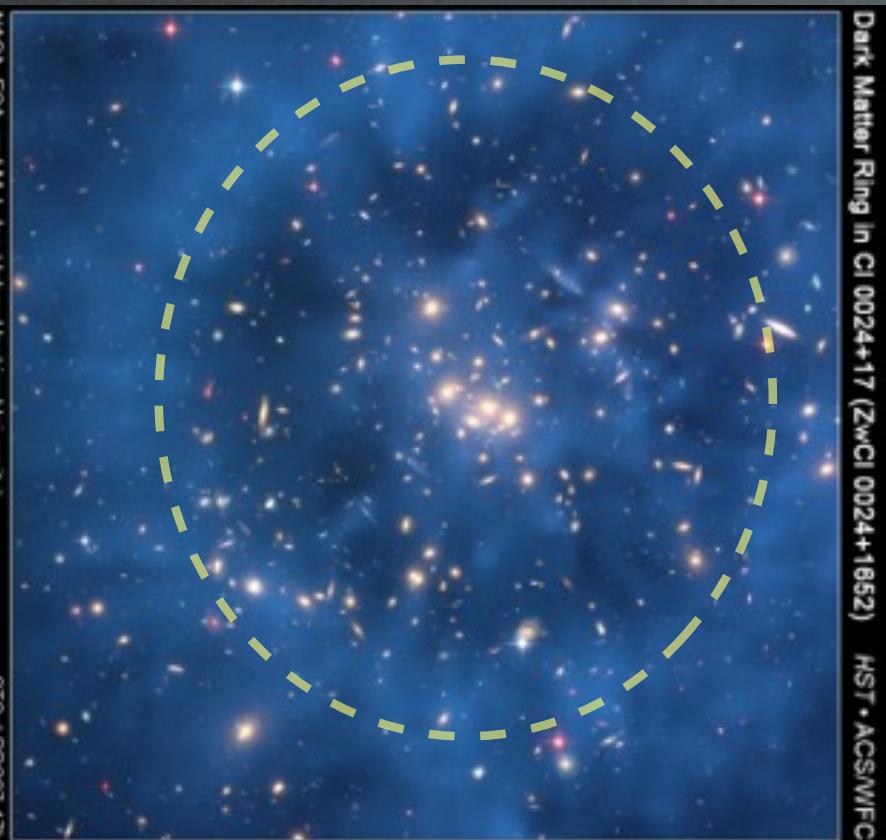
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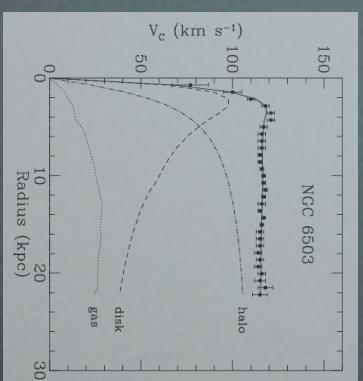
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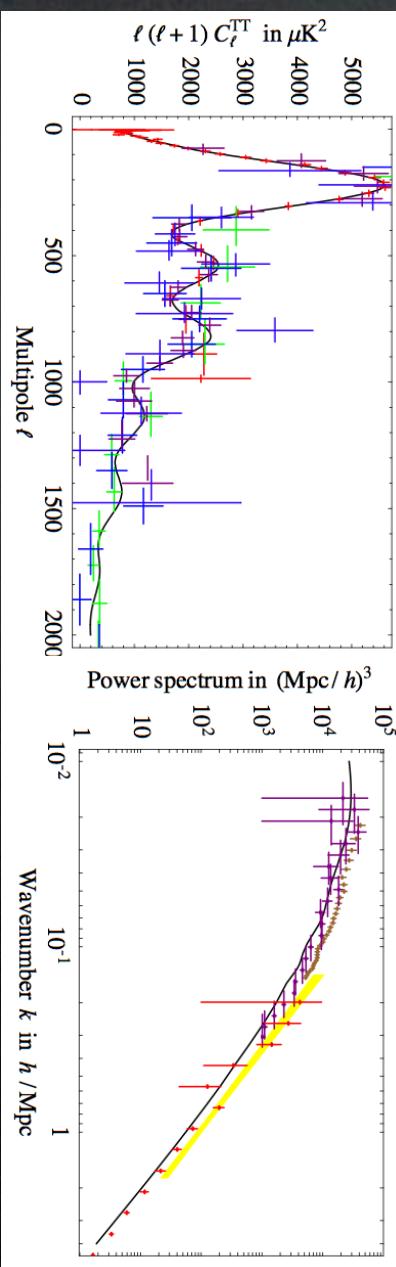
1) galaxy rotation curves



2) clusters of galaxies



3) CMB+LSS(+SNIa:)



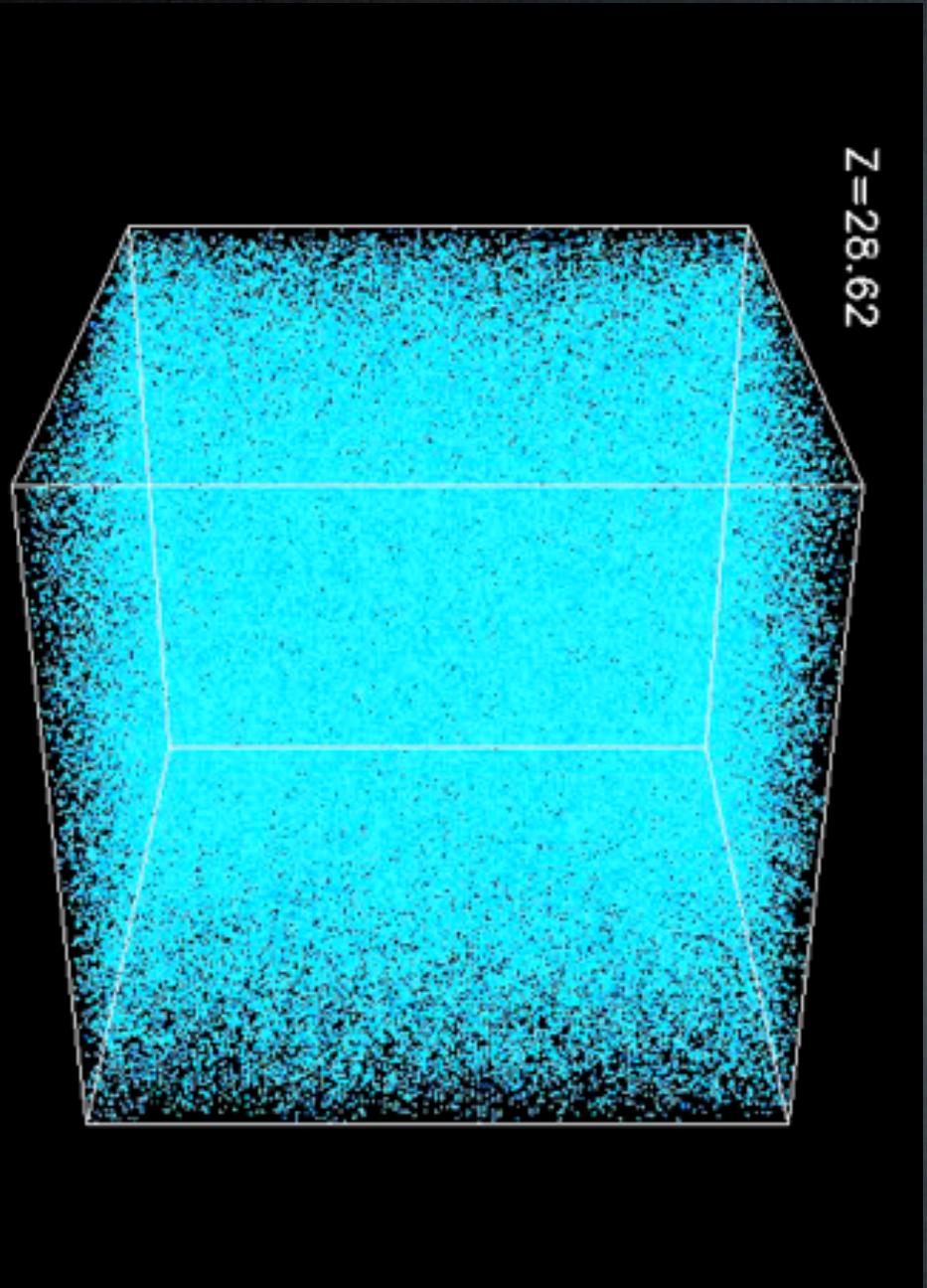
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DM N-body simulations

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

DM N-body simulations

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

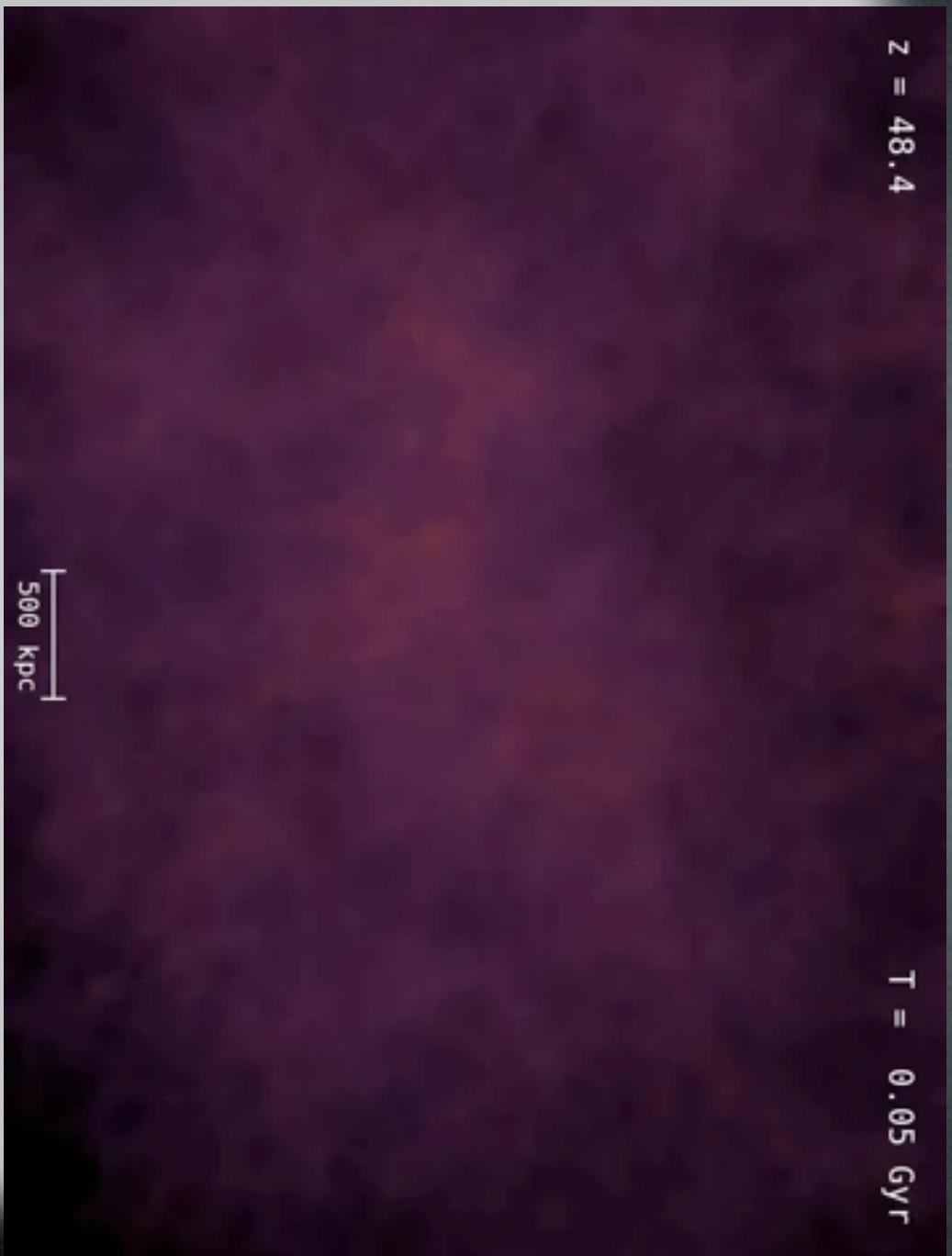


DM N-body simulations

Aquarius project of the VIRGO coll.:
 $1.5 \cdot 10^9$ CDM particles, single galactic halo

$z = 48.4$

$T = 0.05 \text{ Gyr}$



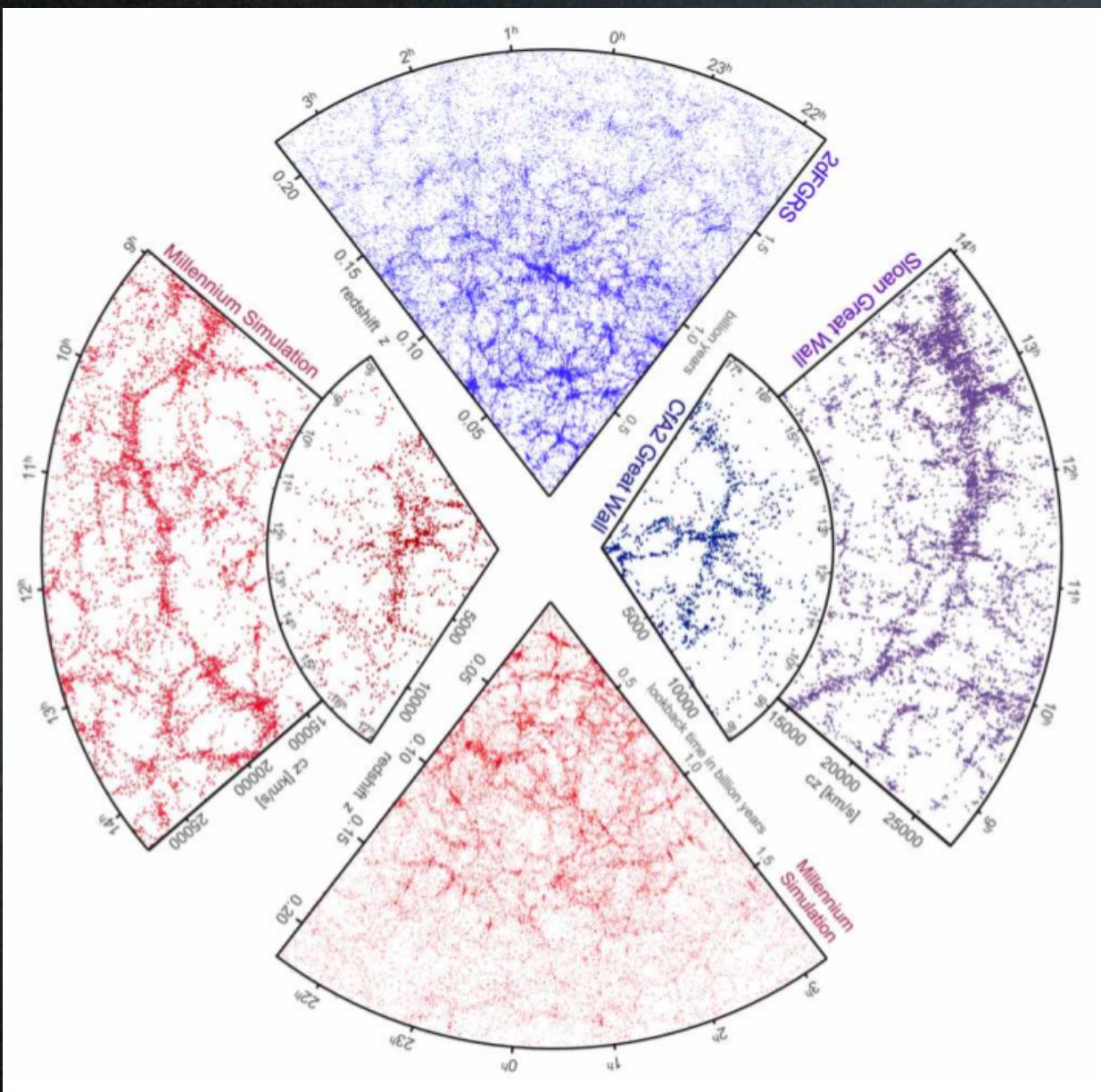
DM N-body simulations

2dF: 2.2×10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr

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

Springel, Frenk, White, Nature 440 (2006)

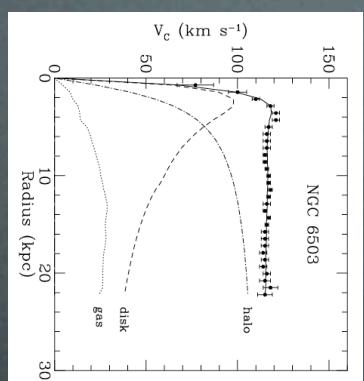


Millennium:
 10^{10} particles,
 $500 h^{-1} Mpc$

[back]

The Evidence for DM

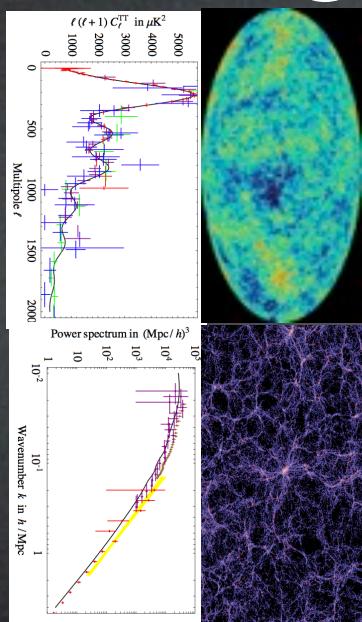
1) galaxy rotation curves



2) clusters of galaxies



3) CMB+LSS(+SNIa:)

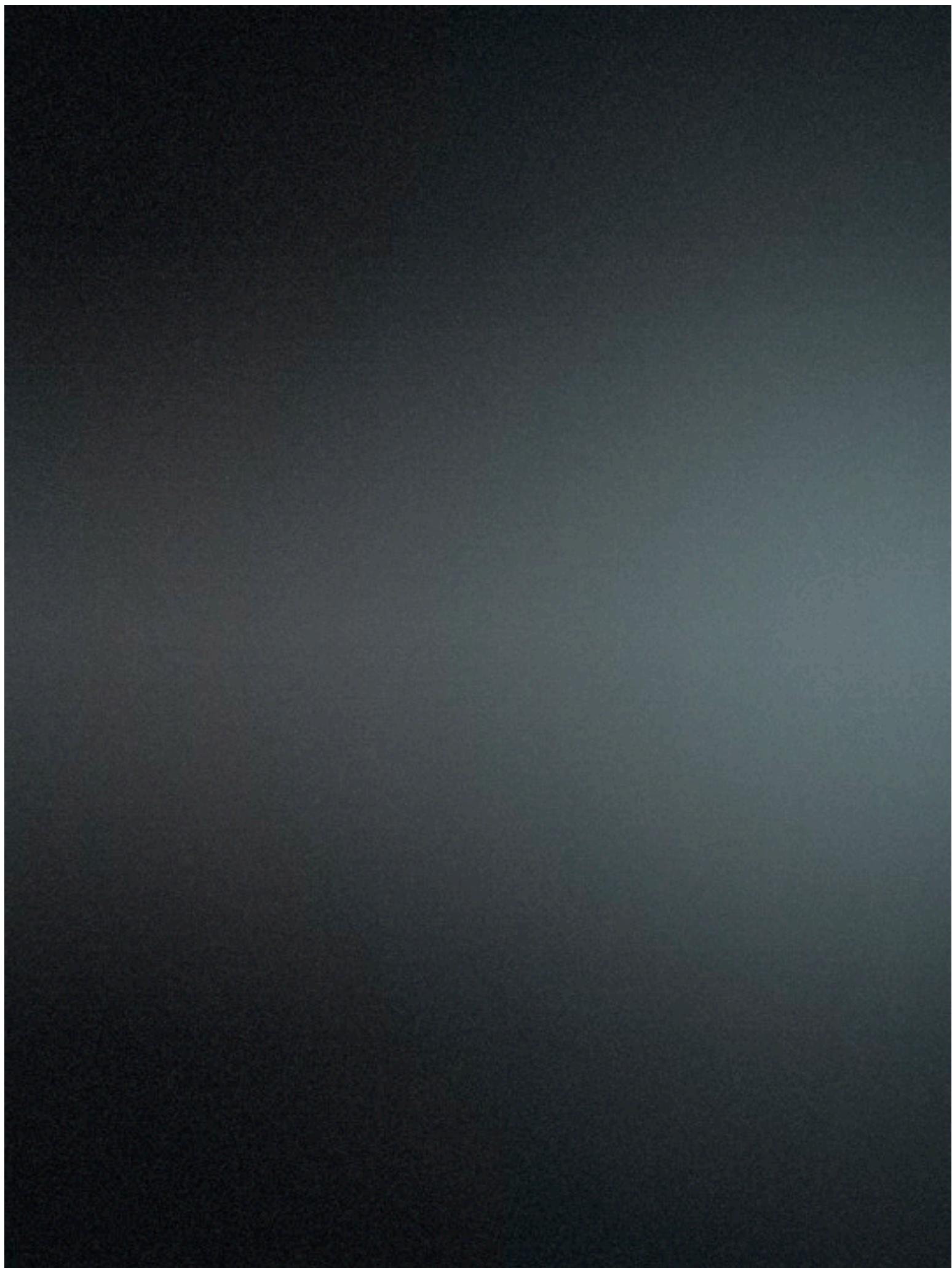


$$\Omega_M \approx 0.26 \pm 0.05$$

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

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*:

~~- neutrinos~~

- gas

- Black Holes

- brown dwarves

DM can NOT be:

an astro *je ne sais pas quoi*:

- ~~neutrons~~
- ~~cccS~~
- Black Holes
- brown dwarves

DM can NOT be:

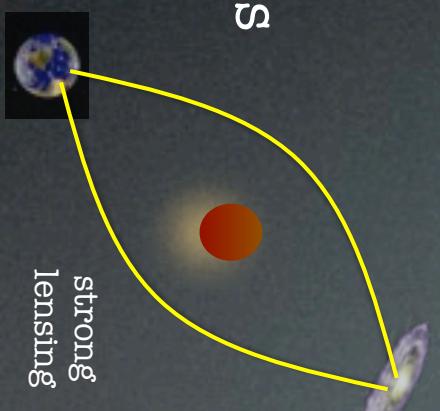
an astro *je ne sais pas quoi*:

- neutrinos

- gcs

- Black Holes

- brown dwarves



DM can NOT be:

an astro *je ne sais pas quoi*:

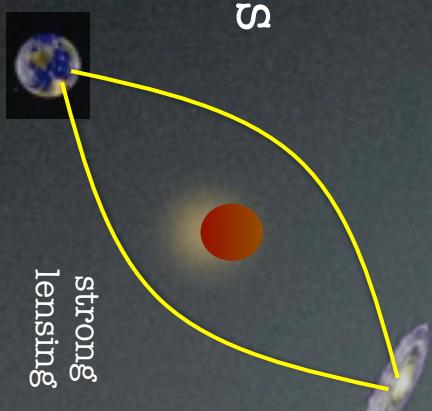
| a baryon of the SM:

- neutrinos

- gcs

- Black Holes

- brown dwarves



DM can NOT be:

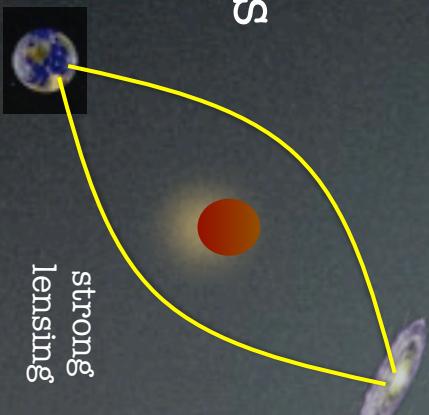
an astro je ne sais pas quoi:

- neutrinos

- gcs

- Black Holes

- brown dwarves



a baryons 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:

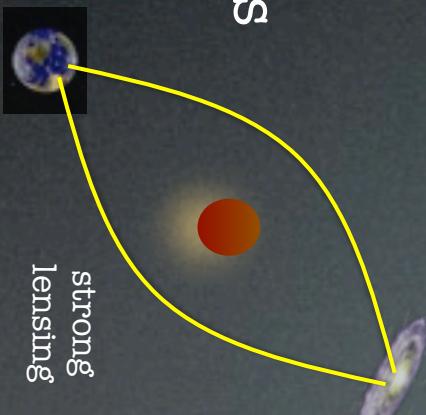
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DM can NOT be:

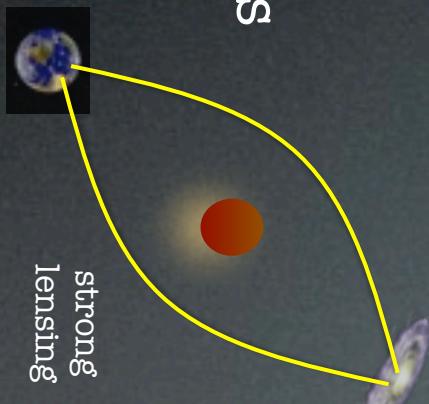
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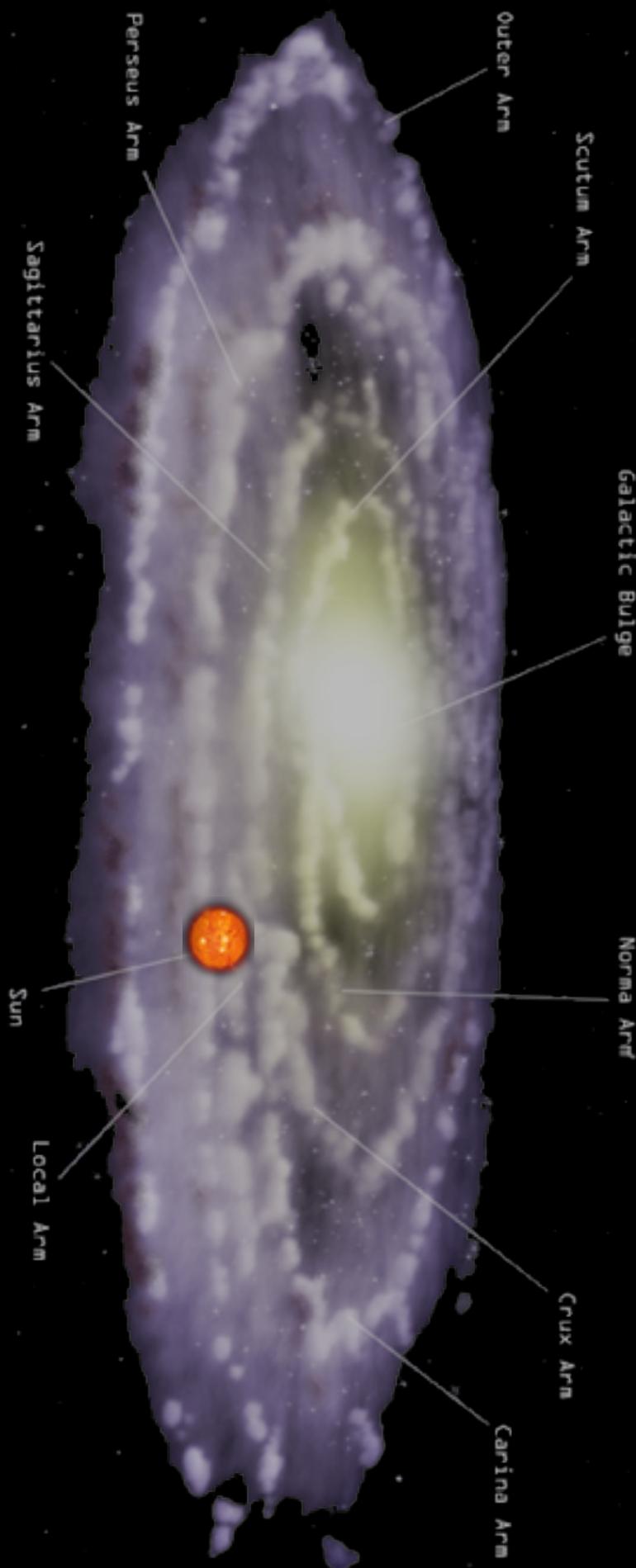
- CMB says baryons are 4% max

~~neutrinos:~~

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

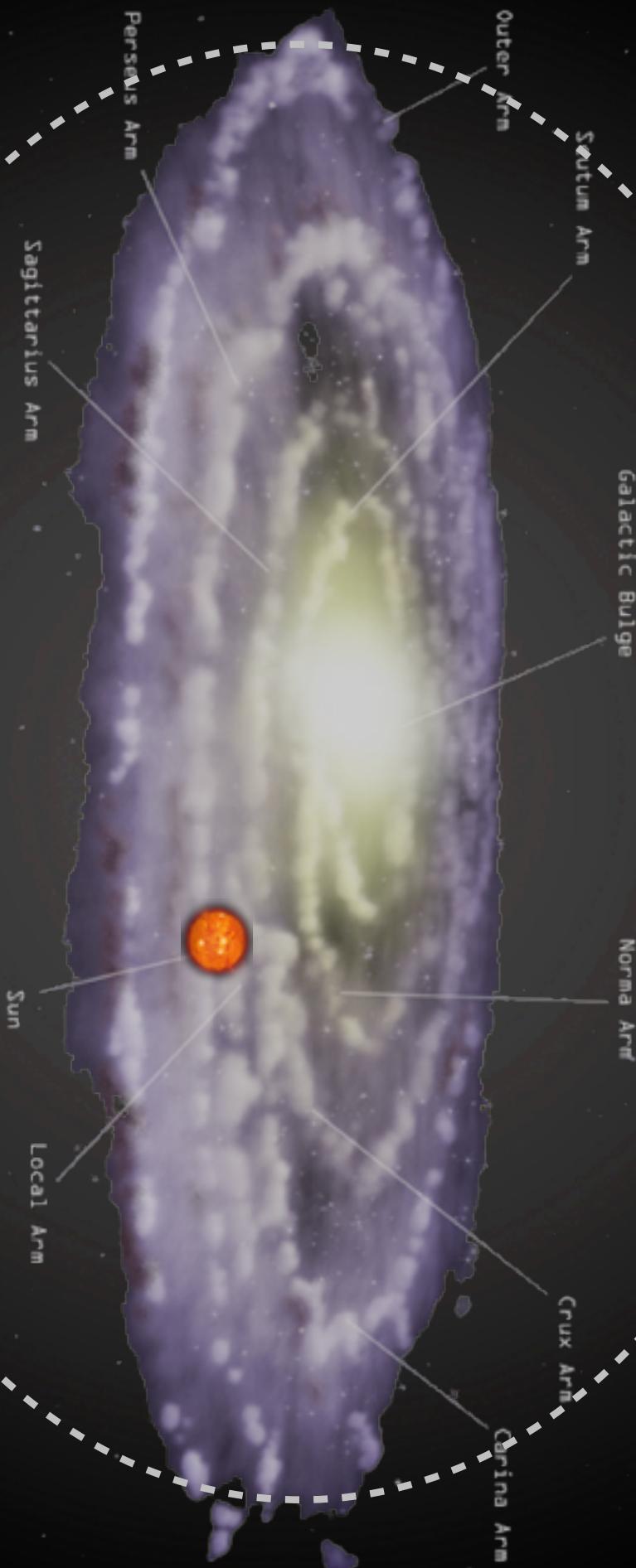
do not have enough mass to act as gravitational attractors in galaxy collapse

Recap: DM factsheet



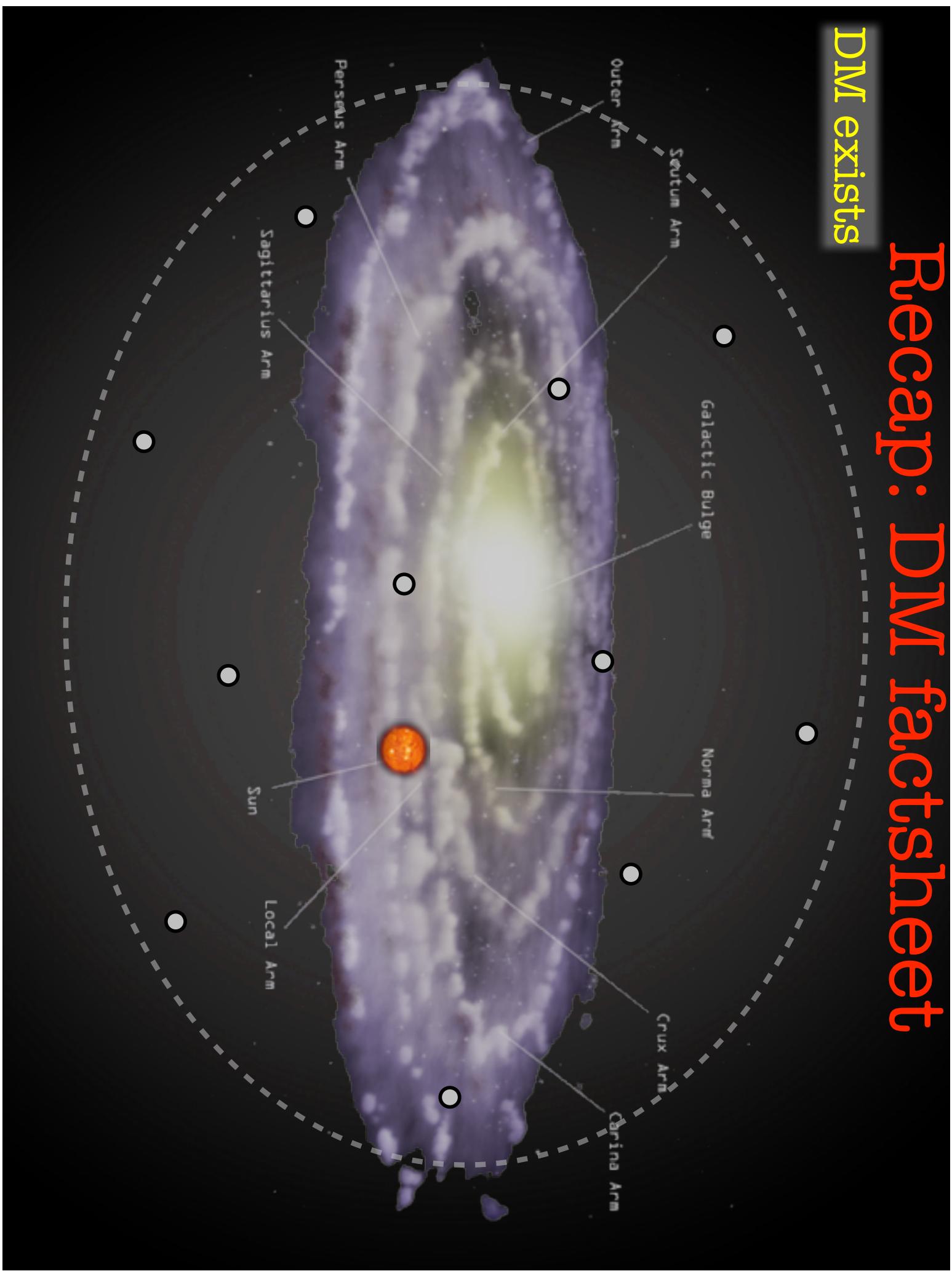
Recap: DM factsheet

DM exists



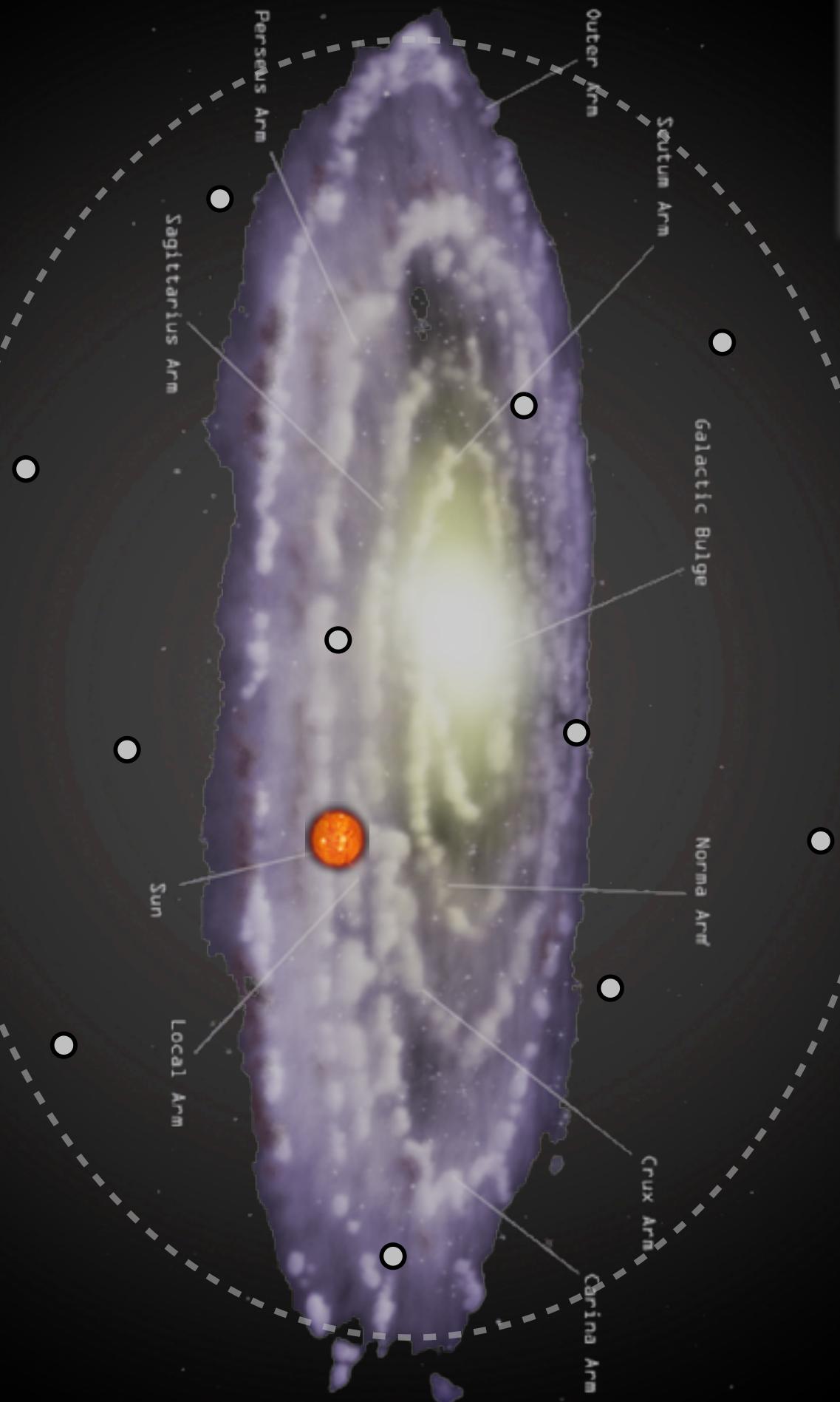
Recap: DM factsheet

DM exists



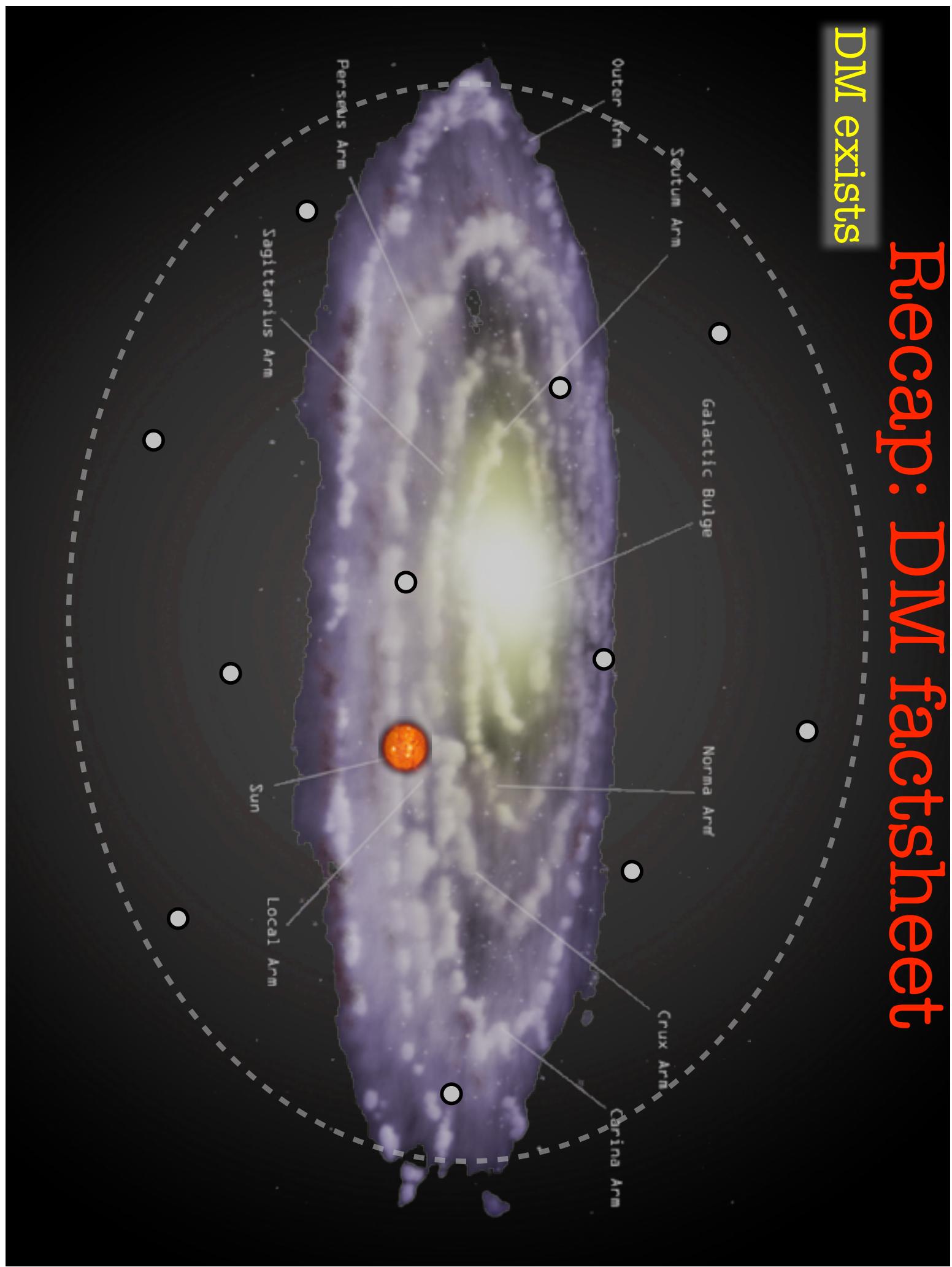
Recap: DM factsheet

DM exists



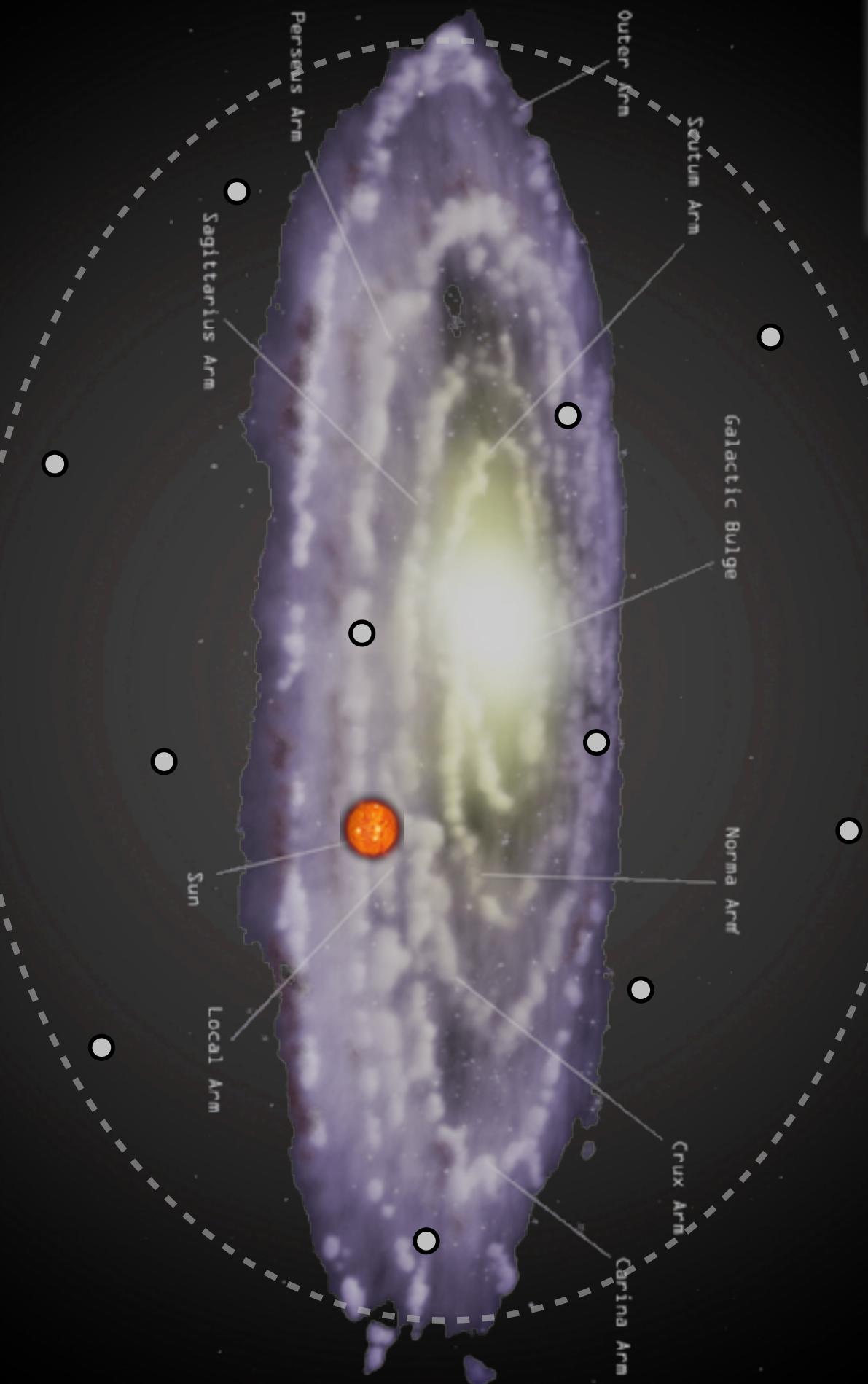
Recap: DM factsheet

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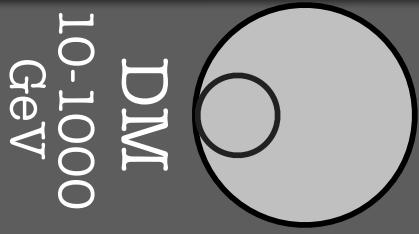
Recap: DM factsheet

DM exists



Recap: DM factsheet

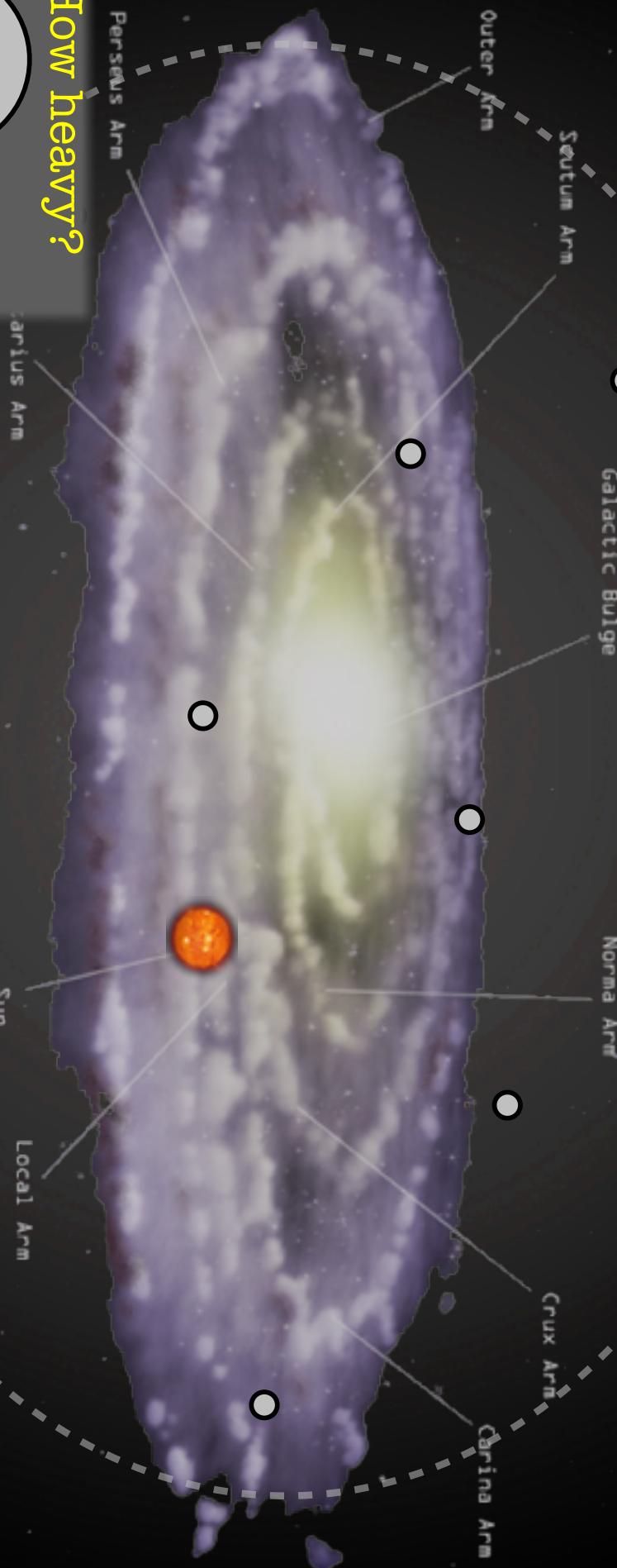
DM exists



DM

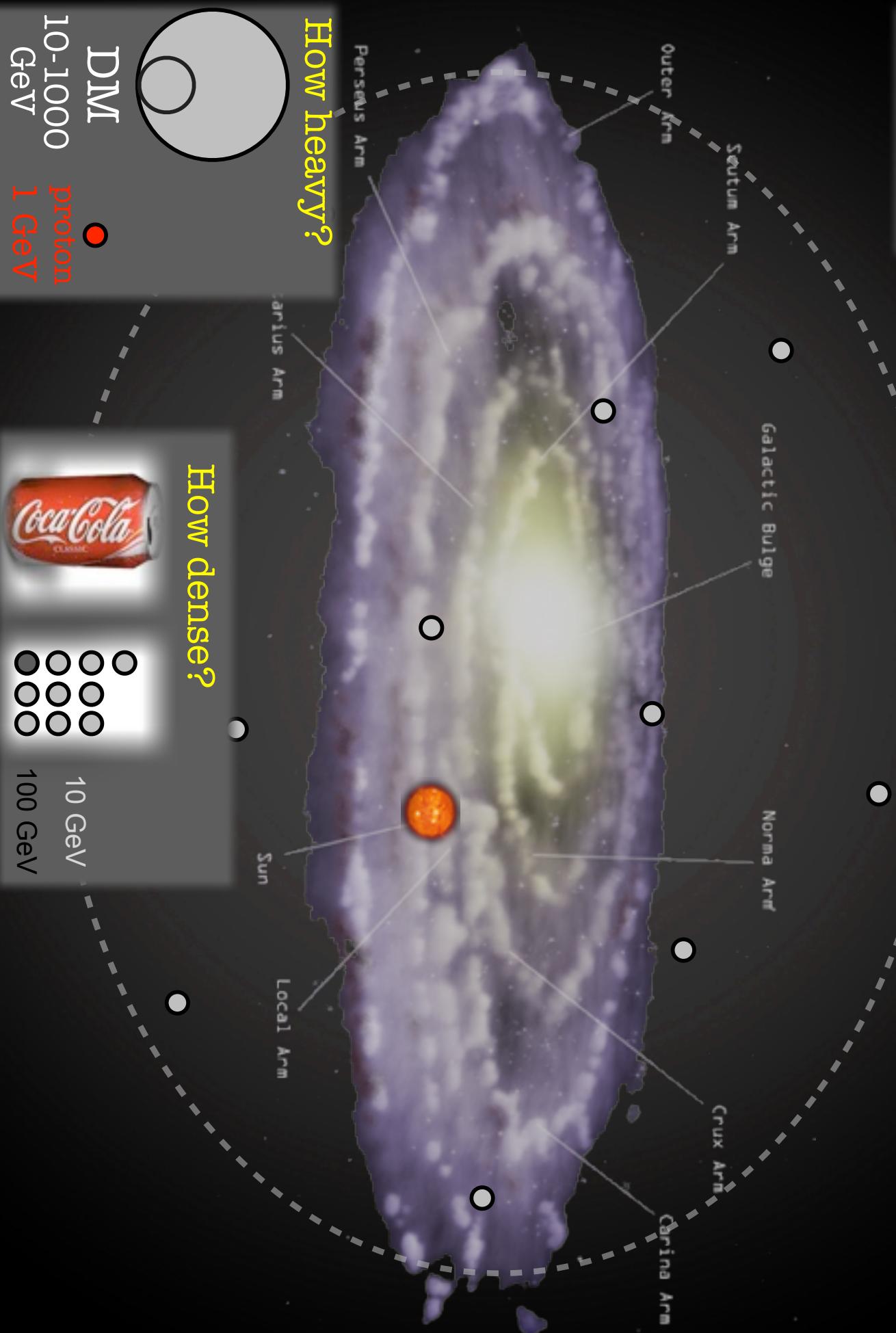
proton
GeV

How heavy?



Recap: DM factsheet

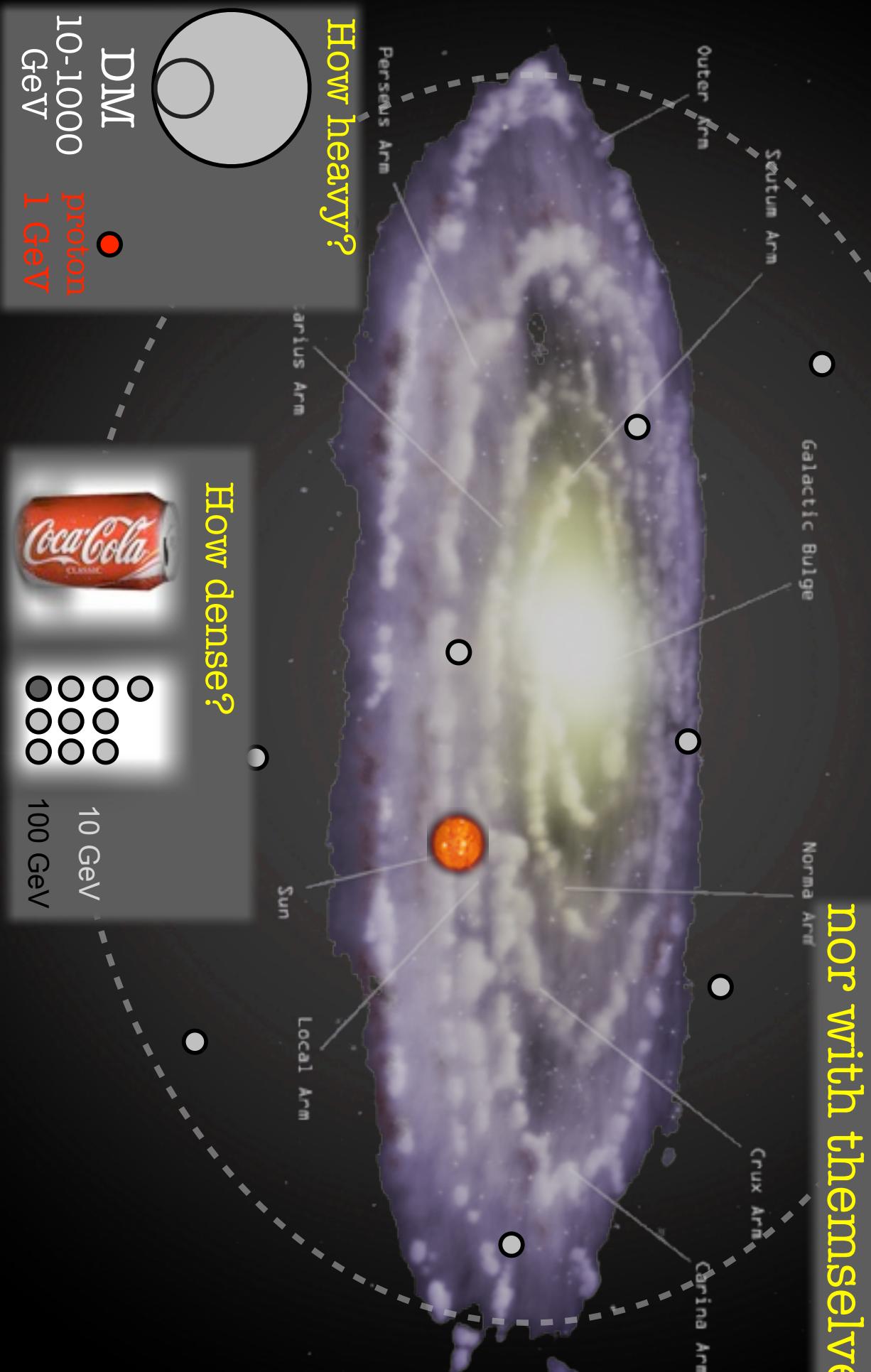
DM exists



Recap: DM factsheet

DM exists

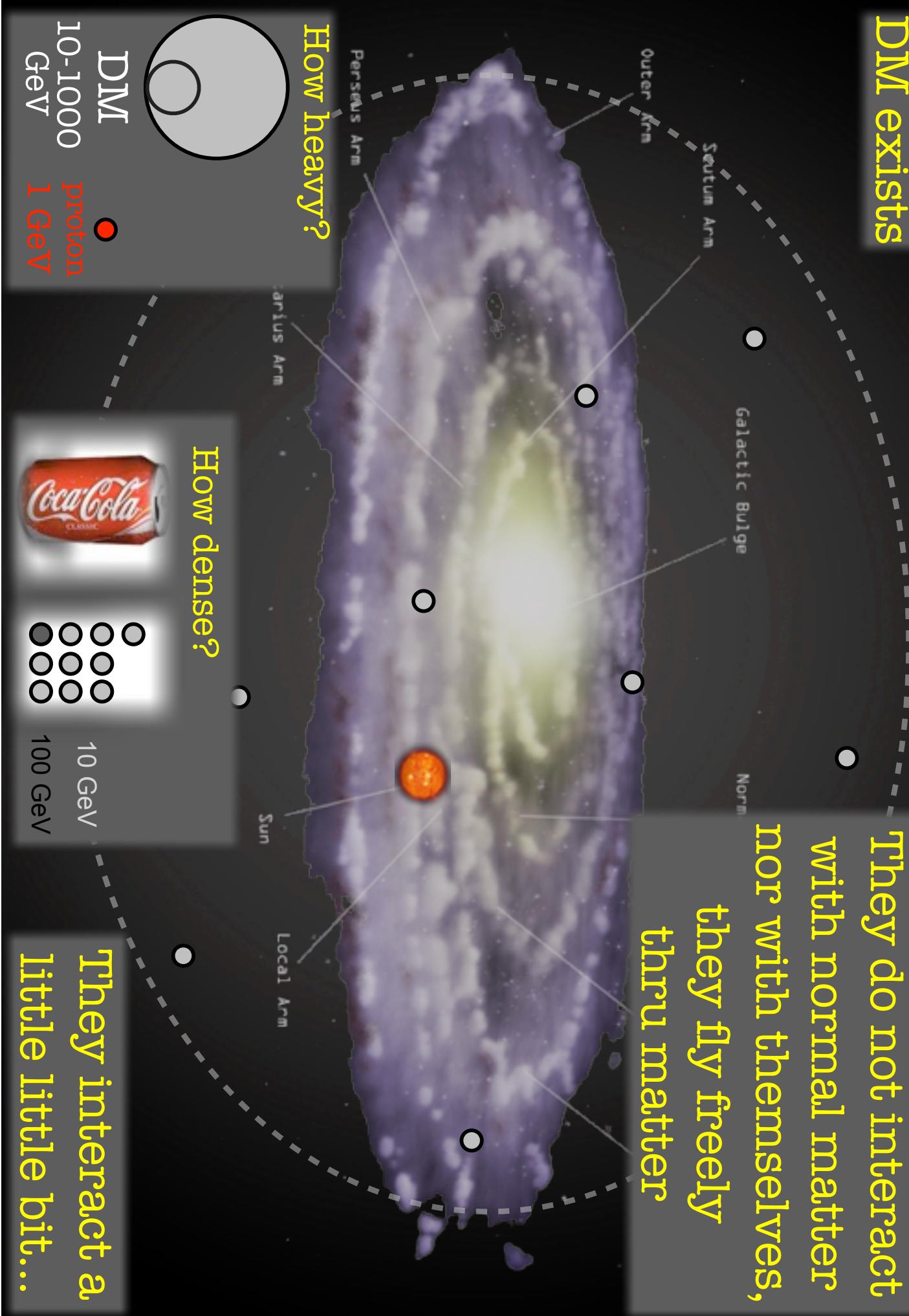
- They do not interact with normal matter nor with themselves



Recap: DM factsheet

DM exists

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



They interact a little little bit...

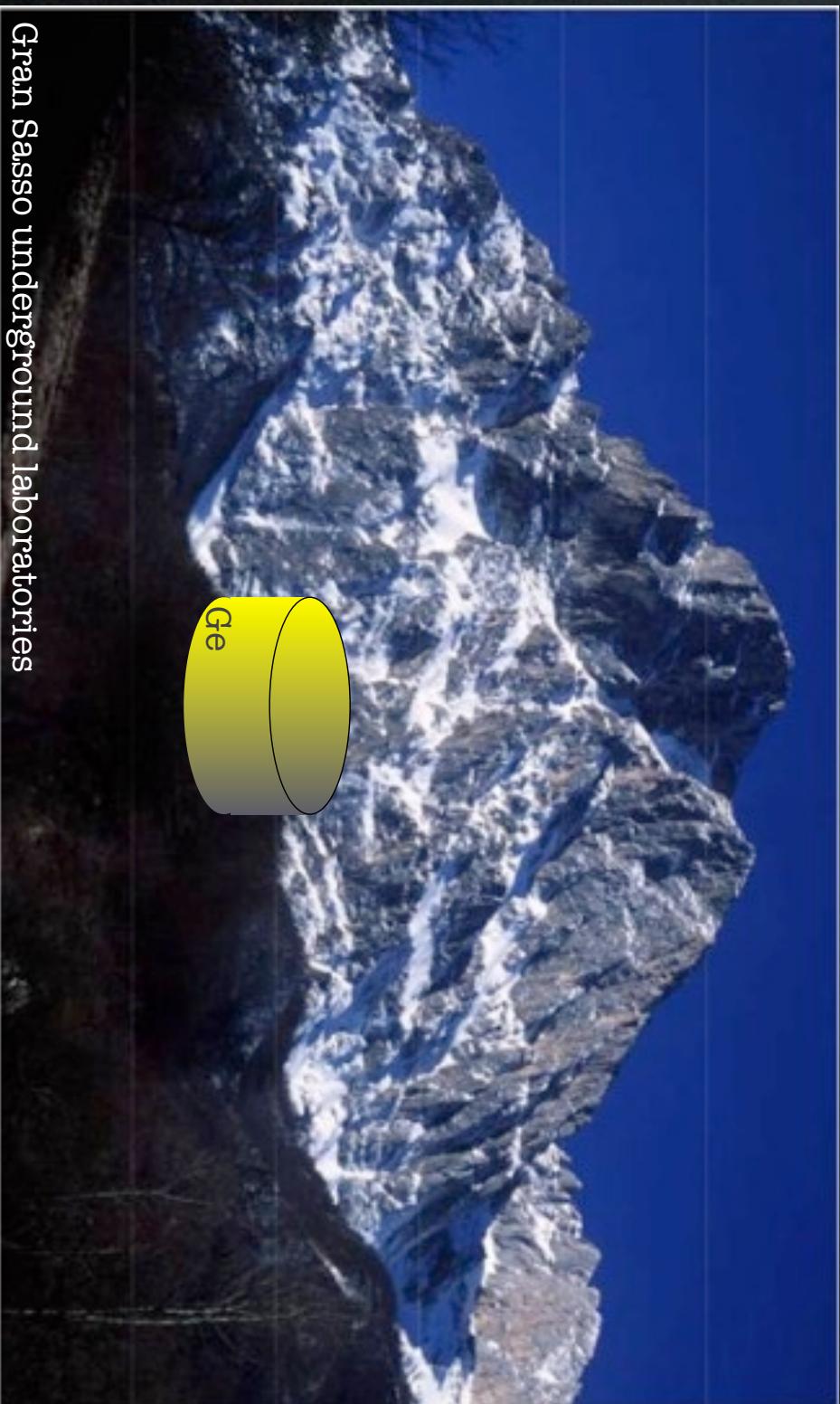
Detecting Dark Matter

1. Direct Detection: basics

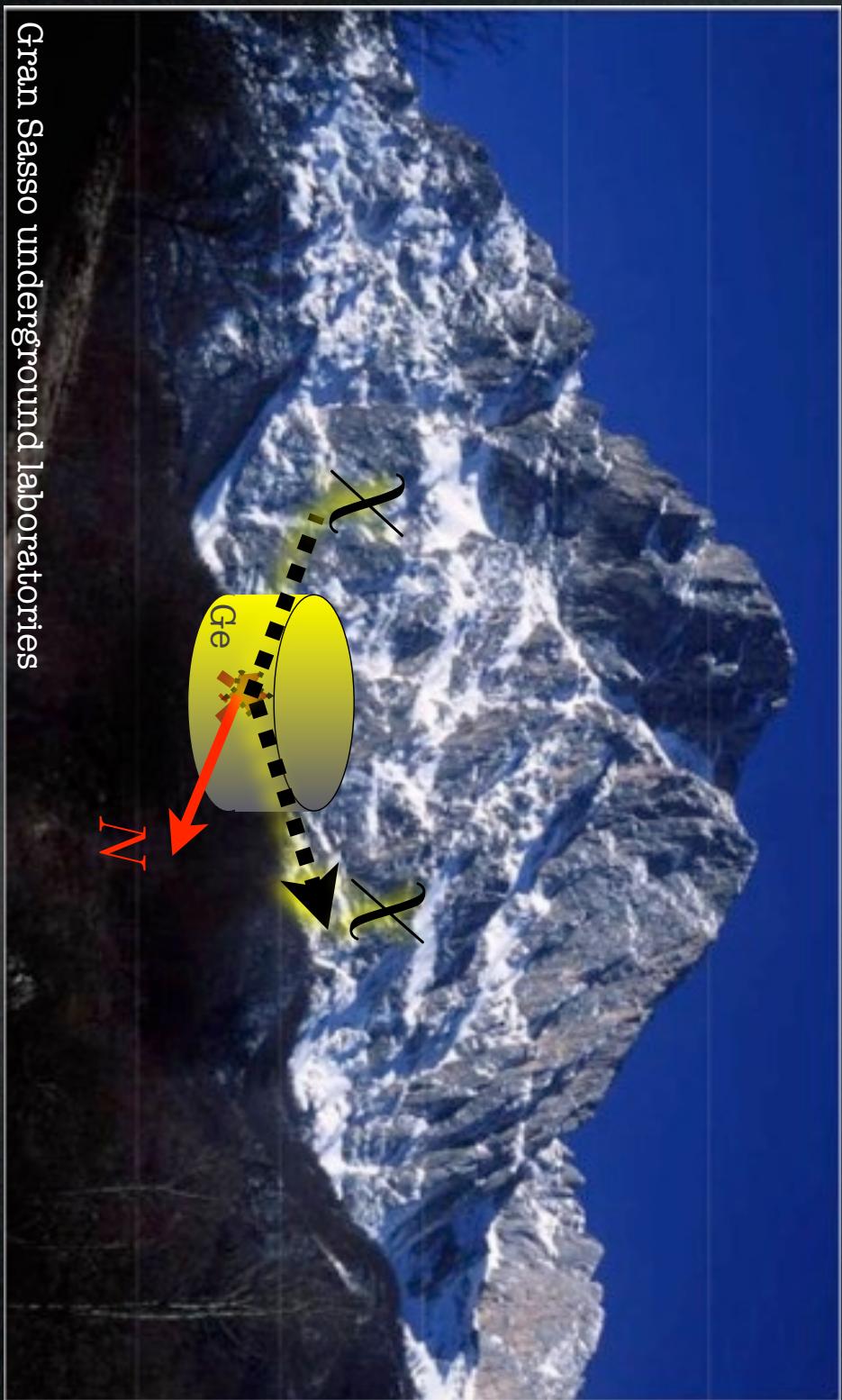


Gran Sasso underground laboratories

Direct Detection: basics



Direct Detection: basics



Direct Detection

Strategy #1: silence the Universe

Direct Detection

Strategy #1: silence the Universe

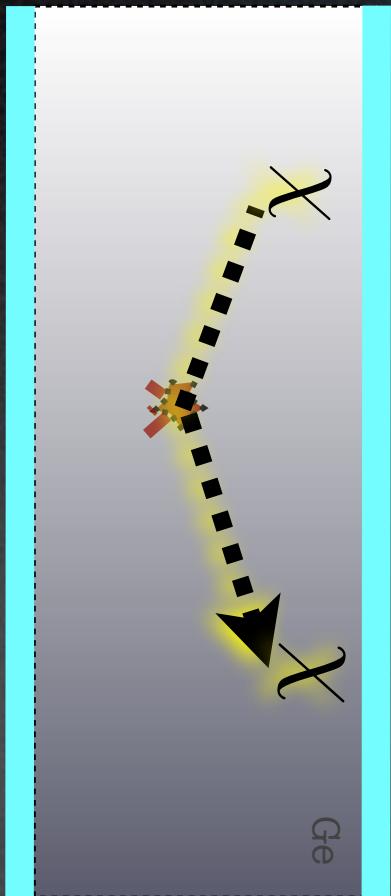
measure two quantities to discriminate Sign & Bkgd,
on event-by-event basis

Direct Detection

Strategy #1: silence the Universe

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

E.g. Edelweiss:



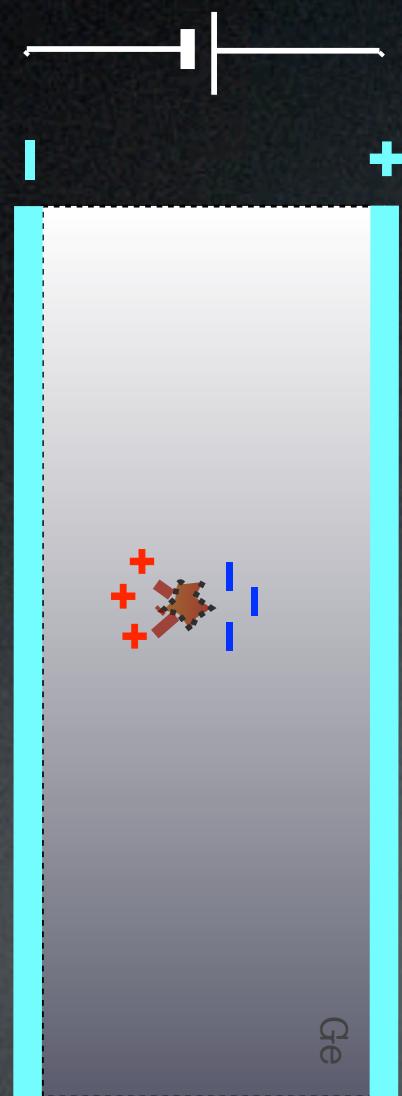
Direct Detection

Strategy #1: silence the Universe

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

E.g. Edelweiss:

ionization



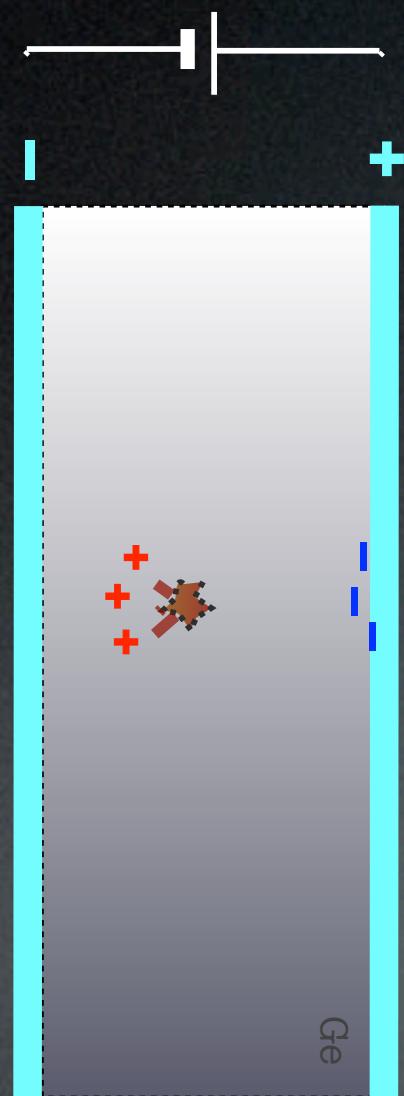
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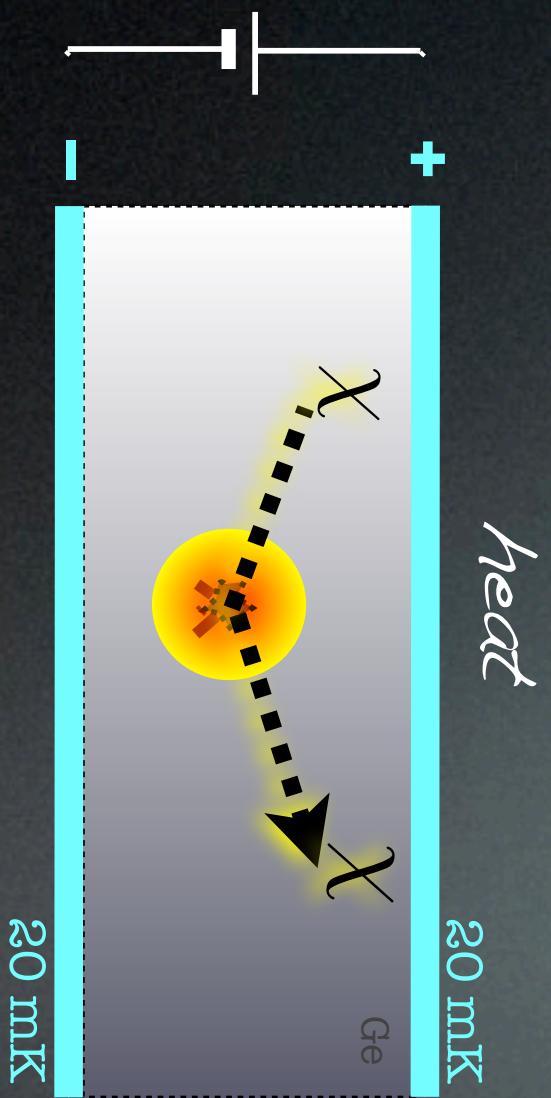


Direct Detection

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Direct Detection

Strategy #1: silence the Universe

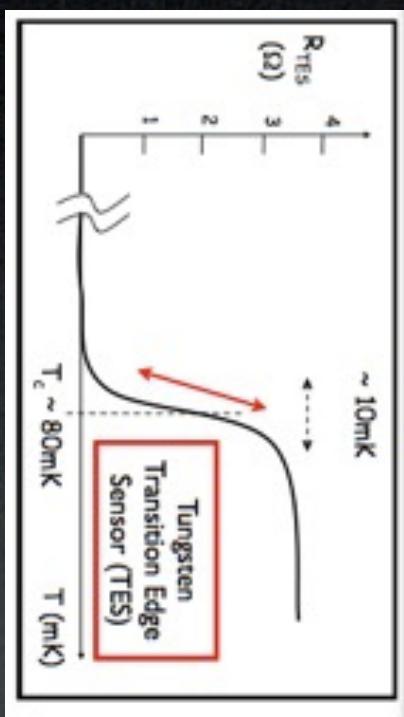
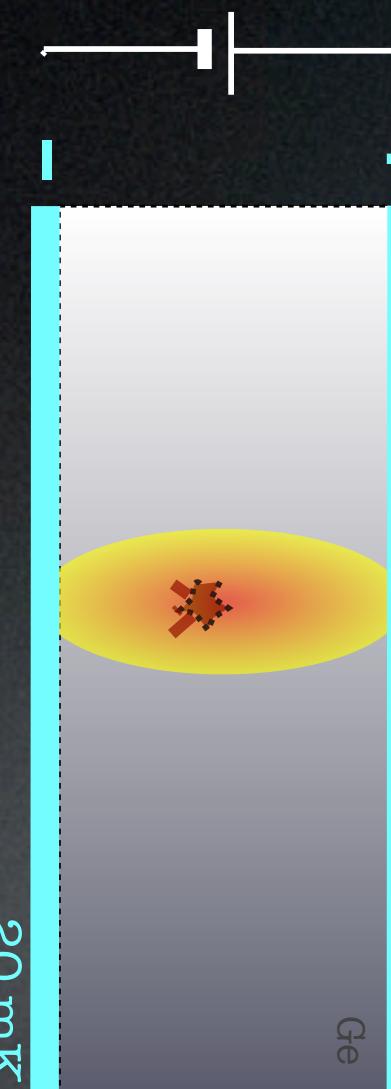
measure two quantities to discriminate Sign & Bkgd,
on event-by-event basis

E.g. Edelweiss:

heat $\gtrsim 20 \text{ mK}$

+

Ge

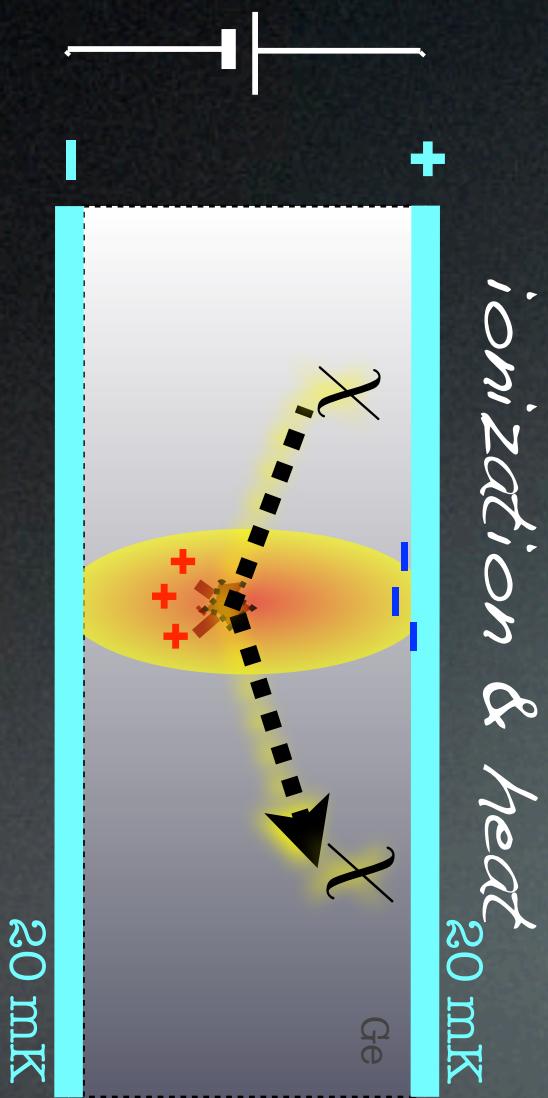


Direct Detection

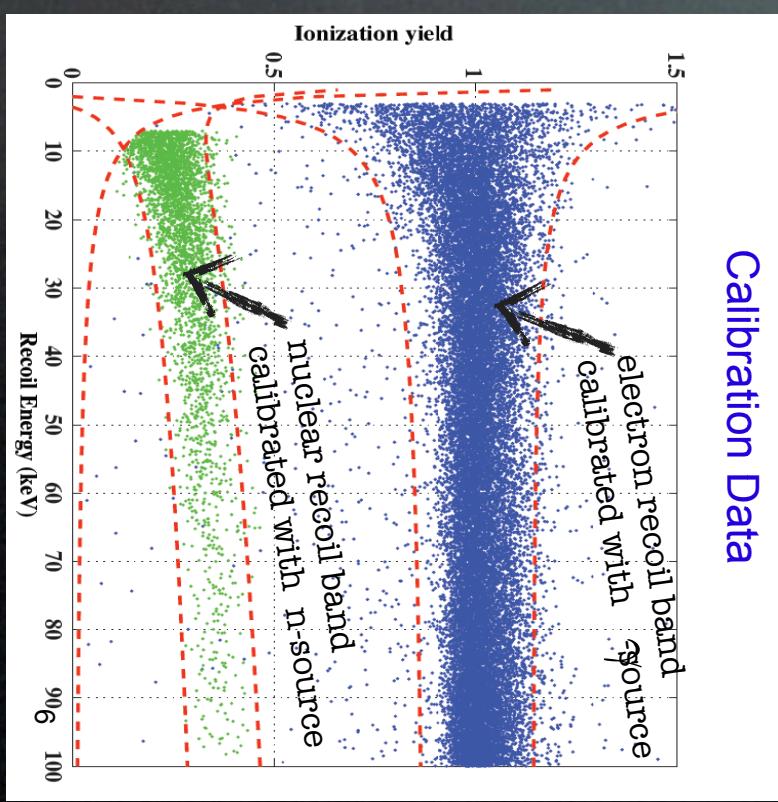
Strategy #1: silence the Universe

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E.g. Edelweiss:



Calibration Data



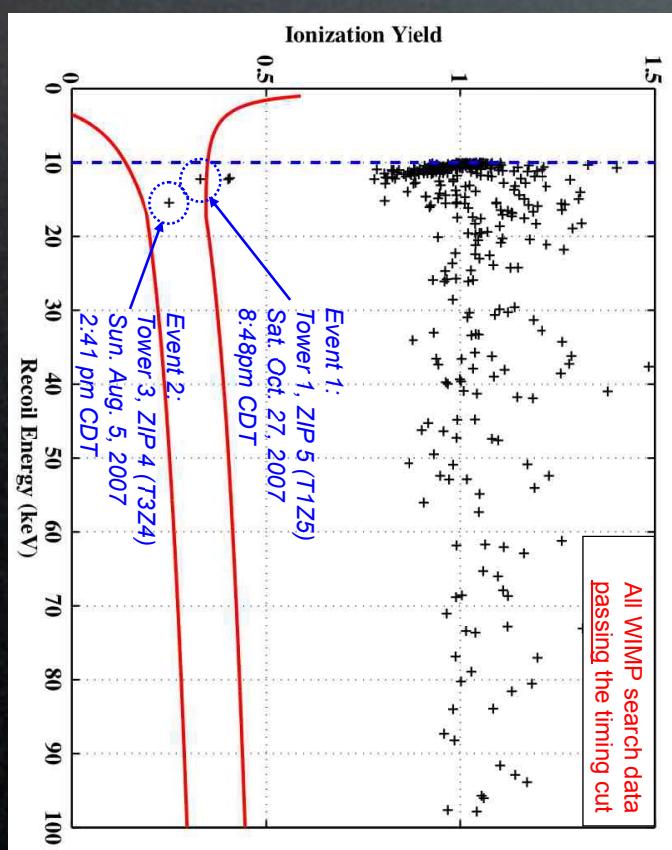
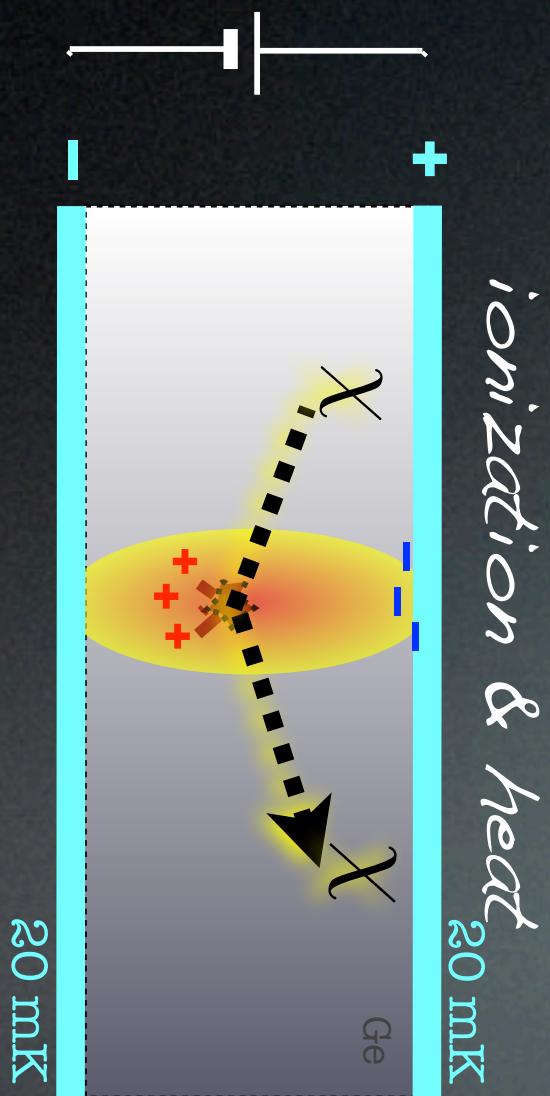
CDMS coll.

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

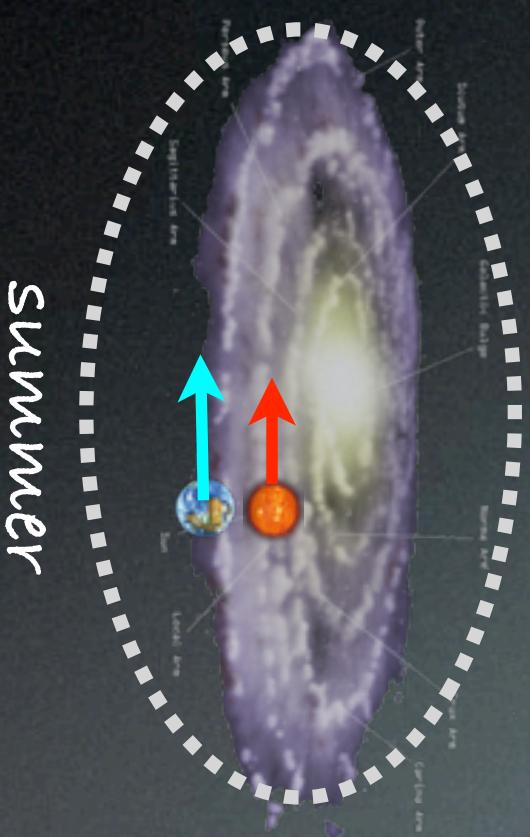
Strategy #2: ride the dark wave

collect all events, and detect an annual modulation

Direct Detection

Strategy #2: ride the dark wave

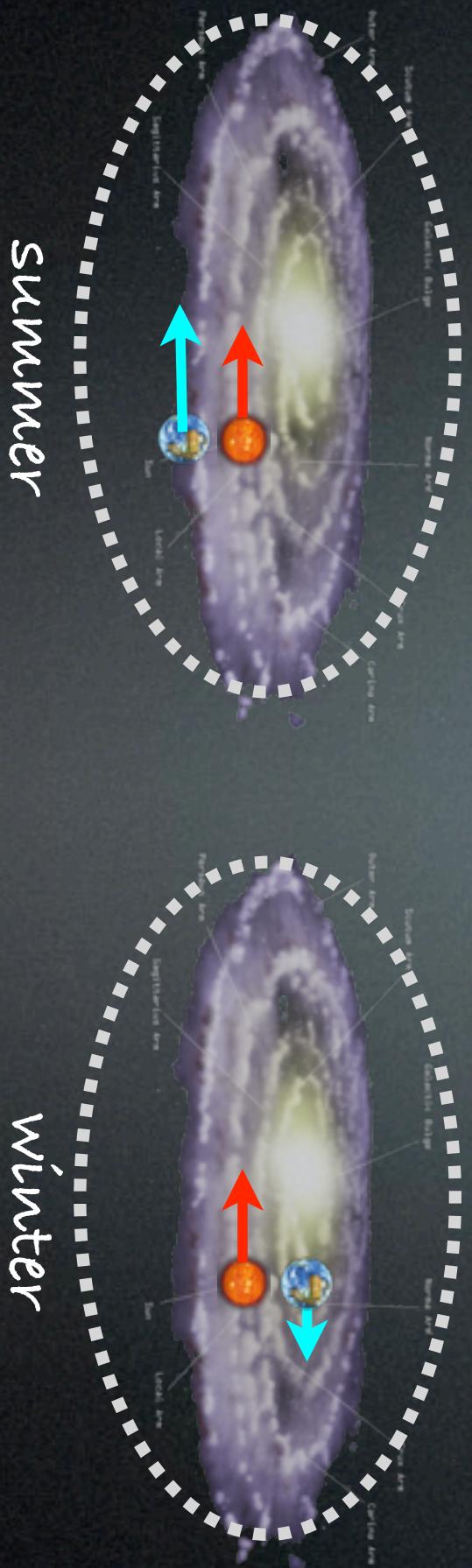
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Direct Detection

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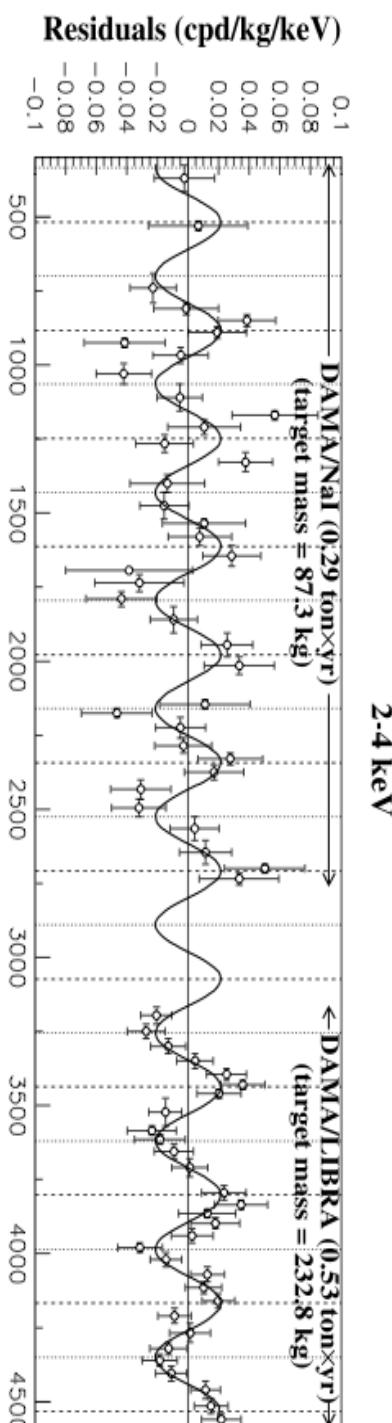
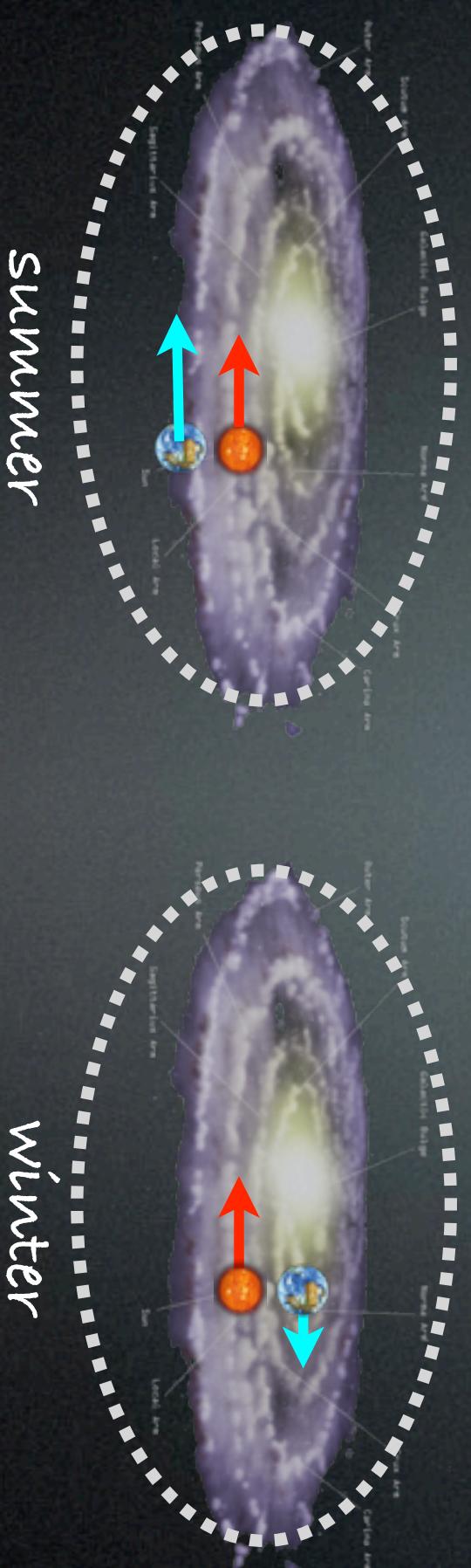
collect all events, and detect an annual modulation



Direct Detection

Strategy #2: ride the dark wave

collect all events, and detect an annual modulation



Direct Detection: Status

• **Dark matter candidate:** neutralino

• **Search strategy:** direct detection

• **Key experiments:** CDMS, XENON, LUX, EDELWEISS

• **Current constraints:** $\sigma \times \text{cross-section} < 10^{-26} \text{ cm}^2/\text{GeV}$

• **Future prospects:** SuperCDMS, LZ, DarkSide, XMASS

• **Open questions:** nature of dark matter, mass scale, interaction strength

• **Challenging assumptions:** no supersymmetry, no dark matter halo

• **Other approaches:** indirect detection, astrophysics, cosmology

• **Conclusion:** significant progress, but many mysteries remain

Direct Detection: Status

DAMA/Libra
(1998-2011)

CoGeNT
(2010-2011)

Dark Matter! DARK MATTER!

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

CDMS
(2001-2011)



Direct Detection: Status

DAMA/Libra
(1998-2011)

CoGeNT
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Dark Matter! DARK MATTER!

Seen an **excess** of events and/or annual **modulation**.

Light (few GeV) DM with large scattering.

CRESST
(2011)

No way.

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

XENON100
(2009-2011)

CDMS (2009)

LUX (2013)

Direct Detection: Status

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CoGeNT
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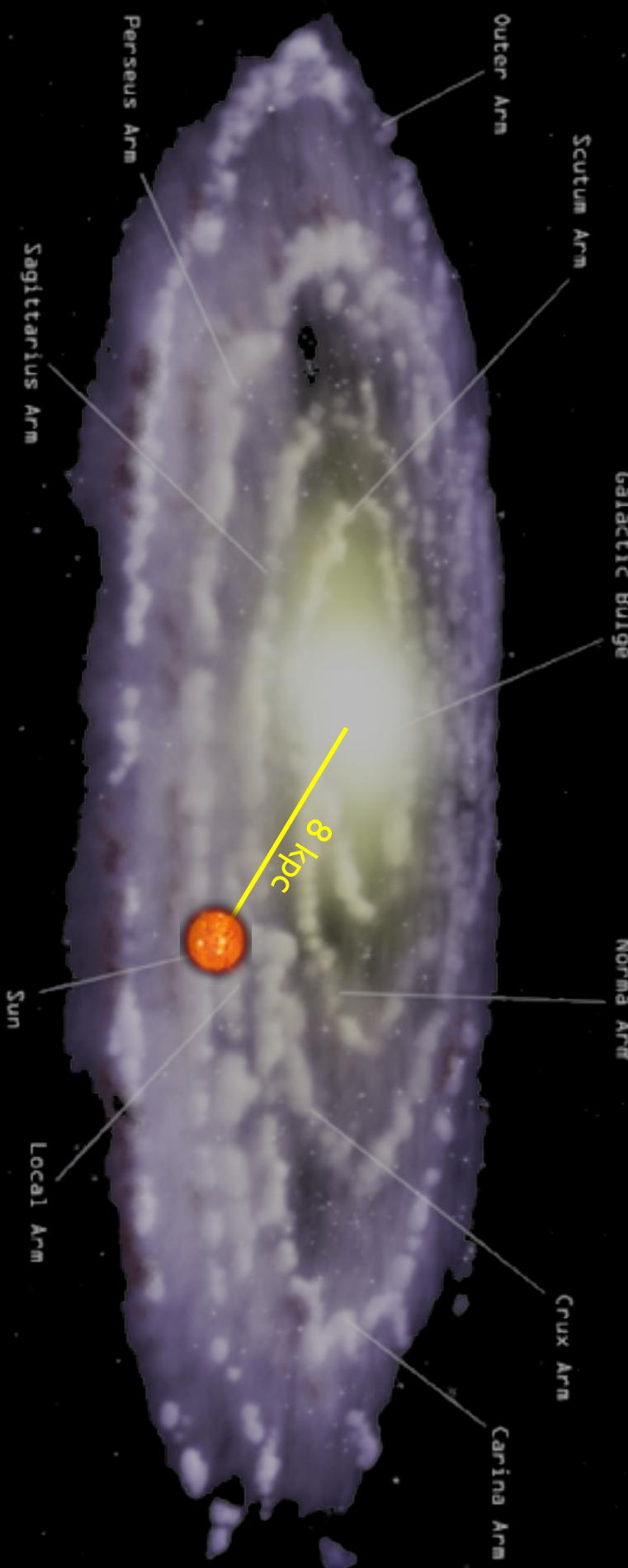
CDMS (2009)

LUX (2013)



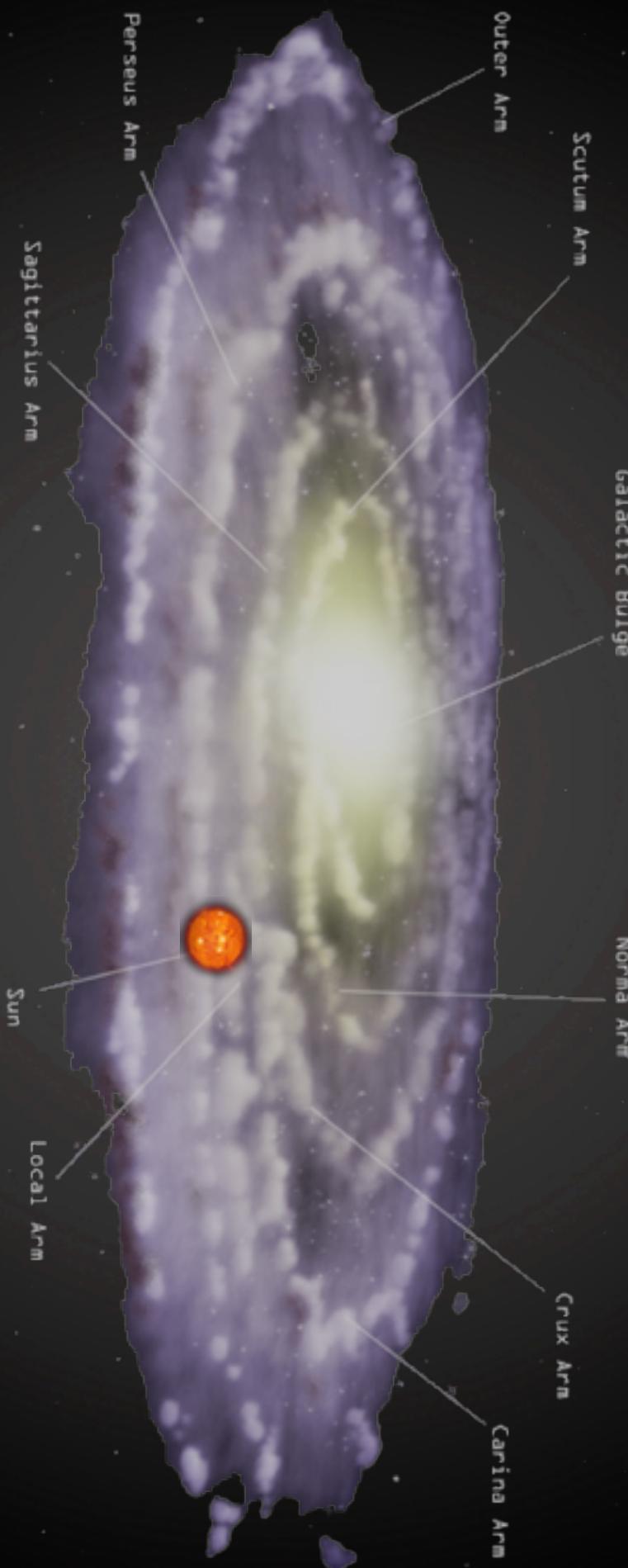
2. Indirect Detection: basics

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



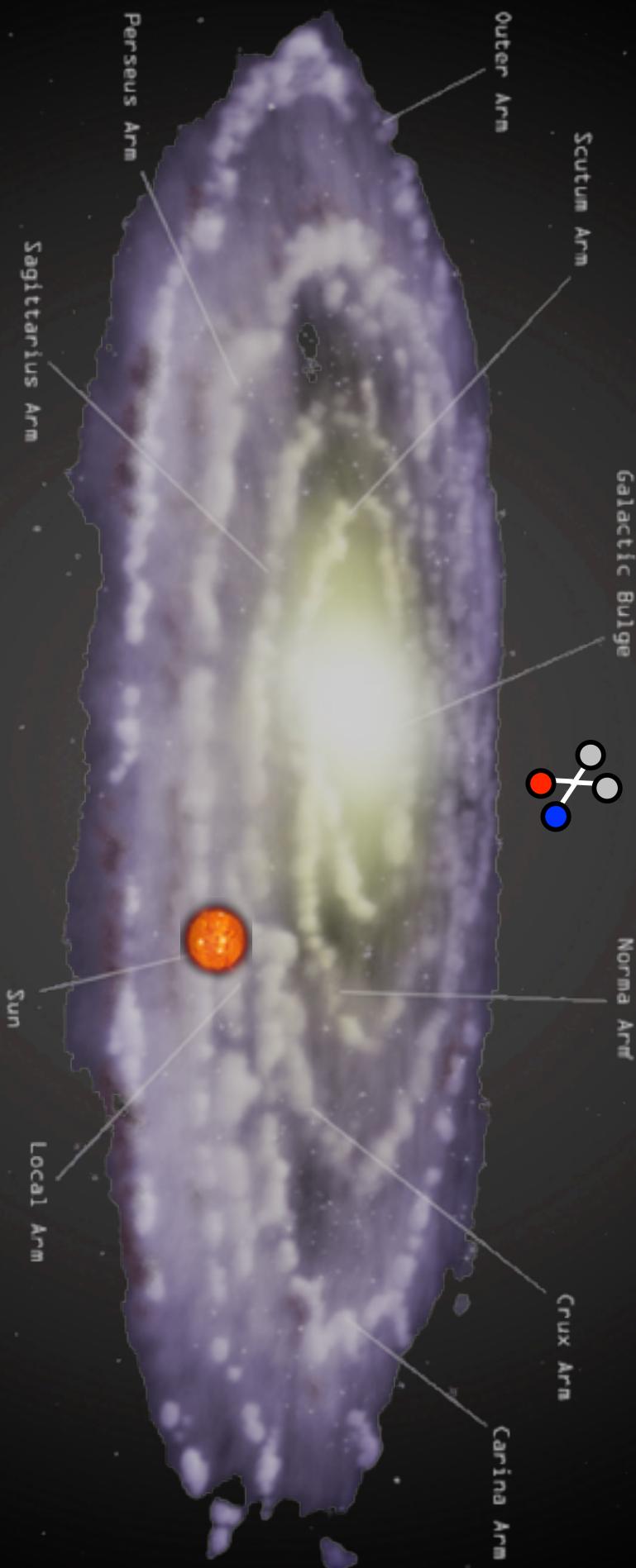
Indirect Detection: Basics

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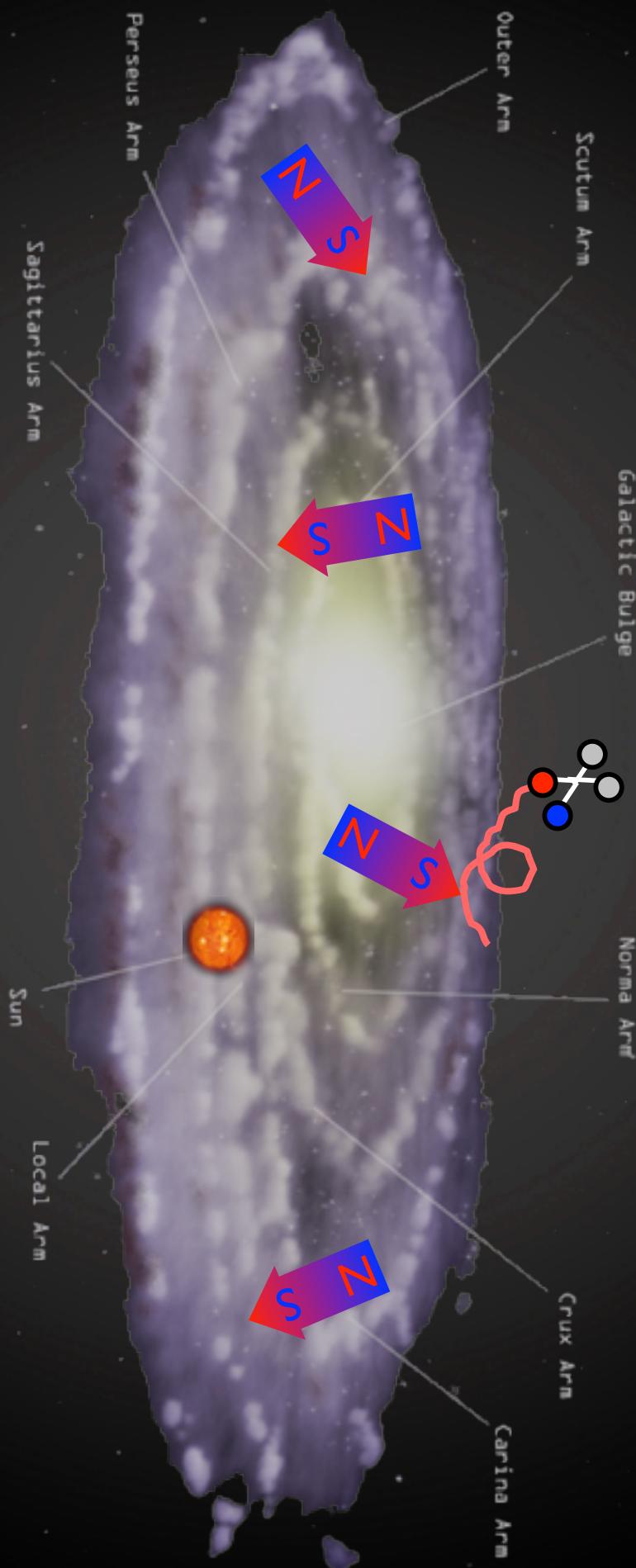
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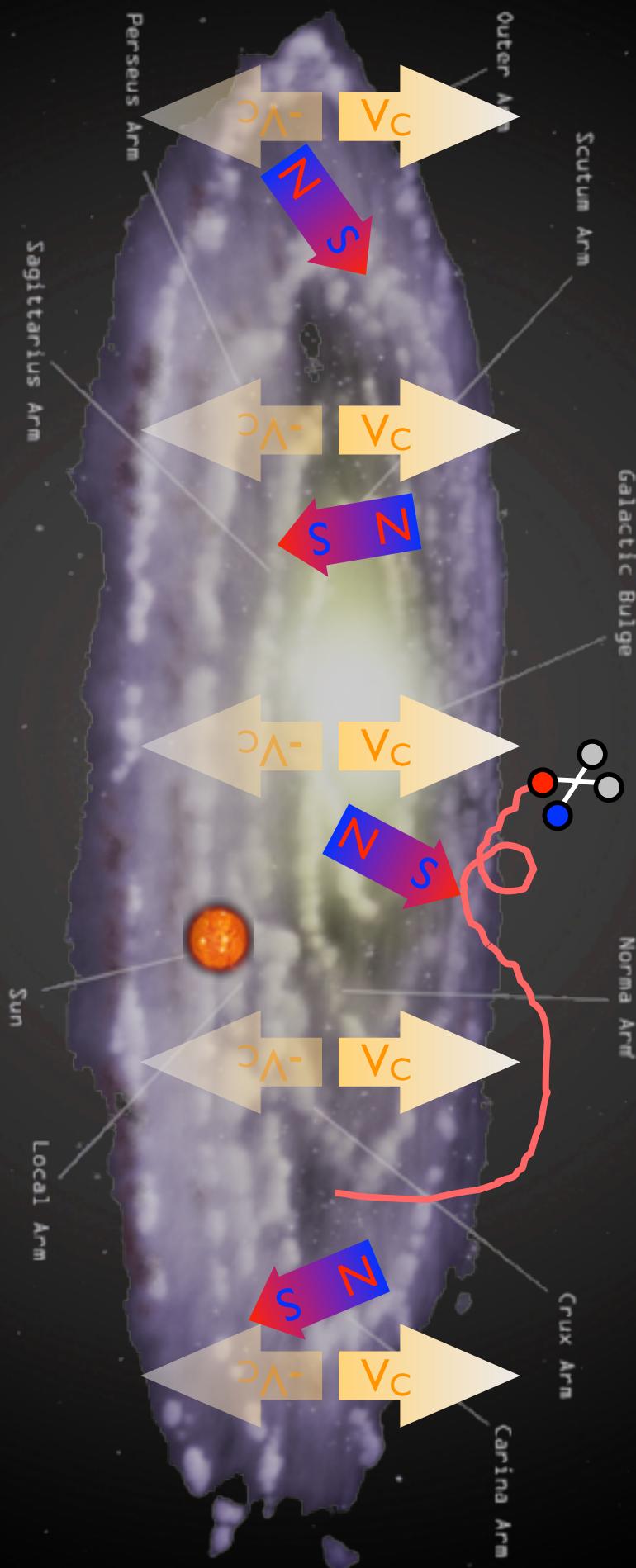
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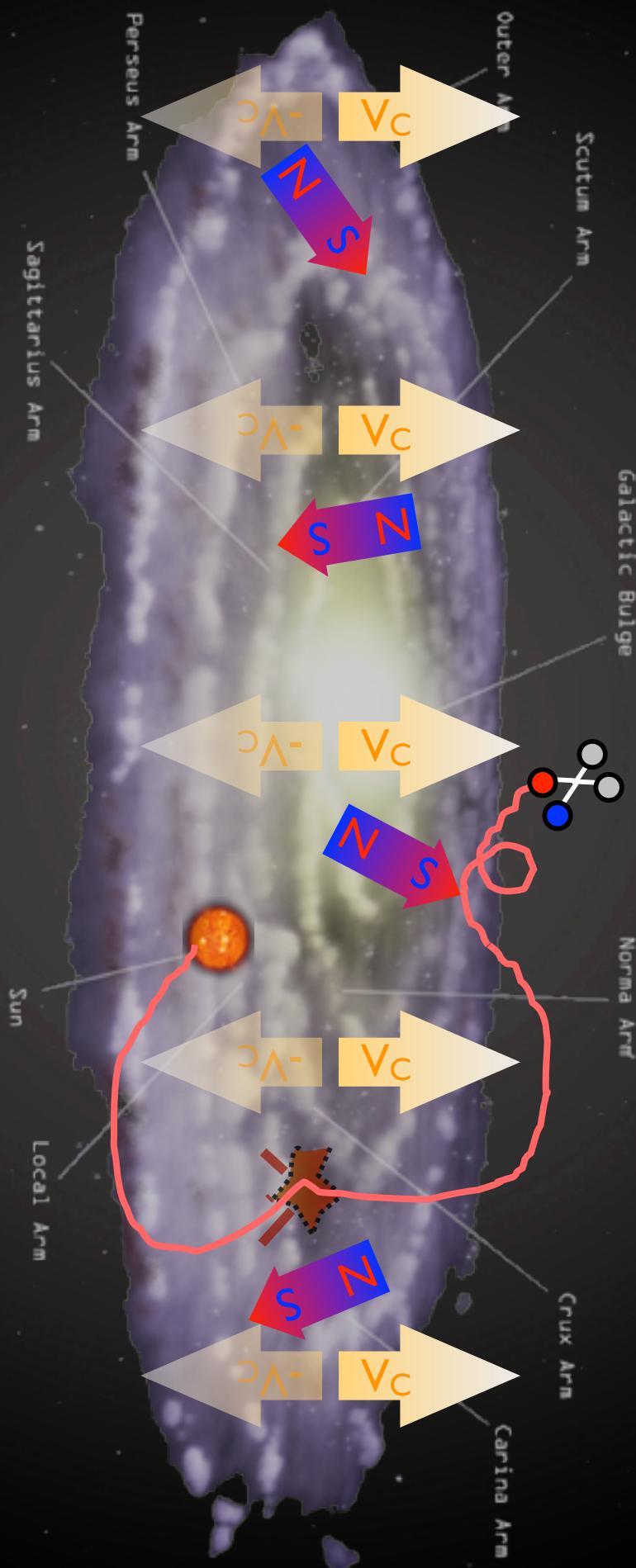
Indirect Detection: Basics

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



Indirect Detection: Basics

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



Indirect Detection: status

Dark Matter! Dark Matter!

Seen a huge excess in positrons

2008



PAMELA

Indirect Detection: status

Dark Matter! Dark Matter!

Seen a huge excess in **positrons**

2008

PAMELA



Mmm, 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**.

FERMI

2009-2013



Indirect Detection: status

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Or maybe yes?...

2009-2013

FERMI



OK, let's go out there
and check.

2013-2014...

AMS-02

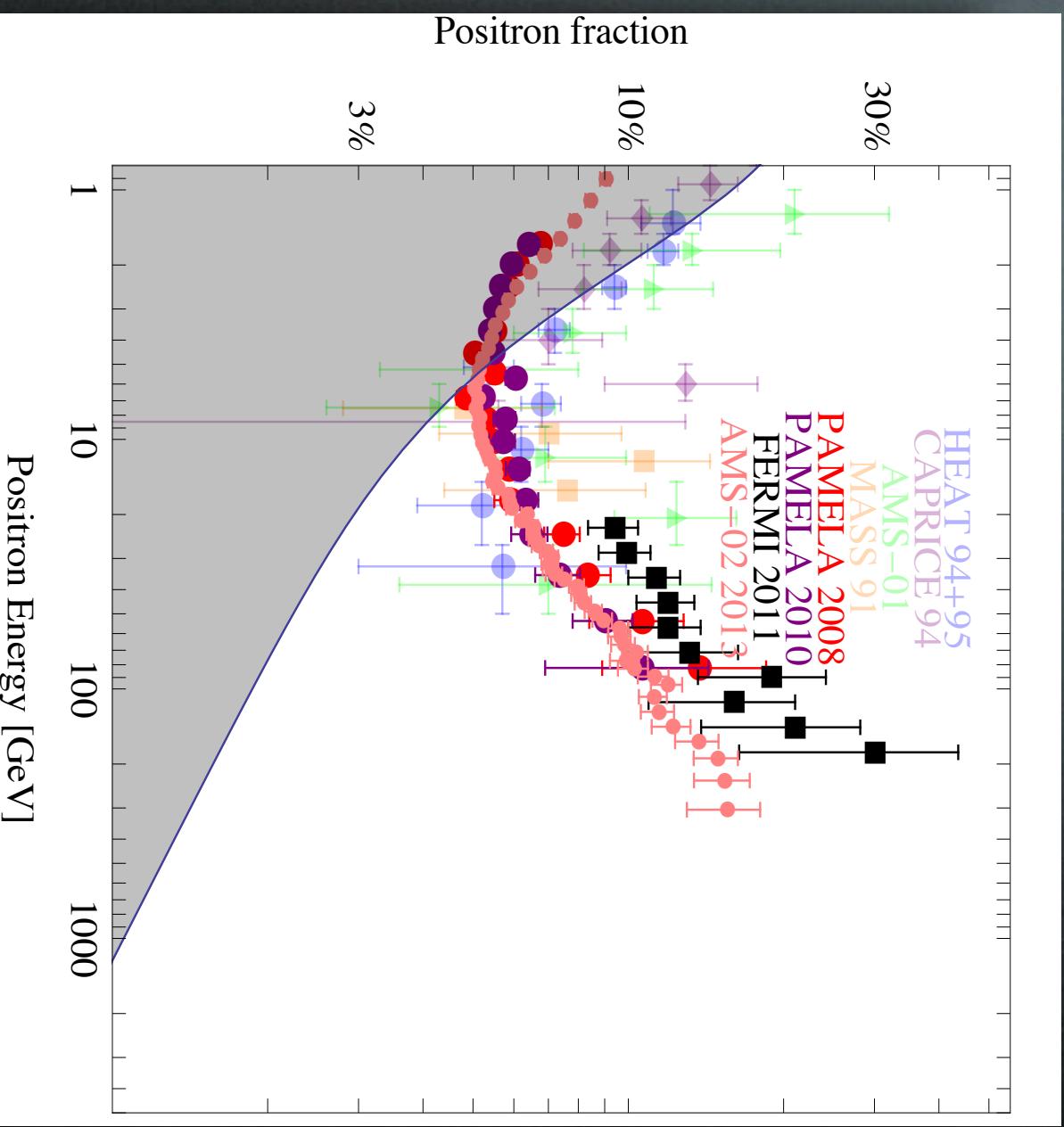


Positrons & Electrons

Positrons from PAMELA and FERMI and AMS-02:

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

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



Adriani et al., Nature 458 (2009) 607; App 34 (2010)¹

Fermi coll., 1109.0521

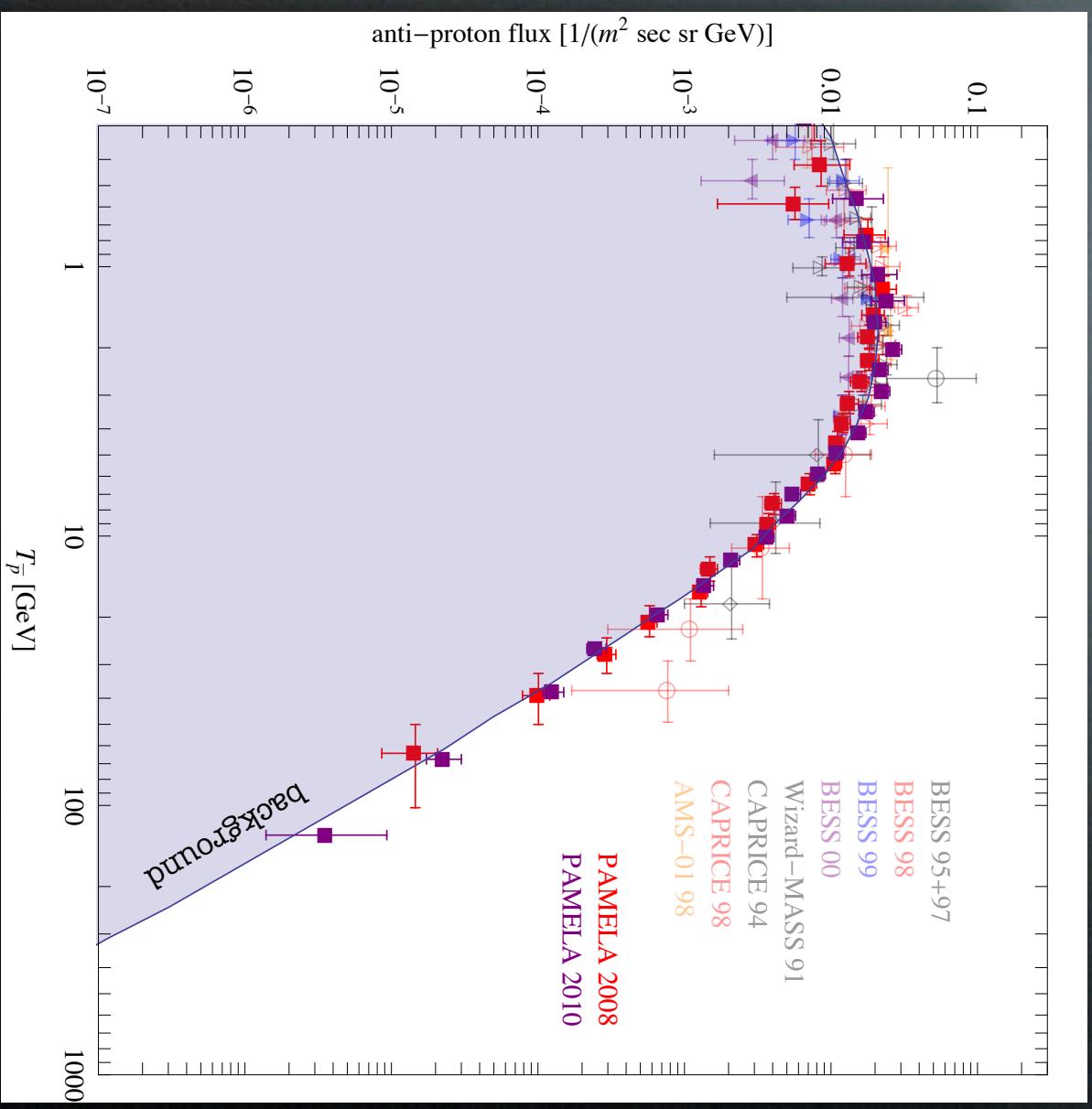
AMS-02 coll., PRL 110, 141102 (2013)

Indirect Detection: hints

Antiprotons from PAMELA:

- consistent with
the background

(about 1000 \bar{p} collected
initially)

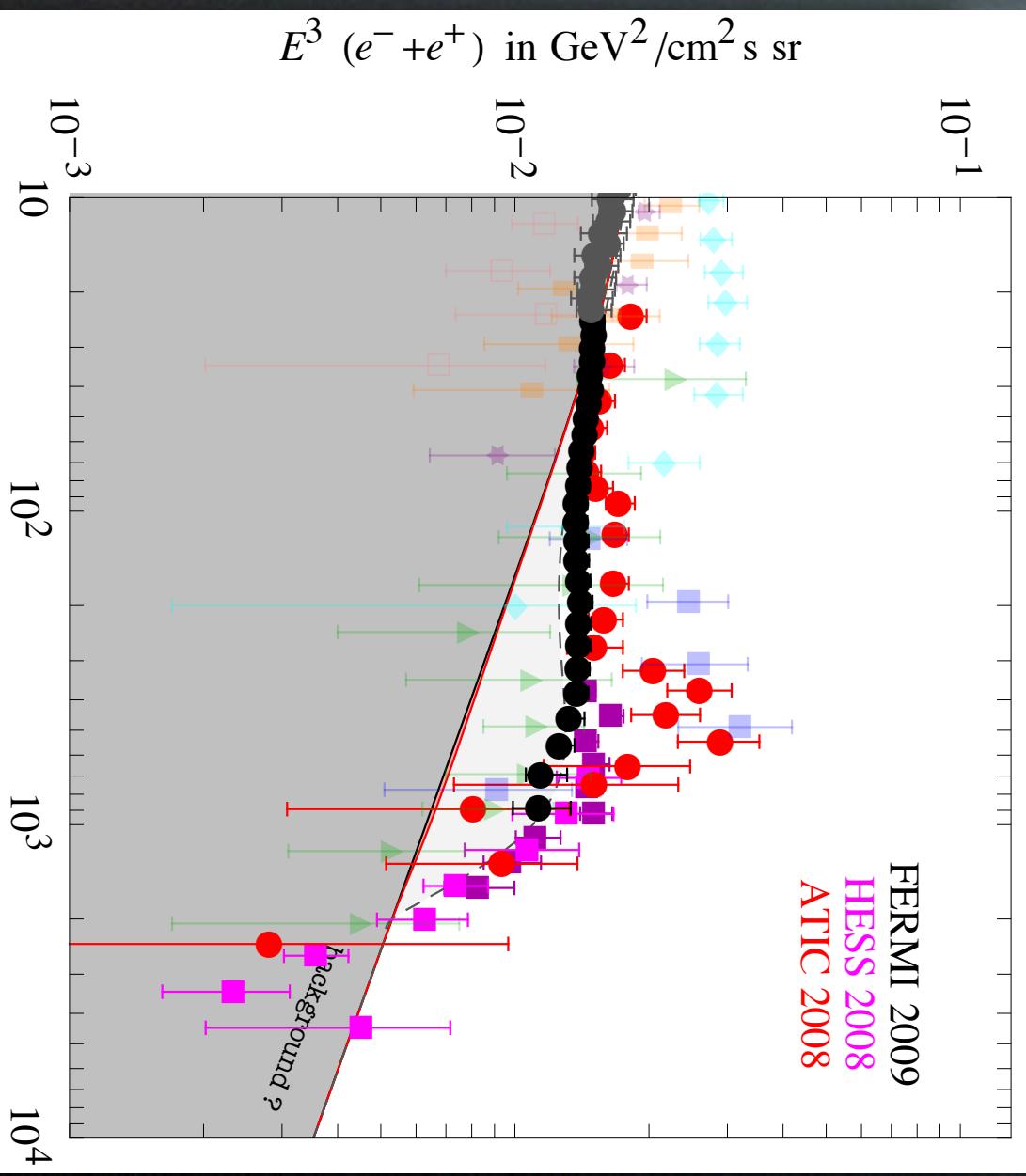


Indirect Detection: hints

Electrons + positrons adding FERMI and HESS:

- no $e^+ + e^-$ excess
- spectrum $\sim E^{-3.04}$

- a (smooth) cutoff?



Indirect Detection: status

Dark Matter! Dark Matter!

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PAMELA



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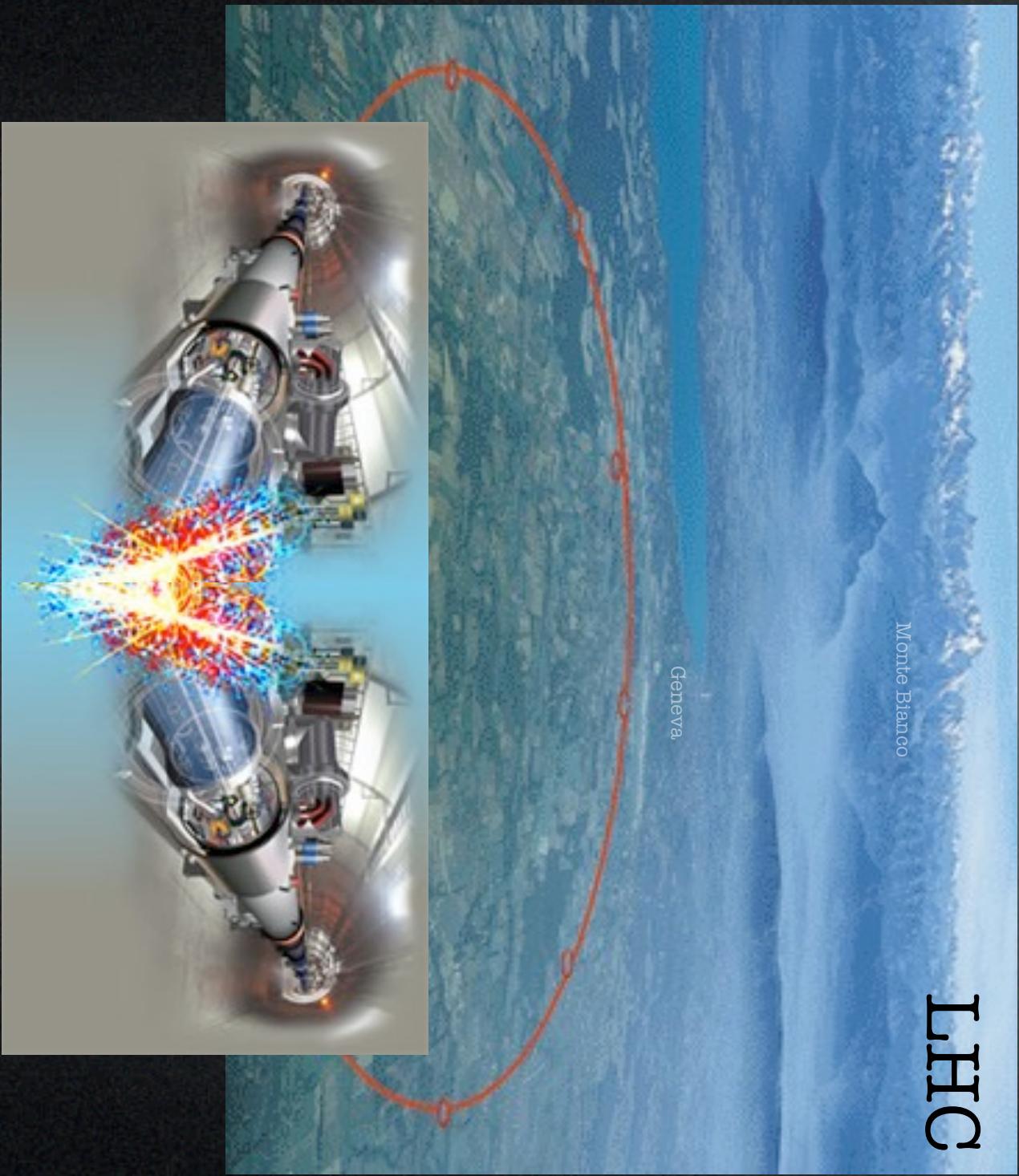


3. Production at colliders

LHC

Monte Bianco

Geneva

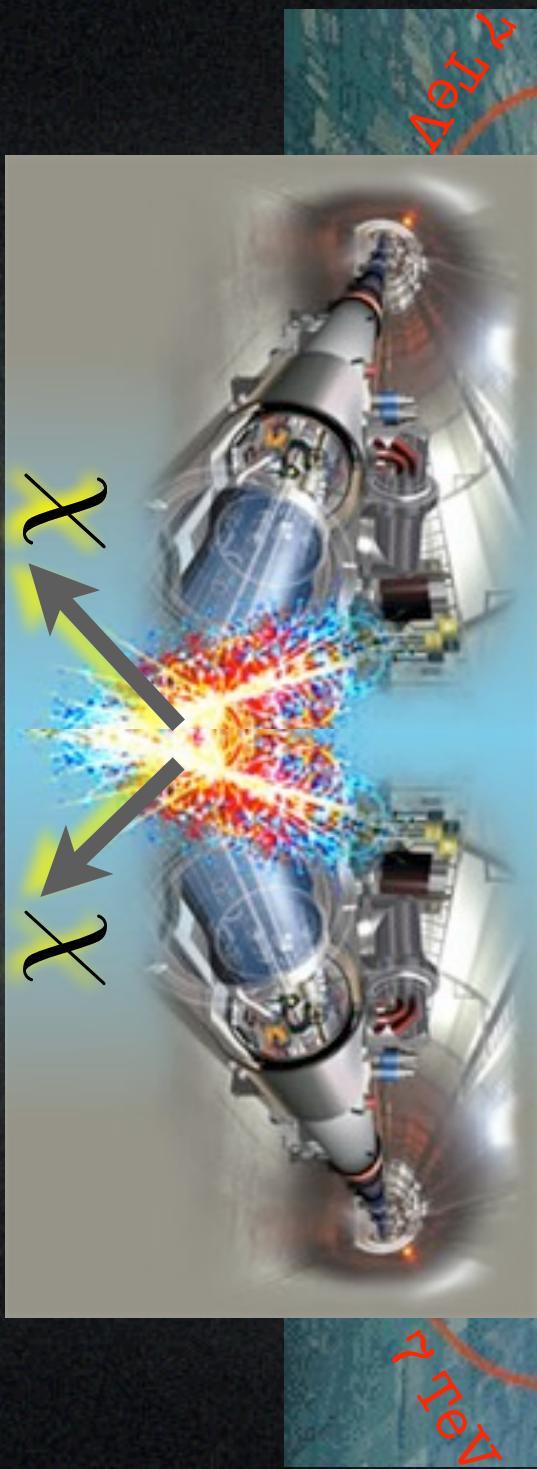
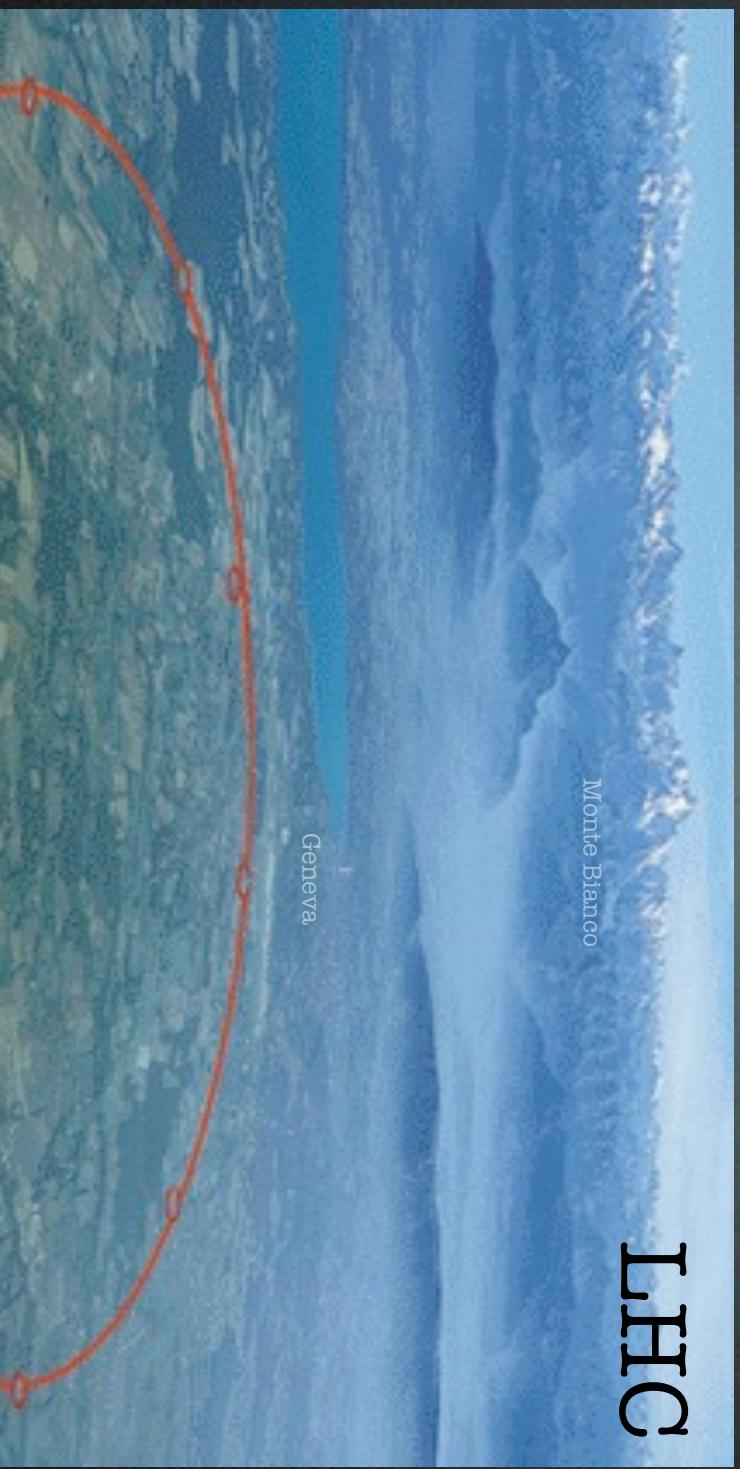


Production at colliders

LHC

Monte Bianco

Geneva

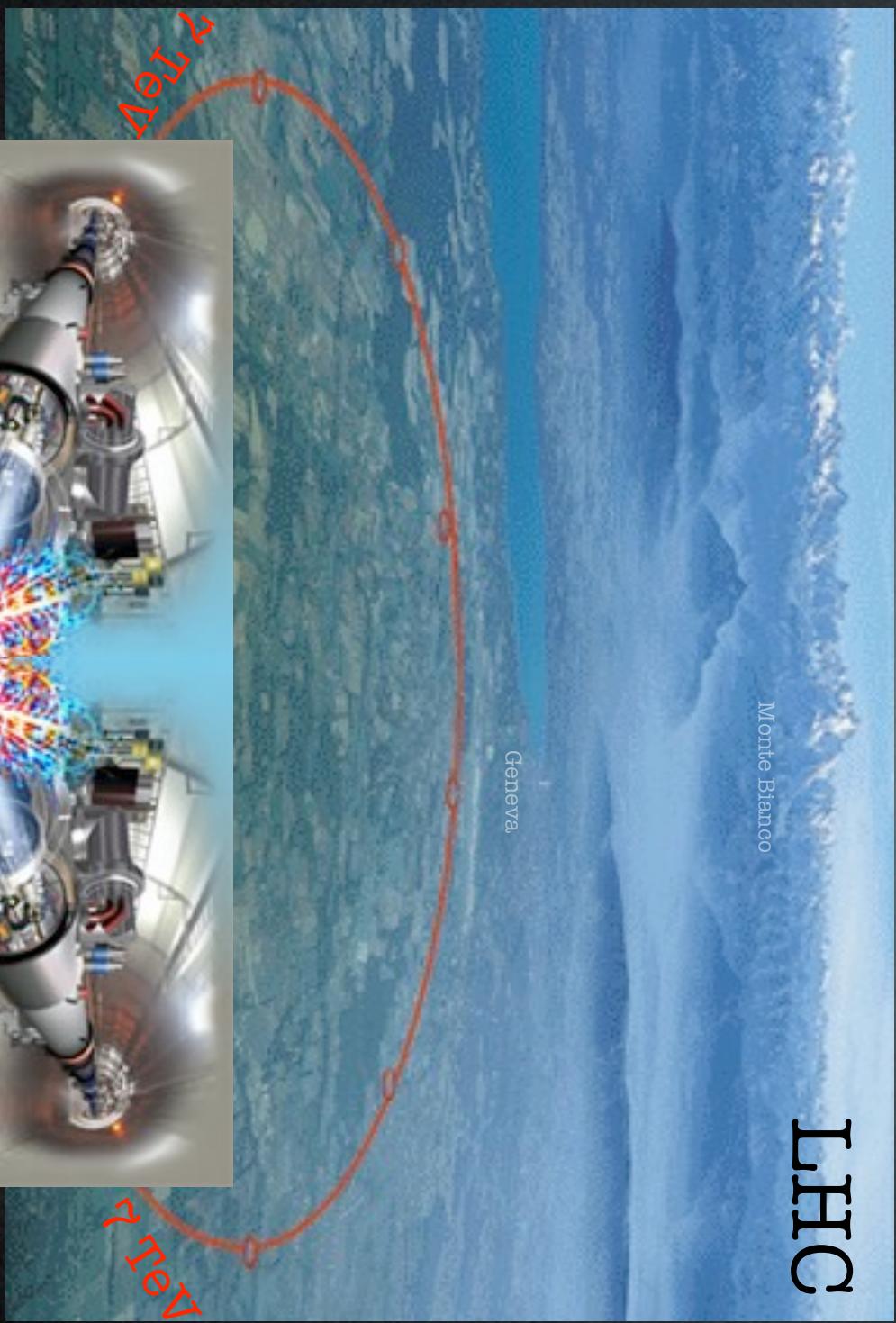


Production at colliders

LHC

Monte Bianco

Geneva

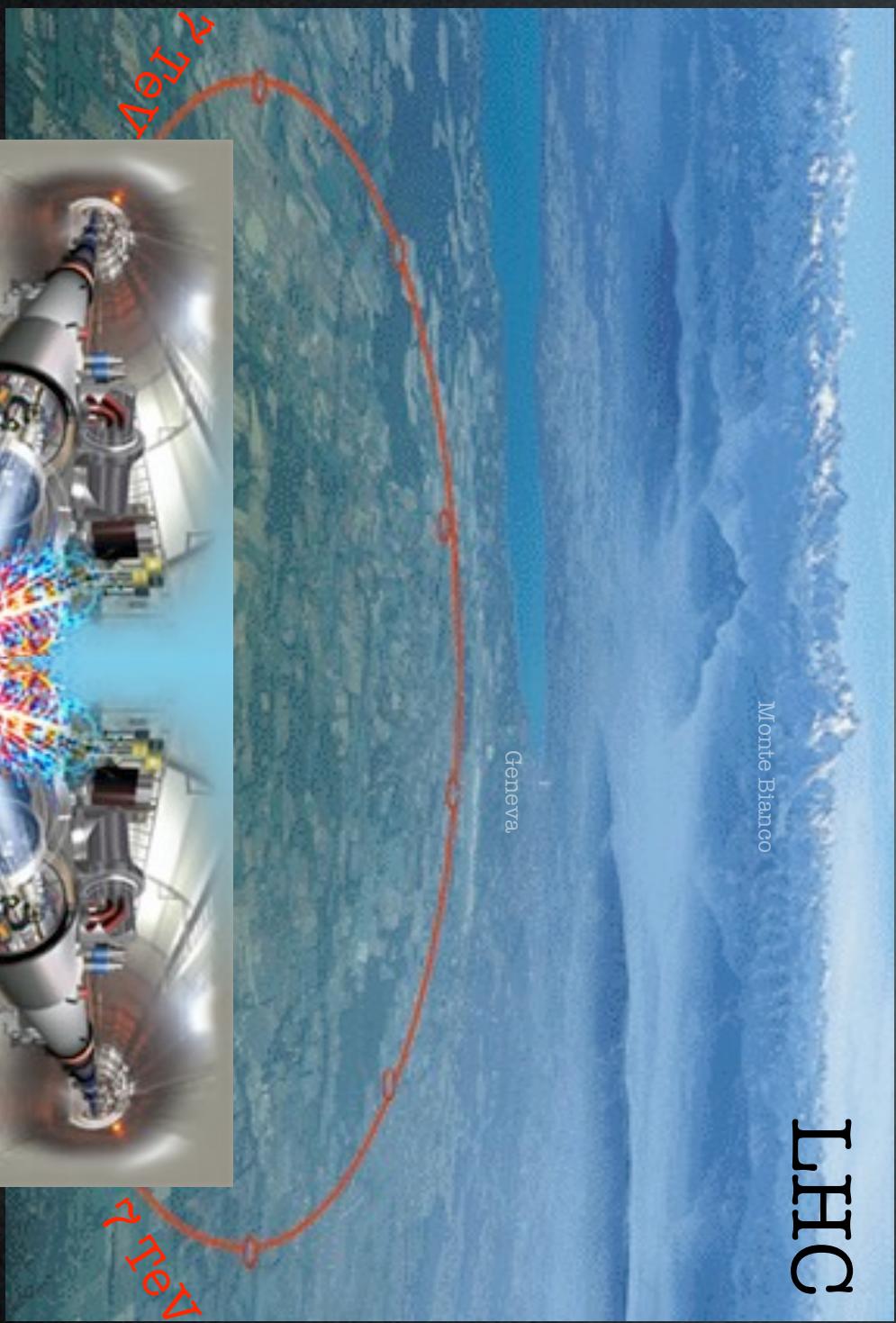


Production at colliders

LHC

Monte Bianco

Geneva



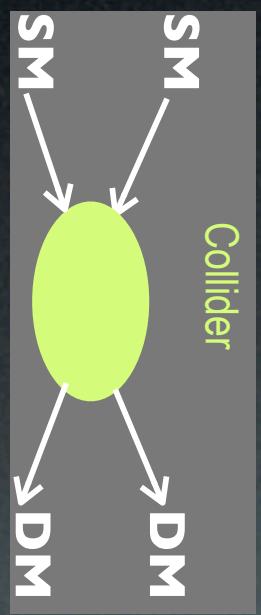
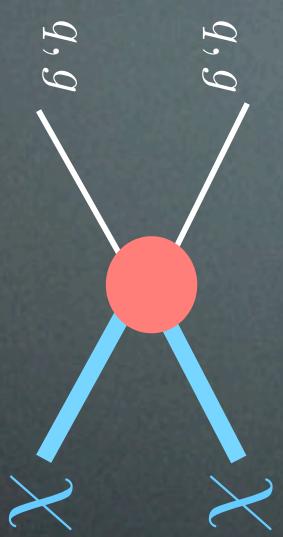
missing
energy

$\chi^0 \rightarrow \chi^+ \chi^-$

missing
energy

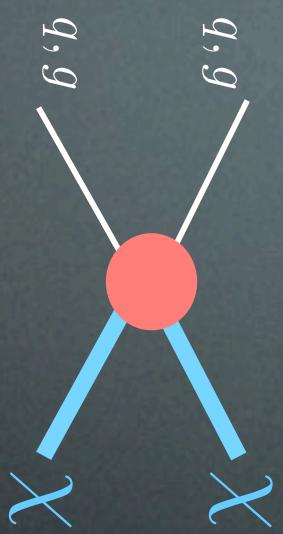
Production at Colliders

At LHC:

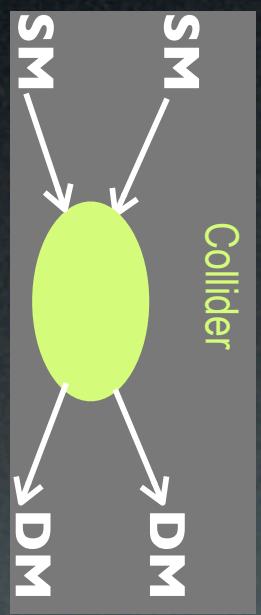


Production at Colliders

At LHC:

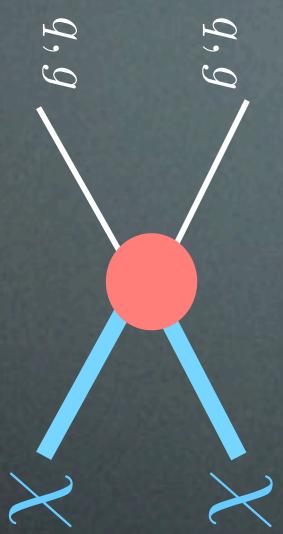


‘Problem’ is: DM flies away

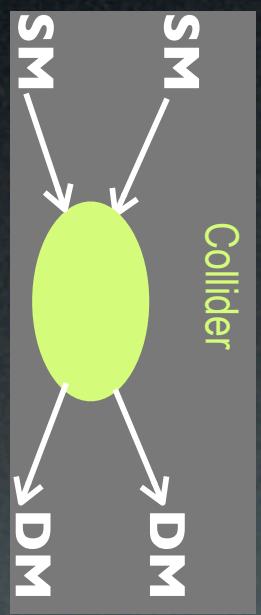


Production at Colliders

At LHC:

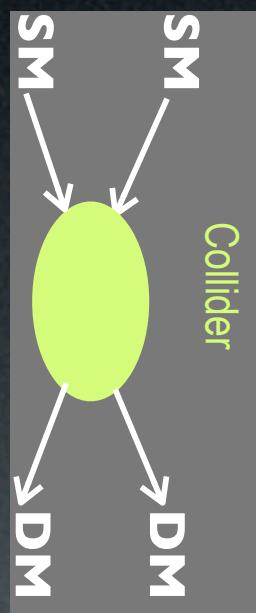
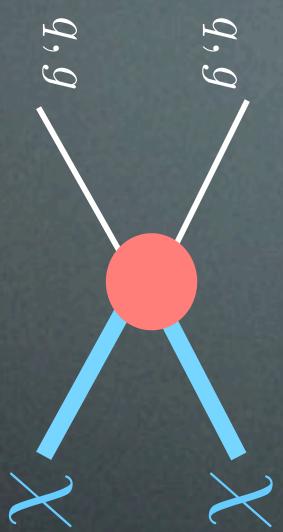


‘Problem’ is: DM flies away
Signature is: missing energy



Production at Colliders

At LHC:

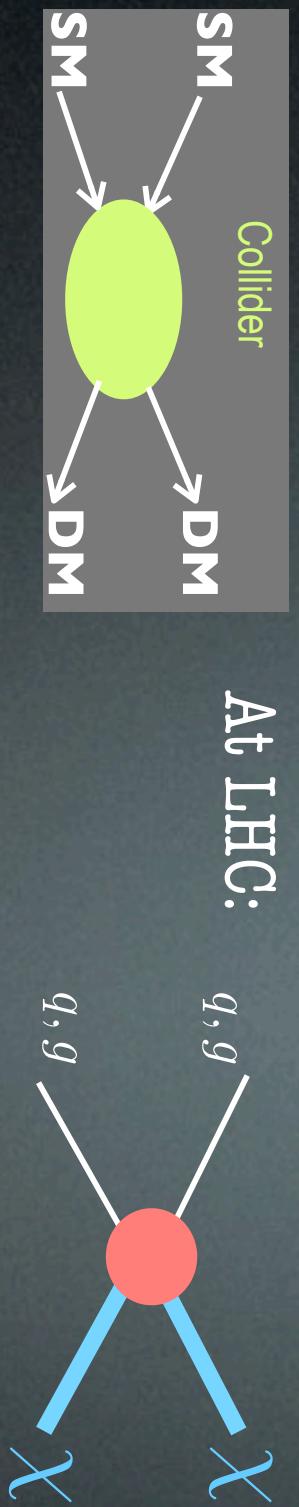


‘Problem’ is: DM flies away

Signature is: missing energy
transverse

Production at Colliders

At LHC:



‘Problem’ is: DM flies away

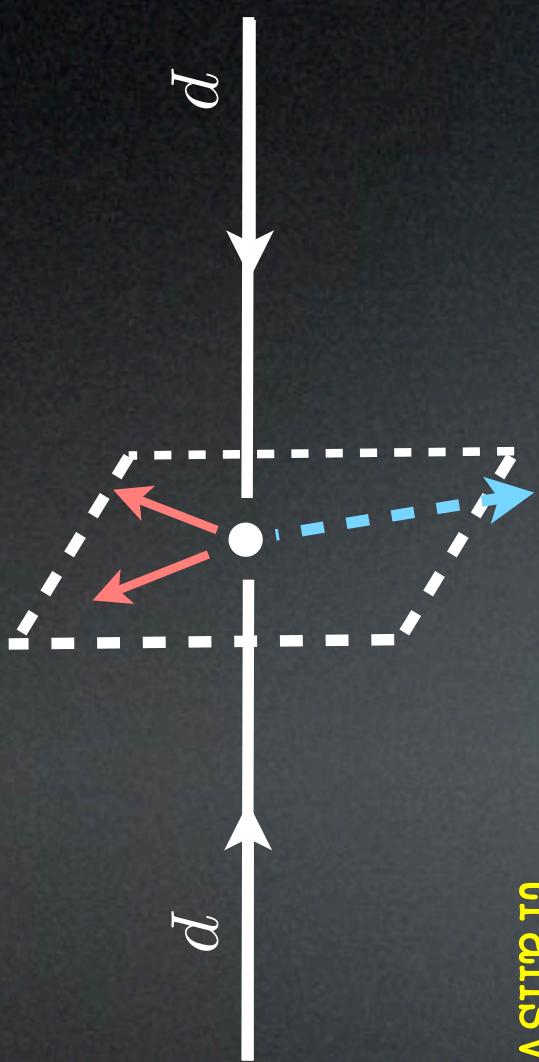
Signature is: missing energy
transverse

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

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

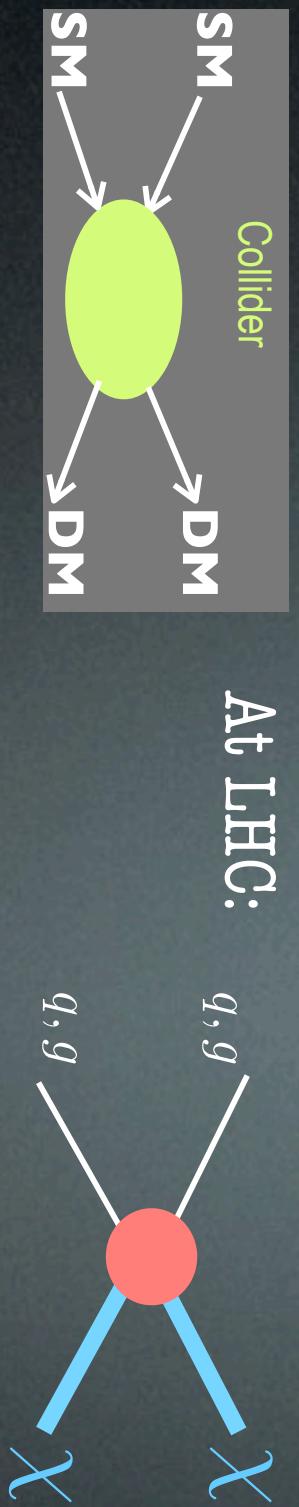
After collision: $\vec{P}_T^{\text{vis}} \stackrel{?}{=} 0$

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?)
- ...

