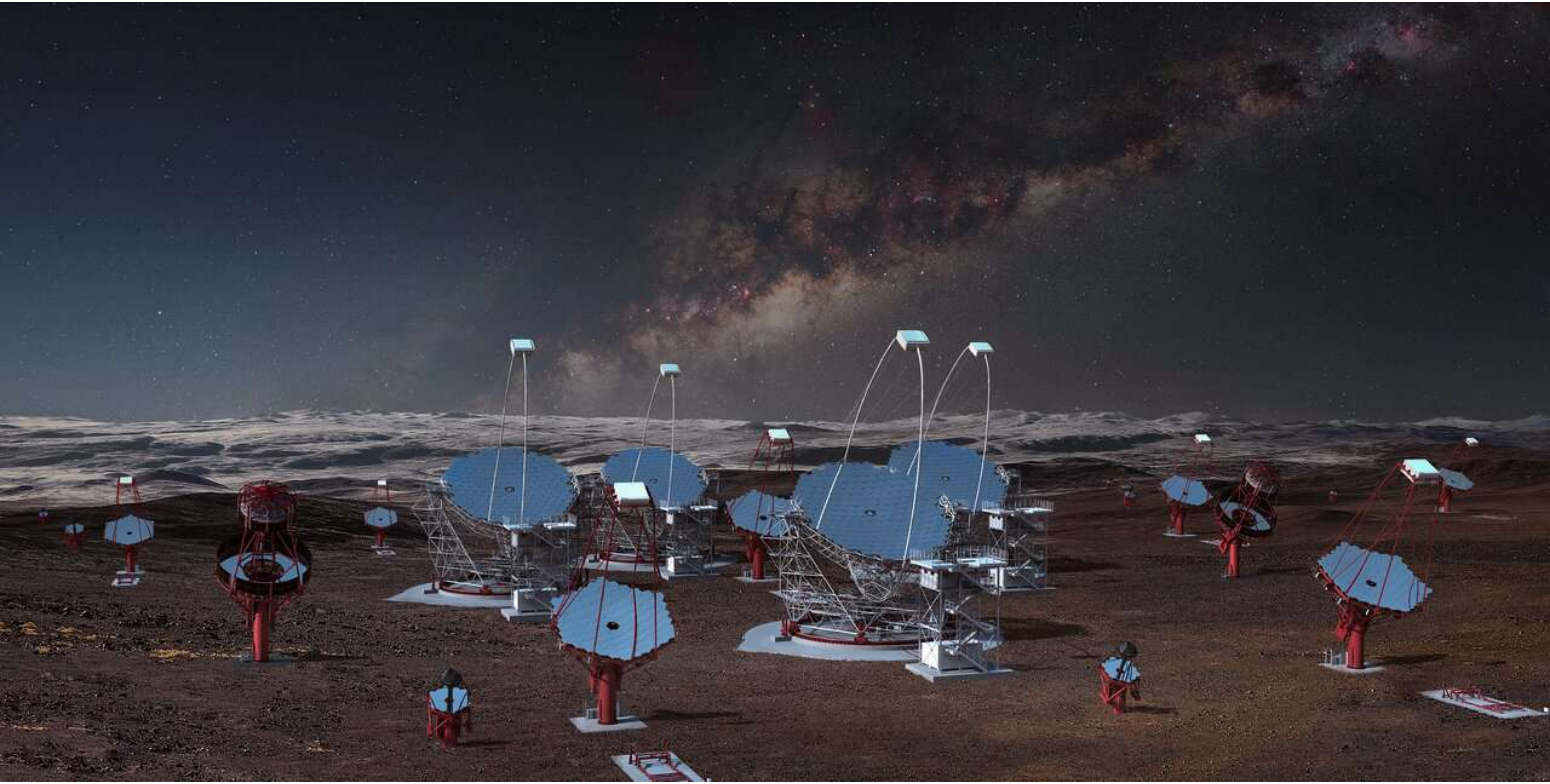


Latin-American School on CTA Science

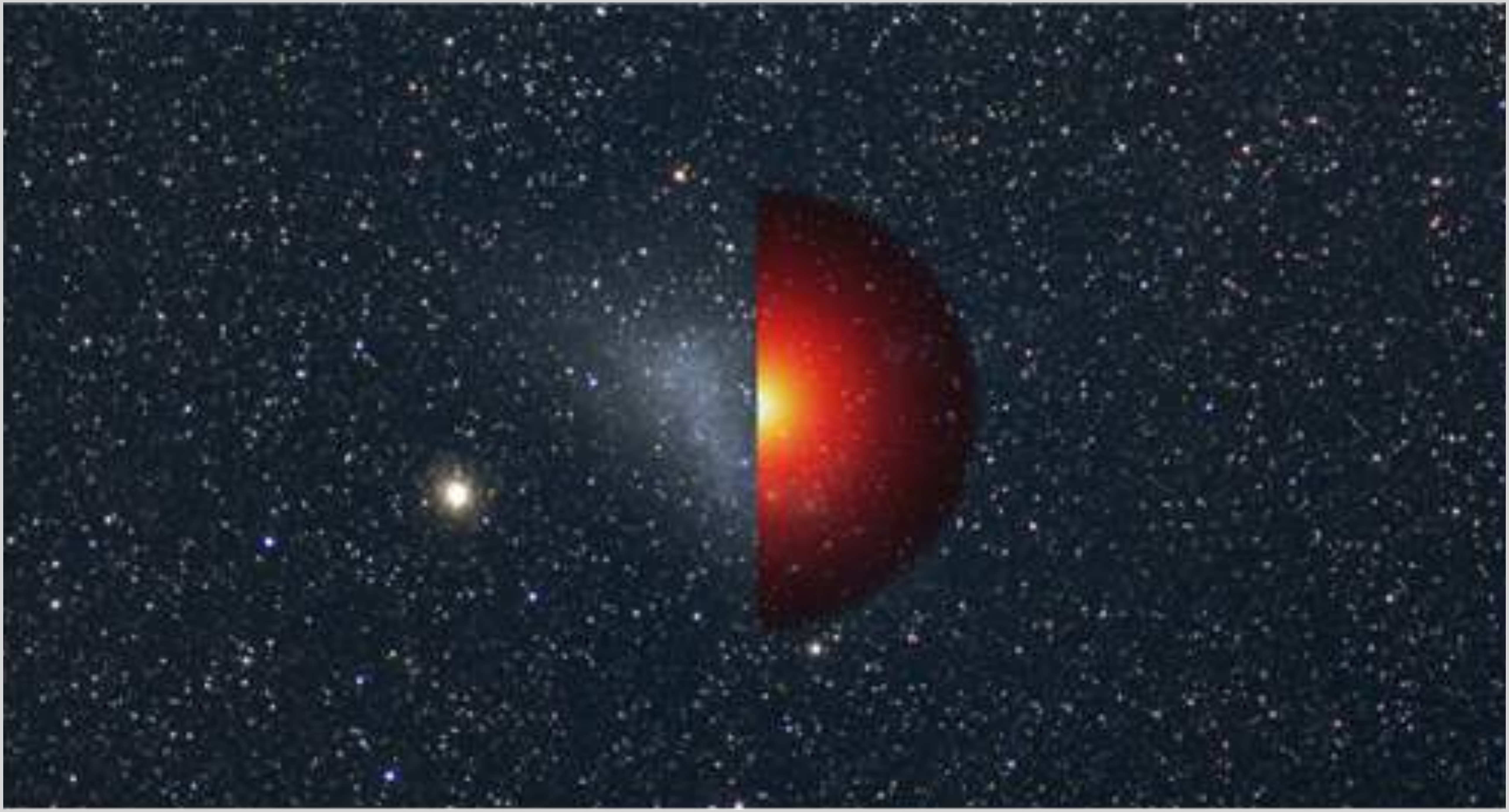
March 27-31, 2023

São Paulo, Brazil

ICTP-SAIFR/IFT-UNESP

FAPESP ICTP unesp IFT - UNESP

Dark matter - candidates and search strategy

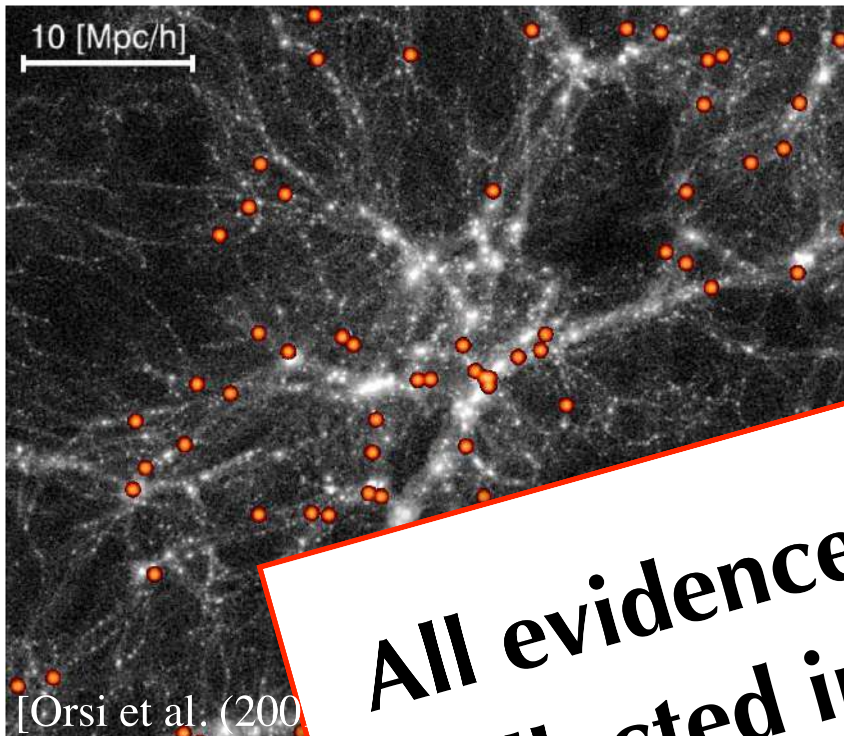


Gabrijela Zaharijas

Centre for Astrophysics and Cosmology, University of Nova Gorica

Dark matter is an essential building block of the Standard Model of Cosmology

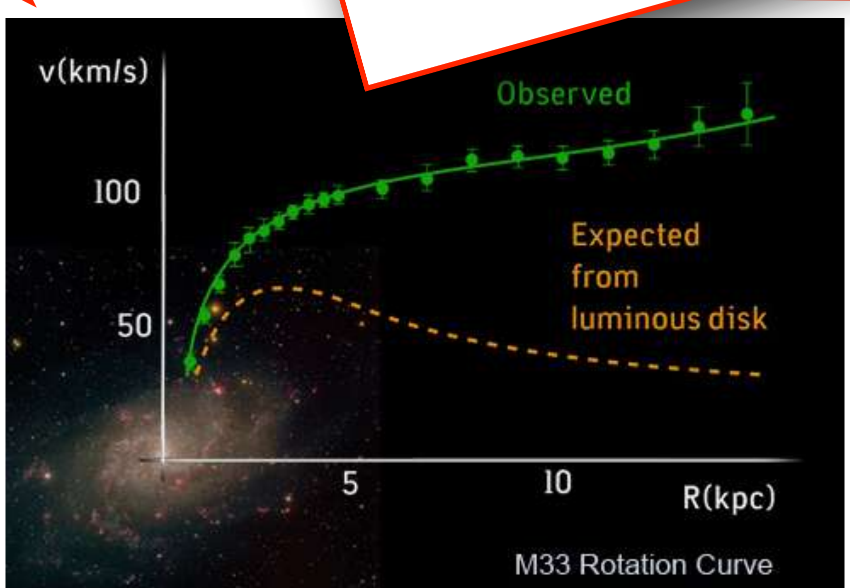
large scale structures — *10s Mpc*



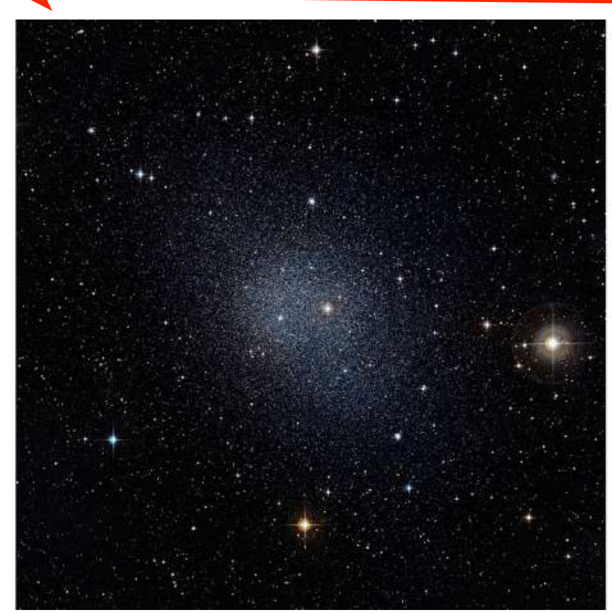
clusters of galaxies — *Mpc*

All evidence so far is gravitational
Collected in astrophysical systems

Milky Wa — *10s kpc*

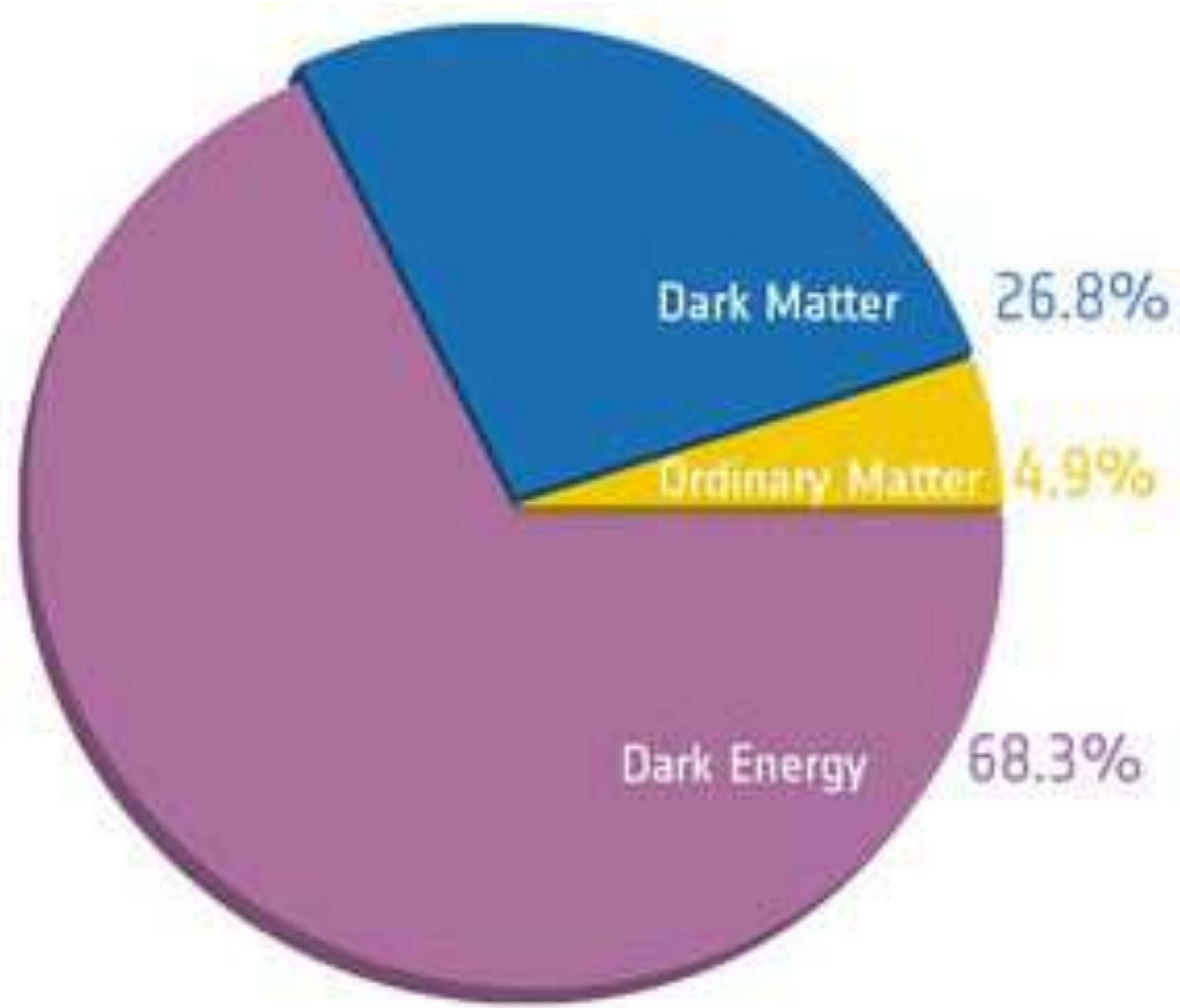


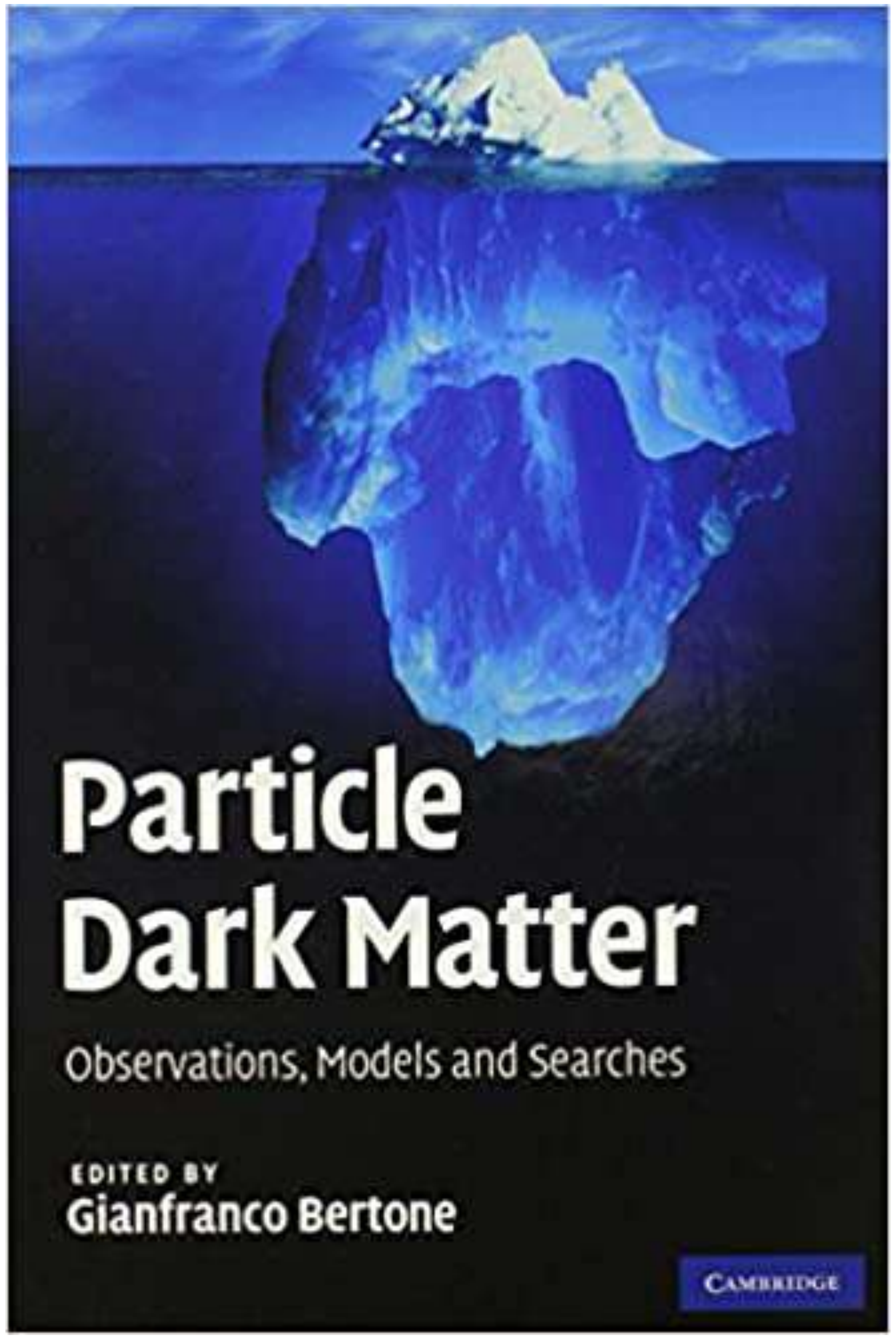
dwarf galaxies — *<~ kpc*



What do we know about DM?

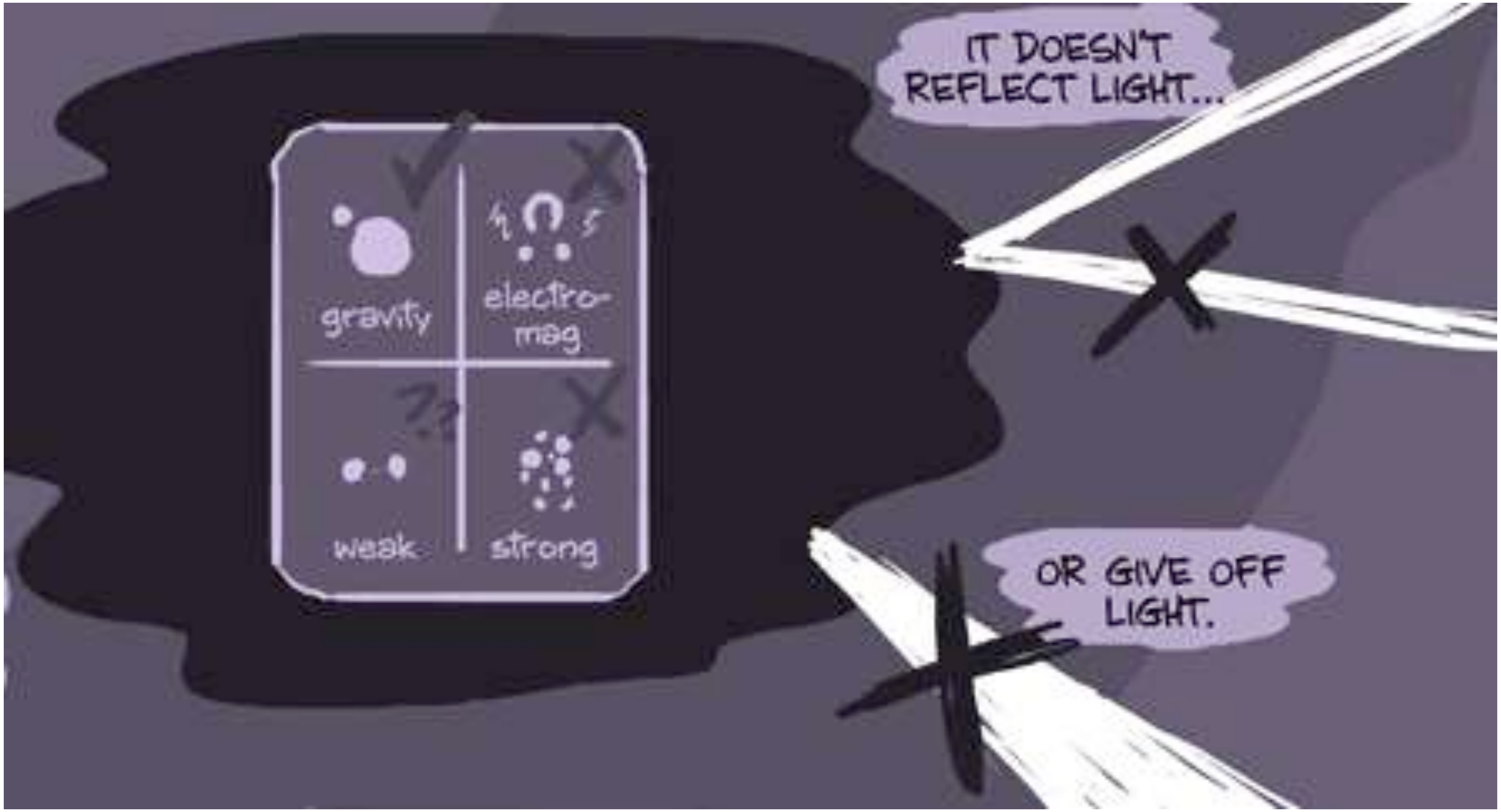
1. stable particle (life time at least age of the Universe)
2. Its amount $\Omega_{CDM} \sim 0.26$ (CMB)





What do we know about DM?

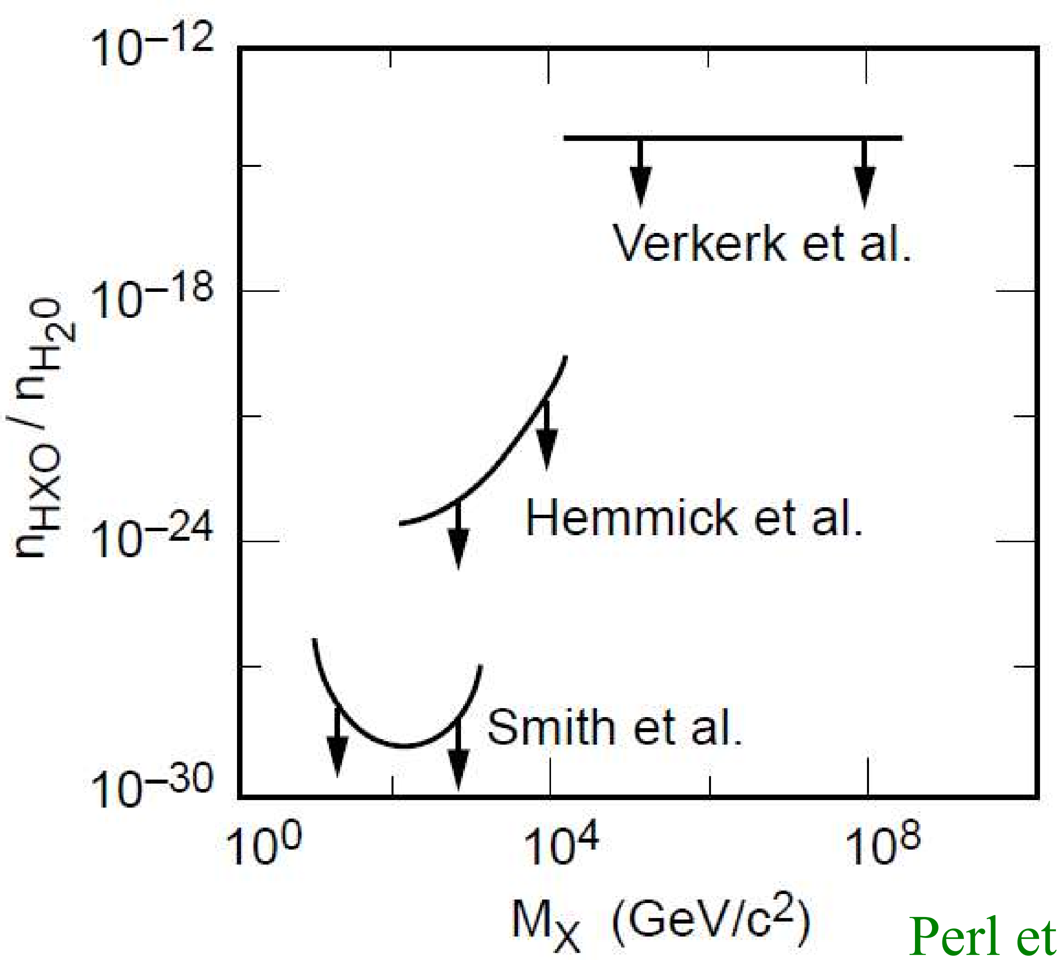
3. electrically neutral: if not, it would interact with photons! (photons couple to charge) DM would not be 'dark' i.e. 'invisible'!

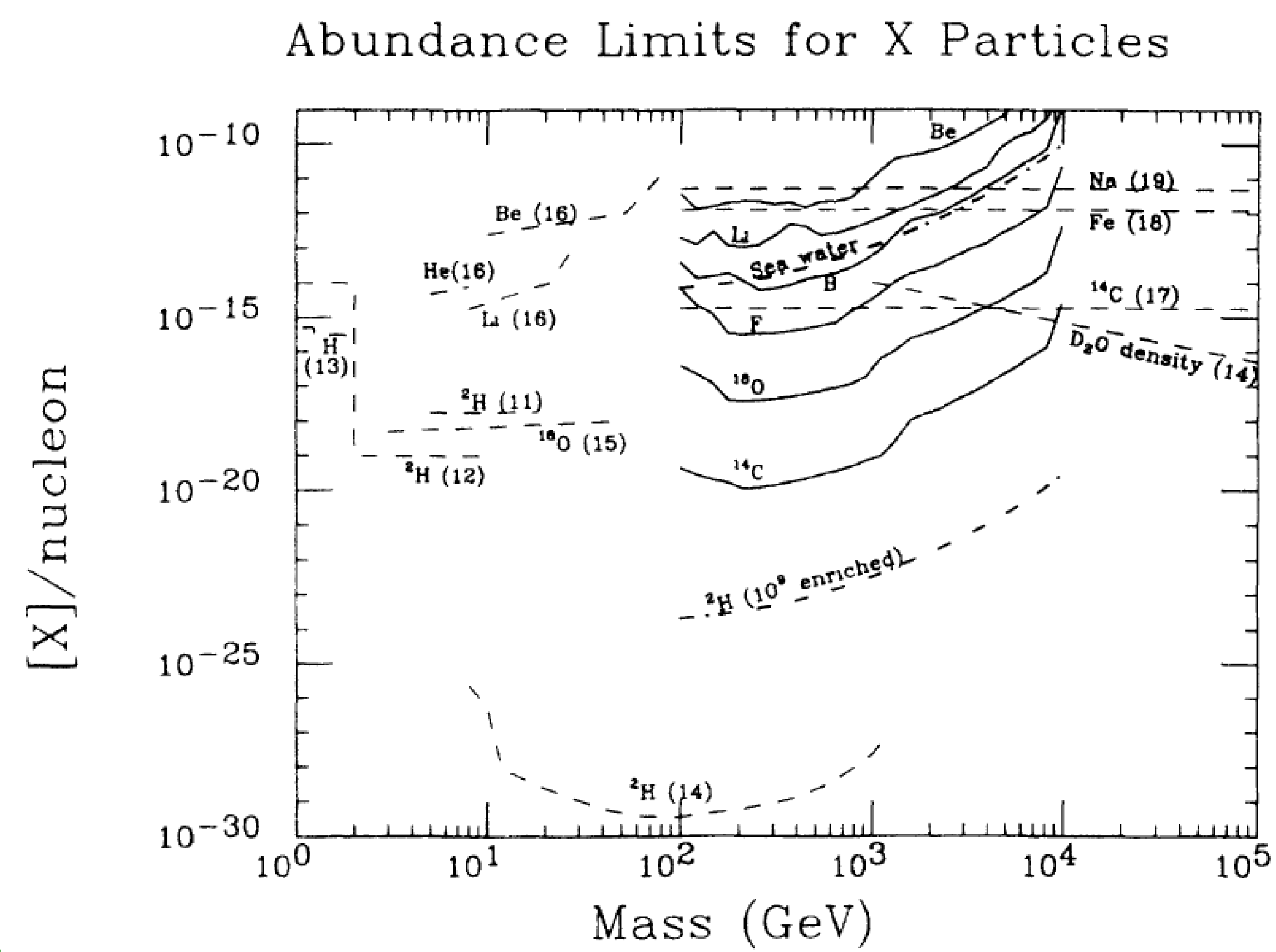


What do we know about DM?

3. electrically neutral:

- it could bind with other charged particles (and form neutral systems), but strong limits on exotic atoms!
- if **X+**, bound states with electron ~**heavy Hydrogen**!
- if **X-** bound to nuclei- **anomalous isotopes**

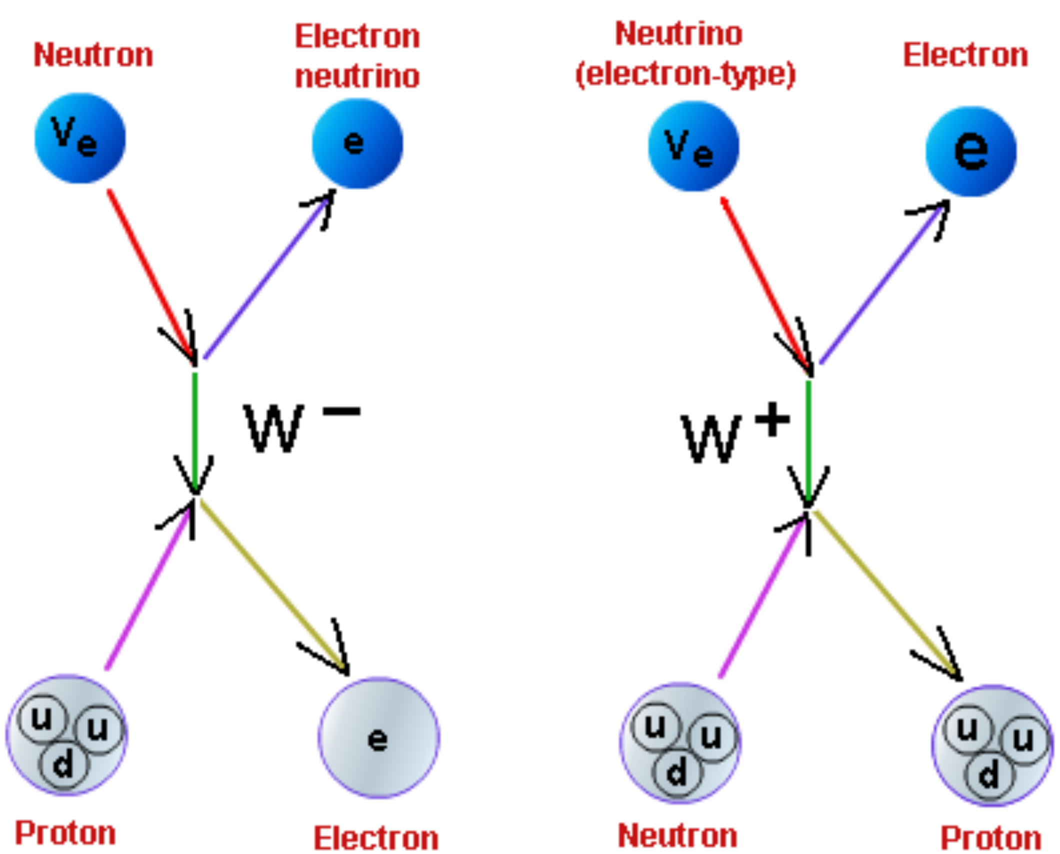


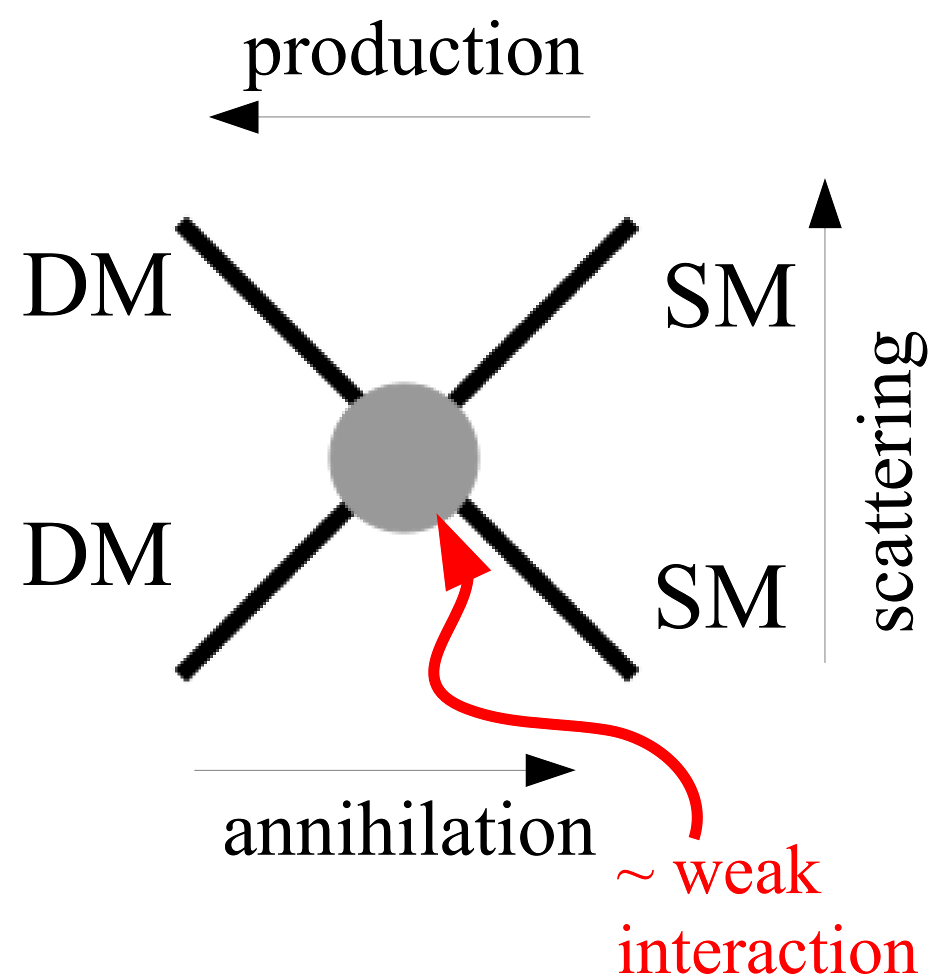


Perl et al.

4. *if* it has non gravitational interactions they must be '**weak**':

- genuine weak interactions, exchange W or Z
- here means generally just un-observably week



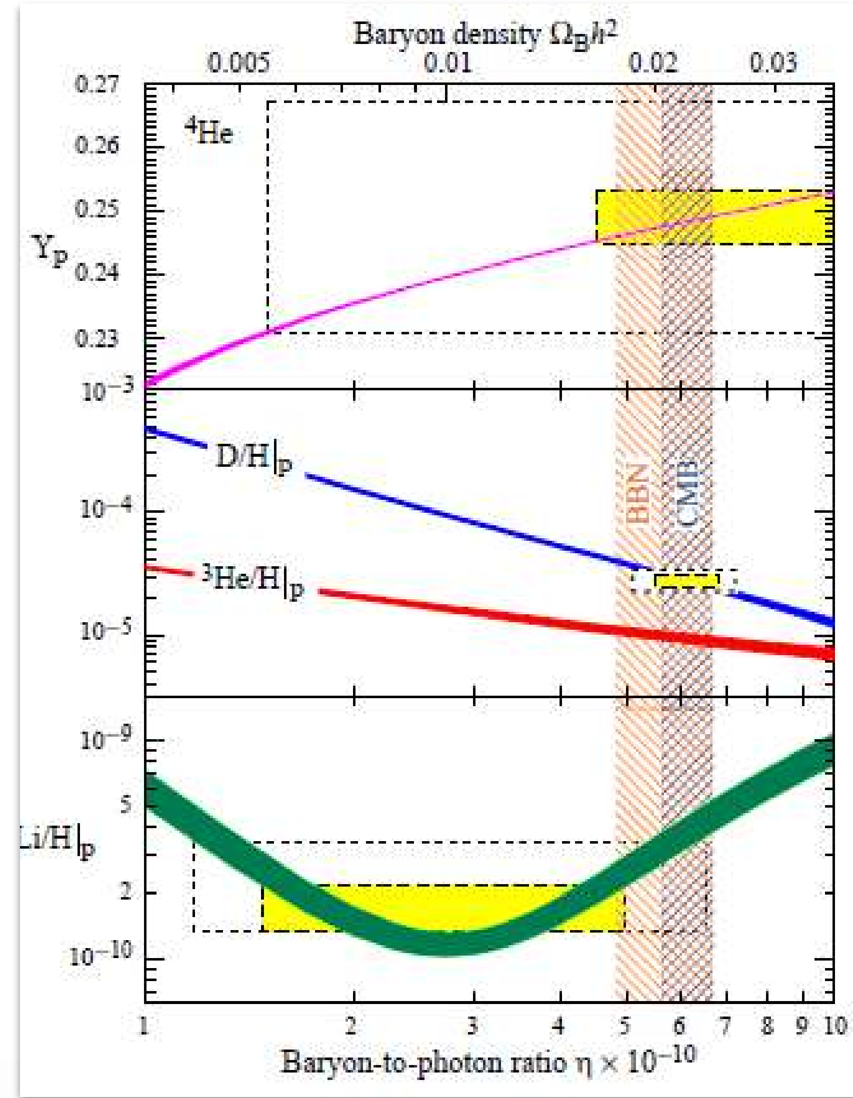


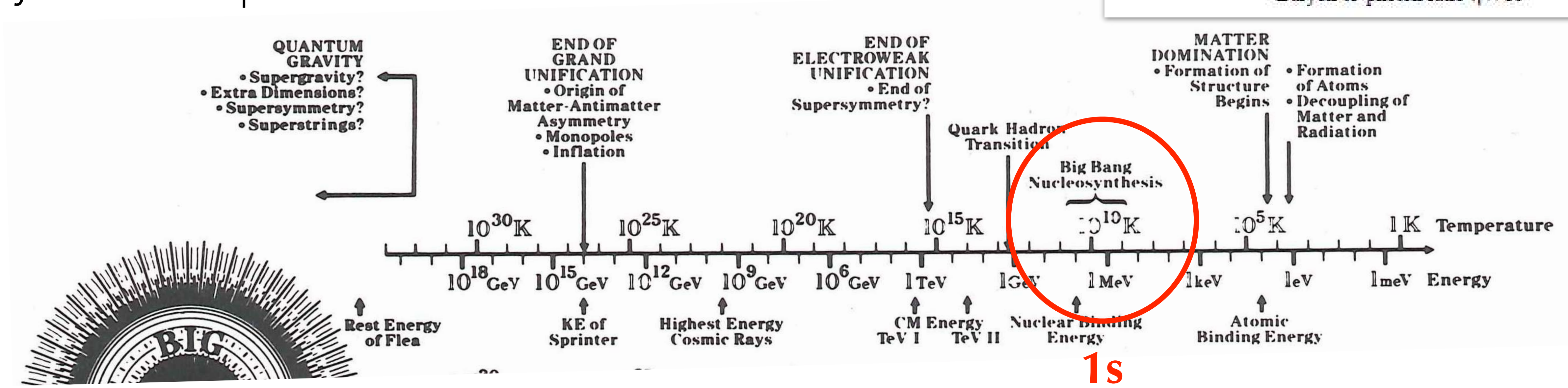
What do we know about DM?

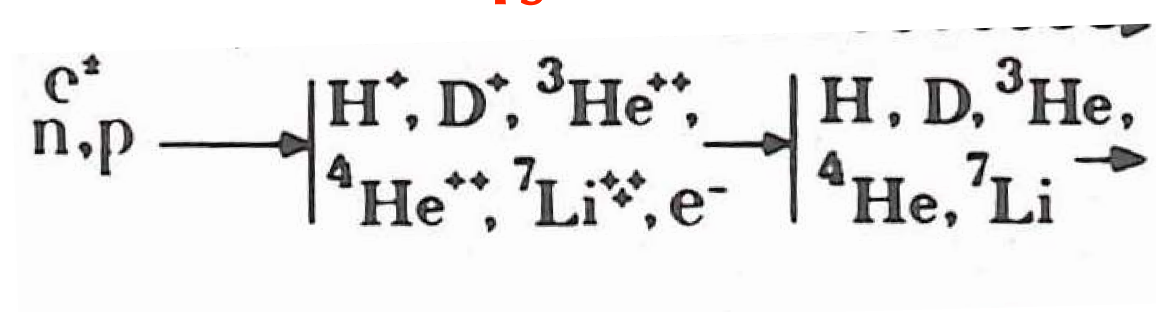
5. 'non-baryonic': does not form atoms and does not dissipate energy like baryons - strong limits from Big Beng Nucleosynthesis (BBN).

From what we know about nuclear physics we can very well predict the sequence of events in which proton, neutron and electrons bound to form H^+, D^+, He^{++}, Li^{+++} (**Thermal decoupling of sorts!**)

DM did not participate in this process! i.e. DM cannot be baryonic, otherwise the abundances of elements measured today would be quite different than what calculated!



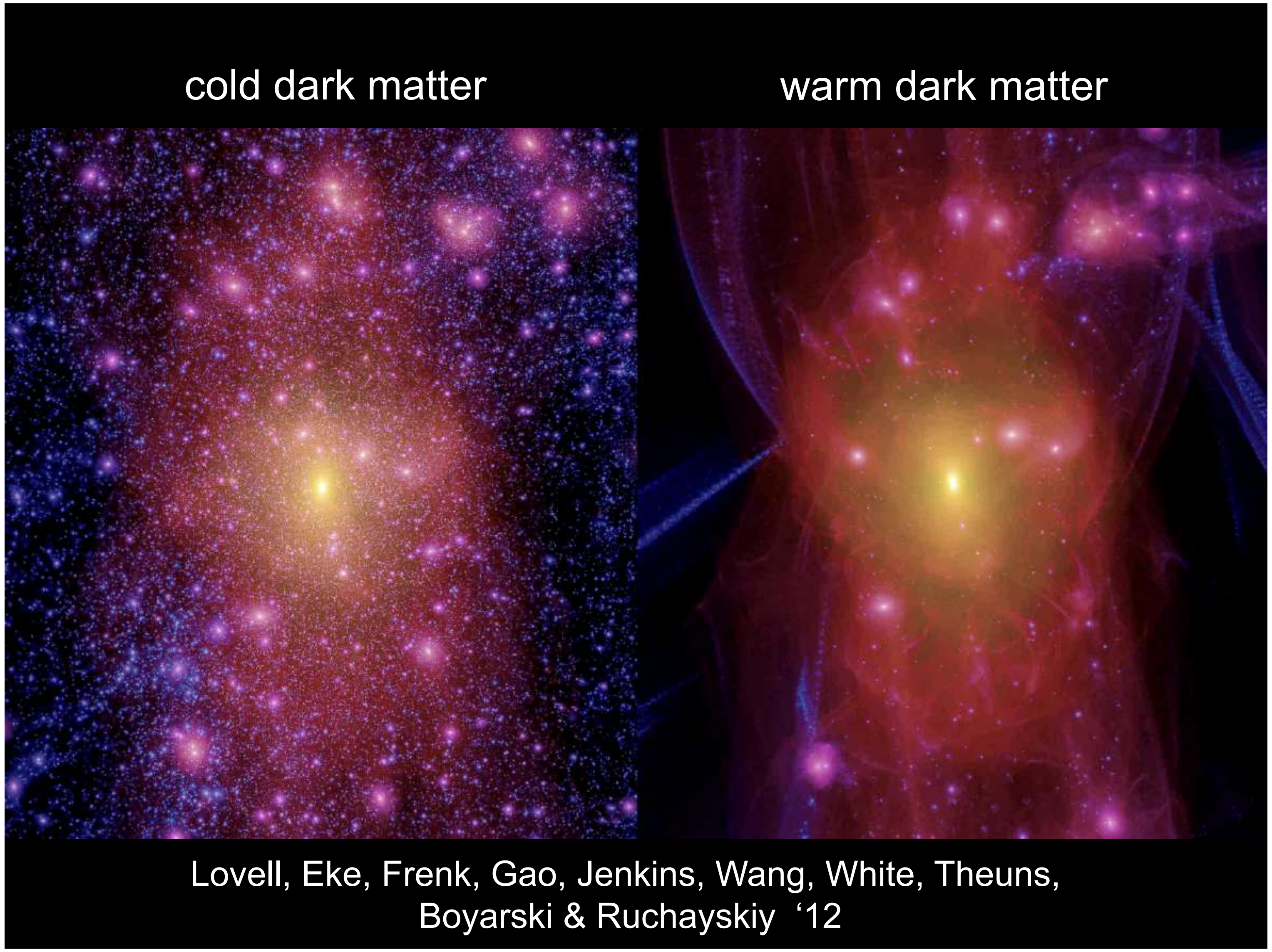


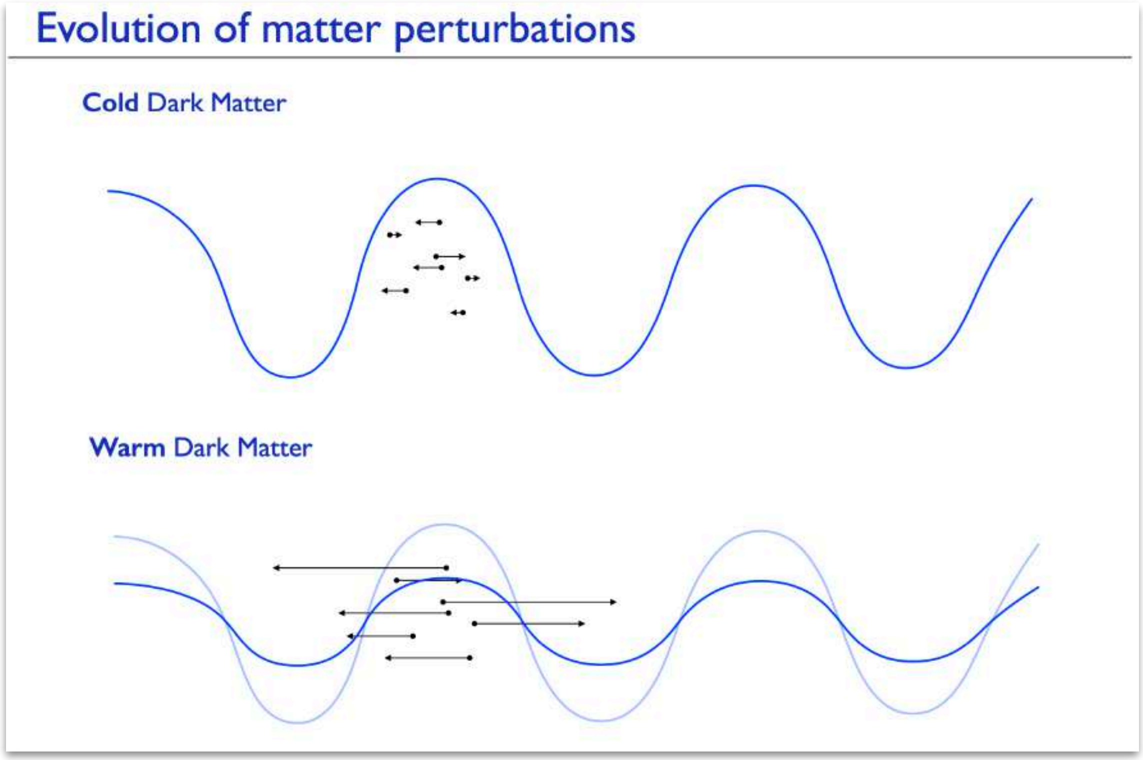


What do we know about DM?

6. it was slow (non relativistic) at the time of formation of first structures (*if in thermal equilibrium*)

N-body simulations find that if DM would be lighter than **keV** small structures would have been erased!

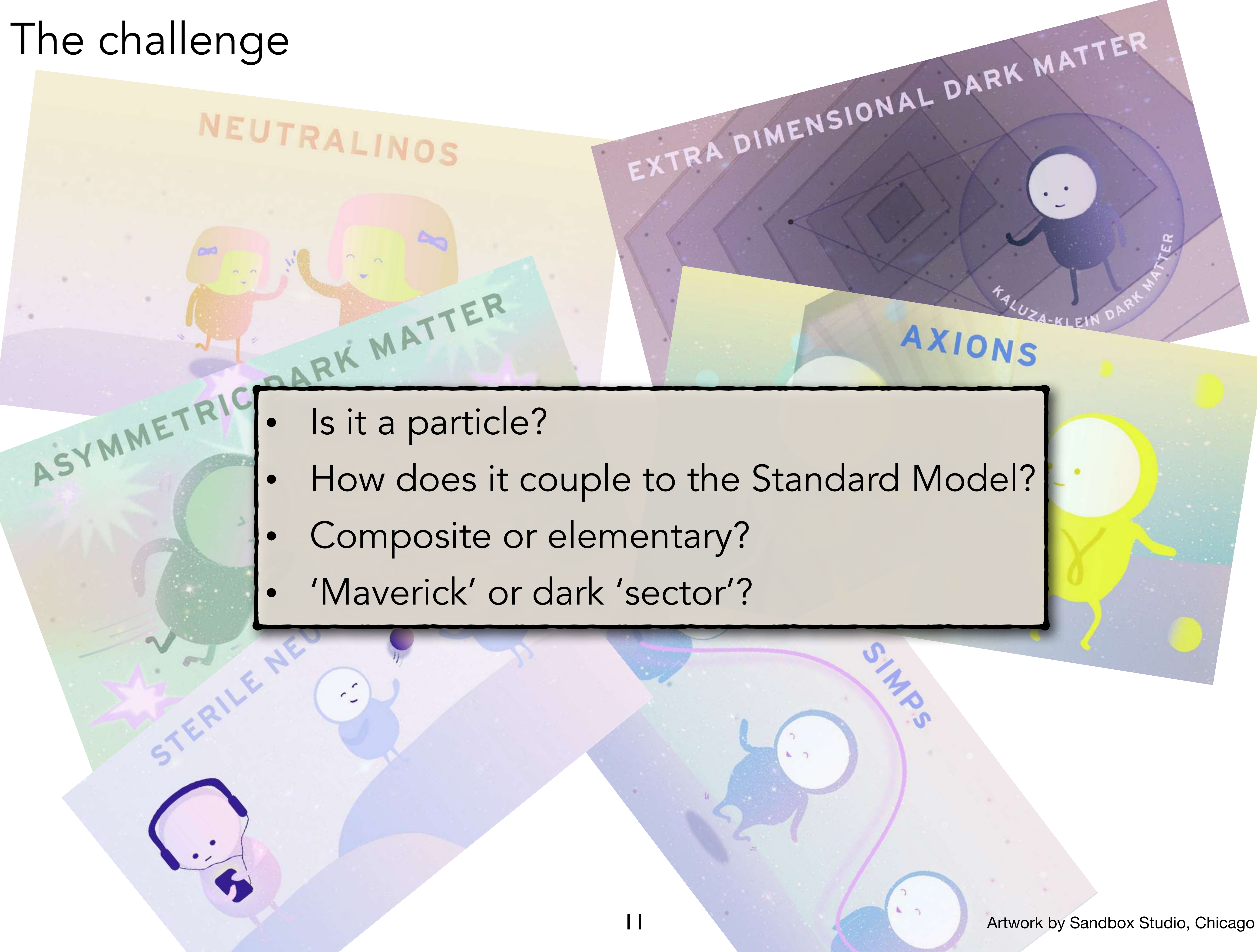




DM check list:

- ☑ stable
- ☑ $\Omega_{CDM} \sim 0.26$
- ☑ electrically neutral
- ☑ ‘weakly’ interacting
- ☑ does not affect BBN
- ☑ non-relativistic at structure formation

The challenge



- Is it a particle?
- How does it couple to the Standard Model?
- Composite or elementary?
- ‘Maverick’ or dark ‘sector’?

Artwork by Sandbox Studio, Chicago

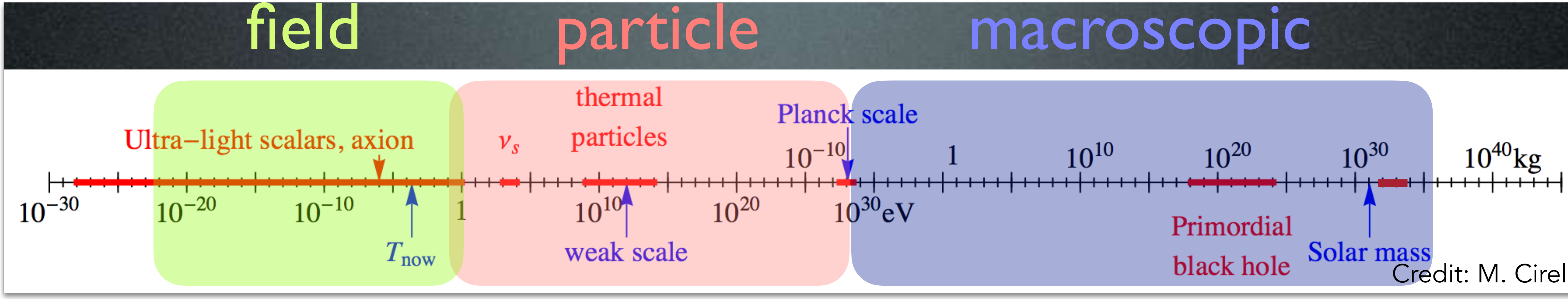
Outline

1. Pre history *a detour*
2. (gravitational) evidence for dark matter
3. DM candidates
4. Experiments
5. Signal & Targets
6. The gamma-ray sky (astro 'backgrounds')
7. Data Analysis strategy
8. Examples of search in particular targets (WIMPs)
   - Galactic center
   - dSphs
   - Galaxy clusters

Today

On Wed

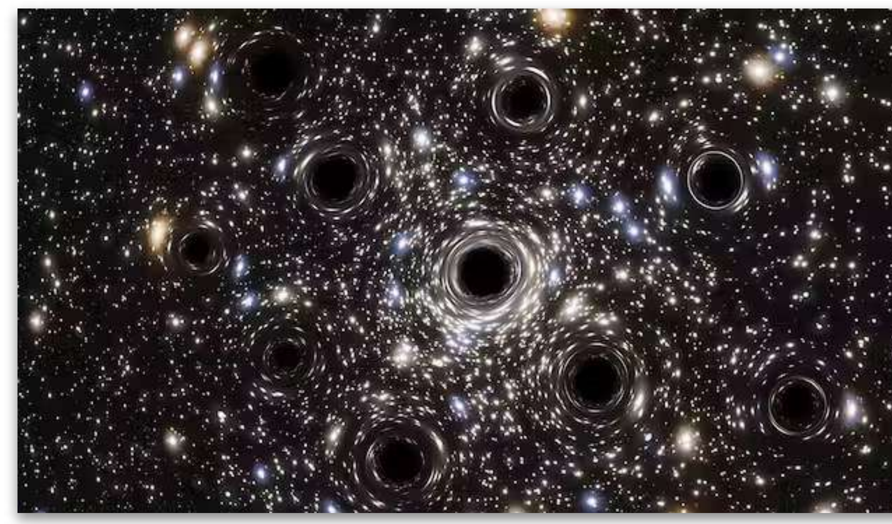
Models



Credit: M. Cirelli

deBroglie
wavelnegth
~cosmological
scales

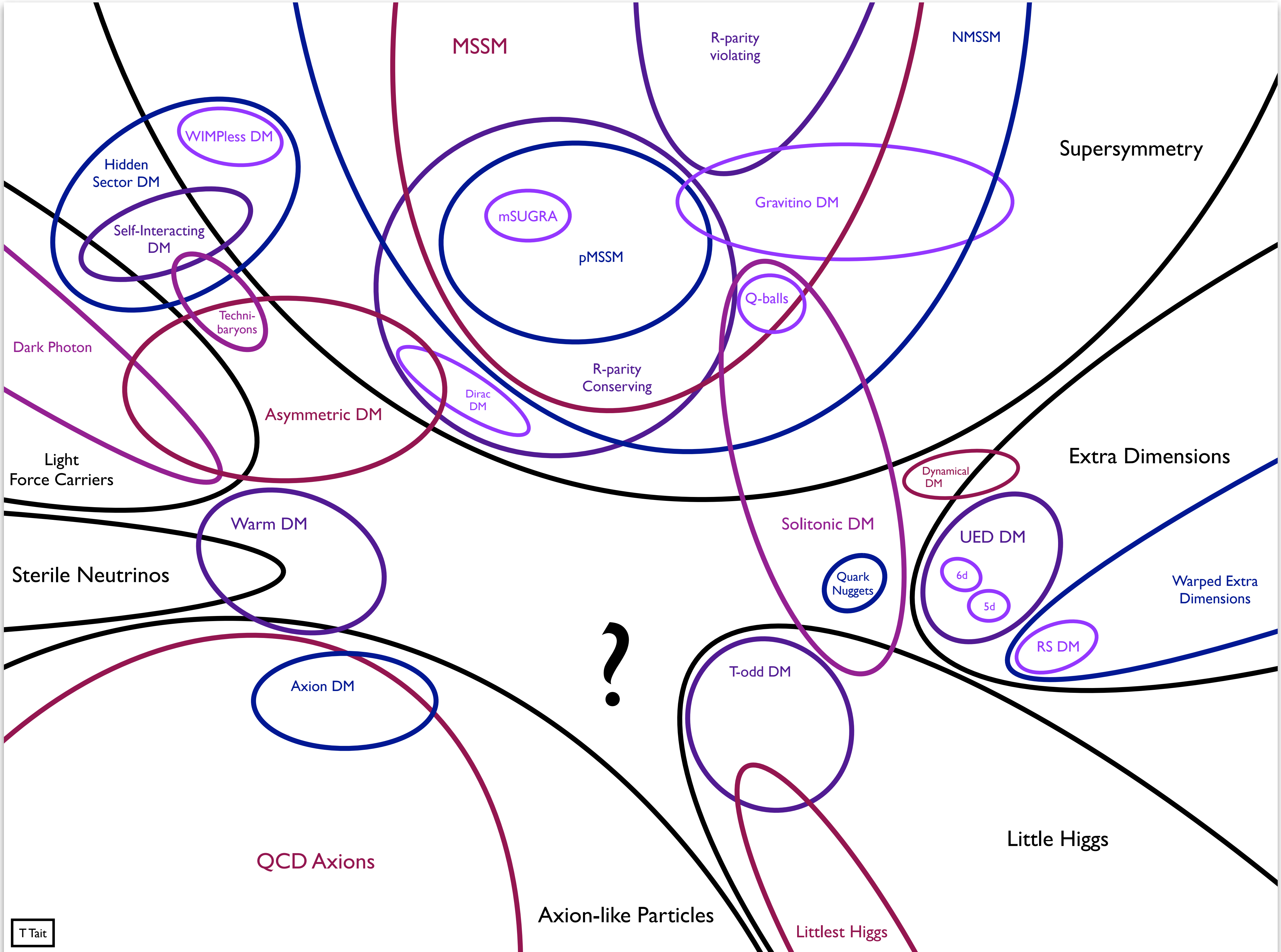
$$\boxed{\lambda = \frac{h}{mv}}$$



90 orders of magnitude in mass…

Particle dark matter models

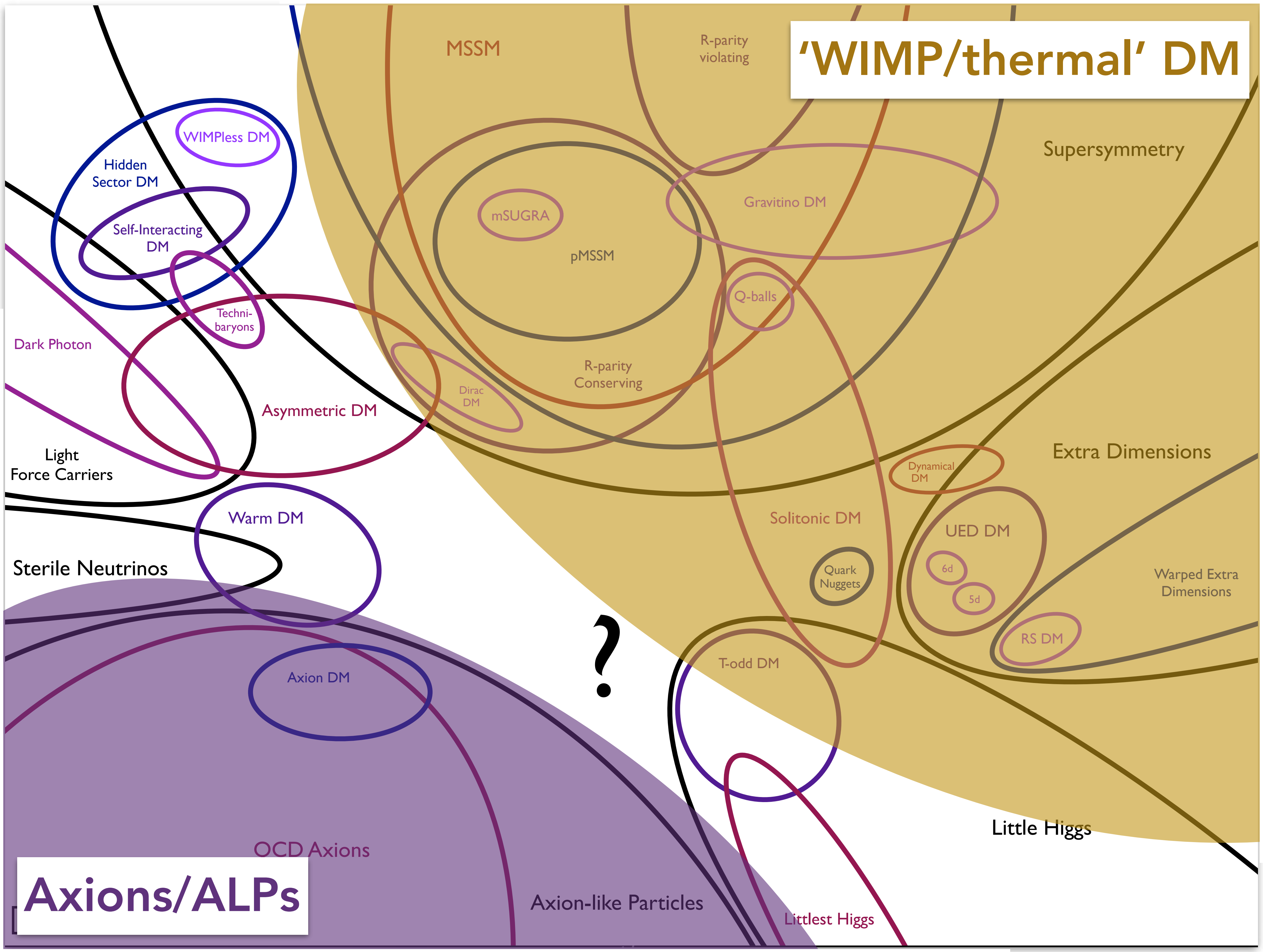
A theorist's 'landscape'



Credit: T. Tait

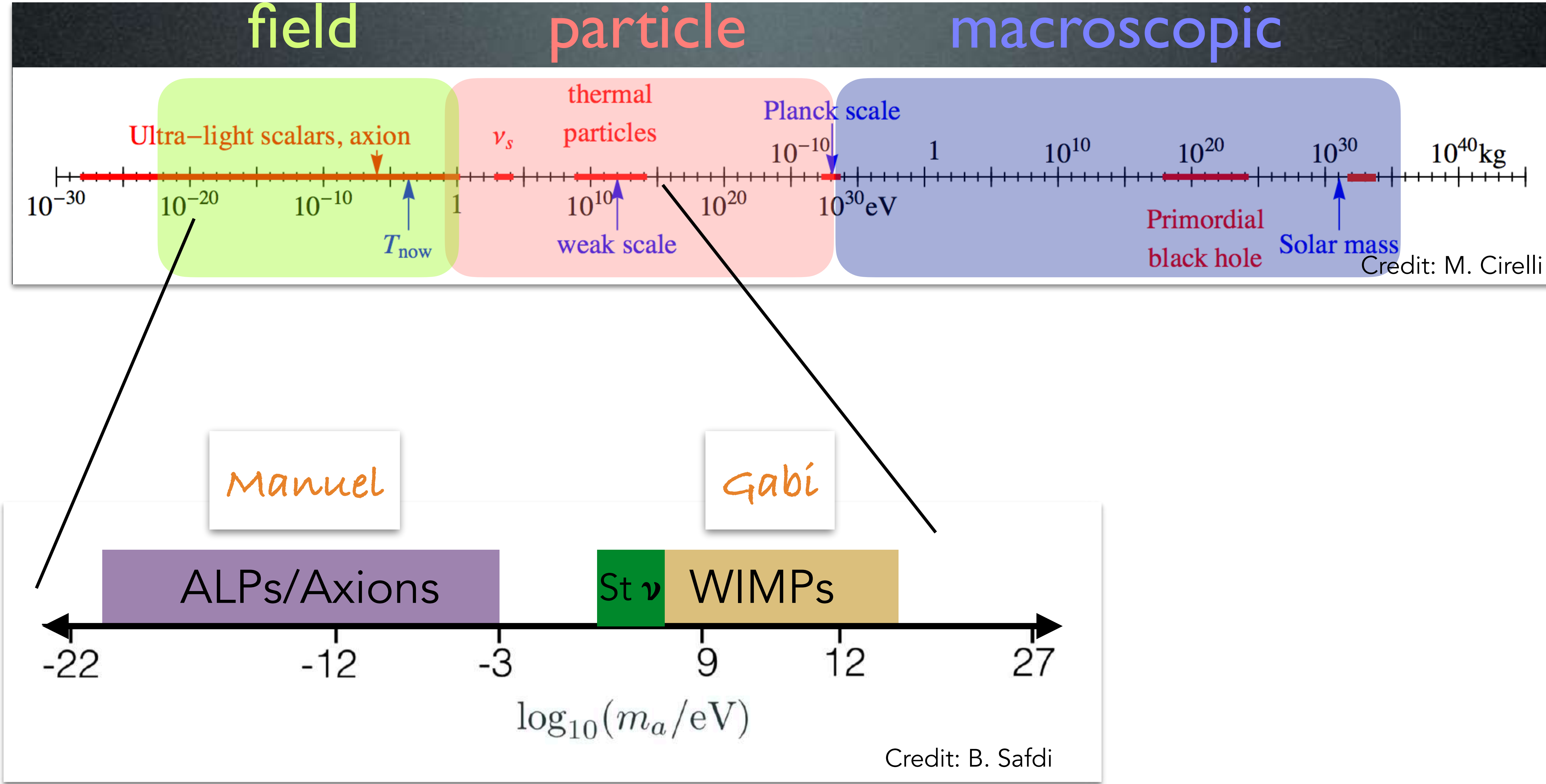
Particle dark matter models

Landscape in terms of (**gamma-ray**) signatures

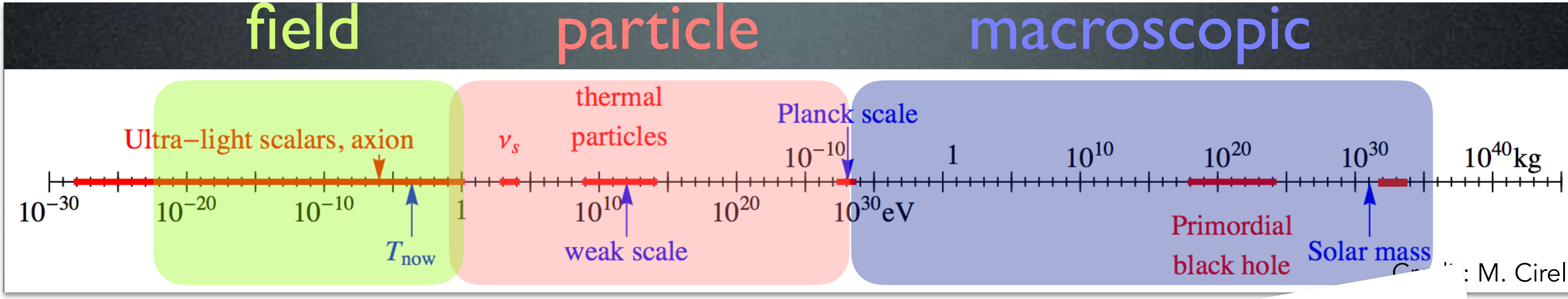


Credit: M. Meyer

Models


field
particle
macroscopic
thermal
particles
Planck scale
Ultra−light scalars, axion
ν_s
10^{-10}
1
10^{10}
10^{20}
10^{30}
10^{40}kg
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
10^{20}
10^{30}eV
T_{now}
weak scale
Primordial
black hole
Solar mass
Credit: M. Cirelli
Manuel
Gabi
ALPs/Axions
St ν
WIMPs
-22
-12
-3
9
12
27
$\log_{10}(m_a/\text{eV})$
Credit: B. Safdi

Models



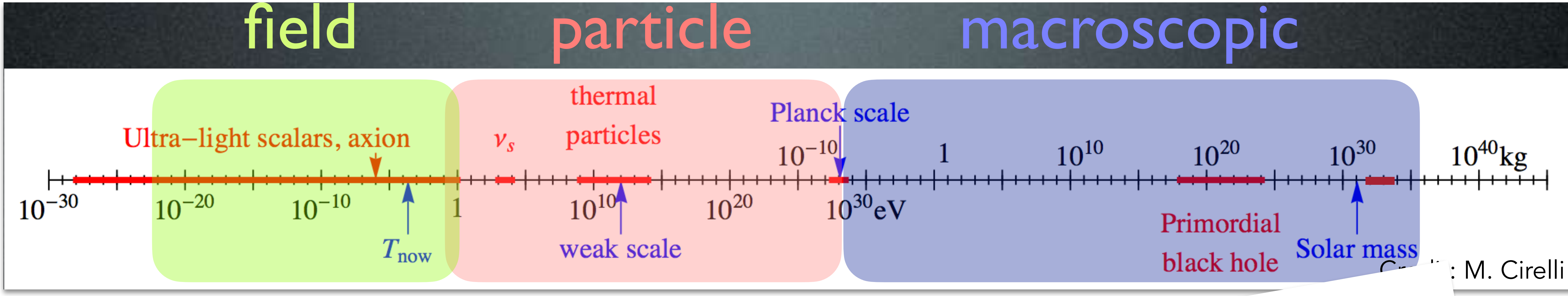
Search under 'theory' lamppost

Some clues about its nature:

One mystery is **why dark matter is stable** - especially if it is heavy enough to be "cold" in the early universe

- Sets stringent limits on DM-SM interactions
- Easiest route: impose some kind of symmetry to prevent DM from decaying

Models



: M. Cirelli

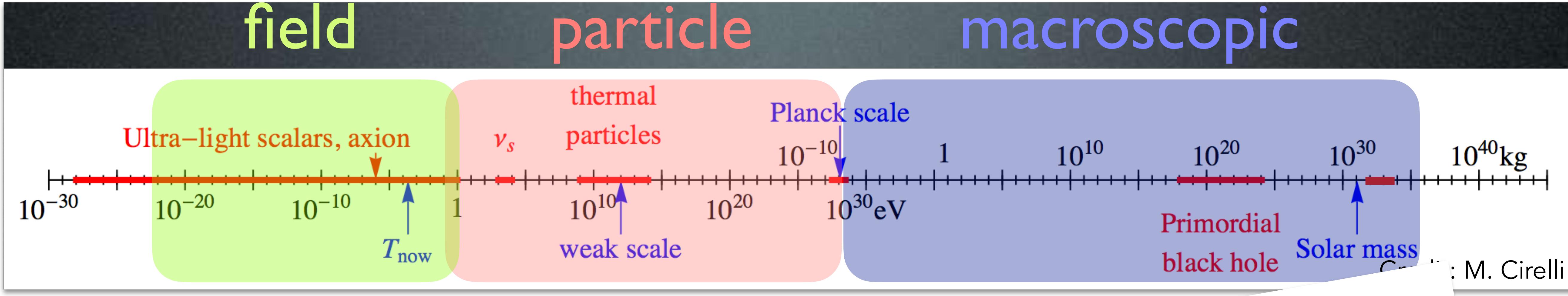
Some clues about its nature:

Any DM model must explain **the abundance of dark matter** at the epoch of last scattering

- **Thermal**: interactions set final abundance
- **Non-thermal**: Initial condition from reheating? -Misalignment mechanism? -Phase transition?

Search under 'theory' lamppost

Models



Search under 'theory' lamppost

Some clues about its nature:

Any DM model must explain **the abundance of dark matter** at the epoch of last scattering

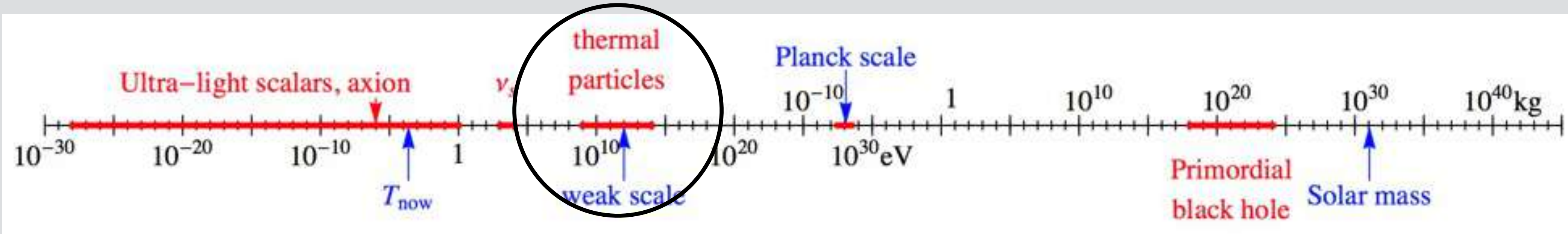
- **Thermal**: interactions set final abundance

This lecture

- **Non-thermal**: Initial condition from reheating? -Misalignment mechanism? -Phase transition?

Manuel

A 'special' model: '**Weakly interacting Massive Particles' (WIMPs) -> Thermal DM**



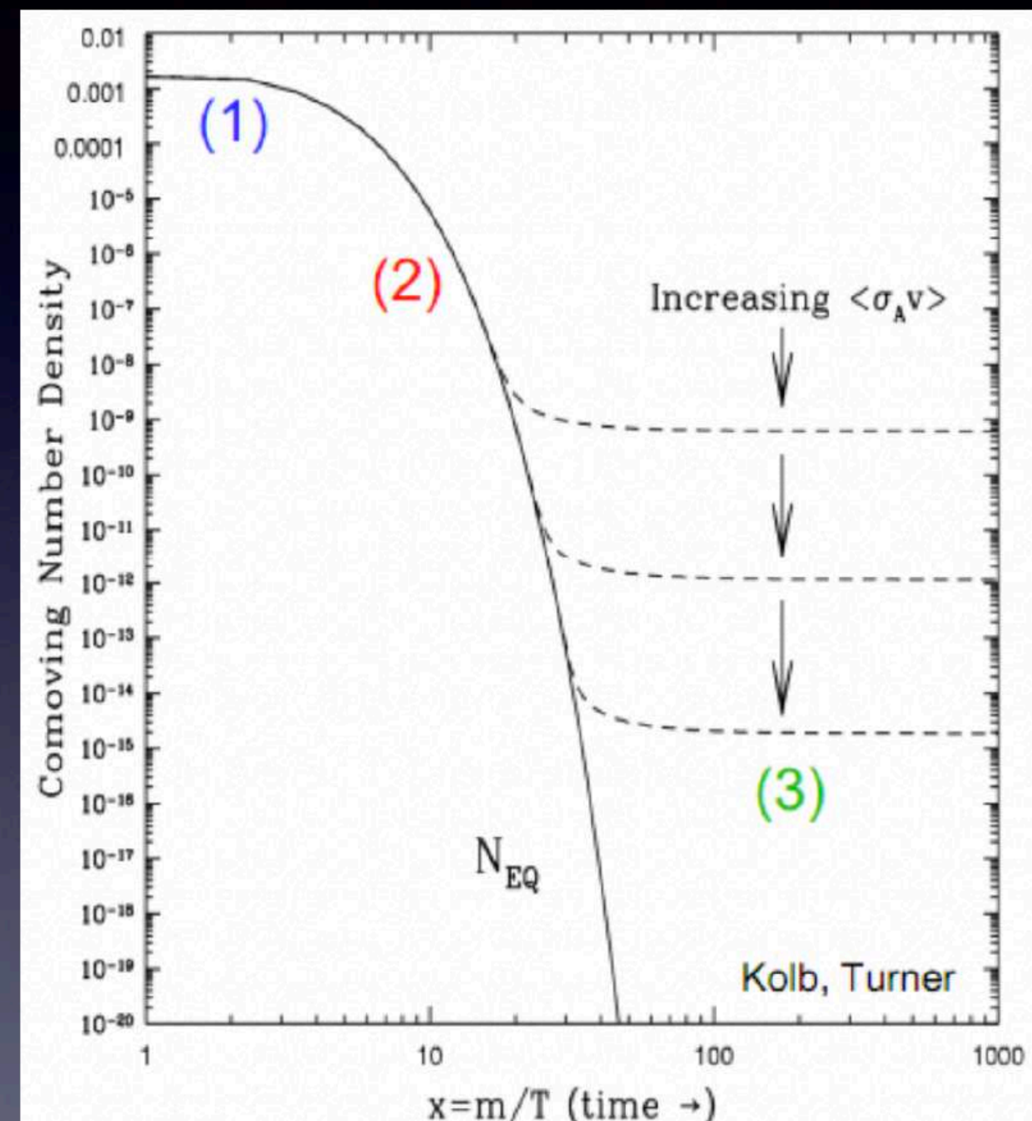
- In the early universe, let the DM particle be thermally coupled to the SM. Can annihilate to SM particles, or SM particles can collide and produce it.

$$\chi\chi \leftrightarrow \mathrm{SM\,SM} \quad (1)$$

- Temperature(universe) < particle mass => can still annihilate, but can't be produced.

$$\chi\chi \longrightarrow \mathrm{SM\,SM}$$
$$\chi\chi \not\leftarrow \mathrm{SM\,SM} \quad (2)$$

- Abundance falls exponentially, cut off when timescale for annihilation ~ Hubble time. The *comoving* dark matter density then freezes out.



So (known) late-time density is set by annihilation rate.

$$\langle\sigma v\rangle \sim 3\times10^{-26}\mathrm{cm}^3/\mathrm{s} \sim \pi\alpha^2/(100\,\mathrm{GeV})^2 \quad (3)$$

Outline of calculation

- Ingredients: annihilation rate for identical particles given by

  $$\text{annihilations / dt / dV} = n^2 \langle \sigma v \rangle / 2$$

- Boltzmann equation:

  $$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{\text{eq}}^2 \right]$$

- Equilibrium density (Boltzmann distribution):

  $$n_{\text{eq}} = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$$

- Temperature of universe (assume radiation domination):

  $$H^2 \propto \rho \propto T^4 \Rightarrow T \propto \sqrt{H} \propto t^{-1/2}$$

Estimating freezeout

- For precision solution, can solve this differential equation numerically
- But we can get a simple estimate of important quantities analytically.
  - Freezeout occurs when timescale for expansion ~ timescale for collision: $H \sim n\langle\sigma v\rangle$
  - Up to freezeout, $n \sim n_{eq}$, so we require $H \sim g(mT/2\pi)^{3/2} e^{-m/T} \langle\sigma v\rangle$
- Defining x=m/T, we have $H(m)x^{-2} = g(m^2/2\pi)^{3/2} x^{-3/2} e^{-x} \langle\sigma v\rangle$
- Transcendental equation $e^{-x} = x^{-1/2}/C$ has approximate solution

$$x \sim \ln C \sim \ln\left(g(m^2/2\pi)^{3/2}\langle\sigma v\rangle/H(m)\right)$$

note: only depends on m and cross section logarithmically

- Abundance at freeze-out:

$$n \sim g(m^2/2\pi)^{3/2} x^{-3/2} e^{-x} \sim H(m) x_f^{-2} / \langle \sigma v \rangle$$

Measured

- For comparison, photon abundanc ut:

$$n_\gamma \sim T^3 \sim m^3/x_f^3 \Rightarrow \boxed{n/n_\gamma \sim \left(H(m)/m^2\right)\left(x_f/m\right)/\langle \sigma v \rangle}$$

- To match measurements of DM mass density from CMB (comparable to critical density and baryon density), DM number density ~9 orders of magnitude below photon number density if $m_{DM} = m_{proton}$. At higher DM mass, number density must be lower (keeping mass density = mass x number density fixed).

$$H(m) \sim m^2/m_{\mathrm{Pl}} \Rightarrow 10^{-9}\,\mathrm{GeV}\, m_{\mathrm{Pl}} \sim \boxed{x_f/\langle \sigma v \rangle \Rightarrow \langle \sigma v \rangle \sim x_f 10^{-10}\,\mathrm{GeV}^{-2}}$$

- Let us estimate $\langle\sigma v\rangle \sim \alpha^2/m^2$, $\alpha \sim 10^{-2}$
- Then from first estimate for cross section, natural mass scale is m~1000 GeV.
- Plug this back into formula for x_f; we find x_f~25.

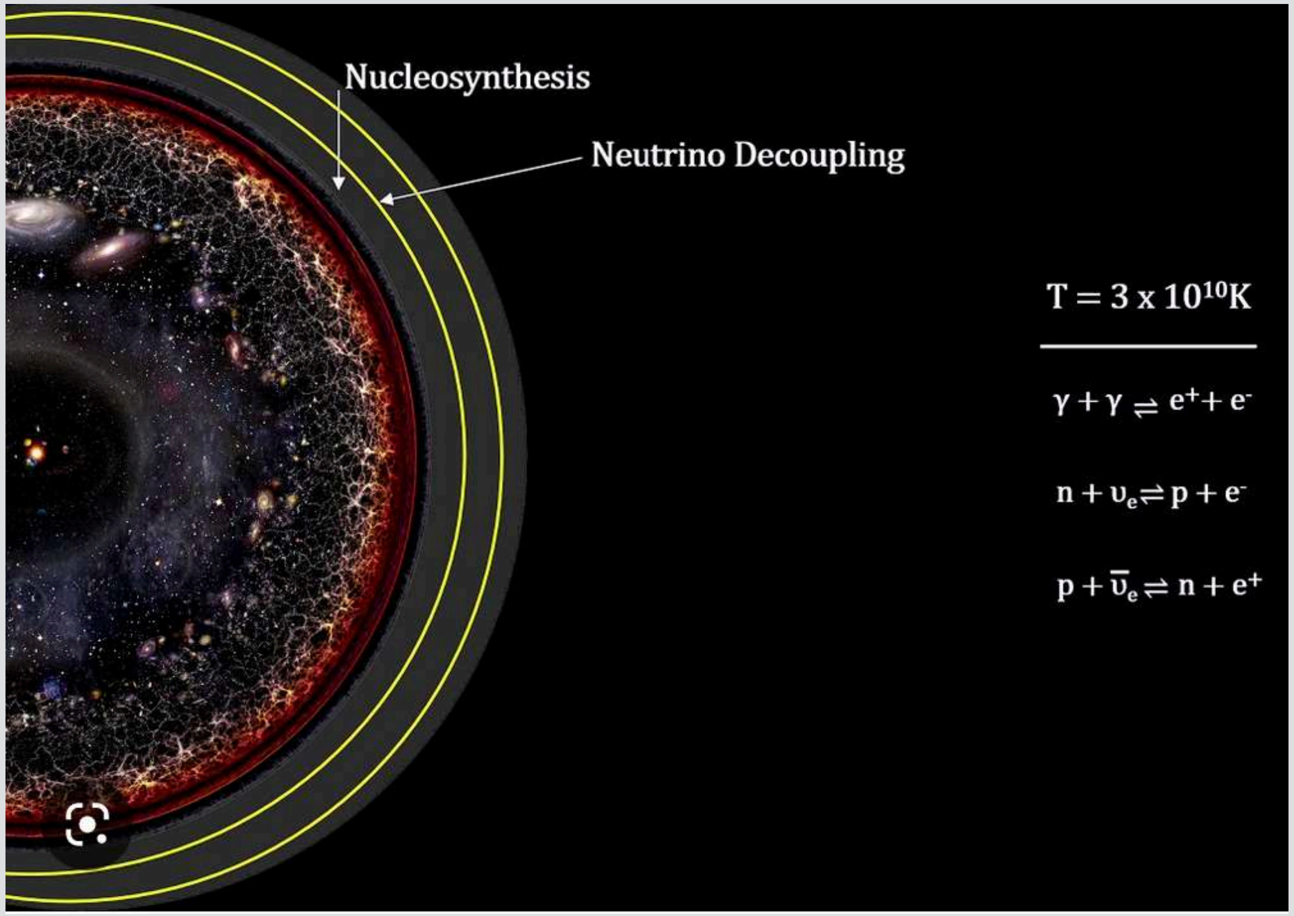
$$x_f \sim \ln\left(g/(2\pi)^{3/2} m m_{\mathrm{Pl}} \langle\sigma v\rangle\right)$$

- This gives us a better cross section estimate:

$$\boxed{\langle\sigma v\rangle \sim 2 \times 10^{-9}\mathrm{GeV}^{-2} \approx 2 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}}$$

If cross section 'weak-like' (assumed 1TeV scale), DM abundance today reproduced with only log dependence on mass

Thermal decoupling?



Thermal decoupling, i.e. the fact that **the present abundance of a given specie is determined by its interaction with the plasma in equilibrium up to the 'freeze-out' moment**, explains many of the events in the early Universe

- Prime example - Cosmic Neutrino Background (CNB): **decoupling of weak interactions for a *relativistic* particle**

The neutrinos decouple when we have the rates comparable, which is

$$\Gamma_H = \Gamma_W.$$

We find the energy scale is MeV while time scale is second. Also notice the decoupling for different flavors should be different.

As a result of expansion, those cosmic background neutrinos should be very cold.

- Number density: 112 neutrinos per cc for each flavor. This 112 includes both neutrinos and antineutrinos.
- Temperature: 1.94K which corresponds to 1.67×10^{-4}eV.

Thermal dark matter

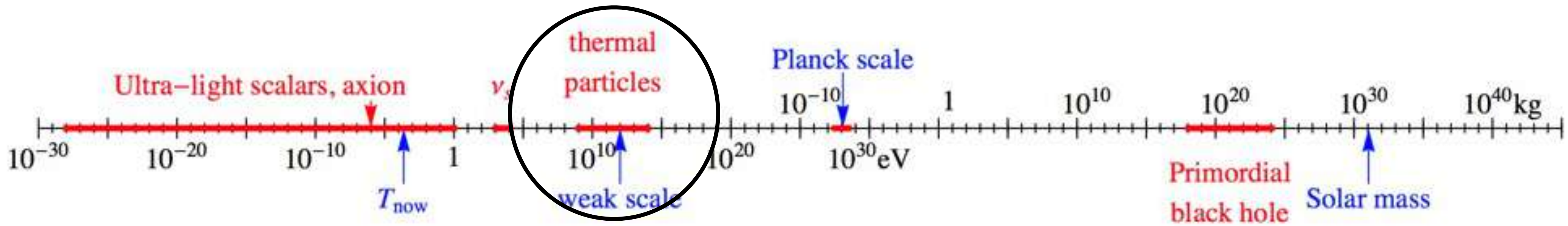
- In a thermal scenario (already at play for most of the events in the Early Universe), weak-scale annihilation cross section naturally yields the observed abundance of dark matter.

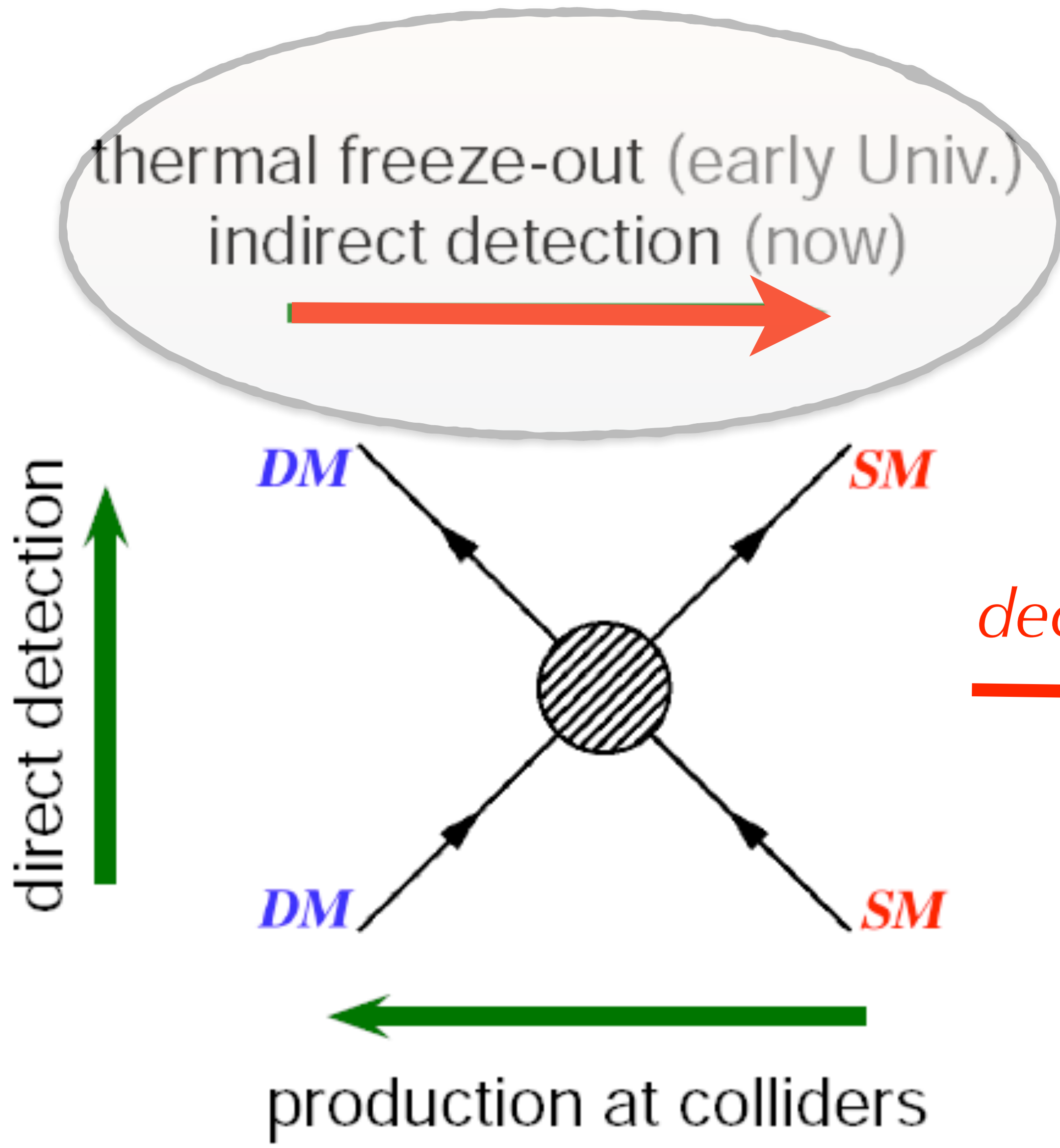
- Suggestive of new physics not too far above the weak scale.

- Stable WIMPs automatically occur in many scenarios for physics beyond the Standard Model, in particular in supersymmetry.

- However, simplest scenarios are challenged by lack of detection on other fronts;

A 'special' model: '**Weakly interacting Massive Particles**' (**WIMPs**)





decay →

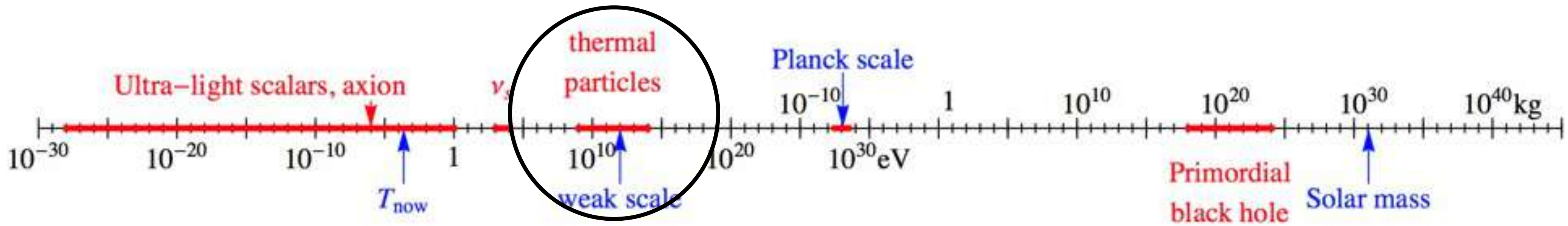
γ, ν, e±, p±, D⁻

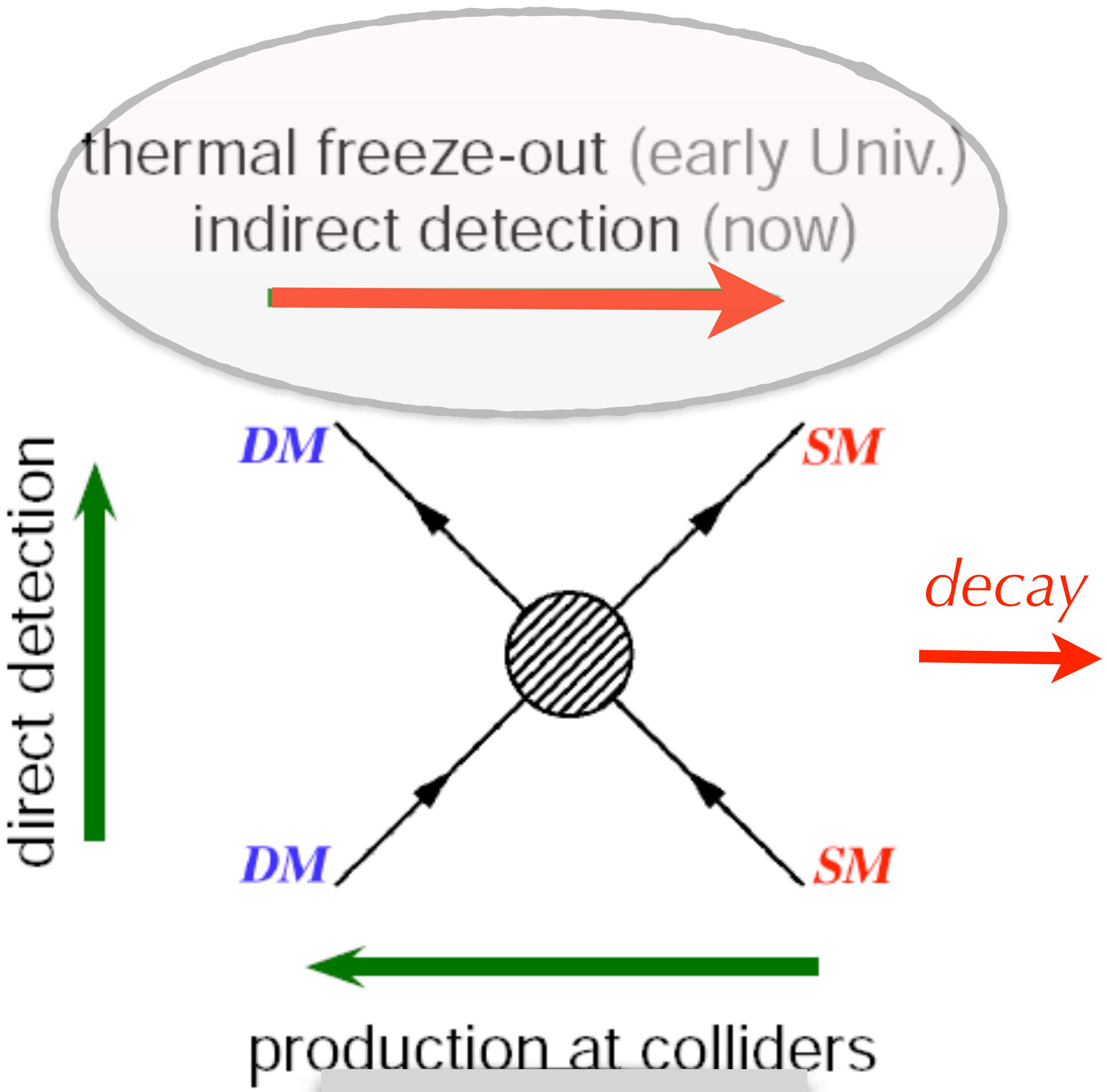
@ $\mathcal{O}(M_Z)$

In the Early Universe: DM kept in equilibrium w SM by self-annihilations $\langle \sigma v \rangle_{thermal}$.

Today, *DM expected to annihilate with the same* $\langle \sigma v \rangle_{thermal}$, *in places where its* **density is enhanced**!

A 'special' model: '**Weakly interacting Massive Particles**' (WIMPs)





γ,
ν,
$e^{\pm}$,
$p^{\pm}$
D^{-}

TeV scale?

What fluxes?

-> $\langle \sigma v \rangle$ *thermal*

@ $\mathcal{O}(M_Z)$

In the Early Universe: DM kept in equilibrium w SM by self-annihilations $\langle \sigma v \rangle$ *thermal*.

Today, *DM expected to annihilate with the same* $\langle \sigma v \rangle$ *thermal*, *in places where its* **density is enhanced**!

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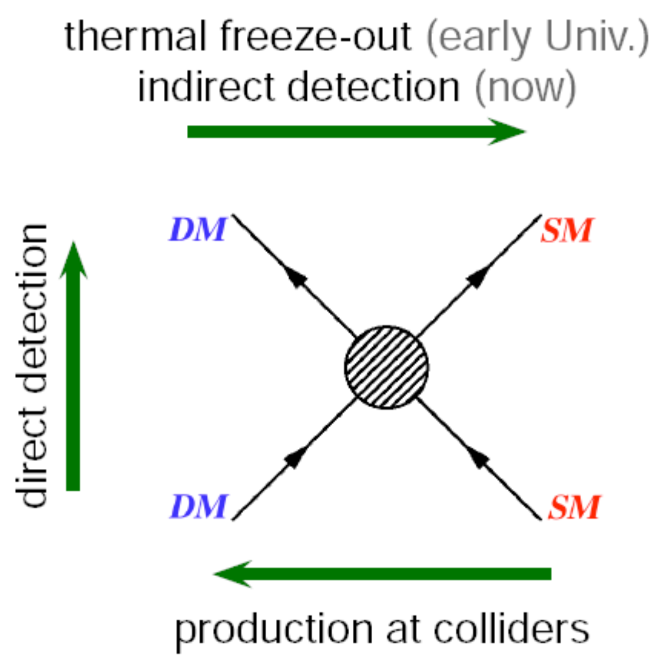
Today

On Wed

Search strategy & tools

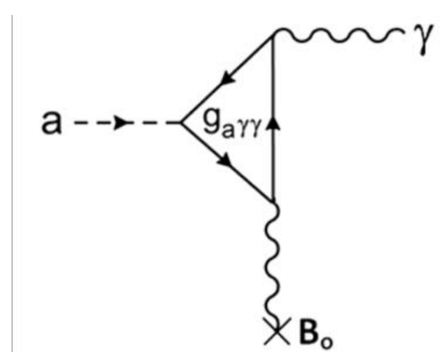


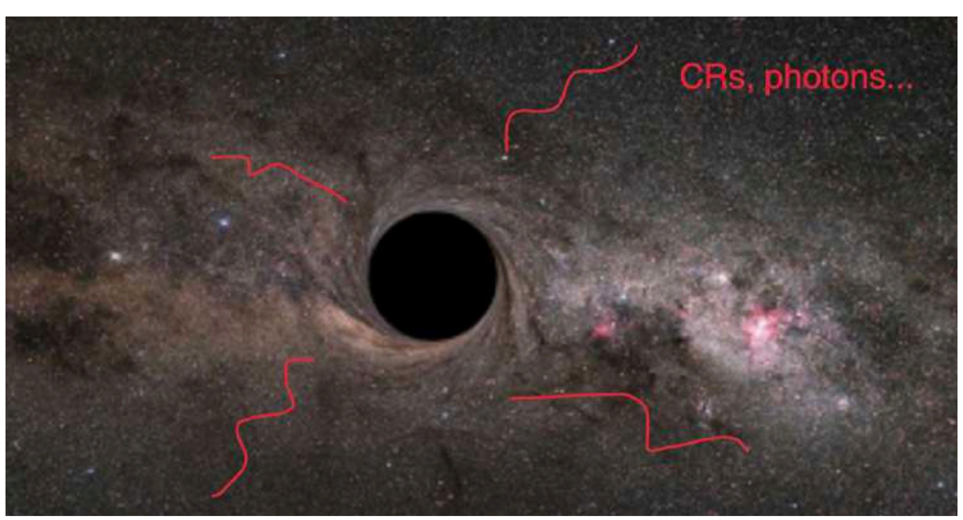
decay

$@\ \mathcal{O}(M_Z)$

γ

ν

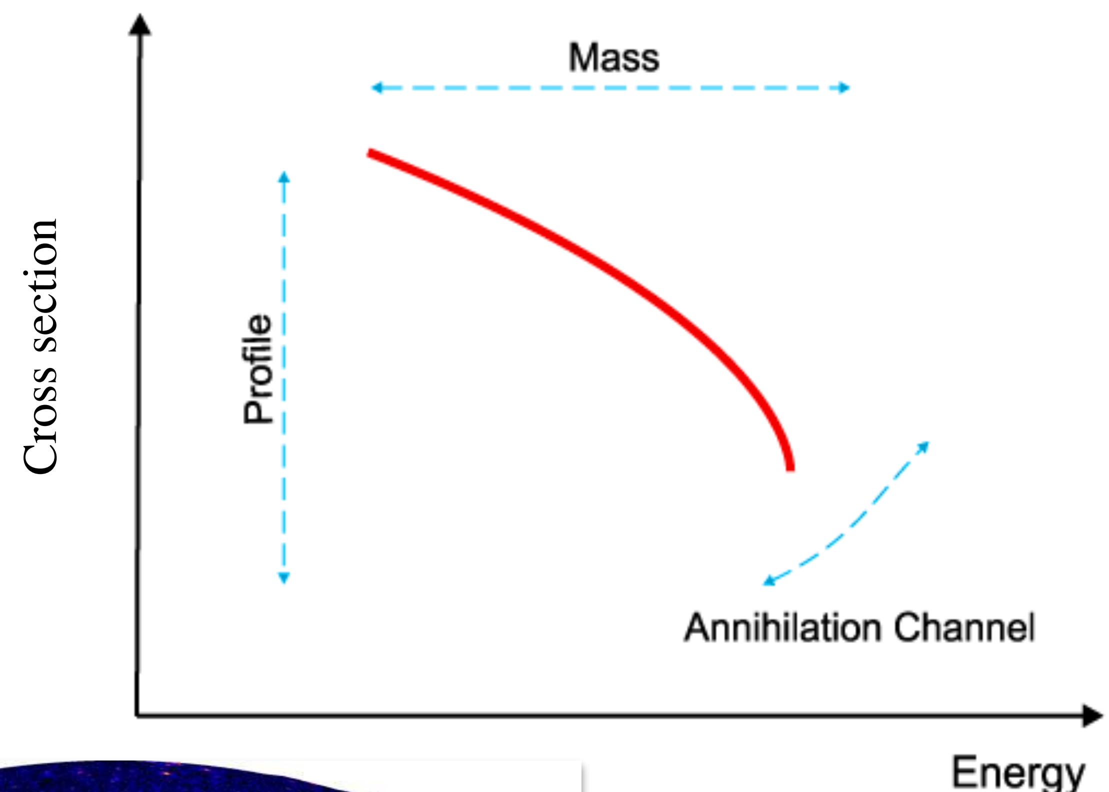




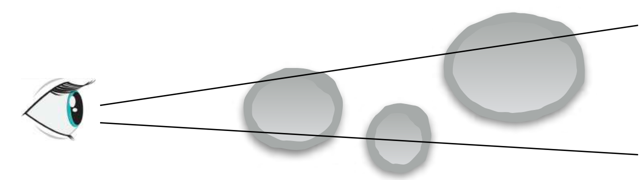
$e^{\pm}$,
$p^{\pm}$
D^{-}

What is the expected DM signal? - γ's and ν's travel in straight lines!

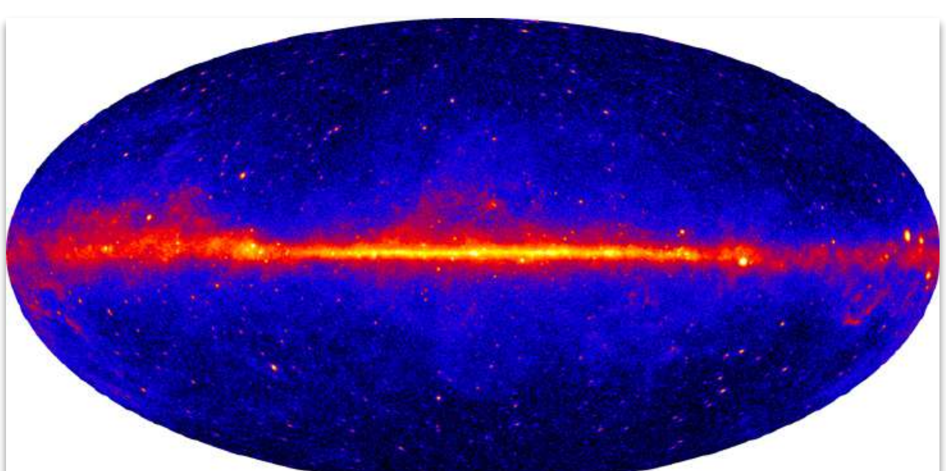
Flux (γ, ν) = particle physics X cosmology

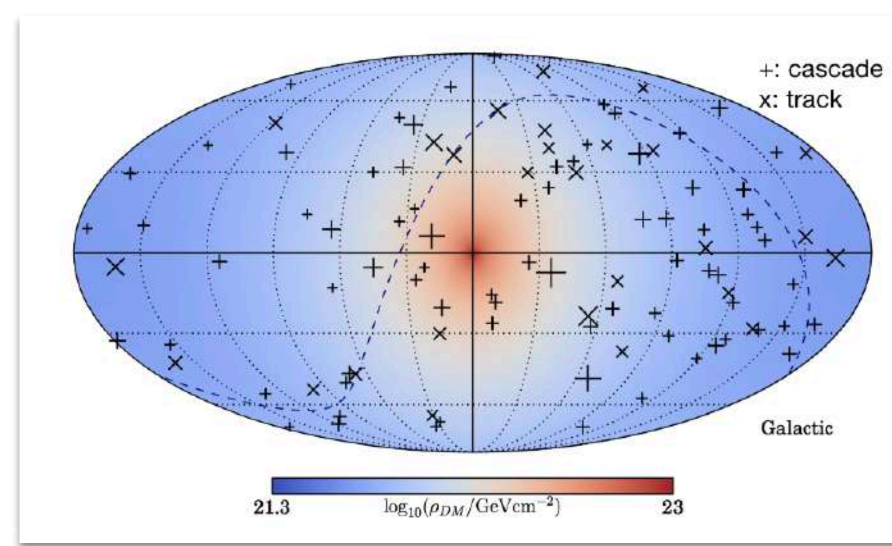


Bertone 2007



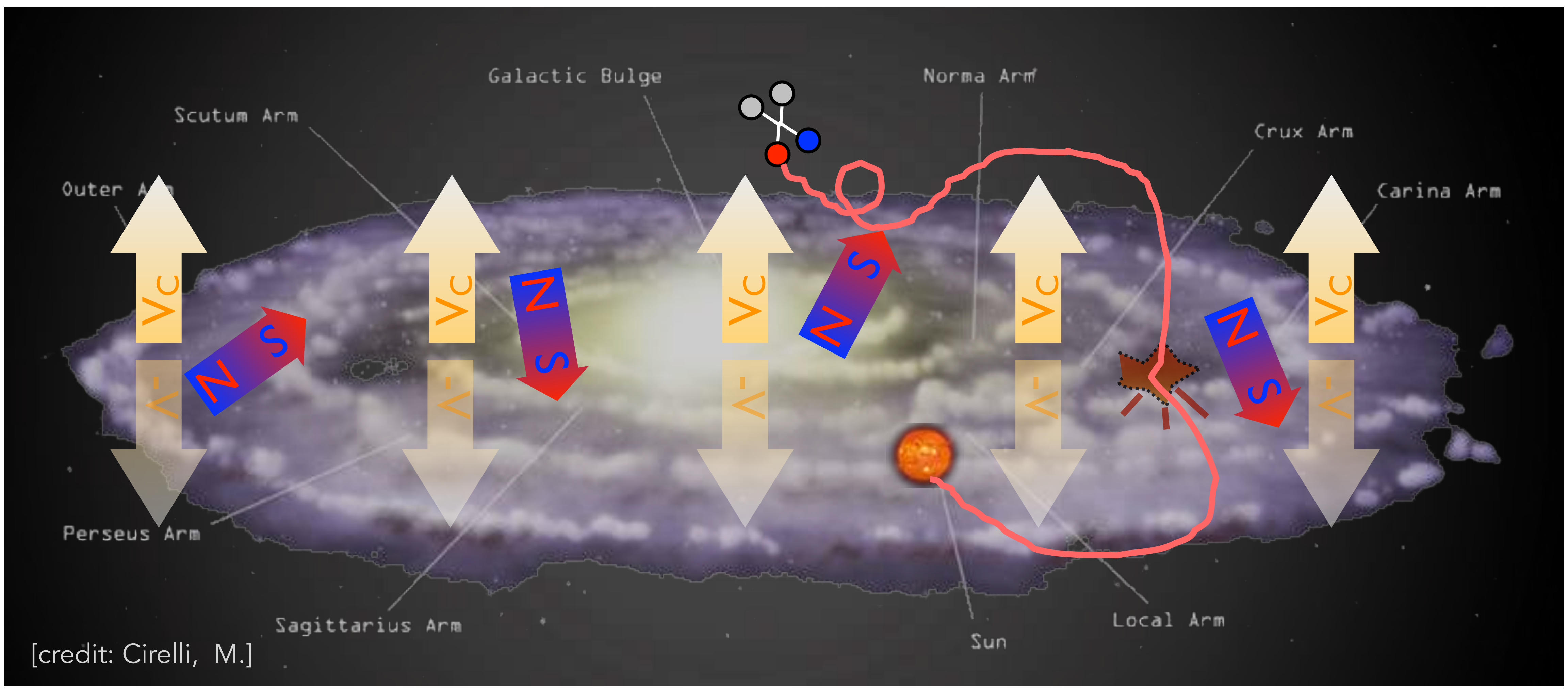
How is DM distributed





What is the expected DM signal? - charged particles

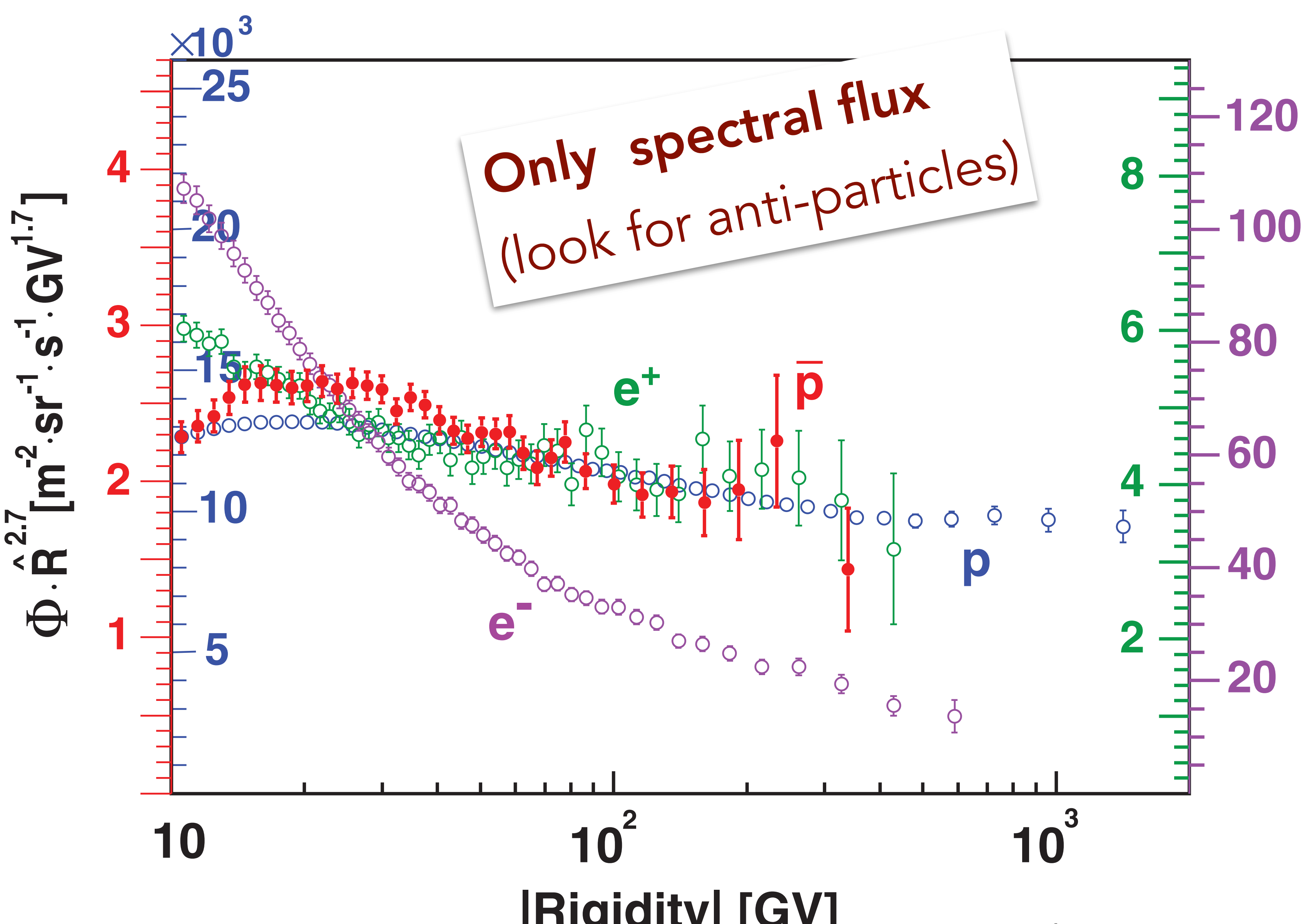
Flux (CRs) = (particle physics X cosmology) astrophysics



What is the expected DM signal? - charged particles

Flux (CRs) = (particle physics X cosmology)

astrophysics



[Aguilar+, PRL117 (2014)]

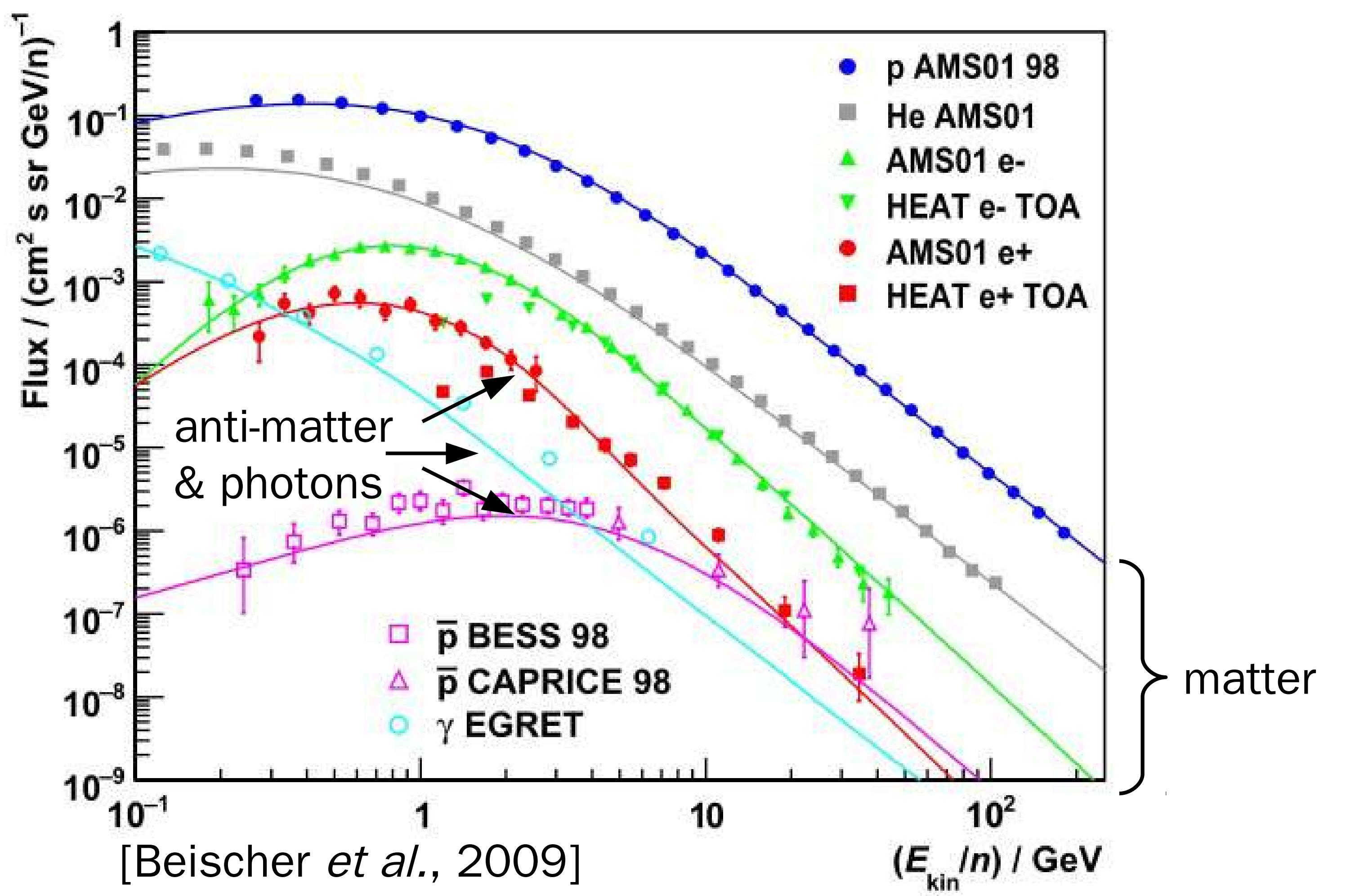
Focus on gamma-rays

PROs:

- **neutral! point back to their source**
- Easier to catch than neutrinos (high(er) statistics)
- => ***with gamma-rays one can study individual identified sources and different sources classes***

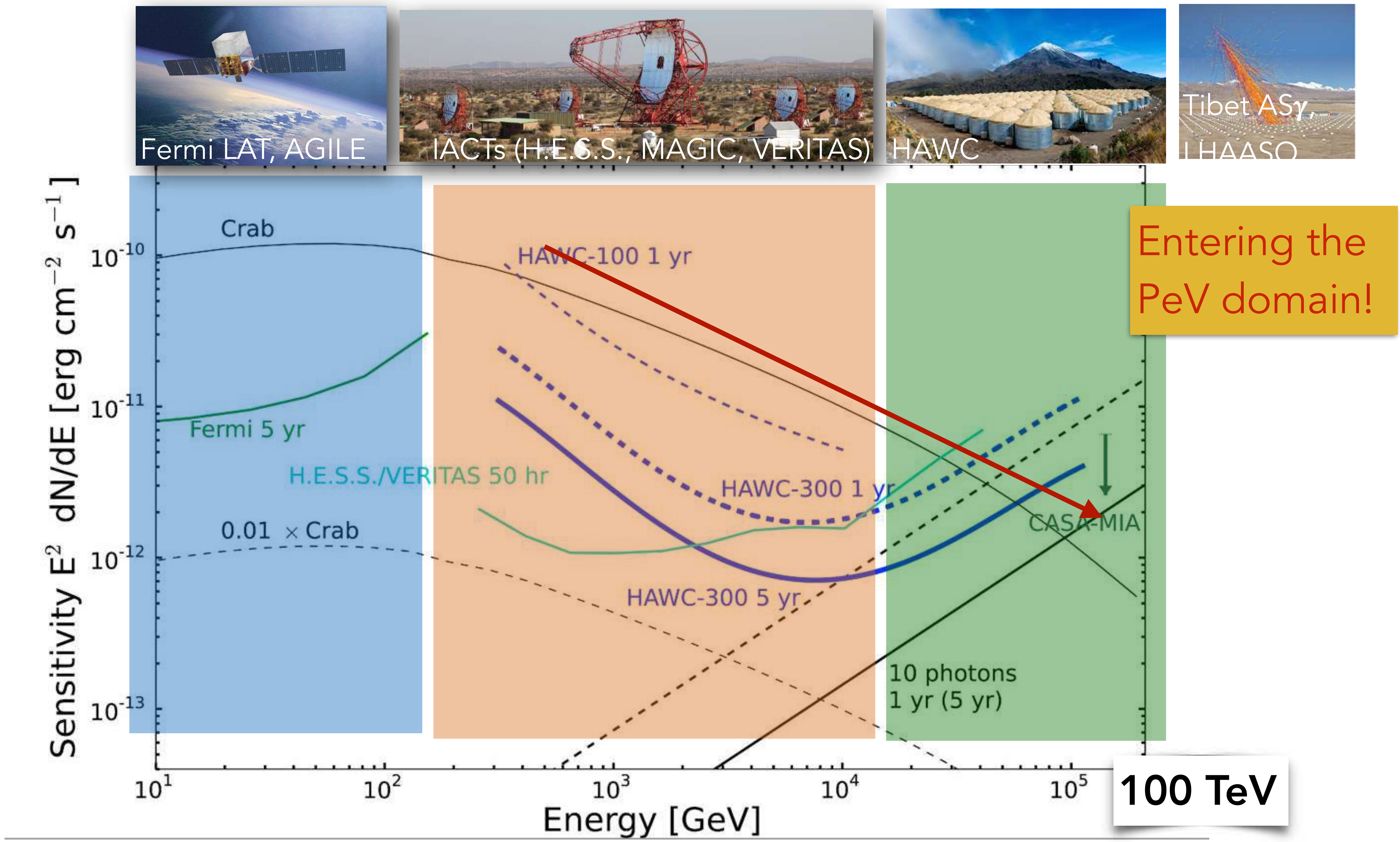
Challenge:

Gamma rays (much) rarer than charged Cosmic Rays

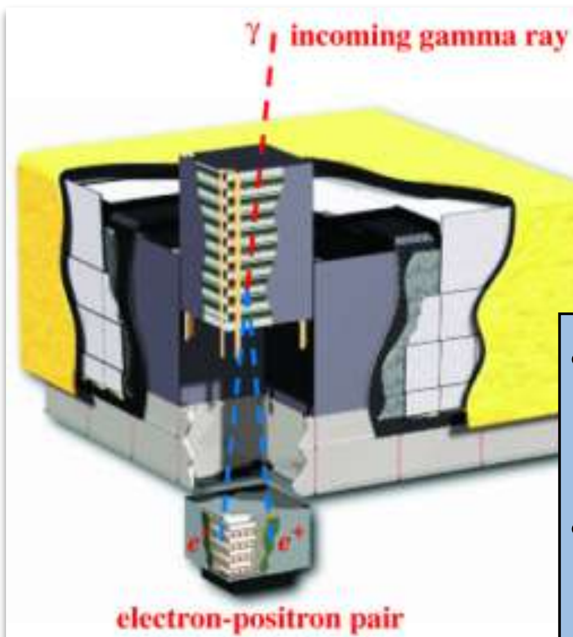


[Beischer *et al.*, 2009]

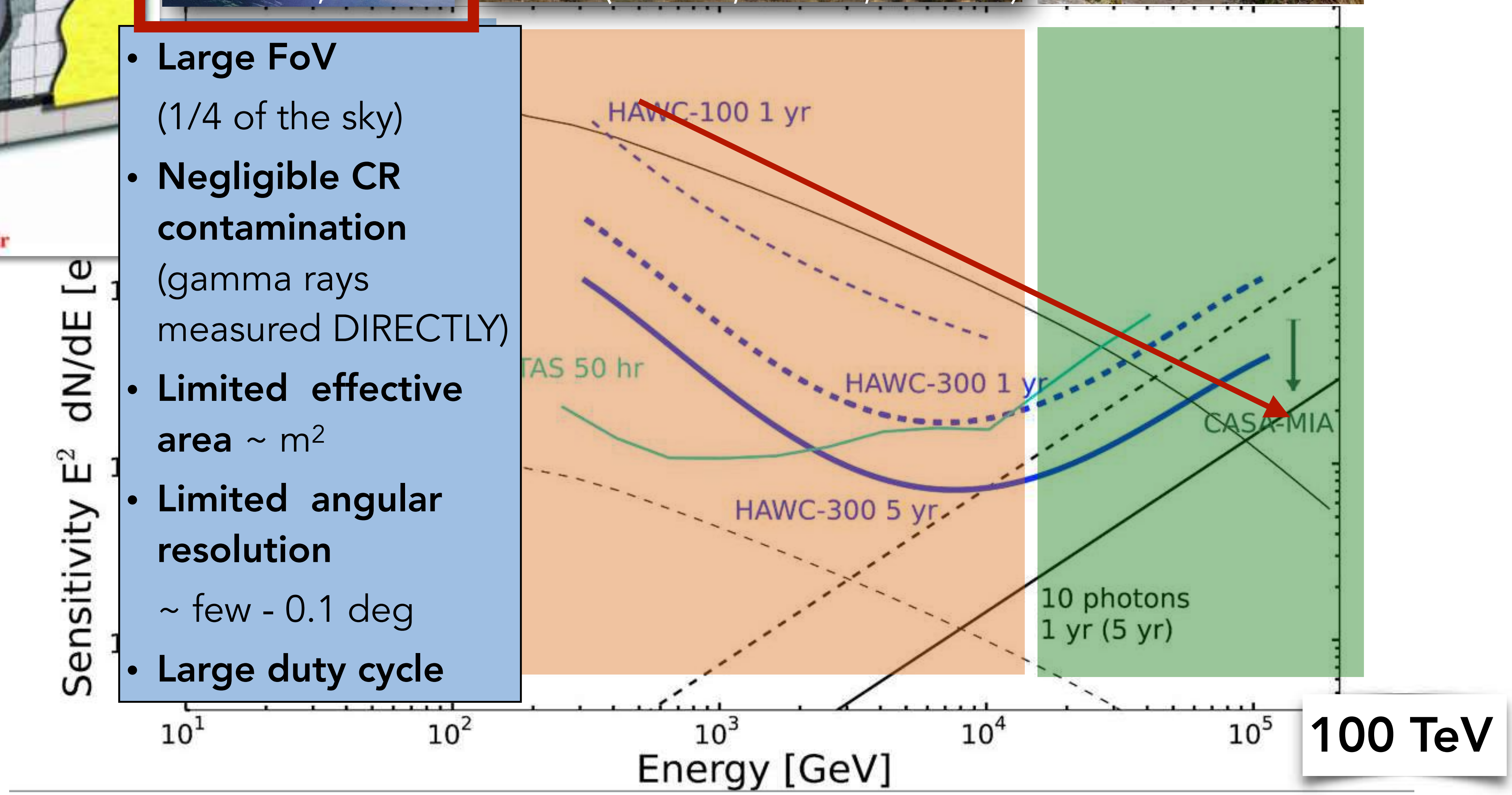
What tools?


Fermi LAT, AGILE
IACTs (H.E.S.S., MAGIC, VERITAS)
HAWC
Tibet ASγ, LHAASO
Entering the PeV domain!
Crab
HAWC-100 1 yr
Fermi 5 yr
H.E.S.S./VERITAS 50 hr
HAWC-300 1 yr
0.01 × Crab
CASA-MIA
HAWC-300 5 yr
10 photons
1 yr (5 yr)
Sensitivity E^2 dN/dE [erg cm^{-2} s^{-1}]
Energy [GeV]
100 TeV

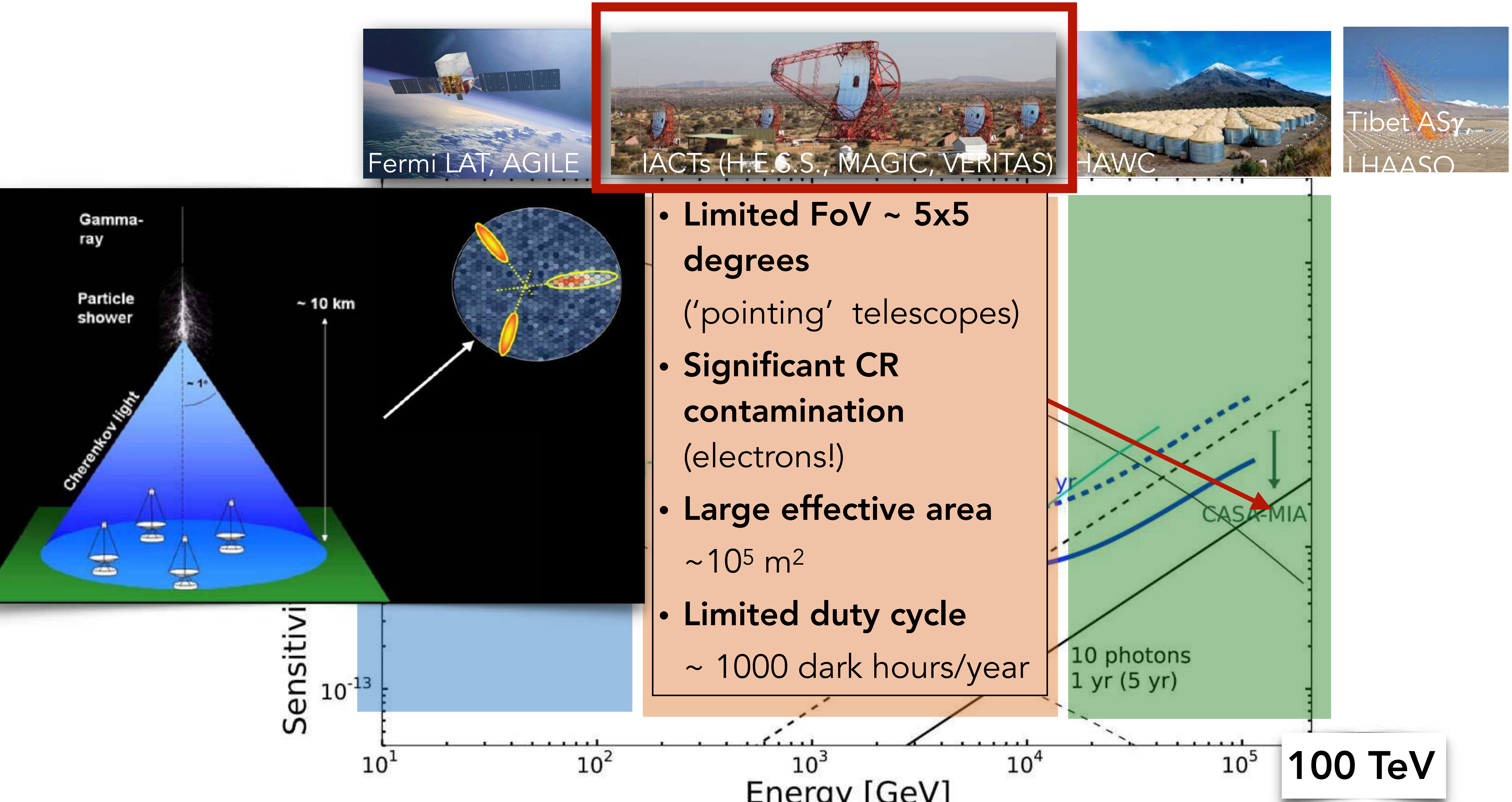
What tools?



- **Large FoV**
  (1/4 of the sky)
- **Negligible CR contamination**
  (gamma rays measured DIRECTLY)
- **Limited effective area** ~ m²
- **Limited angular resolution**
  ~ few - 0.1 deg
- **Large duty cycle**

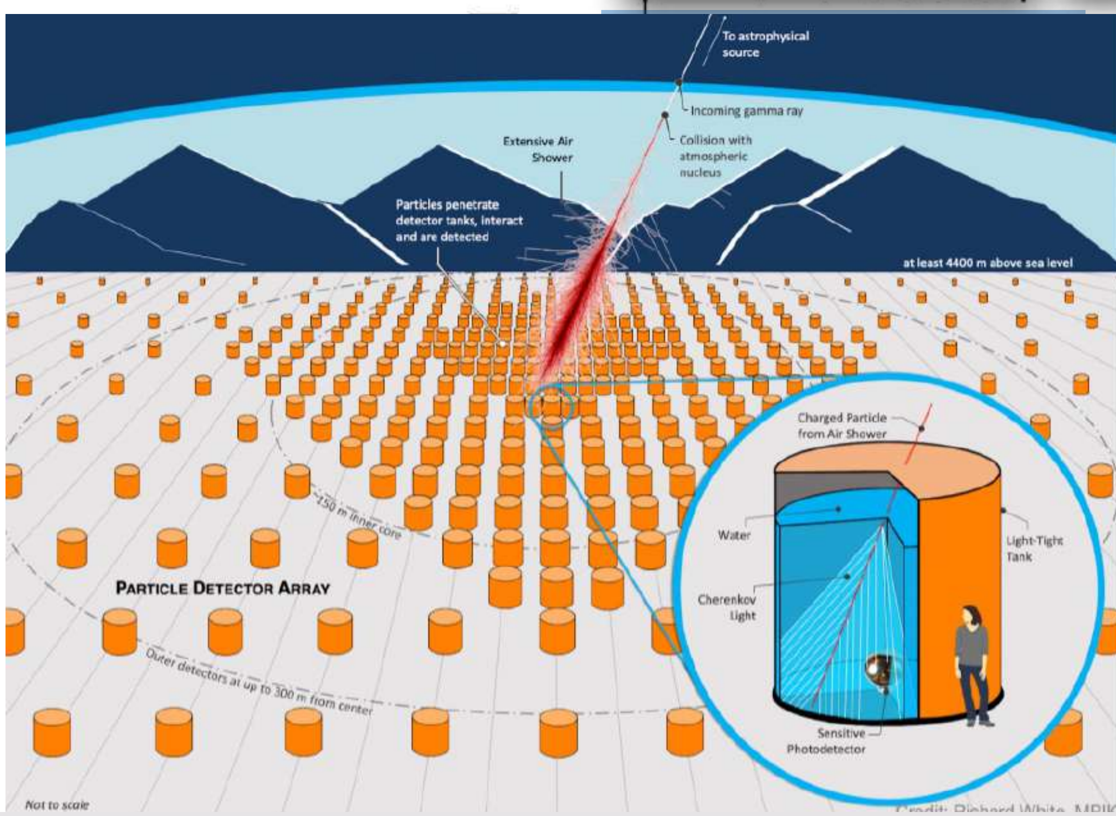


What tools?

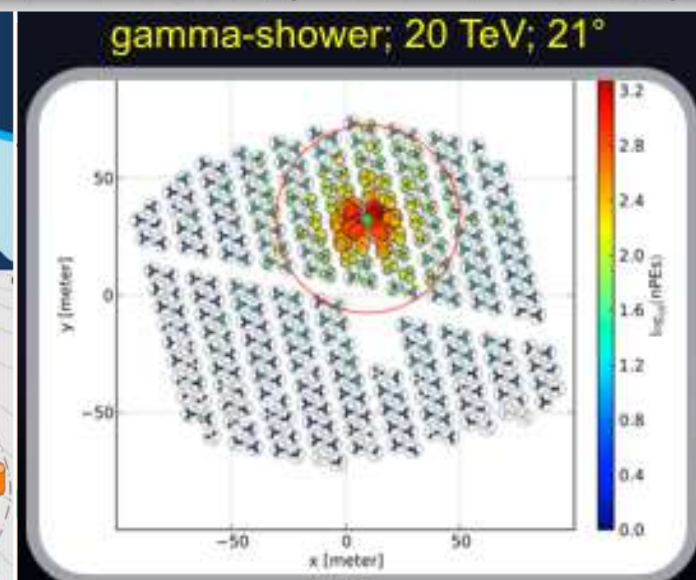


- **Limited FoV ~ 5x5 degrees**
  (‘pointing’ telescopes)
- **Significant CR contamination**
  (electrons!)
- **Large effective area**
  ~10^5 m^2
- **Limited duty cycle**
  ~ 1000 dark hours/year

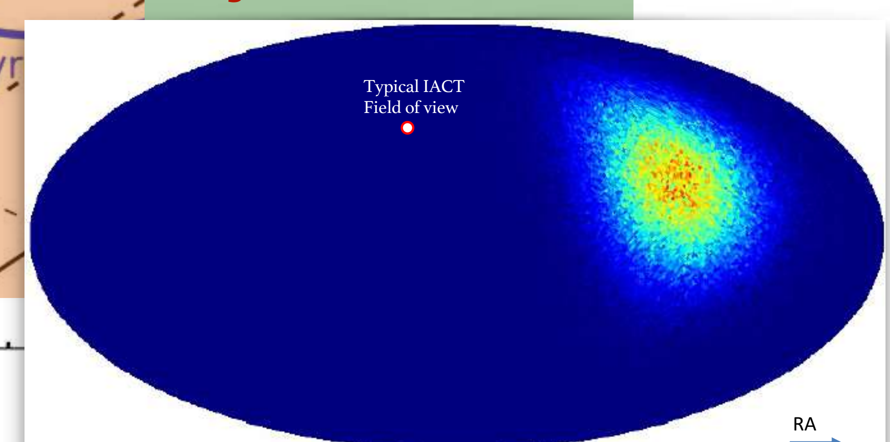
What tools?



300, 7 m x 5 m steel Water Cherenkov Detectors (tanks) with 4 PMTs

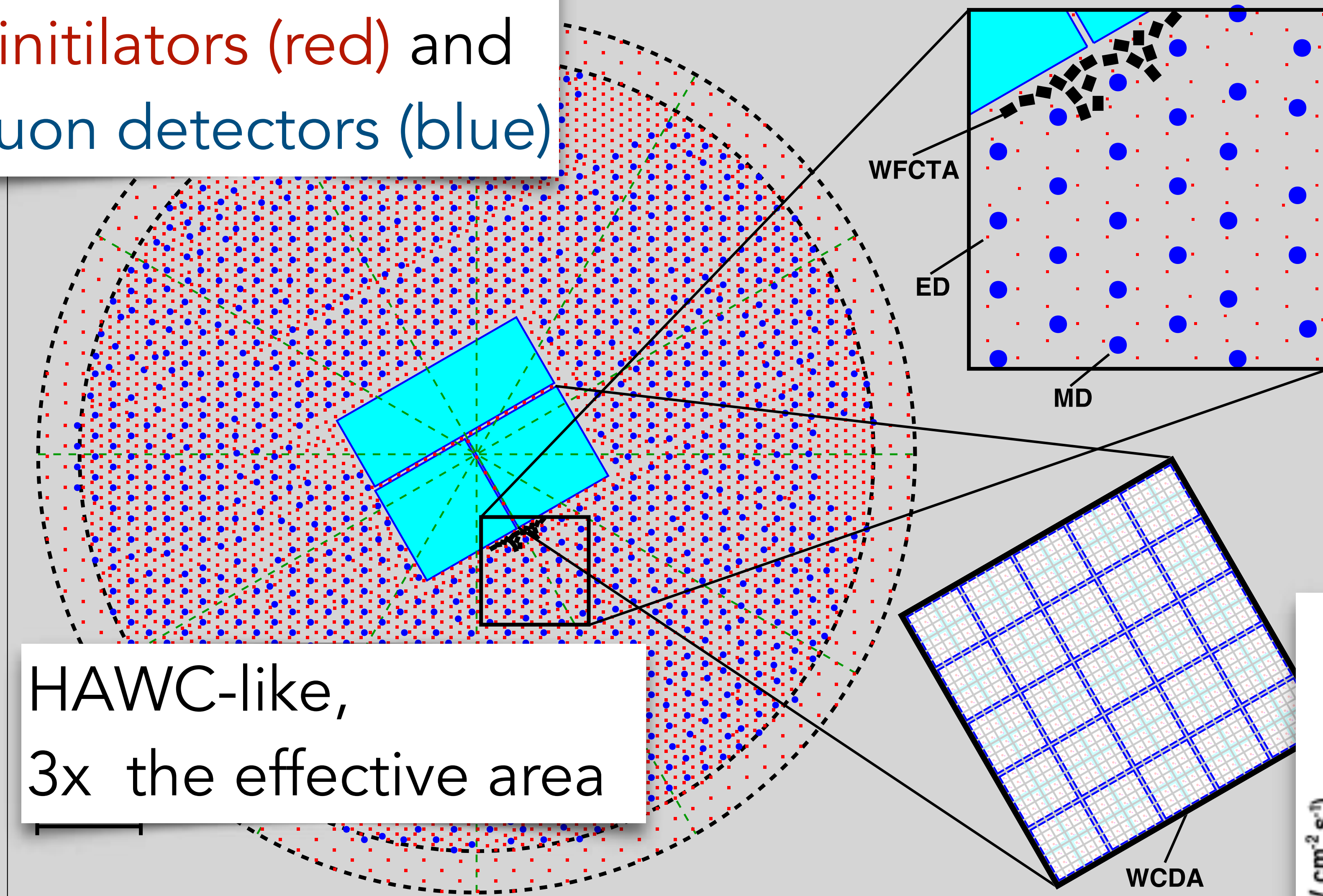


- Large FoV
- Significant CR contamination
- Large effective area
- Large duty cycle



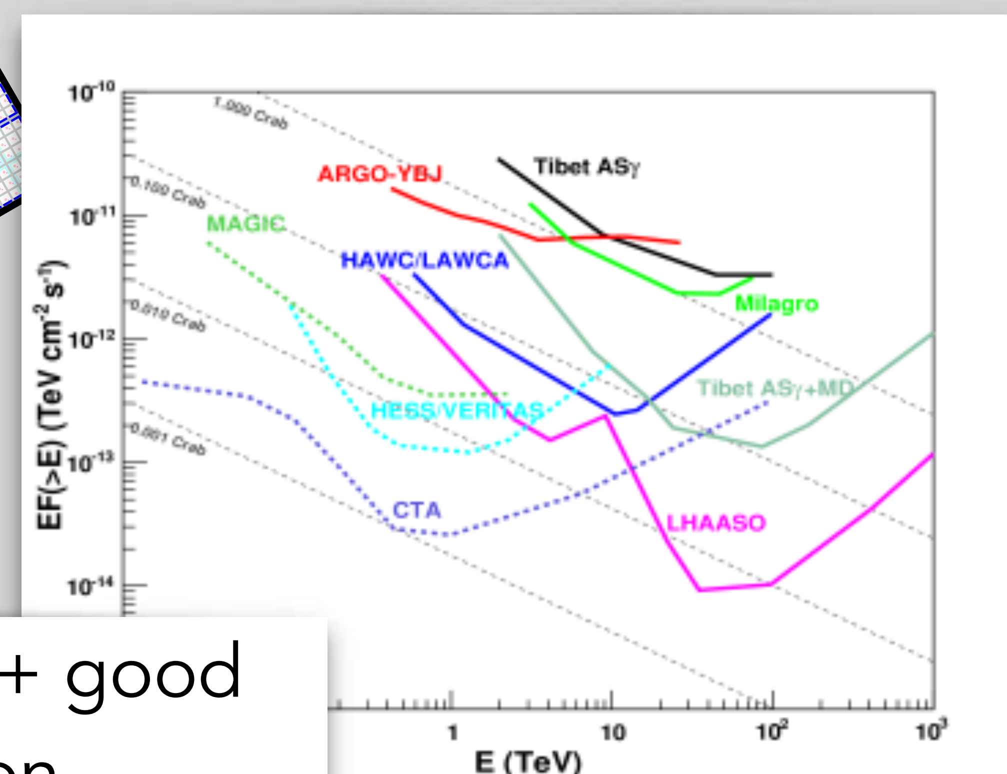
LHAASO - a combination of few techniques

KM2 array w
scinitilators (red) and
muon detectors (blue)



8
telescopes
of WFCTA

HAWC-like,
3x the effective area

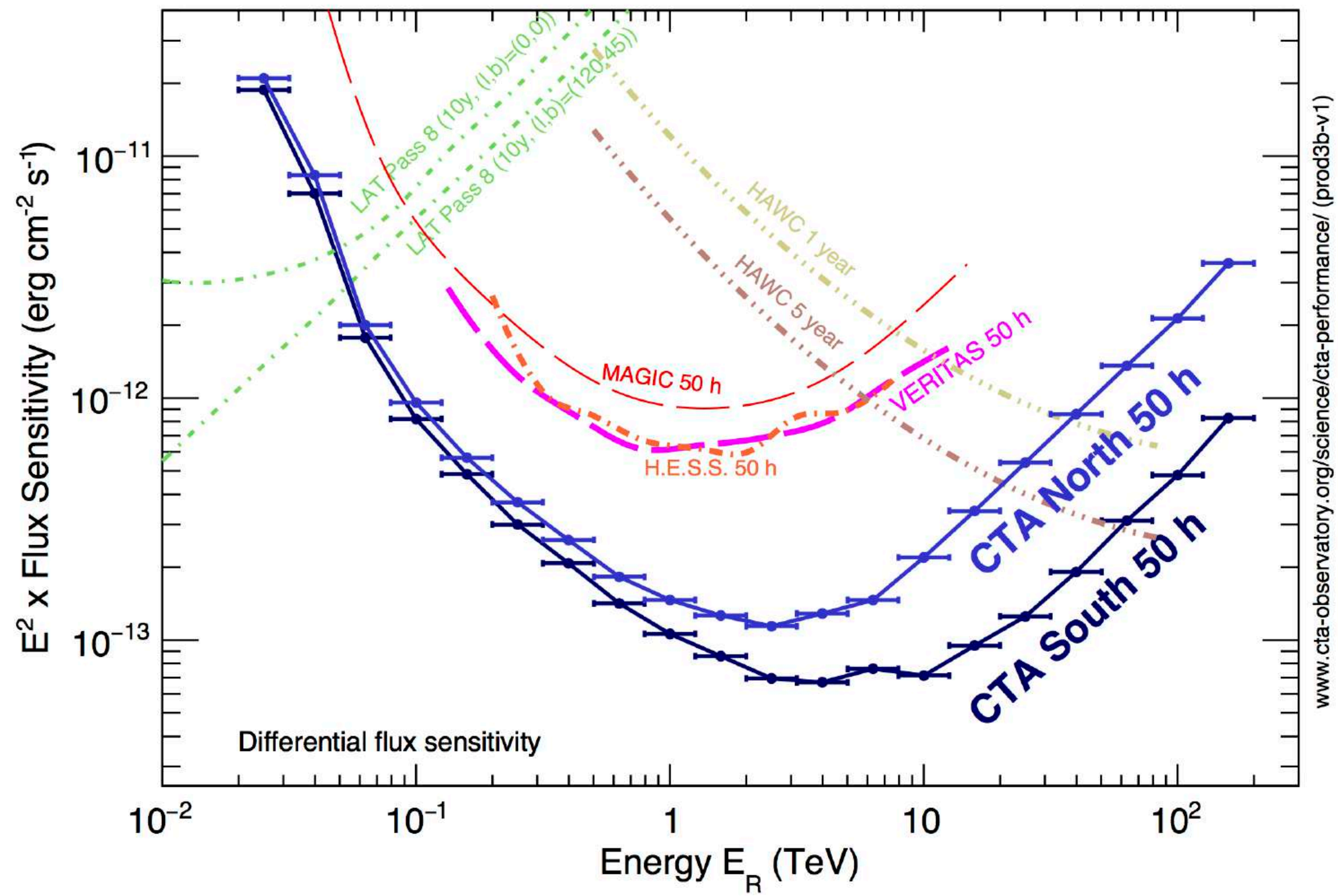


—> wide en coverage + good
CR background rejection

Future?


cta


Tibet ASγ,


LAT Pass 8 (10y, (l,b)=(0,0))
LAT Pass 8 (10y, (l,b)=(120,45))
HAWC 1 year
HAWC 5 year
MAGIC 50 h
VERITAS 50 h
H.E.S.S. 50 h
CTA North 50 h
CTA South 50 h
Differential flux sensitivity
E^2 x Flux Sensitivity (erg cm^{-2} s^{-1})
10^{-11}
10^{-12}
10^{-13}
10^{-2}
10^{-1}
1
10
10^2
Energy E$_R$ (TeV)
www.cta-observatory.org/science/cta-performance/ (prod3b-v1)

Outline

1. Pre history *a detour*
2. (gravitational) evidence for dark matter
3. DM candidates
4. Experiments
5. Signal & Targets

Today

6. The gamma-ray sky (astro 'backgrounds')
7. Data Analysis strategy
8. Examples of search in particular targets (WIMPs)
   - Galactic center
   - dSphs
   - Galaxy clusters

On Wed

The signal

In the case of WIMPs **particle physics** **cosmology**

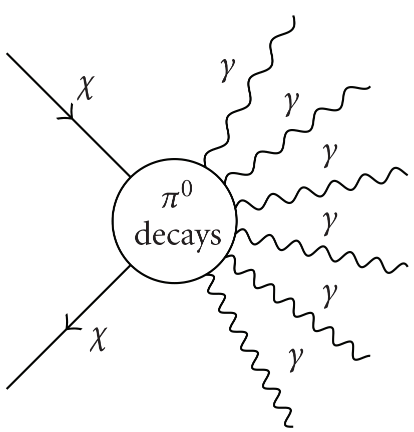
$$\boxed{\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma}} = \boxed{\frac{1}{4\pi}\,\frac{(\sigma_{\mathrm{ann}} v)}{2\, m_\chi^2}} \;\mathrm{X}\; \boxed{\sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma}} \;\mathrm{X}\; \boxed{\int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\, \rho^2(s,\Omega)}$$

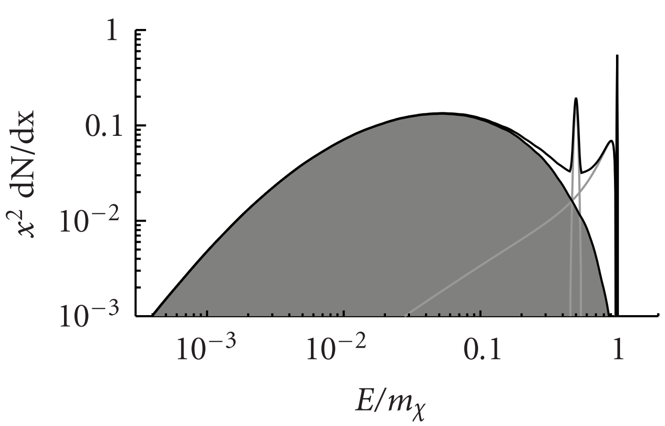
flux of SM particles
per DM annihilation

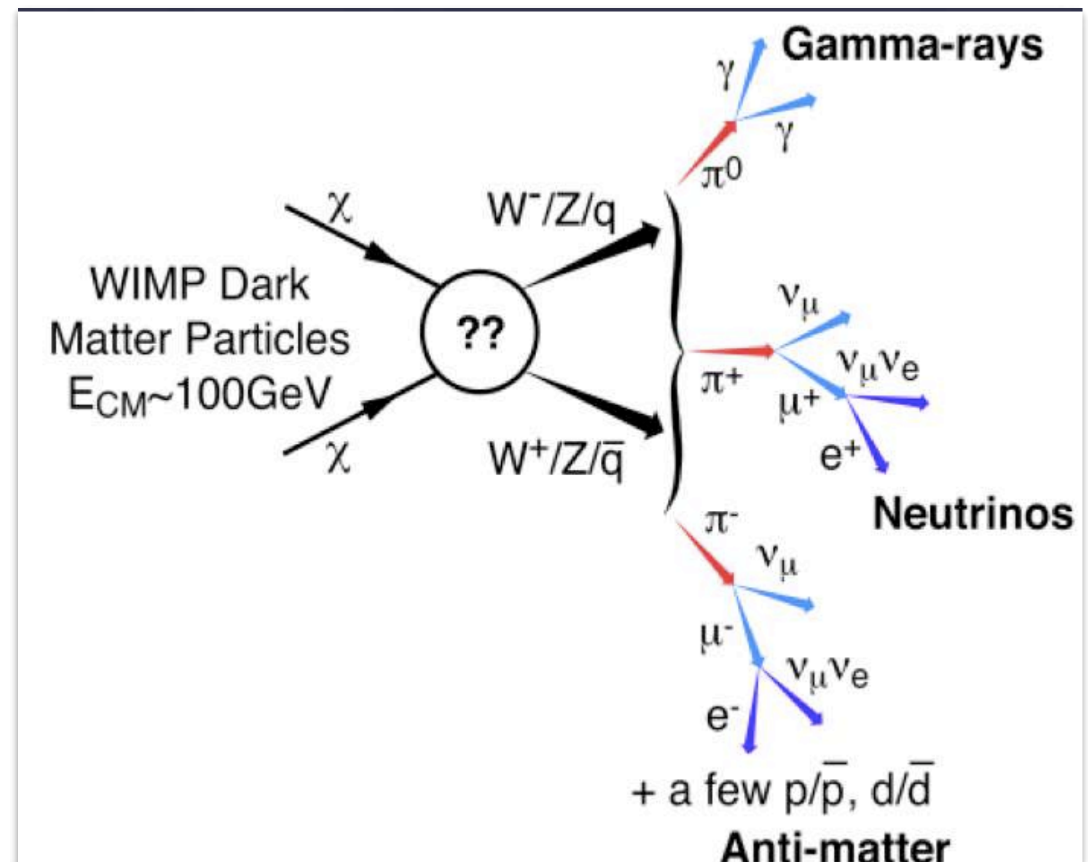
1) featureless spectra for bulk of the channels

quasi-universal spectra

Secondary photons (tree level)







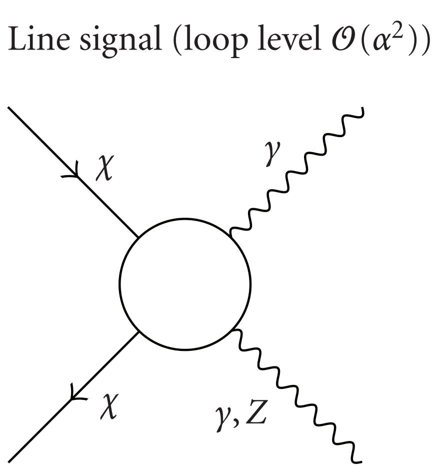
The signal

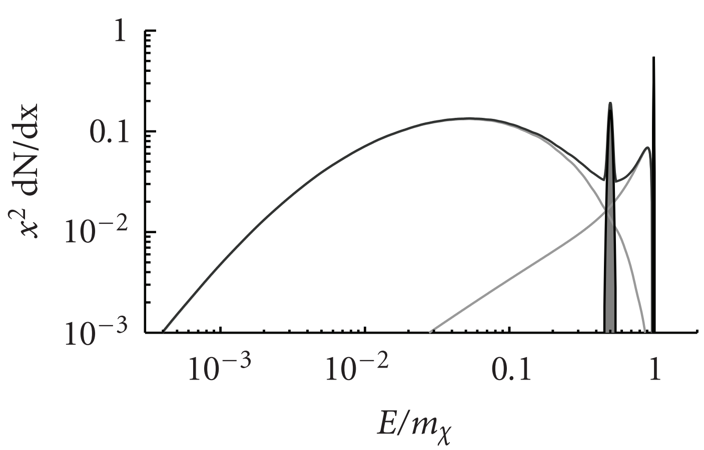
In the case of WIMPs **particle physics** **cosmology**

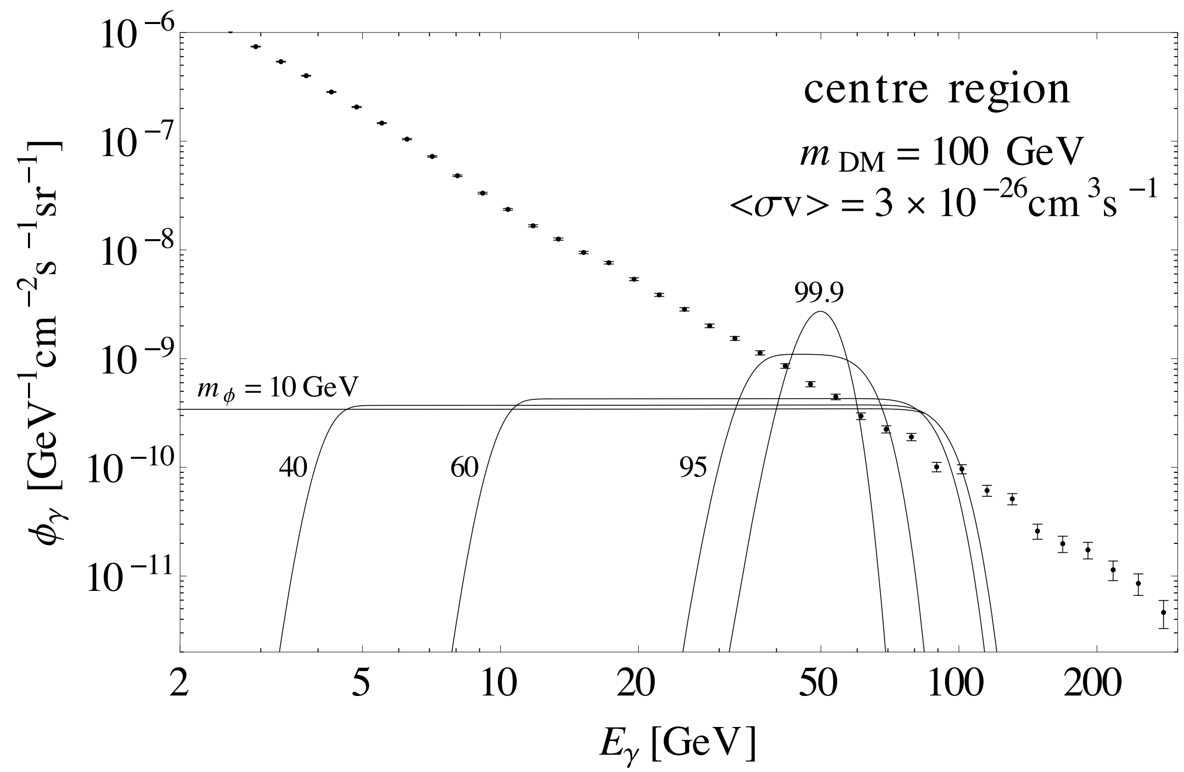
$$\boxed{\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma}} = \boxed{\frac{1}{4\pi}\,\frac{(\sigma_{\rm ann} v)}{2\,m_\chi^2}} \;\mathrm{X}\; \boxed{\sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma}} \;\mathrm{X}\; \boxed{\int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)}$$

flux of SM particles per DM annihilation

2) feature - full spectra







- **photons from Final State Particles (FSR) or internal states (VIB) and annihilation to a γ-ray line** (two photons/Zγ) through loop processes) or box shaped emission, to four photos via an intermediate state.
- **low signals but easier to distinguish from astrophysics radiation**

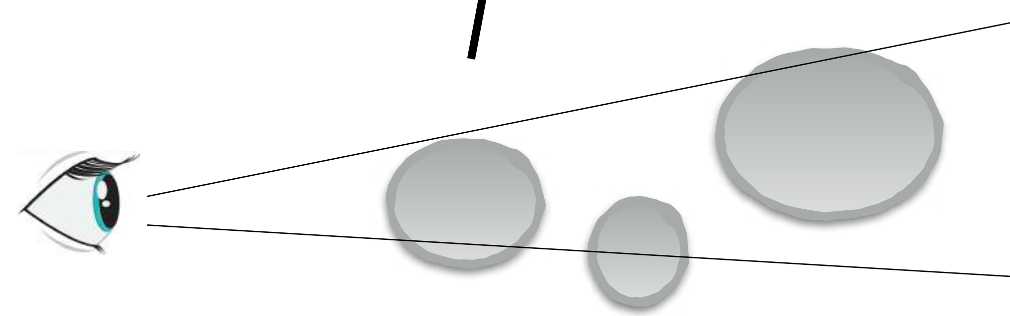
The signal

In the case of WIMPs

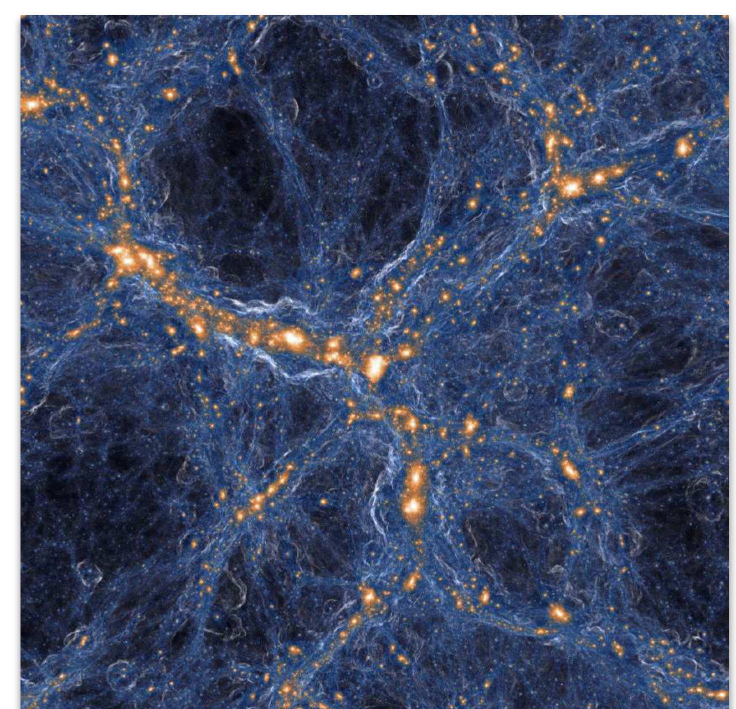
particle physics

cosmology

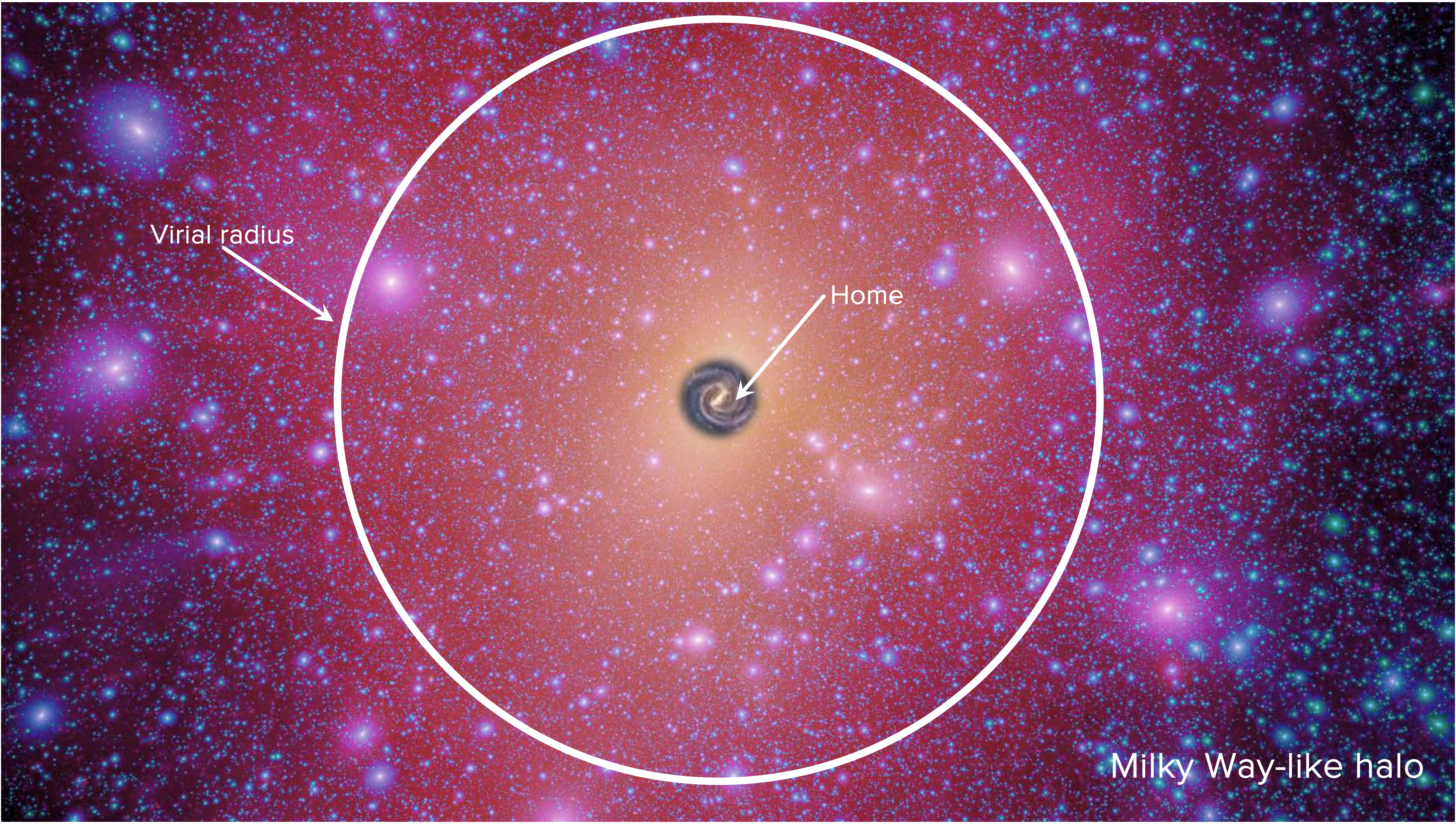
$$\boxed{\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma}} = \boxed{\frac{1}{4\pi}\;\frac{(\sigma_{\mathrm{ann}} v)}{2\, m_\chi^2}} \;\mathrm{X}\; \boxed{\sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma}} \;\mathrm{X}\; \boxed{\int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\, \rho^2(s, \Omega)}$$



- ⋆ **DM density distribution needed**
  - ⋆ **From N-body simulations**
  - ⋆ **Or observations of gravitation field tracers**

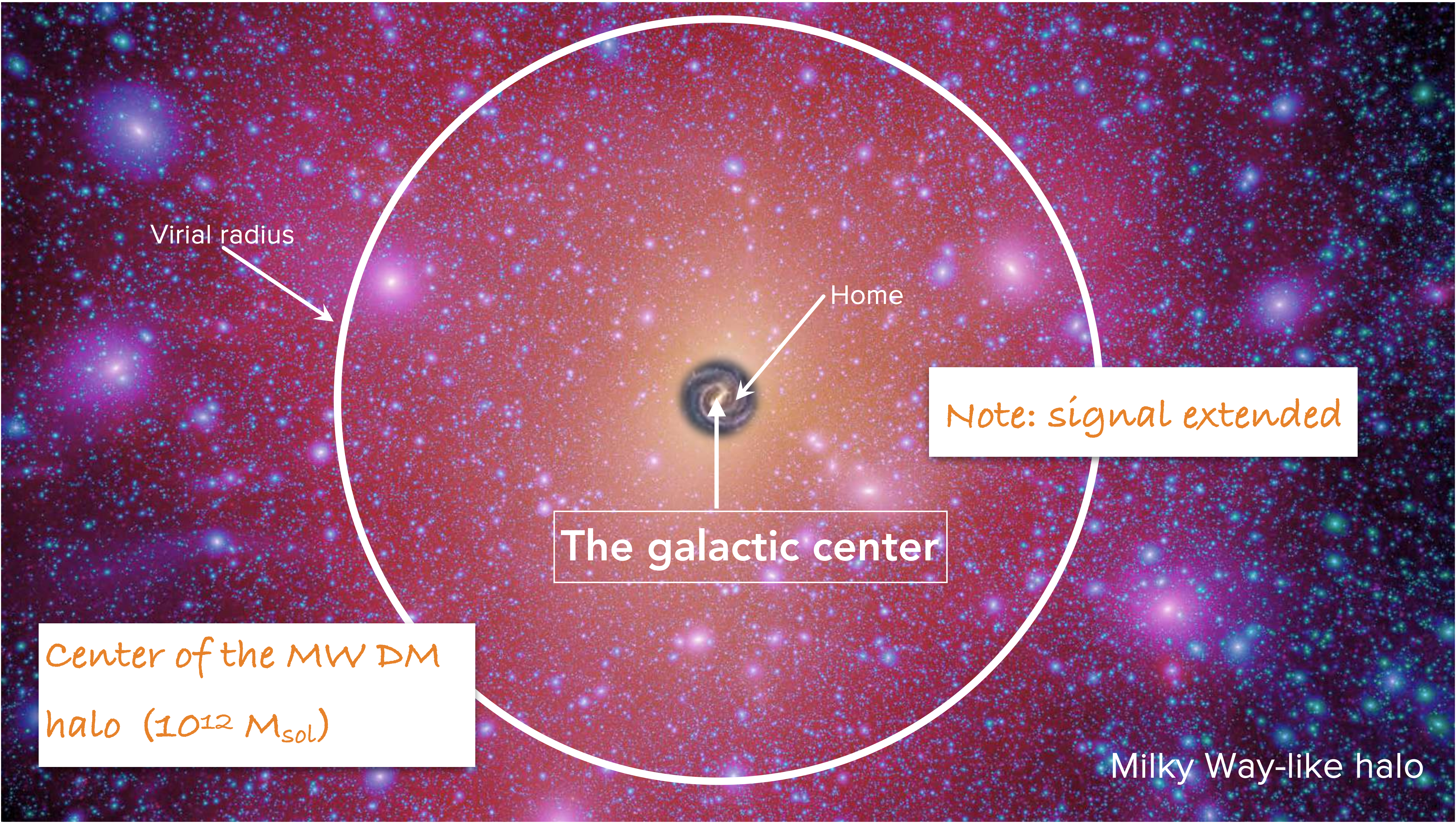


Where to look - DM density map (N-body simulations)



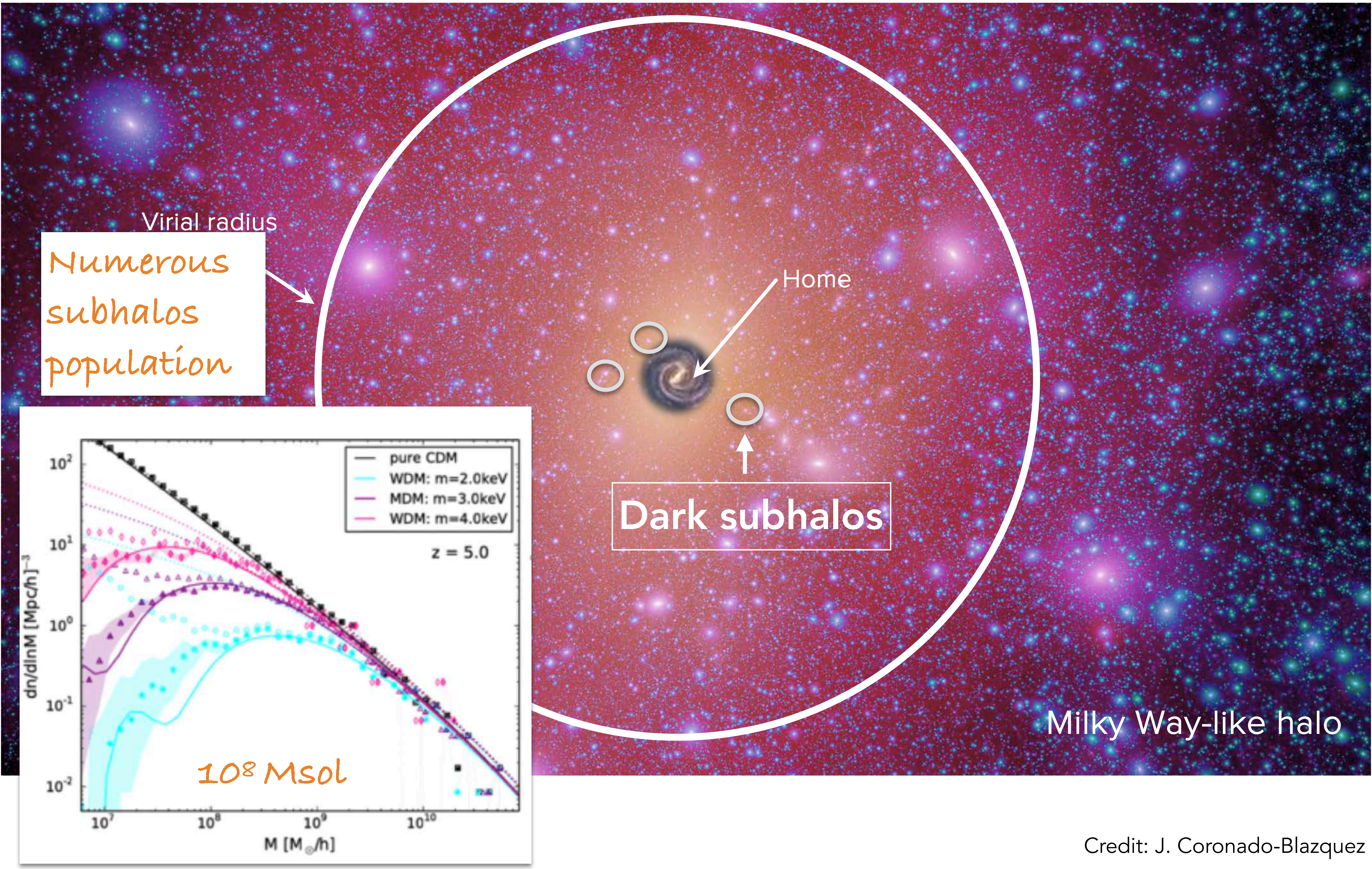
Credit: J. Coronado-Blazquez

Targets



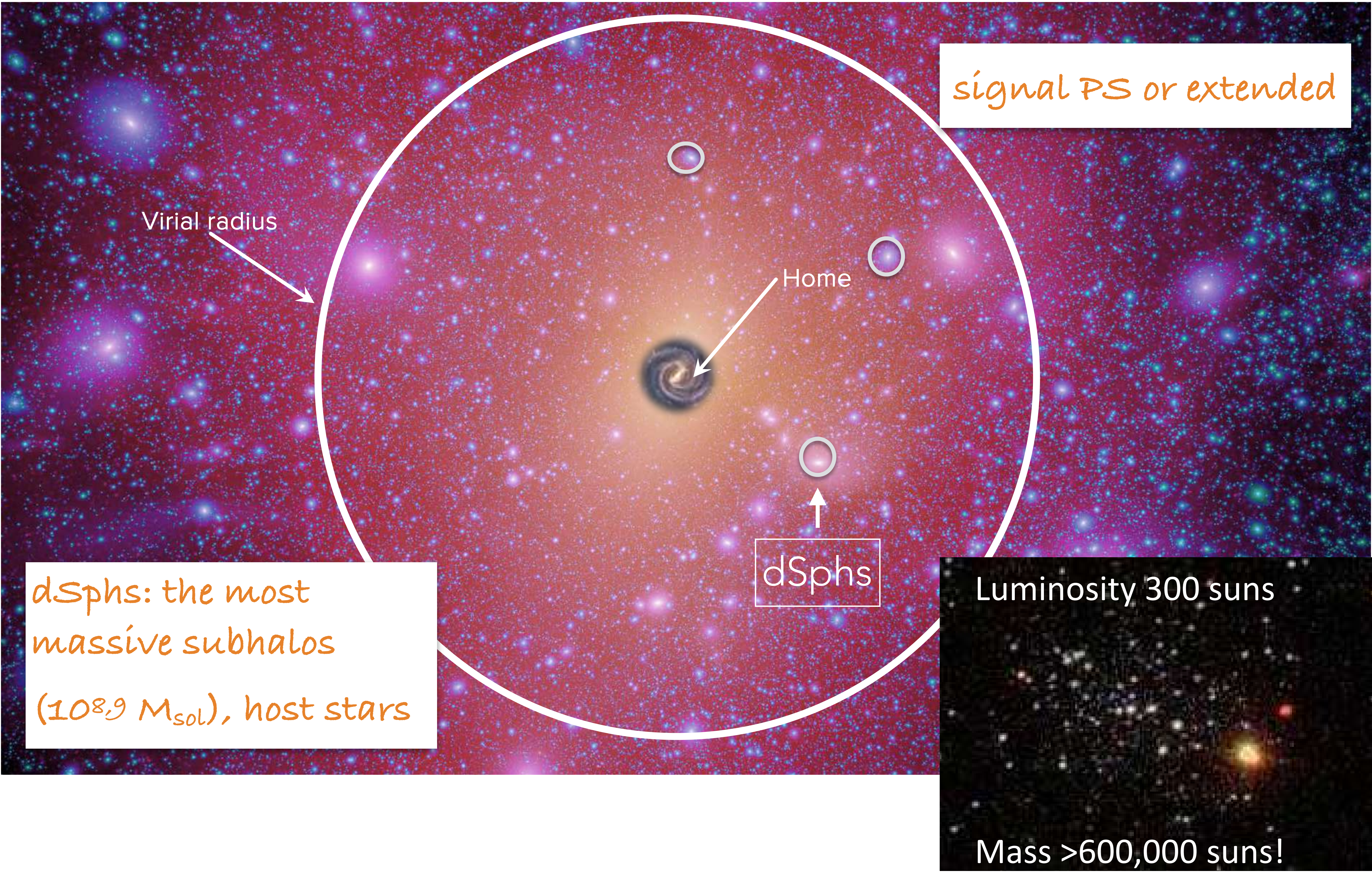
Credit: J. Coronado-Blazquez

Targets



Credit: J. Coronado-Blazquez

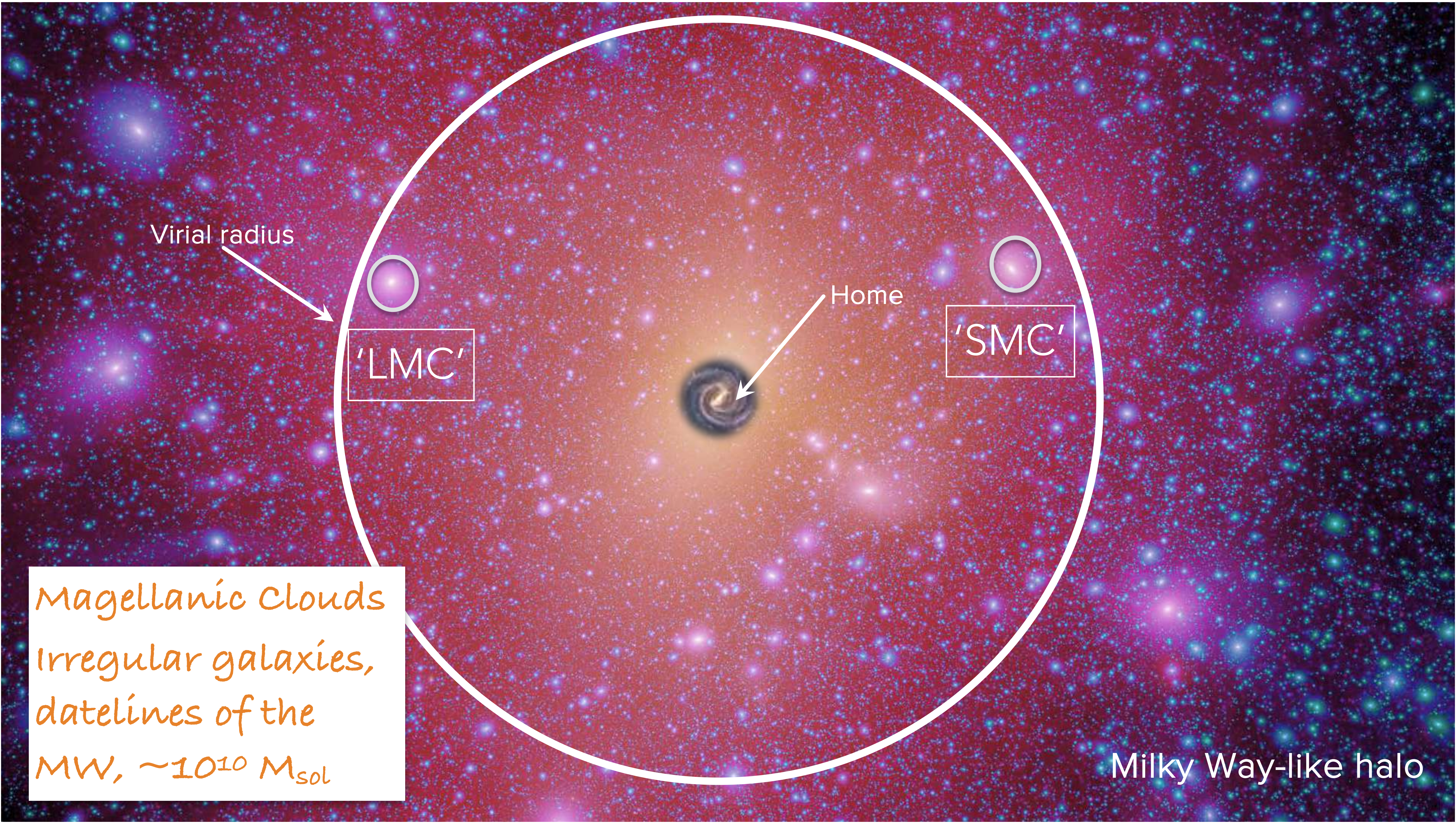
Targets



signal PS or extended

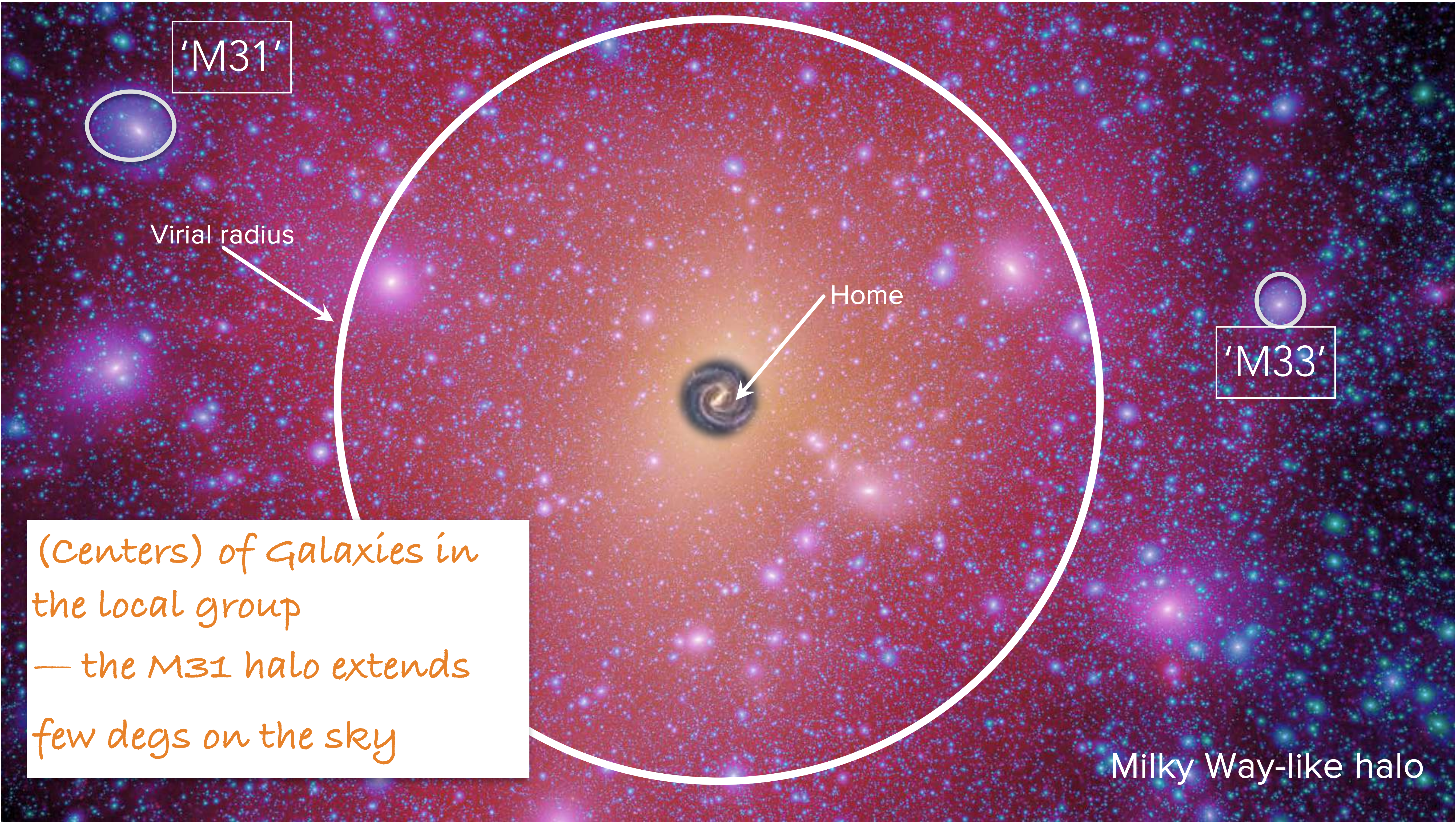
dSphs: the most massive subhalos ($10^{8,9}$ M_{sol}), host stars

Targets



Credit: J. Coronado-Blazquez

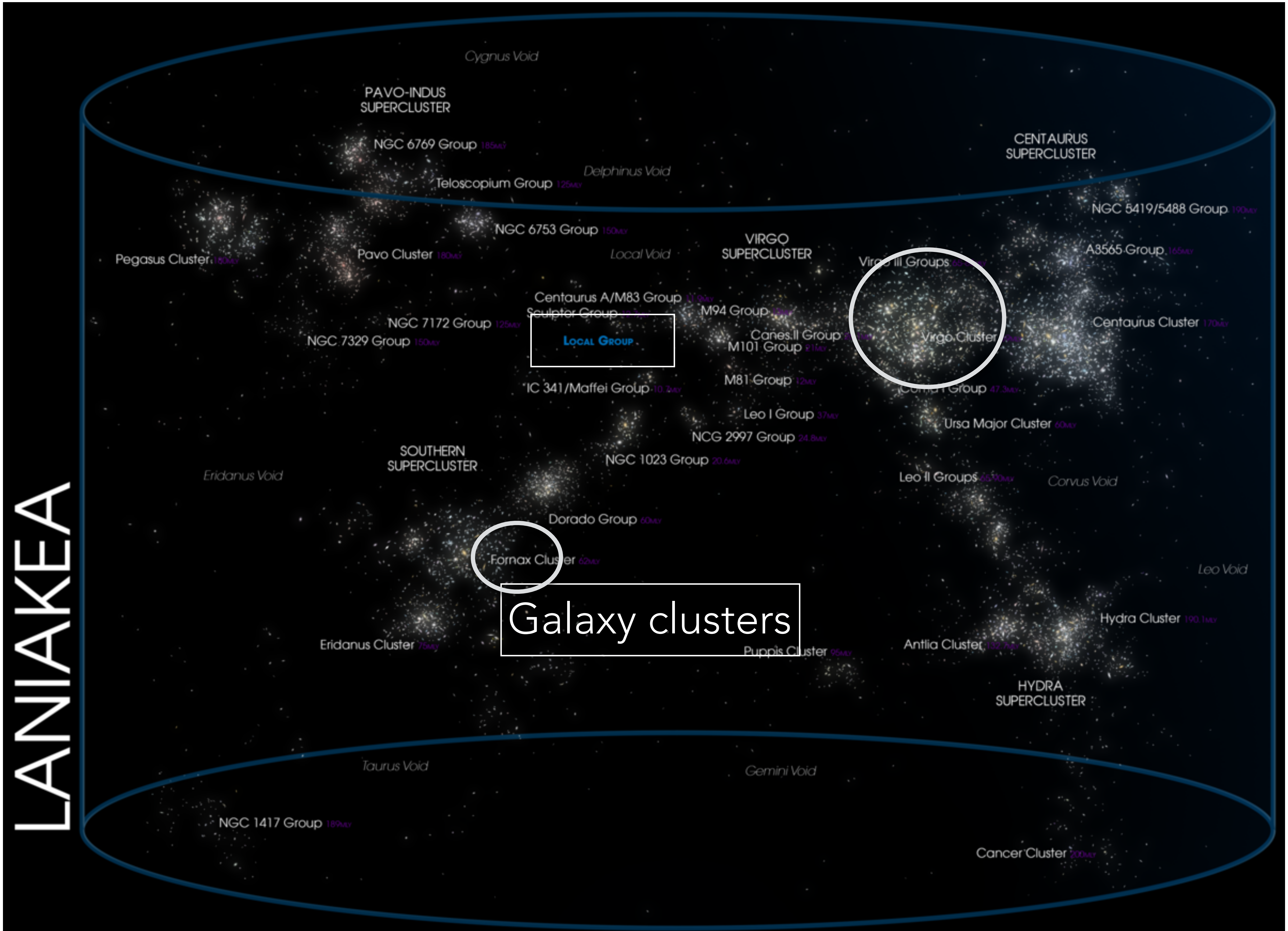
Targets



(Centers) of Galaxies in the local group
— the M31 halo extends few degs on the sky

Credit: J. Coronado-Blazquez

Targets



LANIAKEA
Cygnus Void
PAVO-INDUS SUPERCLUSTER
NGC 6769 Group
Teloscopium Group
Delphinus Void
CENTAURUS SUPERCLUSTER
NGC 5419/5488 Group
NGC 6753 Group
Pegasus Cluster
Pavo Cluster
Local Void
VIRGO SUPERCLUSTER
Virgo III Groups
A3565 Group
Centaurus A/M83 Group
Sculptor Group
M94 Group
NGC 7172 Group
NGC 7329 Group
Local Group
Canes II Group
M101 Group
Virgo Cluster
Centaurus Cluster
IC 341/Maffei Group
M81 Group
Coma I Group
Leo I Group
Ursa Major Cluster
NCG 2997 Group
SOUTHERN SUPERCLUSTER
Eridanus Void
NGC 1023 Group
Leo II Groups
Corvus Void
Dorado Group
Fornax Cluster
Leo Void
Galaxy clusters
Hydra Cluster
Eridanus Cluster
Antlia Cluster
Puppis Cluster
HYDRA SUPERCLUSTER
Taurus Void
Gemini Void
NGC 1417 Group
Cancer Cluster

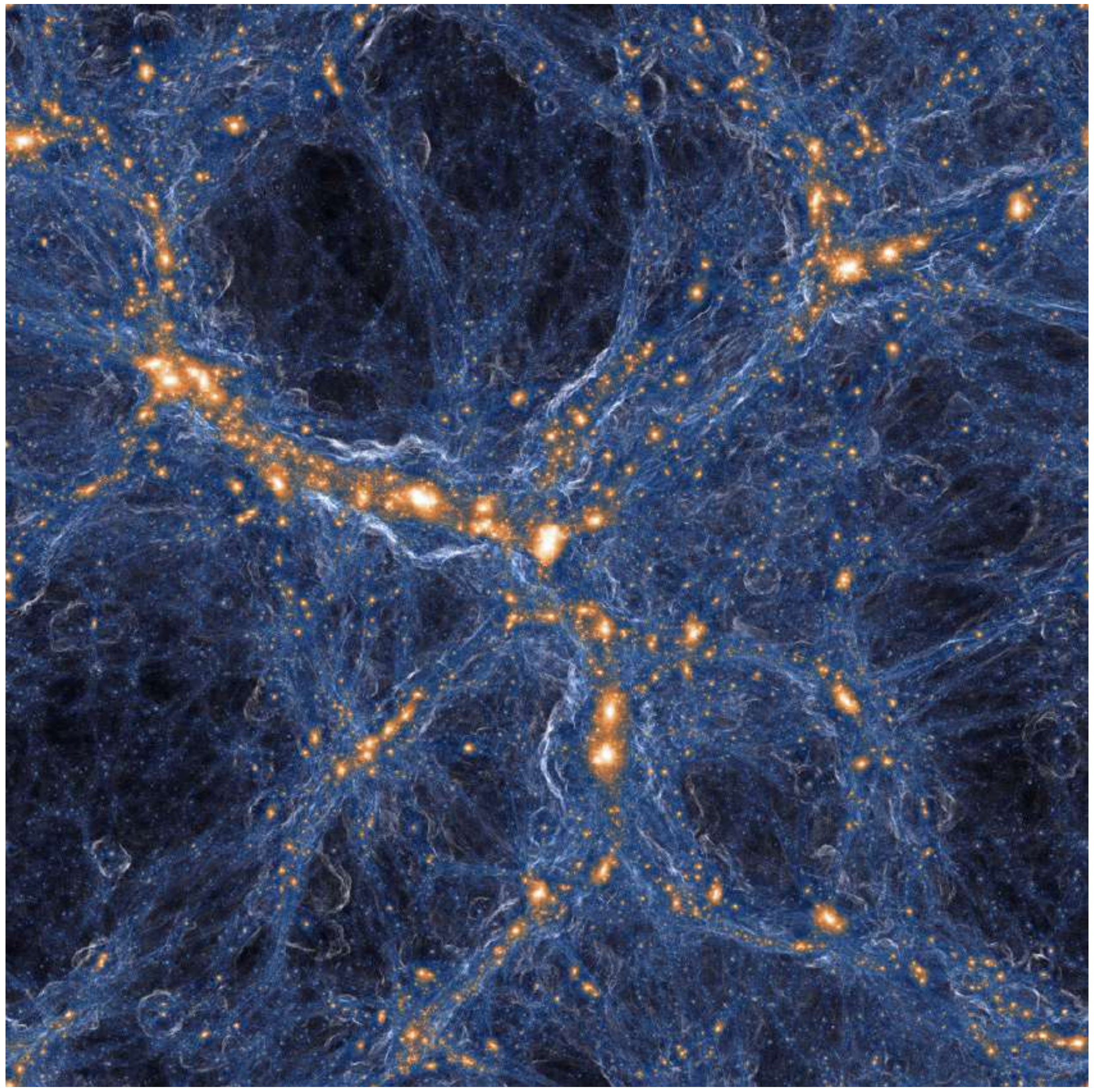
Targets

Together with analysis of individual targets, target ***assembles*** can be used in various statistics frameworks:

— cumulative extragalactic signal

— angular anisotropies

— cross-correlations between gamma ray maps and DM tracer maps (weak lensing, galaxy catalogues..)



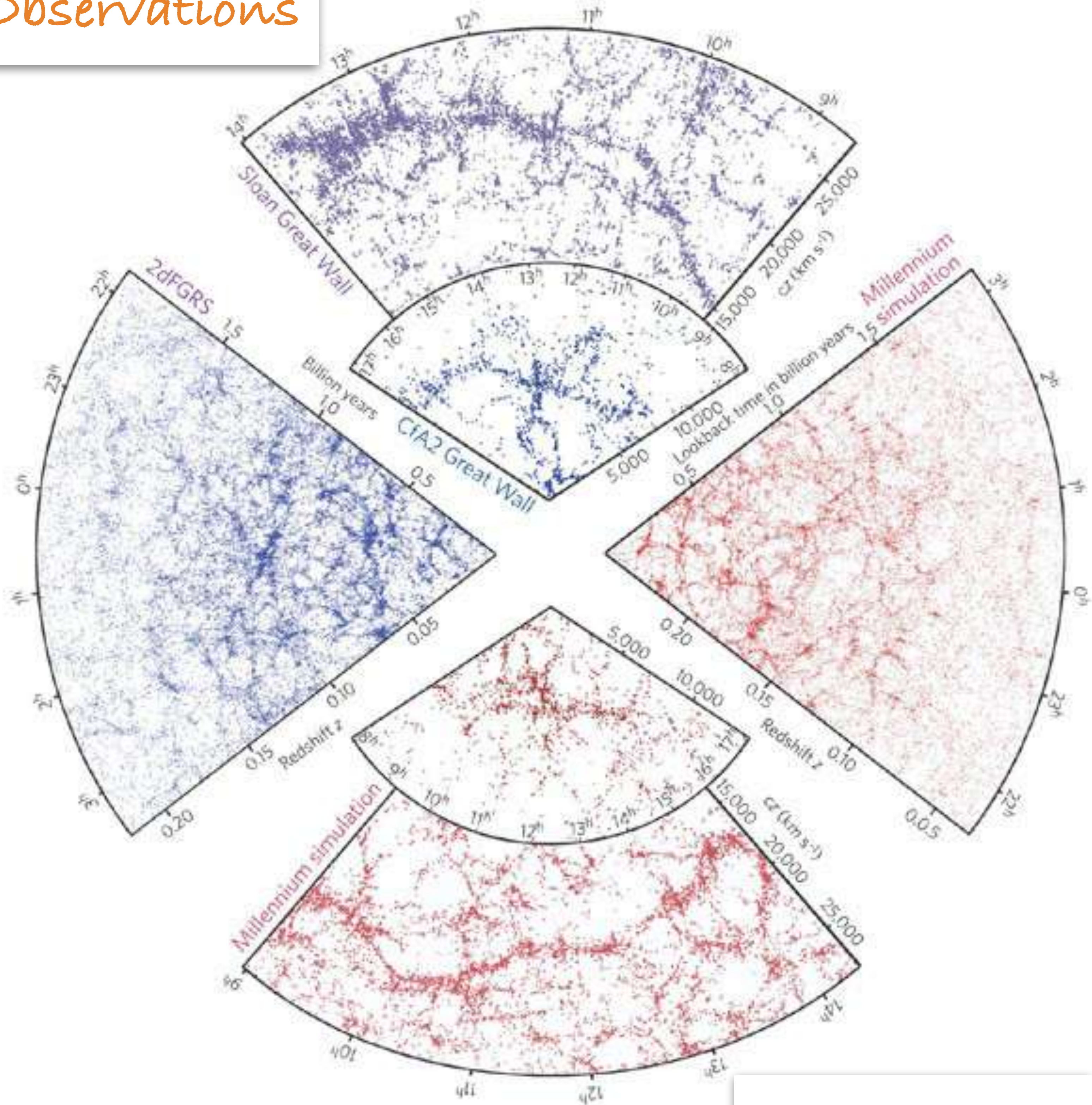
[TNG100 simulation]

Main uncertainties in DM signal prediction

N-body simulations and observations agree on large scales (>~galaxies). However, DM density distribution **poorly constrained on small scales**!

Critical because signal is usually DOMINATED by small scales (e.g. center of our Galaxy) or by annihilation in small halos (which are the most concentrated)

Observations



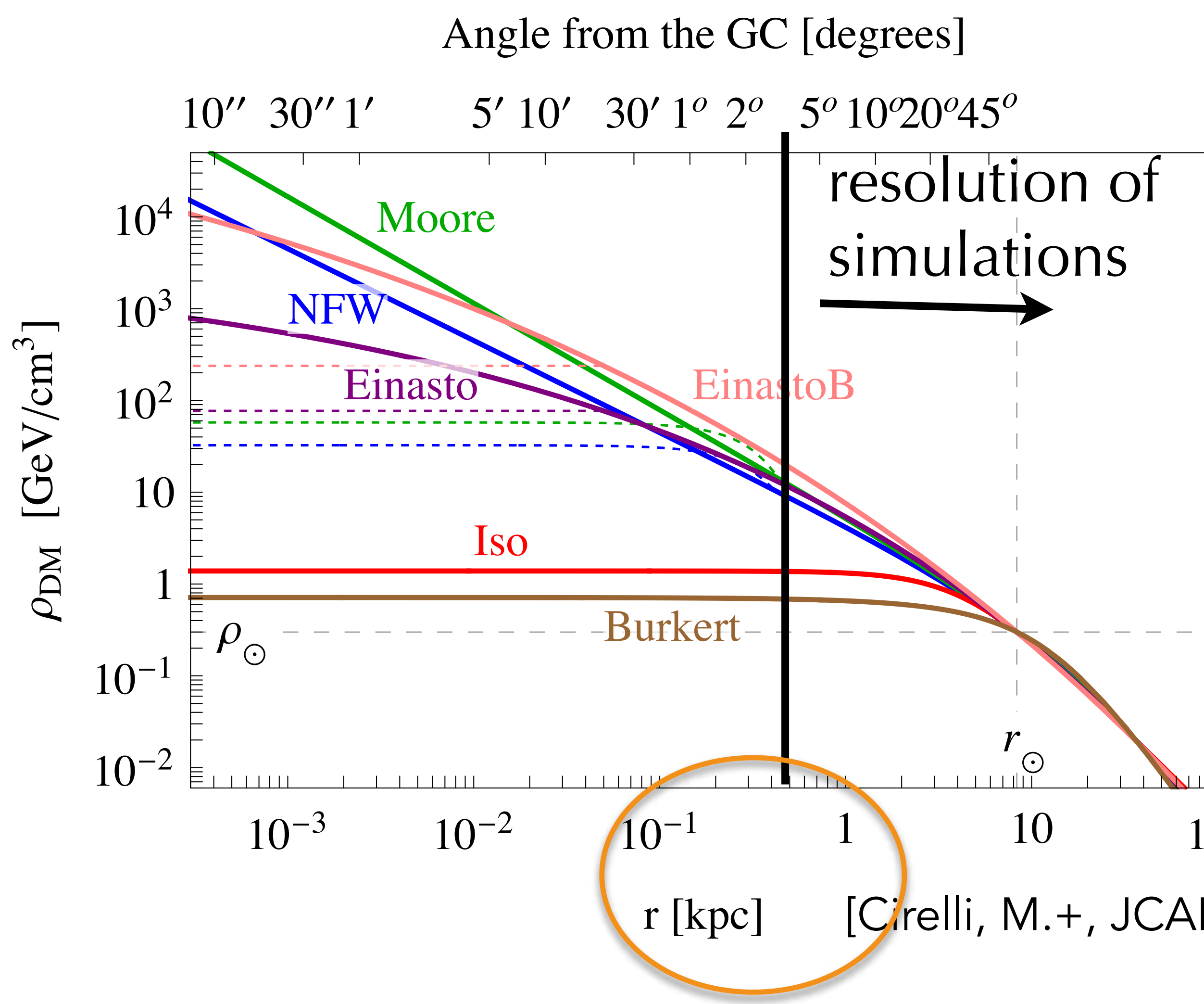
Simulations

Uncertainty in DM density distribution

N-body simulations: issues 01

- ***limited resolution-> small distances and small masses unresolved***.

recall for WIMPs signal~ $$\int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\, \rho^2(s,\Omega)$$



[Cirelli, M.+, JCAP, 2011]

(sub)halos resolved down to >~10^5 M_{sol}.

WIMPs could produce halos as small as 10^{-6} M_{sol}.

Uncertainty in DM density distribution

N-body simulations: issues 02

- ***baryonic feedback*** baryons can dominate gravitational potential at small scales
- Challenge - simulations need to cover a large span of scales

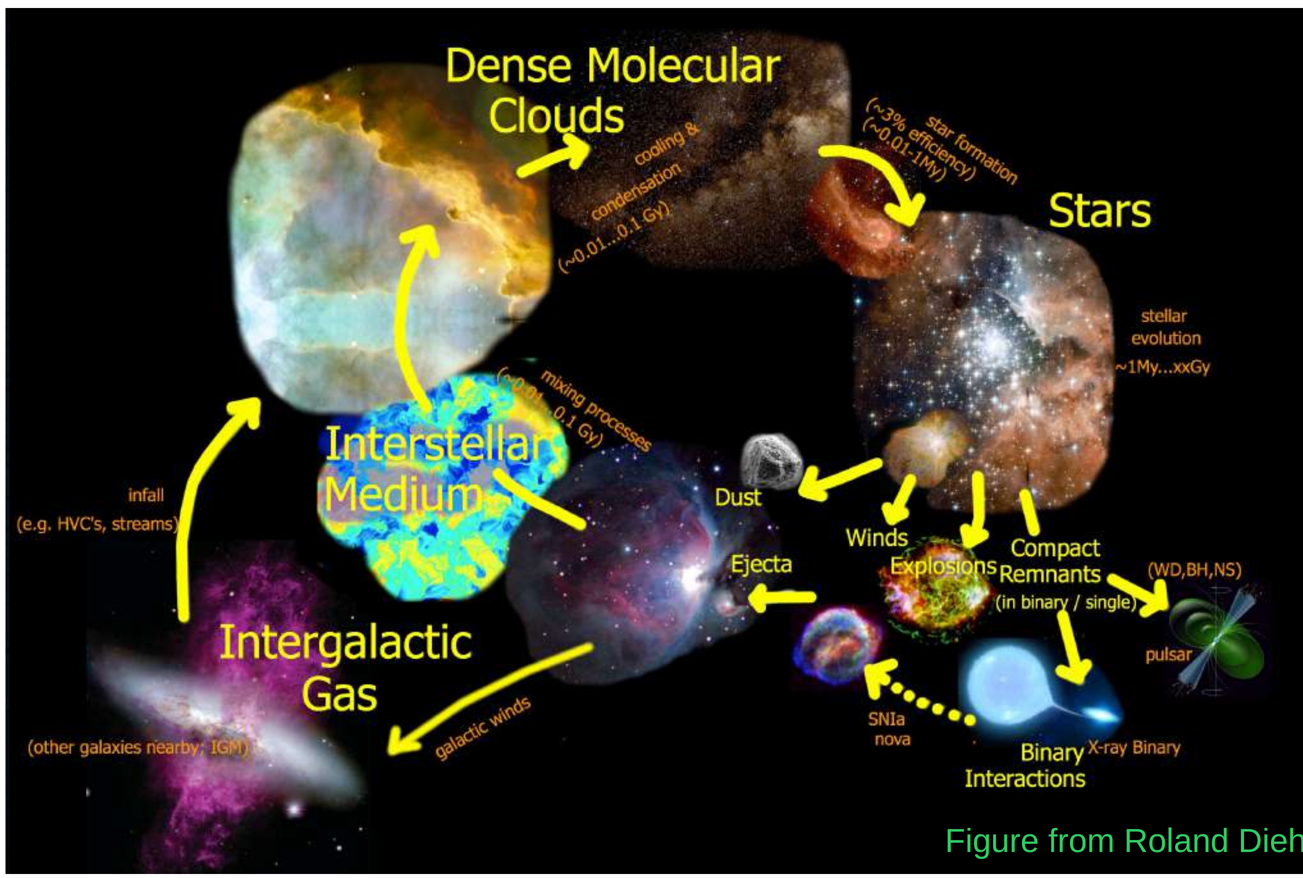
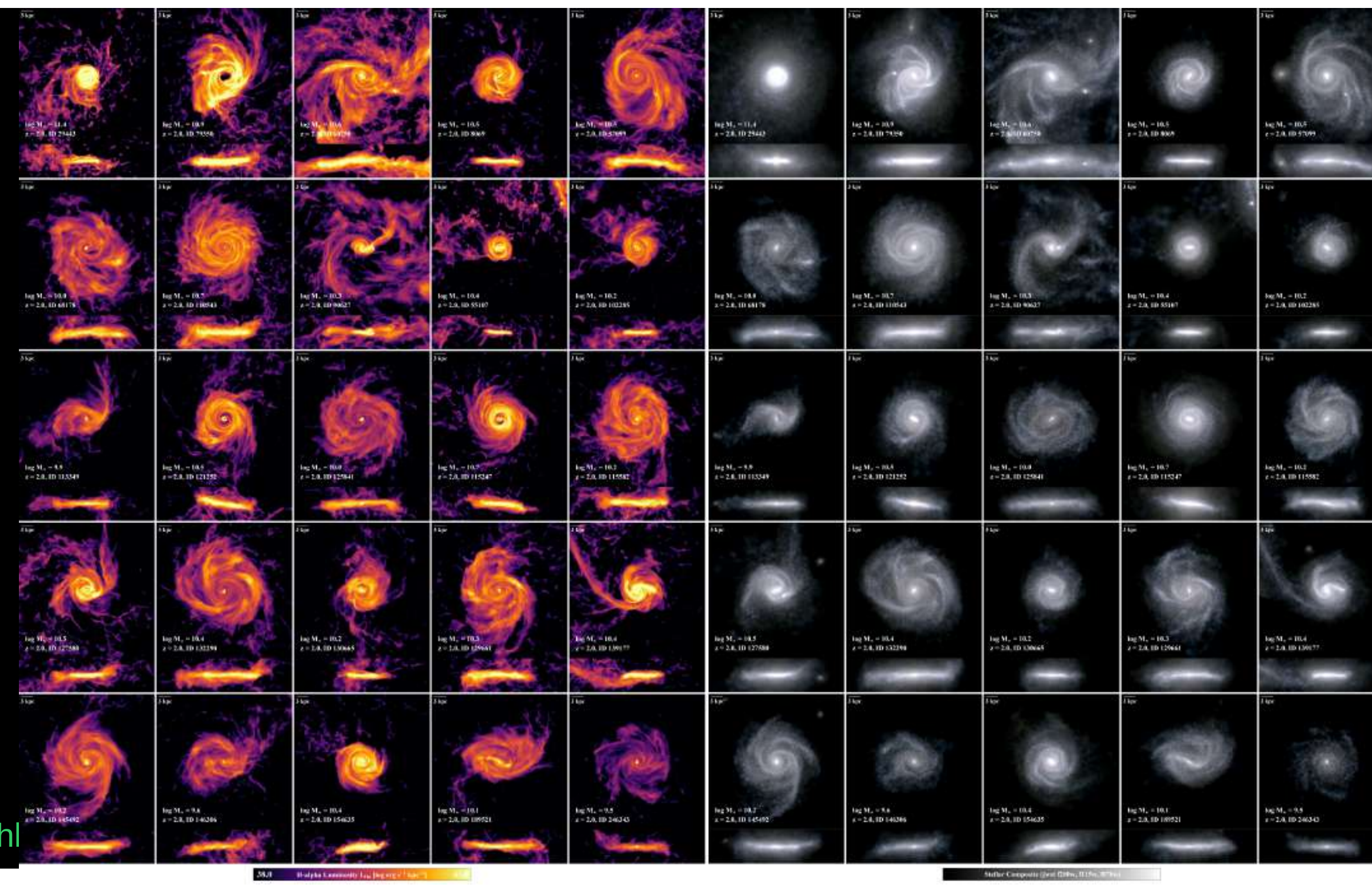


Figure from Roland Diehl



[TNG simulation]

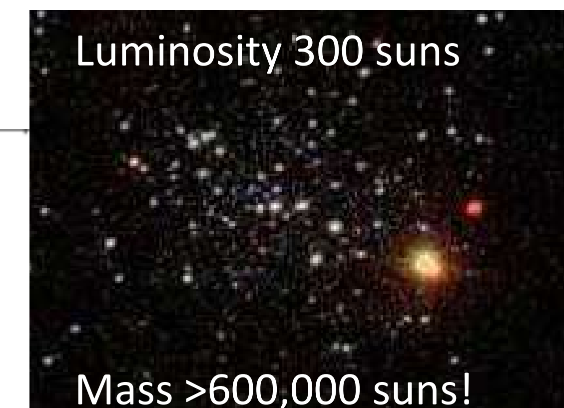
A number of simulations recover realistic disk Galaxies (great progress!), but still a number of open issues

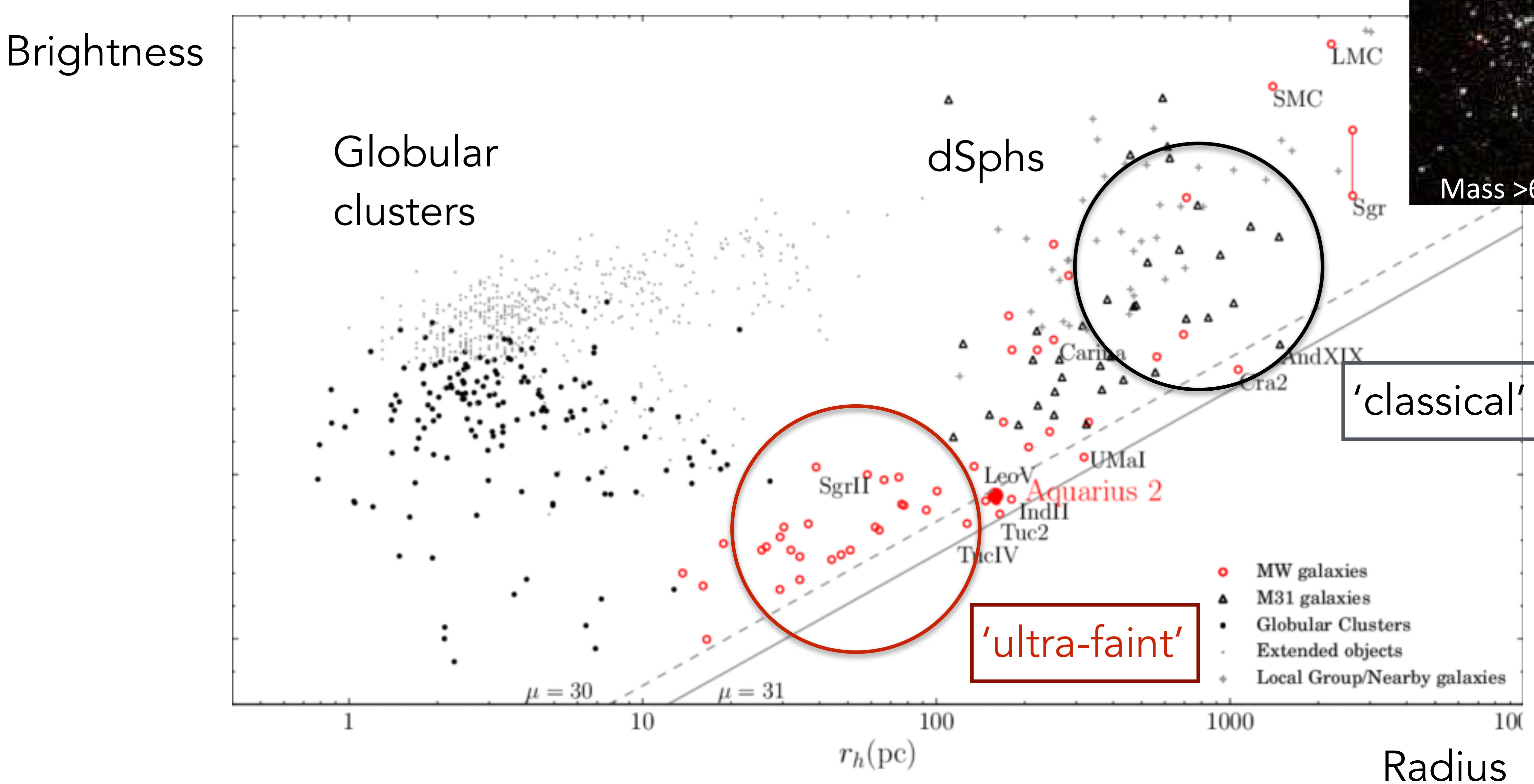
Uncertainty in DM density distribution

Observations - subhalos

different approach is to ***measure*** motion of stellar objects to determine the gravitational potential of DM. For example:

- ***dwarf spheroidal Galaxies:*** the smallest DM halos (10^8, 10^9 Msol) that host stars



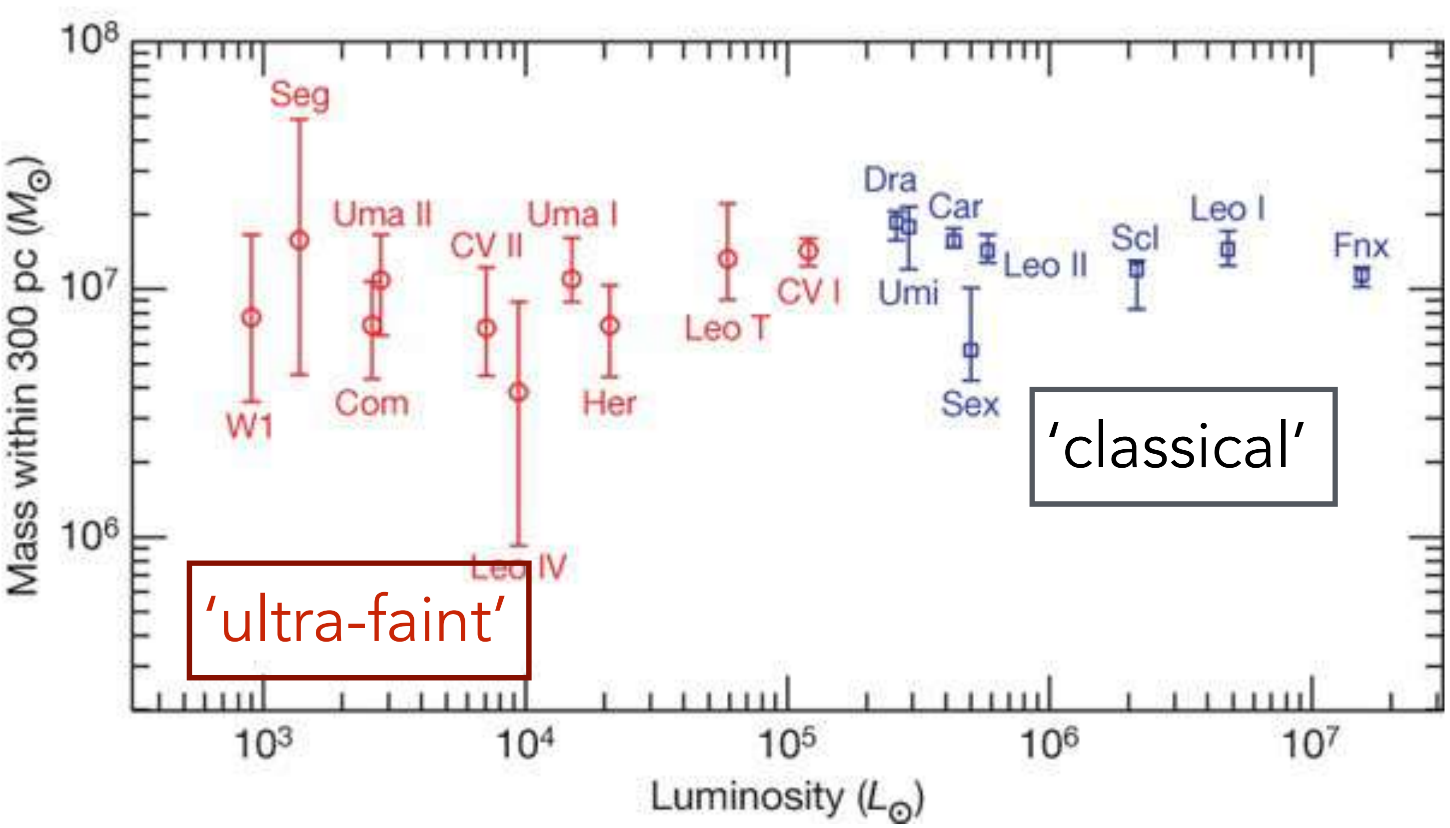


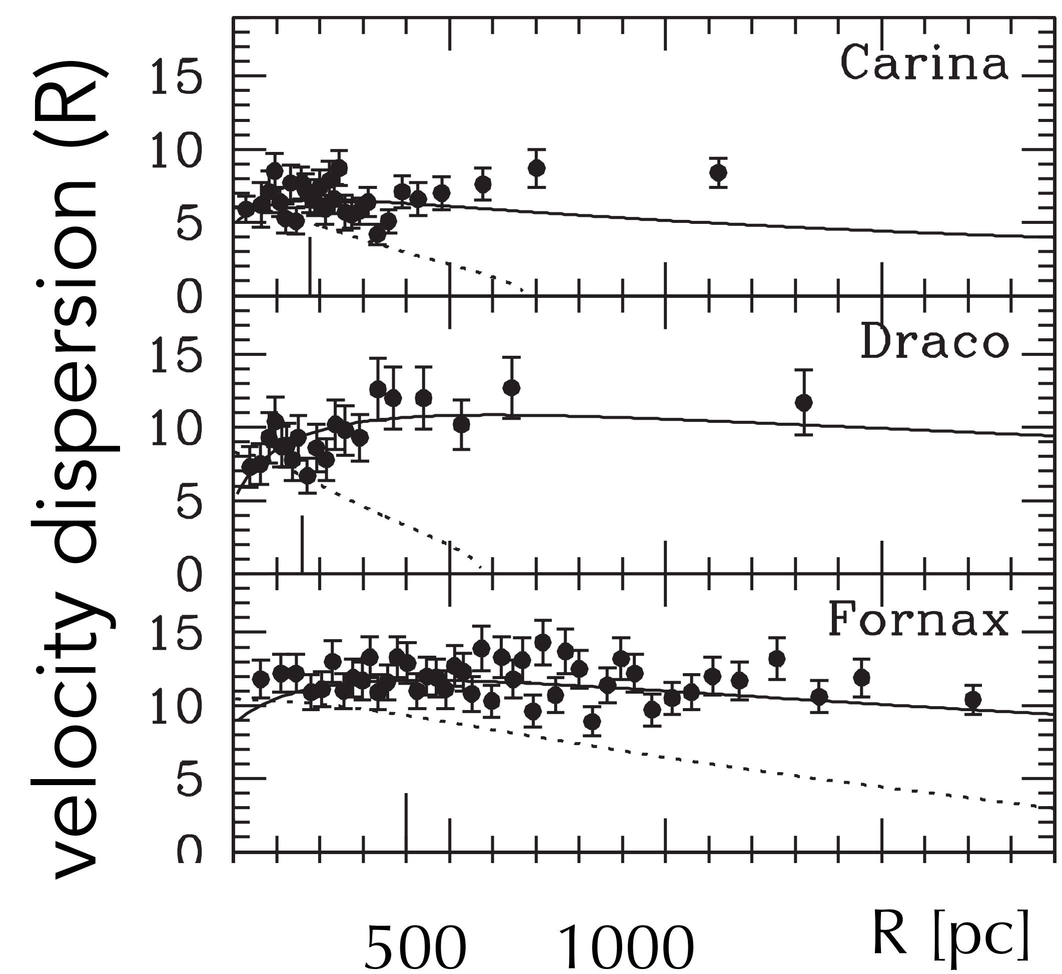
Uncertainty in DM density distribution

Observations - subhalos

different approach is to ***measure*** motion of stellar objects to determine the gravitational potential of DM. For example:

- ***dwarf spheroidal Galaxies:*** Assuming virialization, each population traces the gravitational potential, and we can use the **spherical Jeans equation** to link the measured velocity dispersion and the dSph gravitational potential



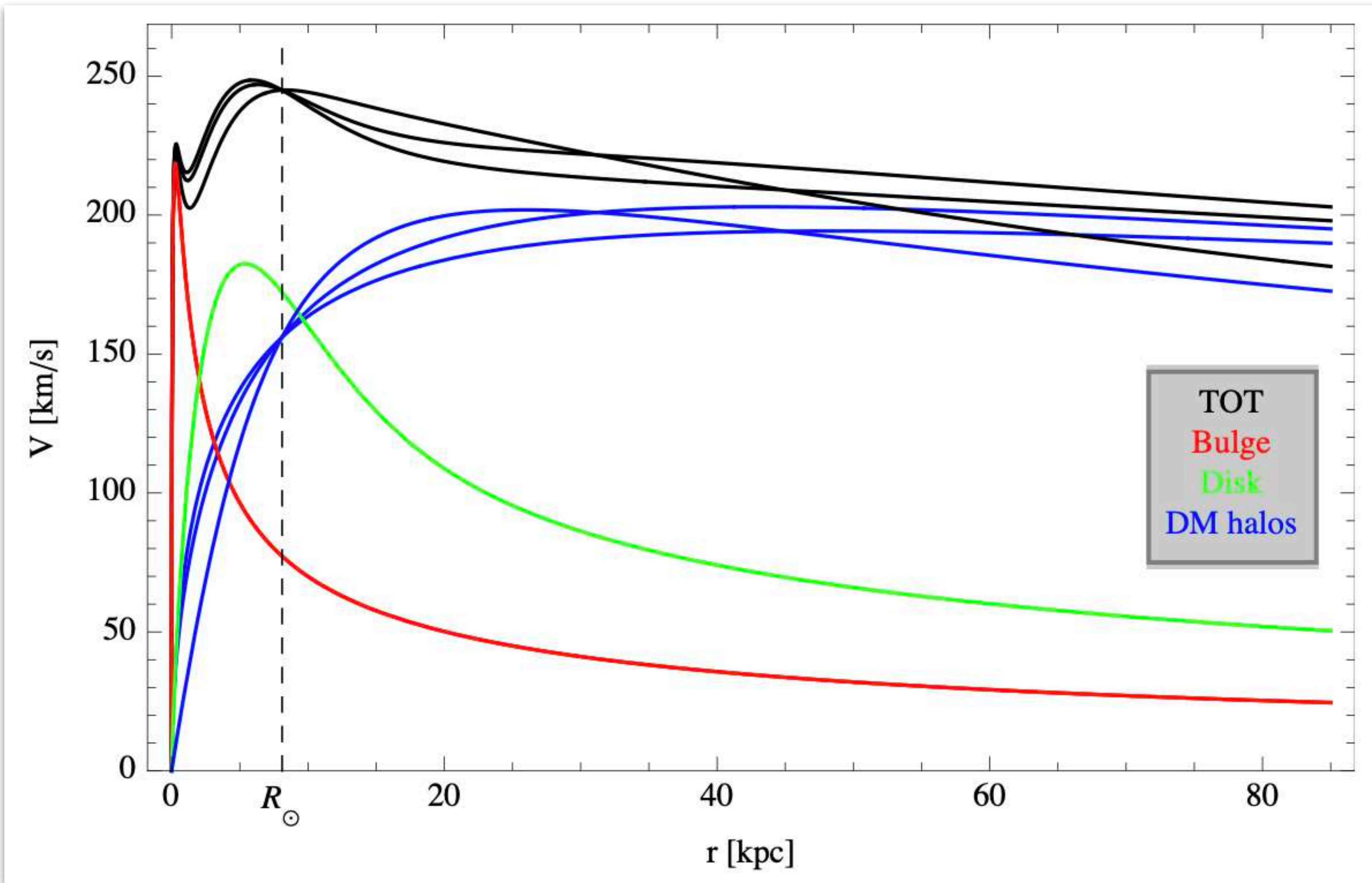


[Walker+, 2007]

Uncertainty in DM density distribution

Observations - galaxy center

- in the very **centers of halos** gravitational potential is usually dominated by baryons, or hard to determine.



Uncertainty in DM density distribution

In a nutshell

We use N-body simulations AND observation of DM tracers to track DM density profile. Both methods ‘fail’ at small scales

- **small (sub)halos** have few or NO stars/unresolved in simulations and
- in the very **centers of halos** gravitational potential is usually dominated by baryons, or hard to determine/unresolved in simulations

➡ **Considerable uncertainties remain!**

Summary

— gamma rays are a great messenger (also for DM search :)
— N-body simulations tell us ‘where to look’
— uncertainties in signal prediction on small scales
— predicted signals often extended on the sky