DARK MATTER OVERVIEW

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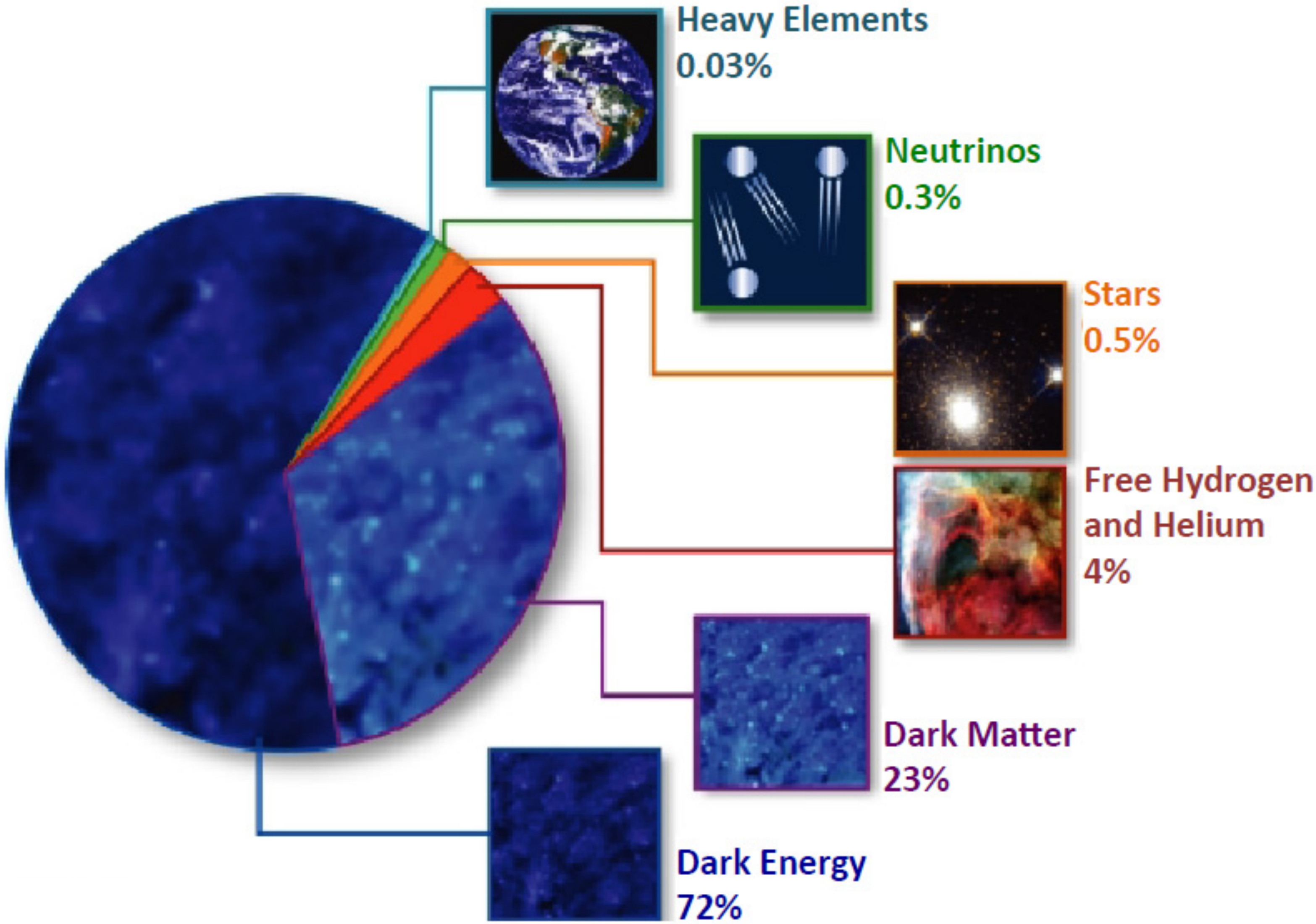
DEPARTMENT OF EXCELLENCE

Accelerating the Search for Dark Matter with Machine Learning

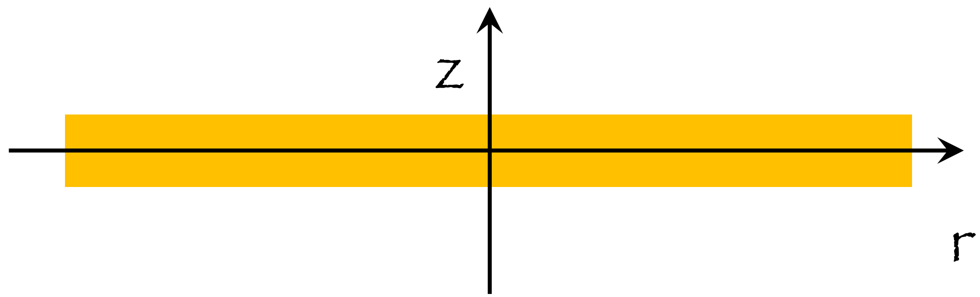
Lorentz Center @ Oort, Leiden – 15.01.2018

The Dark Universe



DM Evidence – Local Scale (Oort)

- Galaxy modeled as a disk



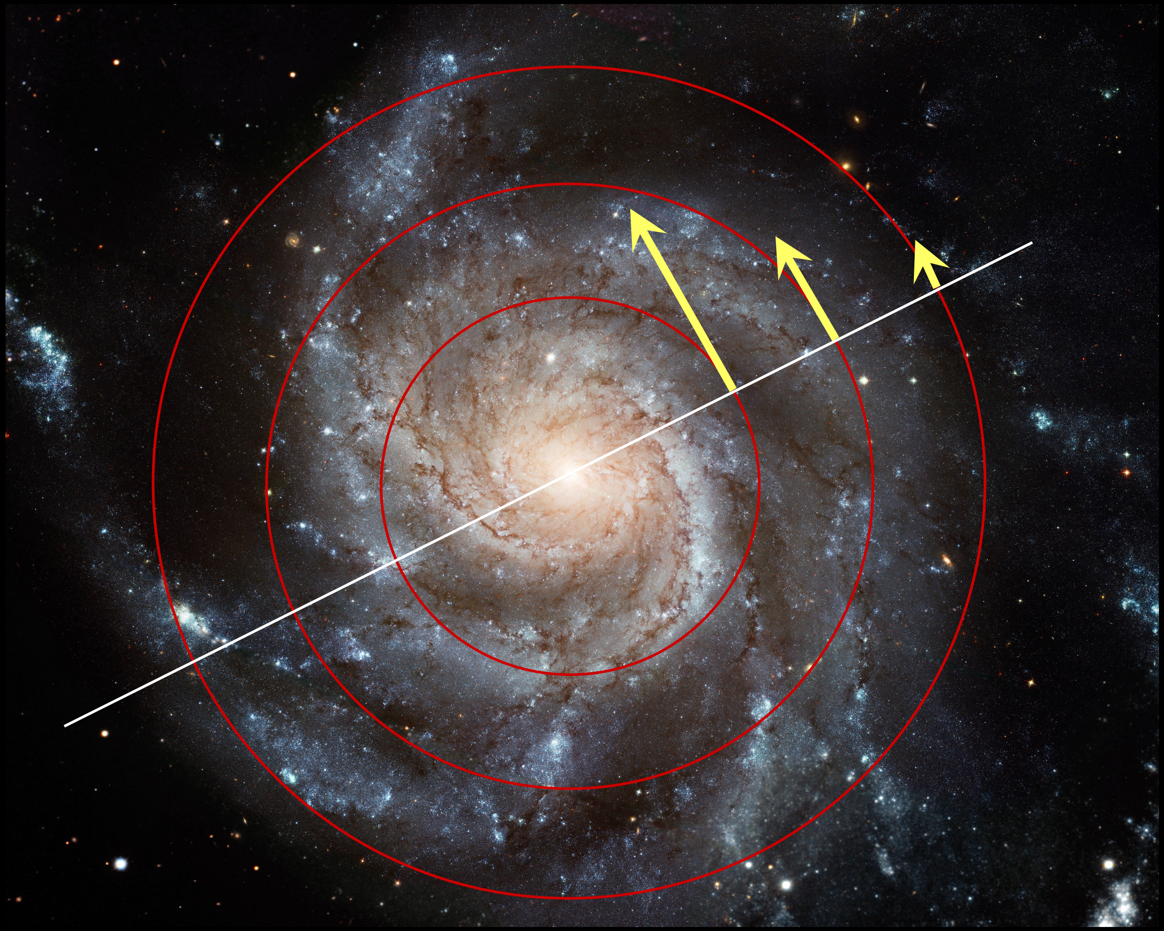
- Dominant gradients are vertical:

$$\frac{1}{n}\frac{d(n\,v_z^2)}{d\,z} = -\frac{d\Phi}{d\,z}$$

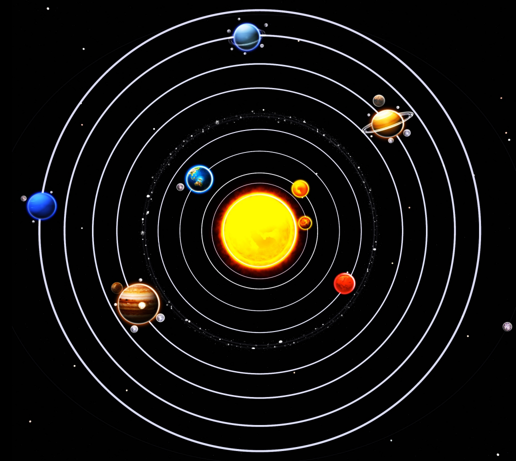
- Two ingredients needed:
  - A tracer of the density above the plane (e.g. bright stars)
  - Measurement of the vertical dispersion velocity of the tracers

$$\Phi \longrightarrow \text{mass density}$$

DM evidence – Galactic scale



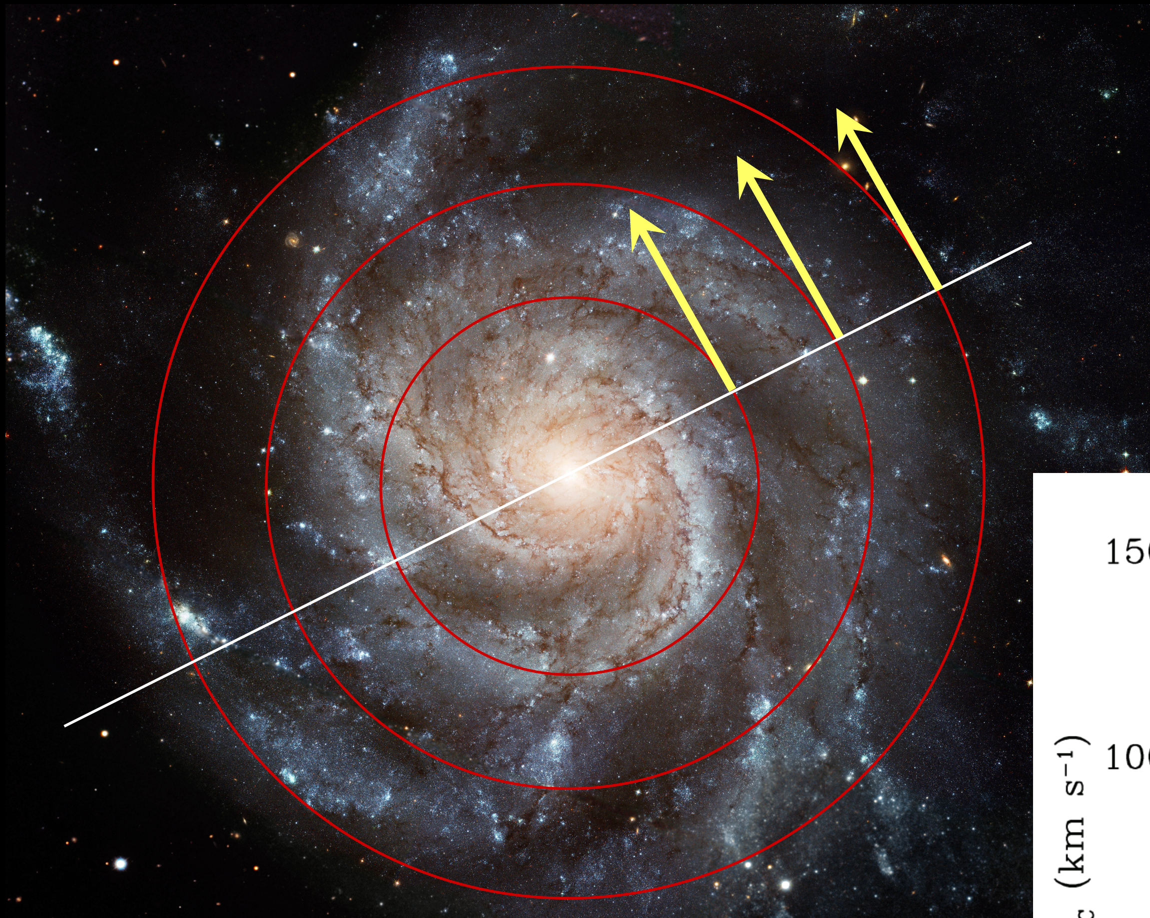
Spiral galaxy



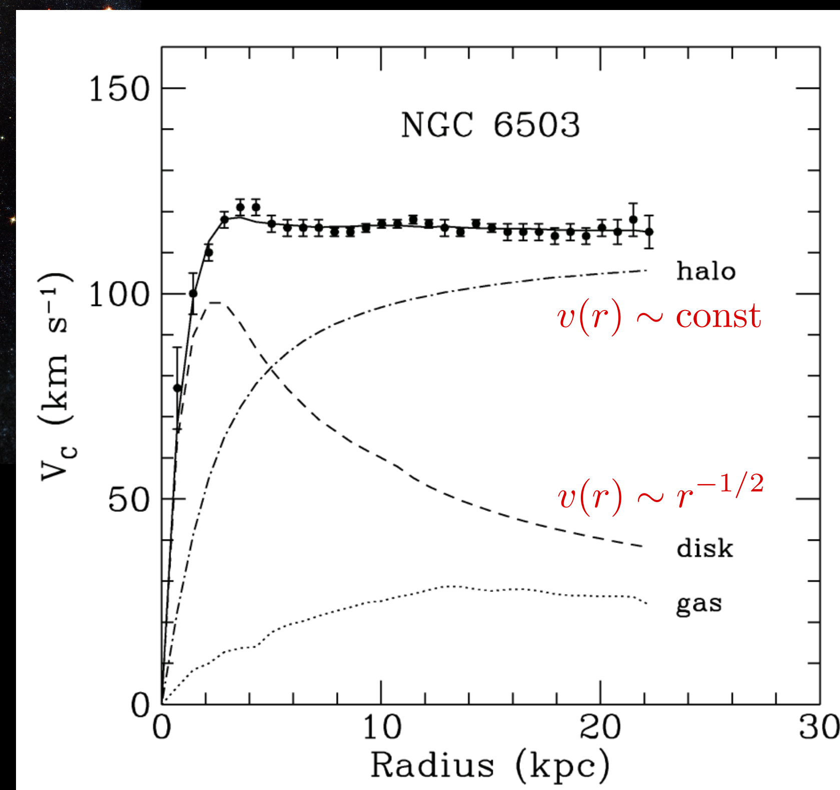
$v(r) \propto r^{-1/2}$

DM evidence – Galactic scale

Rubin (1970)

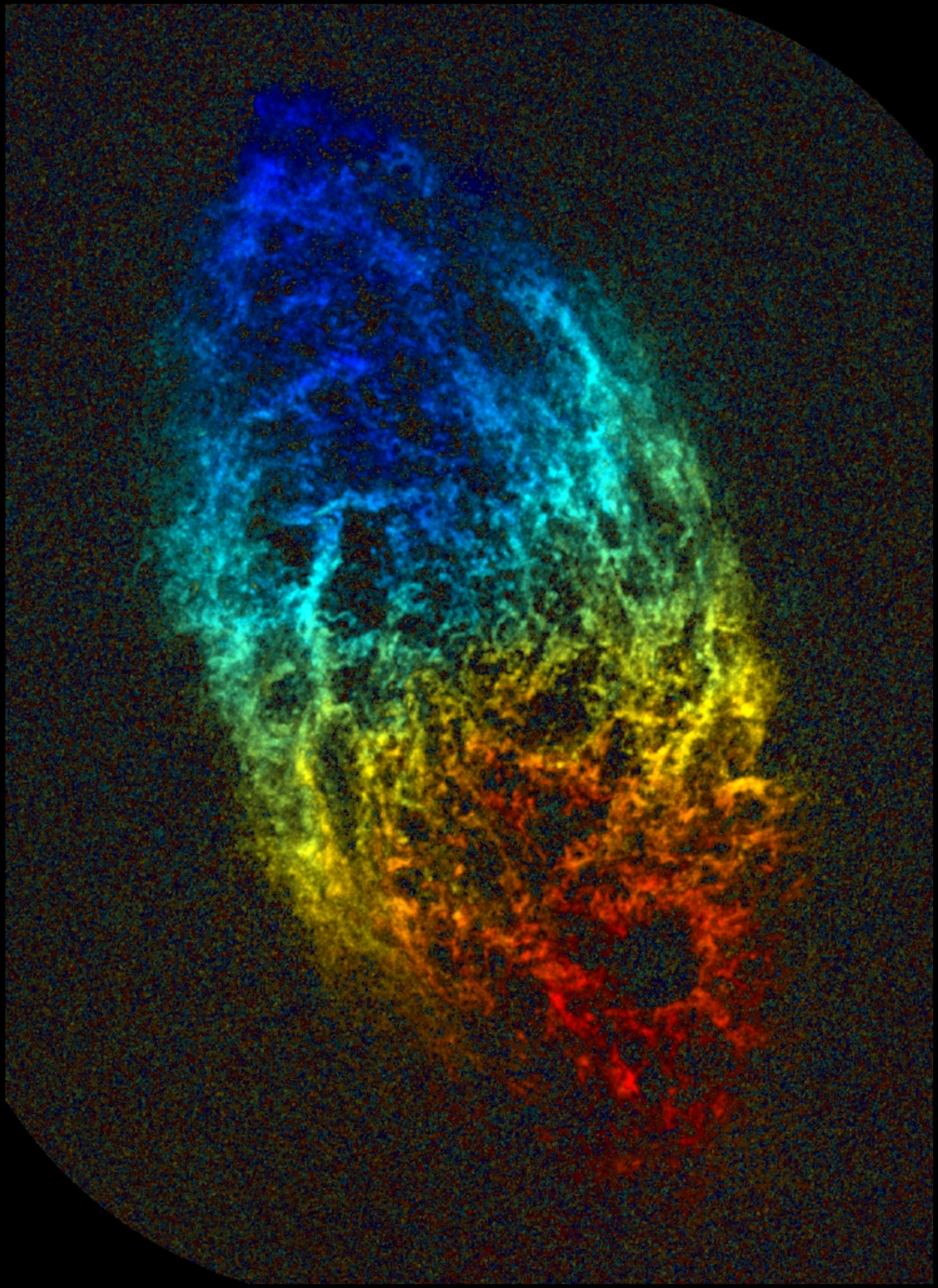


$$v(r) = \sqrt{M(r)/r}$$



Periferic stars and gas are faster than expected

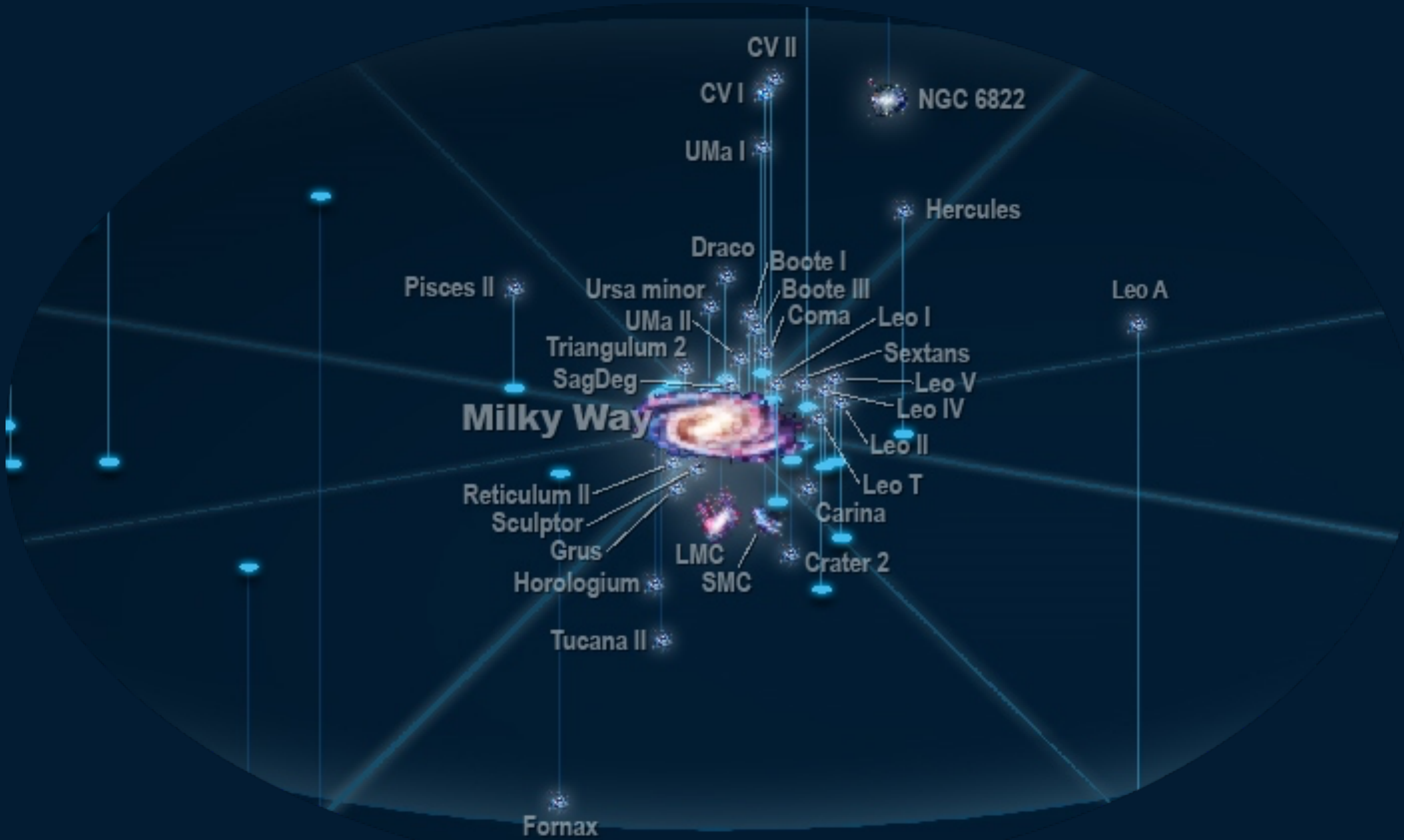
Faster = More mass



M33 (Pinwheel galaxy)
Hydrogen gas
Doppler image

VLA radio telescope

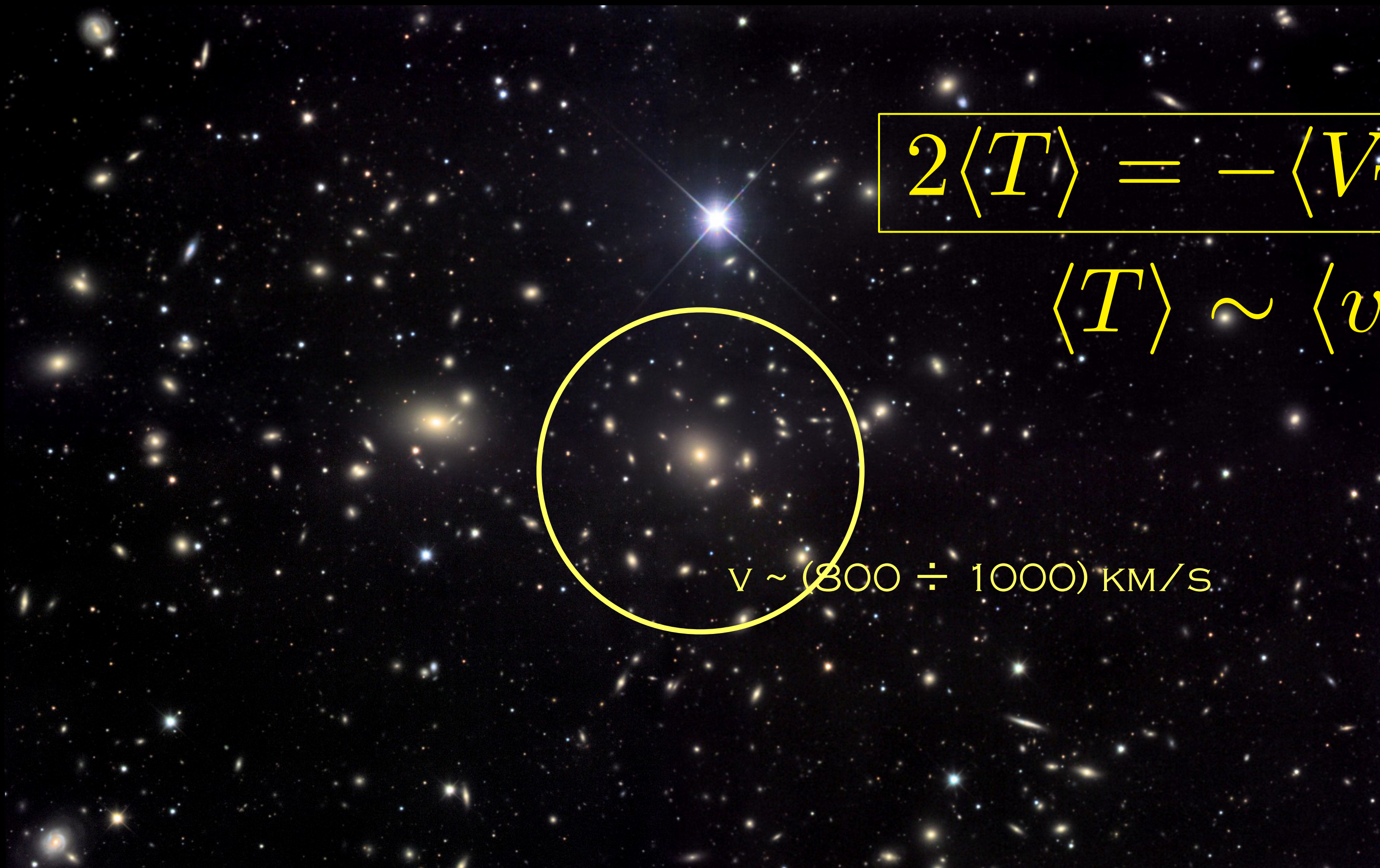
DM Evidence – Galactic Scale



Dwarf galaxies: largely DM-dominated

DM evidence – Cluster scale

Zwicky (1933)



$$2\langle T\rangle = -\langle V_{\mathrm{TOT}}\rangle$$

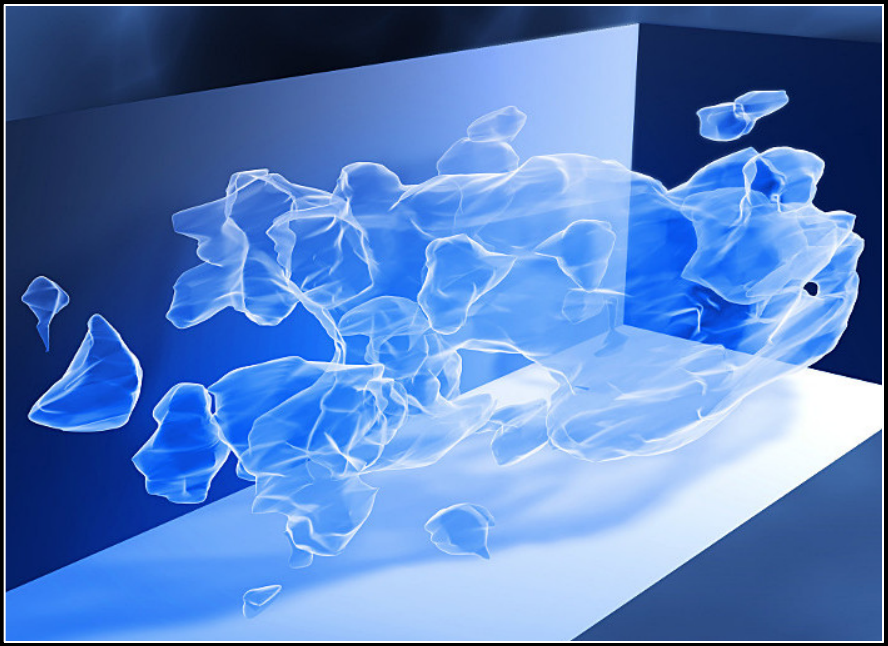
$$\langle T\rangle \sim \langle v^2\rangle$$

Velocity dispersion of galaxies in the cluster is too large: the cluster should "evaporate"

Much more mass than the visible one is needed

DM Evidence – Extragalactic Scale

Strong lensing

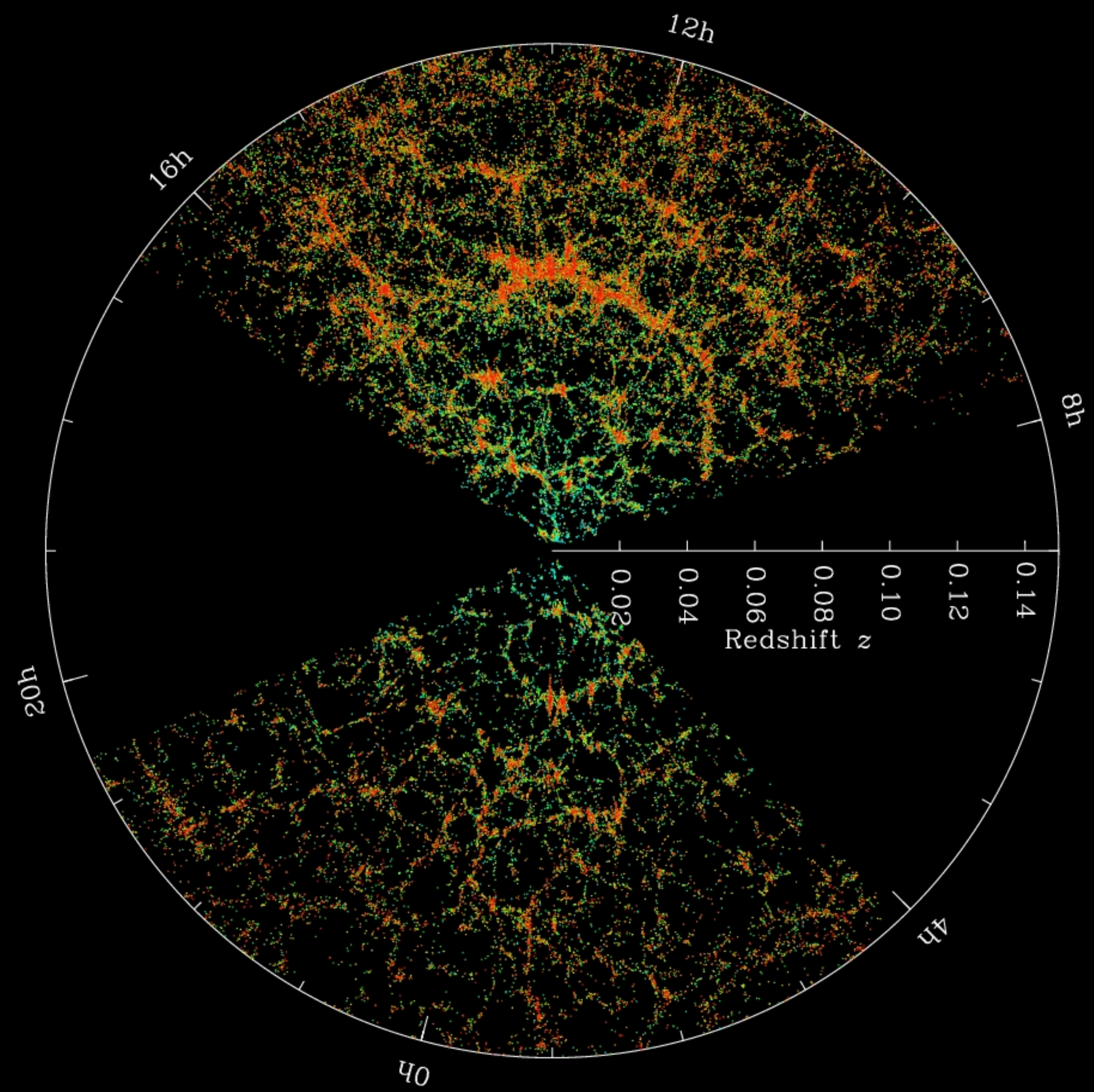


Weak lensing

Gravitational lensing

A large amount of mass between the background galaxies and us is inferred by the lensing effect

DM Evidence – Cosmological Scale



Sloan Digital Sky Survey

Overwhelming evidence

- Rotational curves of spiral galaxies
- Galaxy clusters dynamics
- Gravitational lensing
- Hydrodynamical equilibrium of hot gas in galaxy clusters
- Large scale structure of the Universe
- Energy budget of the Universe
- (The same theory of structure formation)

Overwhelming evidence

- DM evidence is purely gravitational
  - Rotational curves of spiral galaxies
  - Galaxy clusters dynamics
  - Gravitational lensing
  - Hydrodynamical equilibrium of hot gas in galaxy clusters
  - Large scale structure of the Universe
  - Energy budget of the Universe
  - (The same theory of structure formation)

New Particle or Modified Gravity?

- DM evidence is purely gravitational

- This evidence could be ascribed either to:
  - We do not understand gravity beyond our local environment (basically: solar system)
  - A new type of matter, i.e. a new particle, exists
    - No viable candidate in the SM: New Physics

Solutions not involving new particles

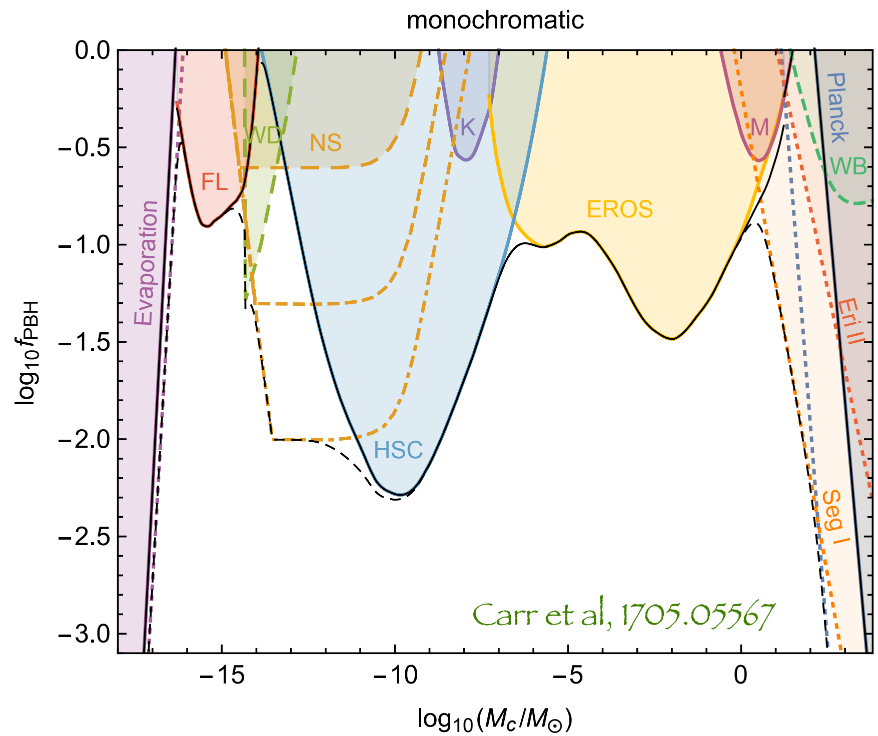
The DM issue is not a problem of particles, but of Gravity

- Modified Newtonian Dynamics
- Gravity beyond General Relativity

Primordial black holes *might* solve the DM problem

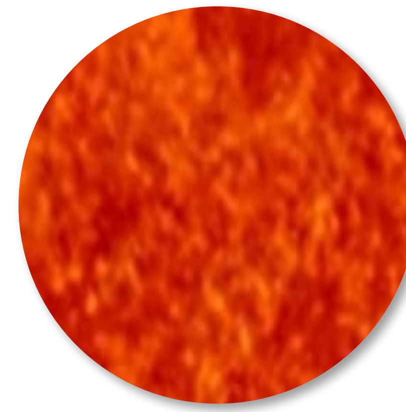
- They do not count as baryonic matter

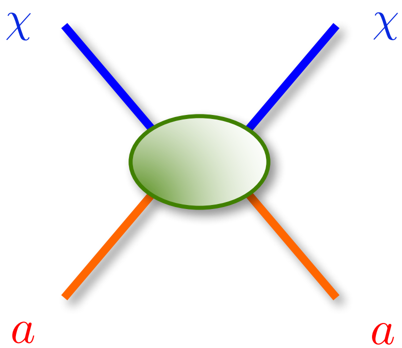
FL:	femtolensing of GRB
NS:	neutron star catpure
WD:	white dwarf explosion
HSC:	microlensing from Subaru
K:	microlensing from Kepler
EROS:	microlensing from EROS
MACHO:	microlensing from MACHO



If a particle, where does it come from?

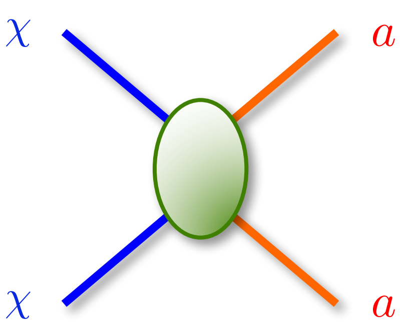
Produced, through some mechanism, in the early Universe, during its plasma epoch





Elastic processes kinetic equilibrium

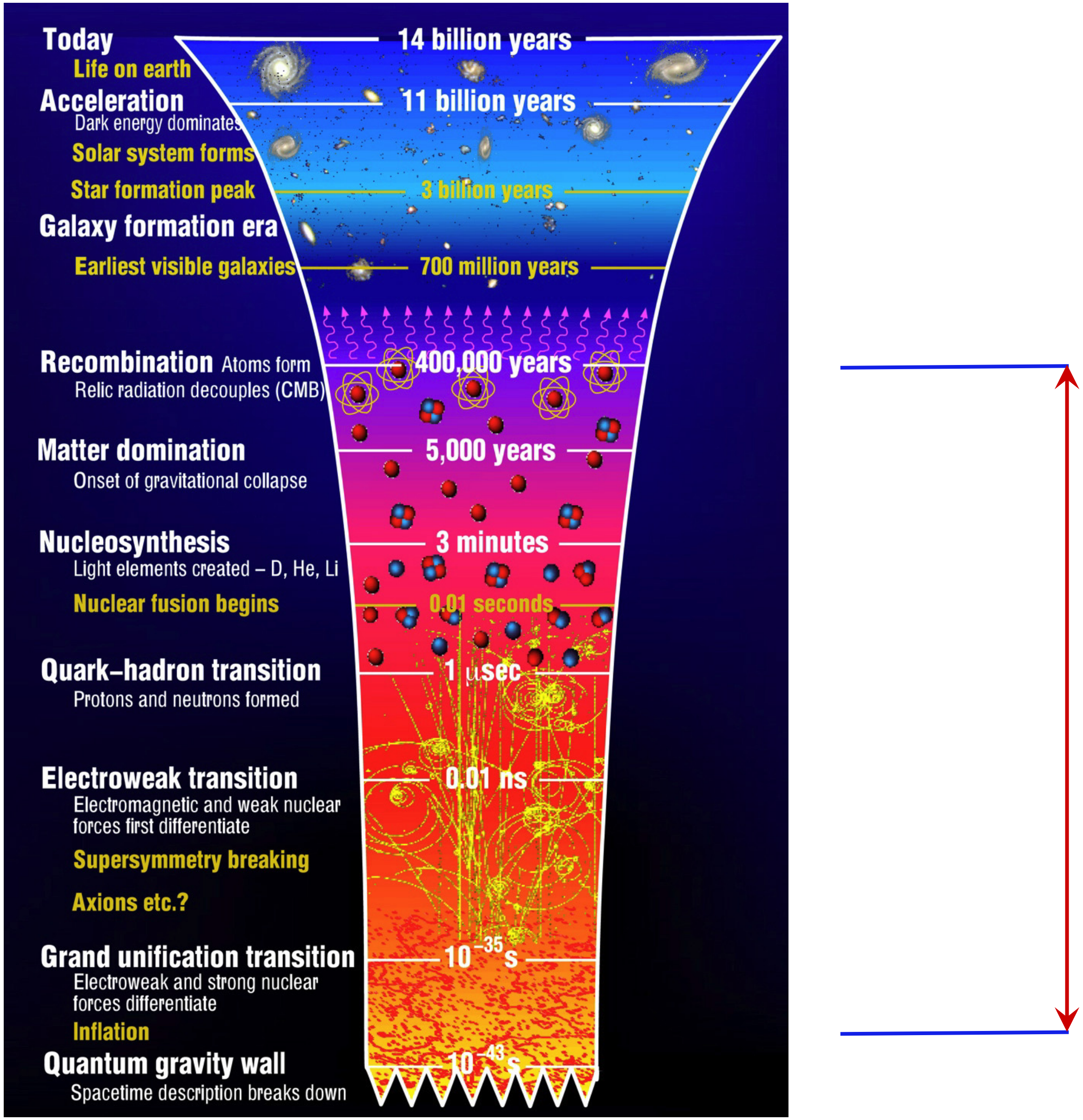
Reshuffle particles energies and momenta



Inelastic processes chemical equilibrium

Create or destroy particles in the plasma

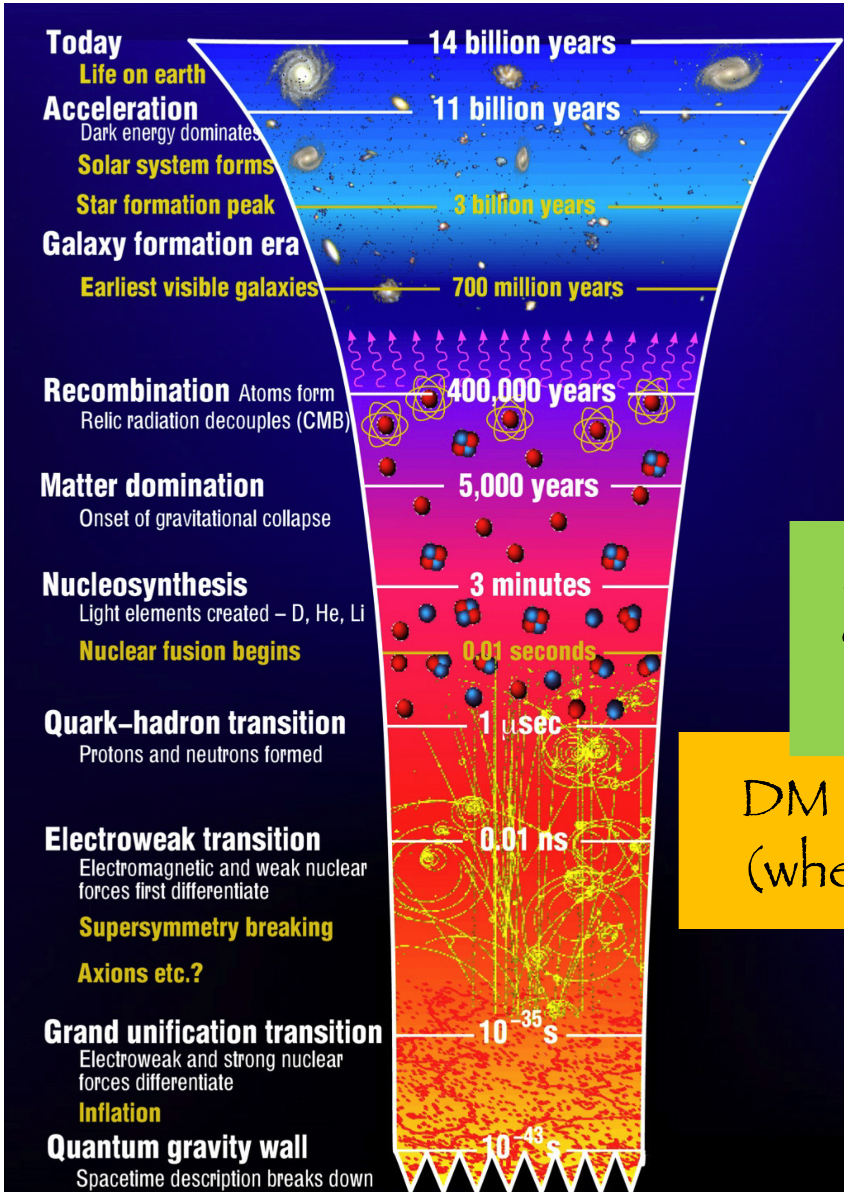
Early Universe



Plasma phase

Particle can be thermally excited

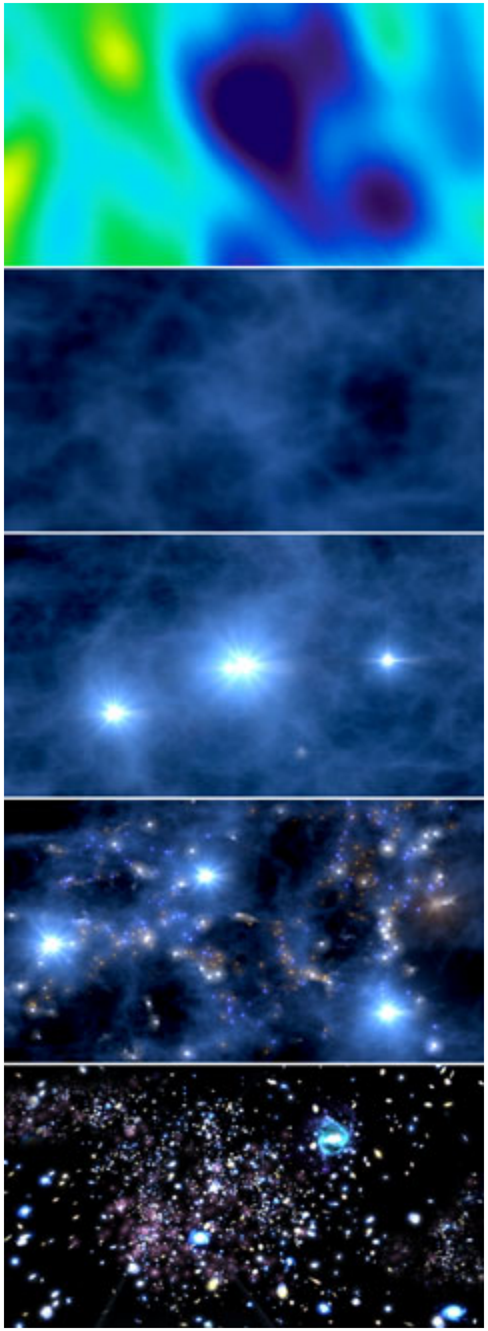
Early Universe



CMB is released
Plasma phase ends
Fluctuations can grow

DM particle kinetically decouples
(when depends on the particle)

DM particle abundance forms
(when depends on the particle)



Primordial fluctuations at CMB

↓

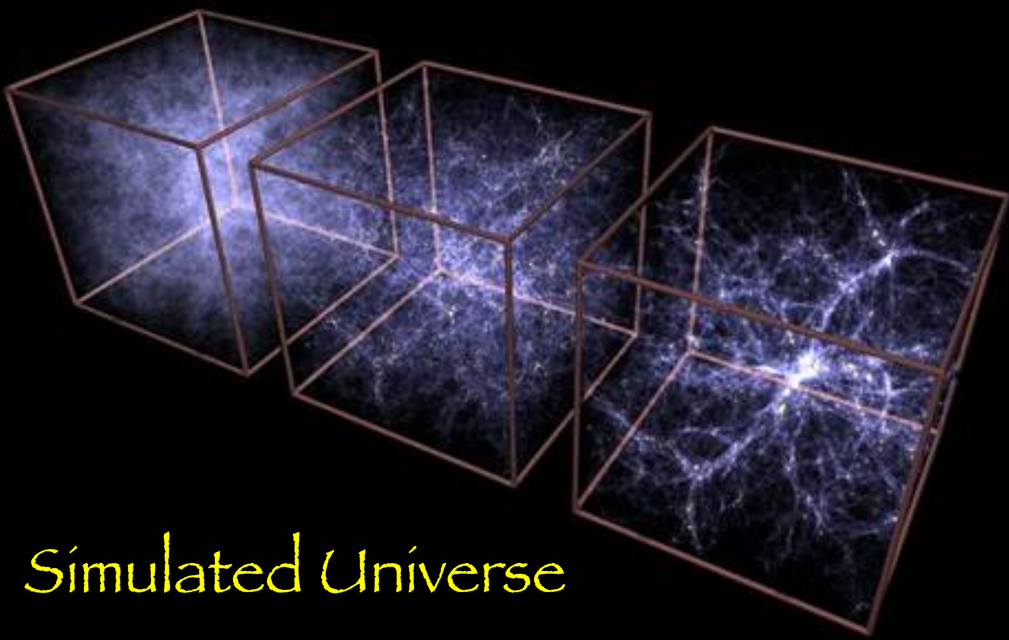
Growth of perturbation by Gravitational instabilities

↓

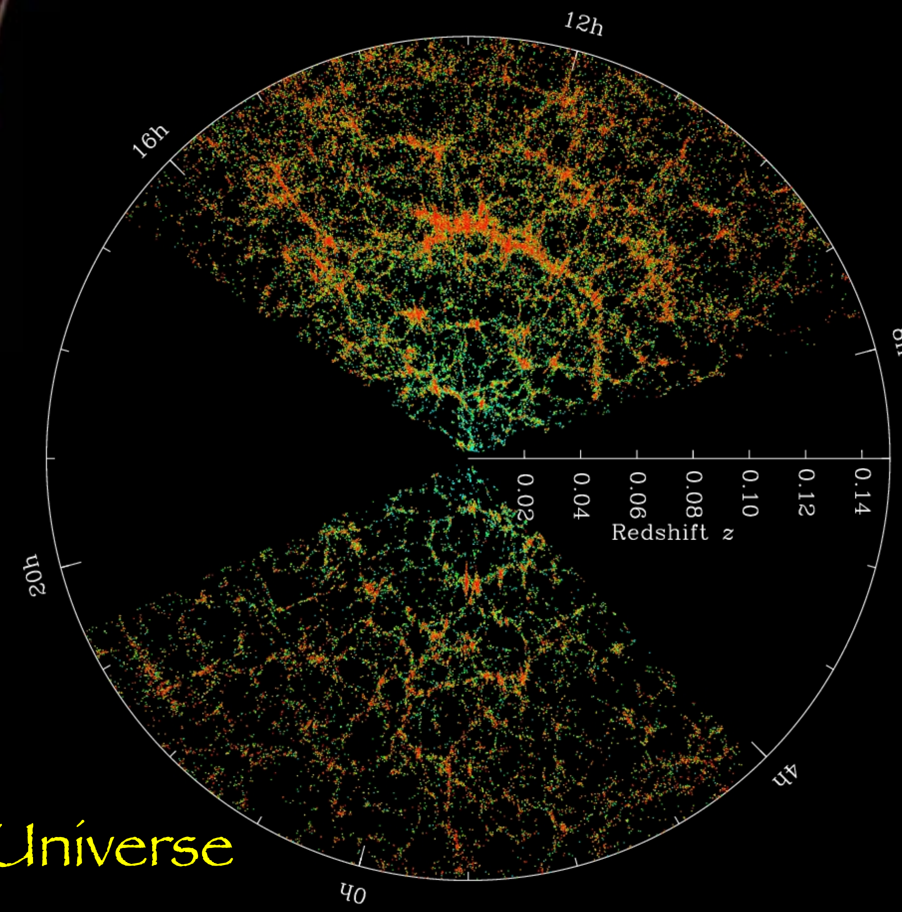
Dark matter acts ac Key element (and is required to be effectively cold)

Structure formation (galaxies, clusters)

Hierarchical structure



Simulated Universe



Observed Universe

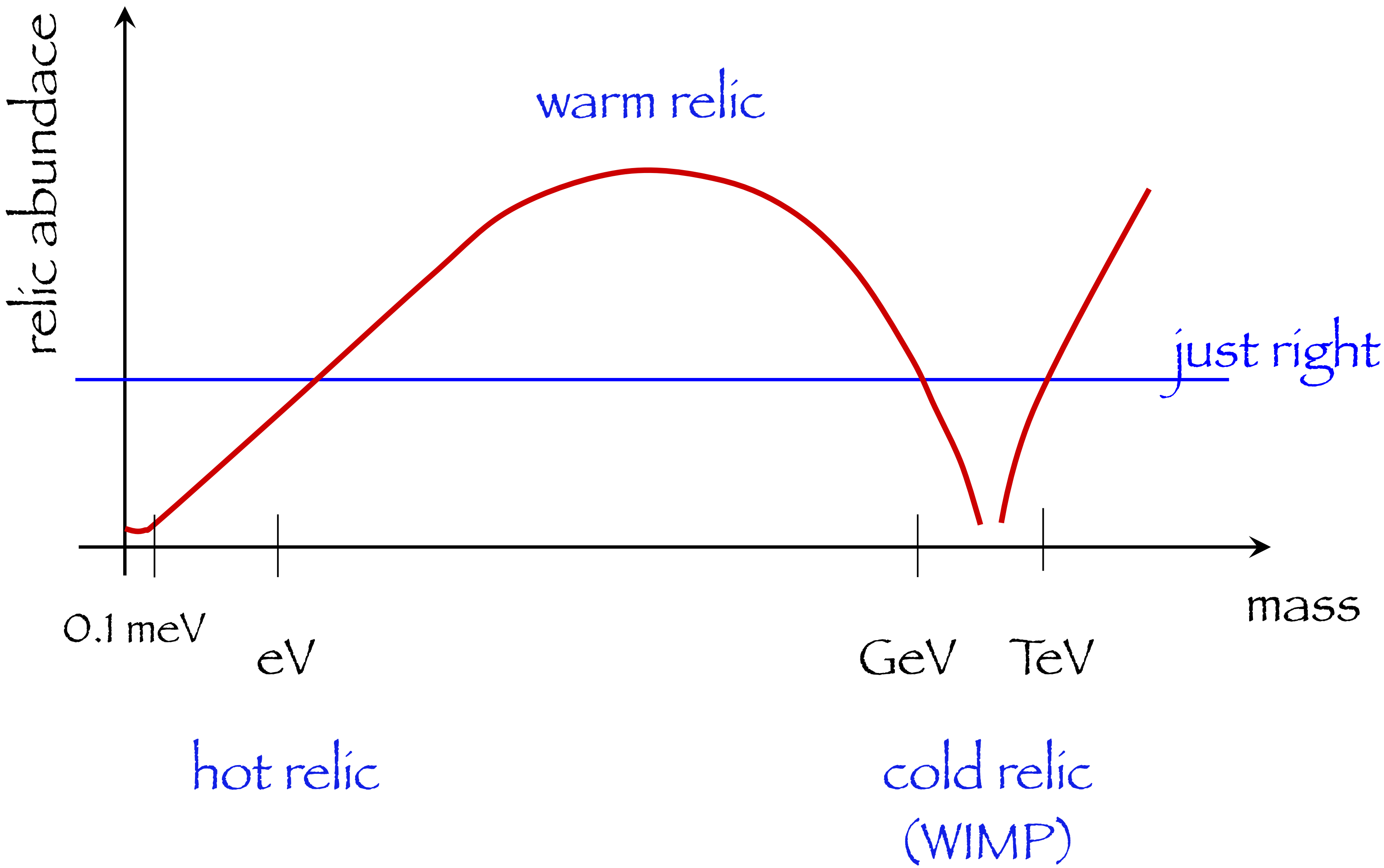
Relevant particle physics properties

Particle mass
Particle interactions

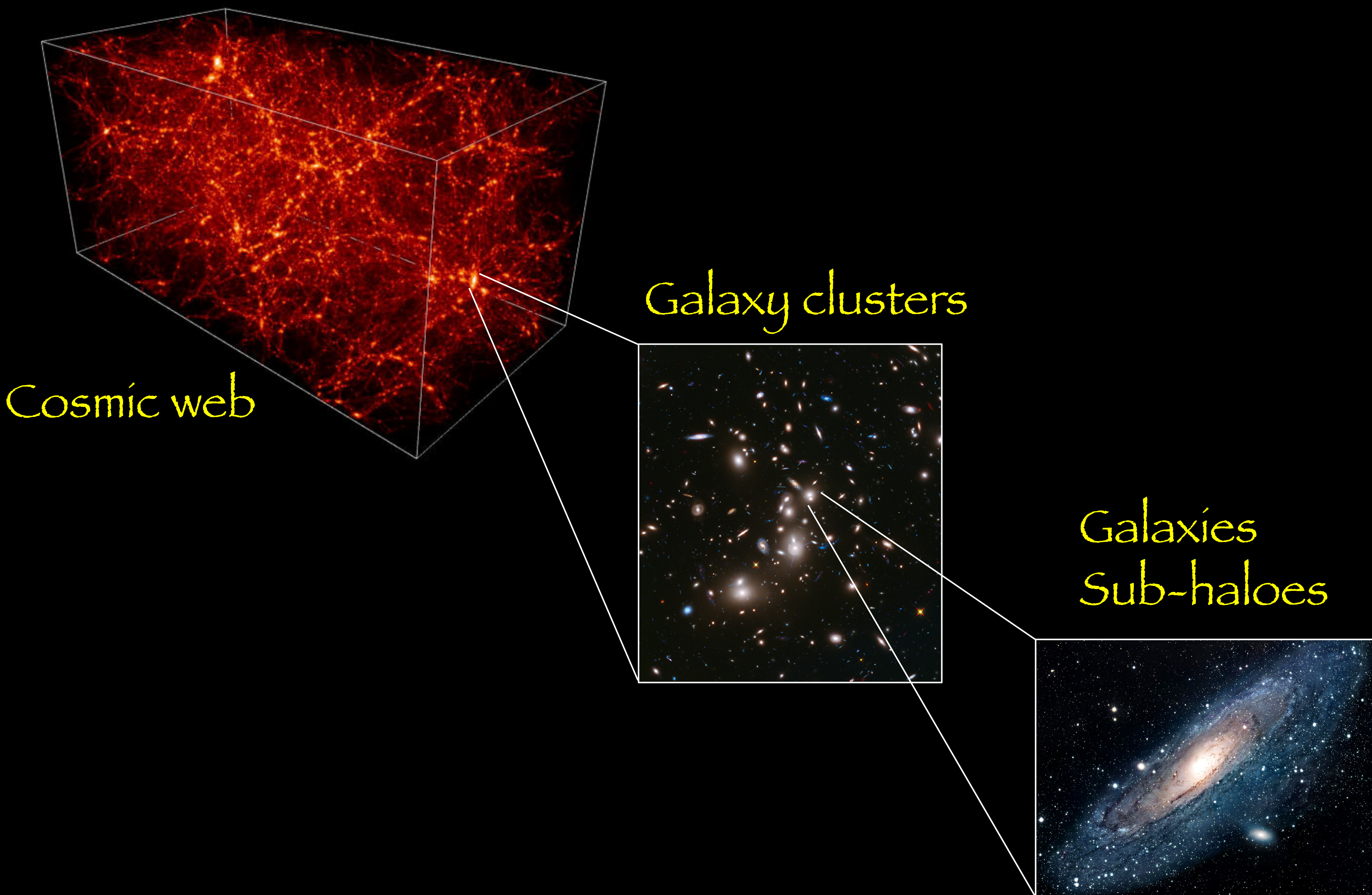
They both act in determining:

- If and when it has been in the plasma
  Full/partial equilibrium
- How much of it is left over
  Relic abundance
- How its abundance is produced
  Freeze-out, freeze-in, from decay, through asymmetry, oscillation
- Its dynamical scale and properties for structure formation
  Free-streaming length, hot/warm/cold

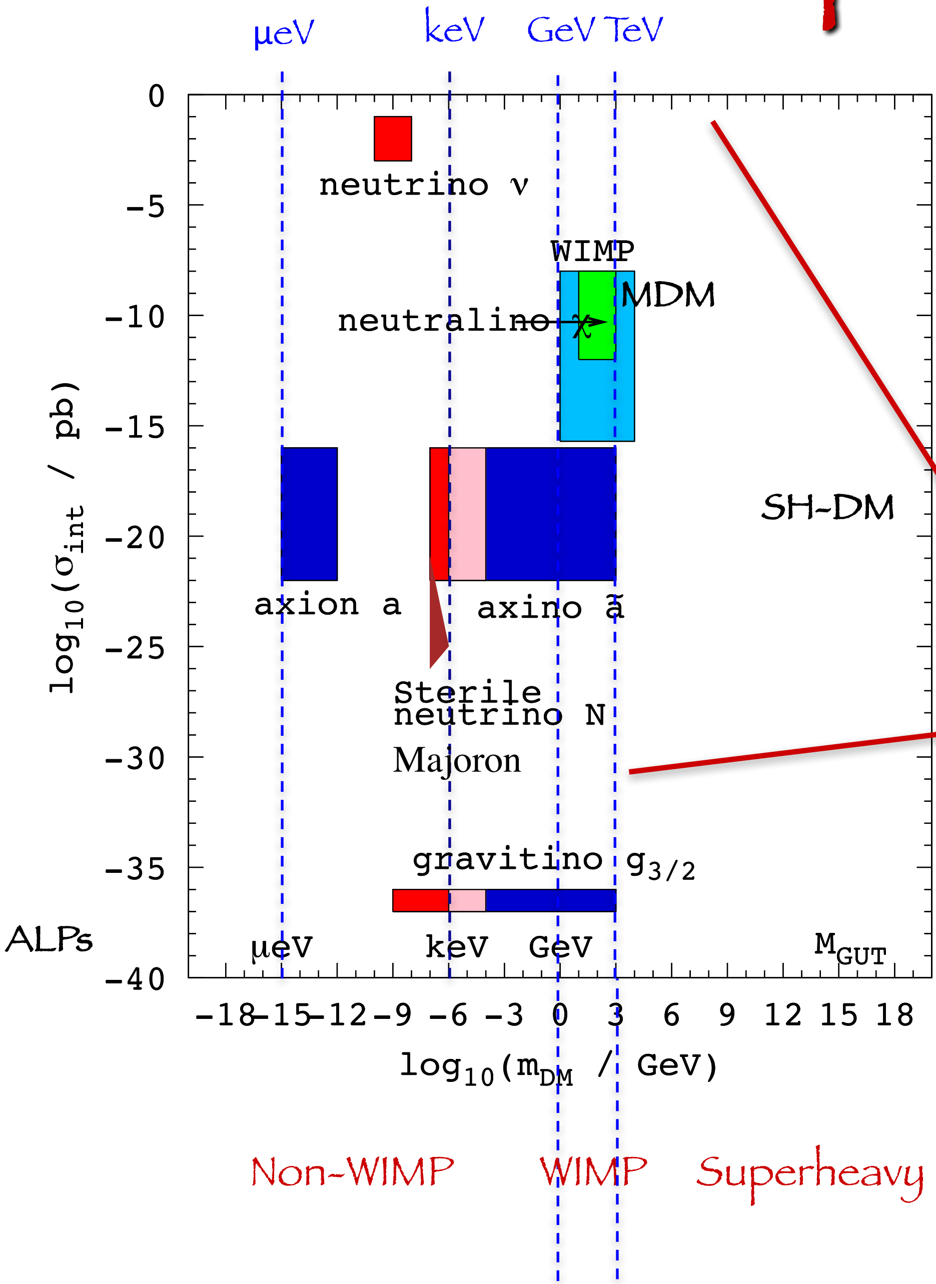
A "miracle" tale: the thermal WIMP



How is it distributed in the Universe ?



What particle?



"Strong (-ish)"

- Self-interacting
- Technicolor DM
- ...

"EM (-ish)"

- Millicharged DM
- Electric/magnetic dipole
- ...

Weak

- WIMP

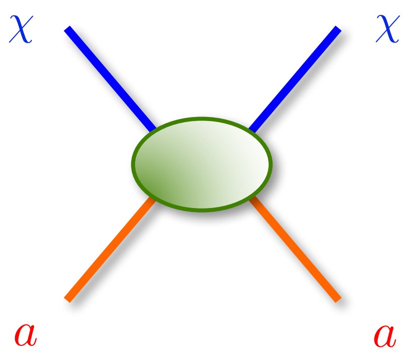
Gravitational

(see De Simone's talk)

What DM can do to manifest itself as a particle?

DM as a particle might ...

Interact with ordinary matter

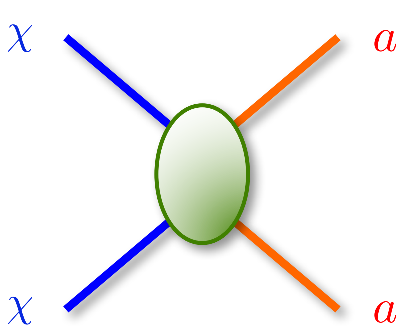


Direct detection

Produce effects in astrophysical environments, like in stars

(see Regis' talk)

Self annihilate or decay



Send us messengers (indirect detection)

Exotic injections that can alter properties of messengers (e.g. CMB: SZ, reionization; gamma-rays absorption)

Cosmic messengers

WIMP
non WIMP
radio

IR

WIMP
non WIMP
X

WIMP
gamma

Photons

Cosmic rays

electrons/positrons — WIMP, non WIMP

antiprotons, antideuterium, antinuclei — WIMP

Neutrinos — WIMP, non WIMP

Gravitational waves — DM = primordial BH

Multi: messenger/wavelength/technique

	radio	IR	X	gamma
	WIMP non WIMP		WIMP non WIMP	WIMP

Photons

Cosmic rays
- electrons/positrons — WIMP, non WIMP
- antiprotons, antideuterium, antinuclei — WIMP

Neutrinos — WIMP, non WIMP

Gravitational waves — DM = primordial BH

Direct detection — WIMP, non WIMP

Multi: messenger/wavelength/technique

Galactic + Extragalactic

radio IR X gamma

Photons

Cosmic rays electrons/positrons Galactic

antiprotons, antideuterium, antinuclei Galactic

Neutrinos Local Galaxy, Galaxy, Extragalactic

Gravitational waves Cosmological

Direct detection Galactic, very local

Multi: messenger/wavelength/technique

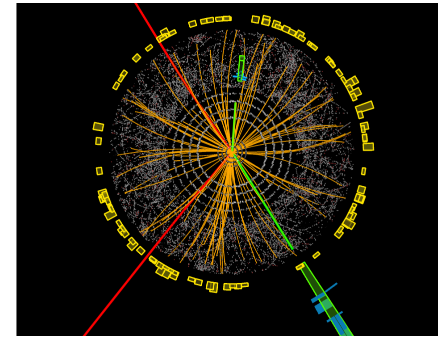
	radio	IR	X	gamma
Photons	WIMP non WIMP		WIMP non WIMP	WIMP

Cosmic rays

electrons/positrons	WIMP, non WIMP
antiprotons, antideuterium, antinuclei	WIMP

Neutrinos	WIMP, non WIMP
Gravitational waves	DM = primordial BH
Direct detection	WIMP, non WIMP
Accelerator searches for New Physics	WIMP, non WIMP

A multiple approach

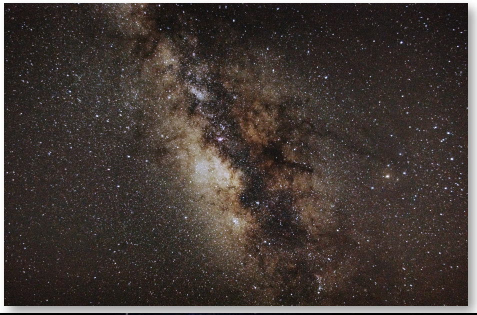


- Astrophysical signals
  - Tests DM as particle in its environment
  - Signals are not produced under our own direct control
  - Complex backgrounds
  - Multimessenger, multiwavelength, multitechnique strategy
- Accelerator / Lab signals
  - Produce New Physics states and help in shaping the underlying model
  - Allows (hopefully) to identify the physical properties of the DM sector
  - Controlled environment

One does not fit all … profit of all opportunities

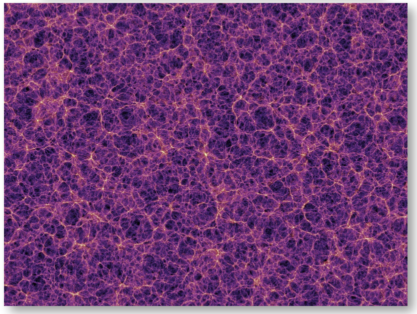
Where to search for a signal

- Our Galaxy
  - Smooth component
  - Subhalos



- Satellite galaxies (dwarfs)

- Galaxy clusters
  - Smooth component
  - Individual galaxies
  - Galaxies subhalos

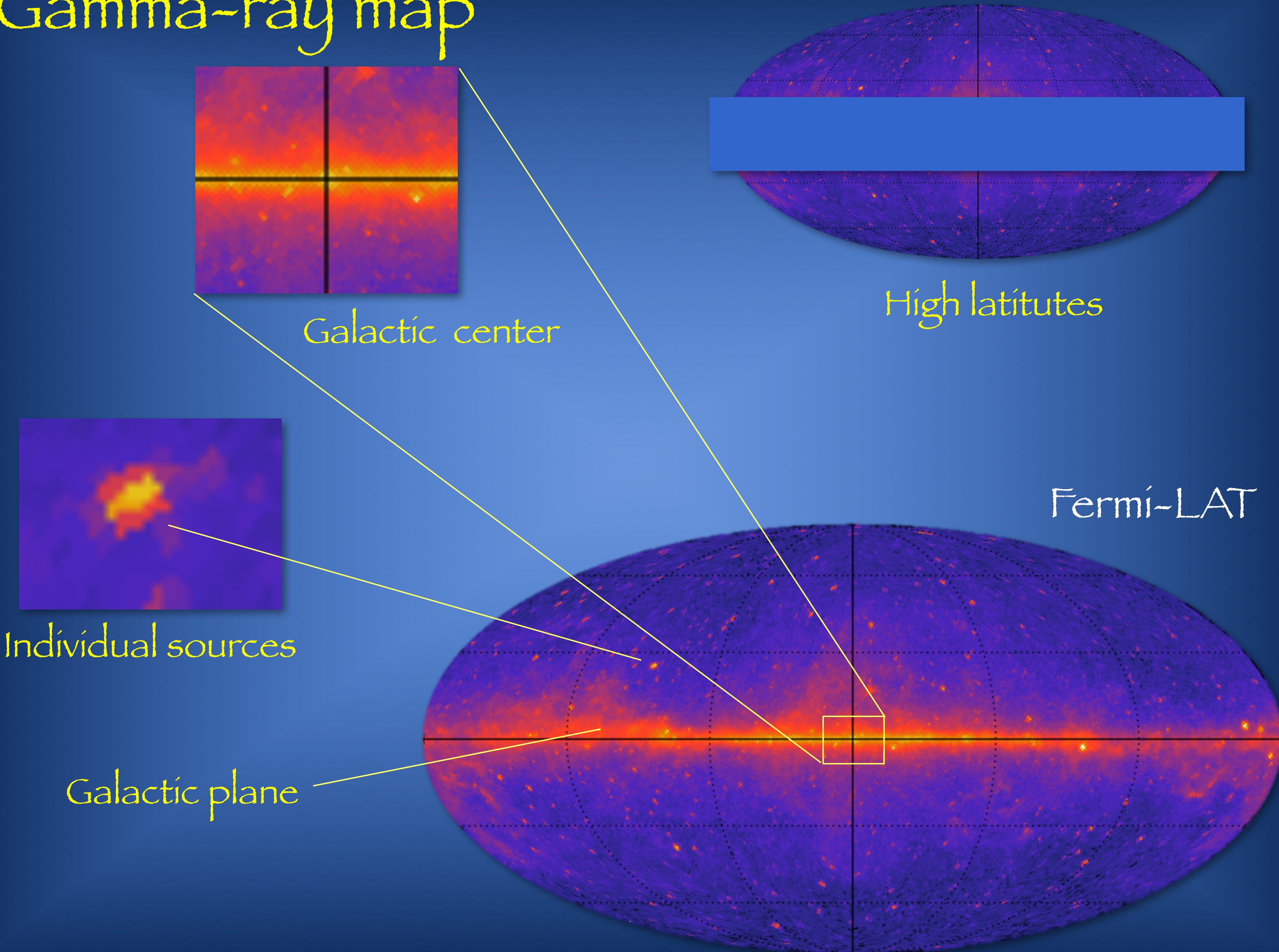


- "Cosmic web"

Example - Photons: diversify strategy

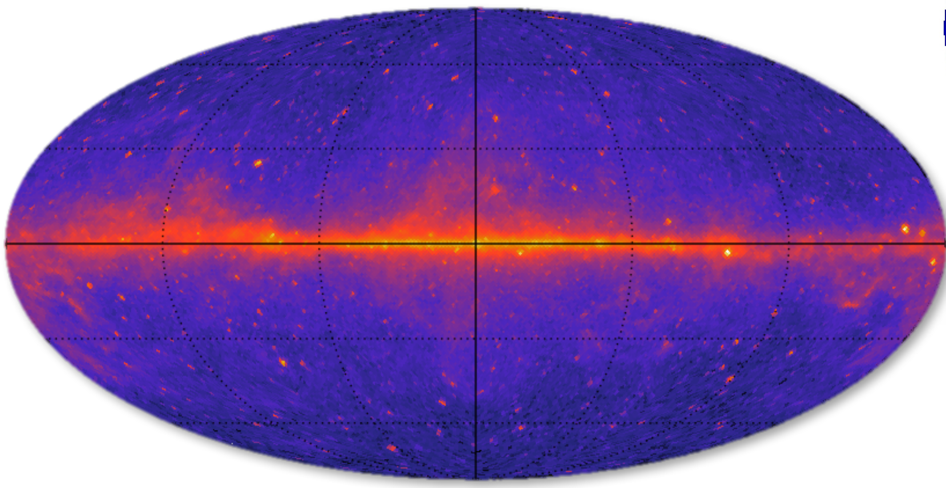
Targets	Galactic center
	Galactic subhalos (clumps)
	Dwarf galaxies
	Individual galaxy clusters
Diffuse	High-lat galactic halo
	Extragalactic (cosmological) cumulative emission

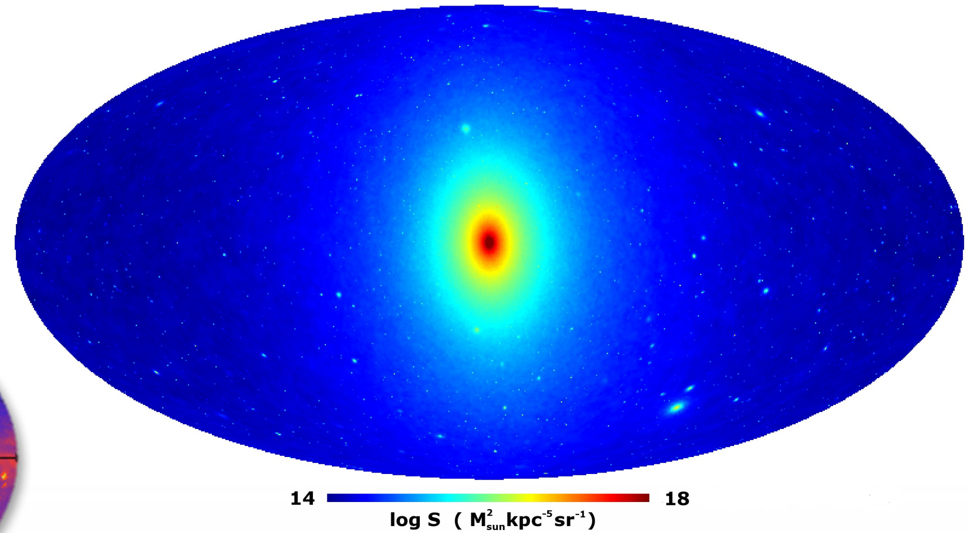
Gamma-ray map

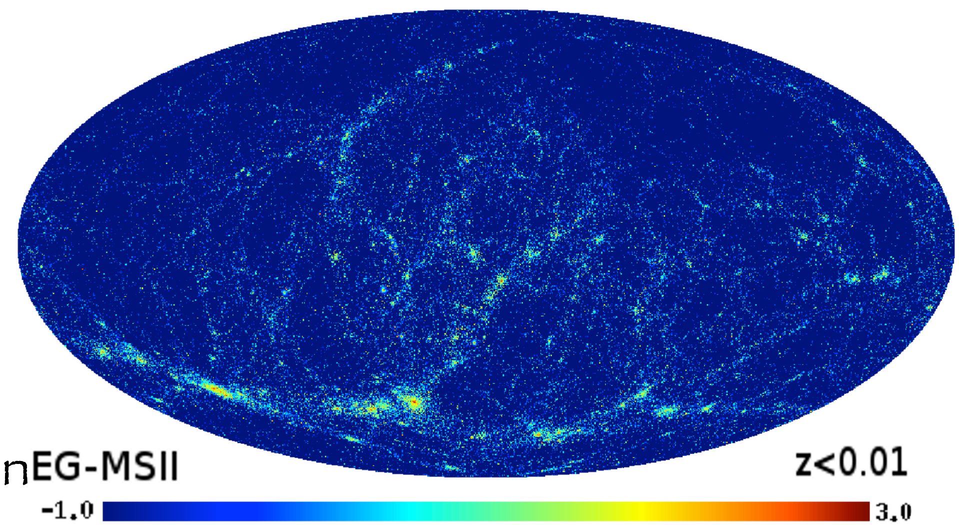


This map is NOT dominated by DM

Real map



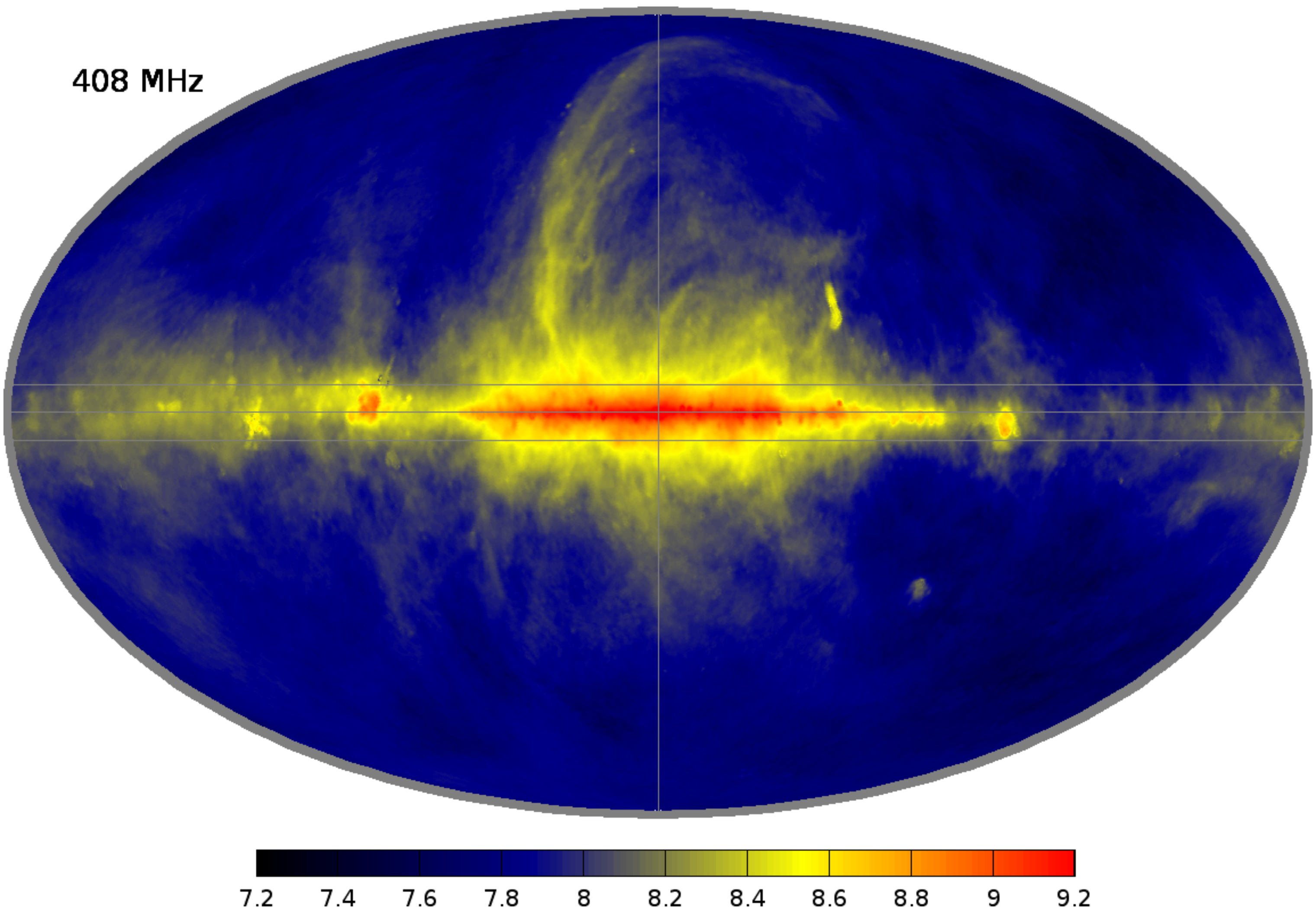




Contains
- Galactic emission
- Point sources
- EG diffuse emission
- Galactic and cosmological DM emission (if any ...)

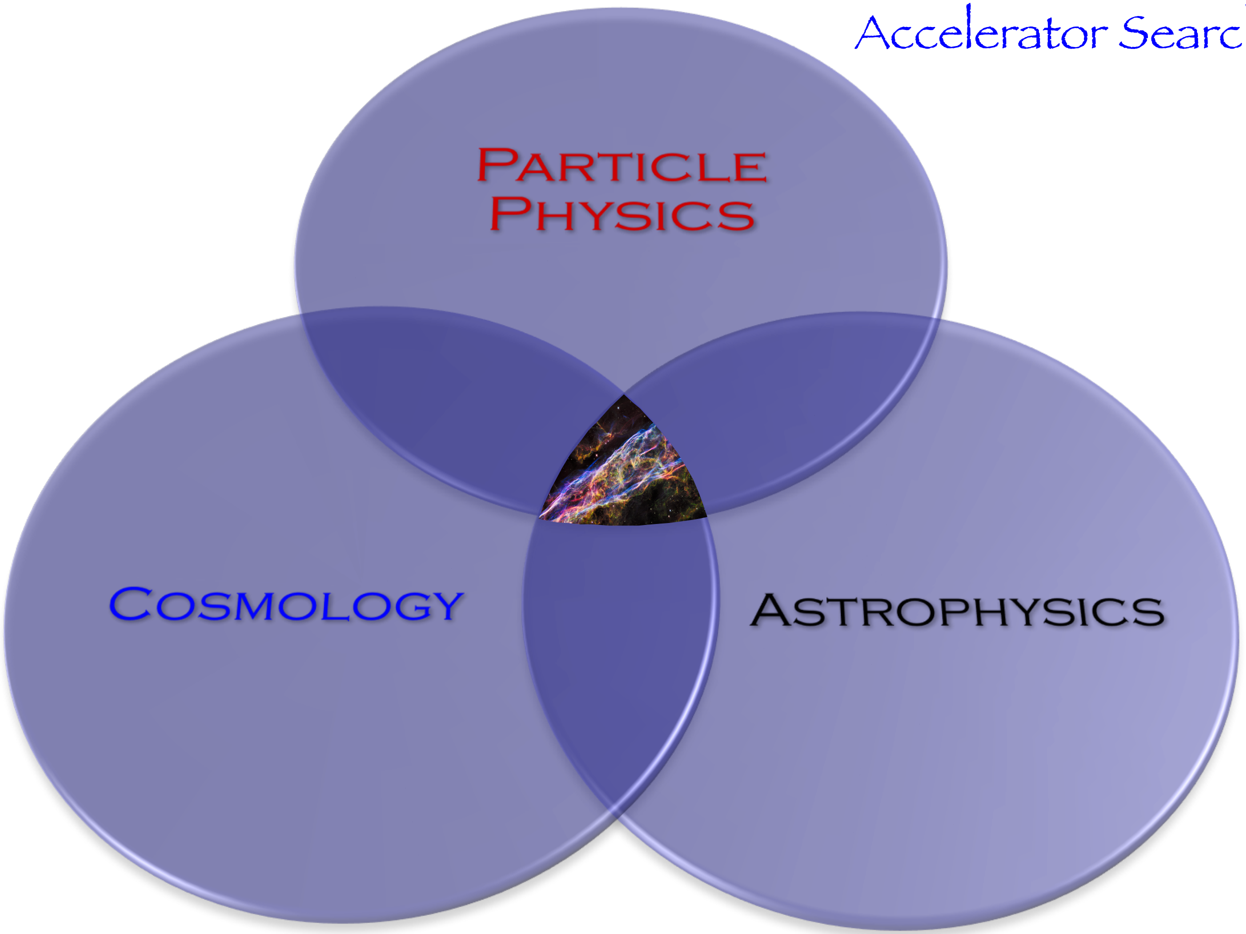
DM signals are (largely) subdominant
(but we are interested in the other components, too)

Another example: radio emission



The Particle Dark Matter Crossroad

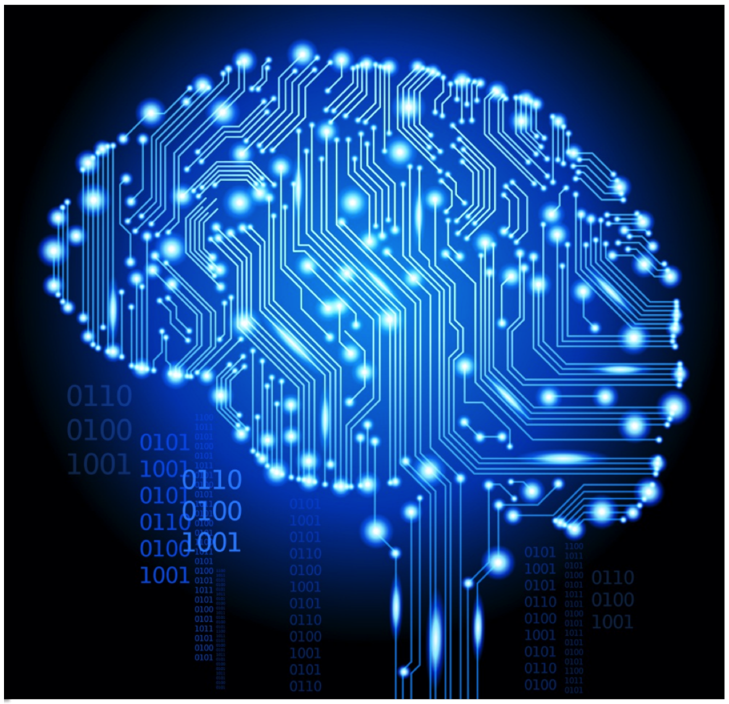
Particle Candidate: Models of New Physics
Accelerator Searches

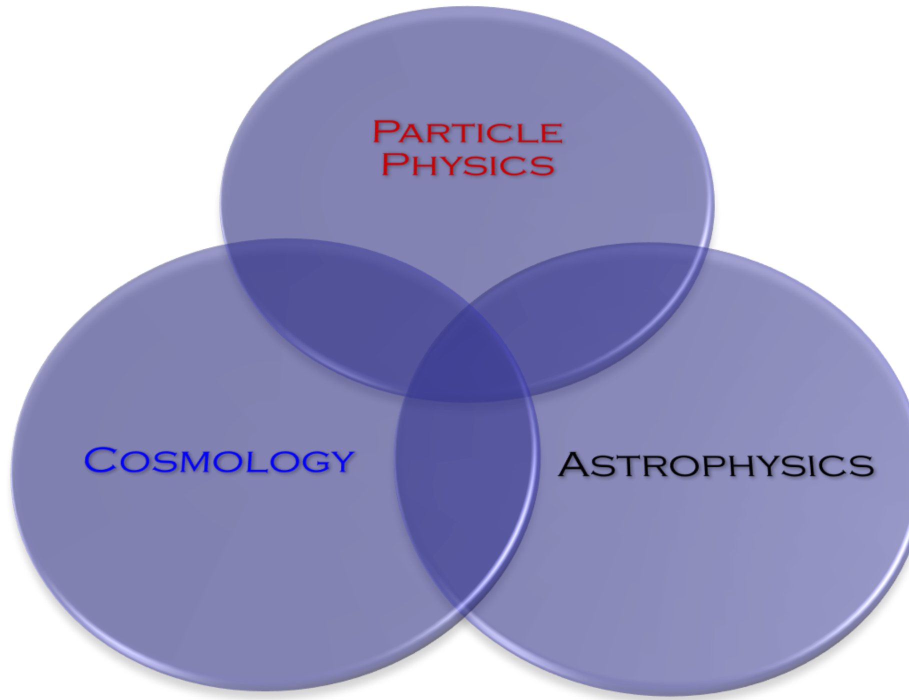


Identification of the presence of DM
Large scale distribution
Cosmology of the DM Particle

Identification of the presence of DM
Small scale distribution
Astrophysical Signals of the DM Particle
Astrophysical backgrounds (sources, etc)

How Machine Learning can help us?





Machine Learning and DM

- What we do have:

  Good wealth of data

Machine Learning and DM

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DM identification: Stellar motions in dwarf galaxies

Machine Learning and DM

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DM identification: Stellar motions in dwarf galaxies

Dynamics of stars in galaxies

Dynamics of galaxies in clusters

Machine Learning and DM

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Dynamics of stars in galaxies

Dynamics of galaxies in clusters

LSS catalogs (galaxies, clusters)

Machine Learning and DM

- What we do have:

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DM identification:

Stellar motions in dwarf galaxies

Dynamics of stars in galaxies

Dynamics of galaxies in clusters

LSS catalogs (galaxies, clusters)

Lensing maps (strong, weak)

Machine Learning and DM

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Particle DM astro signals:

Photons: Maps of large portions of the sky

Machine Learning and DM

- What we do have:

  Good wealth of data

Particle DM astro signals:

Photons:	Maps of large portions of the sky
Charged CR:	Fluxes averaged over the sky Some map at very high energies (Auger, IceCube)

Machine Learning and DM

- What we do have:

  Good wealth of data

Particle DM astro signals:

Photons: Maps of large portions of the sky

Charged CR: Fluxes averaged over the sky
Some map at very high energies (Auger, IceCube)

Direct detection: Events (typically zero) in a low background detector
(See Brown's talk)

Could ML help in signal/background discrimination?
And with specific signatures (modulation, directionality)

Machine Learning and DM

- What we do have:

  Good wealth of data

Particle DM at accelerators

It is (typically) not the DM particle that it's "seen" at accelerators, rather related particles in a New Physics model

Machine Learning and DM

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Particle DM at accelerators

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High-E (mostly for WIMPs): data are already partly analyzed with ML techniques, but with focus not DM-specific
(See Farbin's and Stoyes's talks)

Low-E (axions,ALP, dark photons, etc): search methods vary a lot, use of ML tecnhique to be investigated
(See Ustyuzhanin's and Stoyes's talks)

Machine Learning and DM

- What we do not have [we might not have a proper]

A proper training set

Machine Learning and DM

- What we do not have [we might not have a proper]

A proper training set

We can rely on modeling: simulations

How good is it?

It likely depends on the observable: e.g. lensing [OK!] vs extragalactic photon emission [?]

One successful example: lensing

Fast automated analysis of strong gravitational lenses with convolutional neural networks

Yashar D. Hezaveh[1,2]*, Laurence Perreault Levasseur[1,2]* & Philip J. Marshall[1,2]

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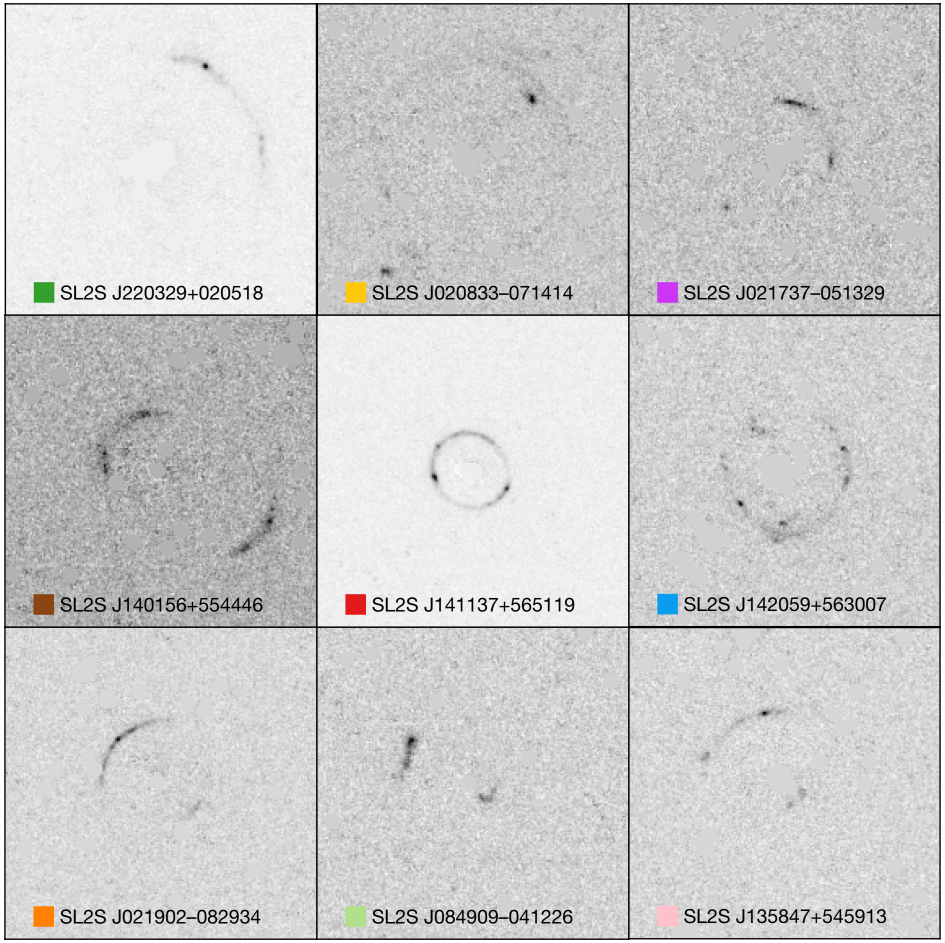
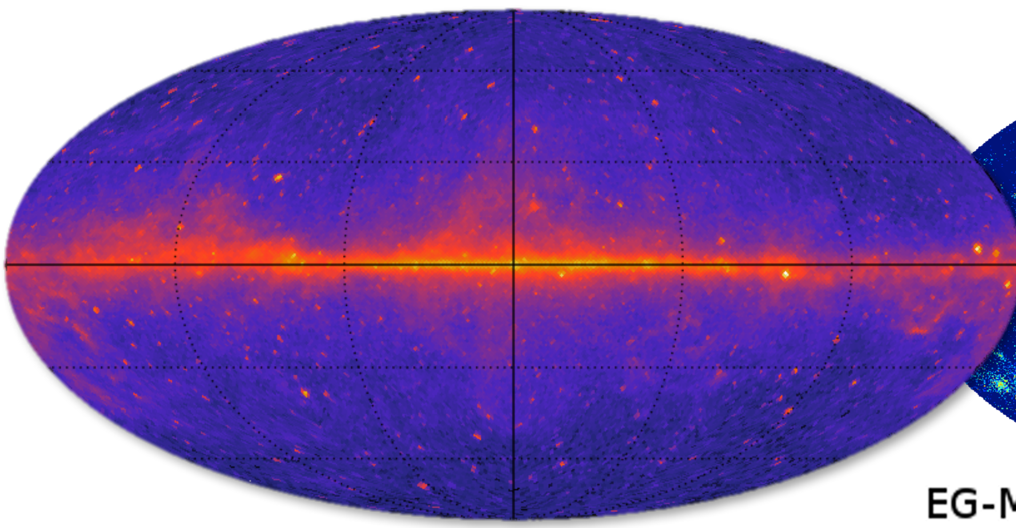


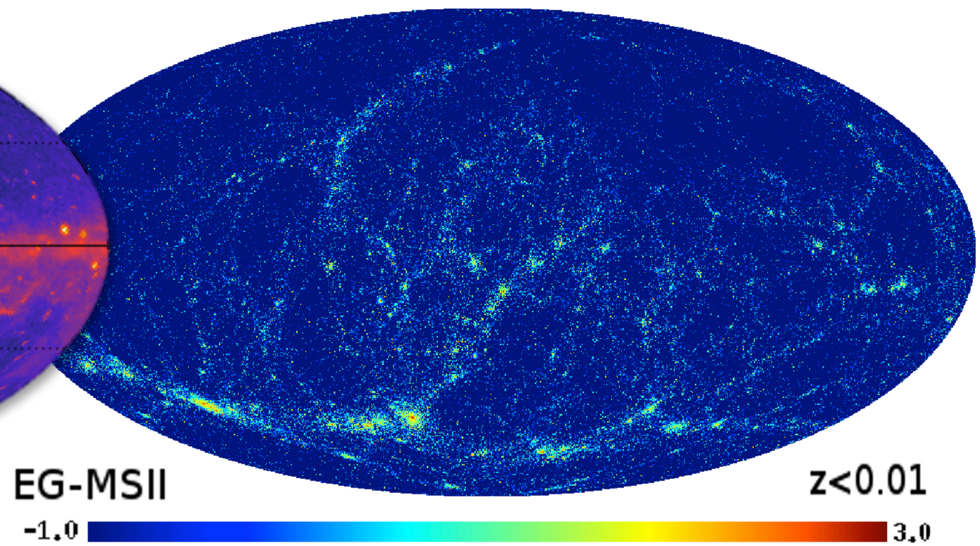
(see Levasseur's talk)

A tricky case: gamma-ray emission

Real map

Simulated map of DM emission





Can simulations be used to construct a proper training set?

Machine Learning and DM

- What we do not have [we might not have a proper]

A proper training set

We can rely on modeling: simulations

How good is it?

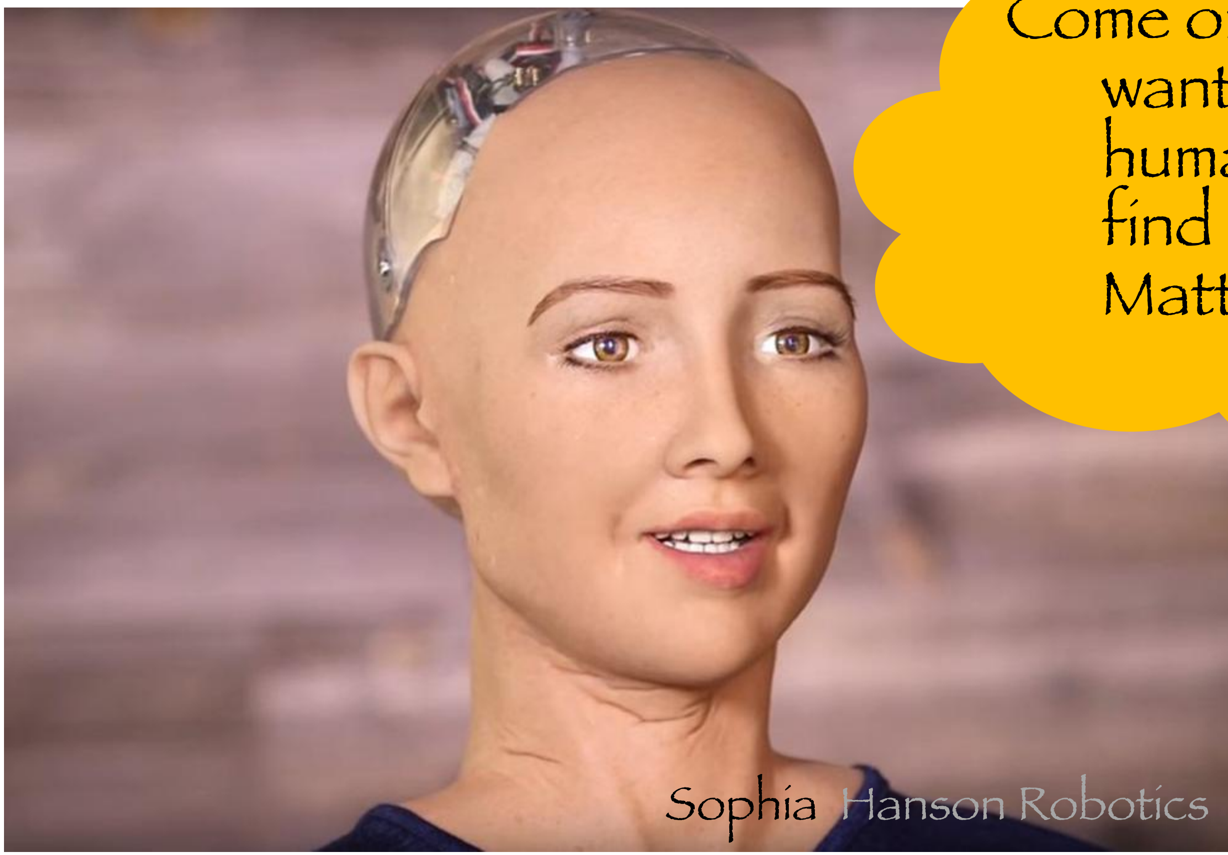
It likely depends on the observable: e.g. lensing [OK!] vs extragalactic photon emission [?]

Methods that do not require training?

We don't know (yet) what's in the juicy DM sandwich

"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

Definitely Machine Learning will help us!



Come on: I don't want to destroy humans, I want to find what Dark Matter is ...