NICPB KBFI

CONNECTING SCIENCES

A pilgrimage to darkness

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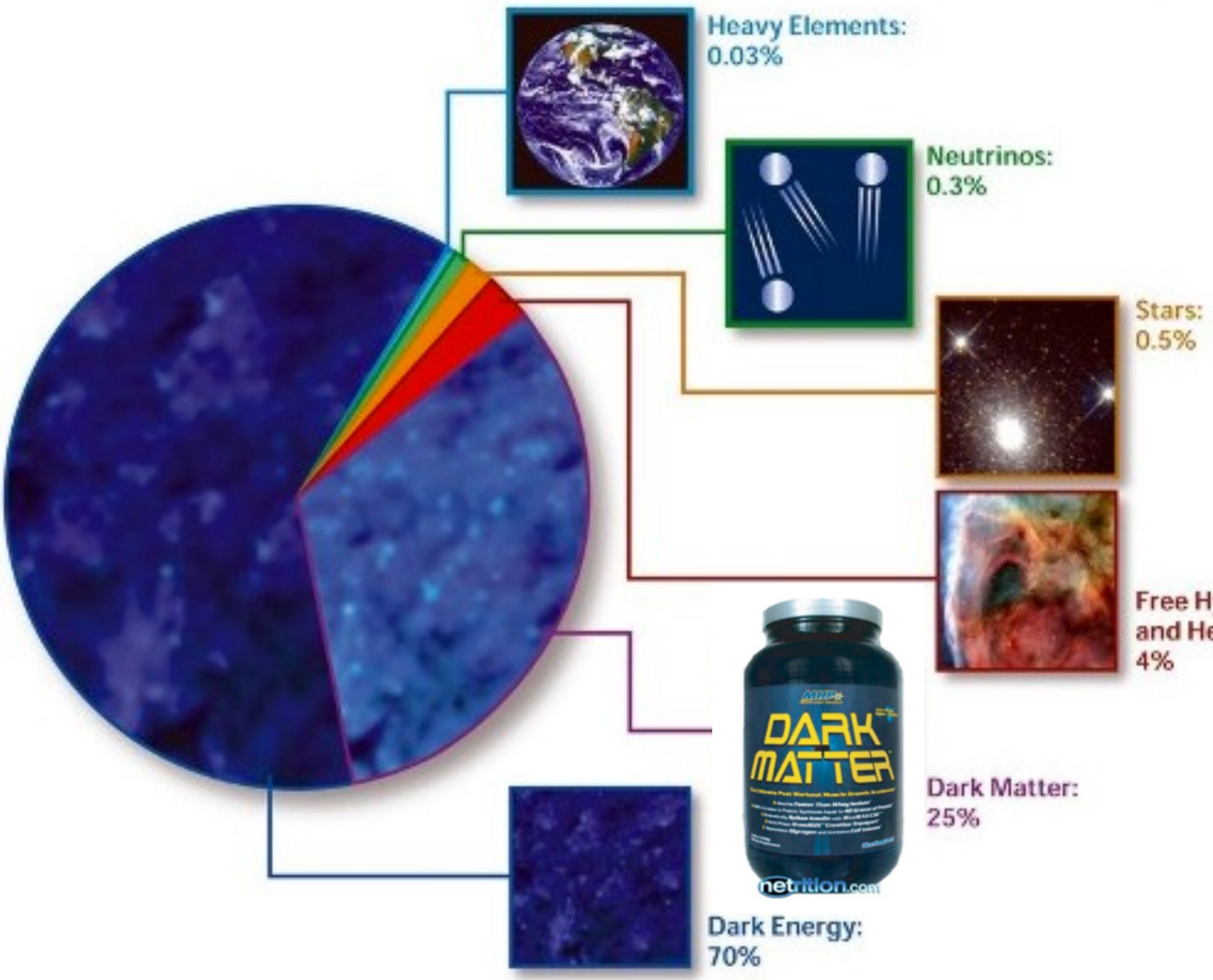
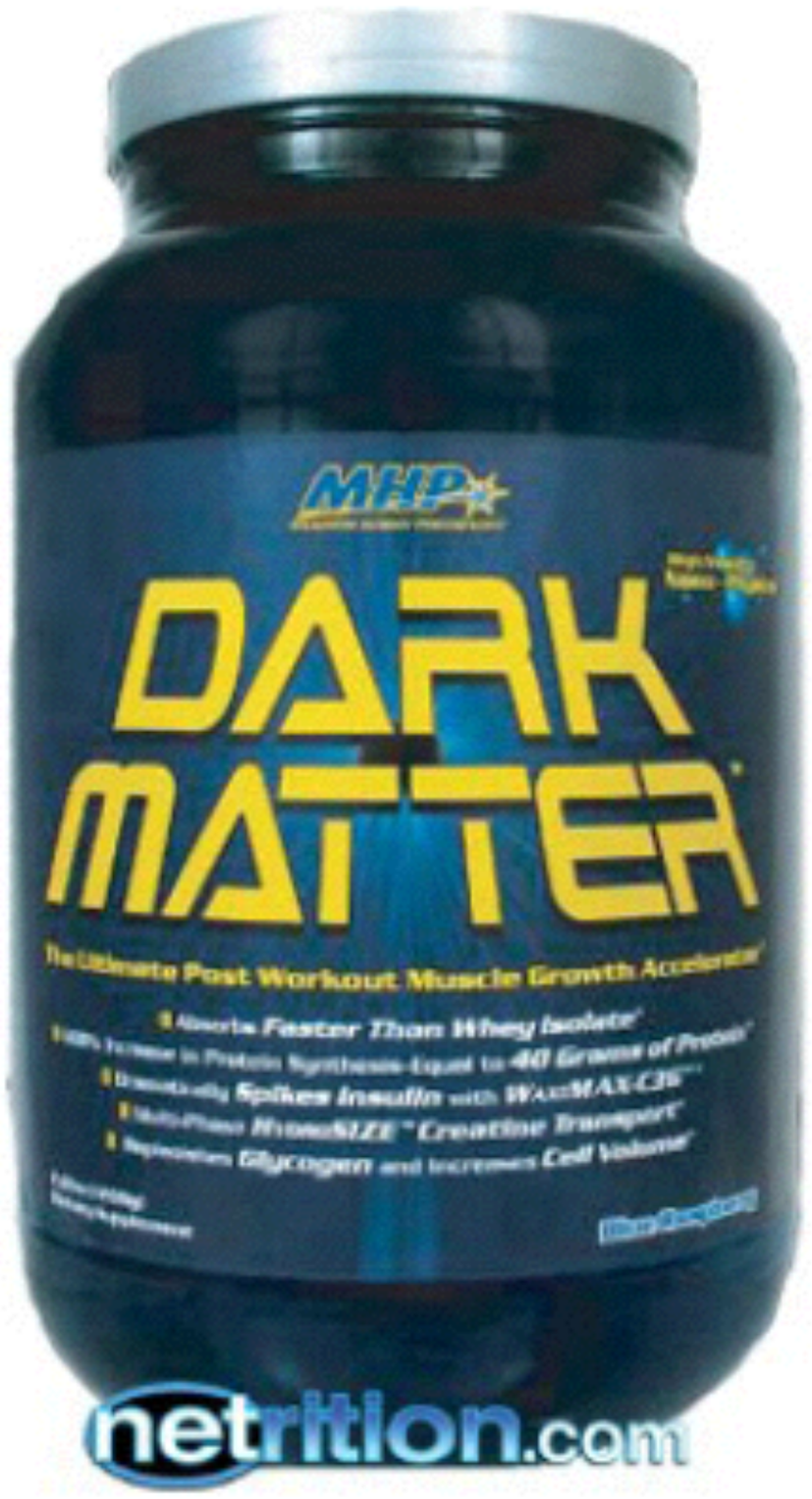
- Gravitational signals of Dark Matter (DM)
- Gravitational signals of DM with extra interaction
- DM signals beyond gravity
- Weakly Interacting DM (WIMP) ant its miracle
- Direct, indirect and accelerator detection of WIMPy DM
- Alternatives of WIMP
- Conclusions

Dark Matter


Heavy Elements:
0.03%
Neutrinos:
0.3%
Stars:
0.5%
Free Hydrogen
and Helium:
4%
DARK
MATTER
netrition.com
Dark Matter:
25%
Dark Energy:
70%

Dark Matter?

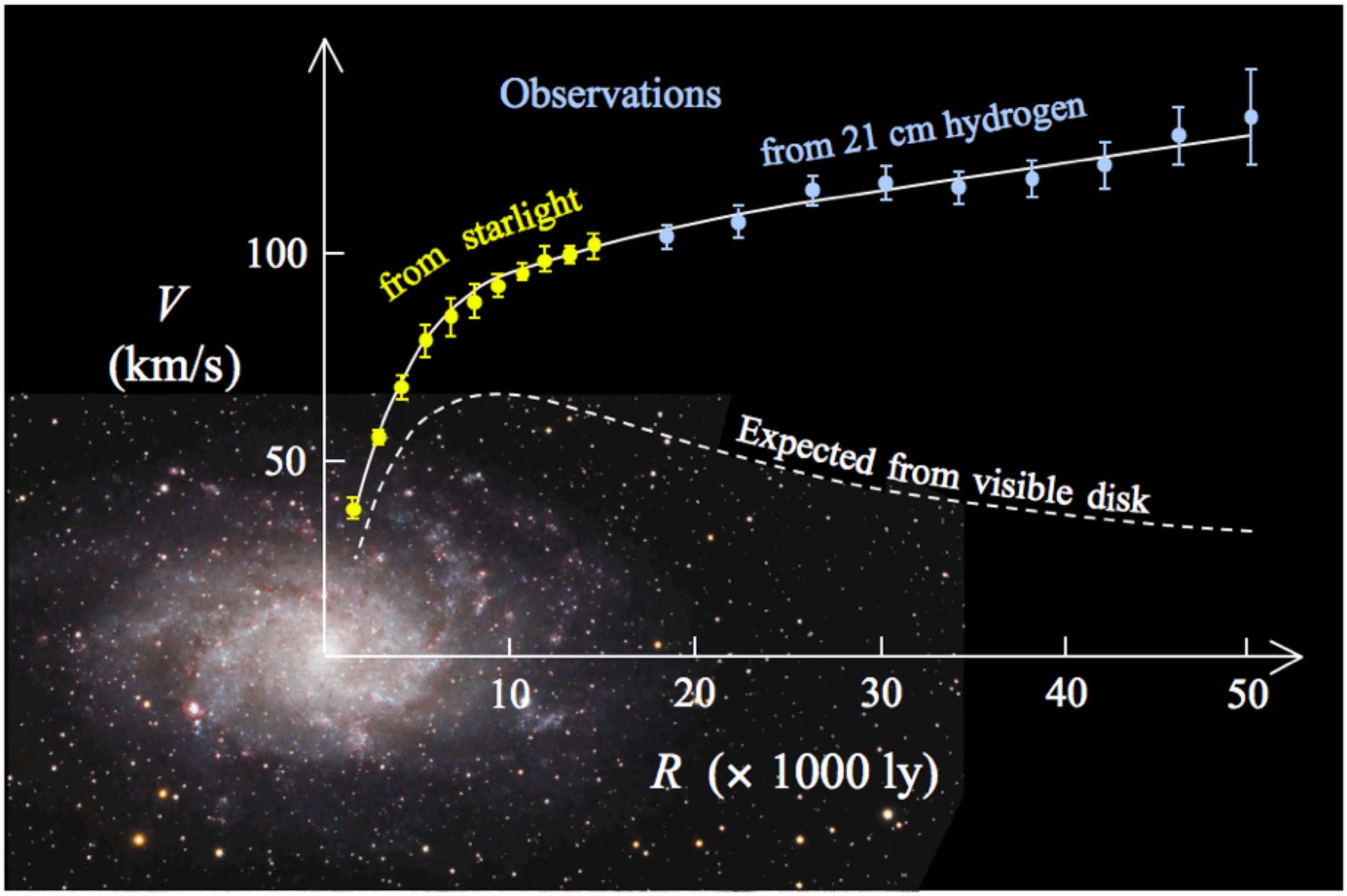

MHP
DARK
MATTER
The Ultimate Post Workout Muscle Growth Accelerator
Absorbs Faster Than Whey Isolate
Spikes Insulin with WAXMAX-CHO
Glycogen and increases Cell Volume
netrition.com

Trump searches for the "dark matter" of politics

Details Last Updated on Tuesday, 14 June 2016 11:12
Published on Tuesday, 14 June 2016 11:12 Hits: 650

It exists mostly in theory and the realm of complicated mathematical equations. But, scientists know it's there. It's called "dark matter" and it makes up a substantial part of our universe. Politics, of course, isn't physics, but in the theater of American elections there is a sort of dark matter as well. We can't always trace its source, sometimes it's completely hidden, but on occasion, it's more evident than we would like to believe. And this year, the dark matter of American politics isn't hard to find at all. It's that undercurrent of hostility that stays just below the surface. Most of us, admit it, come on, have thought some of the outlandish things Donald

How do we know there is Dark Matter?



How do we know there is Dark Matter?

2014 Gruber Cosmology Prize Press Release

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Online Newsroom: www.gruber.yale.edu/news-media

FOR IMMEDIATE RELEASE

Einasto, Freeman, Tully, and Van den Bergh Share $500,000 Gruber Cosmology Prize for Investigations of Nearby Universe

Jaan Einasto

Kenneth Freeman

R. Brent Tully

Sidney van den Bergh

Are we sure about DM?

- Velocity distribution of stars (gas, dust) in galaxies
- Galaxy clusters (by dynamics, X-ray signal and gravitational lensing)
- Baryon acoustic oscillations in CMB and LSS
- Galaxy cluster collusions

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So far all the evidences of DM are gravitational only!

Any alternative of DM?

Any alternative of DM?

Yes, MOND is still there!

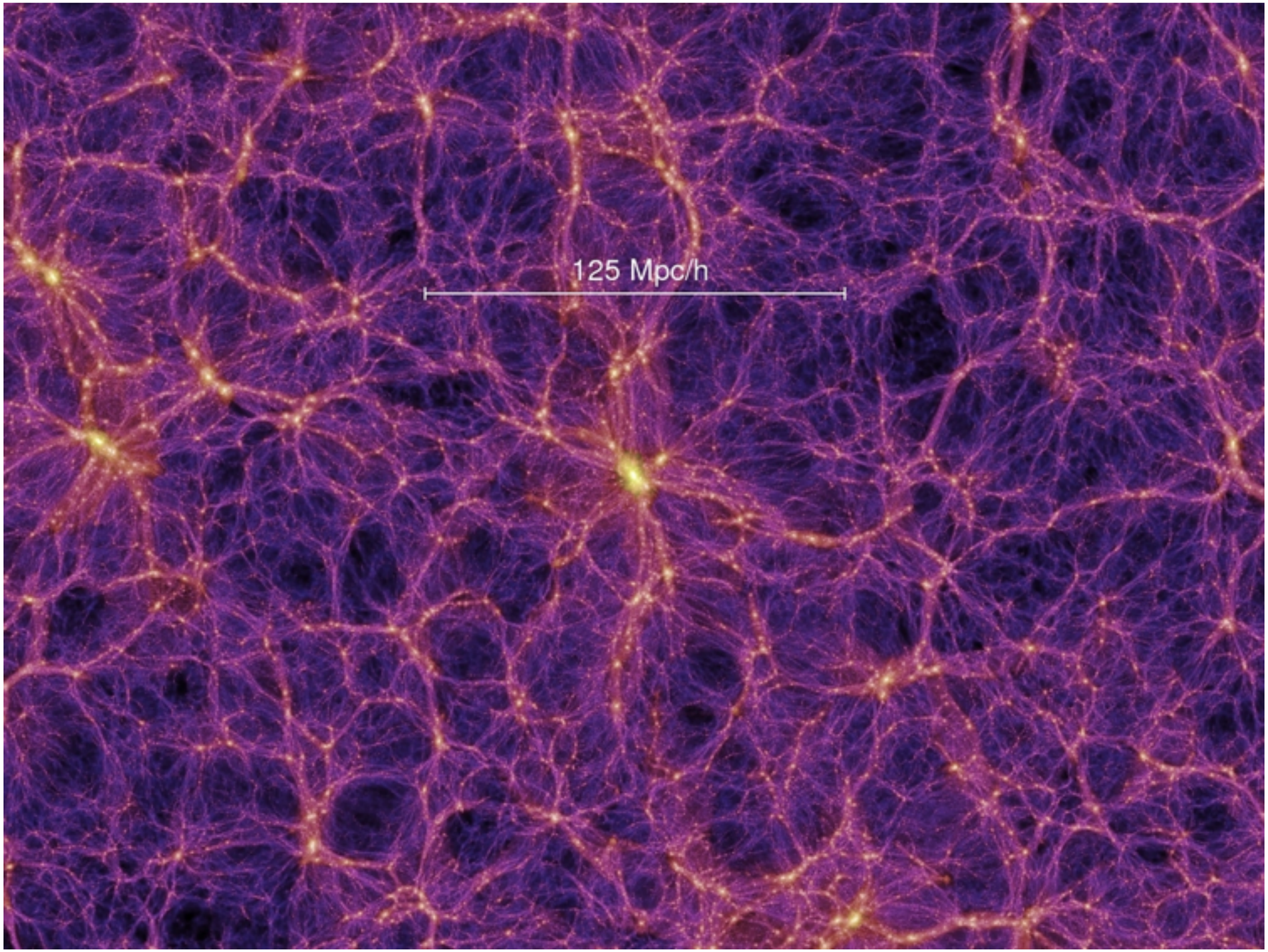
Yes, MOND is still there!

MOND — modified Newtonian dynamics

- Meant to explain the galactic dynamics
- Troubles with the different scales: dwarf galaxies, galaxies, galaxy clusters, super-clusters
- No unification with the (General) Relativity

How can we study DM?
(assuming only gravitationally interacting DM)

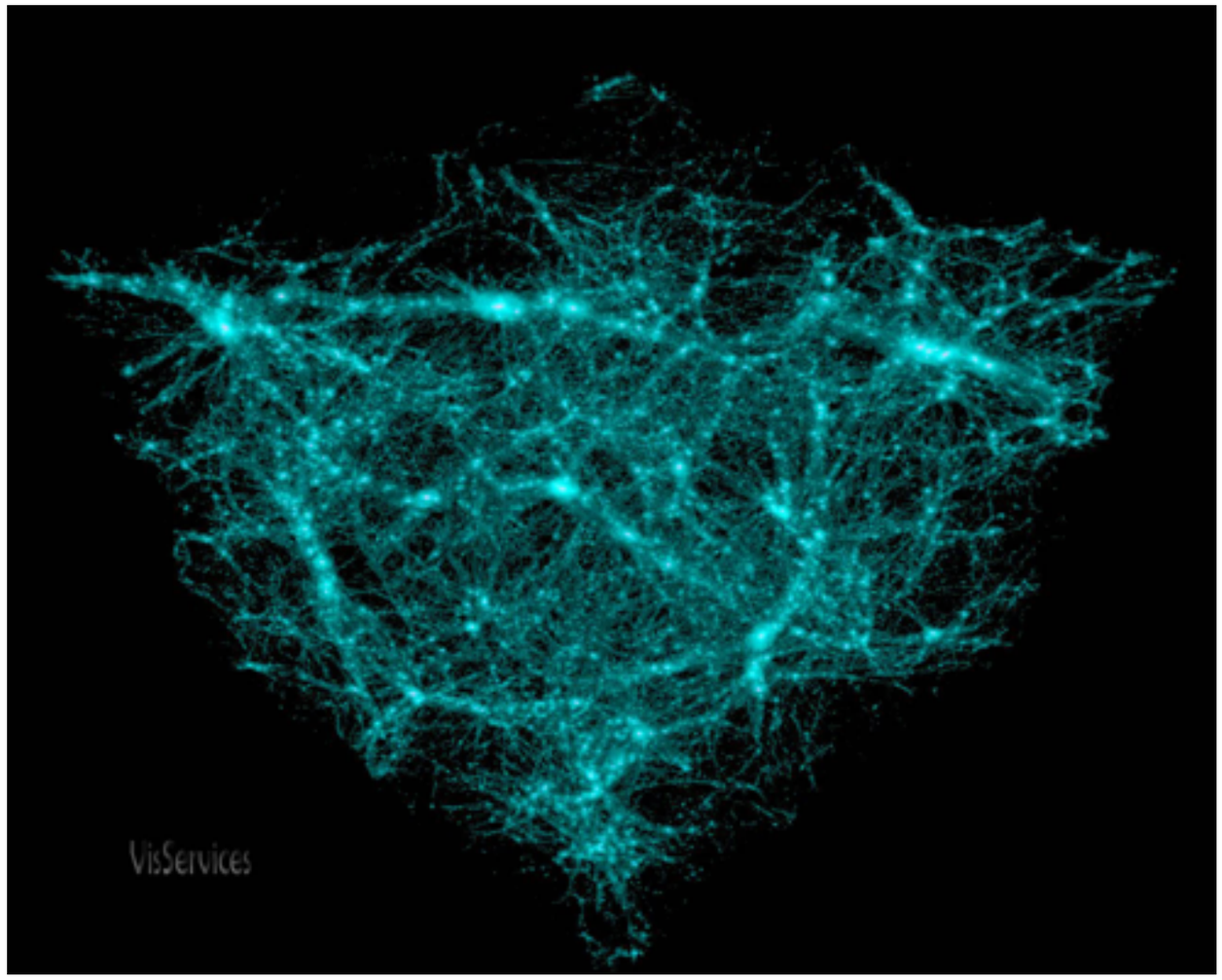
How to model DM?



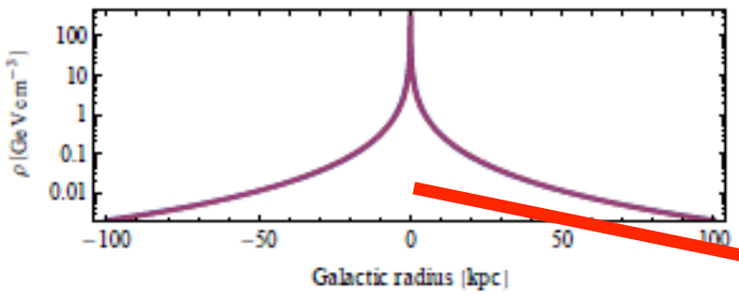
A snapshot from the Millennium N-body simulation

How to model DM?

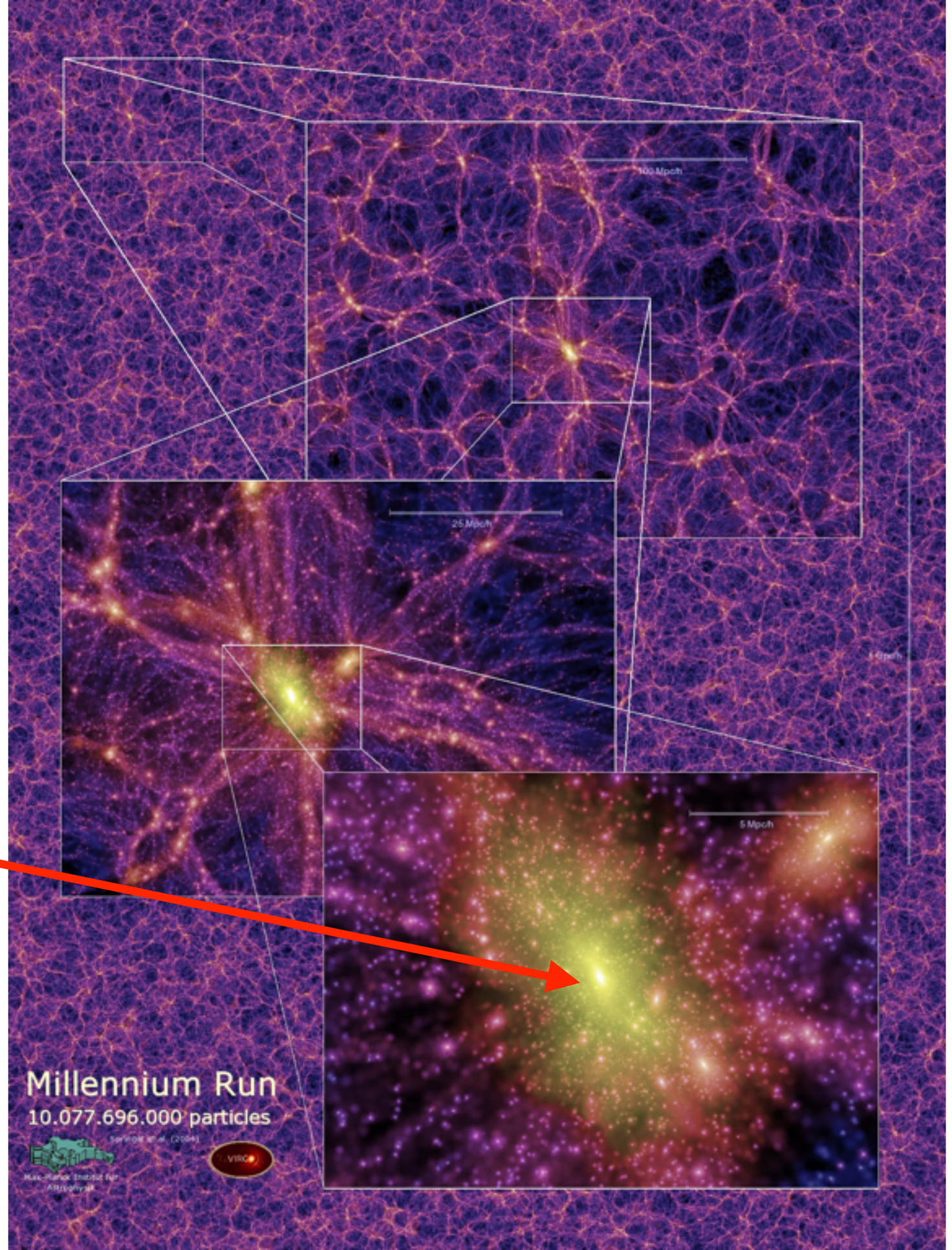
- Linear regime — analytically, perturbation theory
- Nonlinear regime — numerically, N-body simulation



- Linear *versus* non-linear regime

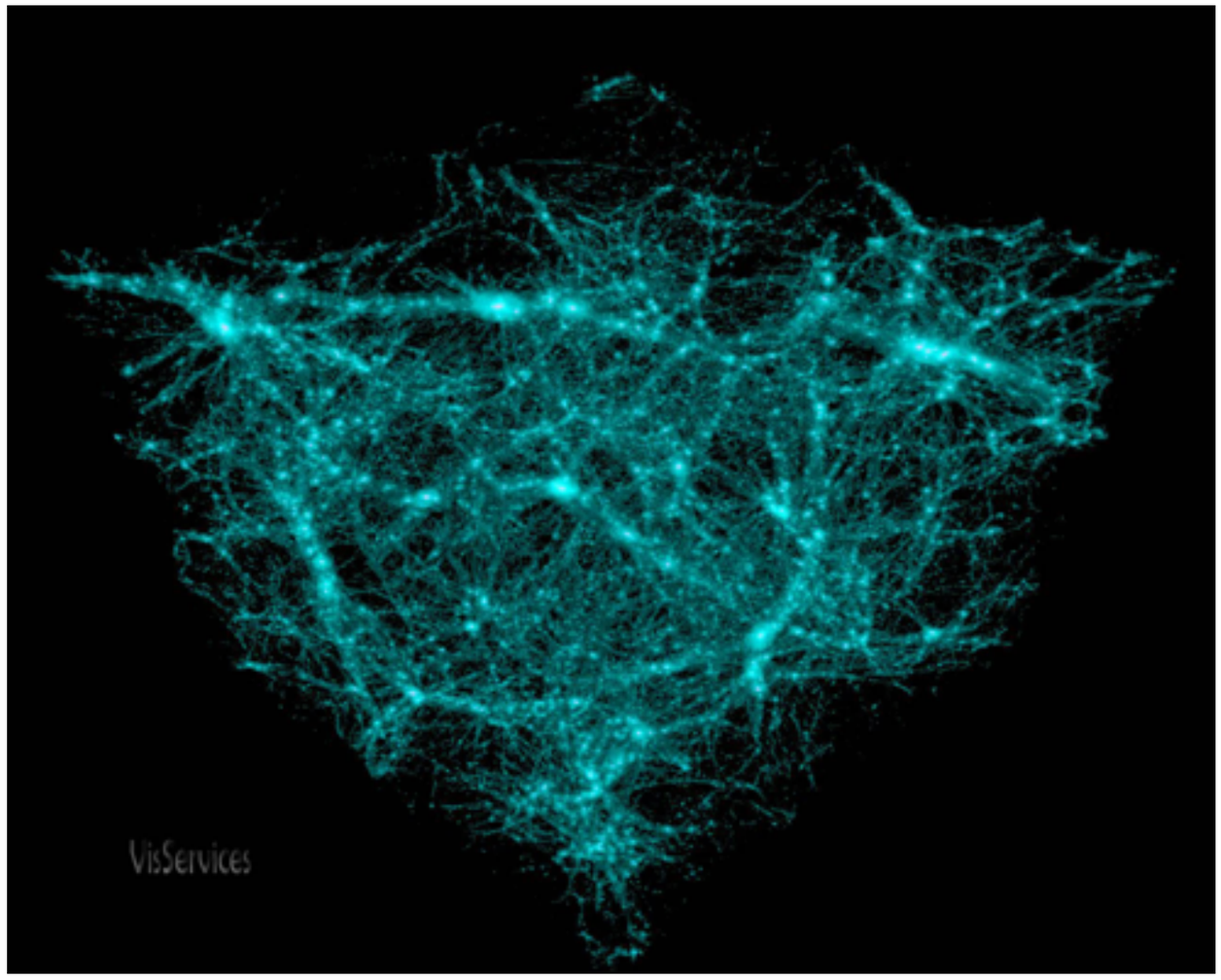


$$J_{\rm annih} \propto \rho^2$$



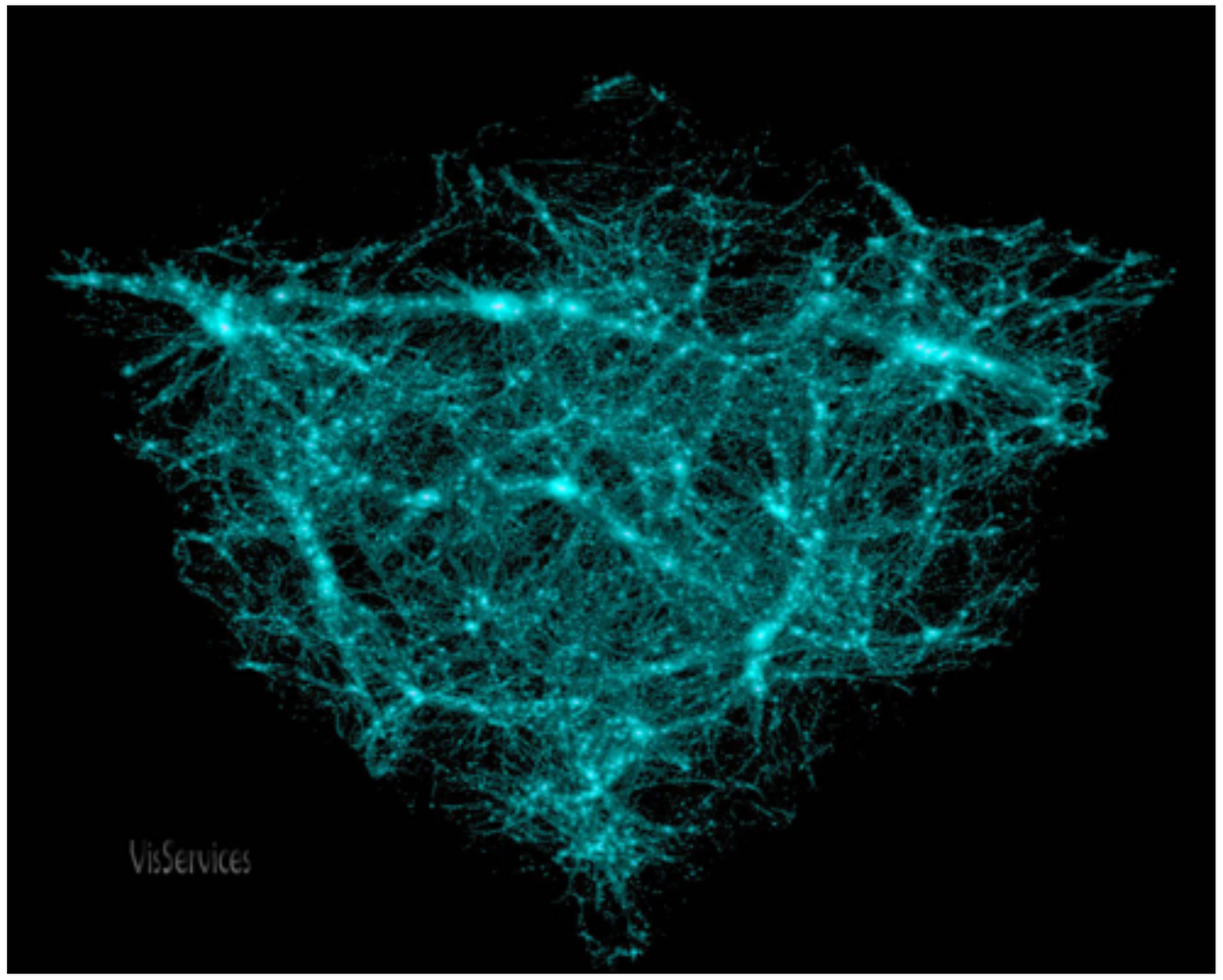
N-body simulation

- Only gravity (‘pure’ N-body) — computationally expensive!
- Gravity + hydrodynamics — more expensive!
- Gravity + hydrodynamics + approximated baryon physics — very-very much more expensive!
- Scales: maximal (~Gpc), a MW-size halo



How to model DM?

- Initial conditions?
- Gaussian field (large scales), a fingerprint of the Inflation!
- Specific objects:
  spherical cloud ('spherical cow'),
  a galaxy size object, galactic mergers,
  cluster collusions ('Bullet cluster') etc



Example of a special initial conditions: colliding clusters to model the Abell 520 system

- arXiv:1603.07324, back on this topic after some slides!

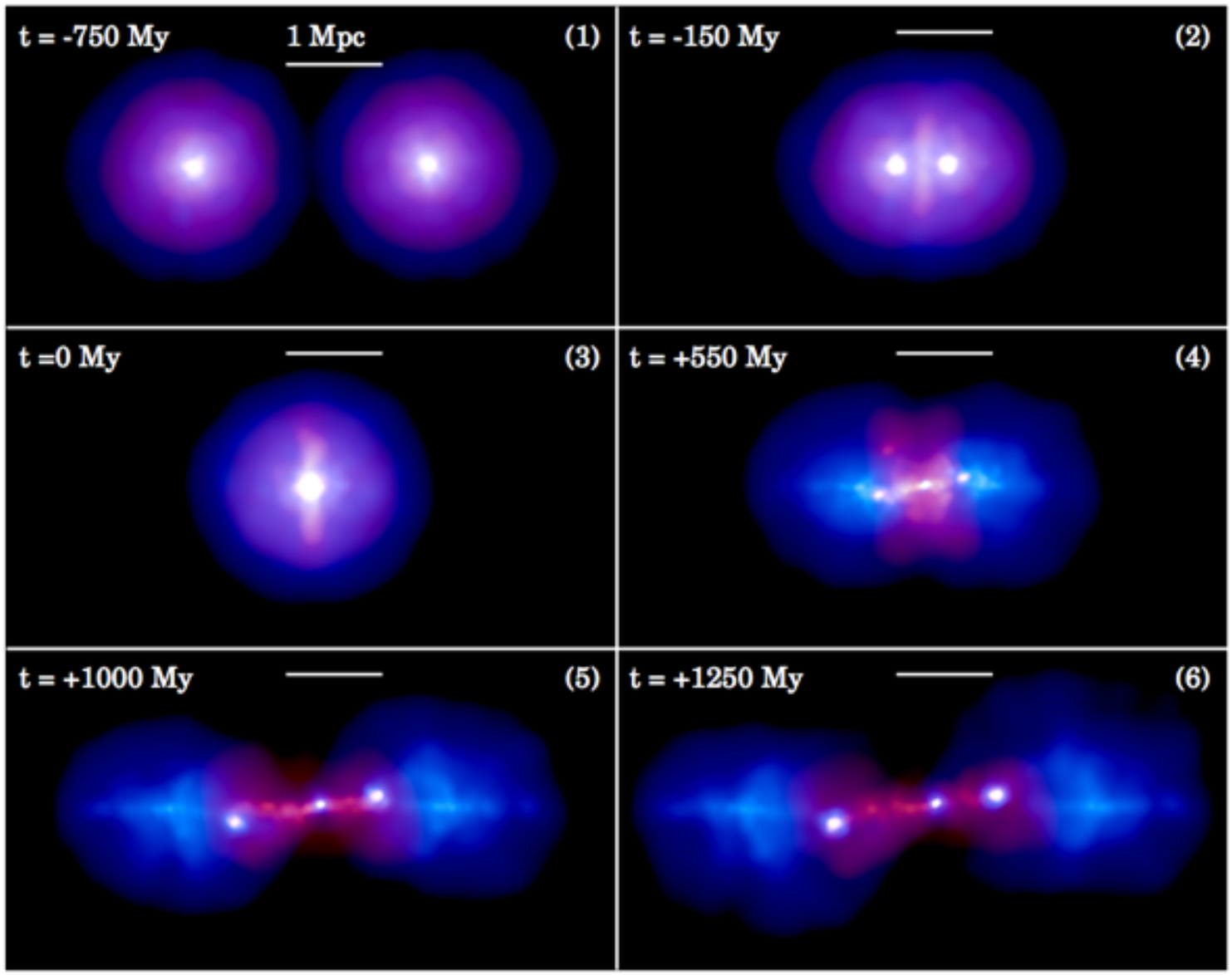
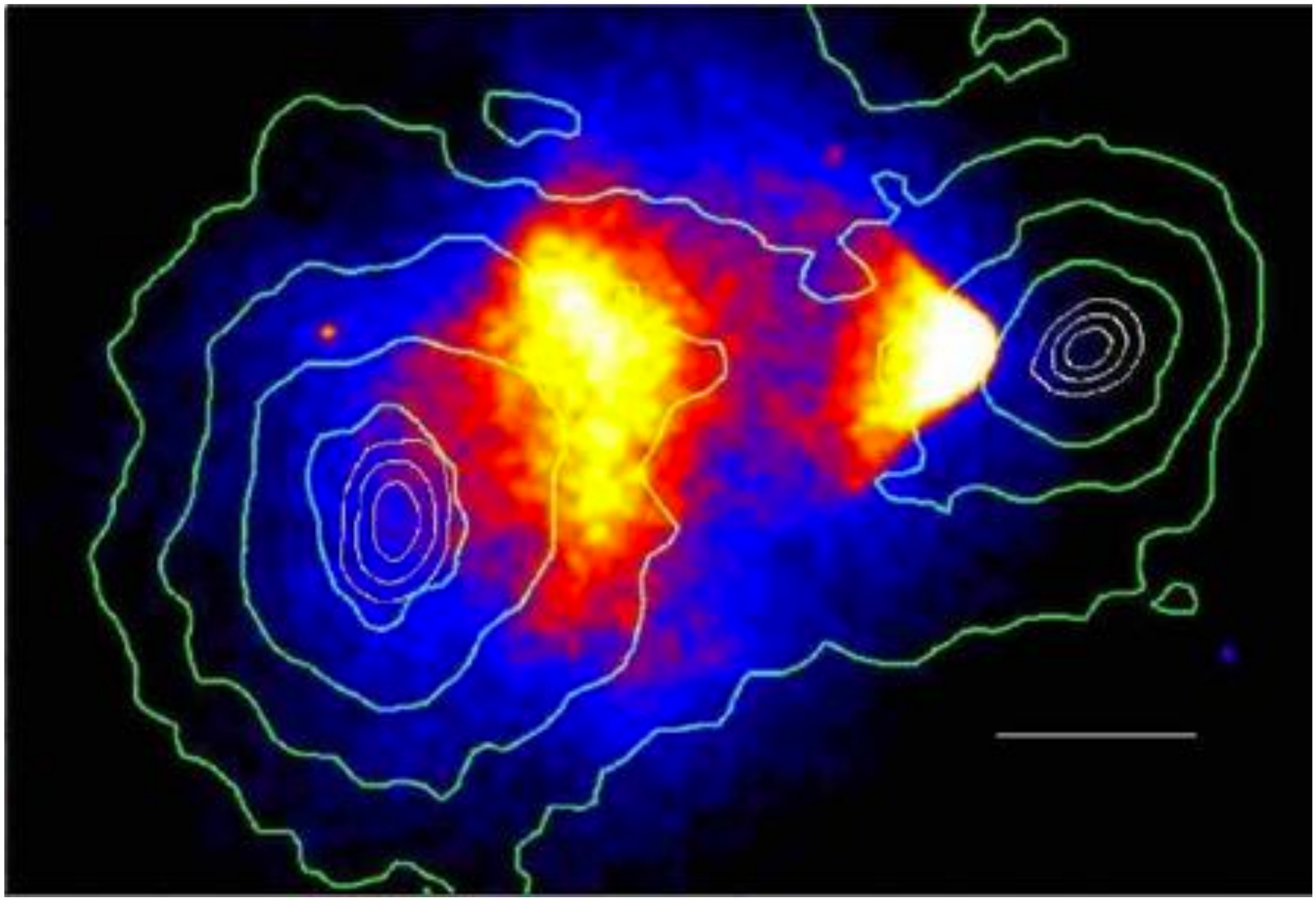


Figure 2. Simulation of Abell520. The non-interacting DM distribution is displayed in blue and the dark plasma distribution in red. The corresponding video is available at http://coe.kbfi.ee/pmwiki/pmwiki.php/Results/Results

Relating simulations to tough real life, some examples

Bullet Cluster

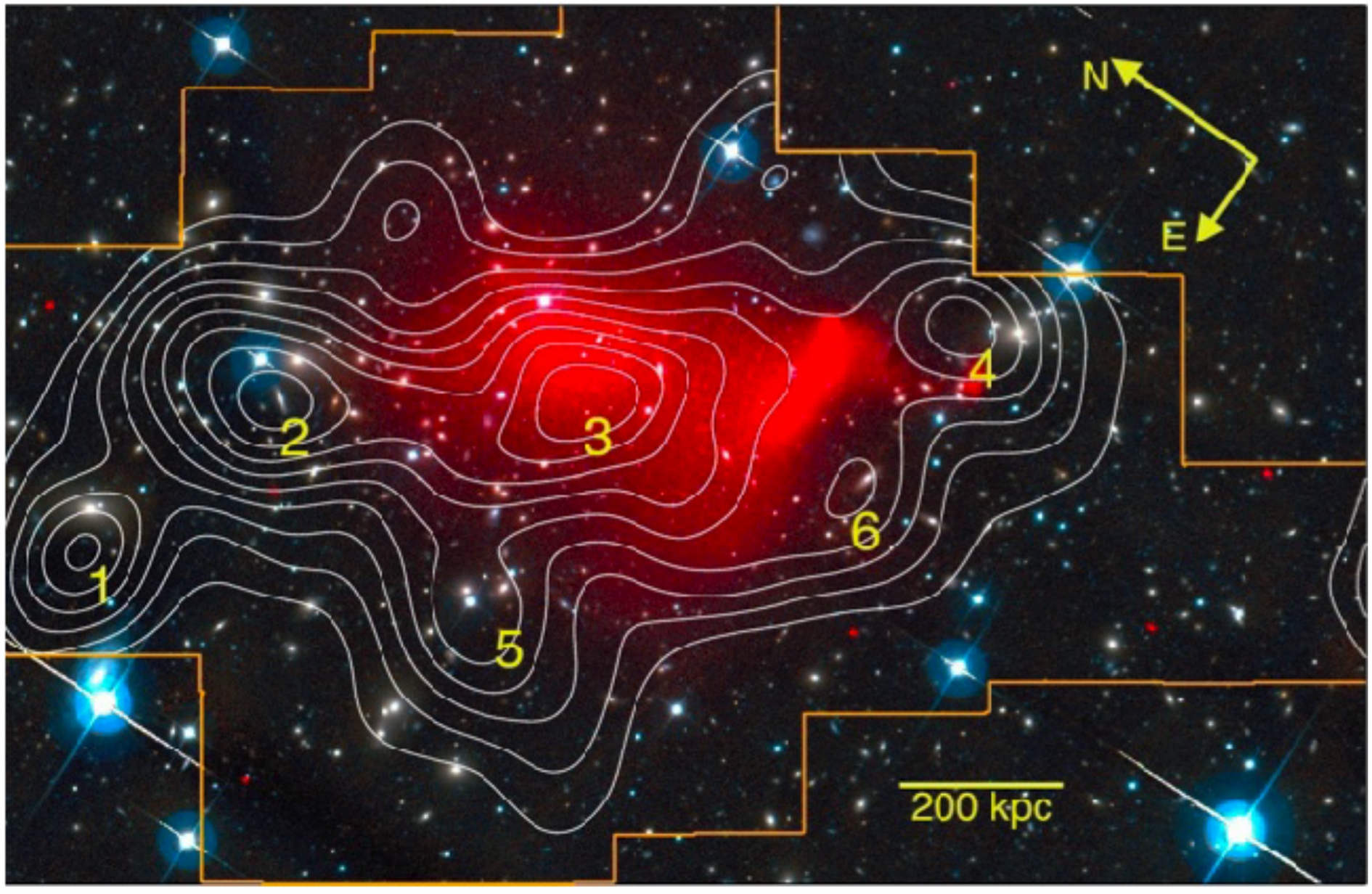
- A strong proof of DM — clear separation between DM and X-ray gas!



Clowe et al. 2006

Abell 520

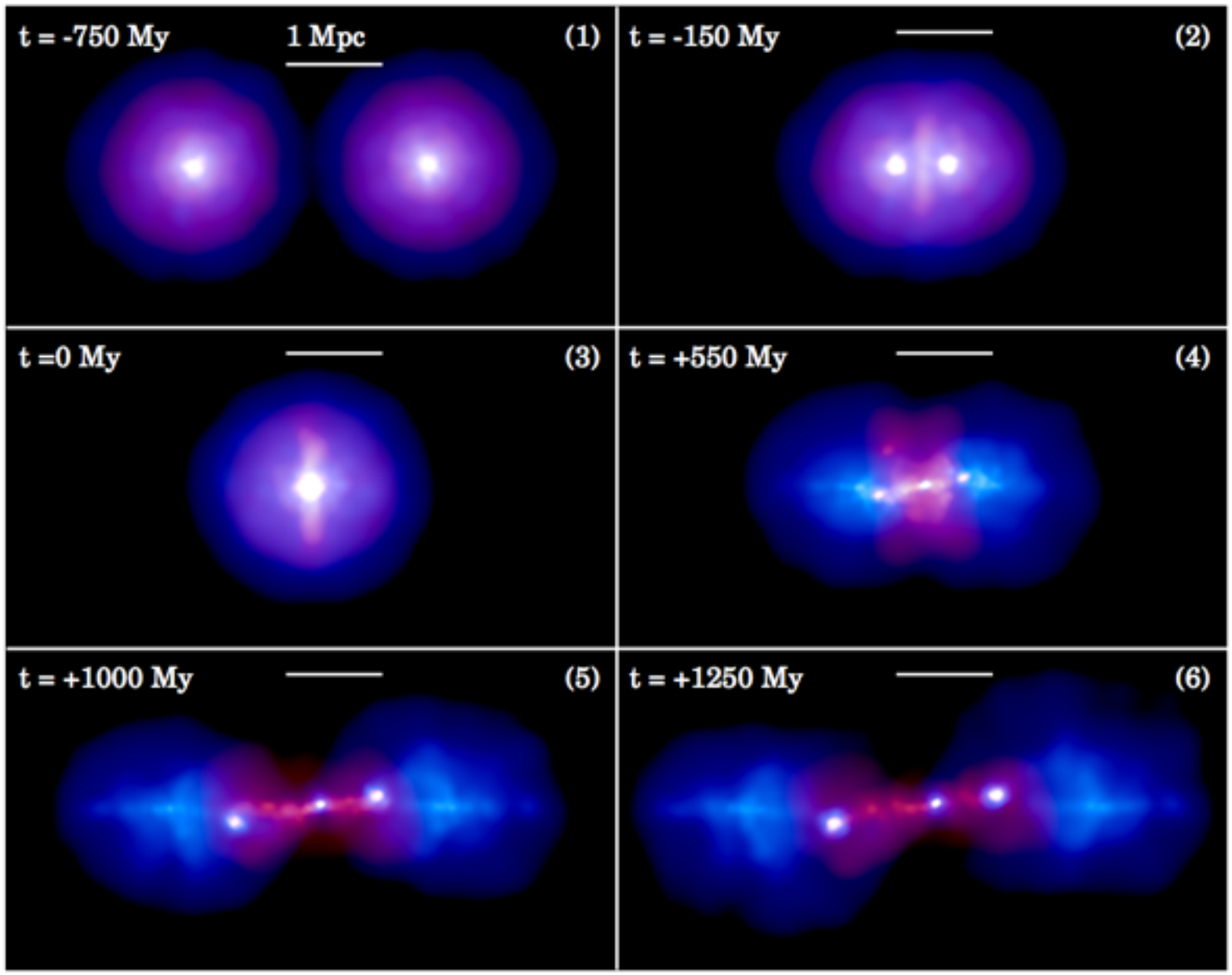
- Lot of DM at the collusion site — interacting DM?



arXiv:1204.2985

Abell 520

- Dark Plasma? See arXiv:1603.07324



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Abell 520

- Dark Plasma — NB! Non-grav. interaction! See arXiv:1603.07324

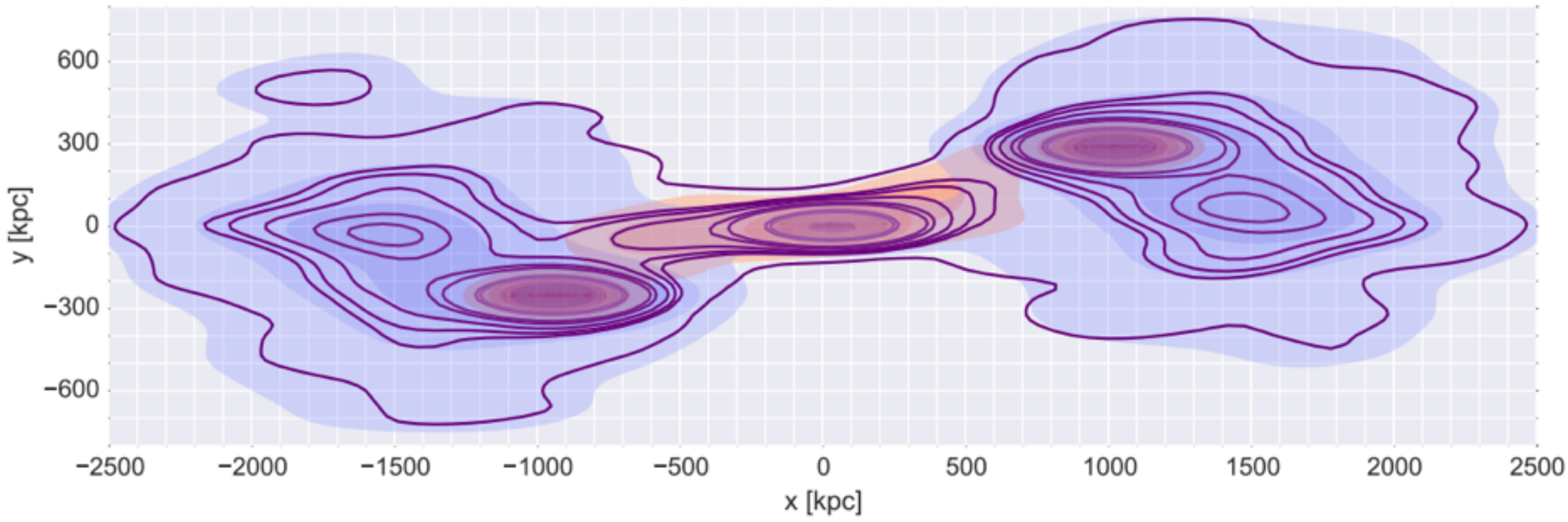
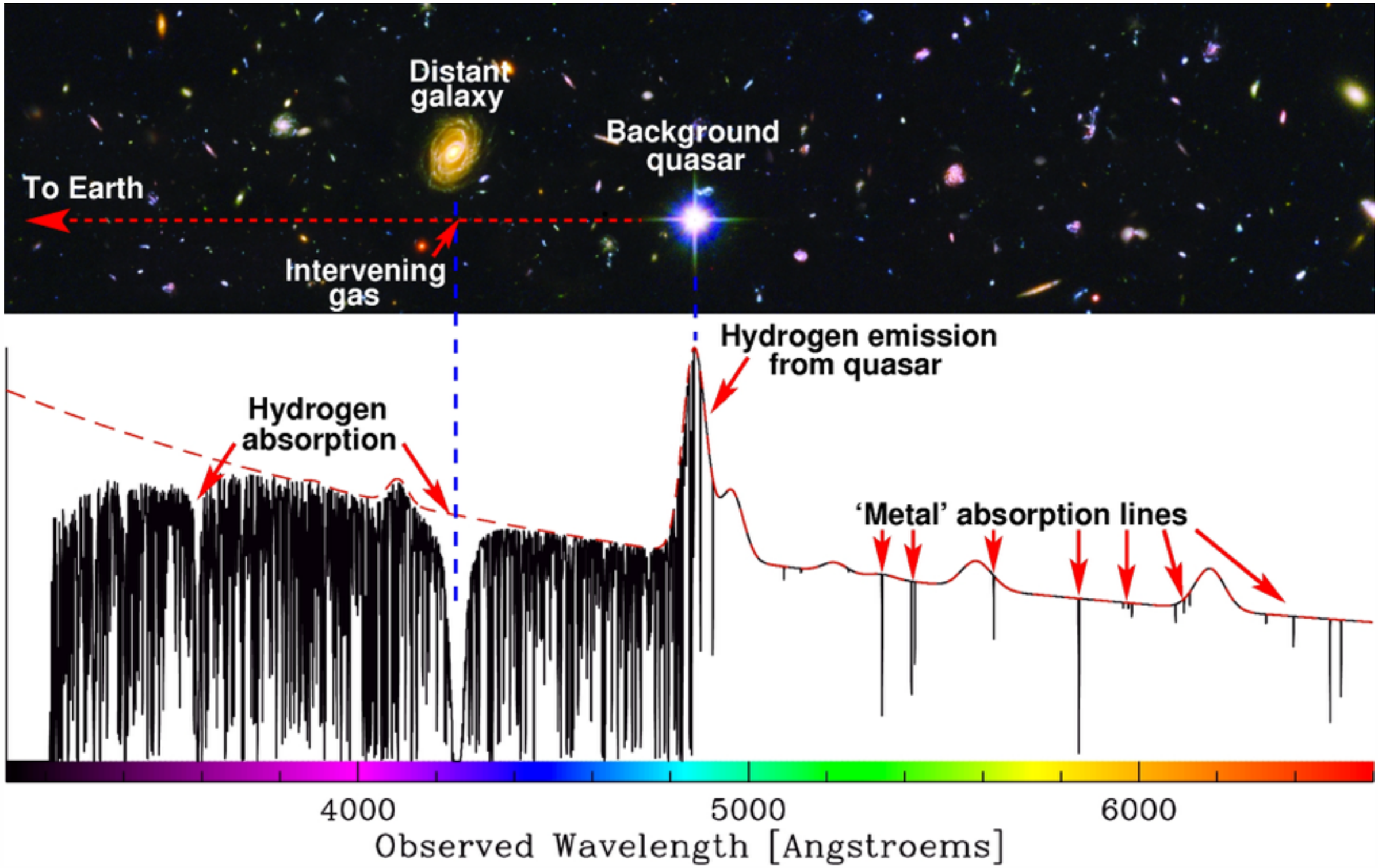


Figure 3. Simulation result of the dark matter distribution in Abell 520. Purple density contours show the mass distribution as it would appear on a lensing image. Red and blue colors represent plasma and non-interacting DM distributions, respectively. Color brightness corresponds to total mass density (plotted on a logarithmic scale).

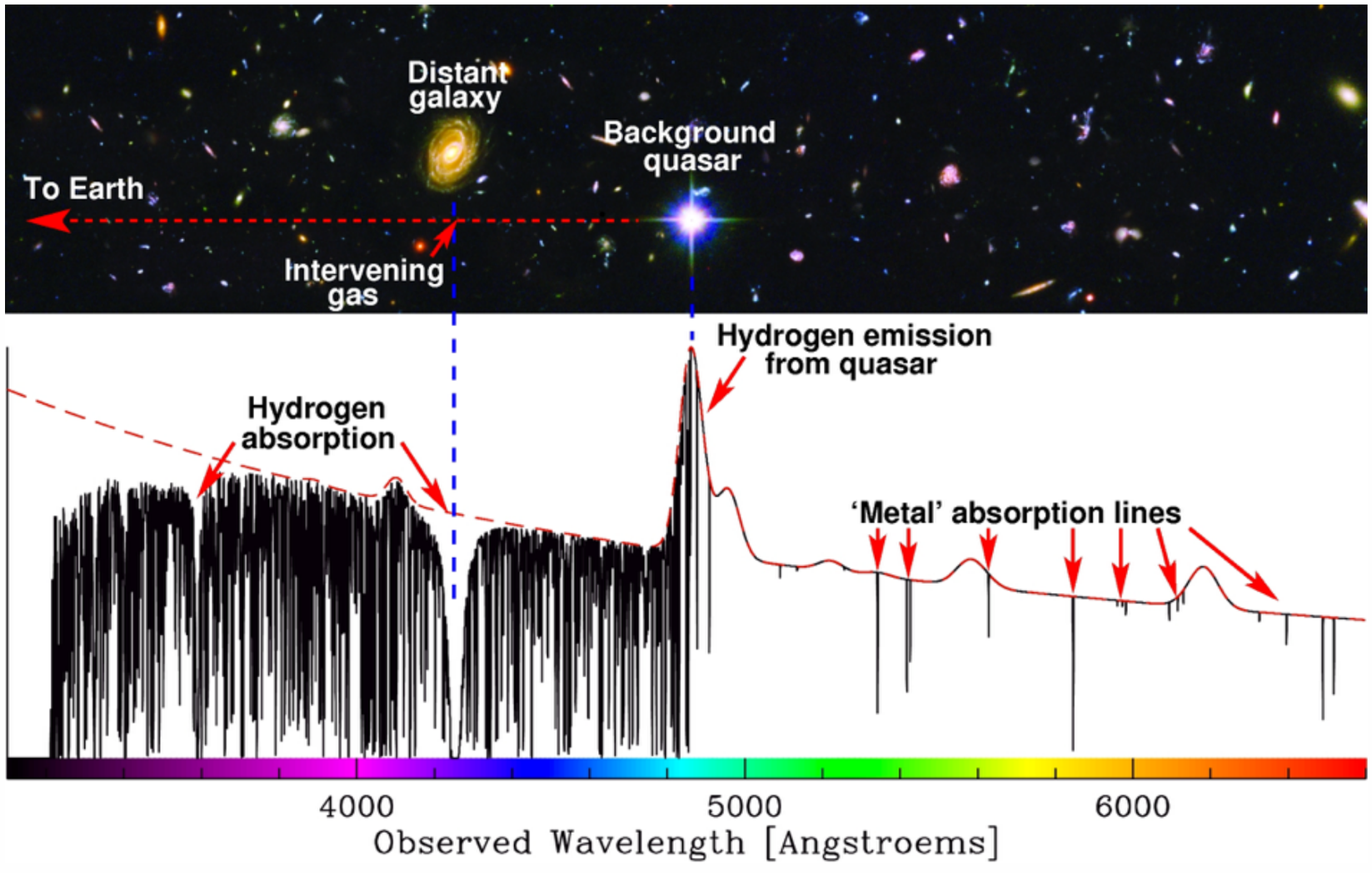
Relating simulations to even tougher real life…

Lyman-alpha forest



Lyman-alpha forest

- N-body simulation + hydrodynamics + something

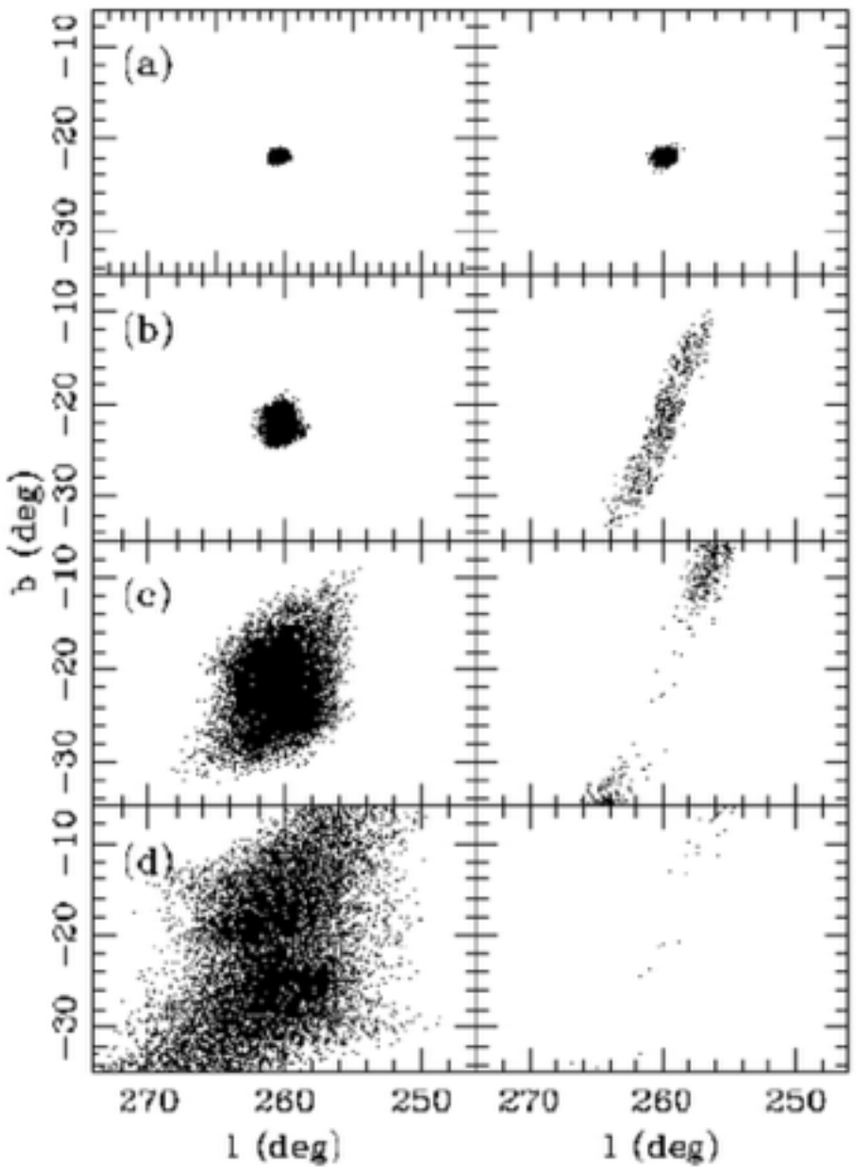


It seems that at smaller scales
(~dwarf galaxy),
there are some troubles…

- ‘Missing satellite problem’ (MW: ~30 versus ~500)
- ‘Core/cusp problem’ (observed versus N-body profile)
- ‘Too big to fail’ (small DM halos have too few stars)

Dwarf galaxies

- N-body simulation + hydrodynamics + baryon physics + something

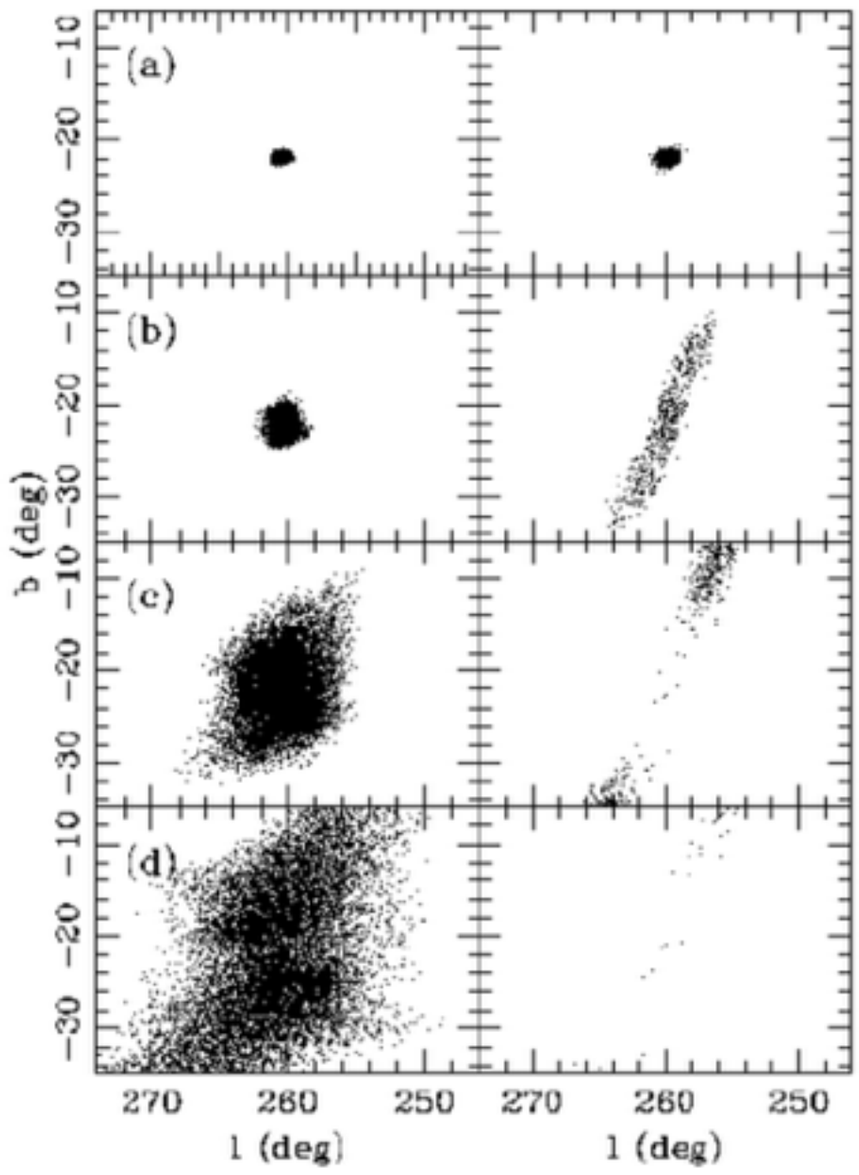


- **'Missing satellite problem'**
- **'Core/cusp problem'**
- **'Too big to fail'**

arXiv:0712.4312

Dwarf galaxies

- N-body simulation + hydrodynamics + baryon physics + something

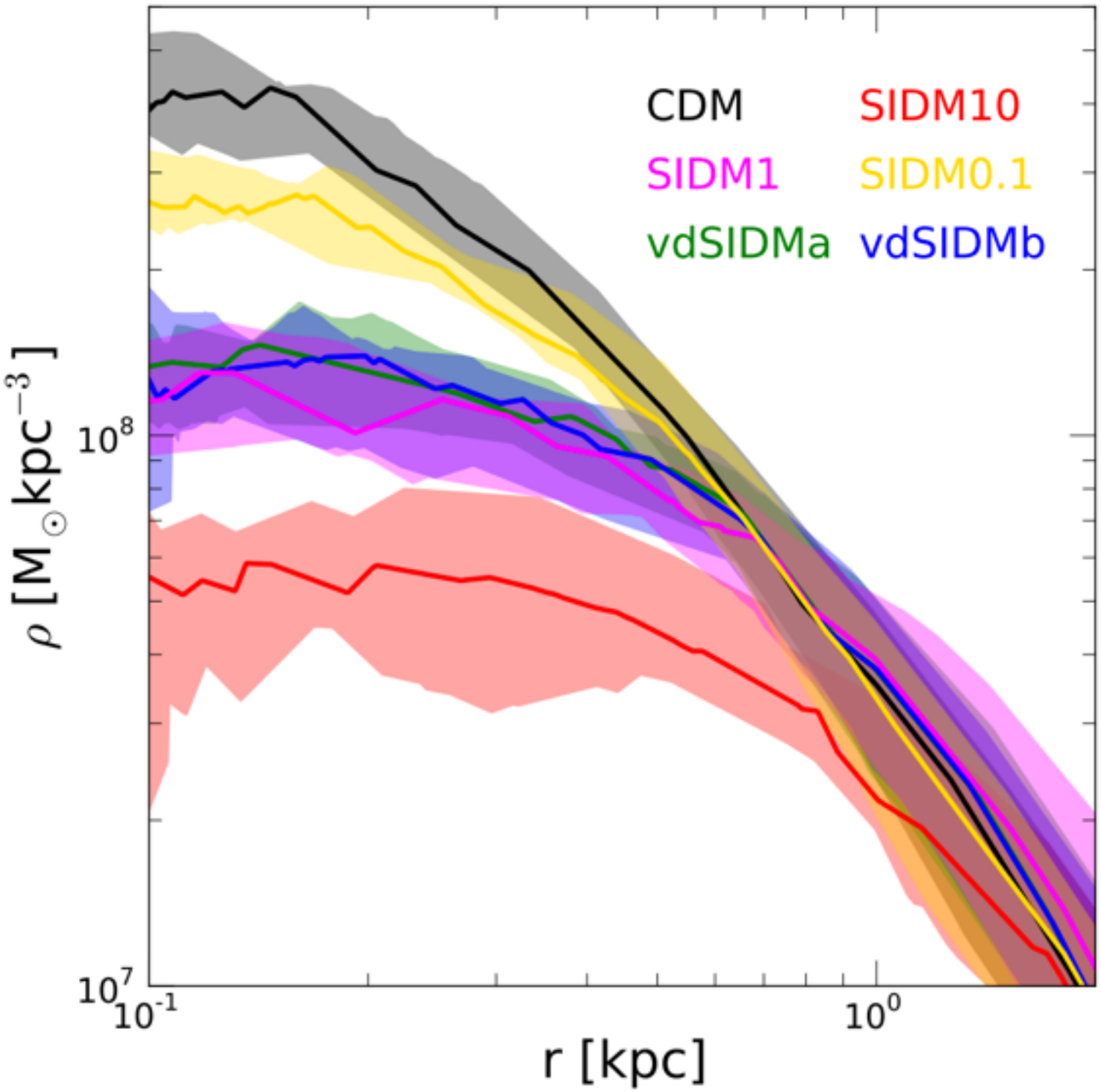


arXiv:0712.4312

- **'Missing satellite problem'**
- **'Core/cusp problem'**
- **'Too big to fail'**

Does extra (non-grav.) self-interaction can help to solve those problems?

- ‘Core/cusp problem’ and ‘self-interacting DM’ (SIDM)



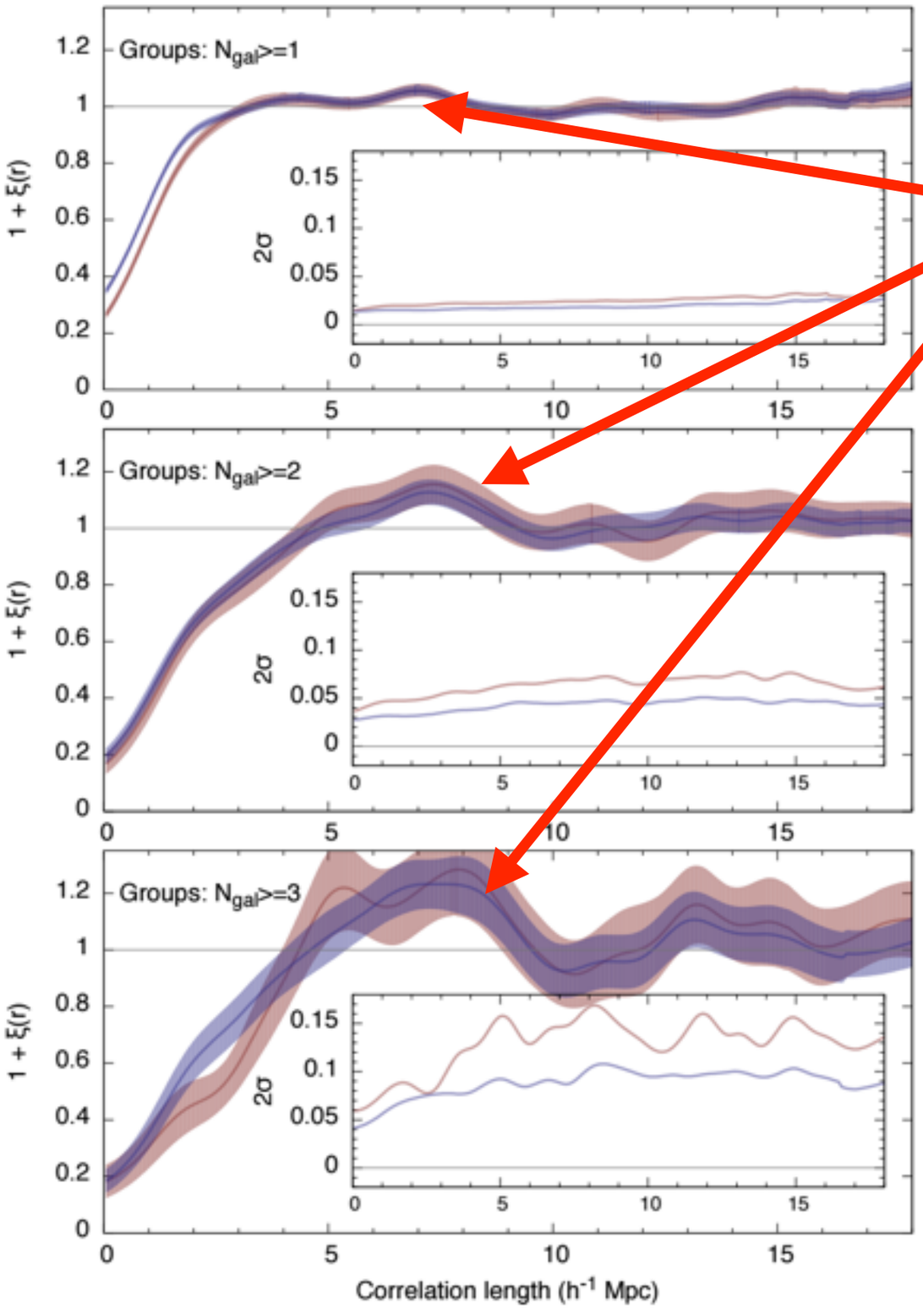
Explained later!

Credits: Zavala et al, arXiv:1211.6426

Is there any trouble at large scales?

Maybe…

Maybe…

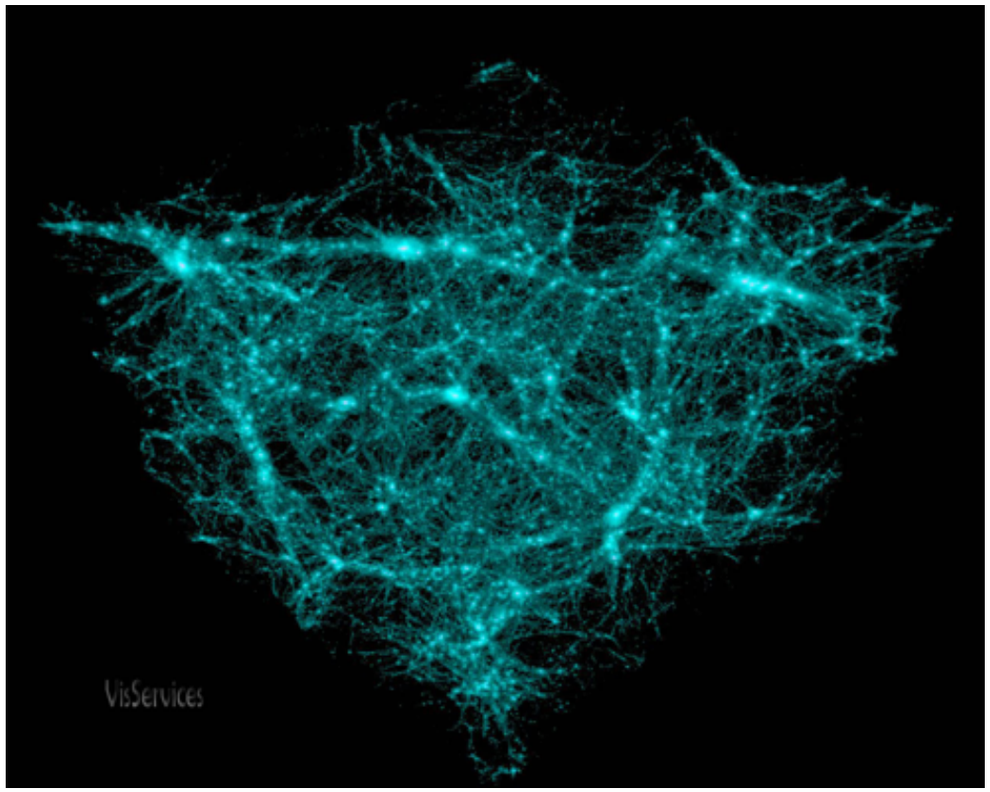


- For example, an anomaly in LSS, arXiv:1406.4357

Can gravity say anything beyond gravity?

(Yes, it can!)

Small scale structure of DM

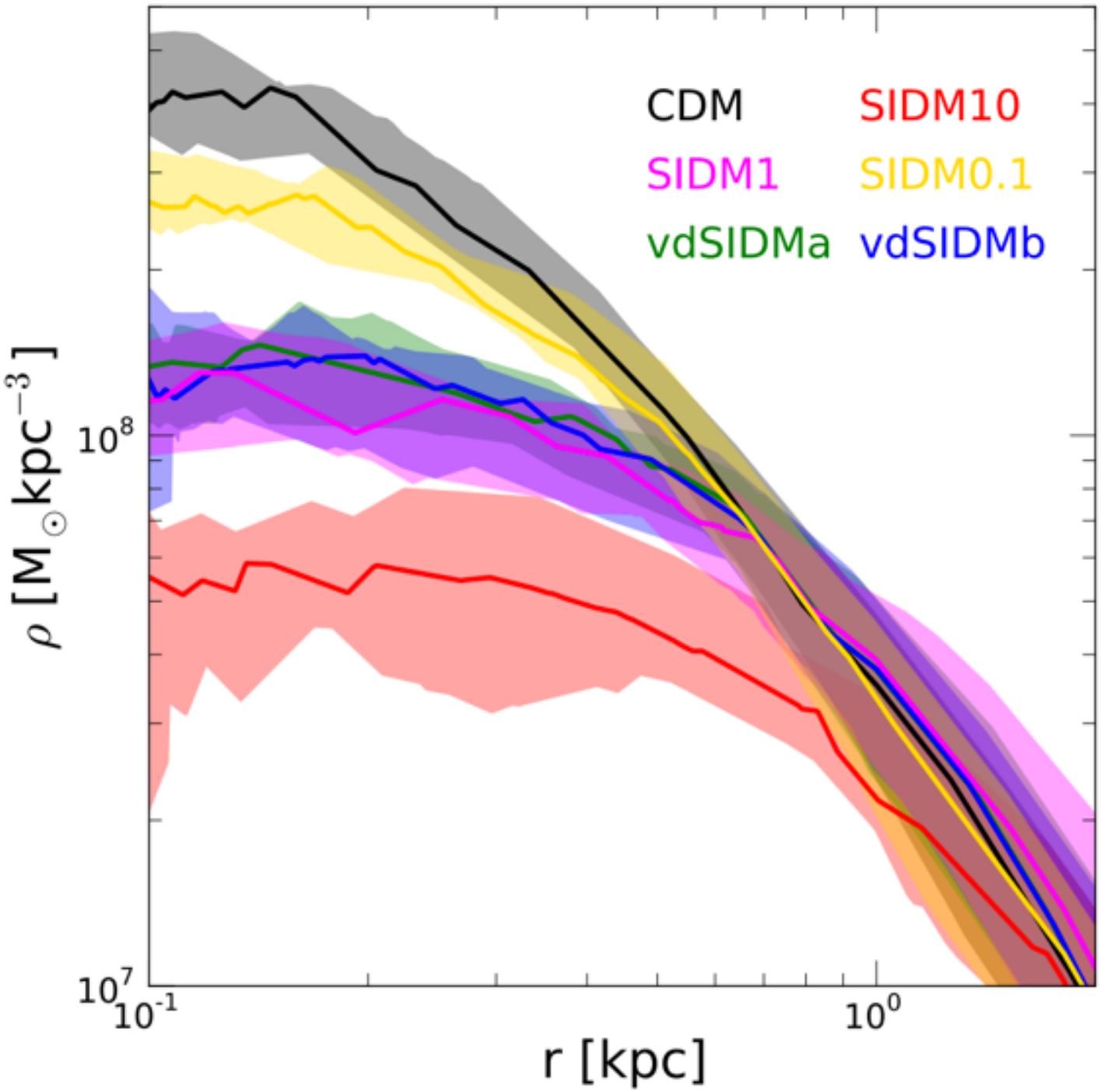


- Small scale structure of DM can say a lot about the properties and origin of DM
- Smallest observable DM clumps — dwarf galaxies
- Some theories predict the lower limit at 10^{-9}…10^{-6} solar mass (WIMP!) — hopeless!
- Kinematics of stars in the Galaxy (Gaia experiment, very soon!)

DM halos

- DM self-interaction or interaction with baryon matter changes the properties of DM halos:
  — sphericality
  — density profile
  — collision properties

- ‘Core/cusp problem’ and ‘self-interacting DM’ (SIDM)



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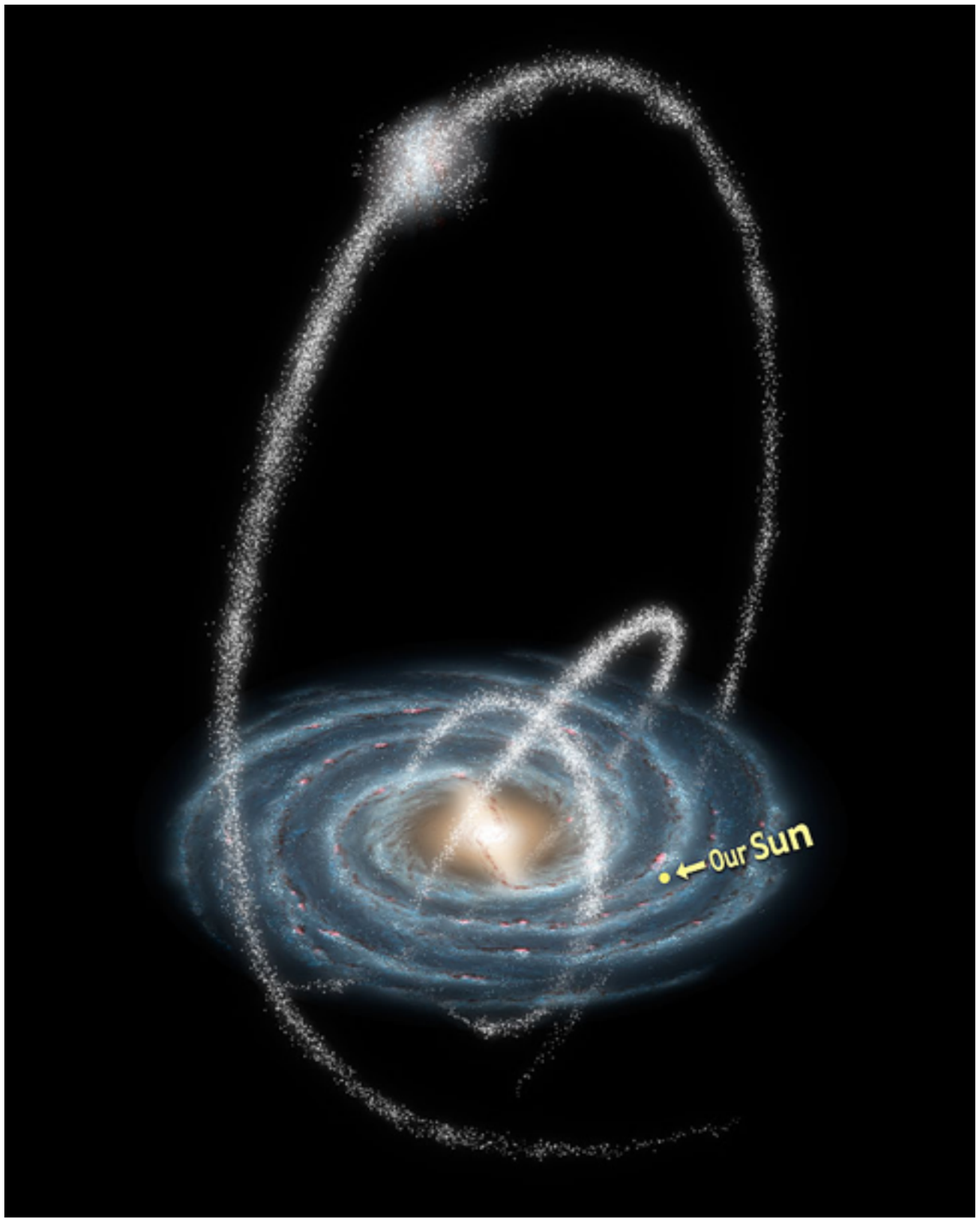
Stellar streams

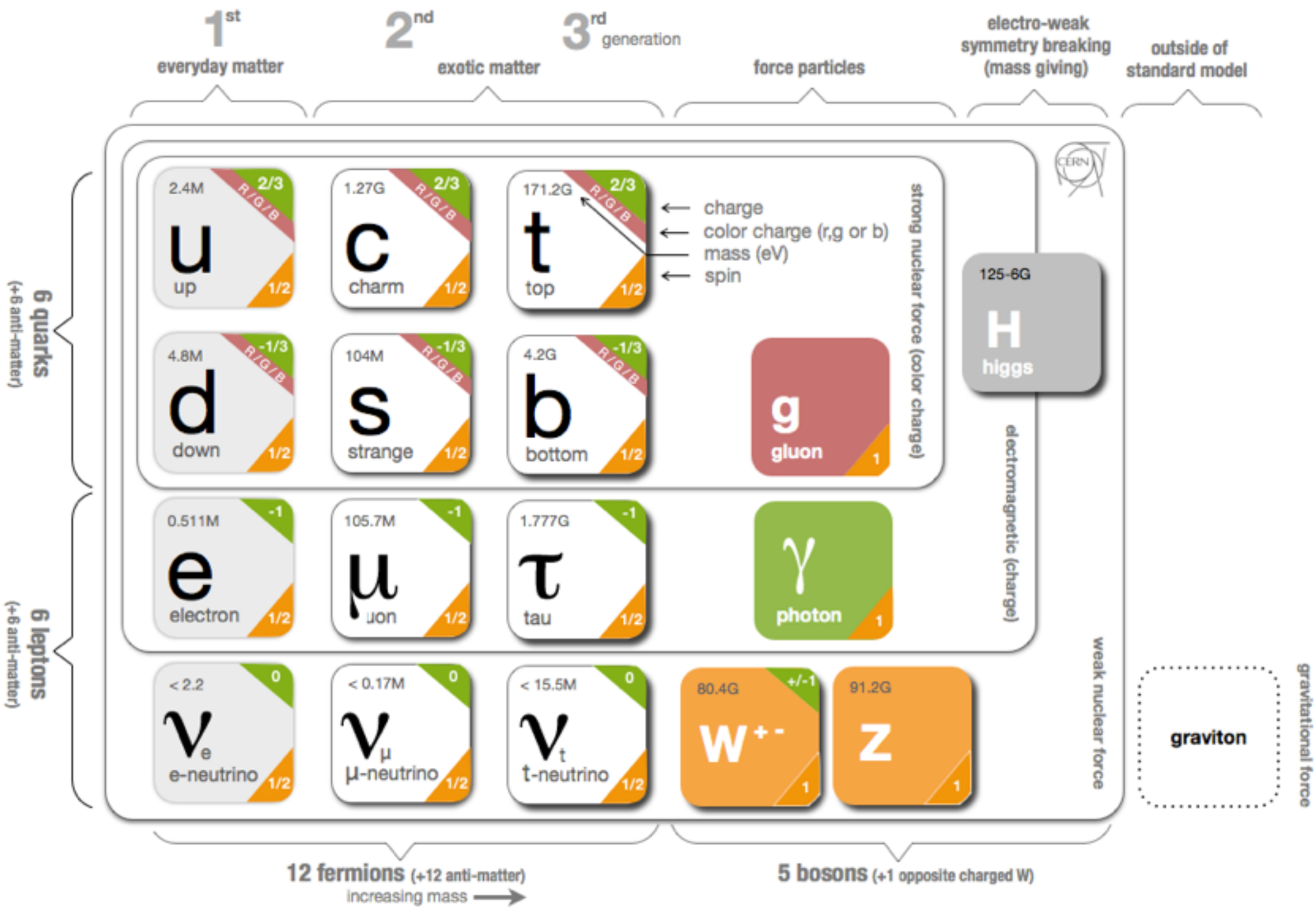


- Having very long lifetime
- Sensitive to the varying gravitational background potential
- Small scale structure of DM spatial distribution provide gravitational background potential

- Answered soon, stay tuned!

Entering mystery world:
DM beyond gravity

DM in the Standard Model?



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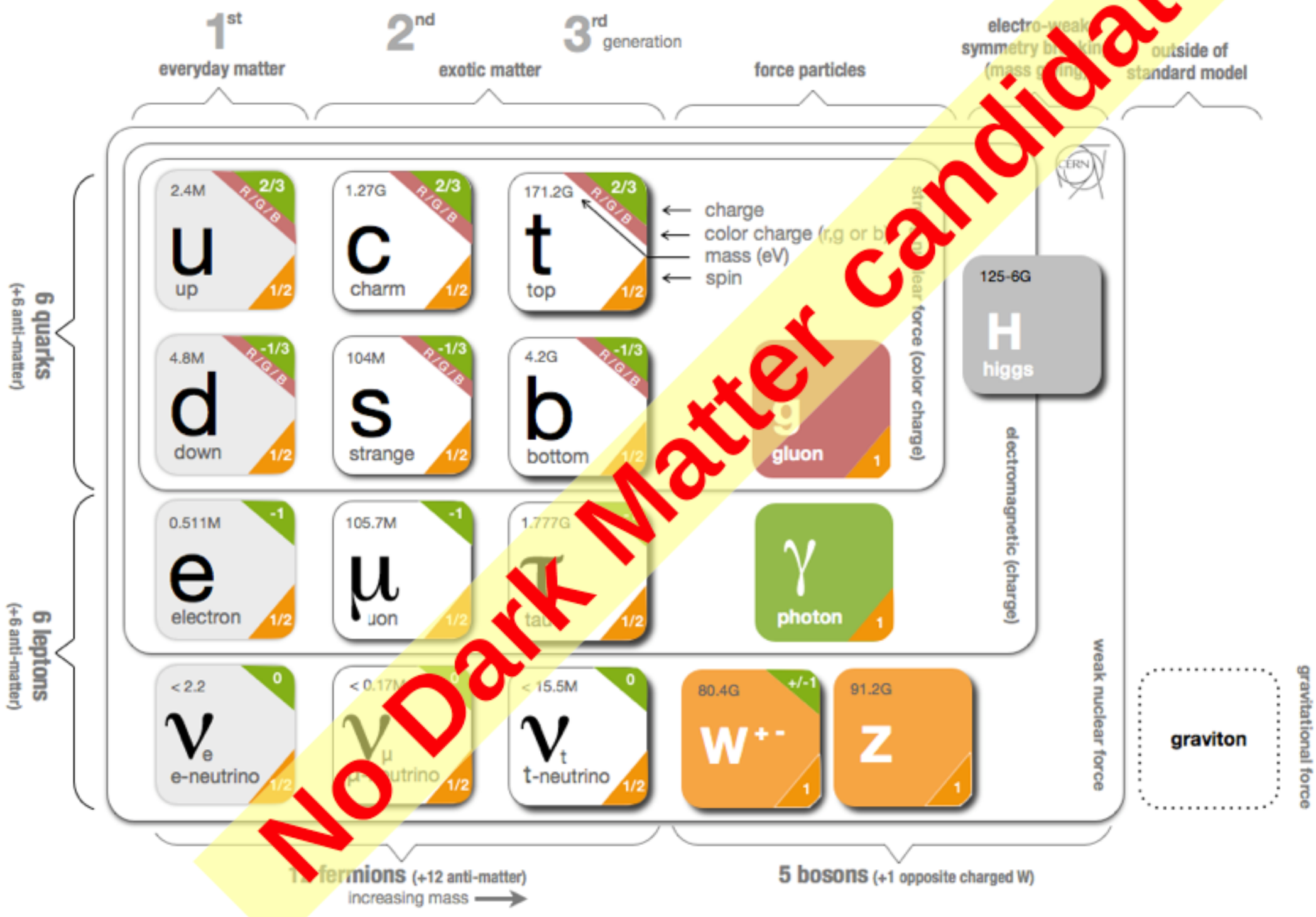
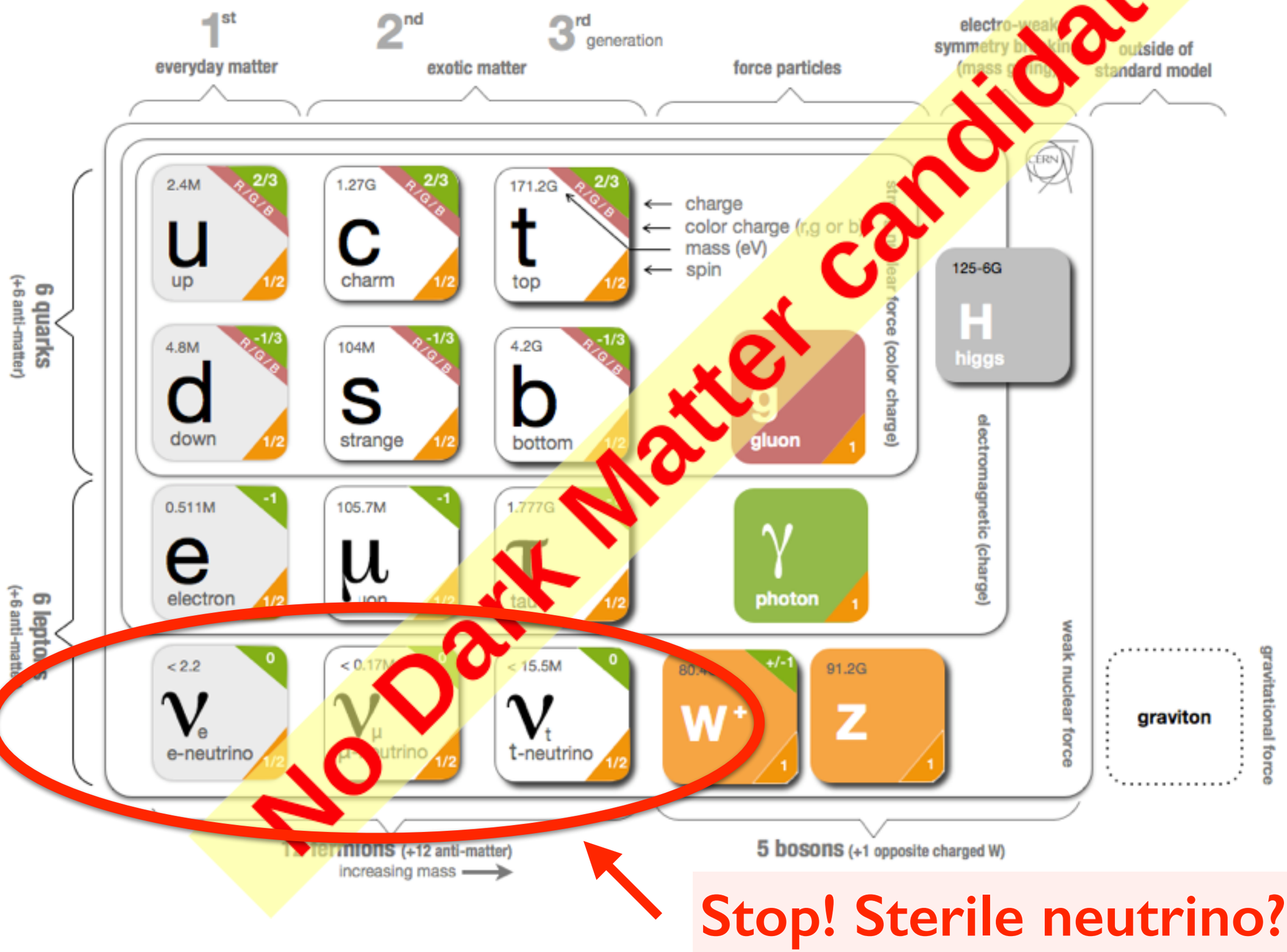


DM in the Standard Model?

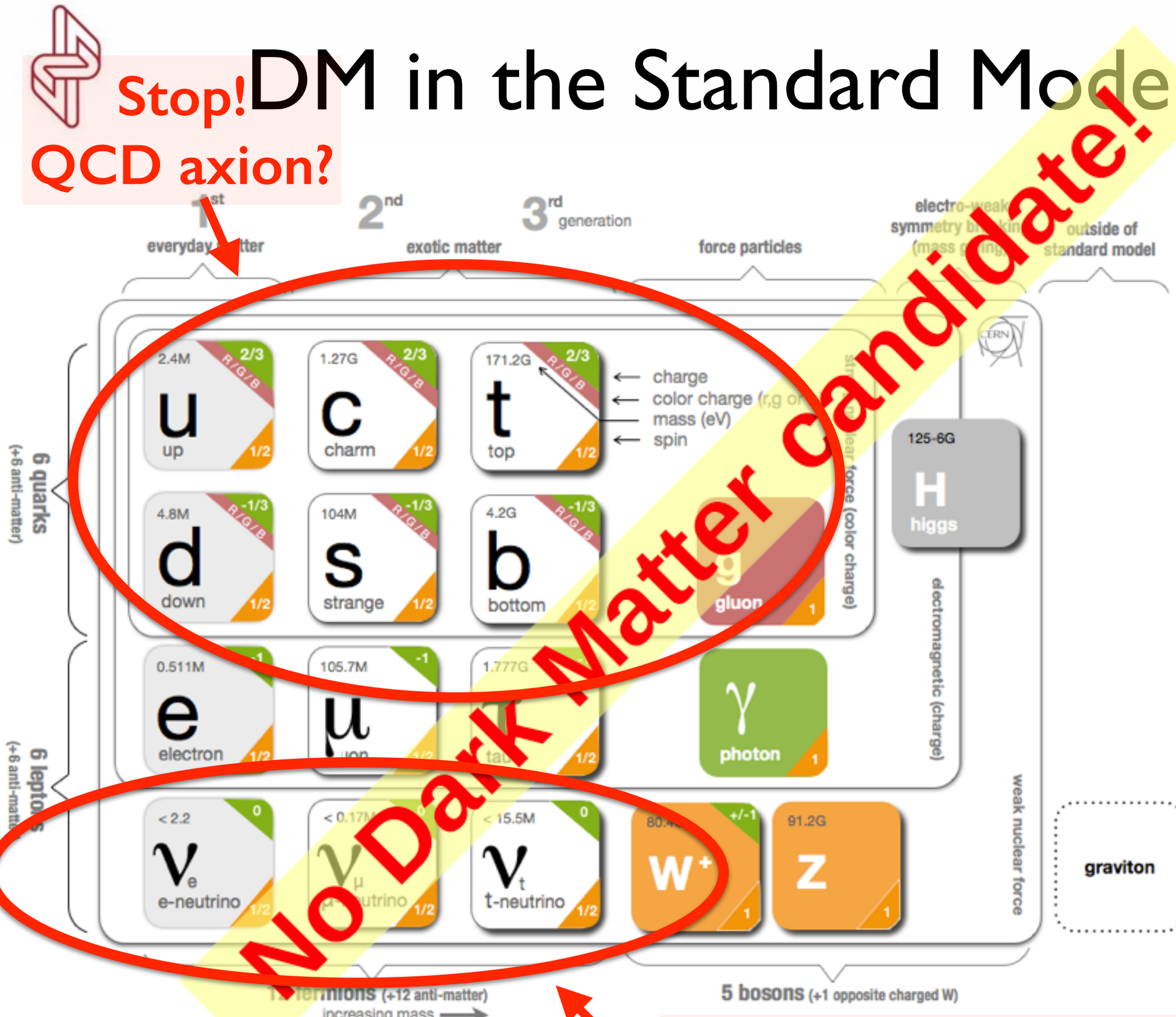


Dark matter candidate!

No Dark Matter

Stop! Sterile neutrino?

DM in the Standard Model?

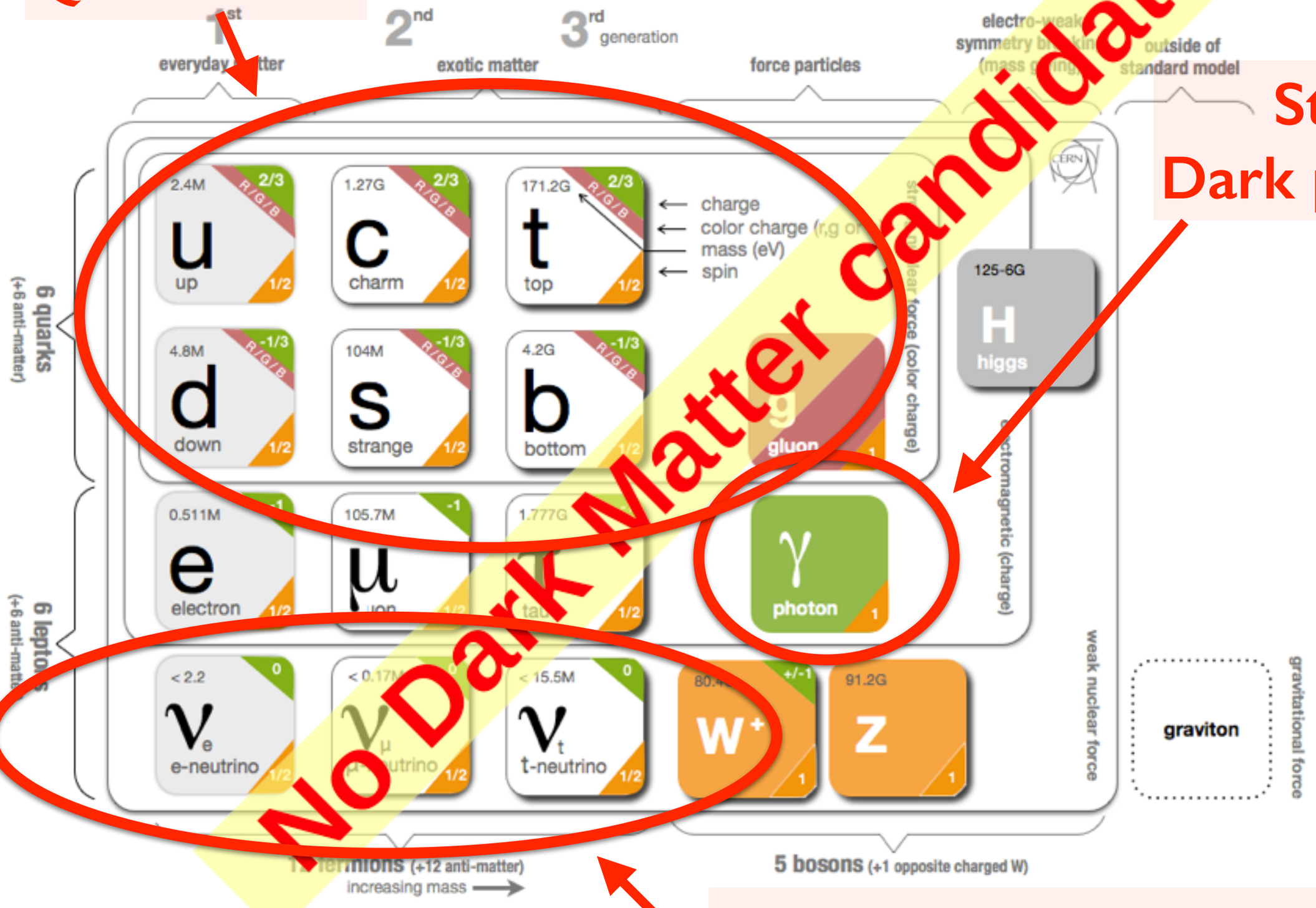


DM in the Standard Model?

Stop!
QCD axion?

Stop!
Dark photon?

No Dark Matter candidate!



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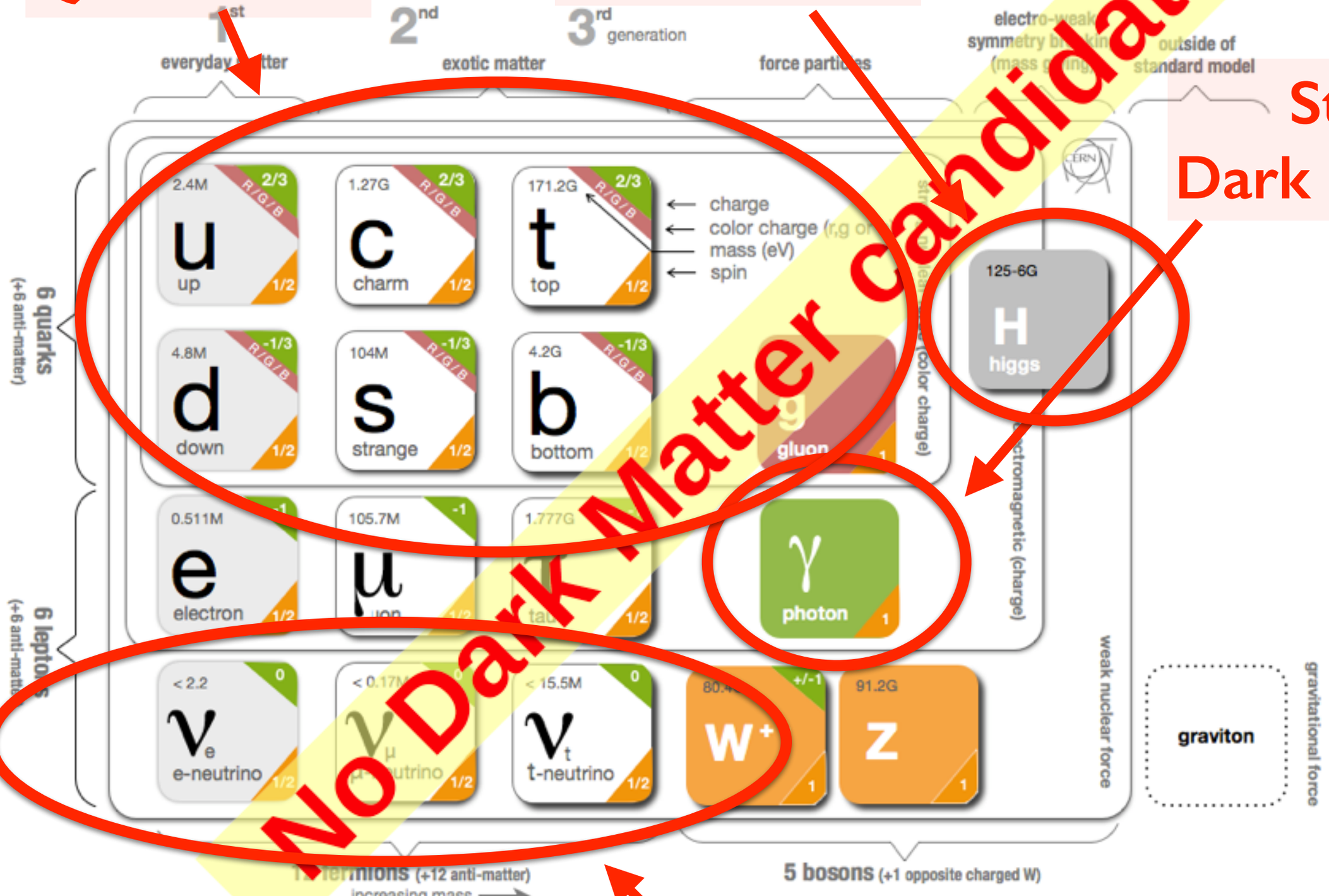


DM in the Standard Model?

Stop!
QCD axion?

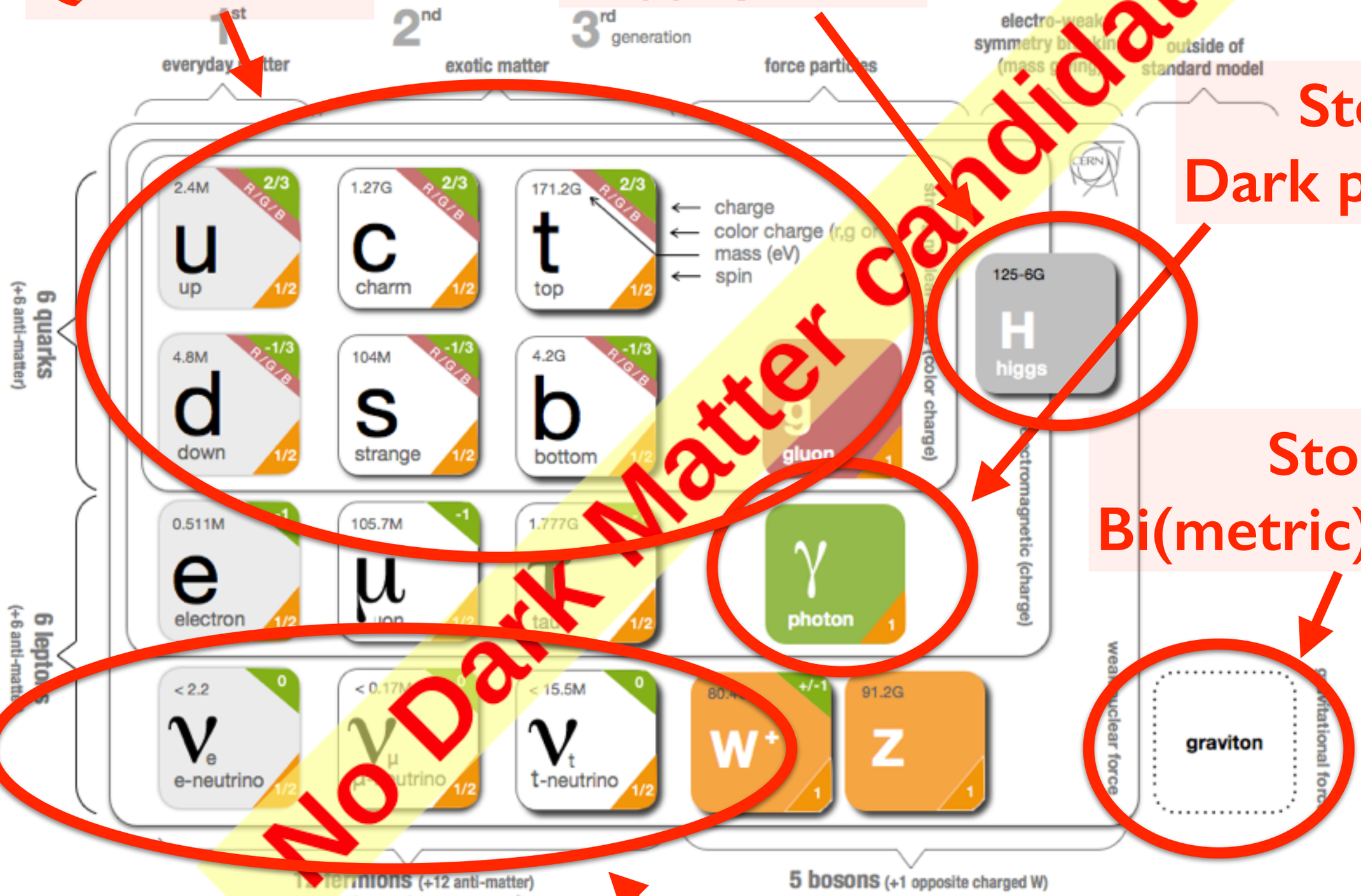
Stop!
Higgs portal?

Stop!
Dark photon?

Stop!
Bi(metric)gravity?

Stop! Sterile neutrino?

No Dark Matter candidate!



But the most popular candidate is not among those…

It is provided by the WIMP miracle!

Paradigm of Weakly Interacting Massive Particle (WIMP)

WIMP 'miracle':

- g* ~ weak interaction
- mass of WIMP ~ the scale of weak interaction, ~ 100 GeV

Observed abundance of DM in the Universe!

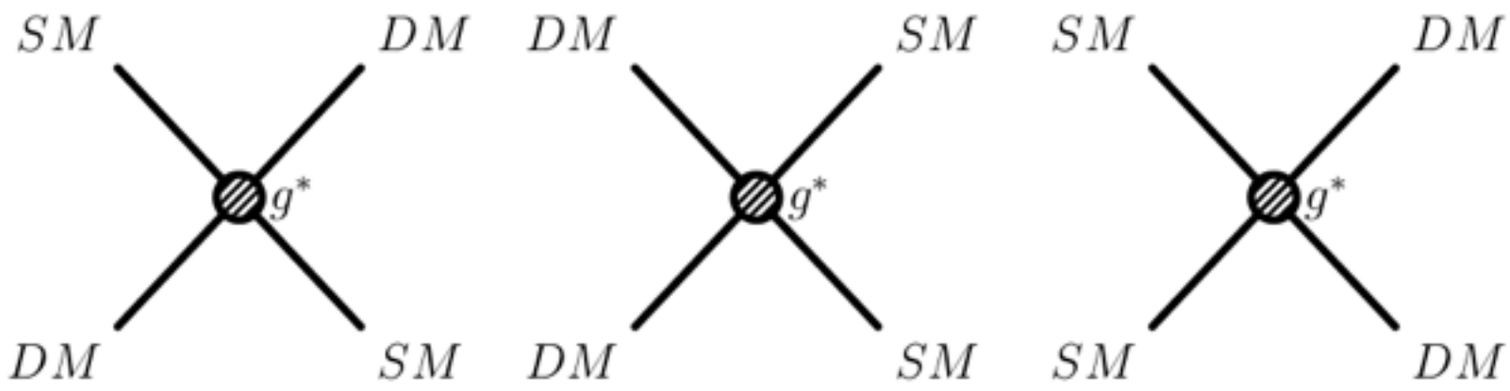
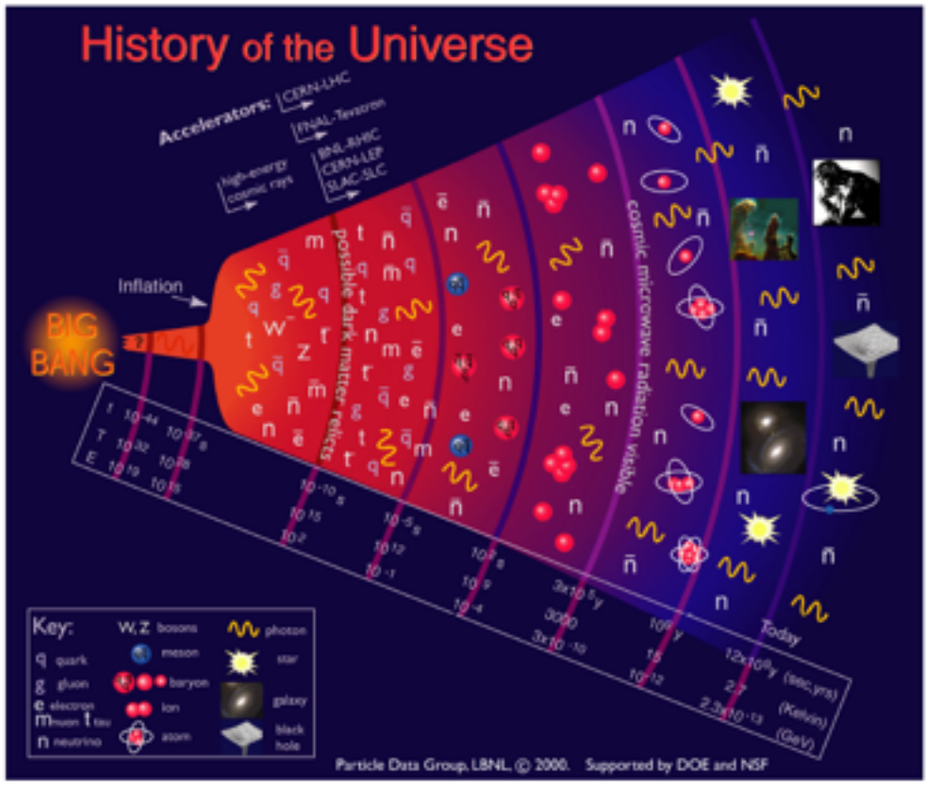
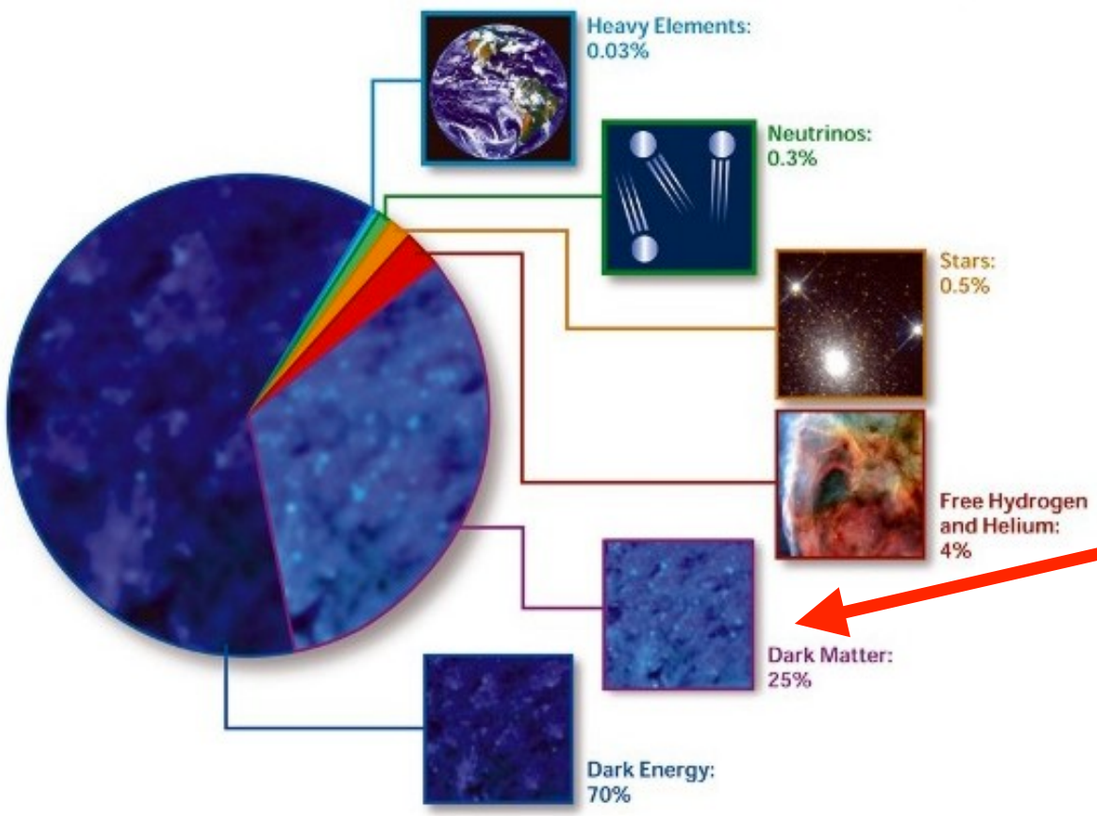


Figure 1.3: The Feynman diagrams for the DM detection, in case of annihilating DM particle. From left to right: direct, indirect and accelerator production. g^* denotes the effective coupling between DM and SM particles.

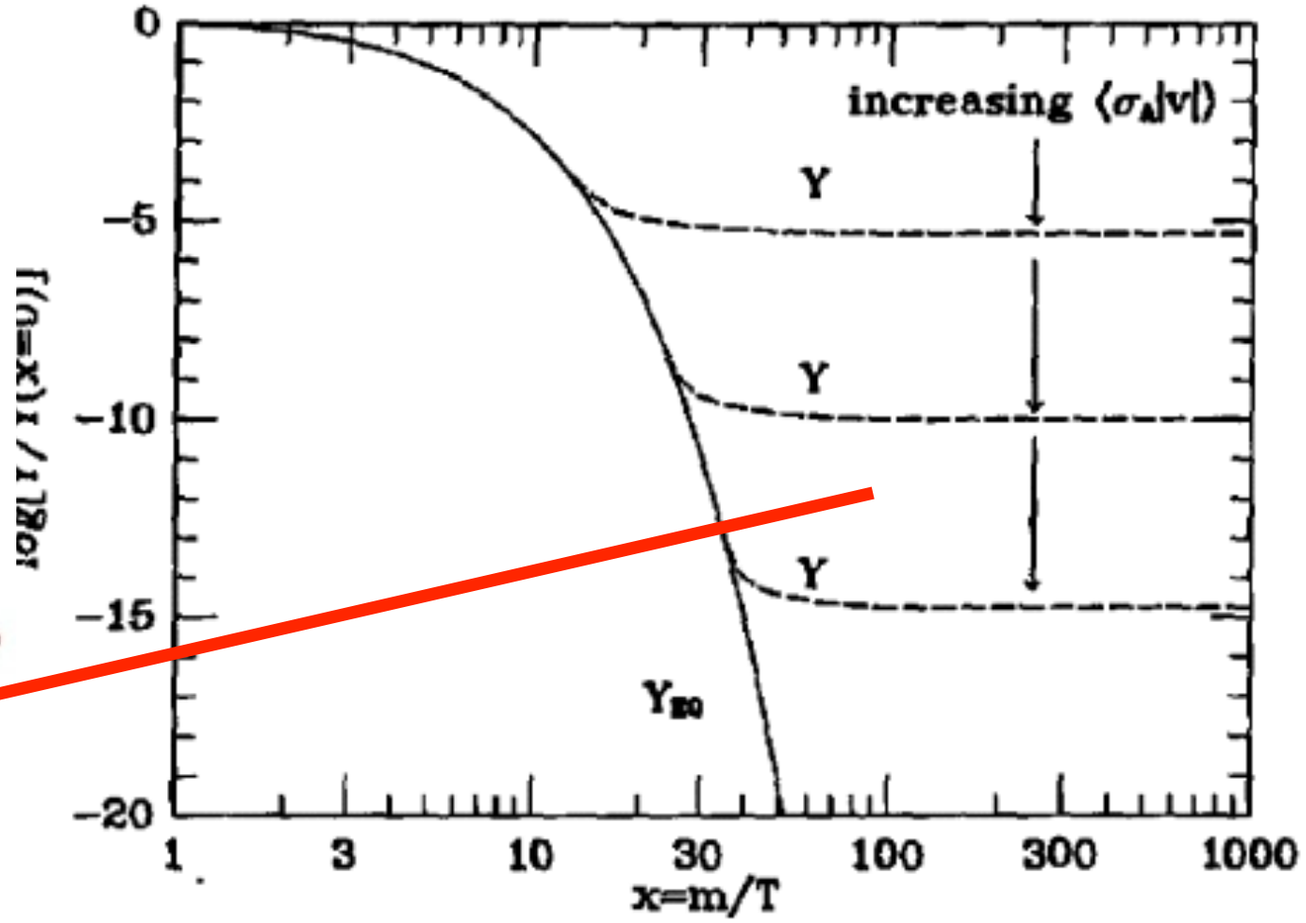
Thermal production of DM: freeze-out





$$\Gamma \gtrsim H \Rightarrow \text{thermal equilibrium}$$

$$\Gamma \lesssim H \Rightarrow \text{decoupled evolution}$$



So the WIMP scenario needs:

- a new particle having weak-like interaction with the SM particles
- the particle has mass around ~100 GeV

Does one has a good candidate for that?

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Does one has a good candidate for that?

So the WIMP scenario needs:

- a new particle having weak-like interaction with the SM particles
- the particle has mass around ~100 GeV

Does one has a good candidate for that?

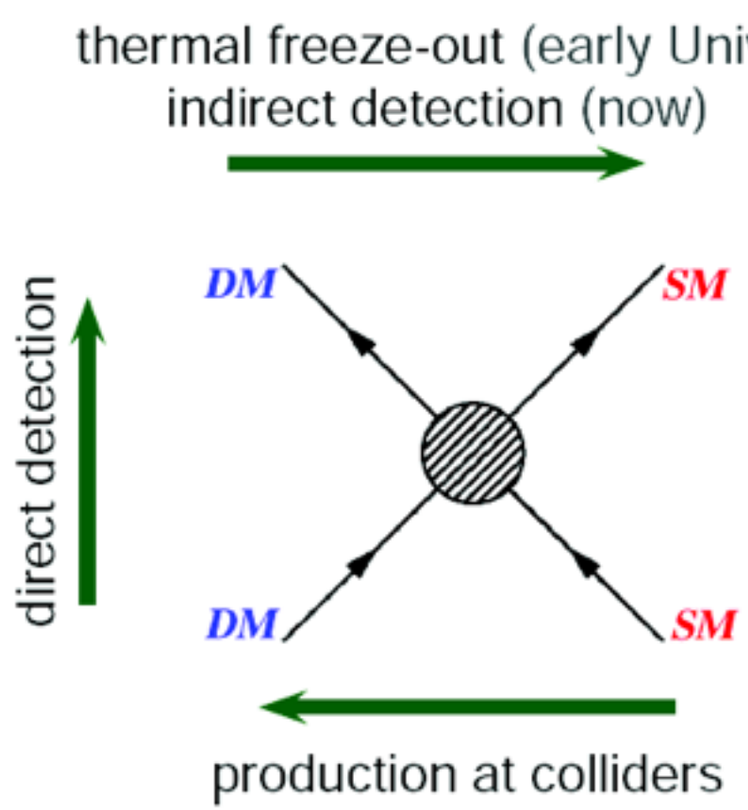
- Supersymmetry: LSP
- extended 2HD, inert HD etc

How one can study WIMP?

- Effective field theory — operator by operator
- ‘Simplified theory’ — including mediator(s), but try to remain ‘model independent’
- Complete model,
  e.g. LSP in a MSSM scenario

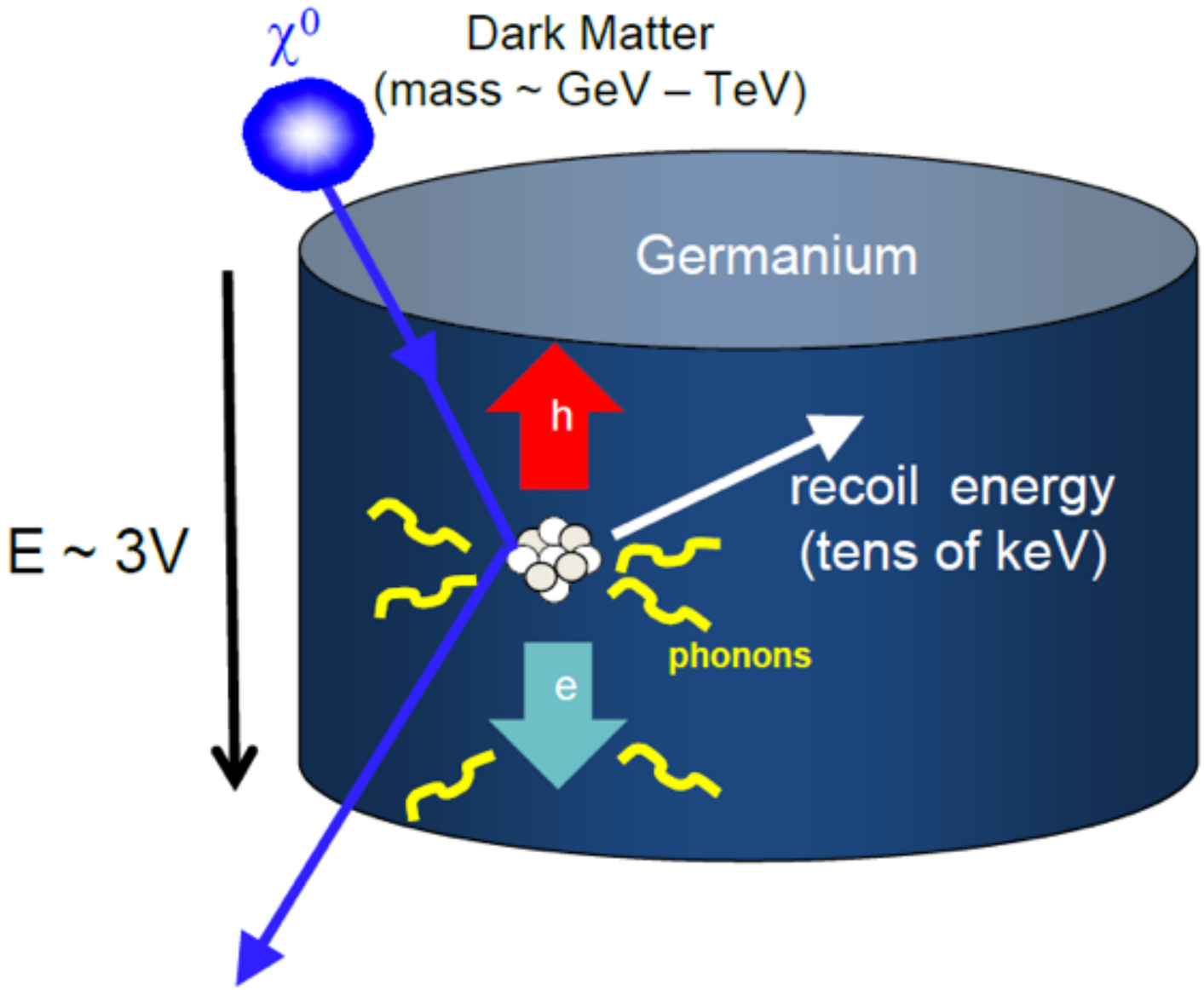
Features of WIMPy physics

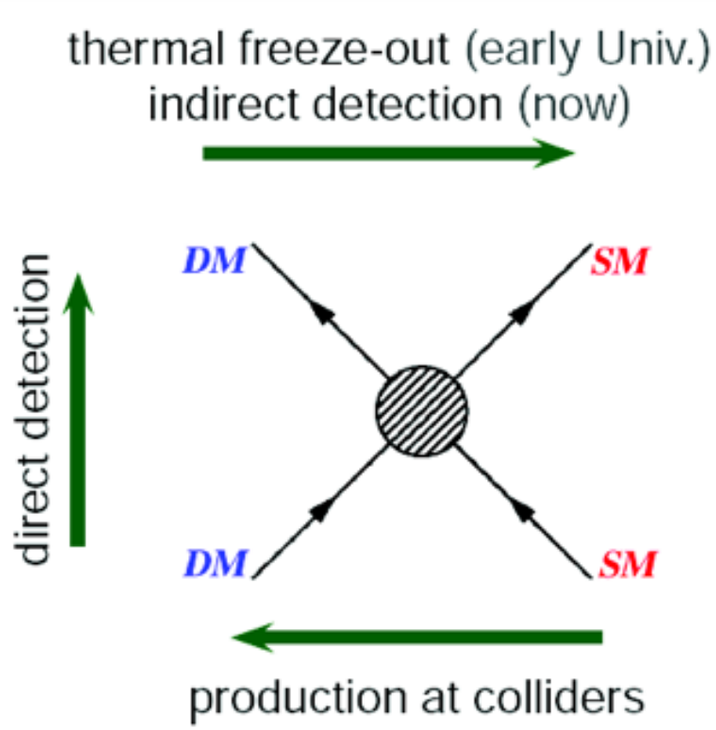
- No question about the initial conditions - thermal equilibrium
- Provides Cold DM, smallest halos typically $<10^{-6}$ solar mass
- **Can be tested by direct, indirect and accelerator experiments**



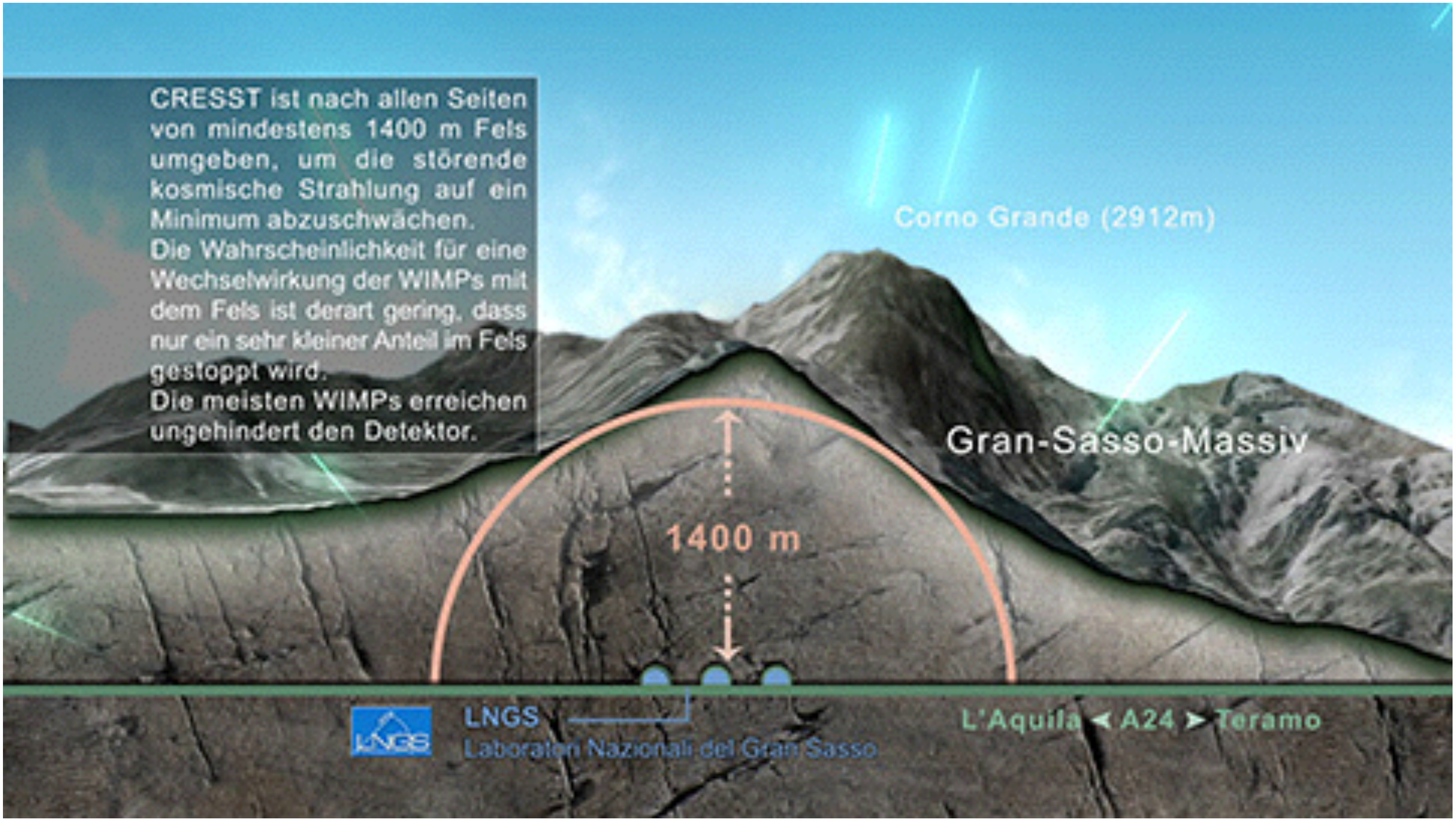
Direct detection of DM — underground life

Direct detection — underground life





Direct detection — underground life

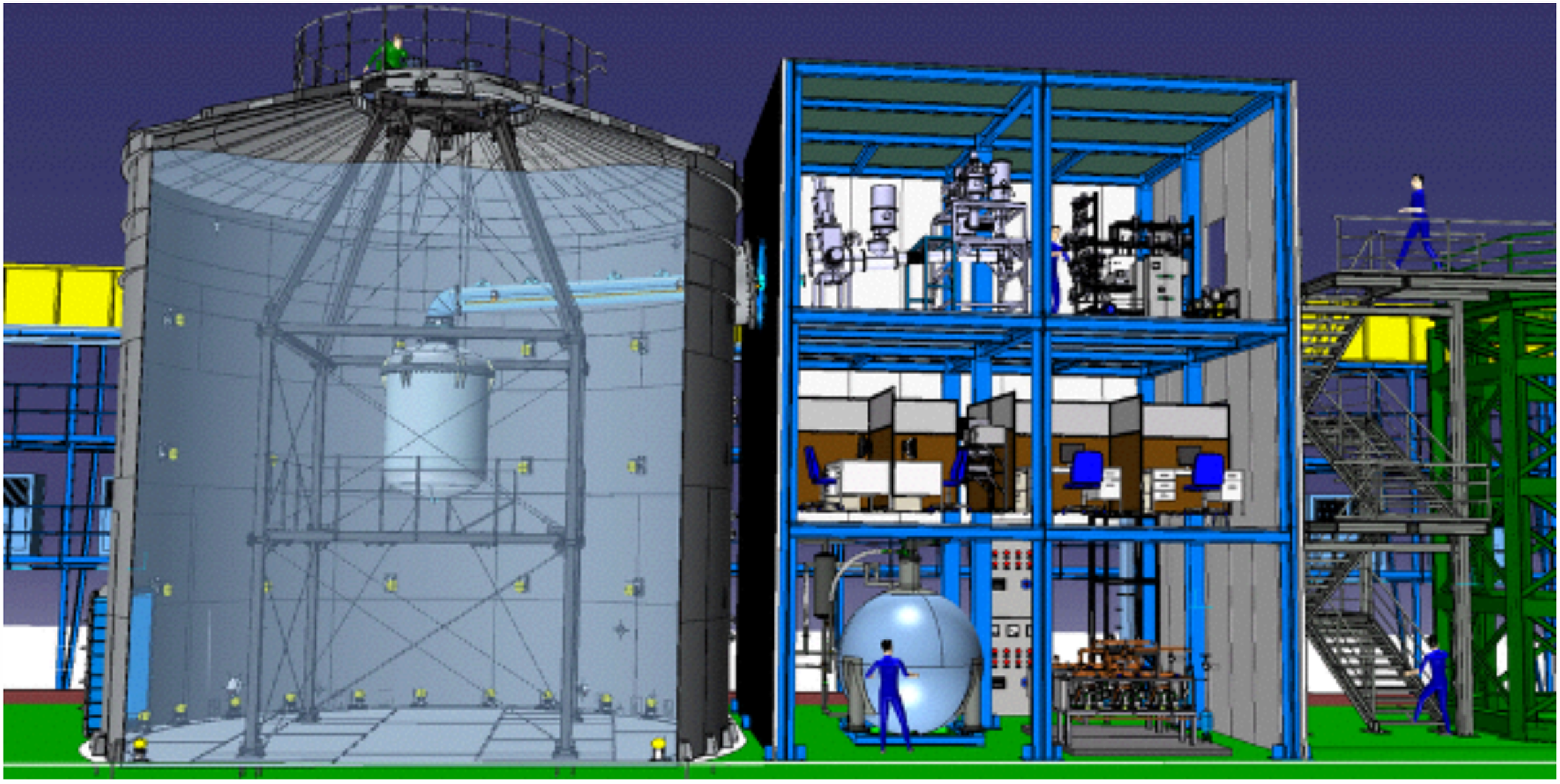


Gran Sasso underground laboratory in Italy

Direct detection — underground life

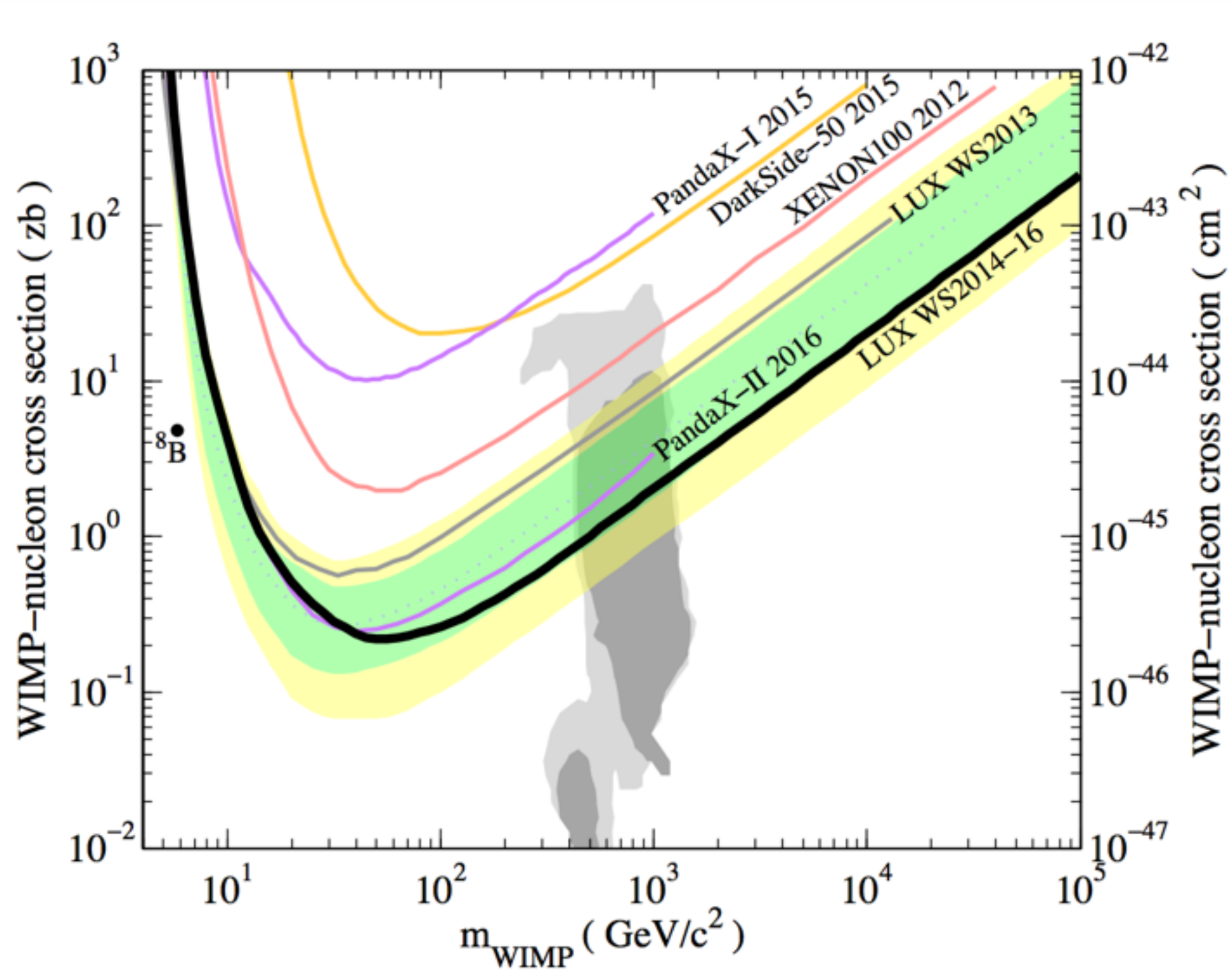
Gran Sasso underground laboratory in Italy

Direct detection — underground life



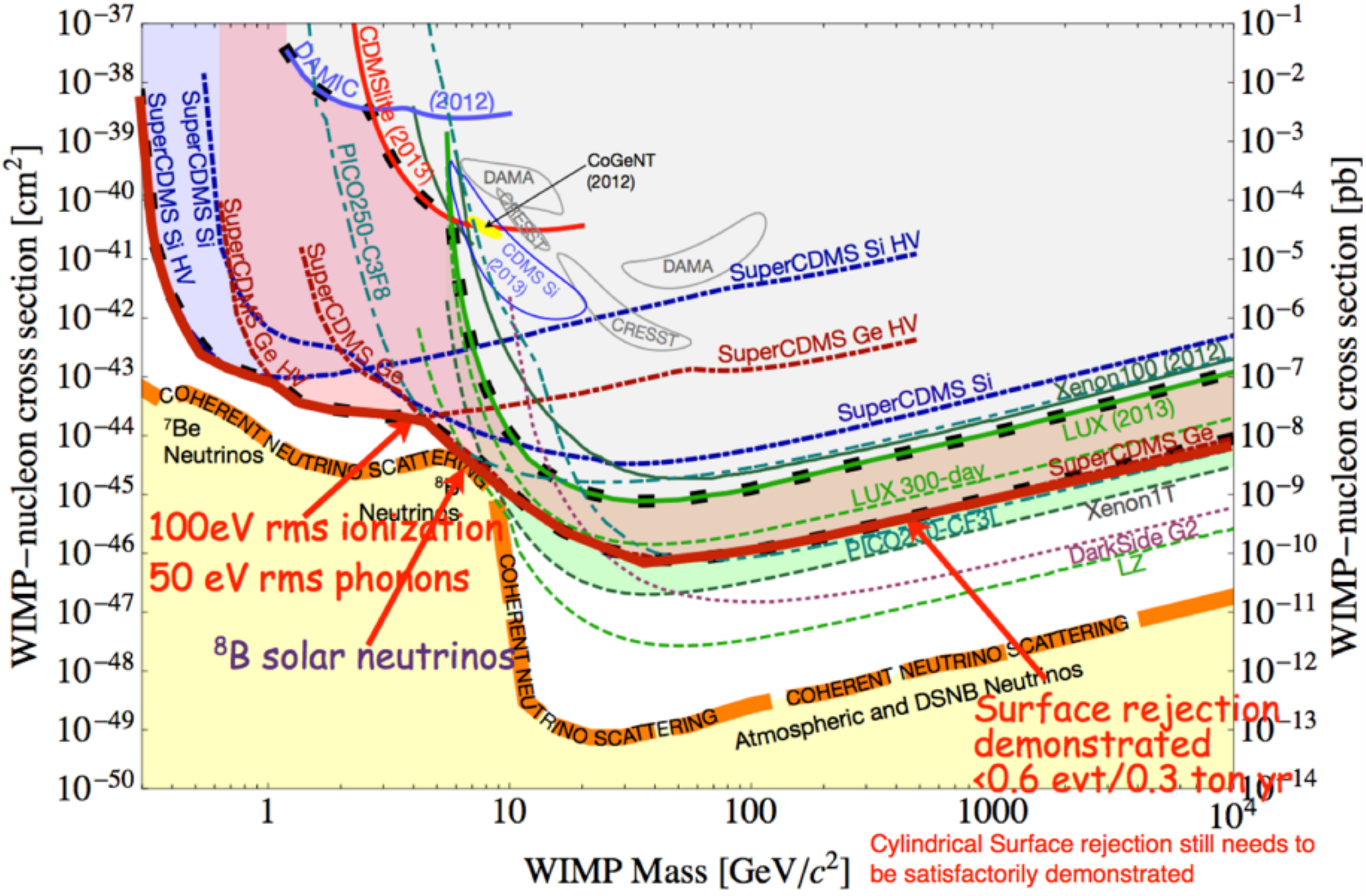
XenonIT experiment at Gran Sasso

Latest results of LUX



Latest result of LUX, arXiv:1608.07648

Clouds in the sky of direct detection — neutrino floor!



Summary on direct detection

- probably the best way to test WIMP
- rapidly improving experiments
- some WIMPs can escape from direct detection:
  — elastic cross-section is suppressed at low velocity, e.g. Coy DM
  — ‘resonance’ freeze-out
  — non-elastic scattering
- Possible future directions: long range interactions
- not helpful in case of non-WIMP DM

Indirect detection of DM — extraterrestrial life

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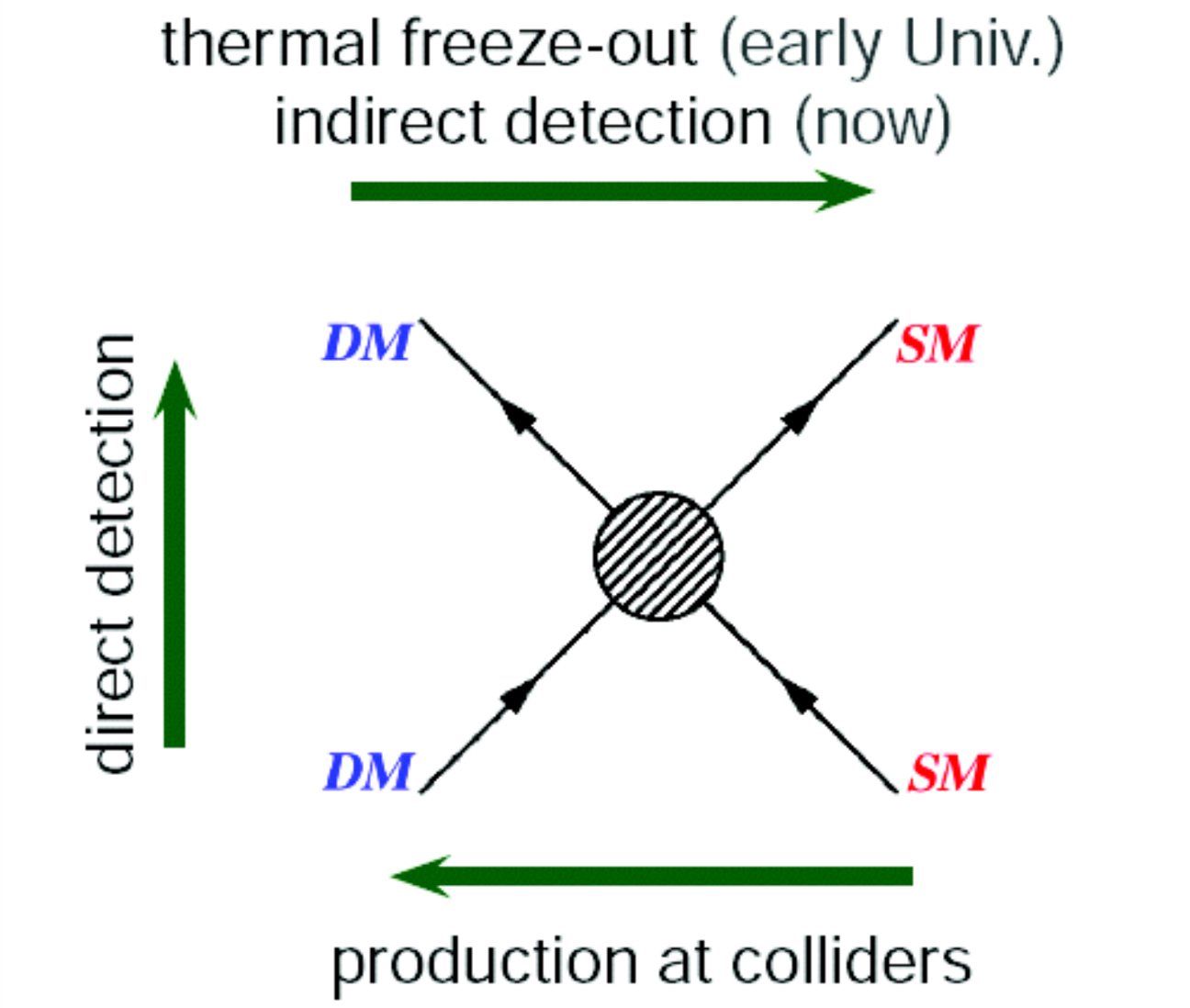
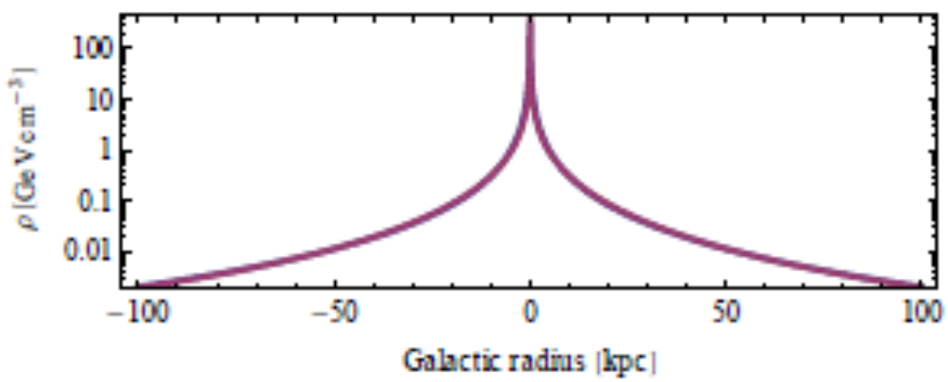
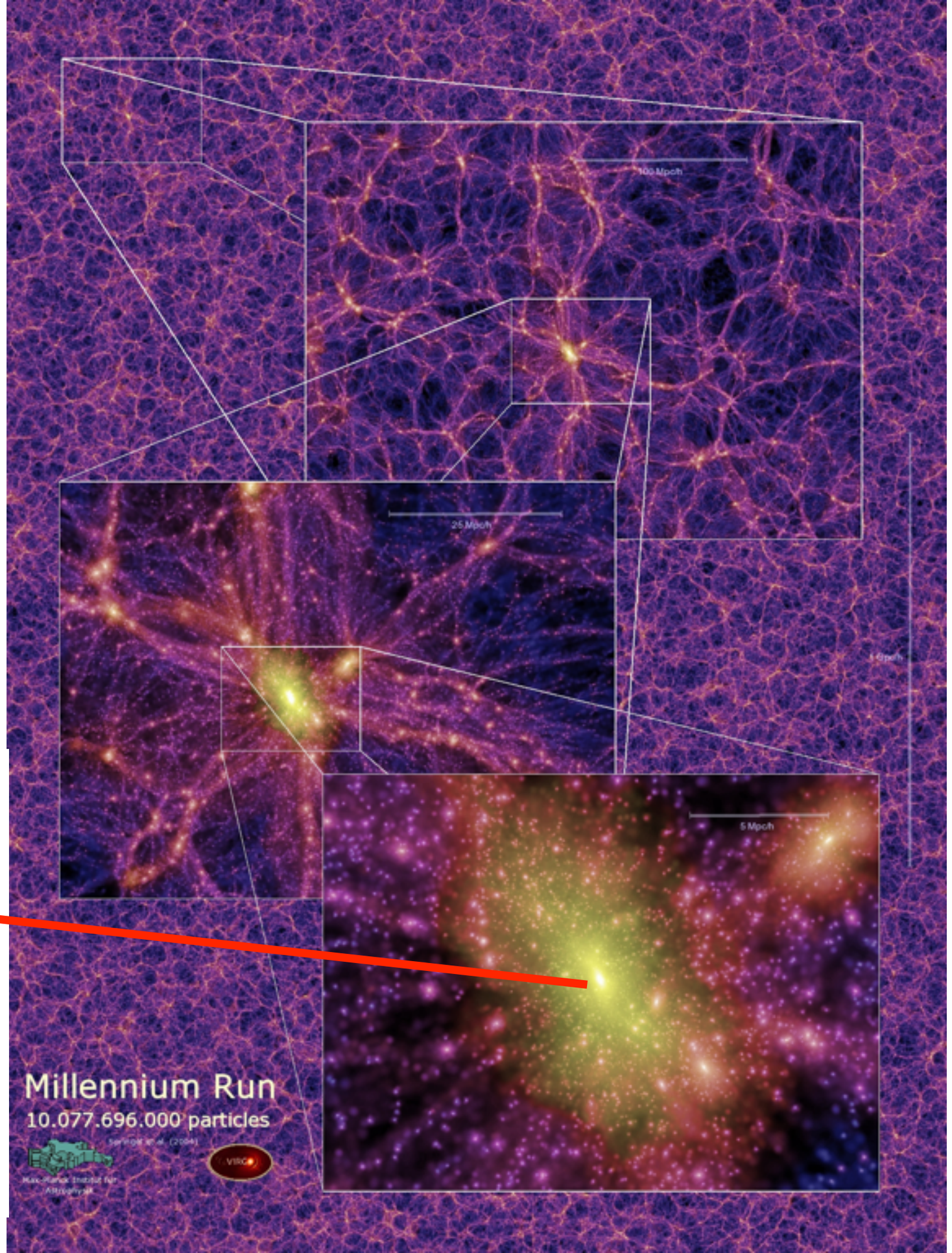


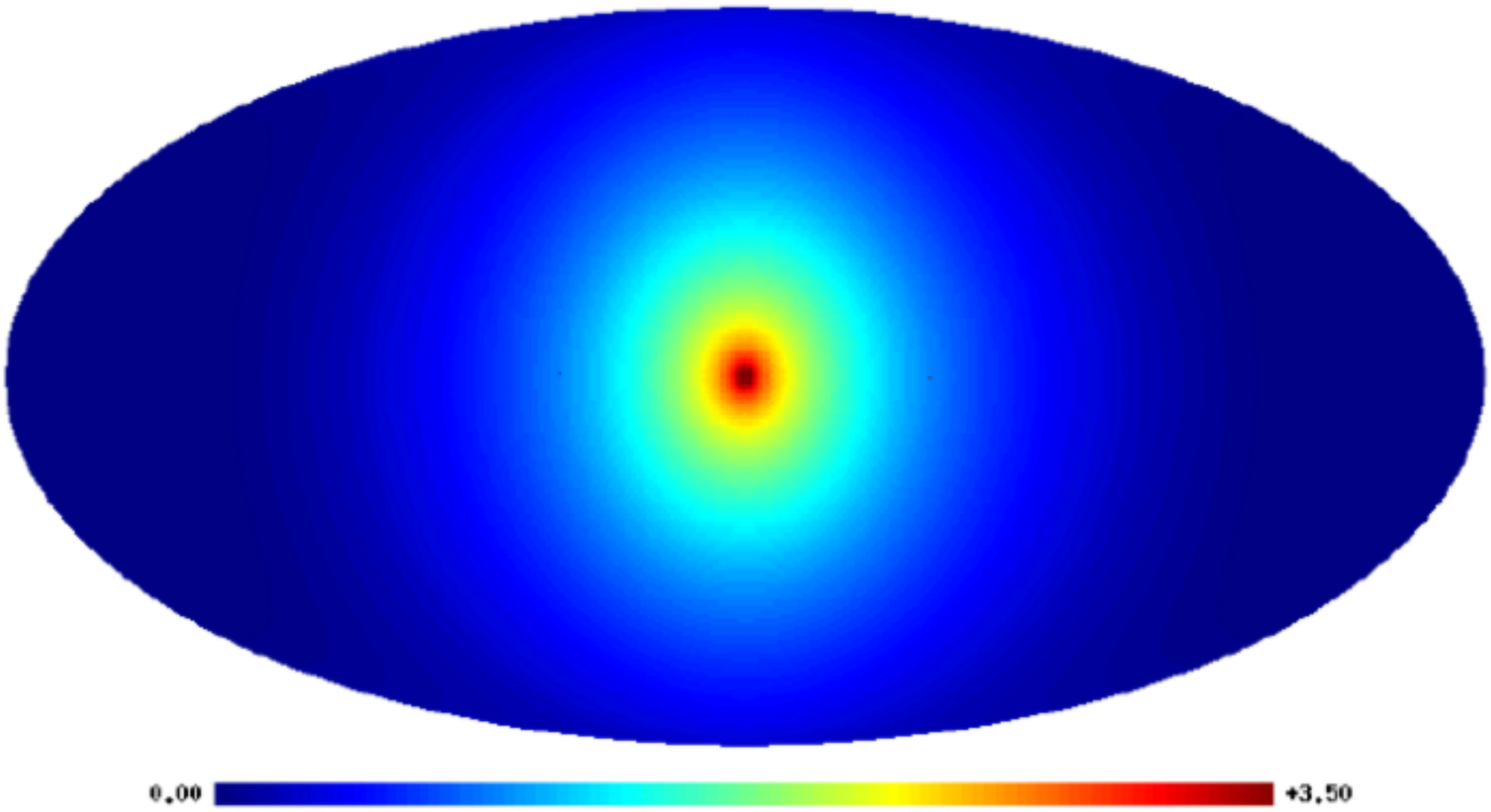
Nonlinear development of density of WIMPs

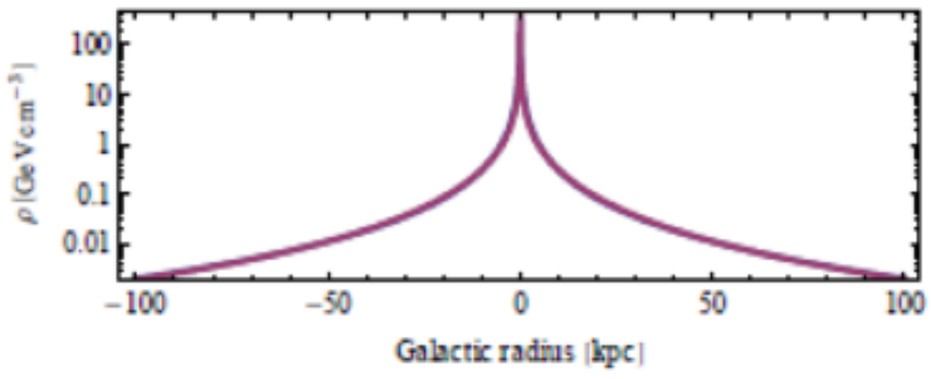


$$J_{\text{annih}} \propto \rho^2$$



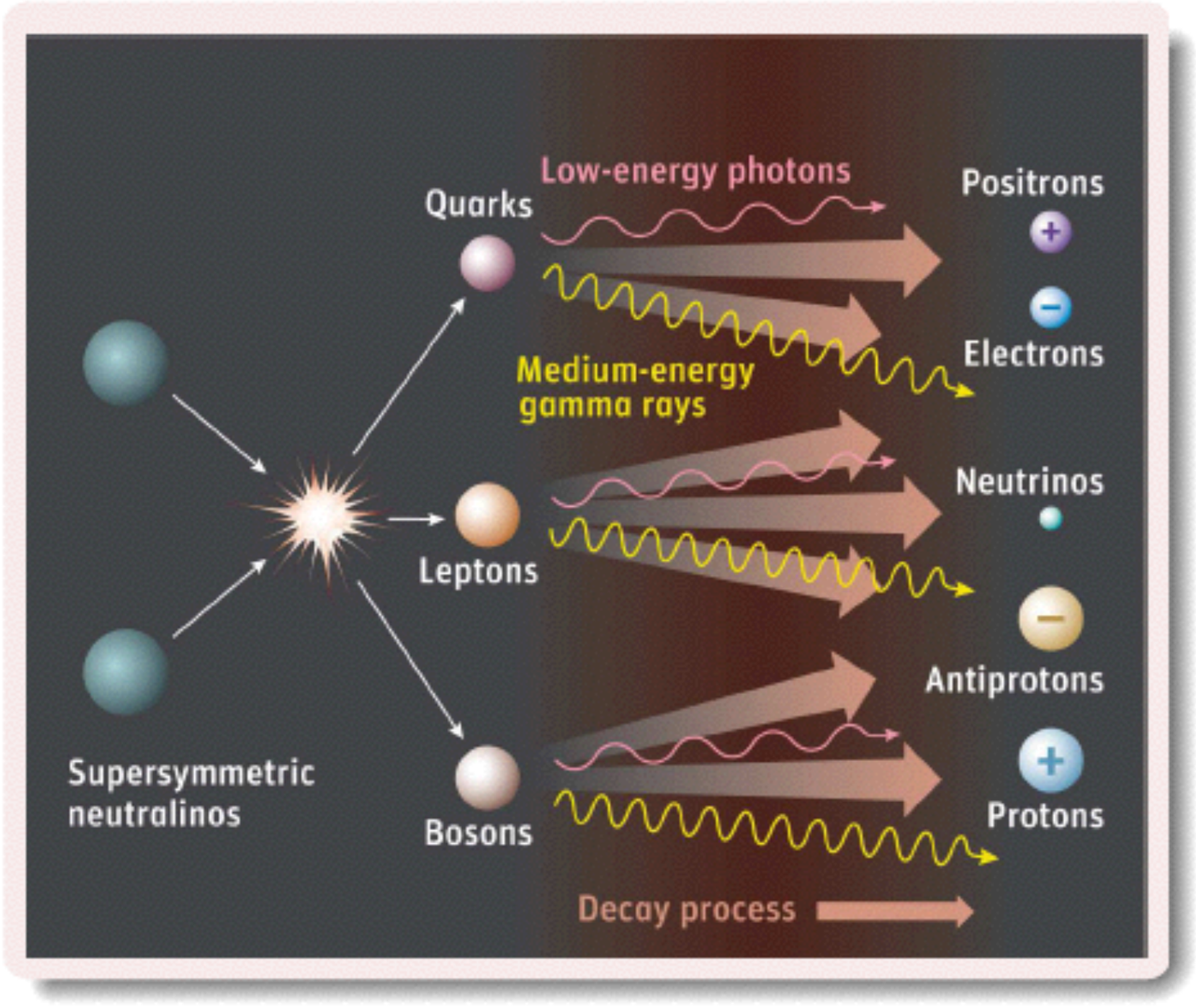
Annihilation signal of DM from a halo





$$J_{\rm annih} \propto \rho^2$$

Annihilation signals of DM



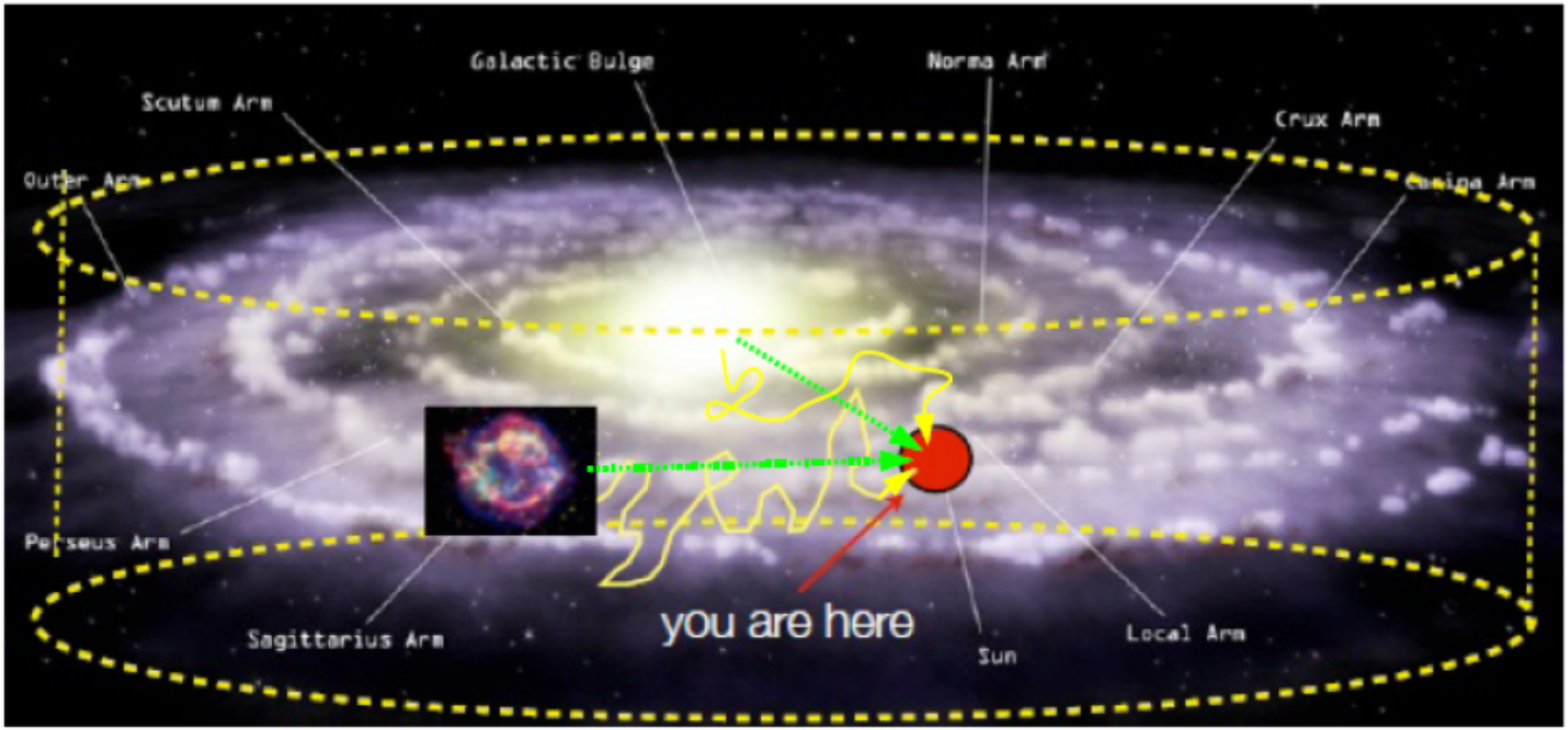
$\gamma \rightarrow$ Fermi, HESS, VERITAS, MAGIC

$e^-, e^+ \rightarrow$ PAMELA, Fermi, balloons

$\bar{p}, \bar{d} \rightarrow$ PAMELA, AMS-02, balloons

$\nu \rightarrow$ IceCube, ANTARES

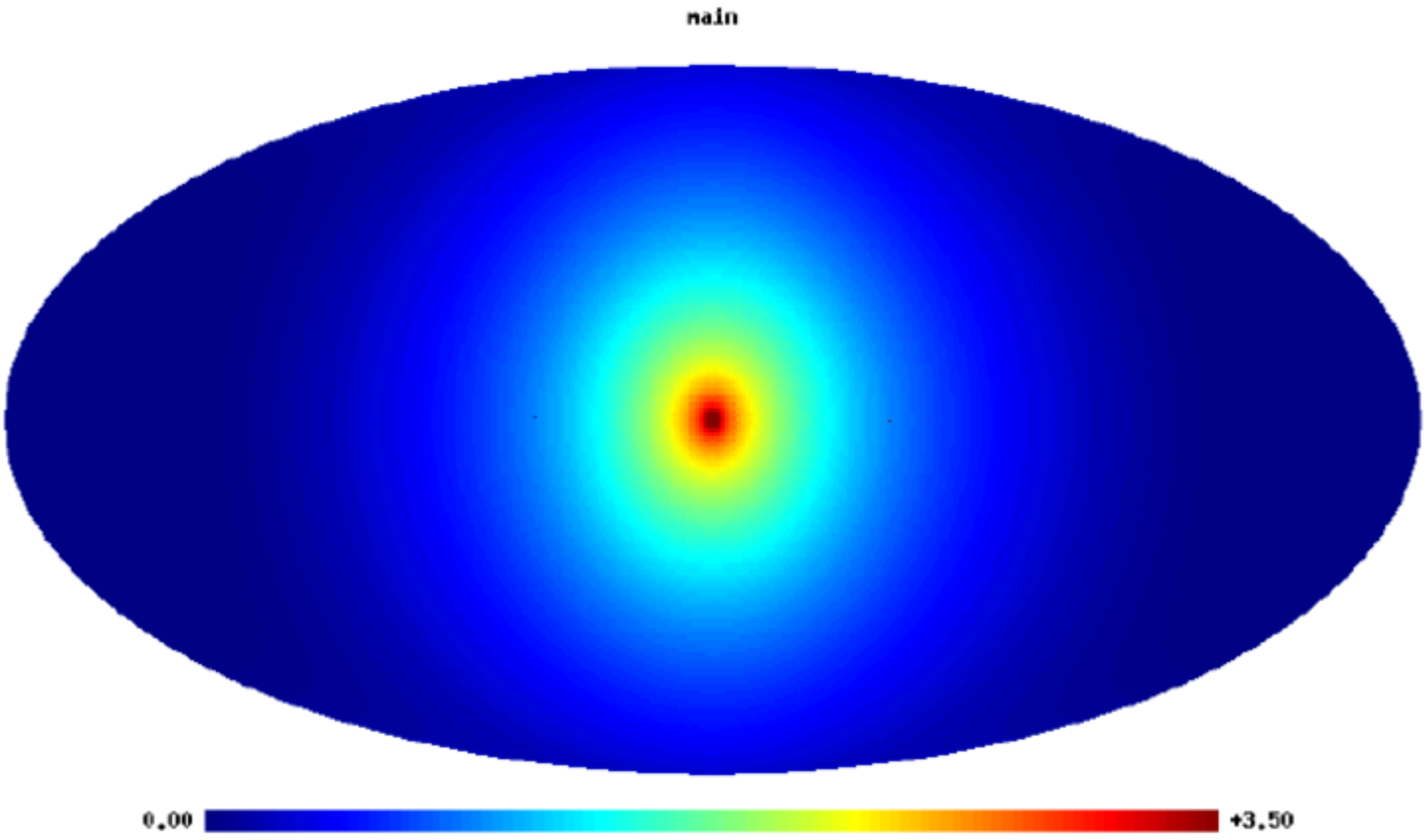
Propagation of the annihilation products of DM in the Galaxy



Diffusion of charged cosmic rays:

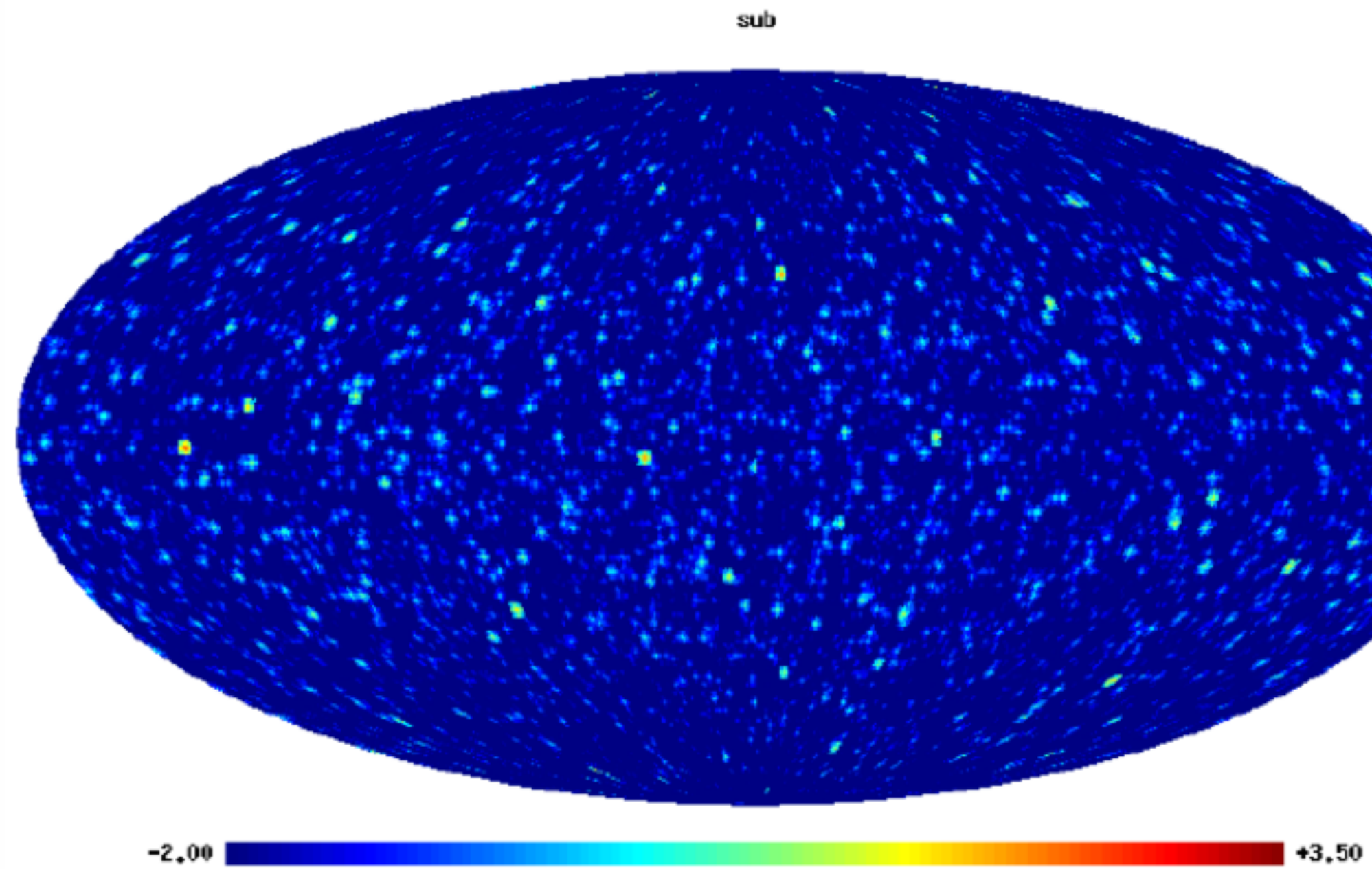
$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

Gamma-rays from DM annihilation: Galactic DM main halo



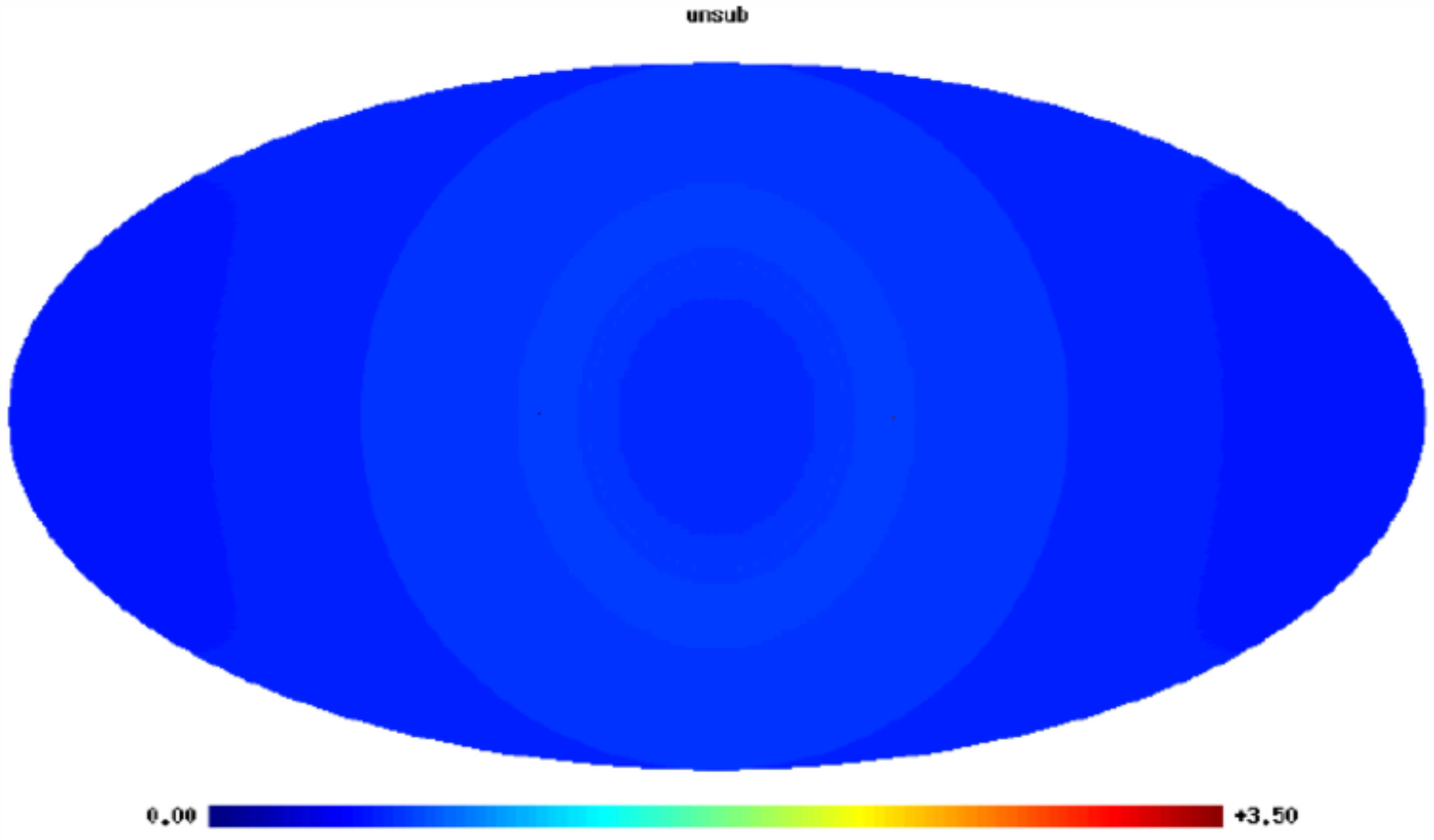
By Yuan et al [1203.5636]

Gamma-rays from DM annihilation: Galactic DM subhalos (resolved)



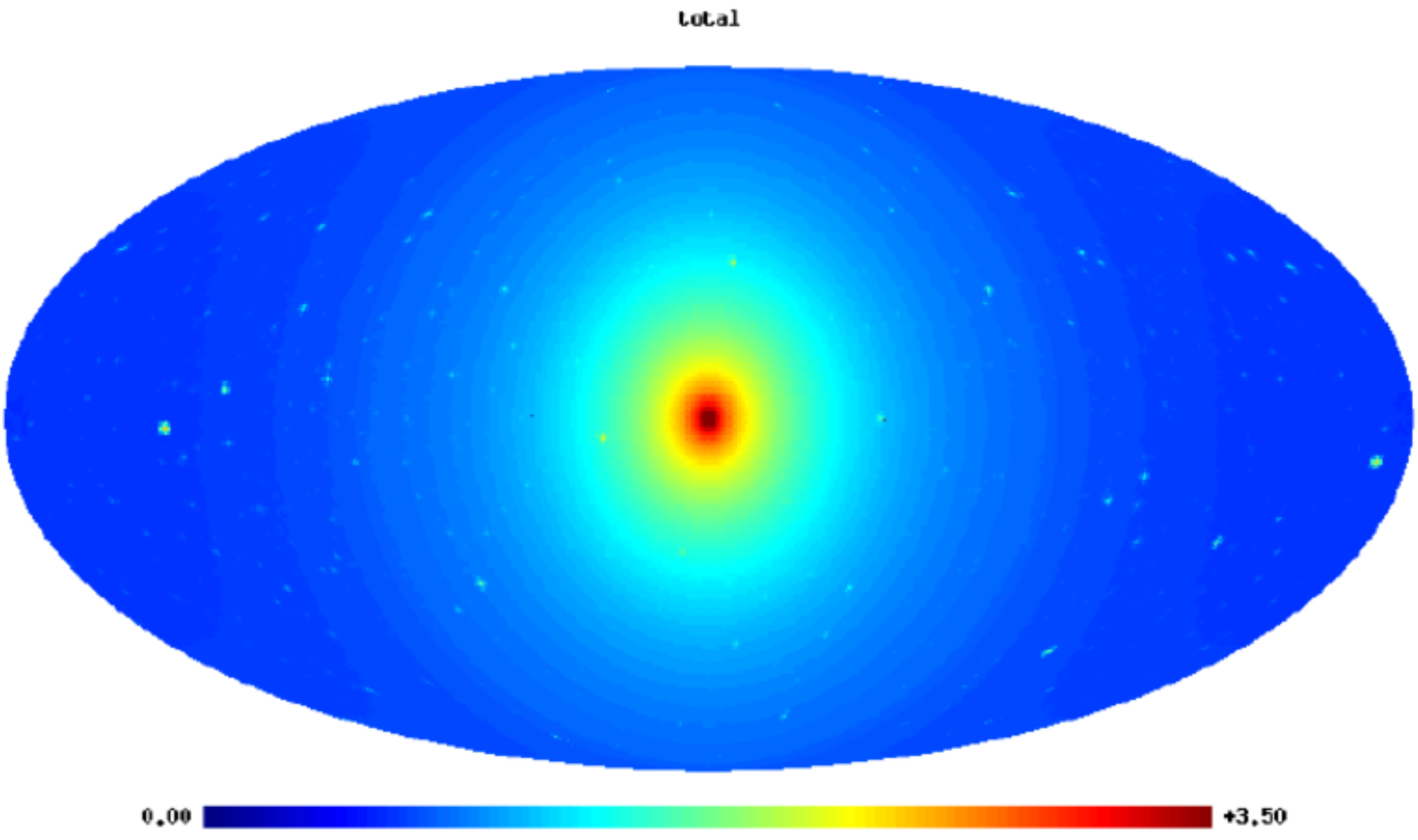
By Yuan et al [1203.5636]

Gamma-rays from DM annihilation: Galactic DM subhalos (unresolved)



By Yuan et al [1203.5636]

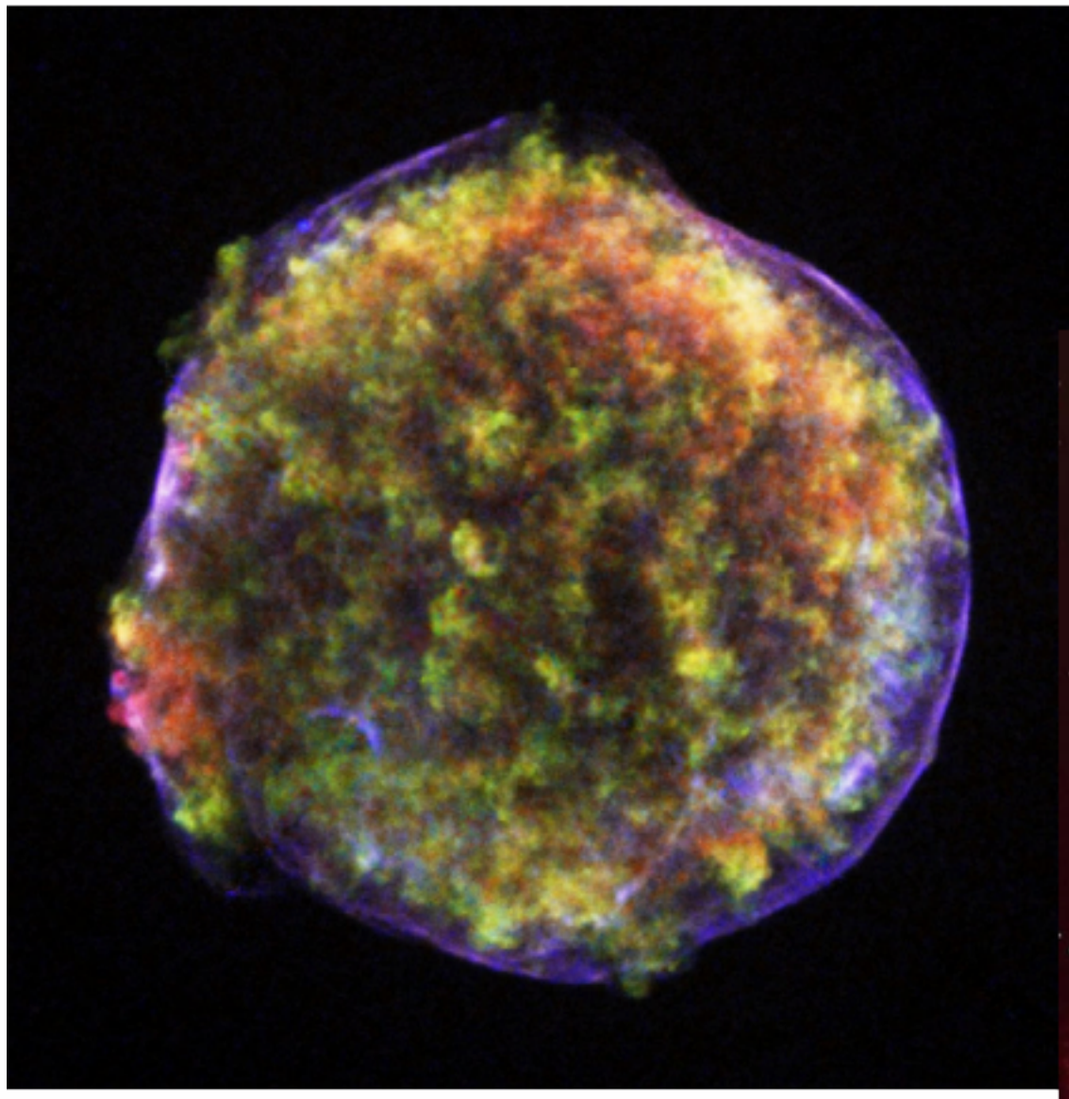
Gamma-rays from DM annihilation: Galactic total



By Yuan et al [1203.5636]

Astrophysical ‘background’: cosmic rays

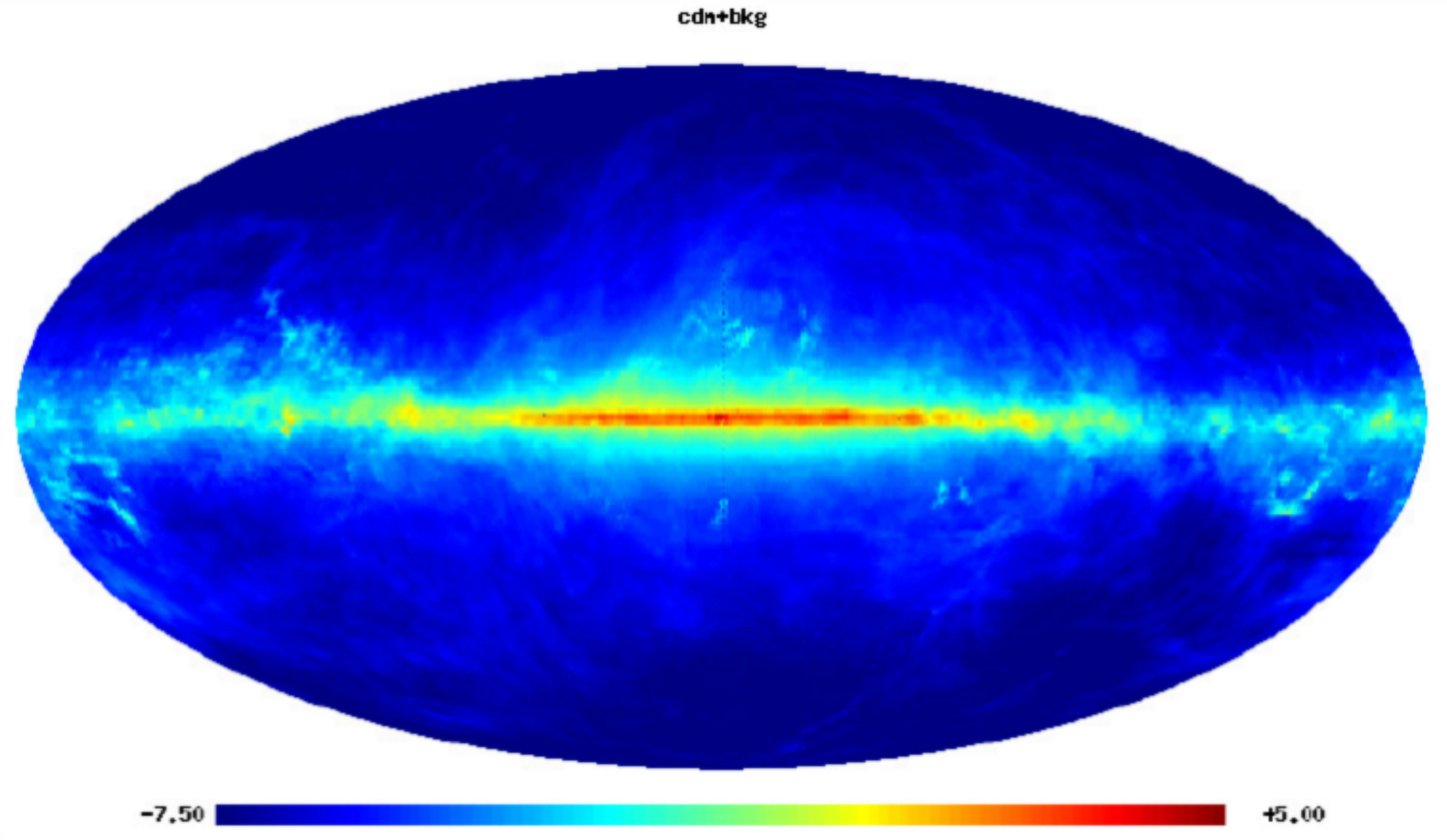
Supernova Remnants (SNR)



Tycho's supernova (SN 1572)

Crab Nebula (M1, NGC 1952, Taurus A)

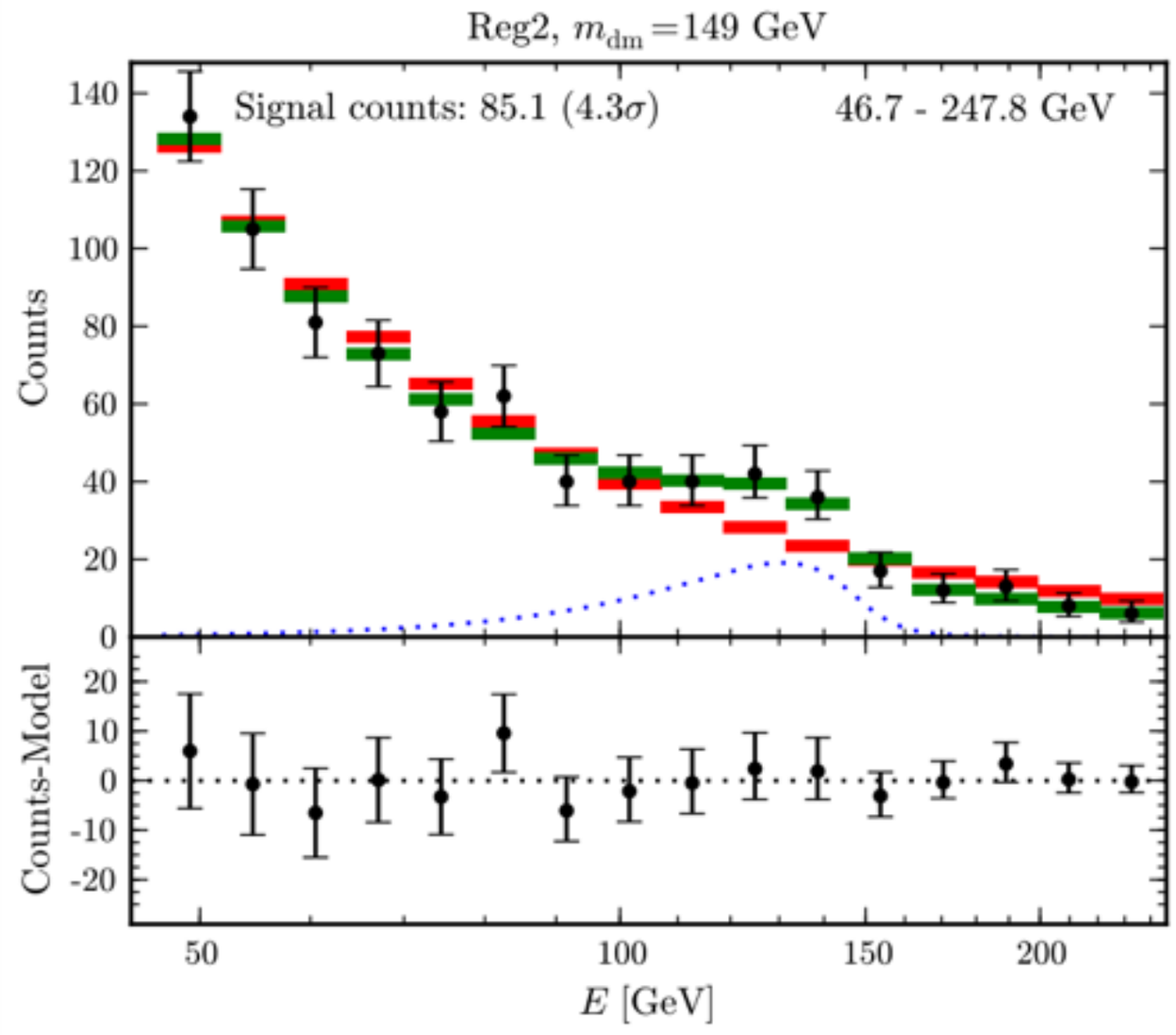
Gamma-rays from DM annihilation:
DM annihilation + background (!)



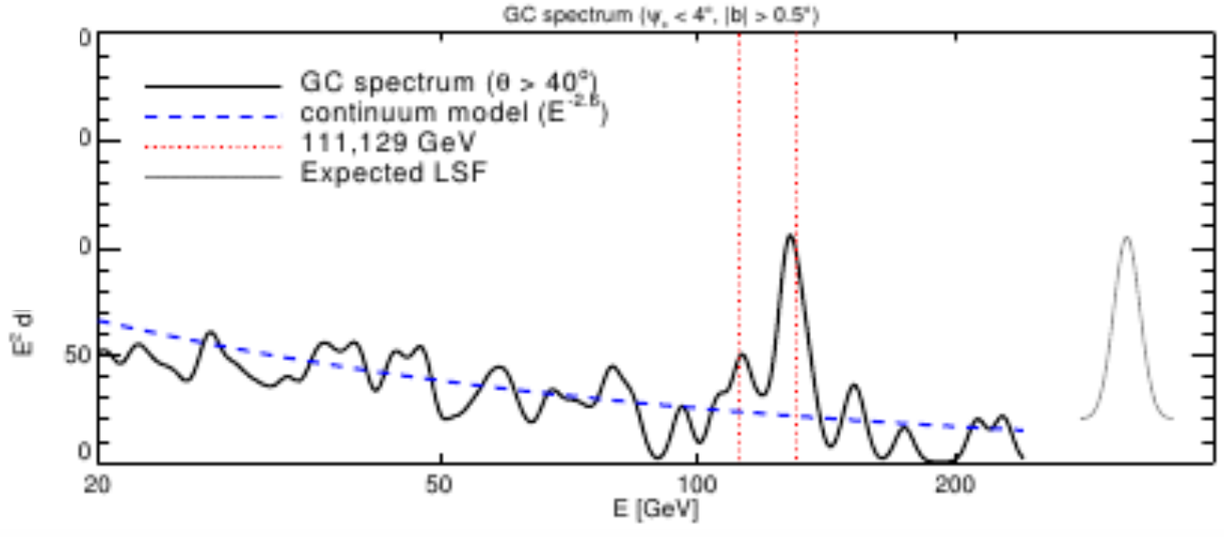
By Yuan et al [1203.5636]

How to discover a faint signal of the DM originated gamma-rays?

Astrophysical background versus the gamma-rays from the annihilation of DM

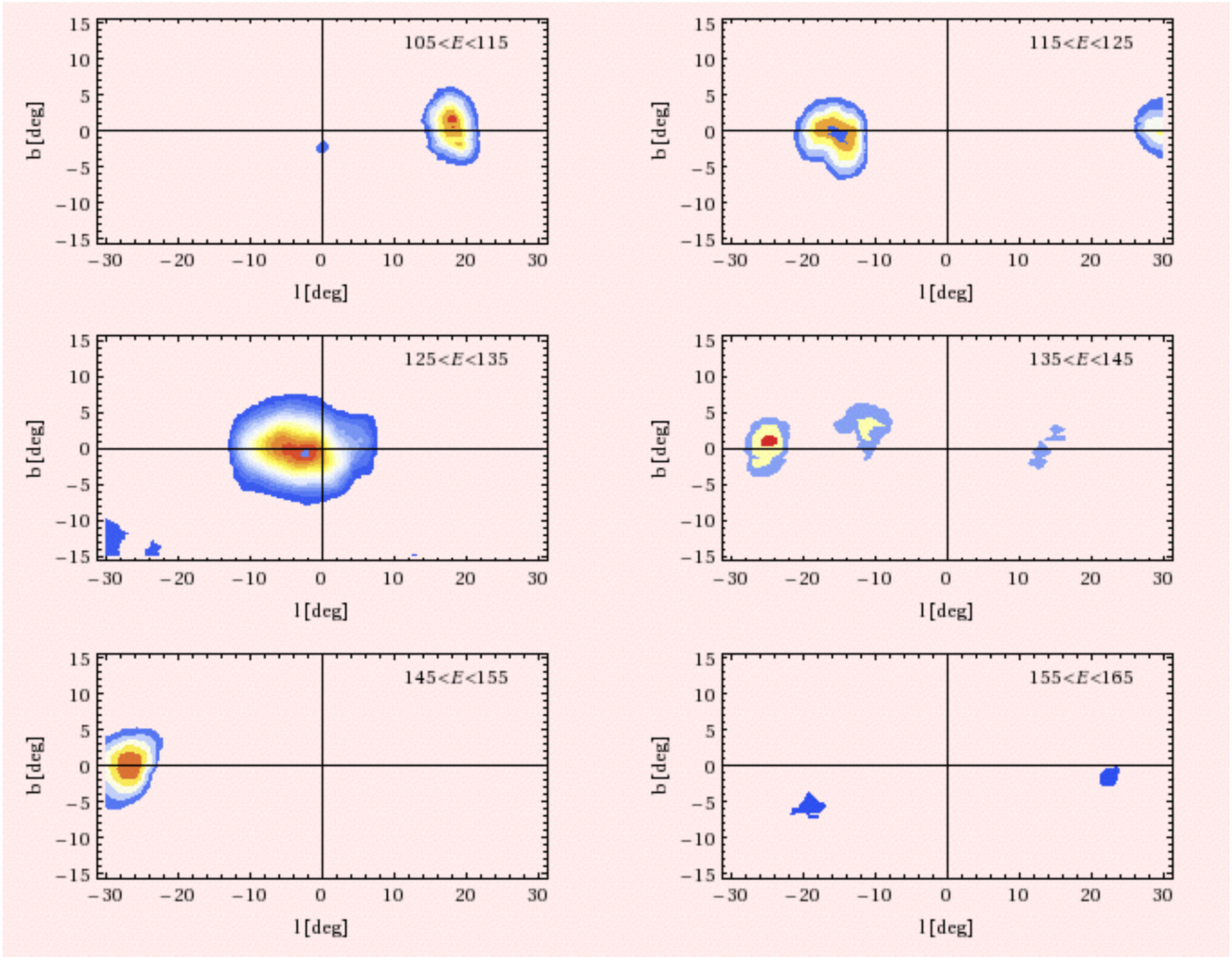


Bringmann et al,1203.1312



Finkbeiner & Su, 1206.1616

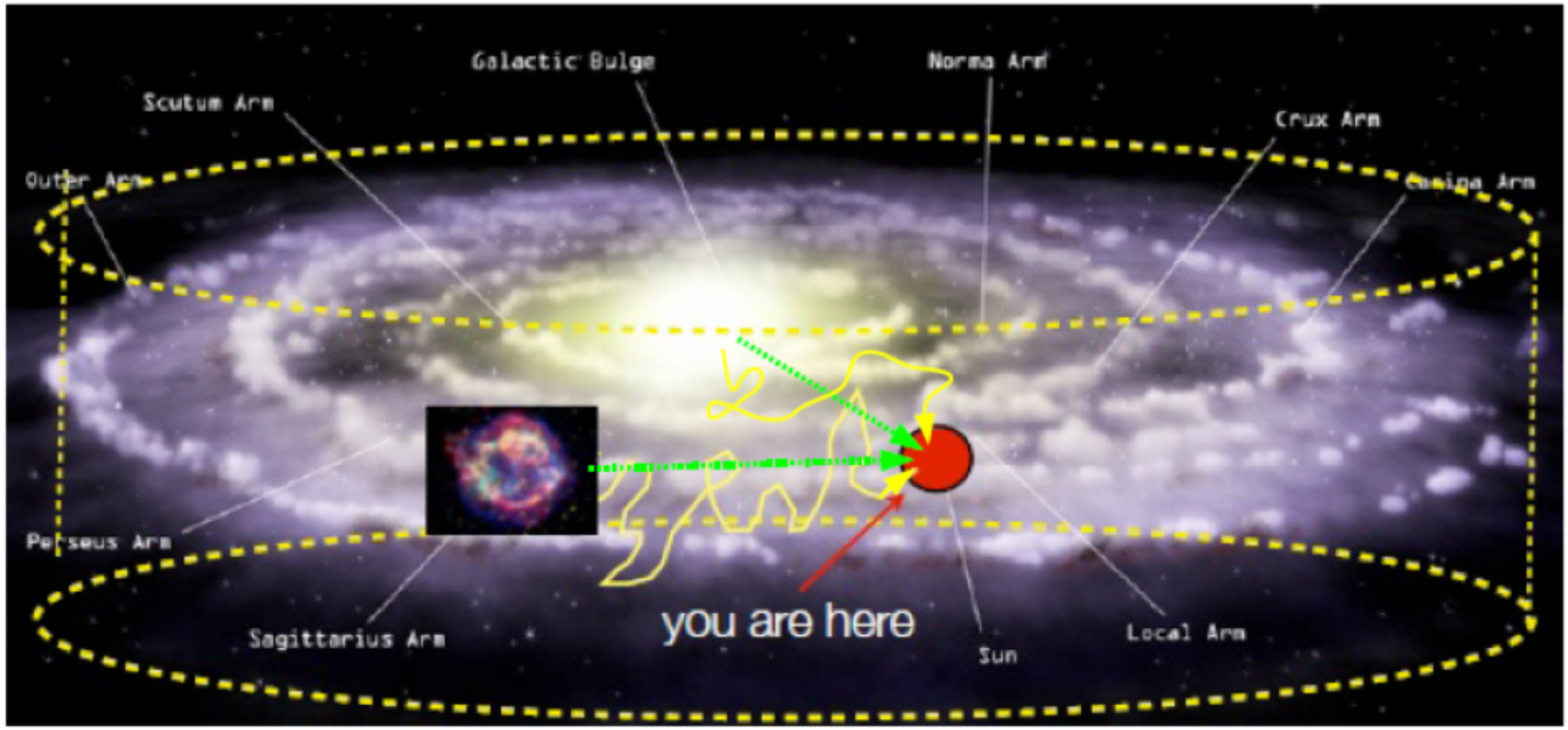
Astrophysical background versus the gamma-rays from the annihilation of DM



Hektor et al, 1205.1045

Other indirect methods

- looking for charged cosmic rays



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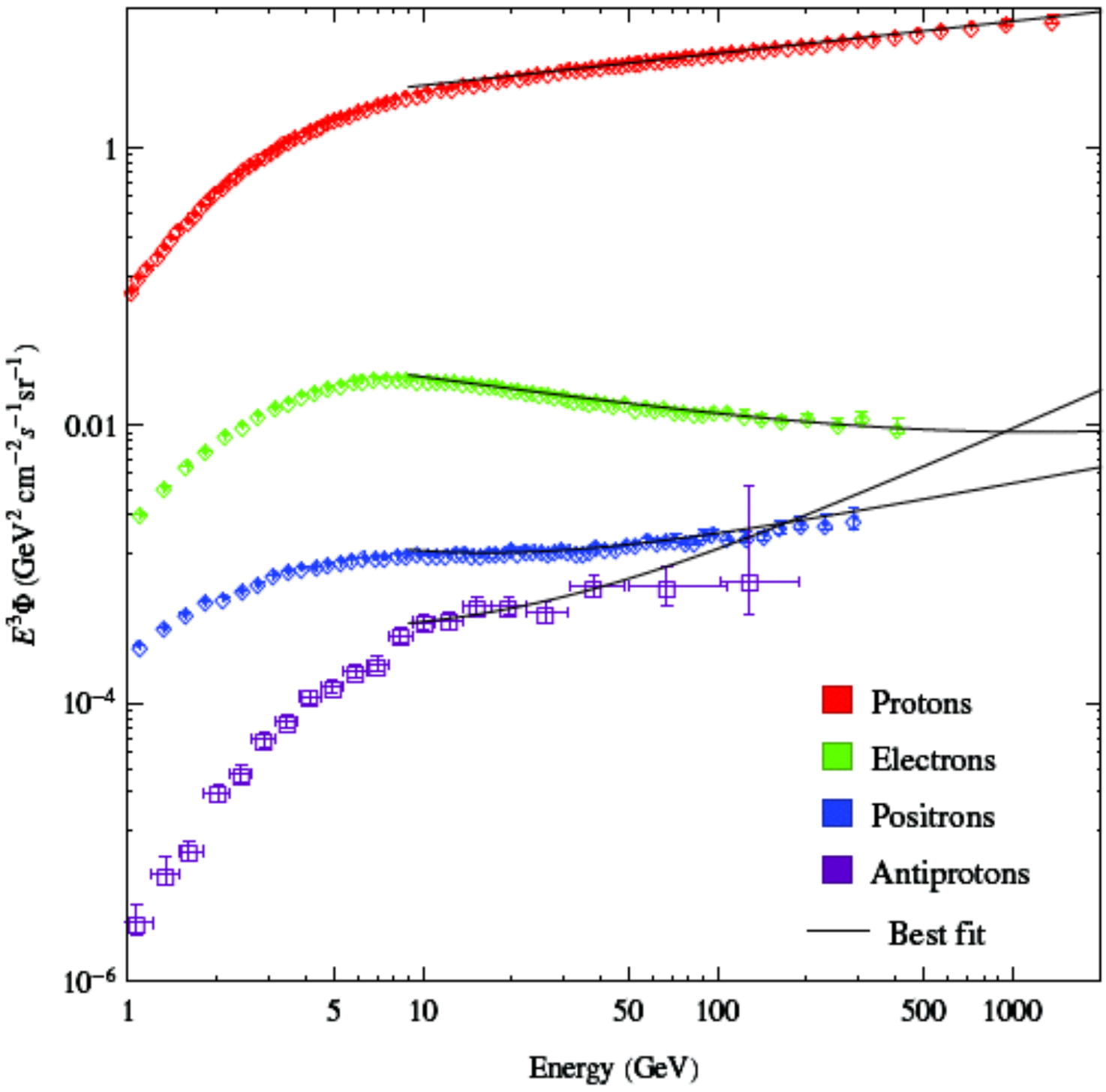
Other indirect methods: smoking gun signals of DM

- positrons — a bit
- antiprotons — a bit more
- antideuteron — definitely! No astrophysical source of antideuteron!

Other indirect methods: smoking gun signals of DM



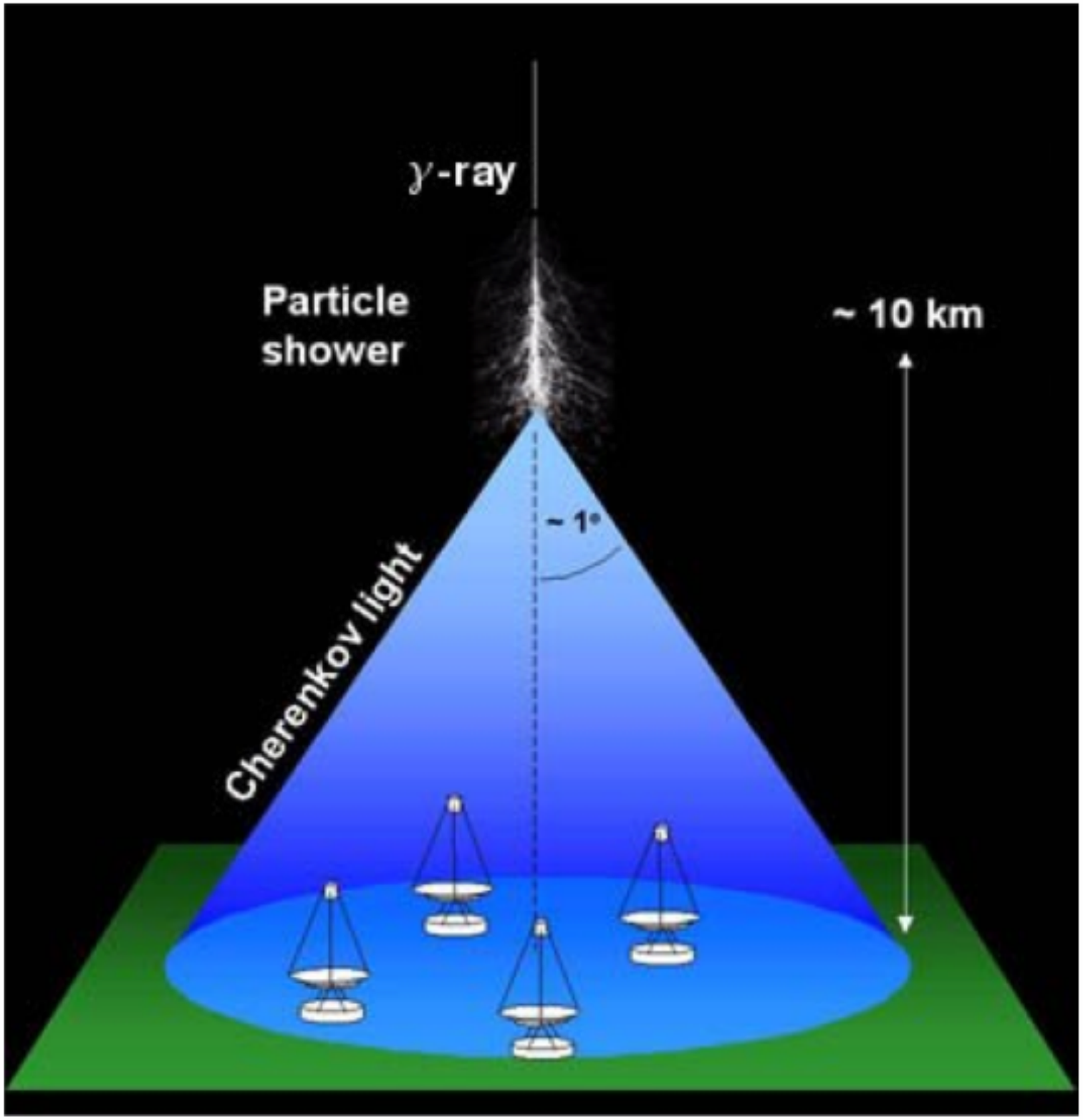
Other (more) indirect methods

- looking for the DM annihilation effects on CMB and 21-cm astronomy
- looking for more secondary signals — radio band (stay tuned, SKA)
- You can come up your own ideas here…

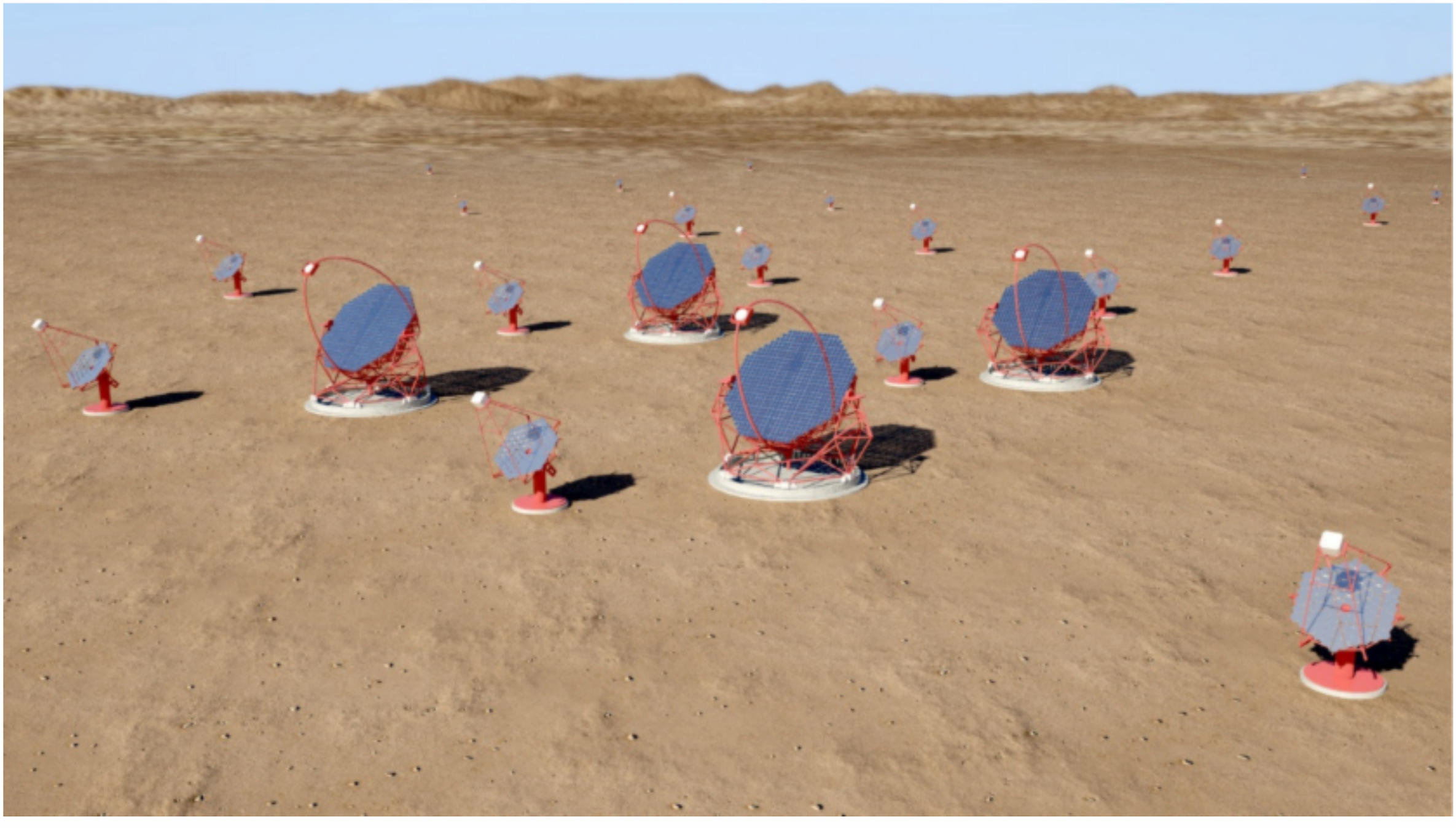
Summary on indirect detection

- A tougher way to test DM, but can provide a lot of new knowledge about astrophysics and cosmology
- A synergetic topics with large astrophysics experiments: AMS02, CTA, SKA, IceCube etc
- It does work on non-WIMPy DM

Cherekov telescopes

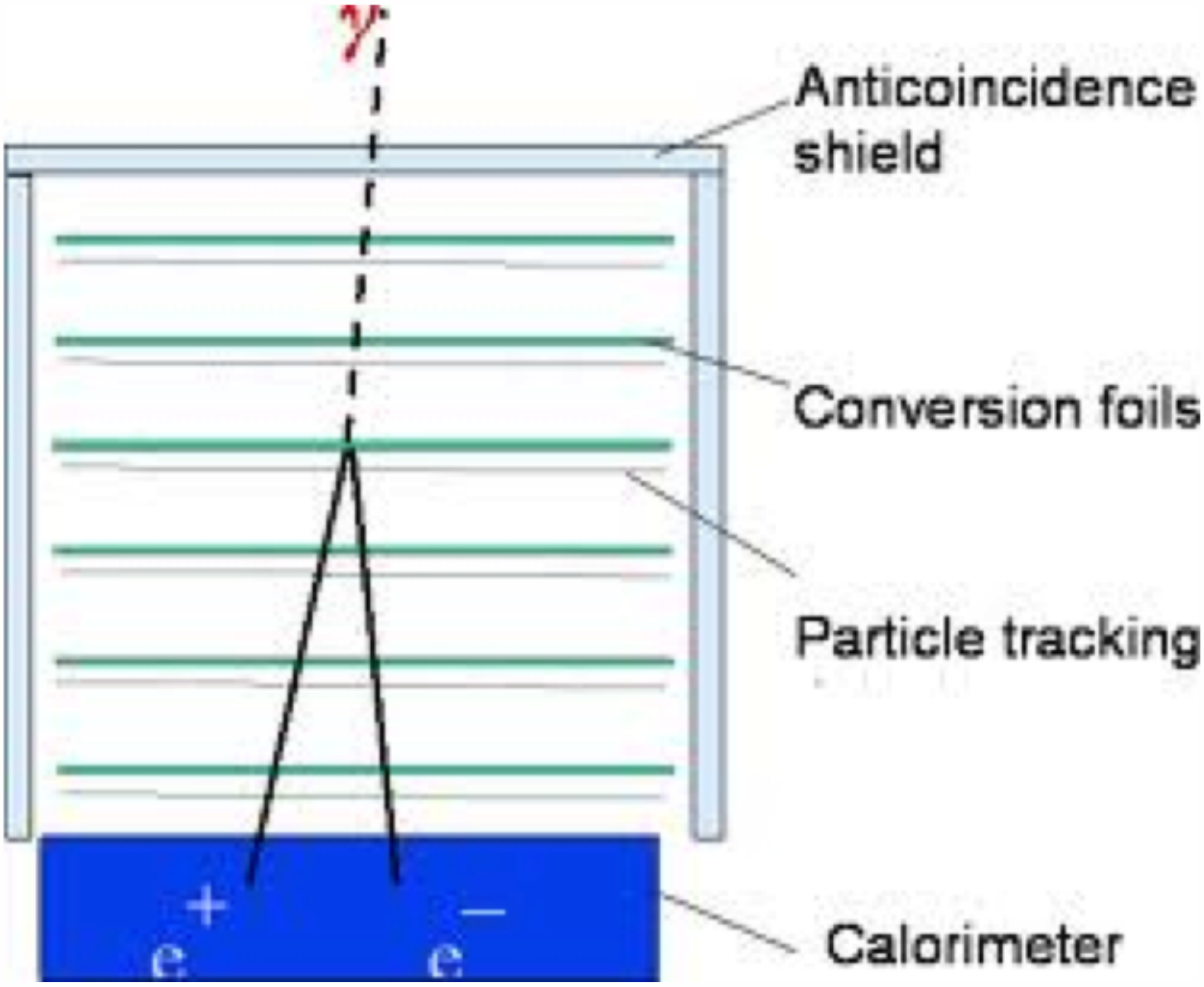


Next generation of the Cherekov telescopes: Cherenkov Telescope Array (CTA)



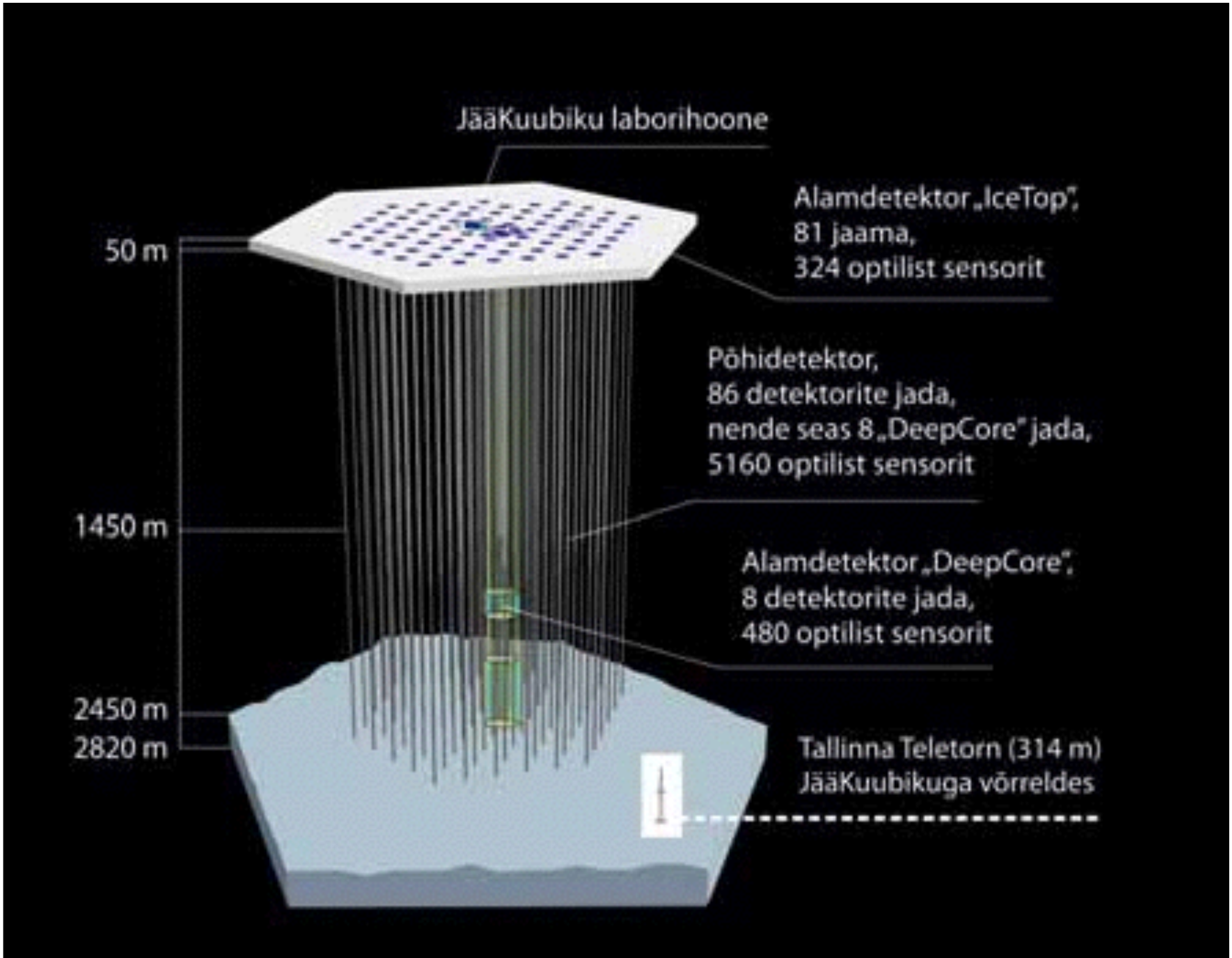
Fermi satellite

Fermi LAT,
a typical gamma ray detector



PAMELA satellite & AMS-02 at ISS

IceCube experiment at the South Pole



Accelerator detection of DM — dangerous life

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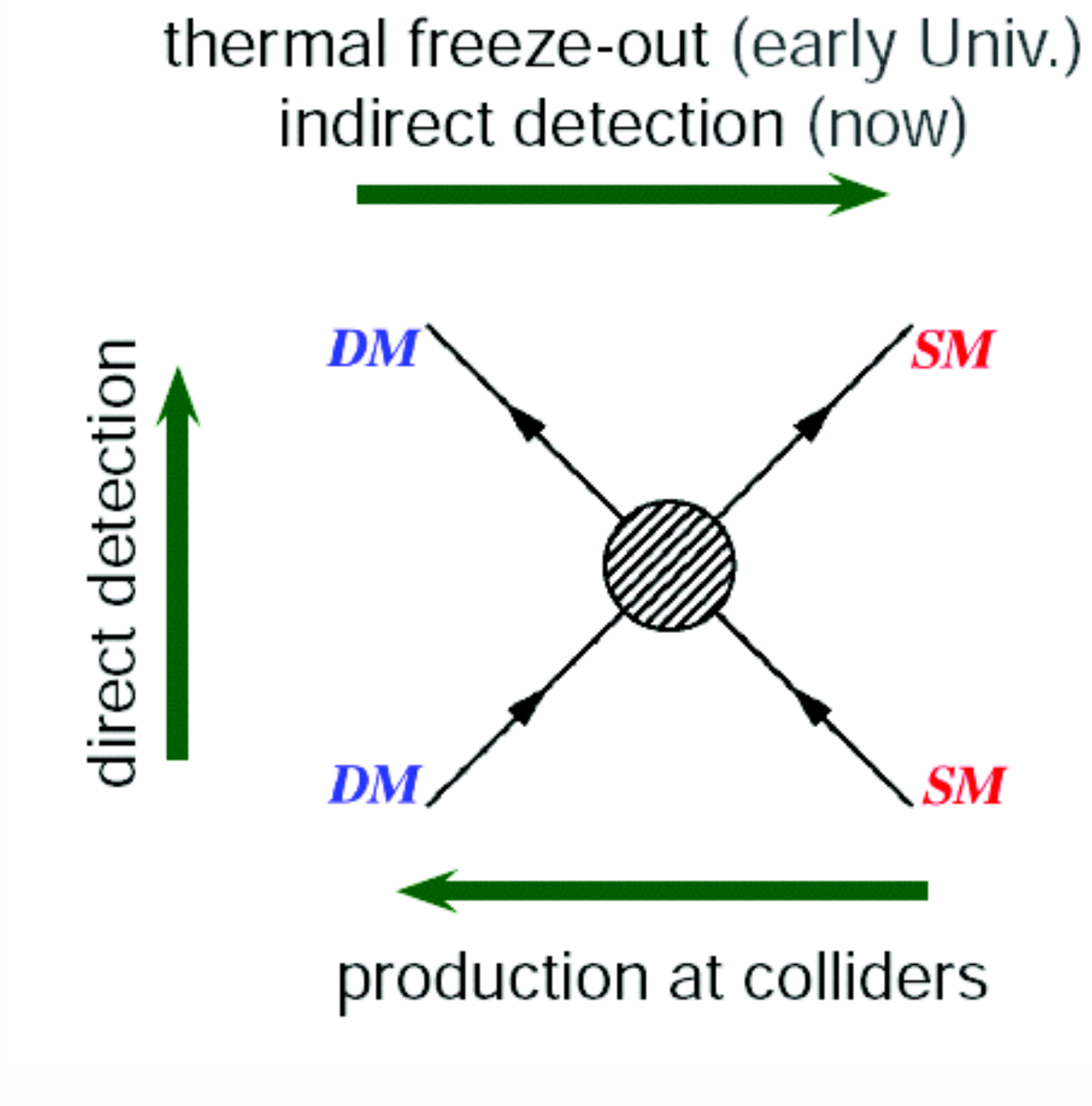
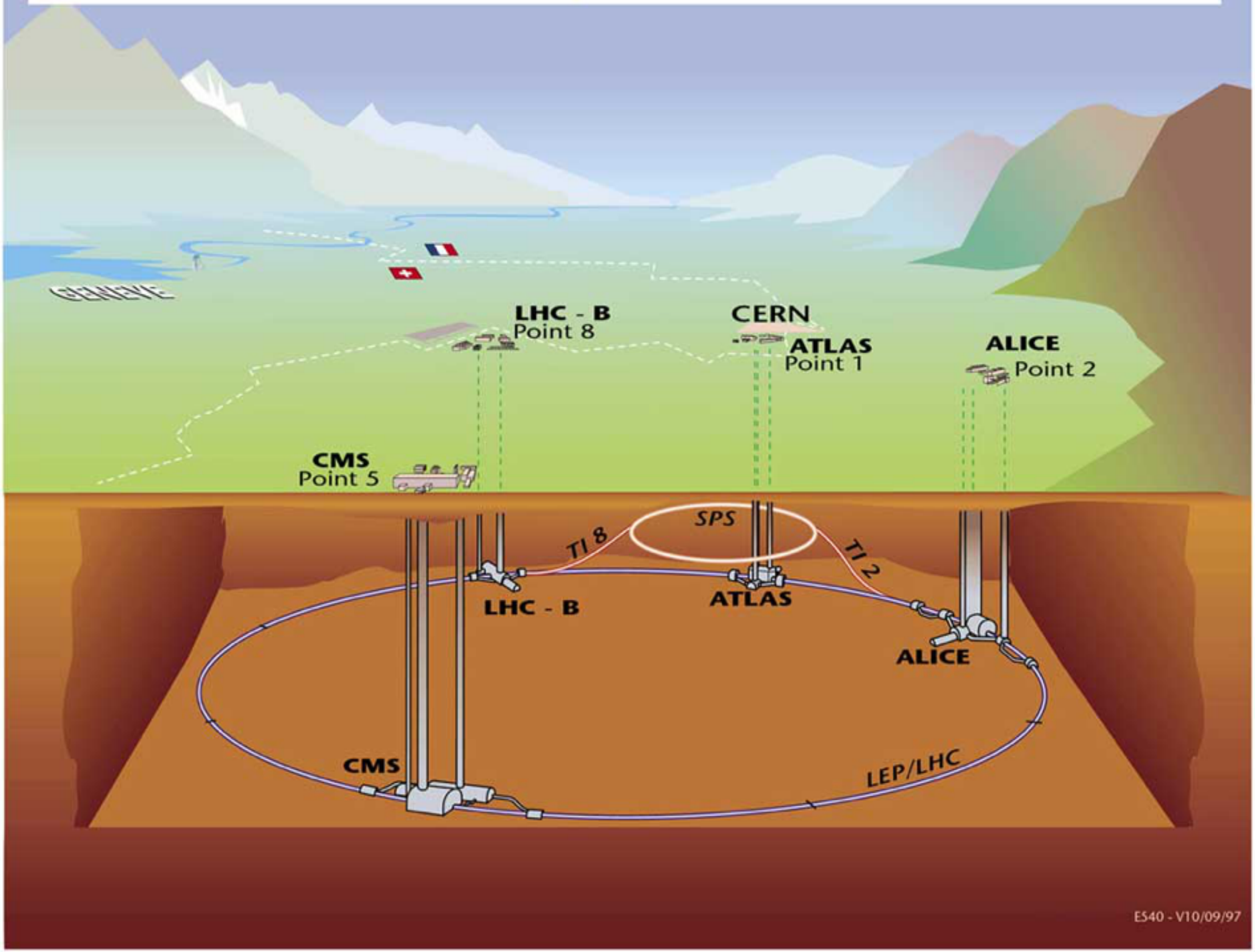


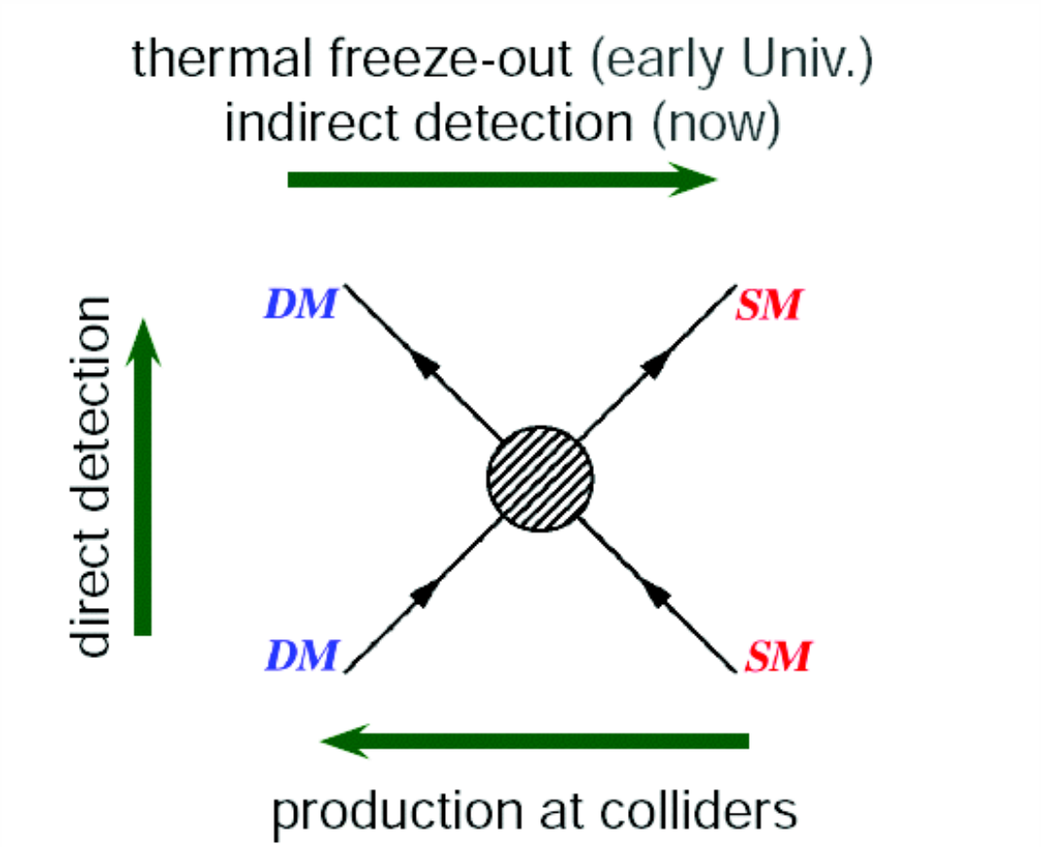
Large Hadron Collider (LHC)

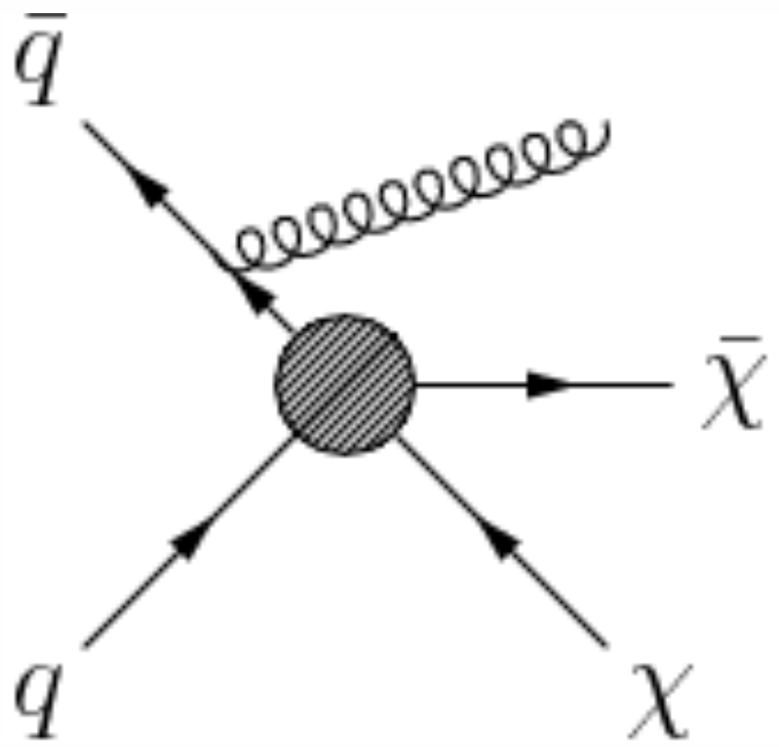
Overall view of the LHC experiments.



Large Hadron Collider (LHC)

Accelerator signal of DM





Summary on accelerator detection

- Good for testing some WIMP scenarios, e.g. LSP DM from supersymmetry
- Limited mass-range of DM particle

Alternatives of WIMP

Alternatives of WIMP

- Very light DM: axion (QCD or not), sterile neutrino
- Very heavy DM: remnants from the Planck scale, inflation etc
- Super-weakly interacting DM:
  — freeze-in scenario
  — 'neutrino-like' DM (needs a lot of extra degrees of freedom, super-weak interaction etc)

More exotic alternatives of WIMP

- Non-particle DM:
  — field defects: monopols, strings, branes etc
  — composite particles/objects
  — black holes (stay tuned, gravitational waves!)

Takeaway messages of the seminar

- Gravitational signals only from DM can say much about the properties of DM (Gaia!)
- We need to study new scenarios of DM
  — axions (many experiments starting soon)
  — multicomponent DM (Gaia?)
  — very heavy DM (CTA)
  — relating DM and muon g-2 (data coming soon!)
  — gravity related models (bimetric gravity)
- Last but not least — we need new ideas for experiments!

Thank you!

Bonus slides