Cosmic ray probes of fundamental physics

- I. Intro: Why should we look for fundamental physics in (high-energy) astrophysics?

- II. Surprises from what *should be there but ain't* (often forgotten example of NP found thanks to CR, not yet understood)

- III. Surprises from excesses, i.e. *finding what should not be there ?*
  - a) The paradigmatic case of Dark Matter (DM) - Intro to DM
  - b) WIMP DM searches
  - c) Non-WIMP searches

- IV. *Something ain't working as it should*: Changes in SM-derived laws

Pasquale Dario Serpico (Annecy, France)
ISAPP, Institut Pascal, 05/04/2022

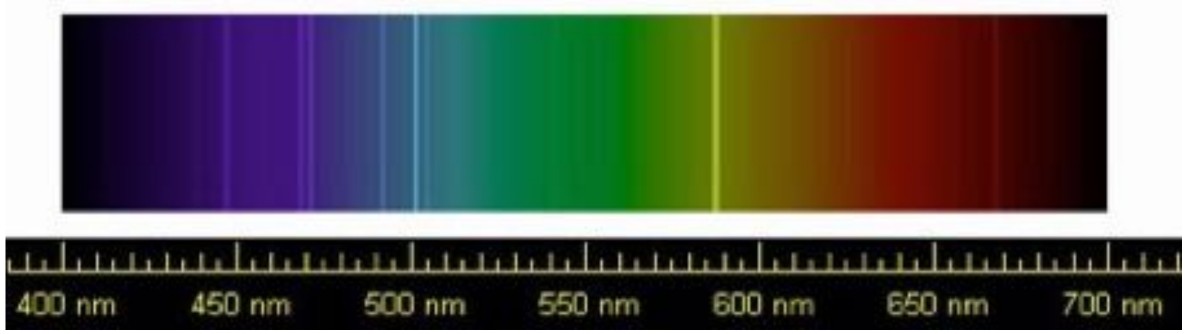
1. Introduction: Why should you give it a shot?

Finding New Physics from ‘astrophysics’ (& CR)?

Simply because it happened in the past!

1868: soon after new tool (spectroscopy) introduced in astro, *new “particle”* (atom) identified *first via astrophysics*:
He in solar spectrum (***Janssen & Lockyer****)
only discovered on Earth ~2 decades later

587.49 nm



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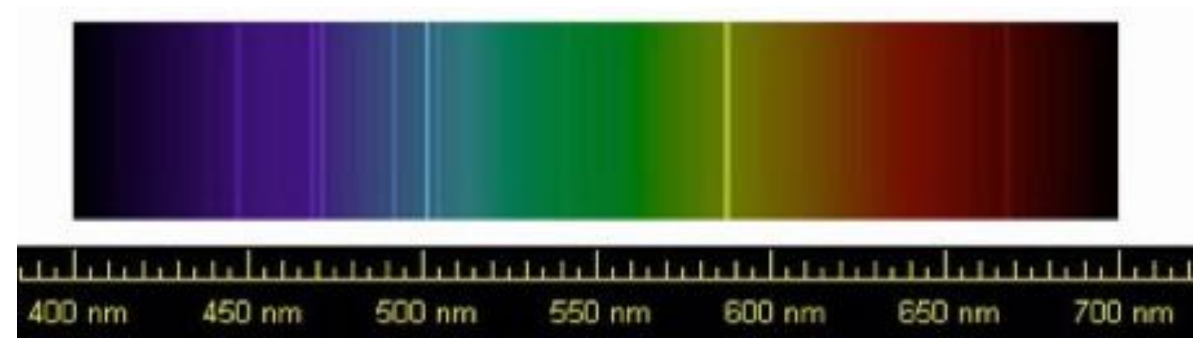

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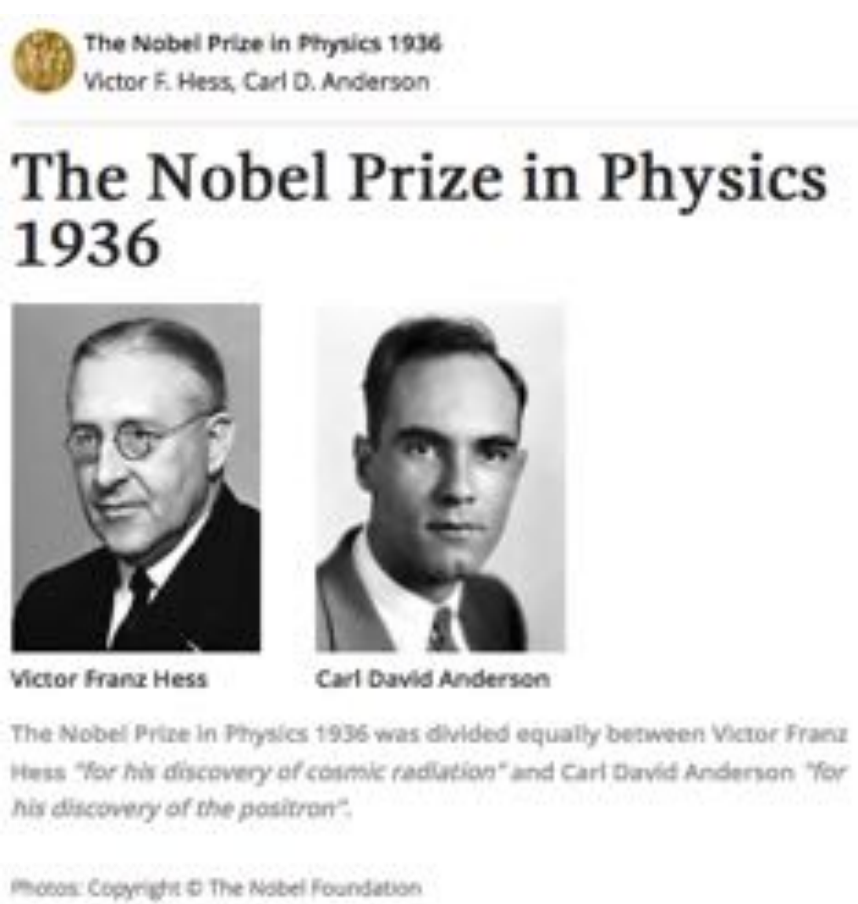
~1932-53: Particle zoo in cosmic rays such as *positron* e^+ (***Anderson*** ’32), predicted by ***Dirac*** in 1930, but also μ, π, strange particles (K, Λ, Ξ, Σ)...



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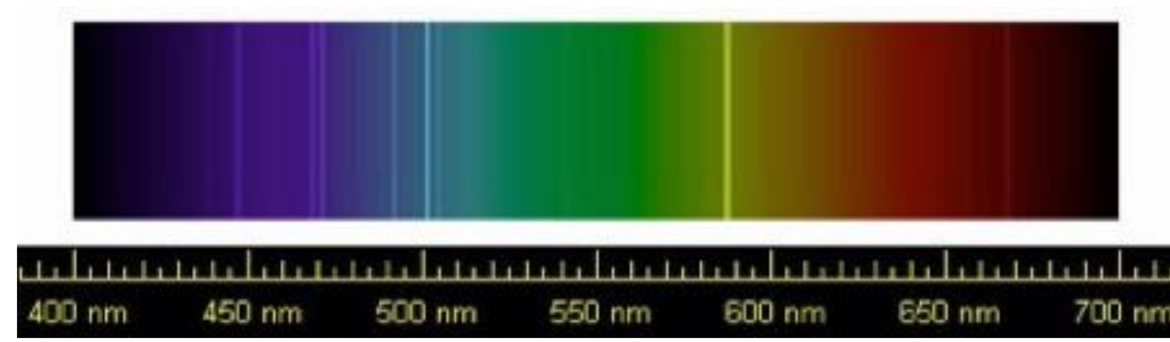

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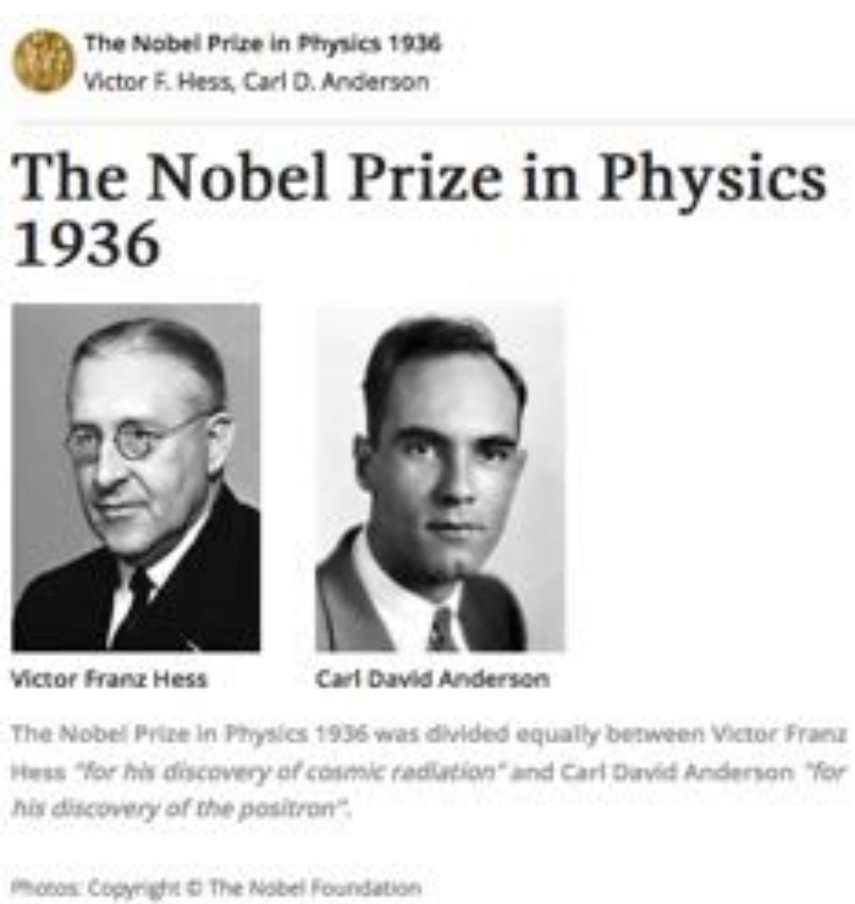
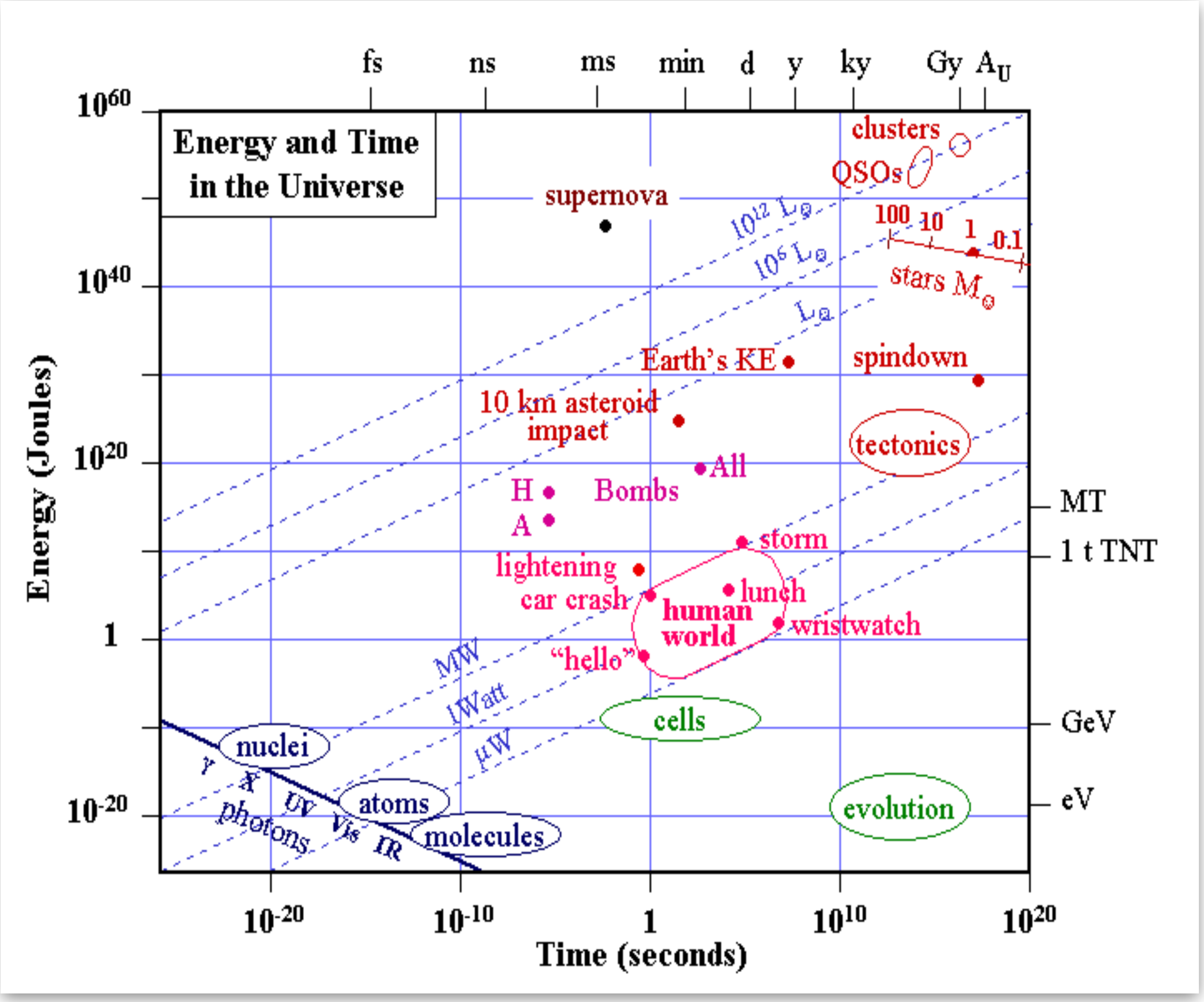


Last decades: systematically detected less ν’s than predicted from the Sun, angular/energy dependence of atmospheric neutrino fluxes:
ν *oscillations (hence m≠0)!*

Just luck or deeper reasons?

- Not surprising, if we think of the unusual scales of density, temperature, size, time, energy… if compared with what achievable in Earth laboratories!
- Orders of magnitude away from familiar ranges: conceivable that some physics extrapolations may fail, highlighting new phenomena/regimes



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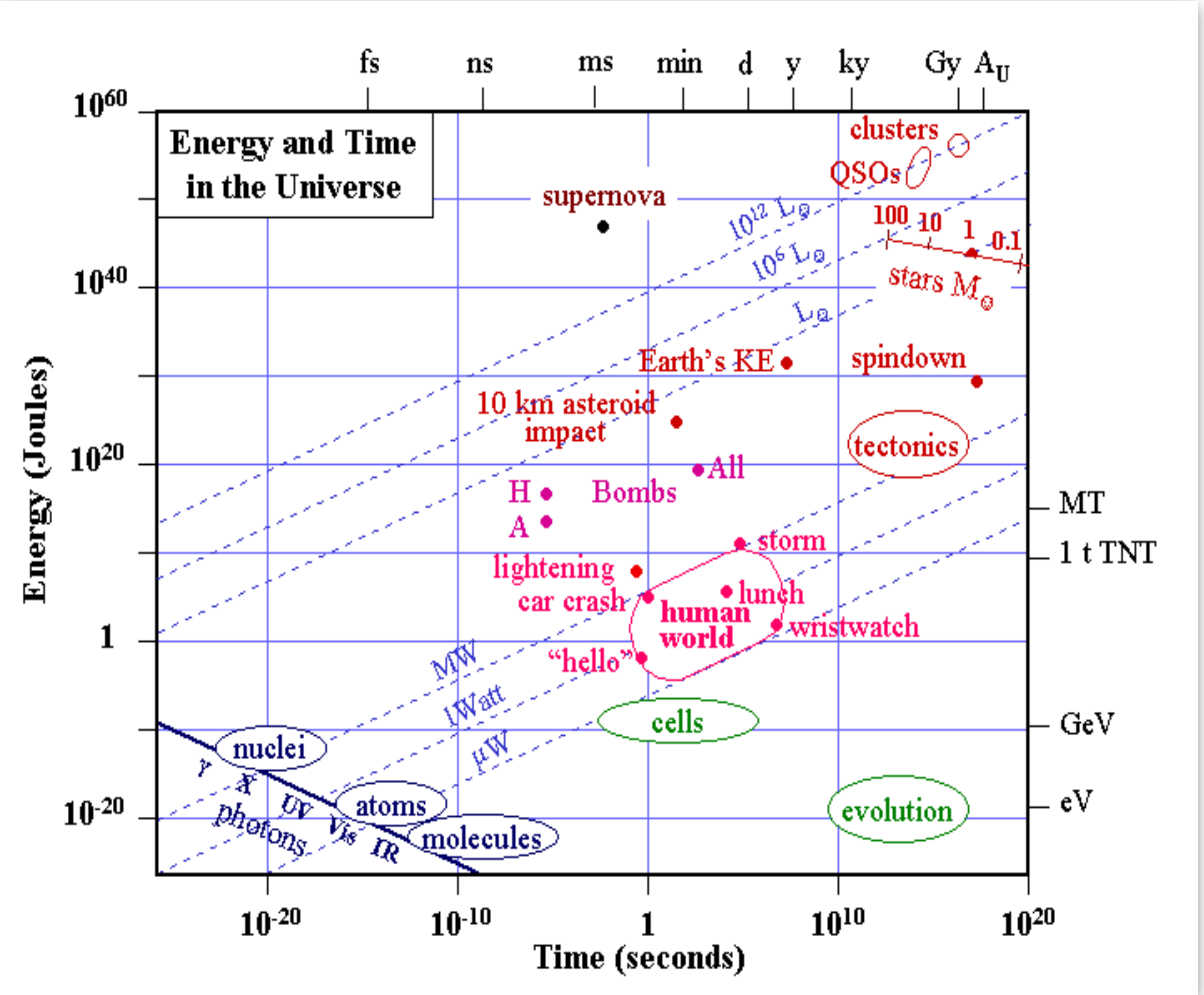


Challenge

We do not control the environment; requires effort in parallel to understand astrophysics, to devise 'robust' signatures, to suggest and cross-check Lab validation.

Necessarily quick and semi-quantitative overview of some possibilities.
Main goal: Help you to schematise some research direction

II. Surprises from what *should be there but ain't*

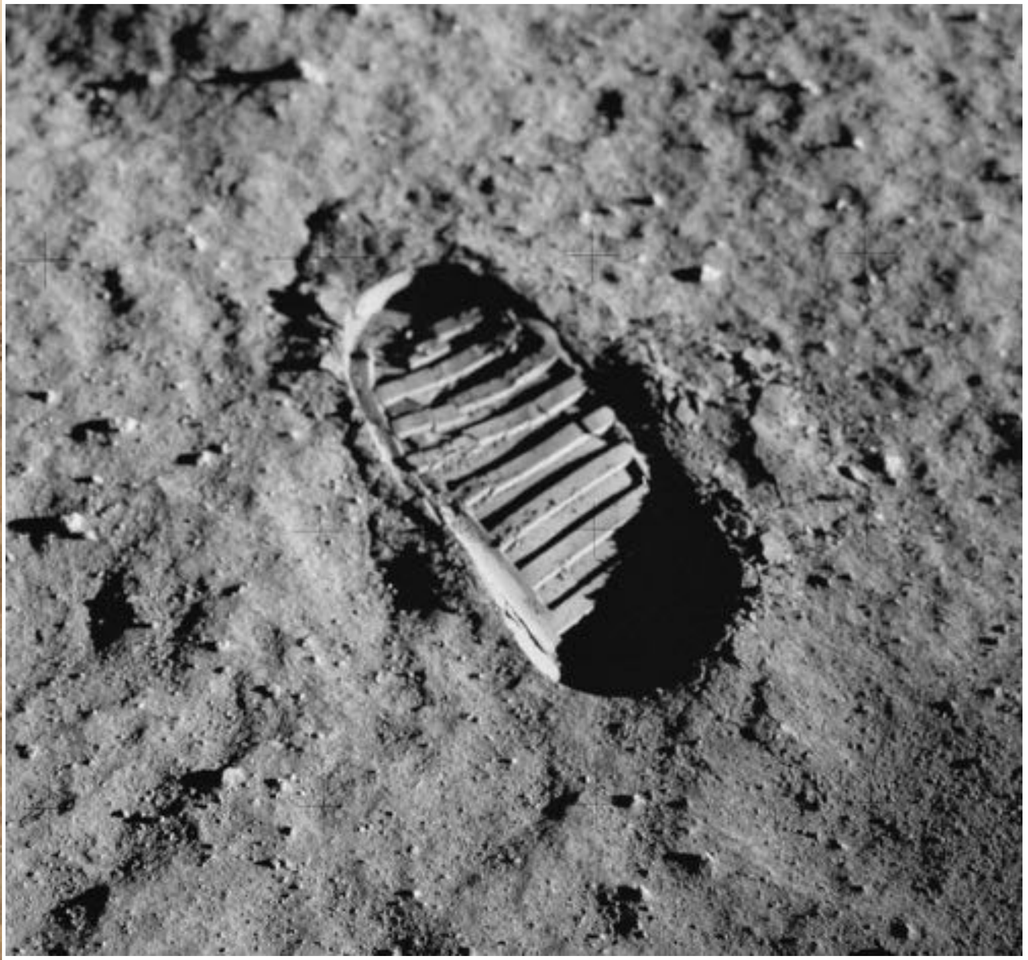
(often forgotten example of new physics we have already found thanks to CR*)

** Here and in the following, I will use 'Cosmic Rays' (CR) in their loose/broad sense of high-energy (thus typically non-thermal) messengers from the universe.*

A fact we give for granted…

Cassini, Titan

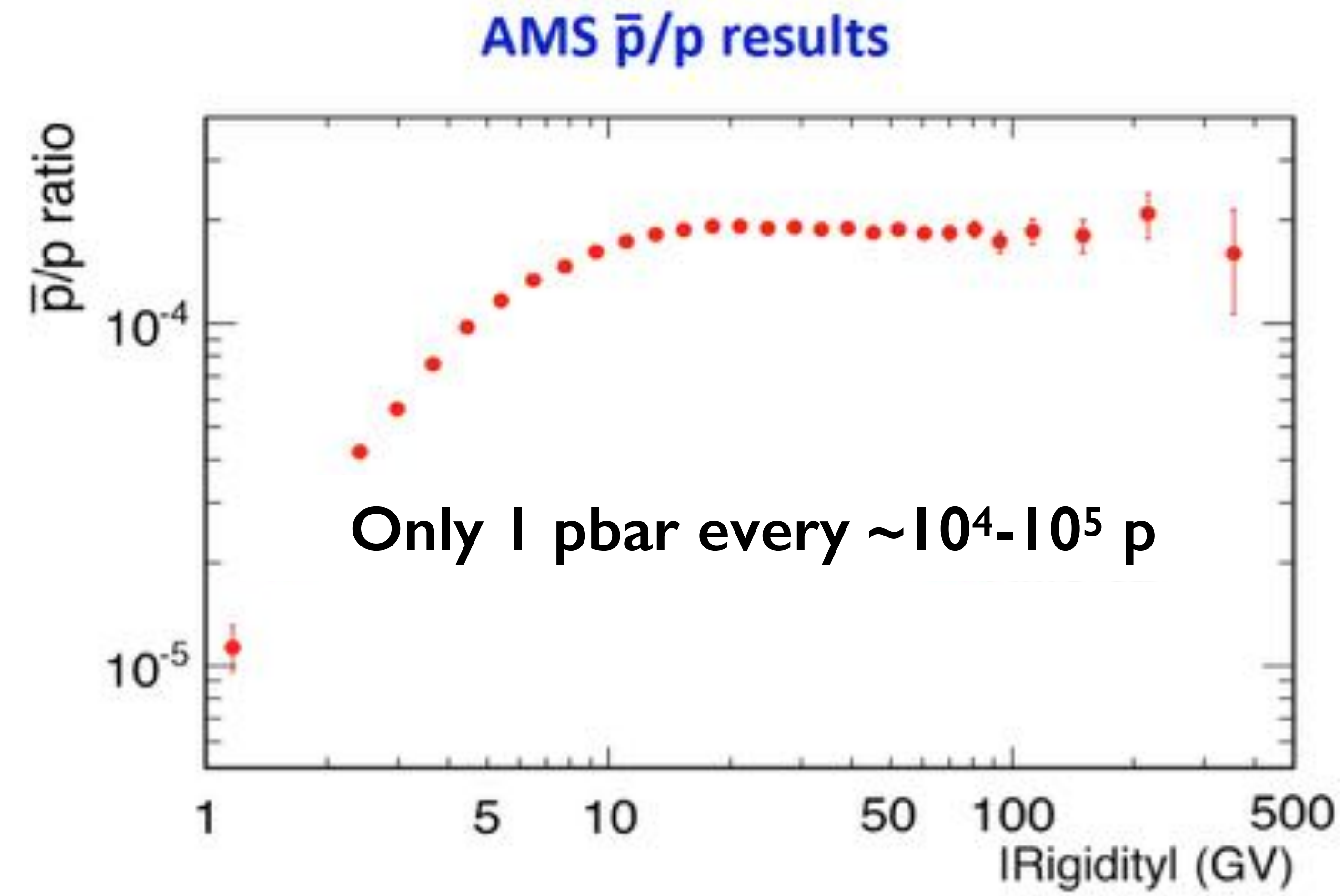
Curiosity self-portrait, Mars

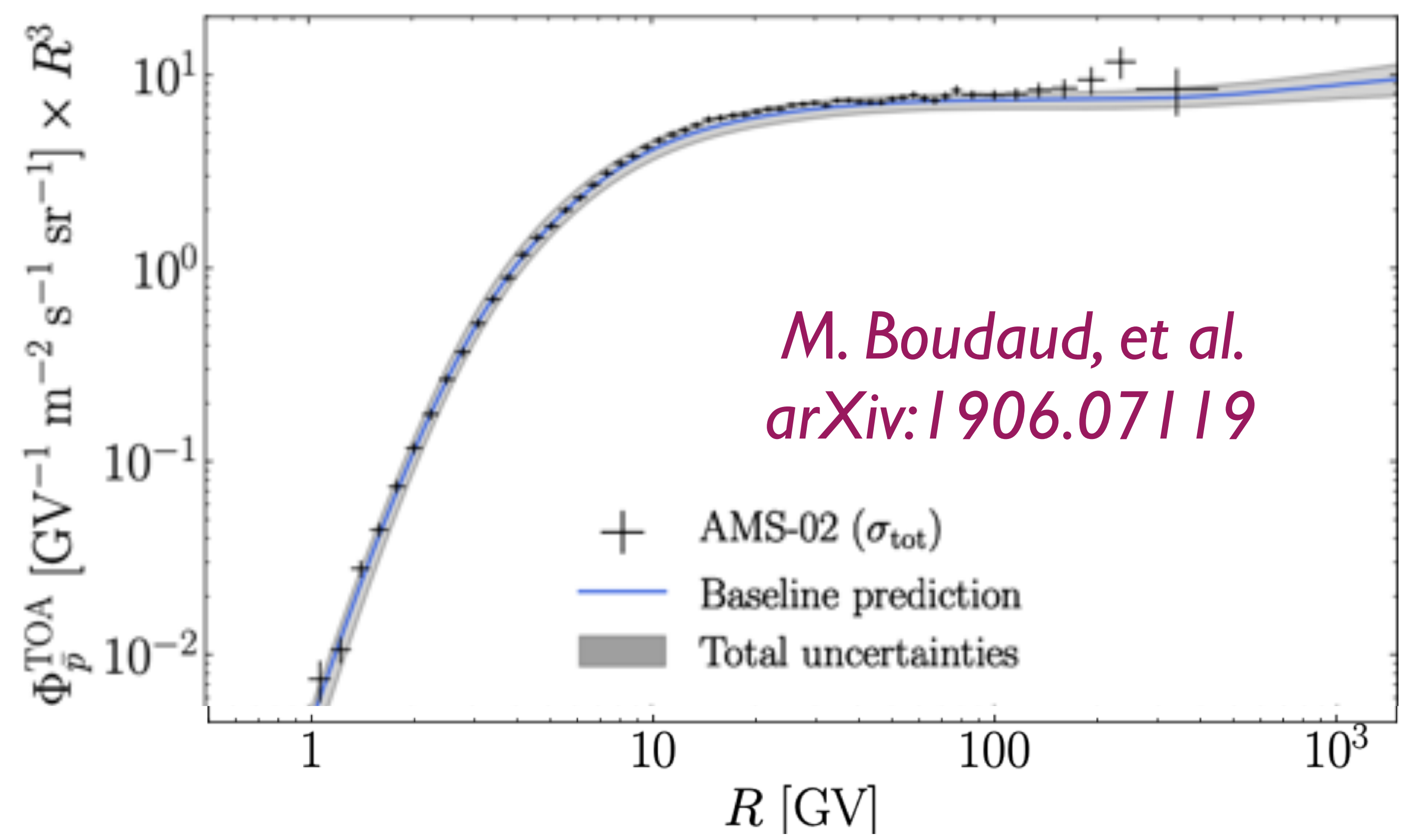


Apollo 11, Moon

Solar systems seems to be made exclusively of matter! What about the rest of the universe?

CRs: Little to no antimatter in the galaxy

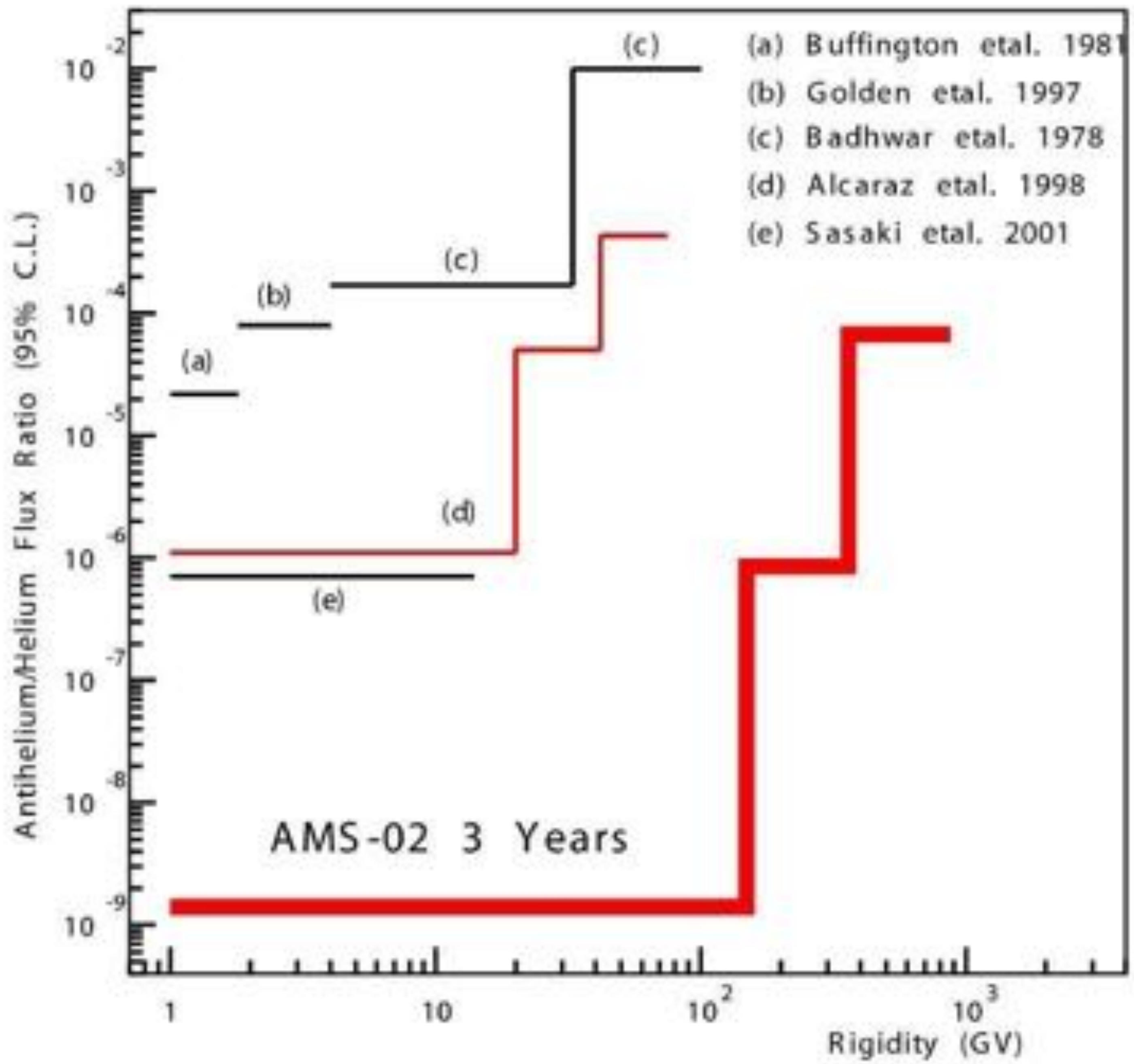




Traces in CRs ; ~ 1 in 10000 (e^+, anti-p) are fully accounted for via rare collisions of cosmic rays (protons, nuclei) in the rarefied interstellar medium

Even tighter bounds from antinuclei

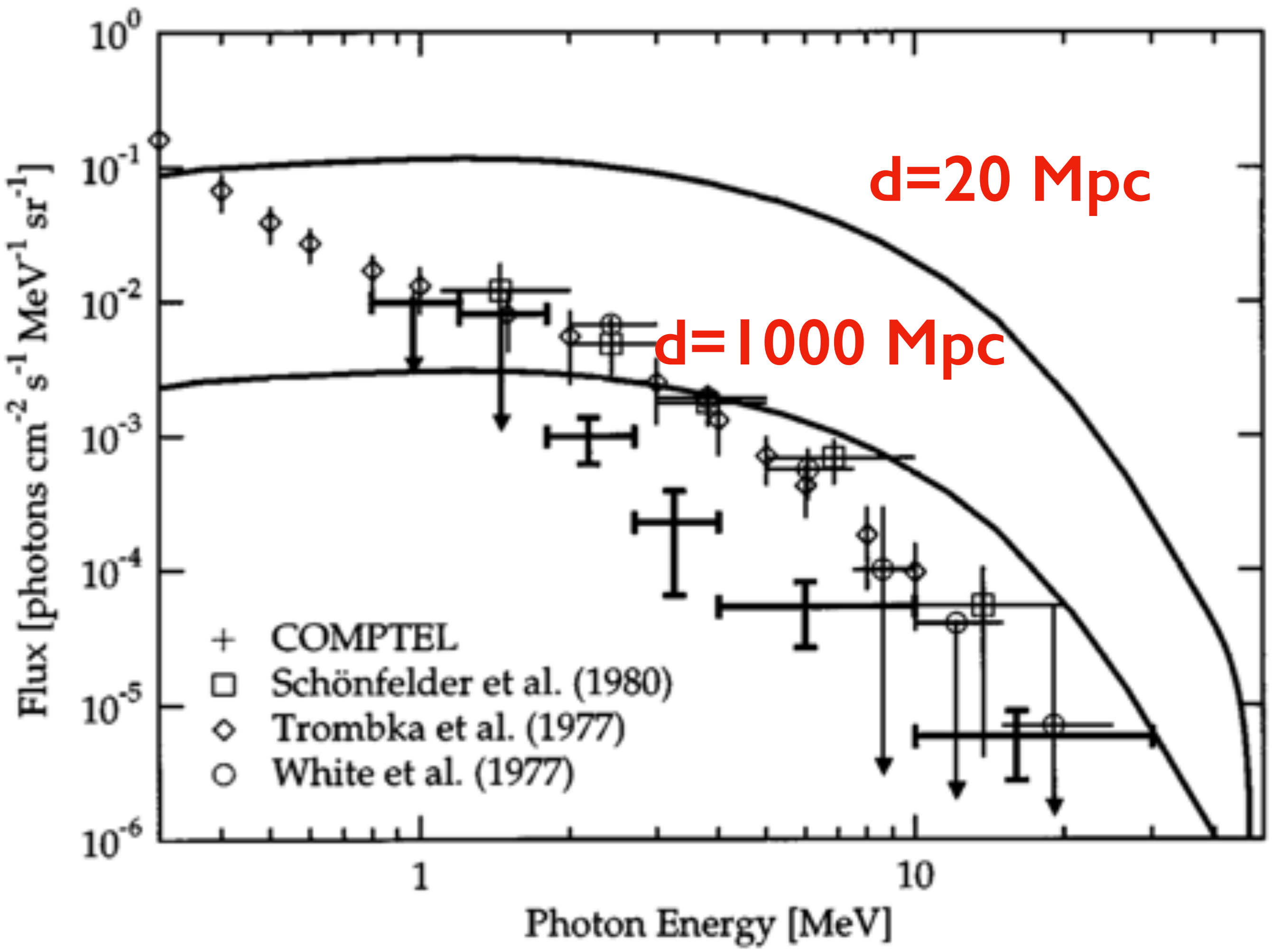
With a comparable number of stars and antistars, one should collect a similar flux of protons and antiprotons, helium and anti-helium, etc.



by Sonia Natale & Martin Pohl

At cosmological scales…

No signs of sizeable traces of antimatter e.g. via gamma annihilation spectra at the borders of matter/antimatter domains



A. G. Cohen, A. De Rujula and S. L. Glashow, "A Matter - antimatter universe?" Astrophys. J. 495 (1998), 539-549 [astro-ph/9707087]

Empirical Fact (here on Earth's labs!):

In any reaction creating matter, antimatter particles are also created in equal amounts.

How is it that we live in a Universe dominated by matter?

One of the biggest mysteries in fundamental physics

Matter-Antimatter Asymmetry

Possible explanations

- **Initial condition: Universe is born with this difference.**

Apart from the scarce epistemological value, seems inconsistent with an inflationary era, which would have diluted enormously the initial asymmetry.

- **Dynamical origin**

Creating dynamically the asymmetry starting from a perfectly symmetric condition.

Remarkably
we know *sufficient* conditions capable of doing that:

A.D.Sakharov, (1967) JETP Letters volume 5, issue 1, pages 32-35

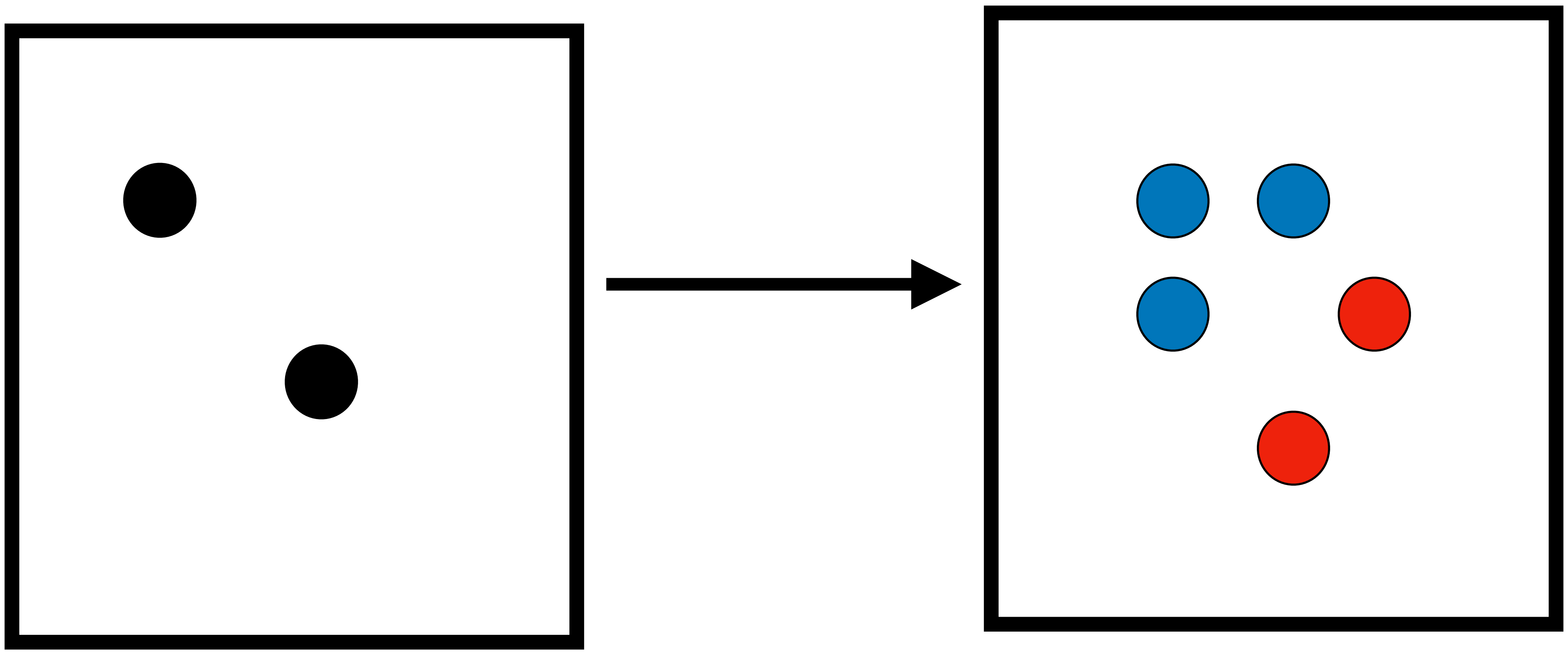
Andrei Sakharov
(1921-1989)

Main designer of Soviet thermonuclear bomb RDS-37. Human rights militant, against nuclear proliferation, promoting reforms in the URSS, Nobel Peace Prize1975

Sakharov condition 1

Must exist reactions breaking the symmetry between matter and antimatter

(B violation)



obvious, since if no process exists yielding a change of B between initial state and final state, a dynamical generation is impossible

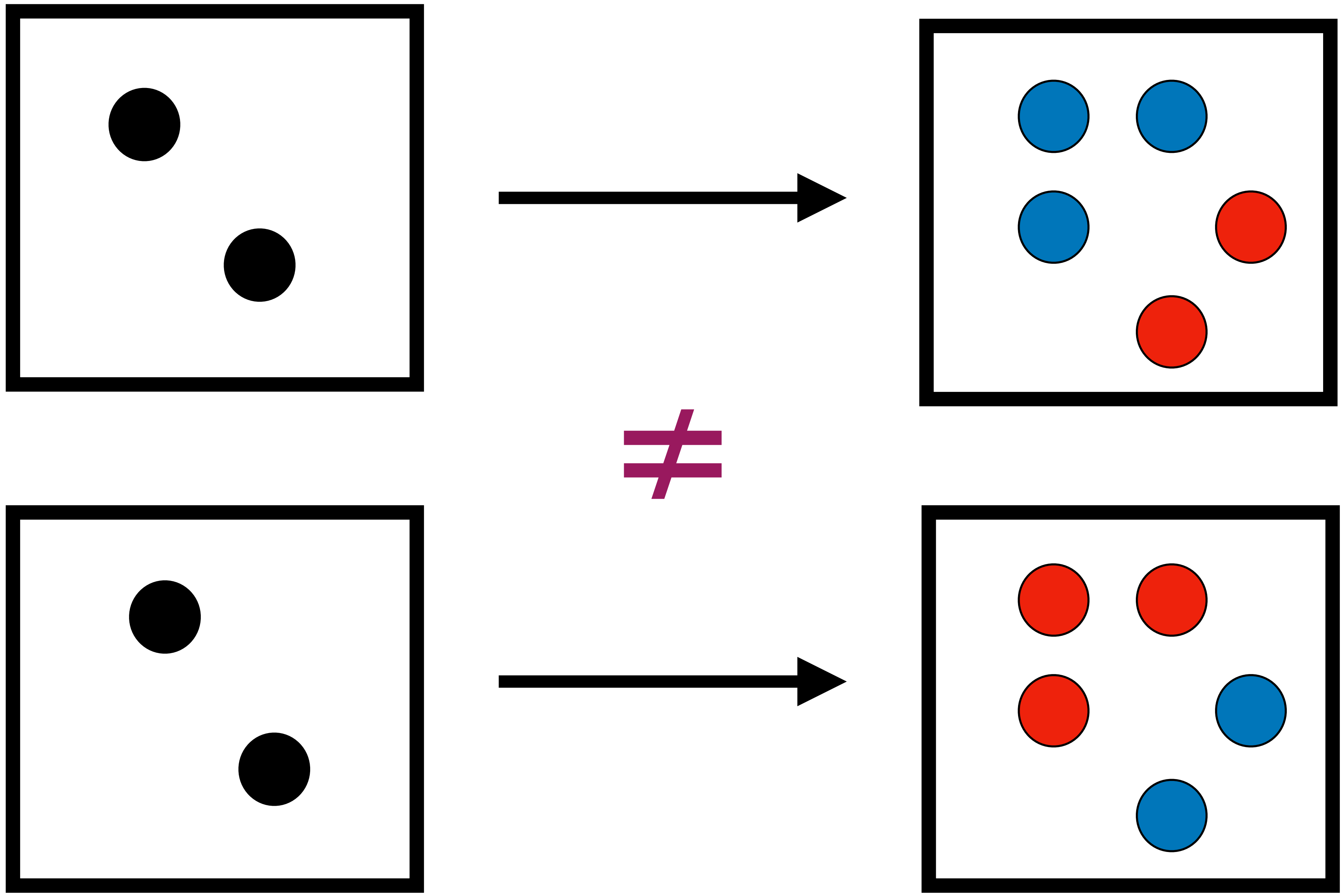
In the SM, B+L violated non-perturbatively (e.g. instantons, sphalerons) since:

- LH and RH currents have different strength
- SU(2) has non-trivial vacuum, i.e. *topologically inequivalent* field configurations going to zero at infinity

Sakharov condition II

B-violating reactions not be compensated by their matter-antimatter conjugates (i.e. different reaction rates!)

(C and CP violation)



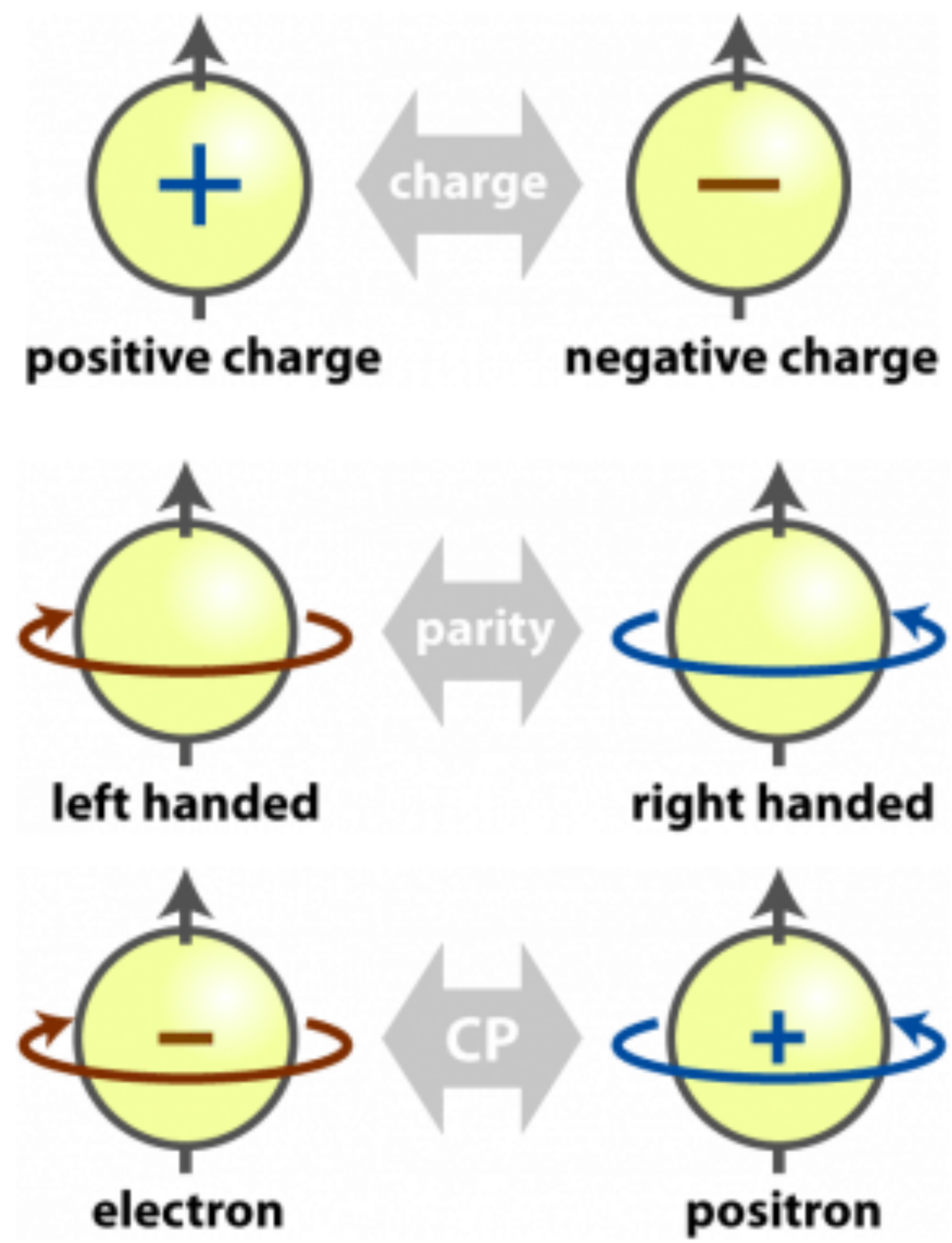
i.e., for a given B-violating process, one needs to make sure that the "anti"processes for the corresponding antiparticles do not have the same yield, otherwise there is no net creation of B.

Sakharov condition II - clarification

Why both C and CP violation?

C converts a particle in the corresponding antiparticle *with the same chirality*.

If CP were preserved, the asymmetry created, once summed over final states of all chiralities, would vanish.



Sakharov condition II - in the SM or beyond

CP violation implies T violation due to CPT theorem (*CPT is an exact discrete symmetry of any local Lorentz-invariant field theory*)

T is anti-unitary: $T i T^{-1} = -i$.

→*CP violation requires complex parameters in the lagrangian.*

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T is anti-unitary: $T i T^{-1} = -i$.

→*CP violation requires complex parameters in the lagrangian.*

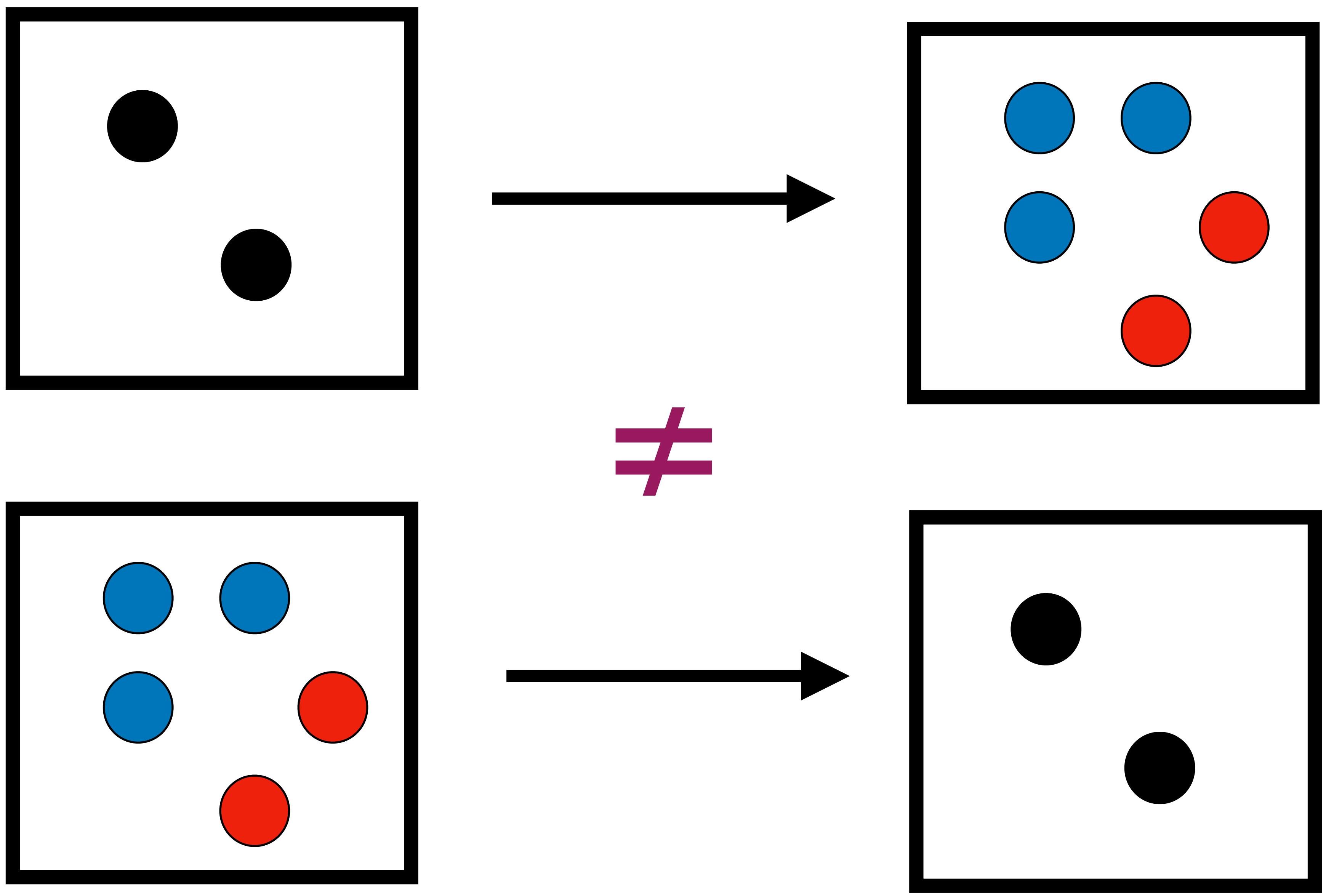
Complex parameters can be achieved by having:

phases in the vacuum expectation values (*spontaneous CP breaking*).
Requires at least two scalars to be possible, so that it ***cannot happen in the SM with a single Higgs doublet***.

phases in the coupling parameters (*explicit CP breaking*)
That's the only origin possible (and known) of CP-violation in the SM, which has *one* physical phase in the Yukawa matrix of the quarks

Sakharov condition III

Departure from thermodynamical equilibrium
(otherwise each reaction balanced by its reverse)



This can take place, for instance, via a (first order) phase transition

Rise and fall of the SM baryogengesis

All conditions could be in principle met in the SM (non-perturbative B-violation, CKM phase, EW transition 1st order) but parameters quantitatively far from successful!

One of strongest motivations for physics beyond the SM

Two main classes of alternatives:

New physics at the EW scale (e.g. supersymmetry).
Can change the nature/strength of EW phase transition (enhance cubic term in V_{eff}), plus additional phases and possibly complex vev allowed by multiple Higgses.
+ : 'in principle testable at colliders'
- : extremely constrained by negative searches

Baryogenesis via Leptogenesis
generate a B-L asymmetry at $T > T_{EW}$, which is then converted into a B asymmetry (by SM sphaleron processes). Departure from equilibrium from heavy particle decays.
Extra phases among which those entering the neutrino mixing matrix.
+ : Compatible with (hinted to by?) tiny mass of neutrinos, EFT reasoning
- : Typically happens at high scales, not directly testable

Lesson learned

There might be cases where 'cosmic rays' are instrumental in pointing to new physics, but as far as we know in this case there is no useful way they can be used to unveil which physics is behind the puzzle…

III. Surprises from excesses, i.e. *finding what should not be there*

The case of dark matter

(...

a) Intro to DM, some misconceptions, some myth-buster

On dark matter

- Sometimes confusing different plans and concepts (discovering/identifying, DM/WIMPs, DM/new physics, etc.)
- Will remind you the classical evidence, the modern evidence, and the key difference between the two
- *b) On DM candidates: WIMPs & links with 'cosmic rays'*
- *c) DM searches beyond WIMPs, some examples*

Complementary to H. Dole's intro lectures

Classical discovery of dark matter

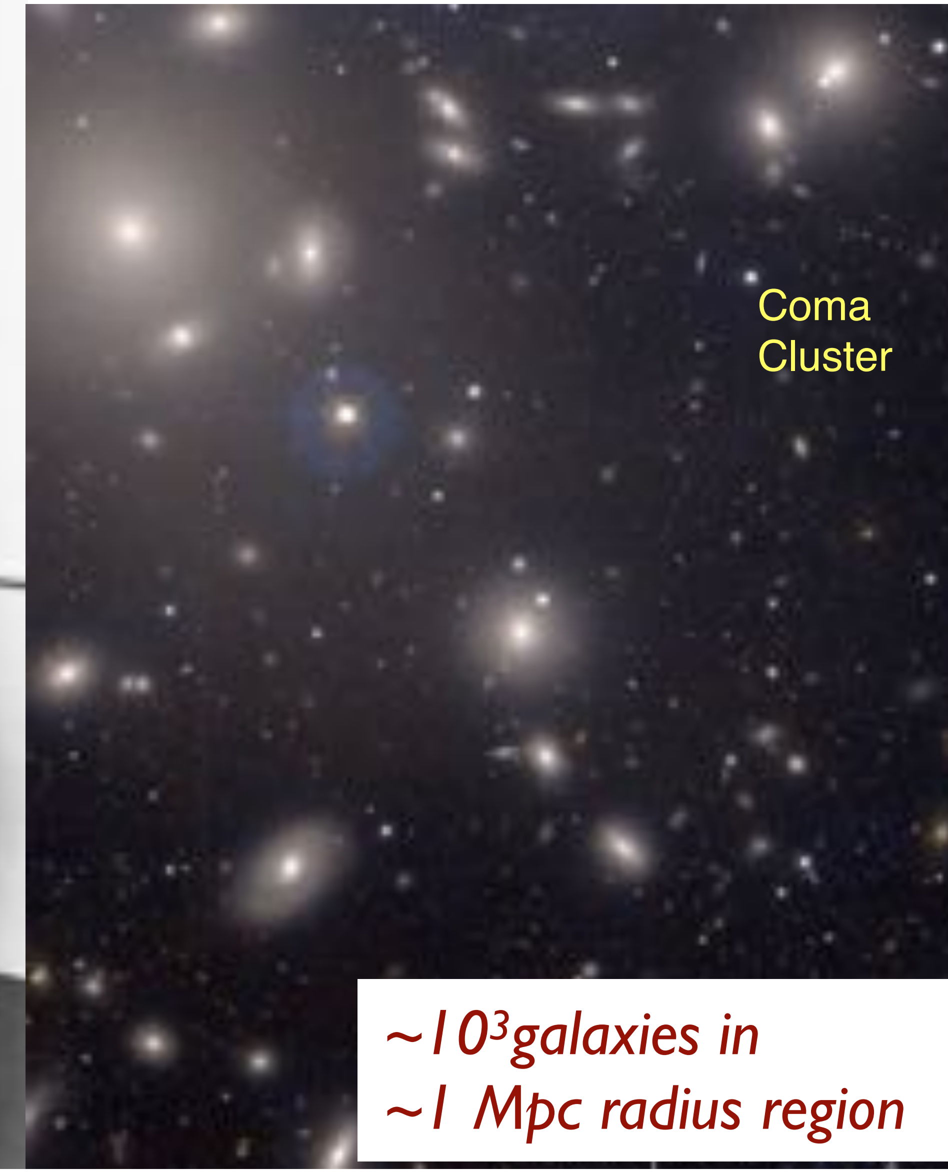
In a number of astrophysical bound systems (clusters, galaxies…) one finds a mismatch between the mass inferred by gravitational probes and the mass inferred by electromagnetic observables, with the former much larger than the latter. The excess of the former with respect to the latter is dubbed DM.

I. **No implication, yet, that DM is an exotic form of matter. It might still be ordinary matter which does not shine (e.g. dim stars, planets, cold and/or rarefied gas, etc.)**

II. **DM notion implicitly assumes that the theory of gravity used (Einstein GR, most often in its Newtonian limit, in fact!) is correct.**

III. **The fact that it is called matter** (as opposed e.g. to radiation) **has to do with the fact that its effects are inferred in bound systems, so that DM clusters and forms structures** (this is very different, for instance, from the effects of the cosmological constant, which does not admit perturbations)

Example: Galaxy motion in clusters



Applied Virial Theorem

$$2\langle T\rangle + \langle U_{tot}\rangle = 0$$

(basically pioneered in astronomy only by Poincaré, previously!) and **realized that this was a puzzle.**

Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta (1933)* ***6****, 110–127.*
"On the Masses of Nebulae and of Clusters of Nebulae", ApJ (1937)* ***86****, 217*

Scale: 0.1-1 Mpc

*Nebula=Early XXth century name for what we call now galaxy (besides proper Nebulae!)

Sketch of the method

$$T = N\frac{m}{2}\langle v^2\rangle \longrightarrow 2T = M\langle v^2\rangle$$

where m is the typical Galaxy mass, M=N m a proxy of the cluster mass

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Estimate the gravitational potential energy of a self-gravitating homogeneous sphere of radius R

$$\langle U_{tot}\rangle \simeq -\frac{3}{5}\frac{G_N M^2}{R}$$

from Doppler shifts in spectra

$$M_{tot} \simeq \mathcal{O}(1)\frac{\langle v^2\rangle R}{G_N}$$

inferred from distance & angular size

weakly depends on geometry/distribution of Galaxies in the cluster

Zwicky found 2-3 orders of magnitude larger M than expected from converting luminosity into mass!

(Issues due to distance scale, presence of gas… but qualitatively the discrepancy is indeed there)

Interlude: Dark matter(s) common in astrophysics

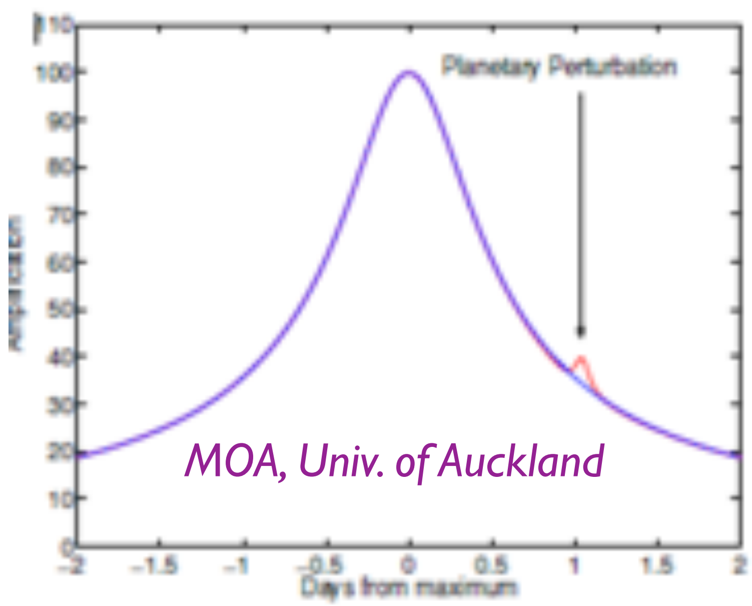
Not shocking to infer presence of "extra stuff" via gravity

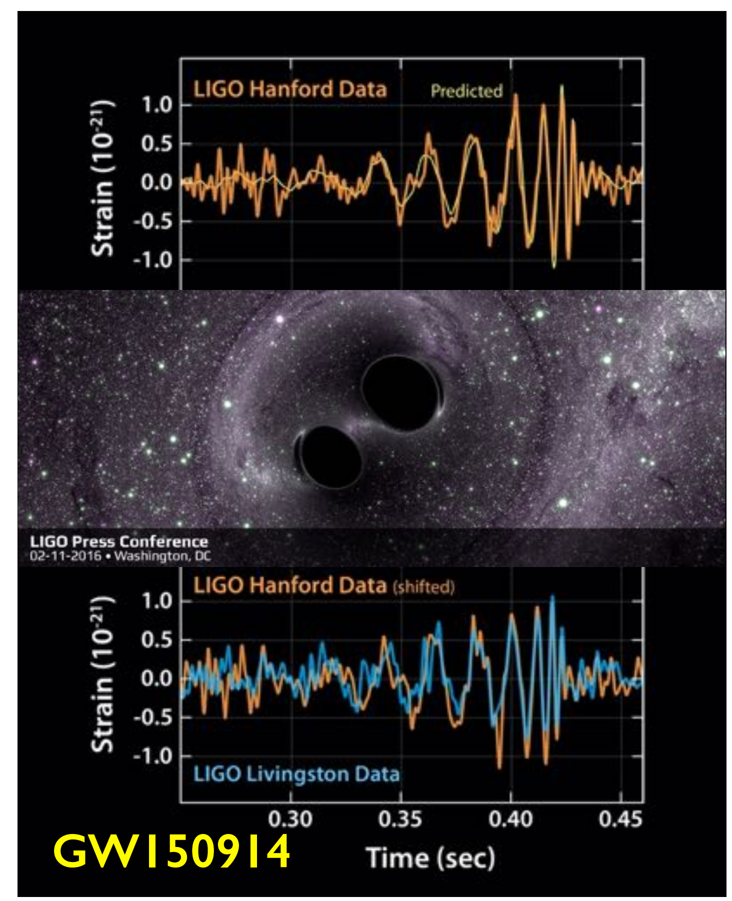
Le Verrier and independently Adams interpreted irregularities in Uranus orbit as due to perturbation by a yet unknown planet, calculating its orbital elements "by inversion"

On September 24, 1846 Galle found that "the planet whose place you [Le Verrier] have [computed] *really exists*" ("indirect DM detection")

Indirect detection of former Solar System DM by Voyager 2

Microlensing routinely used to discover e.g. brown dwarfs (or exoplanets!)





Inferring the existence of objects from their gravitational effect is familiar in astrophysics!

Modern vs. Classical discovery of dark matter

In a number of astrophysical bound systems (clusters, galaxies…) one finds a mismatch between the mass inferred by gravitational probes and the mass inferred by electromagnetic observables, with the former much larger than the latter. The excess of the former with respect to the latter is dubbed DM.

Modern evidence leads to a sharper and more challenging situation

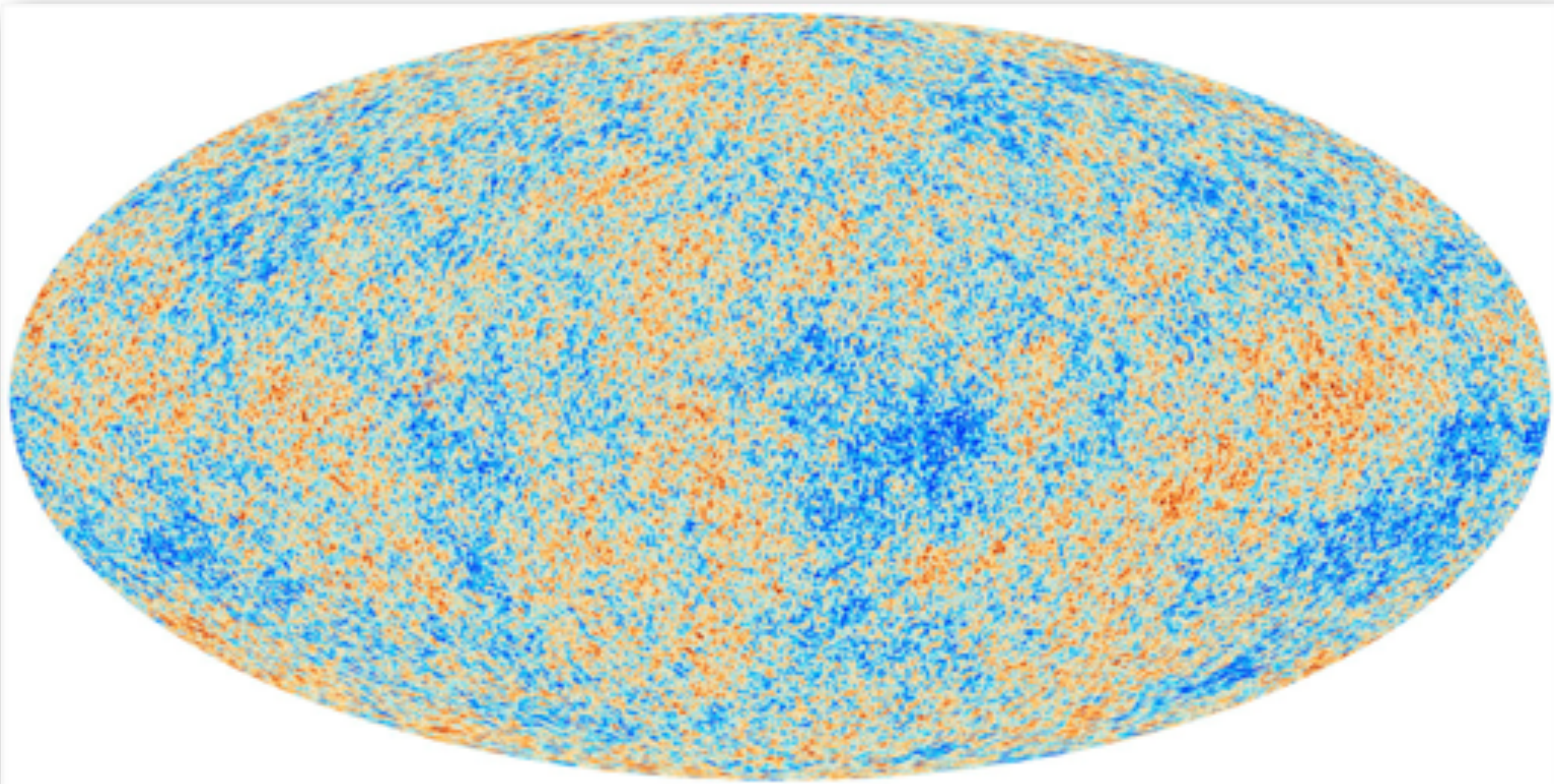
I. **Indication that DM is an exotic form of matter. It cannot be made of ordinary matter which does not shine (e.g. dim stars, planets, cold and/or rarefied gas, etc.)**

II. **Numerous tests that the theory of gravity used leads to consistent results**

III. **The test extends beyond 'gravitationally bound' objects, also to perturbative (and theoretically better controlled) regime**

Example: Growth of structures from CMB 'seeds'

This picture, plus linear theory is a robust proof for the existence of DM!



Key argument

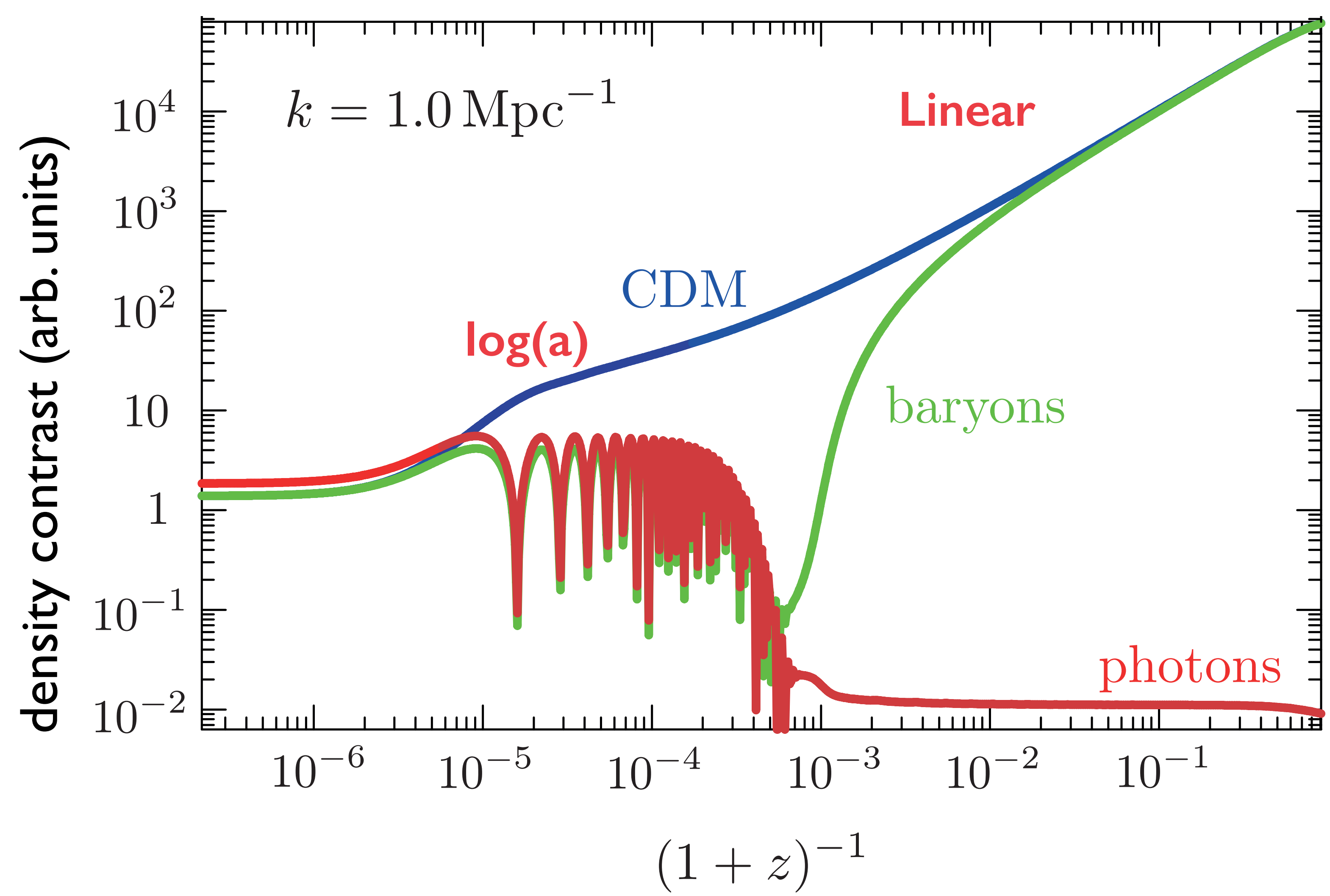
- Before recombination: baryons (elementary plasma form!) & γ's coupled, "share perturbations"
- We measure amplitude ~10^{-5} at recombination (*picture above*)
- Evolving forward in time, insufficient to achieve collapsed structures as we see nowadays, unless lots of gravitating matter (*not coupled to photons*) creates deeper potential wells

Graphical illustration

$$\delta = \frac{\rho}{\langle\rho\rangle} - 1$$

$$= \sum_{\mathbf{k}} \tilde{\delta}_{(\mathbf{k})} e^{i\mathbf{k}\cdot\mathbf{x}}$$

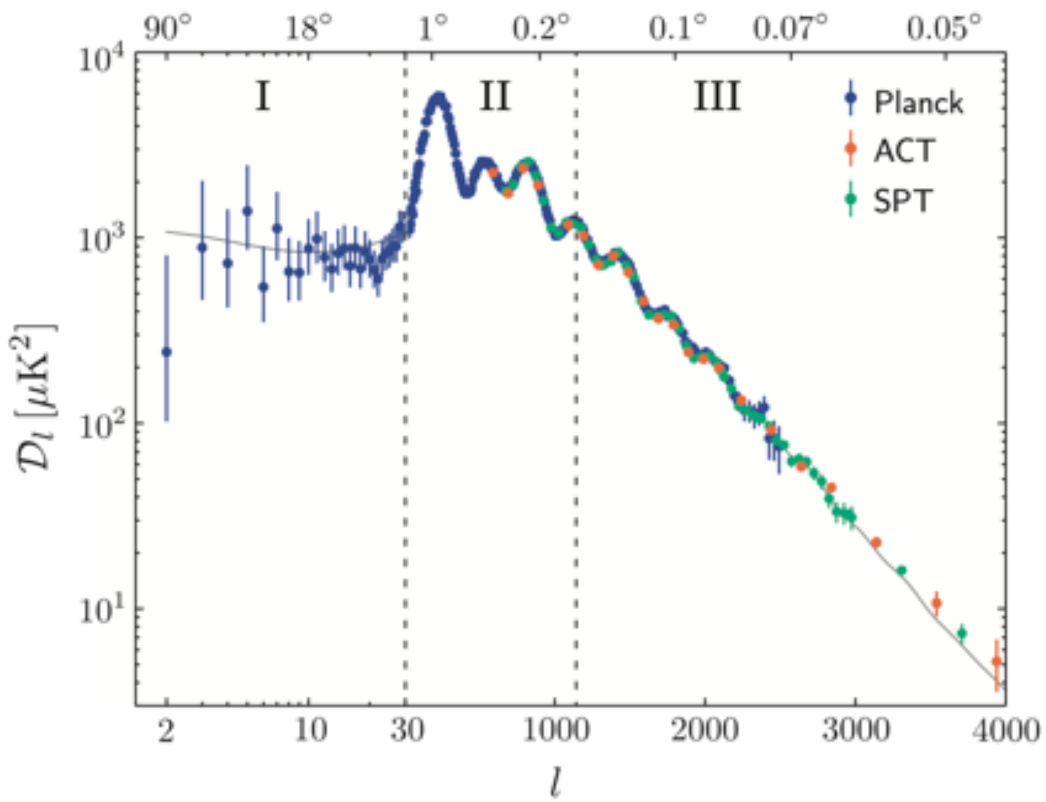
Density contrast for a "mode" (in Fourier space). Indep. evolution in linear theory, its "variance" is the power spectrum *P(k)*

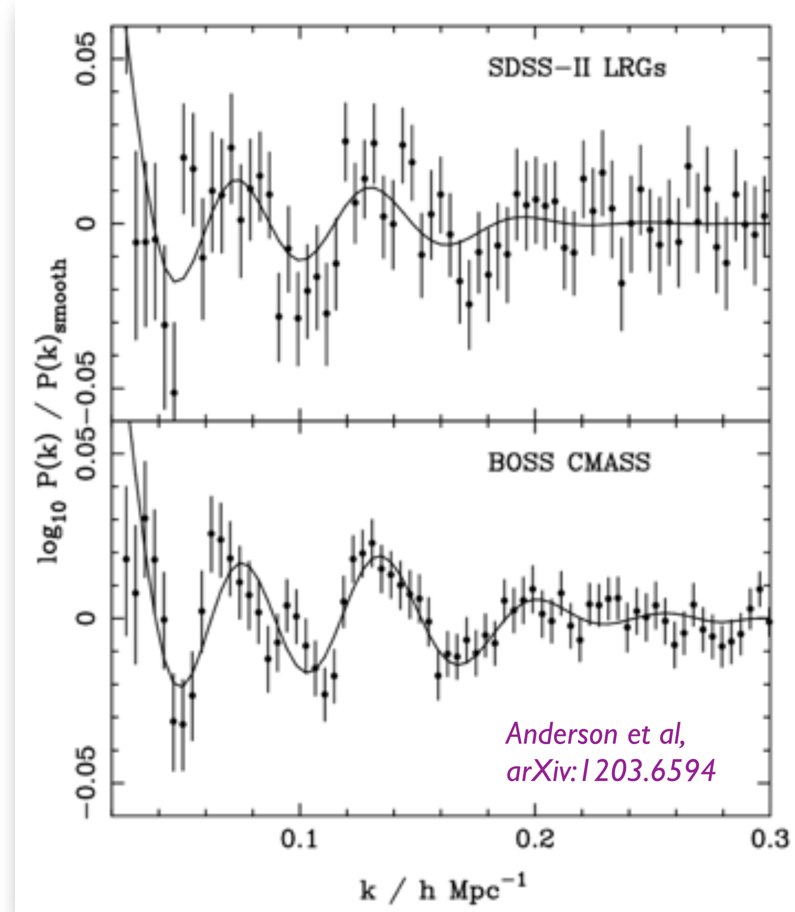


- Ignore evolution at very early times (before entering the Hubble horizon, gauge dependent).
- Upon horizon entry, as long as the baryonic gas is ionized, it is coupled to radiation & oscillates, as pressure prevents overdensities from growing. The (uncoupled, pressureless) CDM mode instead grows, first logarithmically during radiation domination, then linearly in the matter era.
- After recombination, baryons behave as CDM, quickly fall in their "deep" potential wells... but, had not been for CDM, they would need much longer to reach the same density contrast!

But can we trust gravity theory? Consistency checks!

Patterns of oscillations in the CMB angular PS should reflect in clustering properties of Galaxies at low-z. Predicted and later measured (BAO)





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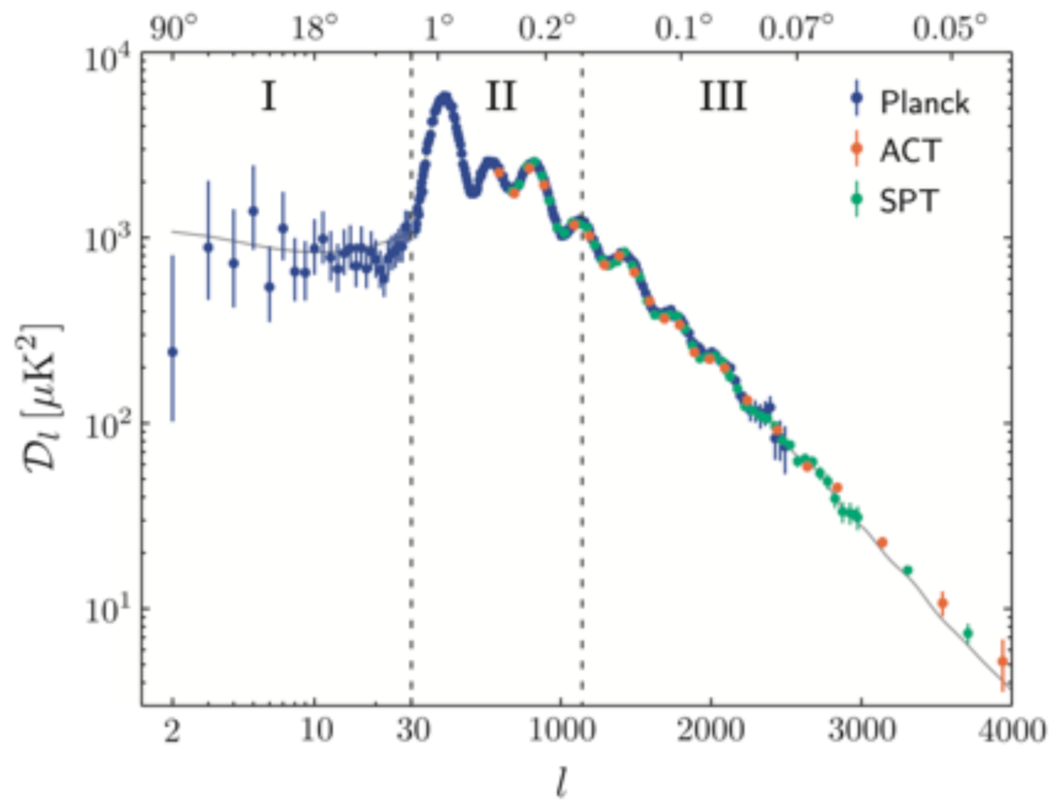
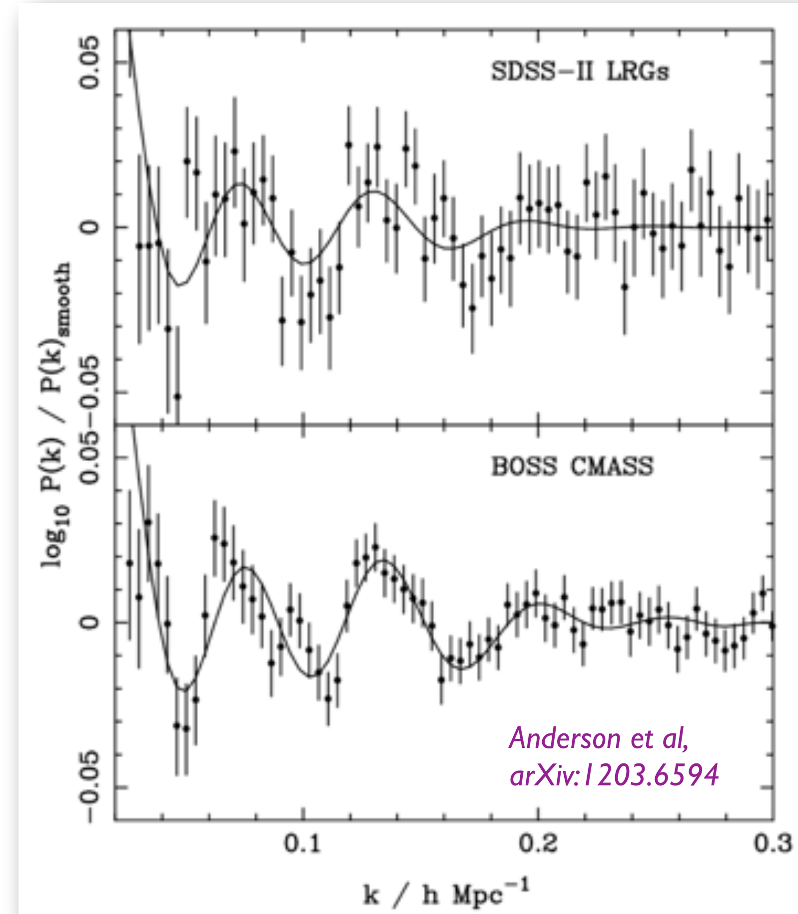
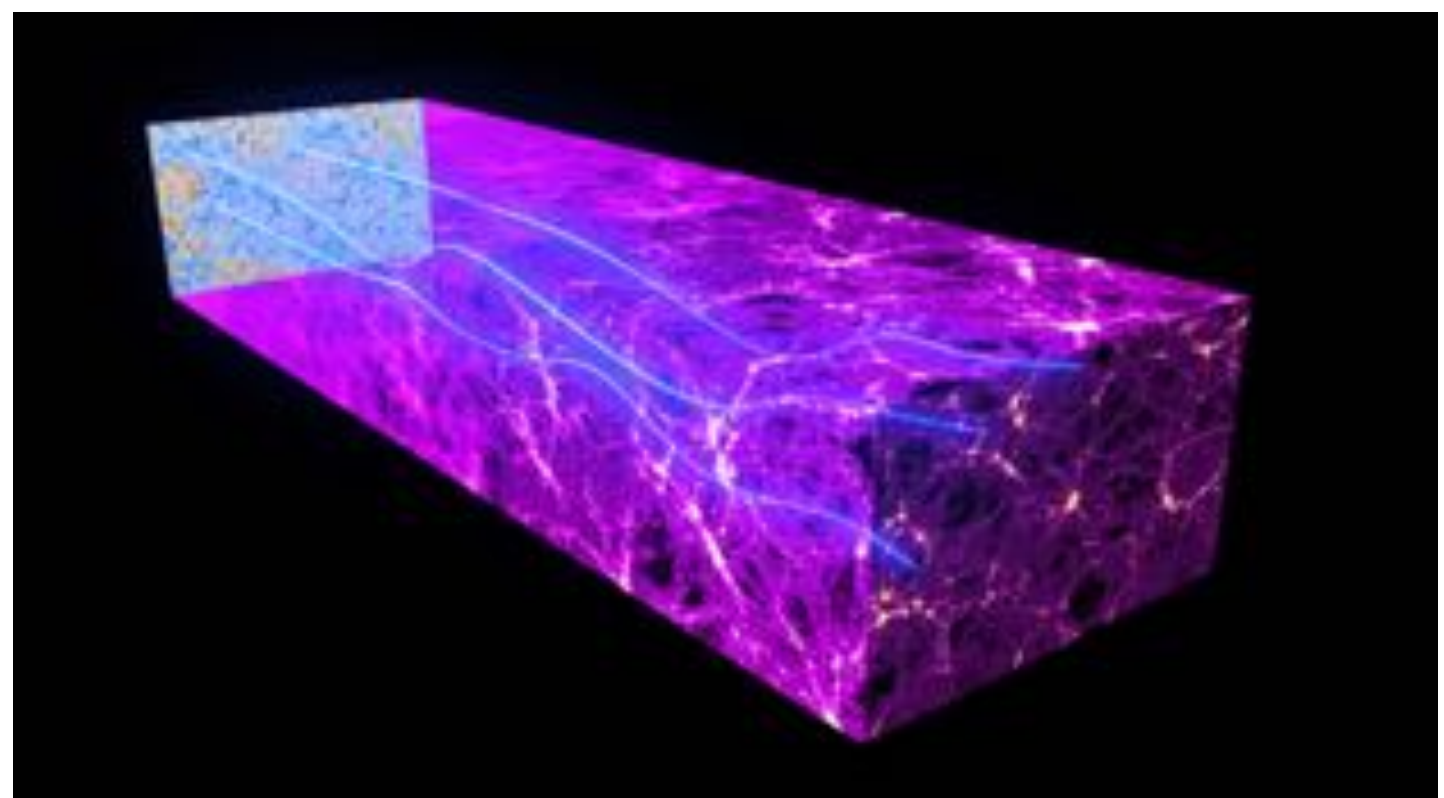


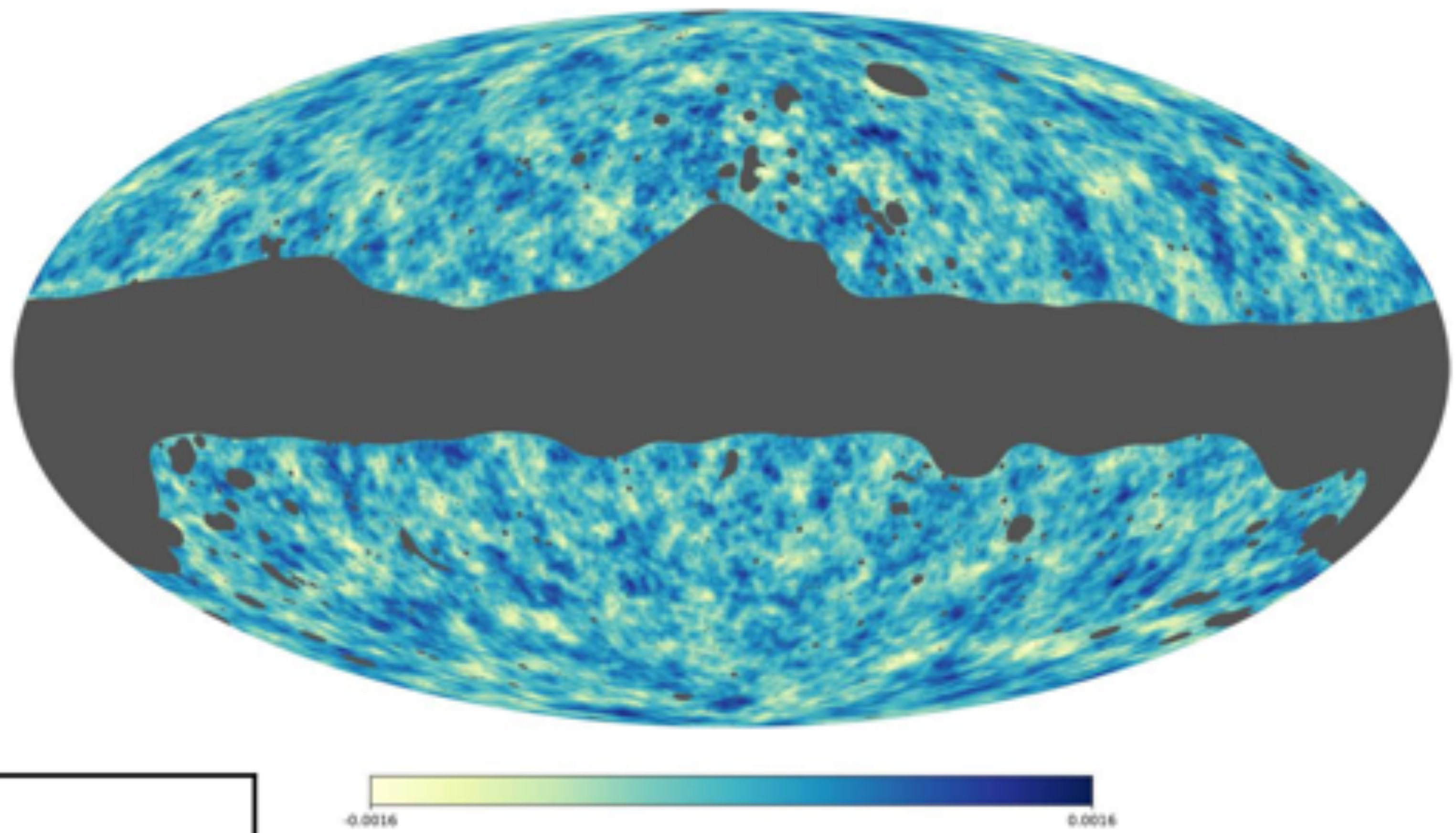


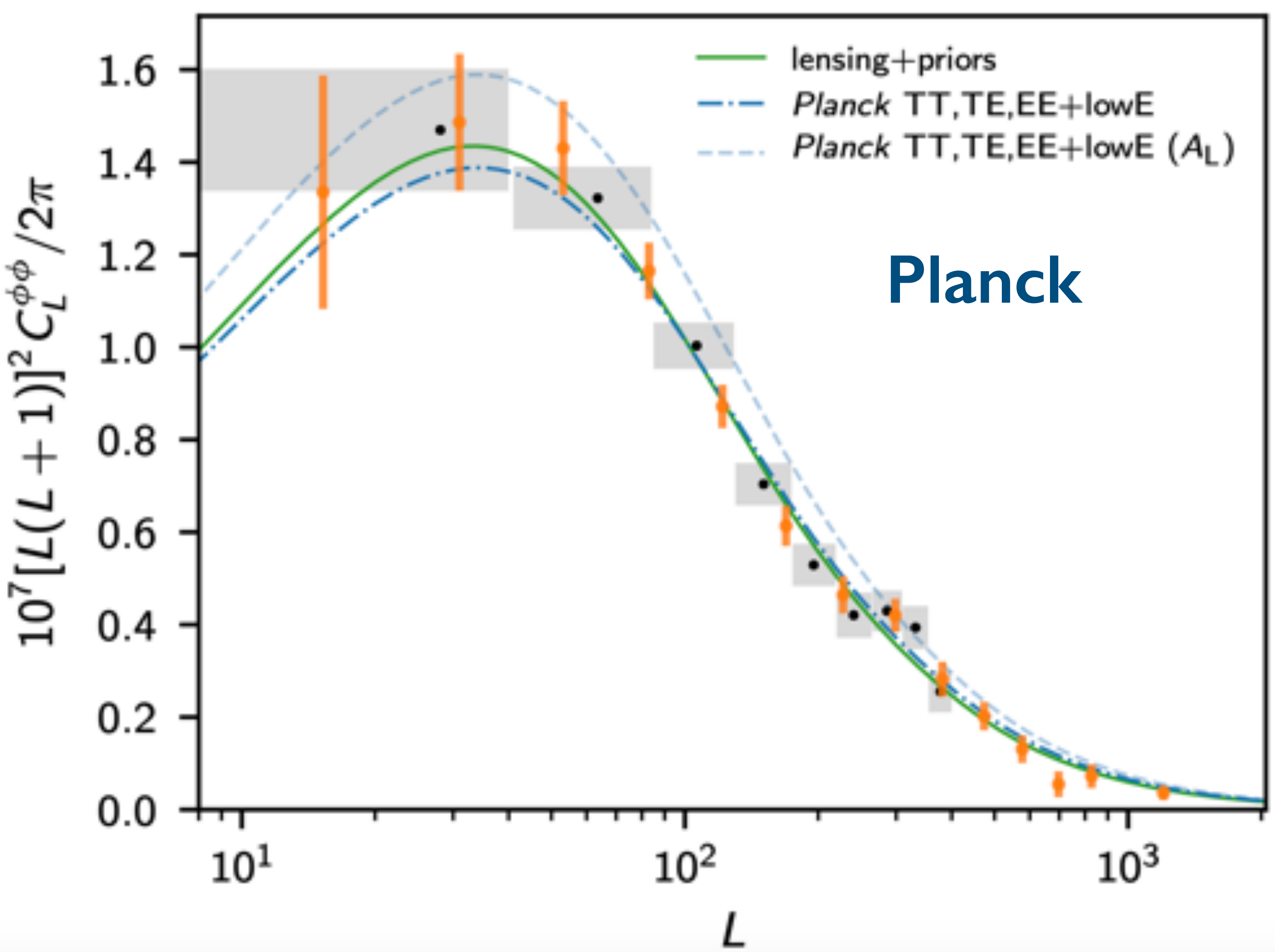
4PCF effects of photons angular maps due to lensing of CMB in intervening matter structures, mostly at low-z



CMB lensing

Reconstructed potential due to intervening matter consistent with inferred predictions based on 2PCF



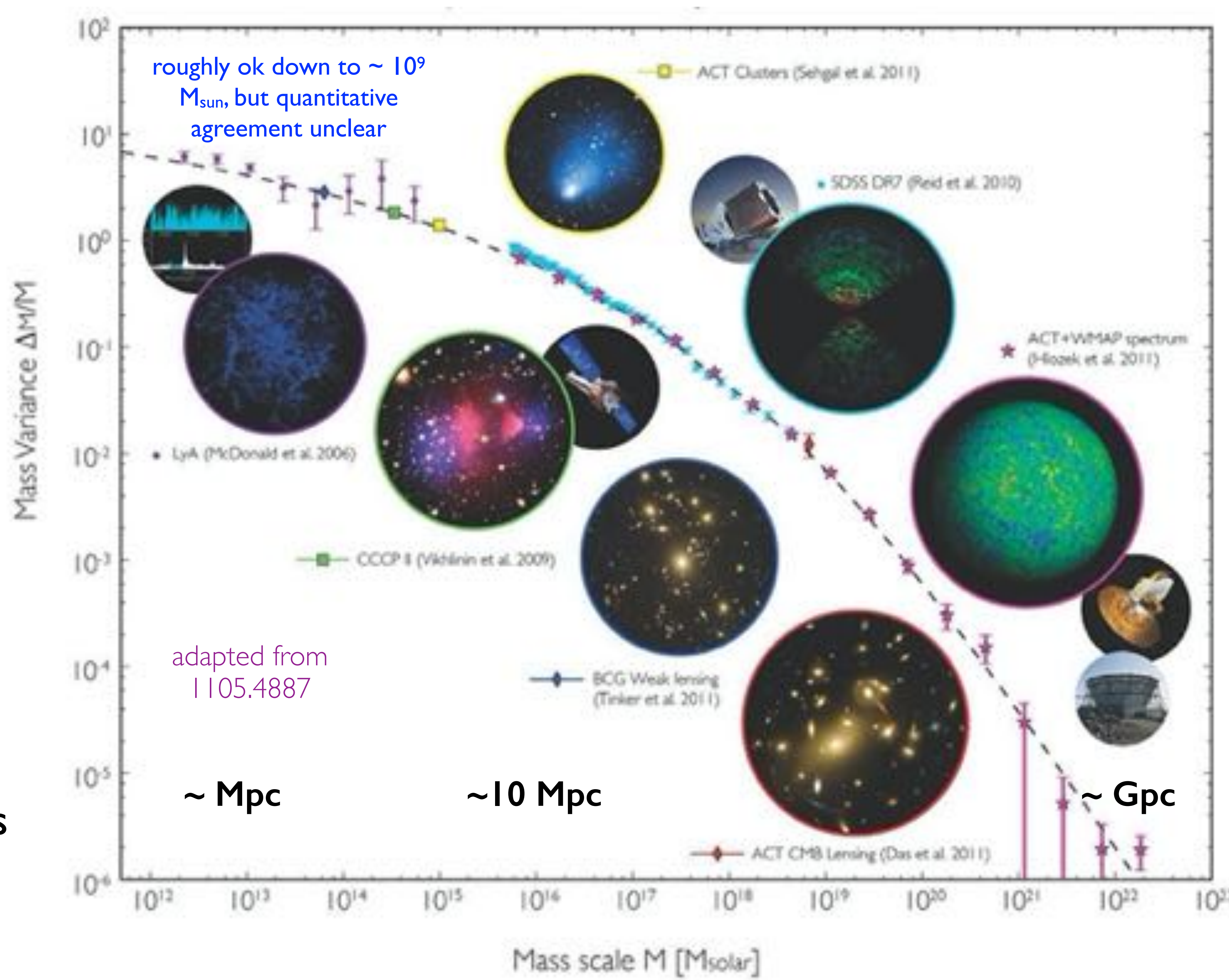


No indication that gravity is failing us…

"Effective" dark matter: What we have discovered

Many spatial scales

Many epochs



DM ~ a fluid

characterised by density only

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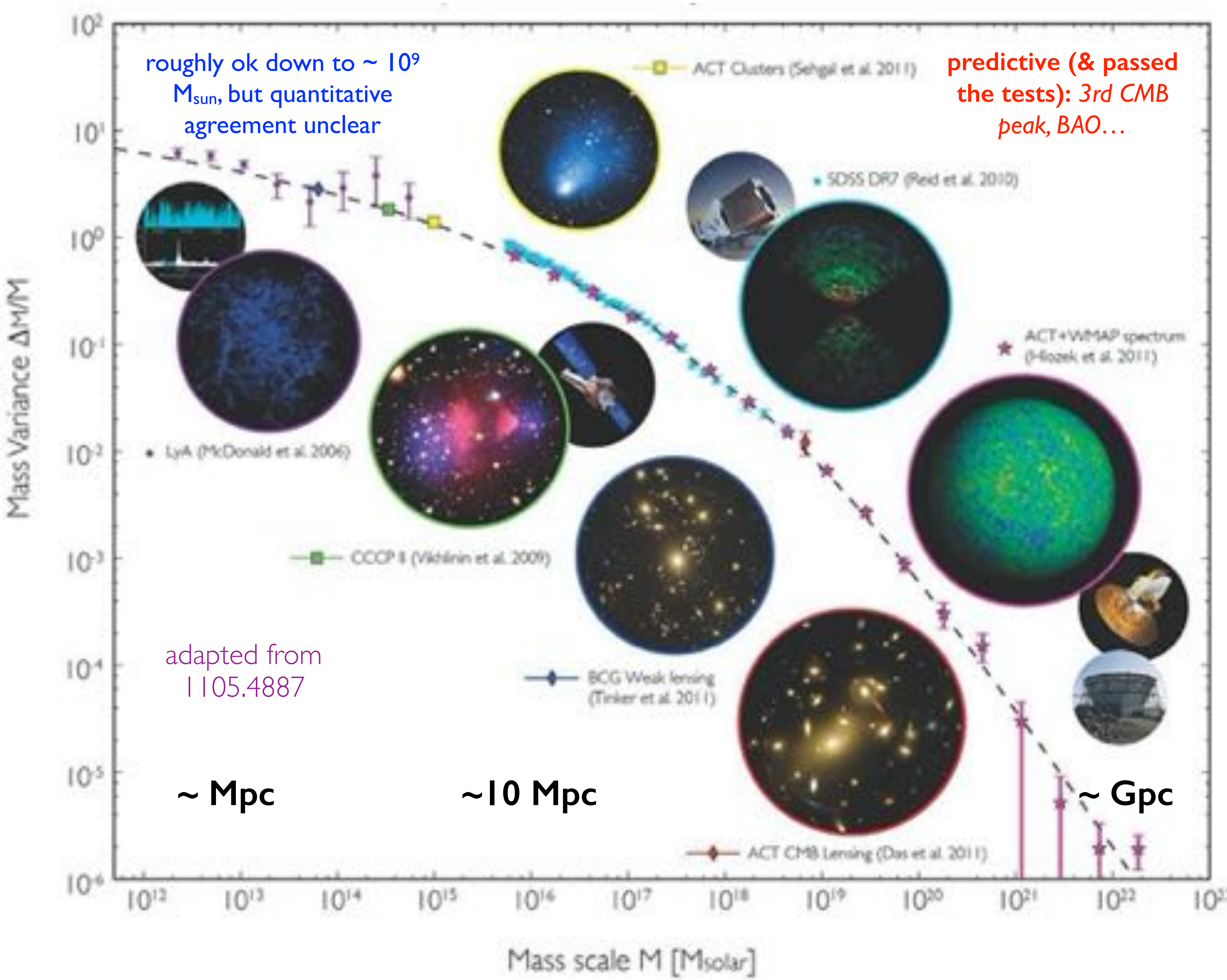

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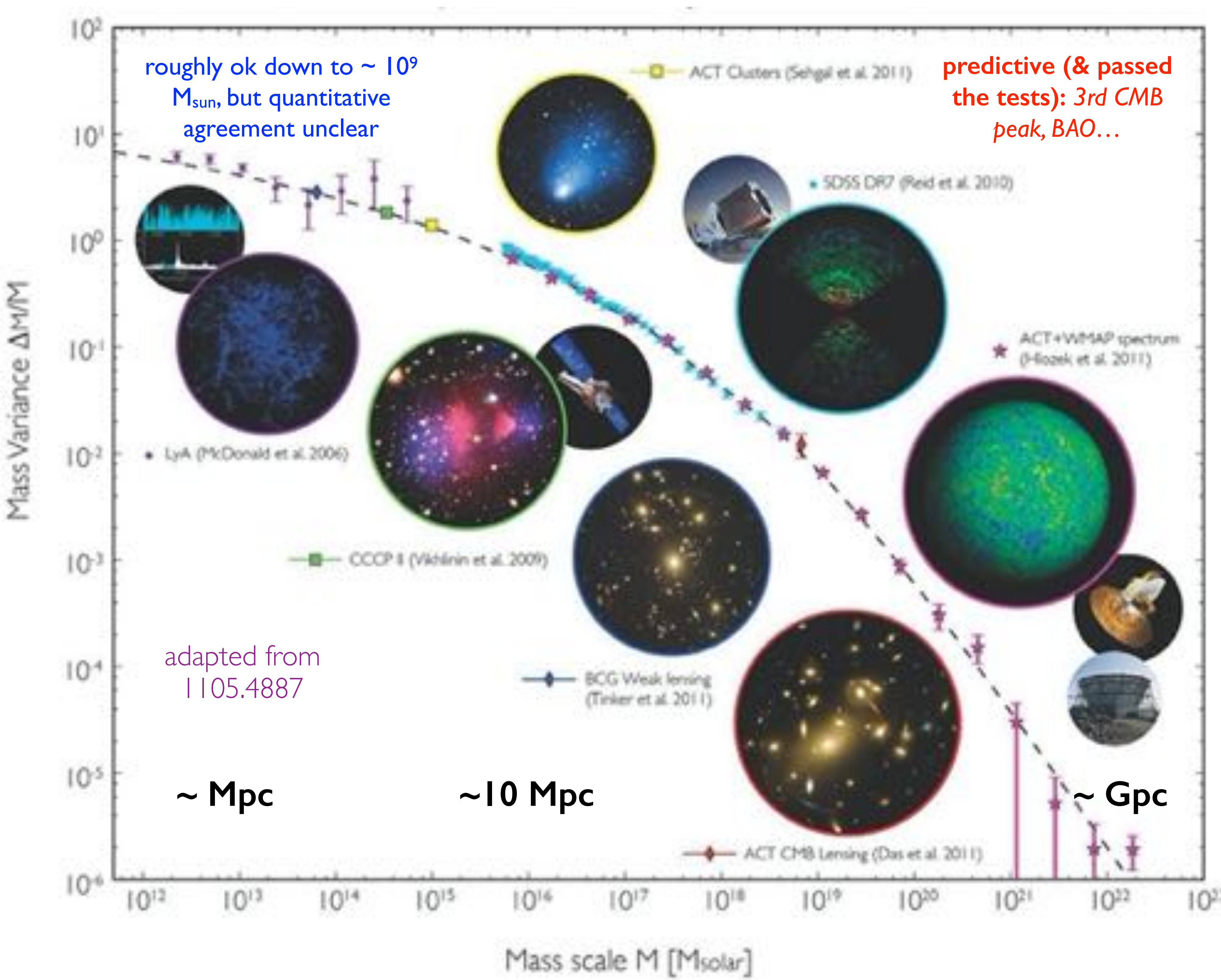

DM ~ a fluid

characterised by density only

At hom. level: No *P*

@ pert. level: No *sound speed nor viscosity*

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G \left(T^{\rm known}_{\mu\nu} + T^{\rm DM}_{\mu\nu} \right) \qquad T^{\rm DM}_{\mu\nu} = \rho^{\rm DM} U_\mu U_\nu$$

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Many spatial scales

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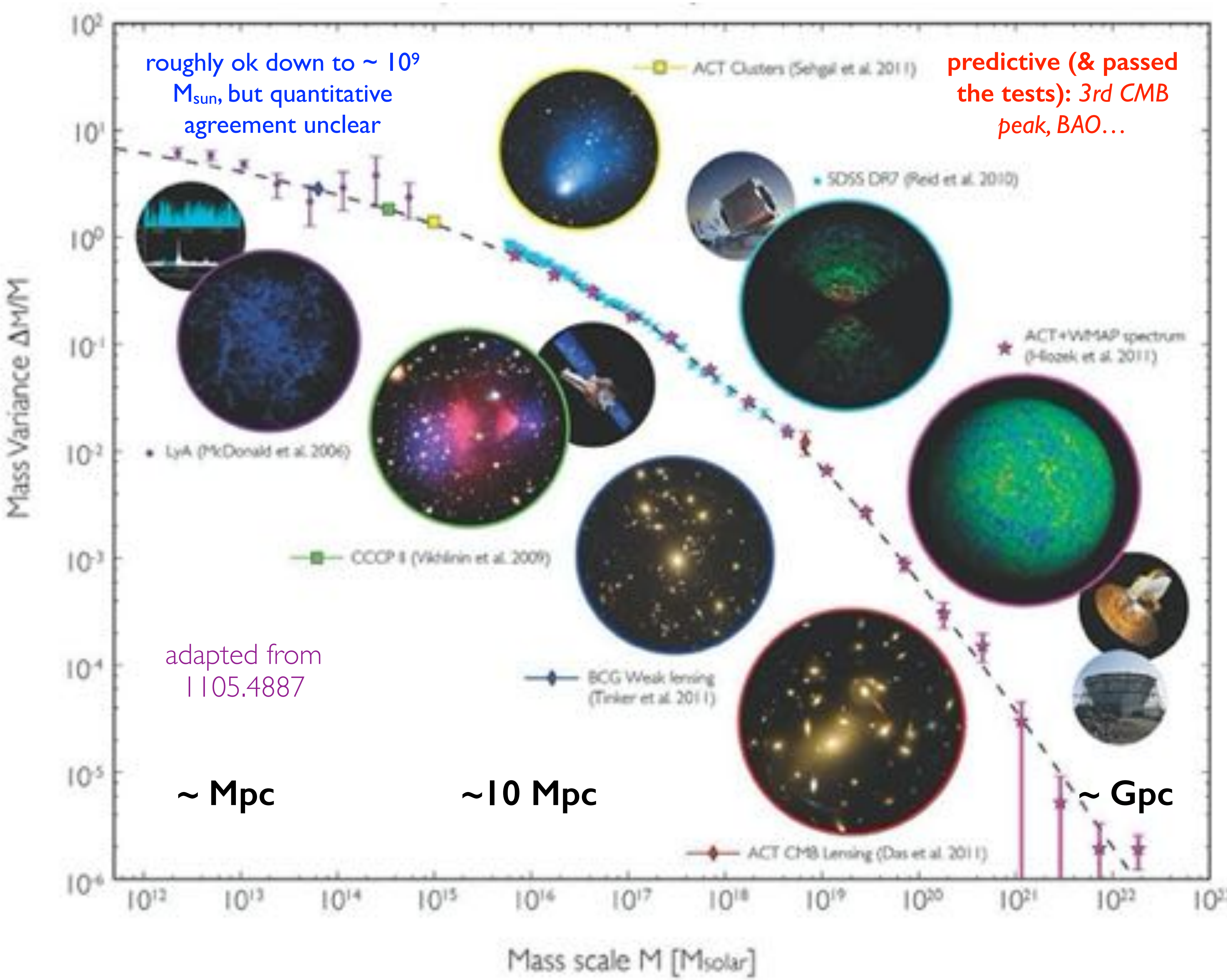

DM ~ a fluid

characterised by density only

At hom. level: No *P*

@ pert. level: No *sound speed nor viscosity*

Would like however to *identify* what it is!

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G \left(T_{\mu\nu}^{\text{known}} + T_{\mu\nu}^{\text{DM}} \right) \qquad T_{\mu\nu}^{\text{DM}} = \rho^{\text{DM}} U_\mu U_\nu$$

...)

End of III.a

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Can we use CR to help us identify its nature?

Intrinsically model-dependent question

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Can we use CR to help us identify its nature?

Intrinsically model-dependent question

The answer is: Potentially Yes, in

b) the most popular framework for DM, WIMPs

‘Traditional’ link DM-particle physics

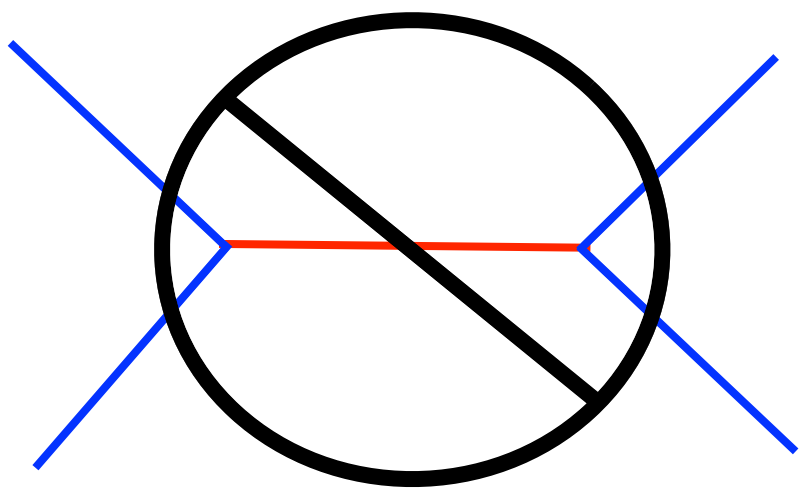
Strong <u>prior for TeV-scale BSM (with SM-like couplings)</u> to cure “the hierarchy problem”:

why is weak scale (notably Higgs mass) insensitive to quantum effects from physics at some much higher energy scale Λ_{UV} (e.g. gravity)?

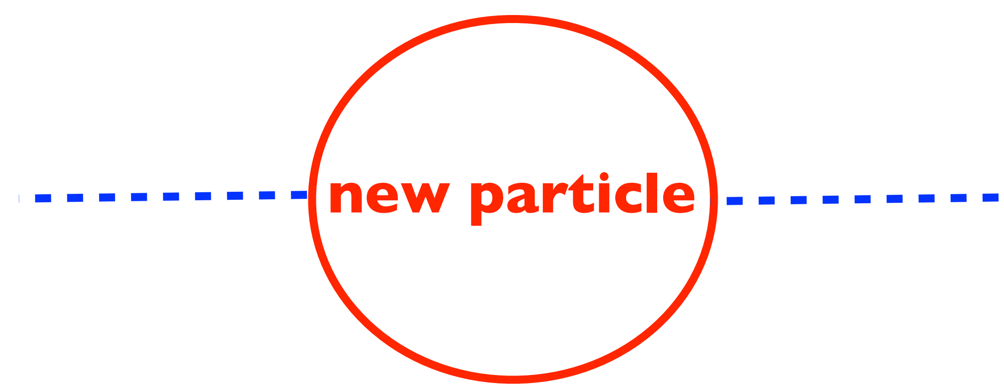
Conjecture: there is some symmetry (e.g. SUSY) @ E~O(TeV), “shielding” low-E pheno from UV.

Precision data suggest that tree-level couplings SM-SM-BSM should be avoided!

we want to avoid!



Ok with it!



One straightforward solution is to impose **some symmetry** (often “parity-like”, relic from some UV-sym): SUSY R-parity, K-parity in ED, T-parity in Little Higgs. New particles only appear in pairs!

➡ Automatically makes **lightest new particle stable!**

➡ It has other benefits, e.g. respect **proton stability** bounds!

The Weakly I nteracting M assive P article Paradigm

Cosmology tells us that the early universe was a hot plasma, with all "thermally allowed" species populated. Notion tested up to T~ few MeV (BBN, cosmo ν's):

What if we extrapolate further backwards, adding to the SM just…

…one ***stable massive particle*** in ***chemical equilibrium with SM*** via ***EW-strength binary interactions*** in early universe down to $T \ll m$ (required for **cold** DM, i.e. non-relativistic distribution function!) ?

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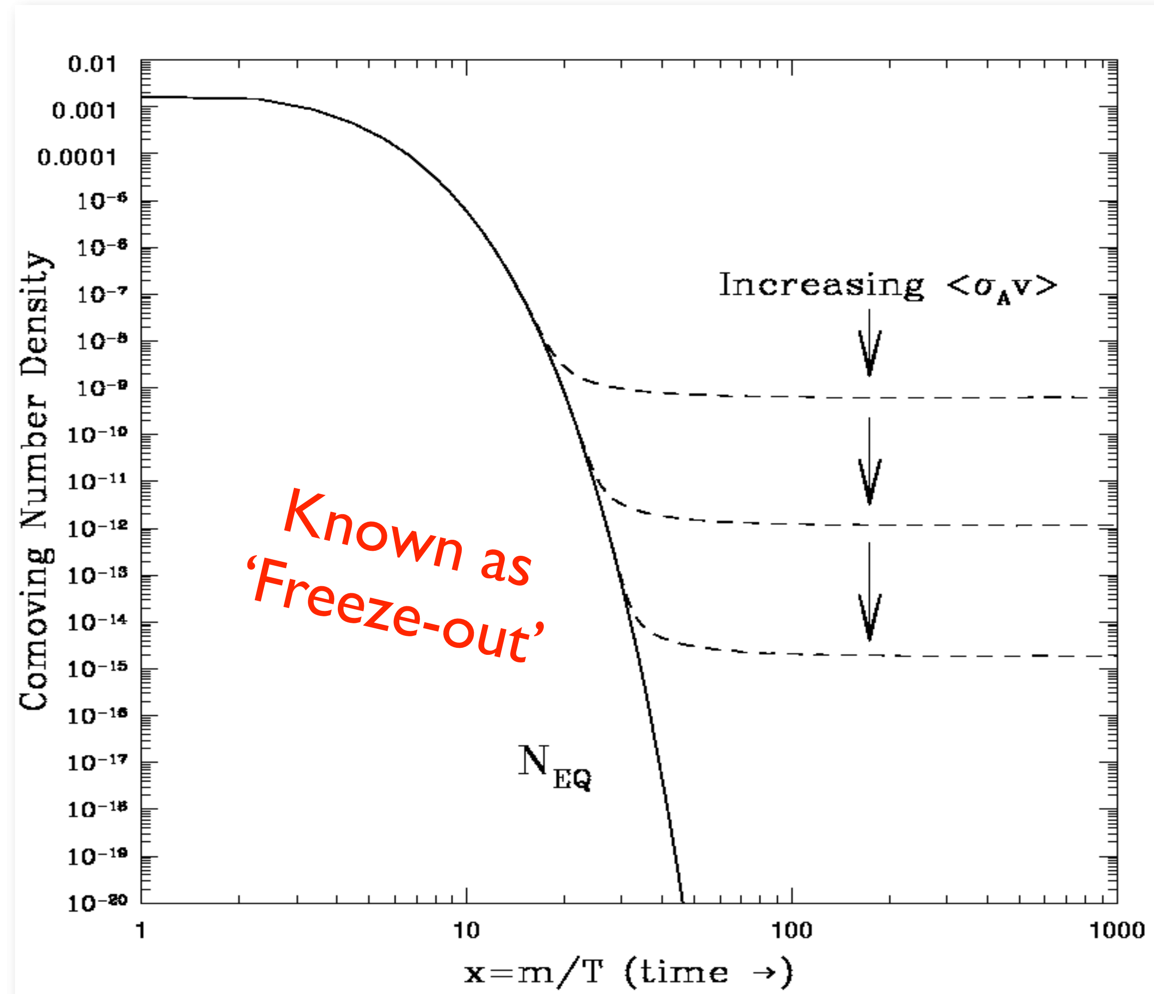


Starts from equilibrium $n=n_{eq}$, eventually its abundance suffers exponential suppression (Non-relat.)
What left depends on when its annihilation rate drops below the Hubble rate:
the stronger the cross section the later, hence the less abundant *X* becomes

Why searching for DM in ‘cosmic rays’?

Rather *expected* within the *WIMP class* of DM particles

a single stable massive particle in chemical equilibrium with SM via EW-strength binary interactions in early universe down to T<<m

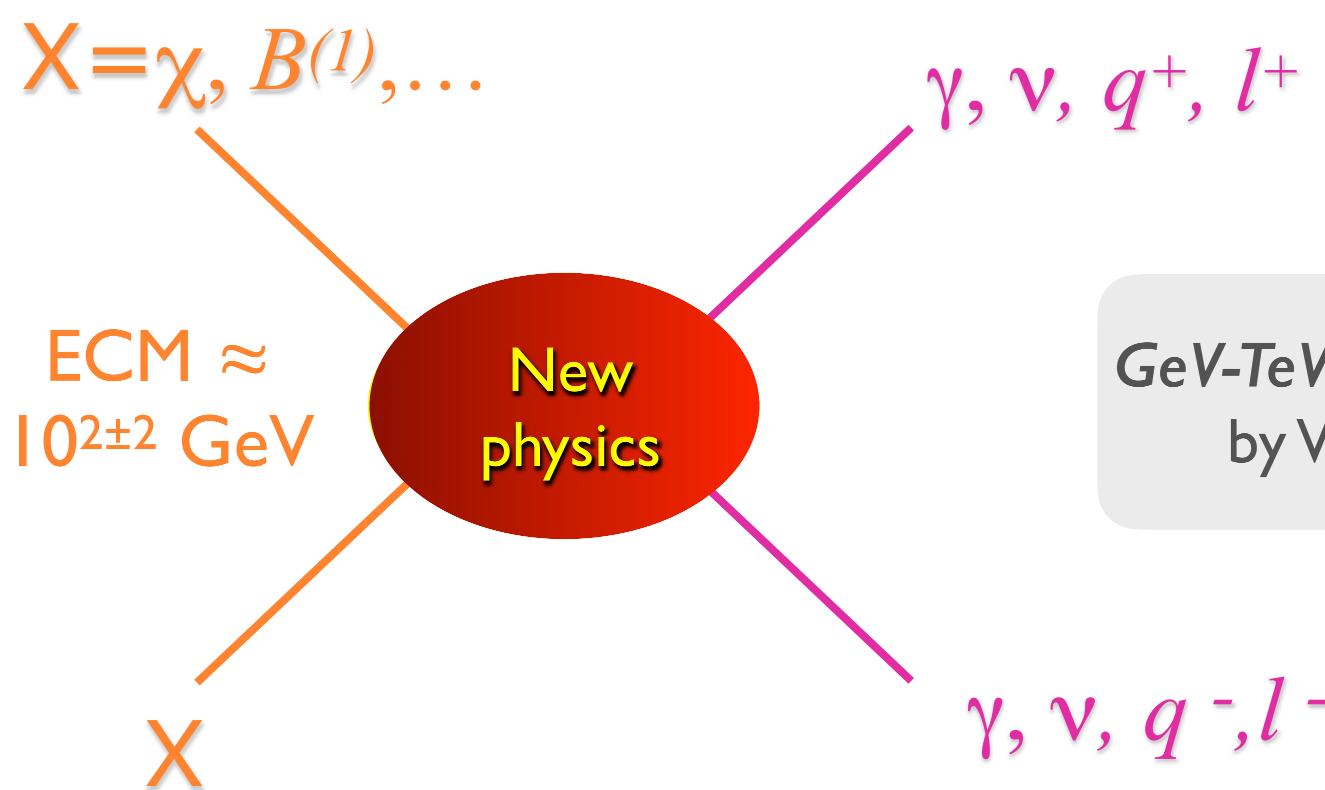
Textbook calculation yields the current average cosmological energy density

$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle\sigma v\rangle}$$

Observationally inferred $\Omega_{DM}h^2$~0.1 recovered for EW scale masses & couplings (aka ***WIMP miracle***)!

$$\langle\sigma v\rangle \sim \frac{\alpha^2}{m^2} \simeq 1\,\mathrm{pb}\left(\frac{200\,\mathrm{GeV}}{m}\right)^2$$

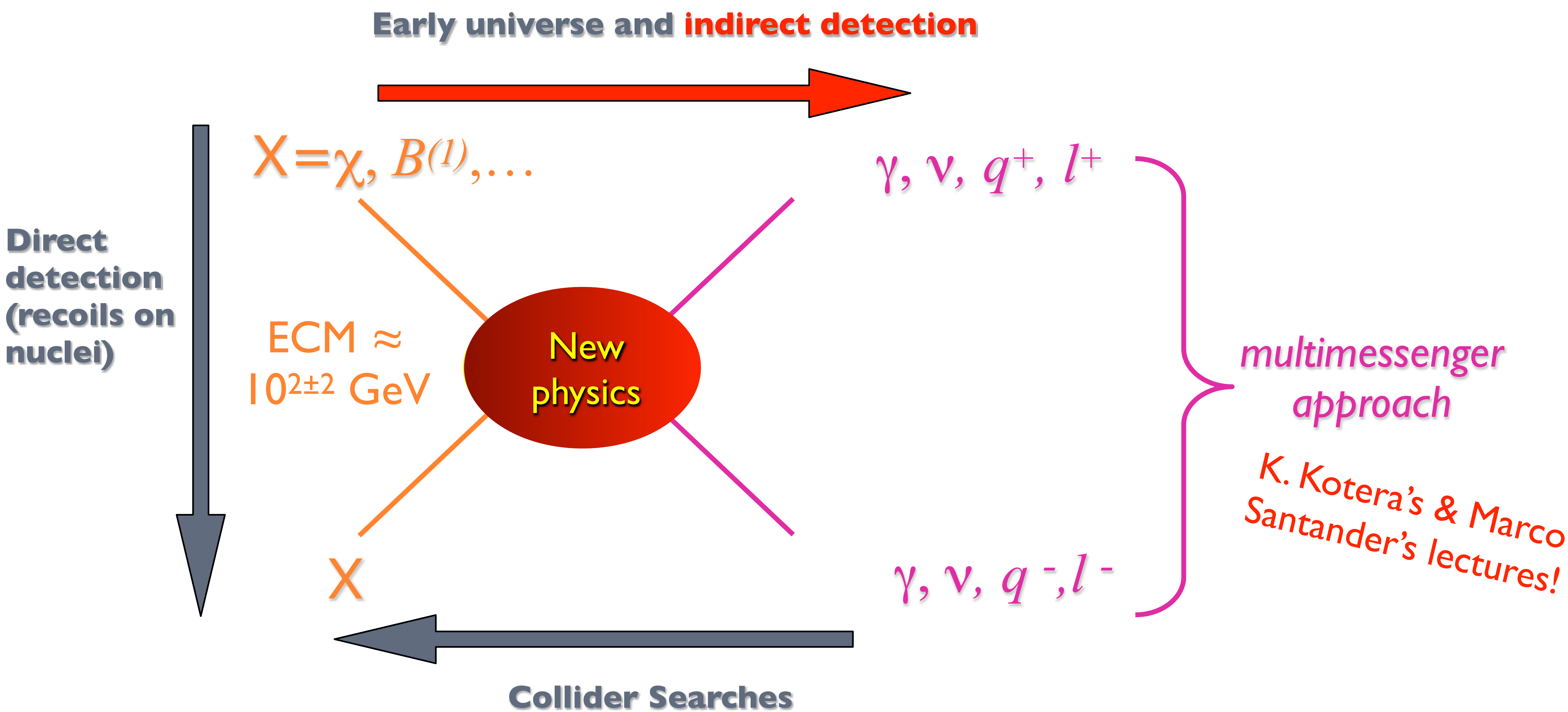
Binary annihilations (relevant in overdense regions) to convert some DM into typically relativistic SM particles



GeV-TeV scale singled-out by WIMP miracle

Indirect WIMP DM searches

look for byproducts of DM annihilations in astrophysical environments (not in the Lab!) where their rate is sufficiently large (e.g. due to high DM density)



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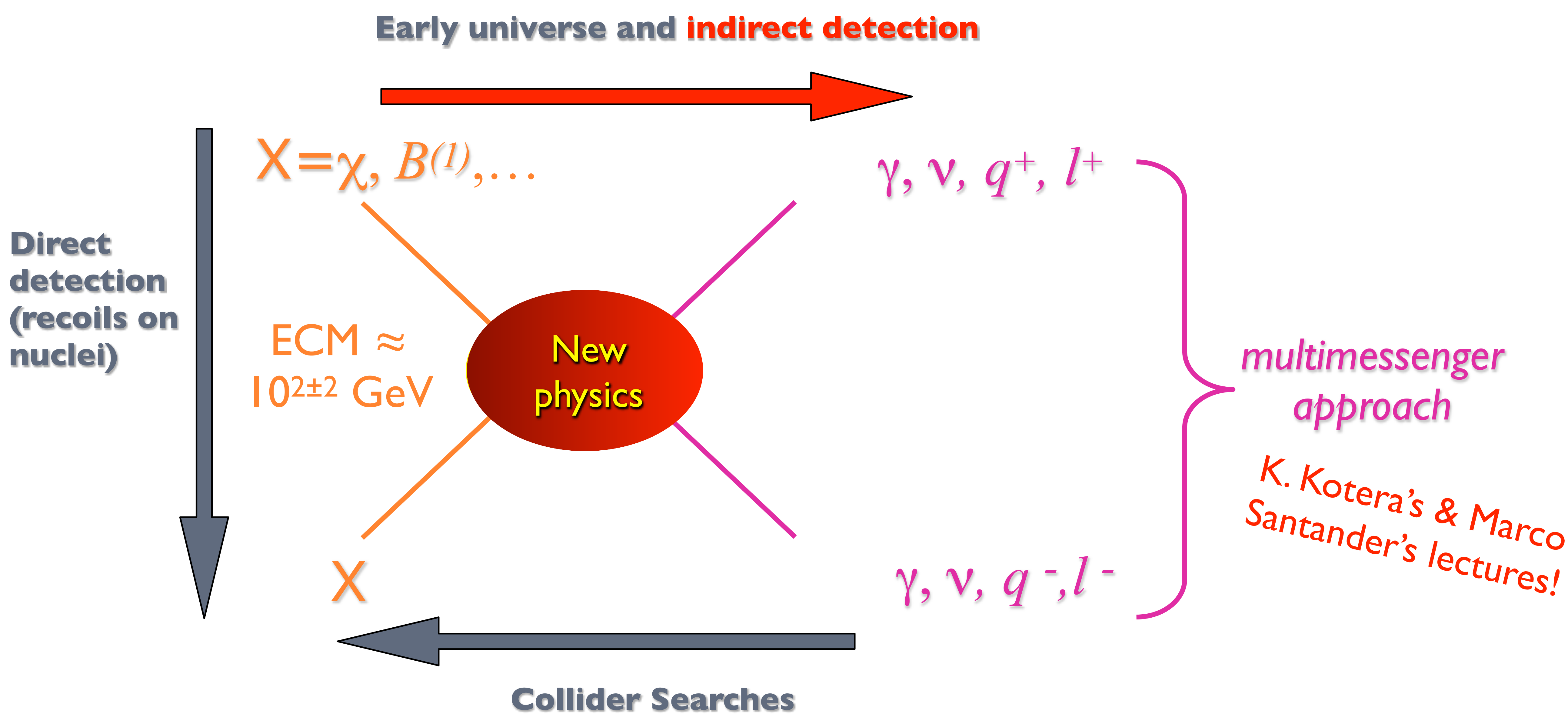

❖ Particle physics dependence: *injected* SM particles depend on the particle physics model.
❖ Astrophysical dependence: Normalisation depends on DM distribution; Fluxes at the Earth can be further affected by propagation effects (E-losses, absorption, diffusion…)

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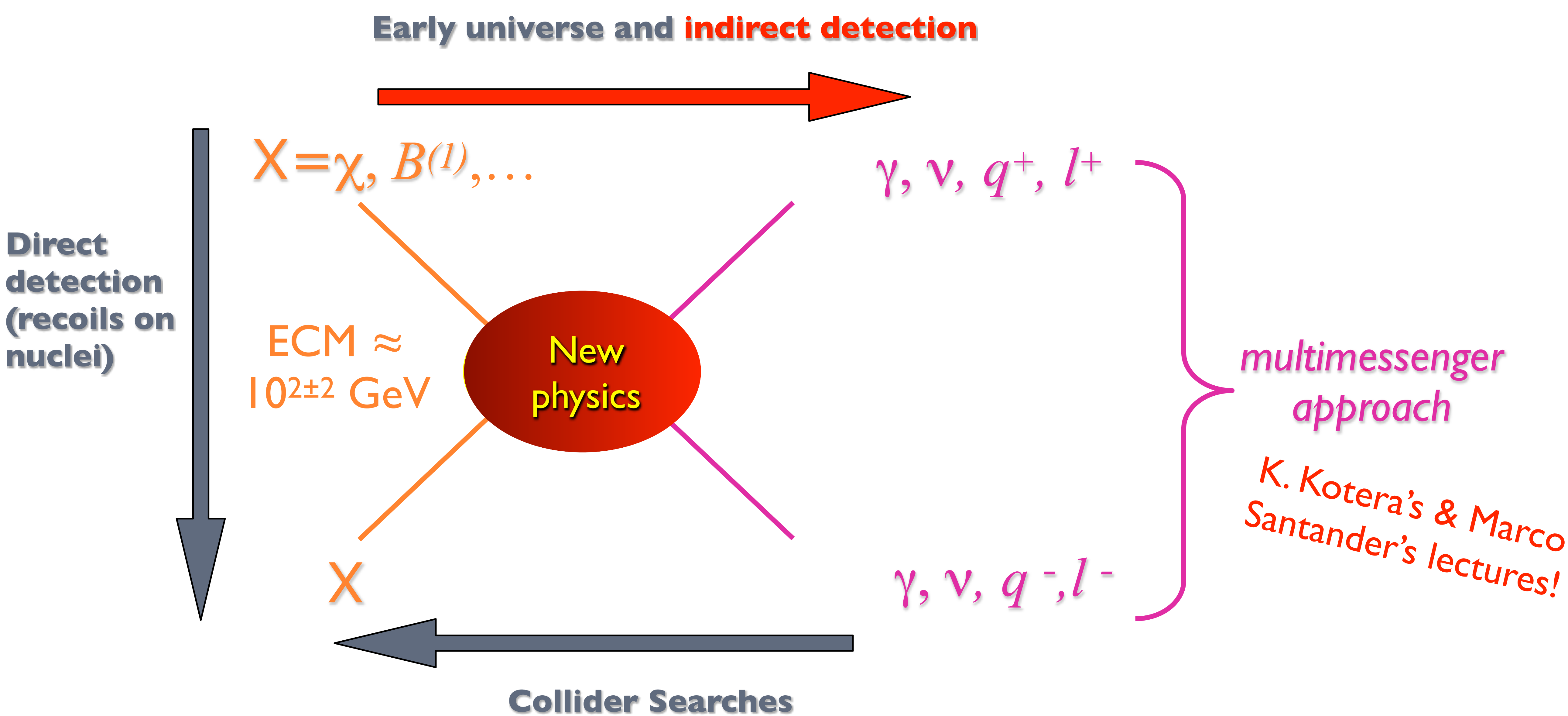

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Need to know:
DM distribution ; competing astrophysical signals ; astro propagation environments

Which particles?

All stable, kinematically accessible SM final states:
protons, nuclei, electrons, γ, ν (and their antiparticles)

γ, ν

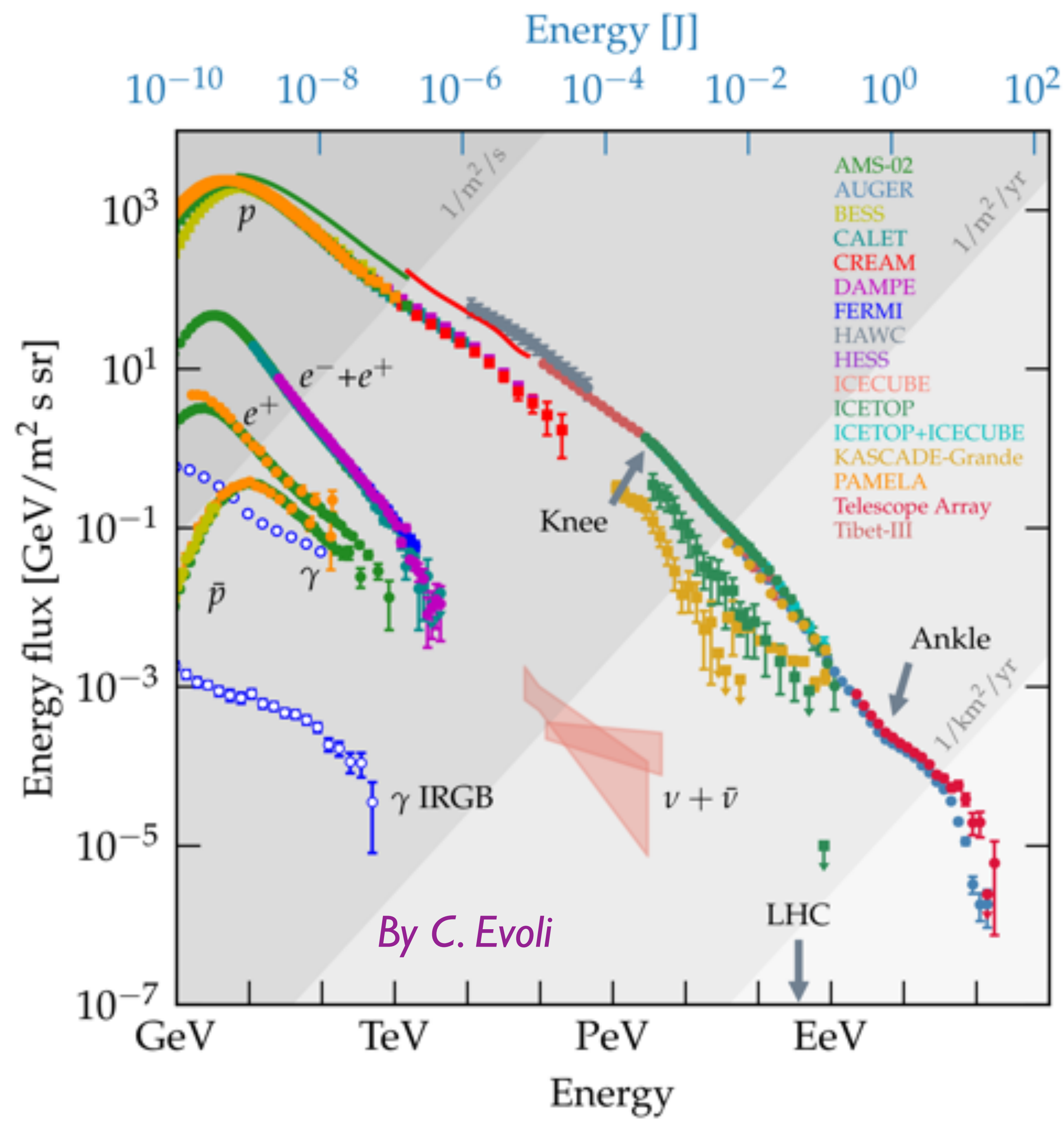
✓ propagate in straight lines, from production to observable fluxes via line-of-sight integration

✗ "Easily" produced in astrophysical processes; hard to detect

protons, nuclei, electrons

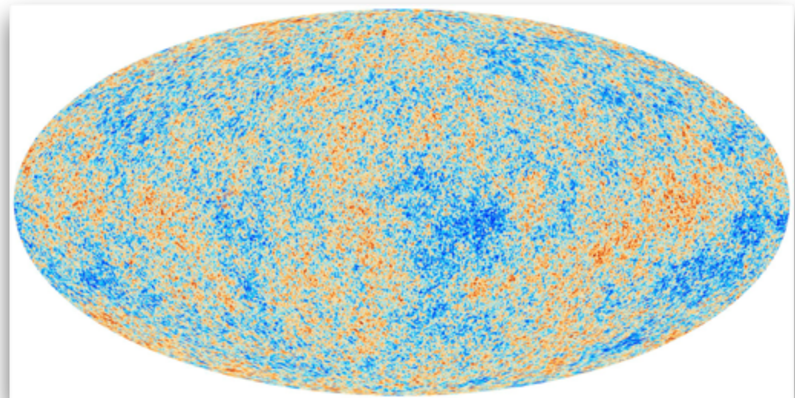
✓ CRs dominated by matter (as opposed to antimatter), 'obvious' background suppression strategy by looking at anti-stuff (DM signal typically expected matter-antimatter symmetric)

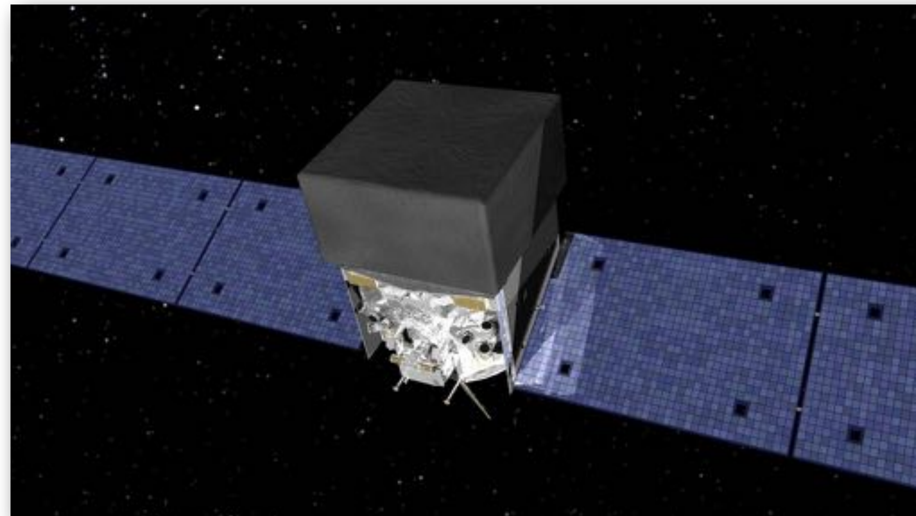
✗ do not propagate in straight lines, sizeable energy-changing processes… harder to compute, both signal and background.

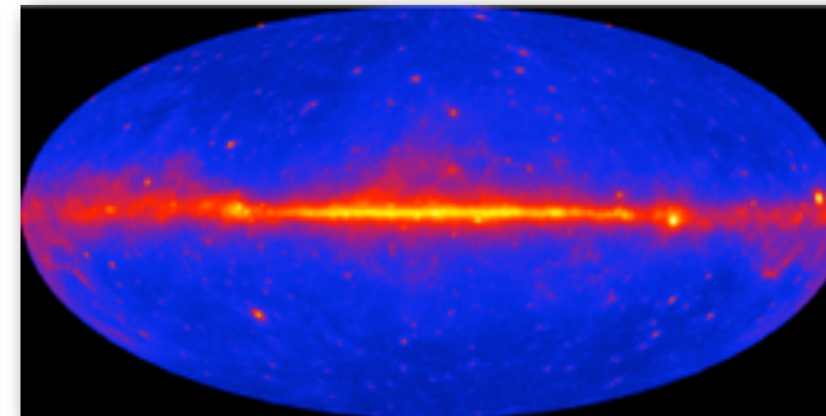


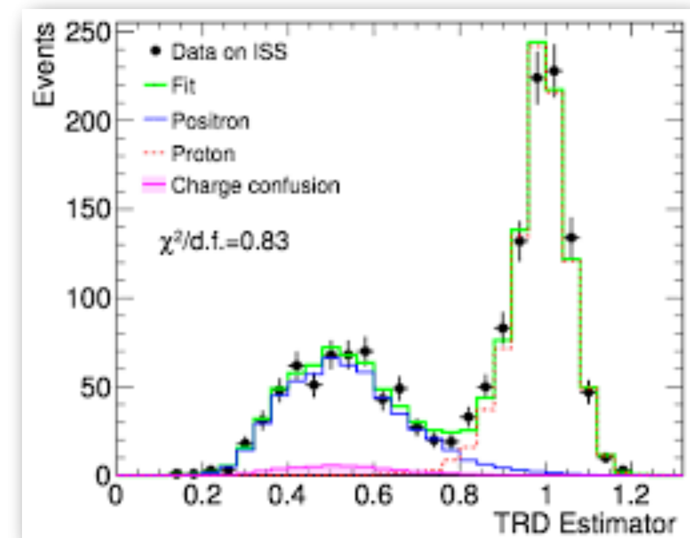
Many channels and approaches

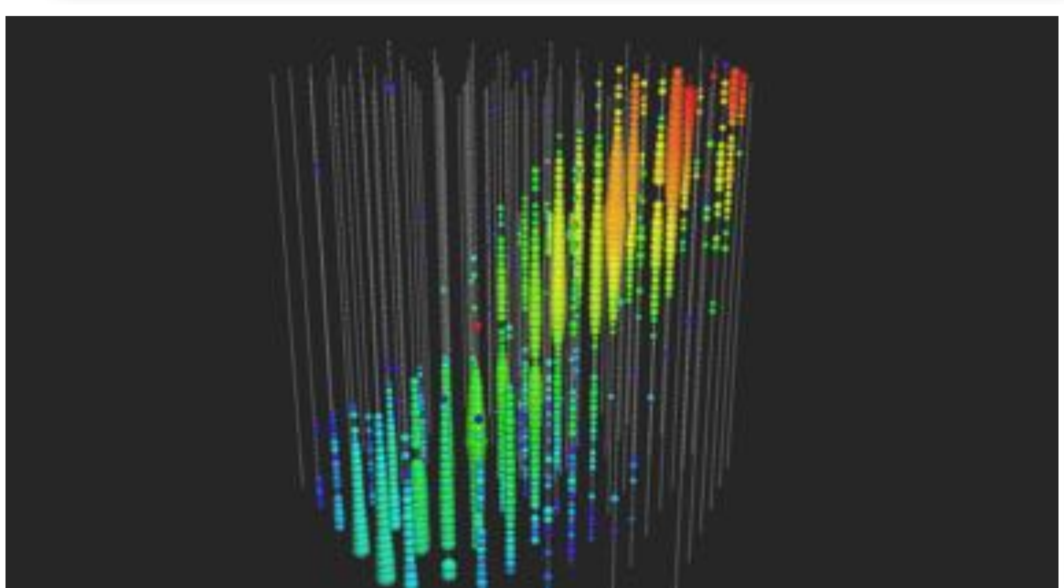
each one with advantages and problems, will review a few











Generalities on the source term

Number of particles of type *i* per unit energy *E* per unit volume per unit time injected at position *x* at time *t* (via s-wave annihilations)

$$Q_i(\mathbf{x}, t, E) = \frac{dN_i}{dE}(E)\, n_X(\mathbf{x}, t) n_{\bar{X}}(\mathbf{x}, t) \langle \sigma v \rangle$$

If interested 'per unit solid angle', further divide the above by 4π

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On the cross-section

In the primordial universe, thermal relic:

$$\langle\sigma v\rangle = \frac{\int \sigma v dn_1^{\rm eq} dn_2^{\rm eq}}{\int dn_1^{\rm eq} dn_2^{\rm eq}} = \frac{\int \sigma v e^{-E_1/T} e^{-E_2/T} d^3p_1 d^3p_2}{\int e^{-E_1/T} e^{-E_2/T} d^3p_1 d^3p_2} \overset{NR}{\rightarrow} a + \frac{3}{2} b \left(\frac{T}{m}\right) + \dots$$

In the current universe

$$\langle\sigma v\rangle \overset{NR}{\rightarrow} a + \mathcal{O}\left(\frac{\langle v^2\rangle}{m}\right)$$

s-wave relic means that the a-term dominates in the nonrel. expansion

Including astrophysical sources

Particle model fixes x-sec, spectrum, mass, self-conjugated nature or not…

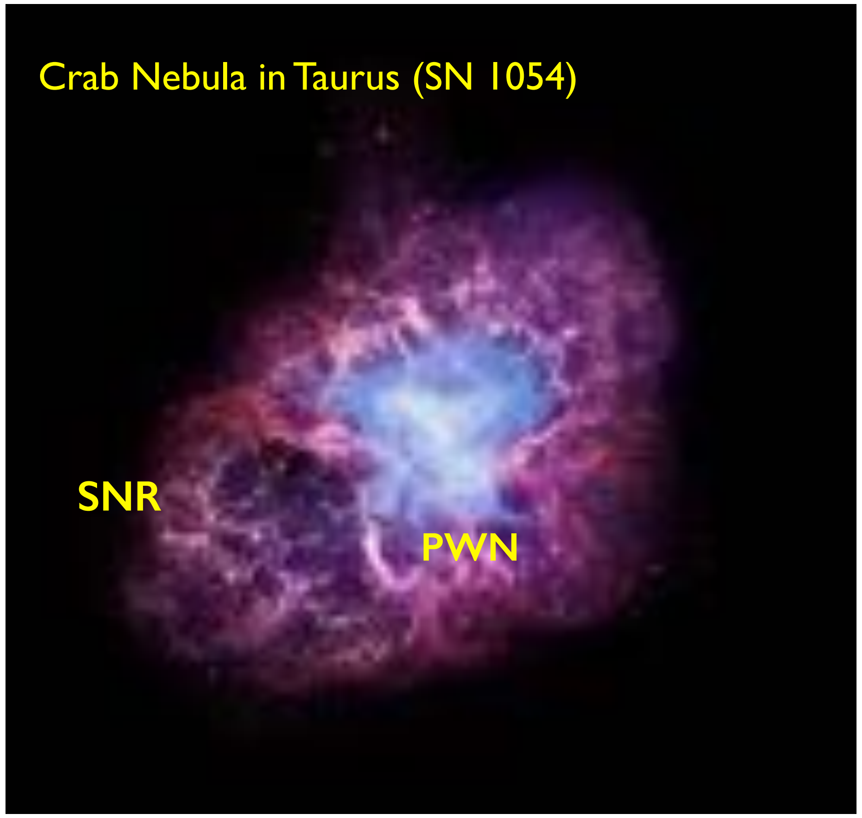
$$Q_{\rm DM}(E,\mathbf{x})$$

Density of DM
Resort to simulations with free parameters fitted to astro data
Can conservatively ignore substructure, or use models

Add a model for **astro** sources (different spectra!)

$$Q_{\rm tot}(E,\mathbf{x}) = Q_{\rm astro}(E,\mathbf{x}) + Q_{\rm DM}(E,\mathbf{x})$$

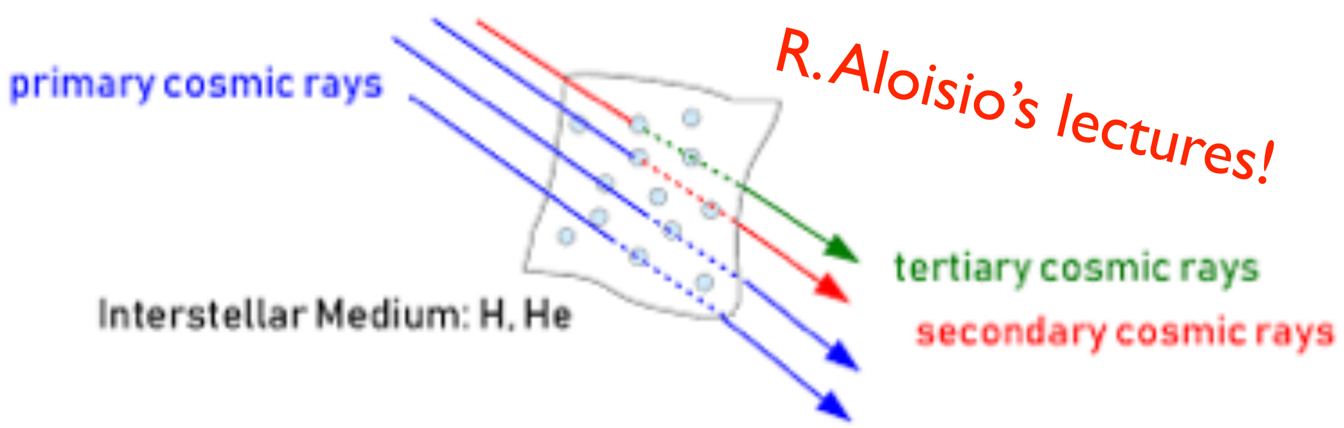
Primary sources *acceleration at SNRs, Pulsar wind nebulae…*



+ some hypotheses (e.g. often continuum injection limit in time and space…)

Secondary sources

Byproducts of collisions in the ISM



Photons

Marco Tavani's and Karl Kosack's lectures

☺ Retain directionality (angular info!)

☺ Relatively easy to detect *in space*
(potentially high statistics)

☹ A lot of backgrounds (known and unknown)

From sources to the observable fluxes

For particles propagating in straight lines, flux (number of particles per unit time, energy, surface and solid angle) obtained as l.o.s. integration

$$\frac{\mathrm{d}\Phi_i}{\mathrm{d}E}(E,b,l) = \frac{1}{4\pi}\int_0^{\infty} Q_i(\mathbf{x},t,E)\, e^{-\tau(E,s,b,l)}\,\mathrm{d}s$$

Possible absorption

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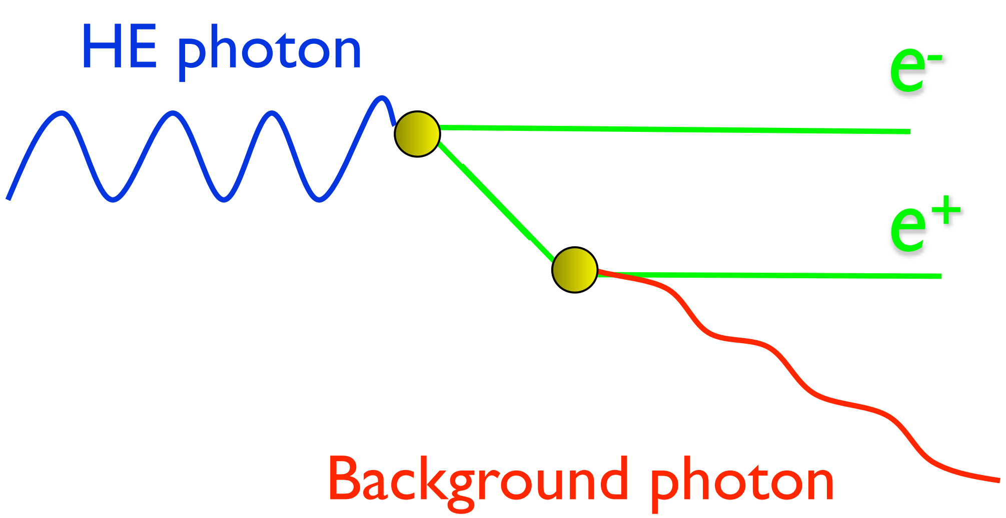
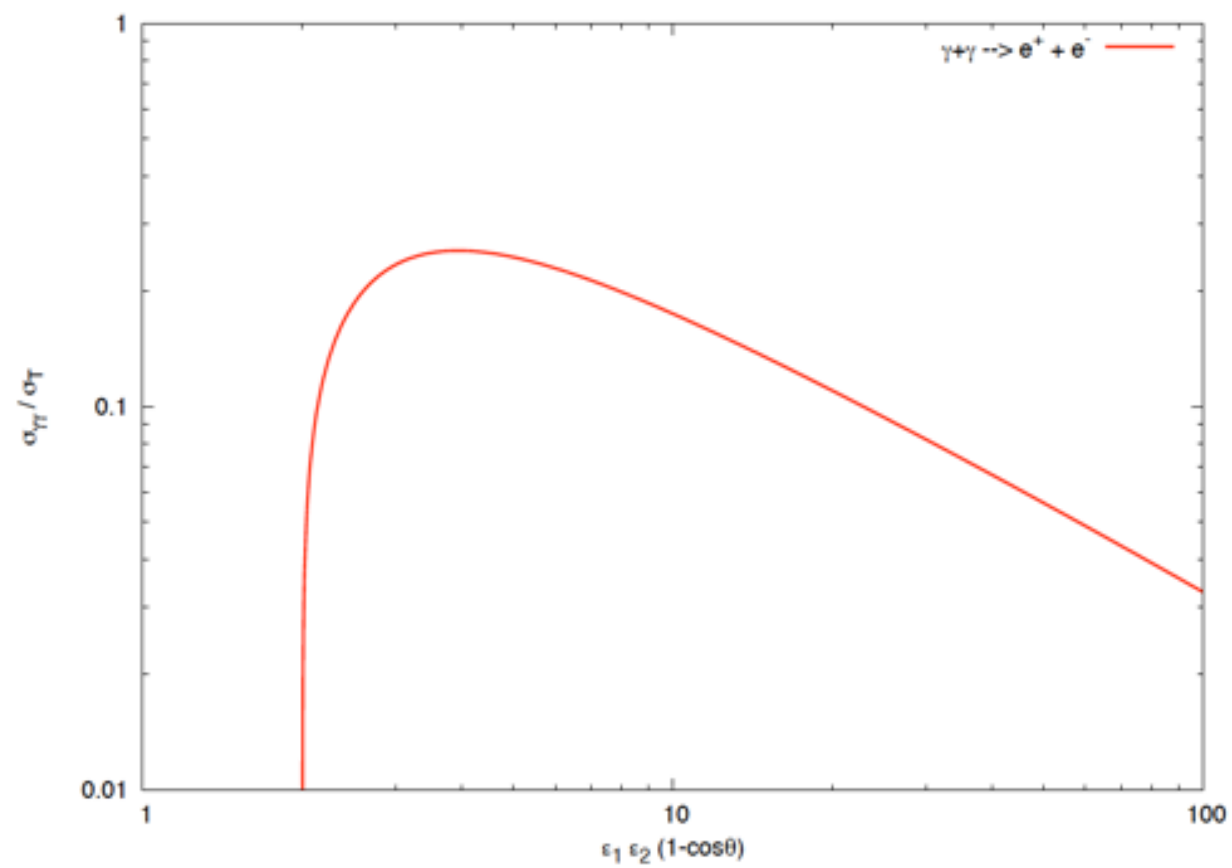
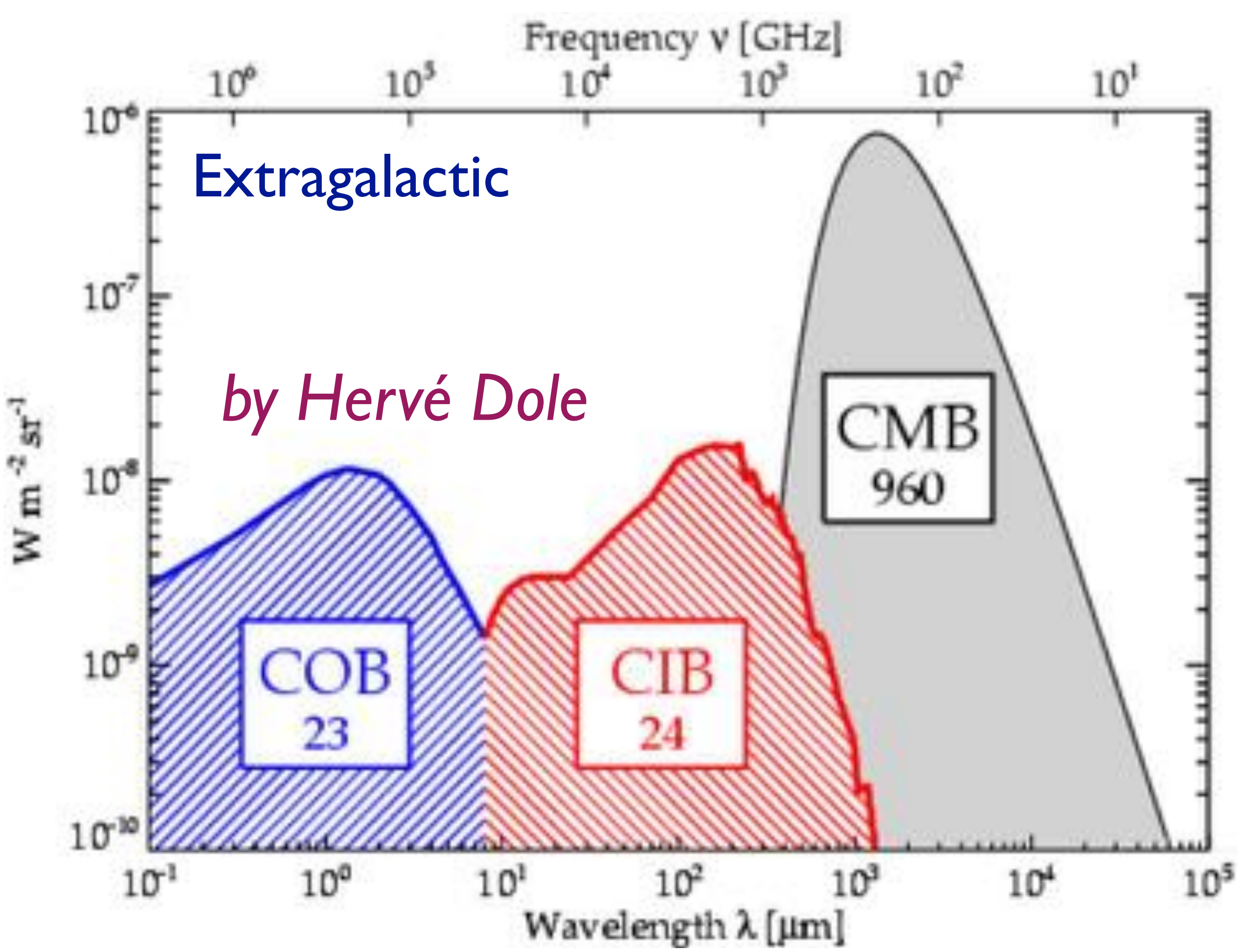
Possible absorption

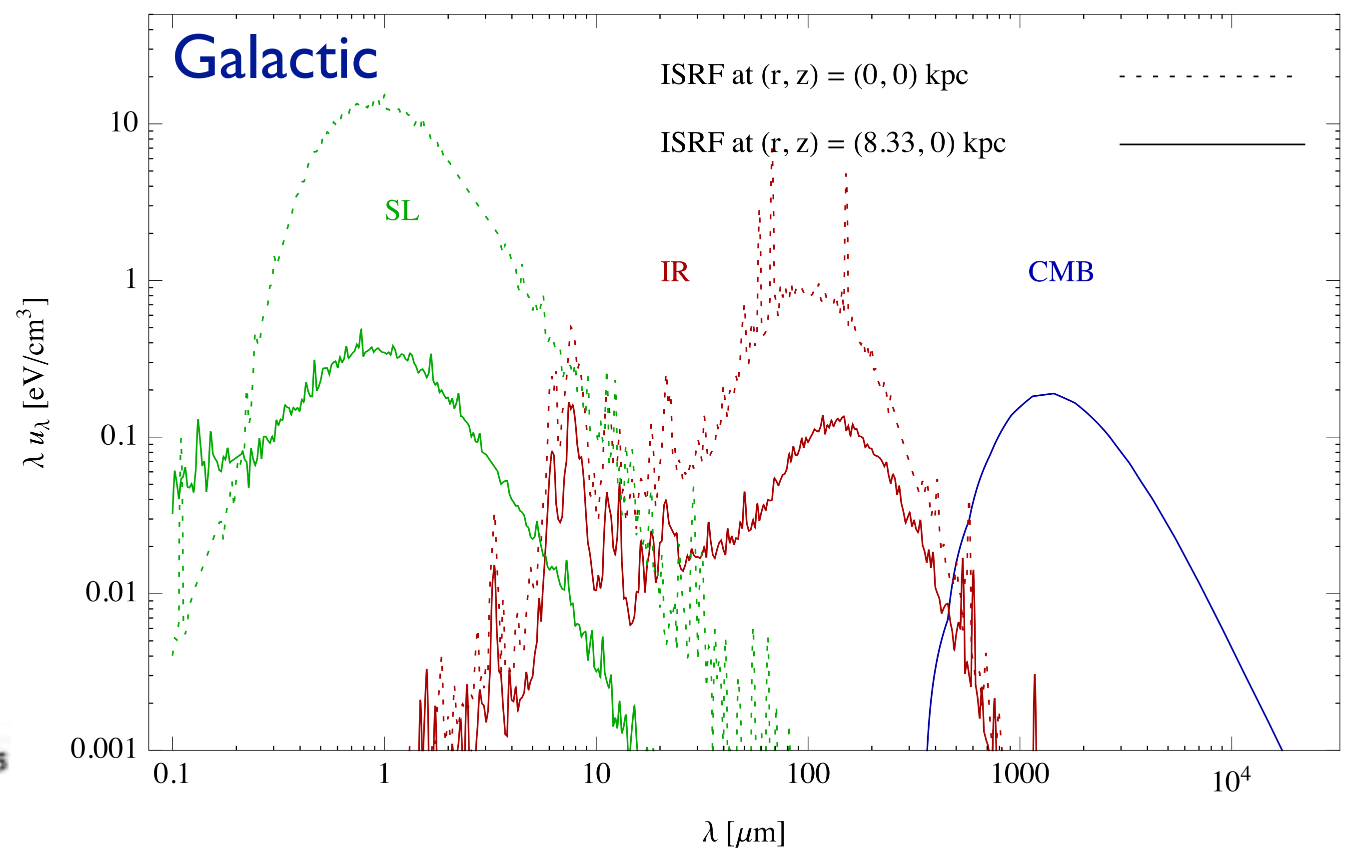
$$\tau\left(E,z,\hat{\Omega}\right) = \int_0^z \mathrm{d}z' \frac{\mathrm{d}s}{\mathrm{d}z'} \int_{-1}^{1} \mathrm{d}\cos\theta \frac{(1-\cos\theta)}{2} \int_{E_{\mathrm{thr}}}^{\infty} \mathrm{d}\epsilon\, n\left(\epsilon,z',\hat{\Omega},s\right) \sigma_{\gamma\gamma}\left(E(1+z'),\epsilon,\theta\right)$$





Background photon distributions





Exercise

Use the fact that $s=(p+k)^2$ is conserved to deduce the threshold energy for pair-production of a HE photon onto a background one

Compute the energy of background photons ***at threshold*** for pair-production for incoming photons of 1 TeV or 1 PeV energy. What type of “light” are these bands corresponding to? In the case of CMB, described by a blackbody spectrum at 2.7 K, compute the mean-free path of a photon of typical PeV energies, assuming a x-sec of 0.1 b.

For prompt source only & neglecting absorption

Ok for most of gamma-ray band between ~GeV and ~TeV

$$\frac{\mathrm{d}\Phi_i}{\mathrm{d}E}(E,b,l) = \frac{\langle\sigma v\rangle \rho_\odot^2\, R_\odot}{8\pi\, m_{\rm DM}^2}\frac{\mathrm{d}N_i}{\mathrm{d}E}(E) J_{\rm ann}(l,b)$$

In terms of a (here, dimensionless) J-factor, depending on DM distribution

$$J_{\rm ann}(l,b) \equiv \int_0^\infty \frac{\rho_{\rm DM}^2(s,b,l)}{\rho_\odot^2}\,\frac{\mathrm{d}s}{R_\odot}\,.$$

At the basis of a factorisation used e.g. in gamma-ray searches

Astrophysical factor: Where to look?

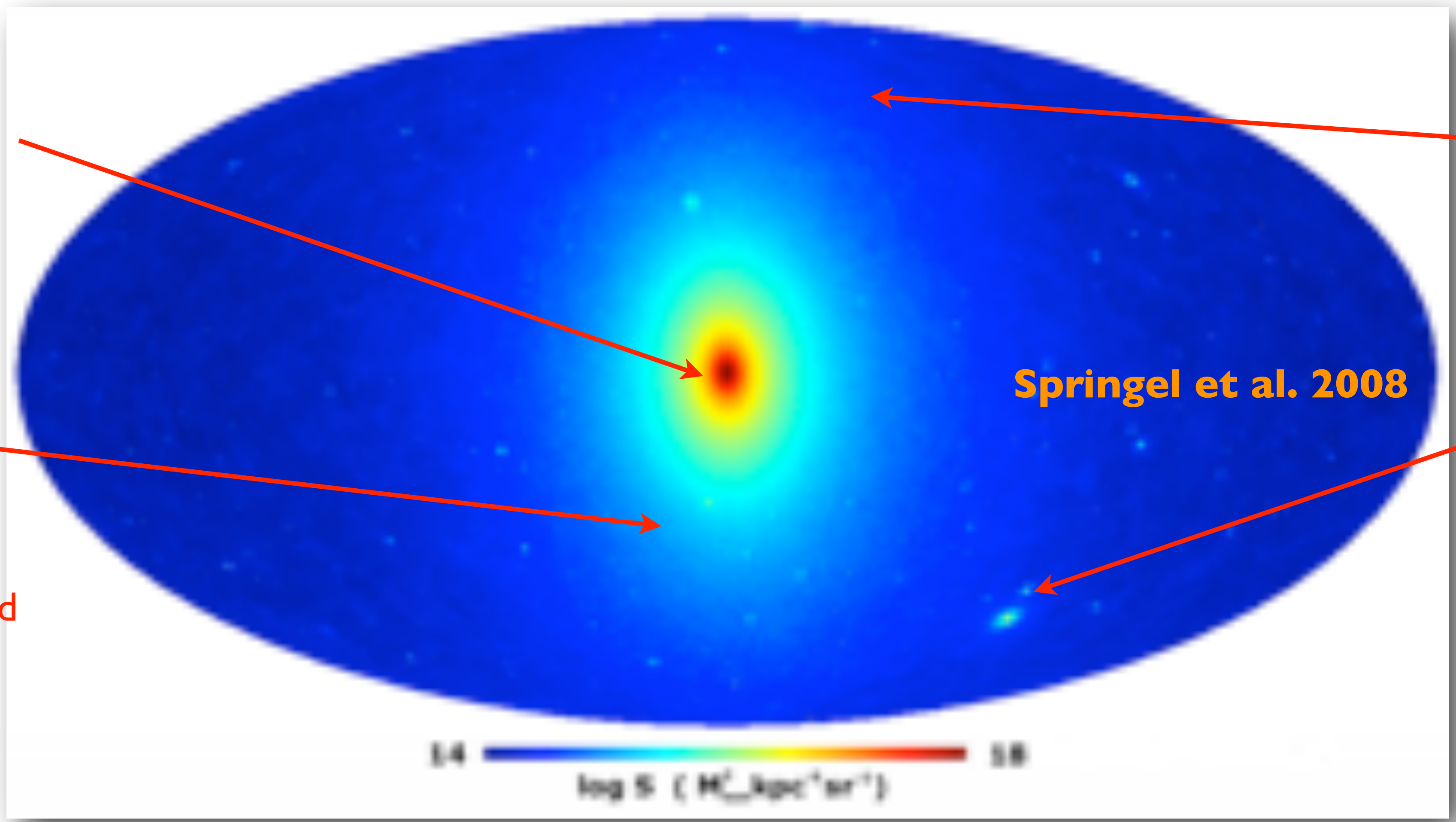
Annihilation depends quadratically on DM density,
i.e. depends on poorly known **clumpiness** of DM

$$\langle \rho^2 \rangle \geq \langle \rho \rangle^2$$

prediction should rely heavily on simulations
(No analytical theory, deep non-linear regime)

Galactic Center
high statistics, point-like
and diffuse backgrounds
halo-model dependence

MW Halo
high statistics,
high diffuse background



Extragalactic
high statistics, lot of
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Satellites
(or Clusters)
low background (?)
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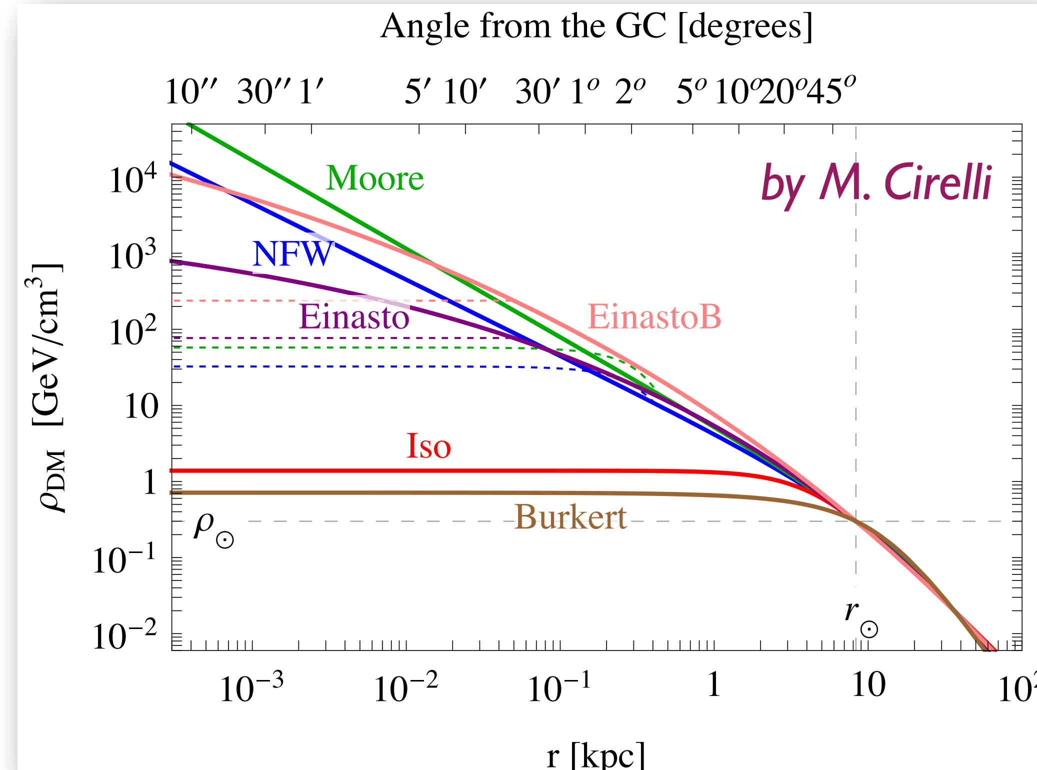

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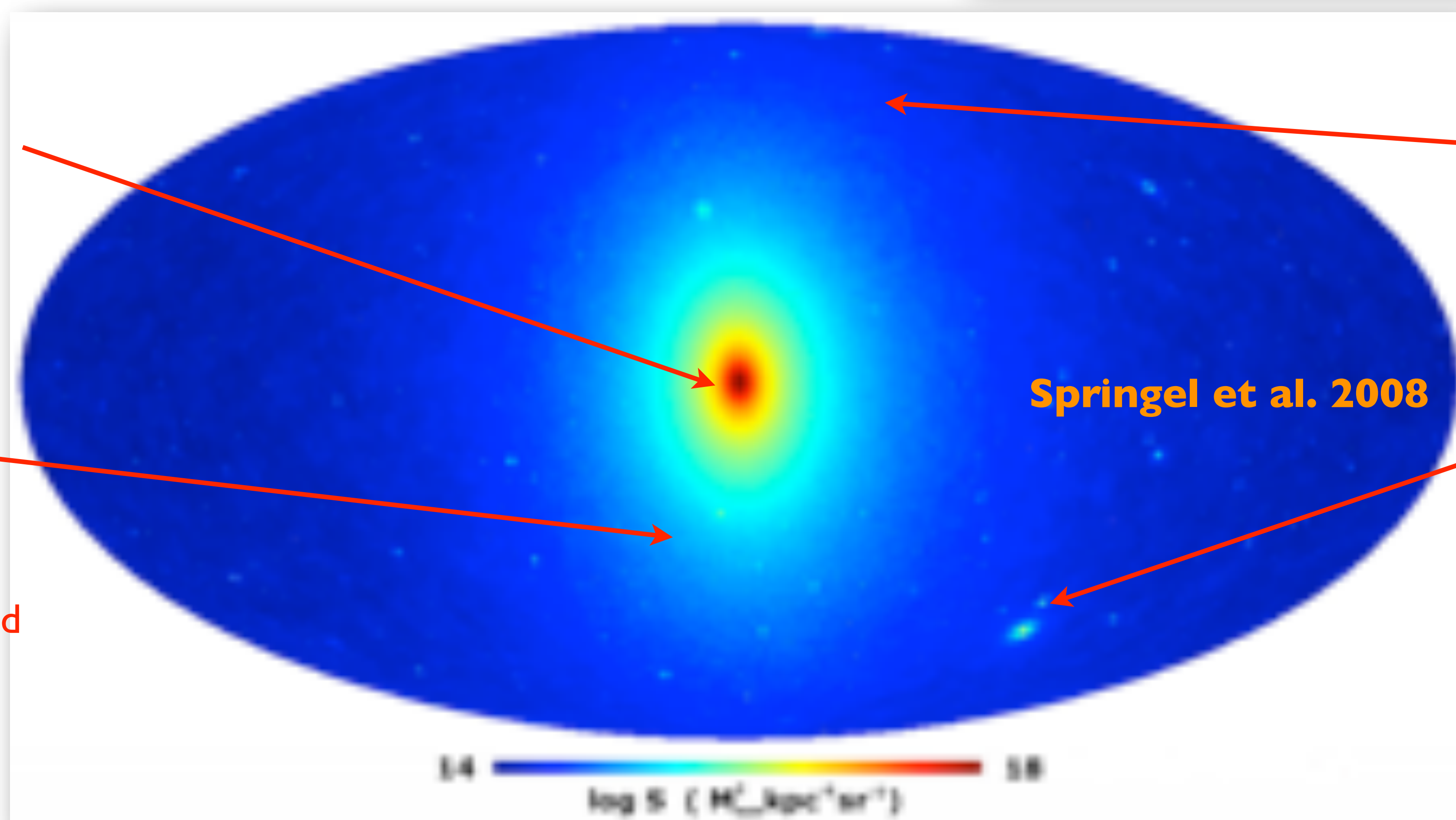

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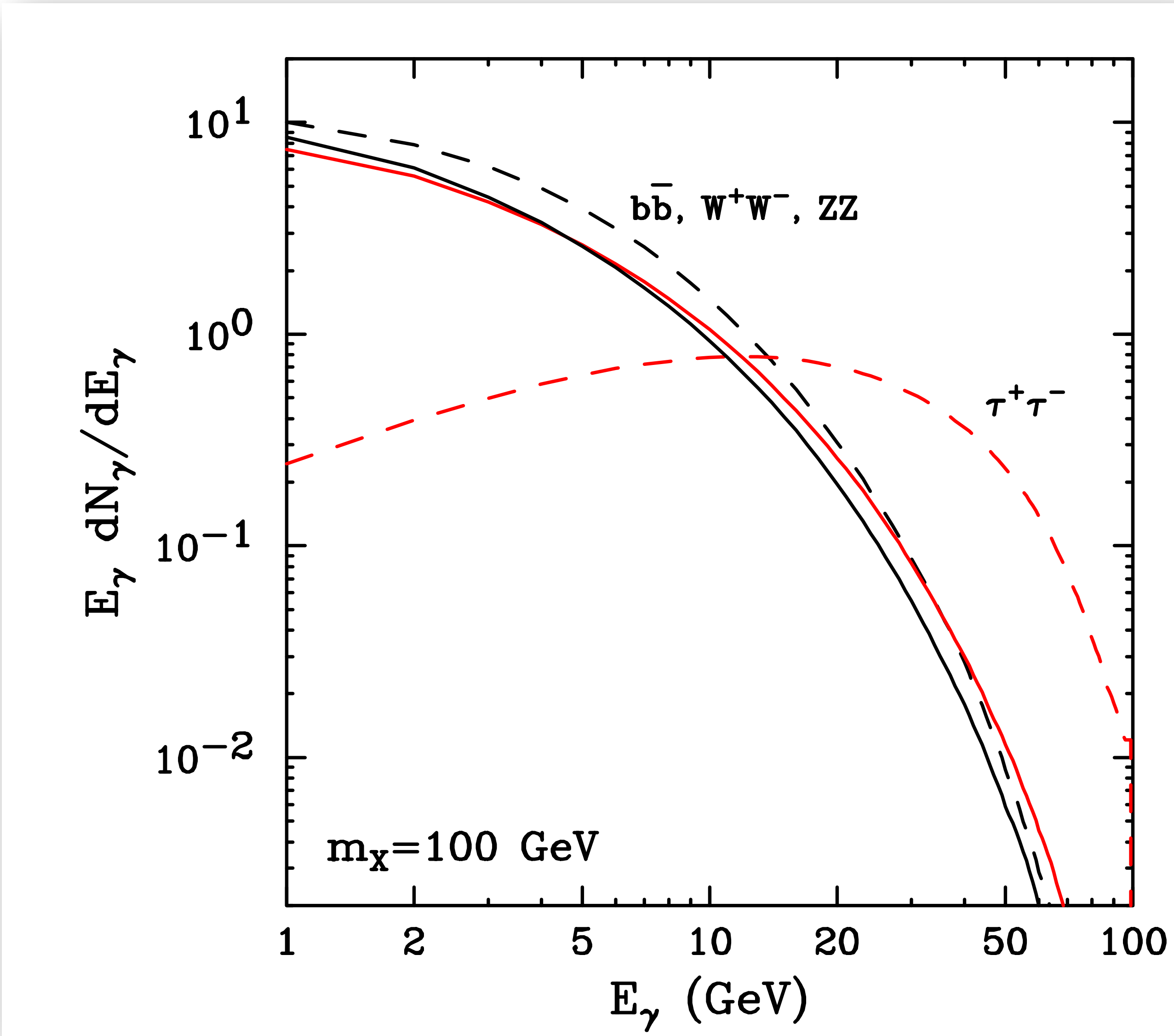

Spectrum typically dominated by continuum photons, with E≲10% m

✓ whenever DM annihilates into quarks or gauge bosons, continuum photon spectrum is quasi-universal, as a result of decays/fragmentations

✓ Near the endpoints (~DM mass), or for leptonic final states, peculiarities may be present.

✓ Significant *secondary* (byproducts of electrons e-losses) gamma radiation may be emitted from electrons. Requires treatment as for charged particles, and astrophysical medium is important.

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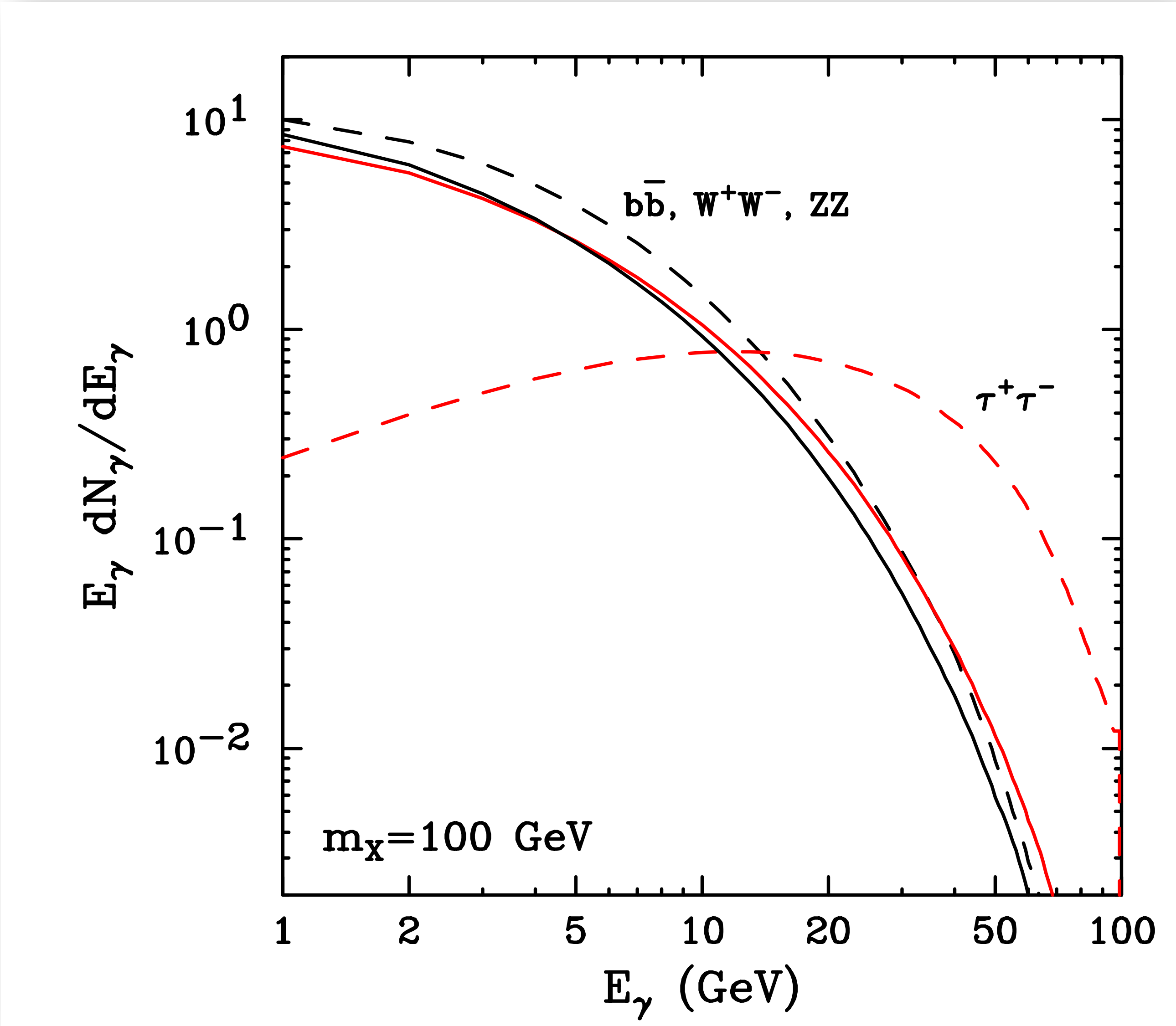

Spectrum typically dominated by continuum photons, with E≲10% m

usually handled via e.g. PYTHIA incorporated in dedicated software, also fitted e.g. in PPPC:

http://www.marcocirelli.net/PPPC4DMID.html

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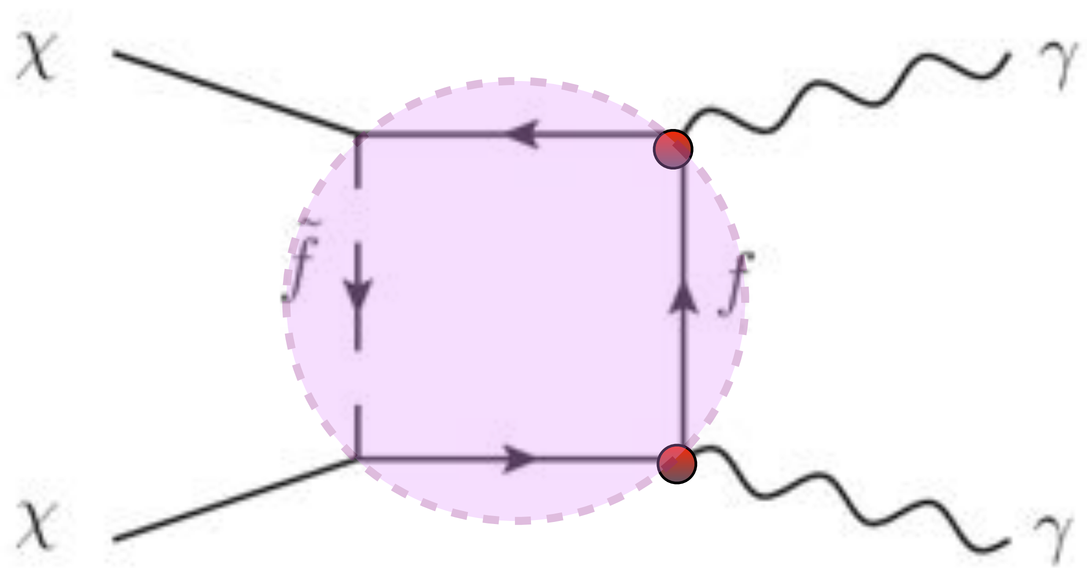
Spectral lines

- Line annihilation requires two-body final state channels containing at least one photon (for SM final states, $\gamma\gamma$, γZ, γH) yielding the spectrum

$$\frac{dN}{dE} \propto \delta(E - E_\gamma)\,, \quad E_\gamma \leq m_\chi$$



- This must be a loop-level process, suppressed with respect to the tree-level by $\alpha^2 \sim 10^{-4}$

- Smoking gun signal, but usually it's theoretically difficult to produce line flux which is observable, while fulfilling bounds on continuum