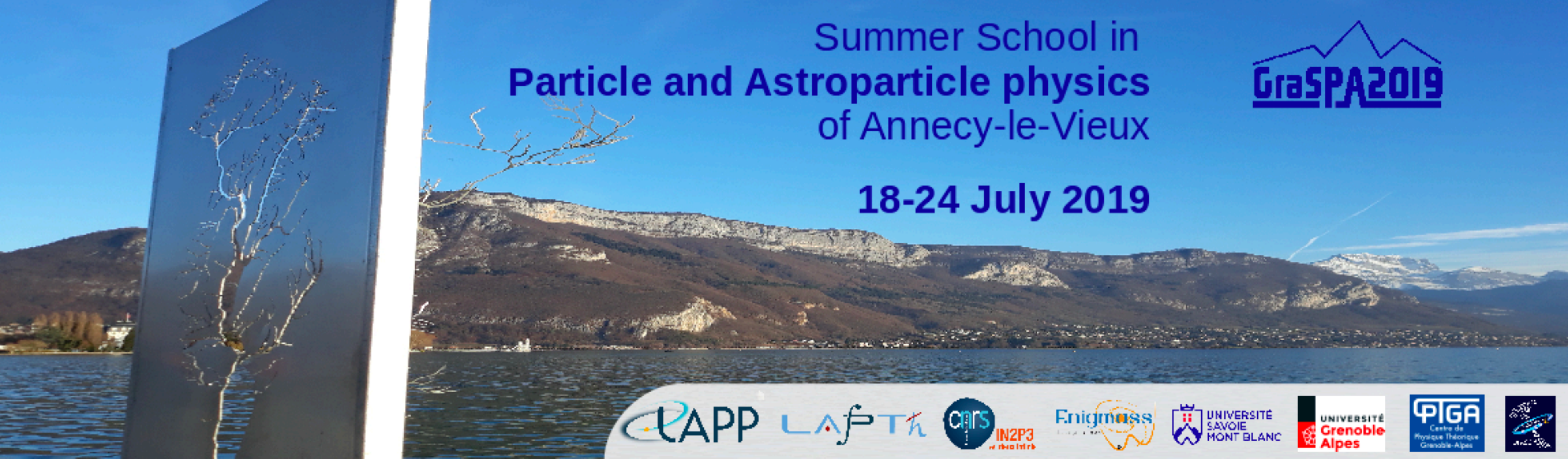

Summer School in
Particle and Astroparticle physics
of Annecy-le-Vieux

18-24 July 2019

GraSPA2019

Astroparticle Theory

Francesca Calore

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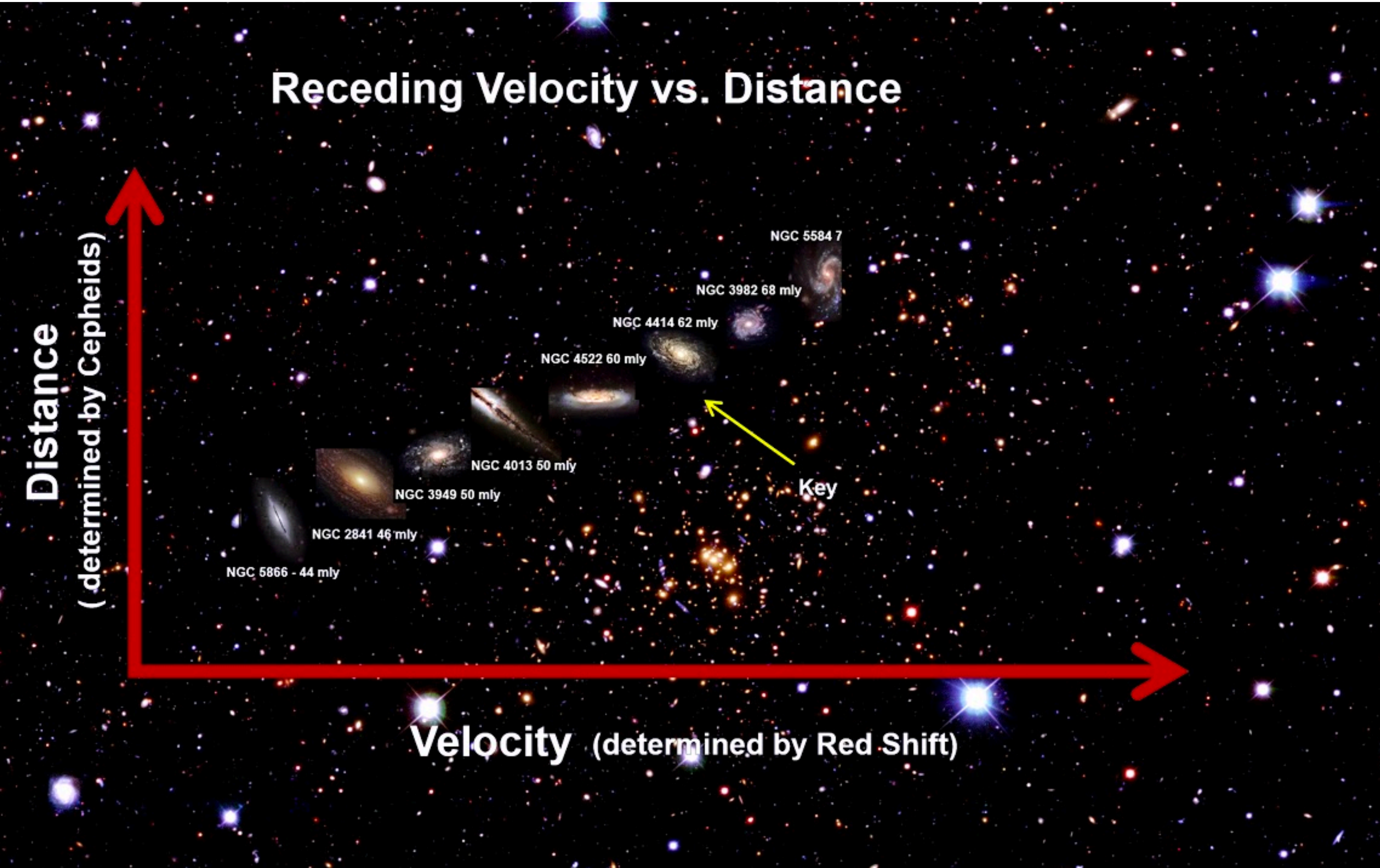
Lecture 1

1. A short introduction to cosmology
2. The early Universe thermal history
3. Boltzmann equations for thermal relics

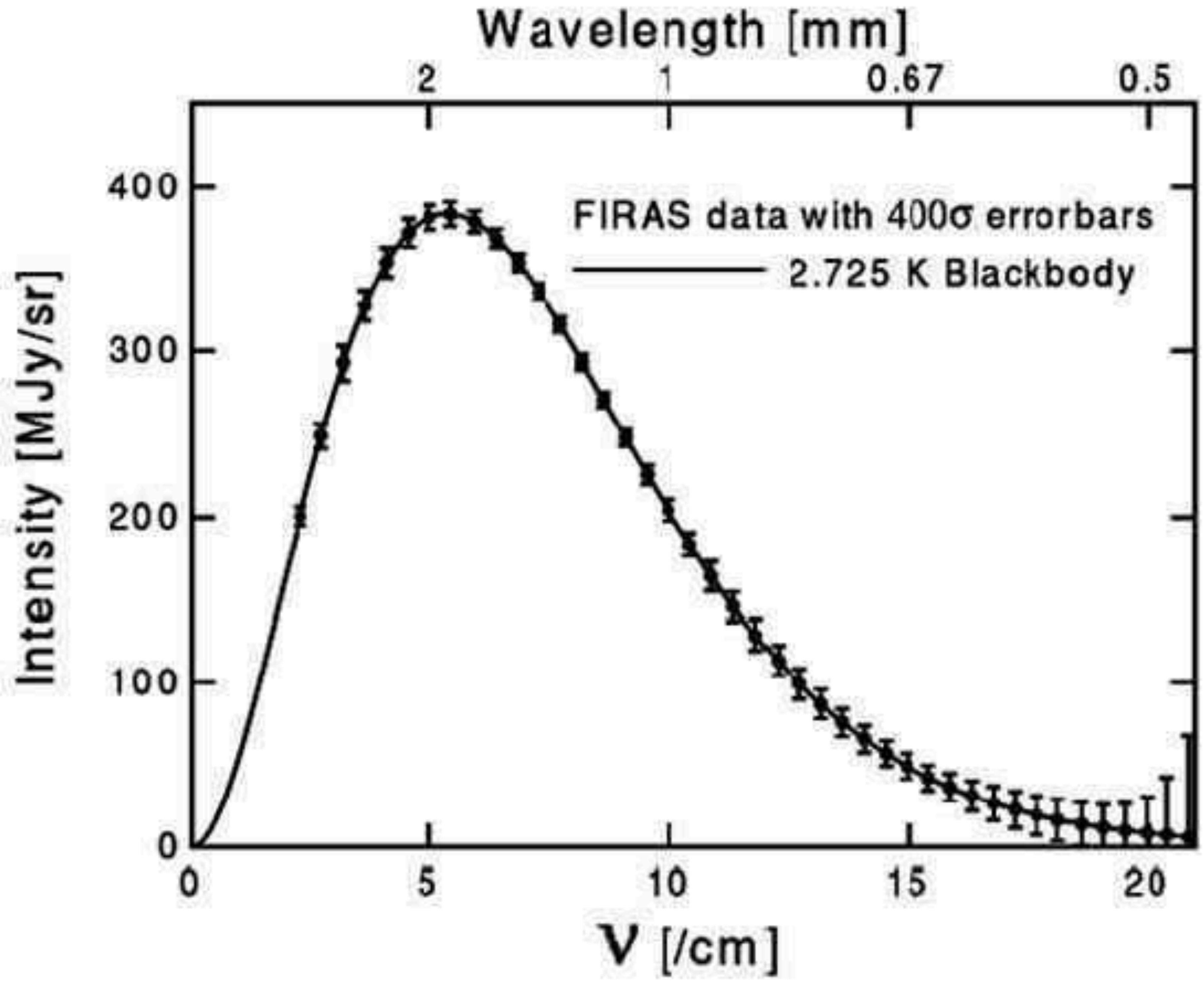
Main reference:

Kolb & Turner, "The Early Universe" (1988)
Chapters 1-3, 5

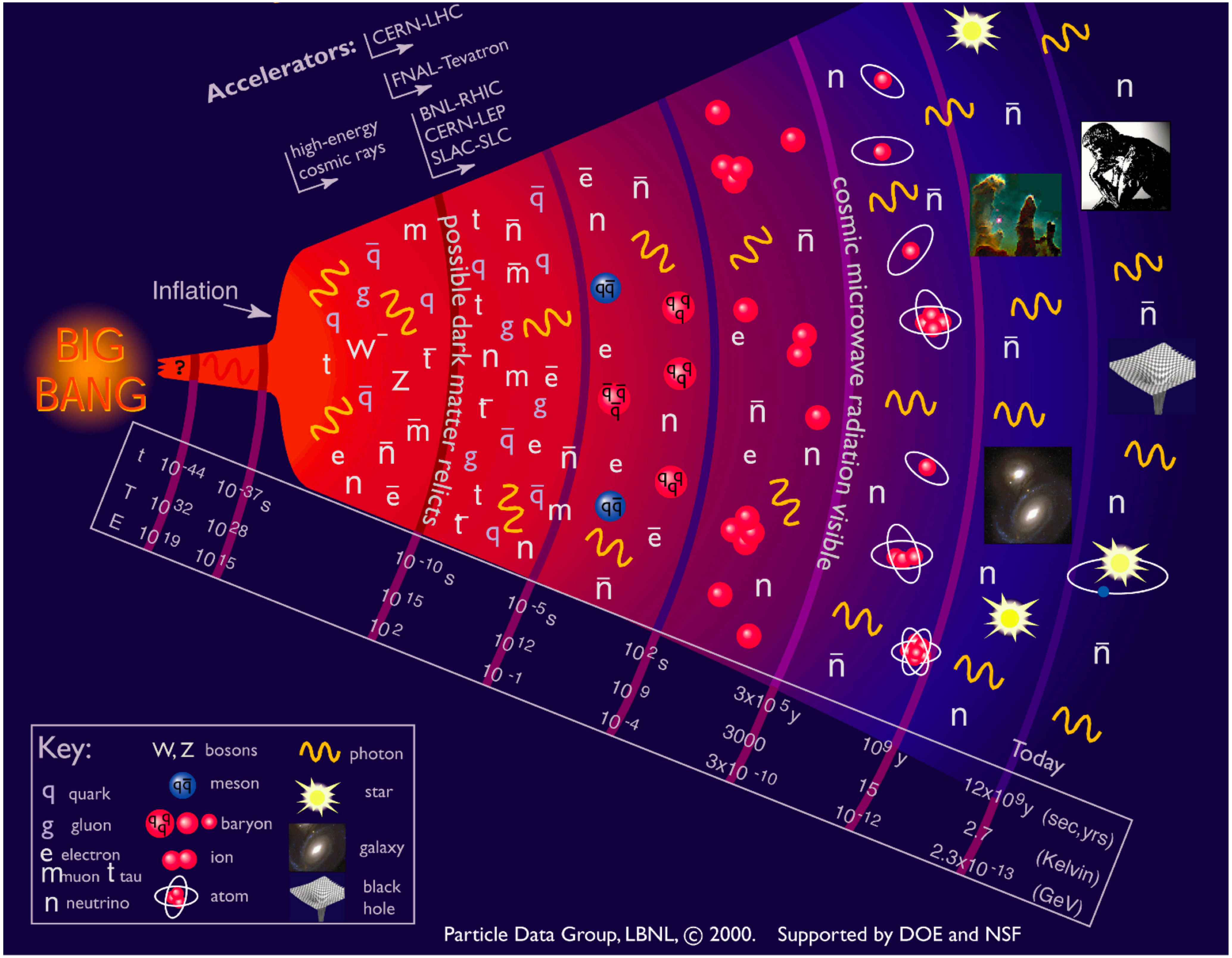
Hubble's law


Receding Velocity vs. Distance
NGC 5584 7
NGC 3982 68 mly
NGC 4414 62 mly
NGC 4522 60 mly
NGC 4013 50 mly
NGC 3949 50 mly
NGC 2841 46 mly
NGC 5866 - 44 mly
Key
Distance
(determined by Cepheids)
Velocity (determined by Red Shift)

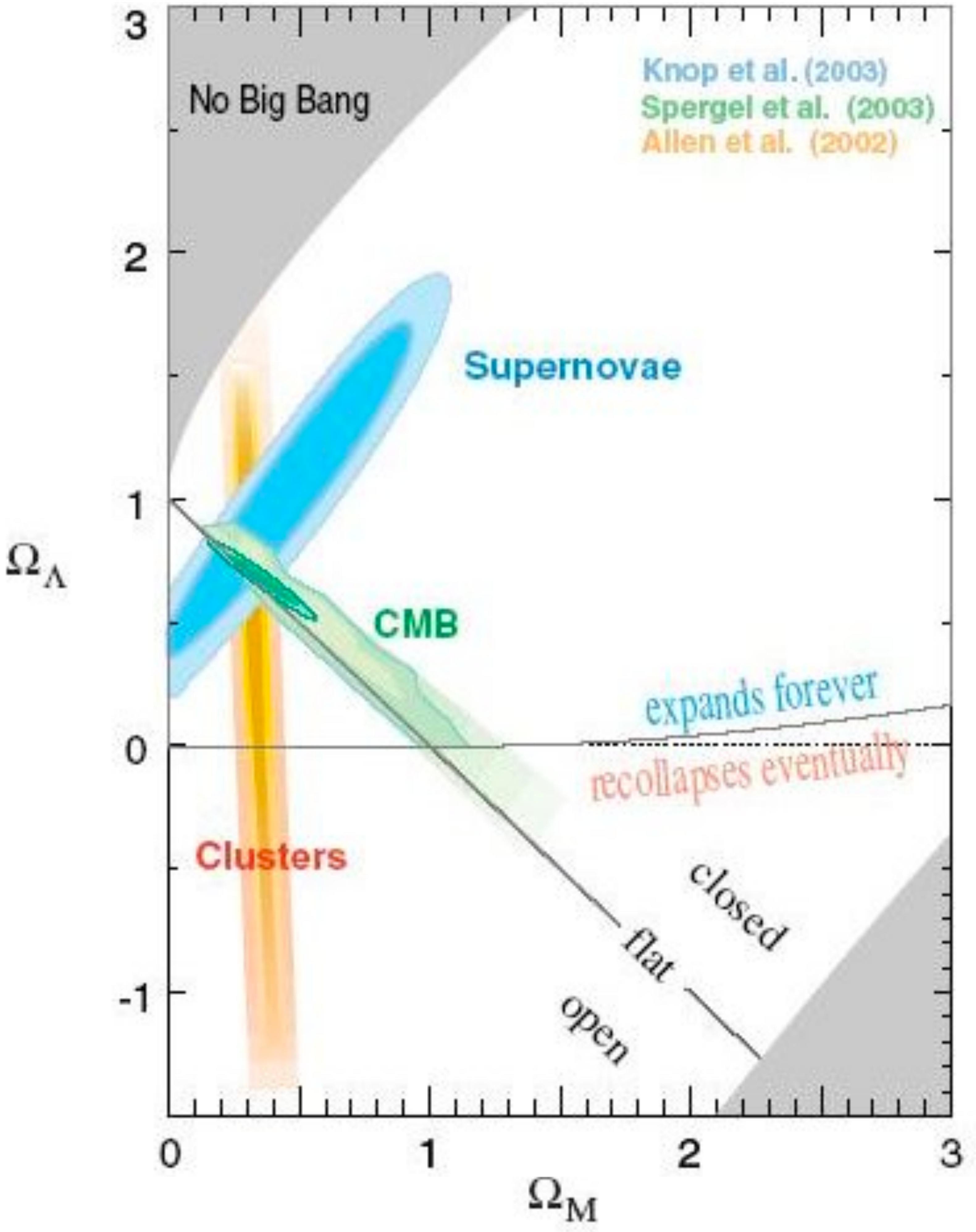
CMB Blackbody spectrum



The evolution of the Universe

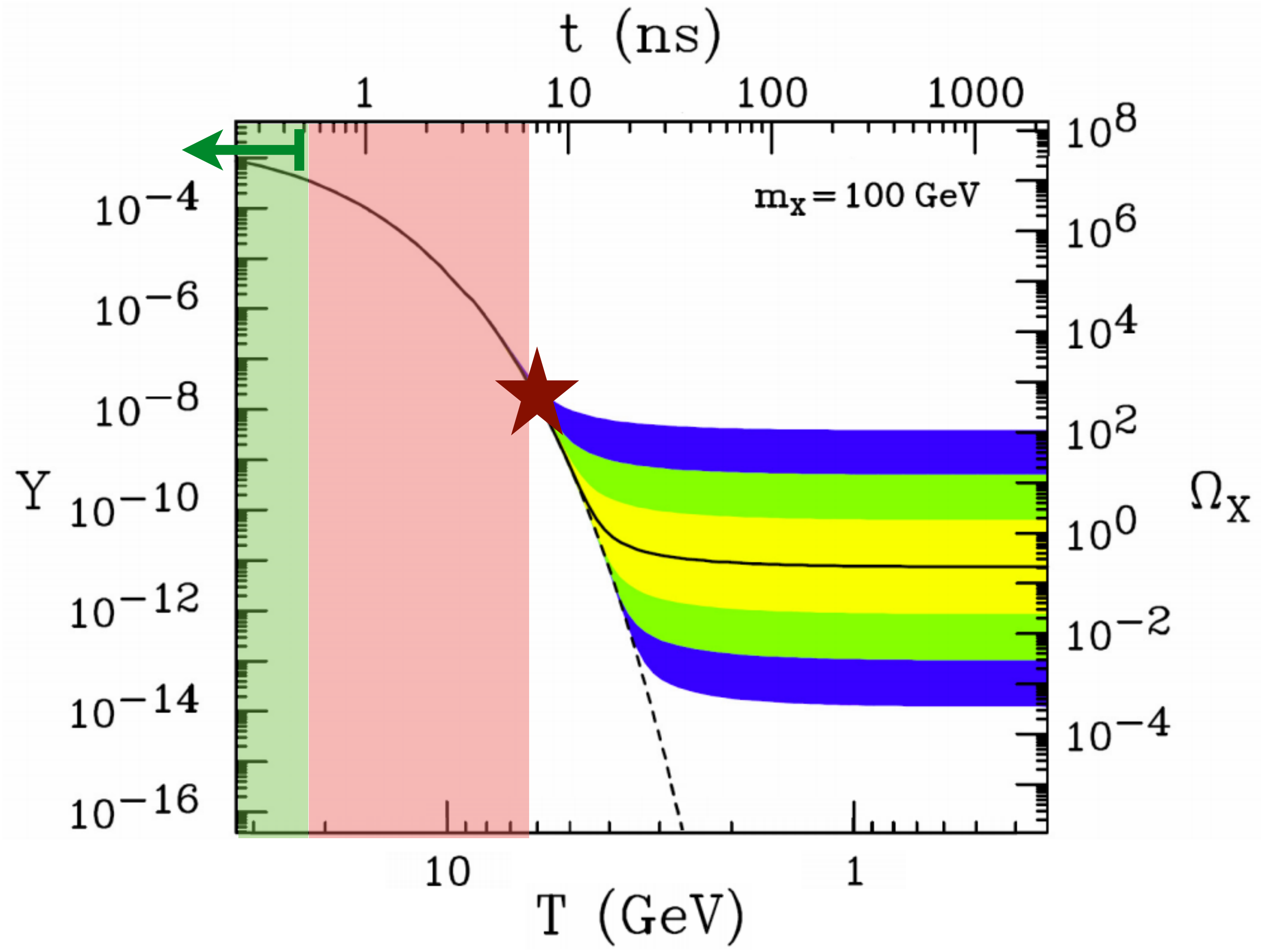


Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



Cosmology Concordance

Thermal decoupling (freeze-out)



$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3$$ comoving number density

$$T \gg m_X \qquad Y_X^{\rm rel} \sim const$$

$$T \ll m_X \qquad Y_X^{\rm non-rel} \sim e^{-m_X/T}$$

★ $Y_X(T_{\rm f.o.}) = Y_0$

Cold relic history very sensitive to details of decoupling because of rapid variation of Yᵢ → Sensitivity to new physics through:

- Interaction rate, i.e. interaction type
- Number of relativistic d.o.f for the evolution of H(T)

[For textbook see Kolb & Turner, “The Early Universe” (1988)]

Thermal decoupling (freeze-out)

Three exceptions in the calculation of the relic abundance

1. Co-annihilation with other particles degenerate in mass (5% —10%); coupled Boltzmann equations
2. Dark matter mass slightly below mass threshold to open up a new channel
3. Annihilation close to a pole of the cross section, i.e. resonant annihilation

Griest & Seckel, Phys.Rev.D 43 (1991) 319
Edsjo & Gondolo, Phys.Rev.D 56 (1997) 1879[hep-ph/9704361]

How to…

MicrOMEGAs: a code for the calculation of Dark Matter Properties
including the **relic density**, direct and **indirect rates**
in a general supersymmetric model
and other models of New Physics

https://lapth.cnrs.fr/micromegas/

Dark SUSY

http://www.darksusy.org/

Lecture 2

1. Observational evidence for Dark Matter
2. Fundamental properties of Dark Matter
3. Searches for Dark Matter

References in the slides

1. Observational evidence for dark matter

Dark matter gravitational evidence

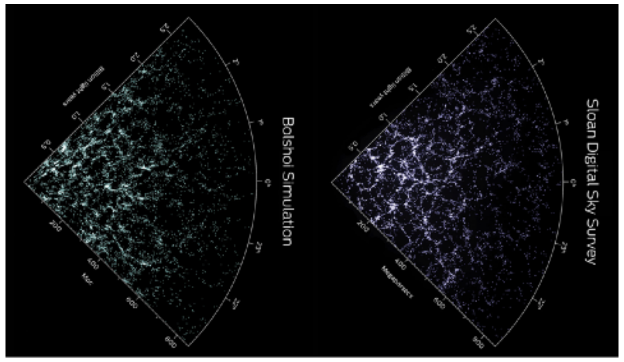
Rotation curves

~kpc

Galaxy clusters

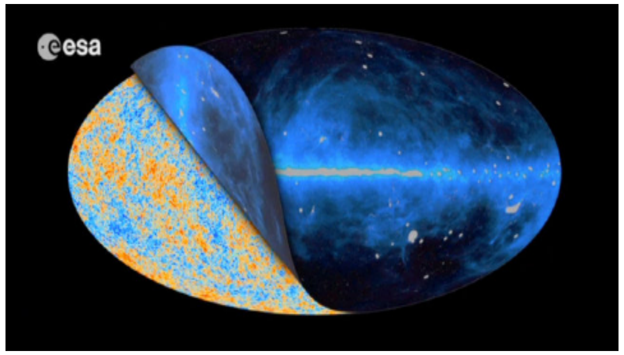
~Mpc

Large Scale structures

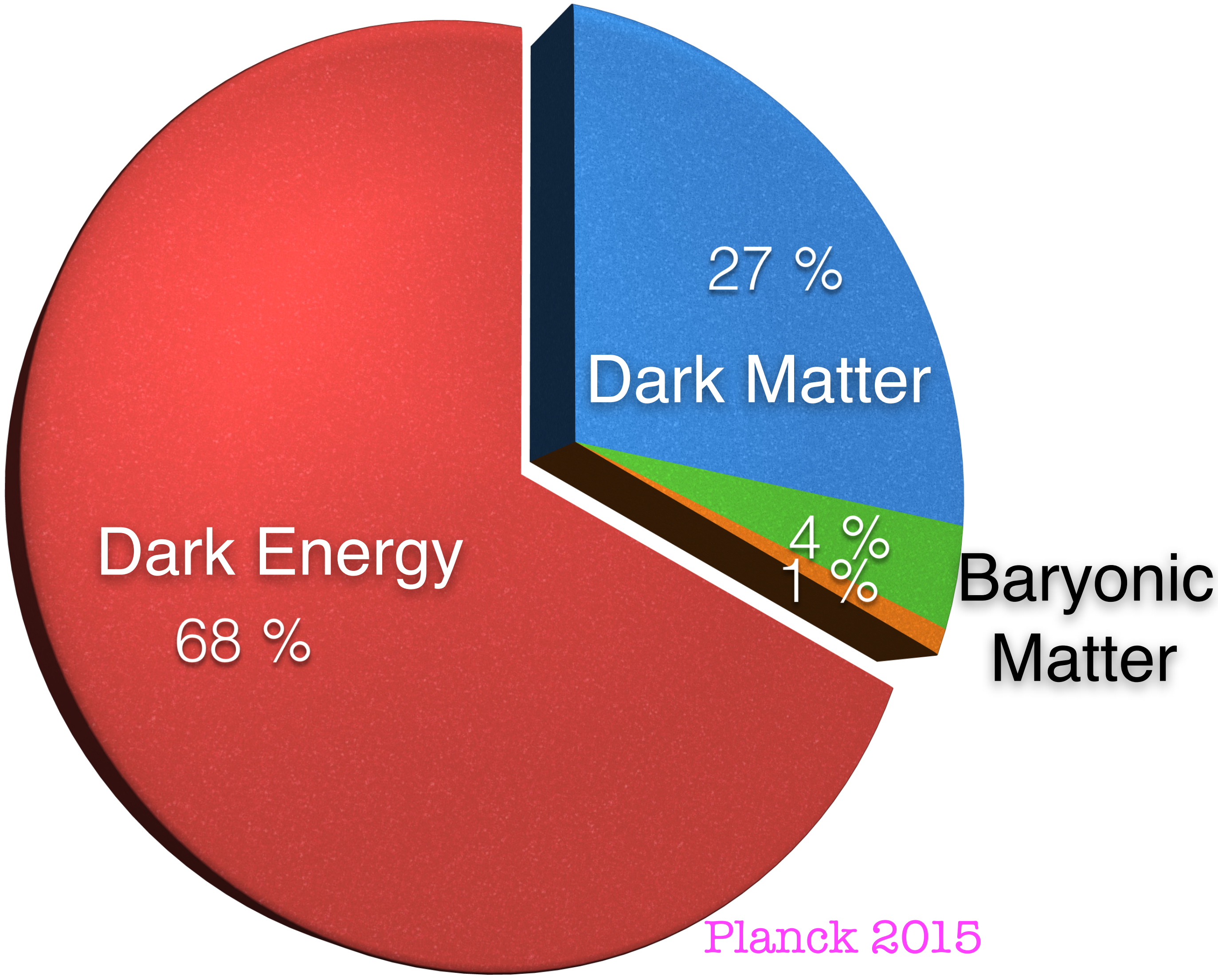


~Gpc

Cosmic microwave background



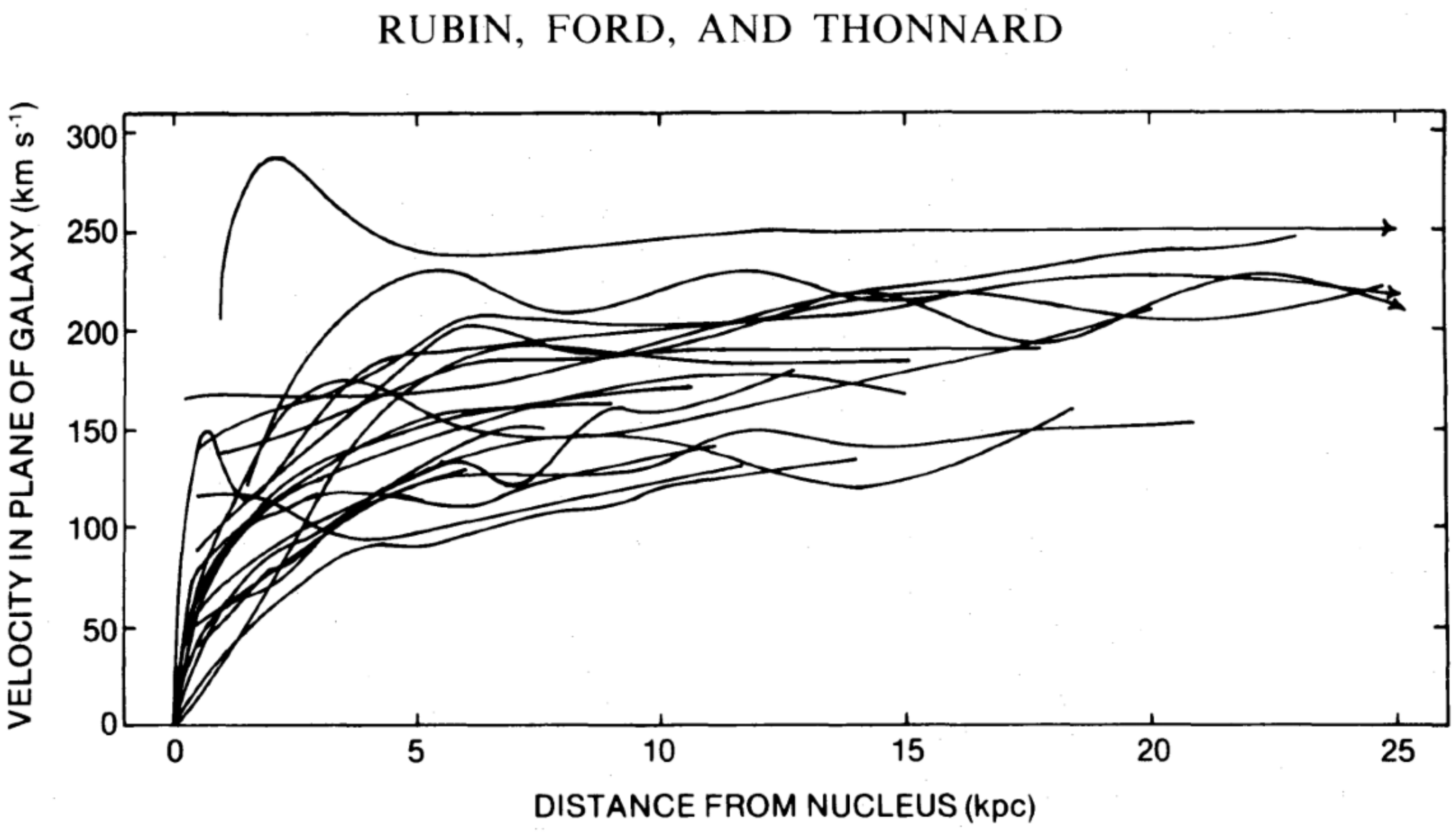
We do not know what most of the Universe is made of!



Planck 2015

Dark matter constitutes about 85% of the matter content of the Universe.

Flat galactic rotation curves



'70/'80: observation of spiral galaxies,
rotation supported systems like the Milky Way

V. C. Rubin and W. K. Ford, Jr., ApJ 159, 379 (1970);
V. C. Rubin, N.Thonnard and W. K. Ford, Jr., ApJ 238, 471 (1980)

$$v_c^2(<R) = R\frac{d\phi_{\rm tot}}{dR} = \frac{GM(<R)}{R}$$

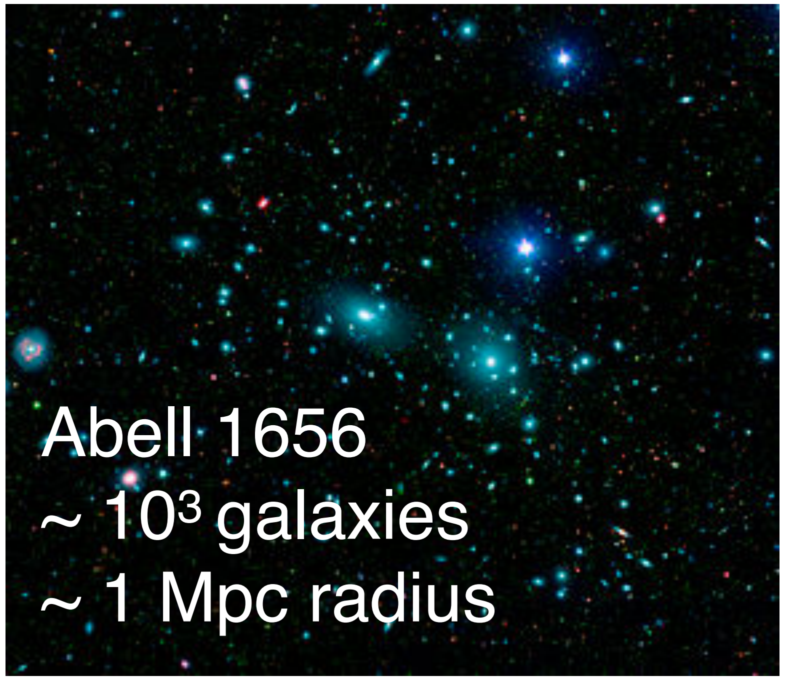
$$M(<R) \equiv 4\pi\int_0^R r^2\rho(r)dr$$

Predicted from visible light: $v_c^2 \propto \frac{1}{R}$

Observed: $v_c^2 \sim constant \longrightarrow \rho(r) \propto \frac{1}{r^2}$

Data are well described by an additional component, dominating the mass profile at distances much larger than the visible mass scale.

Dark matter in the Coma Cluster


Abell 1656
~ 10^3 galaxies
~ 1 Mpc radius

Pioneering application of the virial theorem in astronomy

F. Zwicky, Helvetica Physica Acta (1933) 6, 110-127; ApJ (1937) 86, 217

$$2\langle T\rangle + \langle U_{\rm tot}\rangle = 0 \qquad\qquad U(r) \propto r^{-1}$$

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

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

gravitational potential of a self-gravitating homogeneous sphere of radius R

$$\longrightarrow \qquad M \sim \mathcal{O}(1)\frac{R\langle v^2\rangle}{G_N} \sim 3\times M_{\rm visible}$$

X-rays and gravitational lensing

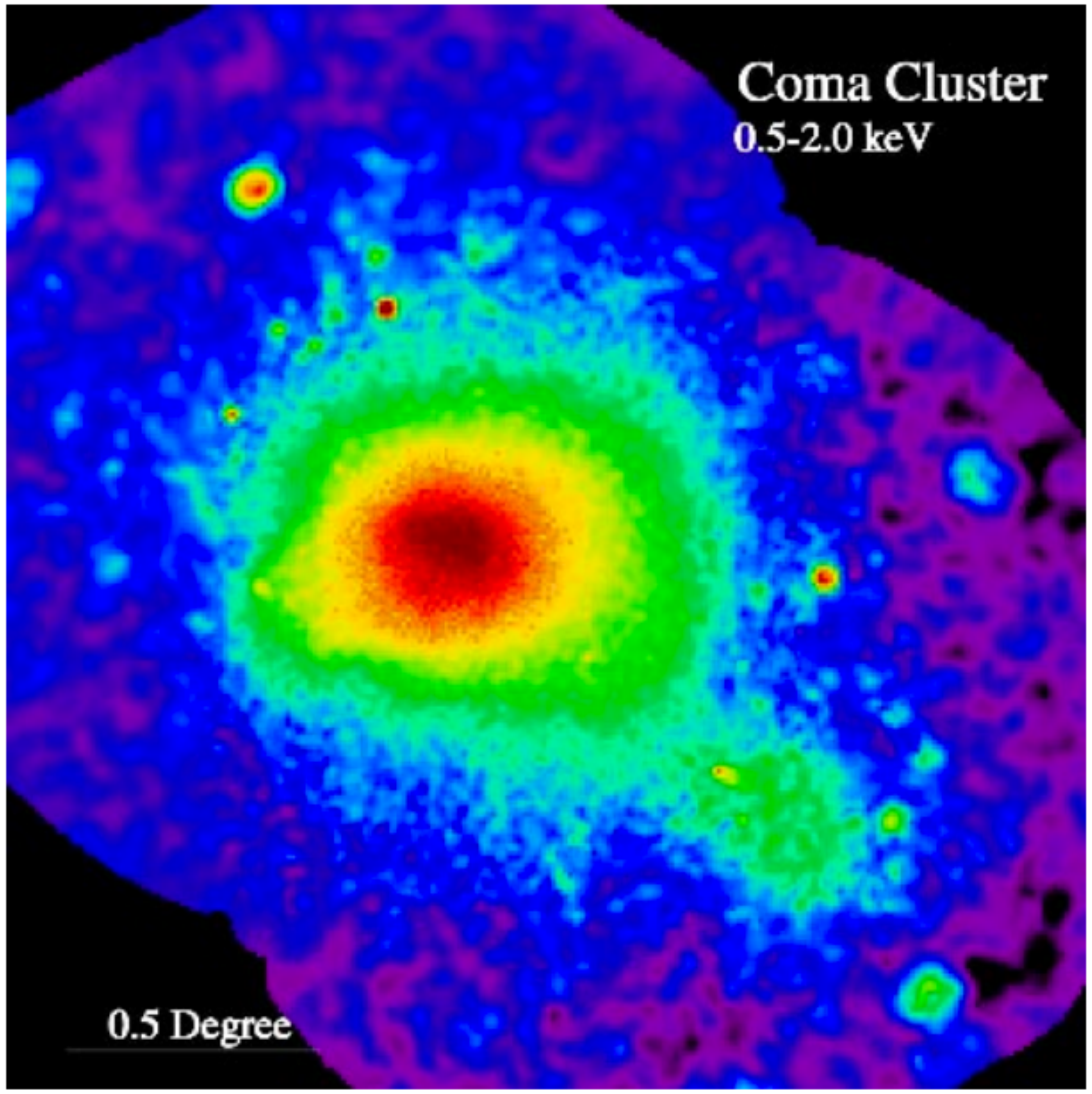
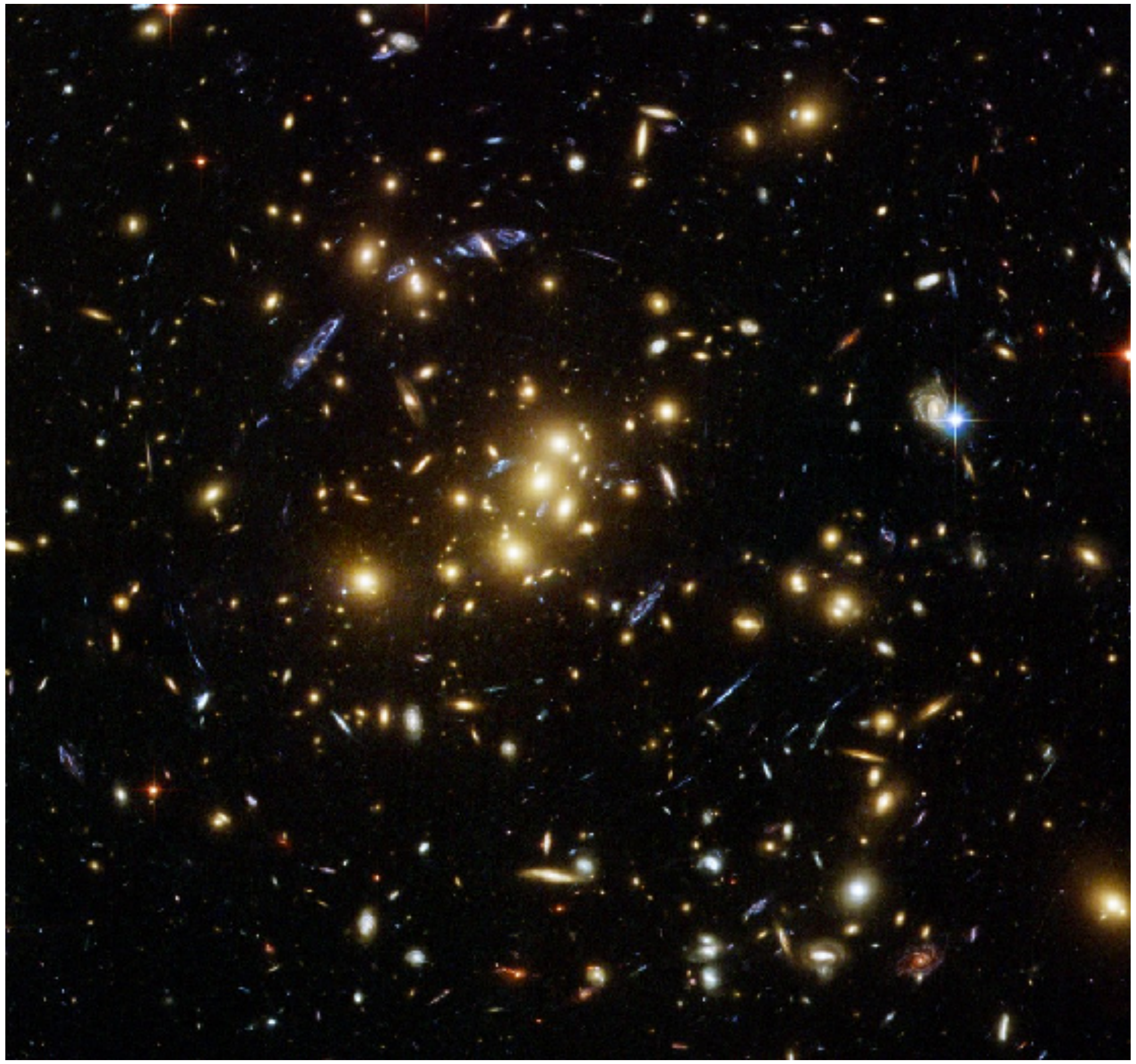


Figure 2. An x-ray image of the Coma cluster obtained with the ROSAT satellite, showing both the main cluster and the NGC4839 group to the south-west. (Credit: S L Snowden, High Energy Astrophysics Science Archive Research Center, NASA.)

Mass in clusters is in the form of hot, intergalactic gas, which can be traced via X rays: X-luminosity and spectrum constrain the mass profile

Lewis, Buote & Stocke, ApJ (2003), 586, 135



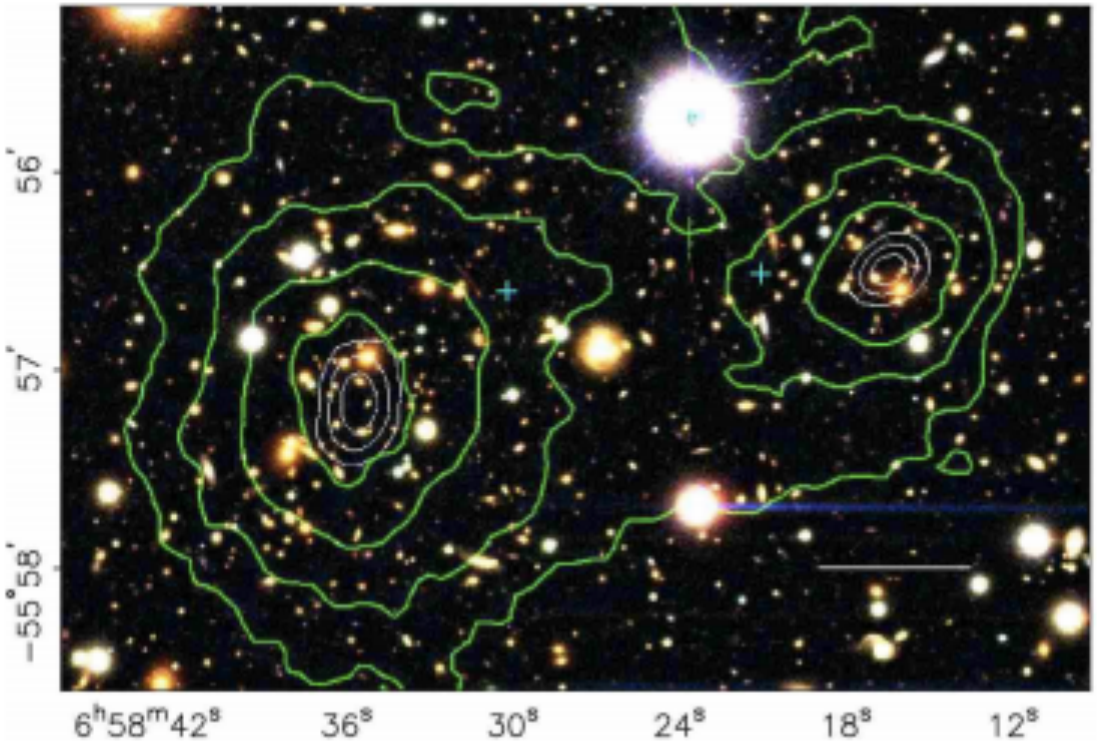
Strong gravitational lensing around galaxy cluster CL0024+17, demonstrating at least three layers projected onto a single 2D image.

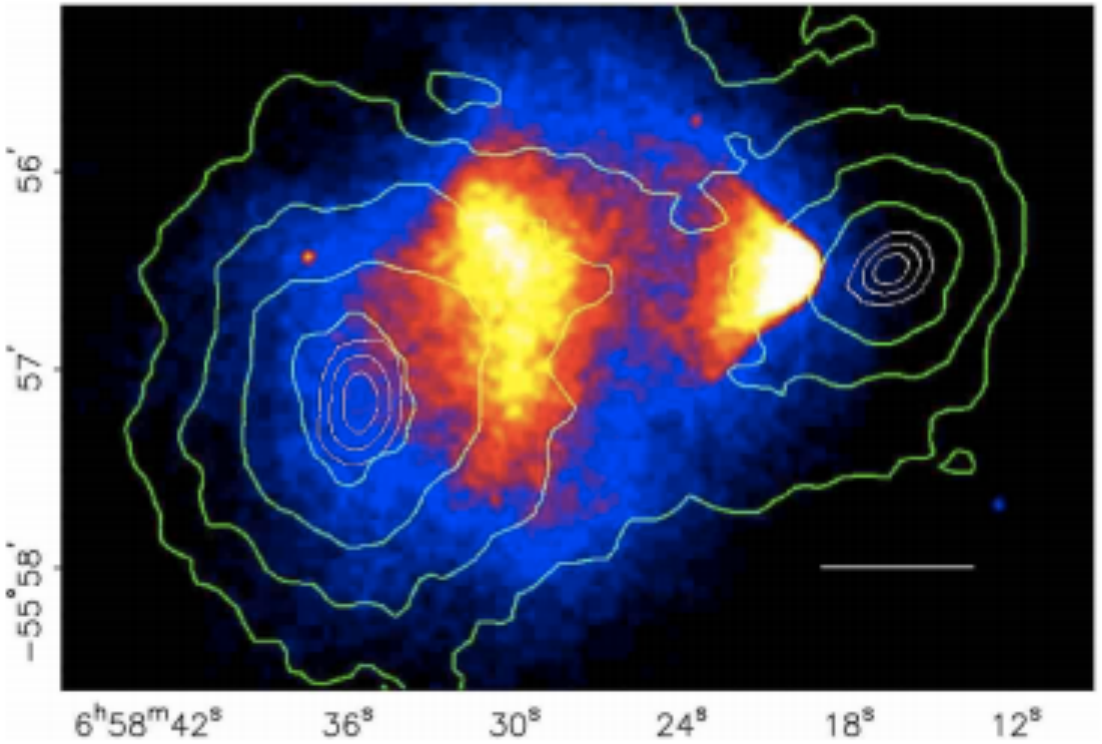
Massey, Kitching & Richard, Rept.Prog.Phys. 73 (2010)

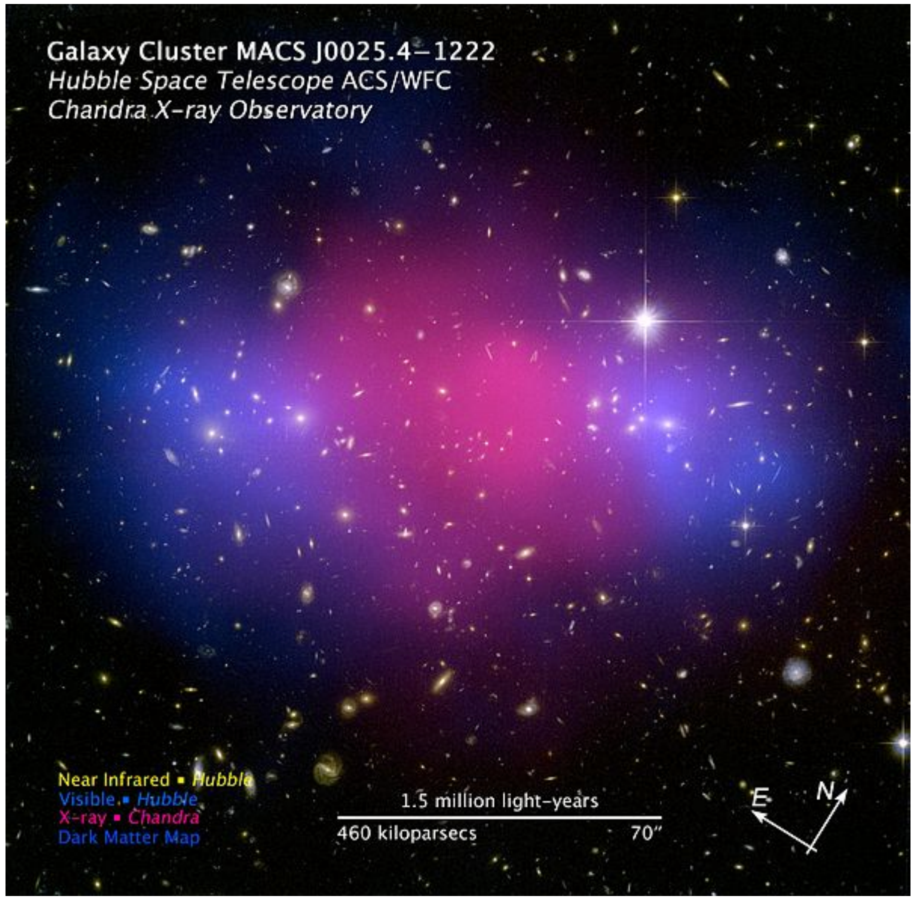
Segregation of matter in clusters

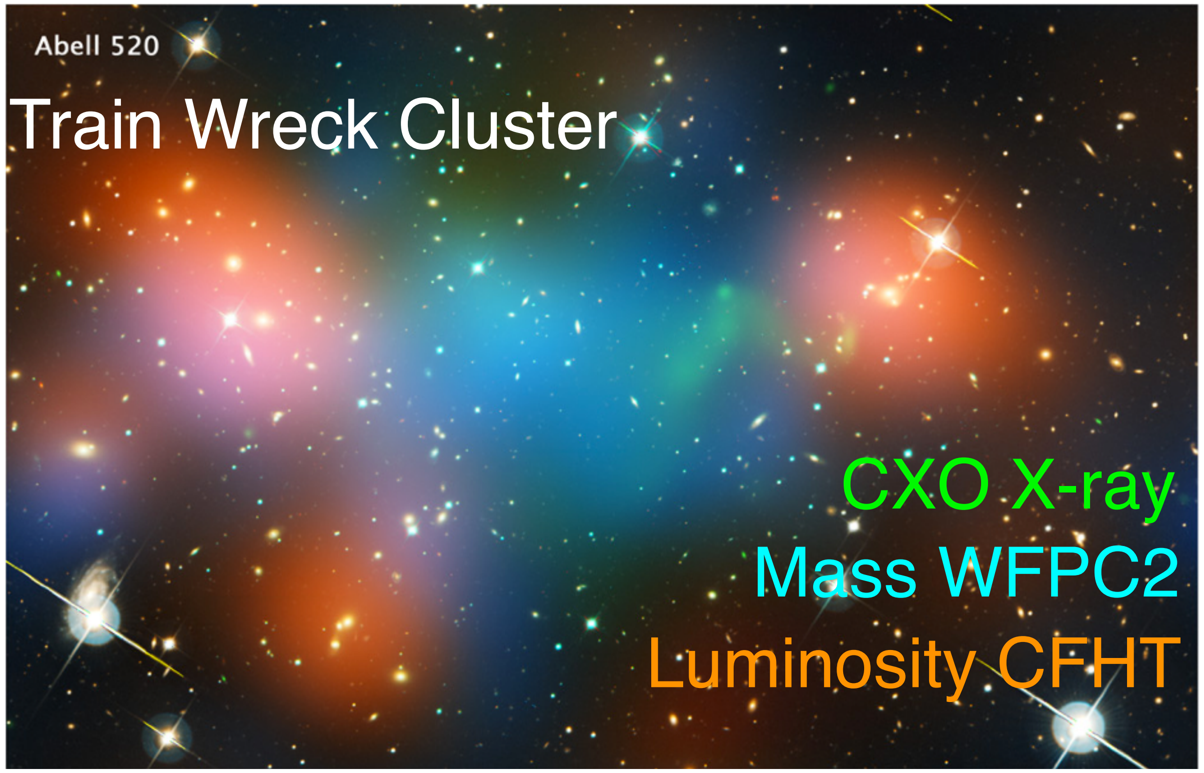
Bullet Cluster (1E 0657-56)

Clowe+, ApJ 604 (2004) 596-603; Clowe+ ApJ, 648 (2006) L109



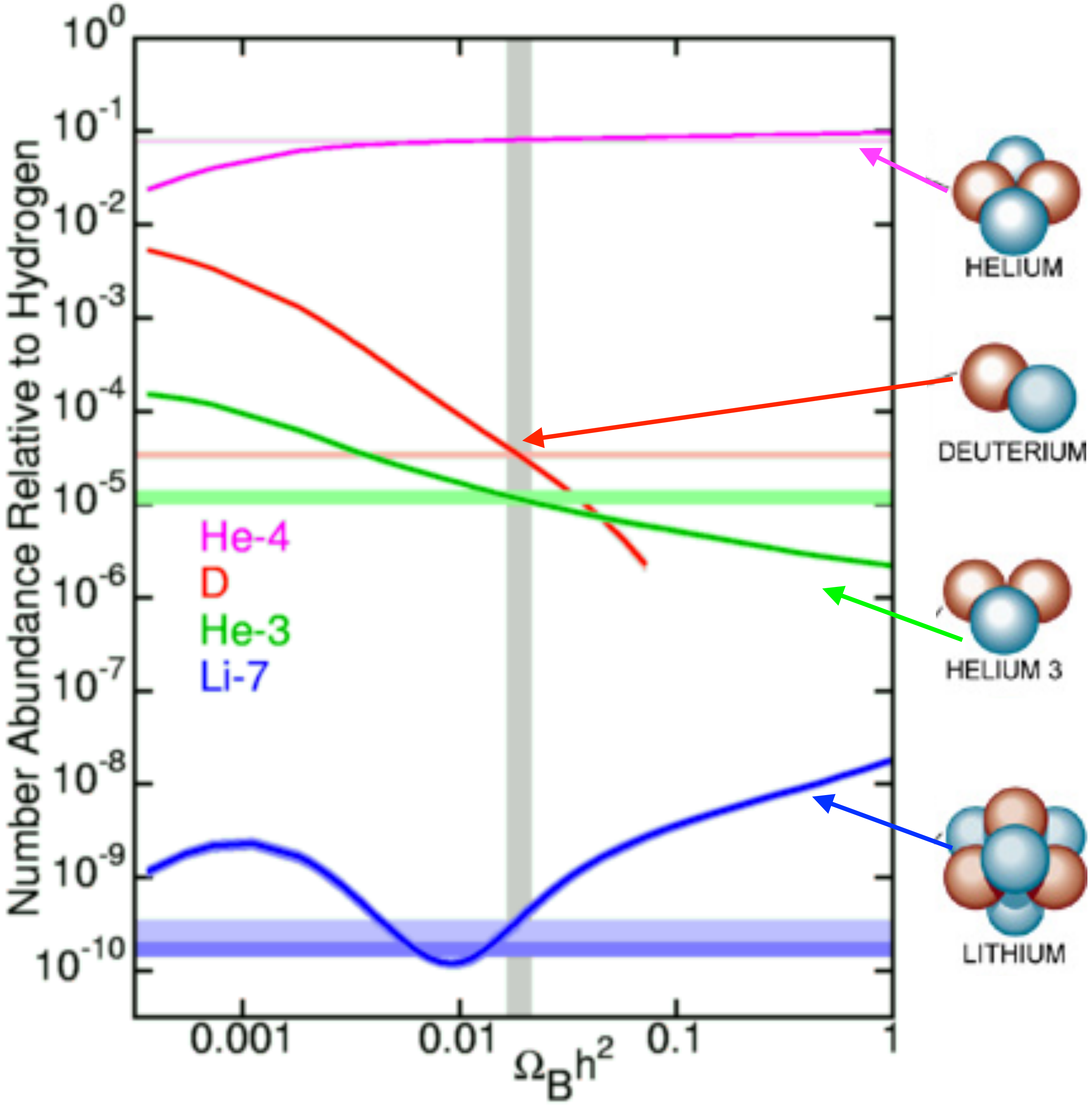






James Jee+, ApJ 783 (2014) 78

Big Bang Nucleosynthesis



Success of Big Bang hypothesis and thermal history of the Universe.

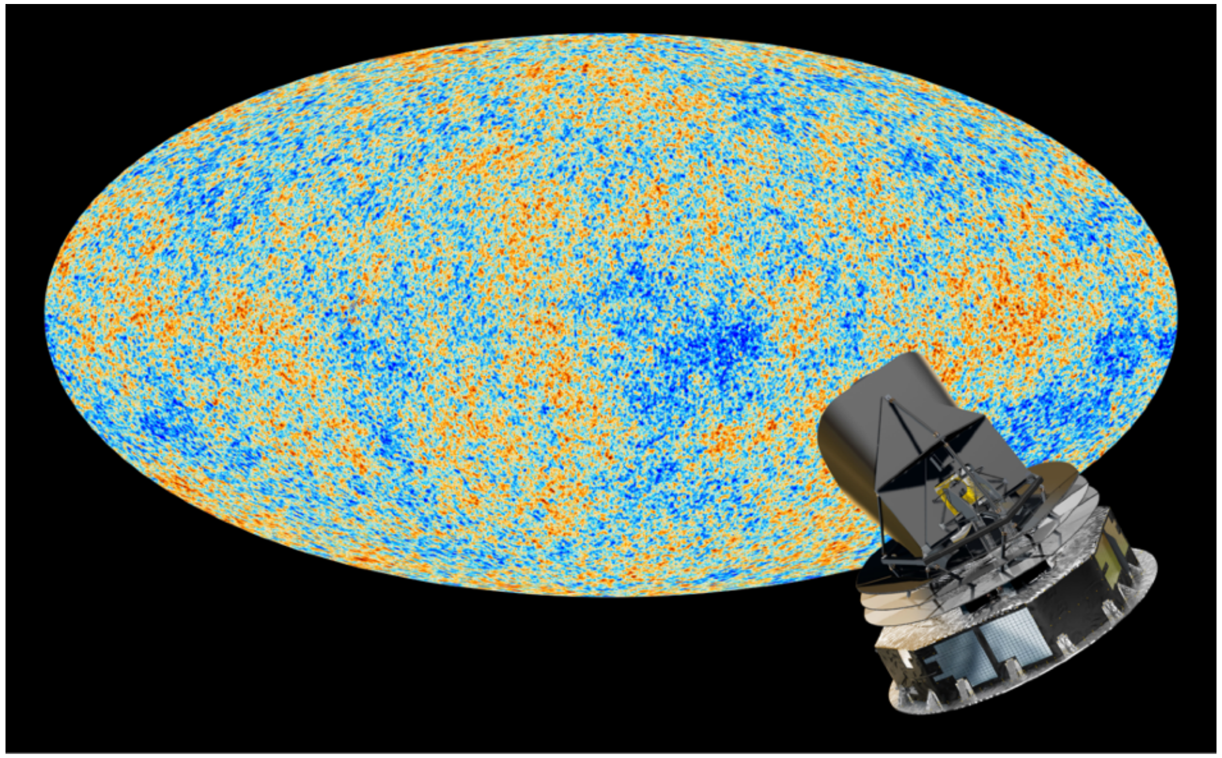
Accurate prediction of abundance of light elements.

Independent measure of abundance of baryonic matter in the Universe.

T ~ MeV nuclear physics (BBN)

$$\Omega_b h^2 \sim 0.02$$

Cosmic Microwave Background



$$\Omega_i \equiv \frac{\bar{\rho}_i}{\rho_c}$$

Abundance species *i*

Critical density
(average density of a flat Universe)

$$\rho_{\rm c} \equiv \frac{3H_0^2}{8\pi G_N}$$

10 protons per cubic meter
[1 GeV ~ 10^{-24} g]

$$\bar{\rho}_{\rm DM} \simeq 0.3\rho_c \longrightarrow \bar{\rho}_{\rm DM} \sim 10^{10}\,\frac{\rm M_\odot}{\rm Mpc^3} \sim 10^{-6}\,\frac{\rm GeV}{\rm cm^3}$$

Galaxy clusters: 10^5 denser!
Galaxies: 10^6 denser!

$$\frac{\delta\rho}{\rho} \gg 1$$

The Universe today is
highly non-linear!

Cosmic Microwave Background

T > T_{CMB} tight coupling between photons and baryons
and presence of primordial overdensities $\delta > 0$

Gravitational vs radiation pressure => acoustic oscillations

$$\frac{\delta n_\gamma}{n_\gamma} \sim 3\frac{\delta T}{T} \sim \frac{\delta n_b}{n_b} \equiv \delta \qquad n_\gamma \propto T^3$$

$$\frac{\Delta T}{T} \sim 10^{-5}$$

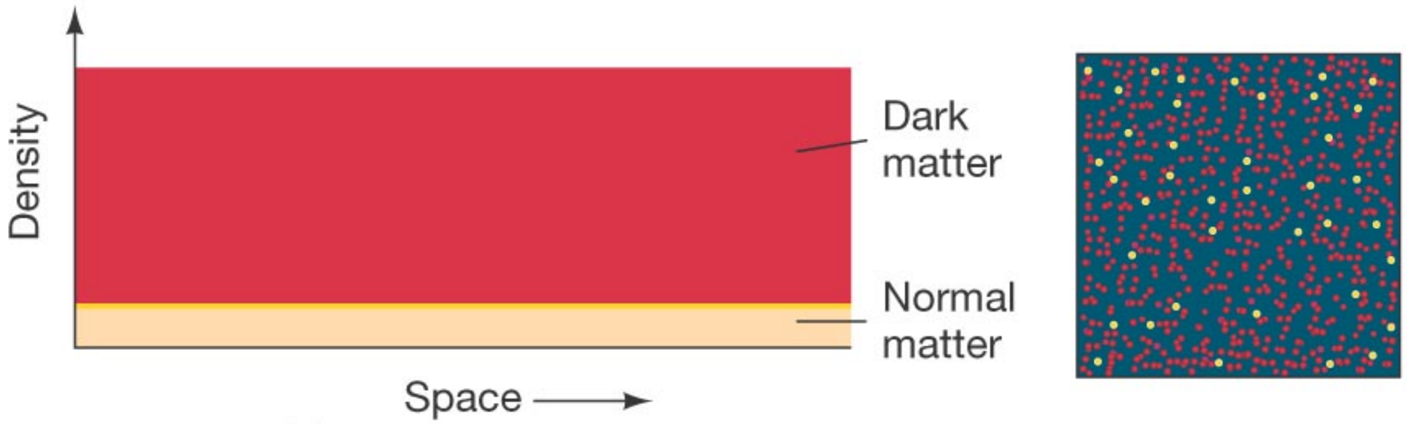
on Mpc scales @ $z_{\mathrm{CMB}} \sim 1100$

$$\frac{\Delta n_b}{n_b} \sim 10^{-5}(1 + z_{\mathrm{CMB}})^{-1} \sim 0.01$$

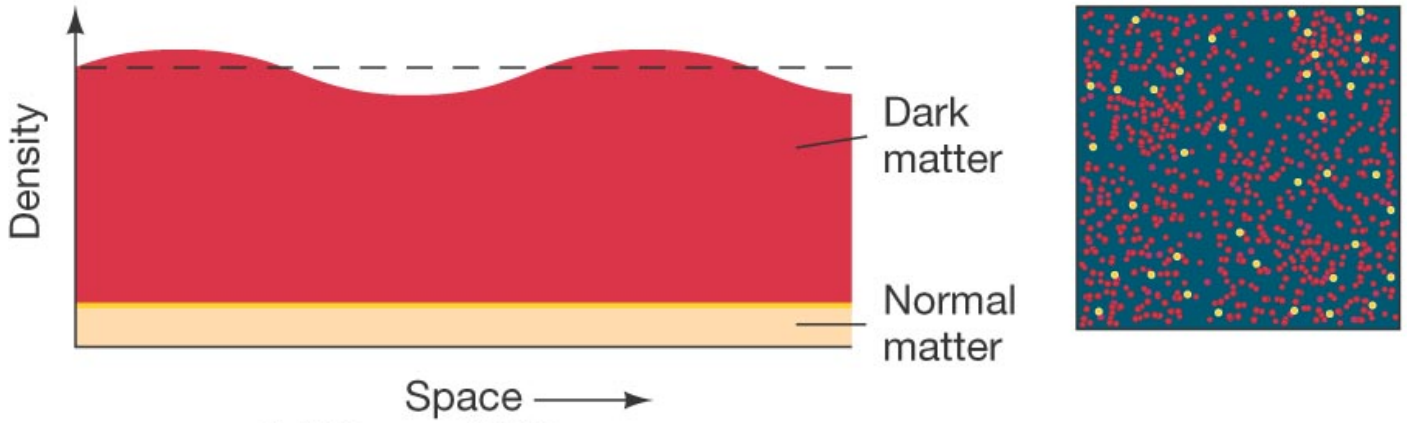
in a matter
dominated
Universe

→ With baryonic matter only, structure formation would be very different! We need a non-baryonic component that decouples from photons early enough to create deep potential wells.

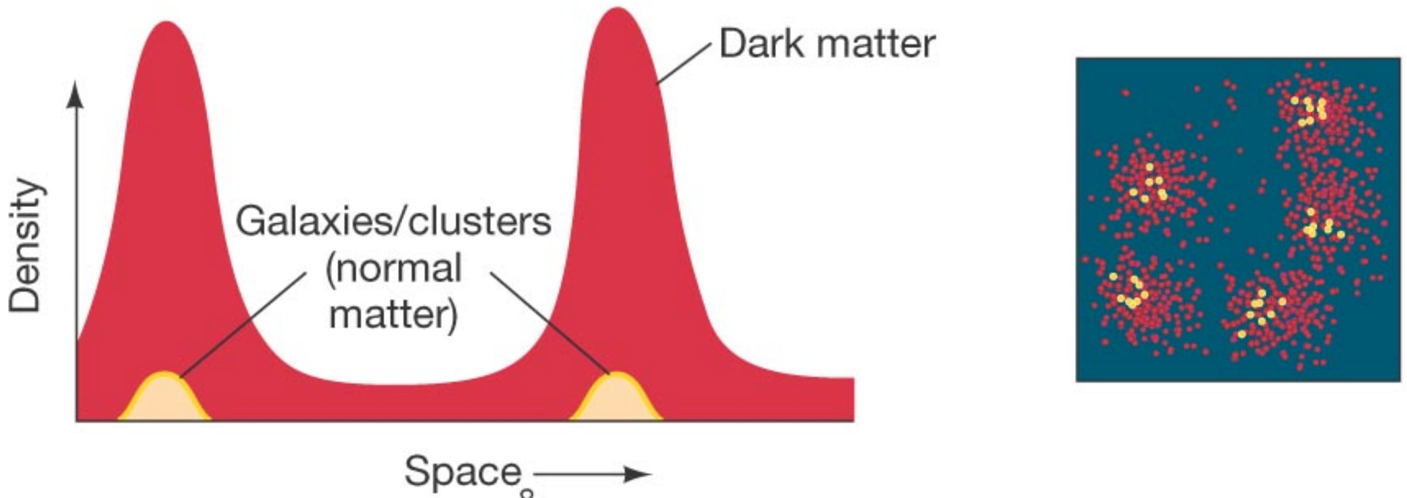
Growth of structures: cartoon



(a) Time = 1 second



(b) Time = 1000 years



(c) Time = 10^8 years

2. Fundamental properties of dark matter

Properties of dark matter

What fundamental properties can we infer from this astro/cosmo evidence?

How much dark matter at cosmological scales?

$\Omega_{\mathrm{CDM}} \sim 0.26$ Planck 2015, 68% CL

The dominant component of dark matter in the Universe should be:

1. Non-relativistic at decoupling, i.e. cold
2. Stable or long-lived
3. Sufficiently heavy, to behave “classically”
4. Smoothly distributed at cosmological scales
5. Dark and dissipationless
6. Collisionless, i.e. not very collisional

DM evidence requires new physics, beyond current theories
=> new d.o.f., appealing from a particle physics perspective

Non-relativistic @ decoupling (CDM)

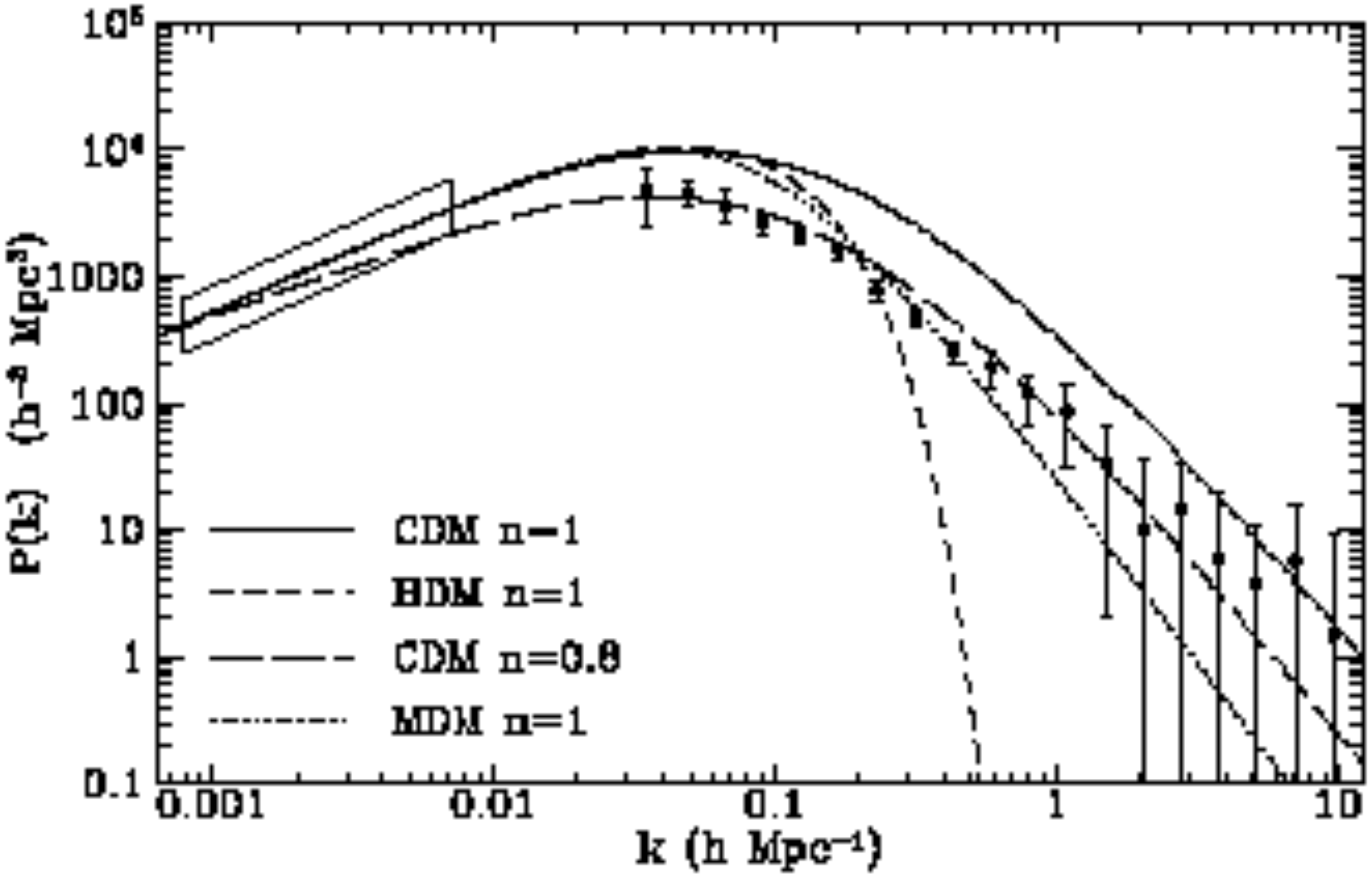
Primordial density fluctuations modified by non-linear effects: gravitation, pressure, dissipation, etc. => N-body simulations are needed to follow the growth in non-linear regime.

Collisions-less species (neutrinos, DM): free stream from overdense to underdense regions and wash out perturbations => damping of small scale density perturbations

$$\lambda_{\rm phys} \lesssim \lambda_{\rm fs}$$

$$\lambda_{\rm fs} \sim \frac{\nu(t_{\rm eq})}{H(t_{\rm eq})}$$

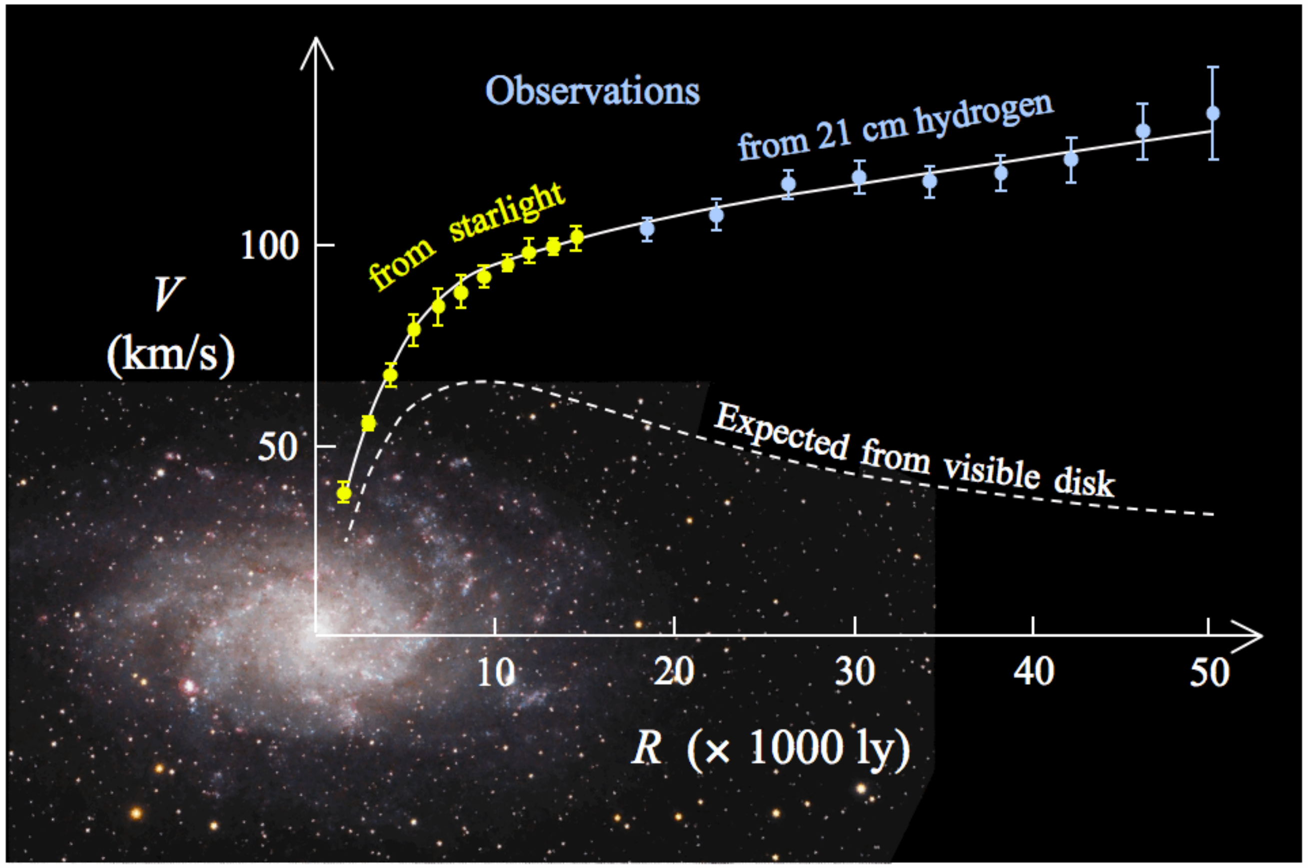
Characteristic imprint in the matter power spectrum and galaxy distribution



Kolb, “Particle Physics in the Early Universe” (1998)

3. Dark Matter in the Milky Way

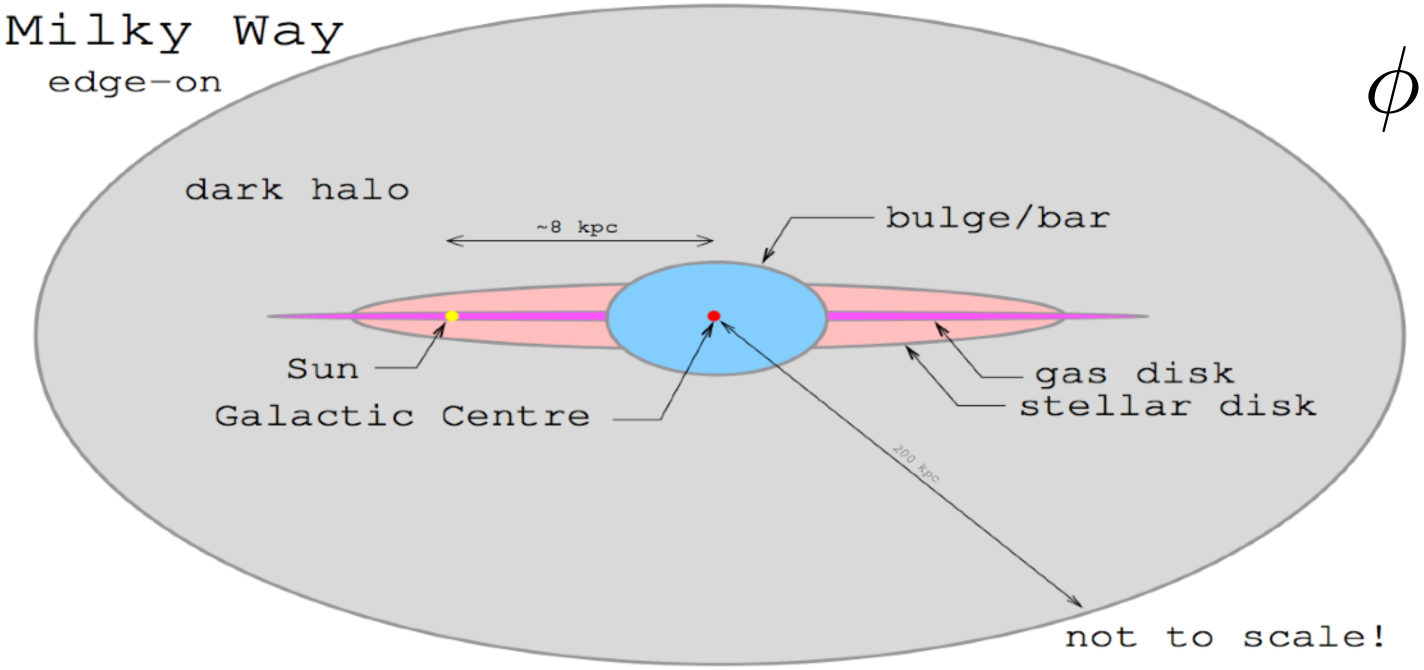
Galactic rotation curve



$$v_c^2(<R) = R\frac{d\phi_{\rm tot}}{dR} = \frac{GM(<R)}{R}$$

$$v_{\rm LSR}^{\rm los}(R) = \left(\frac{v_c(R)}{R/R_\odot} - v_\odot\right)\cos b \sin l$$

Doppler shift from masers, gas and stars
+ distance information (e.g. photo-spectroscopy for stars)



Visible components of the Milky Way

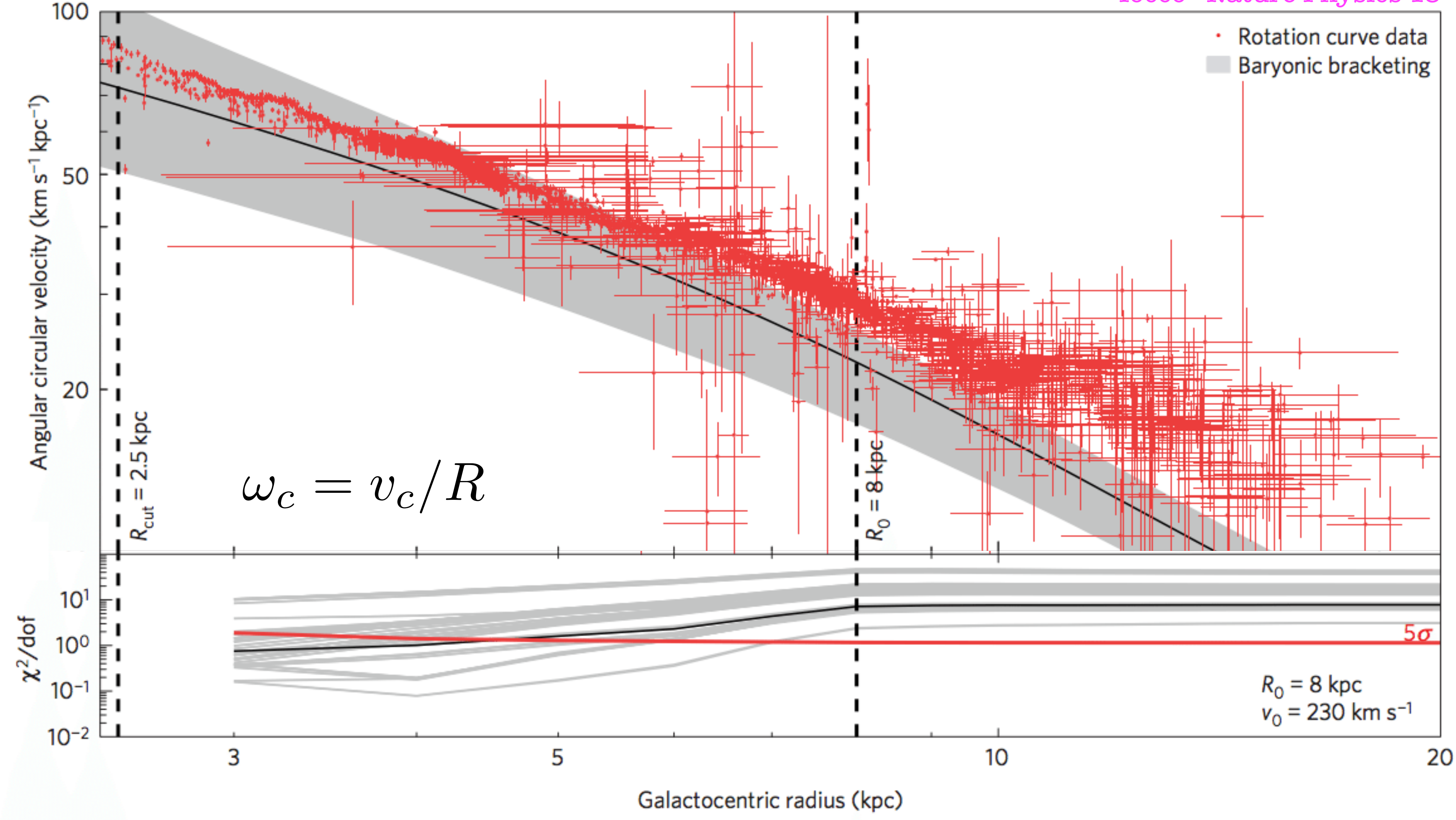
$$\phi_{\rm baryon} = \phi_{\rm bulge} + \phi_{\rm disk} + \phi_{\rm gas}$$

Evidence for additional contribution to the total gravitational potential?

Credit: M. Pato

Galactic rotation curve

Iocco+ Nature Physics'15

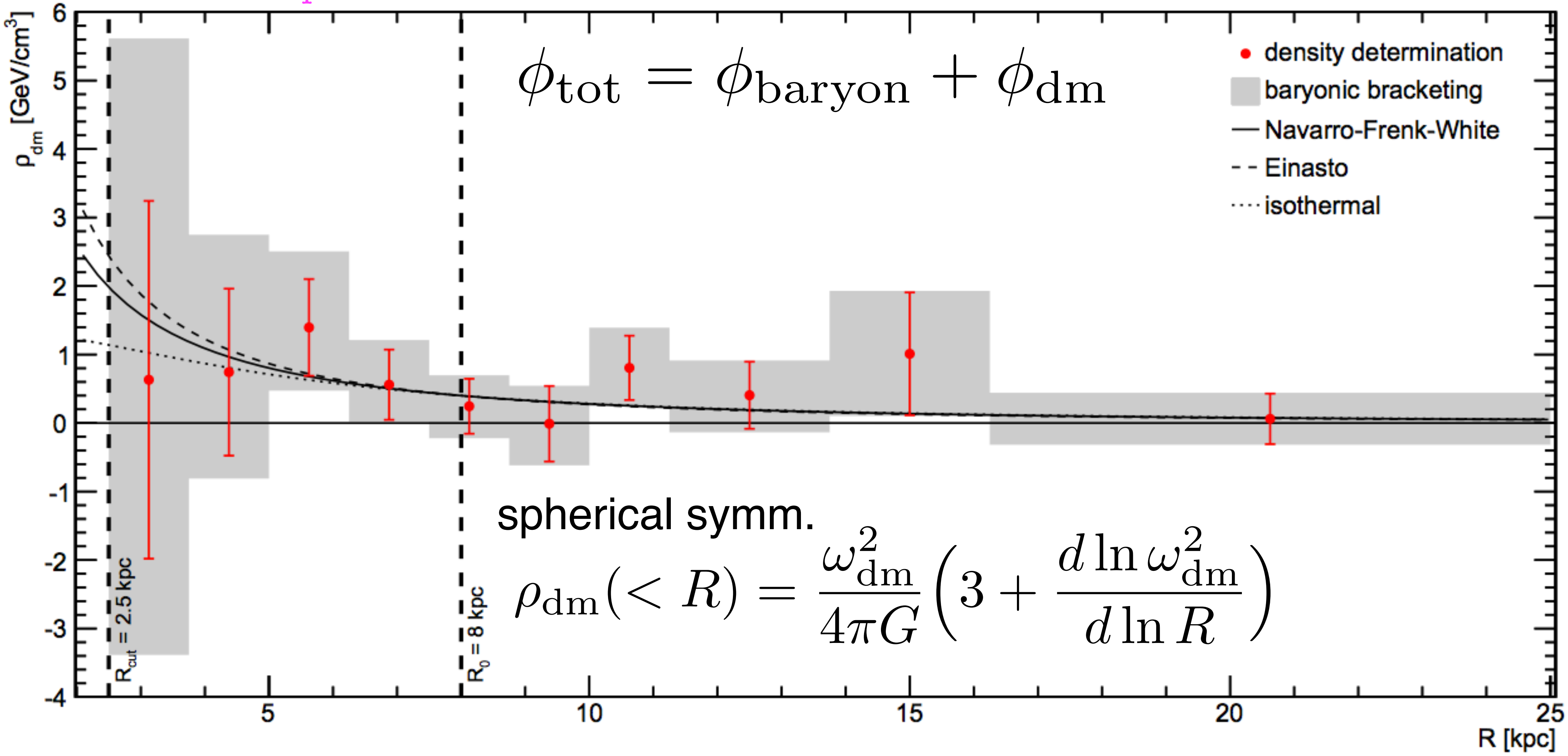


$$\omega_c = v_c / R$$

Comparison between expectation from visible matter and rotation curve data (new compilation) → Additional (dark) component needed within the solar circle.

Reconstructing the dark matter distribution

Pato&Iocco+ ApJ'15



$$\phi_{\rm tot} = \phi_{\rm baryon} + \phi_{\rm dm}$$

spherical symm.

$$\rho_{\rm dm}(< R) = \frac{\omega_{\rm dm}^2}{4\pi G}\left(3 + \frac{d\ln\omega_{\rm dm}^2}{d\ln R}\right)$$

Non-parametric reconstruction: approach free of profile assumptions, but uncertainties are large and hinder discrimination power between different radial behaviours. Pato&Iocco+ ApJ'15; Salucci+A&A'10

[see Persia+ MNRAS'96; Salucci+ MNRAS'07 for external galaxies]

Reconstructing the dark matter distribution

$$\omega_{\rm dm}^2 = \frac{G}{R^3}\int_0^R dr\, 4\pi r^2\, \rho_{\rm dm}(r)$$

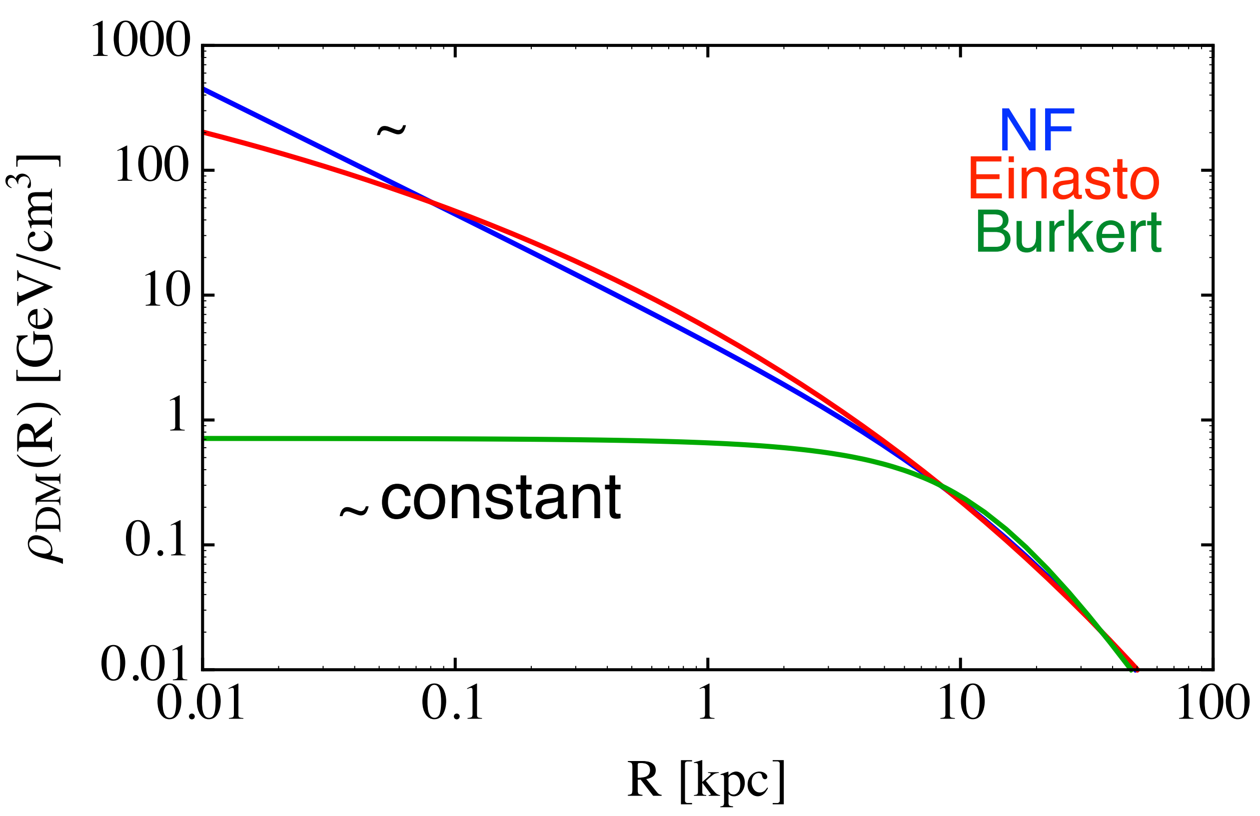
$$\rho_{\rm dm}(R_\odot) \equiv \rho_\odot$$

NFW

$$\rho_{\rm dm} \propto (r/r_s)^{-\gamma}(1+r/r_s)^{-3+\gamma}$$

Einasto

$$\rho_{\rm dm} \propto \exp(-2((r/r_s)^\alpha - 1)/\alpha)$$



Reconstructing the dark matter distribution

$$\omega^2_{\rm dm} = \frac{G}{R^3}\int_0^R dr\, 4\pi r^2\, \rho_{\rm dm}(r)$$

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NFW

$$\rho_{\rm dm} \propto (r/r_s)^{-\gamma}(1+r/r_s)^{-3+\gamma}$$

Einasto

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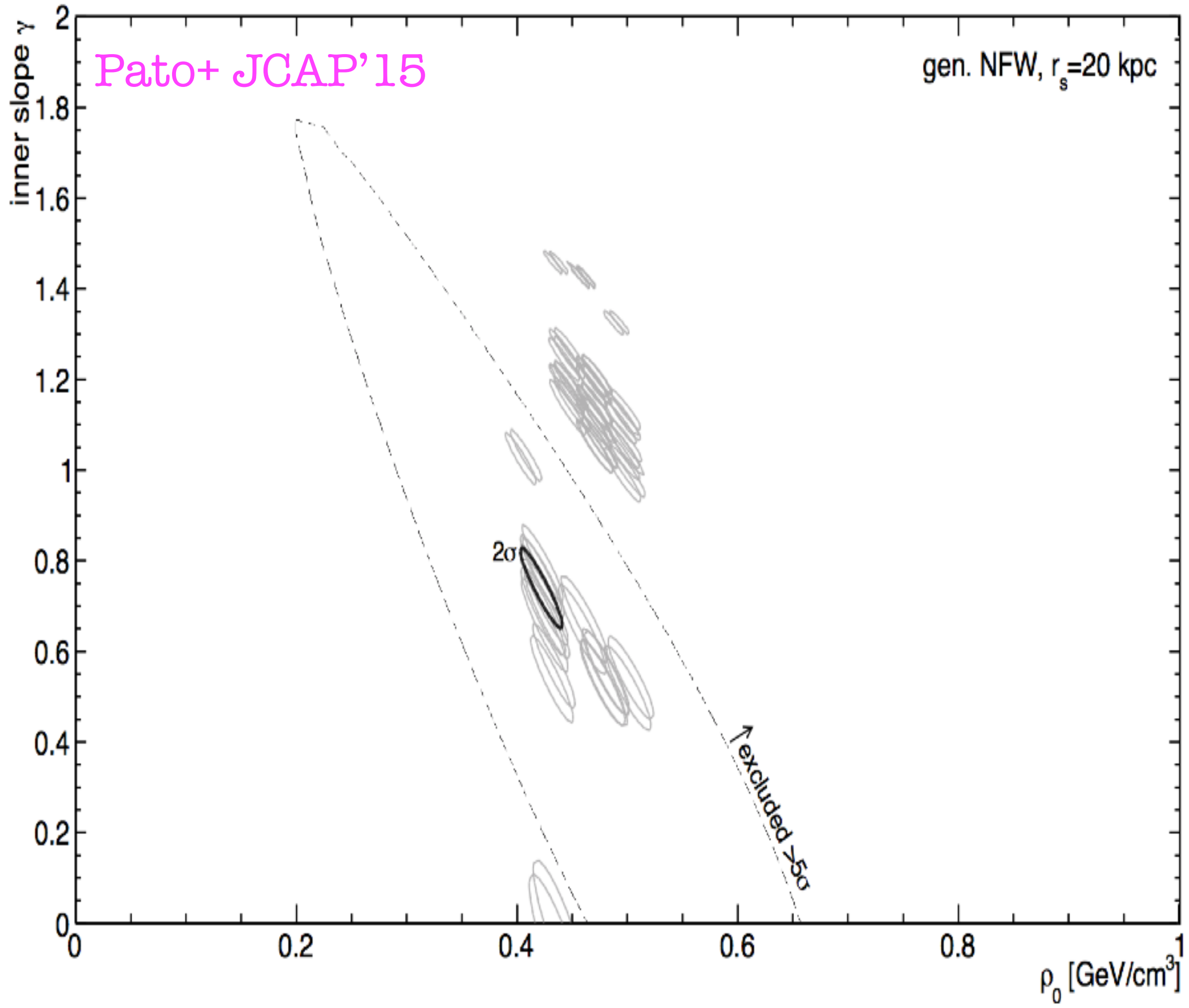
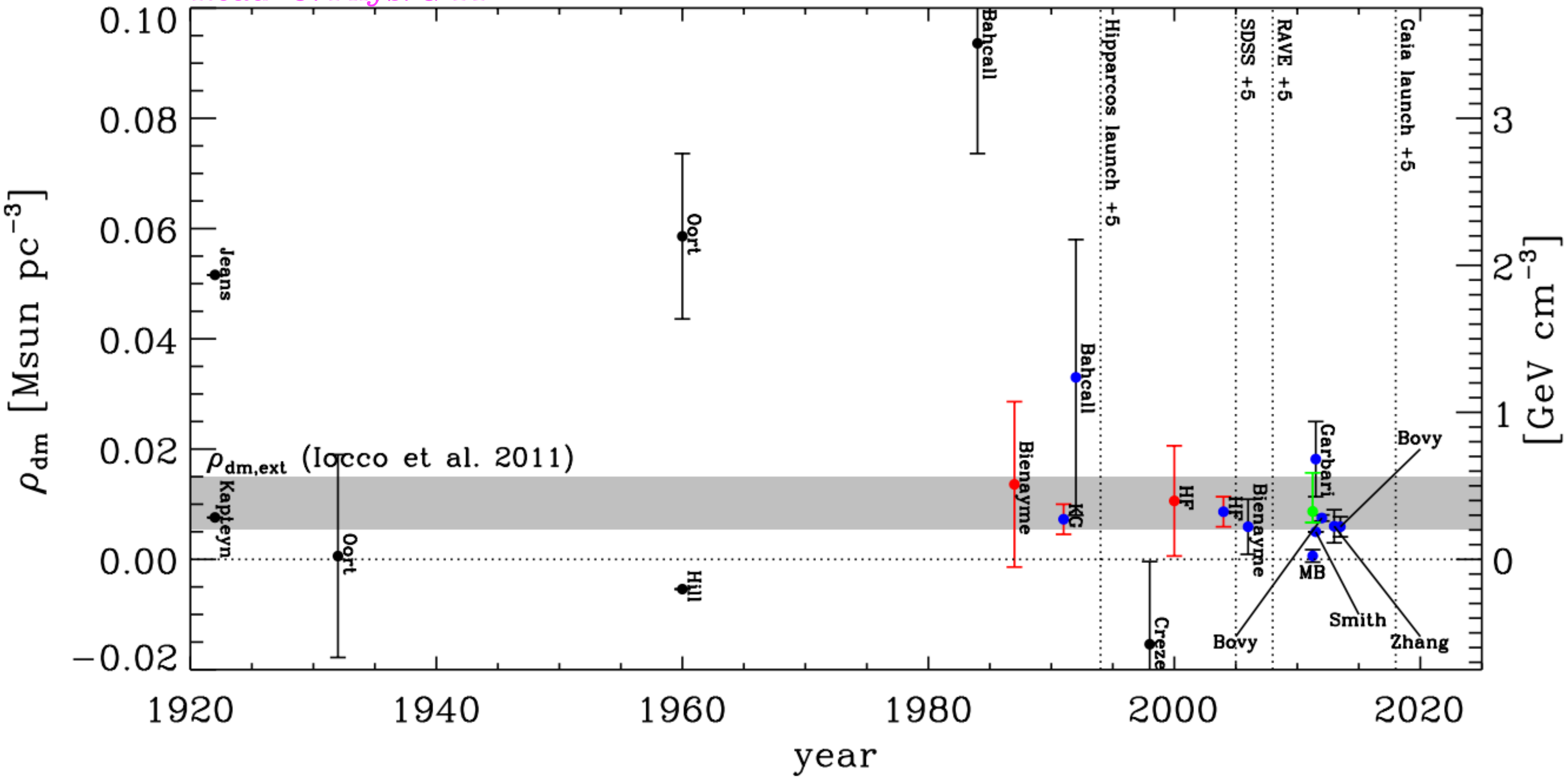


Parametric reconstruction: strong profile assumptions, "global" method to derive local DM density.

e.g: Pato+ JCAP'15; McMillan+ MNRAS'16; Iocco&Benito PDU'17

A full parametric reconstruction of the DM profile should properly account for correlations among parameters.

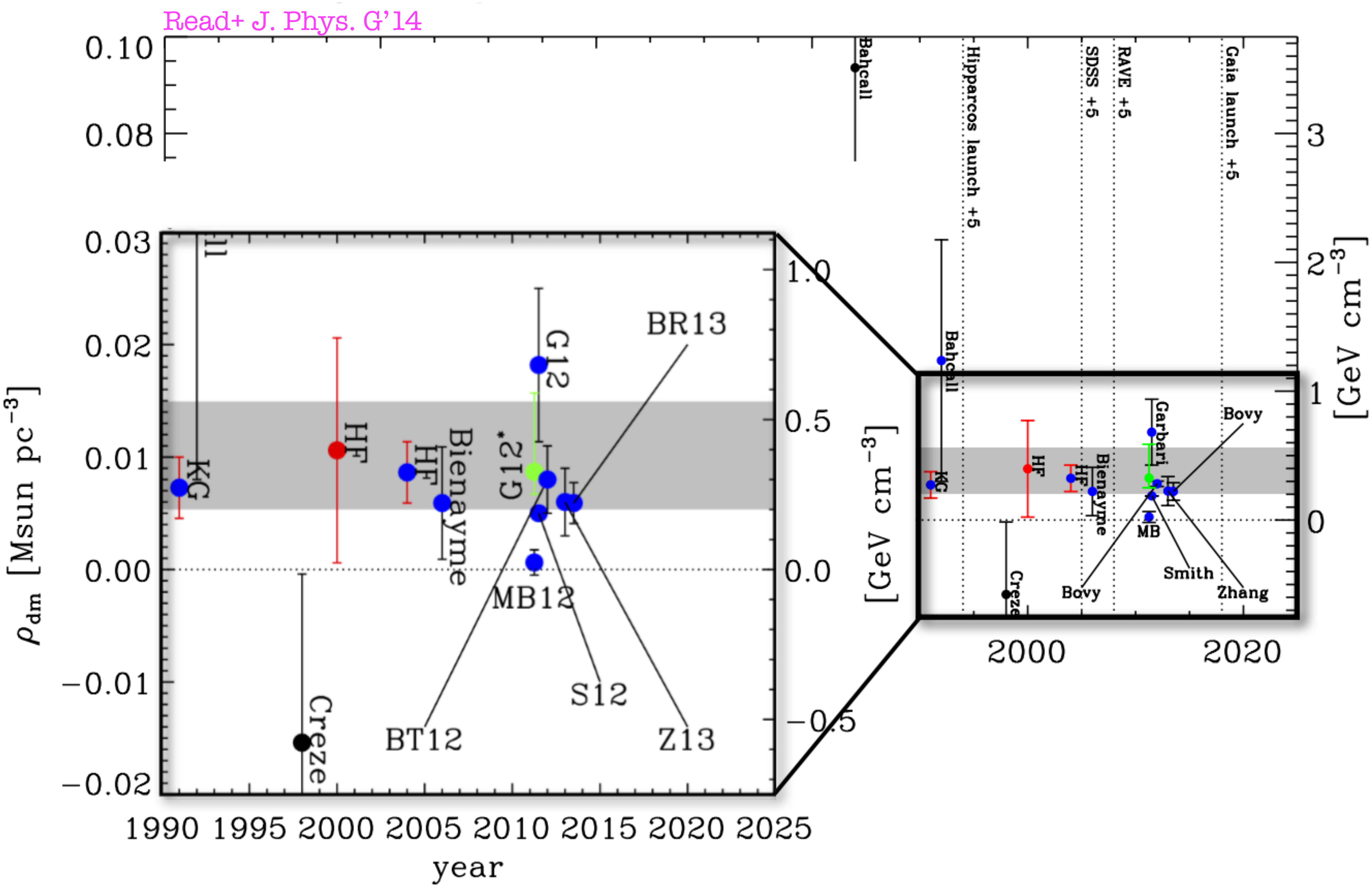
The local dark matter density



Read+ J. Phys. G’14

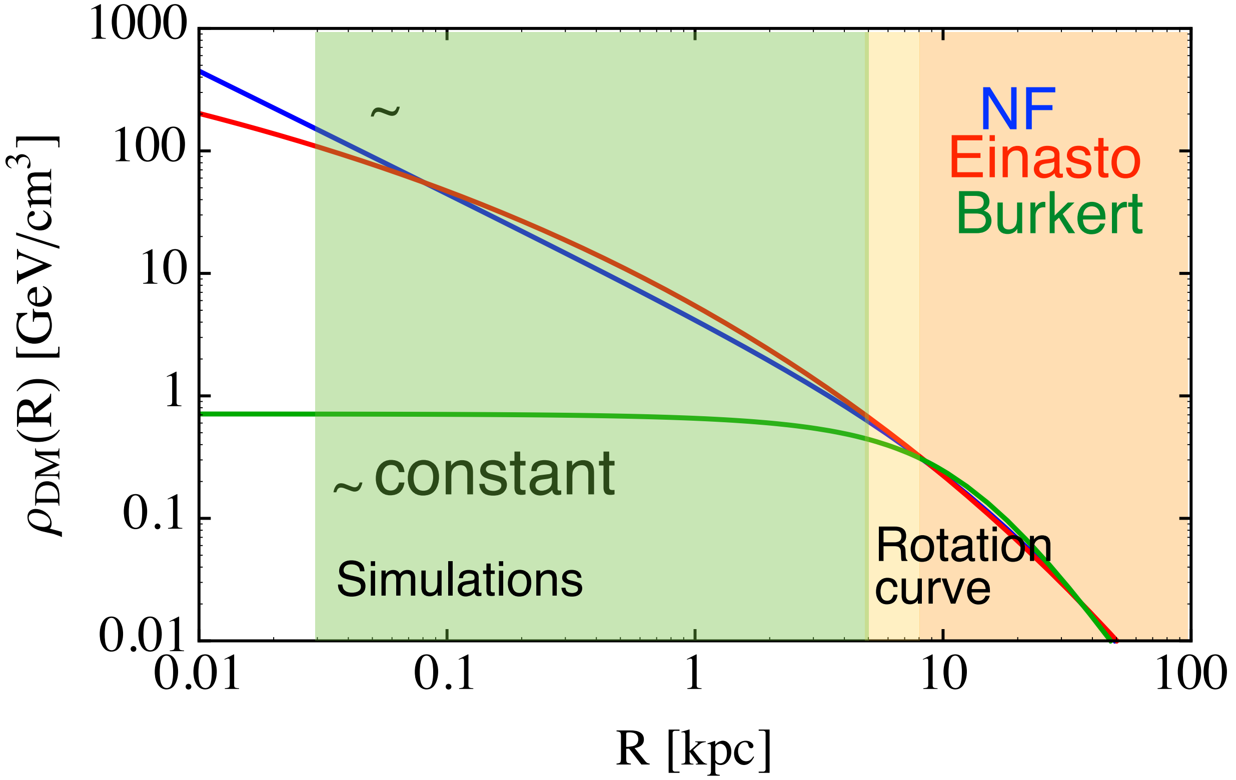
- Local measures use the vertical kinematics of stars (tracers) near the Sun: few assumptions but larger errors.
  e.g: Garbari+ MNRAS’12; Silverwood+MNRAS’16
- Global measures extrapolate DM mass profile from the rotation curve: small errors but strong assumptions on Galactic halo shape.
  e.g: Pato&Iocco JCAP’15
- Combined measurements can probe local shape (oblate/prolate halo)

The local dark matter density



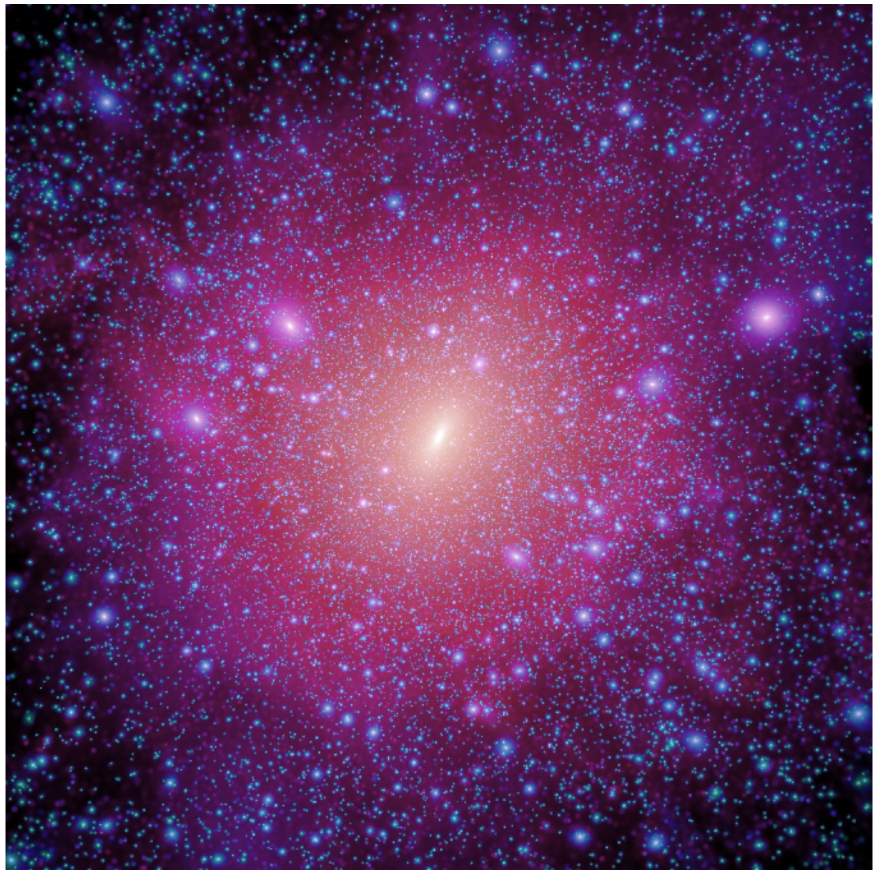
Gaia will move us to precision measurement of the local DM density

The MW dark matter distribution

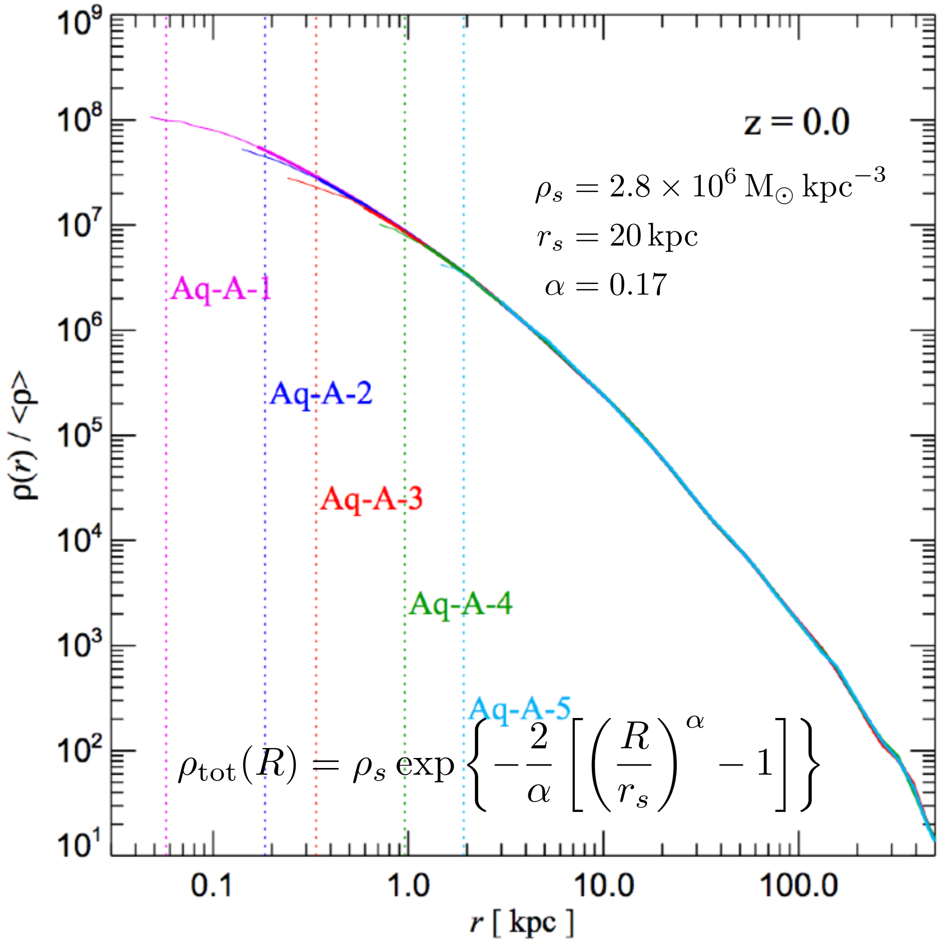


Rotation curve can only probe DM spatial distribution down to a few kpc.

We need to rely on simulations of galaxy formation, which include baryon effects.



Springel+ MNRAS'08



$\rho_s = 2.8\times10^6\,\mathrm{M_\odot\,kpc^{-3}}$

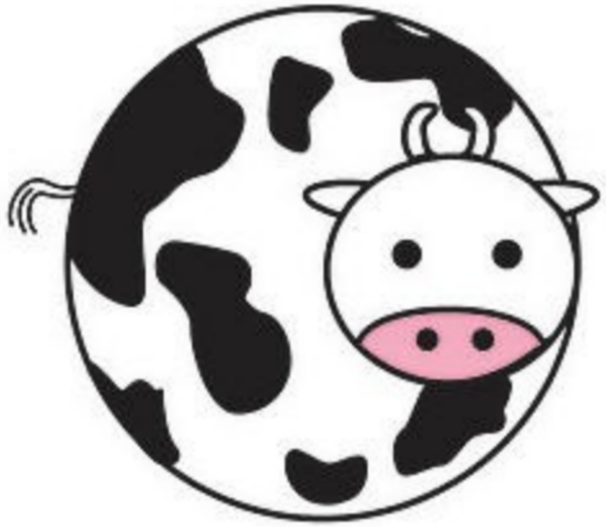
$r_s = 20\,\mathrm{kpc}$

$\alpha = 0.17$

$$\rho_{\rm tot}(R) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{R}{r_s}\right)^\alpha - 1\right]\right\}$$

The standard halo model

WIMP in the halo of the Galaxy are expected to form a Maxwellian distribution of non-relativistic particles



From Galactic (flat) rotation curve
+ spherical symmetry

$$\rho_{\rm DM} \simeq \frac{1}{r^2}$$

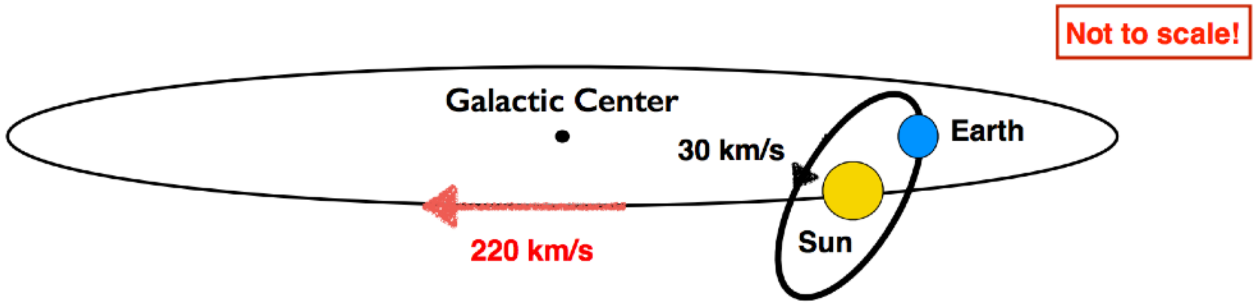
For a dilute gas at constant T
(condition for hydrostatic equilibrium)

$$\frac{v_{\rm rms}^2}{v_{\rm rot}^2} = -3\frac{d\ln R}{d\ln \rho} = \frac{3}{2}$$

Sun velocity around Galactic center

$$v_{\rm rot} \sim 220\,{\rm km/s}$$

$$\longrightarrow \quad v_{\rm rms} \sim 270\,{\rm km/s} \sim 10^{-3}\,{\rm c}$$



Non-relativistic particles

[Thermal equilibrium reached during formation of Galaxy: WIMP are “frozen” into highest-entropy configuration when mixed by the violently changing gravitational potential during gravitational collapse, “violent relaxation”. Confirmed lately by simulations] Lynden-Bell, MNRAS 126 (1967) 101

The velocity distribution

$$f(\mathbf{v}) = \mathcal{F}(\mathbf{x}_\odot, \mathbf{v})/\rho(\mathbf{x}_\odot)$$

It is possible to infer f(v) under some symmetry conditions

Binney & Tremaine, “Galactic dynamics”

$$\rho_{\rm DM}(\mathbf{x}) \equiv \int d^3v F(\mathbf{x}, \mathbf{v})$$

Invert and evaluate F at the solar position

$$v_{\rm tot}^2 = \frac{GM_{\rm tot}(r)}{r}$$

Tot = Visible + DM

Steady state solution to collisionless Boltzmann equation.
Jean’s theorem: steady-state solutions depend on phase space only through integral of motions (E, angular momentum components)

In case of spherical symmetry:

$$F(\mathbf{x}, \mathbf{v}) \equiv F(E)$$

The Eddington's equation

Introducing two new variables (relative energy and potential) it is possible to invert the equation * => Eddington's equation

$$\epsilon = \psi - \frac{1}{2}v^2$$

$$F(\epsilon) = \frac{1}{\sqrt{8}\pi^2}\frac{d}{d\epsilon}\int_0^{\epsilon}\frac{d\rho}{d\psi}\frac{d\psi}{\sqrt{\epsilon - \psi}}$$

Application to isothermal sphere:

$$\rho(r) = \rho_0 (r_0/r)^2 \qquad \psi = \sigma^2 \log(\frac{\rho}{\rho_0}) \longrightarrow \rho(\psi) = \rho_0 e^{\frac{\psi}{\sigma^2}}$$

Eddington's equation → Maxwell-Boltzmann distribution

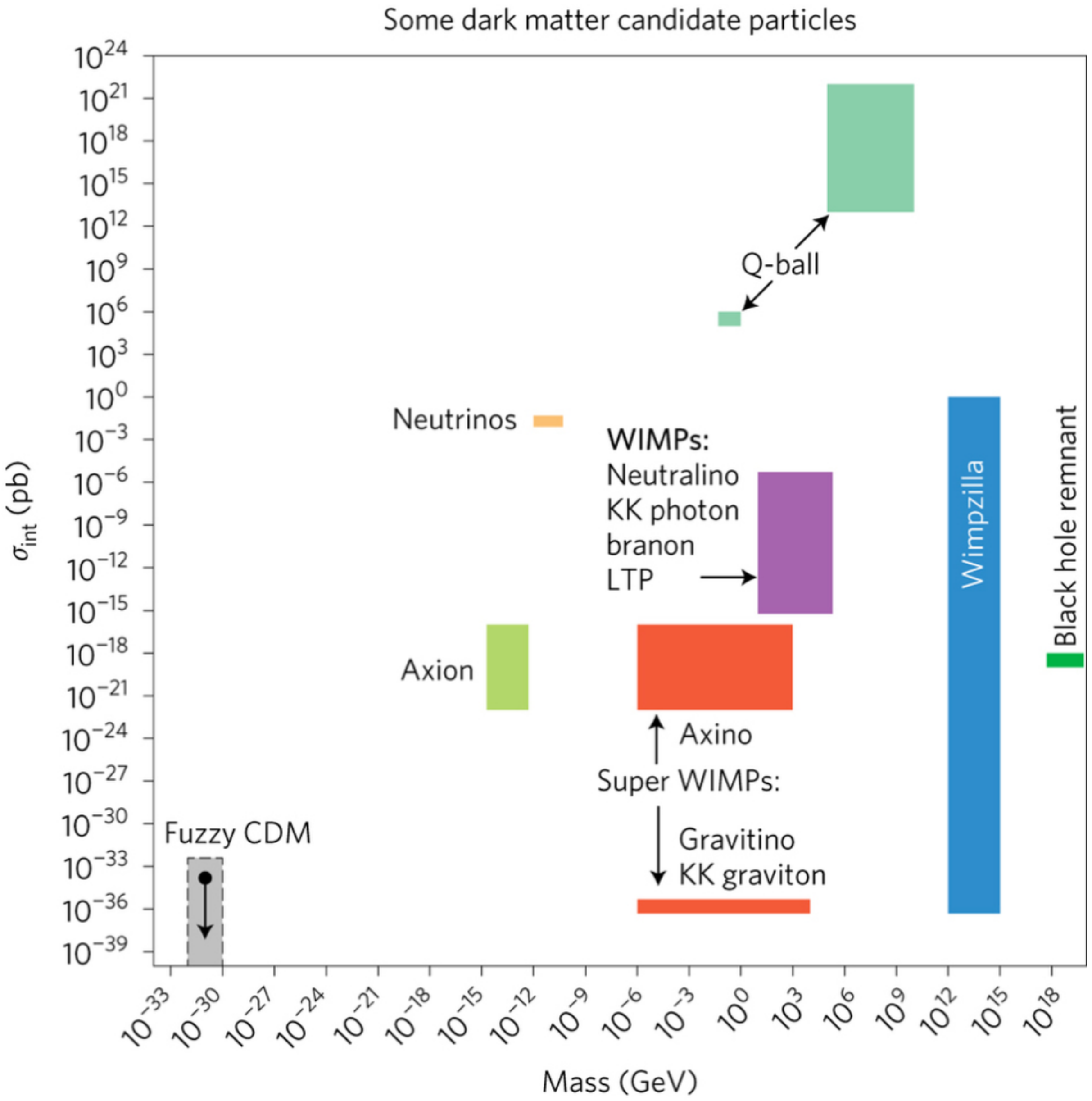
$$F(v) \propto e^{-\frac{3}{2}\frac{v^2}{v_{\rm rms}^2}} = e^{-\frac{v^2}{v_c^2}} \qquad \langle v^2 \rangle \equiv v_{\rm rms}^2 \equiv 3\sigma^2$$

4. Detection strategies for dark matter

How to identify dark matter?

- In order to define a search strategy, we first need to better define the dark matter candidate of interest (input from theory) => **DM zoology**!

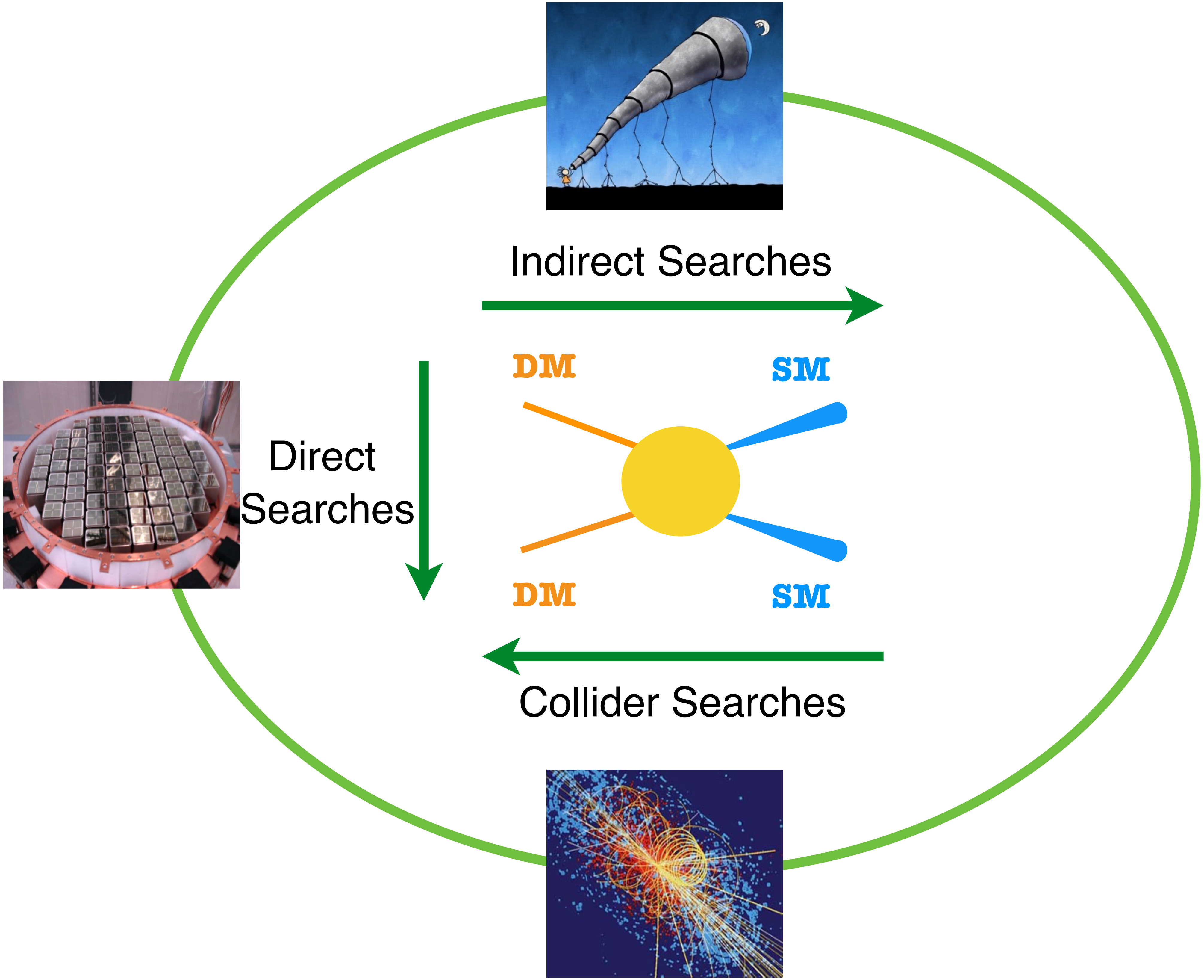
- Once the theoretical context is defined, we can engage in identification strategies which can be more or less model dependent (there is always some theoretical prejudice in DM searches)



Conrad & Reimer, Nature Physics 13 (2017) 224-231

[Review: Feng, Ann. Rev. Astron. Astrophys. 48 (2010) 495]

WIMP detection strategies



Indirect Searches

DM

SM

Direct Searches

DM

SM

Collider Searches

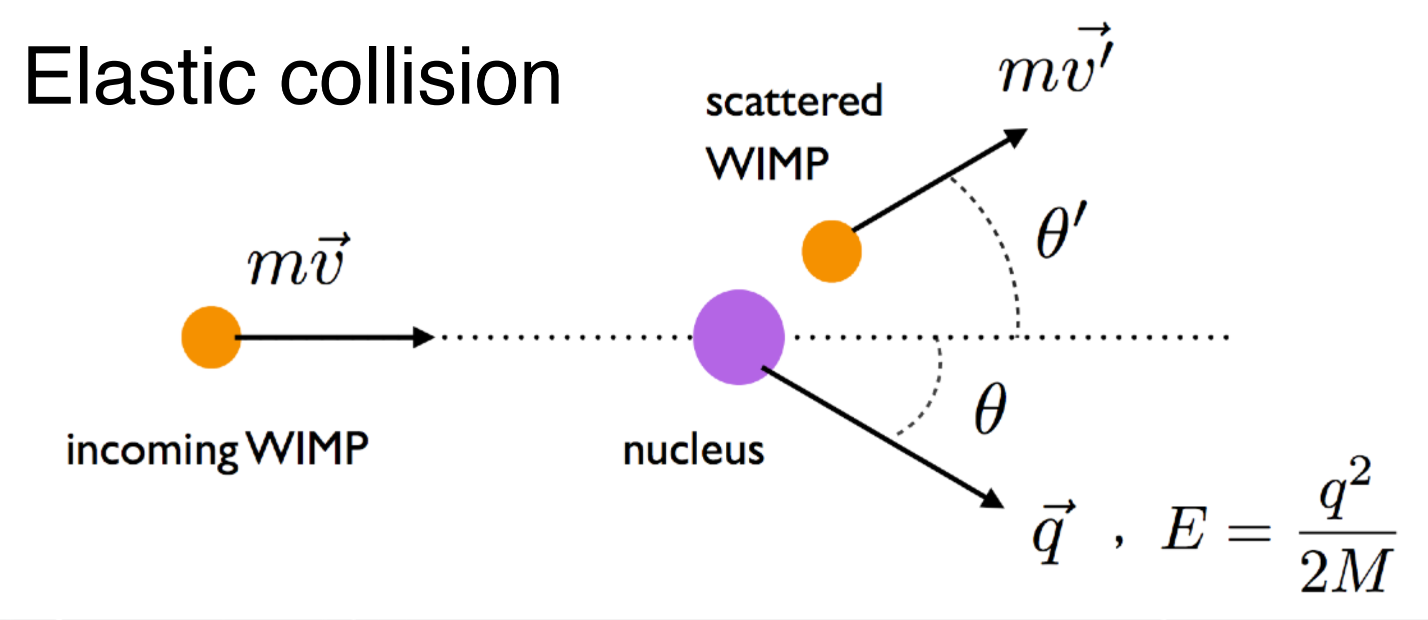
Direct dark matter detection

Lewin & Smith, Astropart.Phys.6 (1996) 87(1996);
Fitzpatrick+ JCAP 1302 (2013) 004

$$R \sim N_A \frac{\rho_{\rm DM}}{m_{\rm DM}} \sigma v$$

DM-nucleus scattering

Elastic collision



Direct detection: differential event rate

$$\frac{dR}{dE} \sim N_A \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{v>v_{\rm min}} d^3v f(\mathbf{v}) v \frac{d\sigma}{dE}$$

Differential rate

$$E \equiv E_R \lesssim \mathcal{O}(100)\,\mathrm{keV}$$

$$v_{\rm min} = \sqrt{\frac{E_R m_A}{2\mu}}$$

$$\frac{d\sigma}{dE} \propto \frac{\sigma_0}{v^2} \longrightarrow \frac{dR}{dE} = \rho_{\rm DM} \frac{\sigma_0 F^2(E)}{2 m_{\rm DM} \mu^2} \int_{v>v_{\rm min}} d^3v \frac{f(\mathbf{v})}{v}$$

Particle Physics

Astrophysics

$$\eta(v_{\rm min}) \equiv \int_{v>v_{\rm min}} d^3v \frac{f(\mathbf{v})}{v}$$

Halo integral

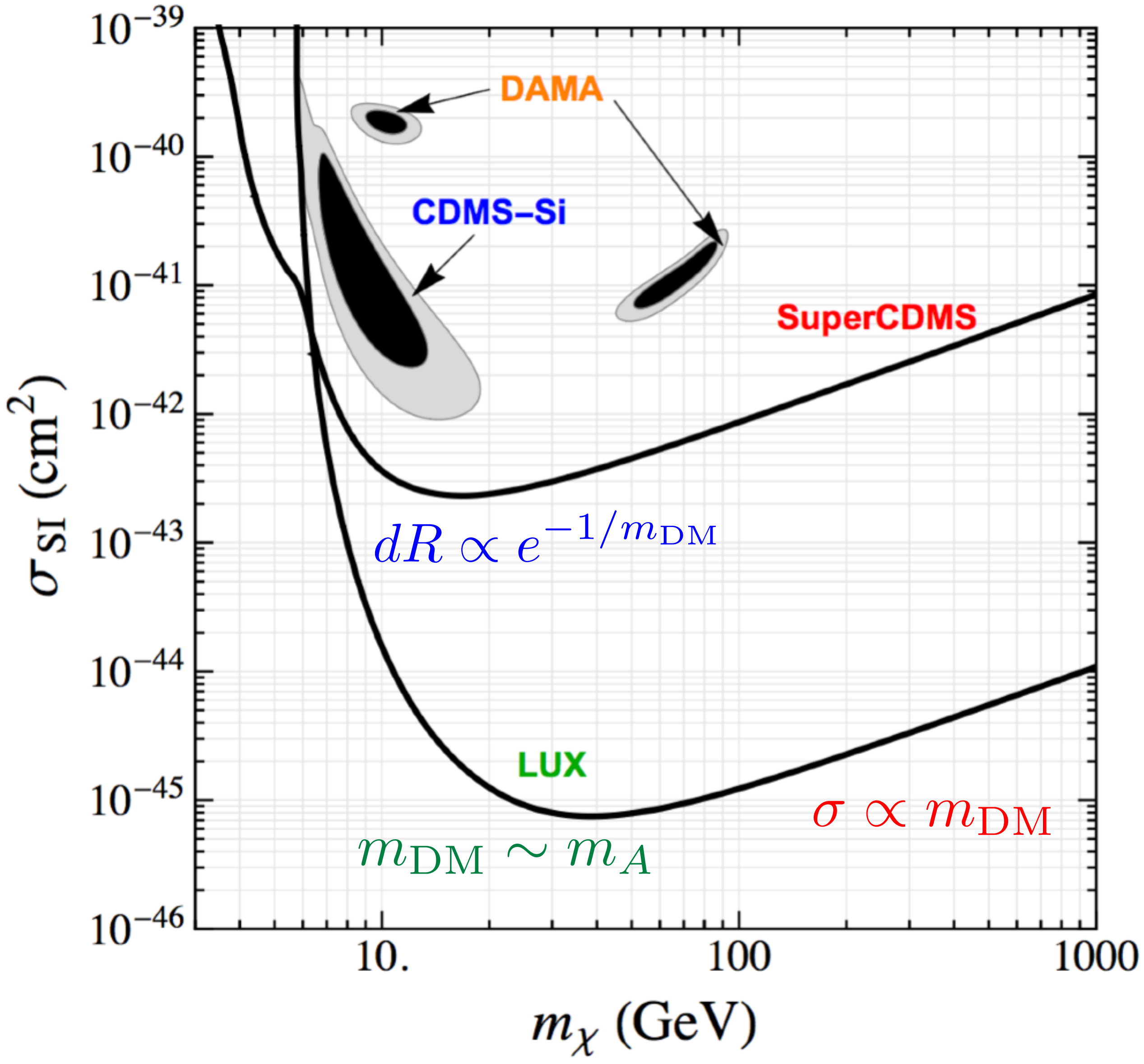
Direct detection: exclusion limits

Hp: Maxwellian velocity distribution

$$f(\mathbf{v}) \propto e^{-v^2/v_c^2} \qquad \longrightarrow \qquad \eta(v_{\rm min}) \propto e^{-v_{\rm min}^2/v_c^2}$$

- For large DM masses, the halo integral is almost independent on the mass.
- For small DM masses, the expected rate decreases as exp(-1/m_{DM})
- Peak of sensitivity @ target mass

$$\frac{dR}{dE} = \rho_{\rm DM}\frac{\sigma_0 F^2(E)}{2m_{\rm DM}\mu^2}\int_{v>v_{\rm min}} d^3v\frac{f(\mathbf{v})}{v}$$

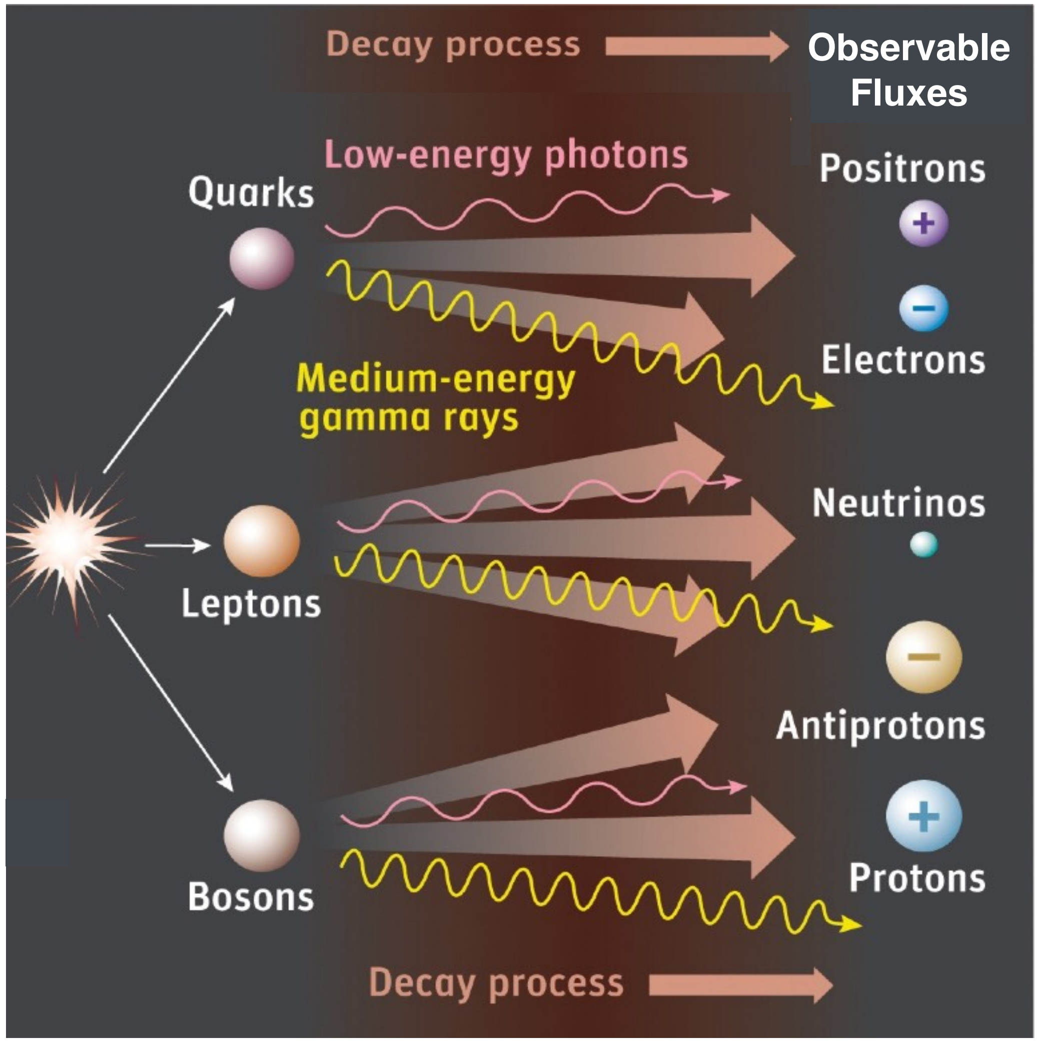


Indirect dark matter detection

<u>Two key-assumptions</u>:

1) Dark matter exists and is the main responsible for the gravitational potential inferred in galaxies, clusters and cosmo.
2) Dark matter is non-gravitationally coupled to standard matter.

DM annihilation/decay



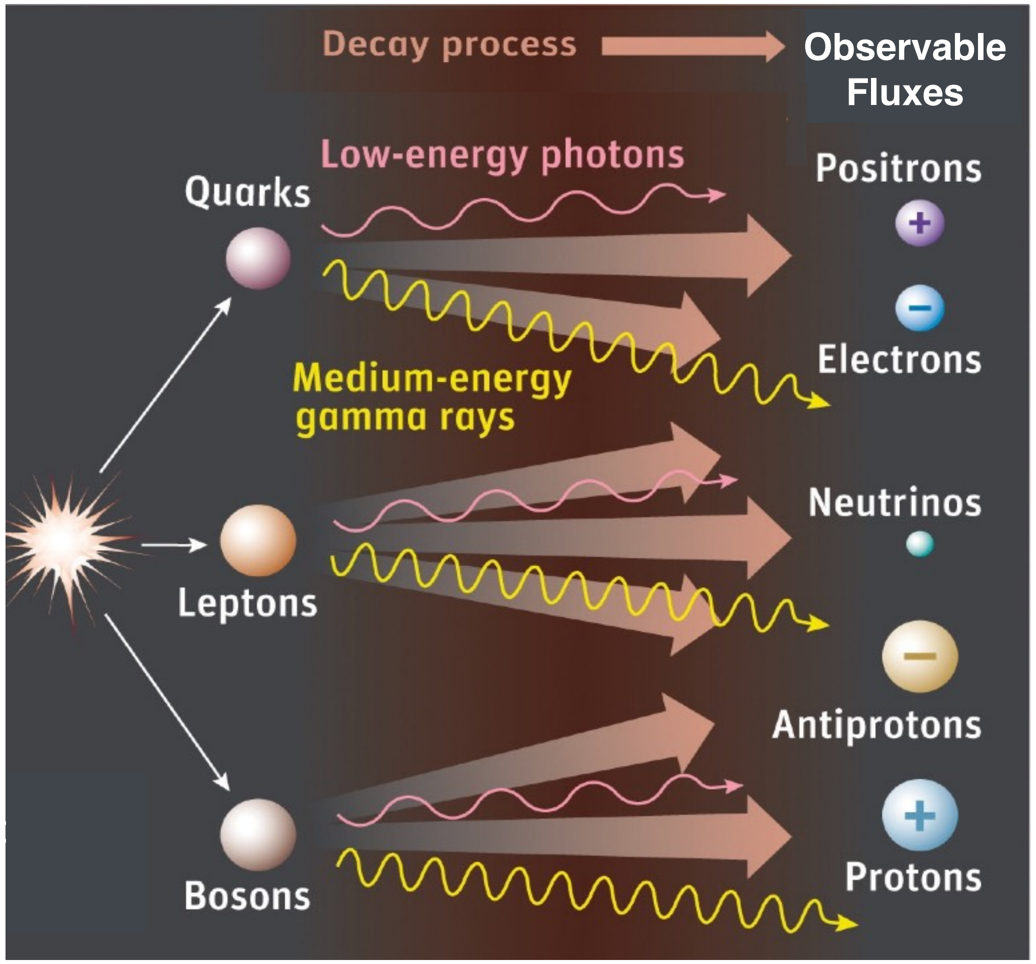
DM annihilation/decay leads to production of observable fluxes of stable particles.

<u>Disclaimer</u>:

1) Not necessarily signatures at the GeV-TeV-scale
2) DM at the electroweak scale is one among possible valuable solutions

Indirect dark matter detection

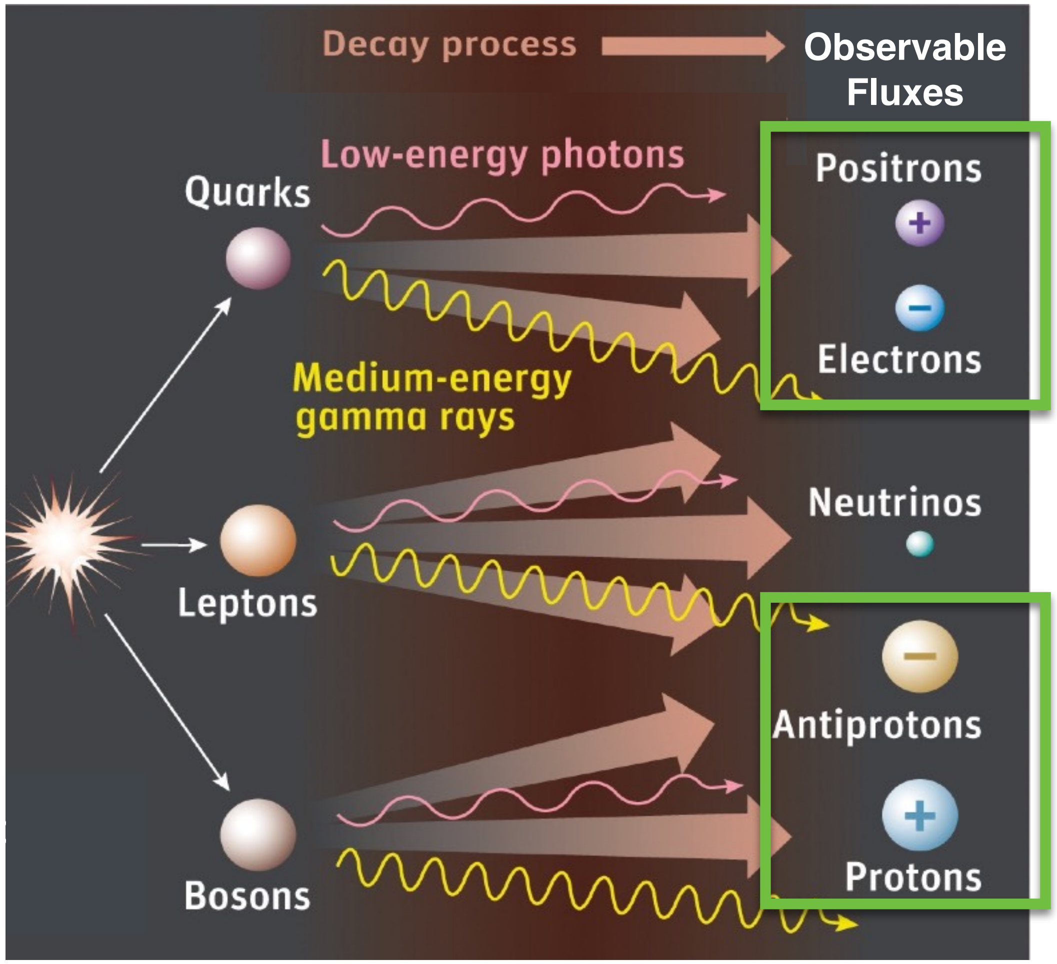
DM annihilation/decay

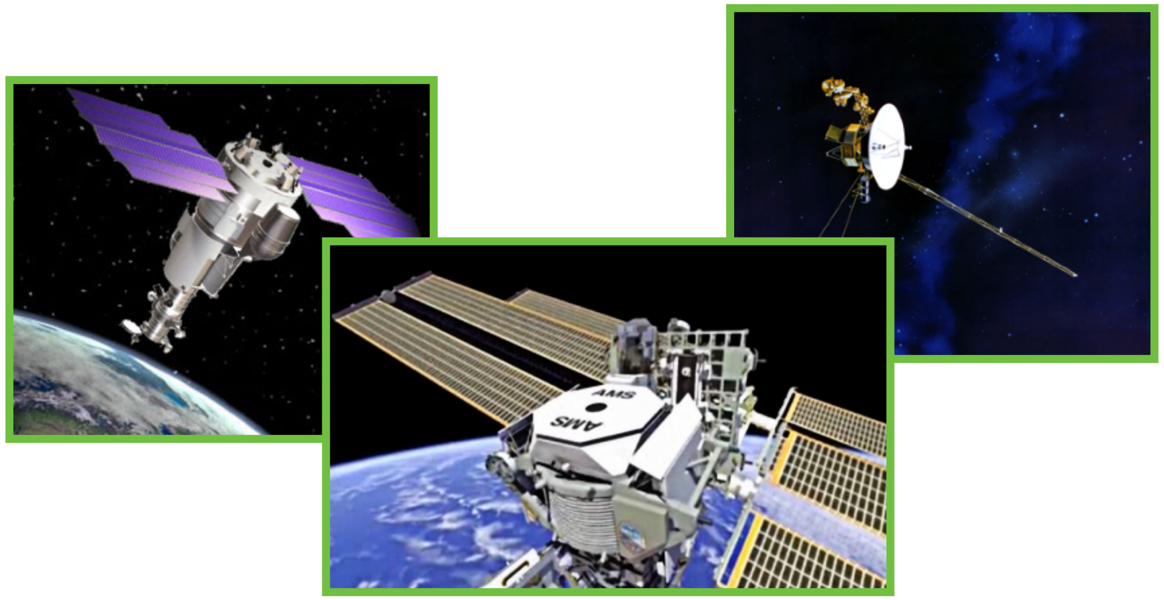


Indirect searches
for stable dark matter annihilation
(or decay) products.

Indirect dark matter detection

DM annihilation/decay





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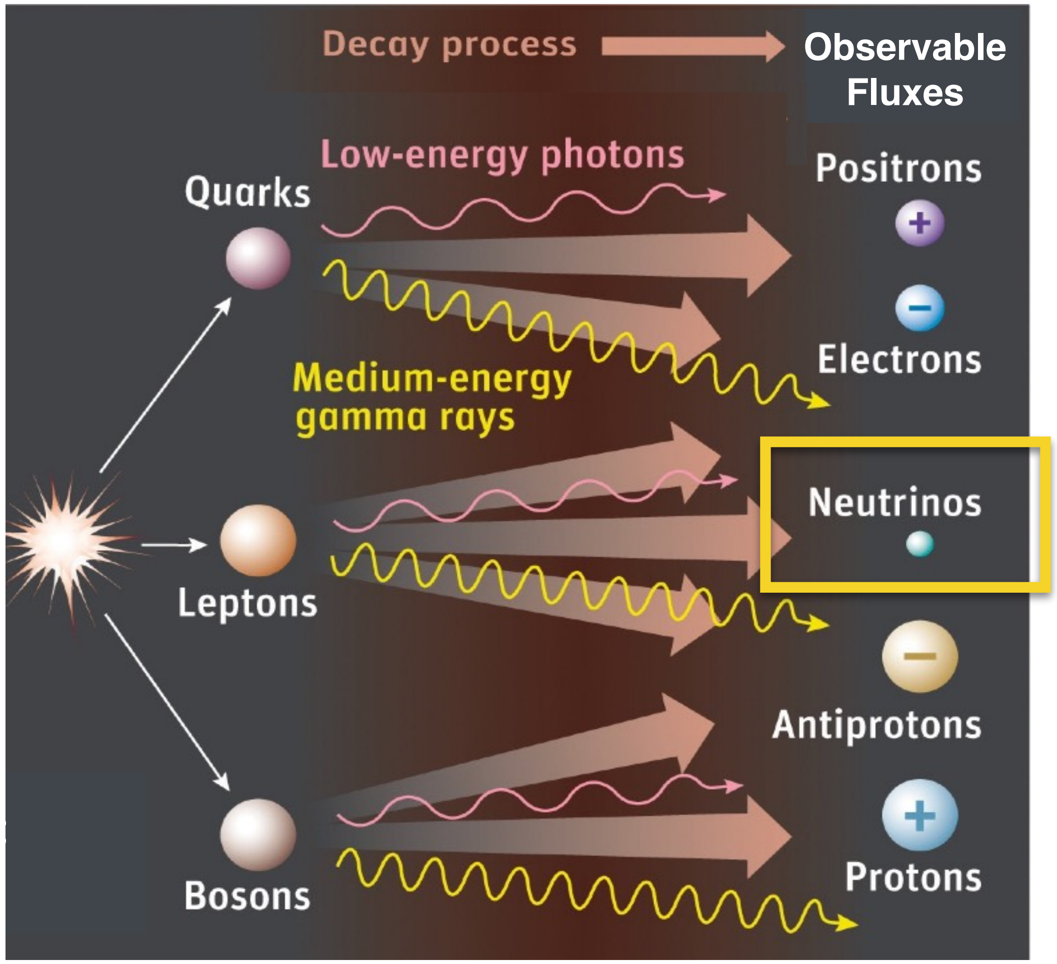
DM annihilation/decay



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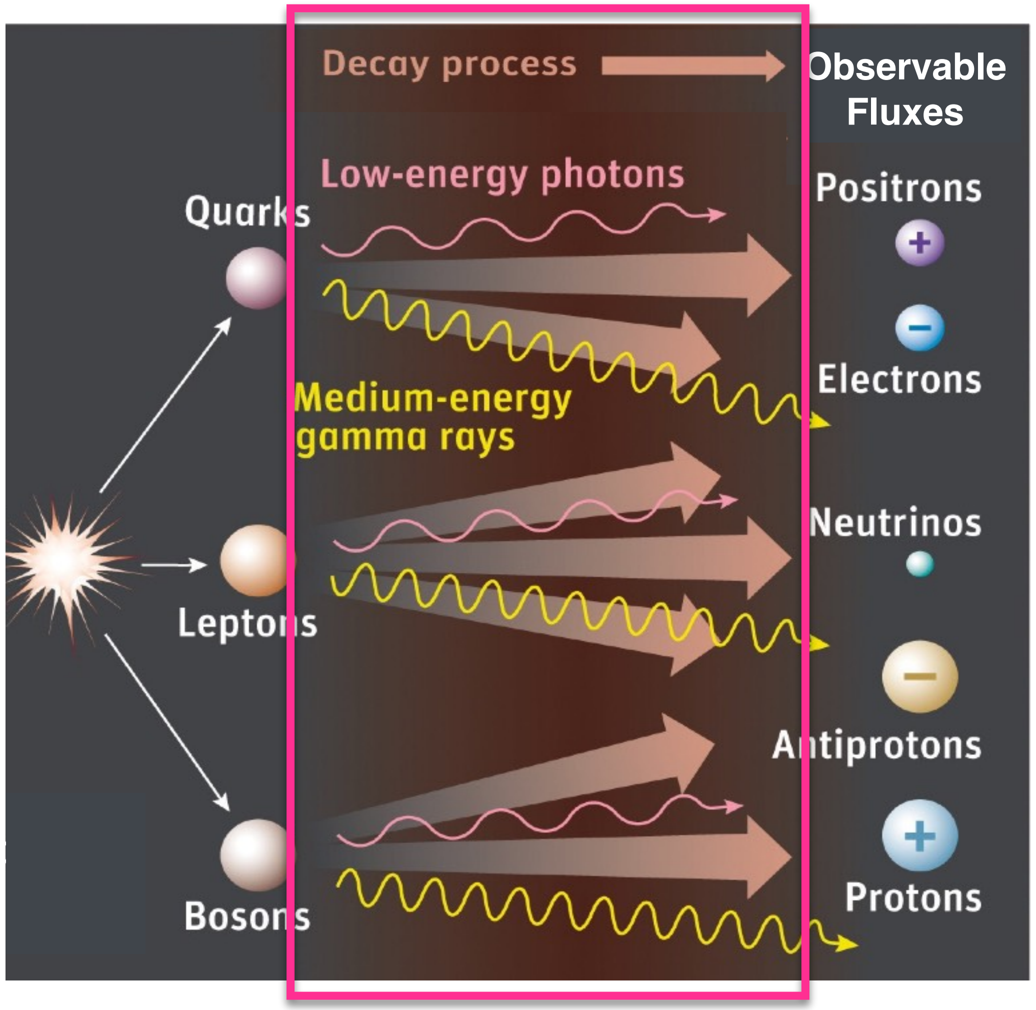

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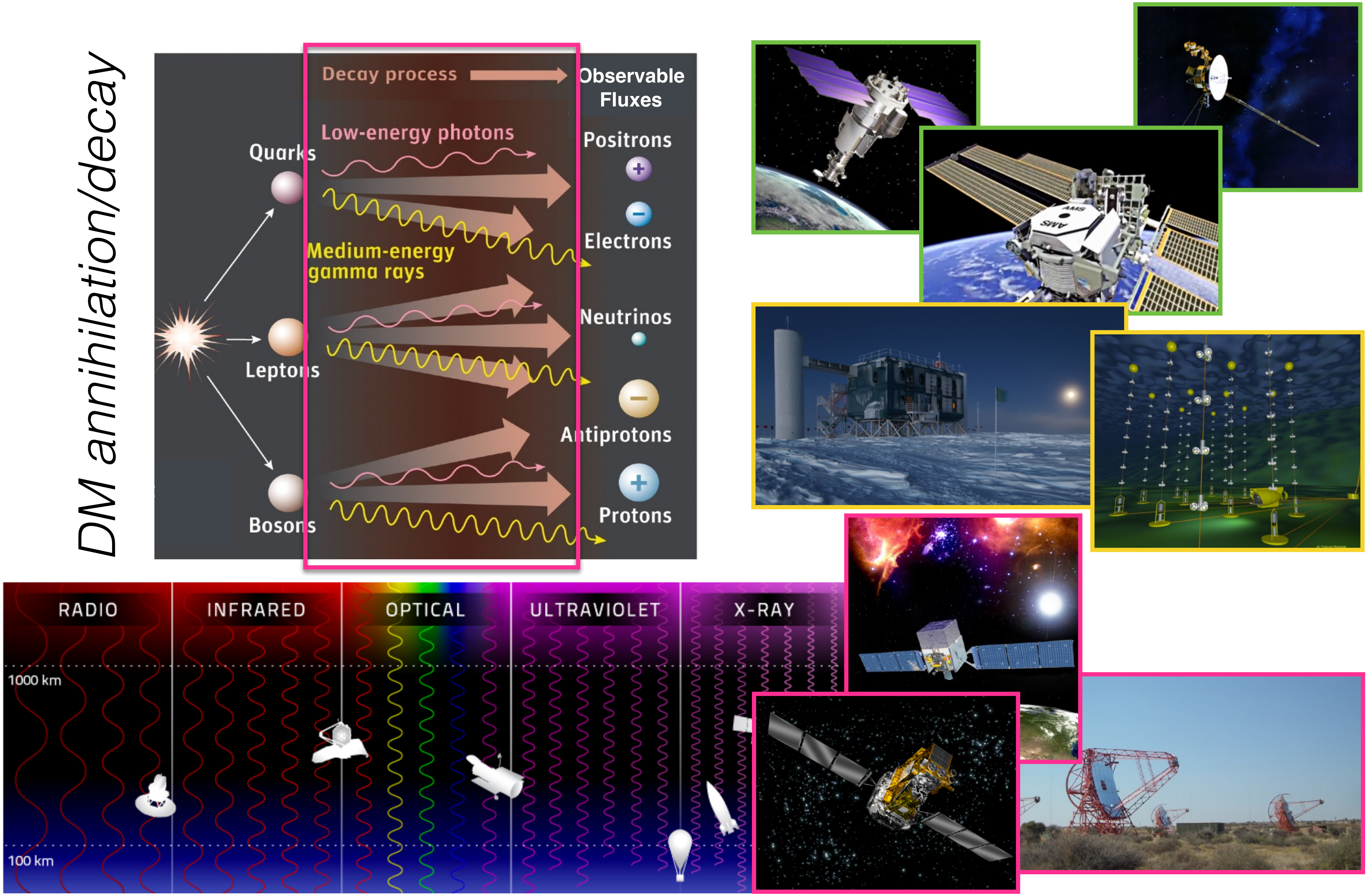
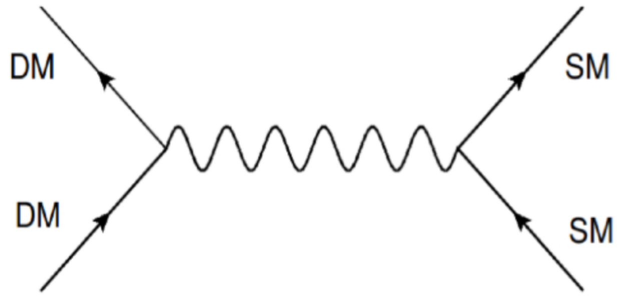


Indirect dark matter signals

Expected values? We know where to look for…

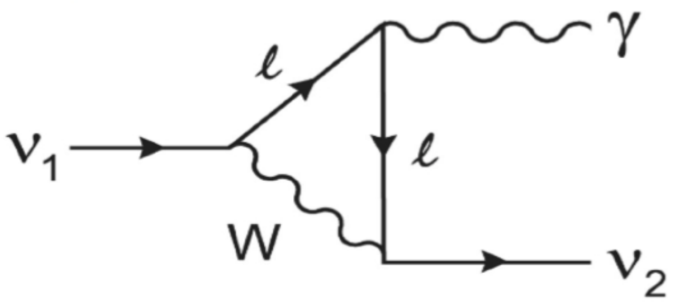
Annihilation



$$\langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

Connection with early Universe
and observed relic abundance
(not always trivial)

Decay



$$\tau_{\mathrm{DM}} \sim 10^{26}\,\mathrm{s}\left(\frac{\mathrm{TeV}}{m_{\mathrm{DM}}}\right)^5\left(\frac{M}{10^{15}\,\mathrm{GeV}}\right)^4$$

Eichler, PRL 1989

As for the proton, DM stability due
to an accidental symmetry

Reviews: Bringmann & Weniger, PDU'15; Ibarra+, Int. J. of Modern Physics A'13

Dark matter source term

$$[\mathrm{GeV}^{-1}\mathrm{s}^{-1}]$$

Annihilation

$$Q_i^{\mathrm{ann}}(r,E) = \langle \sigma_{\mathrm{ann}} v \rangle \times N_{\mathrm{pairs}}(r) \times \sum_f B_f \frac{dN_i^f}{dE}(E)$$

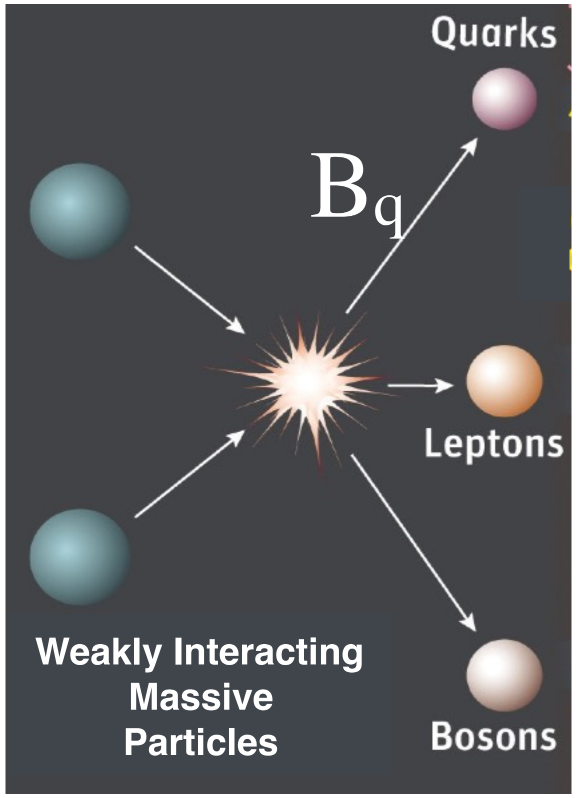
$$N_{\mathrm{pairs}}(r) = s \times N(r) = s \times \frac{\rho^2(r)}{m^2} \qquad s = \left\{ \underset{\text{Majorana}}{\frac{1}{2}}, \underset{\text{Dirac}}{\frac{1}{4}} \right\}$$

Decay

$$Q_i^{\mathrm{dec}}(r,E) = \Gamma_{\mathrm{dec}} \times N(r) \times \sum_f B_f \frac{dN_i^f}{dE}(E)$$

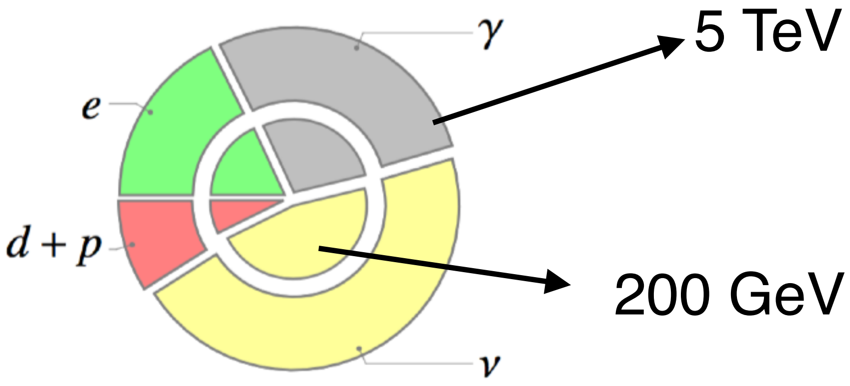
$$N(r) = \frac{\rho(r)}{m}$$

Energy distribution into final state particles



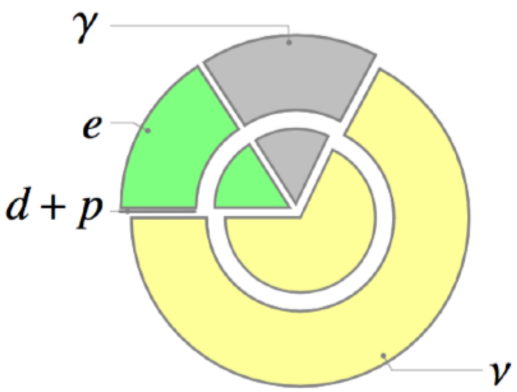
$\mathrm{DM\,DM} \rightarrow \mathrm{SM\,SM}$

DM DM→ b+b



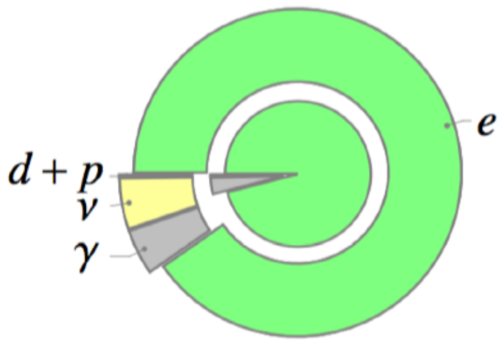
$E_{\gamma+e}/E_{\rm tot} = 0.462\ (0.454)$
$E_{p+d}/E_{\gamma+e} = 0.159\ (0.198)$

DM DM→ $\tau_R^- + \tau_R^+$



$E_{\gamma+e}/E_{\rm tot} = 0.321\ (0.328)$
$E_{p+d}/E_{\gamma+e} = 0.000\ (0.001)$

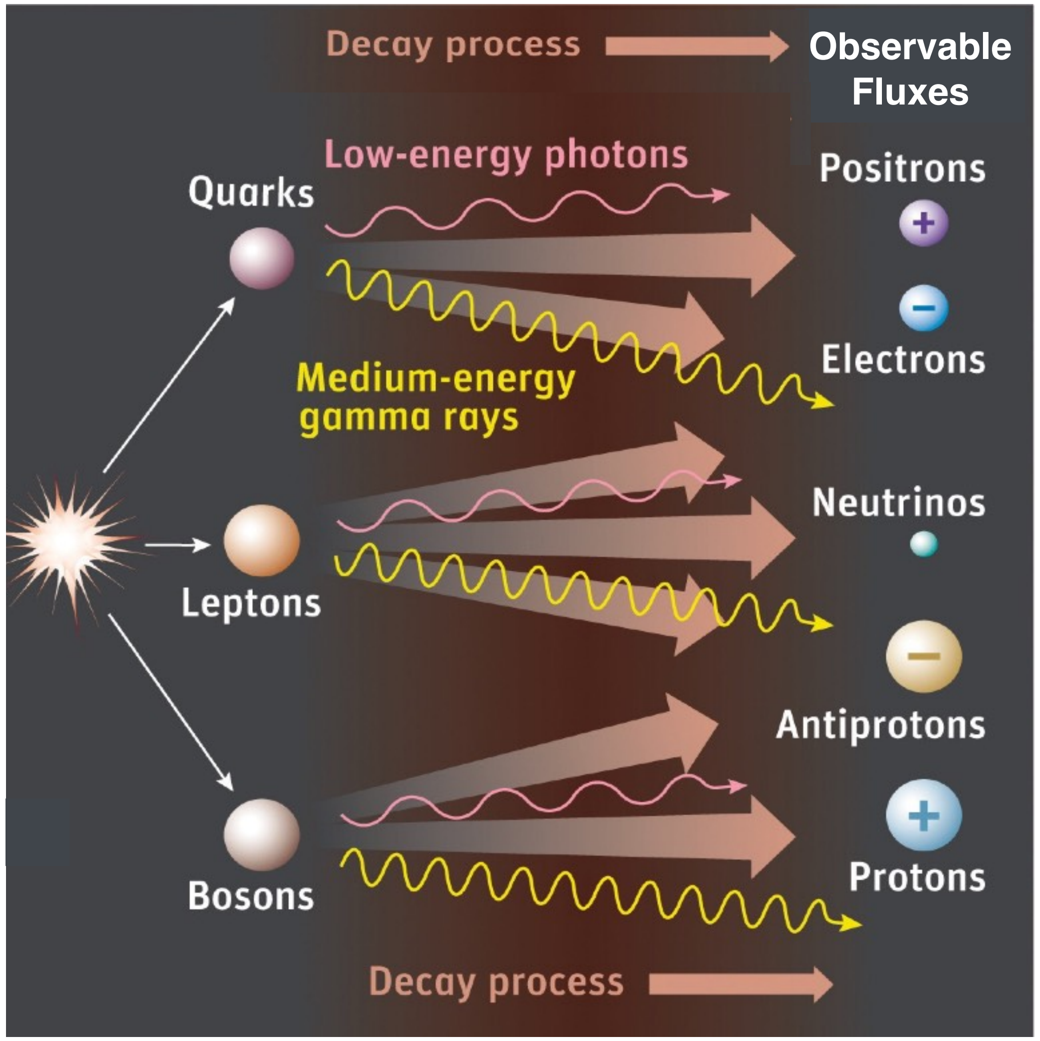
DM DM→ $e_L^- + e_L^+$



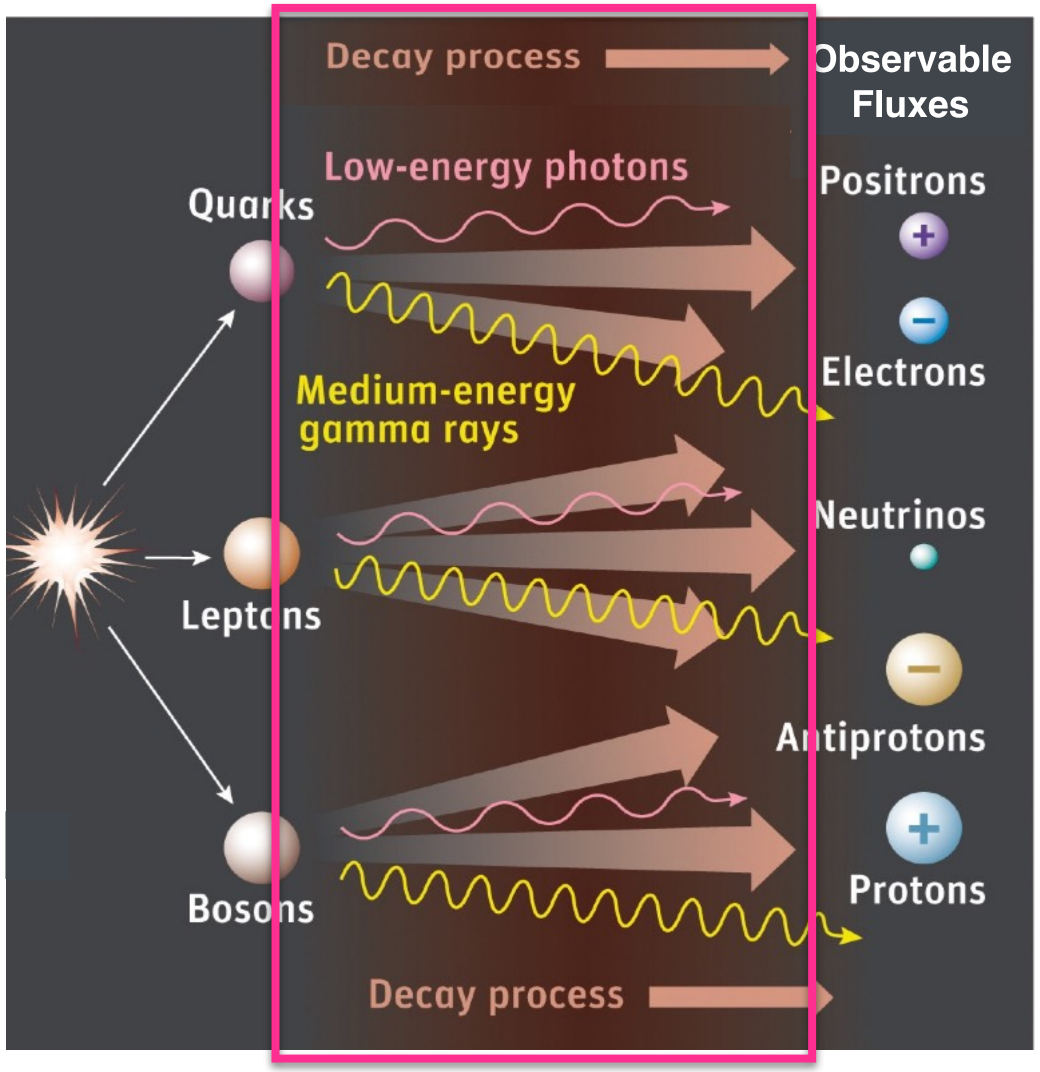
$E_{\gamma+e}/E_{\rm tot} = 0.996\ (0.948)$
$E_{p+d}/E_{\gamma+e} = 0.000\ (0.002)$

- Energy fraction going into photons and electrons (±) with respect to the total.
- Energy fraction into hadronic final states with respect to photons and electrons.

Dark matter emitted radiation



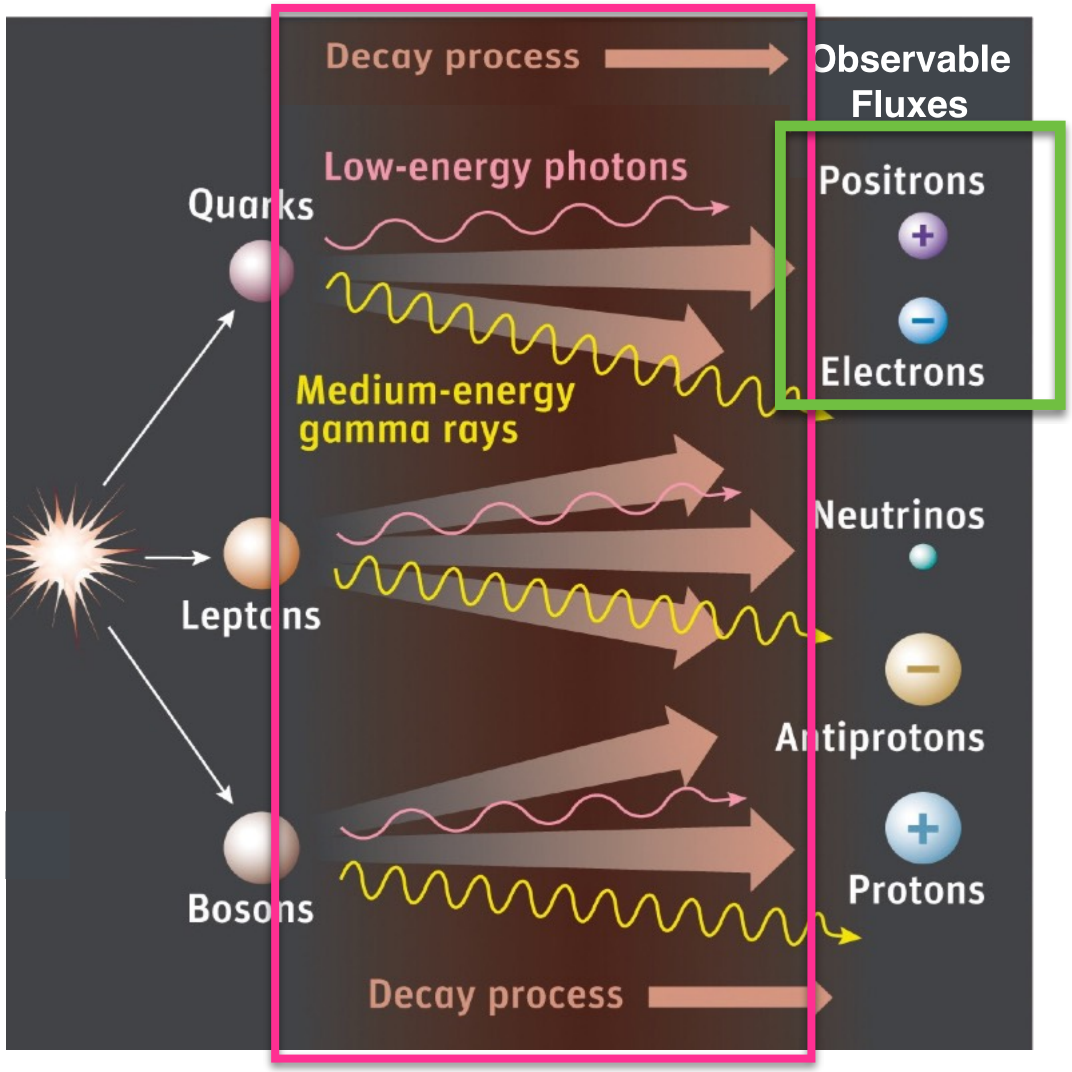
Dark matter emitted radiation



Prompt gamma-ray emission

- Production and decay of neutral pions
- Higher order radiative corrections
- Monochromatic line emission
- Other spectral features?

Dark matter emitted radiation



Prompt gamma-ray emission

- Production and decay of neutral pions
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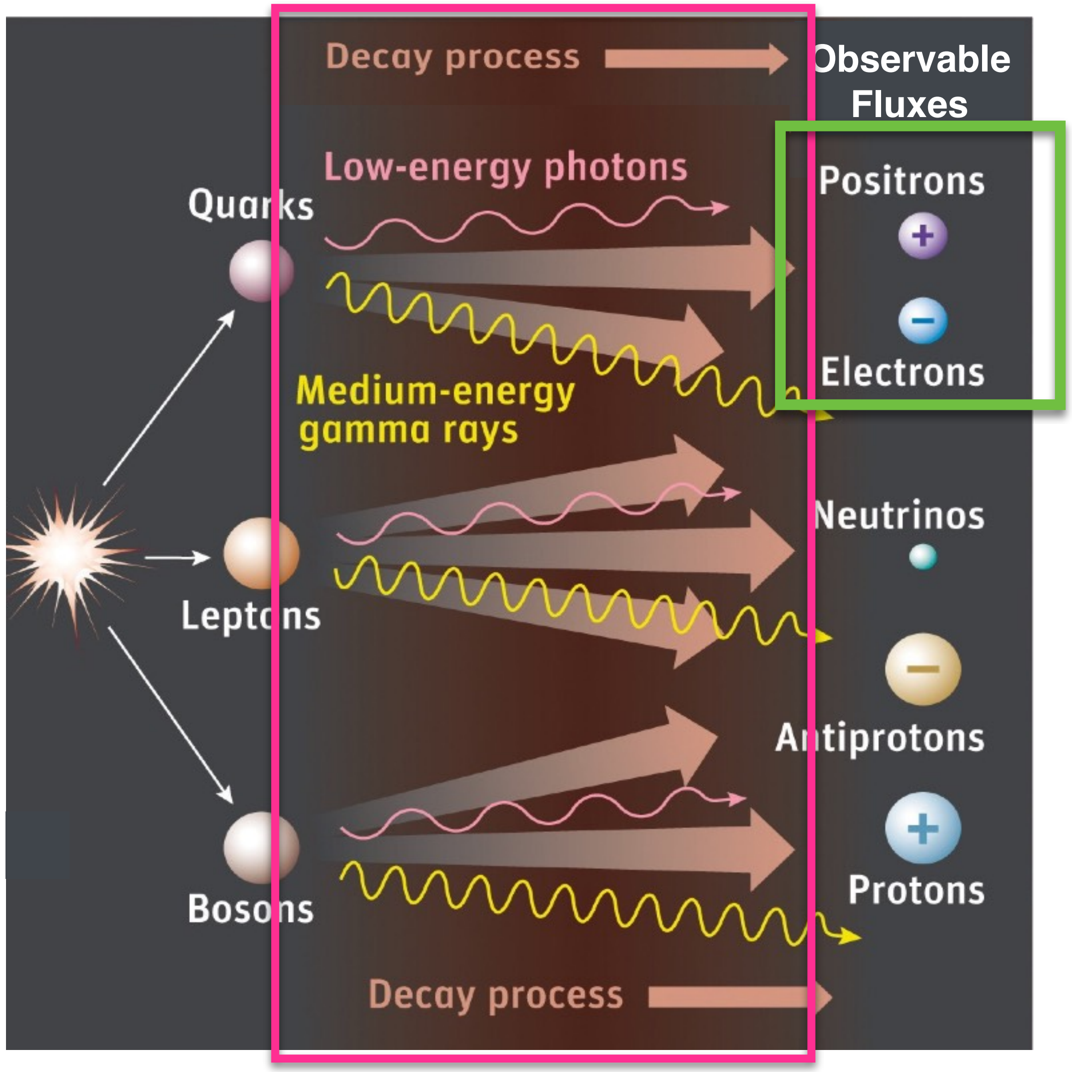
Radiative emission of electrons/positrons

- Inverse Compton scattering
- Synchrotron radiation
- Bremsstrahlung

Dark matter emitted radiation



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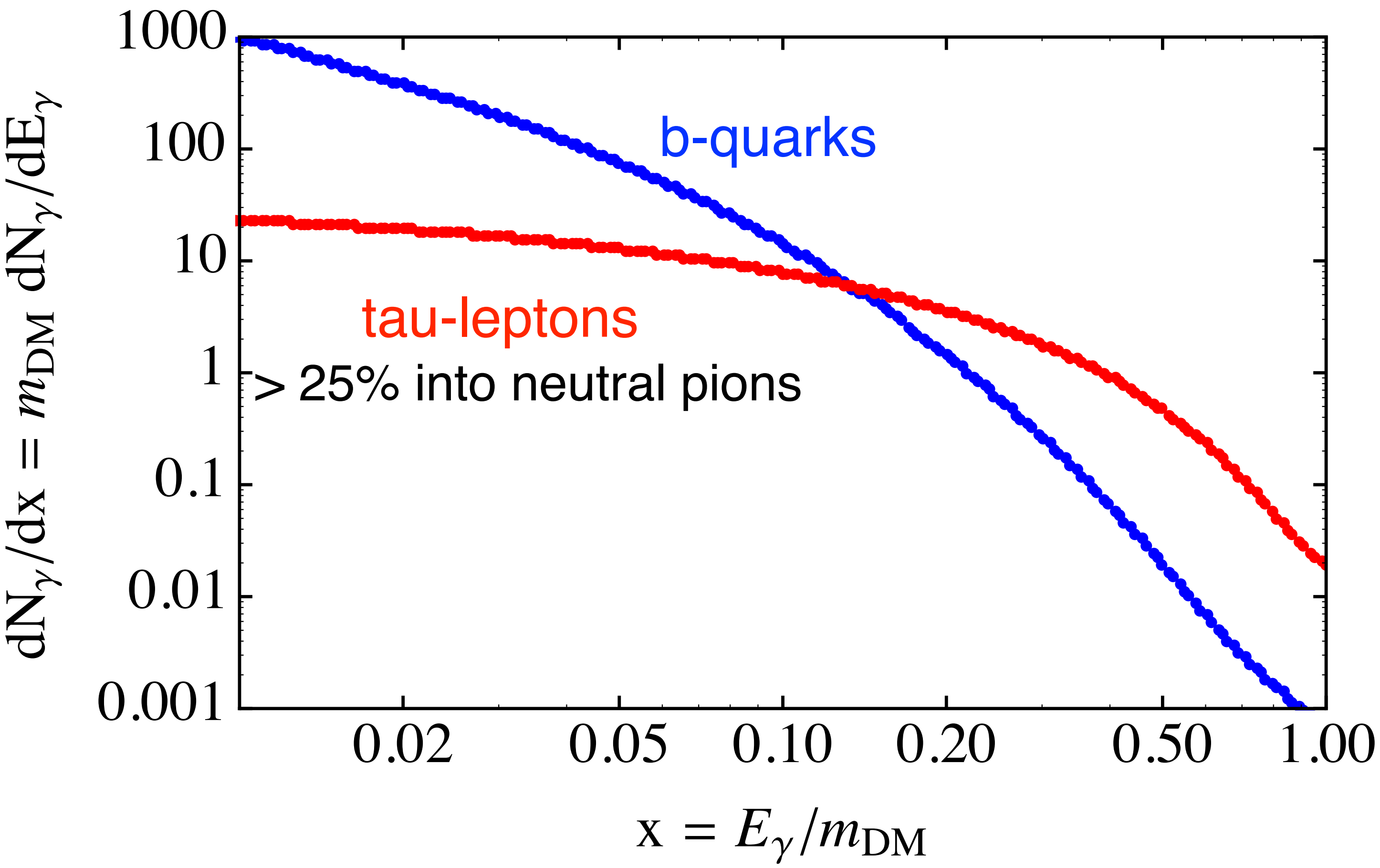
- Synchrotron radiation
- Bremsstrahlung

→ Multiwavelength emission

Spectra of prompt “secondary” photons

$$Q_i^{\rm ann}(r,E) = \langle \sigma_{\rm ann} v \rangle \times N_{\rm pairs}(r) \times \boxed{\sum_f B_f \frac{dN_i^f}{dE}(E)}$$

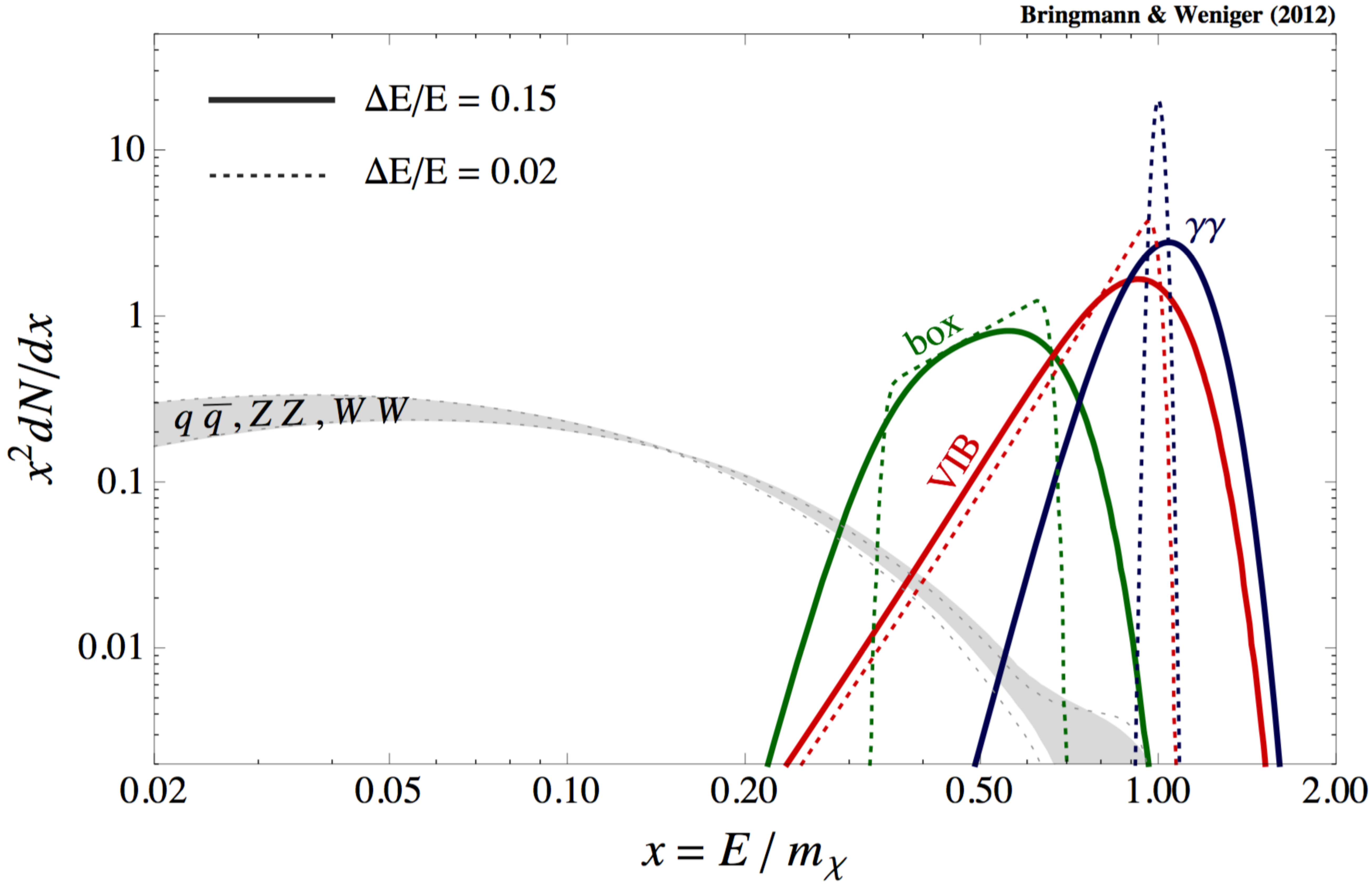
100% Branching ratio (independent on PP model)



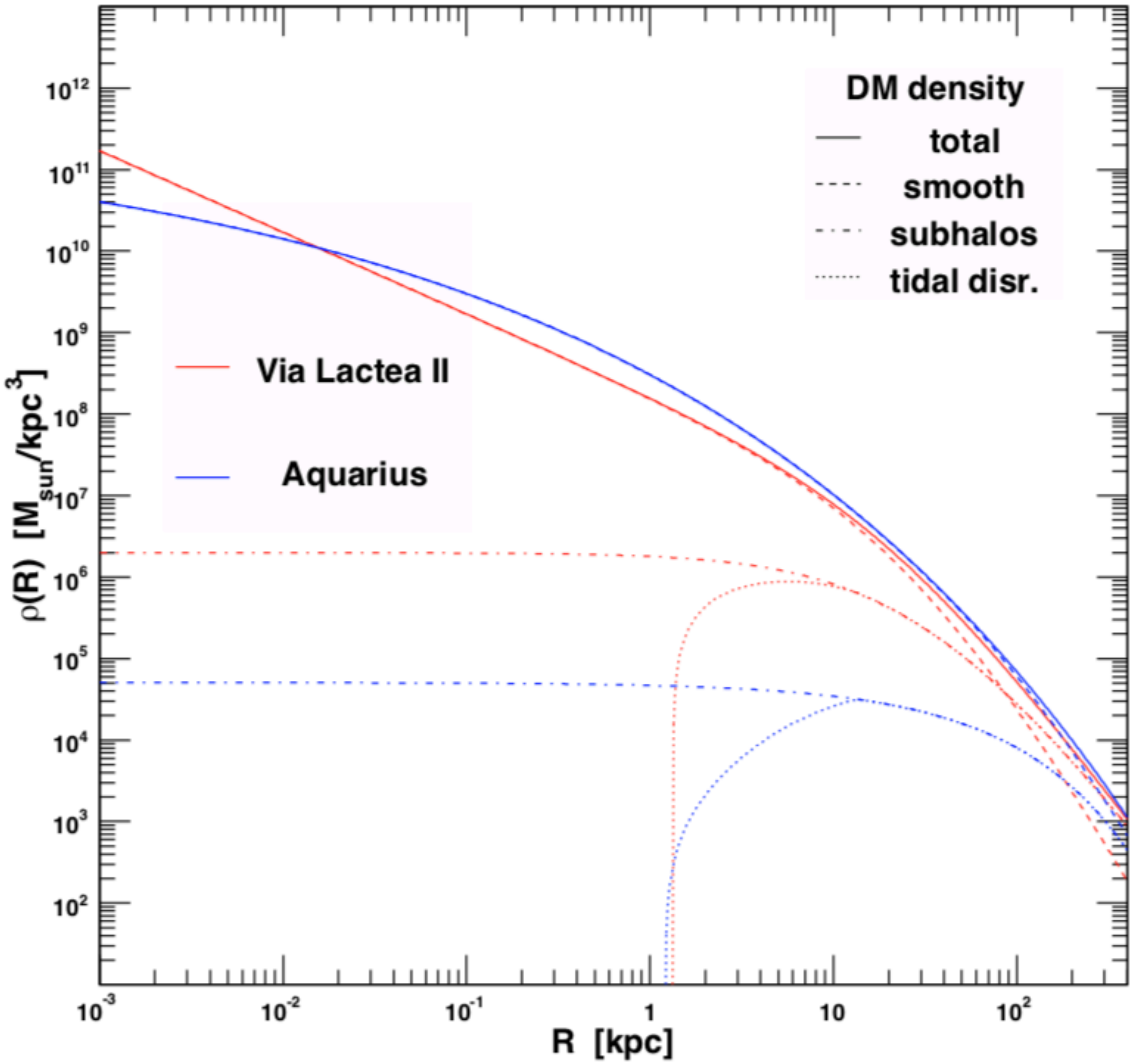
$$x \equiv \frac{E_X}{m_\chi}$$

$$\frac{dN_X}{dx} \equiv m_\chi \frac{dN_X}{dE}$$

The prompt photon emission



DM sub halos



	Via Lactea II	*Aquarius*
$R_{\rm vir}$ [kpc]	402	433
M_h [$M_\odot$]	1.93×10^{12}	2.5×10^{12}
r_s [kpc]	21	20
ρ_s [$10^6 M_\odot$ kpc^{-3}]	8.1	2.8
$\mathcal{F}_0$ [$M_\odot^{-1}$]	10^{-6}	3.6×10^{-6}
ρ_a [$M_\odot$ kpc^{-3}]	-	2840.3
R_a[kpc]	85.5	199
$\langle\rho_\odot\rangle$ [GeV/cm^3]	0.42	0.57
$N_{\rm sub}$	2.8×10^{16}	1.1×10^{15}
$M_{\rm sub}^{\rm tot}(< R_{\rm vir})$ [$M_\odot$]	1.05×10^{12}	4.2×10^{11}
$f_{\rm sub}^{\rm tot}(< R_{\rm vir})$	0.53	0.17

How to…

Analytical fitting functions:

Fornengo, Pieri, Scopel, PRD 2004
Cembranos et al., PRD 2011

Numerical codes for computation of DM spectra:

DarkSUSY http://www.fysik.su.se/~edsjo/darksusy/
Gondolo+ JCAP'04

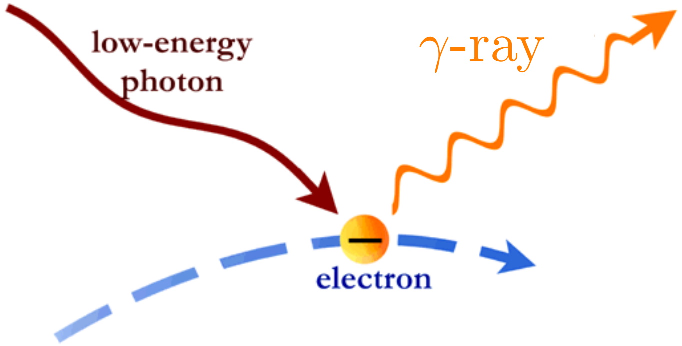
MicrOMEGAs https://lapth.cnrs.fr/micromegas/
Belanger+ JCAP'05

PPC 4 DM ID http://www.marcocirelli.net/PPPC4DMID.html
Cirelli+ JCAP 2012

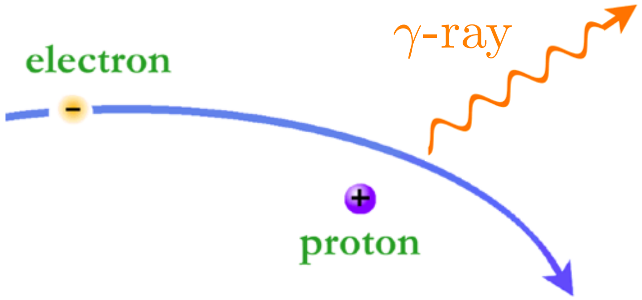
For dependence on event Monte Carlo generators see, e.g.,
Cembranos+ JHEP'13

Radiative emission from leptons

$$\chi\chi \to \left\{ \begin{array}{r} ZZ,\, W^+W^-,\, \gamma\gamma \\ q\bar{q},\, l^+l^-,\, \nu\bar{\nu} \end{array} \right\} \xrightarrow[\text{decays}]{\text{hadronization}} \gamma,\, \boxed{e^\pm},\, \mu^\pm,\, p/\bar{p},\, \pi^\pm,\, \nu/\bar{\nu},\, \ldots$$



Inverse Compton scattering
on CMB, star-light, infrared-light

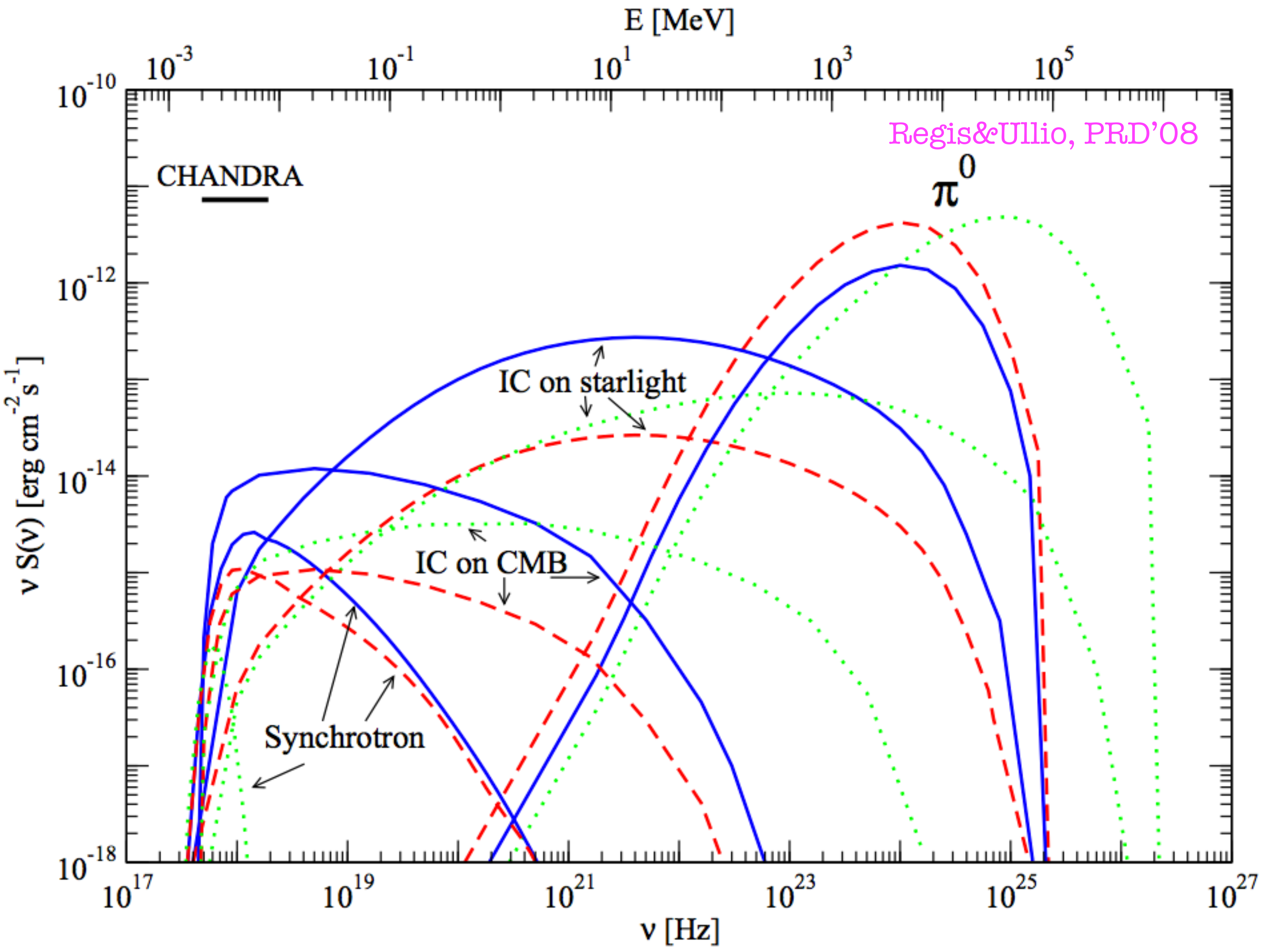


Bremsstrahlung
onto gas of interstellar medium

Synchrotron radiation
magnetic field $\mathcal{O}(\mu\text{Gauss})$
for $e^\pm$ of GeV-TeV
—> MHz-GHz radio signal

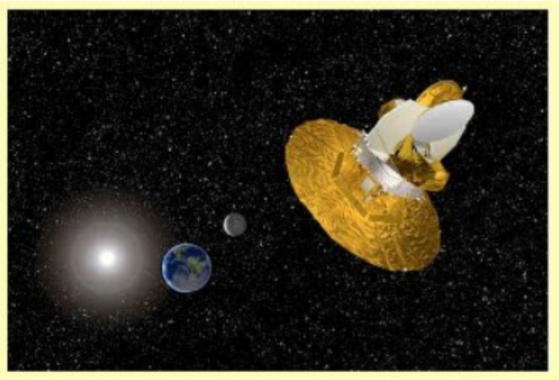
G. Rybicki and A.P. Lightman, 1979, 'Radiative Processes in Astrophysics', John Wiley & Sons Inc.
M. S. Longair, 2011, 'High Energy Astrophysics', Cambridge University Press.

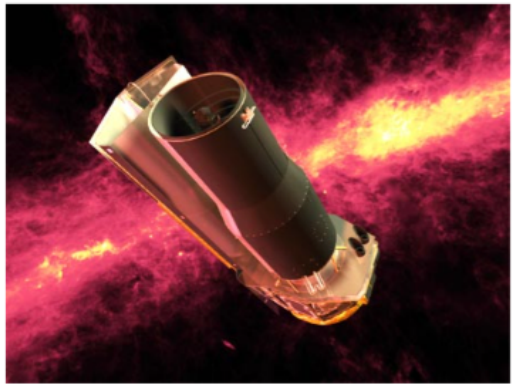
Multi-wavelength DM spectrum

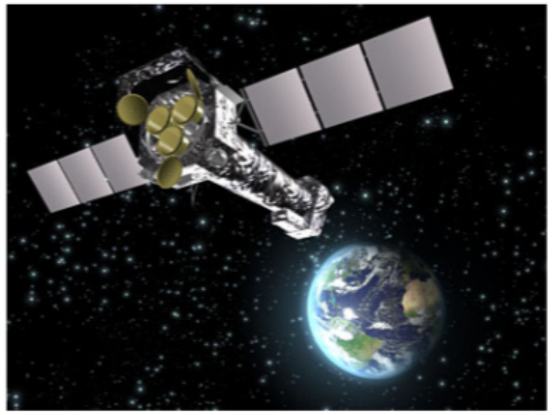


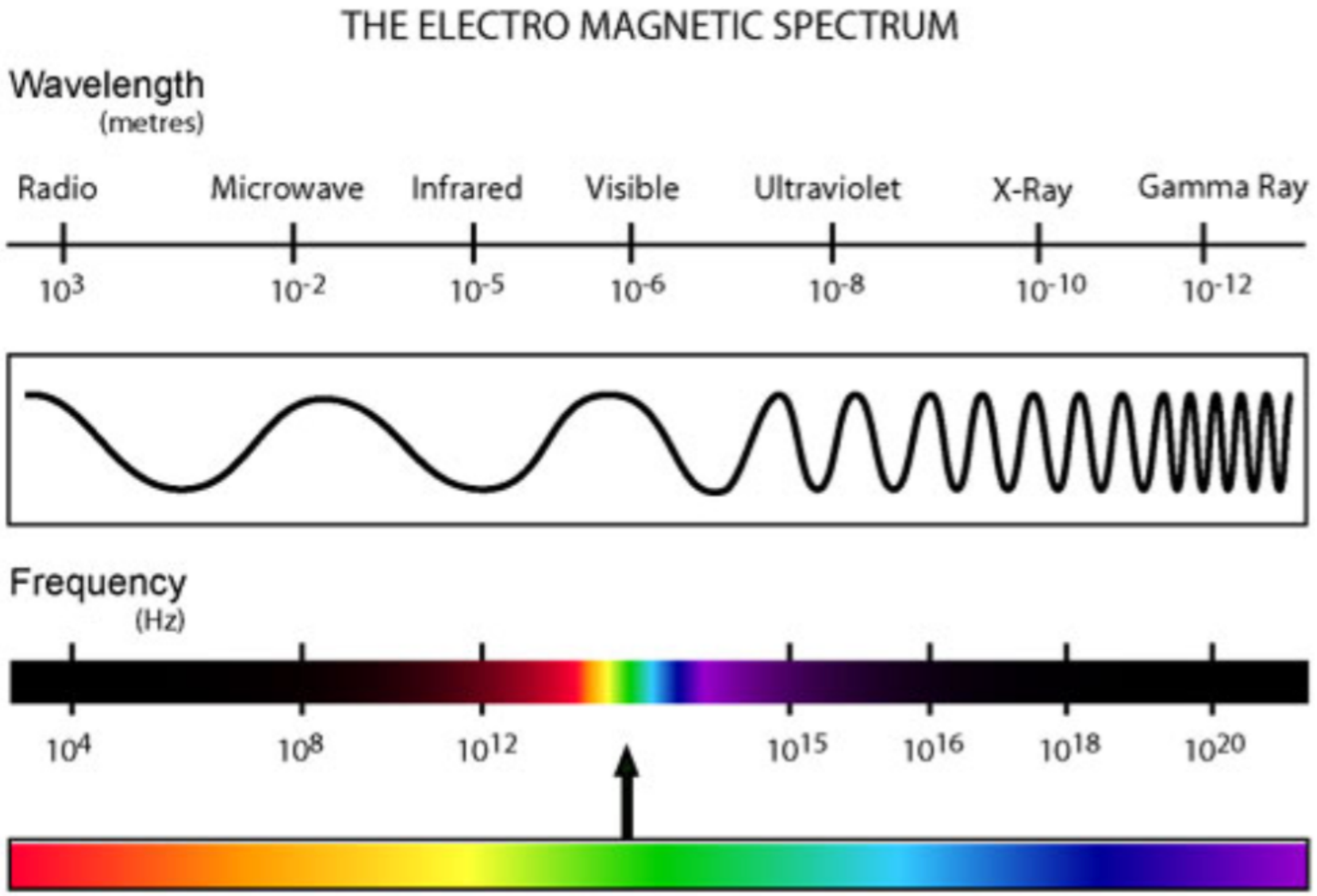
Multi-wavelength spectrum from radio to gamma-ray given by the prompt and secondary DM-induced emissions.

Multi-wavelength astronomy









Courtesy of E. Charles