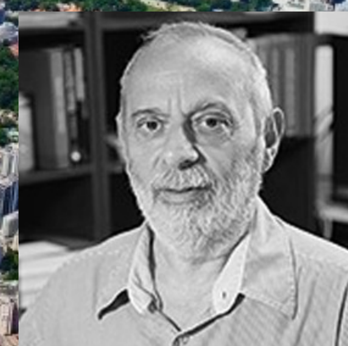
Gravitational Particle Production and Dark Matter — Four Lectures

1. Dark Matter: Evidence and the Standard WIMP
2. Gravitational Particle Production (Schrödinger's Alarming Phenomenon)
3. GPP of Scalar Fields
4. Beyond Scalar Fields



Rocky Kolb, University of Chicago

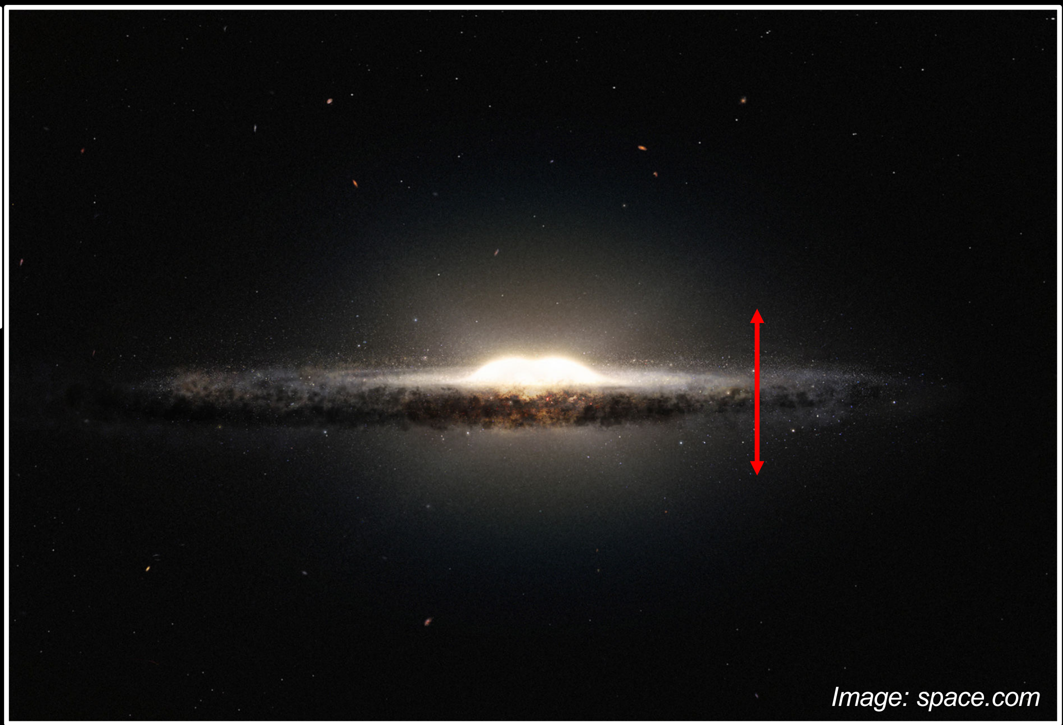
CBPF 9/2022

Nine decades of dark matter

Sun: 2×10^{27} tons; 4×10^{26} watts $\rightarrow$ Mass/Luminosity = 5 tons/watt

Oort 1932 Local Neighborhood Dim $2\text{–}3\times$ too dark

Jan Oort



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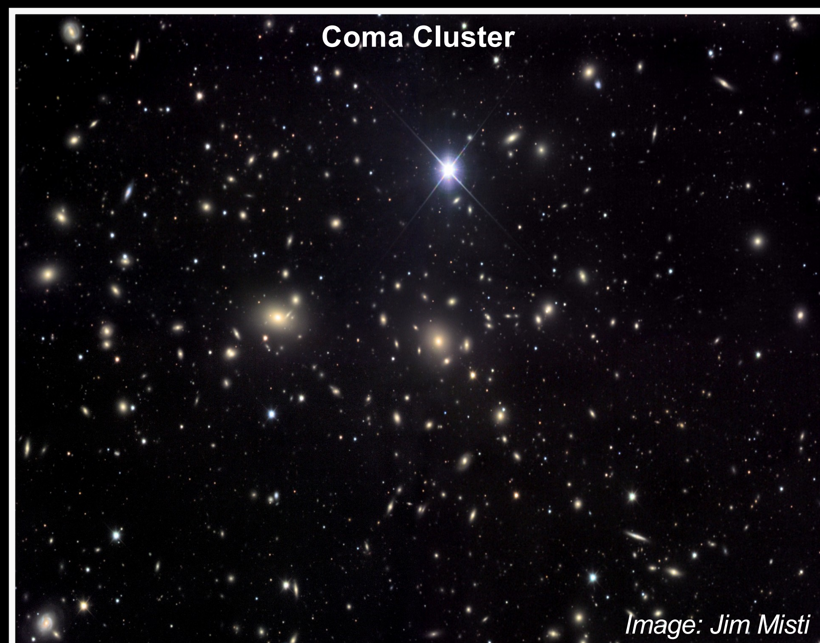
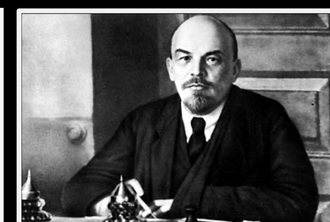
Oort	1932	Local Neighborhood Dim	$2\text{–}3 \times$ too dark
Zwicky	1937	Galaxy Clusters Really Dark	$500 \times$ too dark

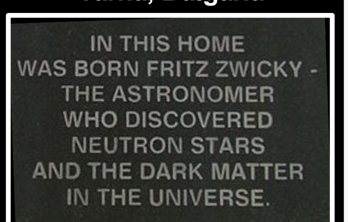
Fritz Zwicky



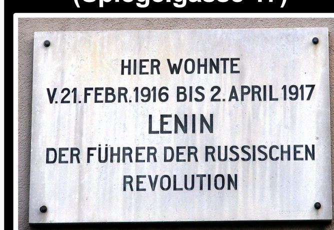


Vladimir Lenin 1916

Varna, Bulgaria



Zurich, Switzerland (Spiegelgasse 17)



Nine decades of dark matter

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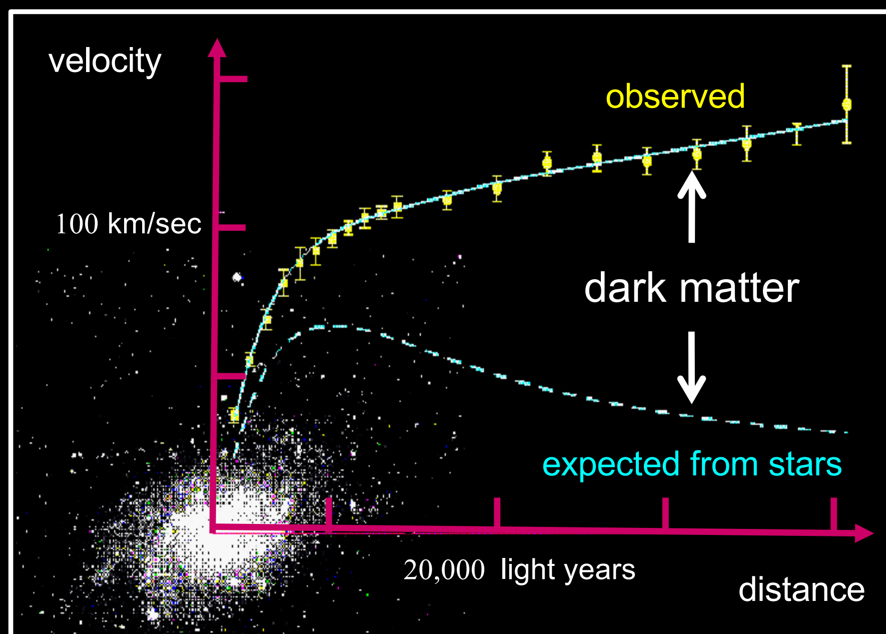
Rubin, Ford & others	1970s	Individual Galaxies Also Dark	60 ×

too dark

Vera Rubin 1970s



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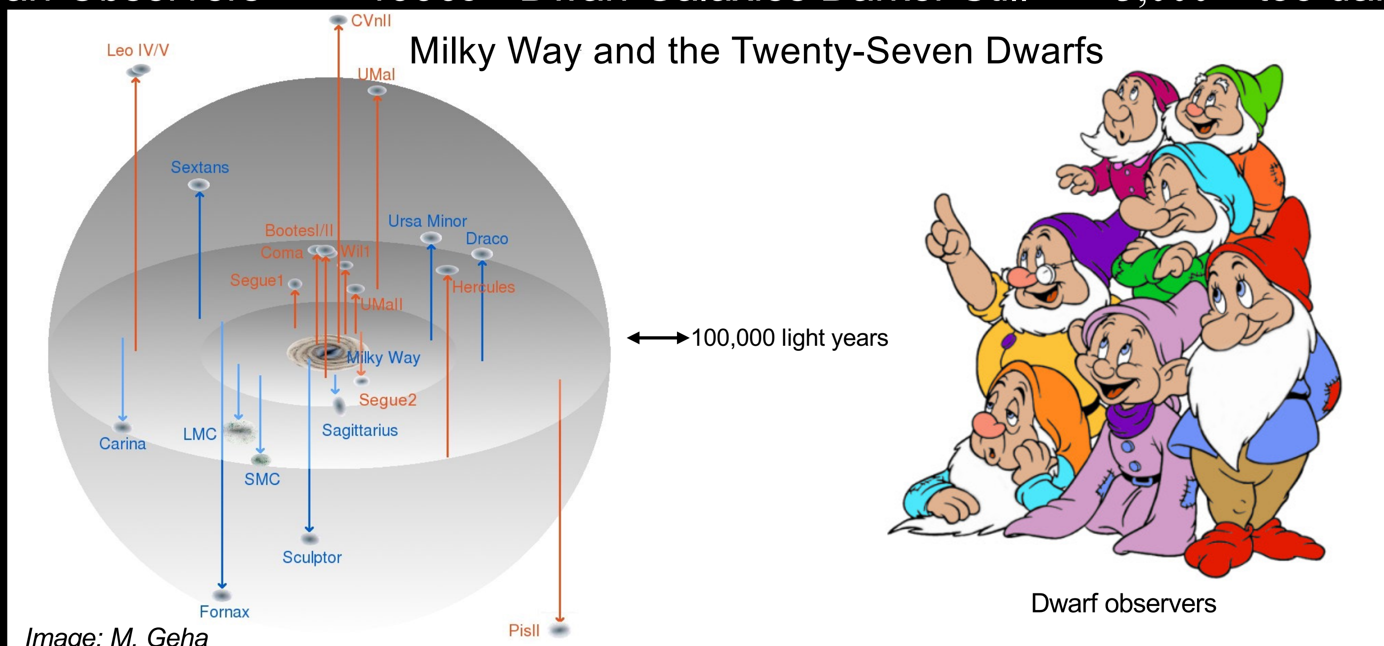
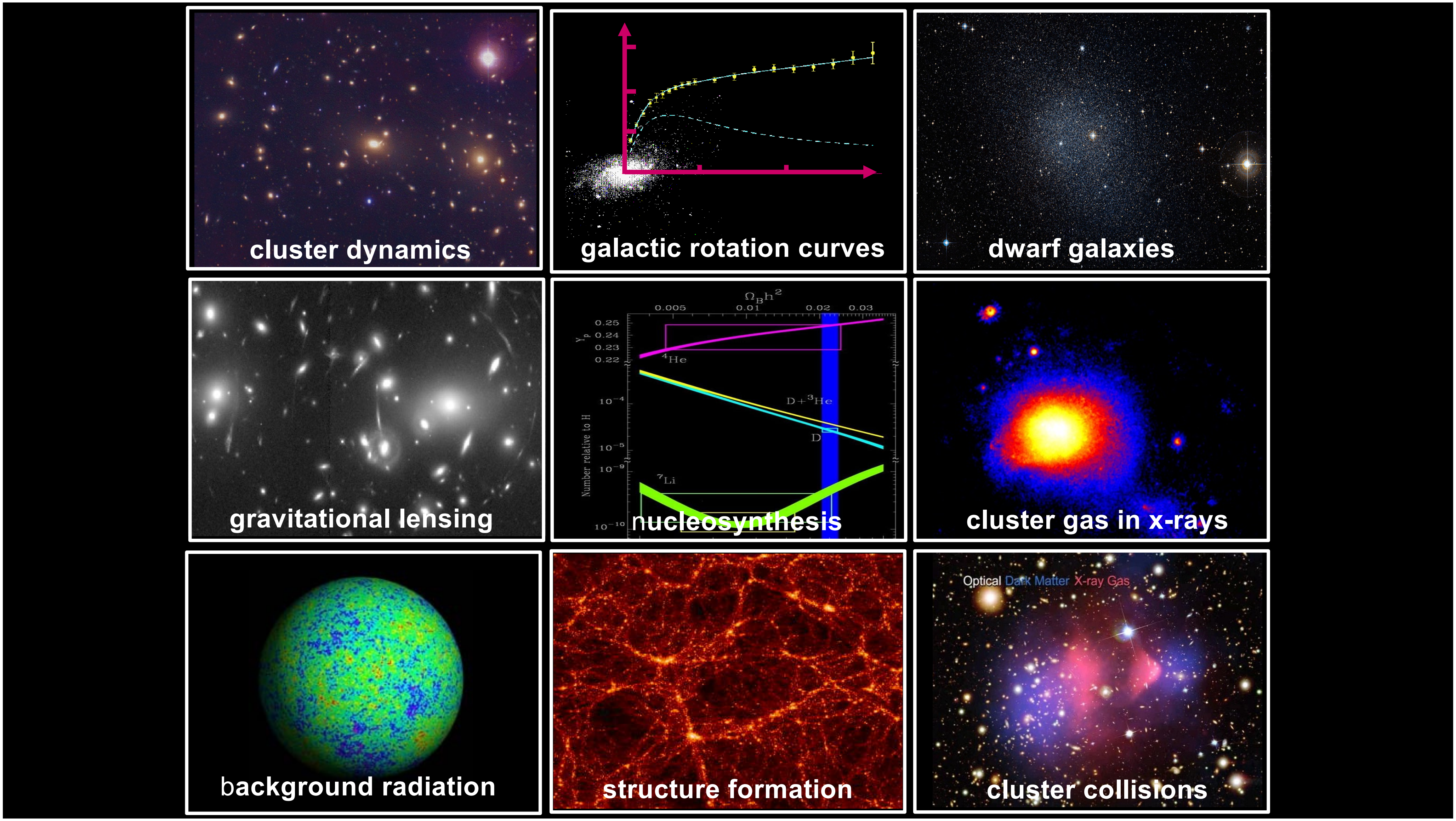
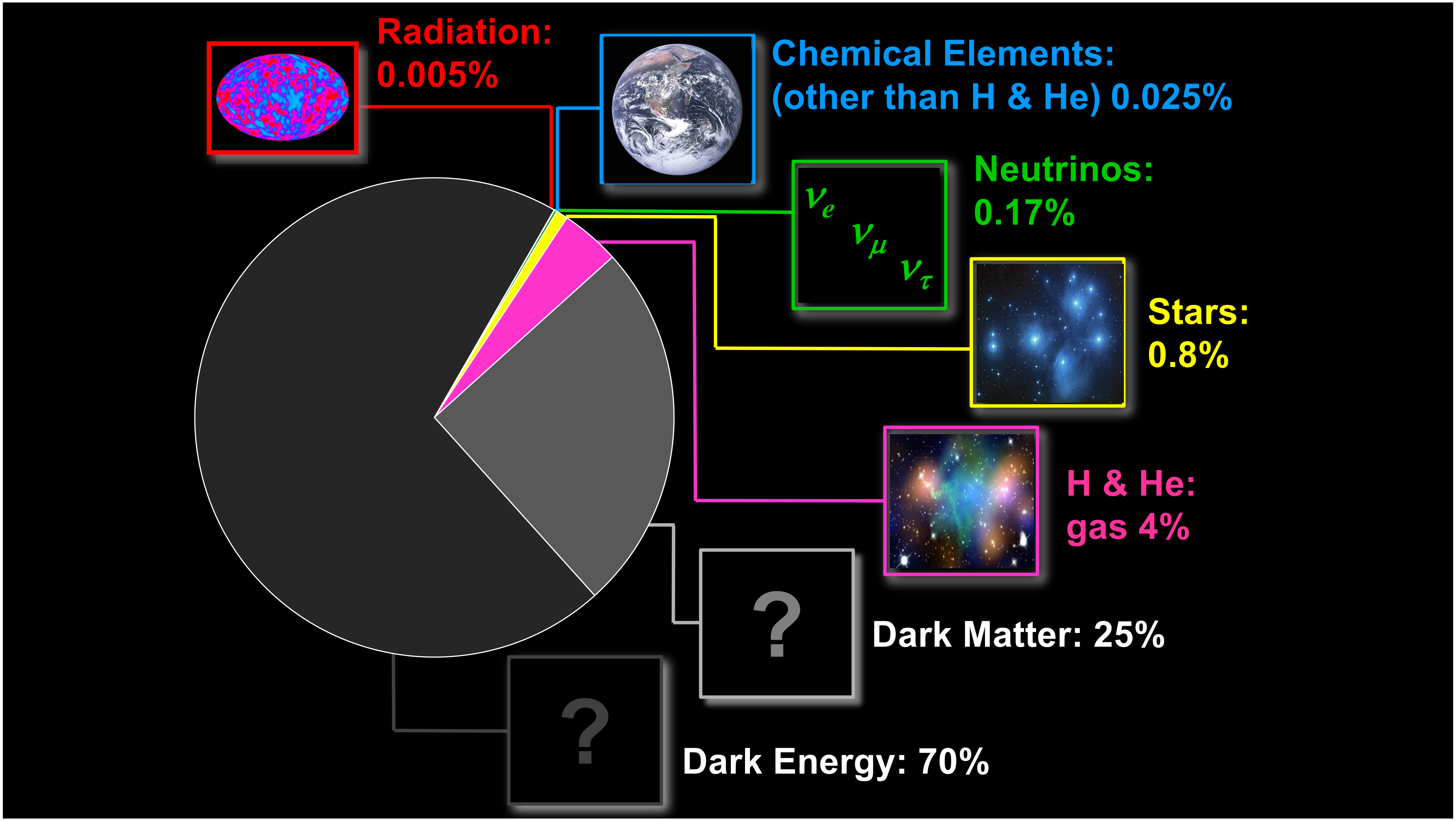
Dwarf Observers	1990s	Dwarf Galaxies Darker Still	3,000 × too dark




cluster dynamics
galactic rotation curves
dwarf galaxies
gravitational lensing
nucleosynthesis
cluster gas in x-rays
background radiation
structure formation
Optical Dark Matter X-ray Gas
cluster collisions



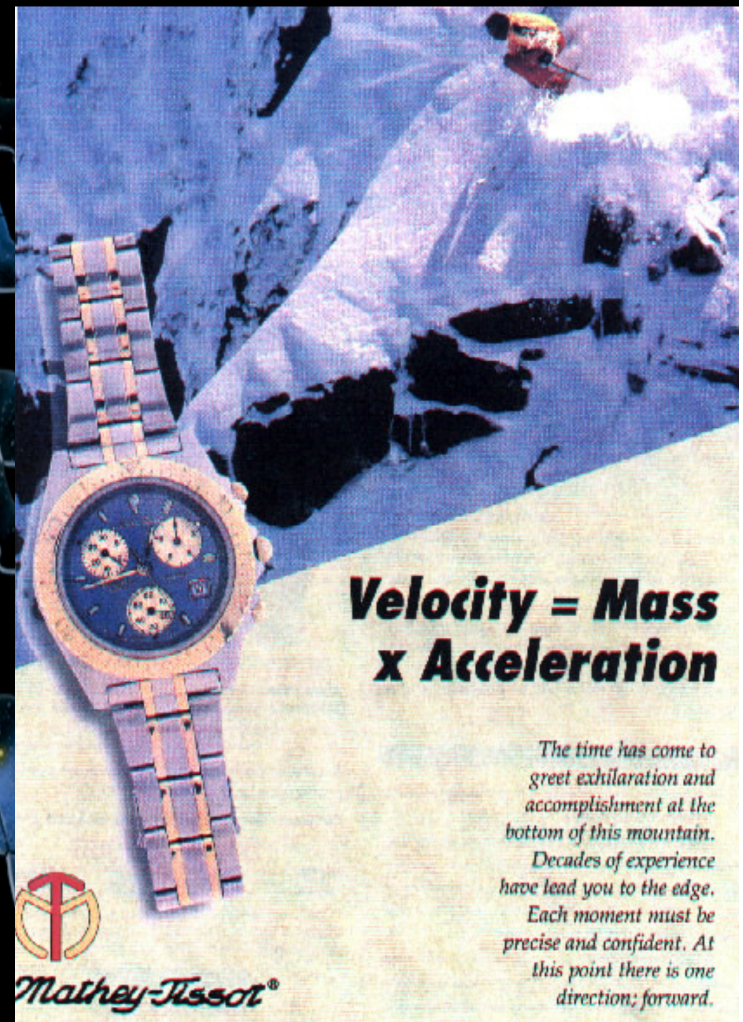
Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
ν_e ν_μ ν_τ
Stars:
0.8%
H & He:
gas 4%
?
Dark Matter: 25%
?
Dark Energy: 70%

Dark Matter

- Einstein didn't have the last word on gravity, or Modified Newtonian Dynamics (MOND)
- Rocky Rogue Planets
- Little Dim Stars
- Big Black Holes

} <u>M</u>assive <u>C</u>ompact <u>H</u>alo <u>O</u>bject<u>s</u> (MACHOs)

- New Elementary Particle Species (WIMPs)



Known particle species

?

Dark particle must be stable and massive and interact weakly

Dark particle must be “A New Particle Species”

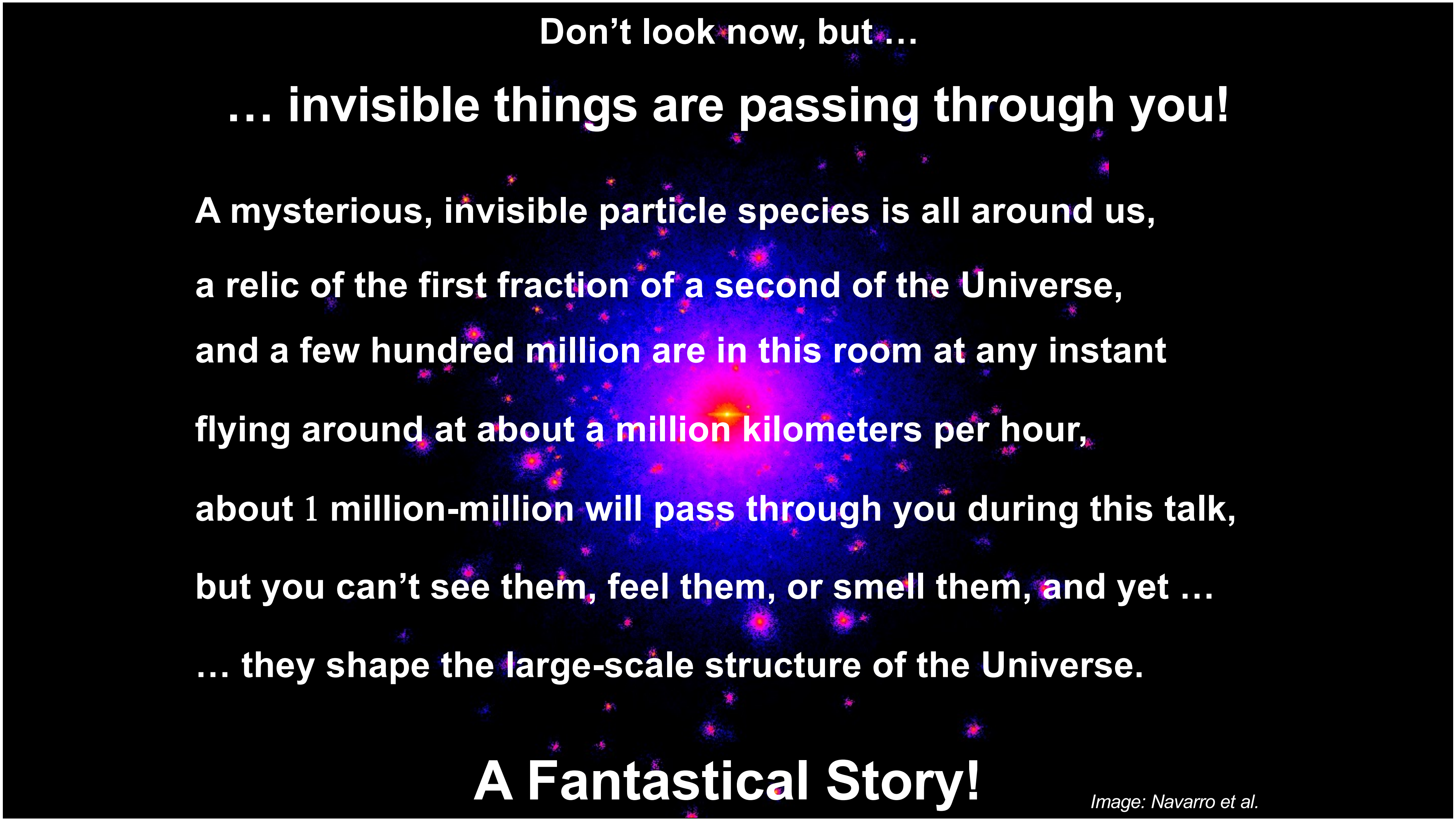


Image: Navarro et al.

Origin of (WIMP) Species

Weakly interacting: hard to make, need a large dark matter factory

WIMPs are massive: takes a lot of energy to make them

WIMPs seem to be universal: in all cosmological structures

Dark Matter is a relic of the big bang!

Dark particle must be stable and massive and interact weakly
Dark particle must be "A New Particle Species"

Why $6{:}1$ in the cosmic recipe?

- What is origin of normal-matter (baryon) density?
- Baryon density determined by baryon *asymmetry* of yet unknown origin:

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 10^{-9}$$

- Asymmetric dark matter: same (yet unknown) mechanism generates DM asymmetry.
- Is ratio $6{:}1$ because DM particle mass: baryon mass $= 6{:}1$?
- For most DM scenarios $6{:}1$ is input, not output.
- Sensitivity of $6{:}1$ on input parameters.

Why 6:1 in the cosmic recipe?

- Dark matter drives structure formation
  - Do we “need” dark matter?
  - Structures would still form (probably top-down)

- Baryon only halos?

- Why so many components?
  - Why is neutrino contribution **0.17%?**

Particle dark-matter bestiary

- (sub-) eV mass neutrinos (WIMPs exist!) (hot)
- sterile neutrinos, gravitini (warm)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)

} thermal relics, or decay of or oscillation from thermal relics

- Bose-Einstein condensates
- axions, axion miniclusters
- solitons (Q-balls, B-balls, …)

} from phase transitions

- supermassive WIMPZILLAs — from inflation

} (from phase transitions, from inflation) nonthermal relics

Mass

10^{-22} eV (10^{-56} g) Bose-Einstein

$10^{-8} M_{\odot}$ (10^{+25} g) axion miniclusters

Interaction Strength

only gravitational: WIMPZILLAs

strongly interacting: B balls

WIMPs and Cold Dark Matter (CDM)

- Cold Dark Matter
  - Cold: have a negligible velocity during structure formation
  - Dark: can't "see" them in any wavelength
  - Matter: are massive

- WIMPs are cold thermal relics
  - Part of the thermal bath in the early universe
  - Present abundance determined by freeze-out
  - Froze out when nonrelativistic (at least semi-relativistic)

- Cold Dark Matter need not be a WIMP
  - Axions are CDM but not a thermal relic
  - Asymmetric relics are CDM

Cold thermal relics*

- DM species in thermal equilibrium at $T > M$ with standard-model particles
- Equilibrium abundance of DM determined by M / T (no asymmetry)
- As universe expanded and cooled, DM species "froze-out"
- Present abundance determined by freeze-out
- Freeze-out: interplay between

    DM—SM interaction strength (particle physics),

    $\Updownarrow$

    and expansion rate of the Universe (gravity).

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* An object of particular veneration.

Some Notation

FLRW model $$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]$$

My convention: scale factor a has dimension of length. An observer "at rest" has constant (r, θ, ϕ) "comoving coordinates"

In early universe $k = 0$

Define conformal time $a d\eta = dt$ $$ds^2 = a^2(\eta)\left[d\eta^2 + d\vec{x}^2\right]$$

Expansion rate $$H = \frac{\dot{a}}{a} = \frac{a'}{a^2}$$ prime indicates derivative wrt conformal time

The Boltzmann Equation

$$n = \frac{g}{(2\pi)^3} \int f(\vec{p})\, d^3p$$

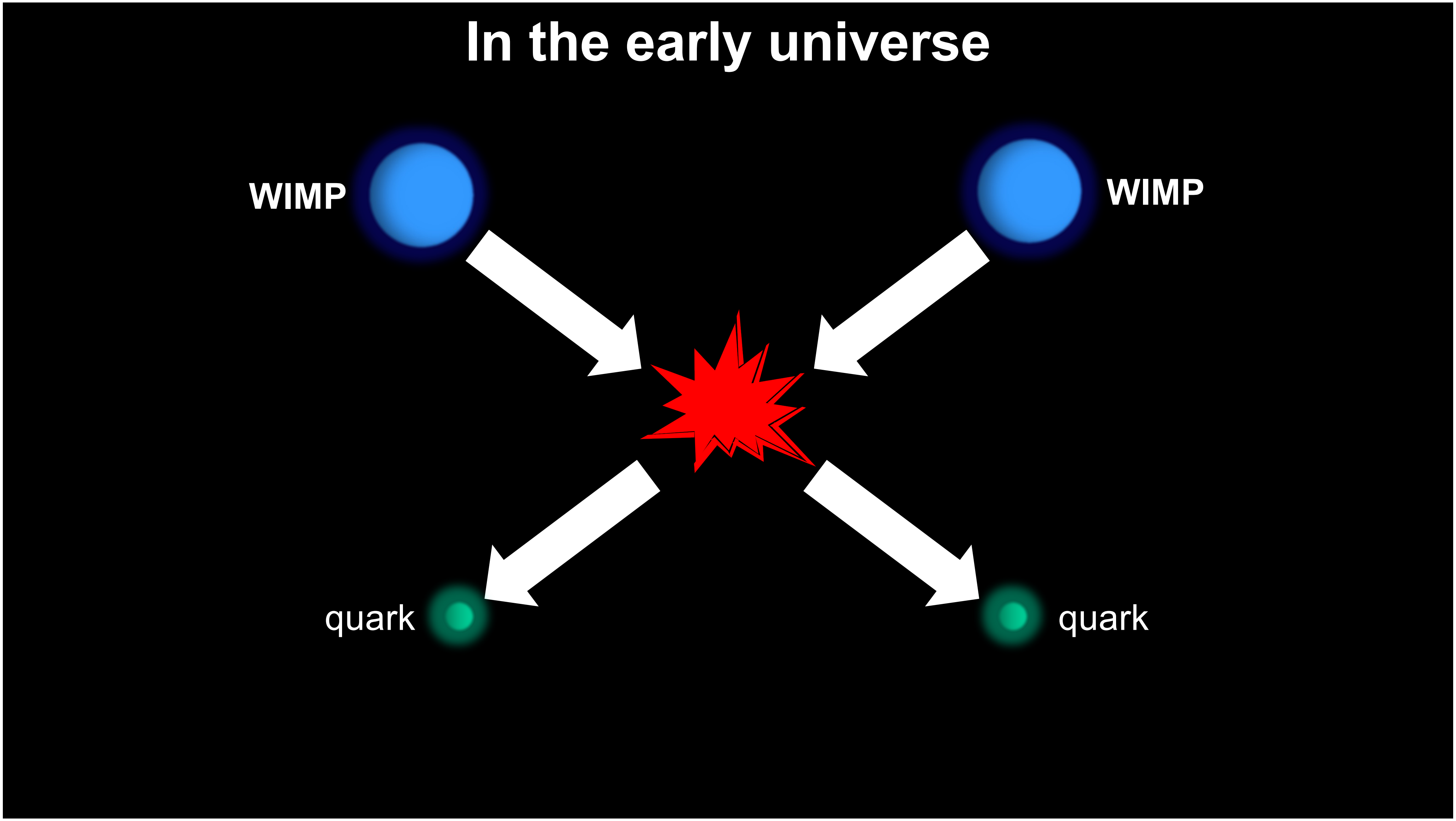
Number density n of a particle species in terms of its phase-space density f

Number density can change through expansion, annihilation, or decay

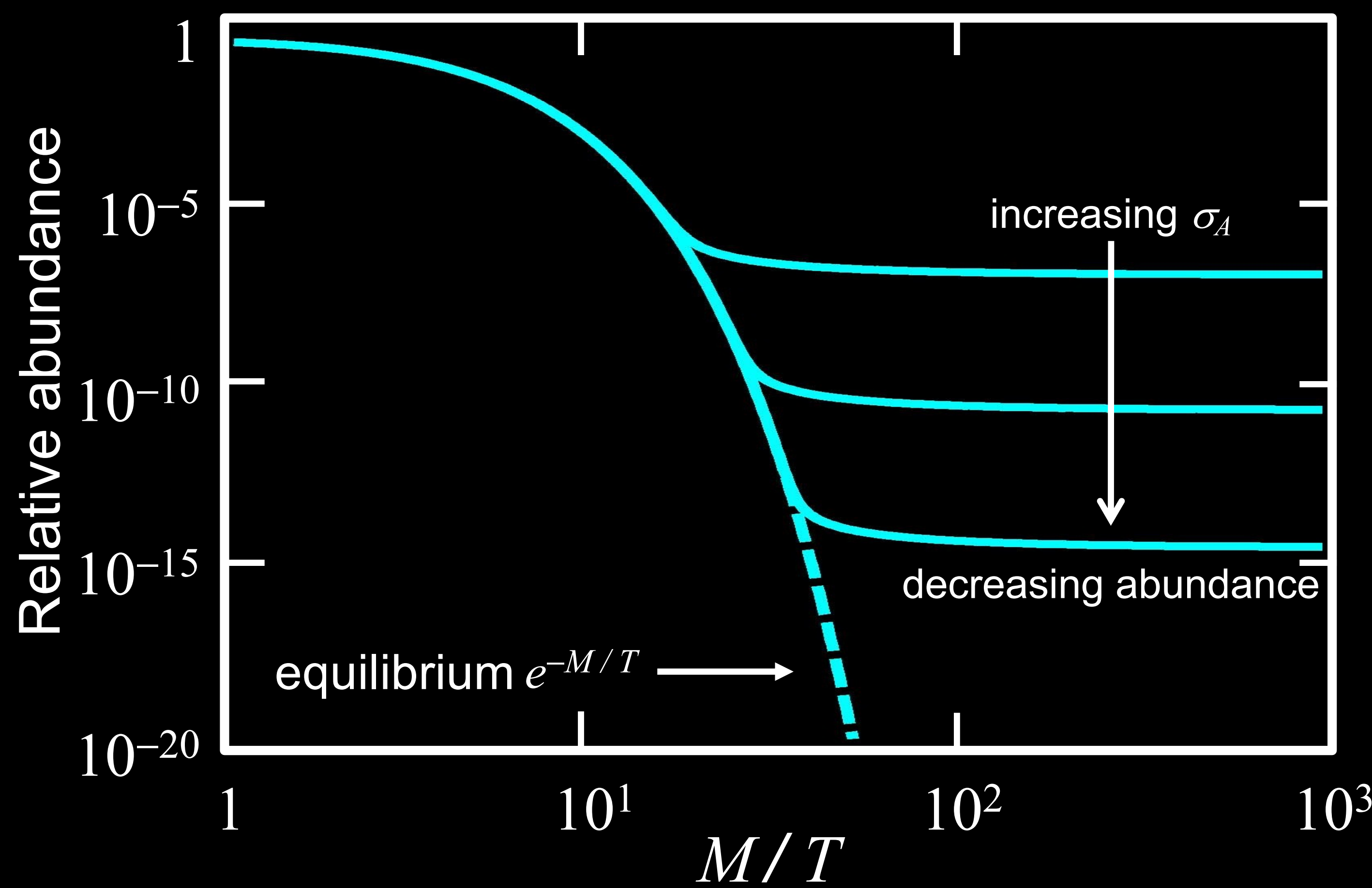
$$\dot{n} = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2) - \Gamma n$$

Evolution of number density: solution of Boltzmann equation

In absence of annihilation or decay, $na^3 =$ constant


In the early universe
WIMP
WIMP
quark
quark

Cold thermal relics



Final freeze-out abundance:

$$\Omega h^2 \approx 0.12 \times \frac{\langle \sigma_A \mathrm{v} \rangle}{3 \times 10^{-26}\ \mathrm{cm}^3 \mathrm{s}^{-1}}$$

$\langle \sigma_A \mathrm{v} \rangle =$ NR annihilation cross section × Møller flux ⟨…thermal average…⟩

$$\sigma = 10^{-36}\ \mathrm{cm}^2 = \frac{\alpha^2}{(150\ \mathrm{GeV})^2}$$

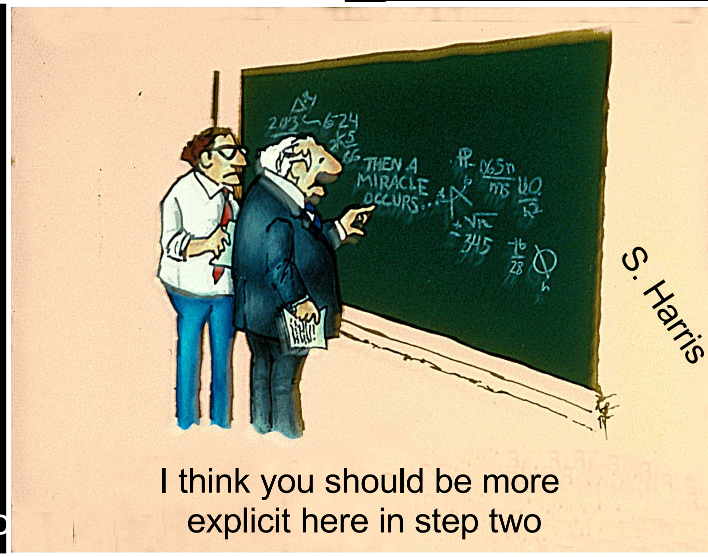
weak scale! → (150 GeV)

Not quite so clean:

- velocity dependence
- resonances
- co-annihilation
- $\log$ dependence on M
- decay production
- spin-dependence
- asymmetries
- …

$\sigma = 10^{-36}$ cm^2: the WIMP "Miracle"

1 : an extraordinary
divine interventio



encyclopedia

. often used to give an
npression of great and
nusual value in a trivial
ontext …

WIMP hypothesis predicts
- DM mass range, and
- DM—SM interaction strength
- (But not 6:1)

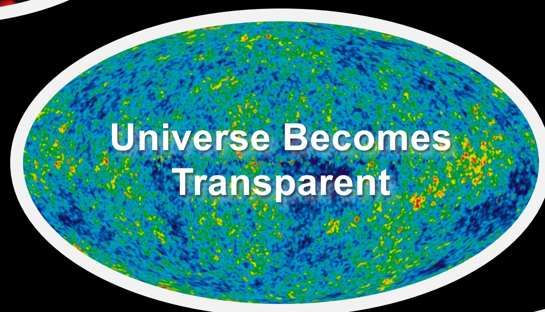
WIMP hypothesis relates
- DM mass and
- DM interactions
- to a "known" scale

Origin of Dark Matter Species

BANG!

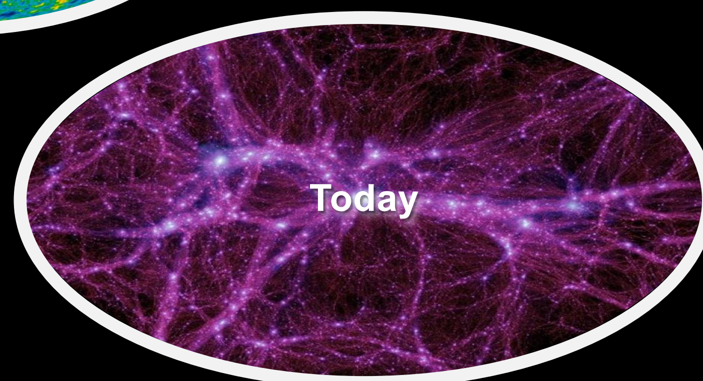
$t = 0$, origin of space and time
$T =$ infinity

$t = 1/1{,}000{,}000{,}000$ second AB
$T = 100{,}000{,}000{,}000{,}000$ degrees

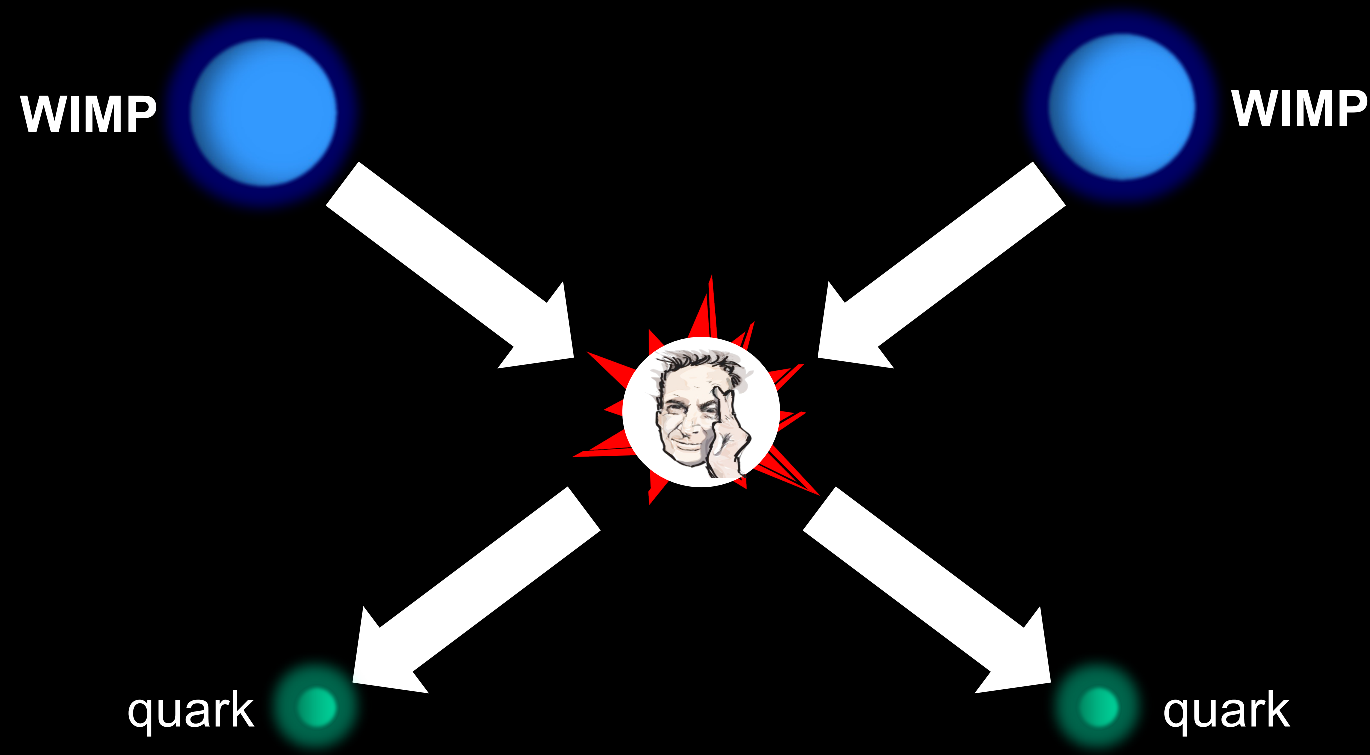


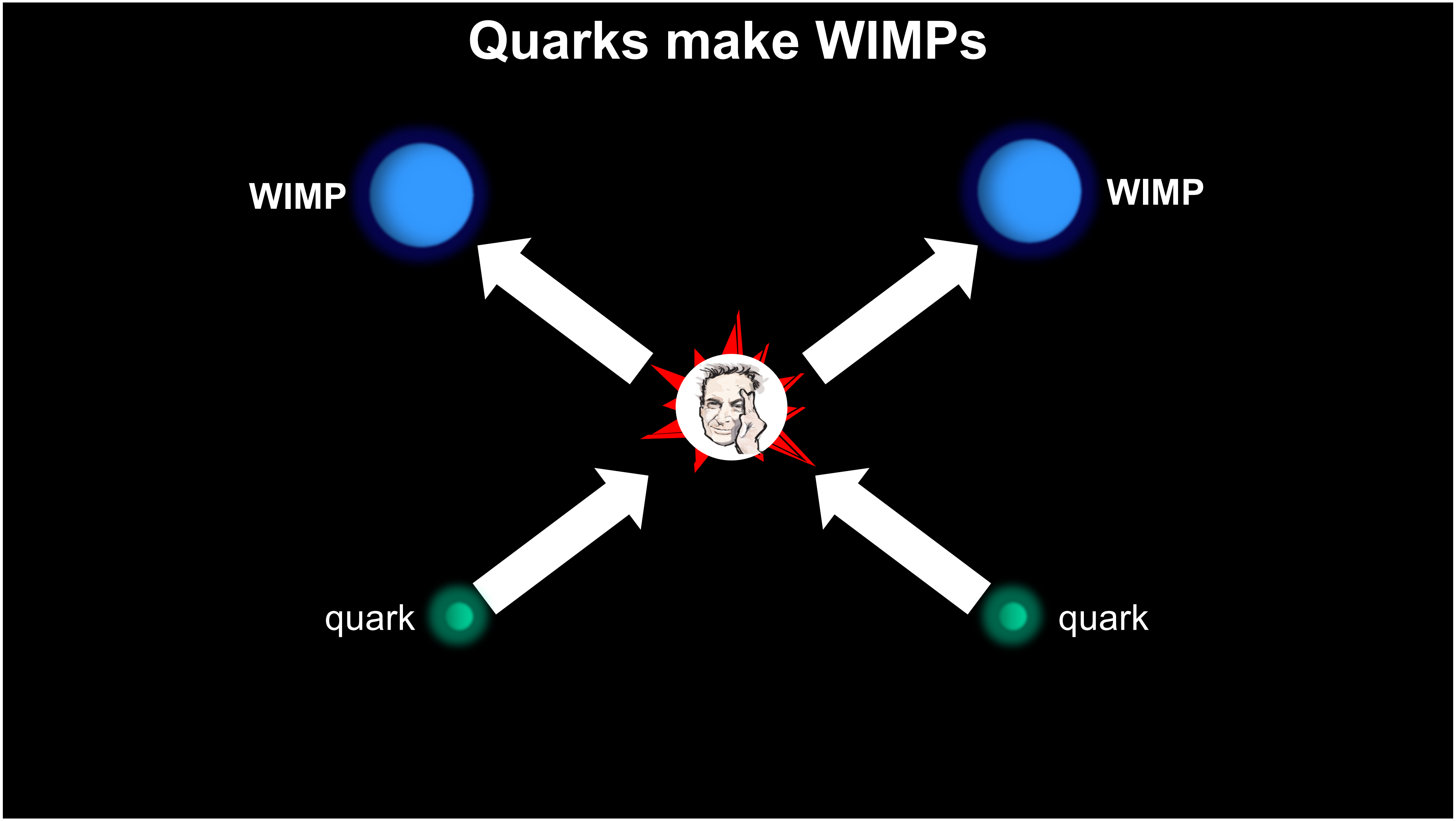
$t = 380{,}000$ years
$T = 5{,}000$ °F

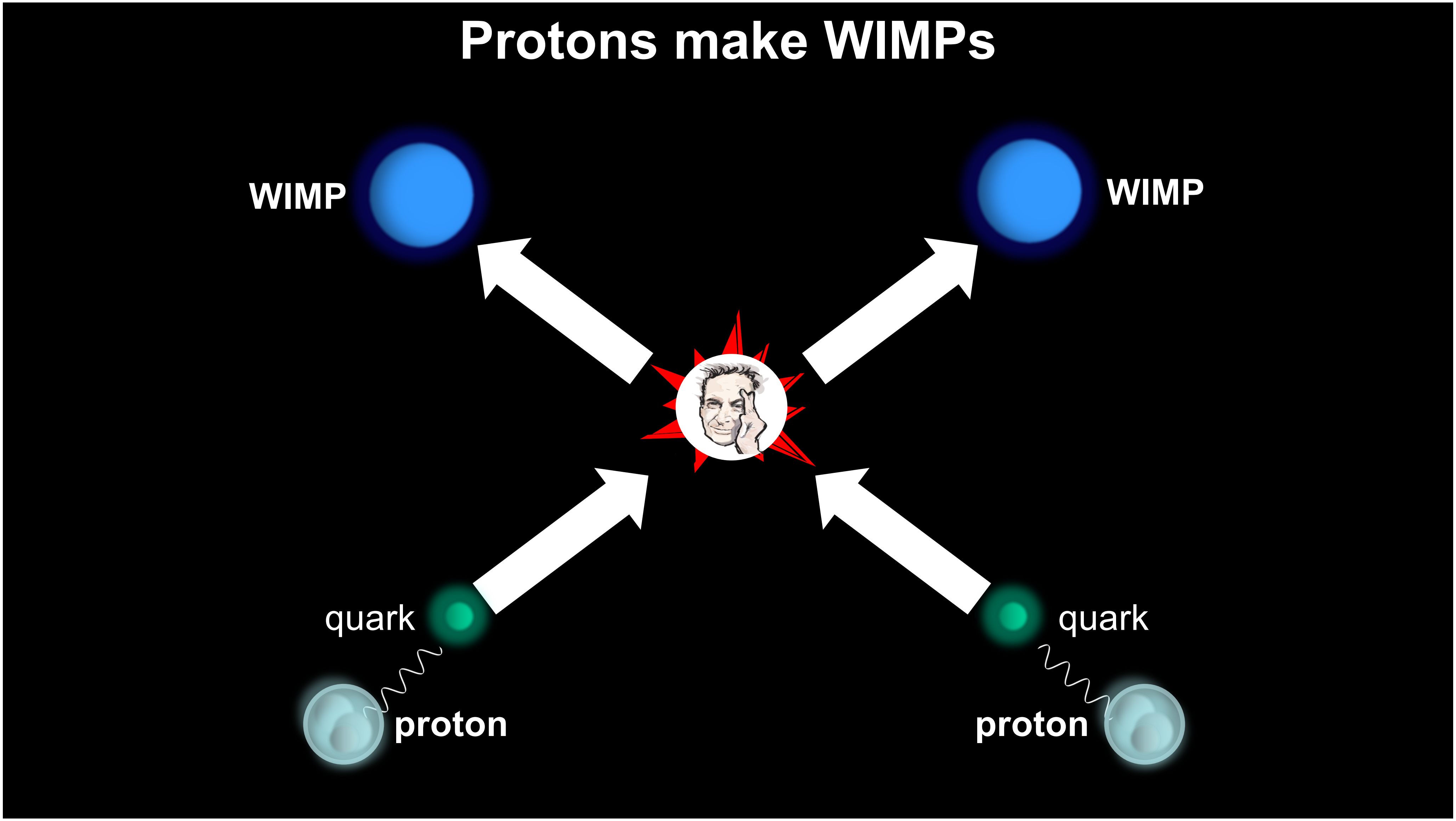
$t = 13.8$ billion years
$T = -455$ °F

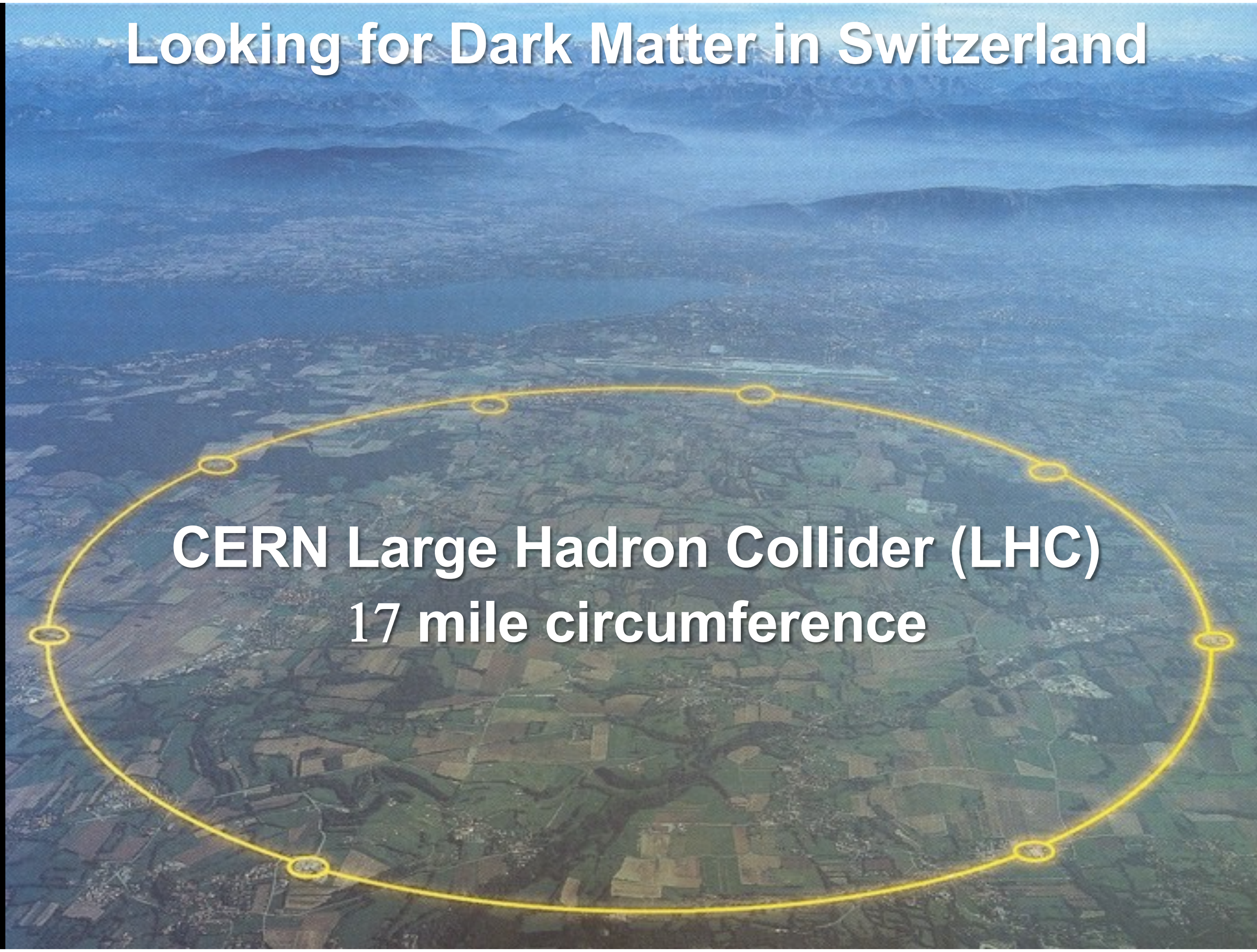


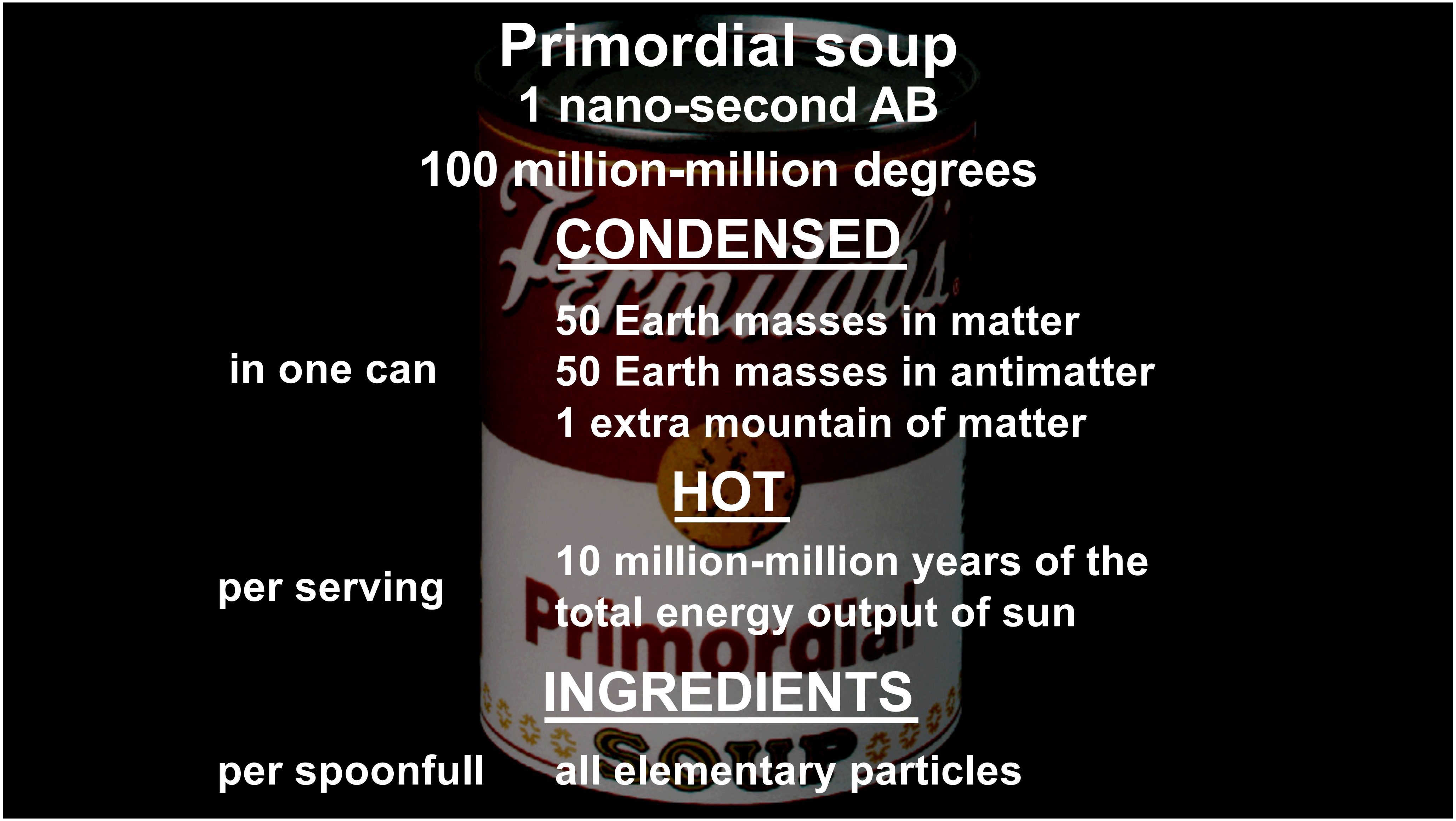
In the early universe



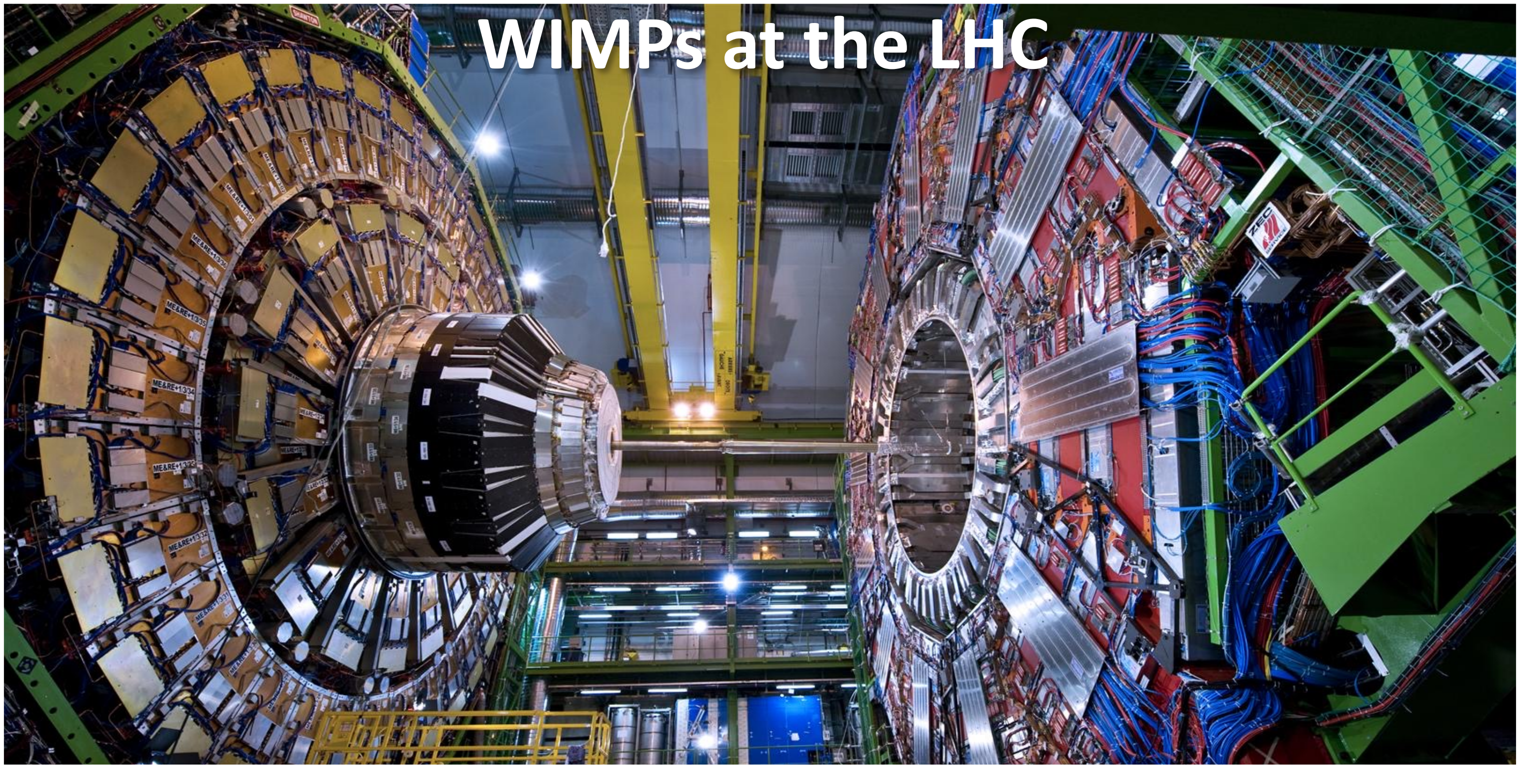

Quarks make WIMPs
WIMP
WIMP
quark
quark

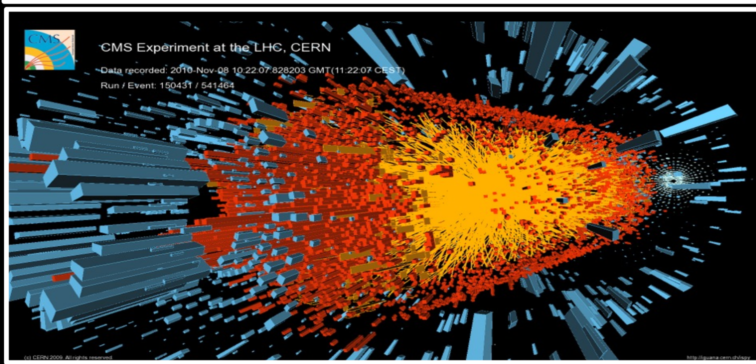

Protons make WIMPs
WIMP
WIMP
quark
quark
proton
proton


Looking for Dark Matter in Switzerland
CERN Large Hadron Collider (LHC)
17 mile circumference


Primordial soup
1 nano-second AB
100 million-million degrees
CONDENSED
in one can
50 Earth masses in matter
50 Earth masses in antimatter
1 extra mountain of matter
HOT
per serving
10 million-million years of the total energy output of sun
INGREDIENTS
per spoonfull
all elementary particles

WIMPs at the LHC

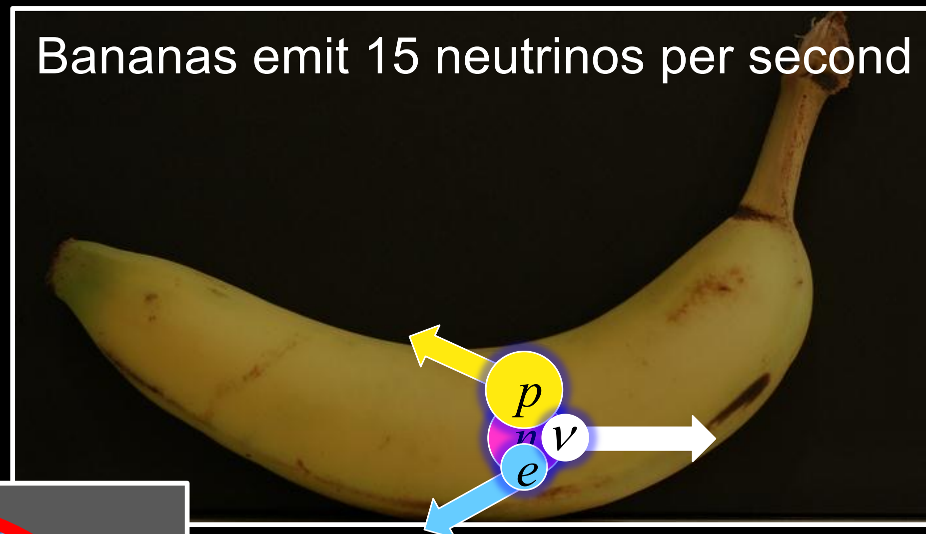


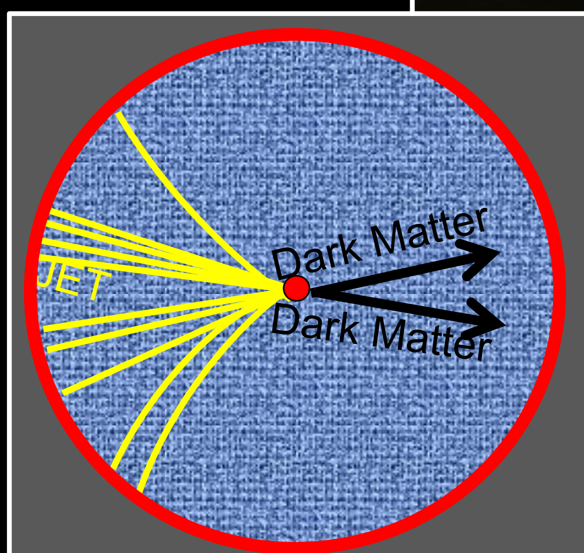


Looking for an
invisible
needle in a haystack

Deducing the Existence of Neutrinos

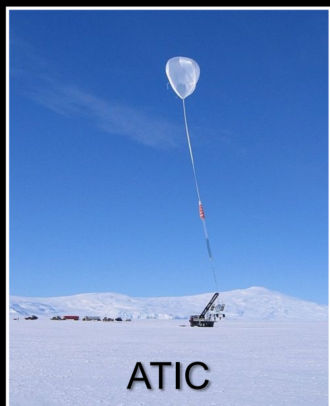
Wolfgang Pauli 1930

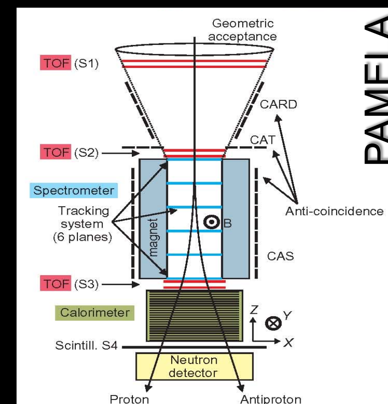




Missing Energy Signals for Dark Matter

Looking for Dark Matter in the Heavens





WIMP annihilation $\langle \sigma_A \mathrm{v} \rangle = 3\times10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

$$\frac{d\Phi_E}{dE} = \frac{dN_{\gamma,\nu}}{dE}\frac{\langle\sigma_A \mathrm{v}\rangle}{4\pi}\int \frac{\rho^2[r,s,l,b]}{2M^2_{\mathrm{WIMP}}}\, ds\ \cos b\, db\, dl$$

What to look for

- Charged particles: $\bar{p}$, high-energy $e^- e^+$
  - easy to detect
  - astronomical backgrounds
  - bent by magnetic field
- Continuum photons, neutrinos
  - γ easy to detect
  - astronomical backgrounds
  - ν hard to detect/often not dominant
- Monoenergetic photon line ($\bar{\chi}\chi \to \gamma\gamma$)
  - low background
  - (probably) low signal
  - "golden" detection channel

Where to look for it

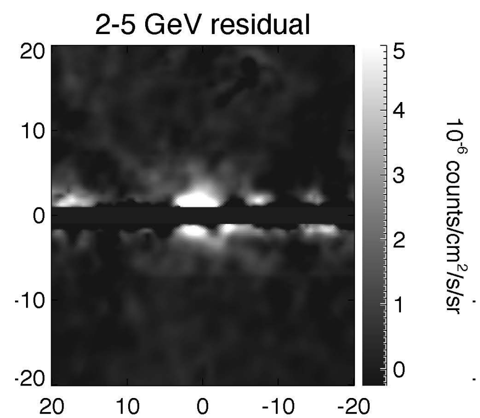
- Galactic Center
  - know where to look
  - largest signal
  - largest backgrounds
- Nearby subclumps
  - clean: no baryons
  - don't know where to look
  - signal down 10^{-3}
- Dwarf spheroidals $(M/L)_\odot > 3000$
  - know where to look (about 20)
  - clean: very few baryons
  - signal down another 10^{-3}

Diffuse γ- rays from the galactic center

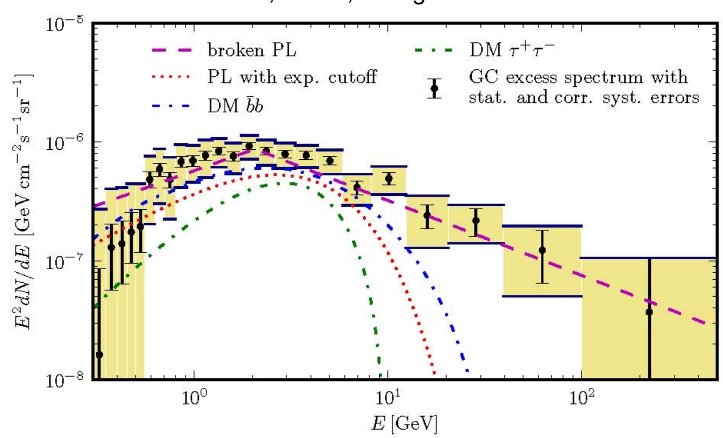
Goodenough, Hooper, Dalyan, Portillo, Rood, Boyarsky, Malyshev, Ruchayskiy, Linden, Abazajian, Kaplinghat, Gordon, Macias, Canac, Horiuchi, Slayter, Berlin, Cholis, McDermott, Lin, Finkbeiner, Calore, Cholis, Weniger, …

- Start with FERMI public data and tools
- Pick search region of interest (around galactic center)
- Remove point sources and model and remove every non-DM astrophysical source
- Fit excess (if any) to cross section & annihilation channel(s)

Dalyan, et al. 1402.6703



Calore, Cholis, Weniger JCAP 2015

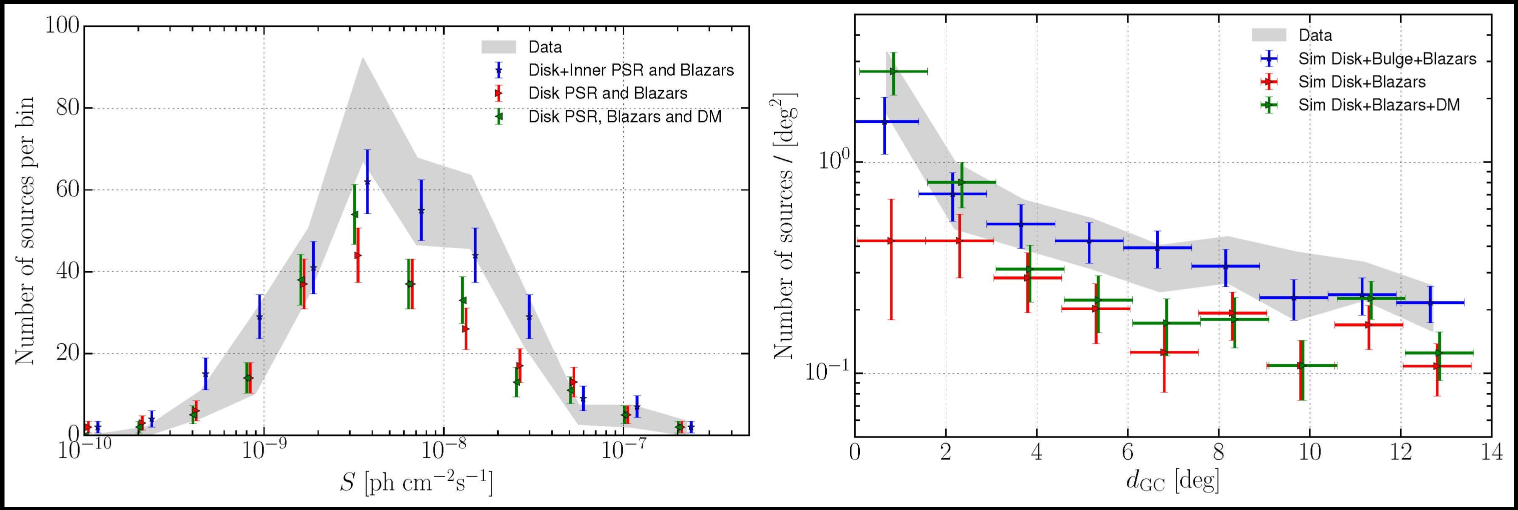


$M = 32.25$ GeV
annihilation to $\bar{b}b$
$\sigma v = 1.7\times10^{-26}$ cm^3/s

Model	Parameters			c^2/dof	p-value
BPL	$a_1 = 1.42^{+0.22}_{-0.31}$	$a_1 = 2.63^{+0.13}_{-0.095}$	$E_B = 2.06^{+0.23}_{-0.17}$ GeV	1.06	0.39
$\bar{b}b$	$M = 49^{+6.4}_{-5.4}$ GeV	$s\,v = 1.76^{+0.28}_{-0.27}$ ¥ 10^{-26} cm^2		1.08	0.36
$\bar{c}c$	$M = 38.2^{+4.6}_{-3.9}$ GeV	$s\,v = 1.25^{+0.2}_{-0.18}$ ¥ 10^{-26} cm^2		1.07	0.37
$\bar{t}t$	$M = 0.337^{+0.047}_{-3.9}$ GeV	$s\,v = 1.25^{+0.2}_{-0.18}$ ¥ 10^{-26} cm^2		1.52	0.06

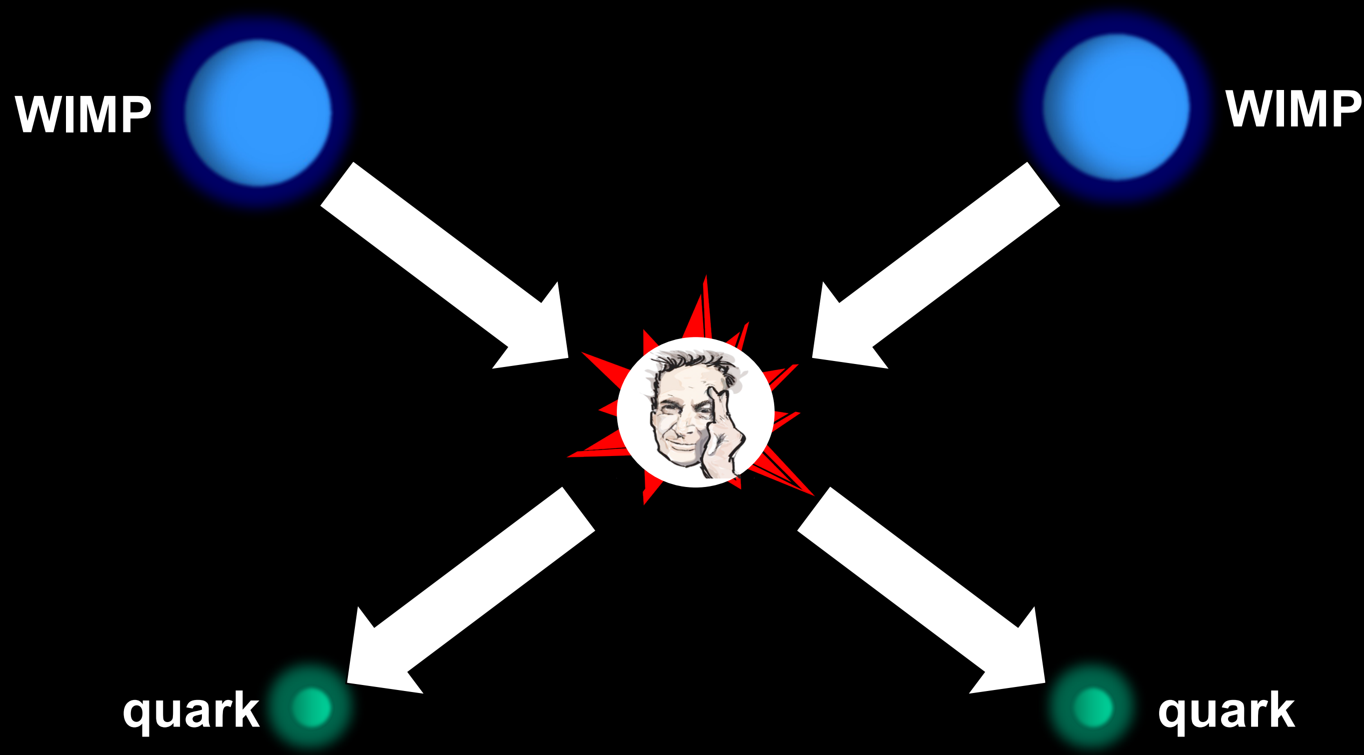
The Fermi-LAT collaboration

Better fit to (large ~ few thousand) number of Pulsars

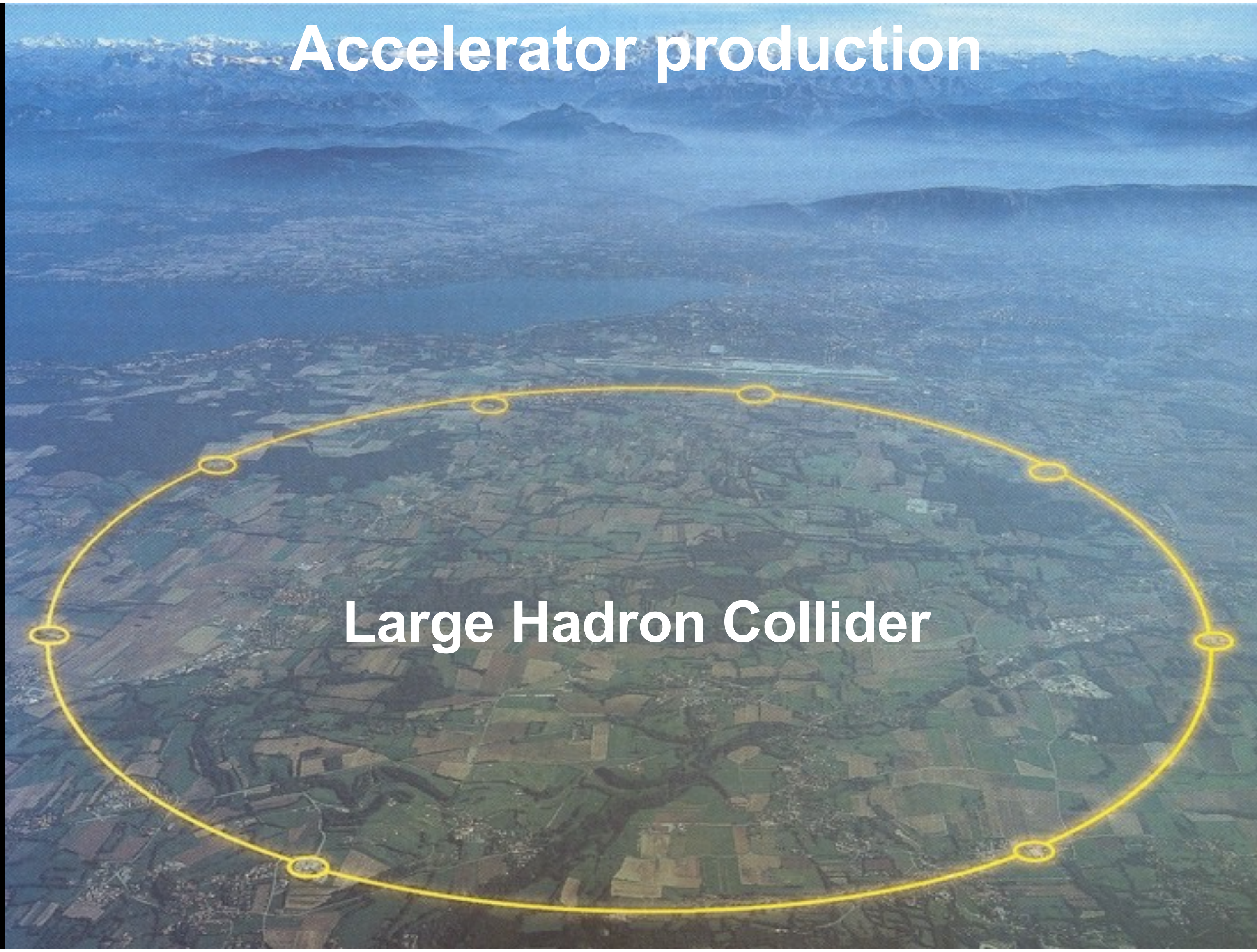


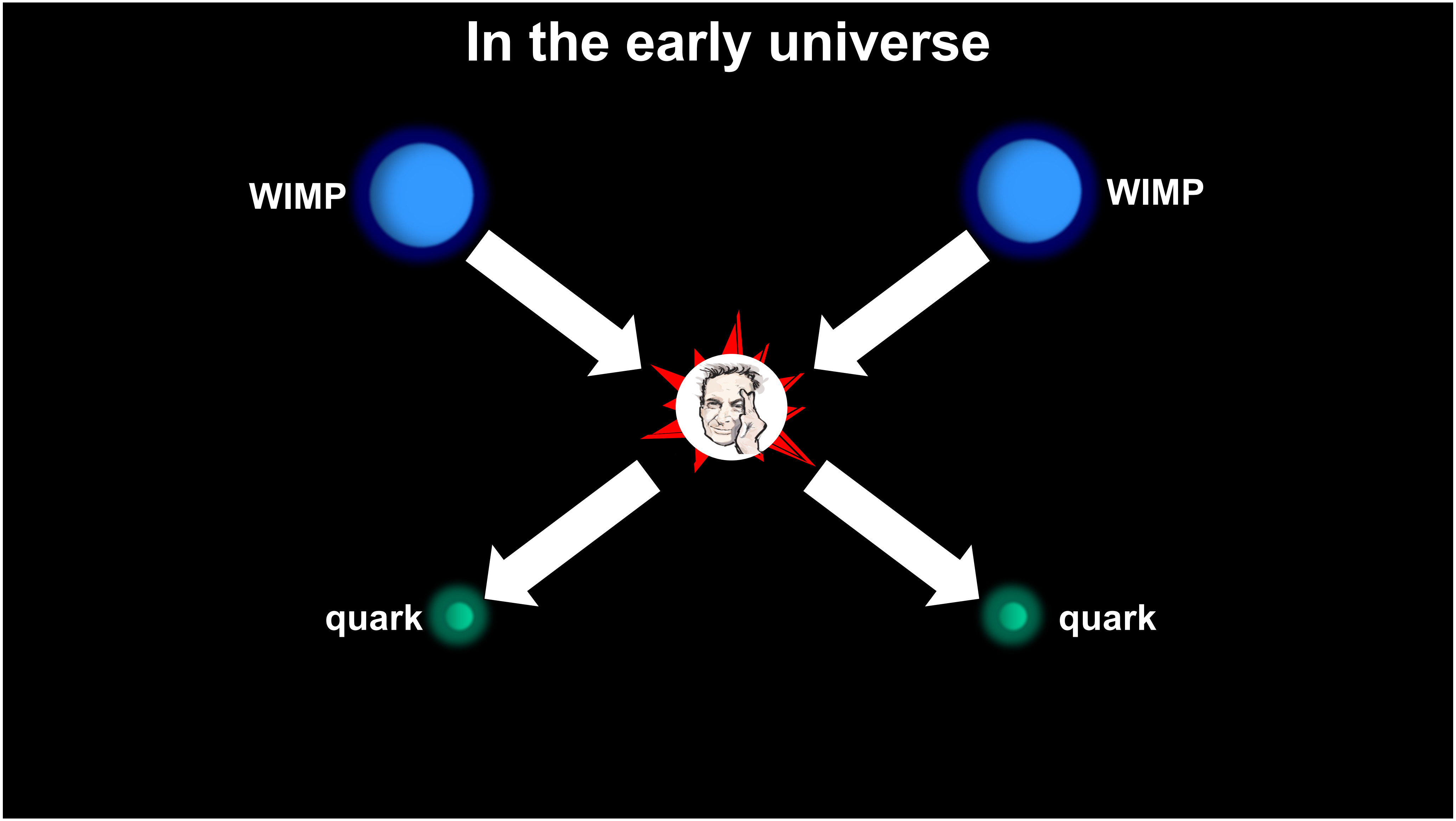
1705.00009

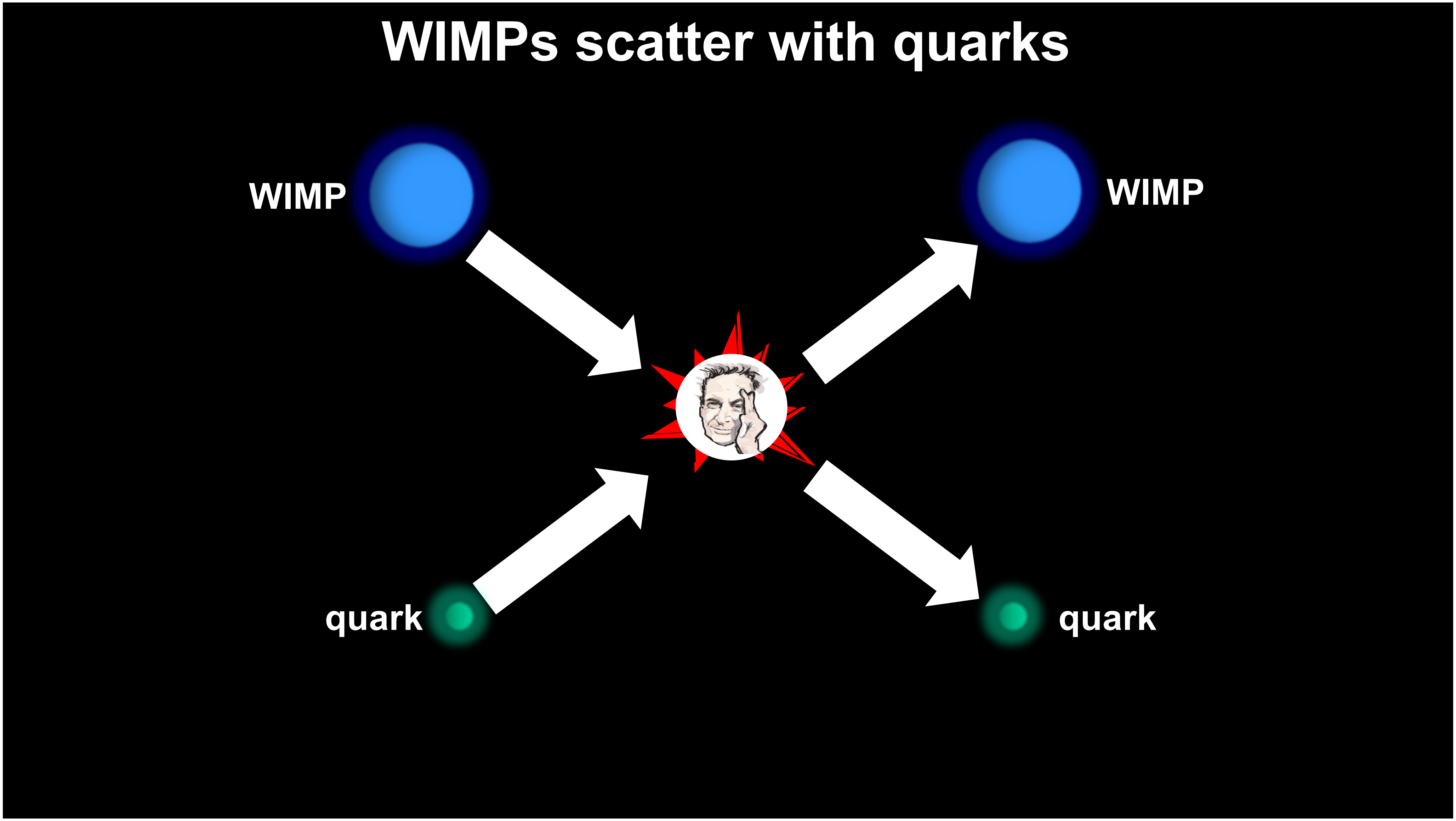
In the early universe

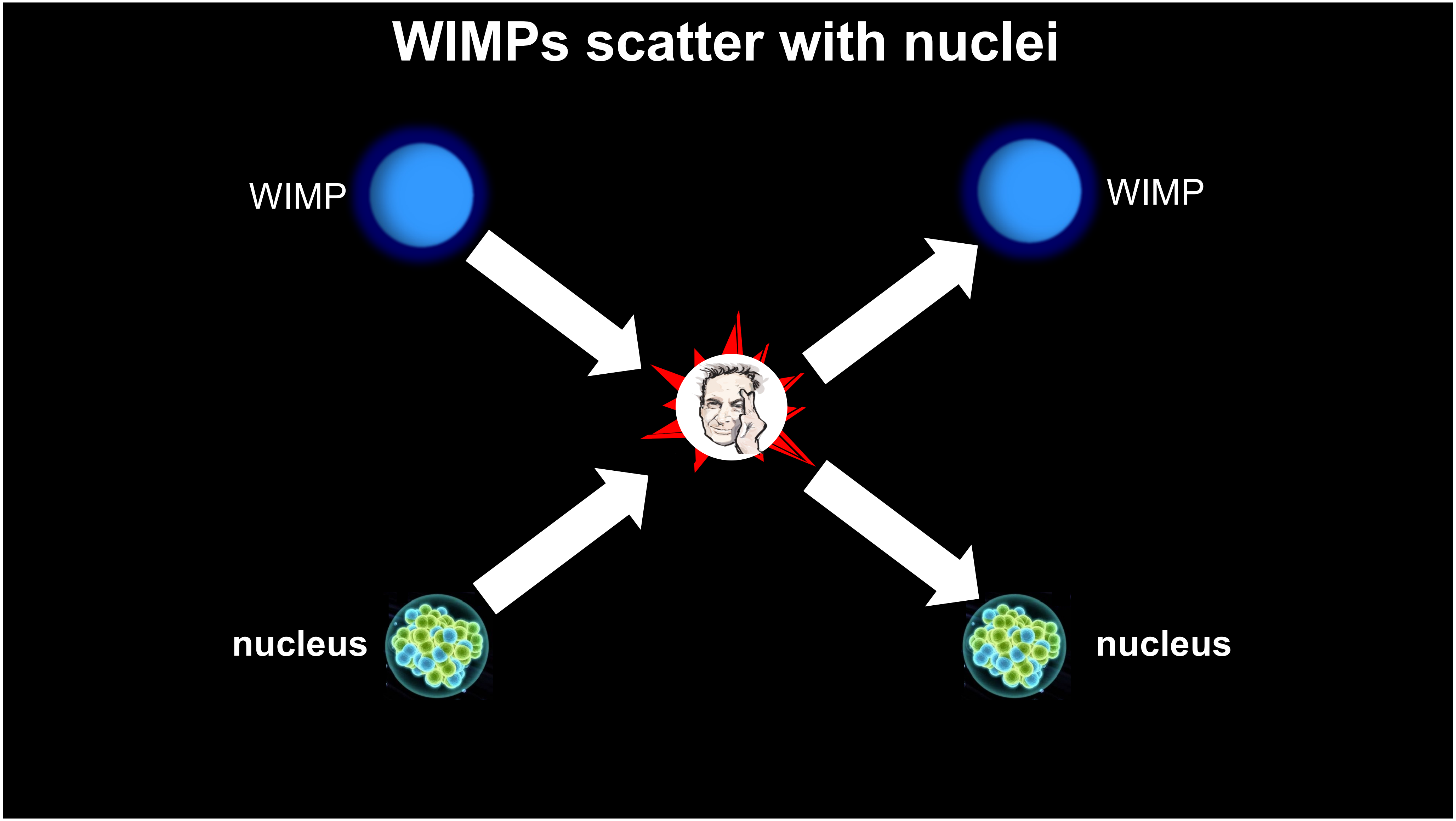


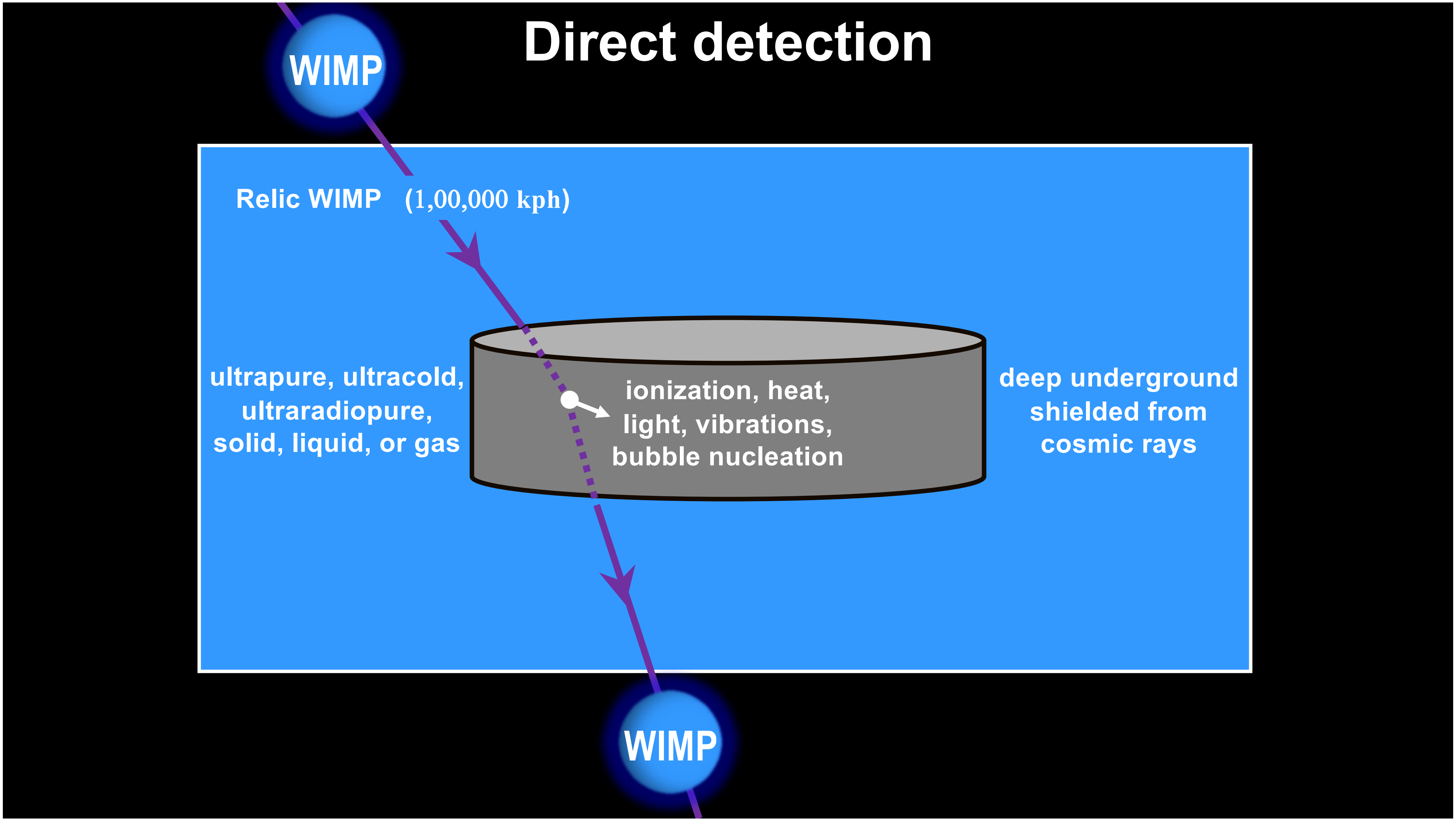
$$\langle \sigma_A v \rangle = 3\times10^{-26}\ \mathrm{cm^3\ s^{-1}}$$


Accelerator production
Large Hadron Collider


In the early universe
WIMP
WIMP
quark
quark

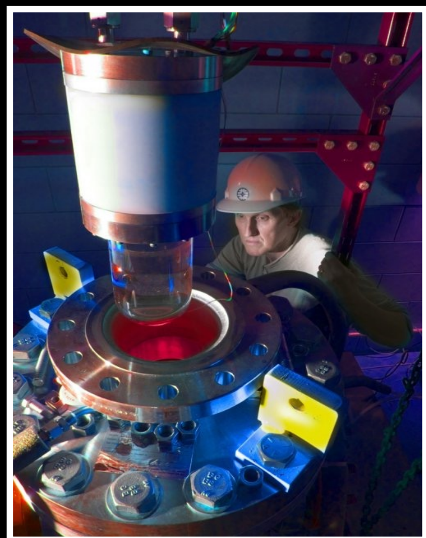

WIMPs scatter with quarks
WIMP
WIMP
quark
quark


WIMPs scatter with nuclei
WIMP
WIMP
nucleus
nucleus

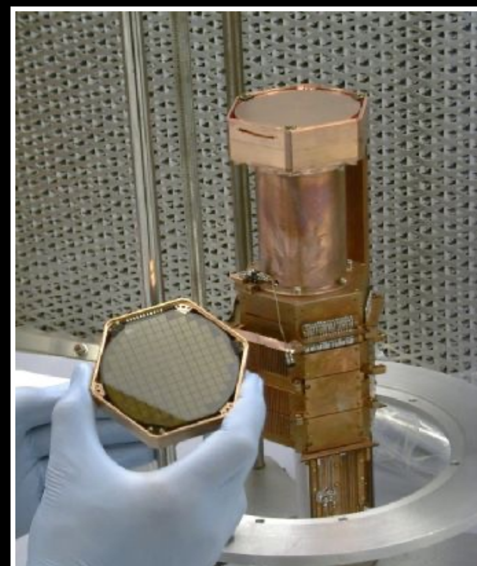

Direct detection
WIMP
Relic WIMP (1,00,000 kph)
ultrapure, ultracold,
ultraradiopure,
solid, liquid, or gas
ionization, heat,
light, vibrations,
bubble nucleation
deep underground
shielded from
cosmic rays
WIMP

Looking for Dark Matter Underground

COUPP



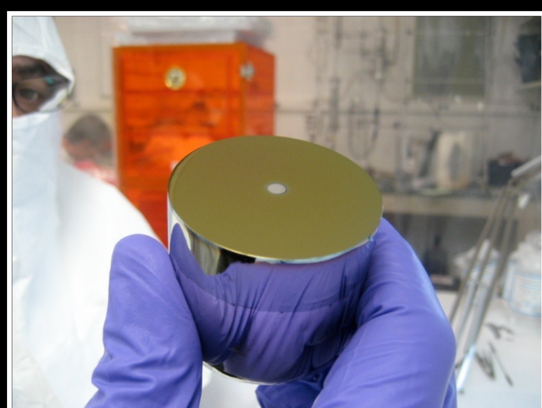
CDMS



CRESST

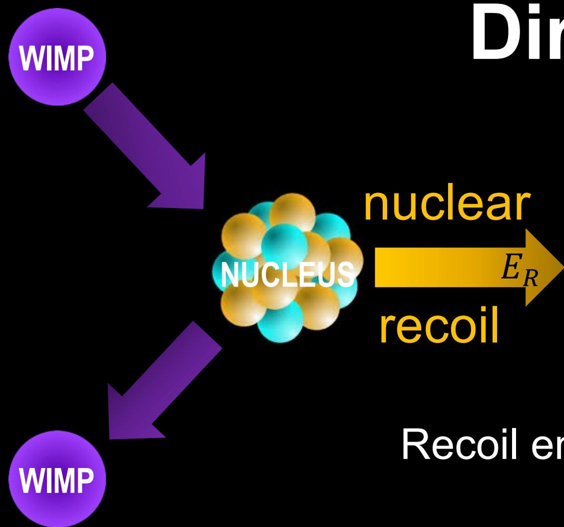
DAMA

CoGeNT



(+ EDELWEISS, XENON, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, ...)

Direct detection



$$\frac{dR}{dE_R} = \frac{1}{M_{\mathrm{Nucleus}}} \frac{\rho_{\mathrm{WIMP}}}{M_{\mathrm{WIMP}}} \int_{\mathrm{v_{MIN}}} \frac{d\sigma(\mathrm{v})}{dE_R(\mathrm{v})}$$

Recoil energies few to few dozen keV

Astrophysics: $\begin{cases} \rho_{\mathrm{WIMP}} \\ f(\mathrm{v}) \end{cases}$

Particle physics: $\begin{cases} M_{\mathrm{WIMP}} \\ d\sigma/dE_R \end{cases}$

Experiment:
- Detector Mass
- Nuclear Target(s) (M_{Nucleus} and J_{Nucleus})
- $E_{\mathrm{Threshold}} = 2\mu_{\chi\mathrm{N}}^2\, \mathrm{v}_{\mathrm{MIN}}^2 \,/\, M_{\mathrm{Nucleus}}$
- $d\sigma/dE_R$

Direct Detection

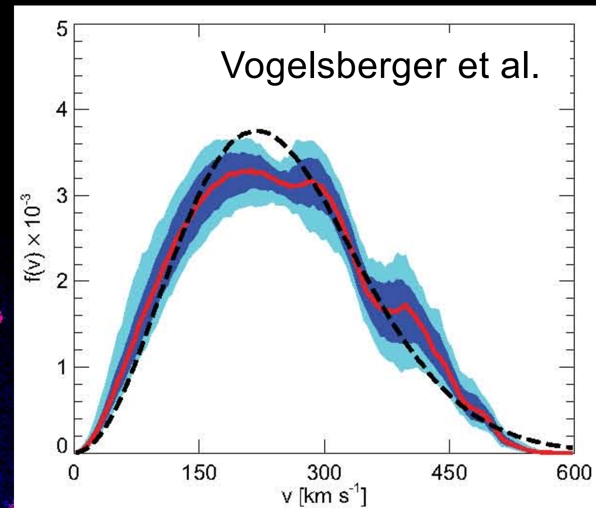
- $f\,(\mathrm{v})$ local WIMP phase-space density
  - Assume: $\rho_{DM} = 0.3$ GeV cm^{-3} (subclumps, streams, cusps,…?)
  - Assume: Maxwellian velocity distribution $\langle \mathrm{v}^2 \rangle^{1/2} = 220$ km s^{-1}
- Spin dependence (axial, tensor)?

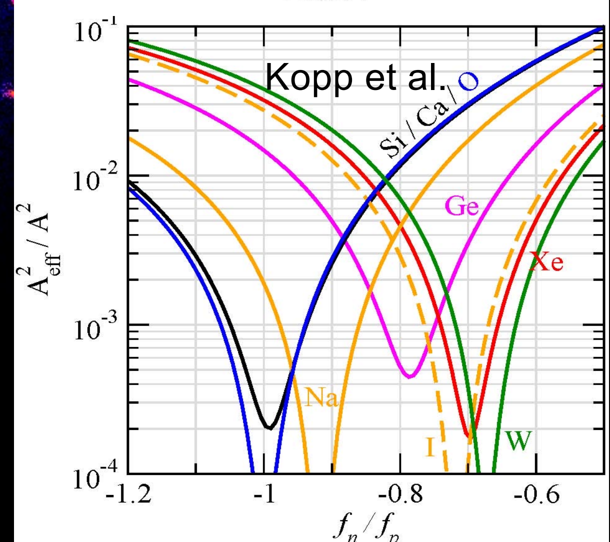
$$\sigma_{\chi N} = \frac{8}{\pi} \frac{m_\chi^2 m_N^2}{(m_\chi^2 + m_N^2)^2} \; \Lambda^2 \; J(J+1)$$

- Same coupling to p and n (scalar)?

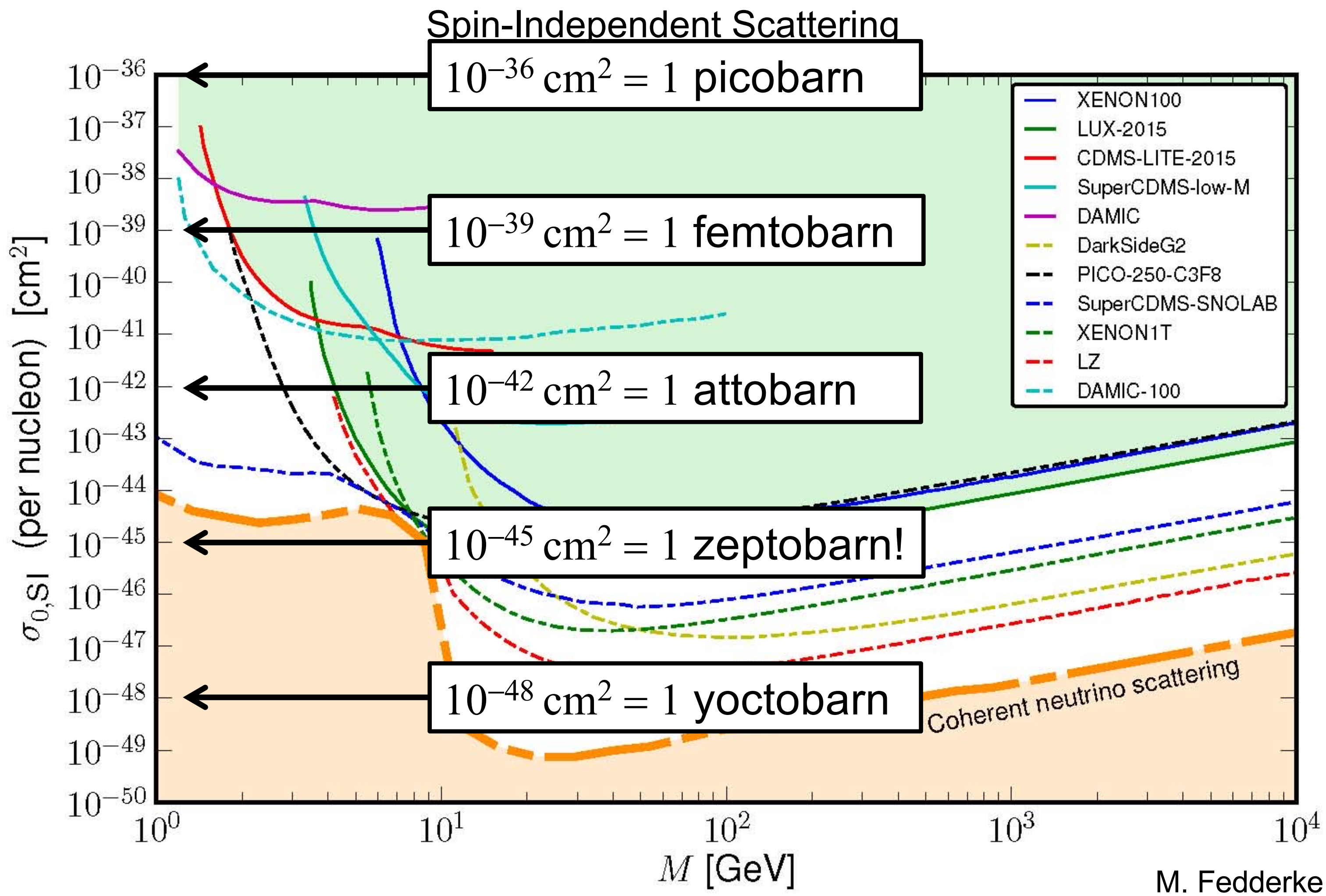
$$\sigma_{\chi N} = \frac{1}{\pi} \frac{m_\chi^2 m_N^2}{(m_\chi^2 + m_N^2)^2} \; [Z f_P + (A - Z) f_n]$$

- Compare different experiments w/ caution





Direct detection



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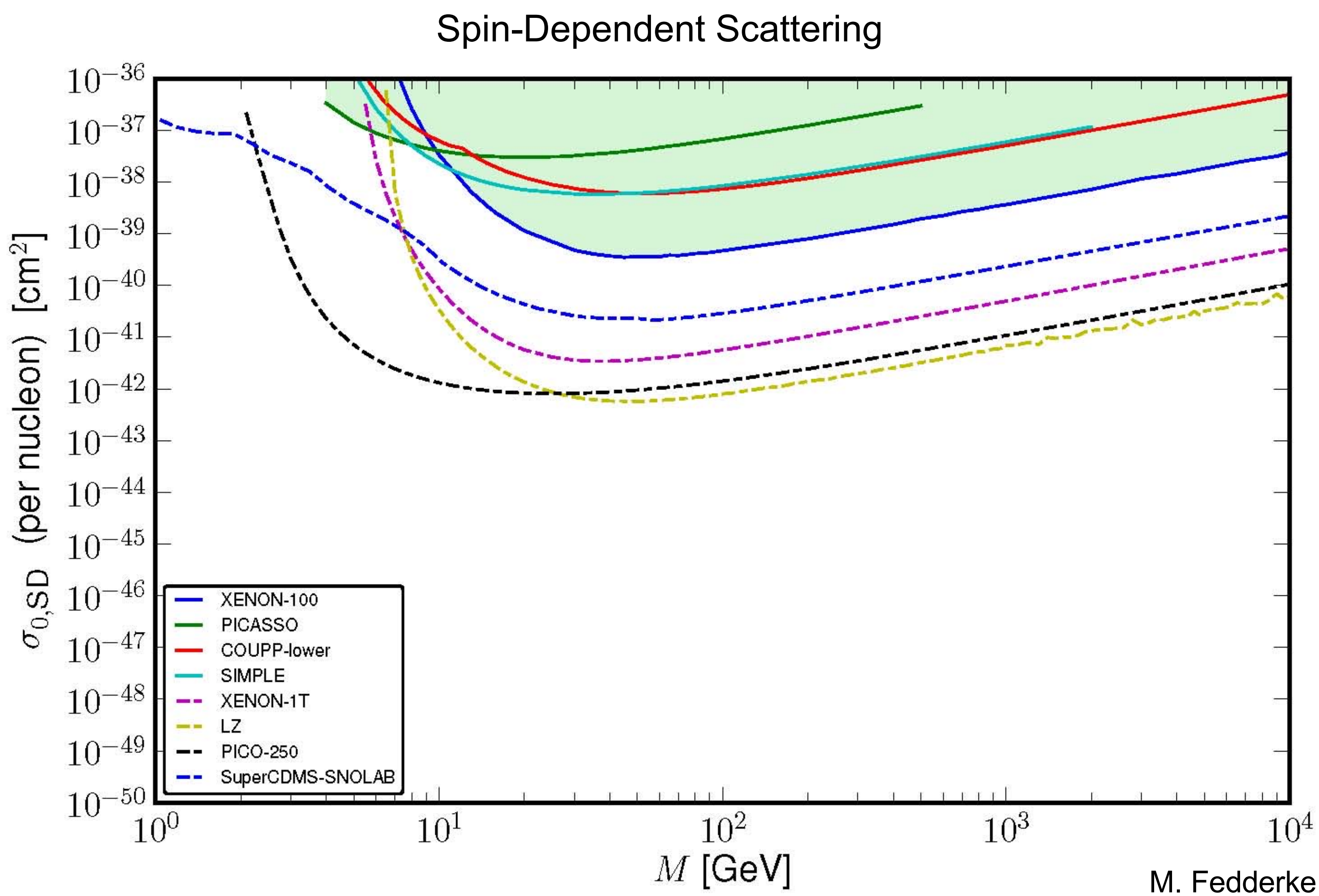
Direct detection



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Dark Matter: if not a WIMP

- If DM not a WIMP, many other possibilities:
  - Axions
  - Asymmetric DM
  - Sterile neutrino DM (e.g., $7\ \mathrm{keV}$ sterile neutrino producing $3.5\ \mathrm{keV}$ X-ray line which may, or may not, be observed)
  - Axino ($7\ \mathrm{keV}$ axino) DM
  - Self-interacting DM
  - Inelastic DM
  - Q-balls or other solitonic DM
  - Quark nuggets
  - Hidden-sector DM
  - WIMPzilla

For 40 Years, Leading Candidate*
"Weak"-Scale Cold Thermal Relic

- Mass: GeV – TeV
- "Weak-scale" interaction strength with SM
- No self-interactions
- Produced by "freeze-out" from primordial plasma. COLD dark matter.
- "Detectable" by direct detection, indirect detection, decay products, production at colliders
- Just BSM

But not (convincingly) seen

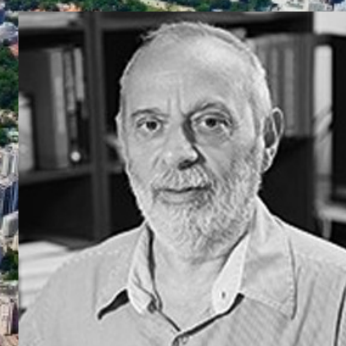
- In Direct detection (but DAMA/LIBRA)
- In Indirect Detection (but galactic-center excess)
- In Decay (but $3.5\ \mathrm{keV}$ γ-ray line)
- In Colliders no BSM signal (but μ_{g-2}, m_W)

What if DM interacts only gravitationally?

- Gravity must play a role in its cosmological production
- But gravity weak!

Gravitational Particle Production and Dark Matter — Four Lectures

1. Dark Matter: Evidence and the Standard WIMP
2. Gravitational Particle Production (Schrödinger's Alarming Phenomenon)
3. GPP of Scalar Fields
4. Beyond Scalar Fields



Rocky Kolb, University of Chicago

CBPF 9/2022