Search for Dark Matter

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Lecturer?

- Jong-Chul Park
  Chungnam National University, Korea

- Particle Physics – Phenomenology:
  Dark Matter, Neutrino, Cosmic Rays,
  Early Universe Cosmology, …

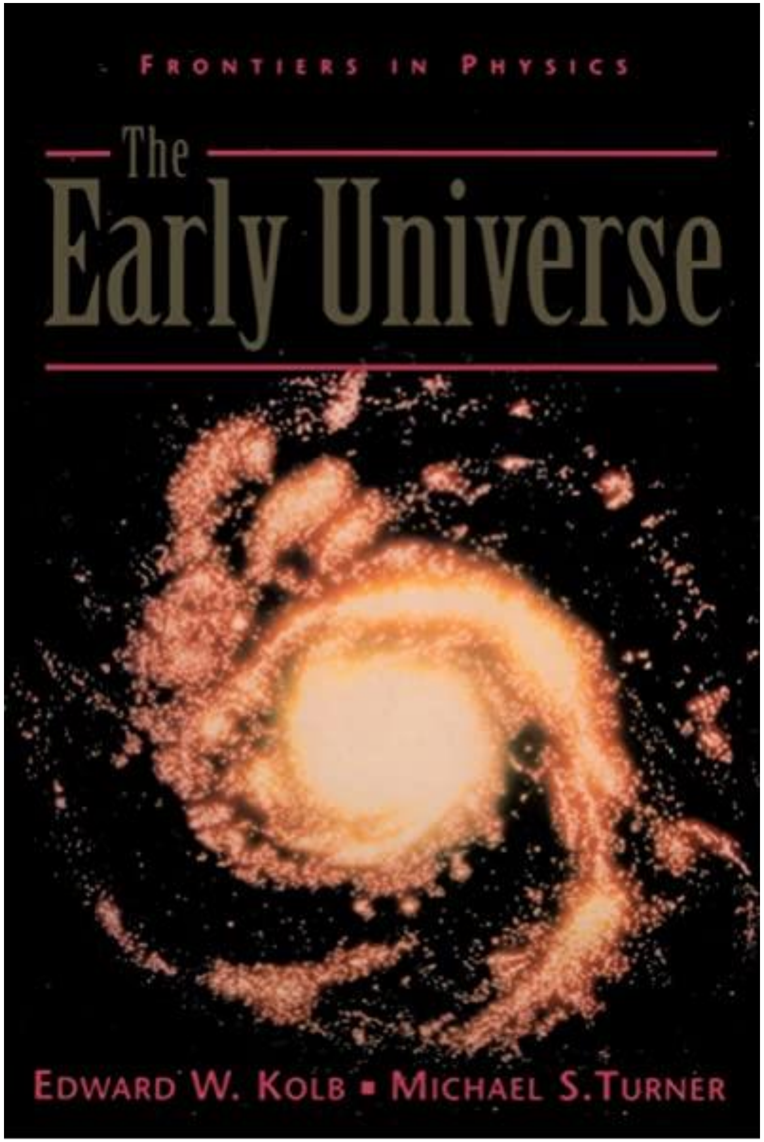
- log1079@gmail.com or jcpark@cnu.ac.kr

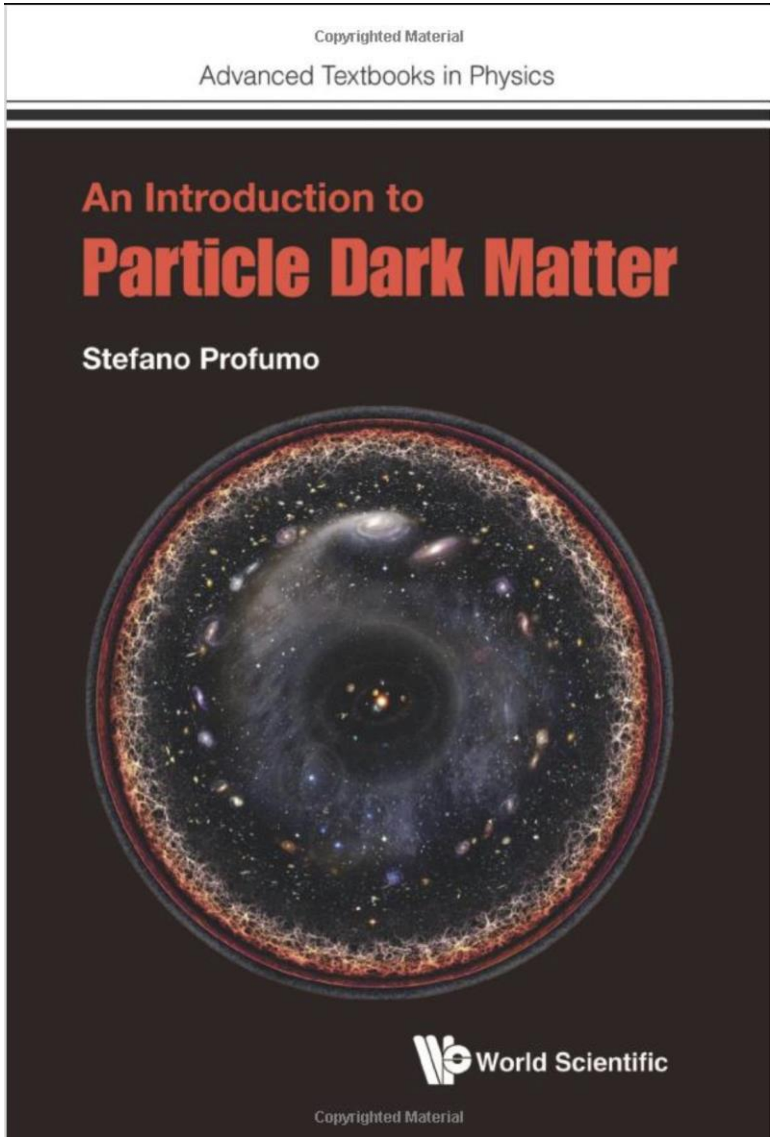
- https://inspirehep.net/literature?sort=mostrecent&size=25&page=1&q=a%20j.%20c.%20park%20and%20d%20%3E%202004

References: Reviews/Lecture Notes

1. https://arxiv.org/abs/1605.04909 ➔ History
2. https://arxiv.org/abs/1703.07364 ➔ General w/ Models
3. https://arxiv.org/abs/1705.01987 ➔ General
4. https://arxiv.org/abs/1903.03026 ➔ Direct Detection
5. https://arxiv.org/abs/1904.07915 ➔ Direct Detection
6. https://arxiv.org/abs/1710.05137 ➔ Indirect Detection
7. https://arxiv.org/abs/1812.02029 ➔ Indirect Detection
8. https://arxiv.org/abs/2109.02696 ➔ Indirect Detection (Extension of 6)
9. https://arxiv.org/abs/1912.04727 ➔ Cosmology
10. ...

References: Books





References: Simulation Tools

1. WimPyDD (https://wimpydd.hepforge.org/)
2. PPPC 4 DM ID (http://www.marcocirelli.net/PPPC4DMID.html)
3. MicrOMEGAs (https://lapth.cnrs.fr/micromegas/)
4. MadDM (https://launchpad.net/maddm)
5. …

Things You Should Have Known ...

- Classical Mechanics, Thermal Physics ?
- Quantum Mechanics, Special Relativity ??
- General Relativity ???
- Quantum Field Theory… ????

Outline

0. Very Short Summary of the Standard Model
1. Observational Evidence of Dark Matter
2. Relic Abundance of Dark Matter
3. Direct Detection – Target particle recoil
4. Indirect Detection – Cosmic rays
5. Collider – Direct production
6. New Approaches

Exercises

1. DM vs Modified gravity/MOND (MOdified Newtonian Dynamics):

(a) What are Modified gravity and MOND?

(b) Compare DM & Modified gravity/MOND: pros and cons

2. DM candidates among SM particles:

(a) Which ones?

(b) Why not? (If possible, Relic density of neutrino)

0. Very Short Summary of the Standard Model

Eternal Questions

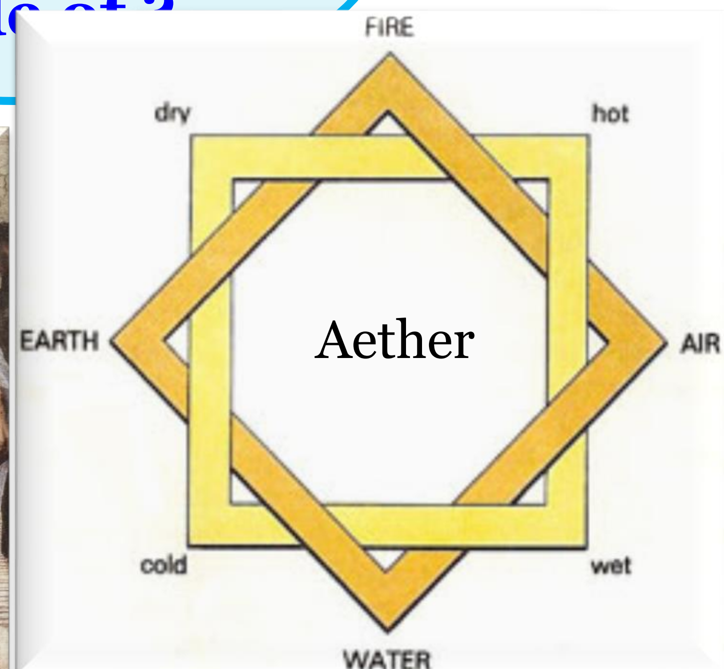
What is the Universe made of ?

Eternal Questions

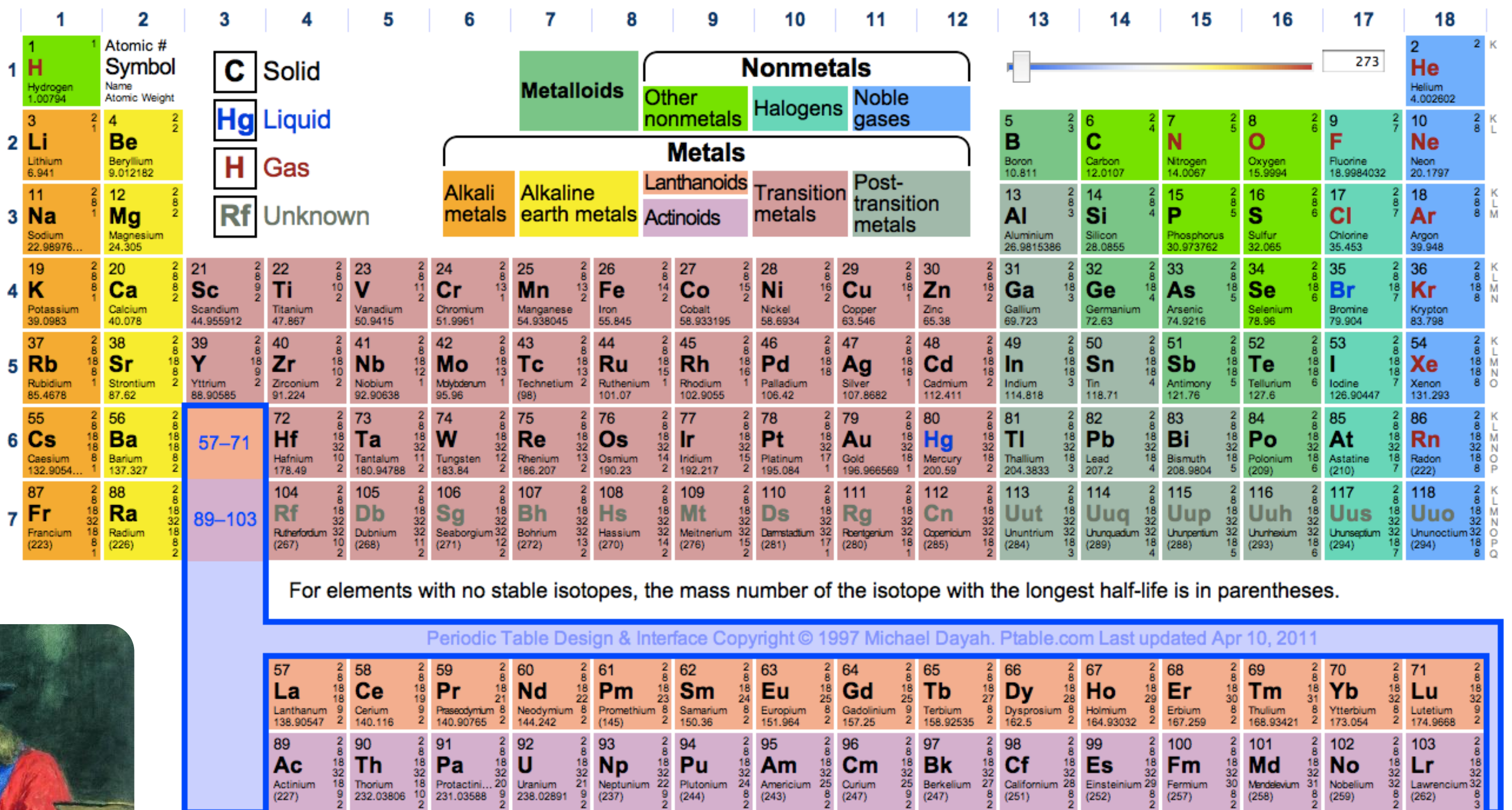
What is the Universe made of ?

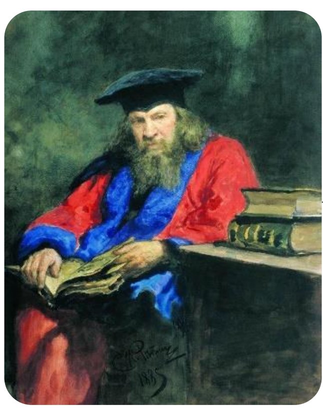
- Ancient Greek:

4 basic elements



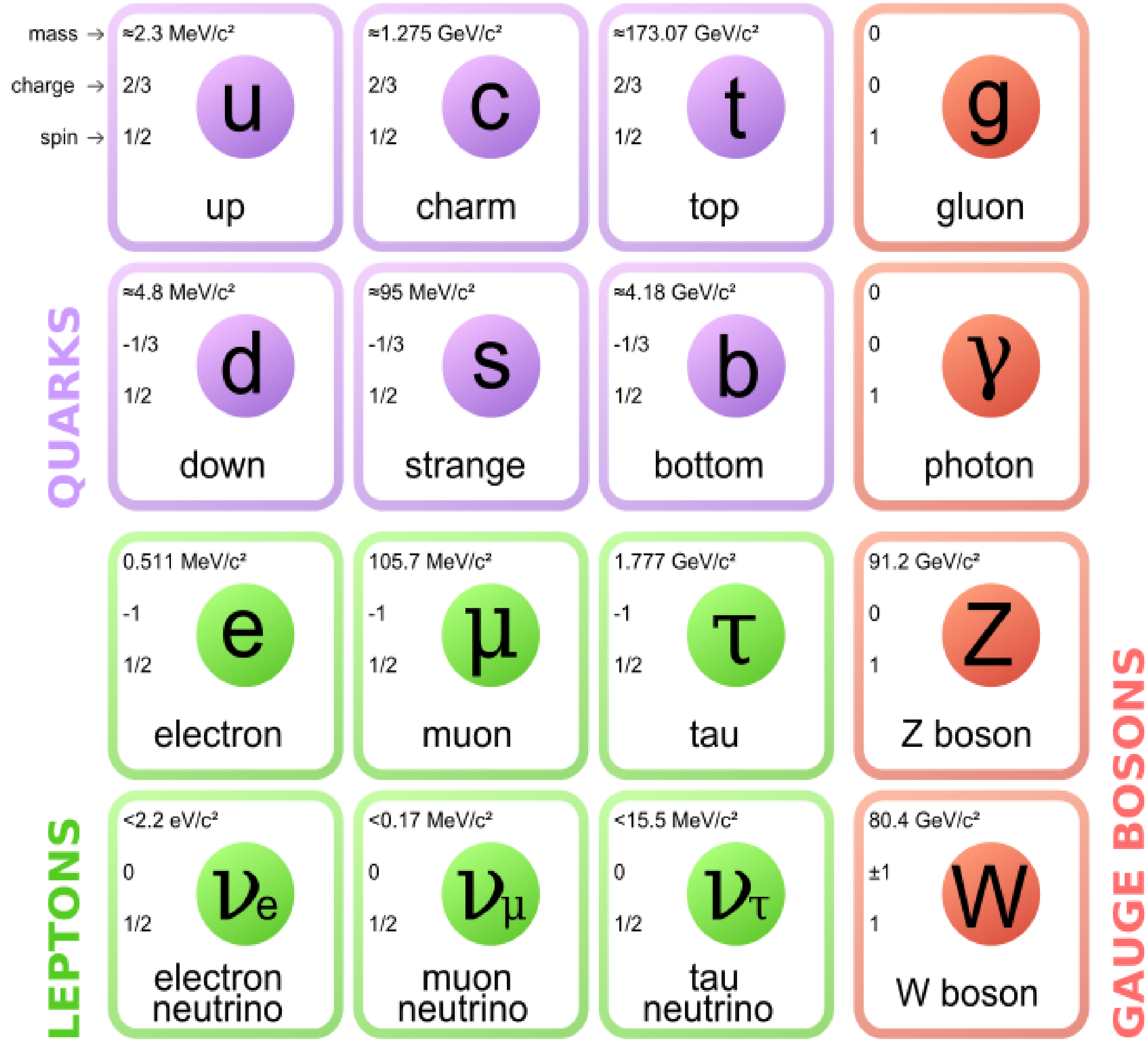
19th c: Periodic Table





Dmitri Mendeleev
(1869)

20^{th} c: Standard Model (SM)



GeV ~ m_p

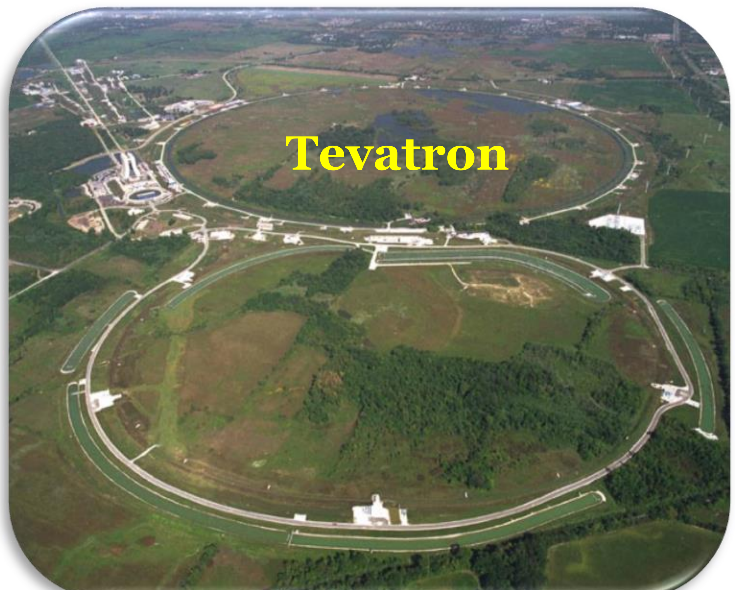
Lectures by Eibun Senaha

Higgs (1964)!

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)



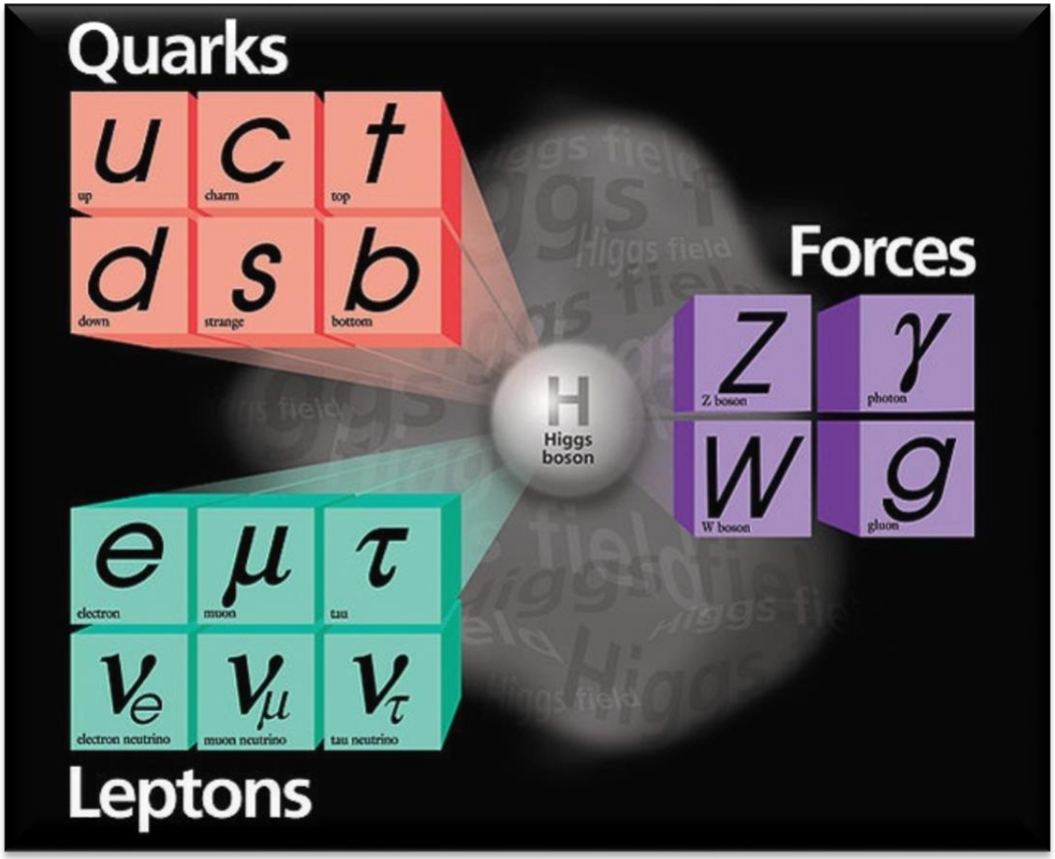
Chicago (USA)

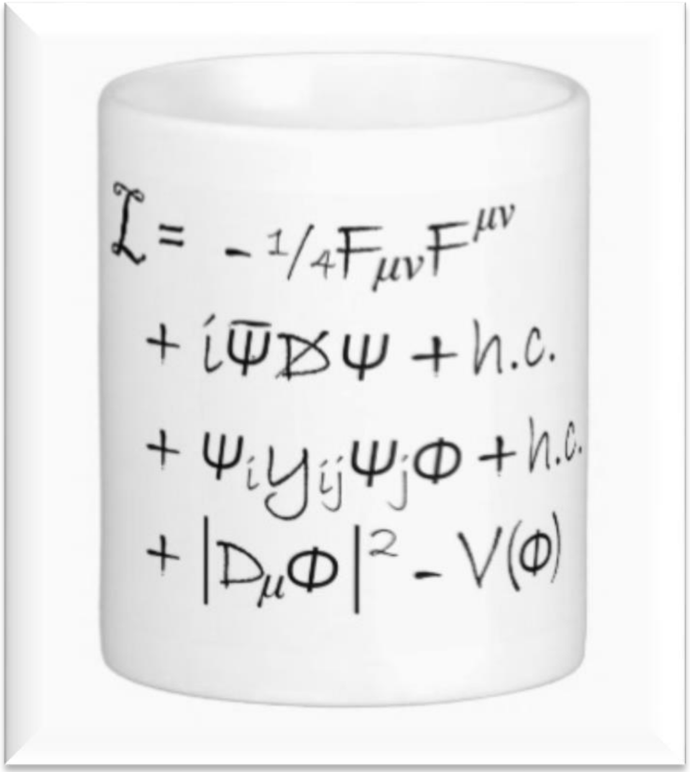
Geneva (Europe)

Higgs (2012)!

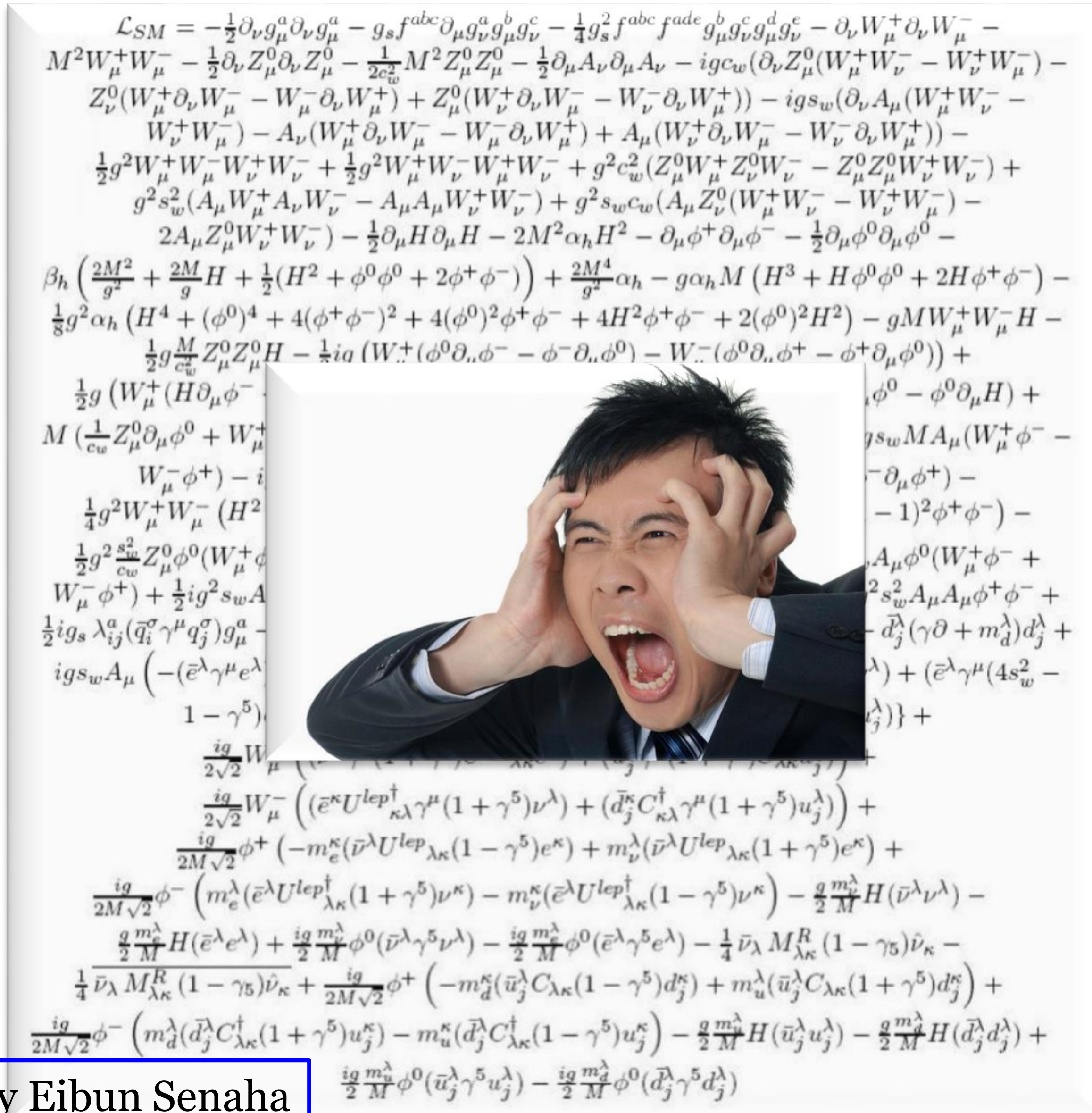
Higgs is discovered!

Now: Standard Model (SM)





Now: Standard Model (SM)



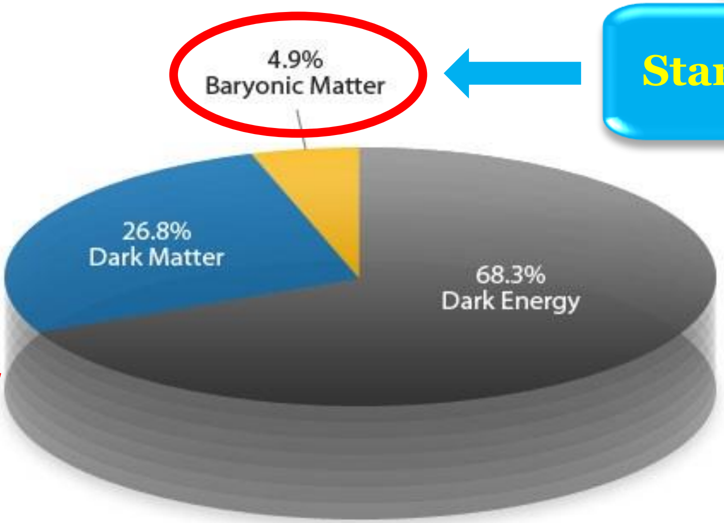
Probably NOT by Eibun Senaha


EIN ROLAND EMMERICH FILM
2012


NEED WORK!

Message from Cosmology

- ❖ Modern cosmology ➔ Cosmic pie



Stars, Galaxies, H, …

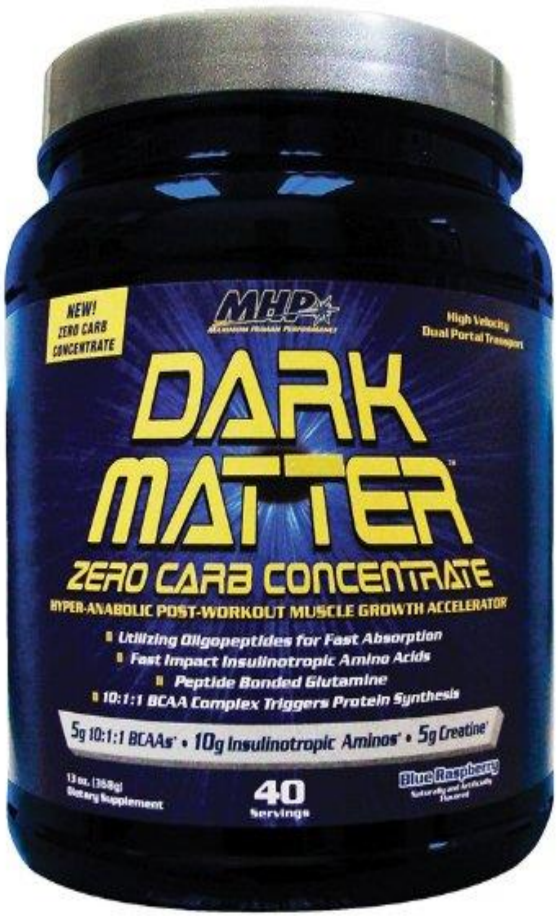
Supernova

CMB

- ❖ The Standard Model explains only ~5% of the total E of the Universe.

See also BSM lectures by Margarete Mühlleitner

Question in the 20th Century!!



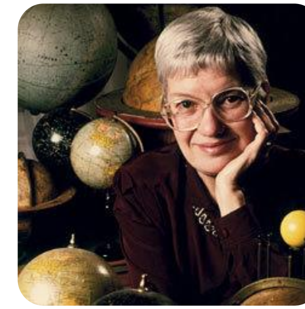
What's
the matter?

↓

What's
Dark Matter?

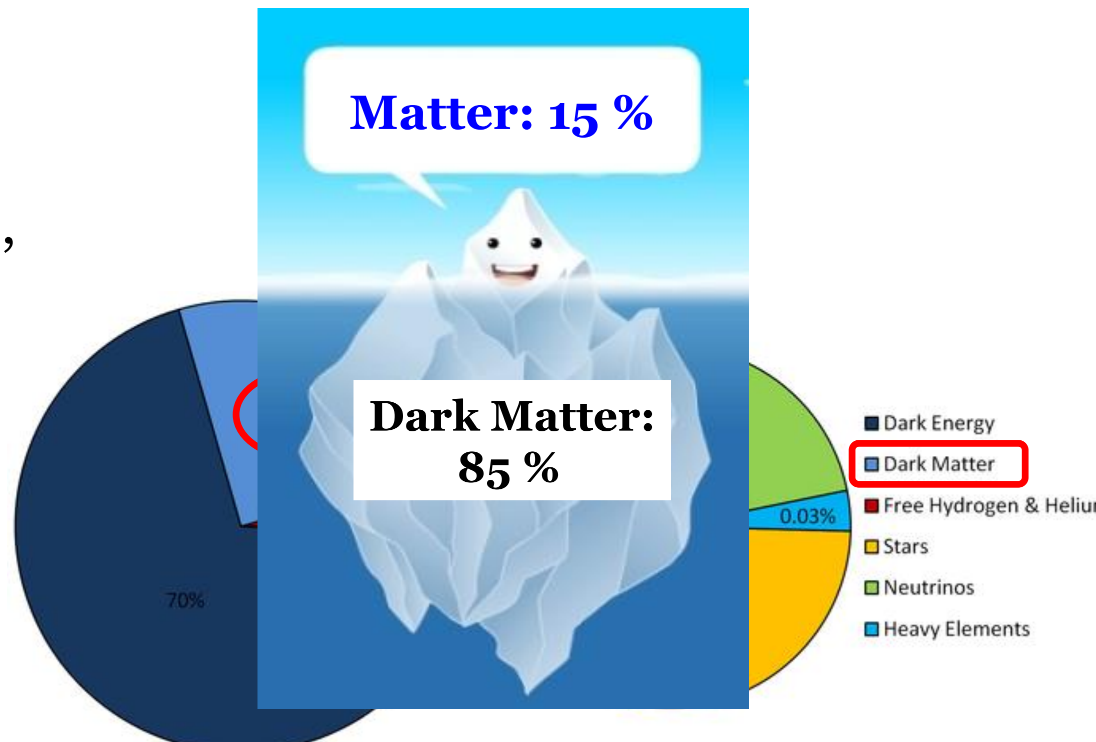
Dark Matter (DM)

- Postulated by Fritz Zwicky in early 1930's
- Rediscovered by Vera Rubin in 1970



- **Compelling paradigm**:
  - ✓ massive,
  - ✓ non-relativistic (→ $v \ll c$),
  - ✓ non-luminous

    (no/tiny EM interaction),
  - ✓ stable particles
  - ✓ ~1/4 of the Universe



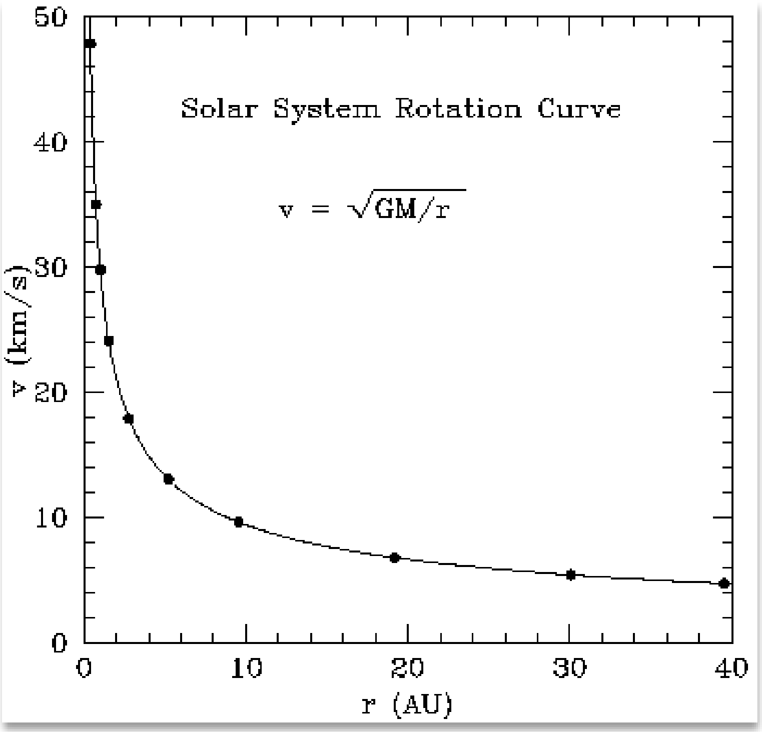

Existence of
Dark Matter?

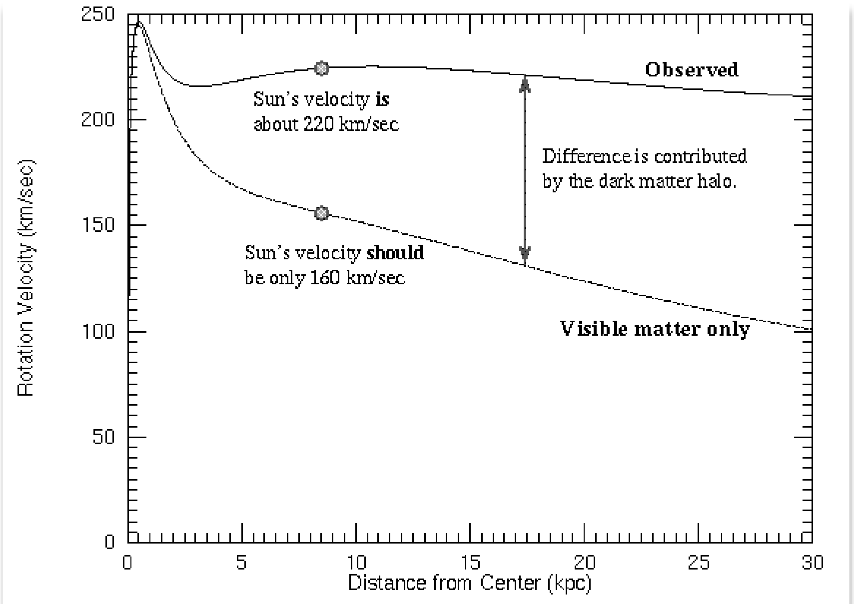
1. Observational Evidence of Dark Matter

Observational Evidence of DM

- ✓ Galaxy rotation curve
- ✓ Coma cluster
- ✓ Gravitational lensing
- ✓ Bullet cluster
- ✓ Structure formation
- ✓ Cosmic microwave background radiation (CMBR)
- ✓ Sky surveys
- ✓ Type Ia supervovae
- ✓ Baryonic acoustic oscillation (BAO)
- ✓ …

Galaxy Rotation Curve

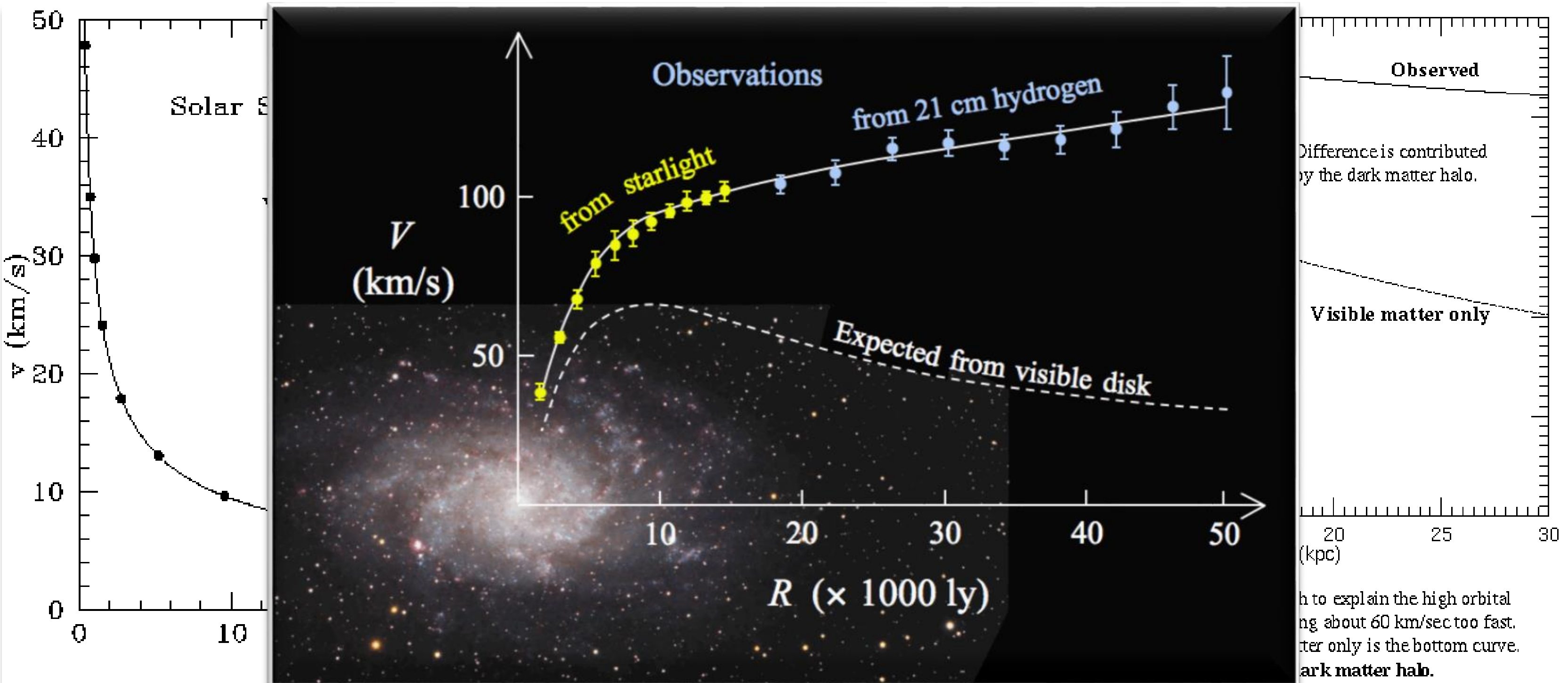




The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

Vera Rubin

Galaxy Rotation Curve



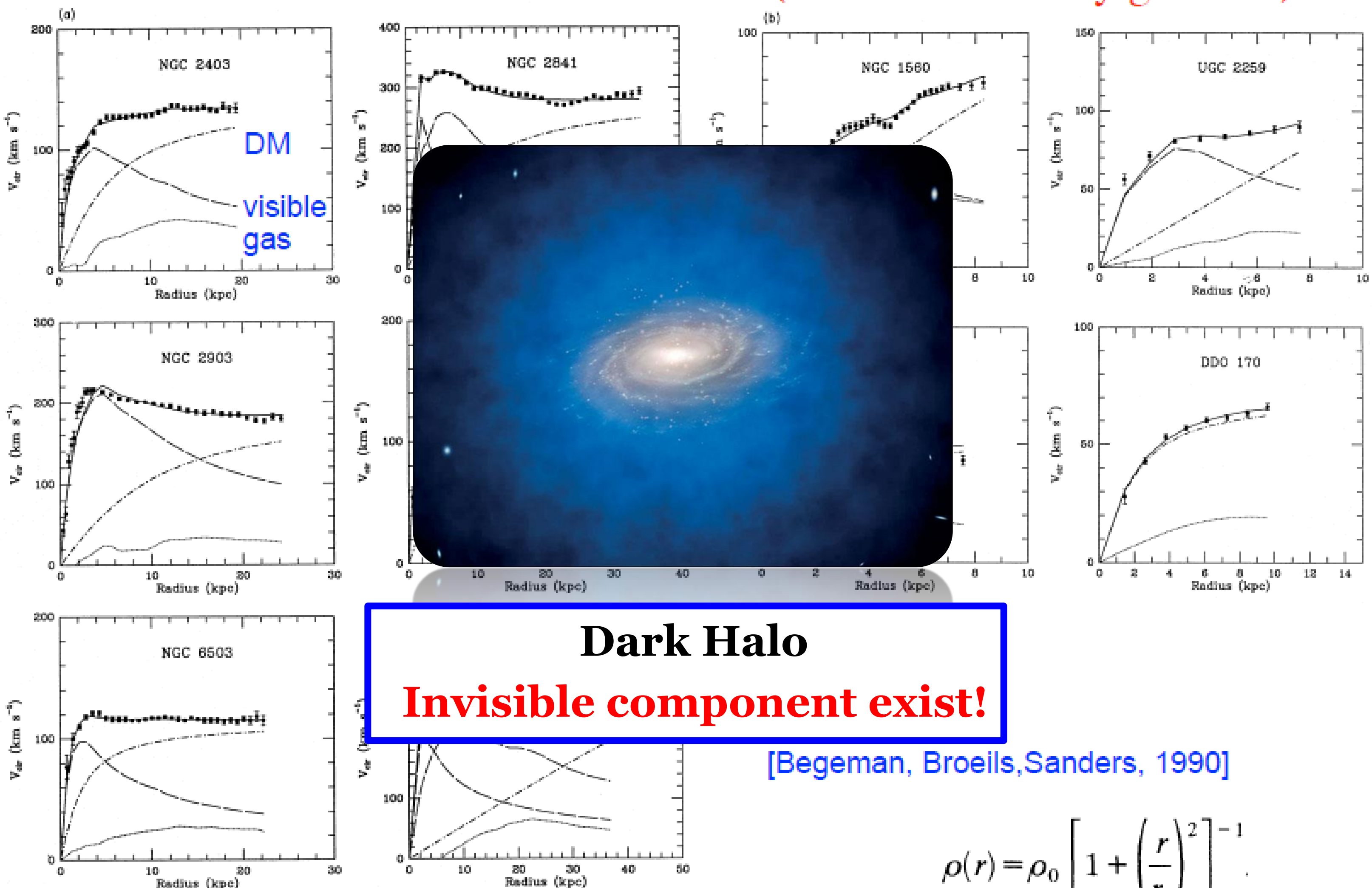
Vera Rubin

$$\frac{GMm}{r^2} = \frac{mv^2}{r} \rightarrow v \propto \sqrt{\frac{GM}{r}}$$

$$v \sim \text{constant} \rightarrow M(r) \propto r$$

❖ Much more galaxies

(Lower luminosity galaxies)



Dark Halo

Invisible component exist!

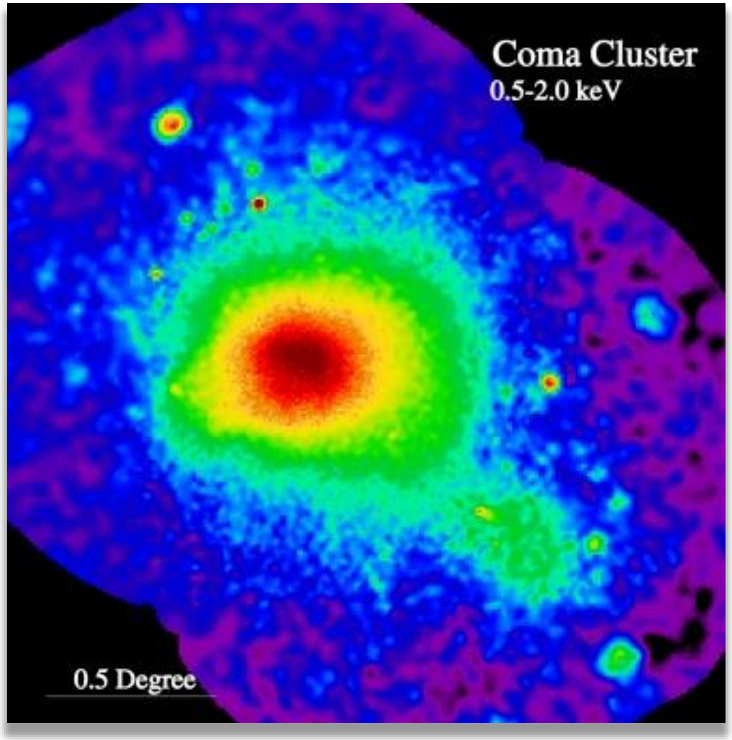
[Begeman, Broeils,Sanders, 1990]

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-1}$$

Figure 1. Three-parameter dark-halo fits (solid curves) to the rotation curves of sample galaxies. The rotation curves of the individual components are also shown: the dashed curves are for the visible components, the dotted curves for the gas, and the dash–dot curves for the dark halo. The fitting parameters are the mass-to-light ratio of the disc (M/L), the halo core radius (r_c), and the halo asymptotic circular velocity (V_∞). The galaxies from the sample of Begeman are shown in (a) and the lower luminosity galaxies in (b). Best-fit values for the free parameters are given in columns 2, 3 and 4 of Table 2.

Coma Cluster

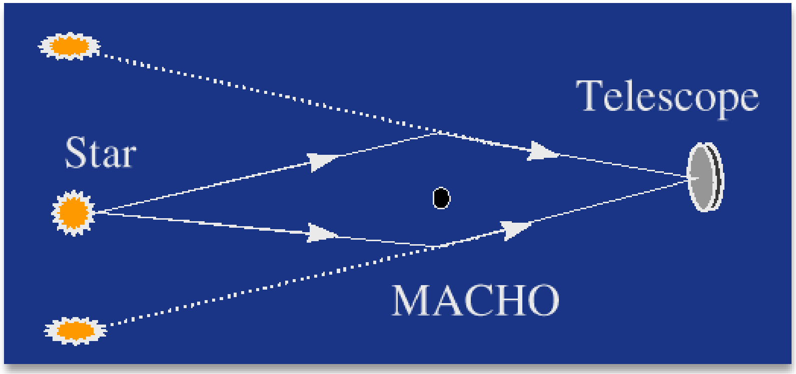
❖ The gravity of the cluster: too weak to contain the hot gas.
→ It would evaporate!: $T \propto v^2 \Leftrightarrow v^2 \propto GM/r$

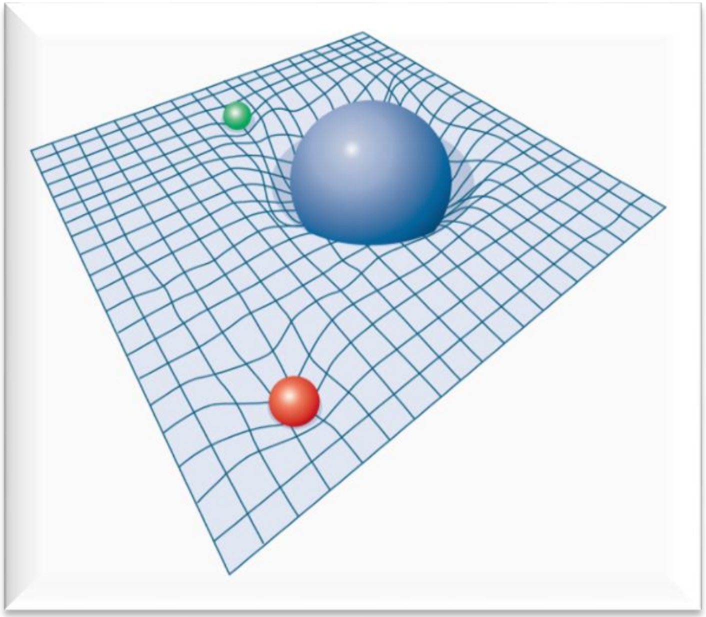


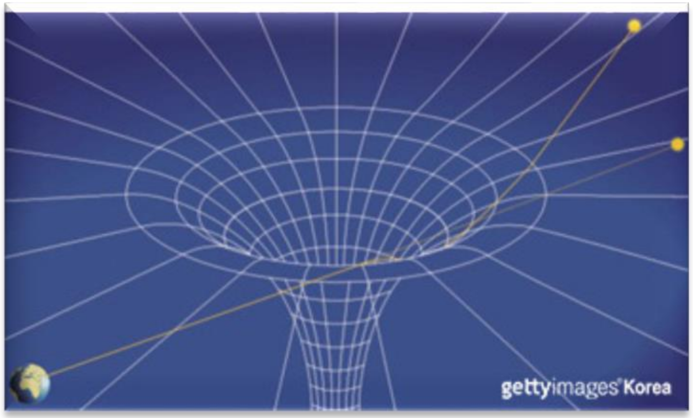
x-ray image from the ROSAT satellite

Gravitational Lensing

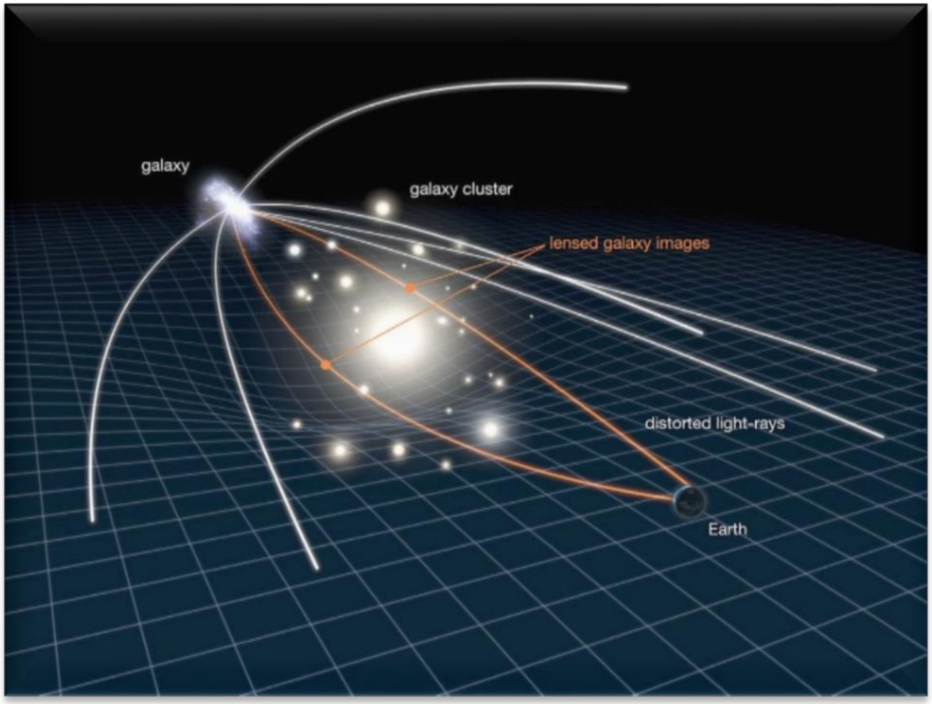
- General relativity: M distorts space-time
  ➔ When light passes around a massive object, it is bent!

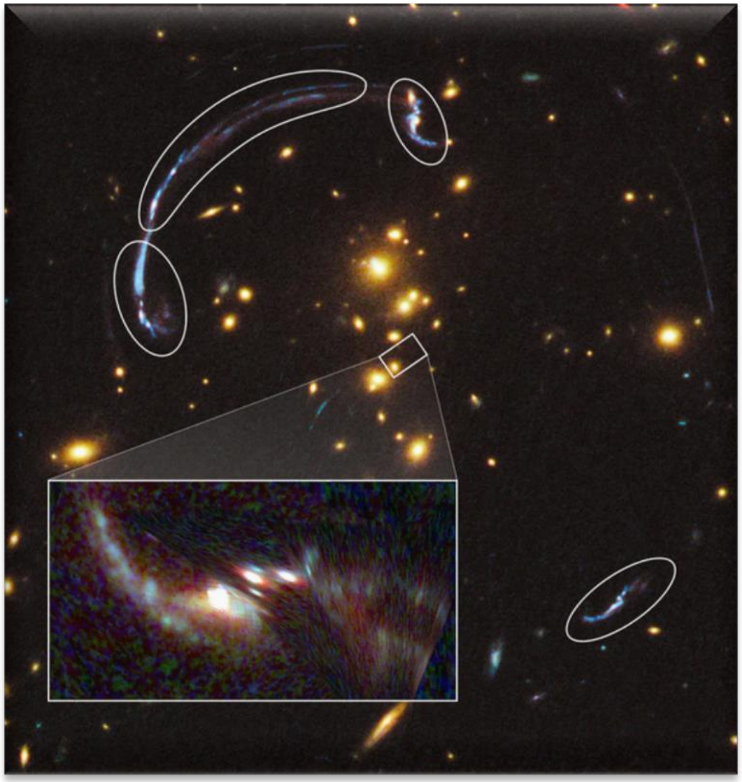






Gravitational Lensing





- Stars and hot gas:

  too small to bend the light from the background galaxies so much

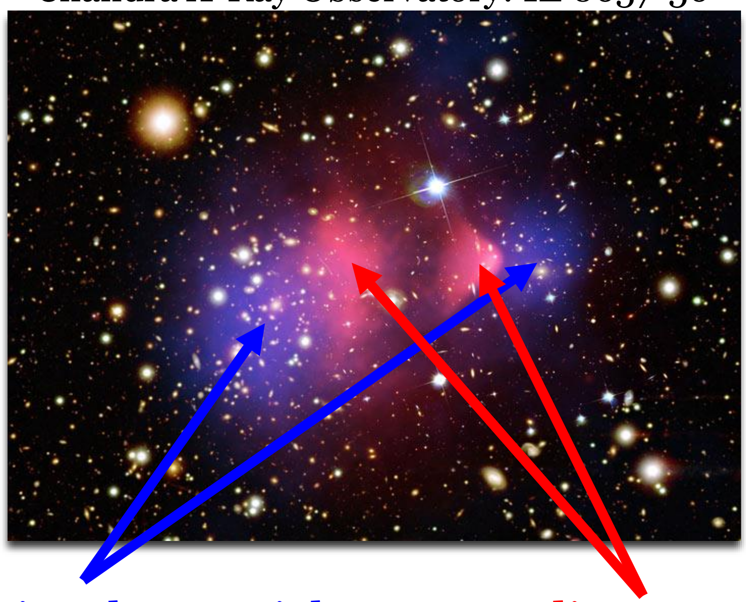
  → **Great concentration of invisible matter: Dark Matter !!**

Bullet Cluster

❖ Two colliding galaxy clusters

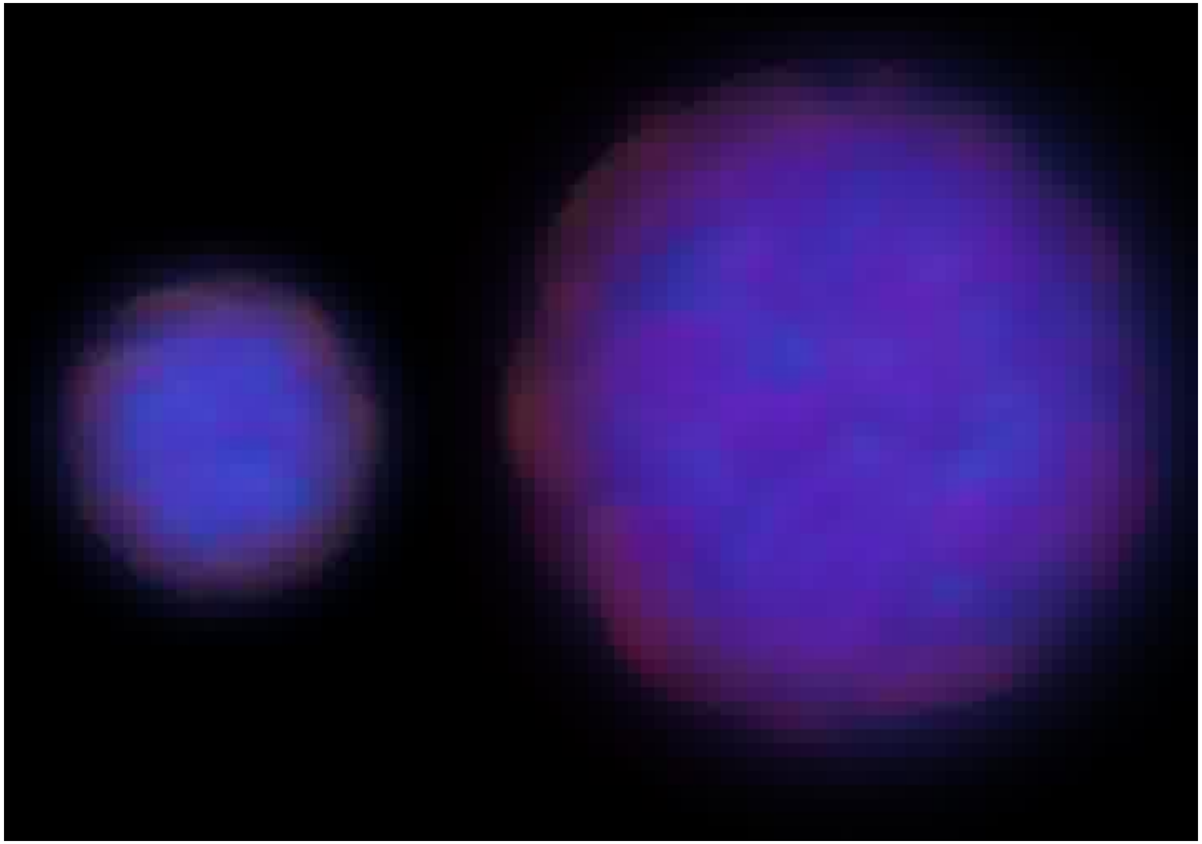
→ significant displacement between their center of visible matter & gravitational potential

Chandra X-Ray Observatory: 1E 0657-56



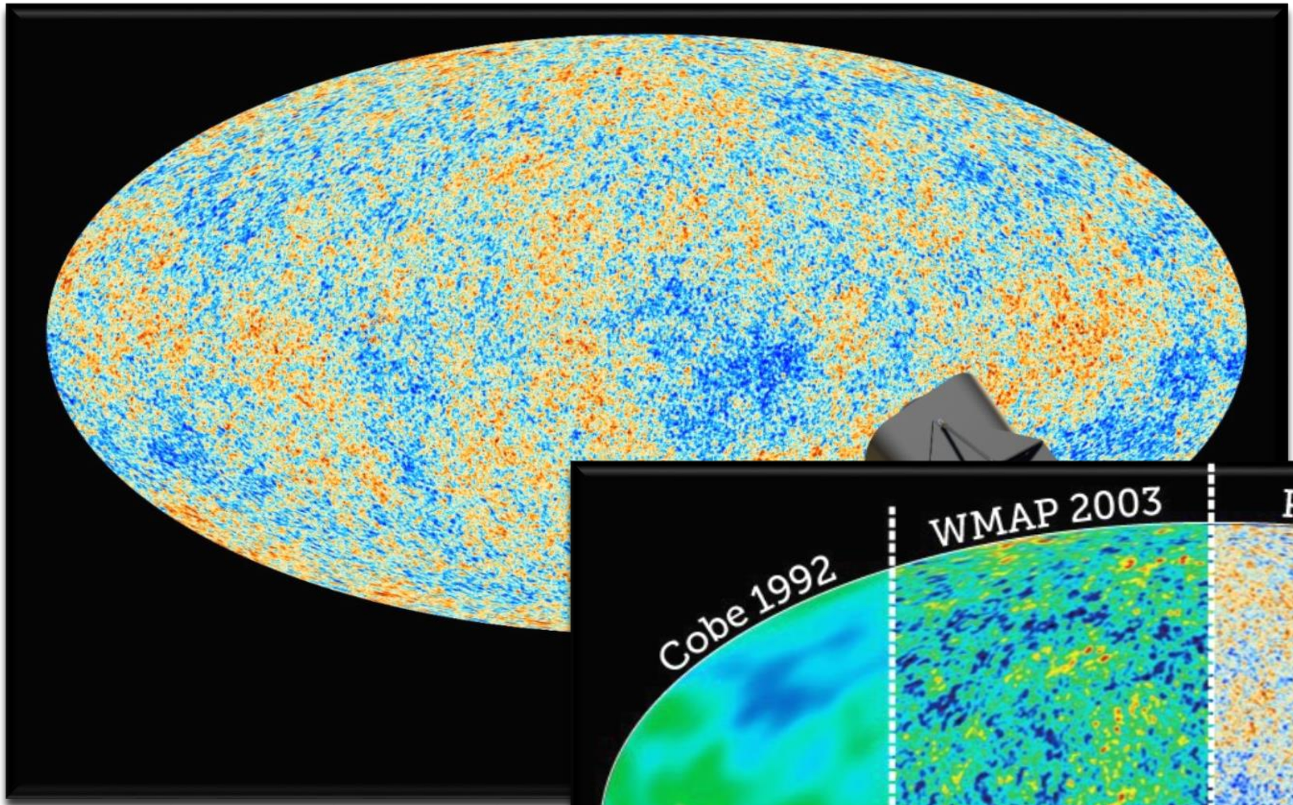
Bullet Cluster

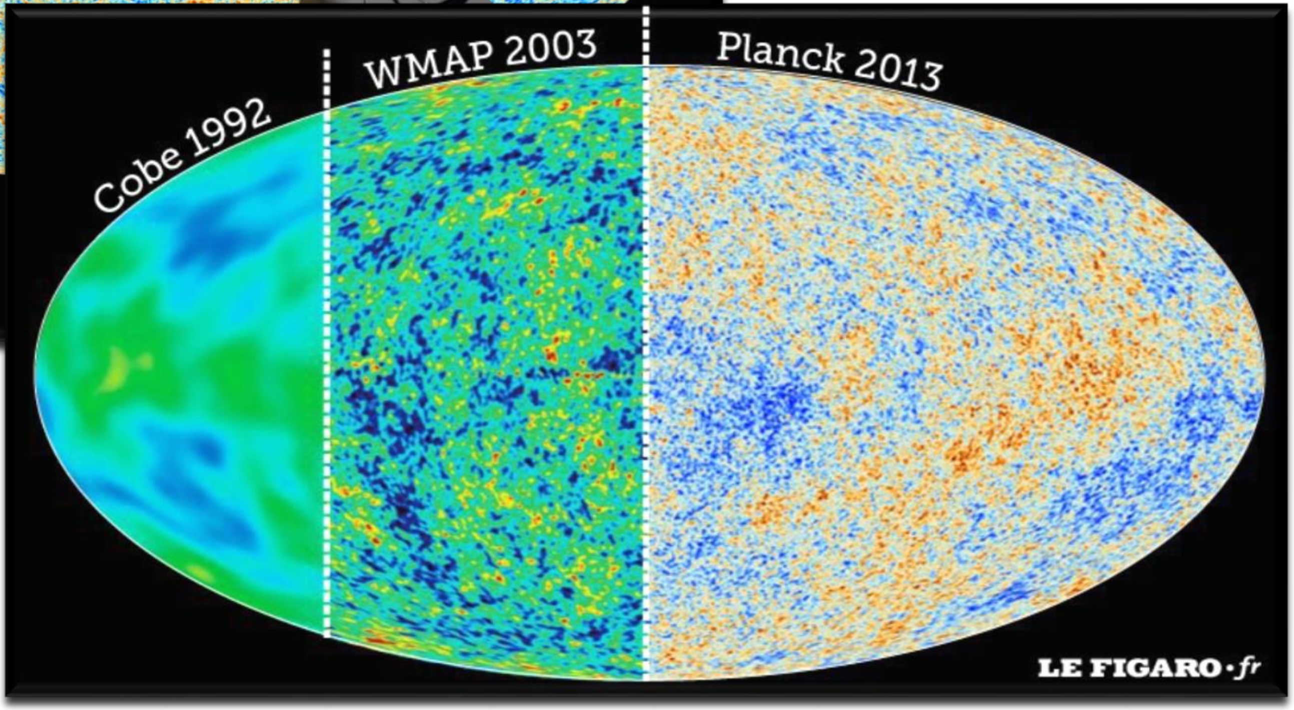
- Simulation of two colliding galaxy clusters



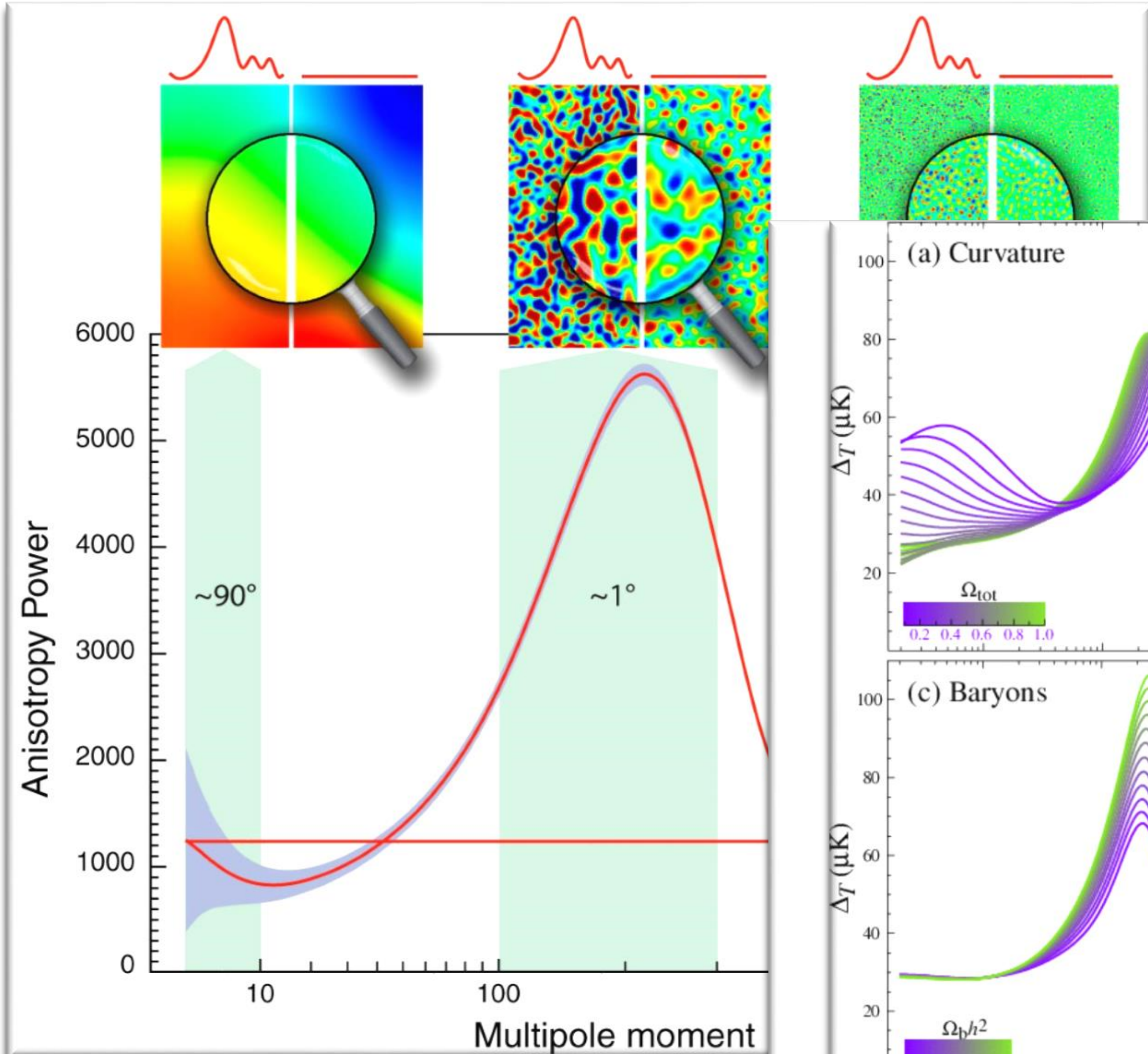
http://chandra.harvard.edu/photo/2006/1e0657/1e0657_bullett_anim_lg.mpg

CMB

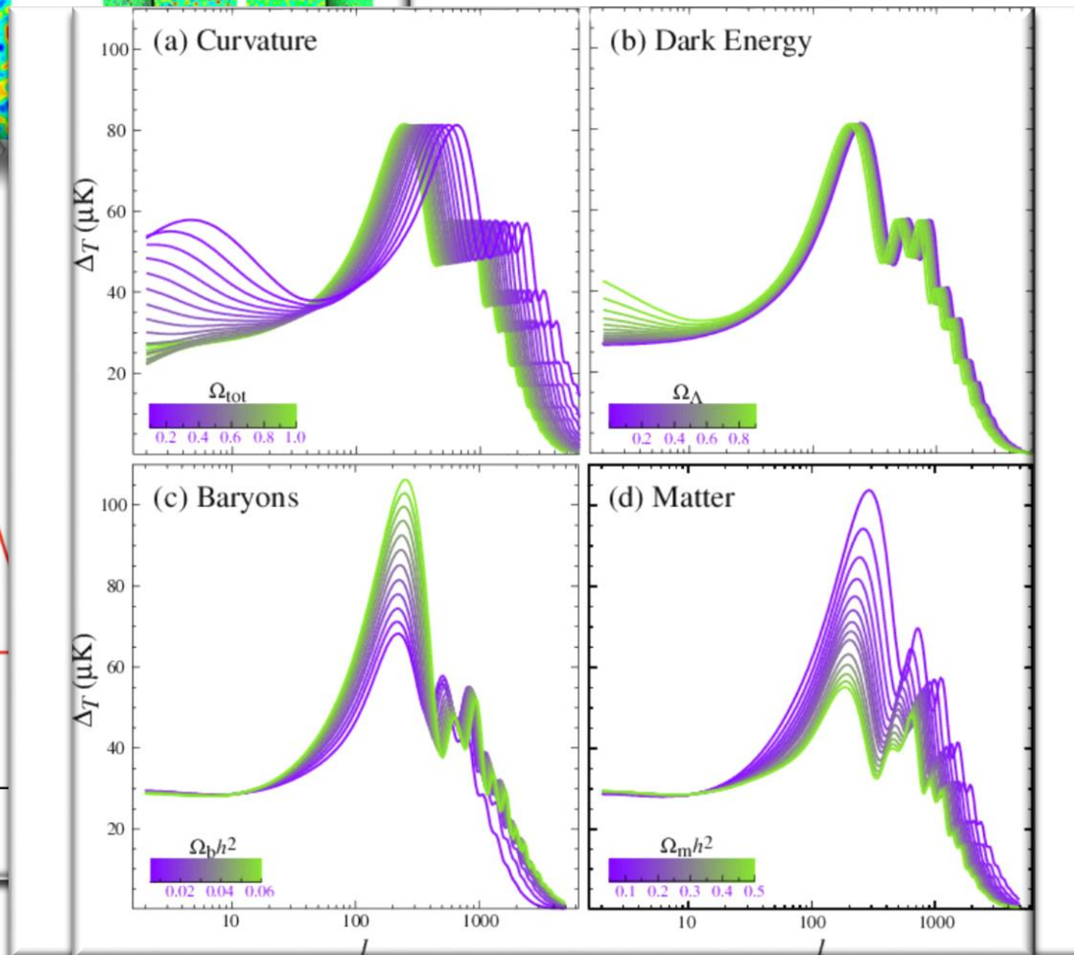




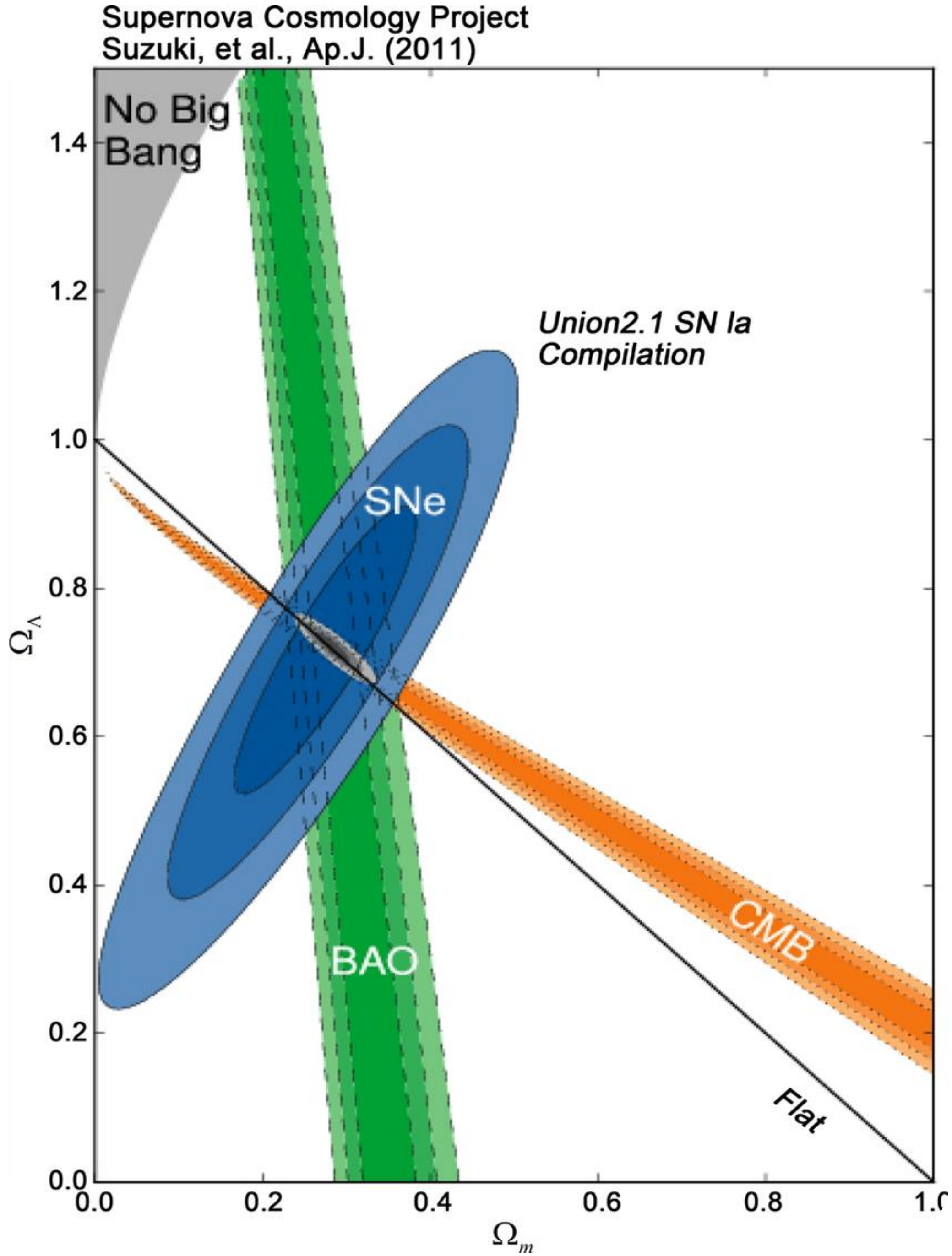
CMB



Anisotropy Power
6000
5000
4000
3000
2000
1000
0
~90°
~1°
10
100
Multipole moment

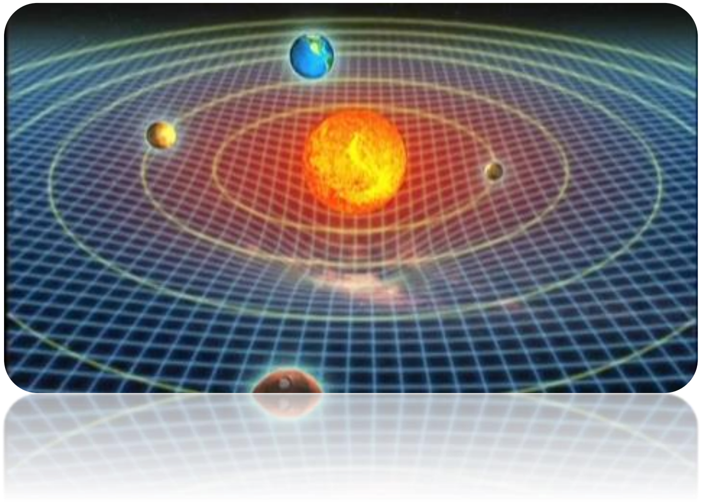


(a) Curvature
(b) Dark Energy
(c) Baryons
(d) Matter
Δ_T (μK)
Ω_{tot}
0.2 0.4 0.6 0.8 1.0
Ω_Λ
0.2 0.4 0.6 0.8
$\Omega_b h^2$
0.02 0.04 0.06
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5
10 100 1000
l



Supernova Cosmology Project
Suzuki, et al., Ap.J. (2011)
No Big
Bang
Union2.1 SN Ia
Compilation
SNe
BAO
CMB
Flat
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Ω_Λ
Ω_m

Observational Evidence of DM



- ✓ Galaxy rotation curve
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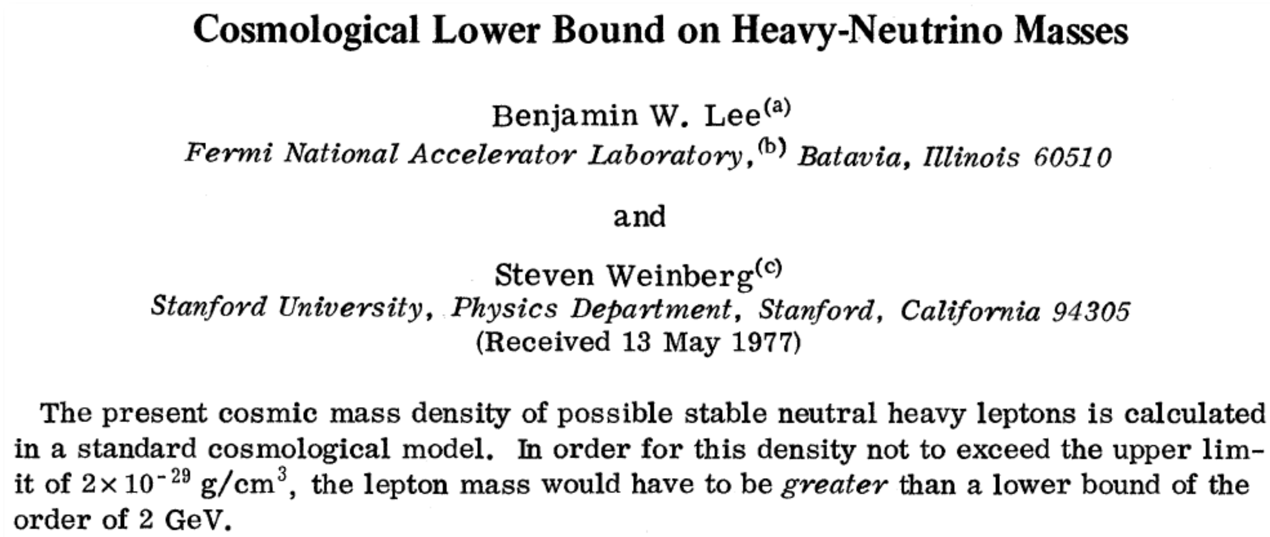
- ✓ …

2. Relic Abundance of Dark Matter

Thermal Freeze-out



Cosmological Lower Bound on Heavy-Neutrino Masses

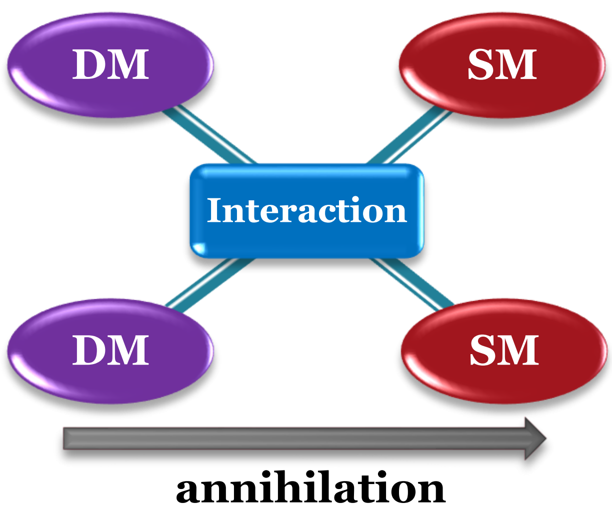
Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.



Basics of Freeze-out

- Boltzmann equation: the statistical behavior of a thermodynamic system not in a state of equilibrium ➔ time evolution of # density:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v \rangle [(n_\chi)^2 - (n_\chi^{eq})^2]$$

- Decoupled when $\Gamma_{int} = \langle \sigma v \rangle n_\chi < H$
- Comoving number density ➔ Scale out the expansion effect:

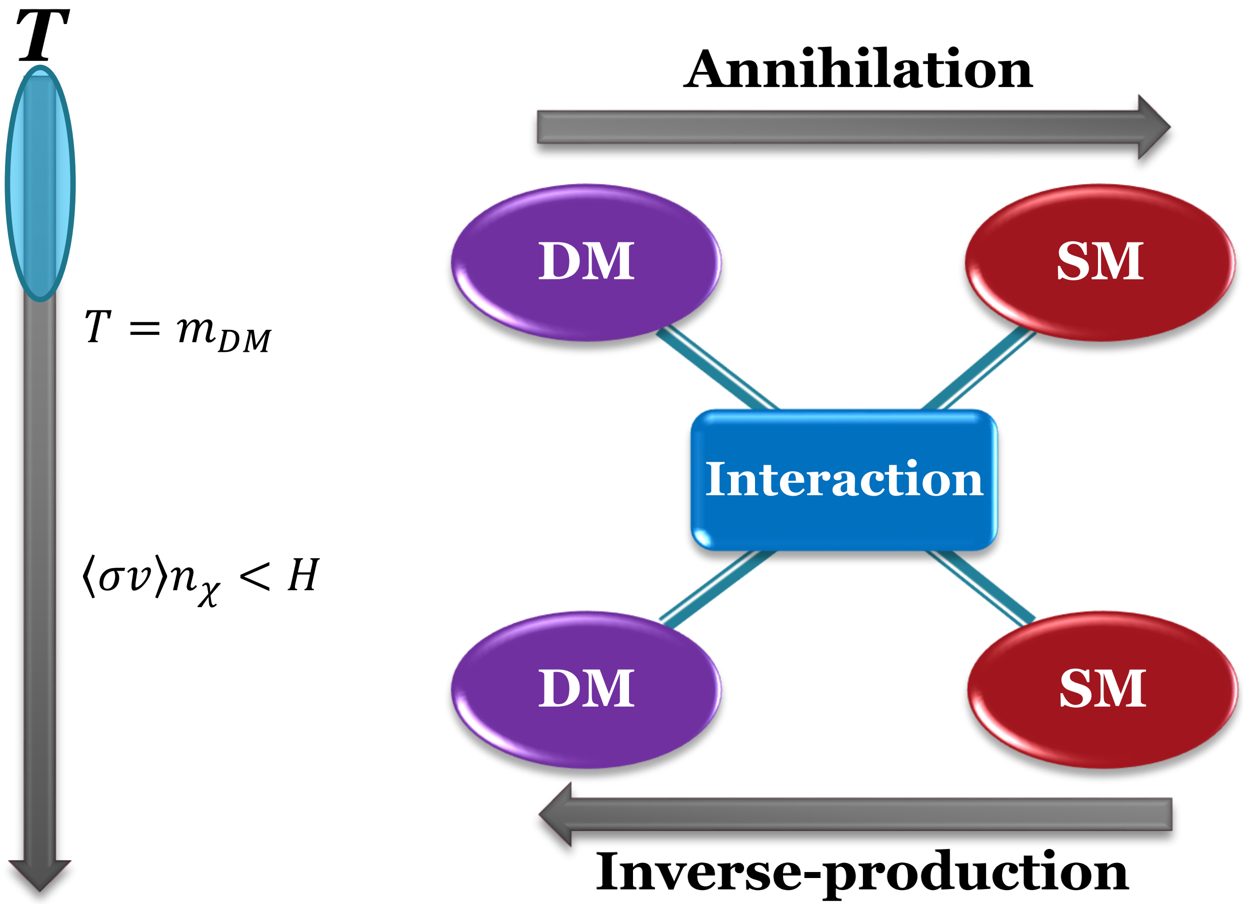
$$(n_\chi/s)_0 = (n_\chi/s)_f \simeq 100/(m_\chi m_{Pl} g_*^{1/2} \langle \sigma_A v \rangle)$$
$$\simeq 10^{-8}/[(m_\chi/\mathrm{GeV})(\langle \sigma_A v \rangle / 10^{-27}\,\mathrm{cm^3\,s^{-1}})]$$

- Relic density in units of the critical density:

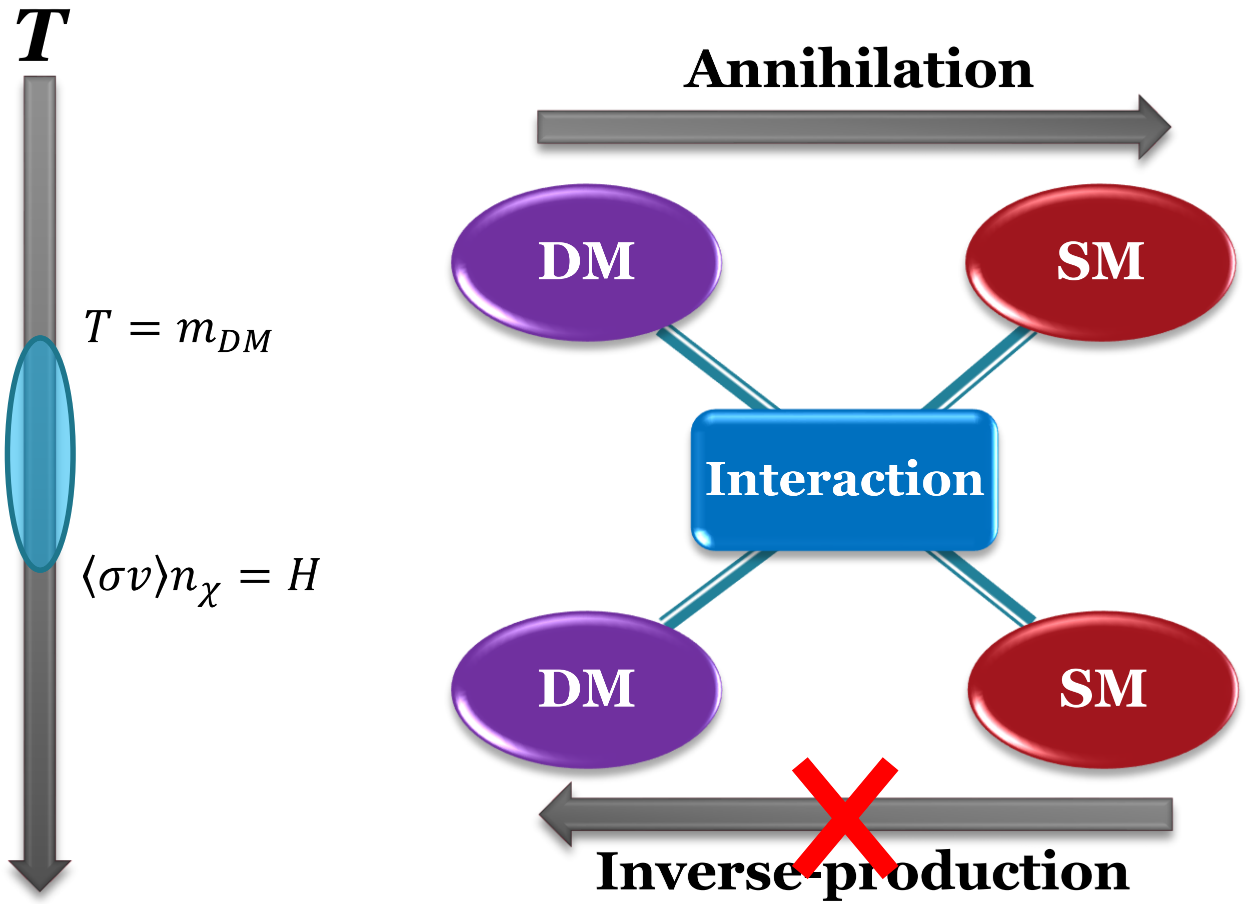
$$\Omega_\chi h^2 = m_\chi n_\chi / \rho_c \simeq (3 \times 10^{-27}\,\mathrm{cm^3\,s^{-1}} / \langle \sigma_A v \rangle)$$

For more details, please see e.g., Ch. 5.1 & 5.2 of "The Early Universe"

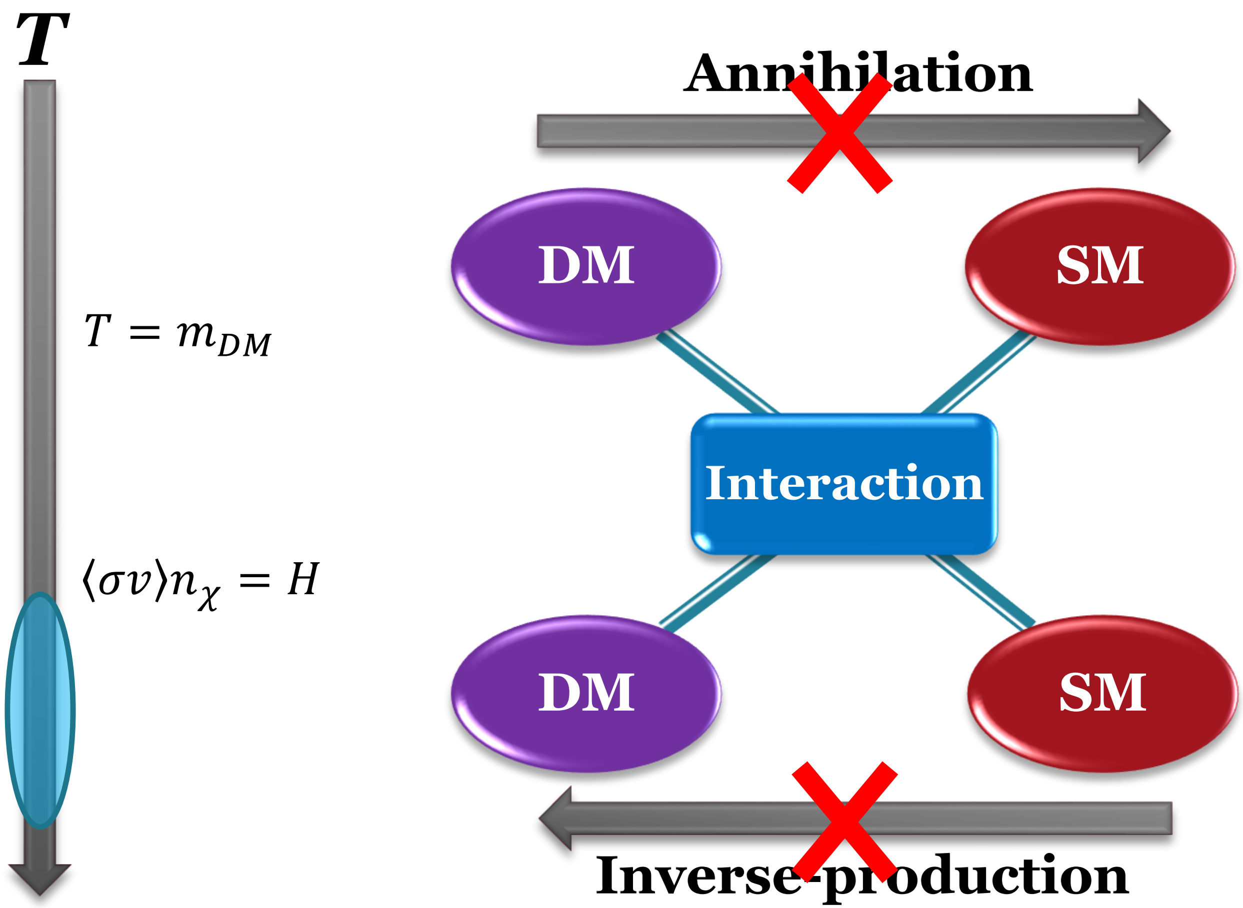
Thermal Freeze-out



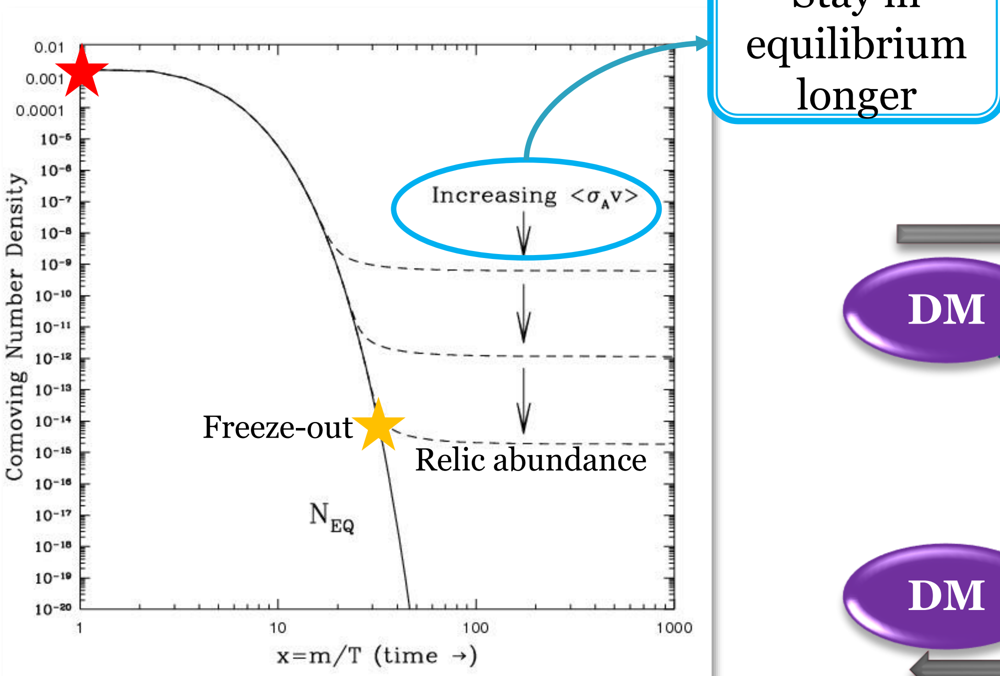
Thermal Freeze-out



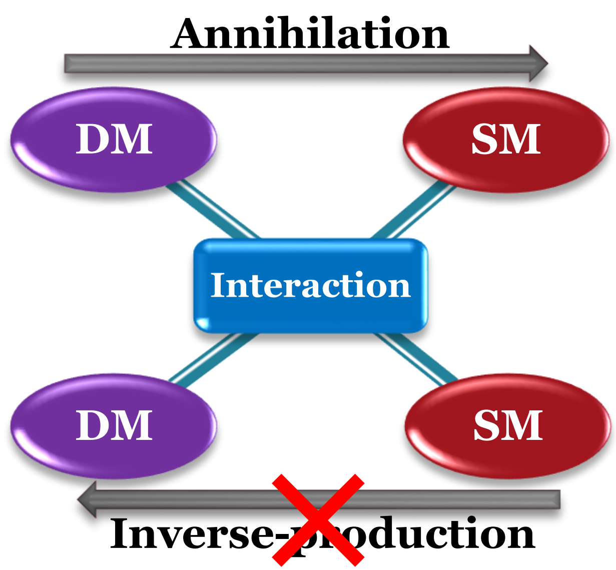
Thermal Freeze-out

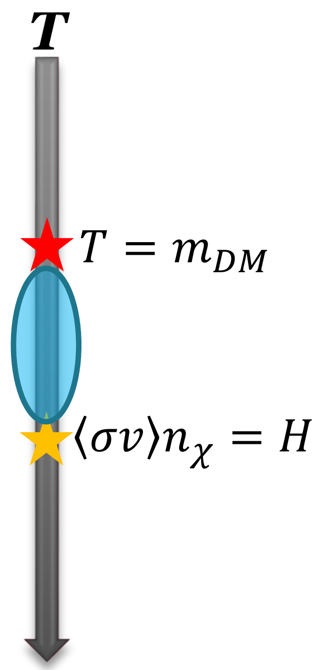


Summary of Conventional Thermal FO



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle\left[(n_\chi)^2 - (n_\chi^{eq})^2\right]$$





- Correct thermal relic abundance:

$$\Omega h^2 \sim \frac{0.1\,pb}{\langle\sigma v\rangle} \sim \frac{3\times10^{-27}\,\mathrm{cm}^3/s}{\langle\sigma v\rangle} \text{ with } \langle\sigma v\rangle \sim \frac{\alpha_\chi^2 m_\chi^2}{M^4} \text{ (}M\text{: dark scale/mediator) vs } \Omega h^2{}_{obs} \sim 0.1$$

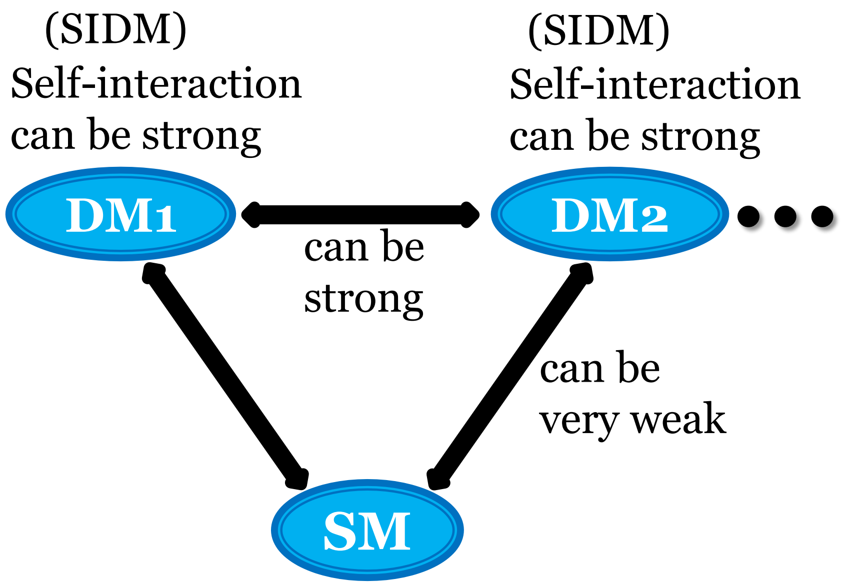
- Weak coupling ➔ Naturally Weak scale mass ➔ WIMP miracle!

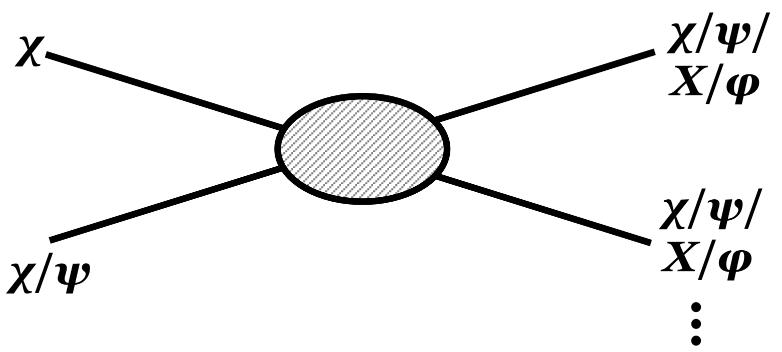
~1 GeV – 10 TeV mass range favored ➔ weak scale (new) physics

New Ideas for DM Relic Abundance

❖ Alternative mechanisms for DM relic determination:

- ✓ Assisted freeze-out [1112.4491]
- ✓ Asymmetric dark matter [0901.4117]
- ✓ Cannibal dark matter [1602.04219, 1607.03108]
- ✓ Co-annihilation [PRD43 (1991) 3191]
- ✓ Co-decaying dark matter [1105.1652, 1607.03110]
- ✓ Continuum dark matter [2105.07035]
- ✓ Co-scattering mechanism [1705.08450]
- ✓ Dynamical dark matter [1106.4546]
- ✓ Dark freeze-out cogenesis [2112.10784]
- ✓ ELastically DEcoupling Relic (ELDER) [1512.04545]
- ✓ Freeze-in [0911.1120]
- ✓ Forbidden channels [PRD43 (1991) 3191 , 1505.07107]
- ✓ Inverse decay dark matter [2111.14857]
- ✓ Pandemic dark matter [2103.16572]
- ✓ Semi-annihilation [0811.0172, 1003.5912]
- ✓ Strongly Interacting Massive Particle (SIMP) [1402.5143, 1702.07860]
- ✓ ...





Freeze-out Scenarios

Single stable particle

New dark sector particles

SM state or decay to the SM

	$\psi_i\psi_j \to \phi\phi'$	$\psi_i\phi \to \psi_j\phi'$	$\psi_i\psi_j \to \psi_k\phi$	$\psi_i \to \psi_j\phi$
Lee-Weinberg	$\checkmark (i=j)$	$\checkmark (i=j)$	$\times$	$\times$
Co-annihilation	$\checkmark$	$\checkmark$	$\times$	$\checkmark$
Multi-component	$\checkmark (i=j)$	$\checkmark (i=j)$	$\times$	$\times$
Semi-annihilation	$\checkmark (i=j)$	$\checkmark (i=j)$	$\checkmark$	$\times$

- $\psi_i\psi_j \to \psi_k\psi_m$: always present

❖ Lee-Weinberg: simplest & usual case. Lee & Weinberg PRL (1977)

❖ Co-annihilation: multi-particles but only one stable particle. Griest & Seckel PRD (1991)

❖ Multi-component: multi decoupled stable particles.

❖ Semi-annihilation: reactions among > 2 stable particles are important in determining DM relic density. D'Eramo & Thaler, JHEP (2010)

Co-annihilation

Griest & Seckel, PRD43 (1991)

- Involves N coupled Boltzmann equations:

$$
\begin{aligned}
\frac{dn_i}{dt} \quad = \quad & -3Hn_i - \sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right) \\
& - \sum_{j \neq i} \left[\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) - \langle \sigma'_{Xji} v_{ij} \rangle \left(n_j n_X - n_j^{\mathrm{eq}} n_X^{\mathrm{eq}} \right) \right] \\
& - \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\mathrm{eq}} \right) - \Gamma_{ji} \left(n_j - n_j^{\mathrm{eq}} \right) \right].
\end{aligned}
$$

- But possible to compute the relic density via standard methods:

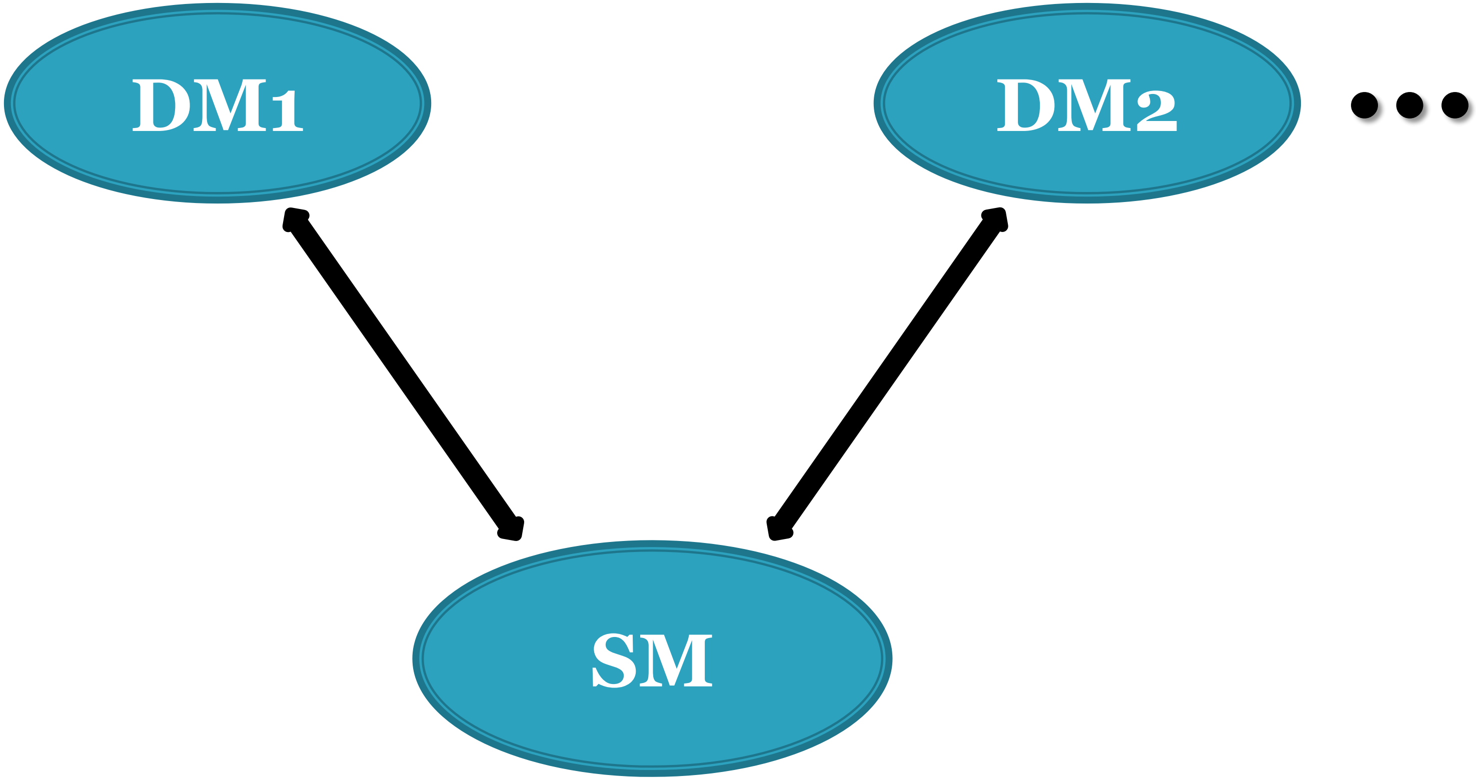
$$
\frac{dn}{dt} = -3Hn - \sum_{i,j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right) \qquad n = \sum_{i=1}^{N} n_i
$$

$$
\frac{dn}{dt} = -3Hn - \langle \sigma_{\mathrm{eff}} v \rangle \left(n^2 - n_{\mathrm{eq}}^2 \right) \qquad \langle \sigma_{\mathrm{eff}} v \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{\mathrm{eq}}}{n^{\mathrm{eq}}} \frac{n_j^{\mathrm{eq}}}{n^{\mathrm{eq}}}
$$

Standard Multi-component

❖ Standard approach: to assume that each particle is thermalized independently.

❖ Total DM density is $\Omega_{\rm DM} = \sum_i \Omega_i$.

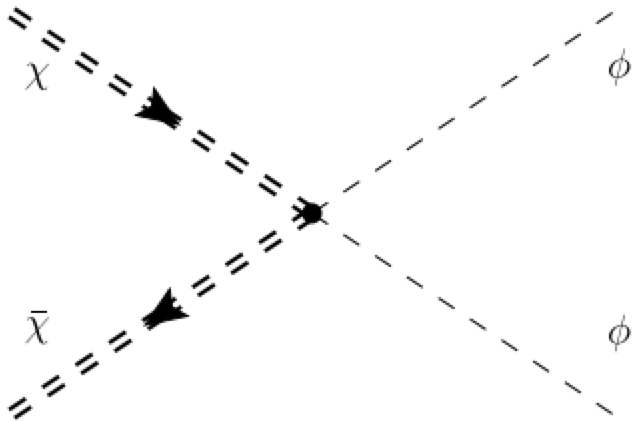


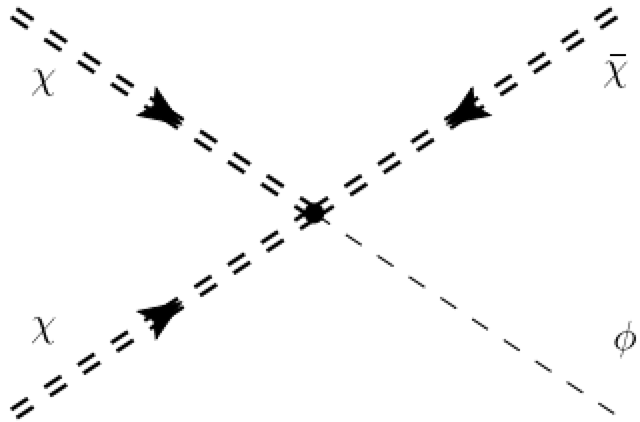
Semi-annihilation

D'Eramo& Thaler, JHEP1006 (2010)

❖ One has to solve a system of coupled Boltzmann equations.

$$\frac{dn_i}{dt} + 3Hn_i = -\langle \sigma_{ii} v_{\rm rel} \rangle \left(n_i^2 - n_i^{\rm eq\,2} \right) - \sum_{j,k} \langle \sigma_{ijk} v_{\rm rel} \rangle \left(n_i n_j - \frac{n_k}{n_k^{\rm eq}} n_i^{\rm eq} n_j^{\rm eq} \right)$$



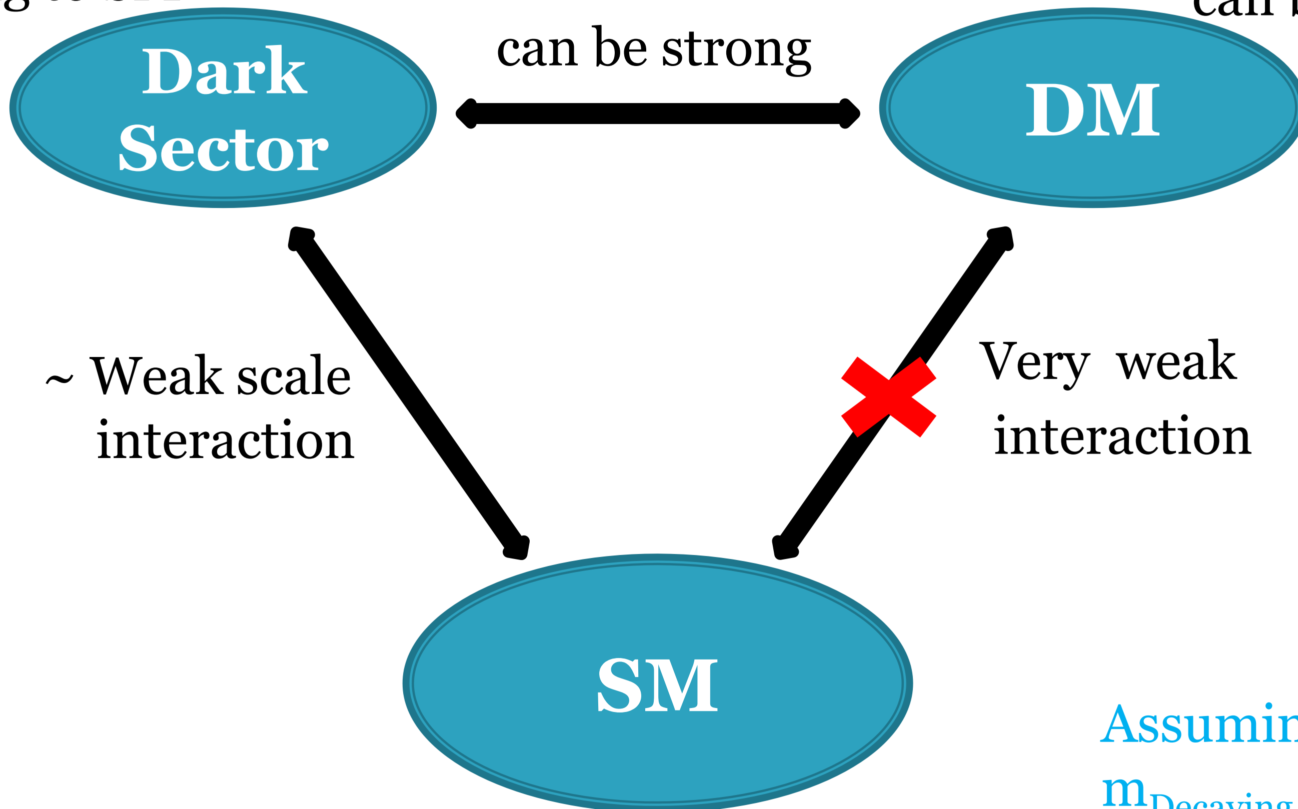


Co-decaying: Basic Set-up

[P. Bandyopadhyay, E. J. Chun & J.-C. Park, 1105.1652]

Dark sector particle
But decaying to SM

Self-interaction
can be strong



Assuming
$m_{Decaying} < m_{DM}$

Co-decaying: Timeline

[arXiv:1607.03110]

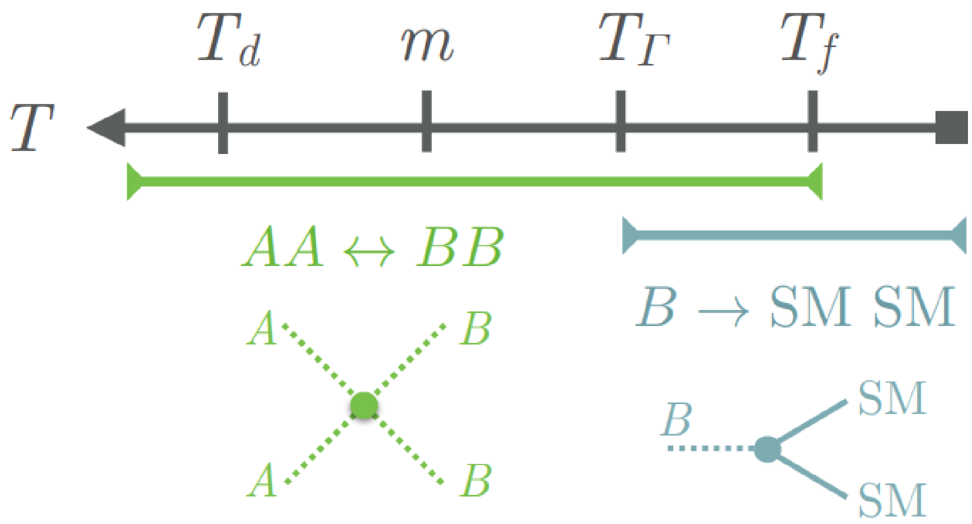
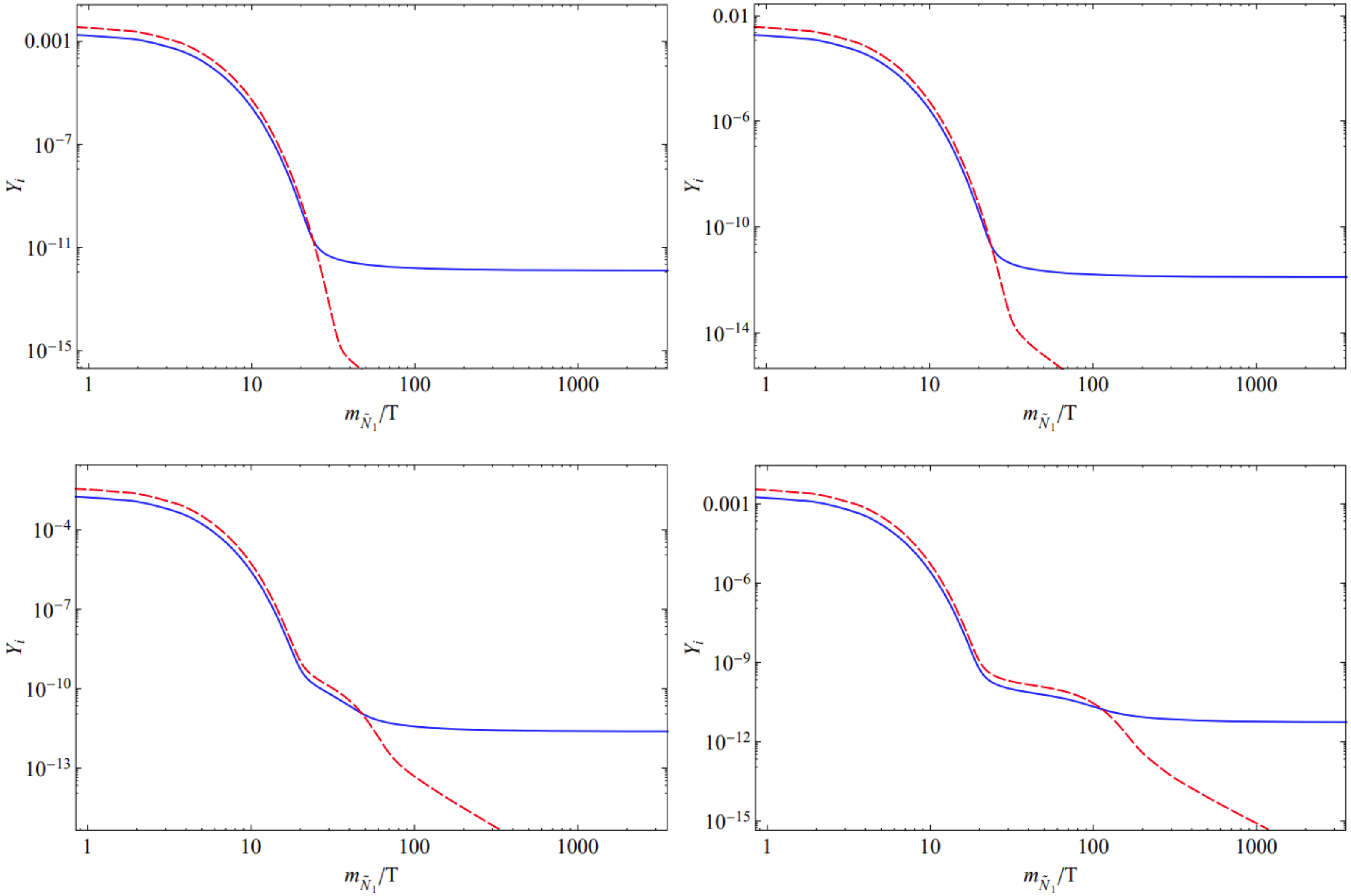


FIG. 1: Co-decay dark matter timeline. At T_d the SM and dark sector decouple; at T_Γ the decay of B's begin to deplete the dark sector density; and at T_f the $AA \leftrightarrow BB$ process freezes out, resulting in a relic abundance for the A particles.

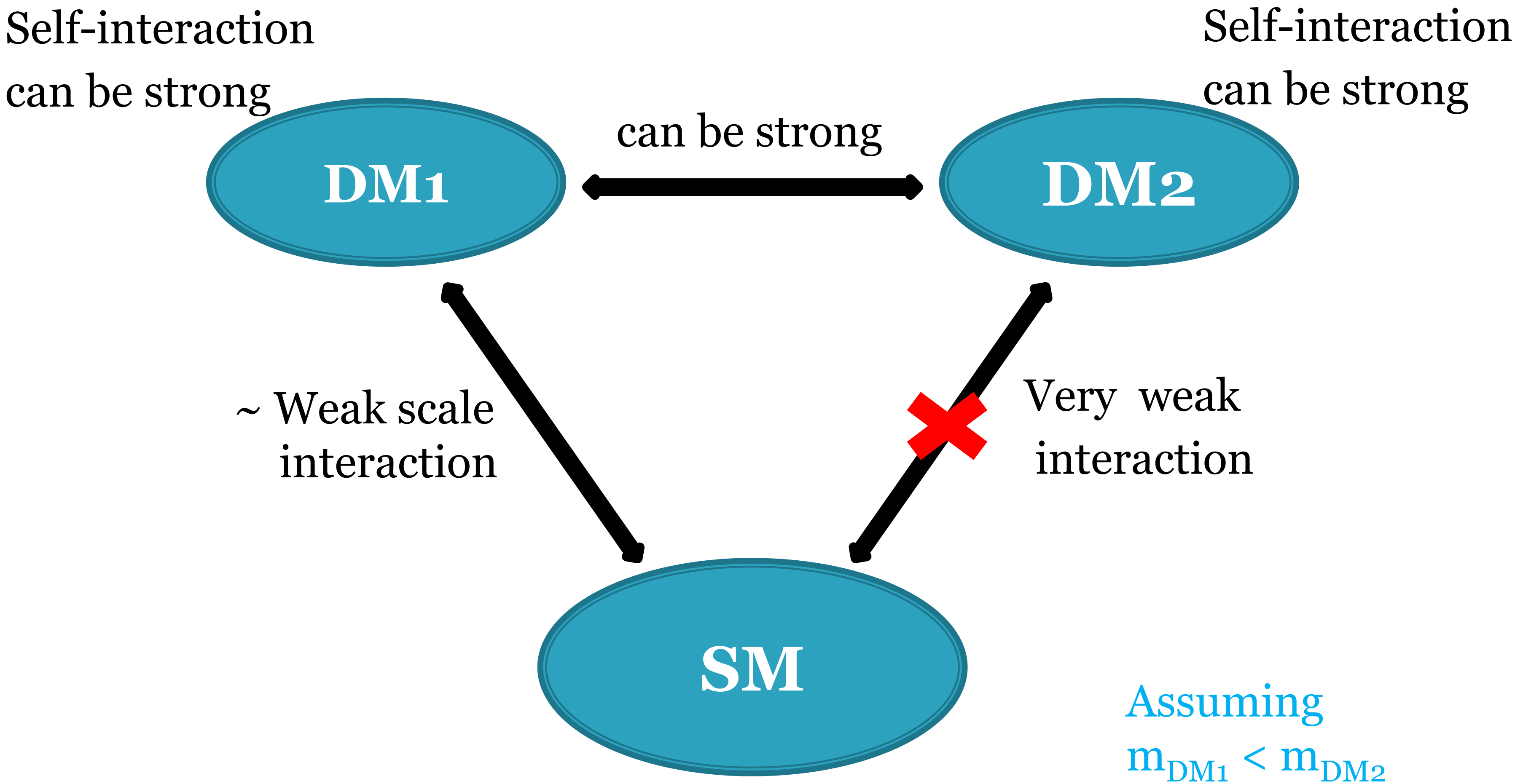
Co-decaying: Abundance Evolution

[P. Bandyopadhyay, E. J. Chun & J.-C. Park, 1105.1652]



Assisted FO: Basic Set-up

[G. Belanger & J.-C. Park, 1112.4491]



Assuming
$m_{DM1} < m_{DM2}$

Assisted FO: Boltzmann Equations

[G. Belanger & J.-C. Park, 1112.4491]

- To find the relic abundances of DM 1&2, we should solve a set of coupled Boltzmann equations.

$$\frac{dn_2}{dt} + 3Hn_2 = -\langle\sigma v\rangle_{22\to 11}\left[(n_2)^2 - \frac{(n_2^{\rm eq})^2}{(n_1^{\rm eq})^2}(n_1)^2\right] ,$$

$$\frac{dn_1}{dt} + 3Hn_1 = -\langle\sigma v\rangle_{11\to XX}\left[(n_1)^2 - (n_1^{\rm eq})^2\right] - \langle\sigma v\rangle_{11\to 22}\left[(n_1)^2 - \frac{(n_1^{\rm eq})^2}{(n_2^{\rm eq})^2}(n_2)^2\right]$$

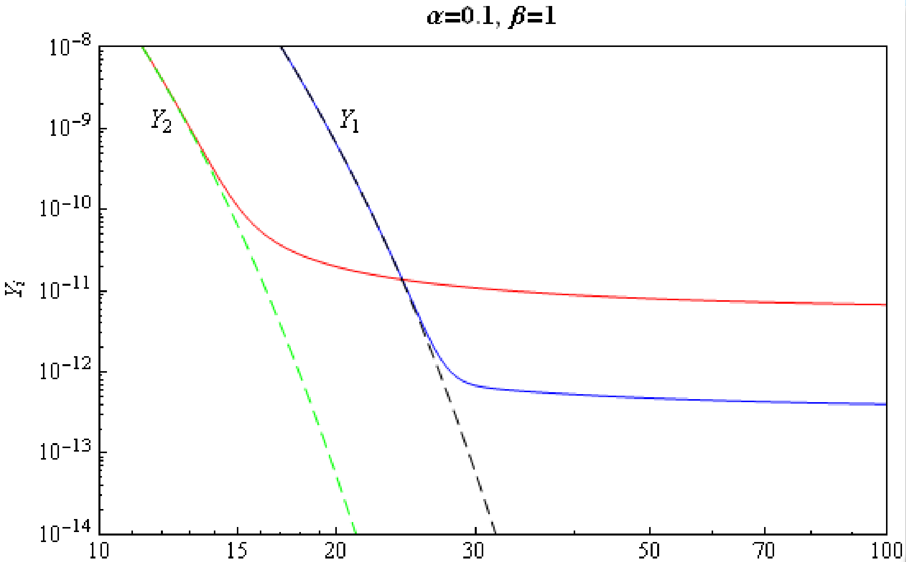
X: SM particles

- If we limit our analysis to s-wave annihilation, we can simply express the relevant matrix elements:

$$\alpha \equiv \mathcal{M}_{22\to 11} = \mathcal{M}_{11\to 22} , \quad \beta \equiv \mathcal{M}_{11\to XX}$$

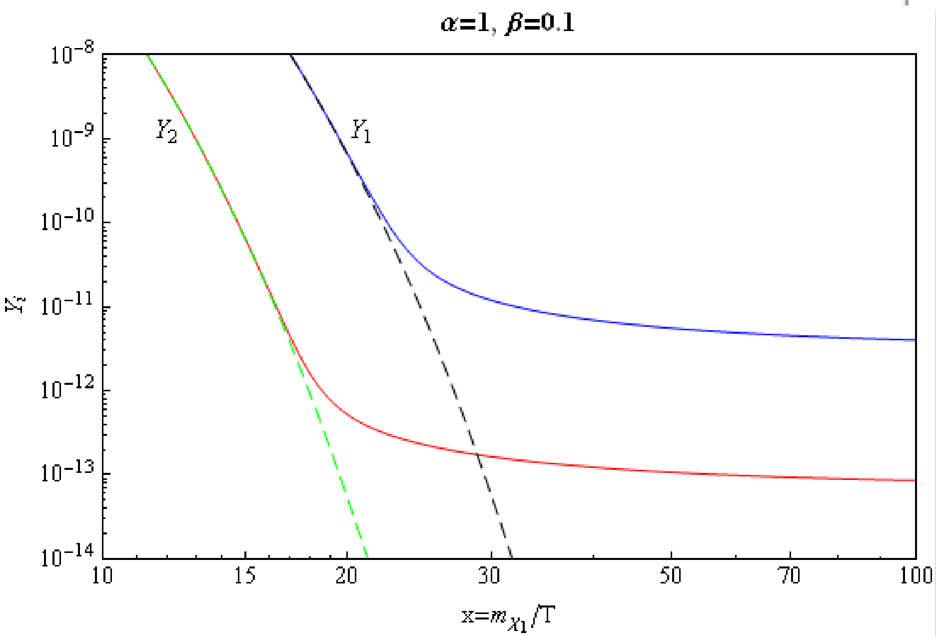
Assisted FO: Abundance Evolution

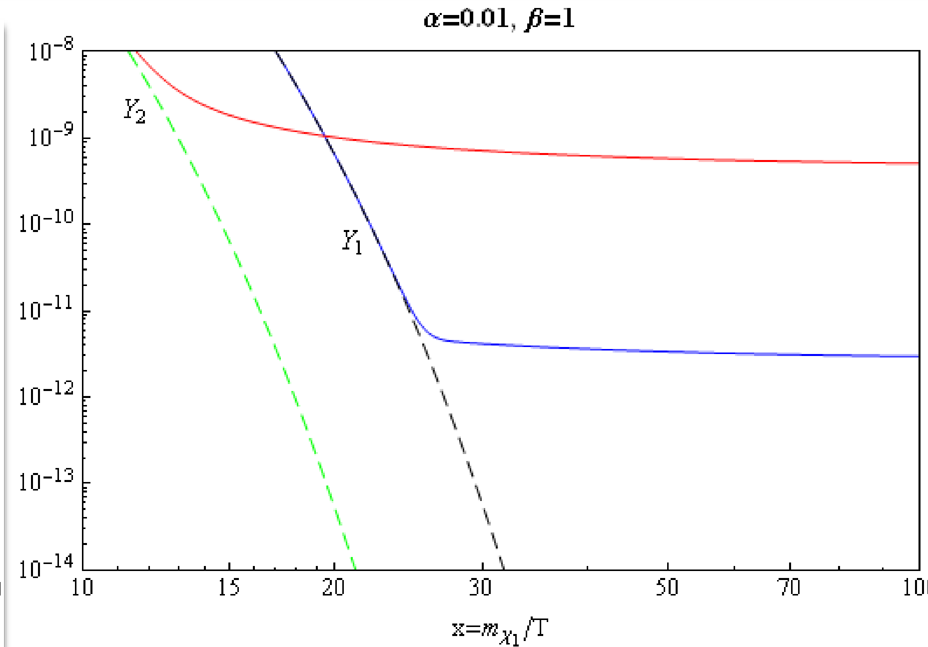
[G. Belanger & J.-C. Park, 1112.4491]



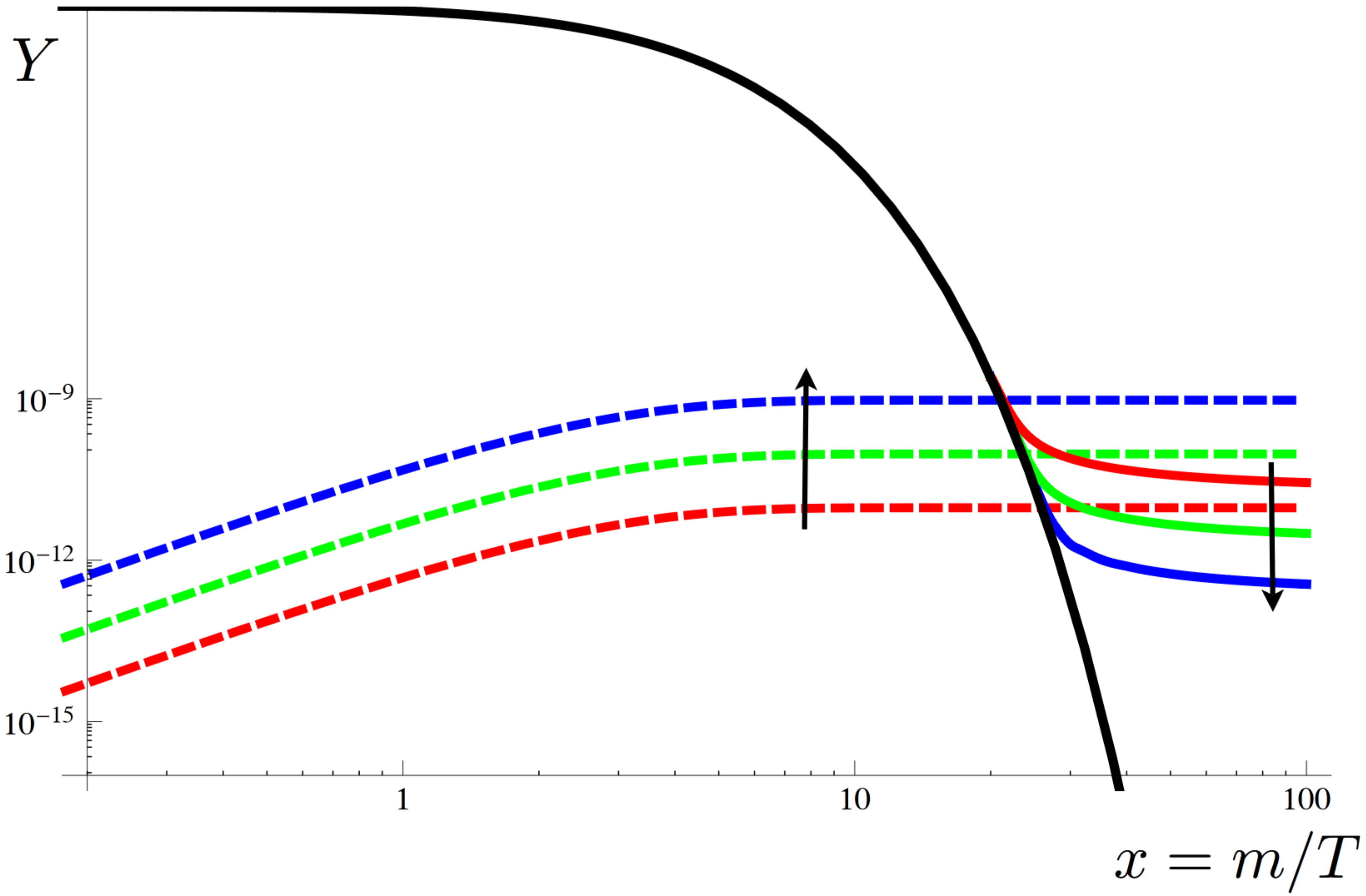
$Y_i = n_i/s$, $x = m_1/T$,
$m_1 = 100$ GeV, $m_2 = 150$ GeV

$$\alpha \equiv \mathcal{M}_{22\to 11} = \mathcal{M}_{11\to 22}\ , \quad \beta \equiv \mathcal{M}_{11\to XX}$$

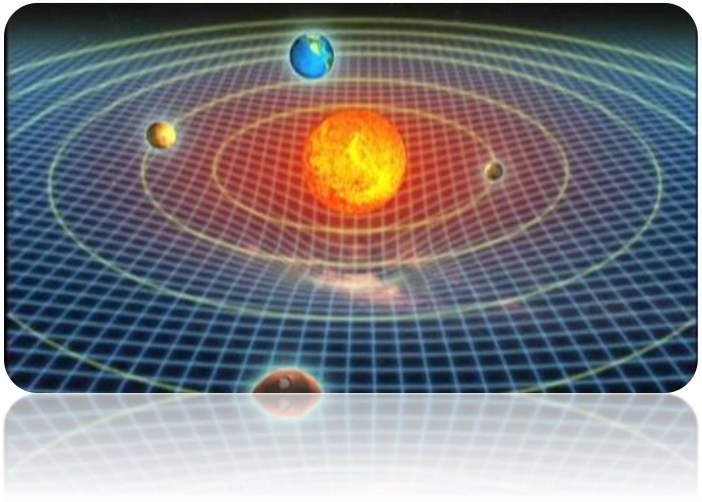




Freeze-in: Abundance Evolution



Observational Evidence of DM



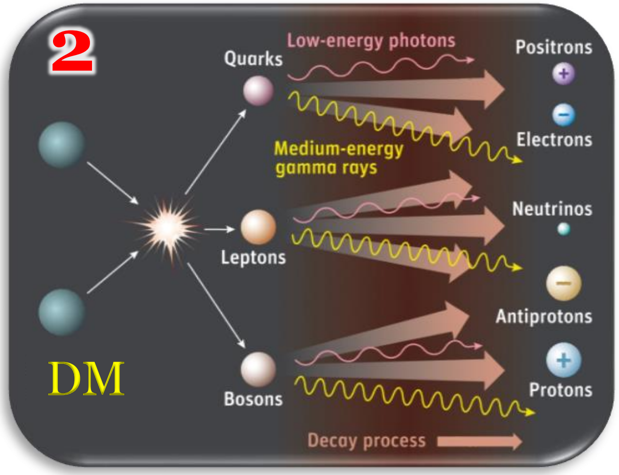
- ✓ Galaxy rotation curve
- ✓ Coma cluster
- ✓ Gravitational lensing
- ✓ Bullet cluster
- ✓ Structure formation
- ✓ Cosmic microwave background radiation (CMBR)
- ✓ Sky surveys
- ✓ Type Ia supervovae
- ✓ Baryonic acoustic oscillation (BAO)
- ✓ …

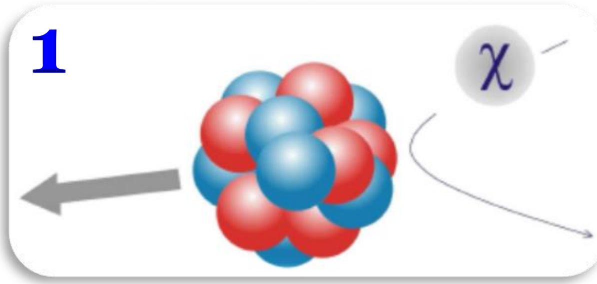
Nature of **DM**?

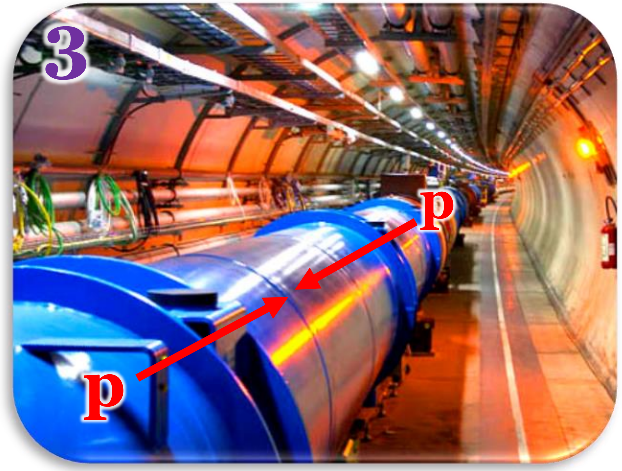
Irene $\subset$ SM

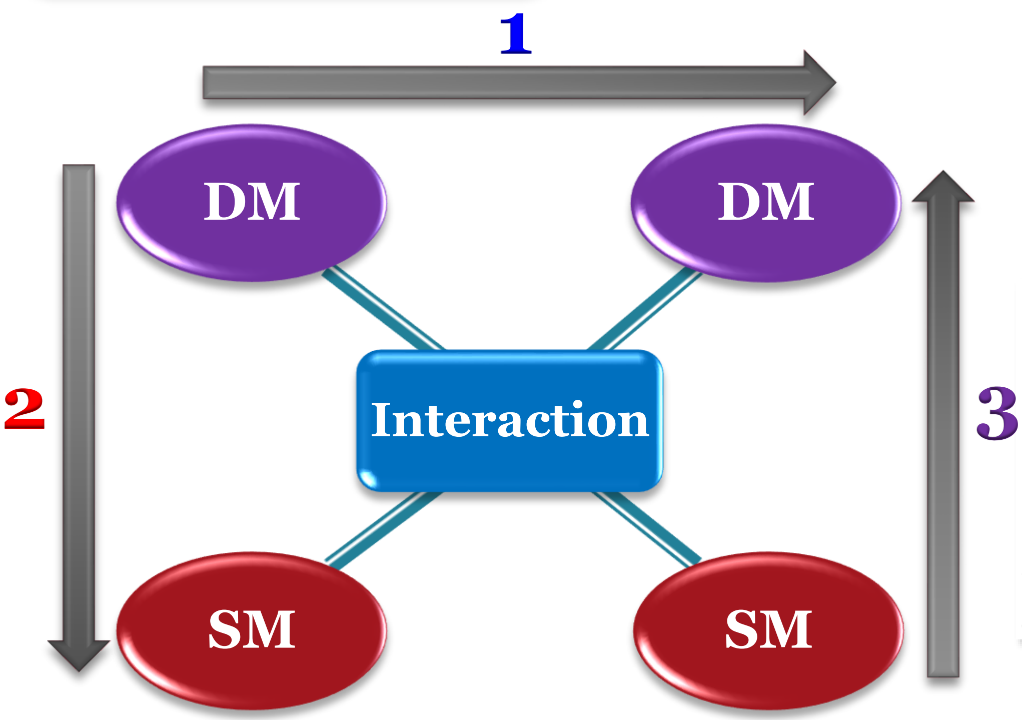
but DM $\not\subset$ SM

Conventional DM Search Strategies









❖ Based on the WIMP paradigm.

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

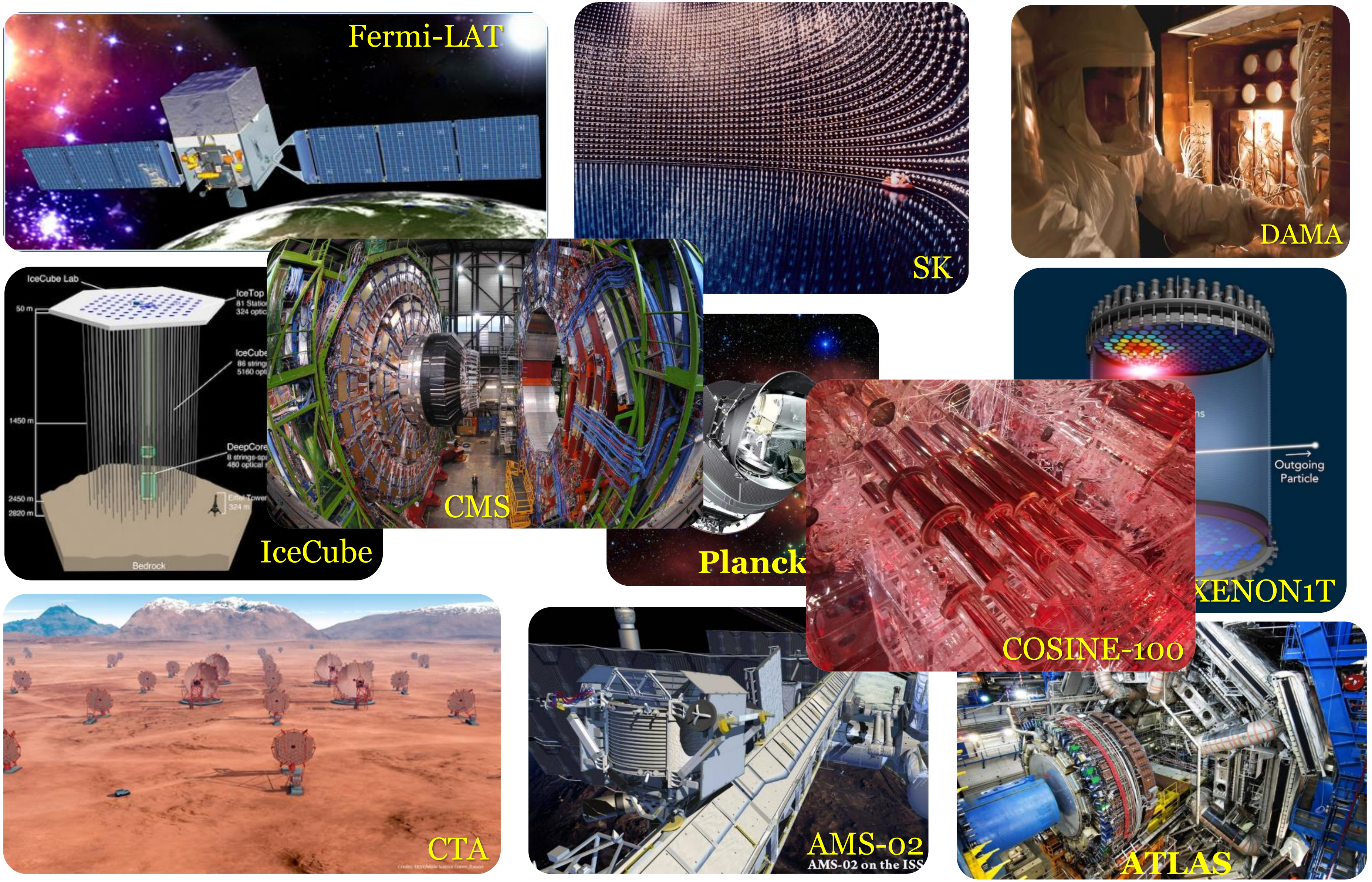
and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

[PRL (1977)]

Diverging Efforts for DM Searches



Exercises

3. Nuclear recoil spectrum in DM direct detection:

(a) $v_{\min} = \sqrt{E_R m_N / 2\mu_{\chi N}^2} = \frac{m_\chi + m_N}{m_\chi} \sqrt{E_R / 2m_N}$

(b) Shape of nuclear recoil spectrum (dependence on m_χ)

4. Fluxes of DM annihilation products, e.g., $e^\pm, \bar{p}$:

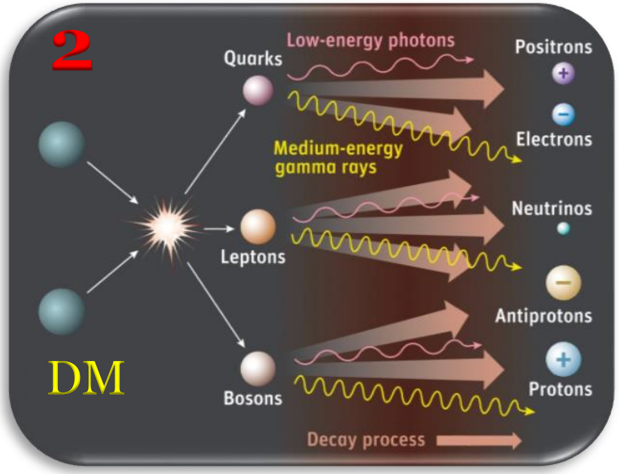
(a) Annihilation cross section dependence

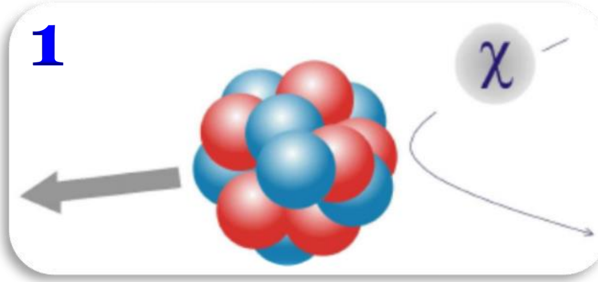
(b) m_χ dependence

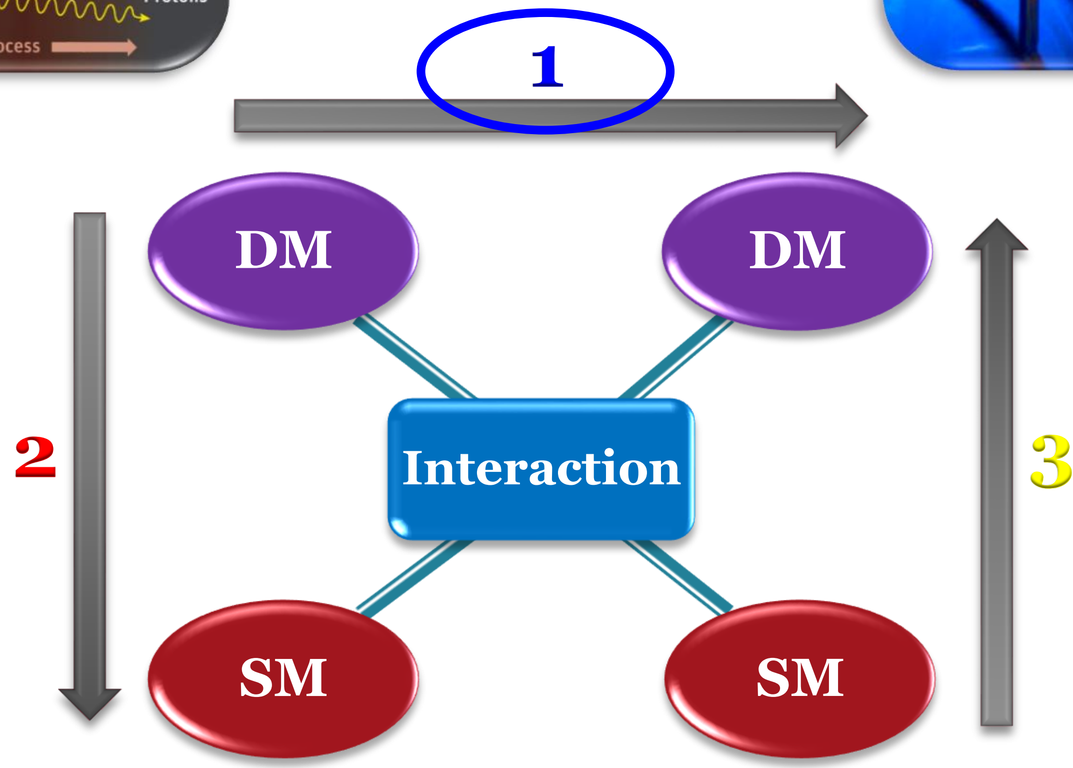
3. Direct Detection

Target Particle Recoil

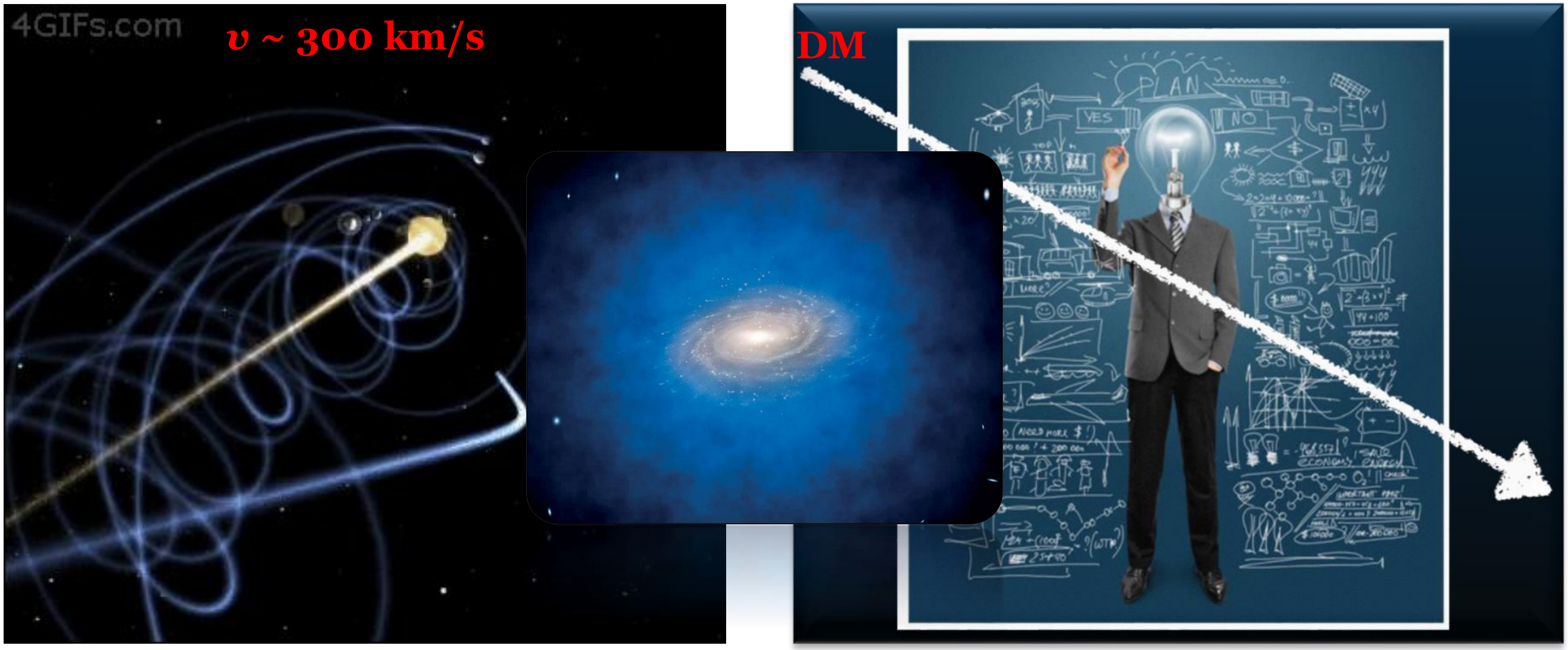
DM Direct Detection







Dark Matter vs Human



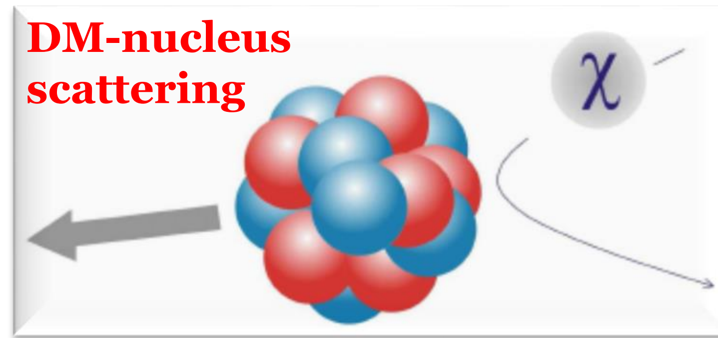
❖ When $m_{\rm DM} \sim m_{\rm p} \sim 0.94$ GeV: $\underbrace{300\ \mathrm{km/s} \times \frac{0.4\ \mathrm{GeV/cm^3}}{0.94\ \mathrm{GeV}}}_{\text{flux}} \times \underbrace{60\ \mathrm{cm} \times 170\ \mathrm{cm}}_{\text{area}}$

$$\approx\ 10^{11}/\mathrm{s}$$

✓ $\Phi_\chi = n_\chi v_{\rm rel}$ & $n_\chi = \rho_\chi / m_\chi$

❖ ~10^{11}/s DM's penetrate our body for $m_{\rm DM} \sim m_{\rm p}$!

DM Direct Detection



- DM: all around us! → recoil of DM-nucleus scattering

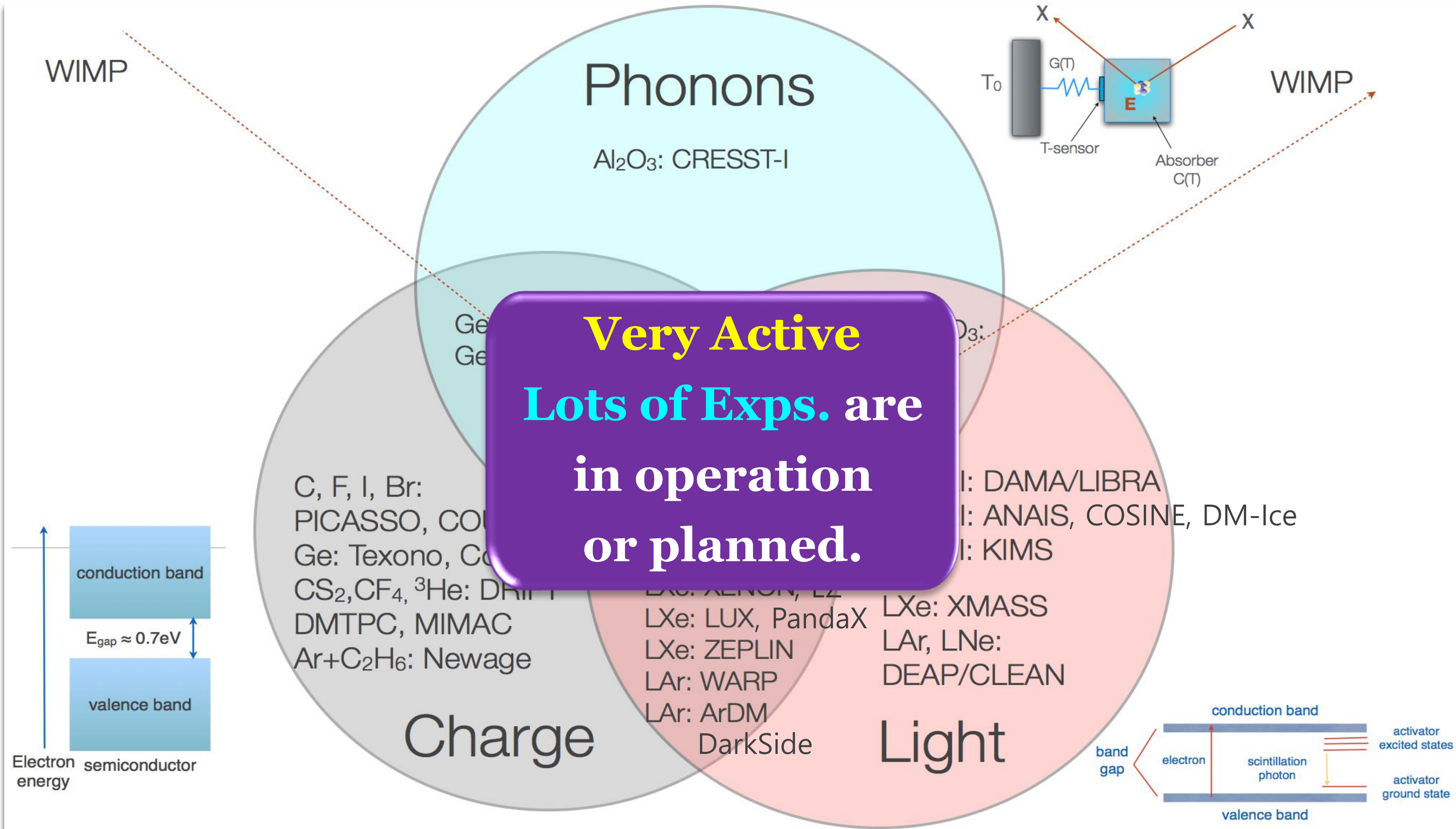
  based on *E* & *p* conservation!

- What is measure: *E* of recoiling nucleus ~ 1-100 keV for m_{DM} ~ 1-100 GeV

  ($E_k \sim mv^2$ with $v/c \sim 10^{-3}$)

- Challenges: very small *E*, small event rate, large backgrounds

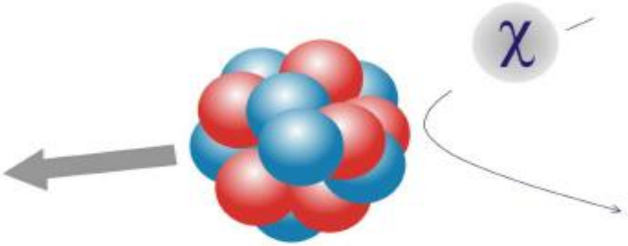
Detection Techniques



DM direct detection

local DM flux: $\phi_\chi \sim 10^5\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{\rho_\chi}{0.4\,\mathrm{GeV\,cm}^{-3}}\right)$

assuming DM has non-gravitational interactions ("WIMP")
look for recoil of DM-nucleus scattering M. Goodman, E. Witten, PRD 1985



cnts / keV recoil energy E_R:

$$\frac{dN}{dE_R}(t) \propto \frac{\rho_\chi}{m_\chi} \int_{v>v_{\min}} d^3v \, \frac{d\sigma}{dE_R} \, v \, f_\oplus(\vec{v}, t)$$

ρ_χ DM energy density, default: 0.3 GeV cm^{-3}
$v_{\min}$: minimal DM velocity required to produce recoil energy E_R

T. Schwetz, PPC11 CERN

Beginning of DM Direct Detection

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

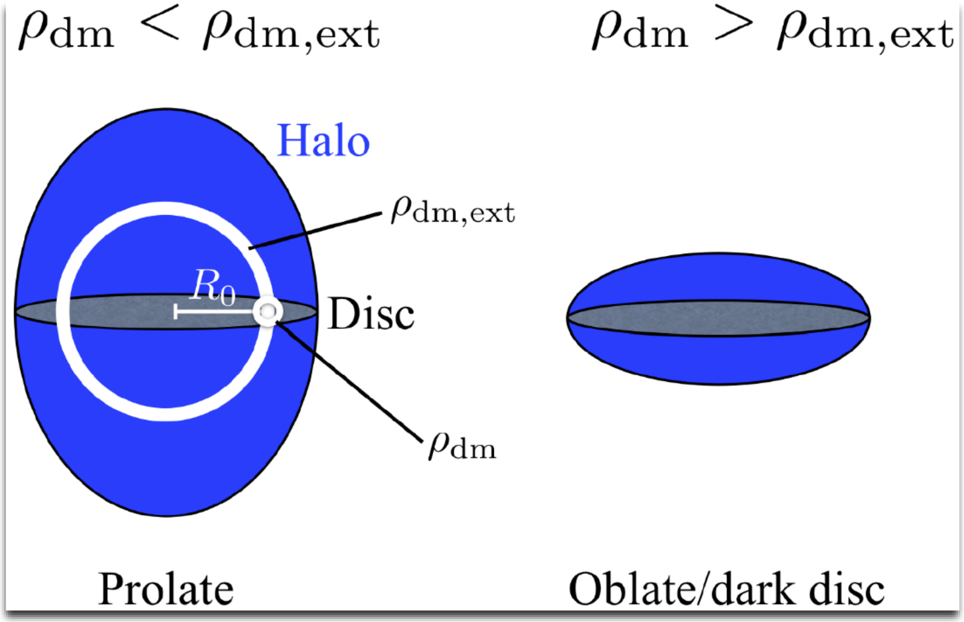
PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

DM Local Density



- Two main approaches to measuring ρ_{DM}
  - Local measures: the vertical kinematics of stars in the local Milky Way ➔ 'tracers'
  - Global measures: inter/extrapolating ρ_{DM} from the rotation curve
- Recently, there have been attempts to bridge two scales.

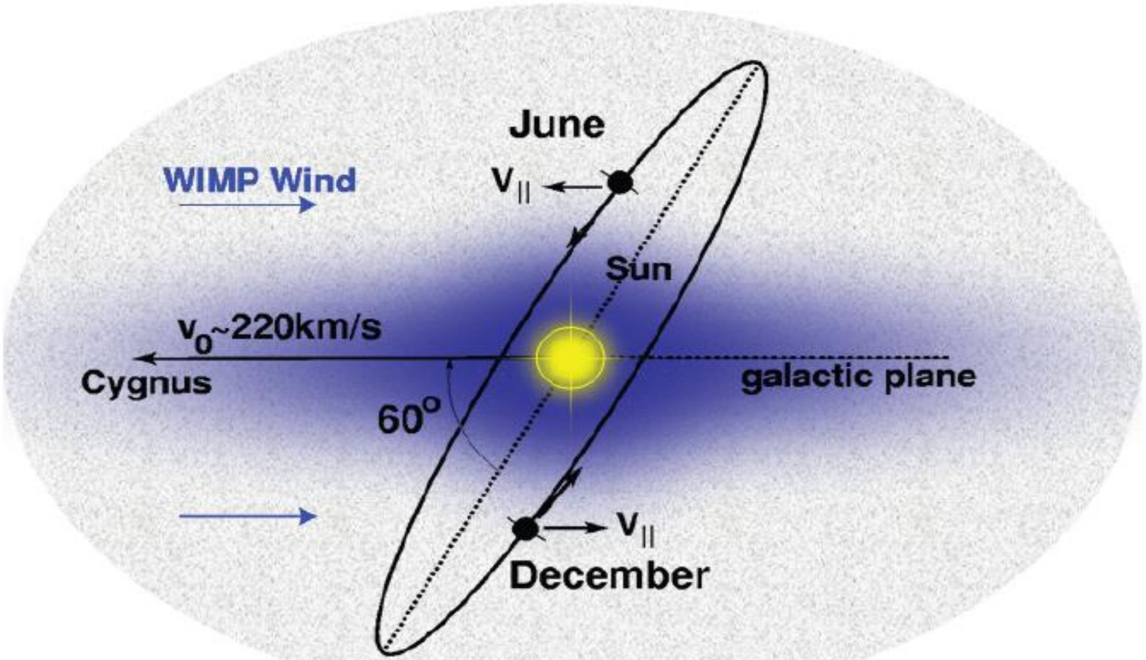
DM velocity distribution

$$f_\oplus(\vec{v}, t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t)) \qquad f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

$\bar{v} \simeq 220\,\mathrm{km/s}$ $\quad v_{\rm esc} \simeq 550\,\mathrm{km/s}$

sun velocity: $\vec{v}_\odot = (0, 220, 0) + (10, 13, 7)\,\mathrm{km/s}$

earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\mathrm{km/s}$

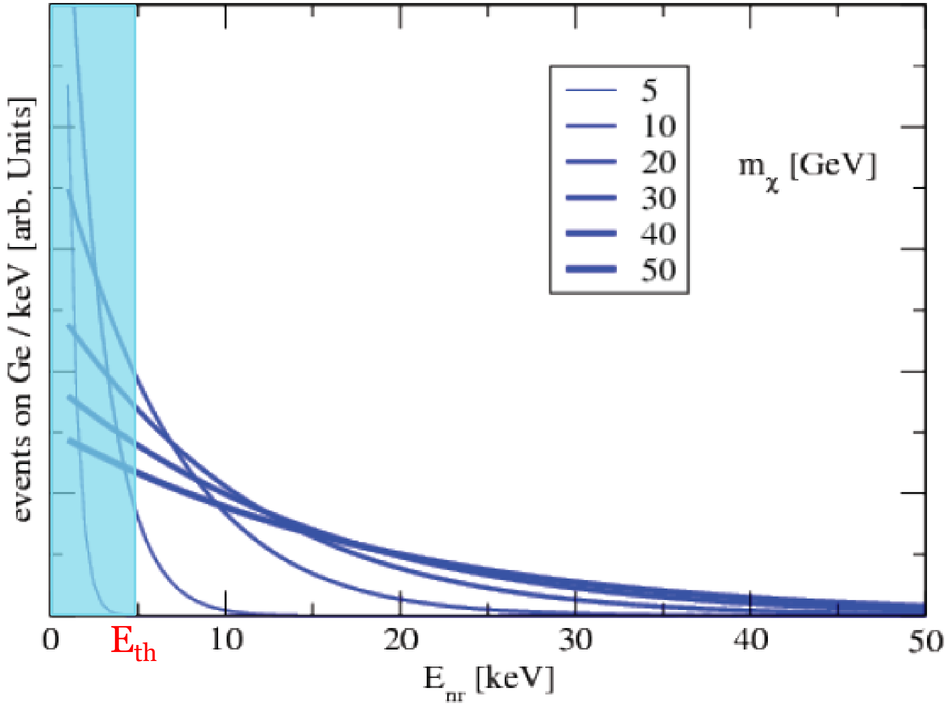


MB distribution is used for describing particle speeds in idealized gases, where the <u>particles move freely inside a stationary container</u> without interacting with one another, <u>except for very brief collisions</u> in which they exchange E & p with each other or with their thermal environment.

Event spectrum

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v > v_{\rm min}(E_R)} d^3v \, \frac{f_\oplus(\vec{v}, t)}{v}$$

$v_{\rm min} = \frac{m_\chi + M}{m_\chi} \sqrt{\frac{E_R}{2M}}$: minimal DM velocity needed for recoil energy E_R



$m_\chi \ll M$:

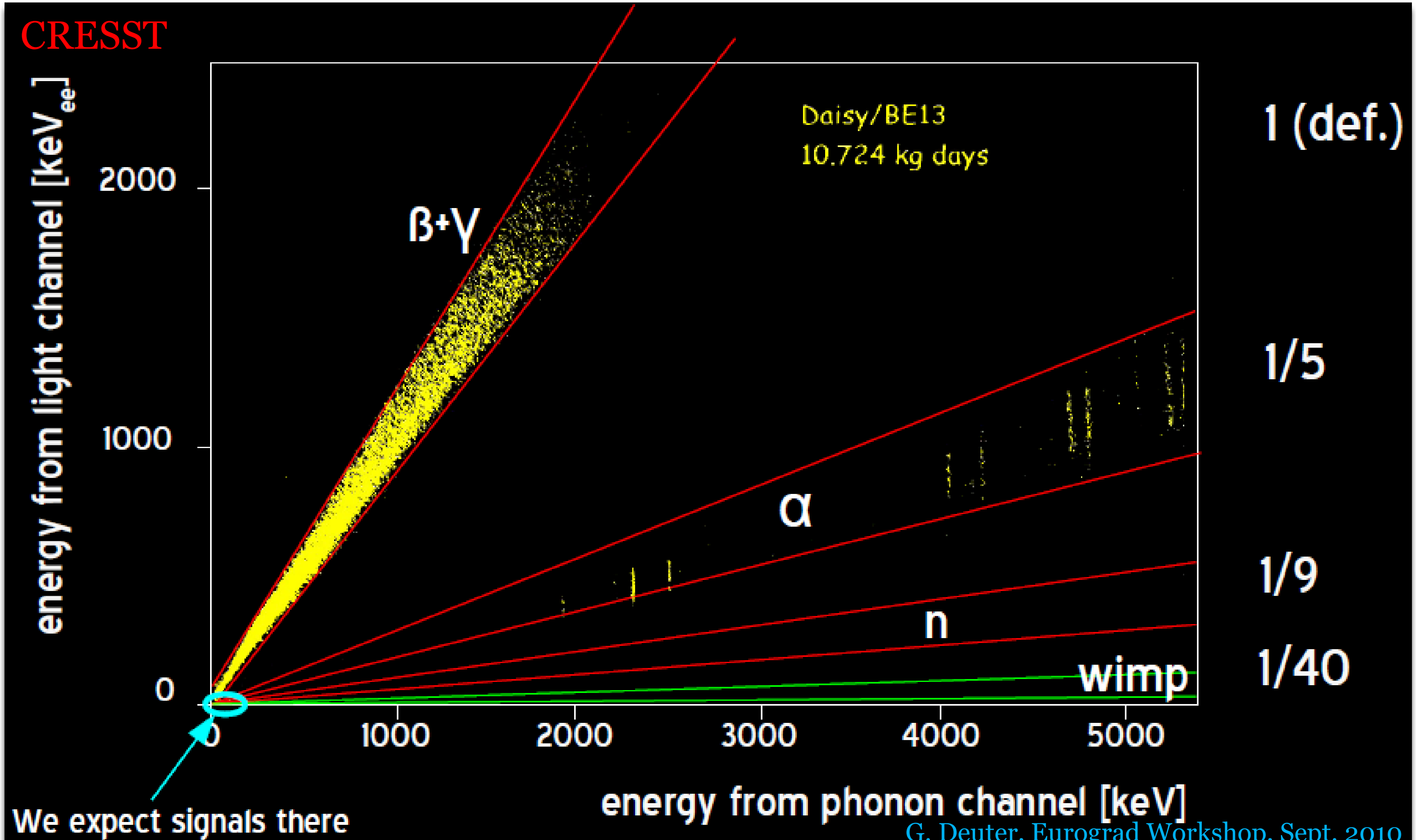
$$v_{\rm min} \approx \frac{\sqrt{ME_R/2}}{m_\chi}$$

spectrum gets shifted to low energies for low WIMP masses

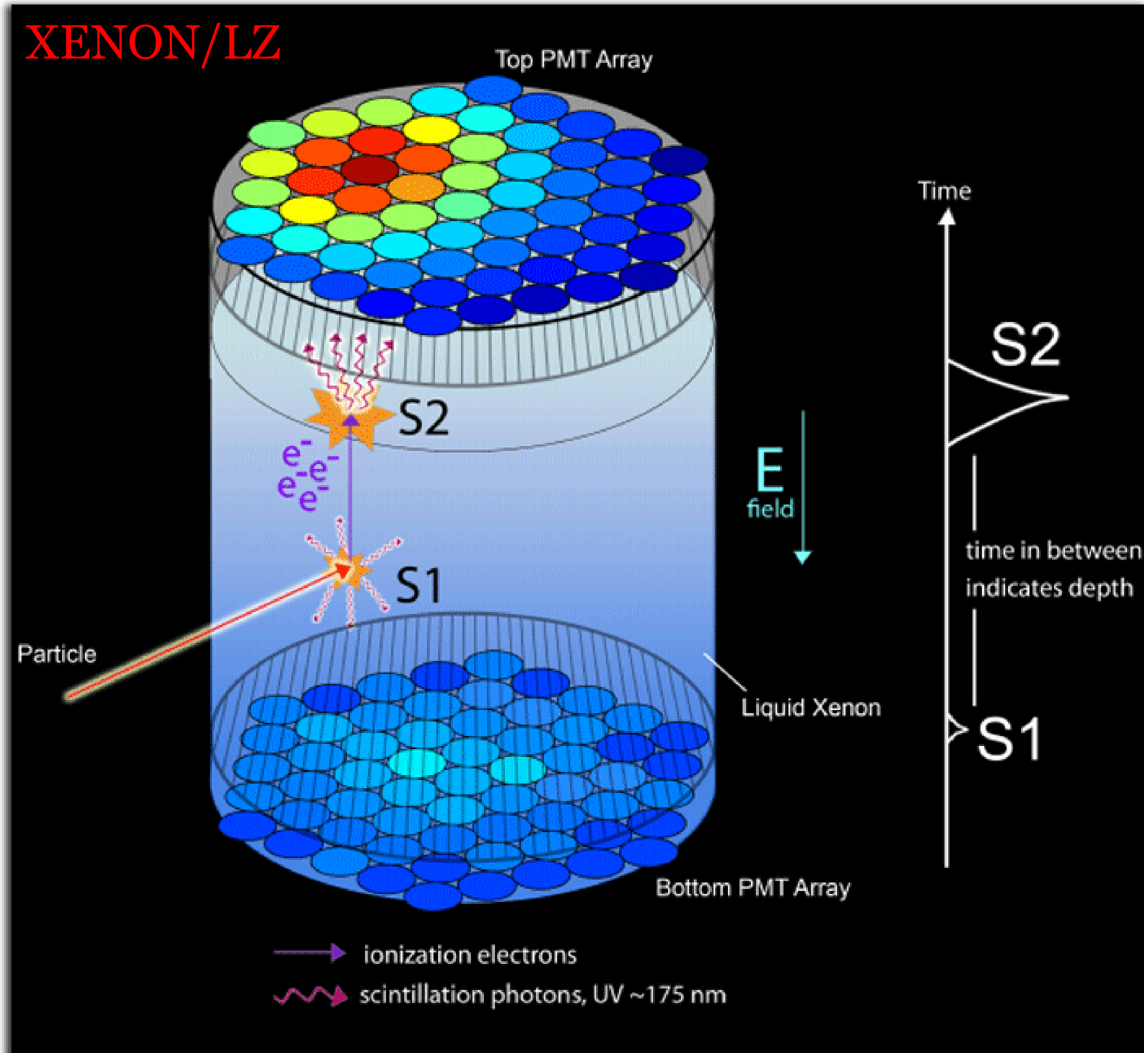
$\Rightarrow$ energy threshold is crucial

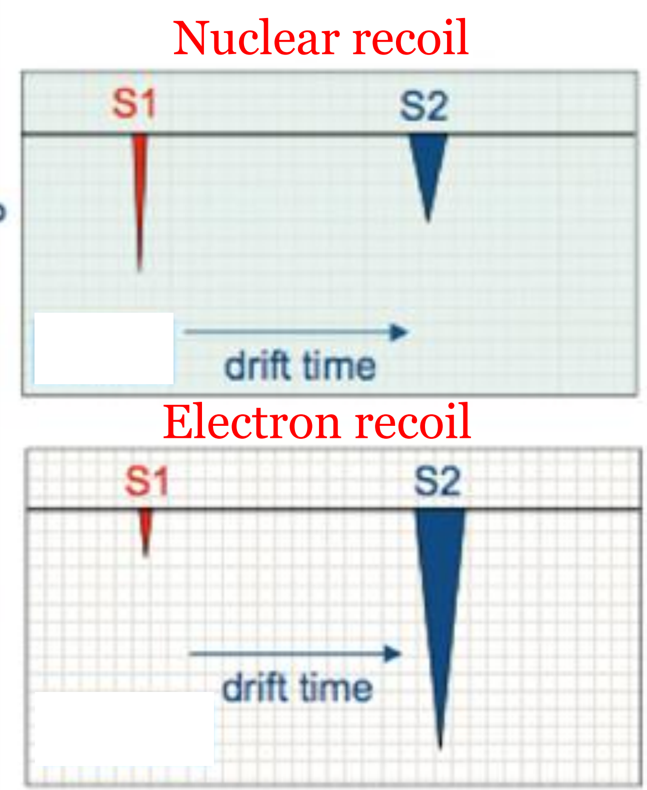
T. Schwetz, PPC11 CERN

Event Discrimination



Event Discrimination

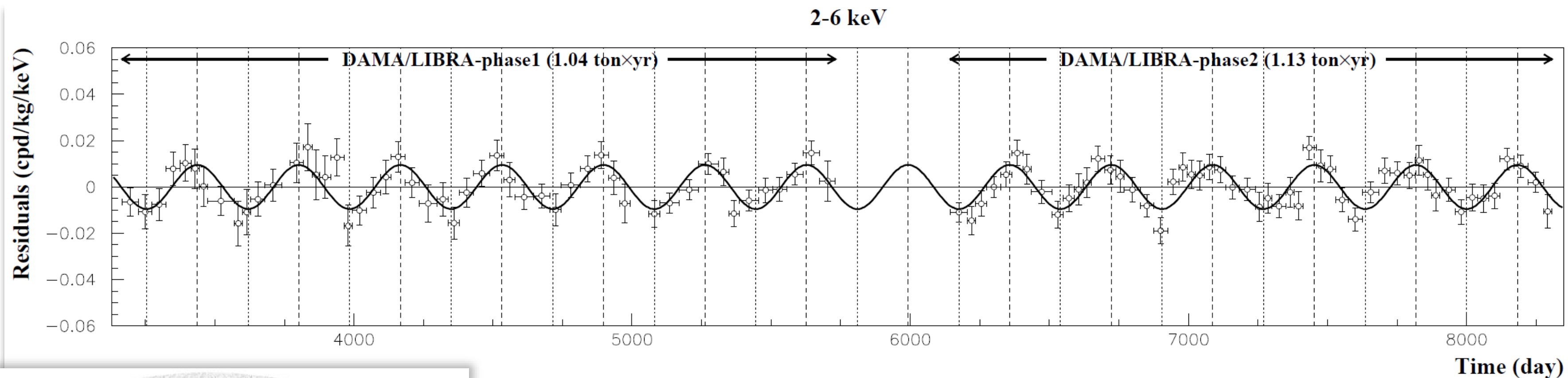


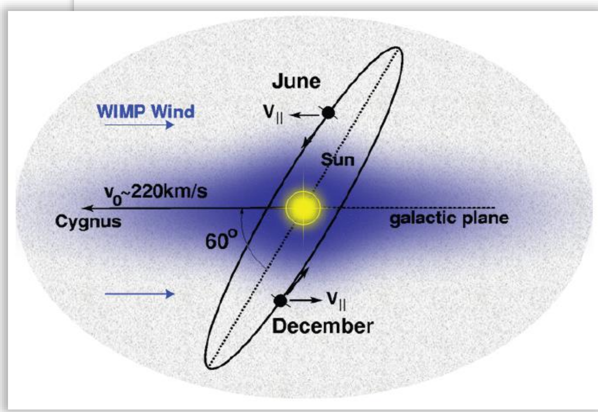


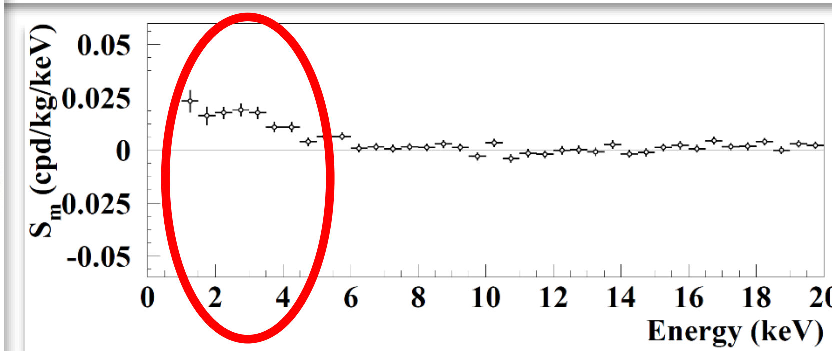
Annual Modulation

DAMA [arXiv: 1805.10486]

- As the Earth orbits the Sun, v of the detector relative to the DM halo varies.
- DAMA has detected an annual modulation in the event rate (12.9 σ significance).
- 14 annual cycles, modulation amplitude: 0.0103 ± 0.0008 in the (2-6) keV
- Phase: 145 ± 5 days (cf. June 2nd), Period: 0.999 ± 0.001 yr



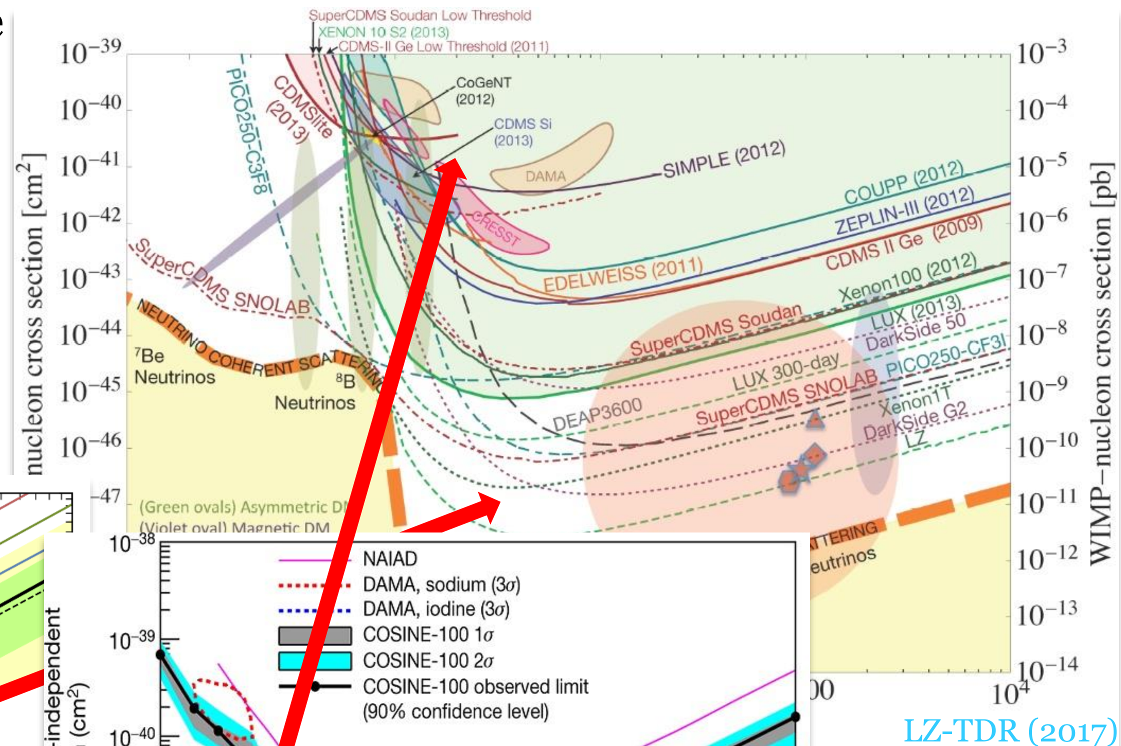


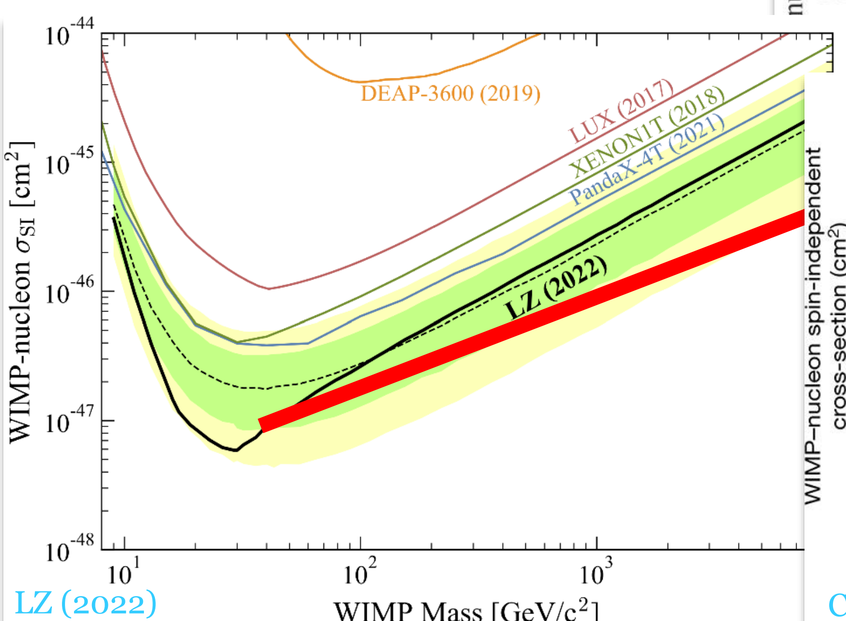


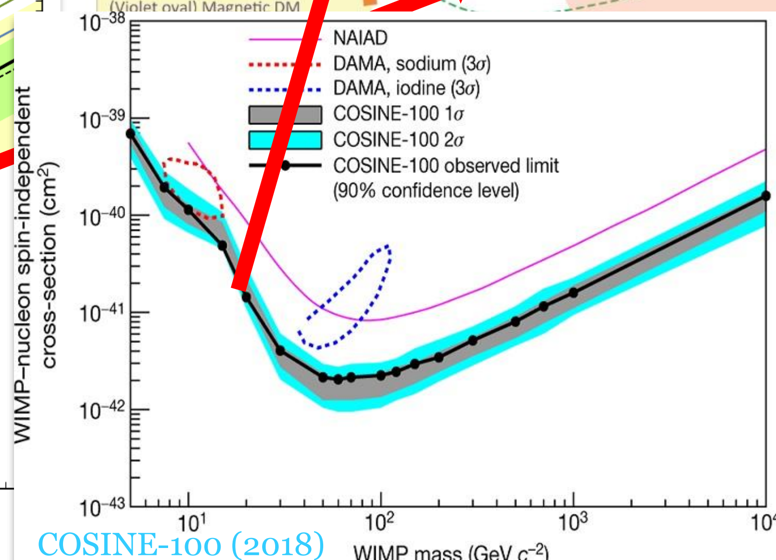
Current Status Direct DM Searches

❖ No (solid) observation of DM signatures w/ BG modeling

➔ Excluding more parameter space





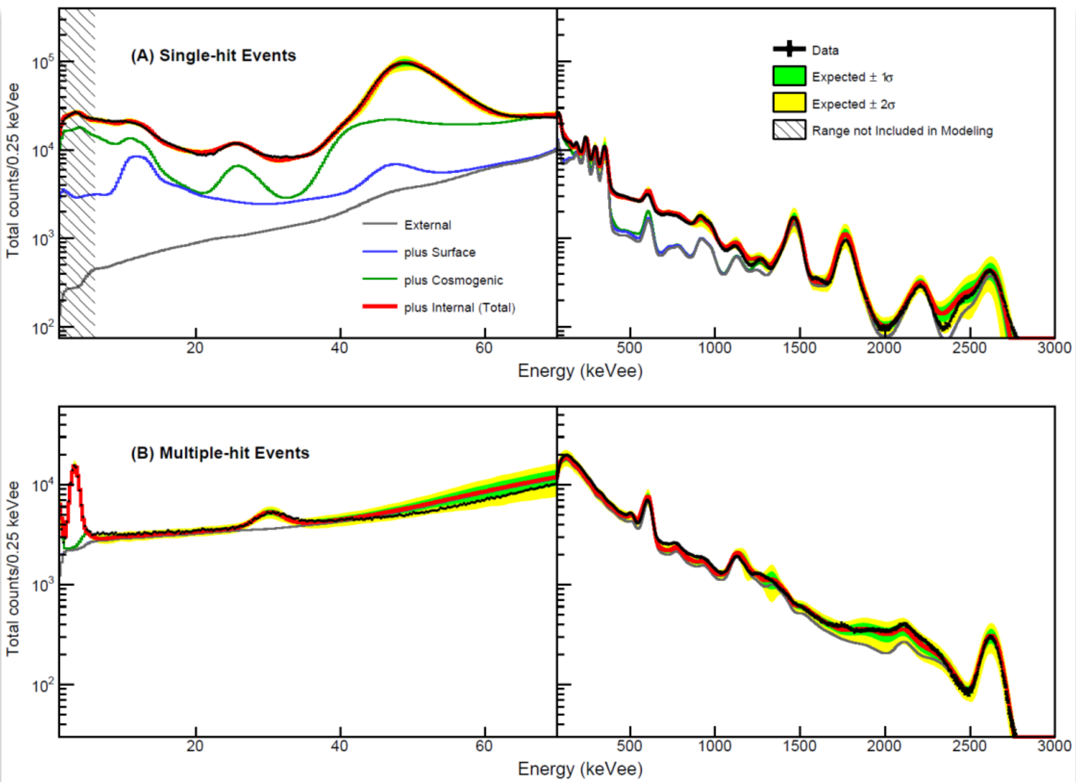


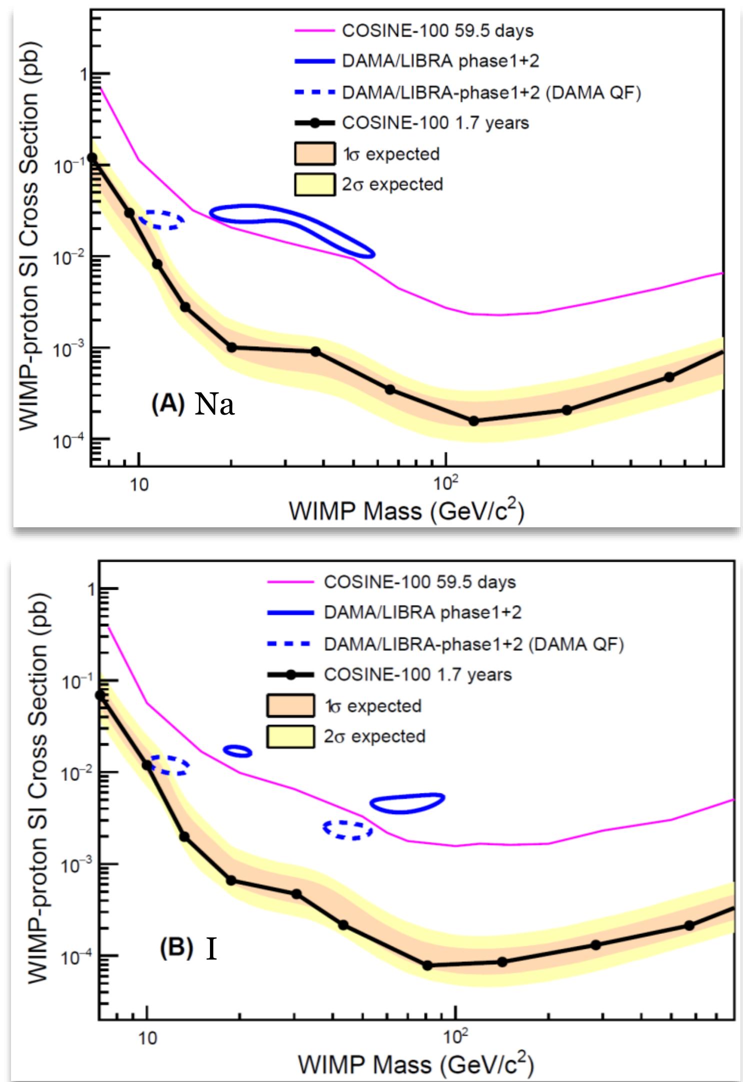
Current Status Direct DM Searches

COSINE-100 [arXiv: 2104.03537]

❖ No (solid) observation of DM signatures w/ BG modeling

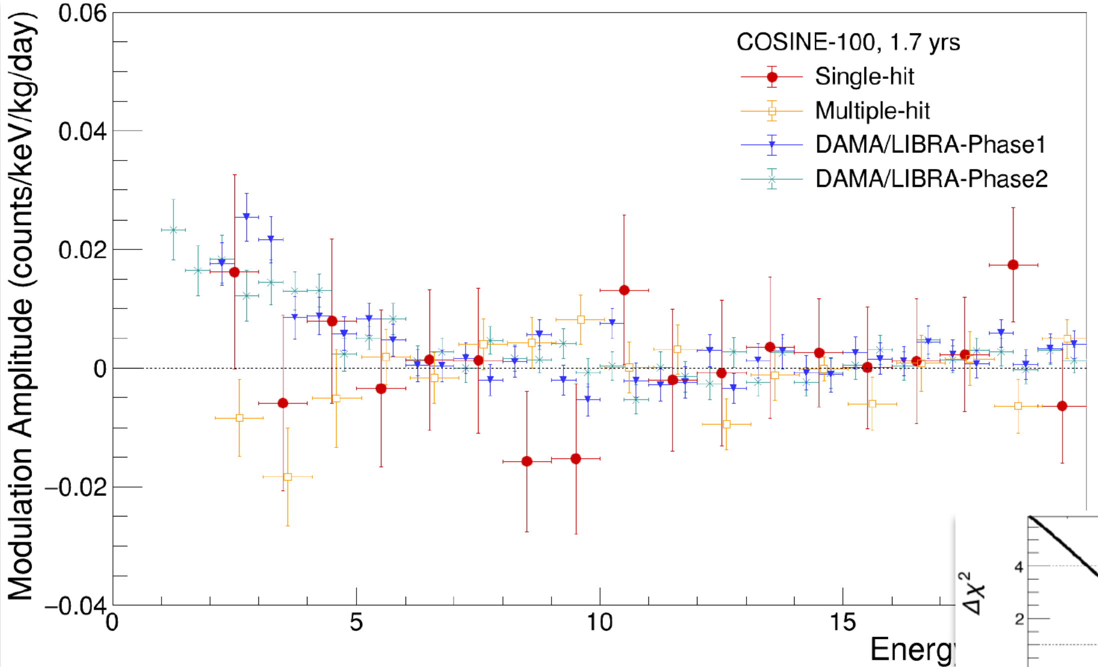
➔ Excluding more parameter space

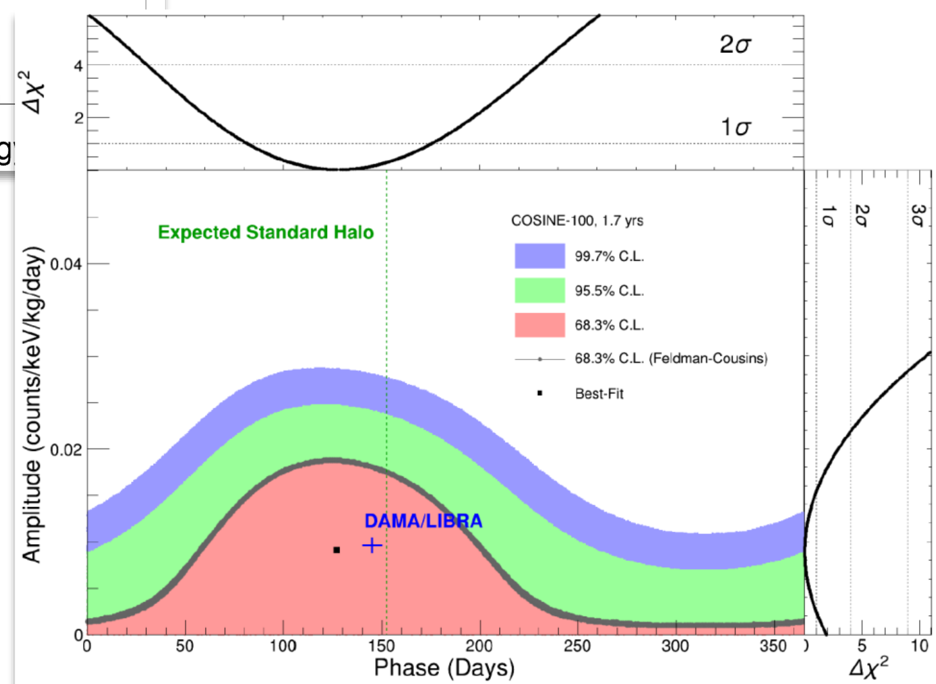




Current Status of Annual Modulation

COSINE-100 (2019)

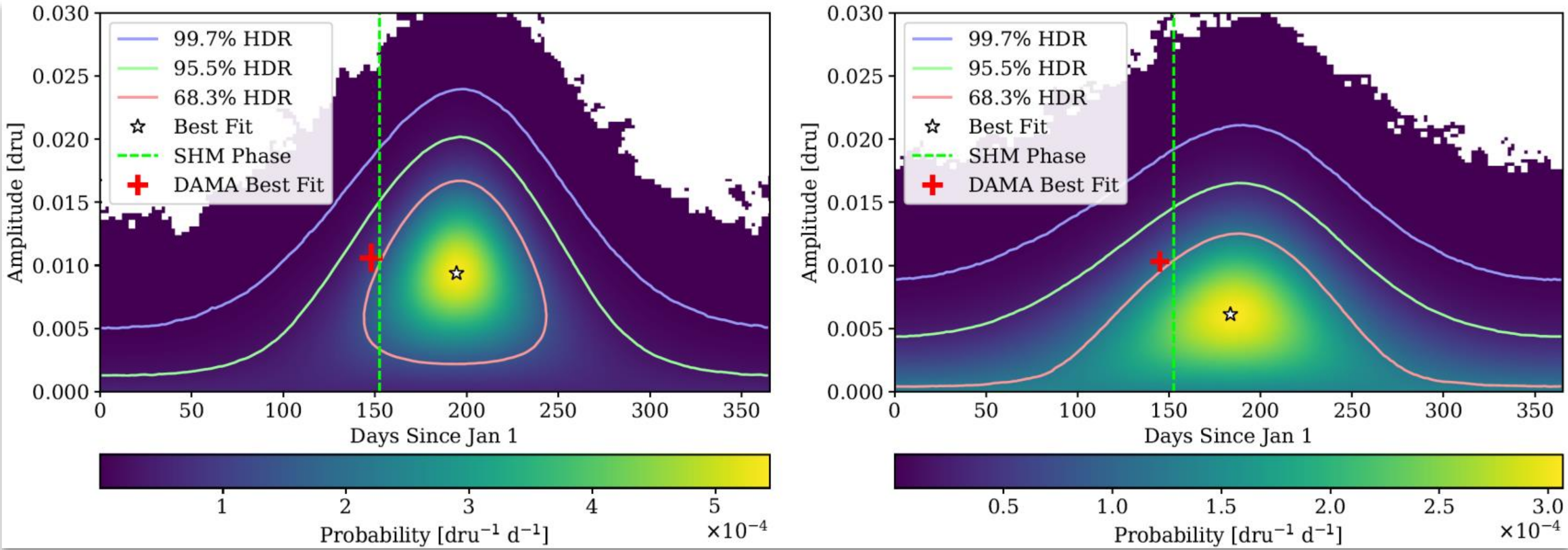




In summary, we report the results from the search for a dark matter–induced annual modulation signal in NaI(Tl) based on 1.7 years of COSINE-100 data. A fit to the 2–6 keV energy range returns a modulation amplitude of 0.0092±0.0067 cpd/kg/keV with a phase of 127.2±45.9 d. At 68.3% C.L., this result is consistent with both the null hypothesis and DAMA/LIBRA's 2–6 keV best fit value.

Current Status of Annual Modulation

COSINE-100 [arXiv: 2111.08863]



Configuration	Amplitude [dru]	Phase [days]
COSINE-100 1–6 keV (This result)	0.0067±0.0042	152.5 (fixed)
COSINE-100 2–6 keV (This result)	0.0050±0.0047	152.5 (fixed)
COSINE-100 2–6 keV (2019 result [14])	0.0083±0.0068	152.5 (fixed)
ANAIS 1–6 keV (2021 result [16])	-0.0034±0.0042	152.5 (fixed)
ANAIS 2–6 keV (2021 result [16])	0.0003±0.0037	152.5 (fixed)
DAMA/LIBRA 1–6 keV (phase2 [7])	0.0105±0.0011	152.5 (fixed)
DAMA/NaI+LIBRA 2–6 keV [7]	0.0102±0.0008	152.5 (fixed)
COSINE-100 1–6 keV (This result)	$0.0094^{+0.0073}_{-0.0072}$	$194.5^{+49.0}_{-50.5}$
COSINE-100 2–6 keV (This result)	$0.0061^{+0.0064}_{-0.0061}$	Unconstrained
COSINE-100 2–6 keV (2019 result [14])	0.0092±0.0067	127.2±45.9
DAMA/LIBRA 1–6 keV (phase2 [7])	0.0106±0.0011	148±6
DAMA/NaI+LIBRA 2–6 keV [7]	0.0103±0.0008	145±5