Fermi Gamma-ray Space Telescope

Dark Matter

R. Caputo
UCSC

24 March 2016
Future MeV Mission Workshop
NASA Goddard

Overview

- Mission Assumptions
  - MeV Space-Based
- A Brief History
- Dark Matter
  - Back in the 1970s…
  - Dark Matter producing MeV/GeV photons
    - The WIMP (and not exactly a WIMP) story
    - Axion and Axion-like particles
- Other
  - Complementary detections,
  - multi-wavelength/messenger,
  - fundamental physics

MeV Mission Assumptions

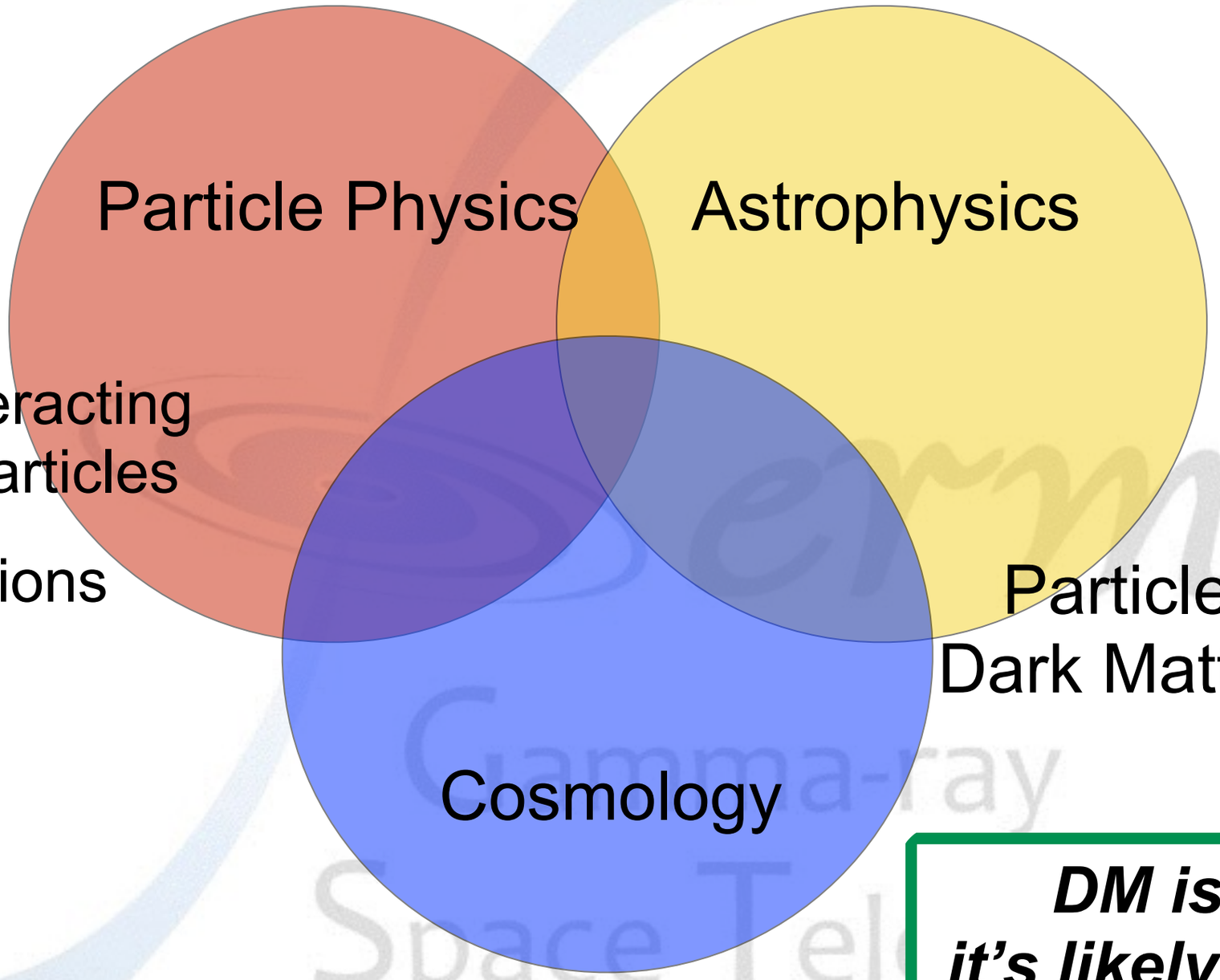
- **An idea of mission capabilities (typically MIDEX class)**

Mission	Energy Range [MeV]	Energy Resolution [$\Delta E/E$]	Angular Resolution	FOV	Flux Sensitivity [MeV cm^{-2}s^{-1}]
TPCs (polarimetry)					
AdEPT	5-200	~30% at 70 MeV	~0.6° at 70 MeV	3.14 m^{2}sr	<3×10^{-5}
LArGO	0.1 - 10^5	~3% at 1 MeV	~1° at 100 MeV	large (>2.5 sr?)	
HARPO	1-100	6/15/30% at 1/10/100 MeV	~0.3° at 40 MeV	4π(?) sr	<10^{-6}
Spectrometers/mappers					
GRX/COSI	0.2-few	1/0.1% at 0.2/1 MeV	~4° at 1 MeV	3.14 m^{2}sr	<2×10^{-5}
Continuum/survey mapper					
ComPair	1-500	2/4/12% at 1/10/100 MeV	~7(1)° at 1(100) MeV	3.5 sr	<2×10^{-6}
AstroGAM	0.3-100	1/7% at 1/10 MeV	~1° at 100 MeV	~2.6 sr	<6×10^{-6}
Current					
Fermi-LAT	20->3×10^5	18/7% at 10^2/10^3 MeV	~3(0.04)° at 100(10^5) MeV	~2.5 sr	<10^{-6}

Benchmark: 1 MeV-1 GeV, E Res best at 1 MeV
Large FOV, Flux sensitivity ~10^{-6} MeV cm^{-2}s^{-1}

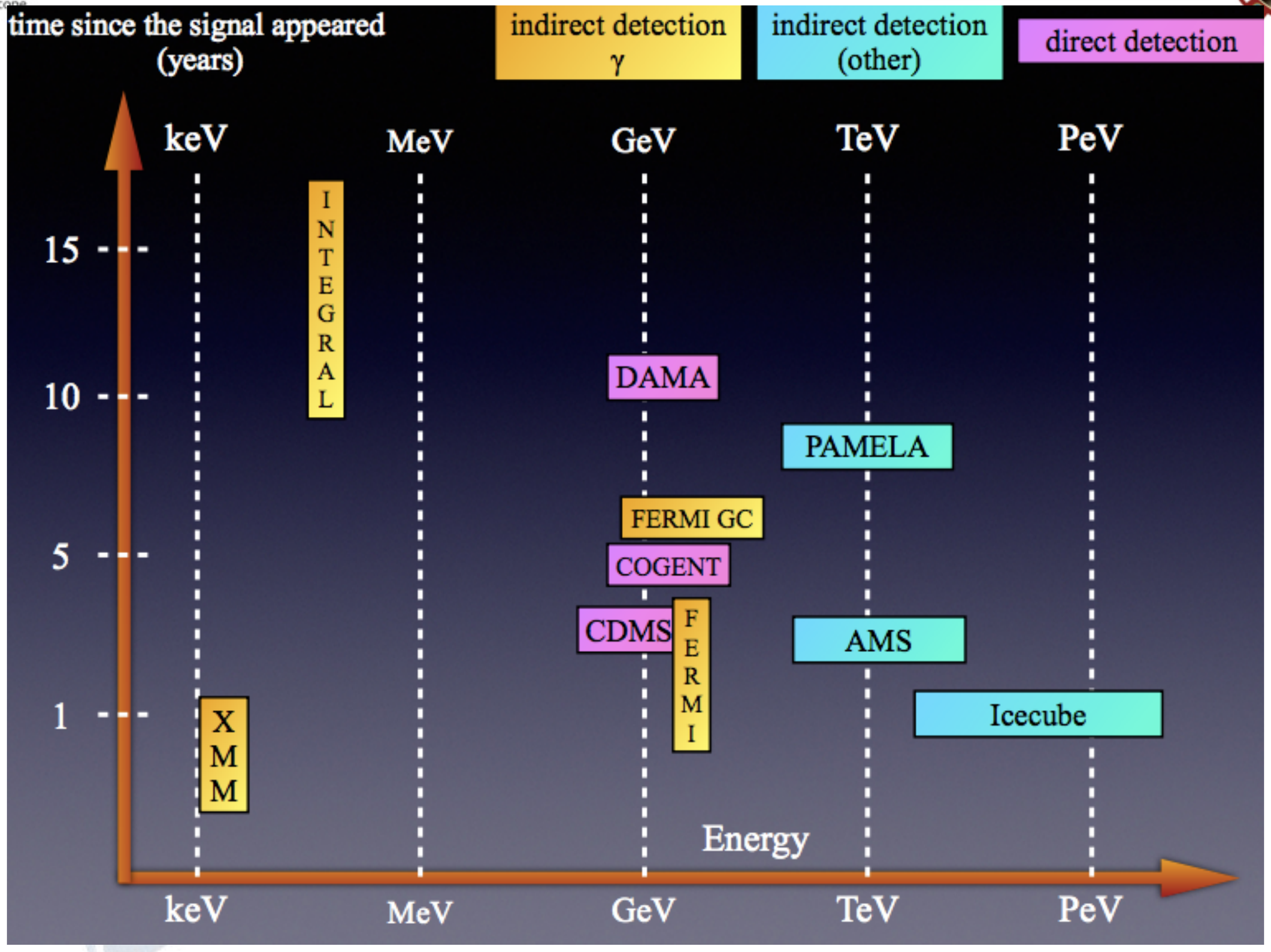
An attempt to get common parameters among missions
Not meant to be exhaustive list - only to define parameter space for new physics searches

A Brief History of Dark Matter



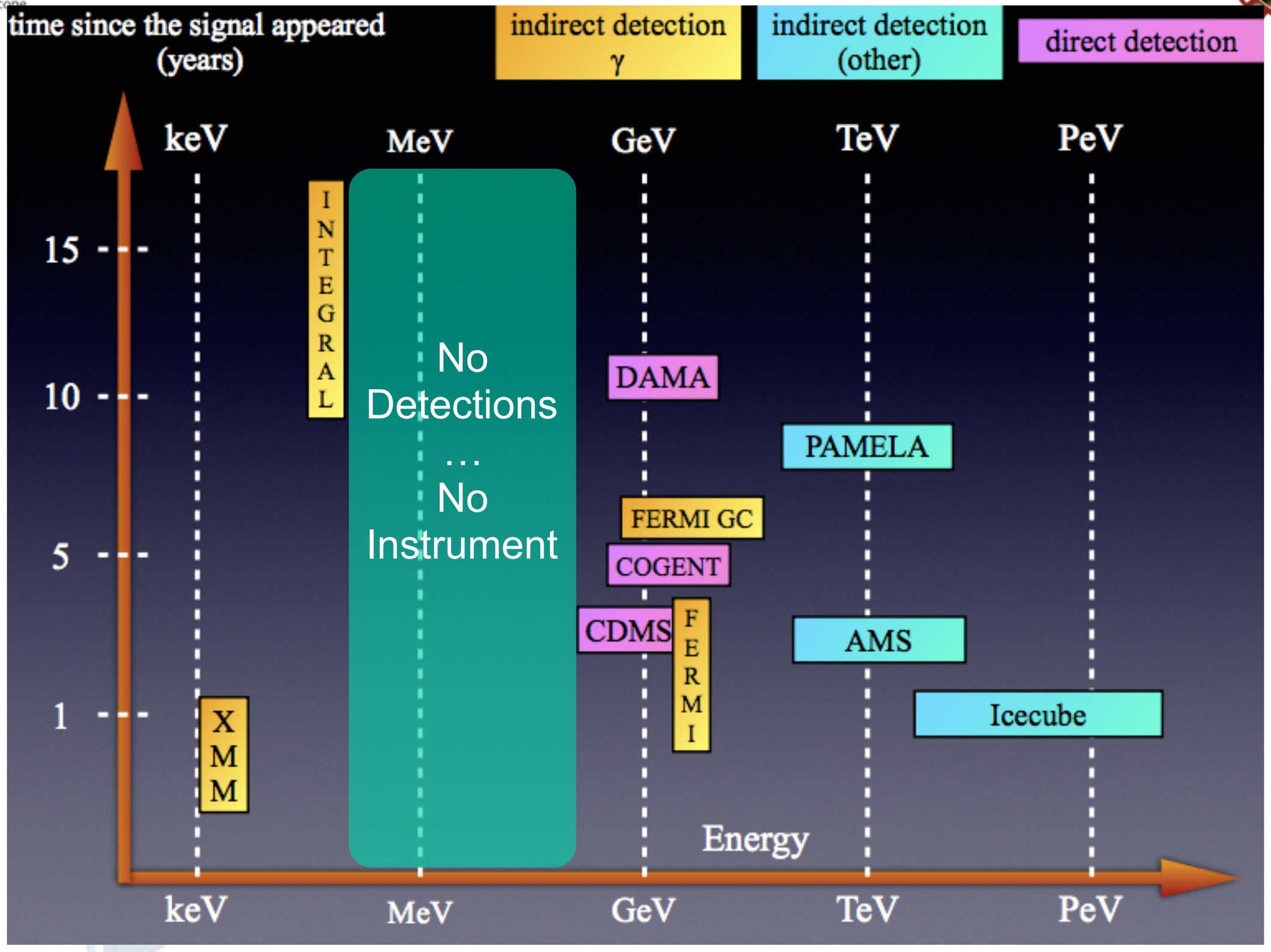
DM is there,
it's likely a particle
it could be many

Dark Matter Detections



Slide from Y. Mambrini, 2nd AstroGAM workshop

Dark Matter Detections



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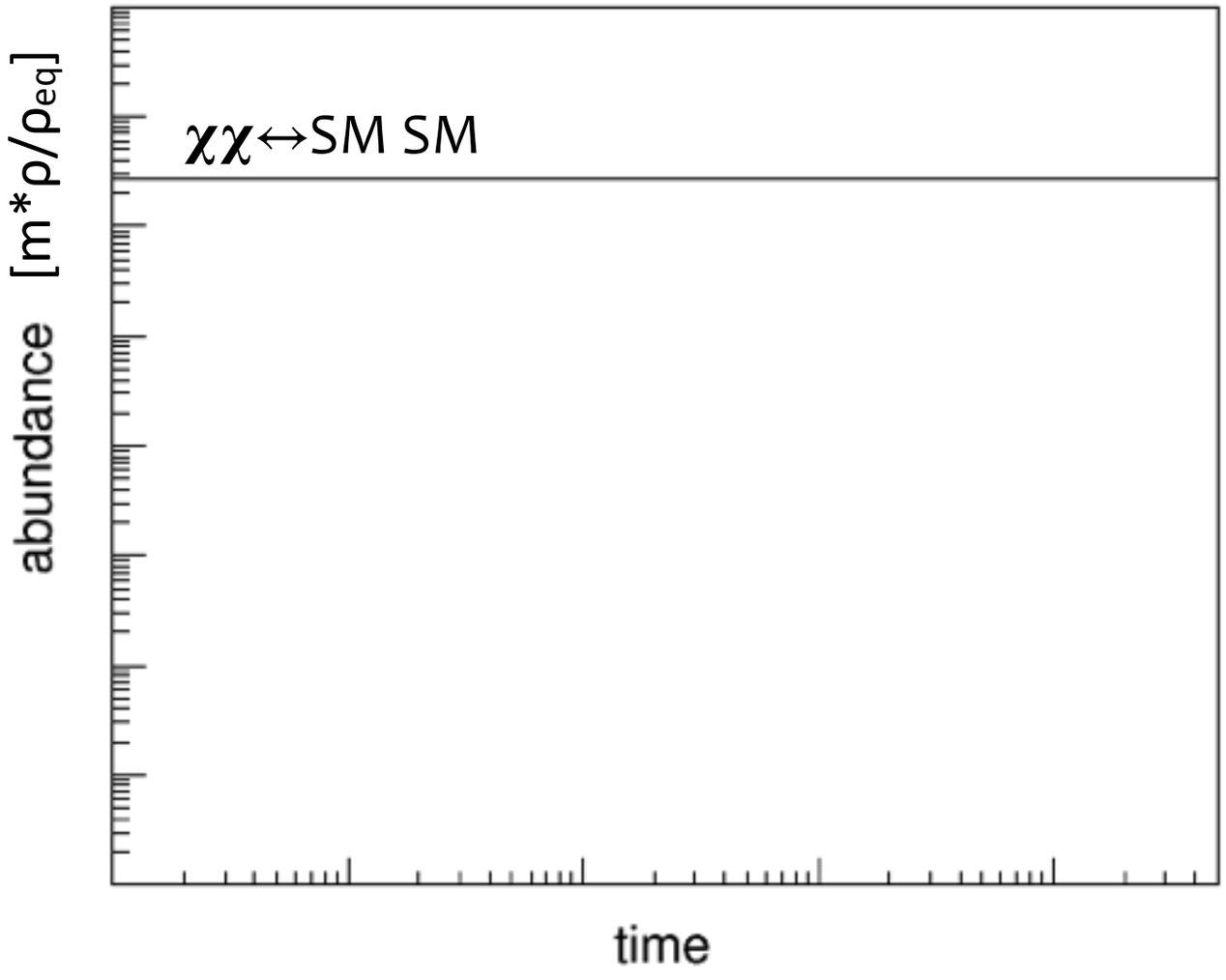
Portrait of a Candidate

G. Steigman, et al., Phys.Rev. D86 (2012) 023506

Portrait of a Candidate

Cosmology and Thermodynamics

DM = χ



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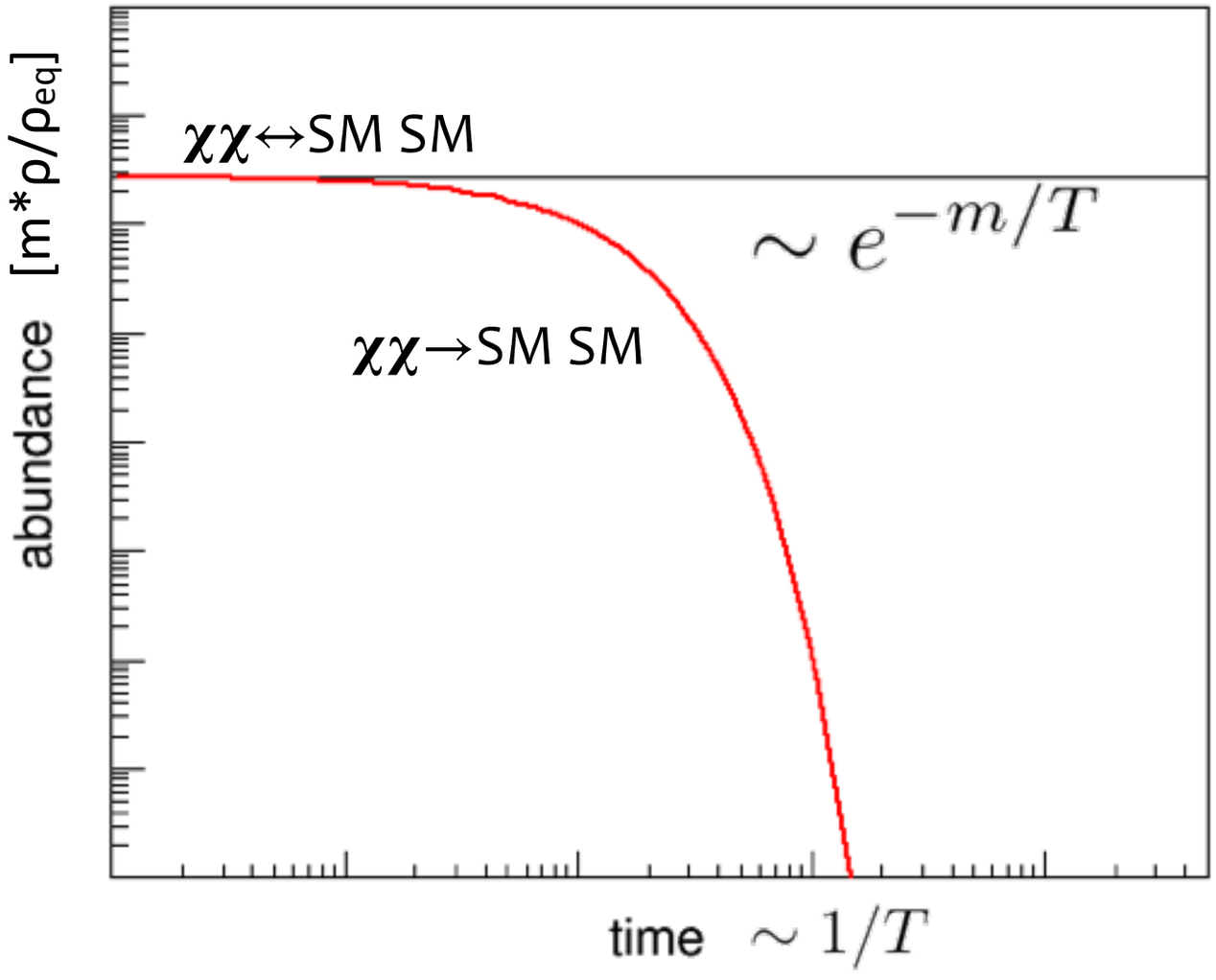

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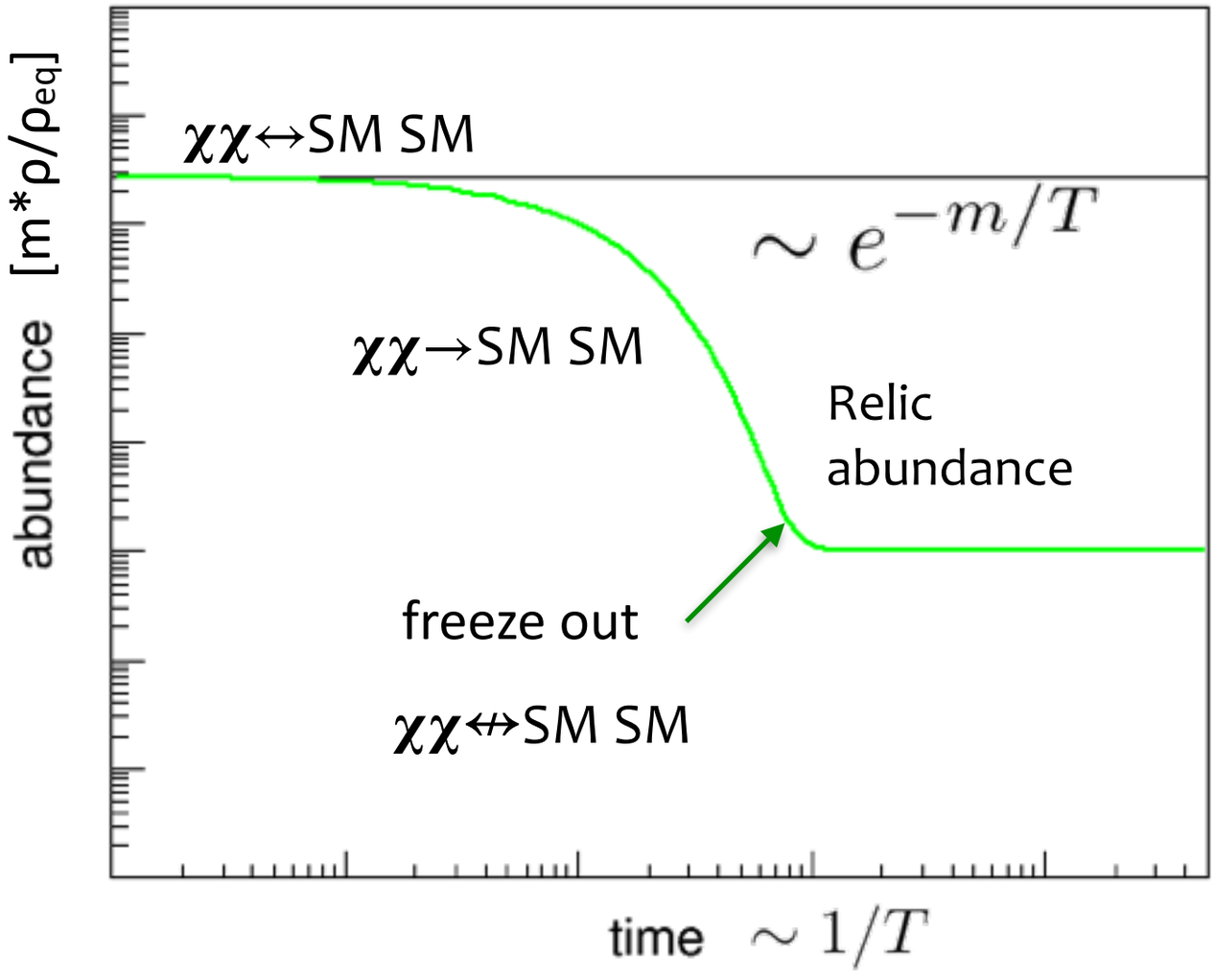

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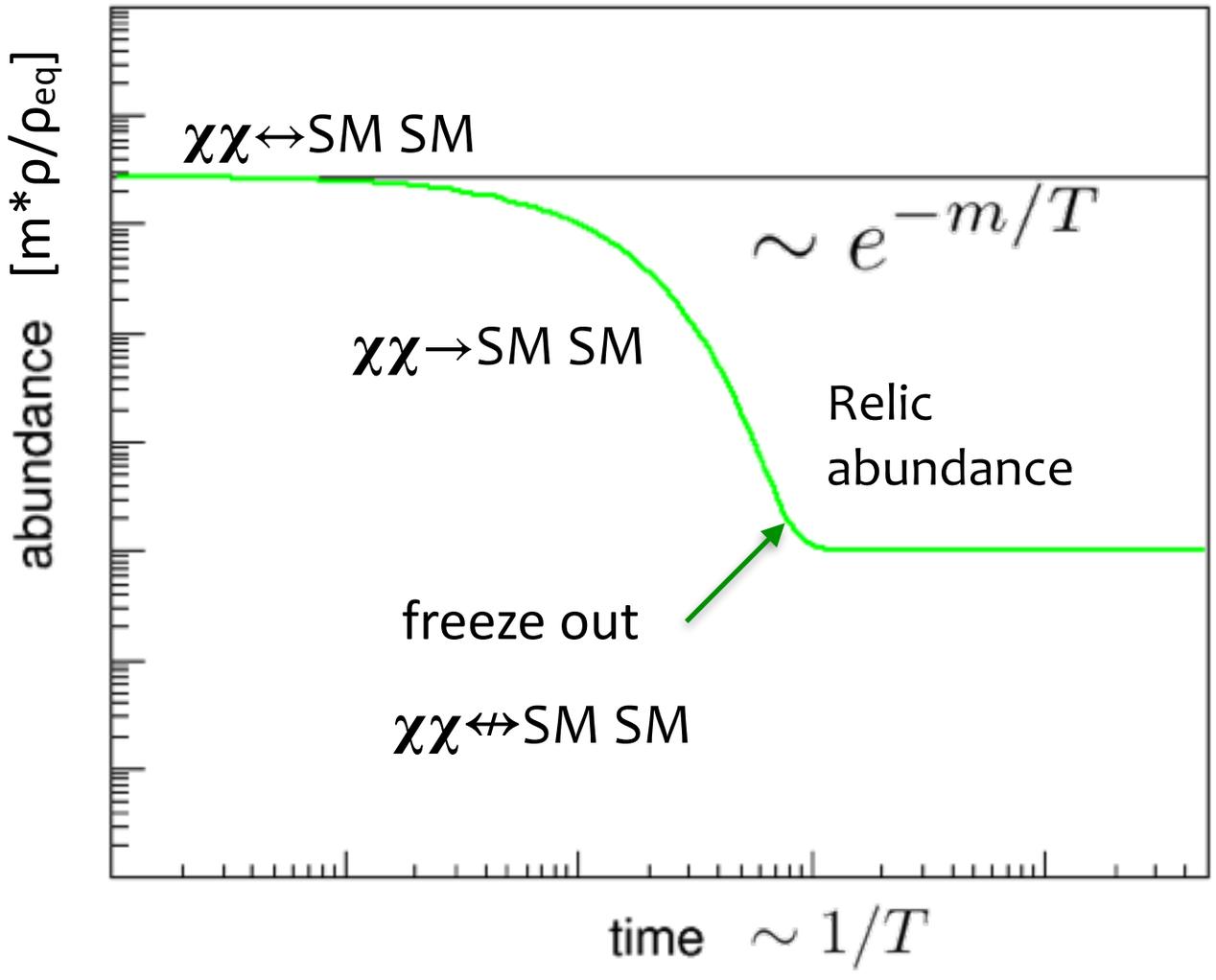

Abundance

$\langle\sigma v\rangle n_{eq} \sim H$

$\langle\sigma v\rangle \sim 10^{-26}$ cm^3/s

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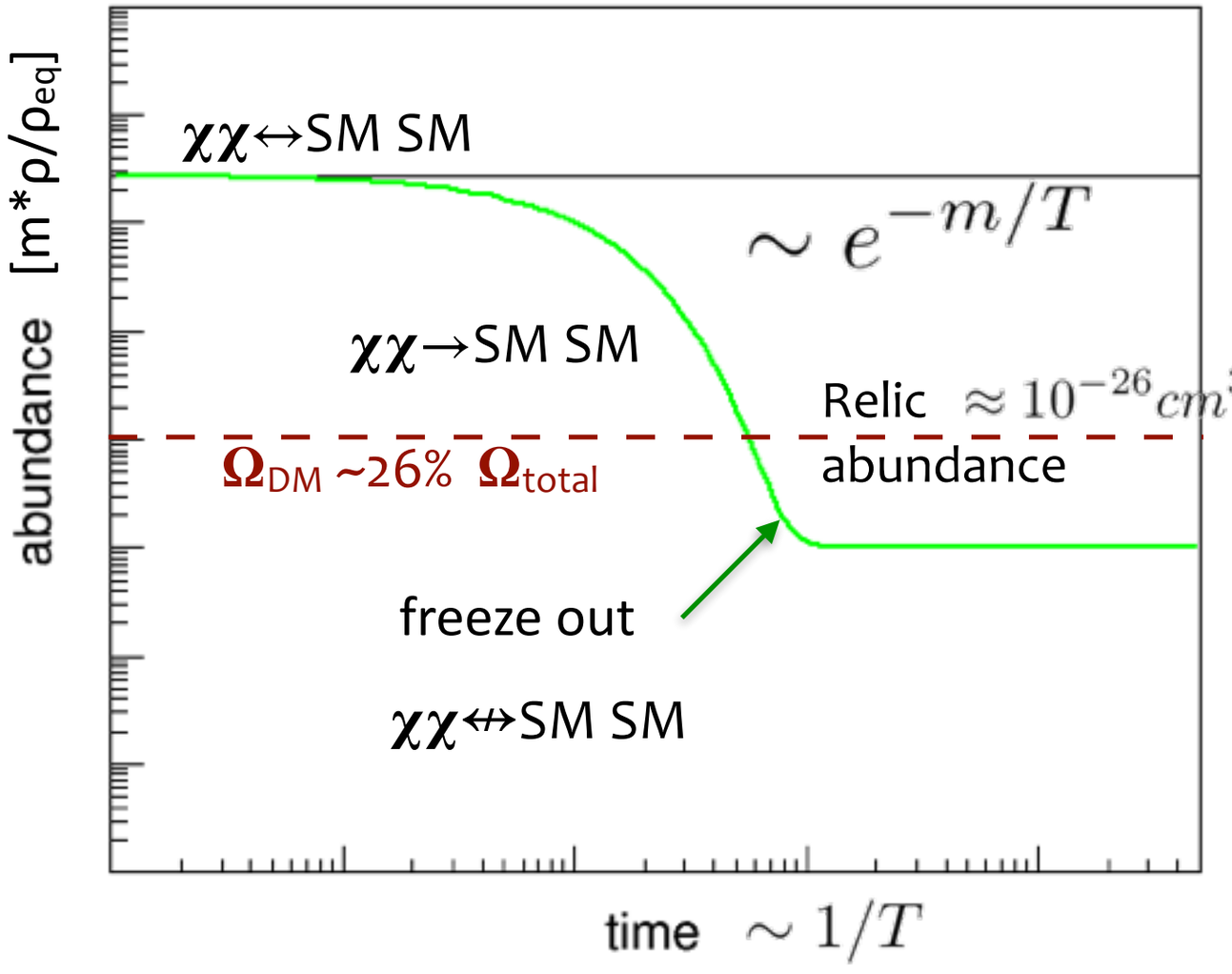

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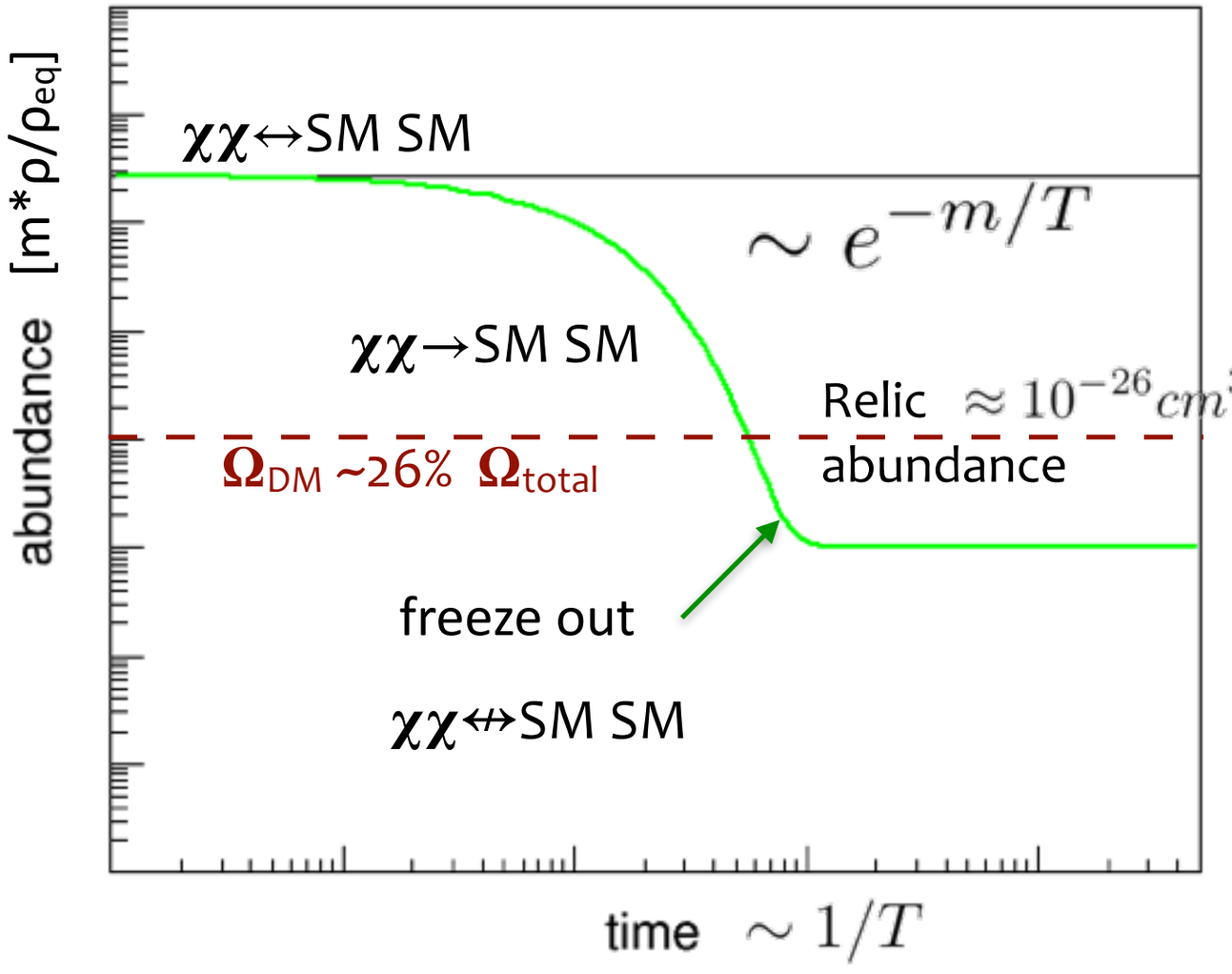

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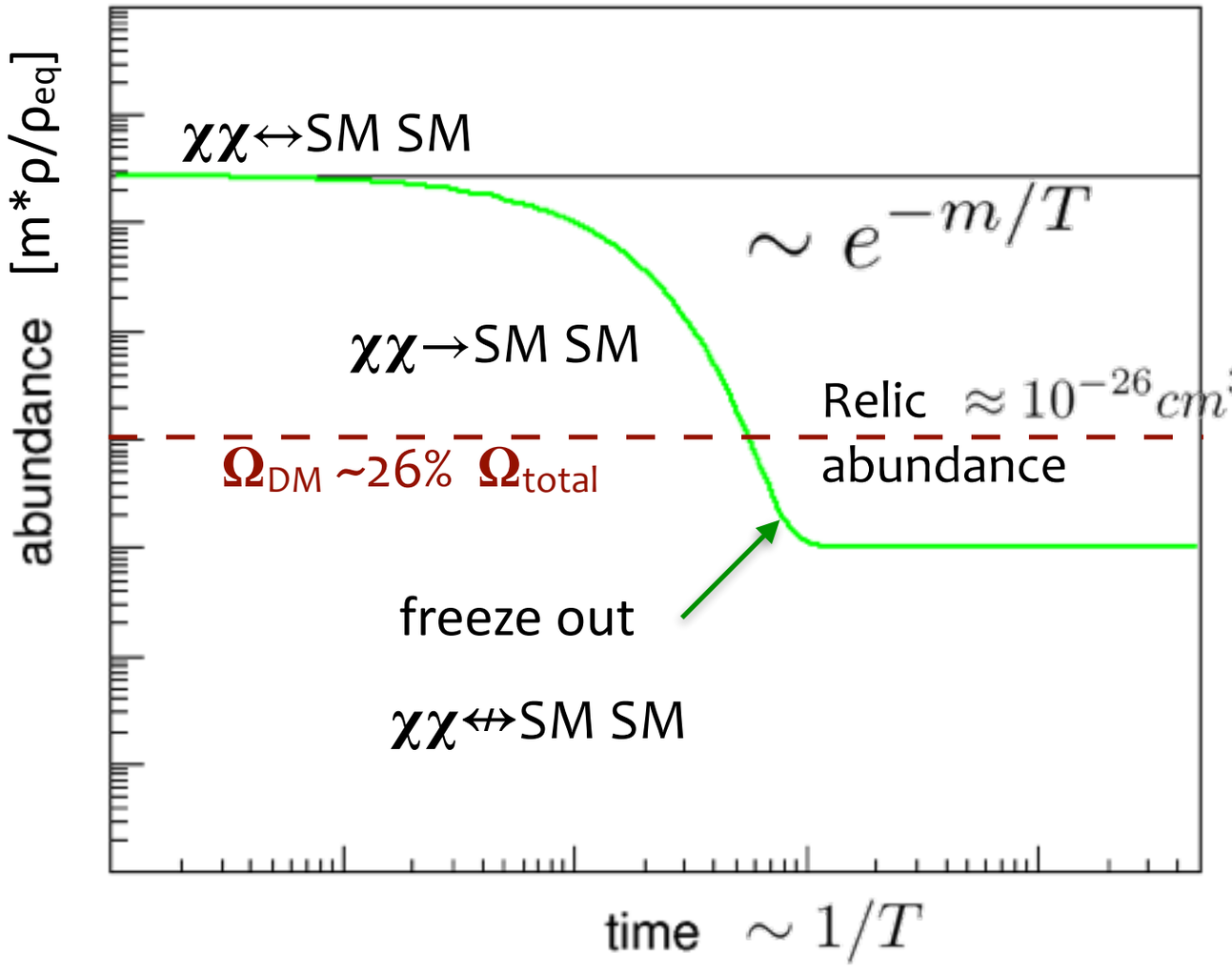

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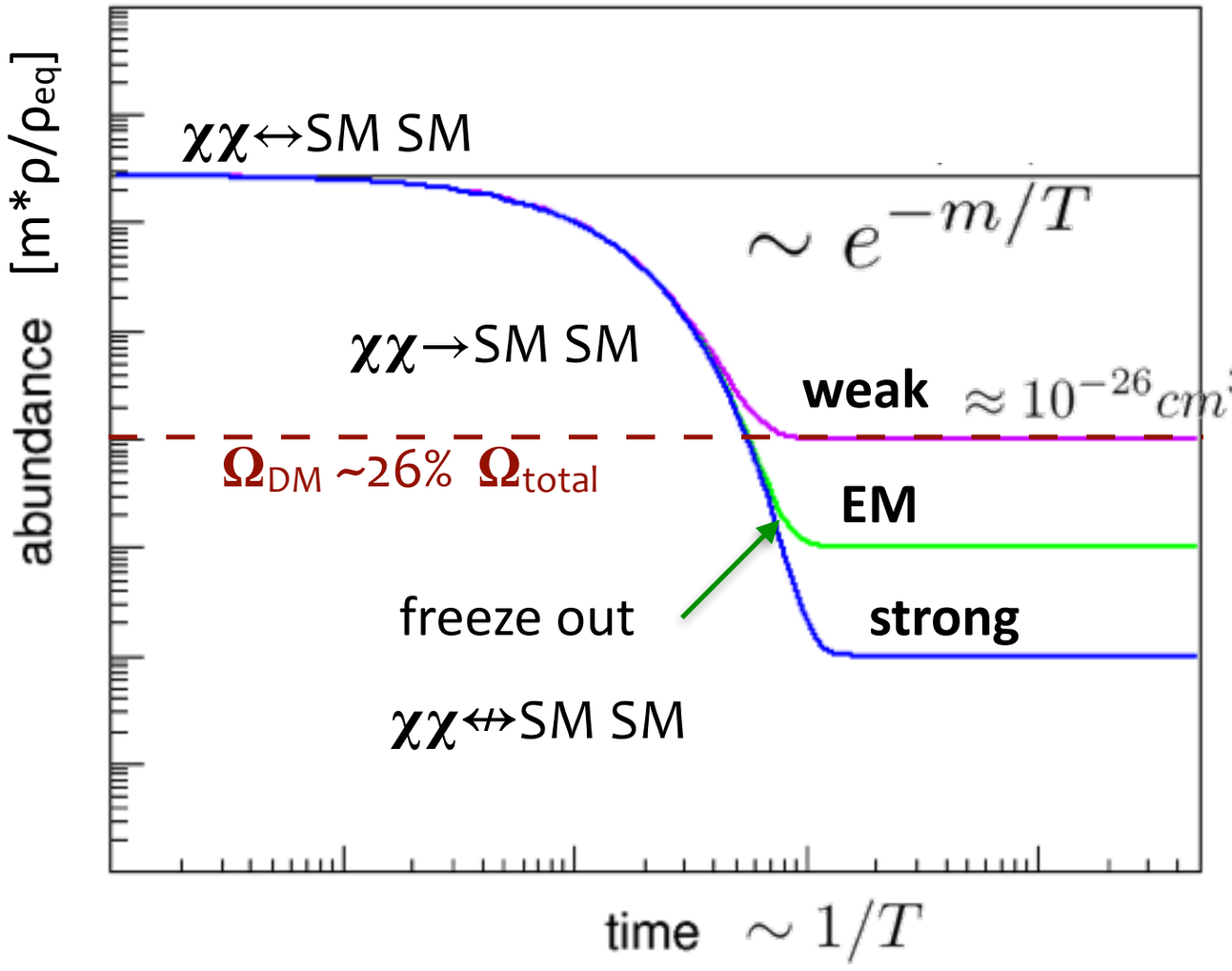

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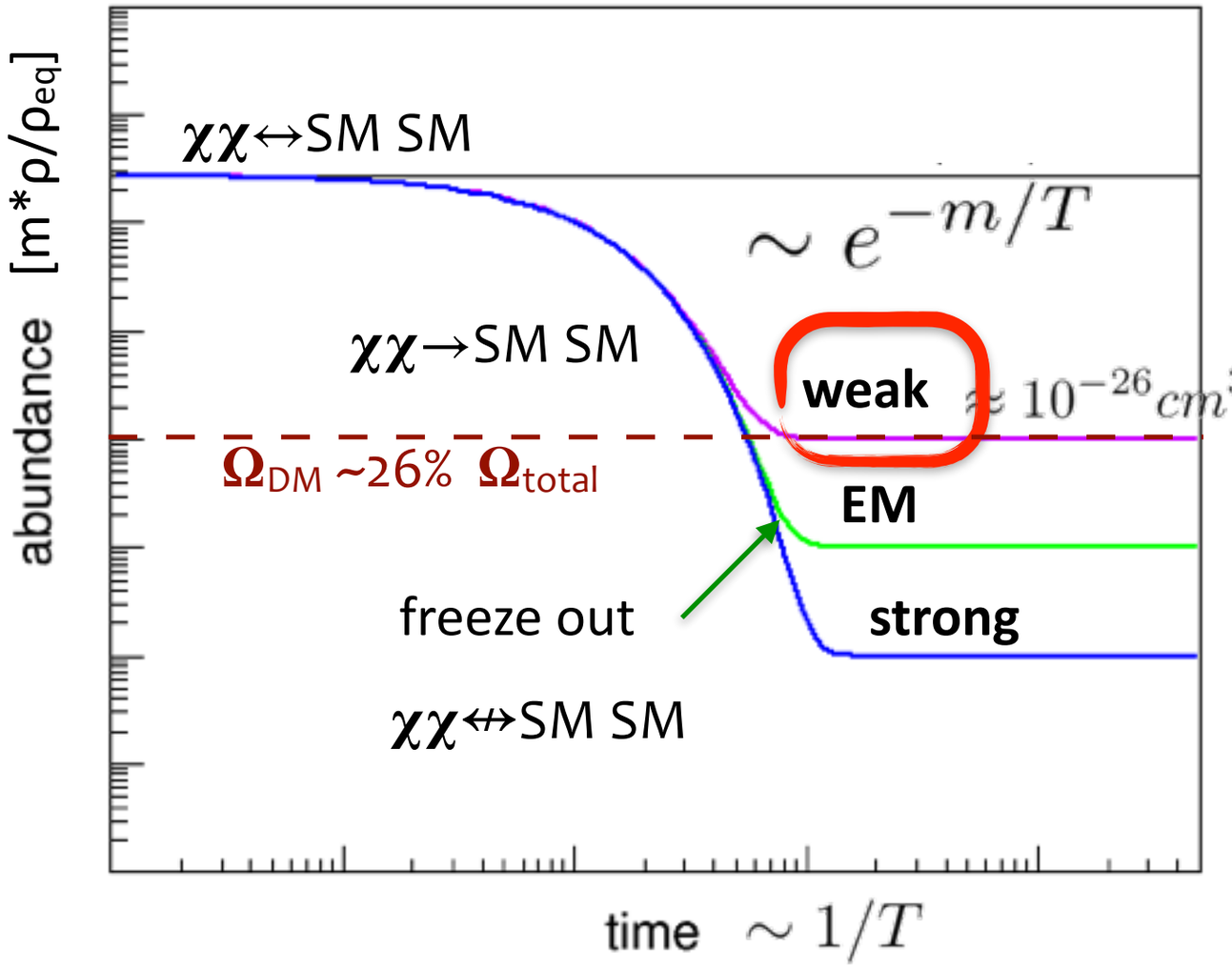

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Weakly Interacting Massive Particles

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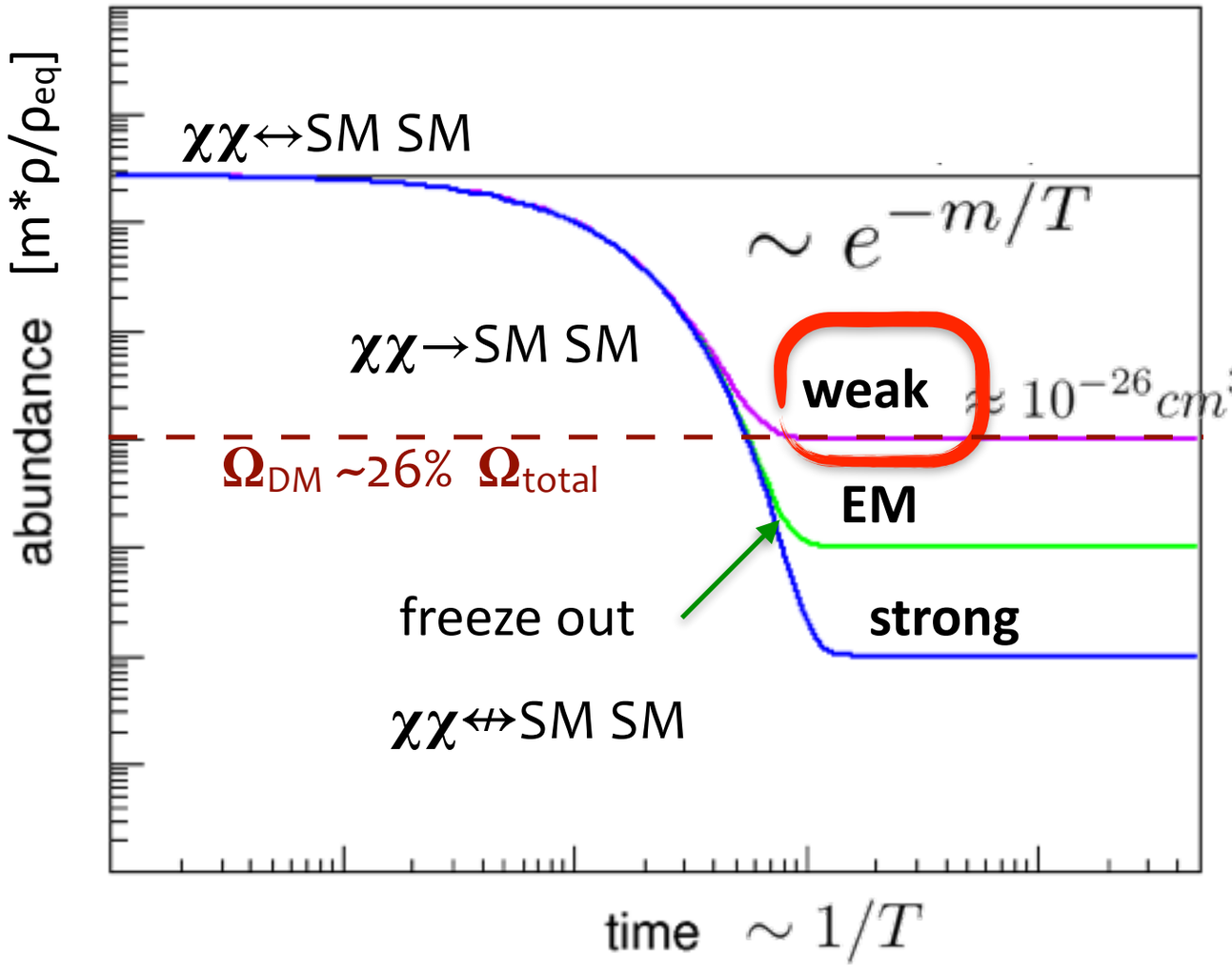

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The WIMP Miracle…

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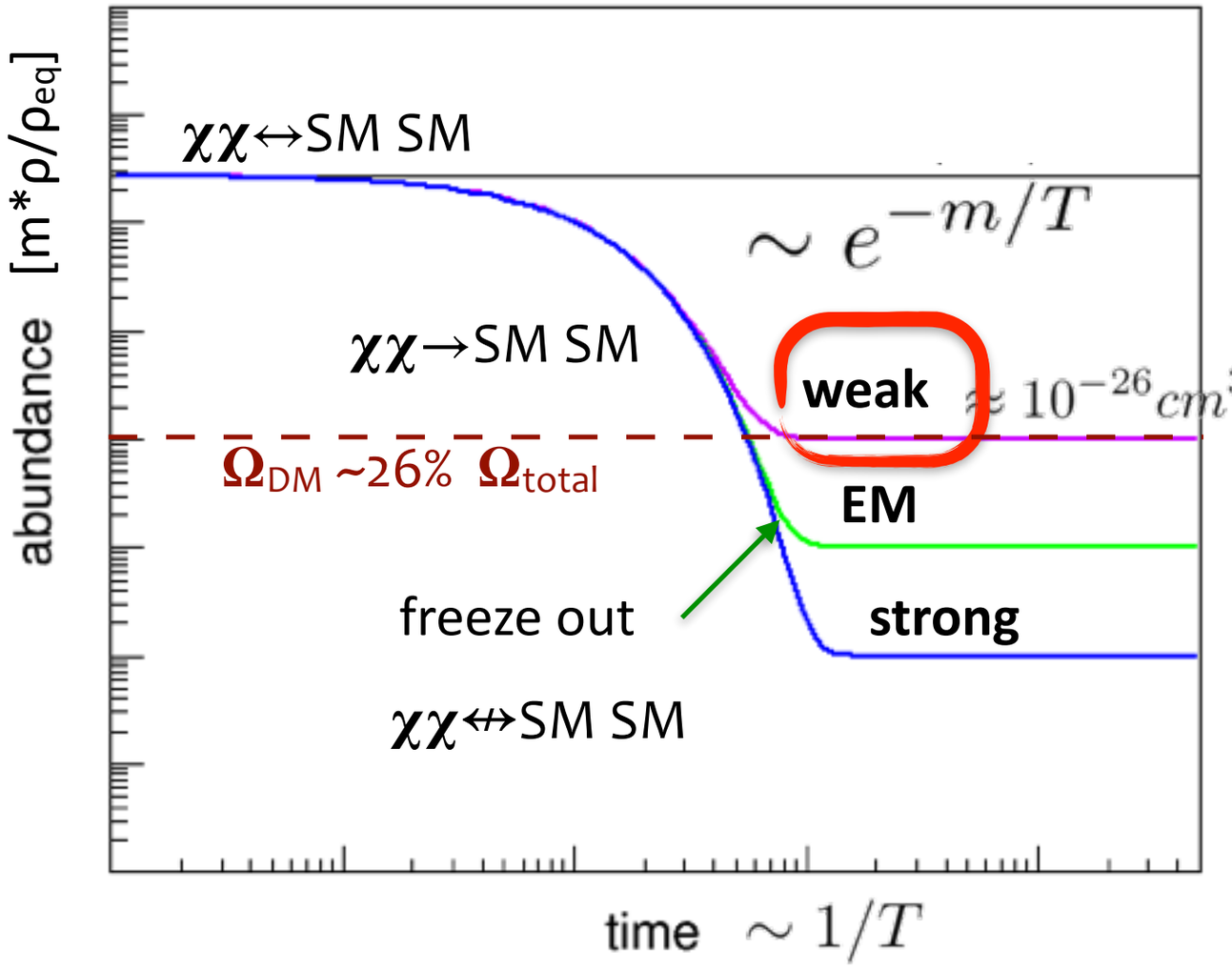

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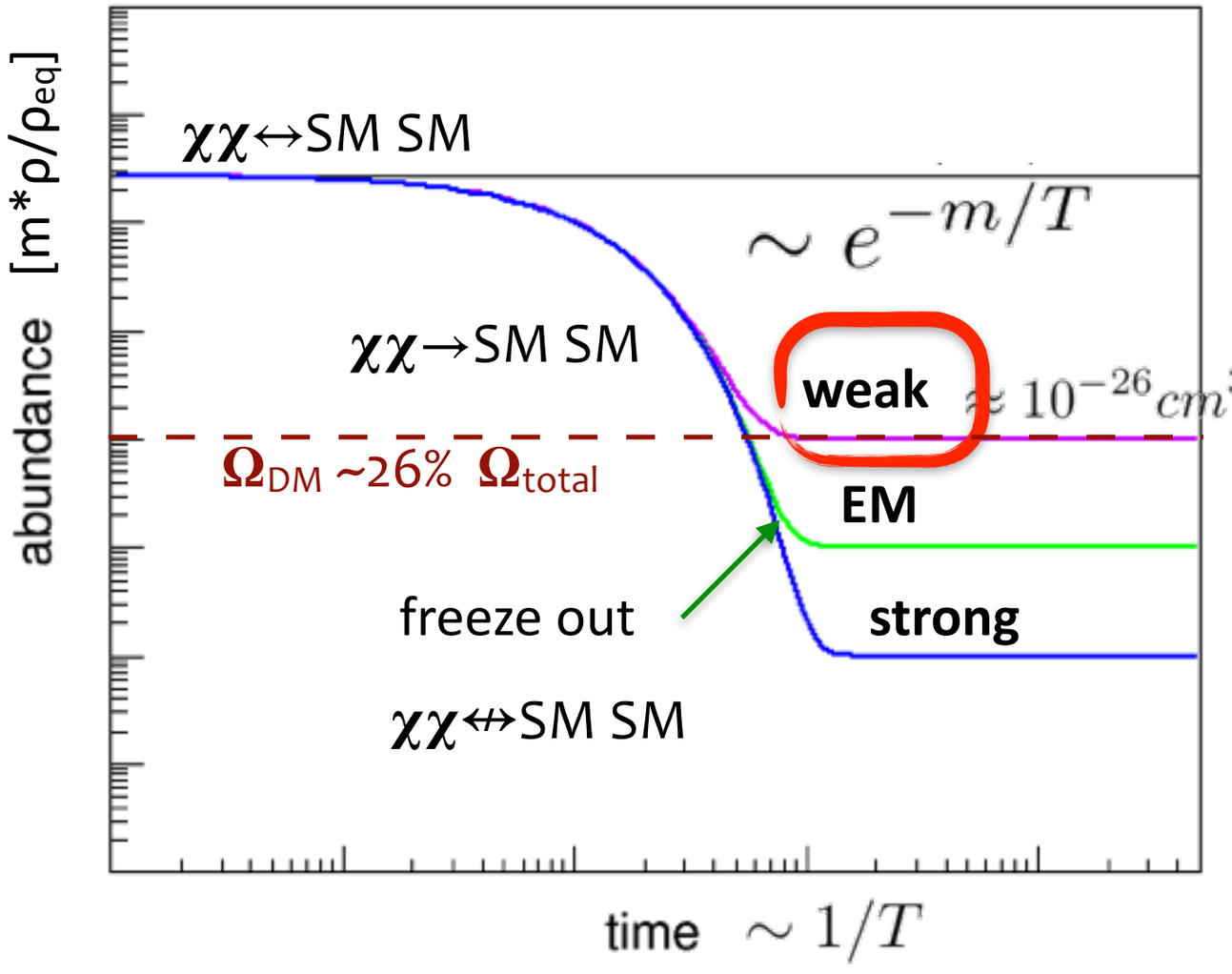

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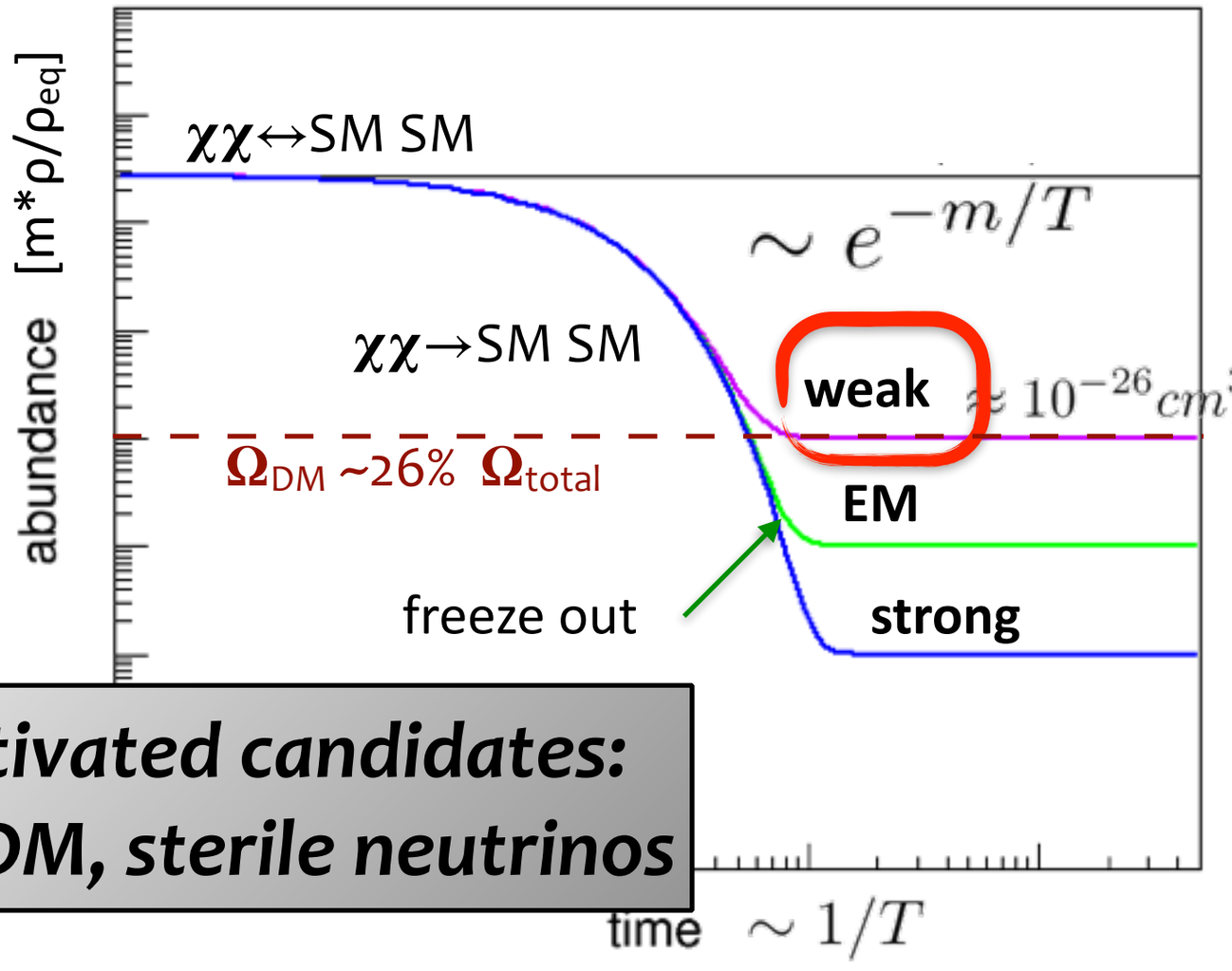

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Weakly Interacting Massive Particles

Other well motivated candidates: axions, asym. DM, sterile neutrinos

G. Steigman, et al., Phys.Rev. D86 (2012) 023506

Detecting WIMP Dark Matter

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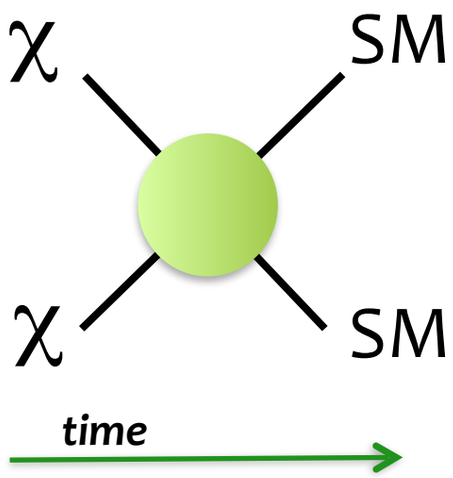
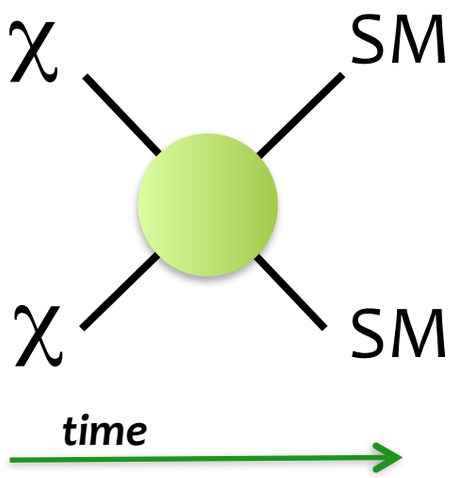


Indirect Detection

Detecting WIMP Dark Matter



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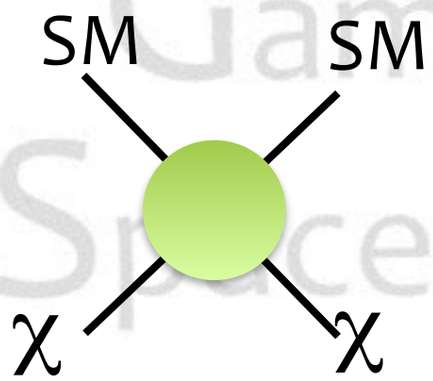

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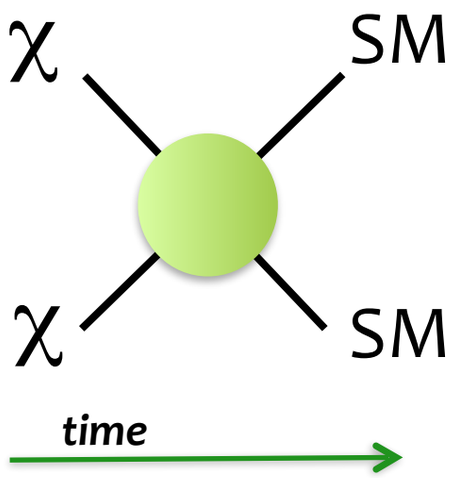

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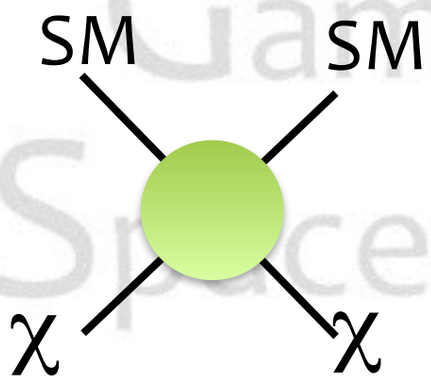
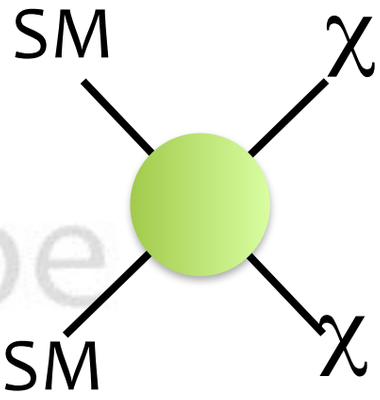


Collider



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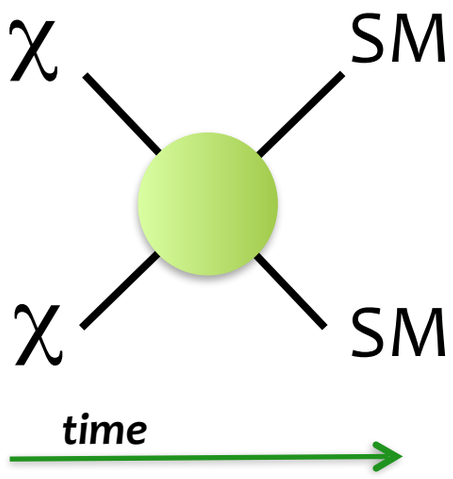
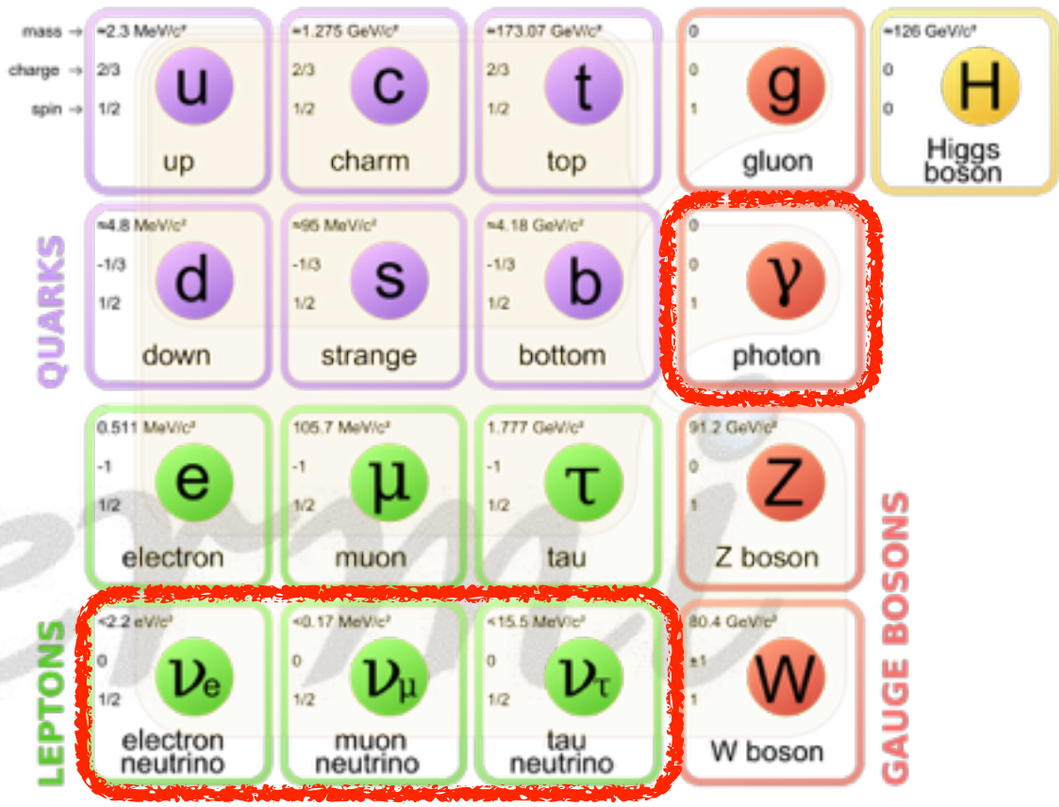


Indirect Detection

information about mass, point back to source

SM:



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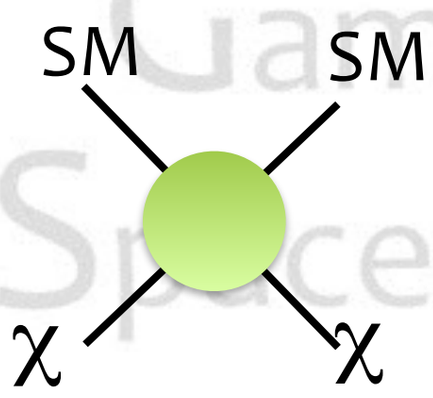

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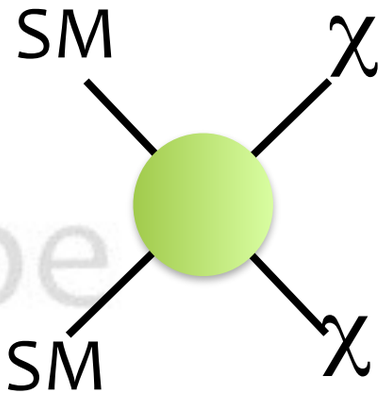

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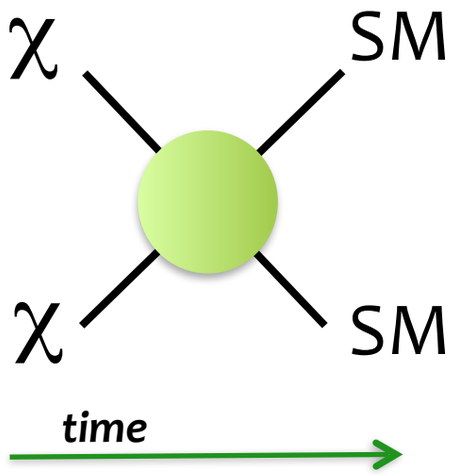

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eventually can get to photons

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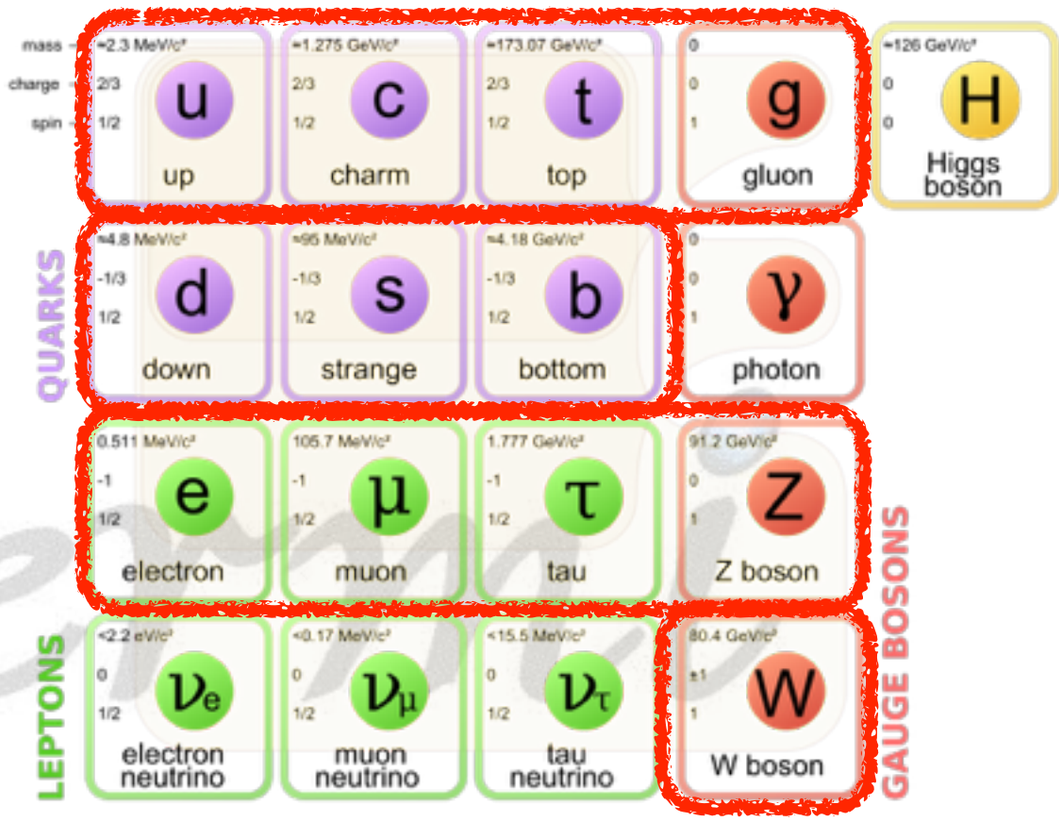

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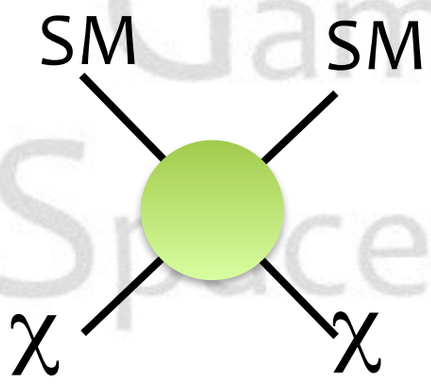

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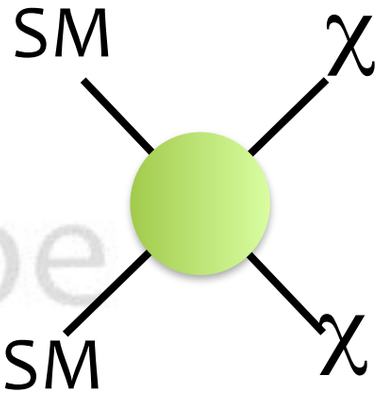

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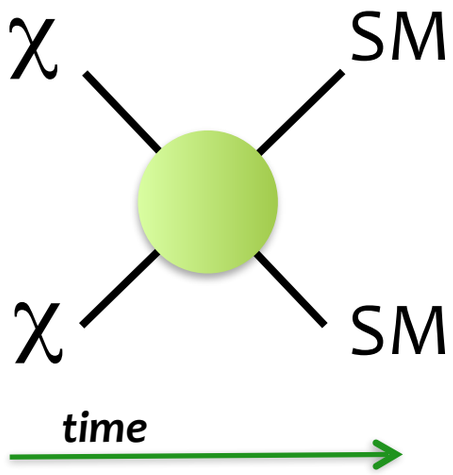

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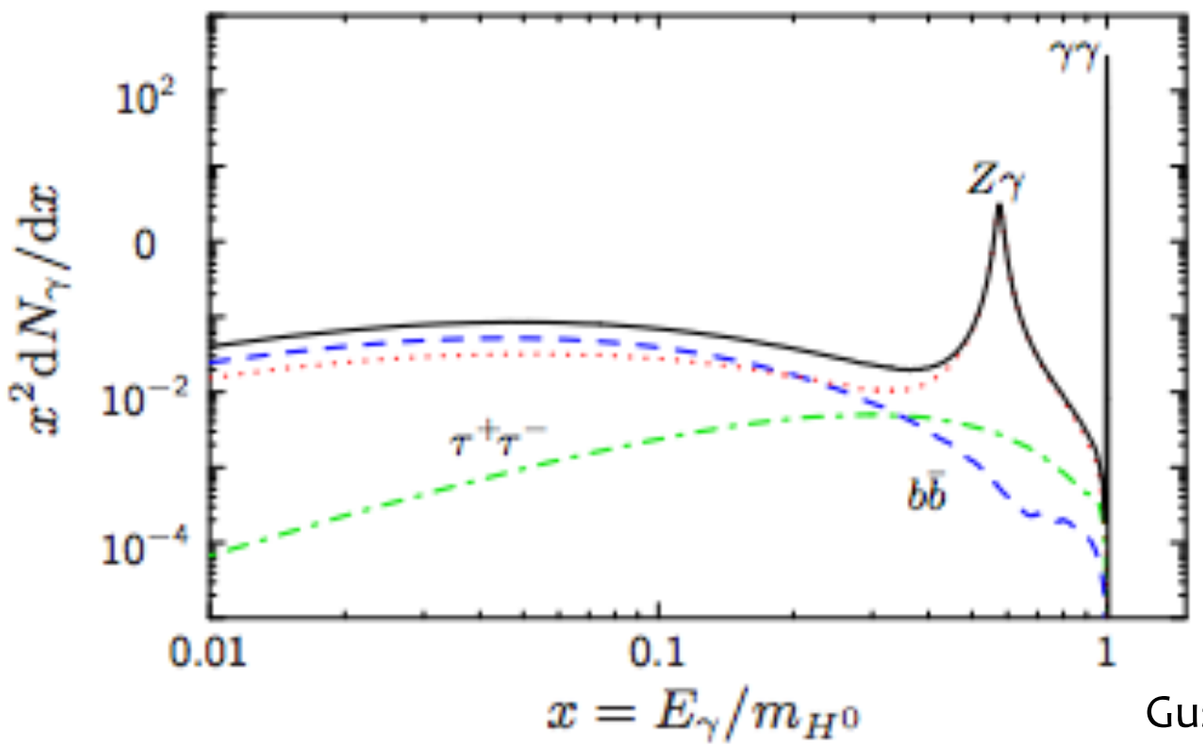

Gustafsson et al.
PRL 99.041301

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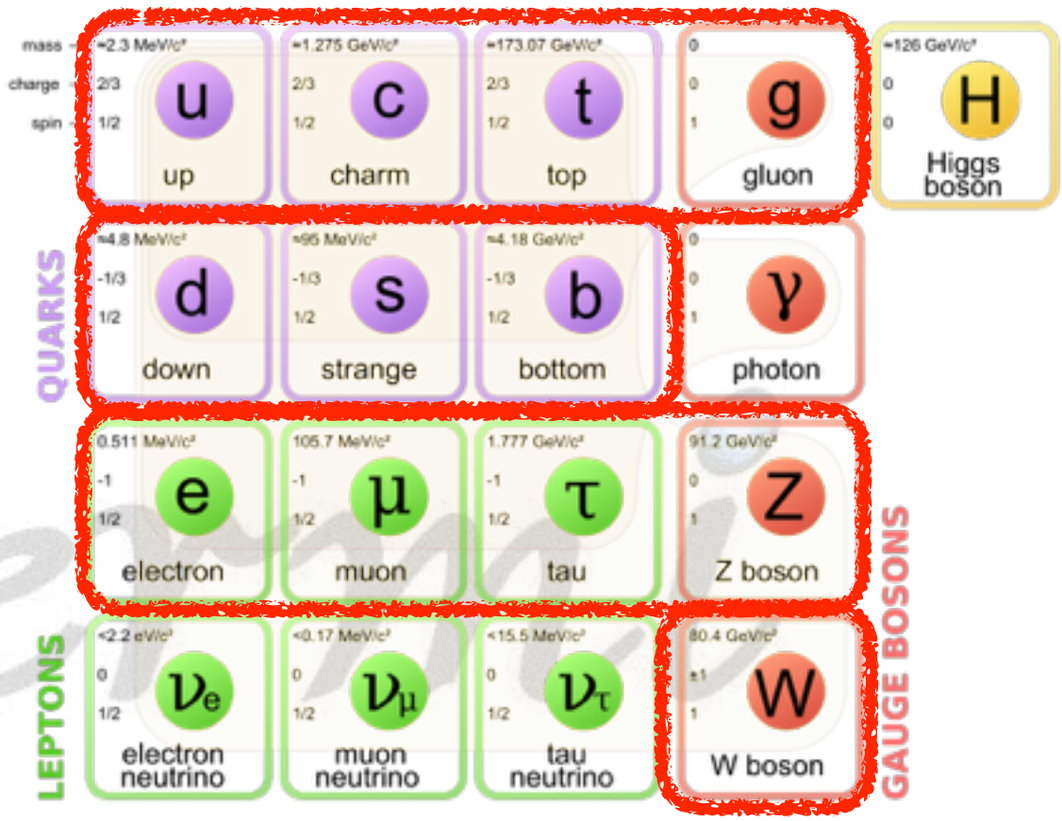

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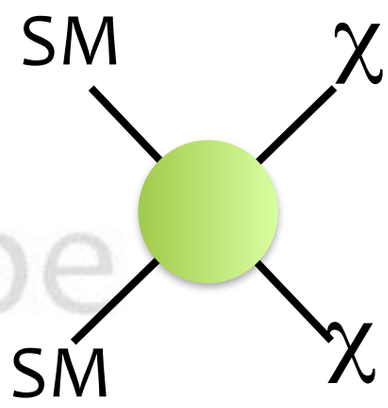
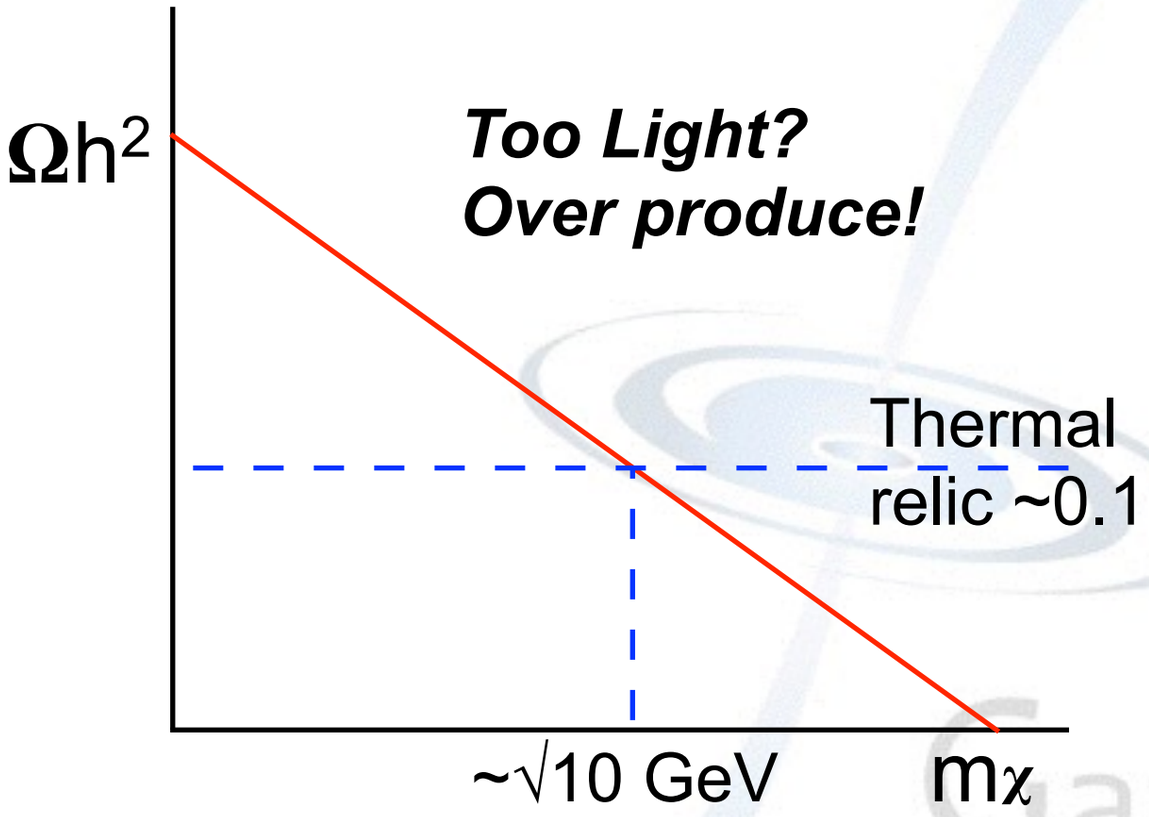


MeV Dark Matter: WIMPs

- **Why MeV (WIMP-ish) Dark Matter? Circa 1970**
  - **Lee-Weinberg: Cosmological lower bound on heavy neutrino mass (1977)**



Two Scenarios:

1. $G_F^2 m\chi^2 \Longrightarrow G'^2_F m\chi^2$

   Non-SM interaction
   (not strictly Weakly Interacting)

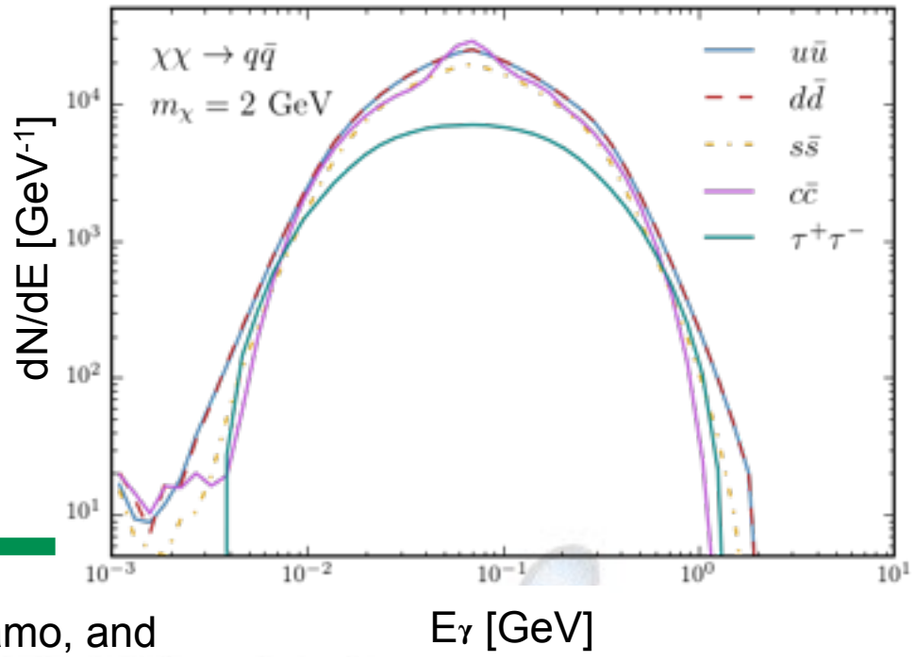
2. Or not strictly a thermal relic
   (bound by BBN ~1 MeV)

$$\Omega h^2 \propto \langle\sigma v\rangle = G_F^2 m\chi^2 > 10^{-9}\ \mathrm{GeV}^{-2}$$

MeV Dark Matter: Slightly not WIMPs

Model Name	DM Particle Mass [MeV]	Final State BR (%)	Notes
A1	2,000	τ, μ, e, c, u, d, s	Univ. Fermions
A2	2,000	τ, μ, e	Univ. Leptons
A3	2,000	τ (67%), c (33%)	p-wave supp. fermions
A4	2,000	τ	p-wave supp. leptons
B1	200	μ, e, u, d, s	Univ. Fermions
B2	200	μ, e	Univ. Leptons
B3	200	μ (55%), s (45%)	p-wave supp. fermions
B4	200	μ	p-wave supp. leptons
C	100	e	(any, no γ's)
D	20	e	(any, no γ's)
E	1	e (80%), γ (20%)	
F	0.2	γ	

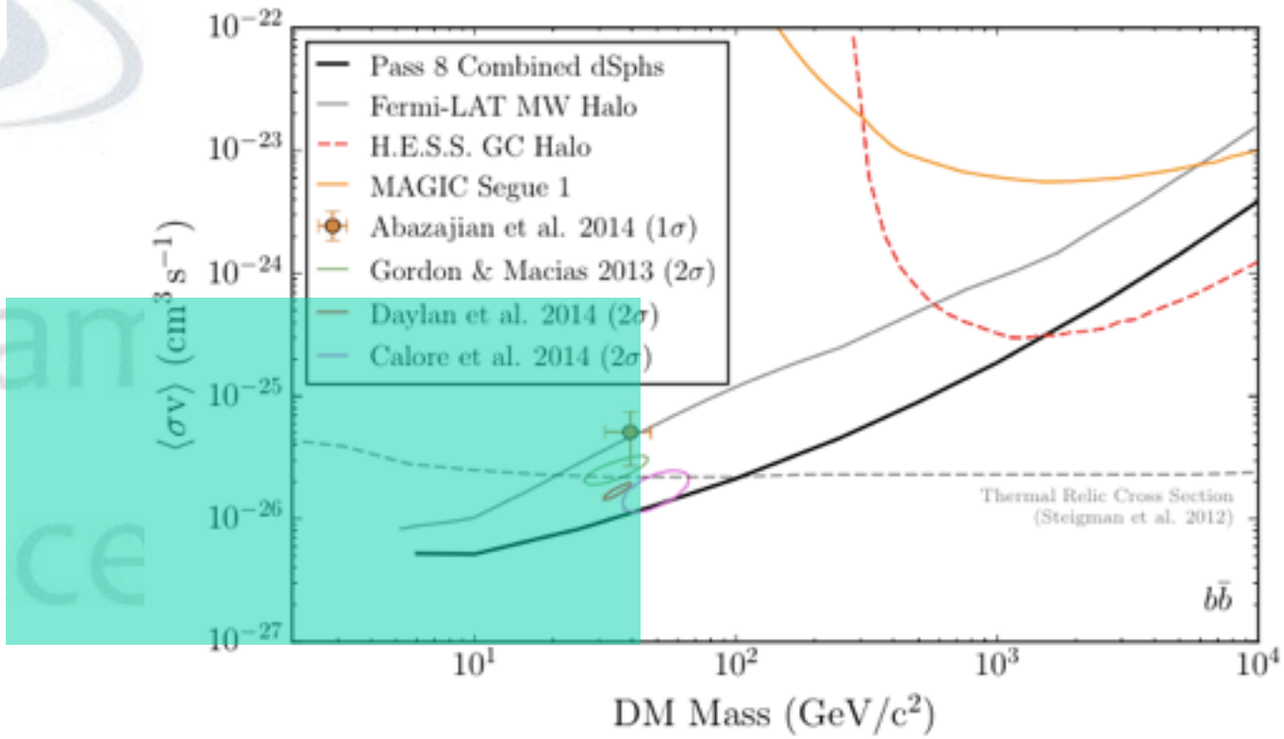
Scan new MeV DM parameter space to develop a gamma-ray spectrum



RC, E. Carlson, F. D'Eramo, and S. Profumo: in preparation

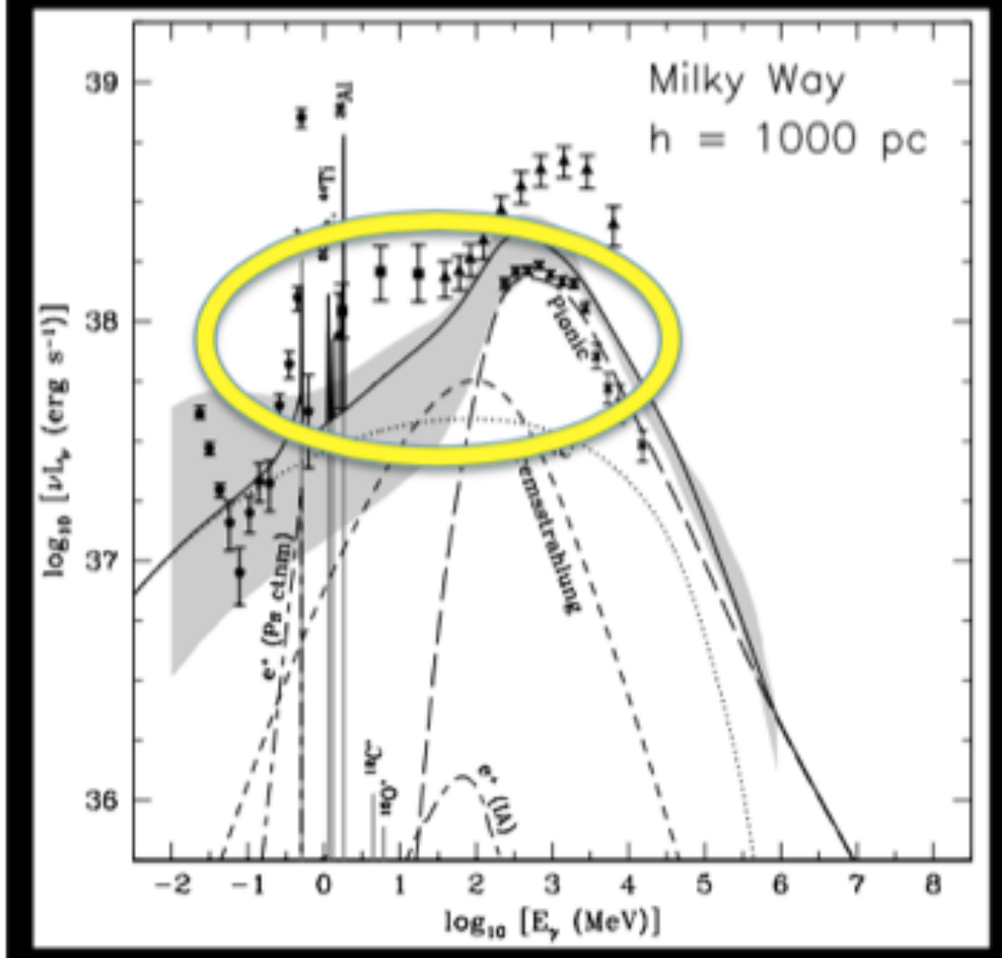
Complement current parameter space…

gamma-rays ~order(-1) DM mass

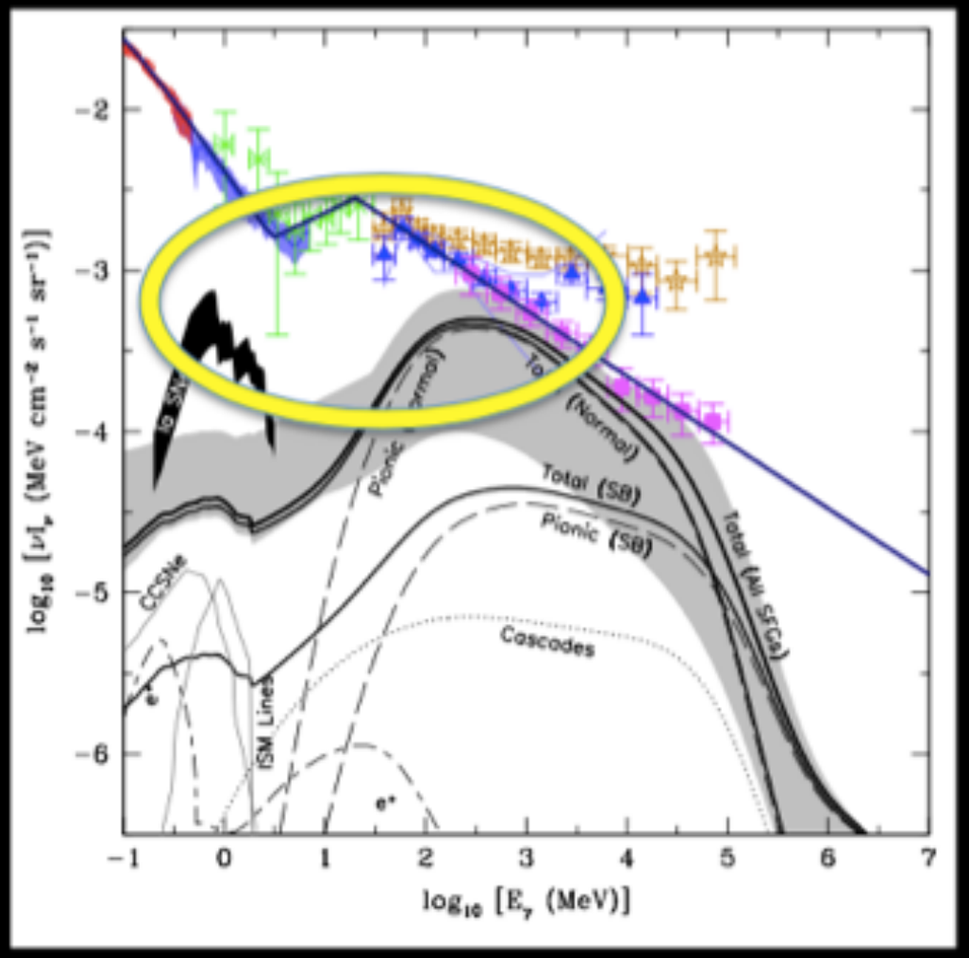


MeV Messes are Holding Back Progress

MeV Excess: Galactic



MeV Excess: Cosmic



Lacki, Horiuchi, Beacom 2014

see also Strong, Moskalenko, Reimer 2004 (x2)

Also: 511 keV excess unsolved, Type Ia supernovae not understood, MeV sky never properly studied

New MeV missions are essential and urgent

John Beacom, The Ohio State University — Dark Matter and Gamma Rays, Austria, December 2015 — 29

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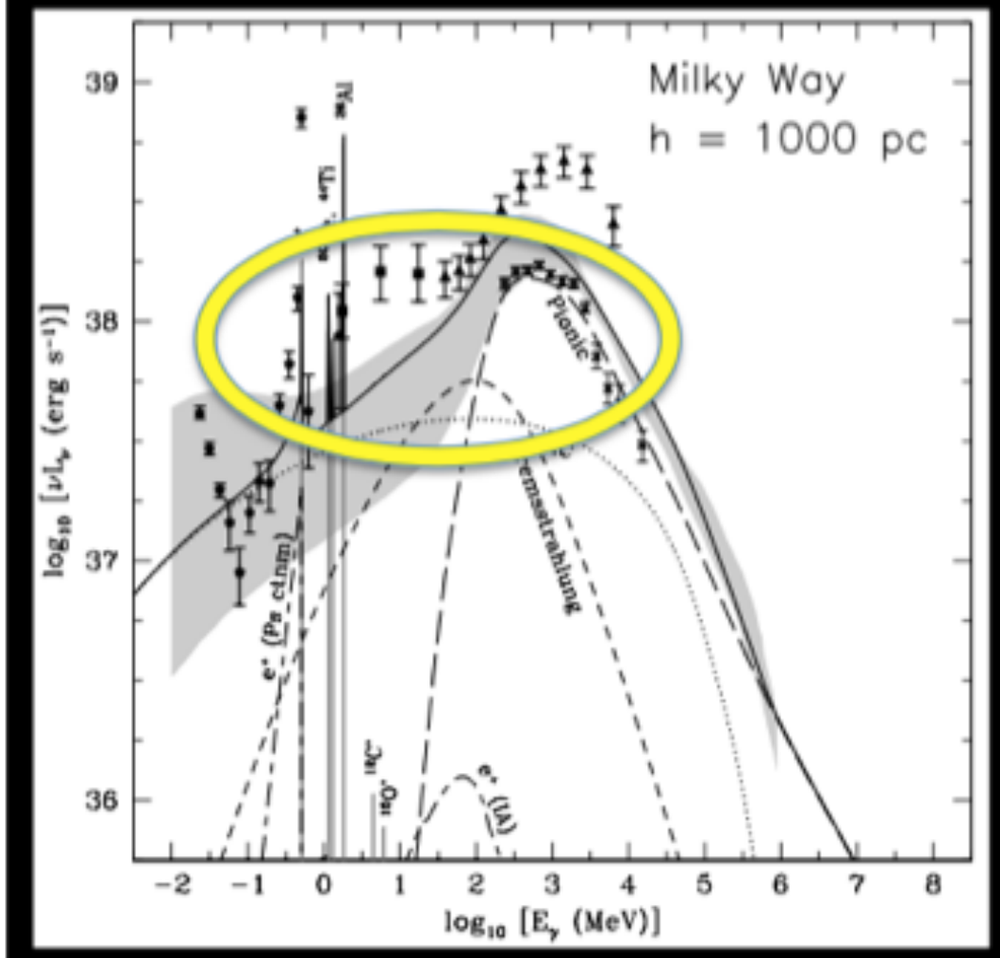
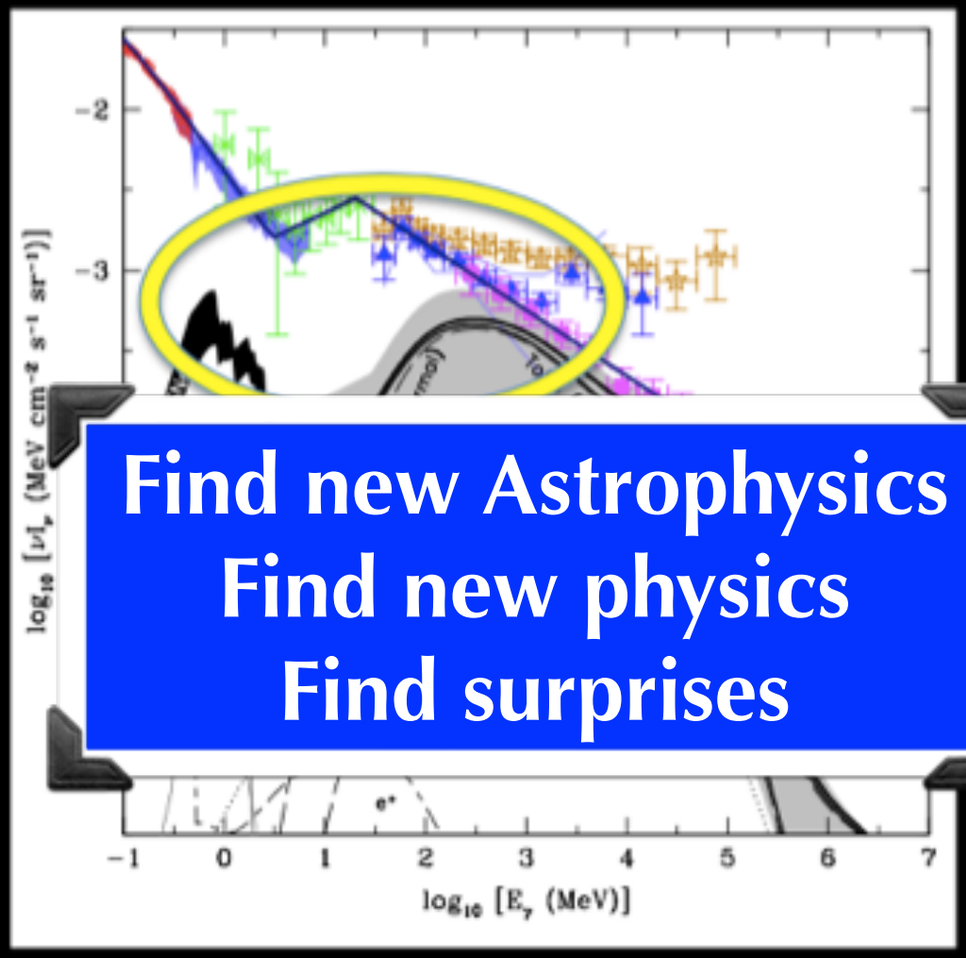


MeV Excess: Cosmic



Lacki, Horiuchi, Beacom 2014

See also Strong, Moskalenko, Reimer 2004 (x2)

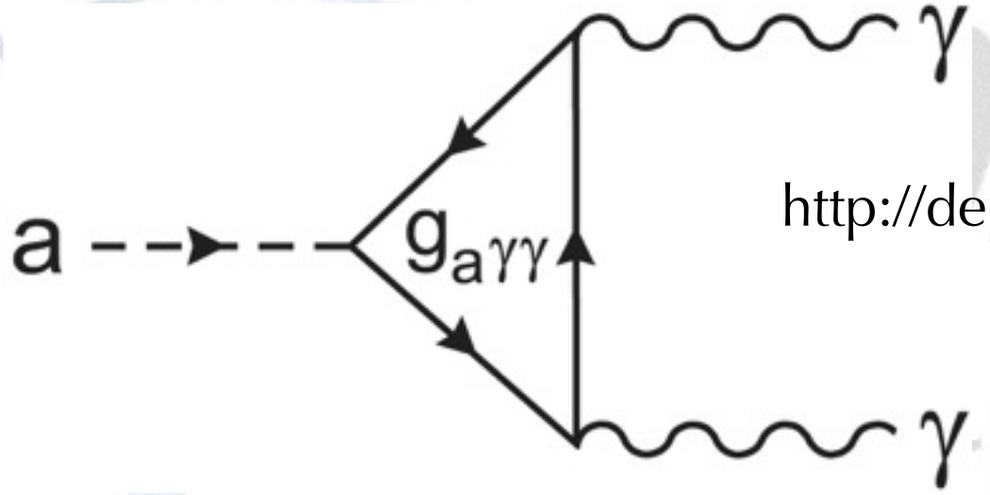
Find new Astrophysics
Find new physics
Find surprises

Also: 511 keV excess unsolved, Type Ia supernovae not understood, MeV sky never properly studied

New MeV missions are essential and urgent

Portrait of Another Candidate

- **Axions**
  - **solution to the QCD CP problem**
    - **should happen, we don't observe it**
  - **additional symmetry $U(1)_{PQ}$: (also ~1970s)**
    - **"QCD axion", mass ~10^{-5} to 10^{-3} eV (can be DM candidate)**
  - **couple to photons in external magnetic fields**

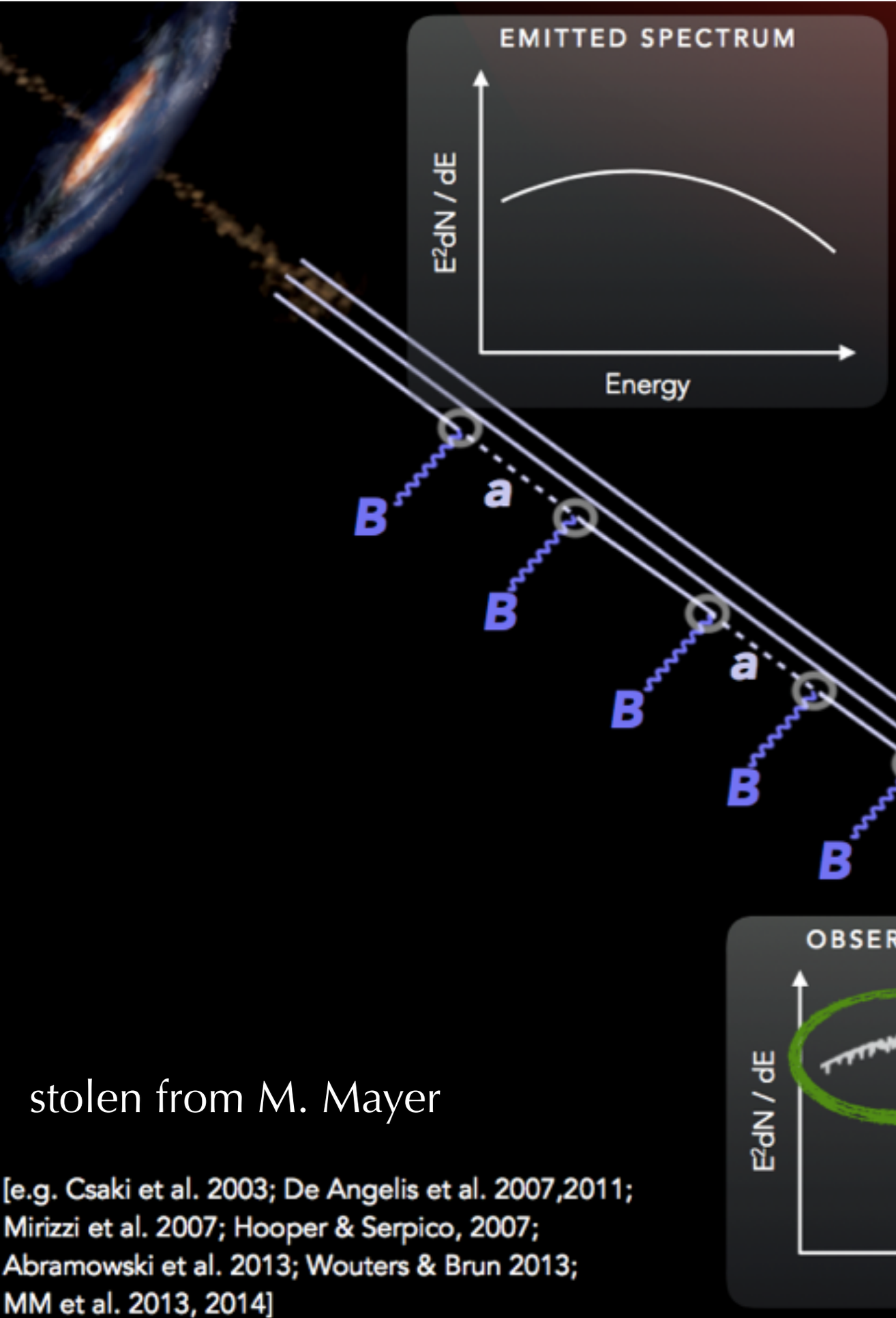


http://depts.washington.edu/admx/index.shtml

- **Axion-Like Particles (ALPs) <— this one**
  - **breaking another $U(1)_x$ symmetry**

arXiv:1603.06978v1

PHOTON-ALP OSCILLATIONS



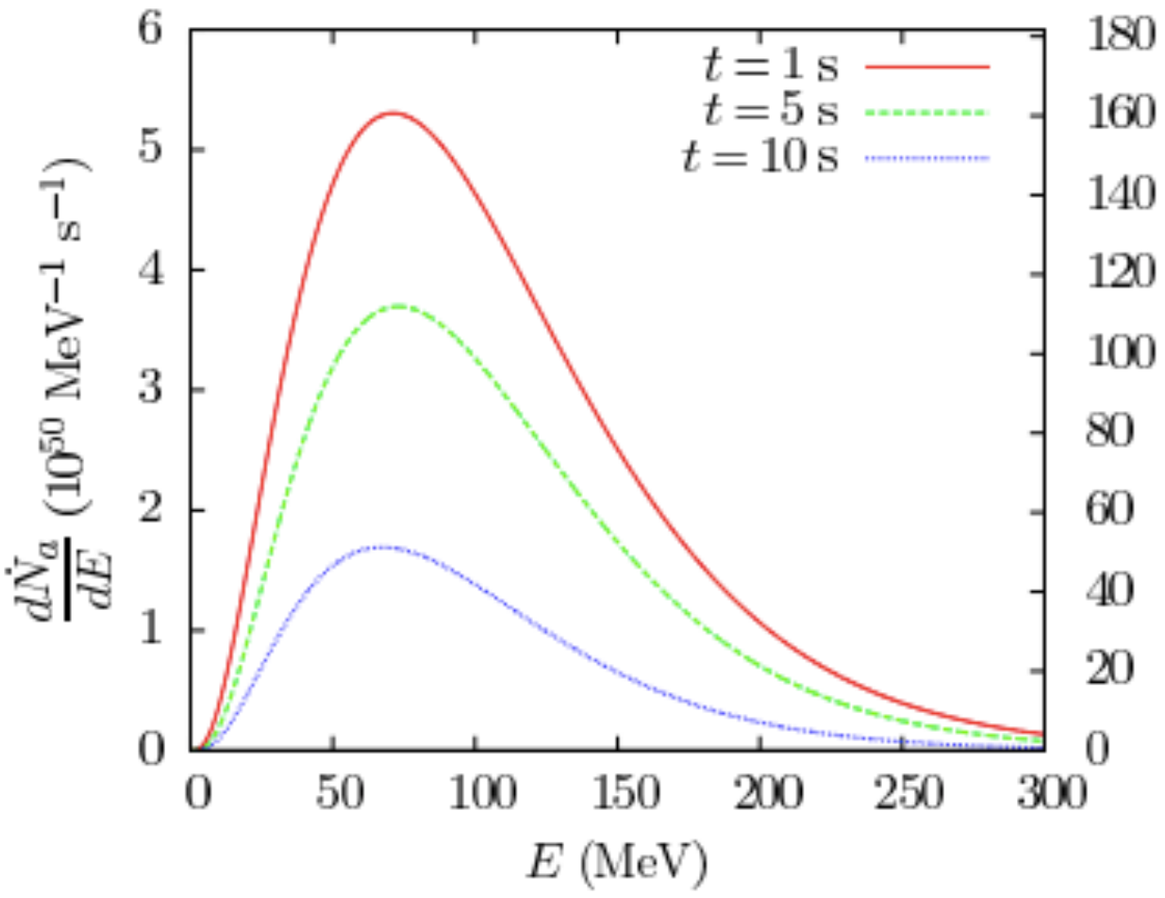
- **Interact with SM via photon-ALP oscillations**
  - **mass/photon coupling ind. parameters**
  - **DM candidate!**
  - **coupling to gamma-rays in astrophysical B fields**
    - **light ALPs $m_a \lesssim \mu eV$**

stolen from M. Mayer

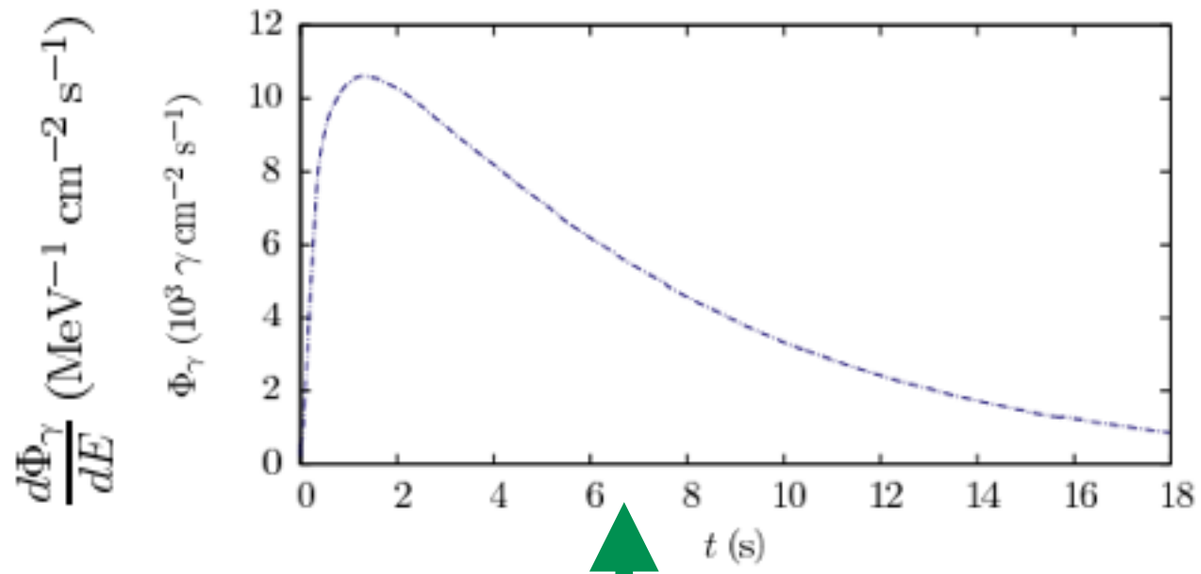
[e.g. Csaki et al. 2003; De Angelis et al. 2007,2011; Mirizzi et al. 2007; Hooper & Serpico, 2007; Abramowski et al. 2013; Wouters & Brun 2013; MM et al. 2013, 2014]

MeV Dark Matter: Axions

- **Axions in neutron stars (hep-ph/0505090)**
  - **emission process for axions with mass up to a few MeV**
  - **production in Gamma Ray Bursts**

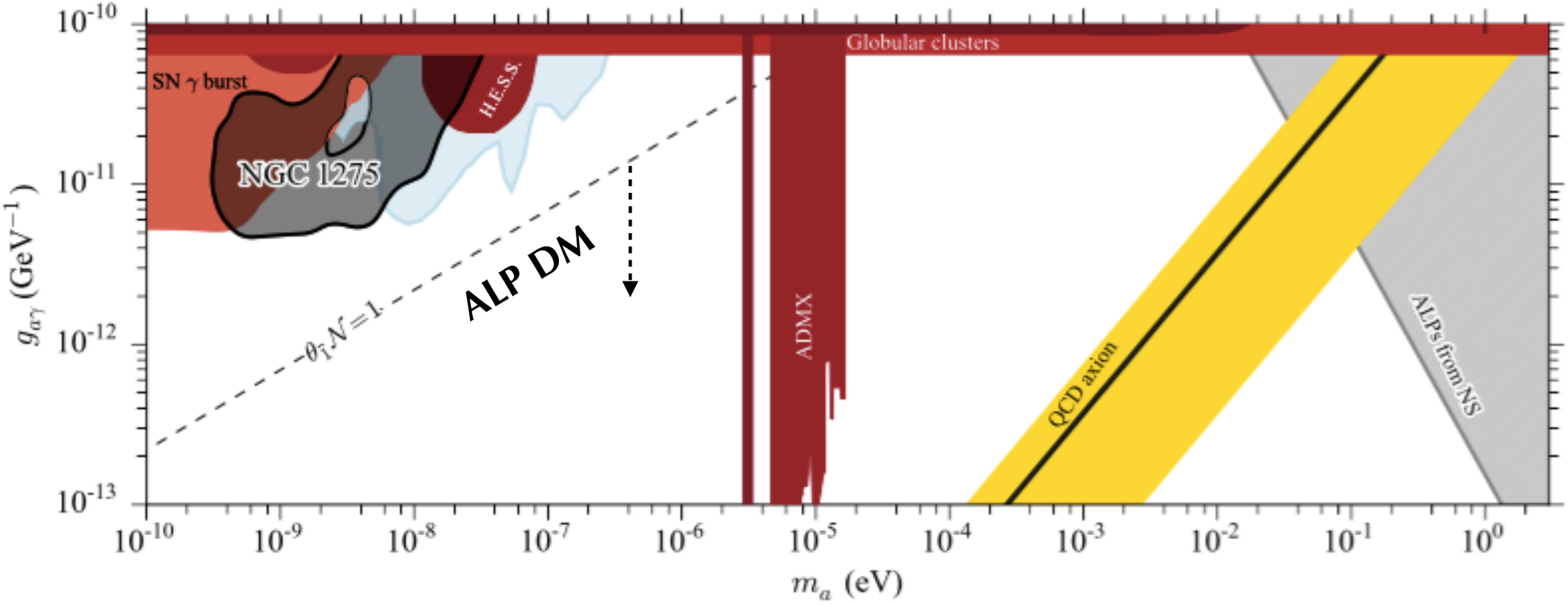


ALP ($m_a \sim 10^{-11}$ eV)
with $g_{a\gamma} = 10^{-10}$ GeV^{-1}
18 M_{sol} progenitor



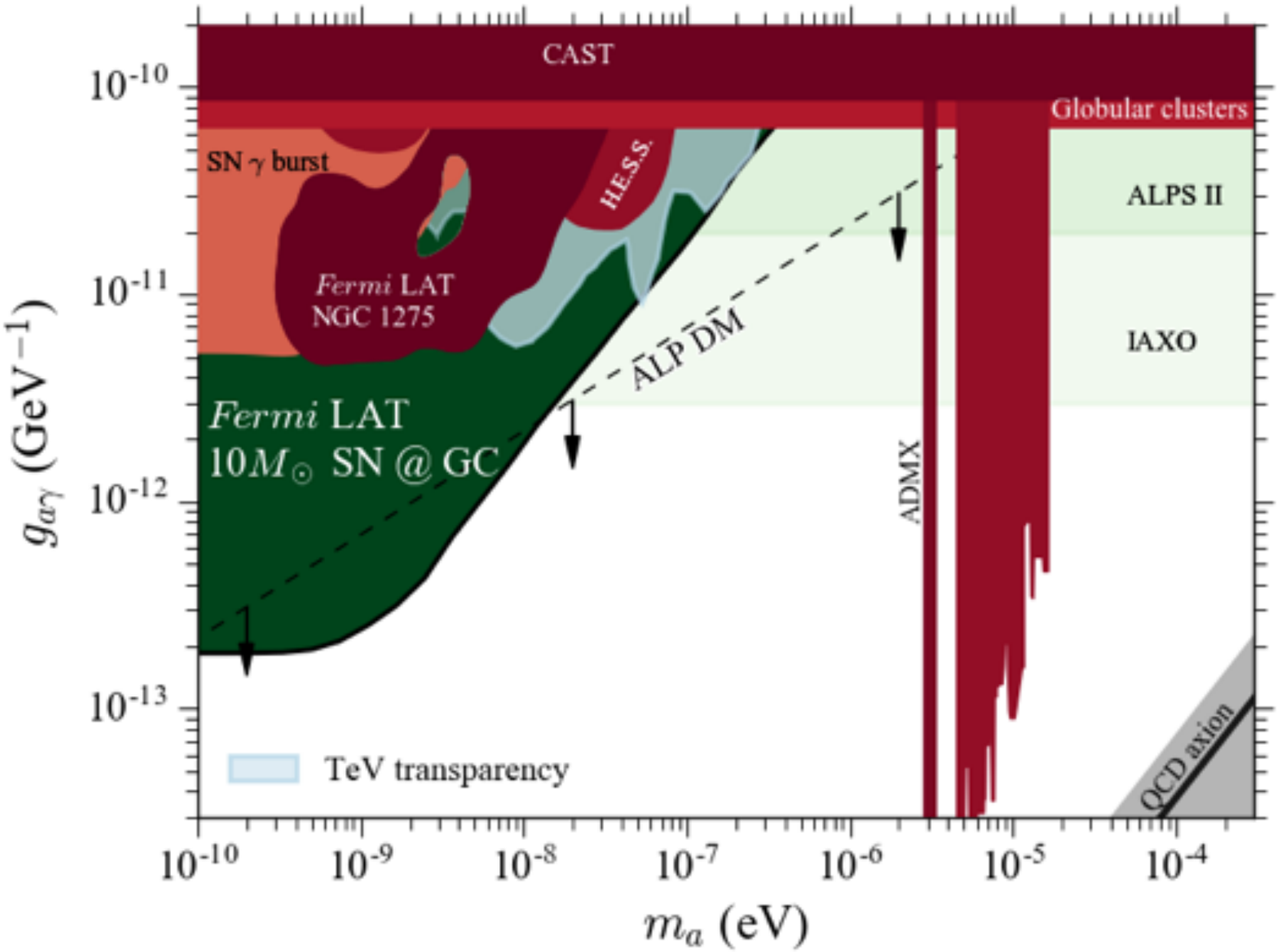
timing of
photons between
(25-100 MeV)
with $g_{a\gamma} = 10^{-10}$ GeV^{-1}
18 M_{sol} progenitor

Current Axion Limits



MeV Dark Matter: Axions

- **Axions produced in supernovae (arXiv:1410.3747)**
  - **core collapse supernova (SN1987A)**



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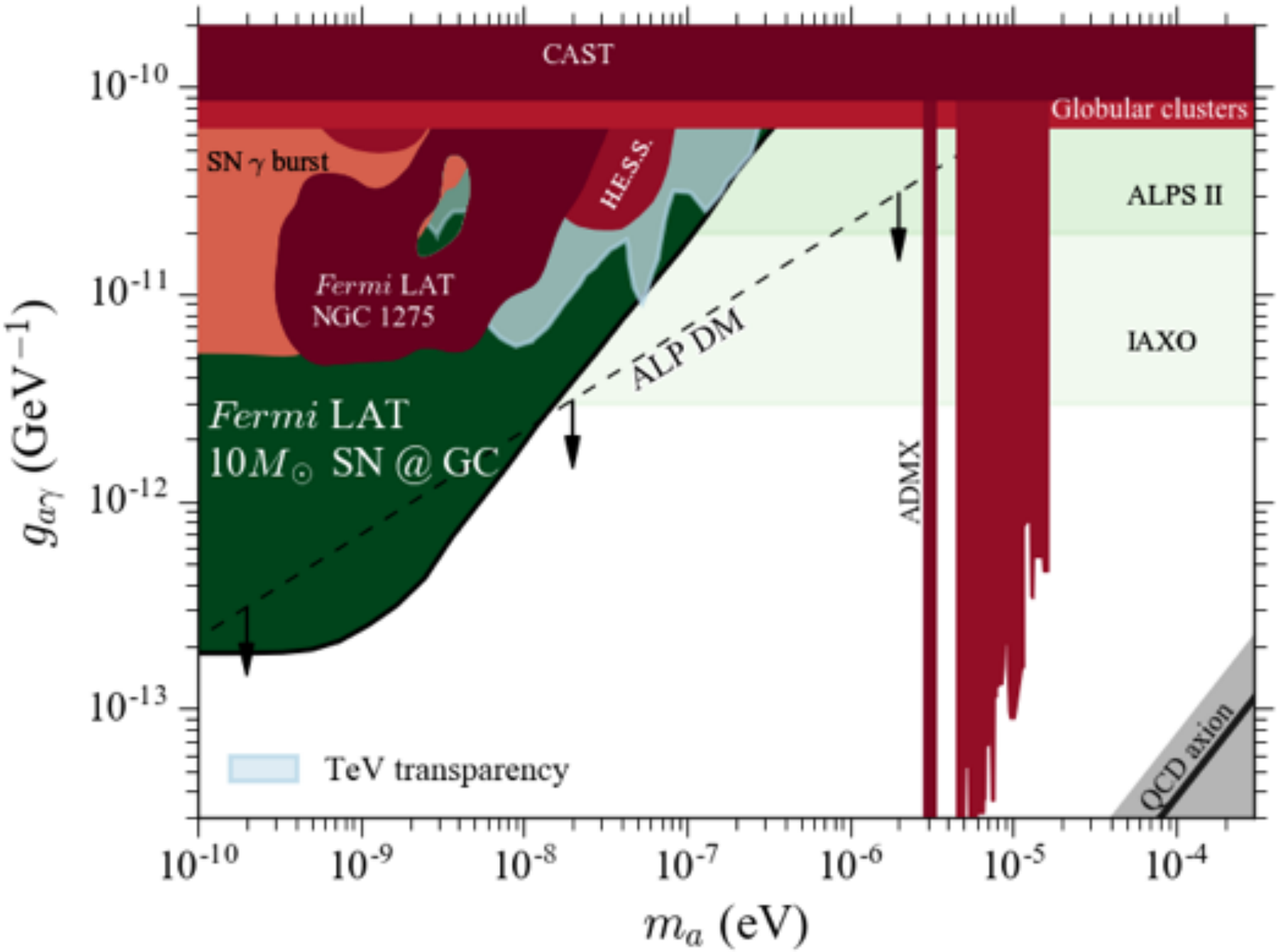

Limited by PSF @<100 MeV

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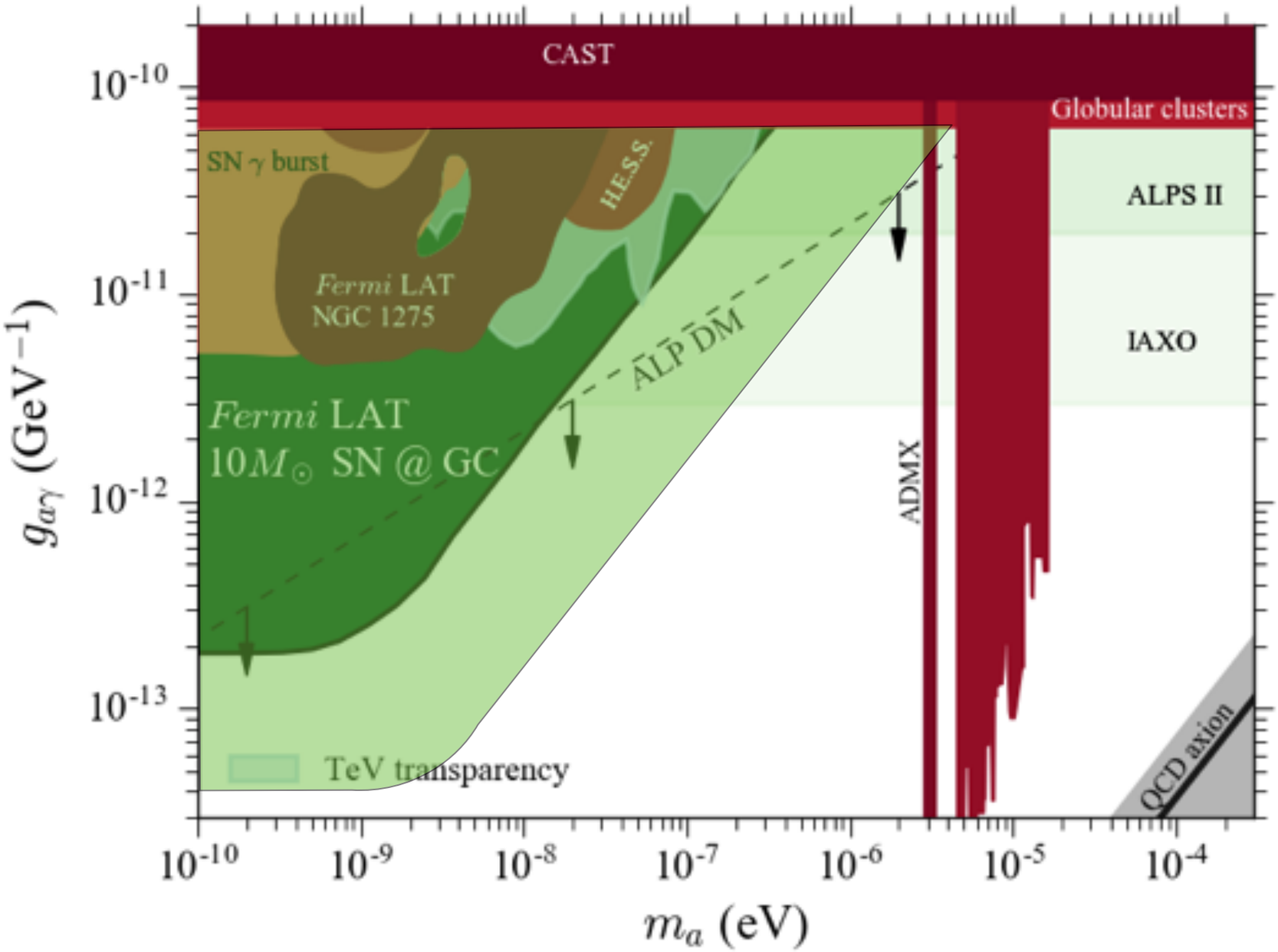


Limited by PSF @<100 MeV

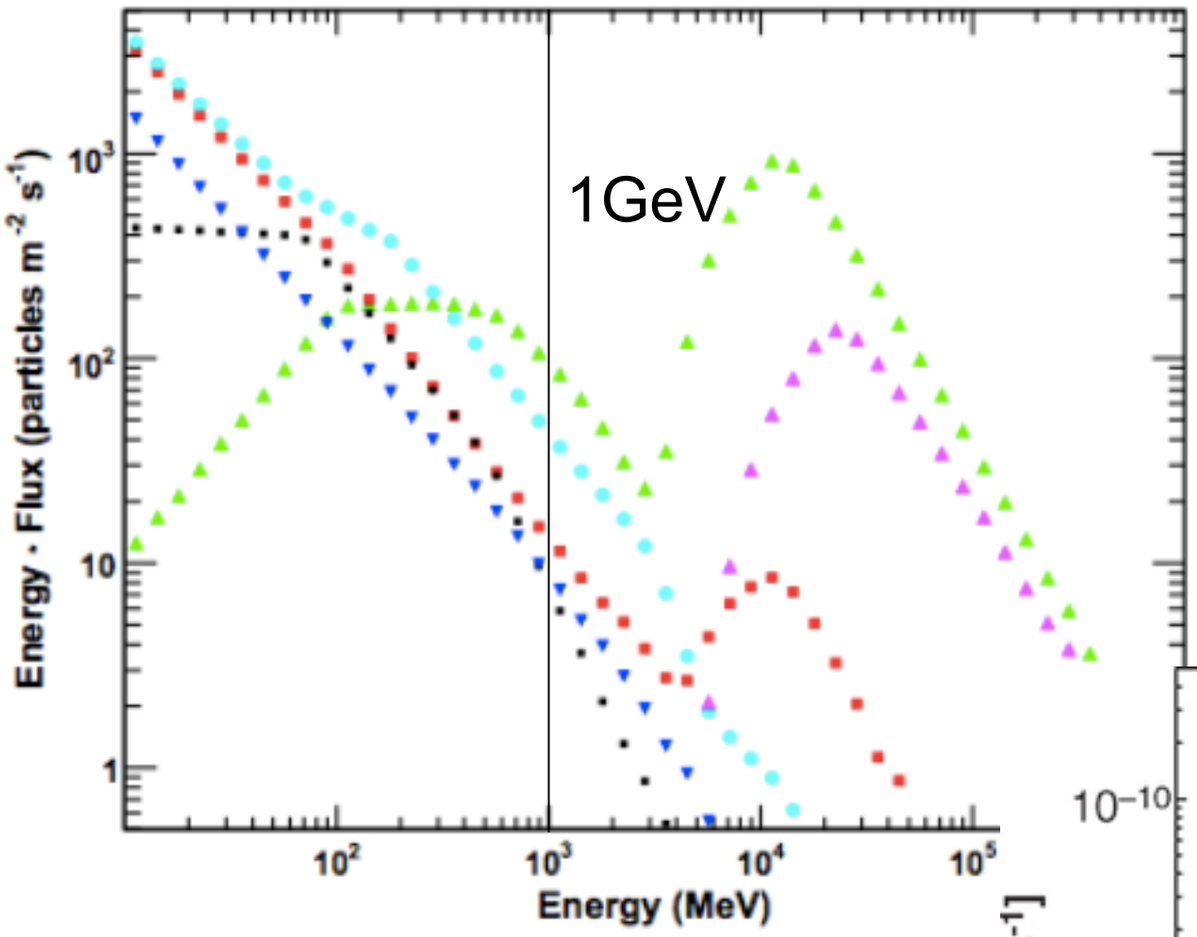
Fin

- **Summary**
  - **We can learn a lot about "W"IMPs**
    - **maybe at least what it isn't**
  - **We can learn a lot about axions**
    - **what it is and what it isn't**
  - **MeV needs to be studied**

Discussion!

What Happens at the MeV scale?

- **Fluxes shown as a function of total kinetic energy of particles**



Backgrounds:
protons (green filled triangles up),
He (purple filled triangles up),
electrons (filled red squares),
positrons (light blue squares),
Earth albedo neutrons (black squares), and
Earth albedo γ-rays (dark blue filled triangles down).

Gamma-Ray production:
below 100 MeV gammas from
π^0 decay drops