KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Beyond the Standard Model

Hitoshi Murayama (Berkeley, Kavli IPMU Tokyo)

Invisibles School, June 17, 2015

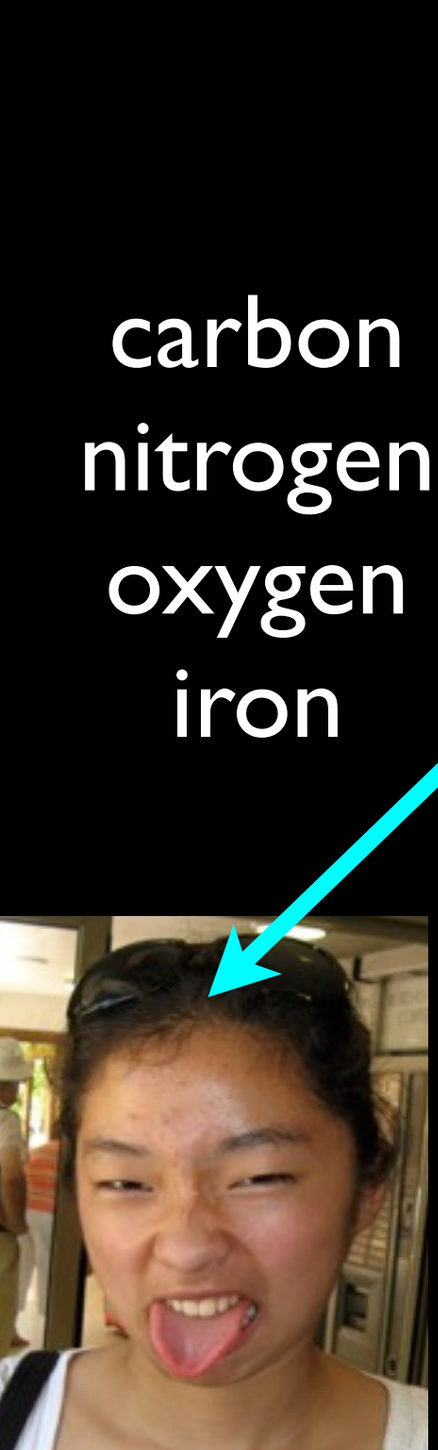
BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

hydrogen
helium

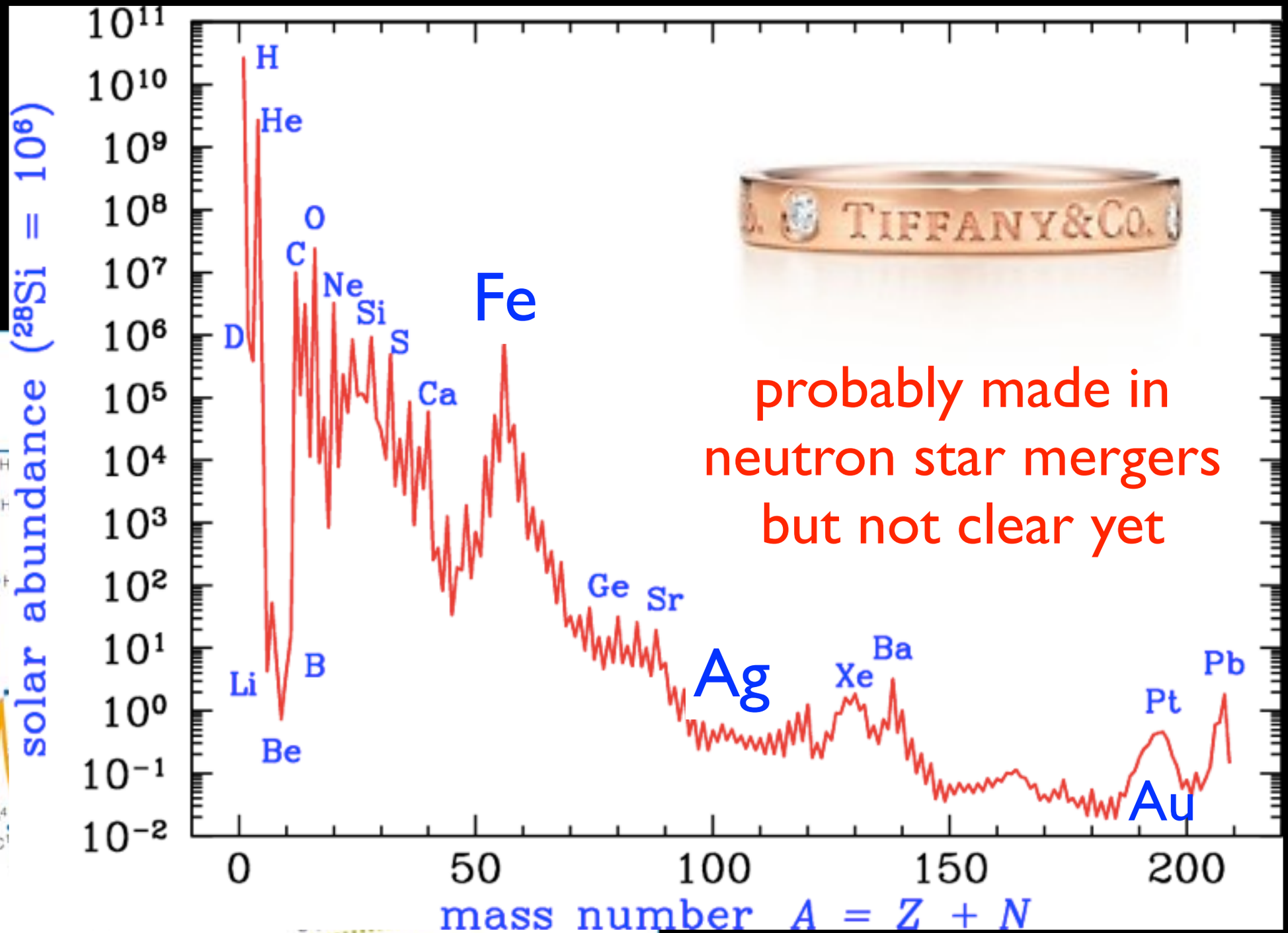
carbon
nitrogen
oxygen
iron

neutrinos
160,000 light years

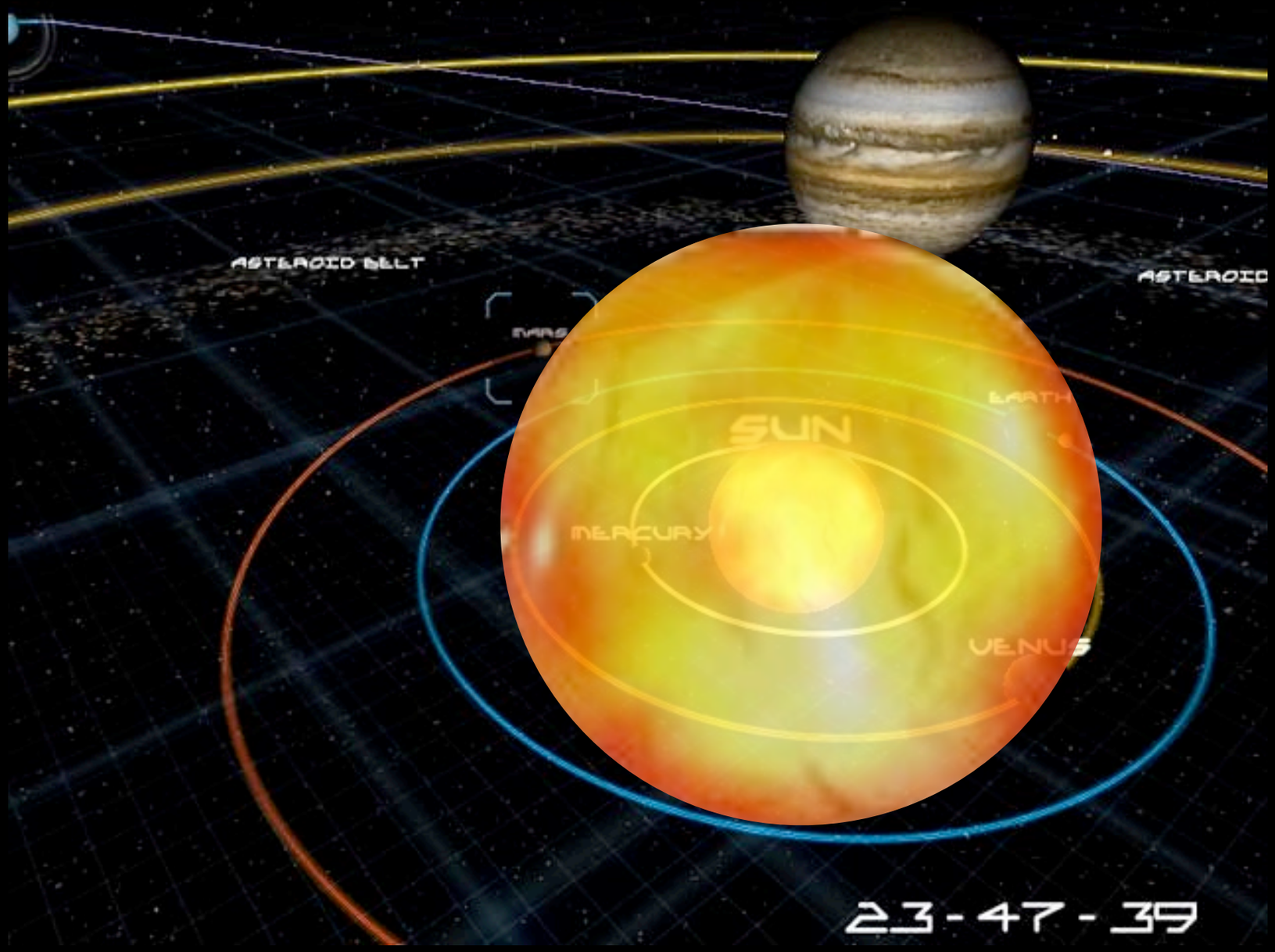


We are star dust

but only up to iron



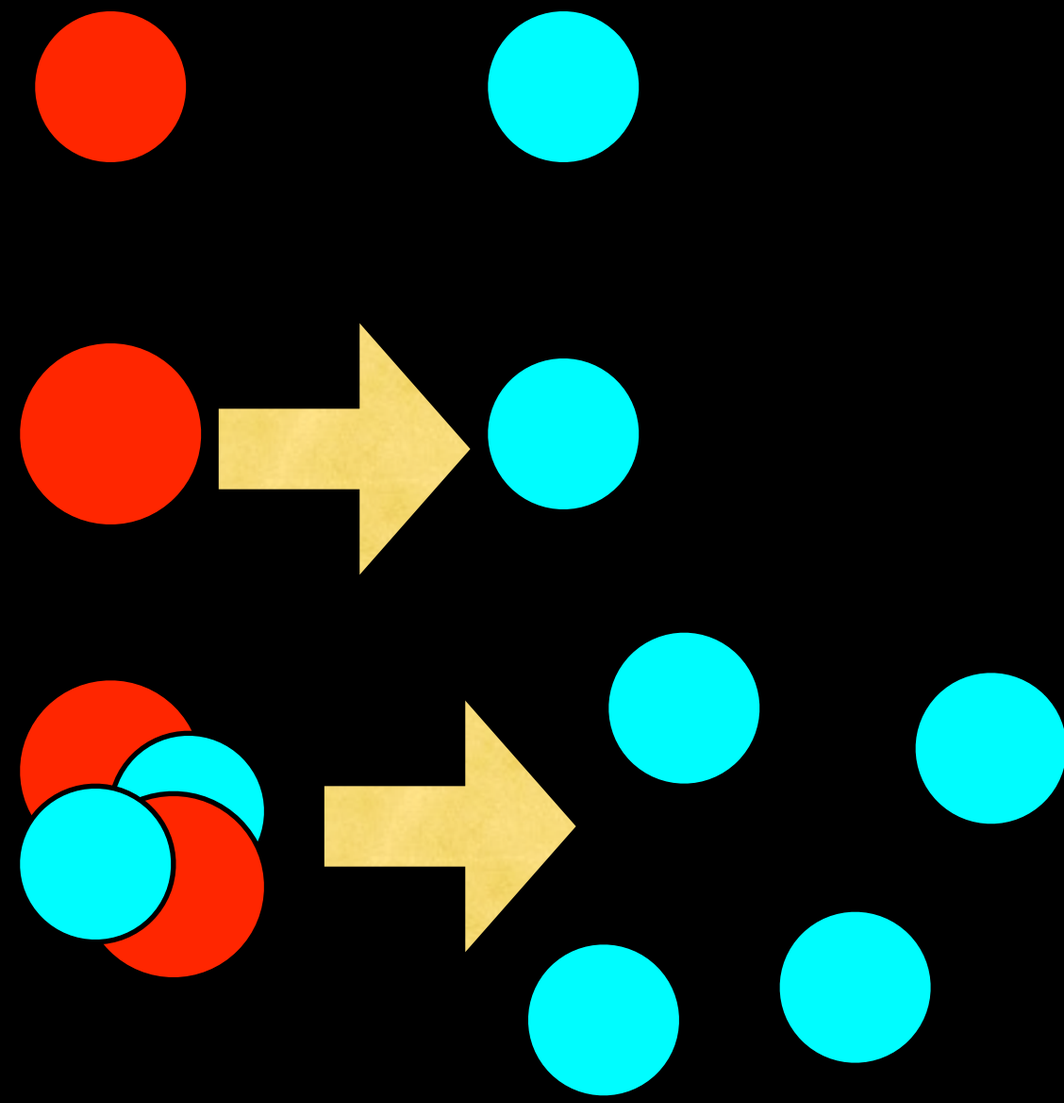
fate of the Sun in 4.5 billion years




STAR
WARS

anthropic?

- protons and neutrons weigh very similar
- if v is bigger by 20, neutron is 20% heavier than proton, all neutrons decay into protons
- no nuclei possible!
- This is why $v \ll M_{Pl}$? (Barr et al)

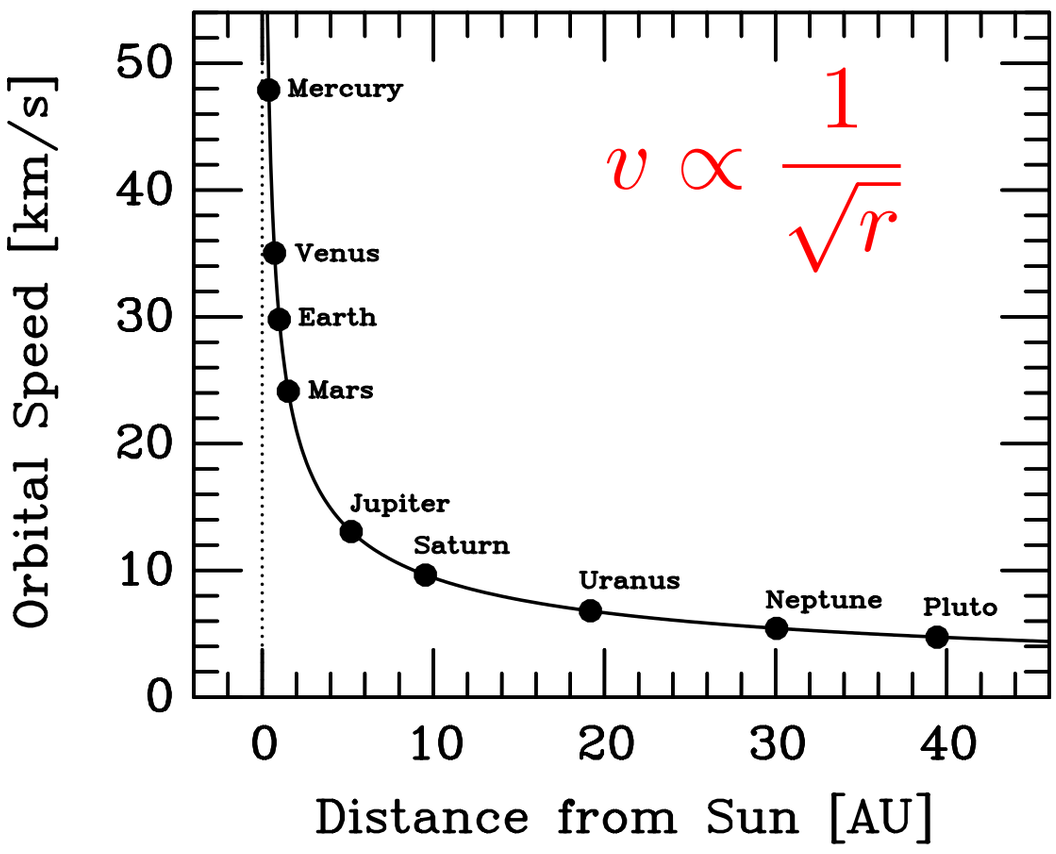


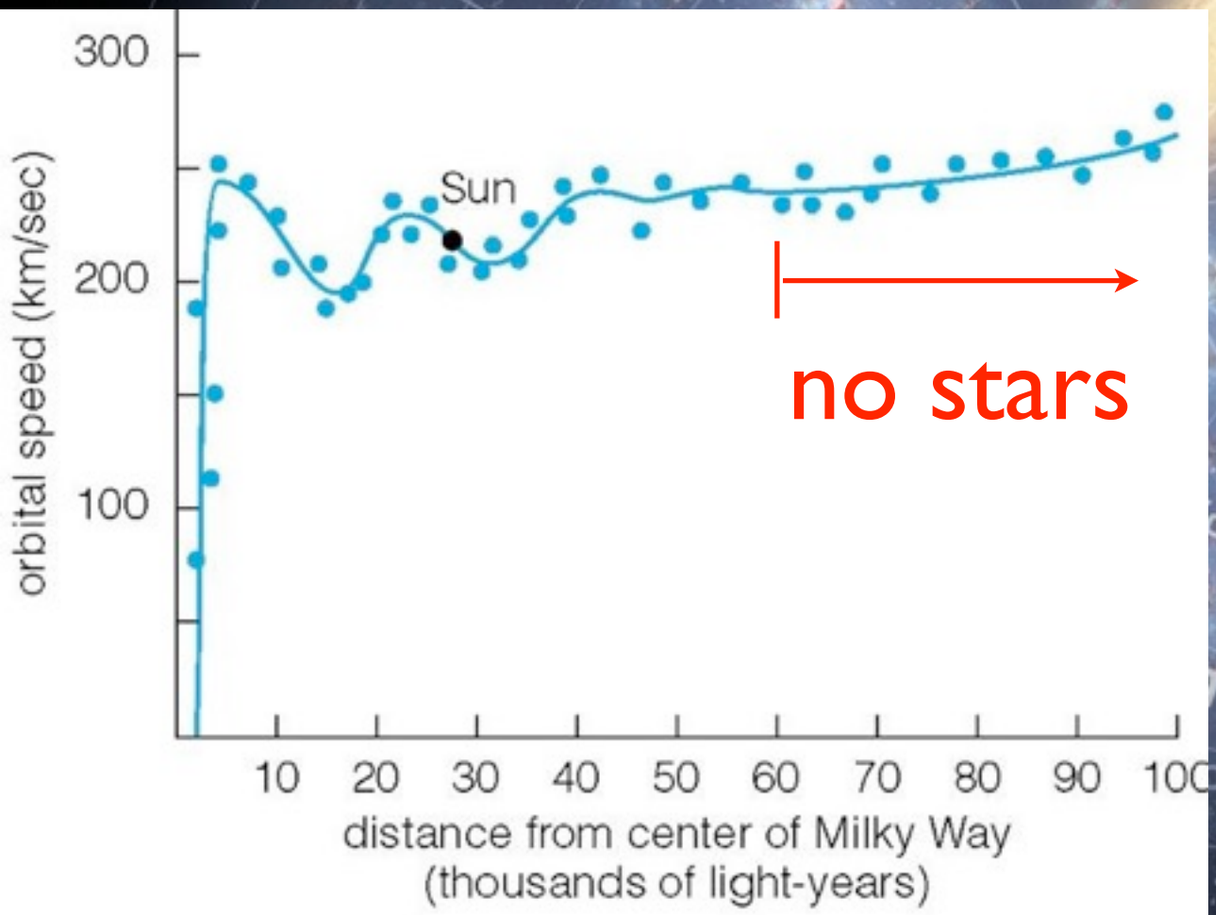
OK, atoms came from stars.

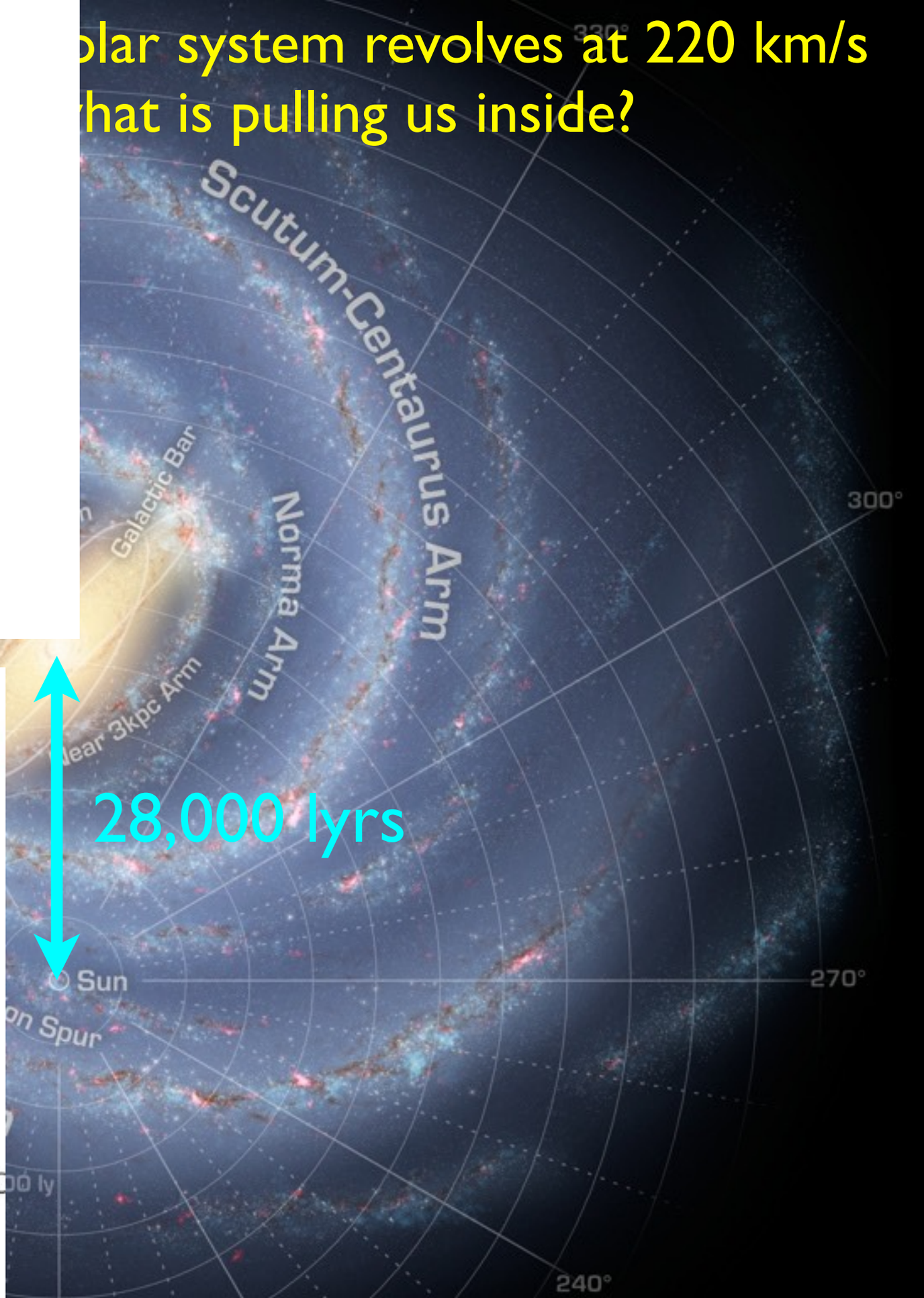
What about stars themselves?

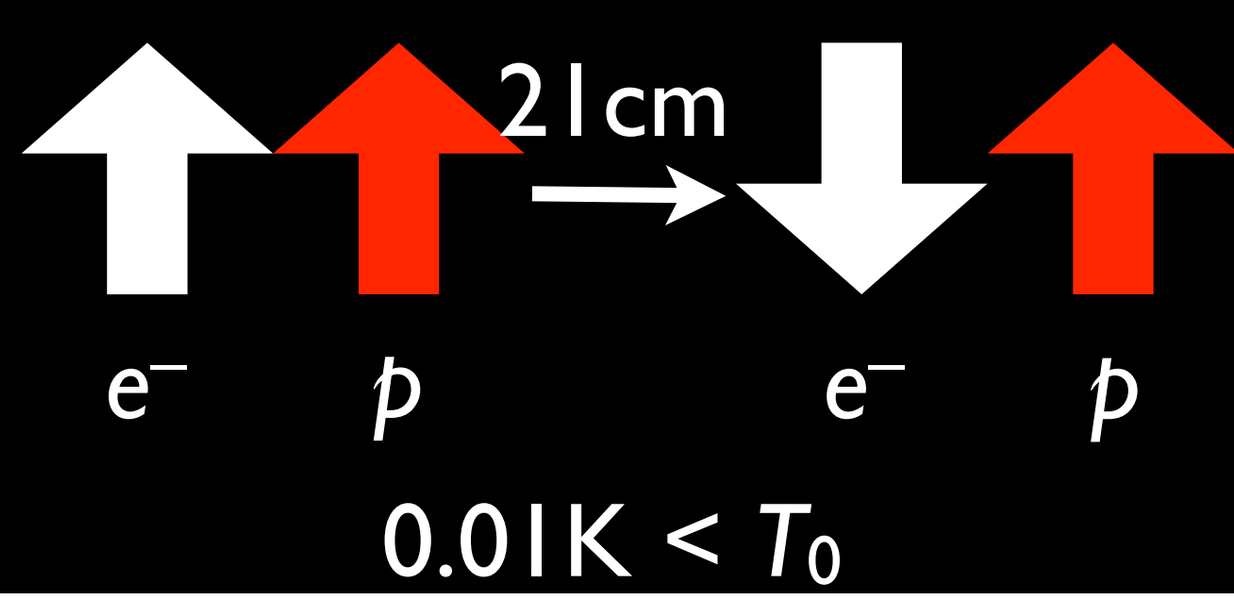
Dark Matter

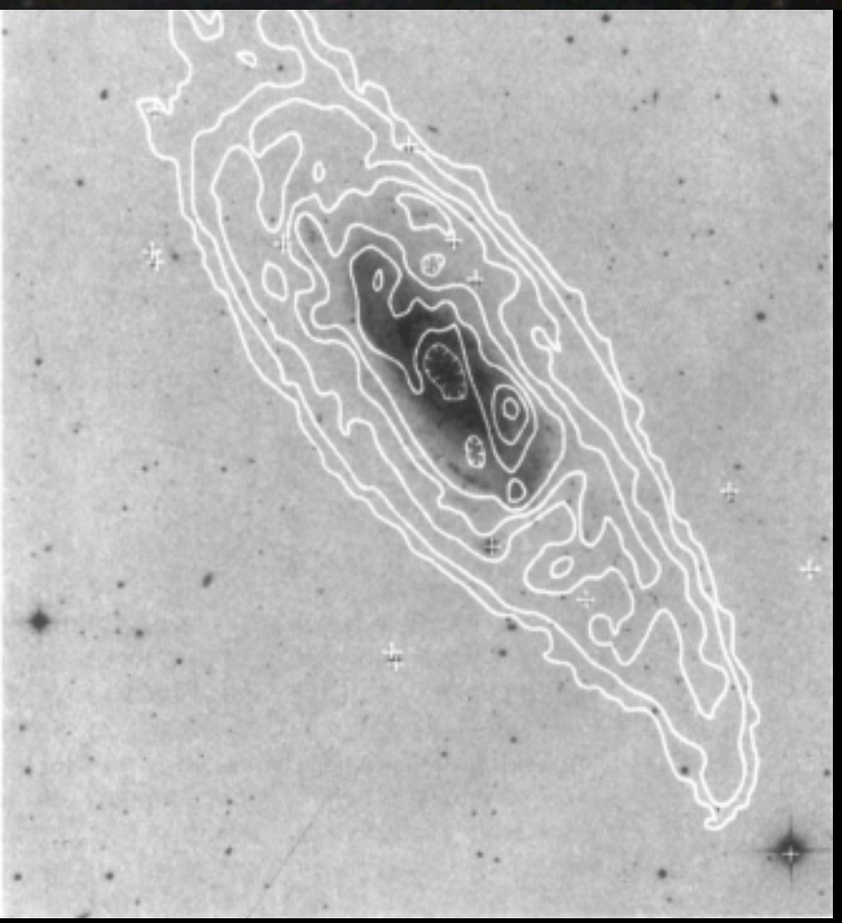
olar system revolves at 220 km/s
hat is pulling us inside?

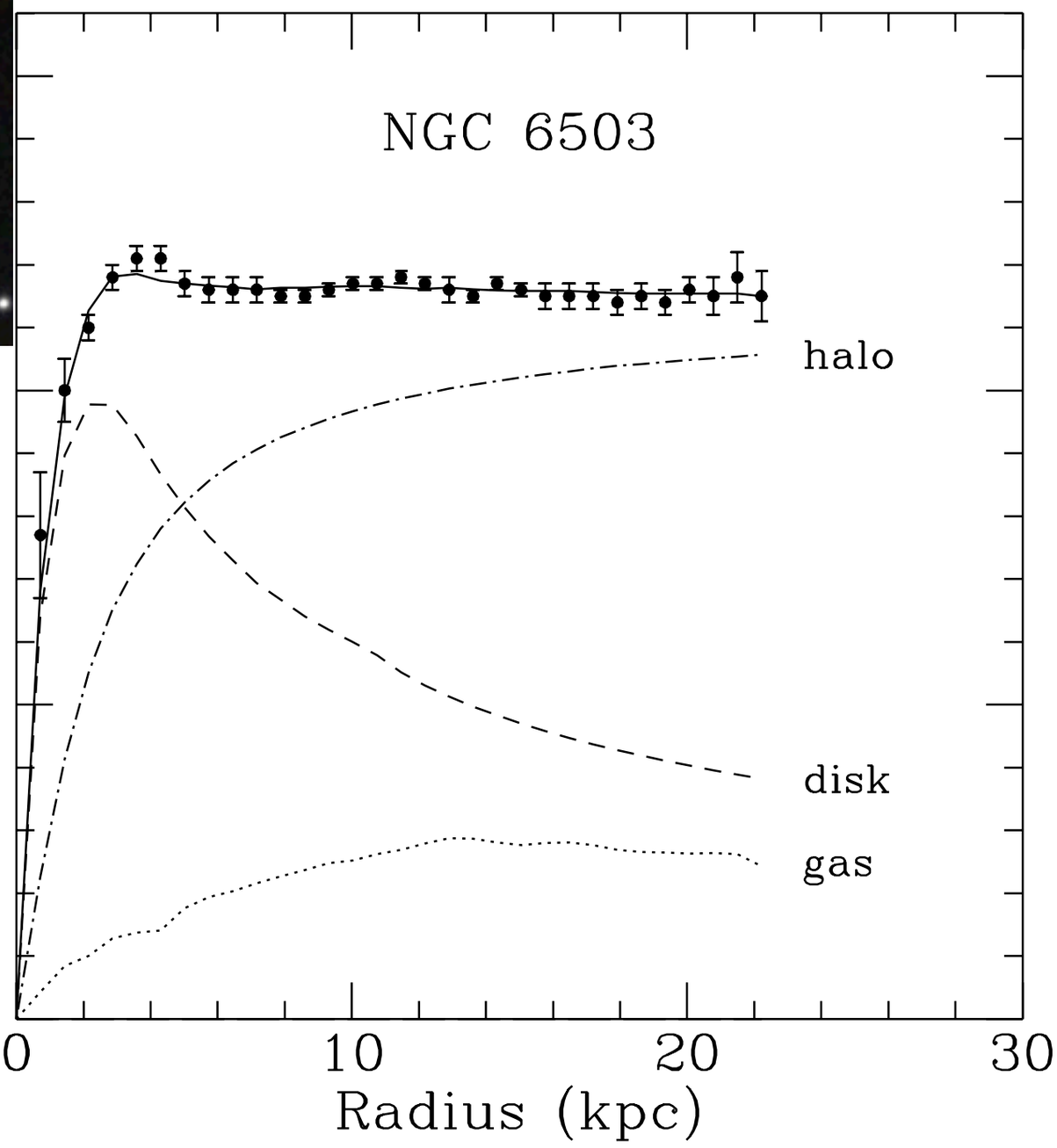







21cm
e⁻
p
e⁻
p
0.01K < T_0



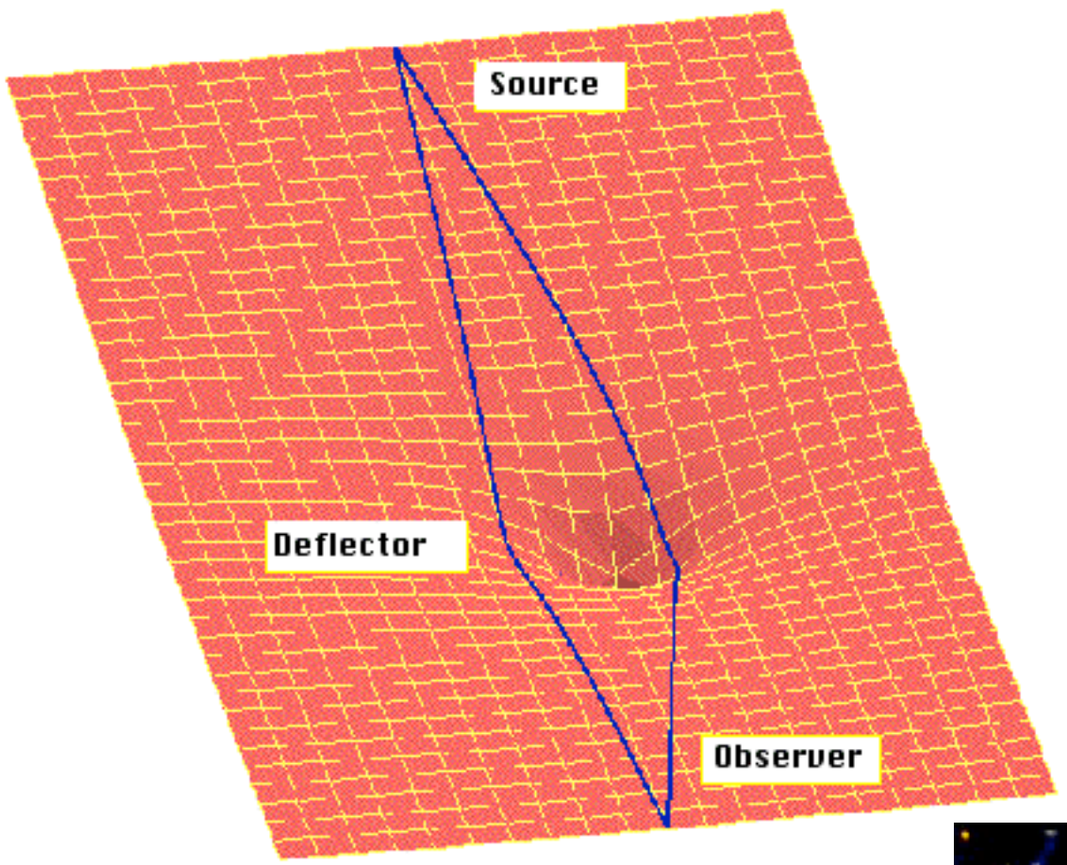

NGC 6503
halo
disk
gas
V_c (km s^{-1})
0
50
100
0
10
20
30
Radius (kpc)

Vera Rubin

1970's

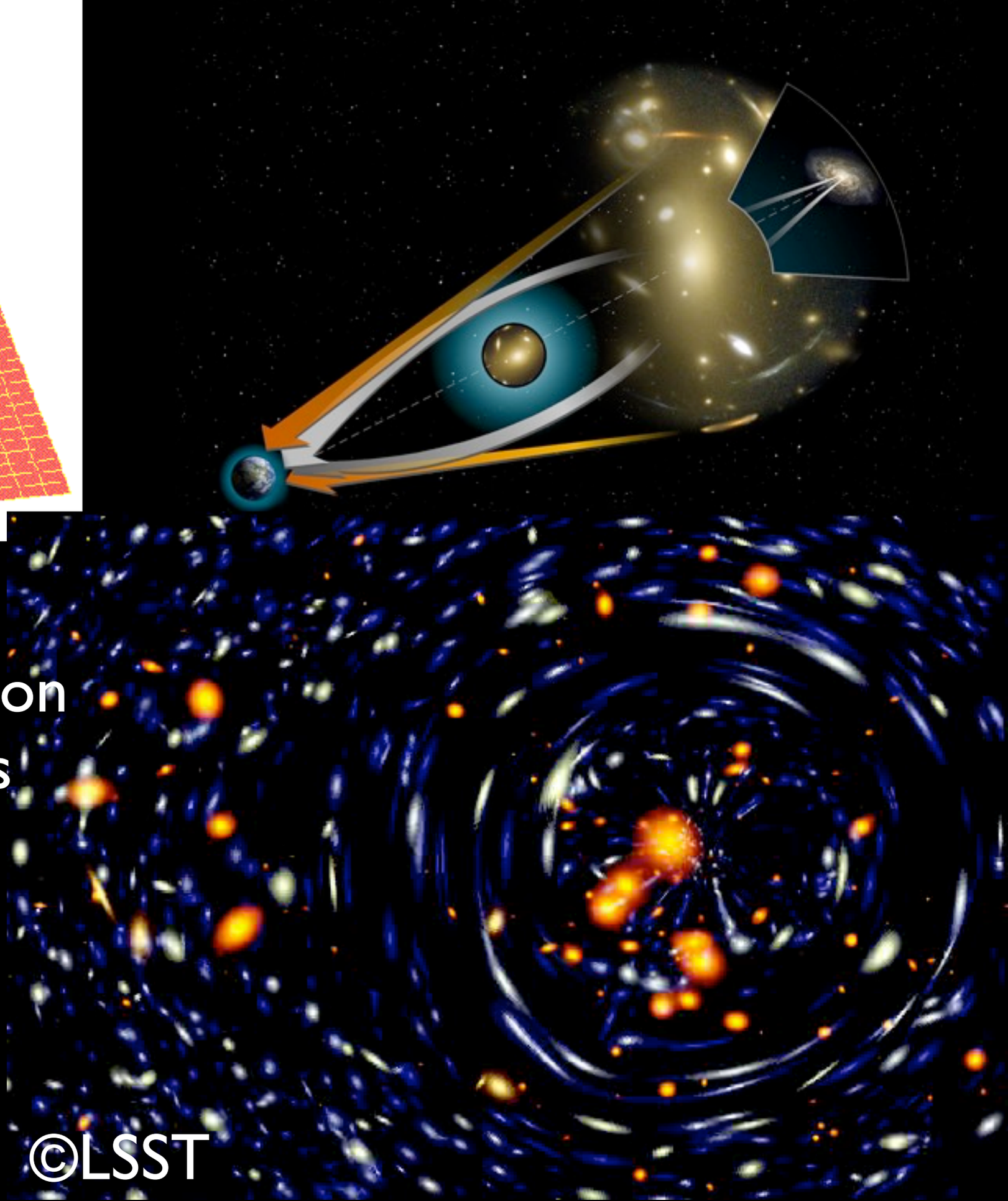
cluster of galaxies
2.1 billion light years

Abell 2218



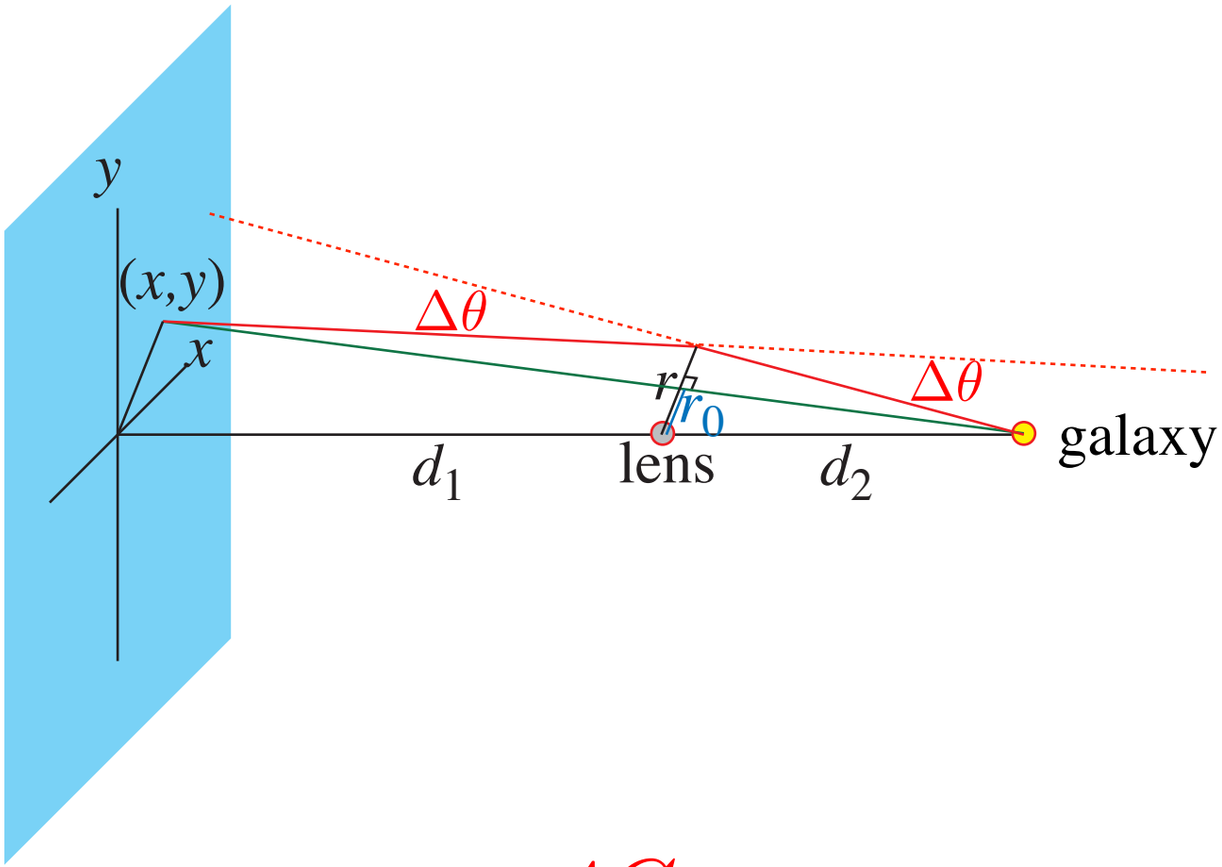
Homework
Work out the deflection angle by a point lens

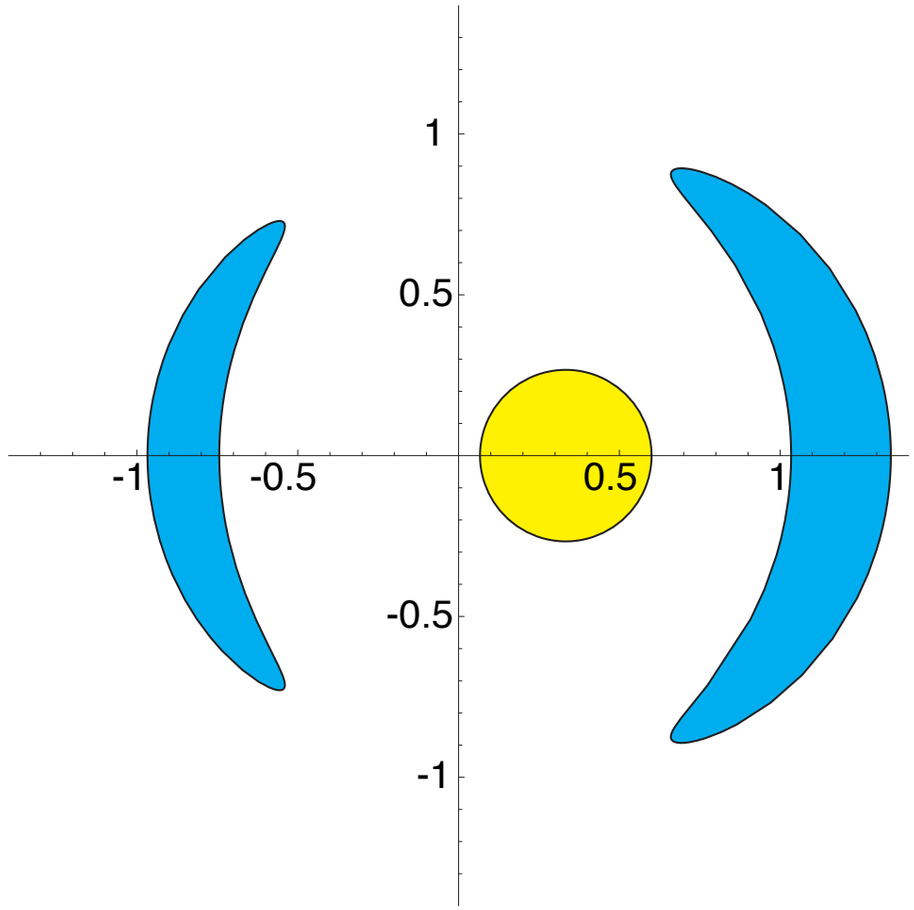
$$\Delta\theta = \frac{4G_N m}{c^2 r_c}$$



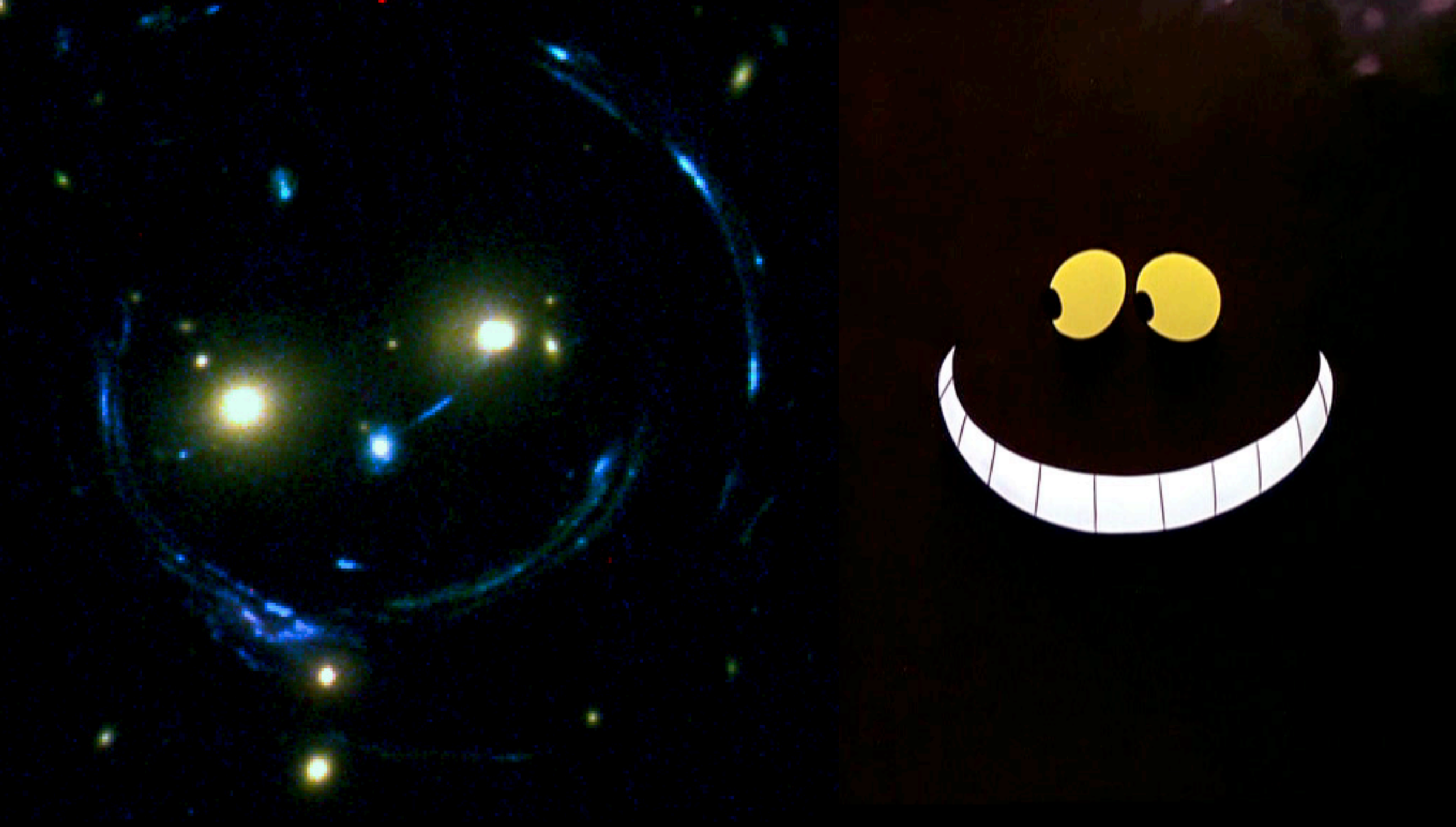
Homework

Show how images can be distorted like this





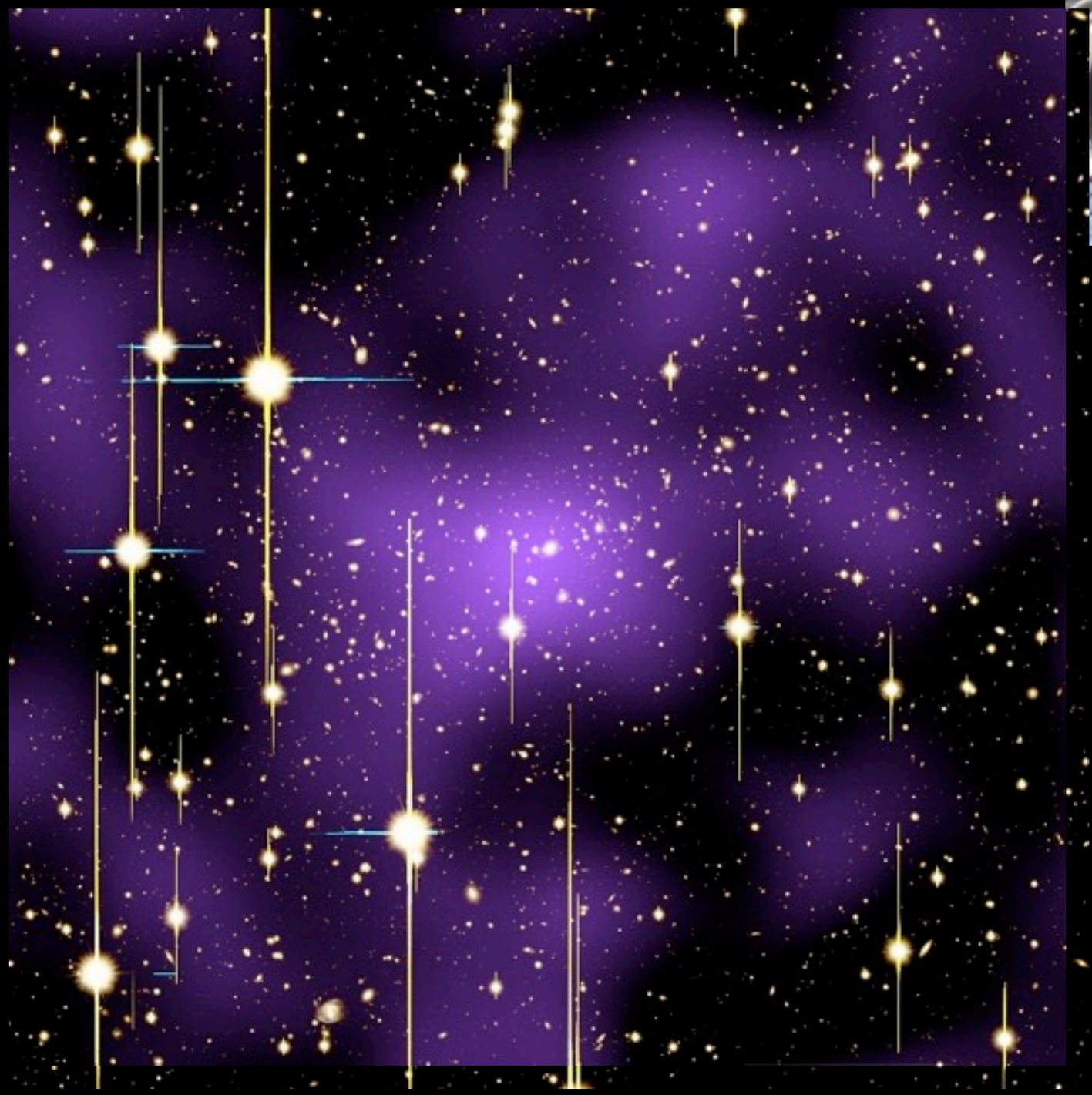
$$\Delta\theta = \frac{4G_N m}{c^2 r_c}$$



Cheshire cat

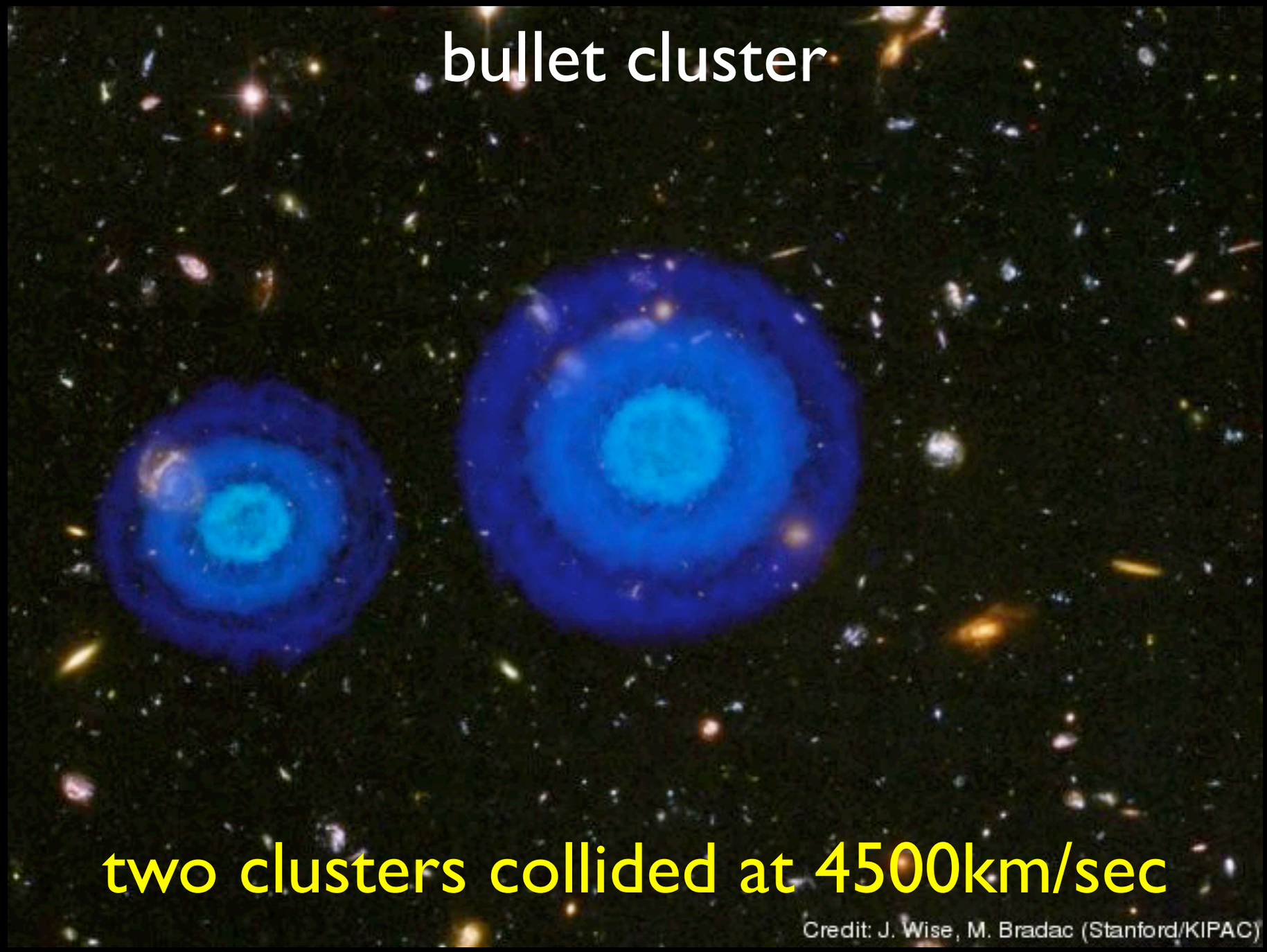
KAVLI IPMU

image invisible dark matter

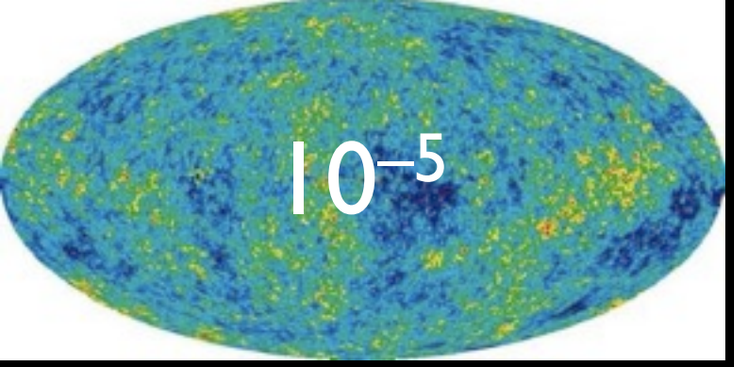


more than 80% of matter in the Universe is not atoms

$$\frac{\sigma_{\rm scatt}}{m} \lesssim \frac{10^{-24}{\rm cm}}{\rm GeV}$$



4B lyrs away

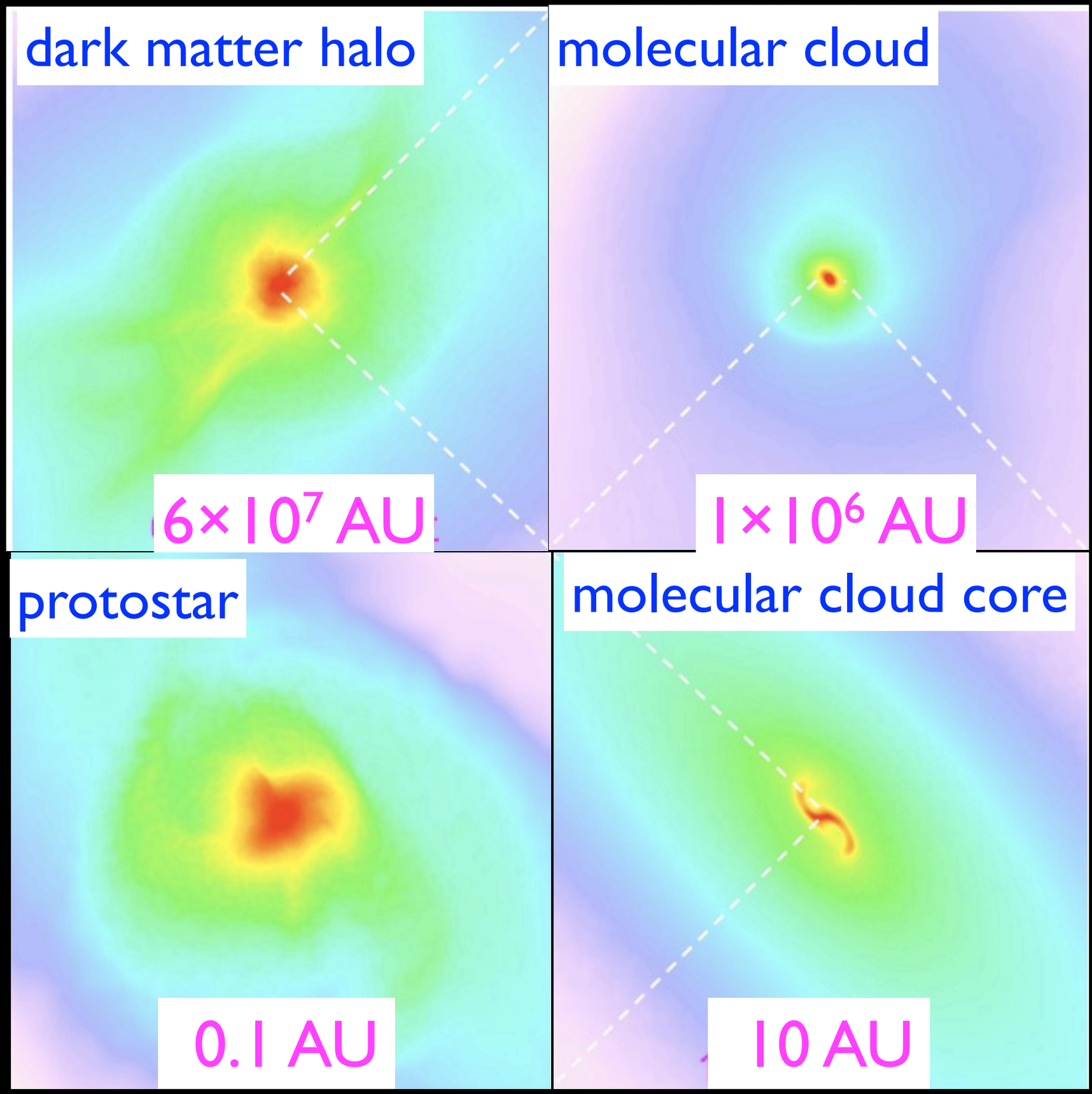


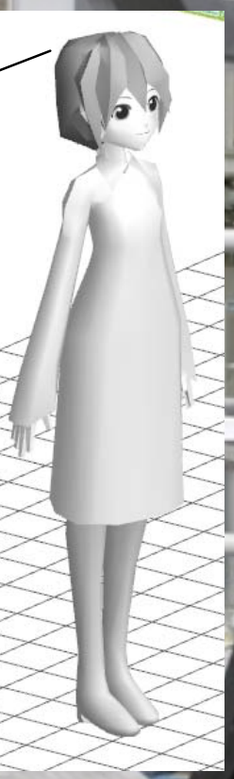
dark matter is our mother

without dark matter

with dark matter

birth of a star

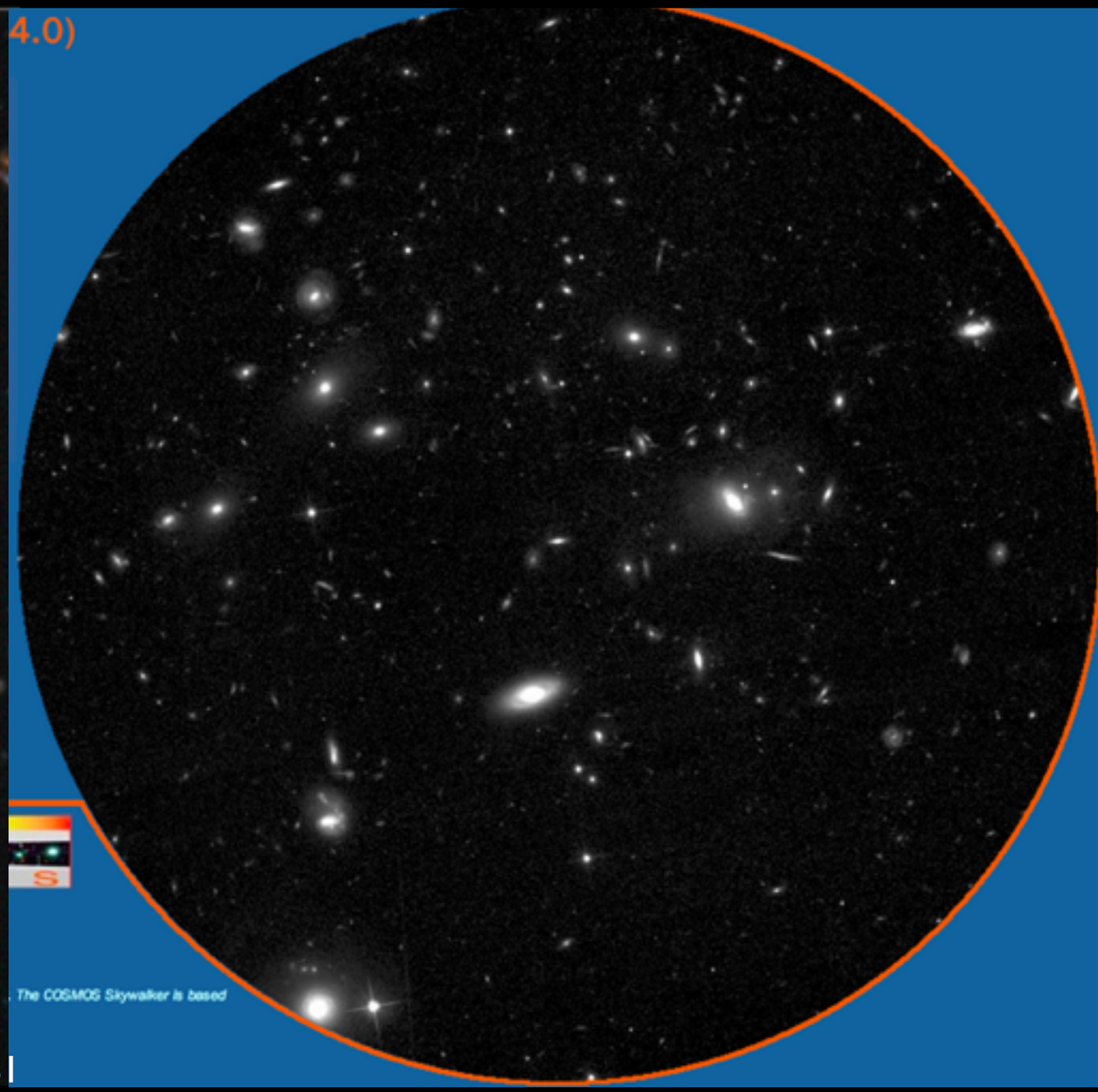




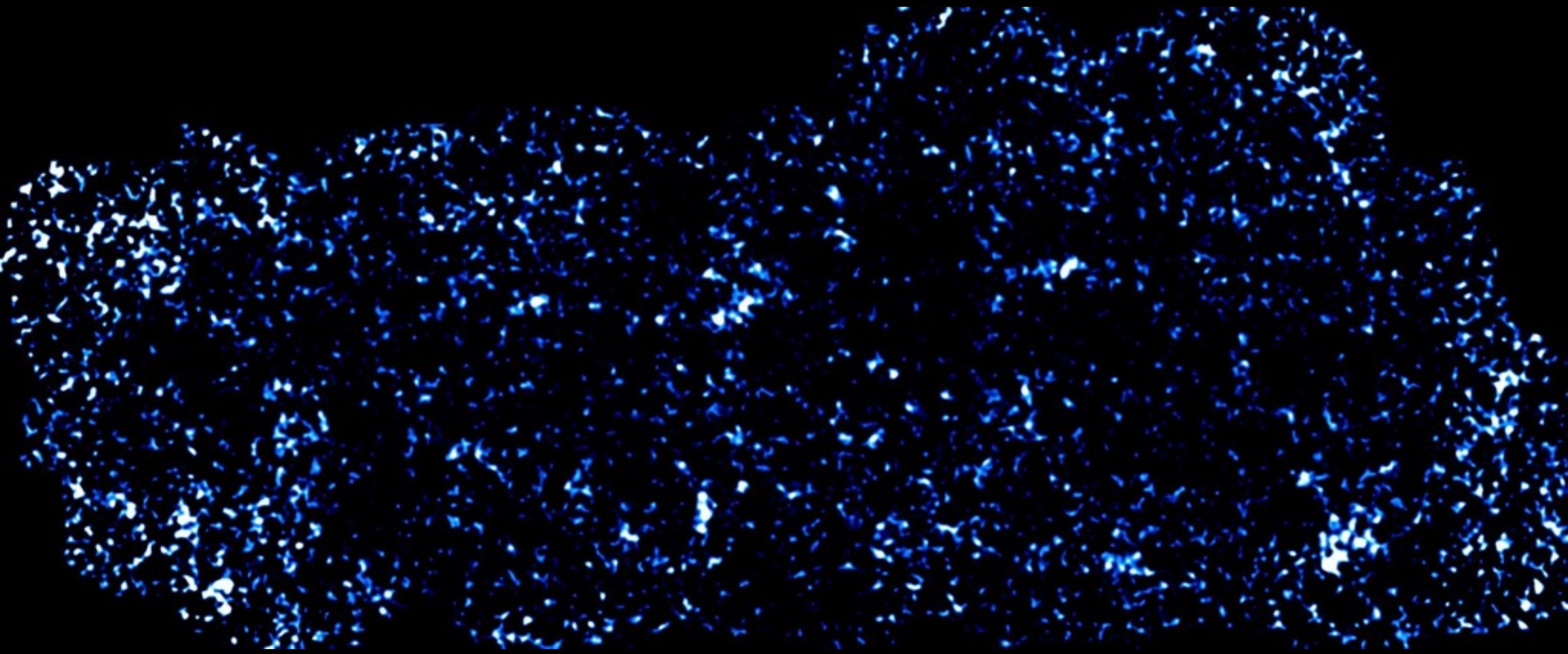
superb performance

HSC: 3 colors in 2.5hours

HST: 1 color in 500 hours



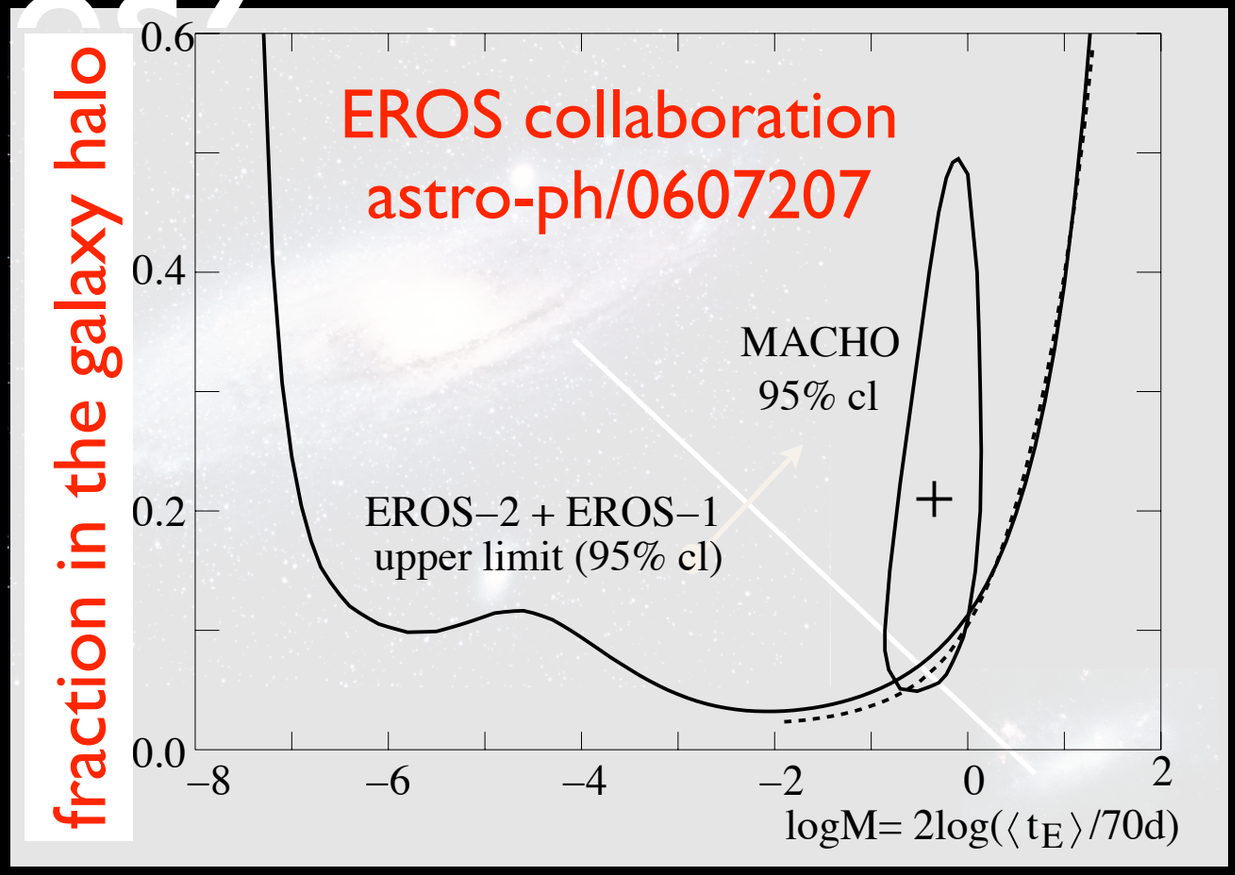
Weak lensing mass map for ~20 sq. degrees field (*2hrs data*)



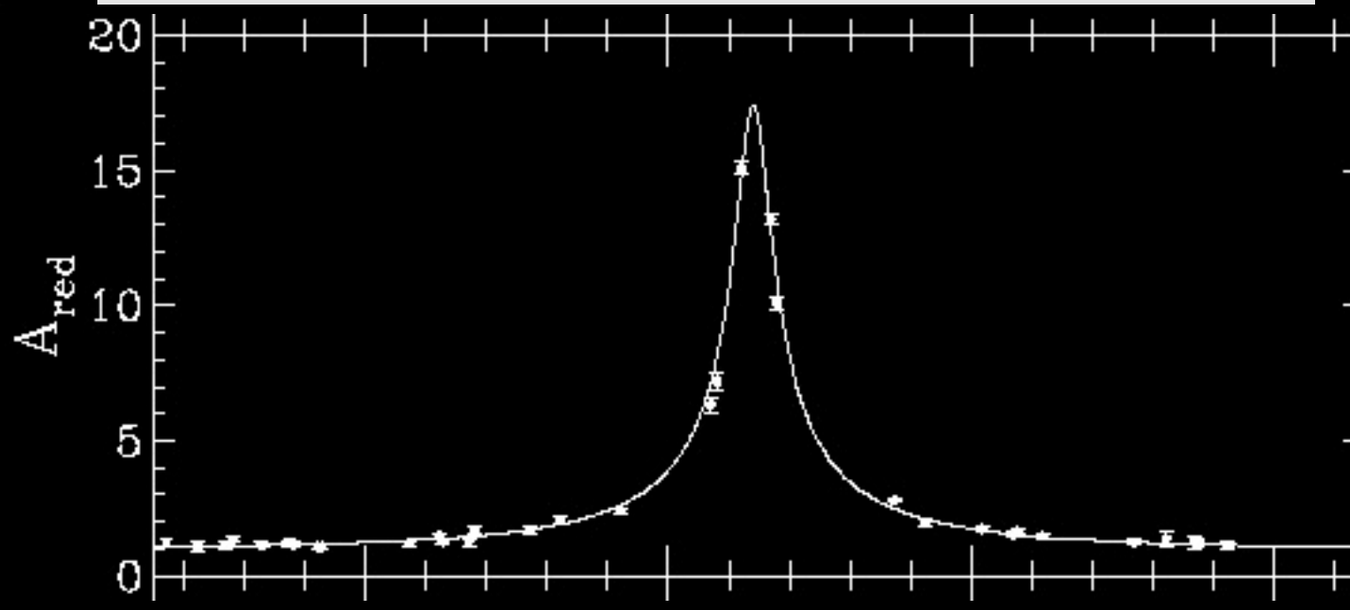
What is dark matter?

Dim Stars? Black Holes?

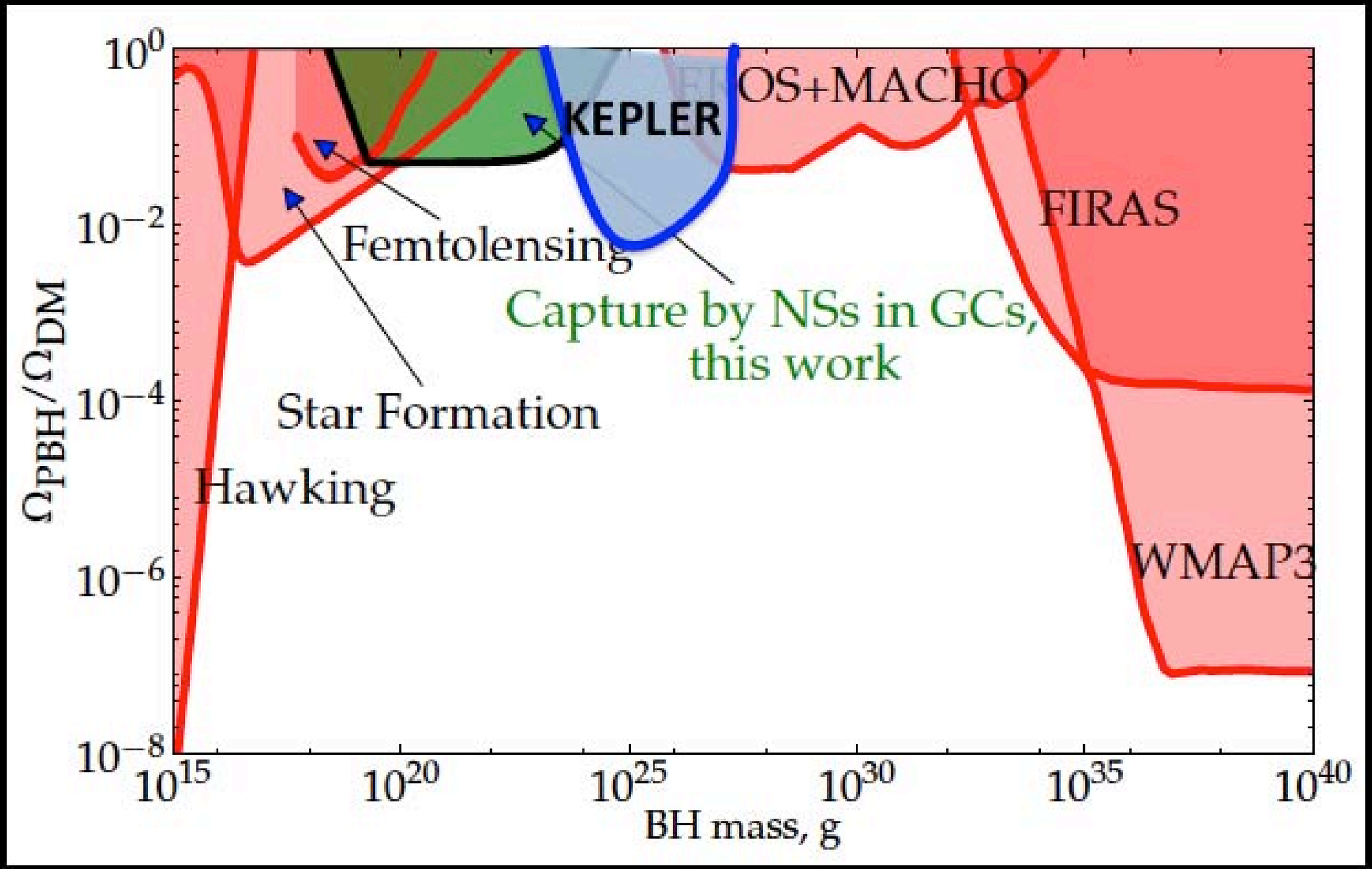
Search for MACHOs
(Massive Compact Halo Objects)



Not enough of them!



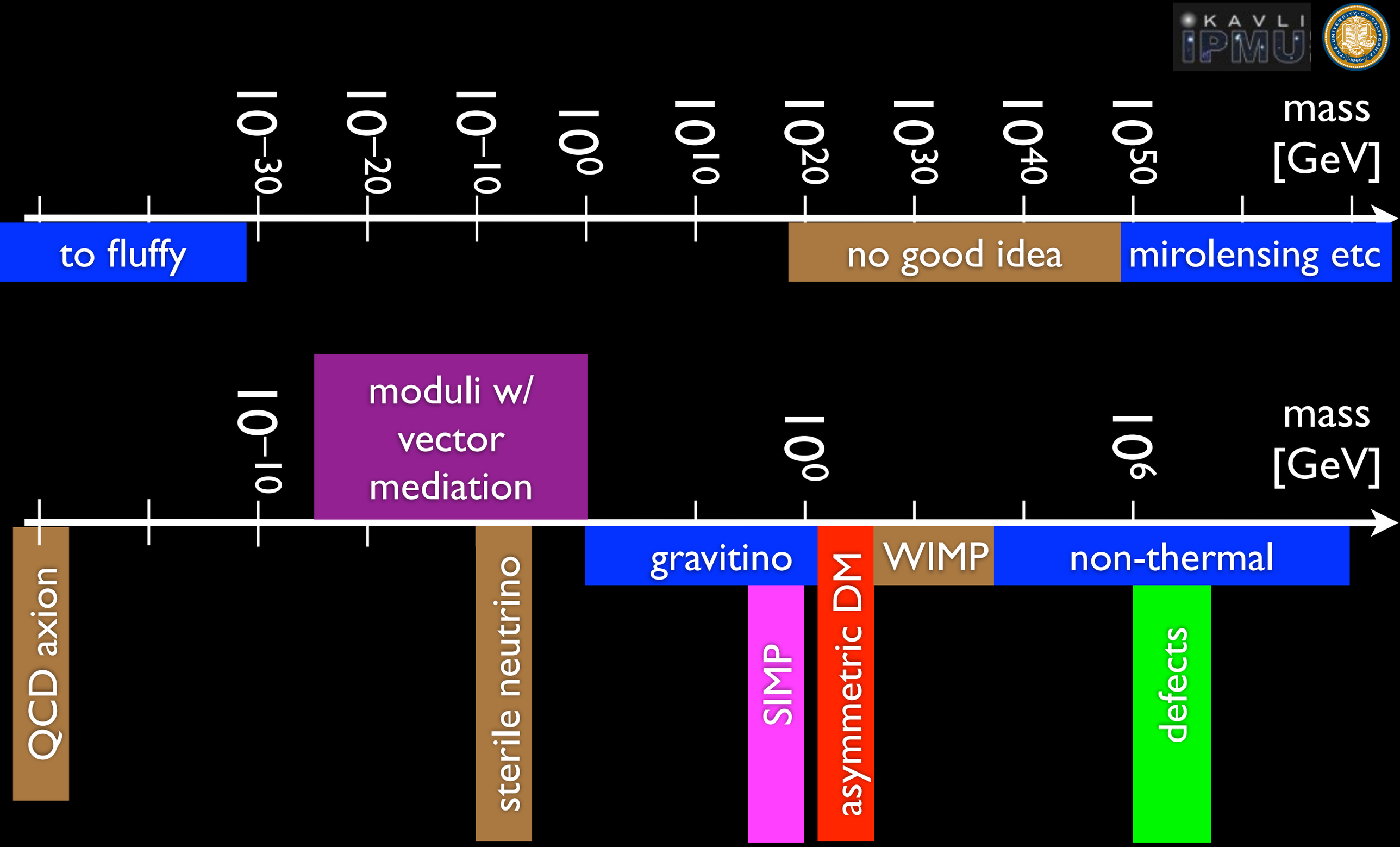
Closing the PBH as DM window



Capela, Pshirkov, & Tinyakov: arXiv:1301.4984

Mass Limits "Uncertainty Principle"

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m > 10^{-22} eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)



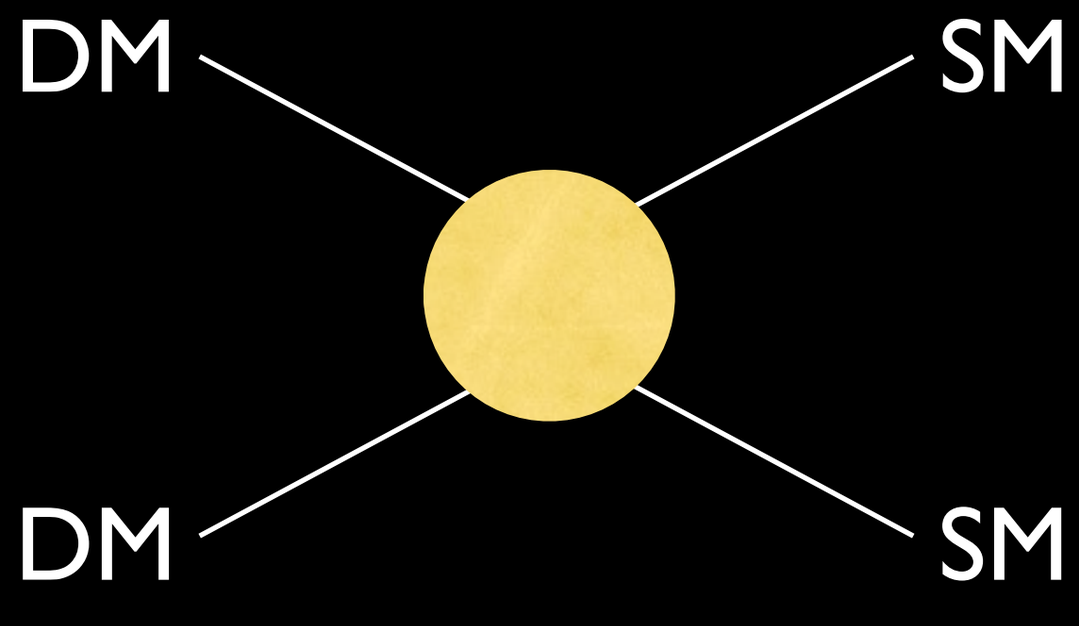
discuss various possibilities

highly biased list

most references are *mine*

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10}\,{\rm GeV}\,\frac{}{m_{\rm DM}}$$

WIMP Miracle



$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300\ {\rm GeV}$$

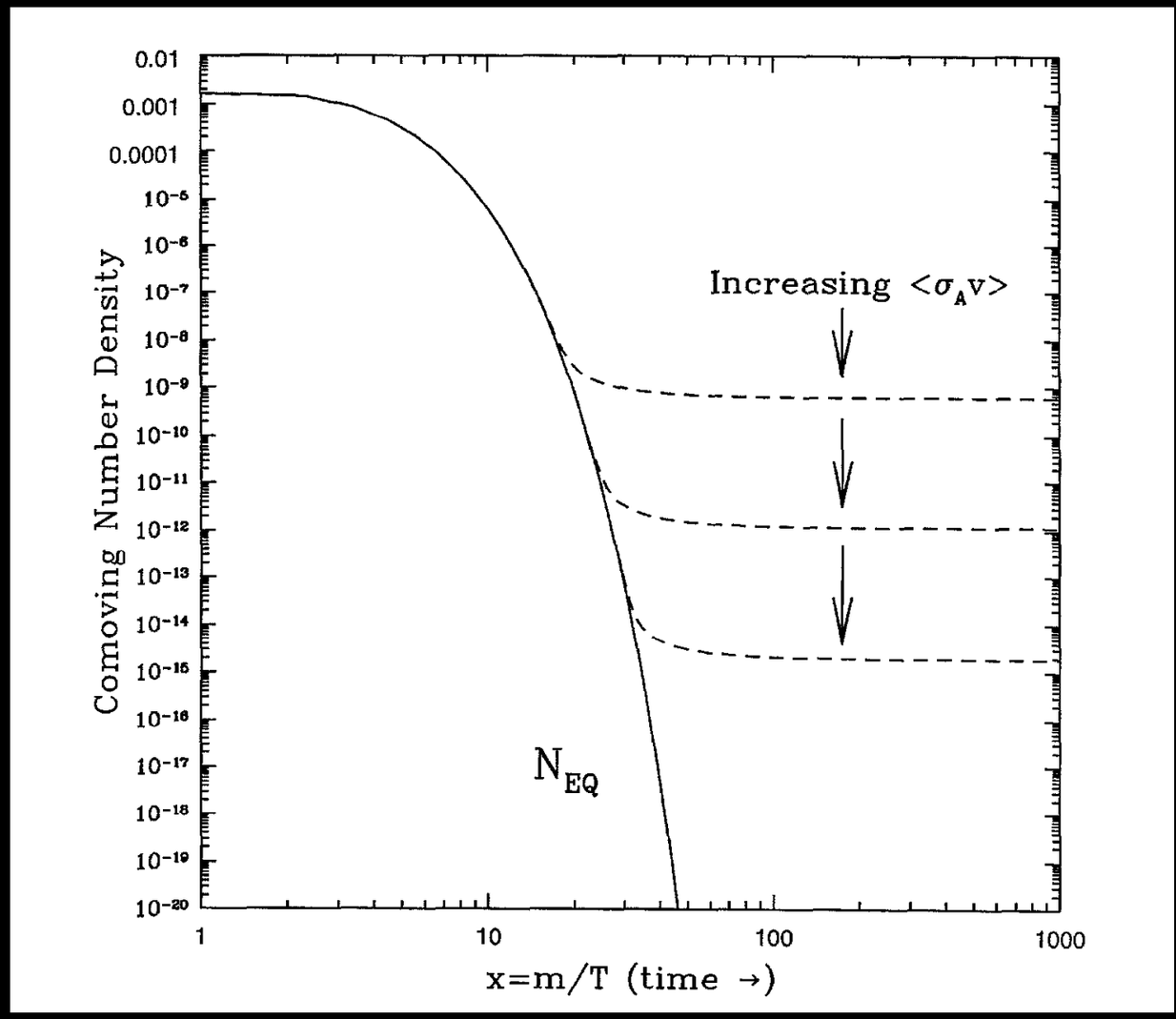
“weak” coupling
“weak” mass scale

correct abundance

Miracle^2

thermal relic

- thermal equilibrium when $T>m_\chi$
- Once $T<m_\chi$, no more χ created
- if stable, only way to lose them is annihilation
- but universe expands and χ get dilute
- at some point they can't find each other
- their number in comoving volume "frozen"



Freeze-out

- WIMP freezes out when the annihilation rate drops below the expansion rate
- Yield Y=n/s constant under expansion
- stronger annihilation ⇒ less abundance

$$H \approx g_*^{1/2} \frac{T^2}{M_{Pl}}$$

$$\Gamma_{\rm ann} \approx \langle \sigma_{\rm ann} v \rangle n$$

$$H(T_f) = \Gamma_{\rm ann}$$

$$n \approx g_*^{1/2} \frac{T_f^2}{M_{Pl} \langle \sigma_{\rm ann} v \rangle}$$

$$s \approx g_* T^3$$

$$Y = \frac{n}{s} \approx g_*^{-1/2} \frac{1}{M_{Pl} T_f \langle \sigma_{\rm ann} v \rangle}$$

$$\Omega_\chi = \frac{m_\chi Y s_0}{\rho_c}$$

$$\approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

Order of magnitude

- "Known" Ω_χ=0.23 determines the WIMP annihilation cross section

$$\Omega_\chi \approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{1.12 \times 10^{-10} {\rm GeV}^{-2} x_f}{g_*^{1/2} \Omega_\chi h^2}$$

$$\sim 10^{-9} {\rm GeV}^{-2}$$

- simple estimate of the annihilation cross section

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\pi \alpha^2}{m_\chi^2}$$

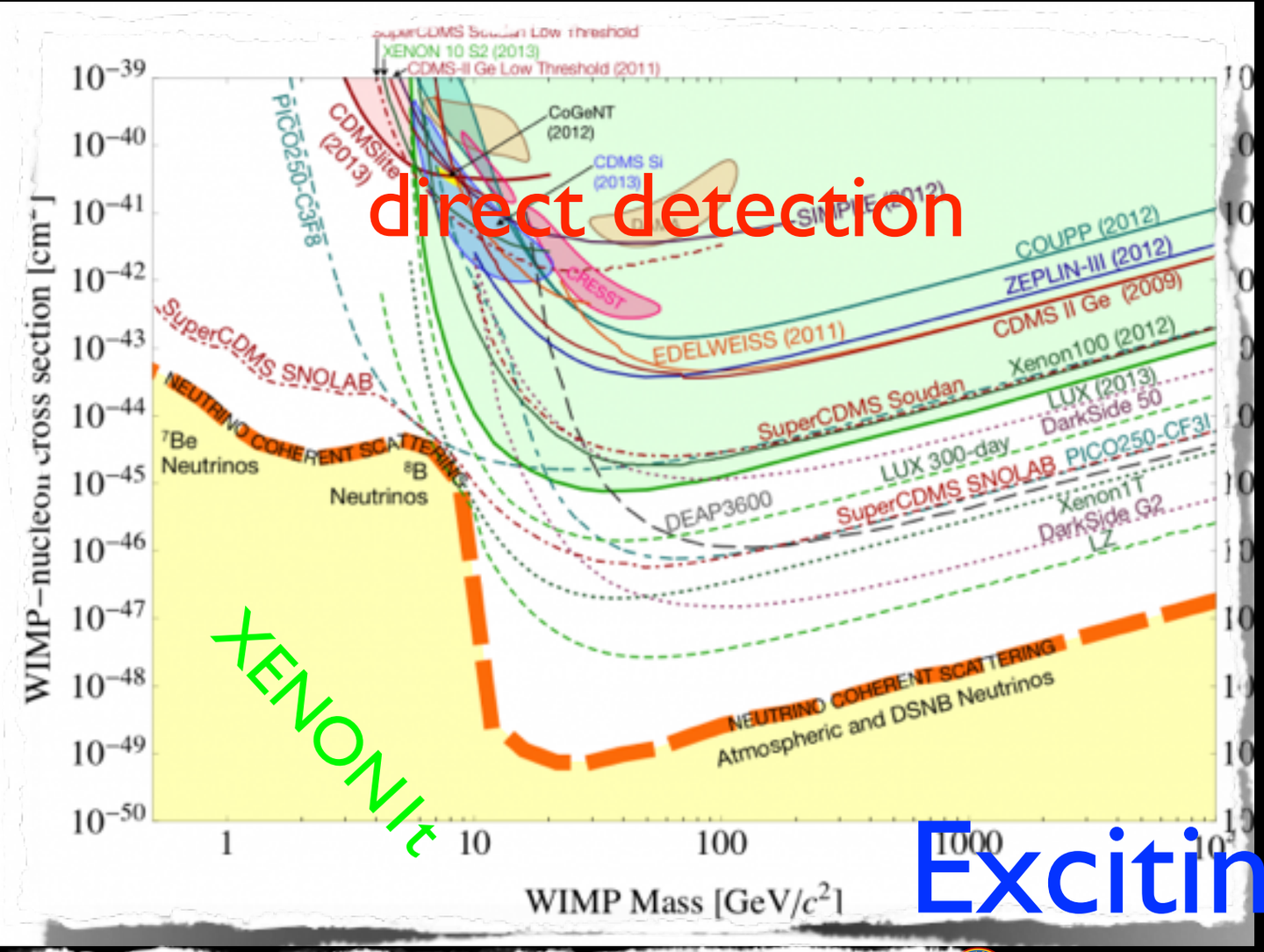
- weak-scale mass!!!

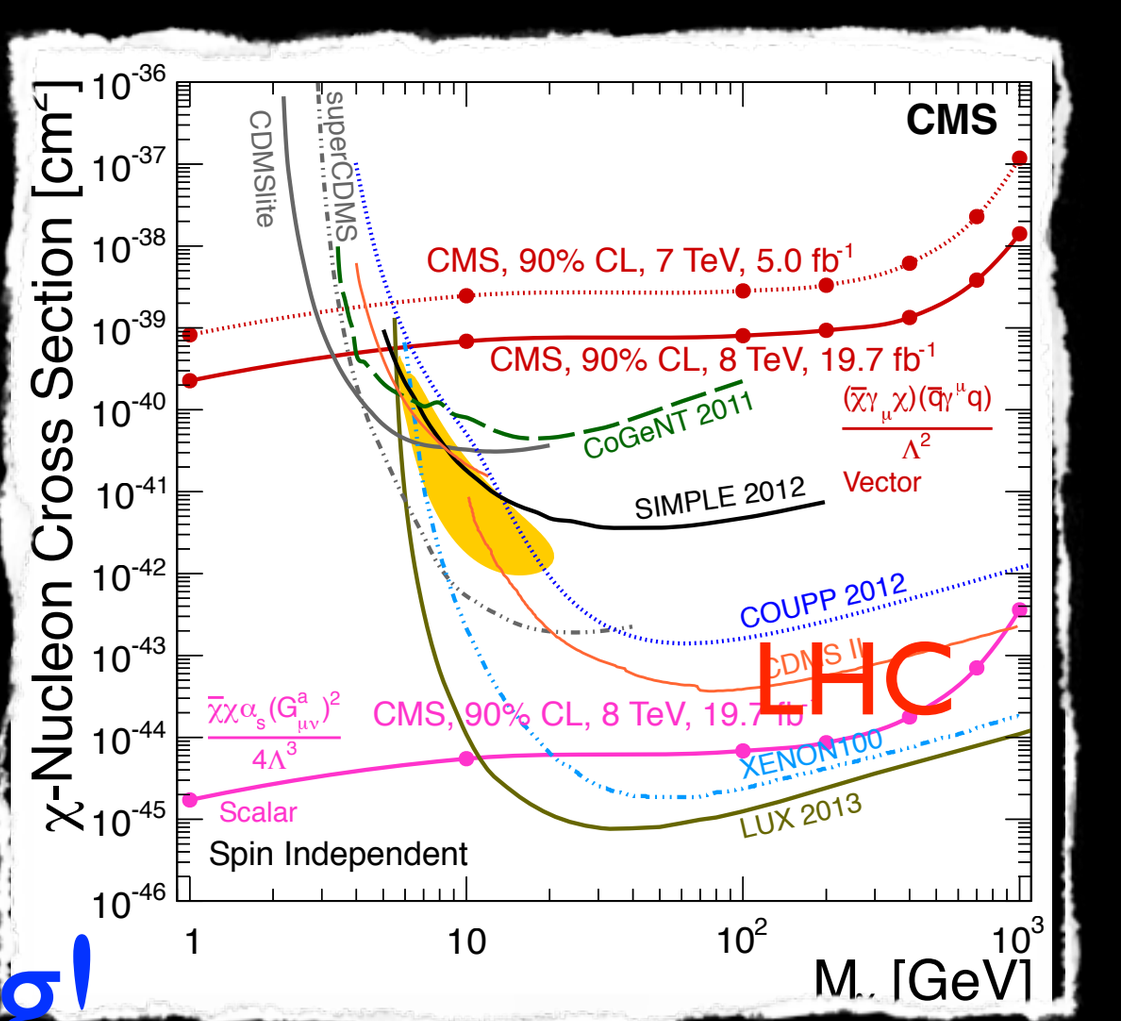
$$m_\chi \approx 300 \ {\rm GeV}$$

$$\langle \sigma_{\rm ann} v \rangle \simeq 2.2 \times 10^{-26} {\rm cm}^3/{\rm sec}$$

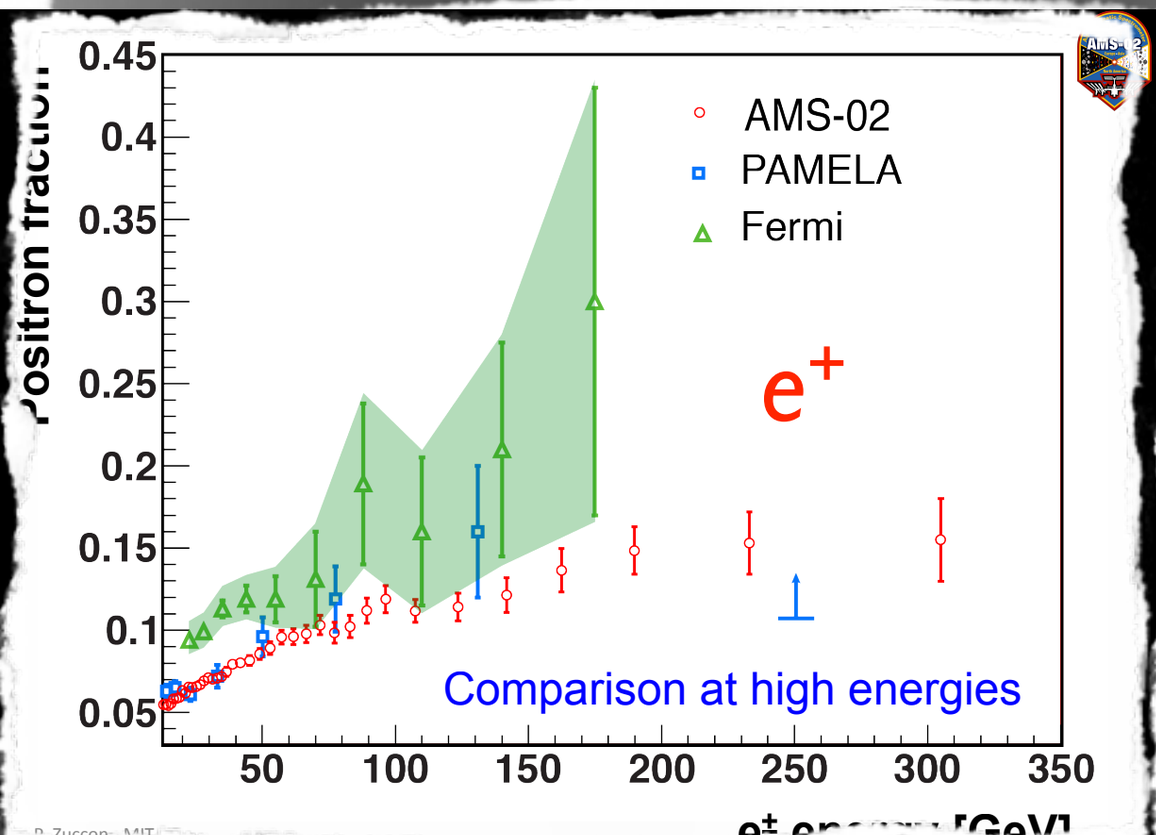
"WIMP Miracle"

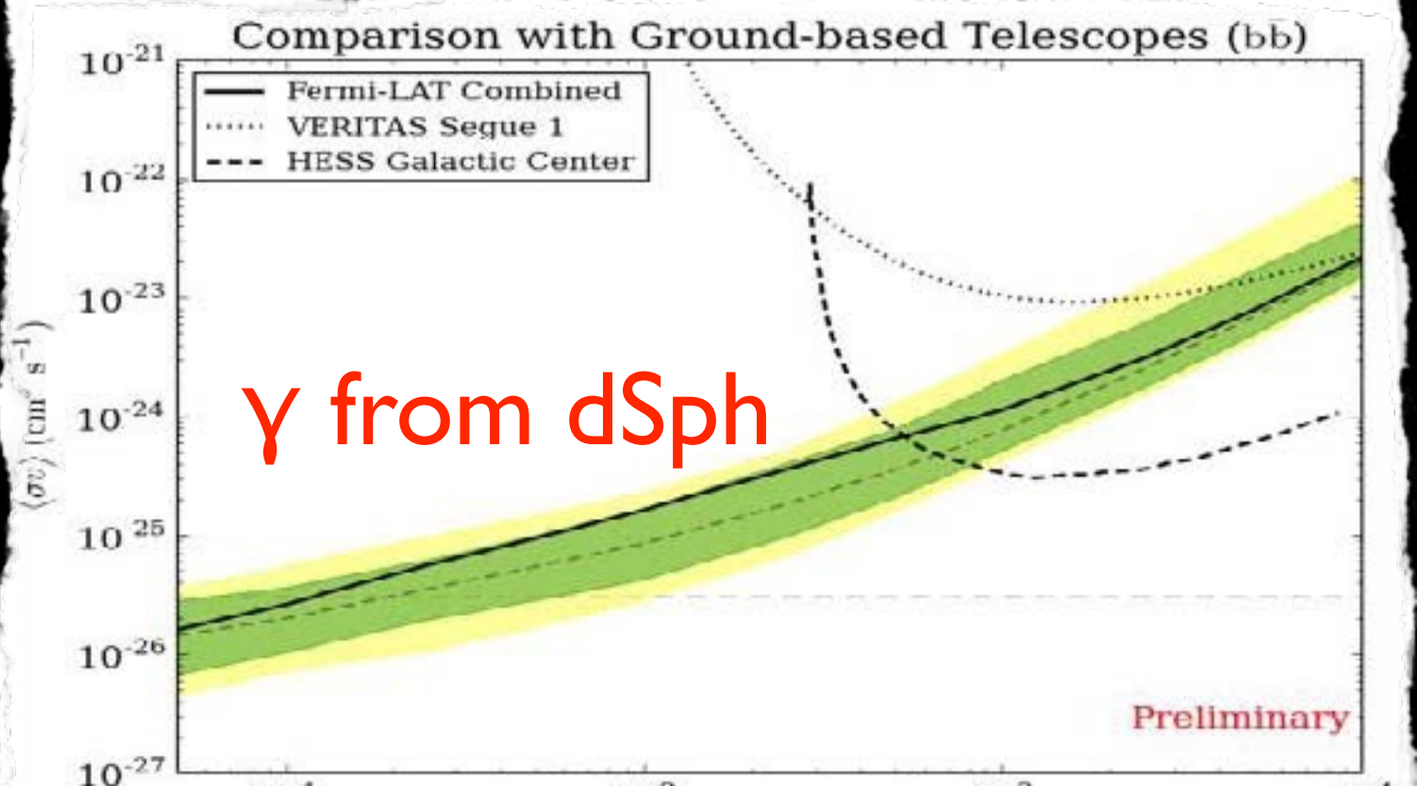
- A stable particle at the weak scale with "EM-strength" coupling naturally gives the correct abundance
- This is where we expect new particles because of the hierarchy problem $m_W \ll M_{Pl}$
- Many candidates of this type: supersymmetry, little Higgs with T-parity, Universal Extra Dimensinos, etc
- If so, we may even create dark matter at accelerators

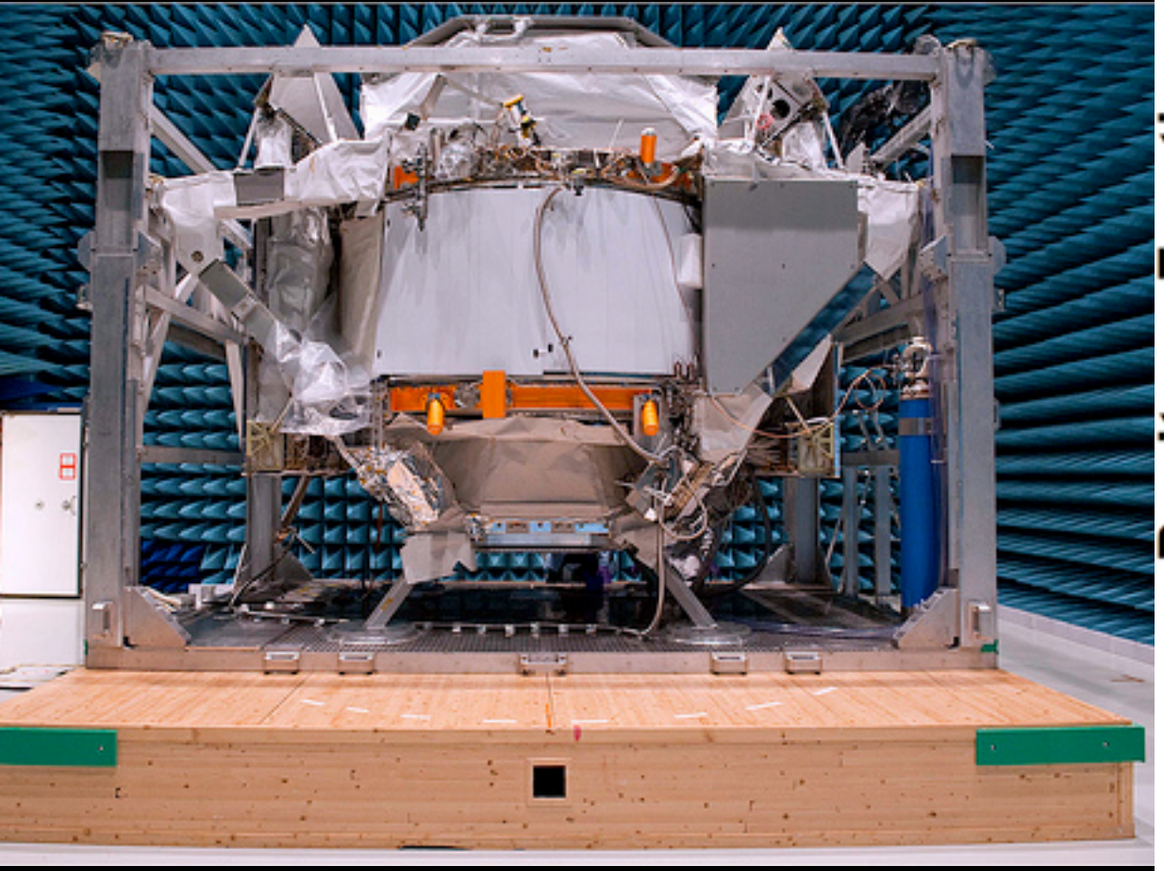

direct detection
WIMP−nucleon cross section [cm²]
WIMP Mass [GeV/c²]
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
CRESST
EDELWEISS (2011)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
SuperCDMS Soudan
Xenon100 (2012)
LUX (2013)
DarkSide 50
LUX 300-day
DEAP3600
SuperCDMS SNOLAB, PICO250-CF3I
Xenon1T
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
XENON1T

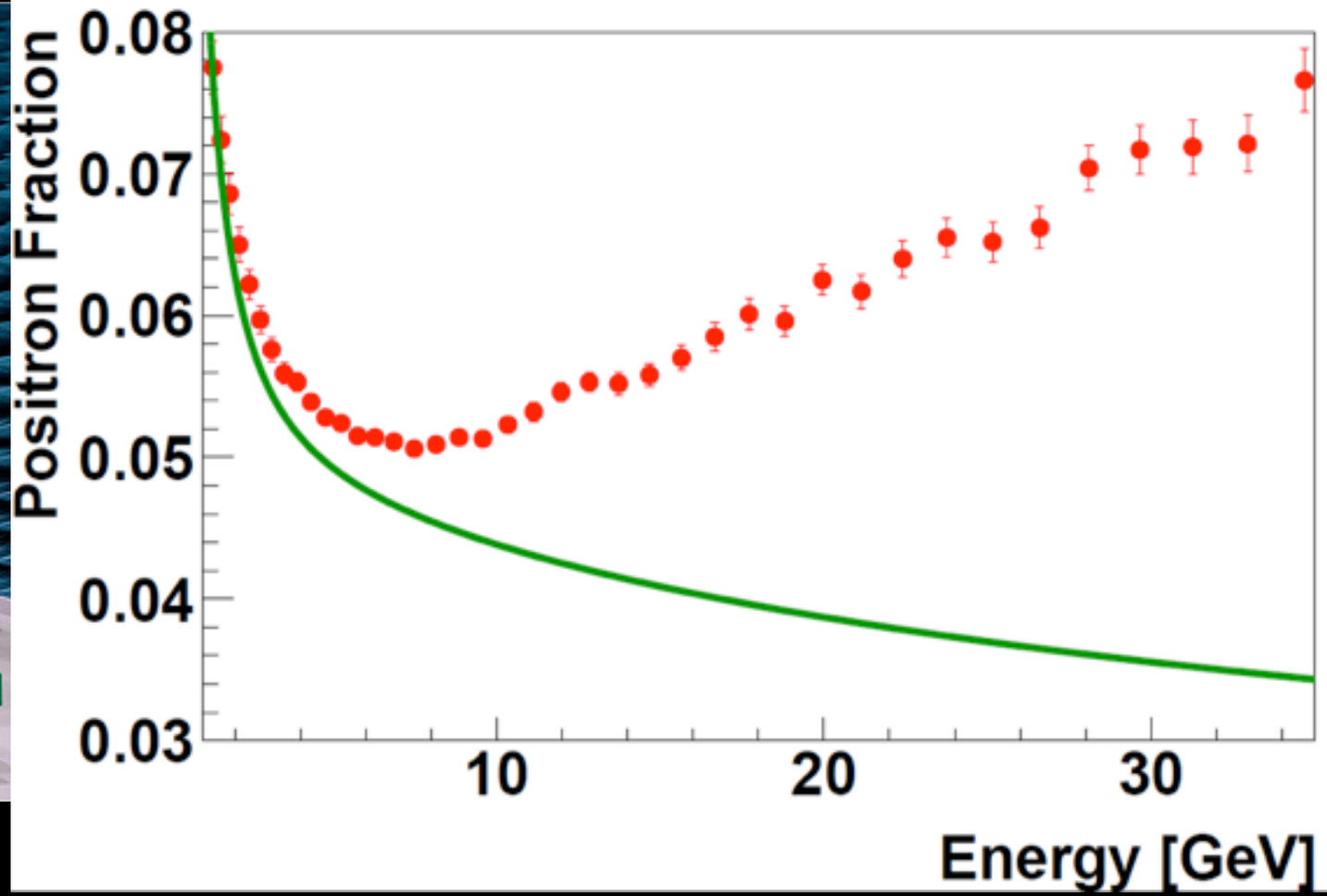

CMS
χ-Nucleon Cross Section [cm²]
M_χ [GeV]
CDMSlite
superCDMS
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
CoGeNT 2011
SIMPLE 2012
COUPP 2012
CDMS II
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
XENON100
LUX 2013
Scalar
Spin Independent
Vector
LHC

Exciting!

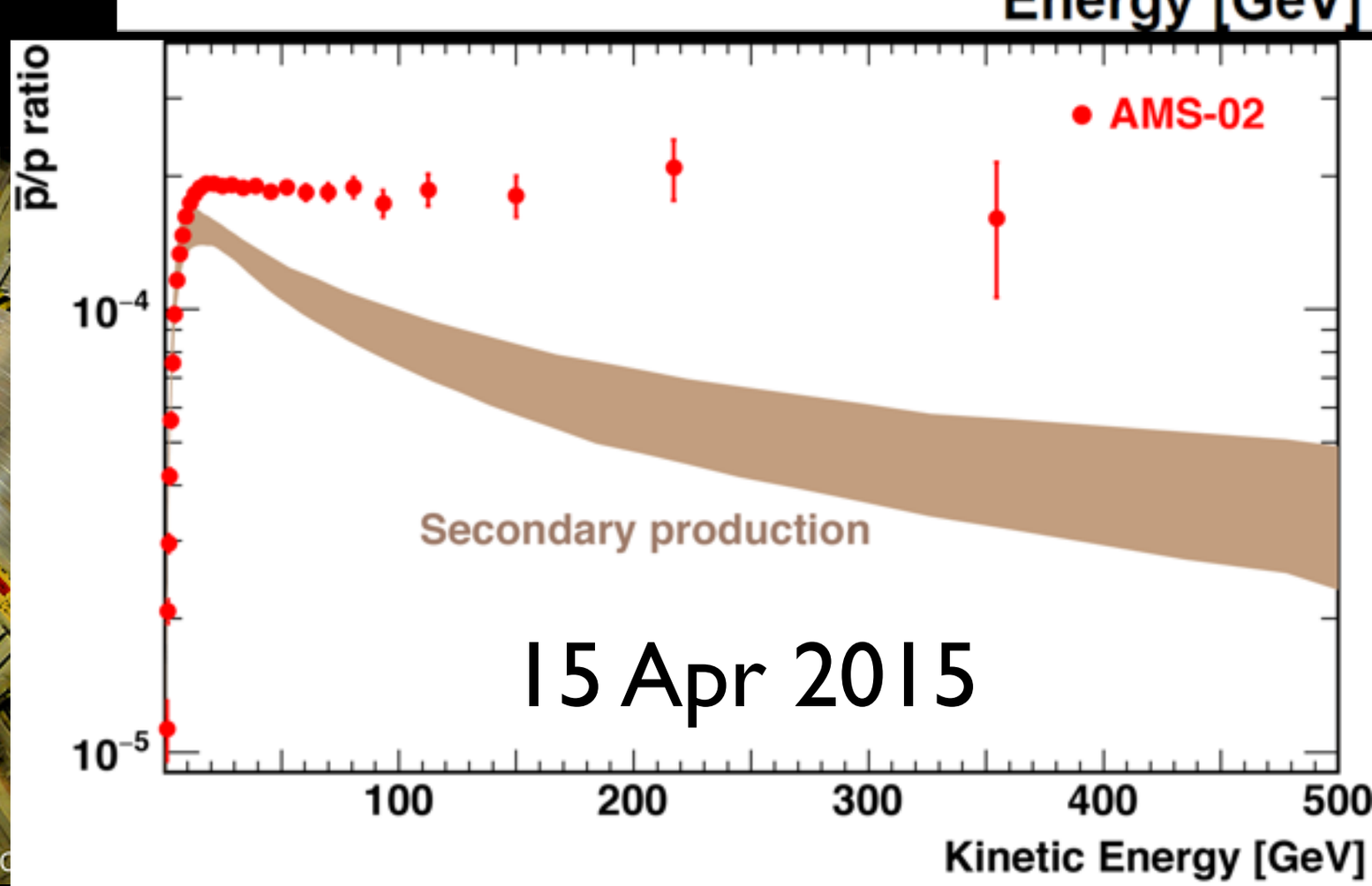

Positron fraction
AMS-02
PAMELA
Fermi
e⁺
Comparison at high energies
e± energy [GeV]


Comparison with Ground-based Telescopes (bb)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
γ from dSph
Preliminary

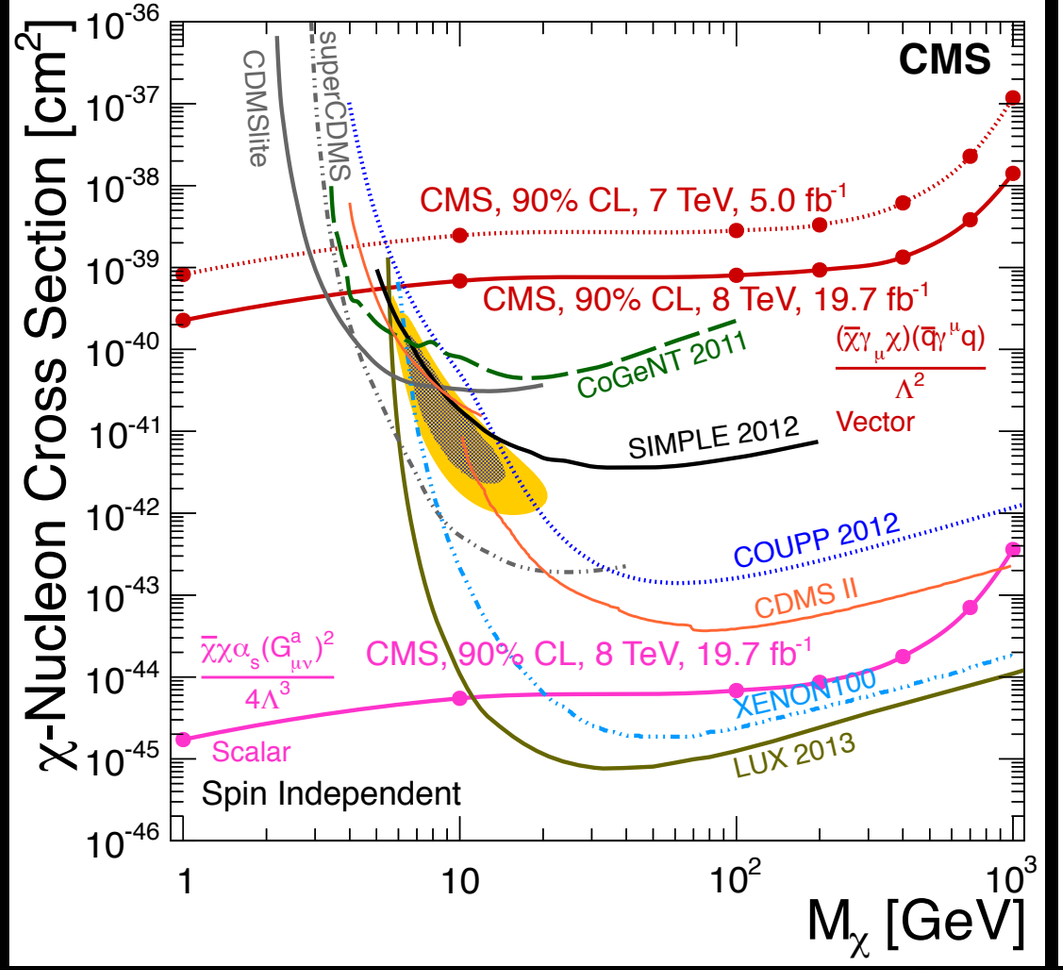


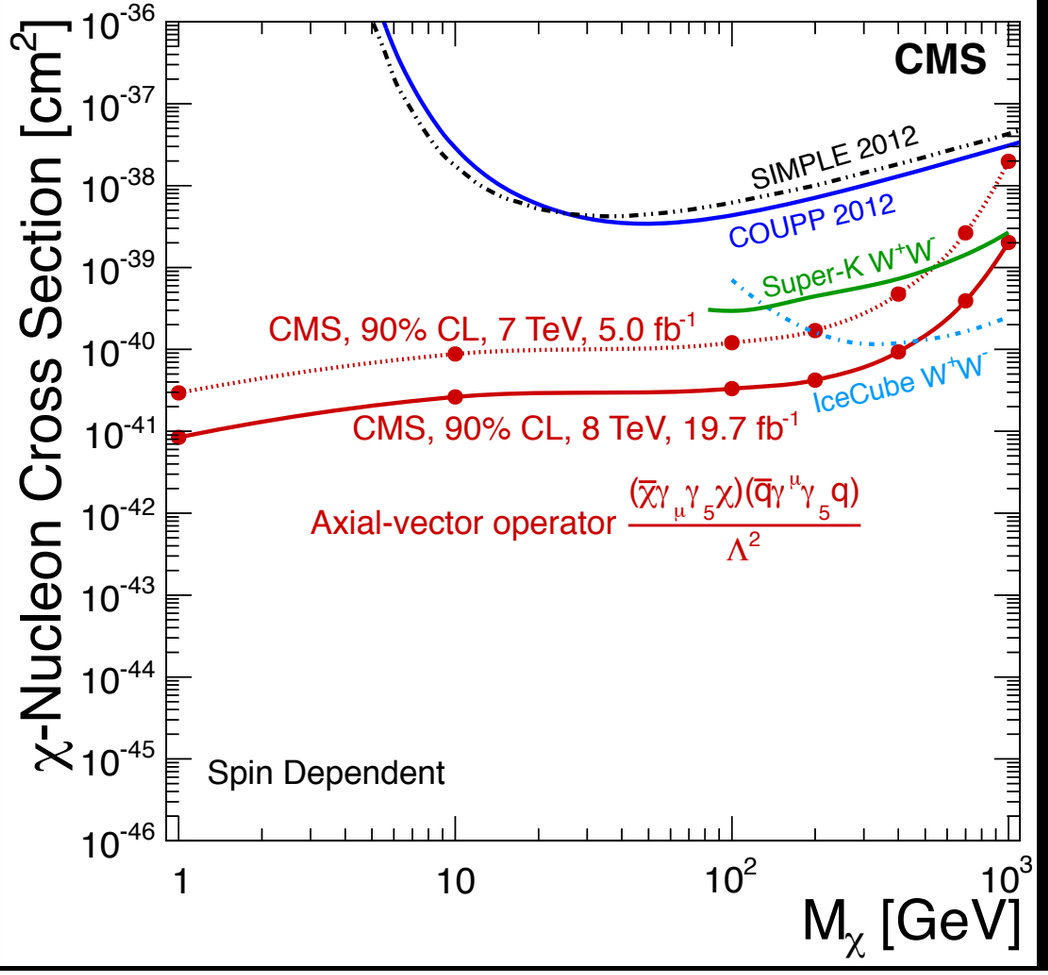


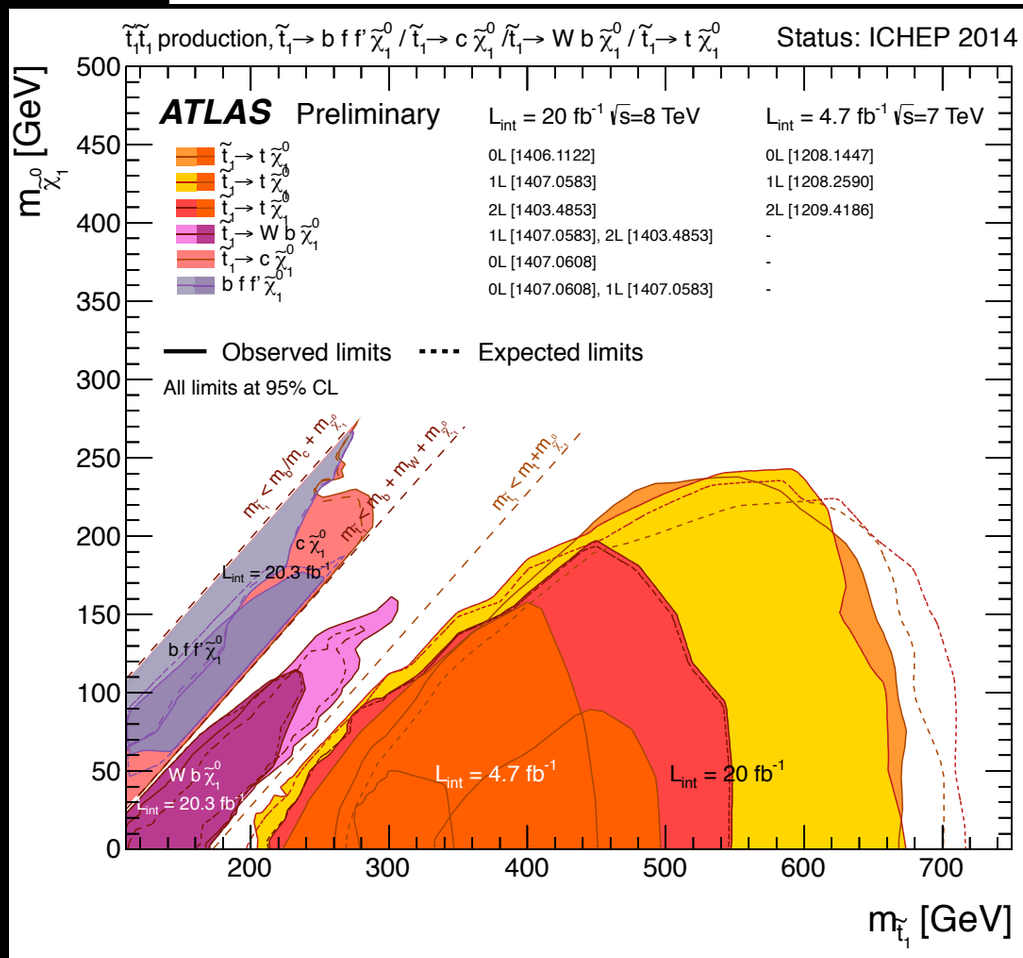
AMS

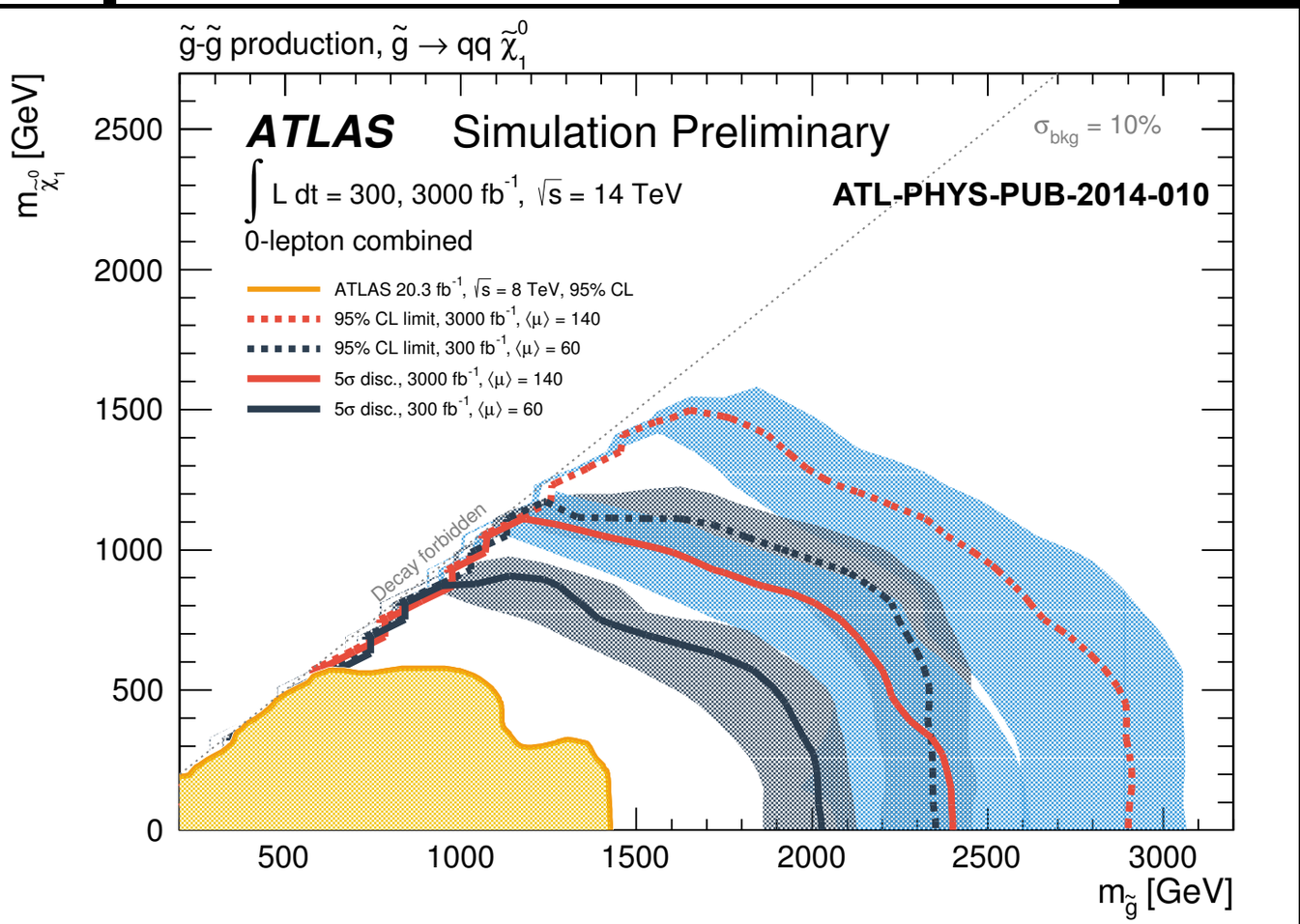


15 Apr 2015

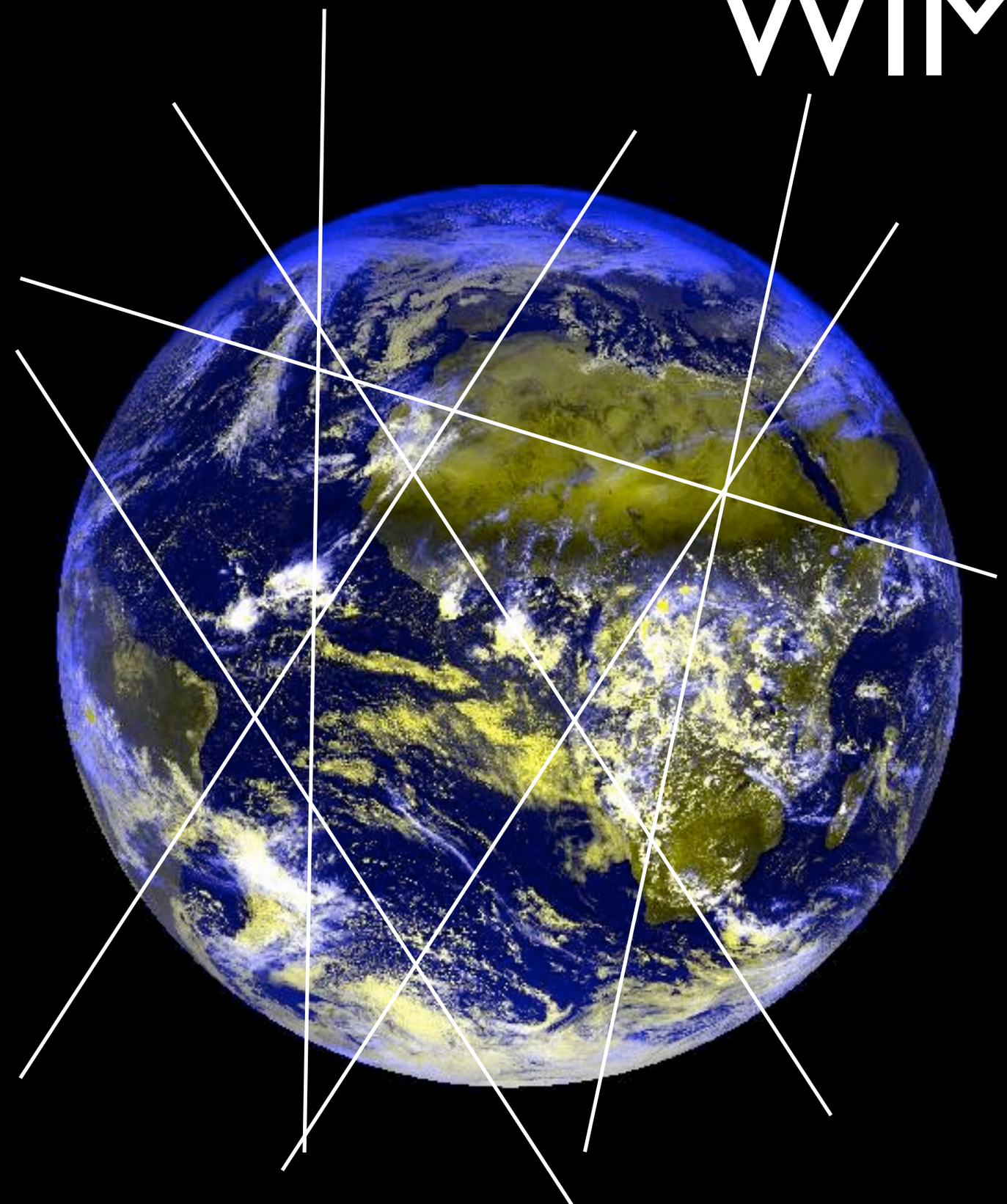

CMS
CDMSlite
superCDMS
CMS, 90% CL, 7 TeV, 5.0 fb-1
CMS, 90% CL, 8 TeV, 19.7 fb-1
CoGeNT 2011
SIMPLE 2012
COUPP 2012
CDMS II
XENON100
LUX 2013
Vector
Scalar
Spin Independent
χ-Nucleon Cross Section [cm2]
Mχ [GeV]


CMS
SIMPLE 2012
COUPP 2012
Super-K W+W-
IceCube W+W-
CMS, 90% CL, 7 TeV, 5.0 fb-1
CMS, 90% CL, 8 TeV, 19.7 fb-1
Axial-vector operator
Spin Dependent
χ-Nucleon Cross Section [cm2]
Mχ [GeV]


ATLAS Preliminary
Observed limits
Expected limits
All limits at 95% CL
Status: ICHEP 2014
Lint = 20.3 fb-1
Lint = 4.7 fb-1
Lint = 20 fb-1
mt̃1 [GeV]
mχ̃01 [GeV]

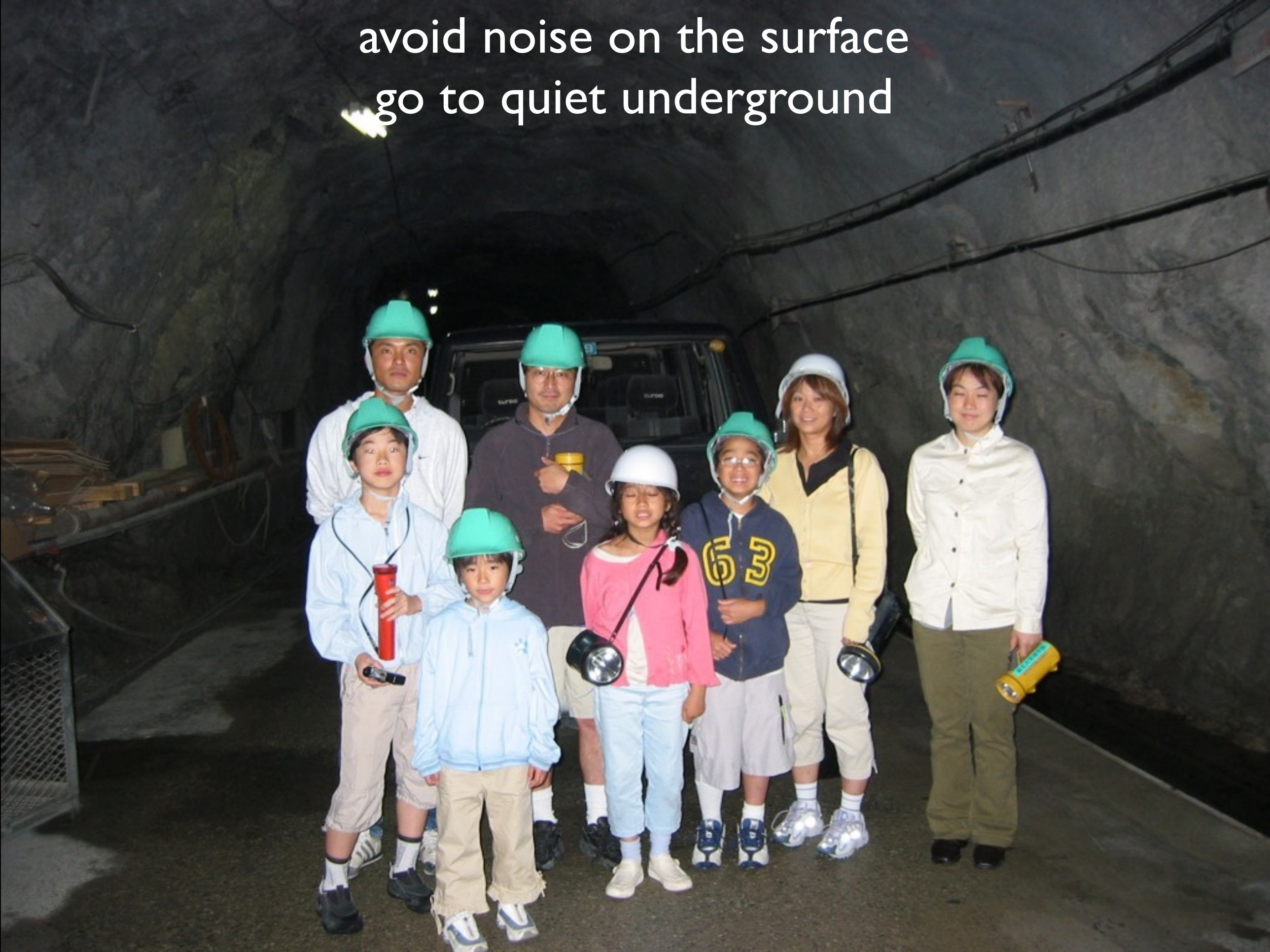

ATLAS Simulation Preliminary
ATL-PHYS-PUB-2014-010
0-lepton combined
ATLAS 20.3 fb-1, √s = 8 TeV, 95% CL
95% CL limit, 3000 fb-1, ⟨μ⟩ = 140
95% CL limit, 300 fb-1, ⟨μ⟩ = 60
5σ disc., 3000 fb-1, ⟨μ⟩ = 140
5σ disc., 300 fb-1, ⟨μ⟩ = 60
Decay forbidden
mg̃ [GeV]
mχ̃01 [GeV]

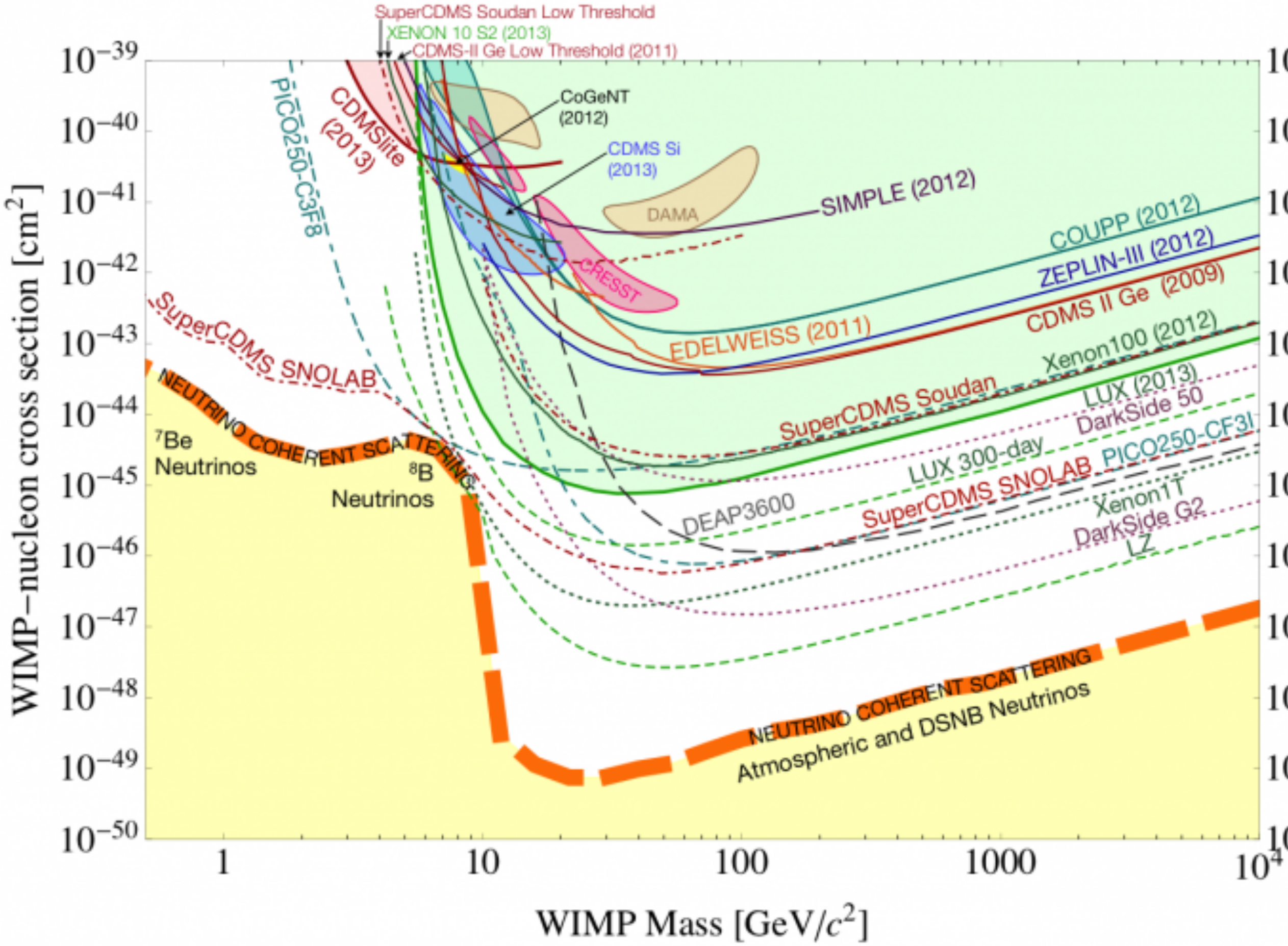
WIMPs



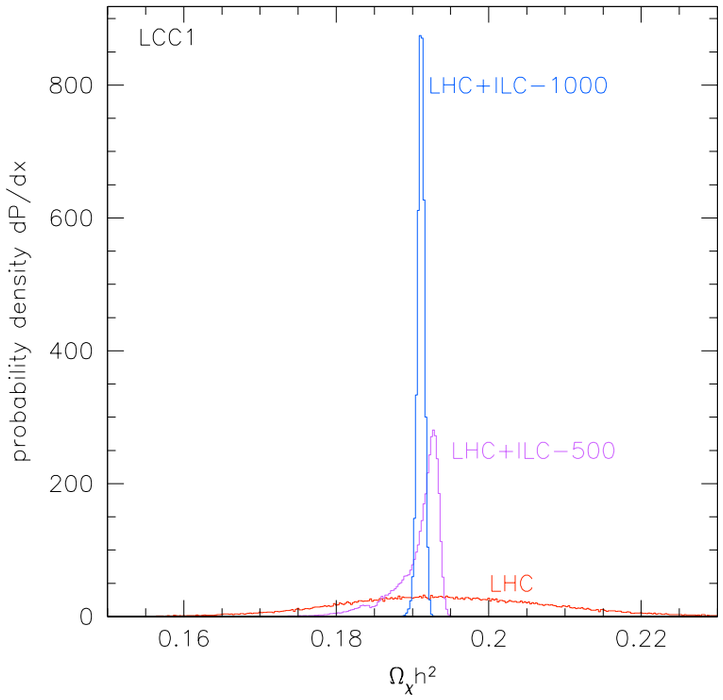
- It is probably WIMP (Weakly Interacting Massive Particle)
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation
- millions of them go through your body every second

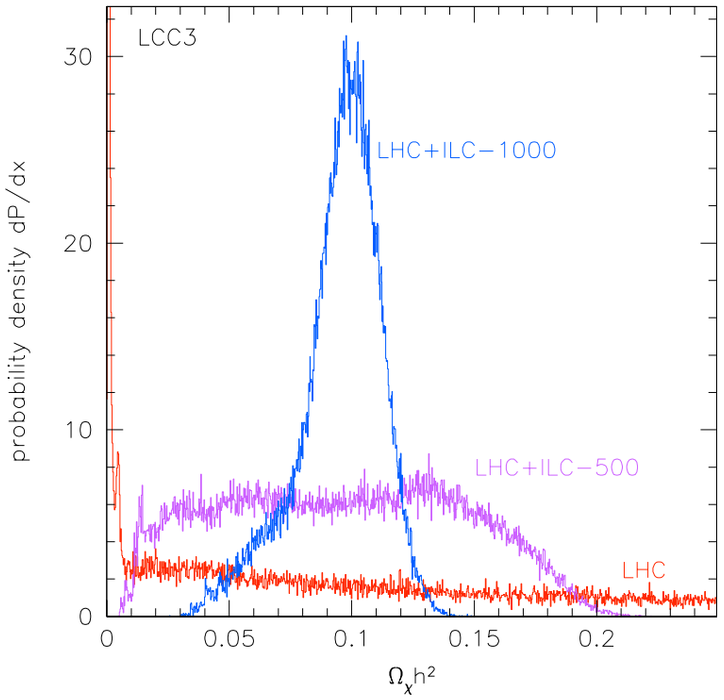
avoid noise on the surface
go to quiet underground

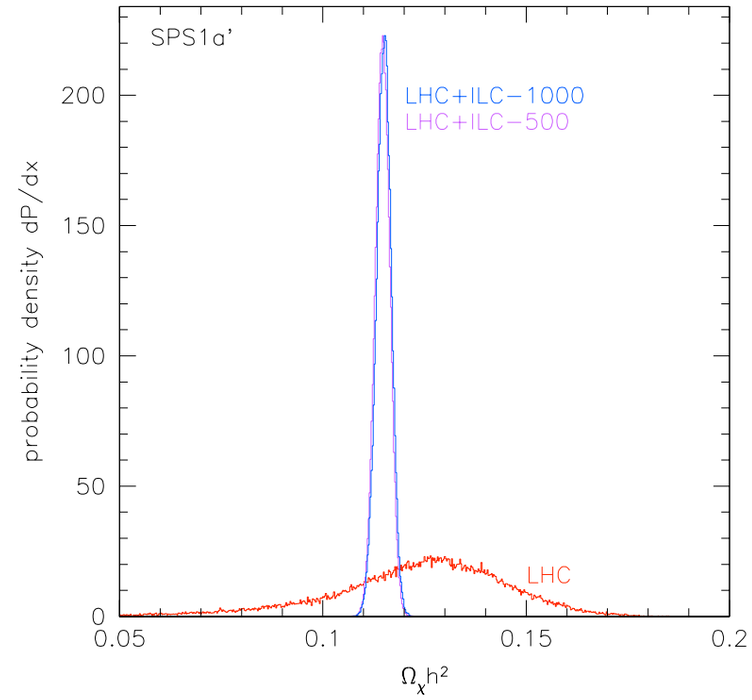


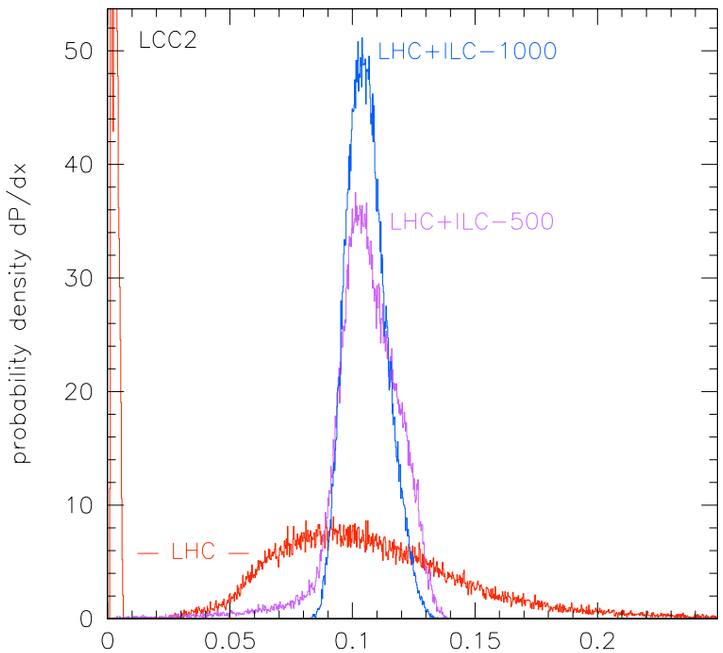

SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CDMSlite (2013)
PICO250-C3F8
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
SuperCDMS SNOLAB
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
1
10
100
1000
10^4

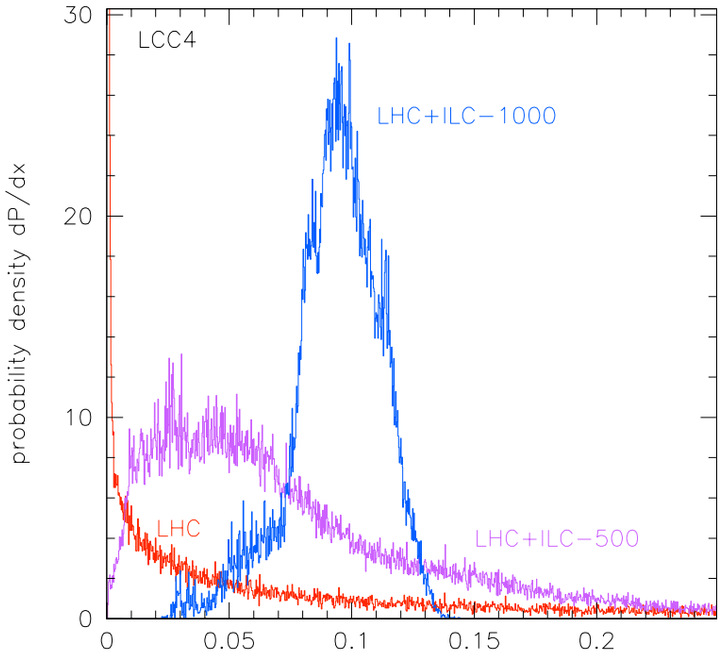
Omega from colliders











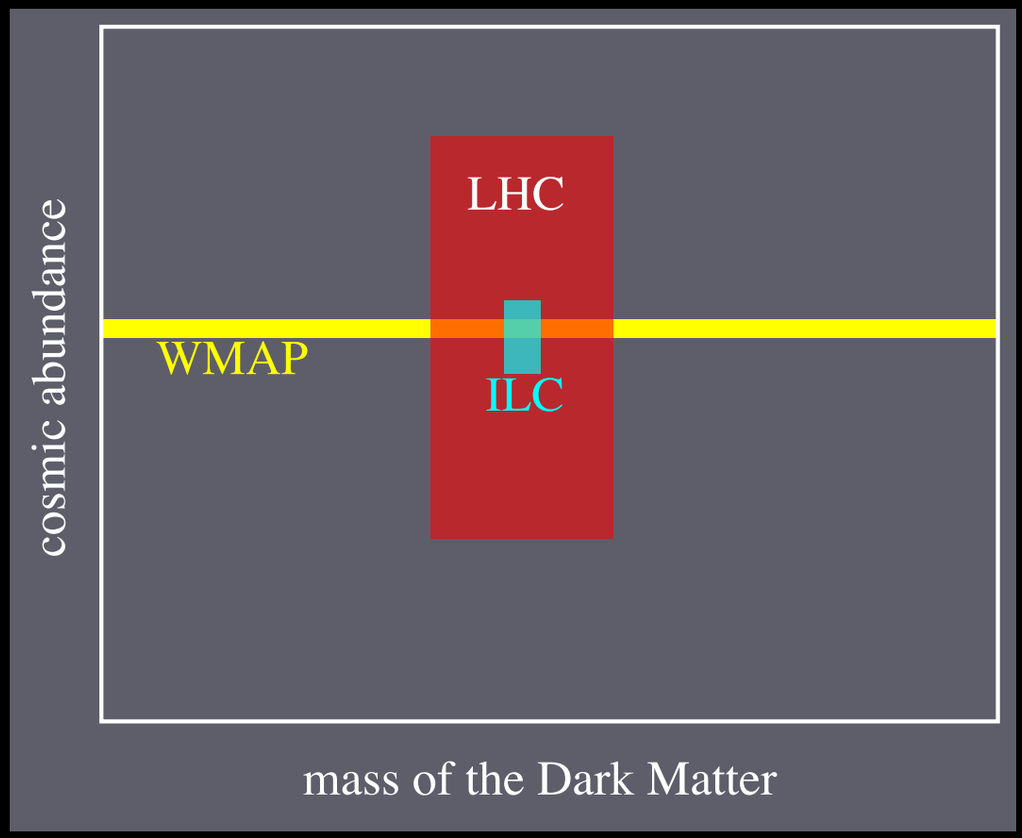
SUSY case study
Baltz, Battaglia, Peskin,
Wizansky hep-ph/0602187

program

- telescope measurement of dark matter
- underground detection experiments
- production with accelerators
- If they agree with each other:

⇒ Will know *what Dark Matter is*

⇒ Will understand universe back to $t \sim 10^{-10}$ sec



History of the Universe

3min

380k yrs

13.8Bzyrs

10⁻¹⁰ sec

erators

on

high-energy cosmic rays

Inflation

BIG BANG

?

possible dark matter relicts

DM

CMB

cosmic microwave radiation visible

t 10⁻⁴⁴ 10⁻³⁷ s
T 10³² 10²⁸
E 10¹⁹ 10¹⁵

10⁻¹⁰ s
10¹⁵
10²

10⁻⁵ s
10¹²
10⁻¹

10² s
10⁹
10⁻⁴

3x10⁵ y
3000
3x10⁻¹⁰

10⁹ y
15
10⁻¹²

12x10⁹ y (sec,yrs)
2.7 (Kelvin)
2.3x10⁻¹³ (GeV)

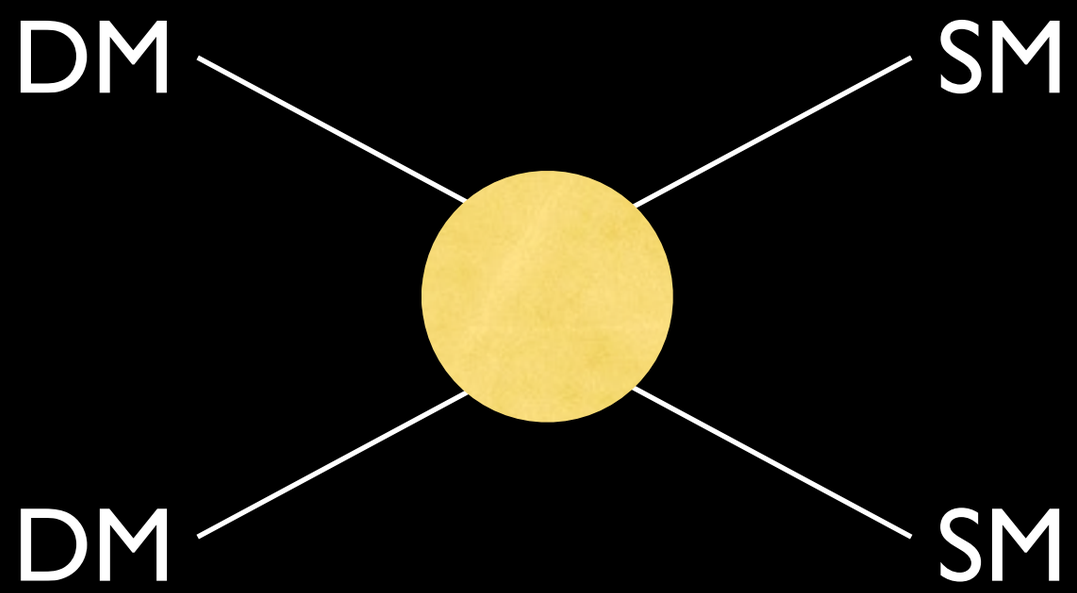
Today

Key:

- W, Z bosons
- photon
- q quark
- meson
- galaxy
- g gluon
- baryon
- star
- e electron
- ion
- μ muon τ tau
- atom
- black hole
- ν neutrino

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10}\,\frac{\rm GeV}{m_{\rm DM}}$$

Miracles

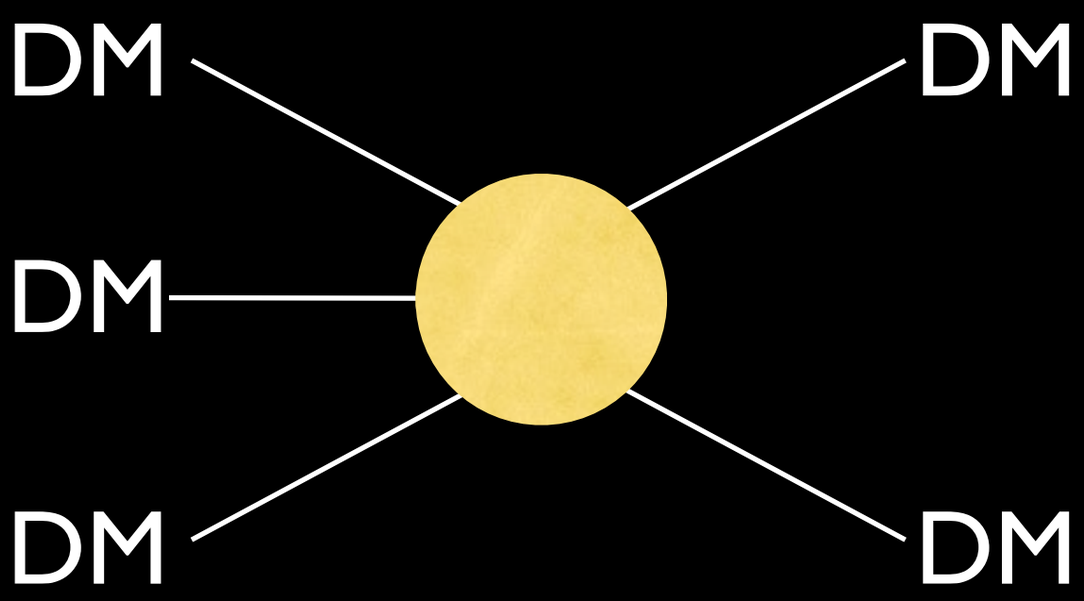


$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300\ \text{GeV}$$

WIMP miracle!



$$\langle \sigma_{3\to 2} v^2 \rangle \approx \frac{\alpha^3}{m^5}$$

$$\alpha \approx 4\pi$$

Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

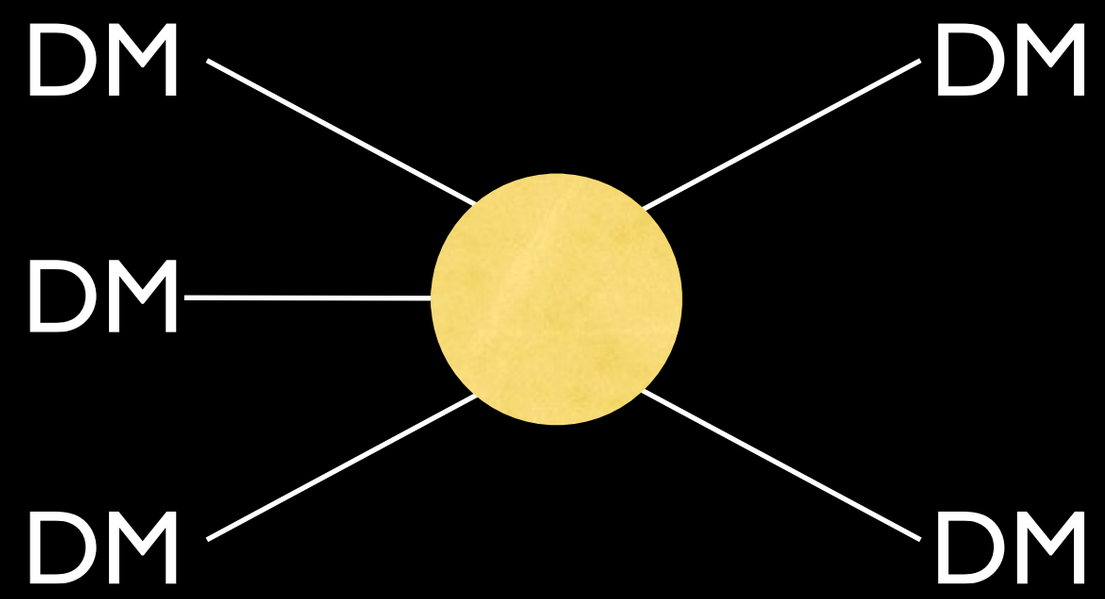
$$m \approx 300\text{MeV}$$

SIMP miracle!

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10}\,{\rm GeV}\,\frac{}{m_{\rm DM}}$$

SIMPlest Miracle

- Not only the mass scale is similar to QCD
- dynamics itself can be QCD! Miracle^3
  - DM = pions
  - e.g. SU(4)/Sp(4) = S^5



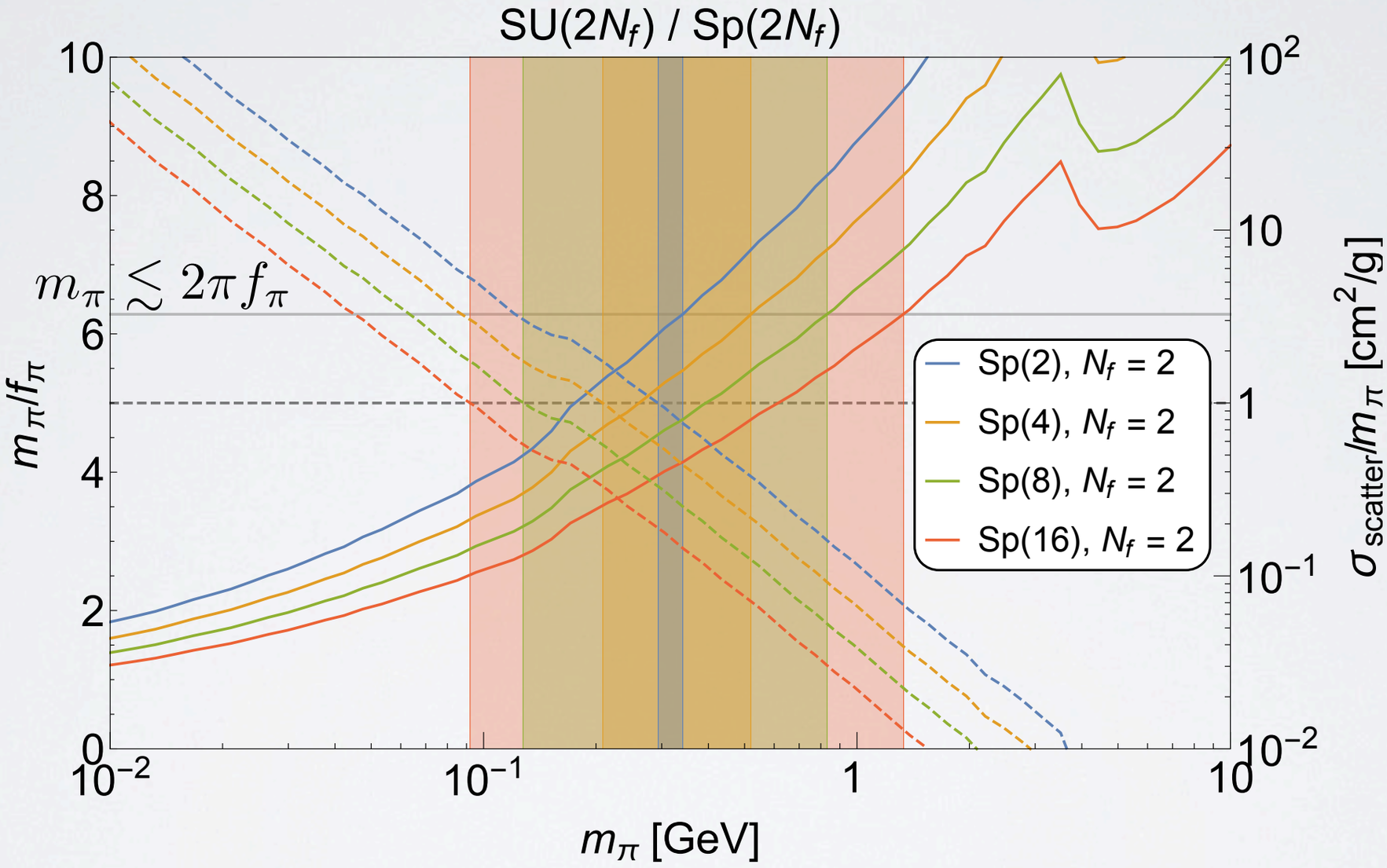
+HM
arXiv:1411.3727

$$\mathcal{L}_{\rm chiral} = \frac{1}{16 f_\pi^2}{\rm Tr}\partial^\mu U^\dagger \partial_\mu U$$

$$\mathcal{L}_{\rm WZW} = \frac{8N_c}{15\pi^2 f_\pi^5}\epsilon_{abcde}\epsilon^{\mu\nu\rho\sigma}\pi^a\partial_\mu\pi^b\partial_\nu\pi^c\partial_\rho\pi^d\partial_\sigma\pi^e + O(\pi^7)$$

$$\pi_5(G/H) \neq 0$$

THE RESULTS



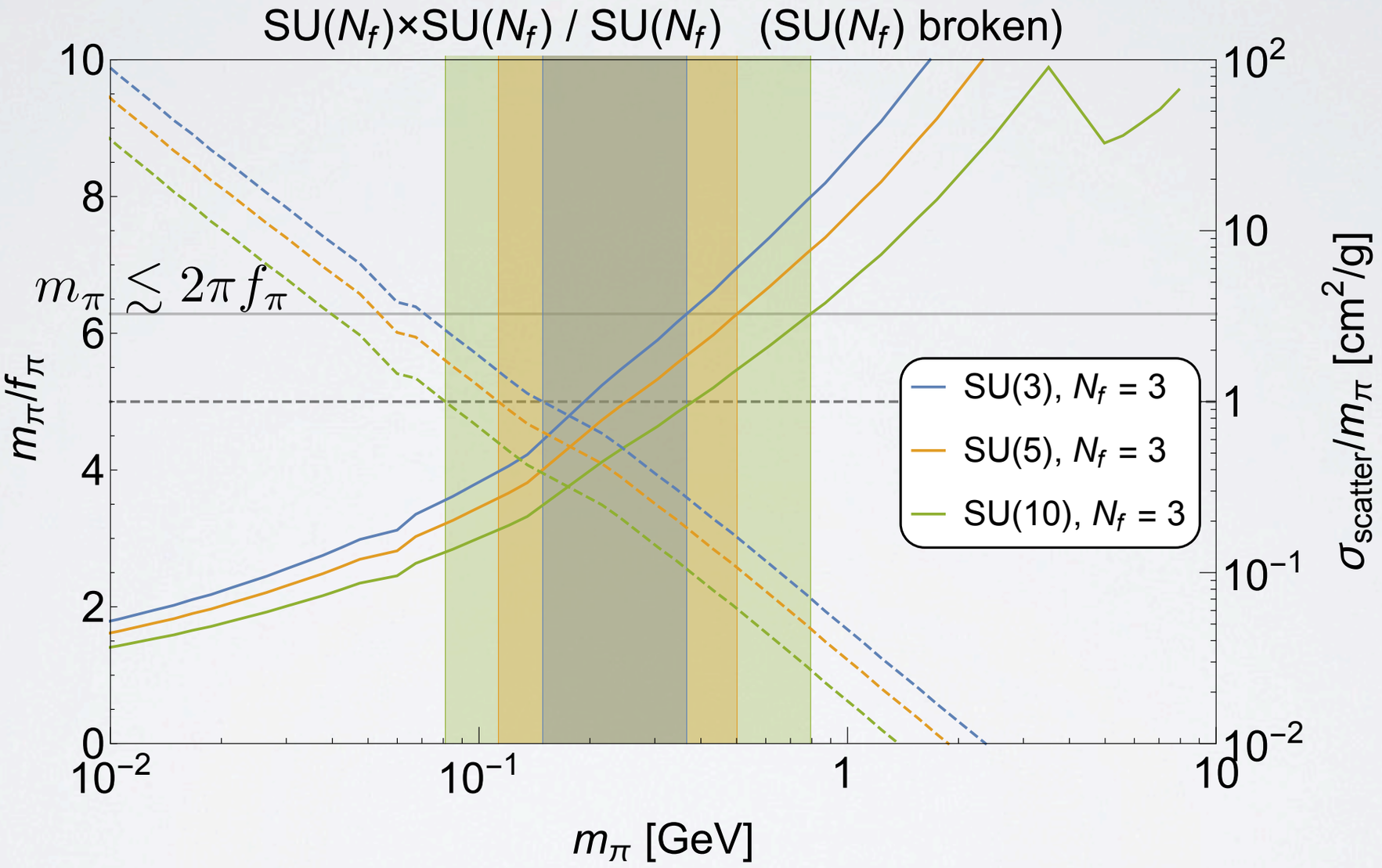
Solid curves: solution to Boltzmann eq.

$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

Dashed curves: along that solution

$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

THE RESULTS



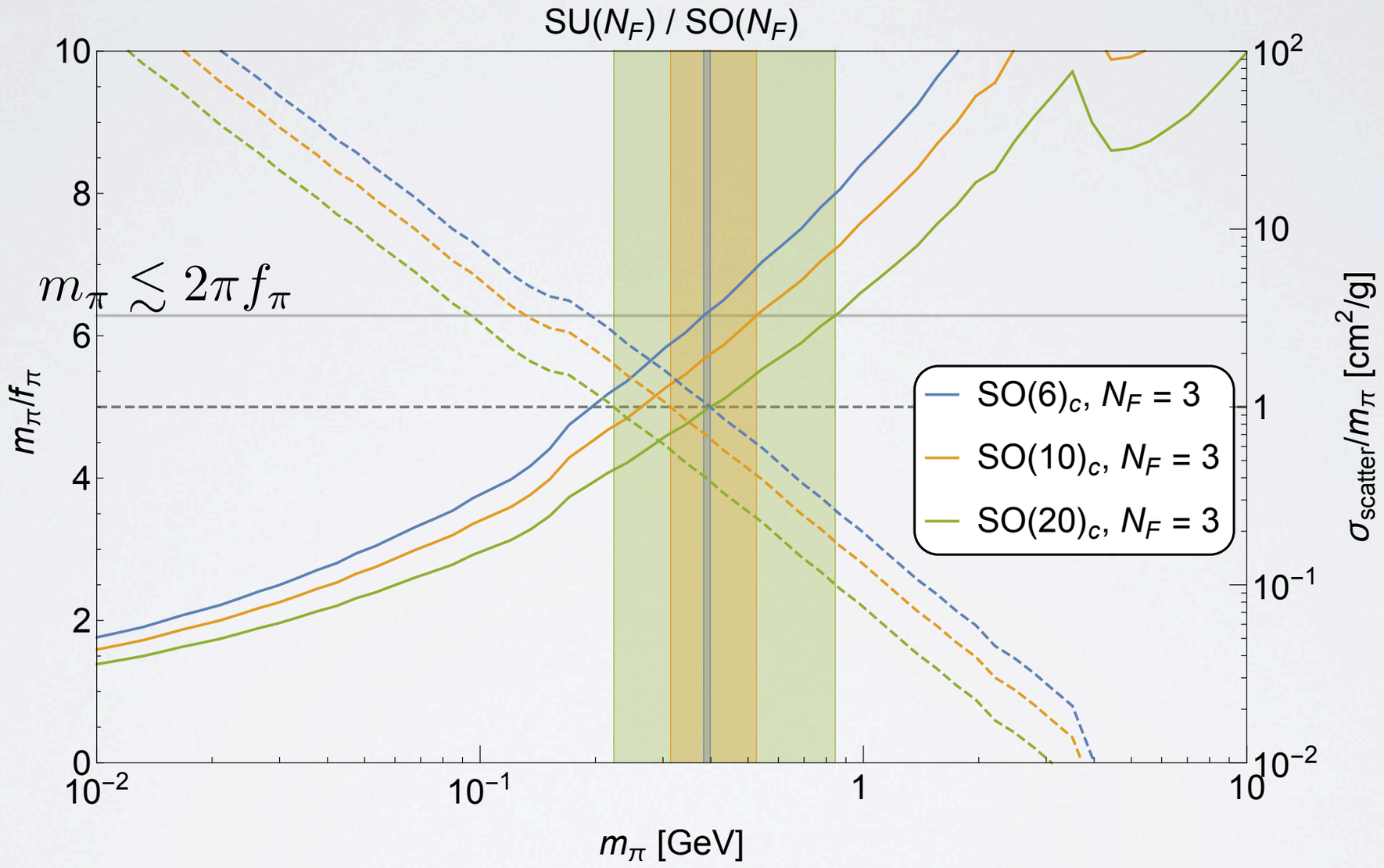
Solid curves: solution to Boltzmann eq.

$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

Dashed curves: along that solution

$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

THE RESULTS



Solid curves: solution to Boltzmann eq.

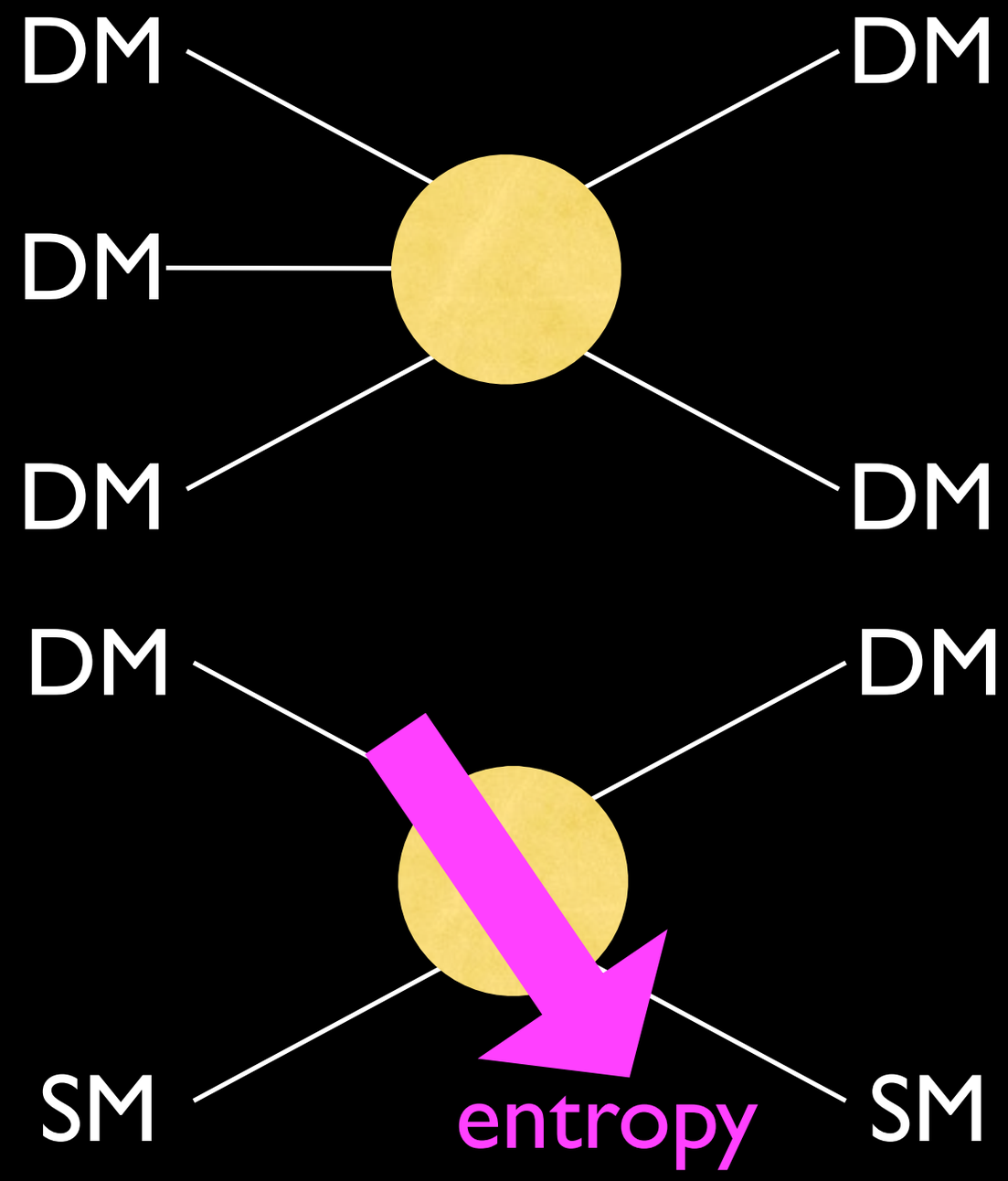
Dashed curves: along that solution

$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

communication

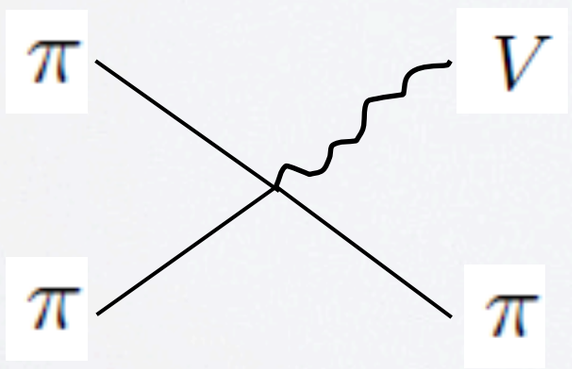
- 3 to 2 annihilation
- excess entropy *must* be transferred to $e^{\pm}$, γ
- need communication at some level
- leads to experimental signal



VECTOR PORTAL

- Gauge a U(1) subgroup of the flavor symmetry
  - New gauge-boson kinetically mixed with the hyper charge gauge boson

Avoid semi-annihilation:

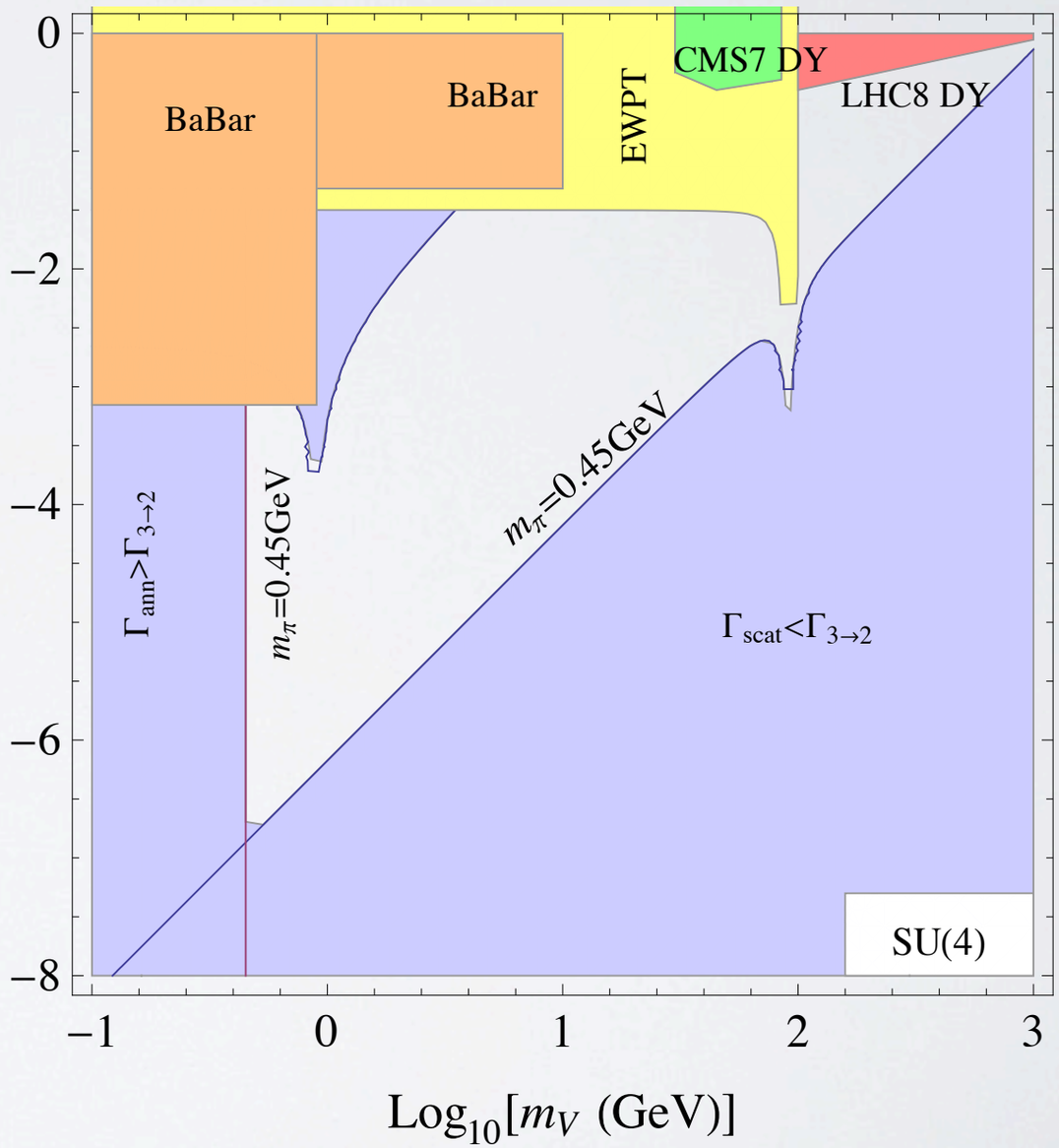


$$m_V > m_\pi$$

KINETICALLY MIXED U(1)

- e.g., SU(4) gauge group with Nf=3
- gauged U(1): $\begin{pmatrix} 1 & & \\ & -1 & \\ & & -1 \end{pmatrix}$
- kinetic mixing induced by:

$$\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$$

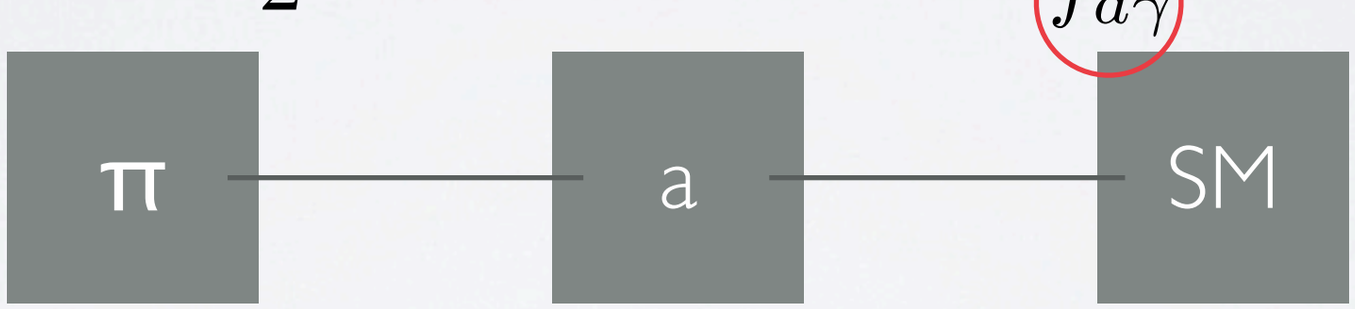


[Lee, Seo 1504.00745]

AXION PORTAL

- e.g., SU(2) gauge group with 2 flavors and coupling to photons

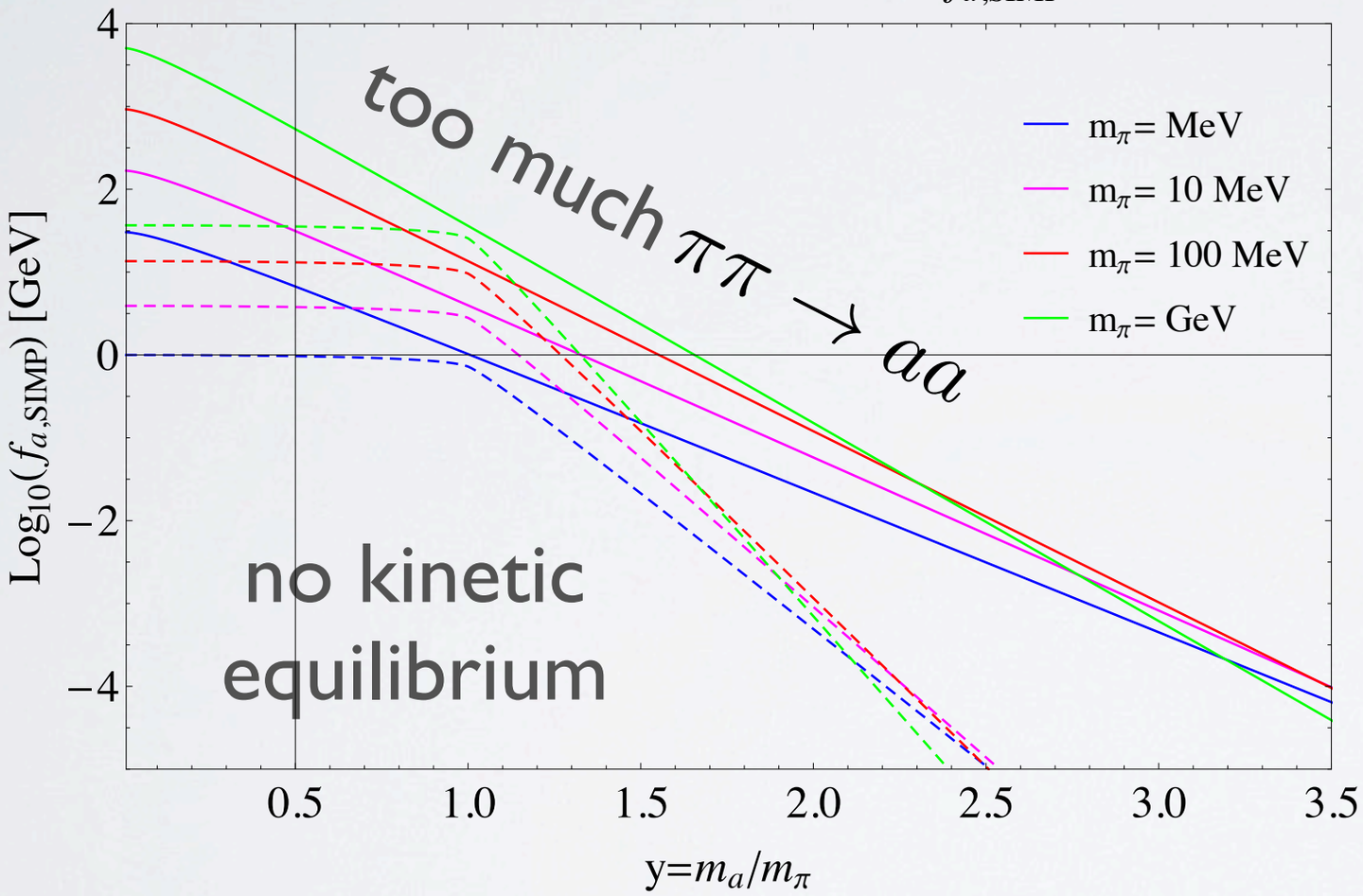
$$\mathcal{L}_{\text{axion}} = -\frac{1}{2} m_q e^{ia/f_a} J^{ij} q_i q_j + \frac{1}{f_{a\gamma}} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



$$m_a^2 = \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

AXION PORTAL

Axion portal $L = \lambda_1 a^2 \pi^2$, $\lambda_1 = \dfrac{{m_\pi}^2}{4\,{f_{a,\mathrm{SIMP}}}^2}$



Coupling to photons, $L = \dfrac{1}{f_{a\gamma}}\, a\, F\, F^{\mathrm{tilde}}$