

Dark Matter and Dark Energy

Rocky I: Evidence for dark matter and dark energy

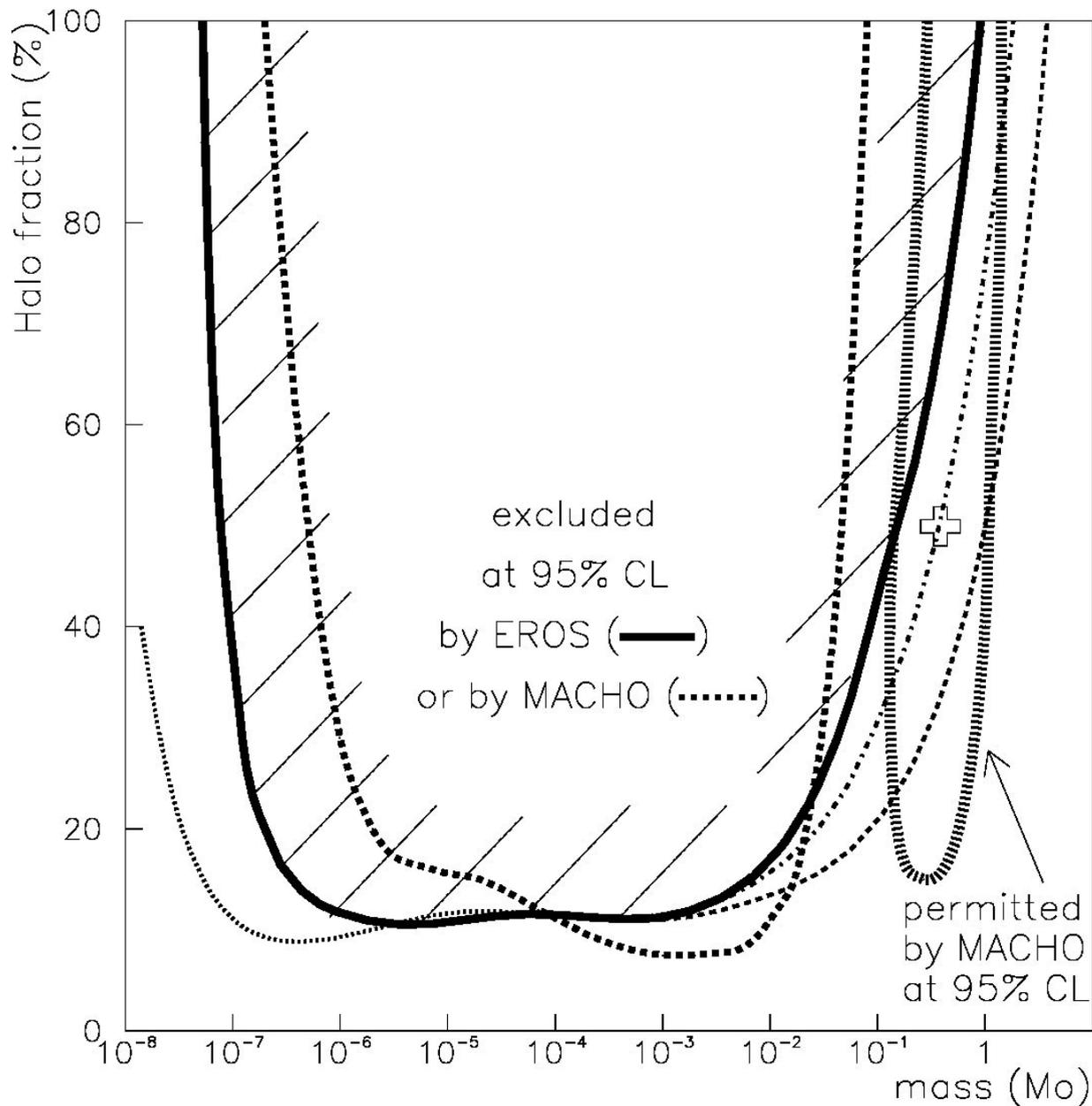
Rocky II: Dark matter candidates

Rocky III: Dark energy reloaded

SLAC Summer Institute, August 2003

Rocky Kolb, Fermilab & The University of Chicago

Microlensing limits

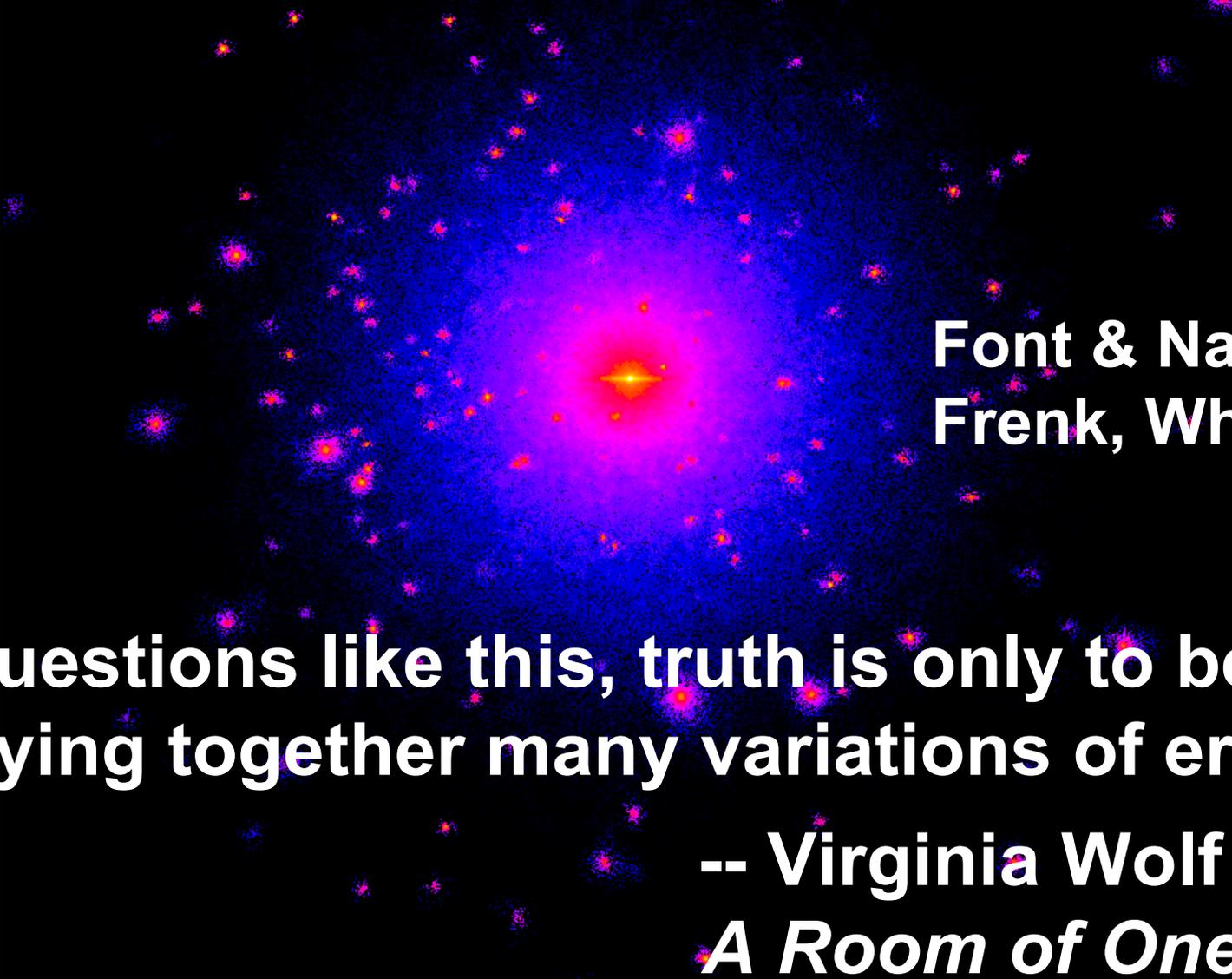


Dark matter?

- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars
 - brown
 - red
 - white
- Black holes
- Nonbaryonic particle dark matter

Epicycle II – Dark matter

What is dark matter?



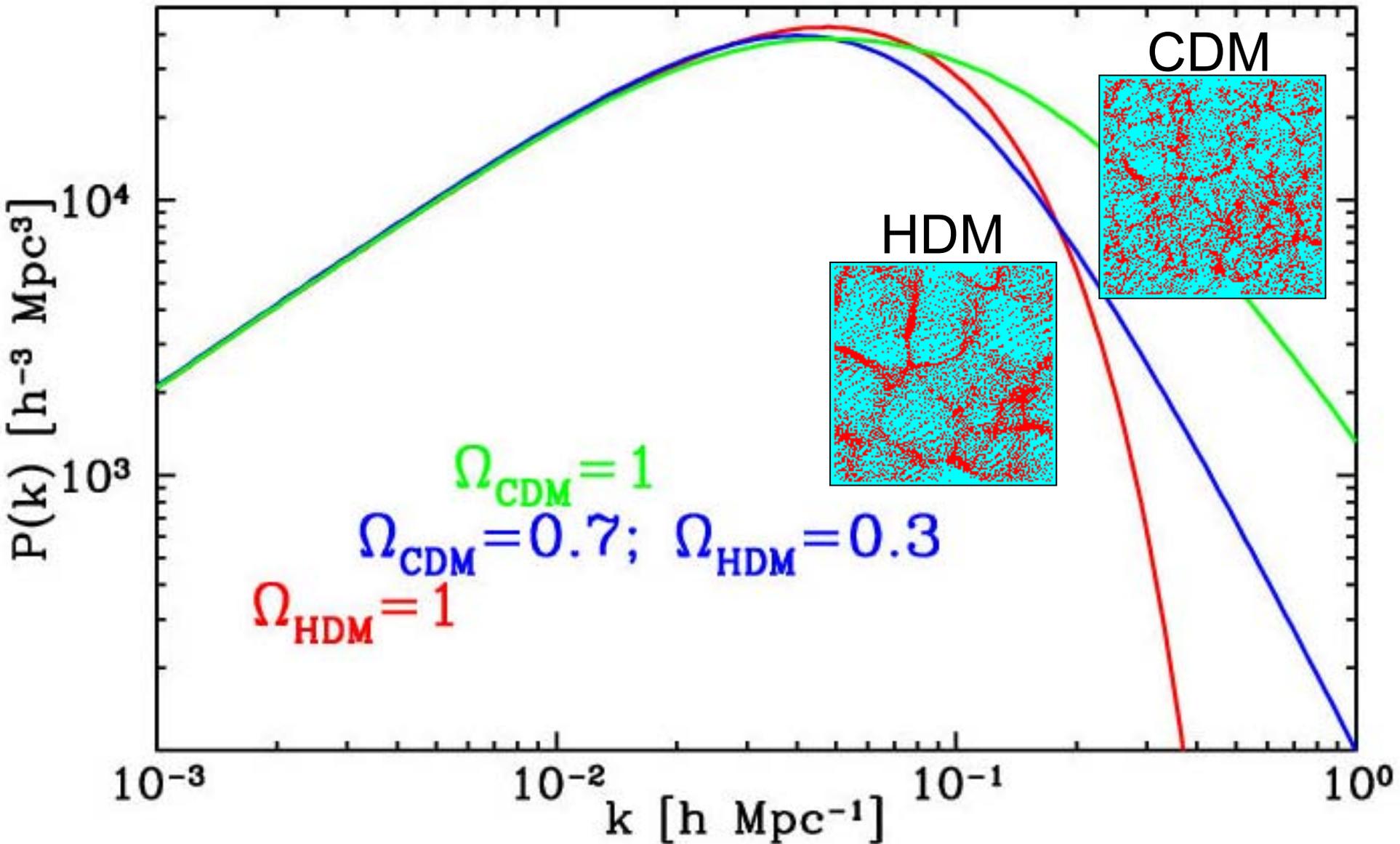
Font & Navarro
Frenk, White, . . .

“In questions like this, truth is only to be had by laying together many variations of error.”

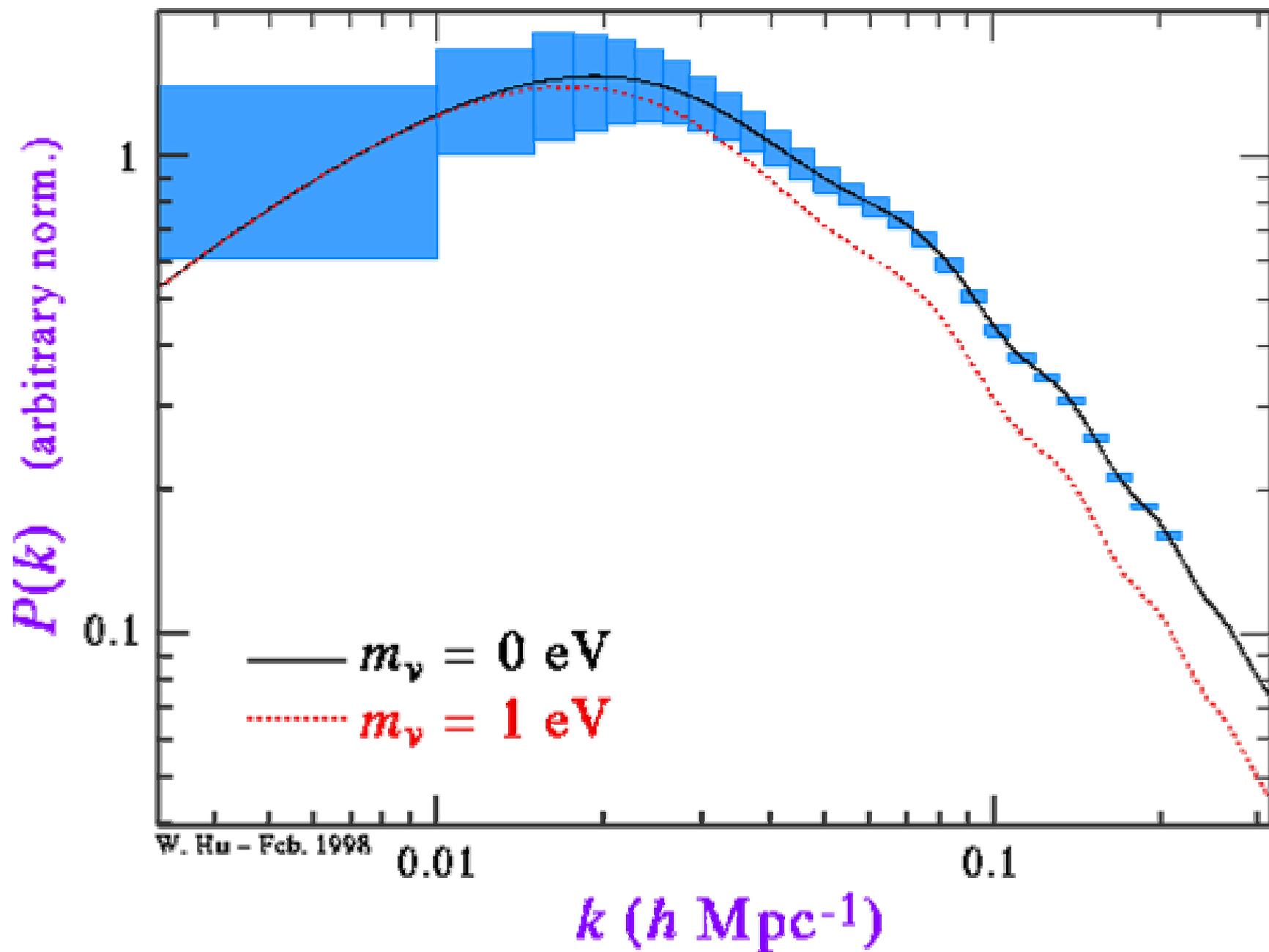
-- Virginia Wolf

A Room of Ones Own

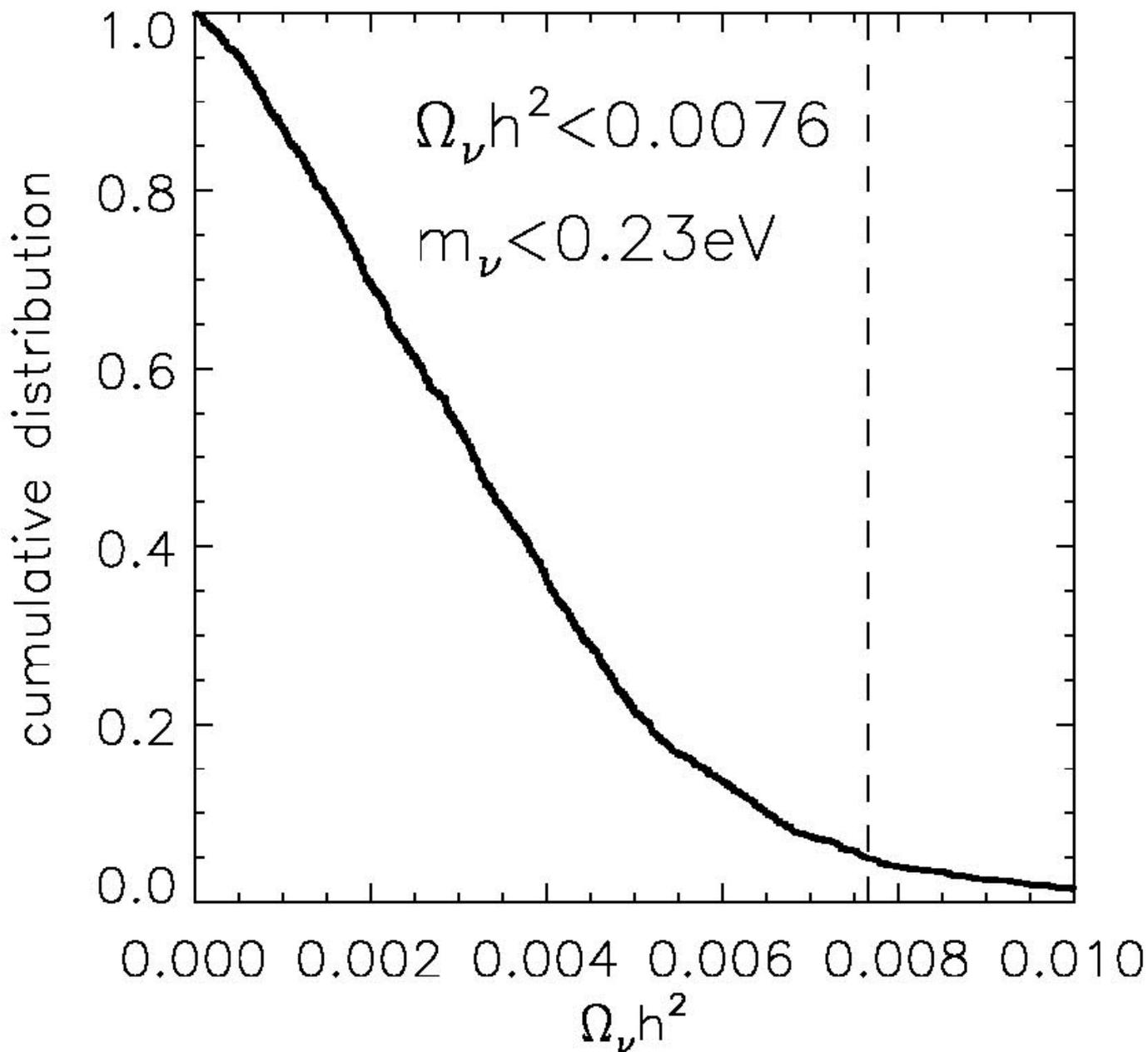
Collisionless damping of HDM



Projected SDSS BRG



WMAP + results



Nonbaryonic dark matter

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)

Sterile neutrinos & gravitinos

- weaker interactions
- decouple earlier
- diluted more
- can have larger mass
- smaller velocity
- “warm”
- satellite & cusp problem?

Particle models with sterile neutrinos or gravitinos in desired mass range are “unfashionable.”

Warm Dark Matter

Nonbaryonic dark matter

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, axino, ...) (cold dark matter)
- LKP (lightest Kaluza-Klein particle)
- axions, axion clusters
- solitons (Q-balls; B-balls; Odd-balls, Screw-balls....)
- supermassive relics



Mass range

• 10^{-6} eV (10^{-40} g) axions

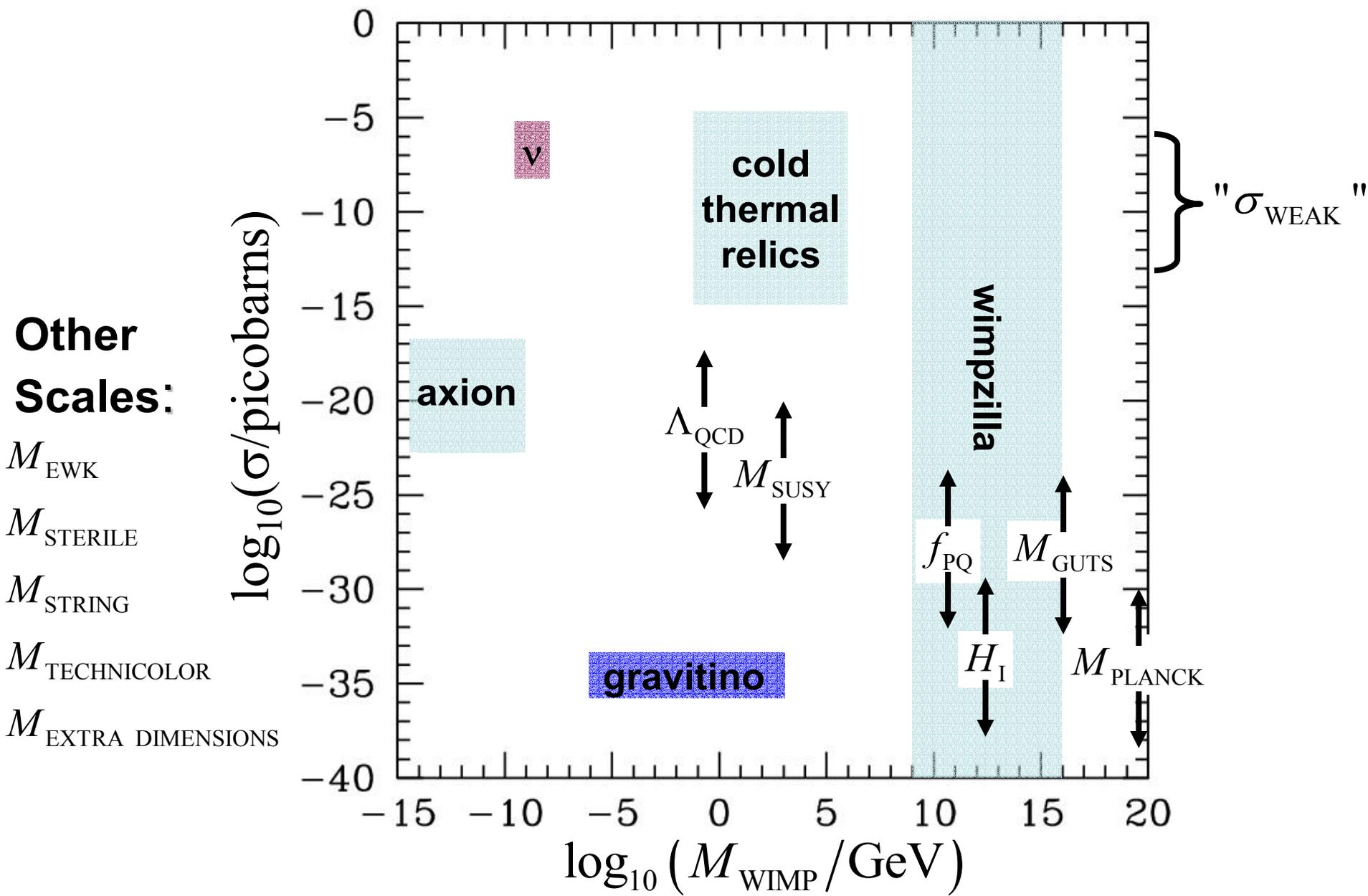
• $10^{-8} M_{\odot}$ (10^{25} g) axion clusters

Interaction strength range

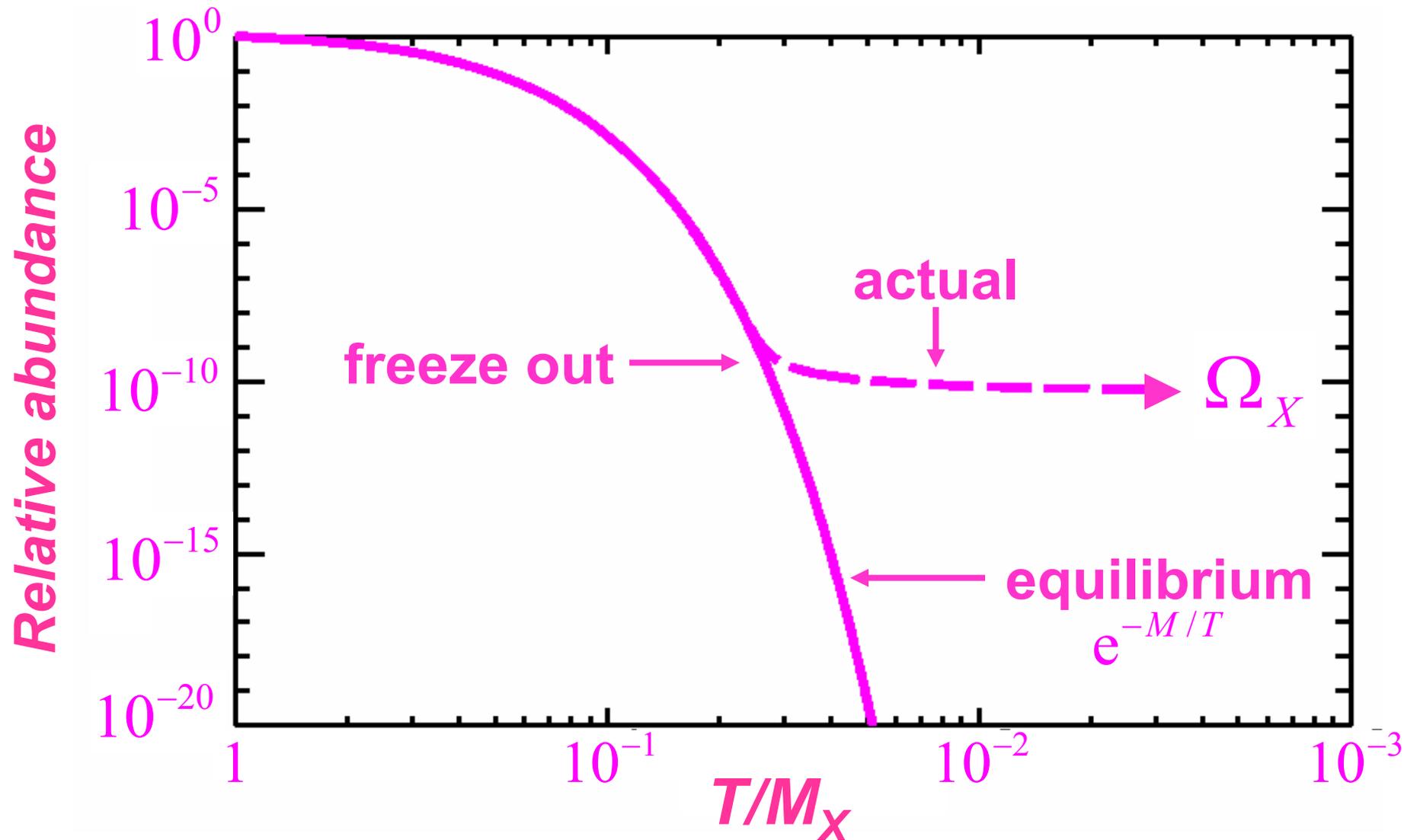
Noninteracting: wimpzillas

Strongly interacting: B balls

Particle Dark Matter Candidates



Cold thermal relics

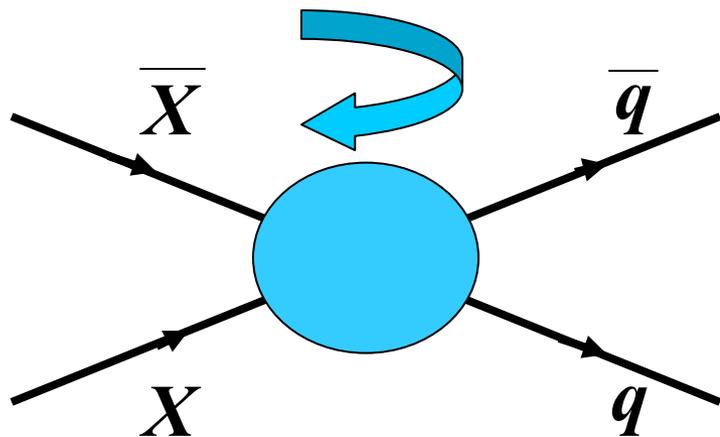


$$\Omega_X \propto \sigma_A^{-1} \quad (\text{independent of mass})$$

Cold thermal relics

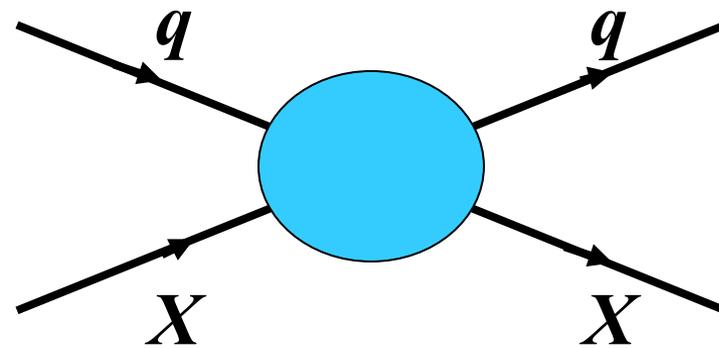
$$\Omega_X h^2 \sim \langle \sigma_A v \rangle^{-1}$$

$$\sigma_A \Leftrightarrow \Omega_X$$



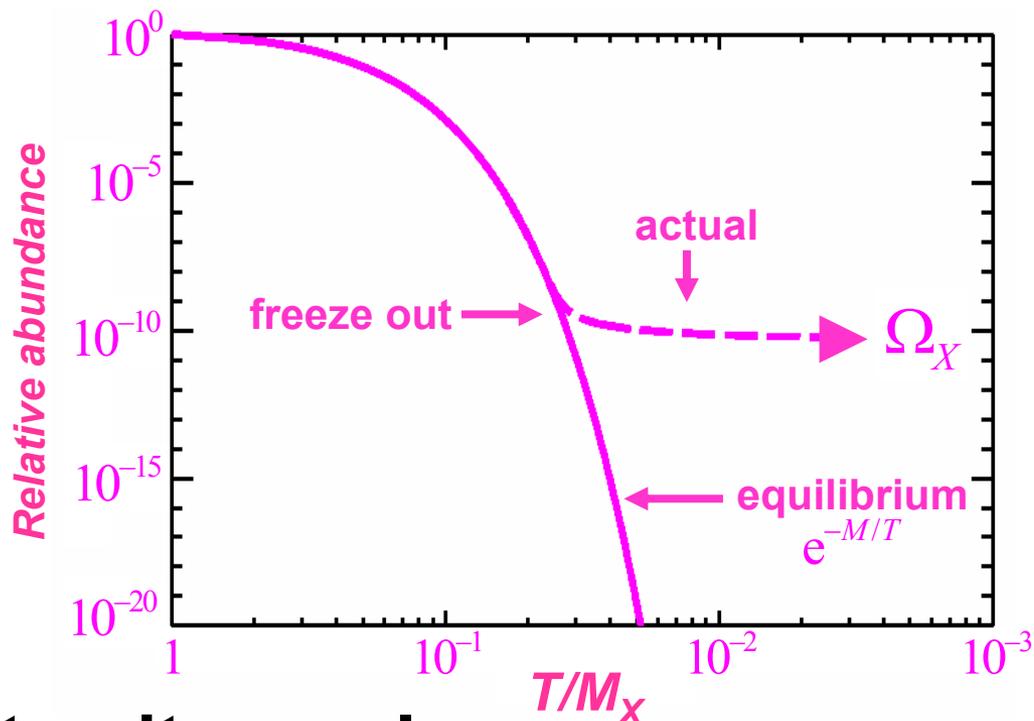
$$X + \bar{X} \rightarrow q + \bar{q}$$

$$\sigma_A \Leftrightarrow \sigma_S$$



$$X + q \rightarrow X + q$$

Cold thermal relics



Not quite so clean:

- s-wave or p-wave?
- annihilation or scattering cross section?
- co-annihilation?
- sub-leading dependence on mass, g_* , etc.
- targets are nuclei (spin-dependence)

SUSY

MSSM: The minimal supersymmetric standard model
18 + 106 parameters

MSUGRA: Minimal SUGRA
18 + 5 parameters $A_0, m_0, m_{1/2}, \tan \beta, \text{sign} \mu$

PhenoMSSM: Simplified weak-scale MSSM
18 + 7 parameters $A_b, A_t, M_2, m_A, \tilde{m}, \tan \beta, \mu$

Lightest neutralino: $\tilde{\chi} = a\tilde{\gamma} + b\tilde{Z} + c\tilde{H}_1 + d\tilde{H}_2$

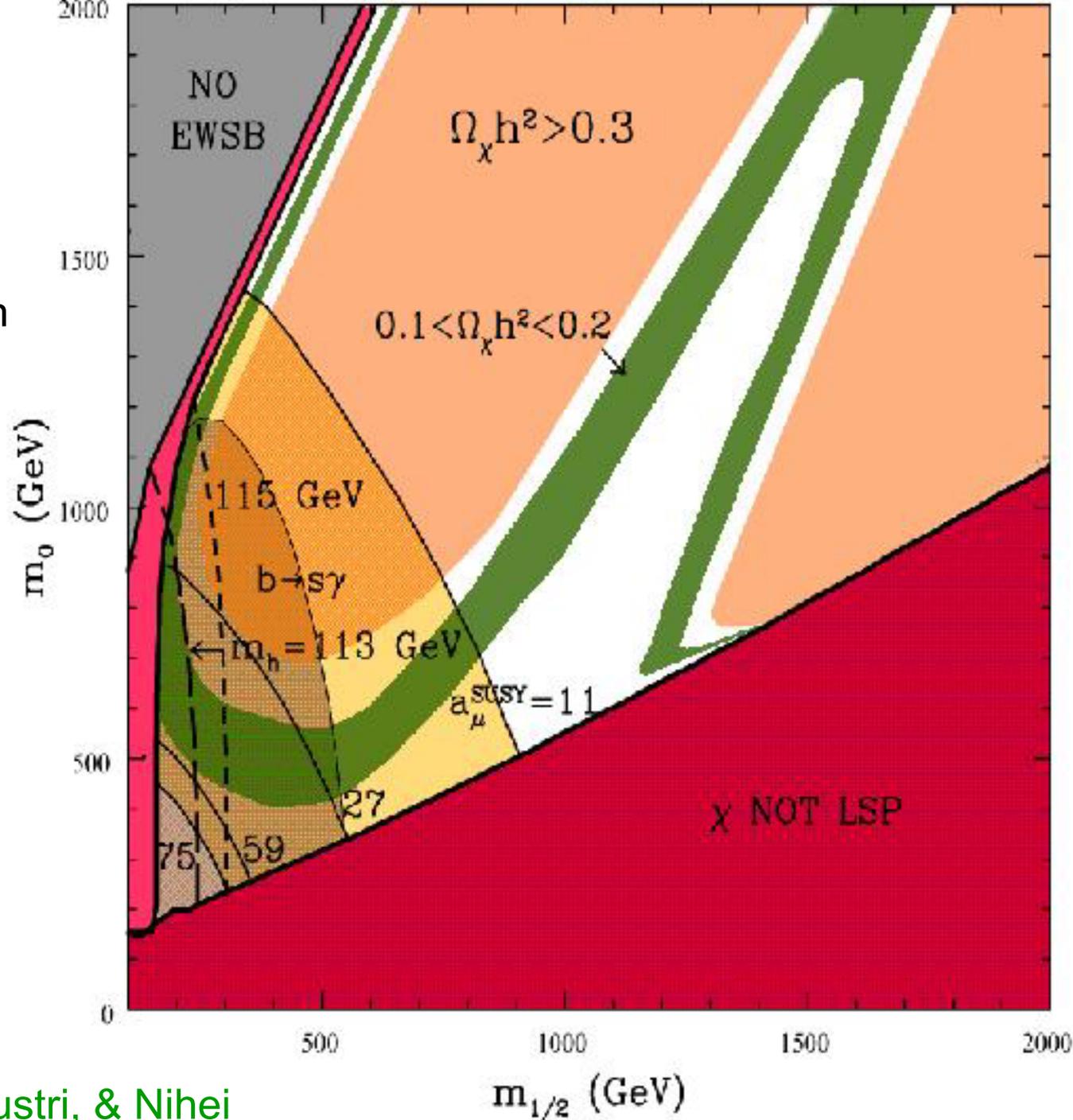
- often lightest R-odd particle
- weakly interacting
- massive ($M \geq 30 \text{ GeV}$)

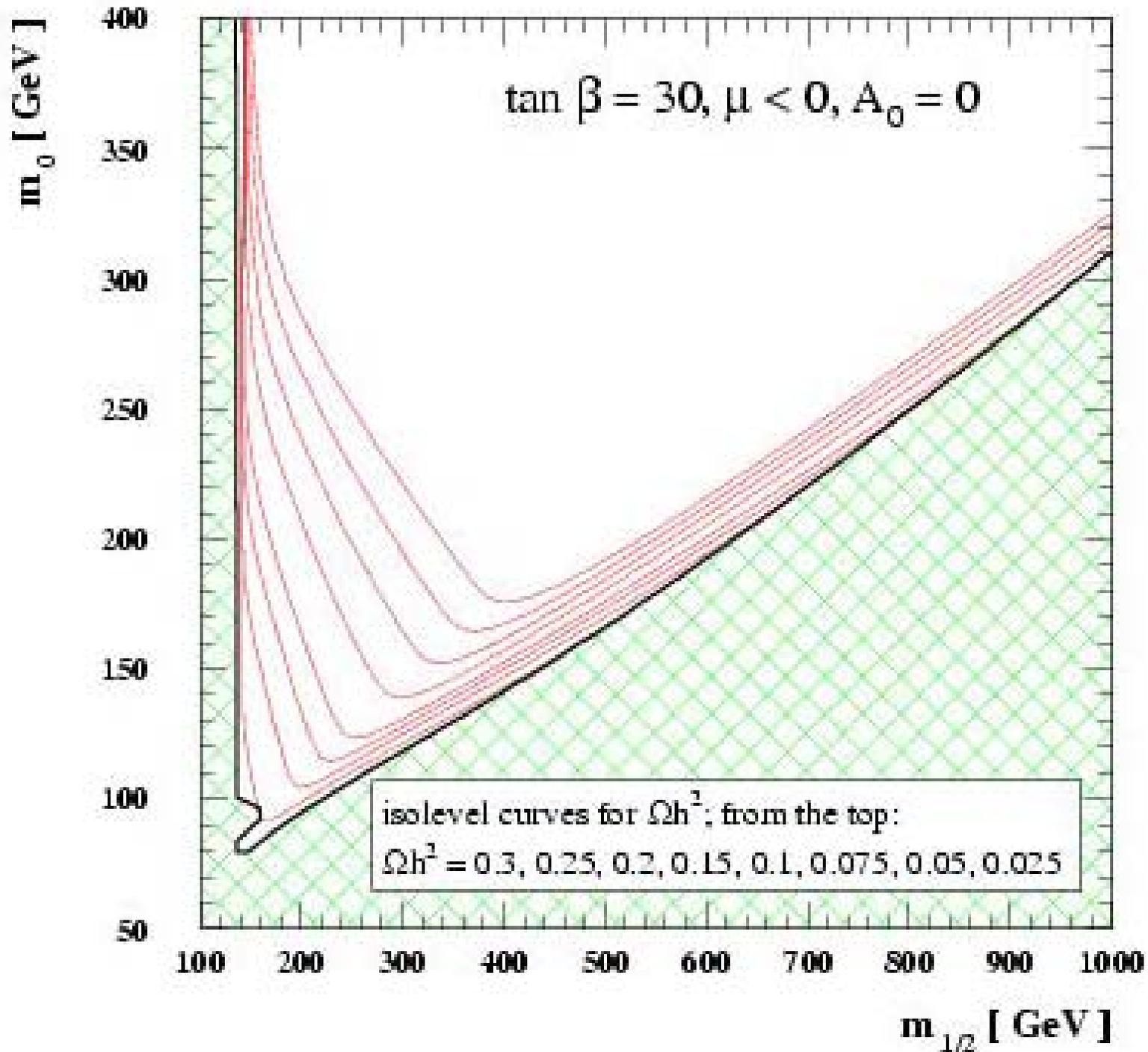
SUSY

- **Neutralino dark matter**
- **Direct detection**
- **Indirect detection**
- **Role of halo substructure**

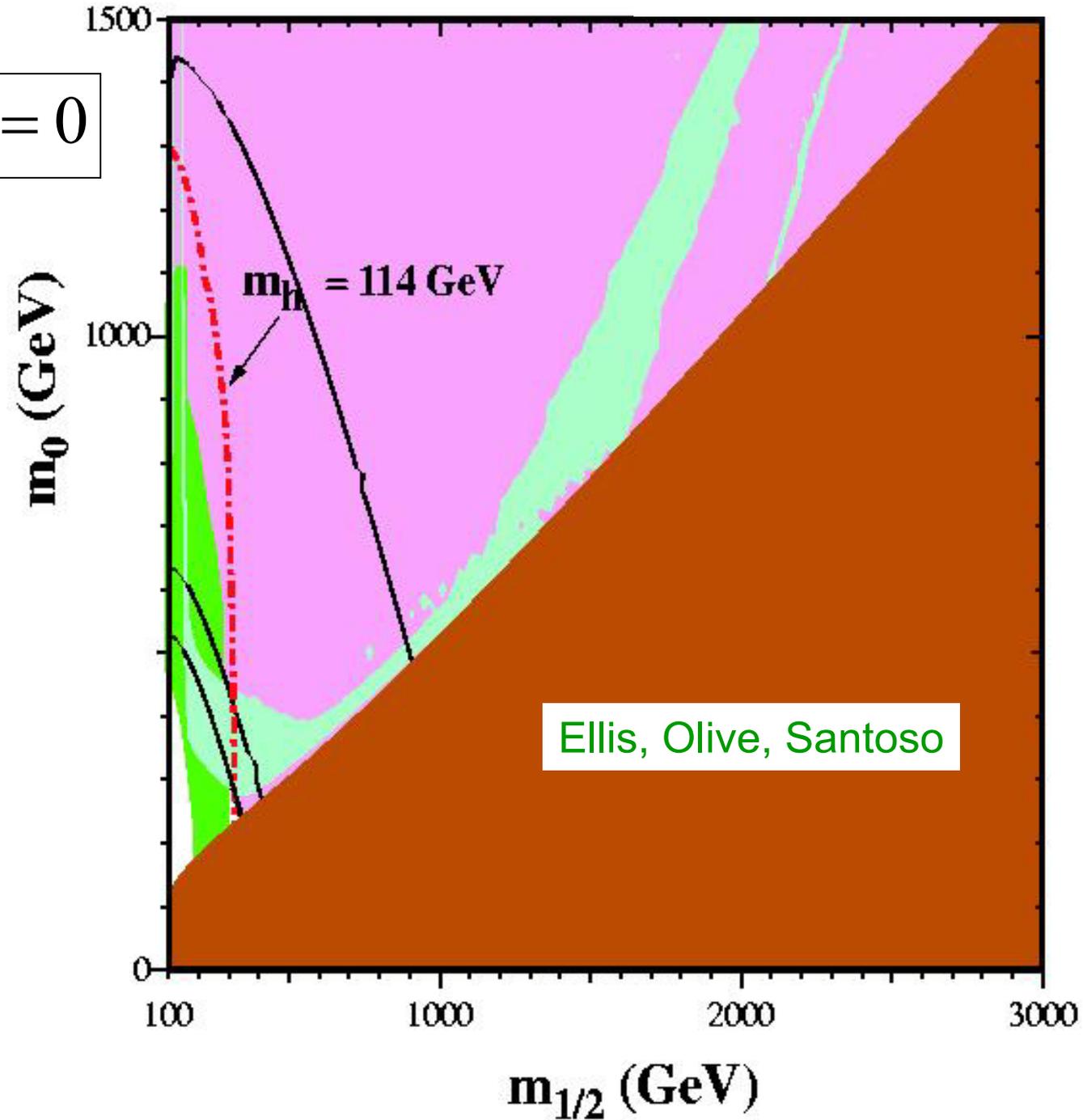
$$\tan \beta = 50$$

wide resonance in
neutralino annihilation



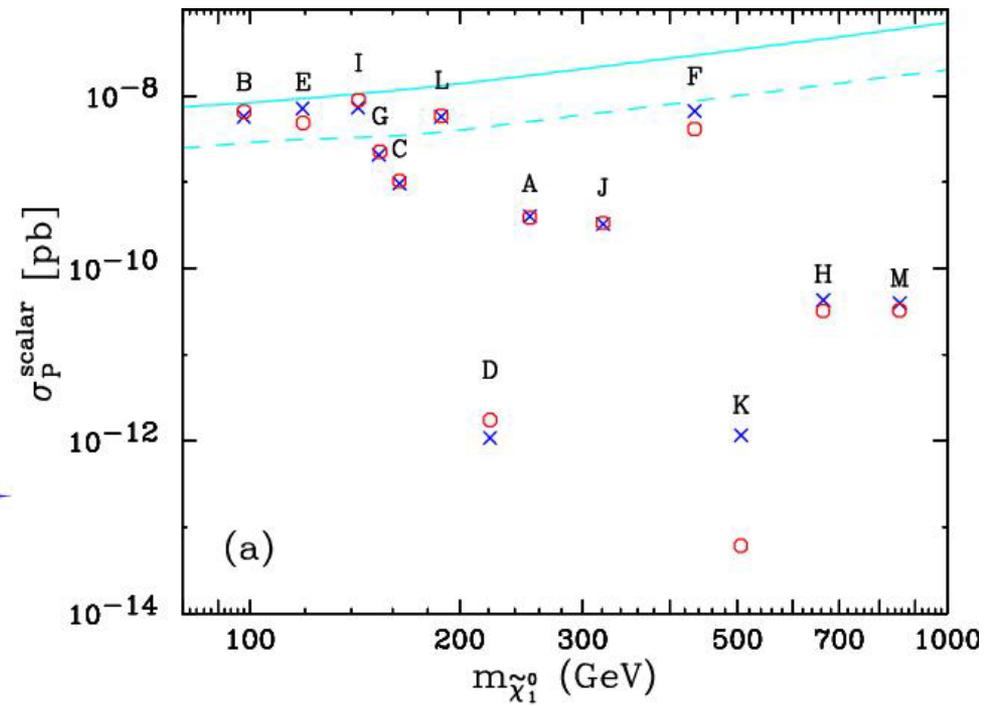
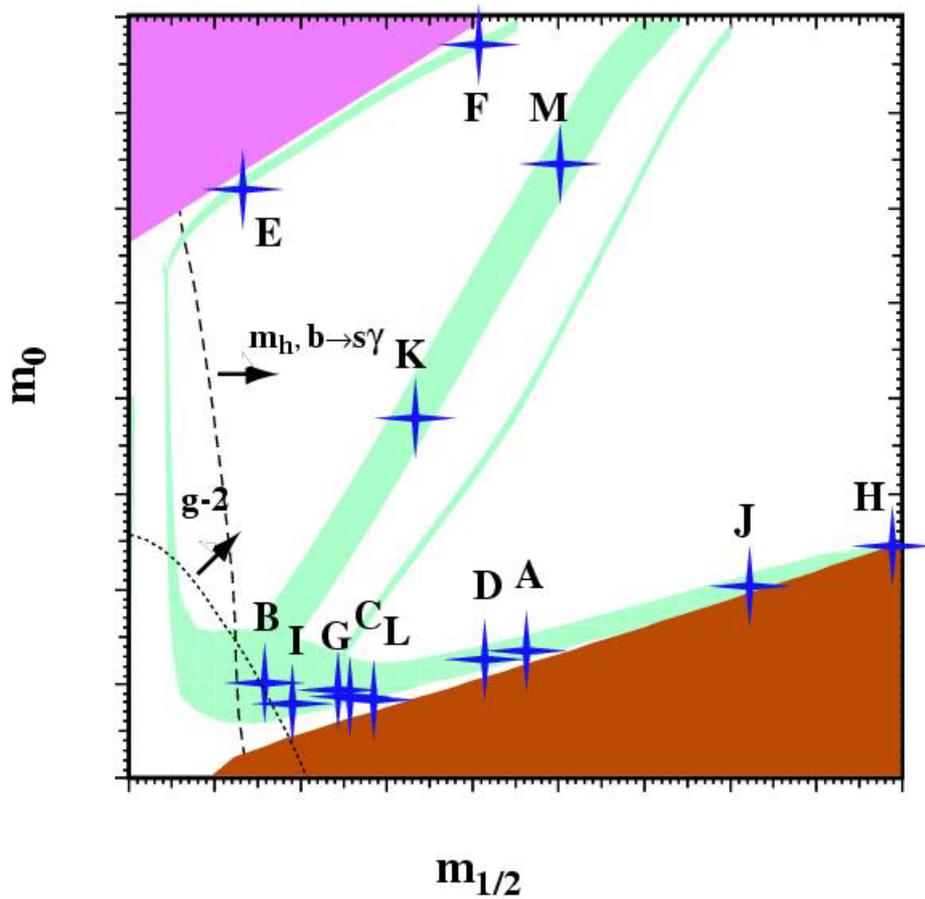


$\tan \beta = 50 \quad A_0 = 0$

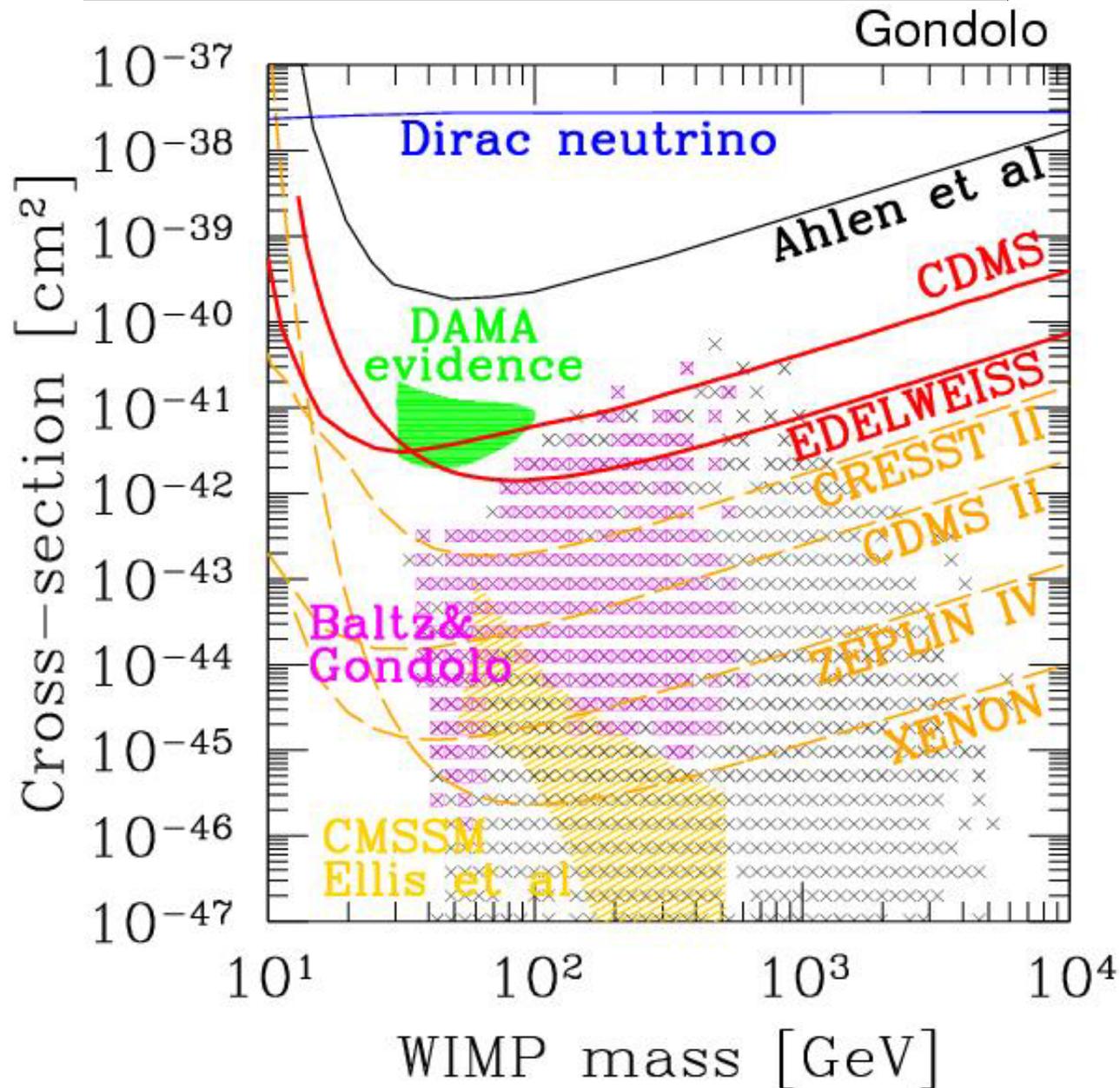


SUSY

Ellis, Olive, Santoso



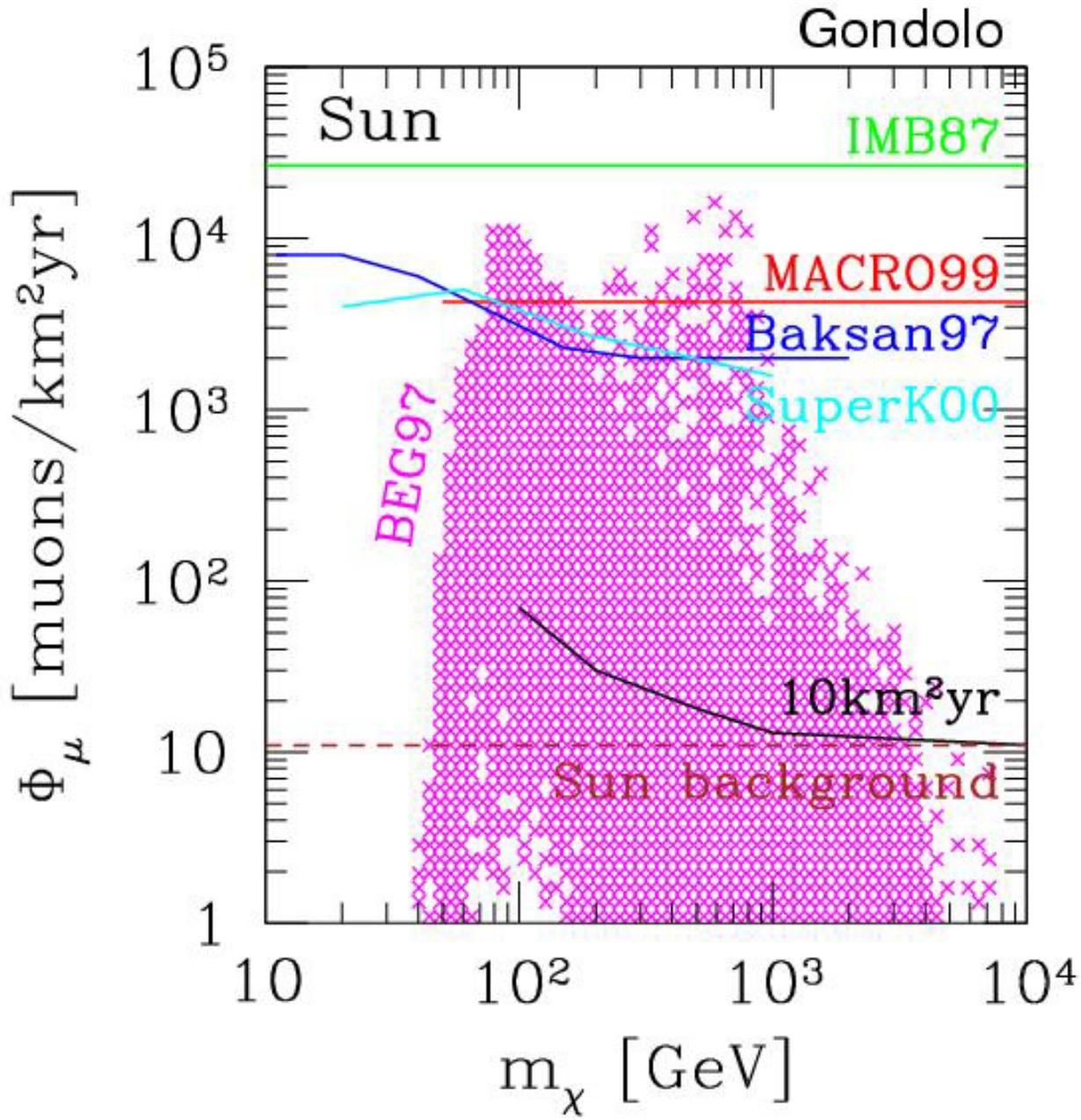
Cold thermal relics

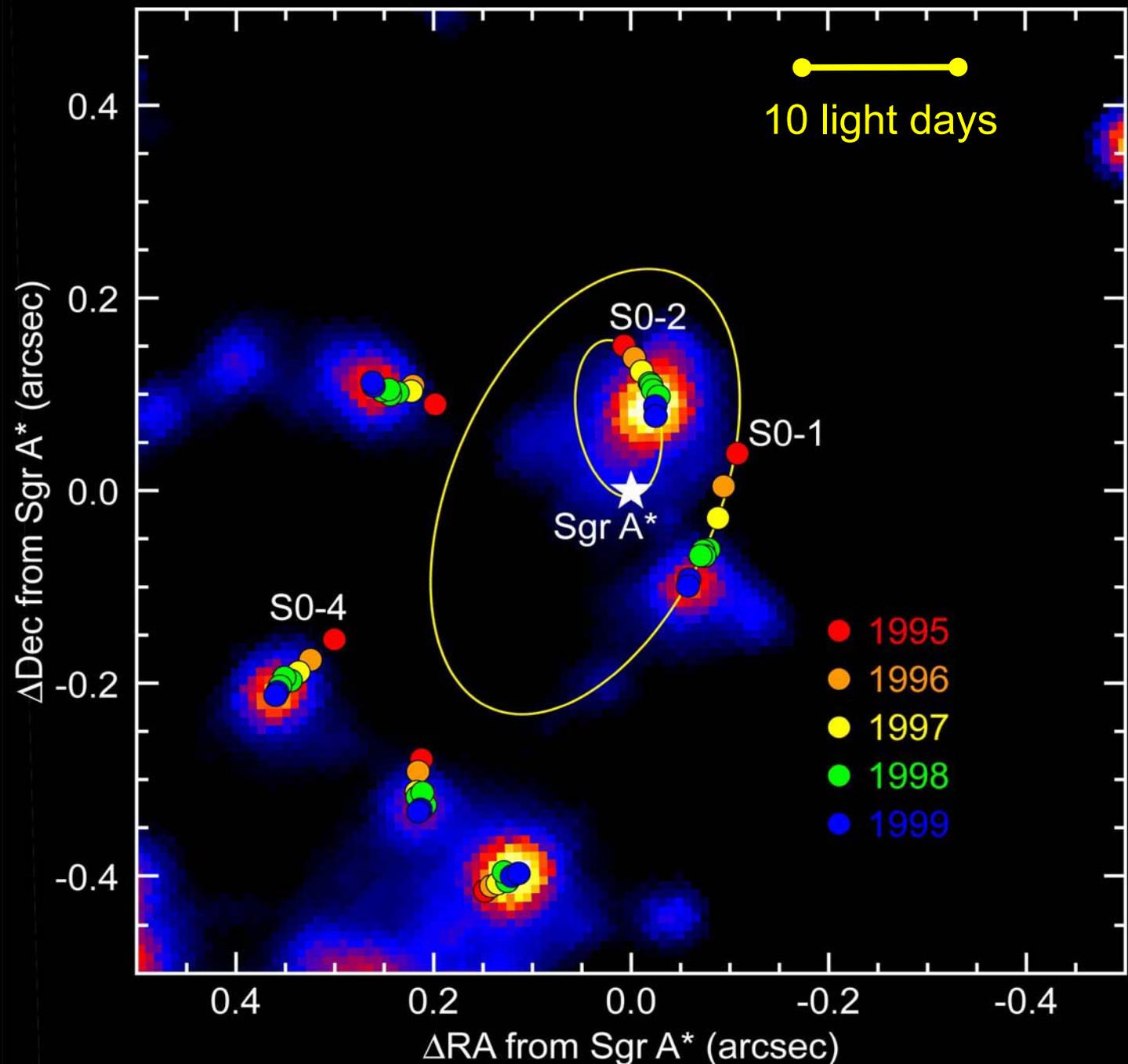


Indirect detection

- **Neutrinos from the sun or Earth**
 - **Anomalous cosmic rays and γ rays from galactic halo(S)**
 - **Neutrinos, g rays , radio waves from our galactic center**
- (Rene Ong)
- **Role of halo substructure (Avishai Deckel)**
rate $\propto (\text{density})^2$
Galactic center: spike cusp, ???
Black hole in the galactic center

Muons from the sun

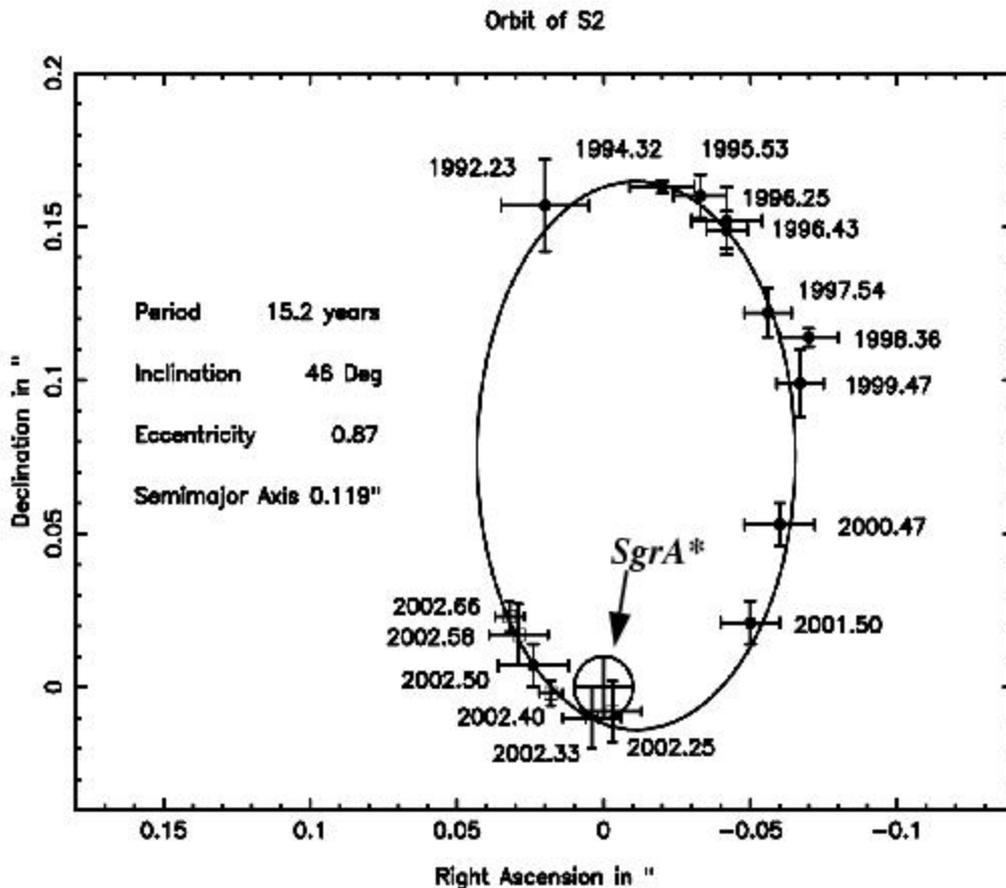




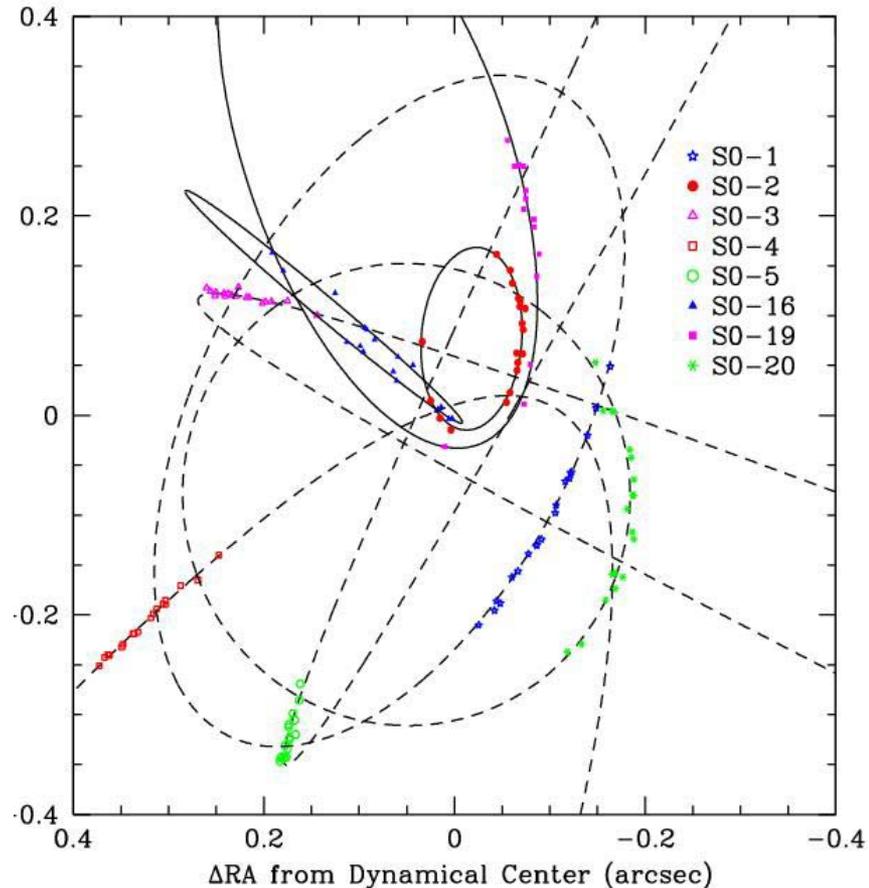
Orbits near the galactic center

S2: $15M_{\odot}; 7R_{\odot}$

Pericenter passage: $100\text{AU}=2000R_S; 11 \times 10^6 \text{ mph}$

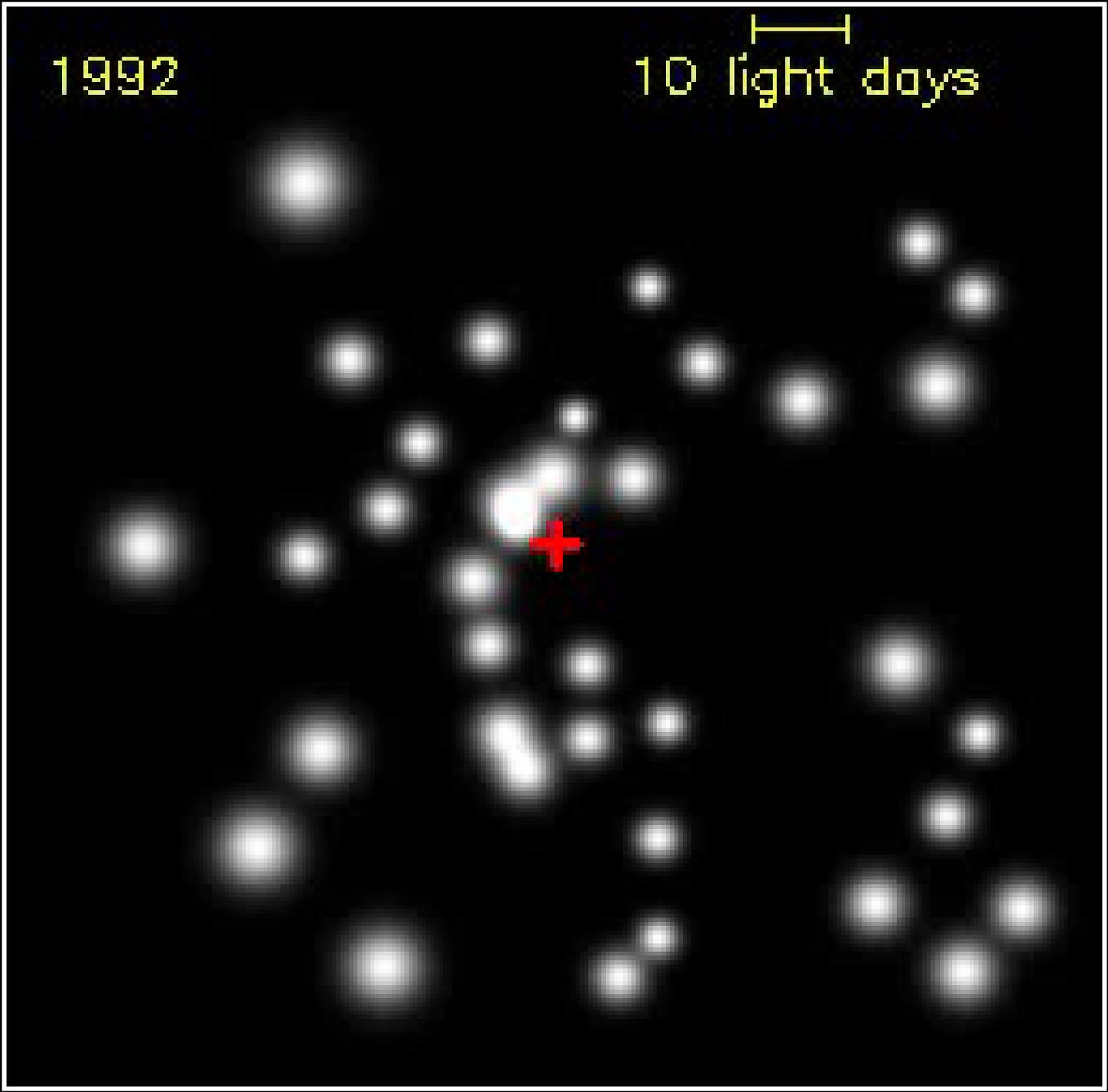


Schodel et al. (2002)

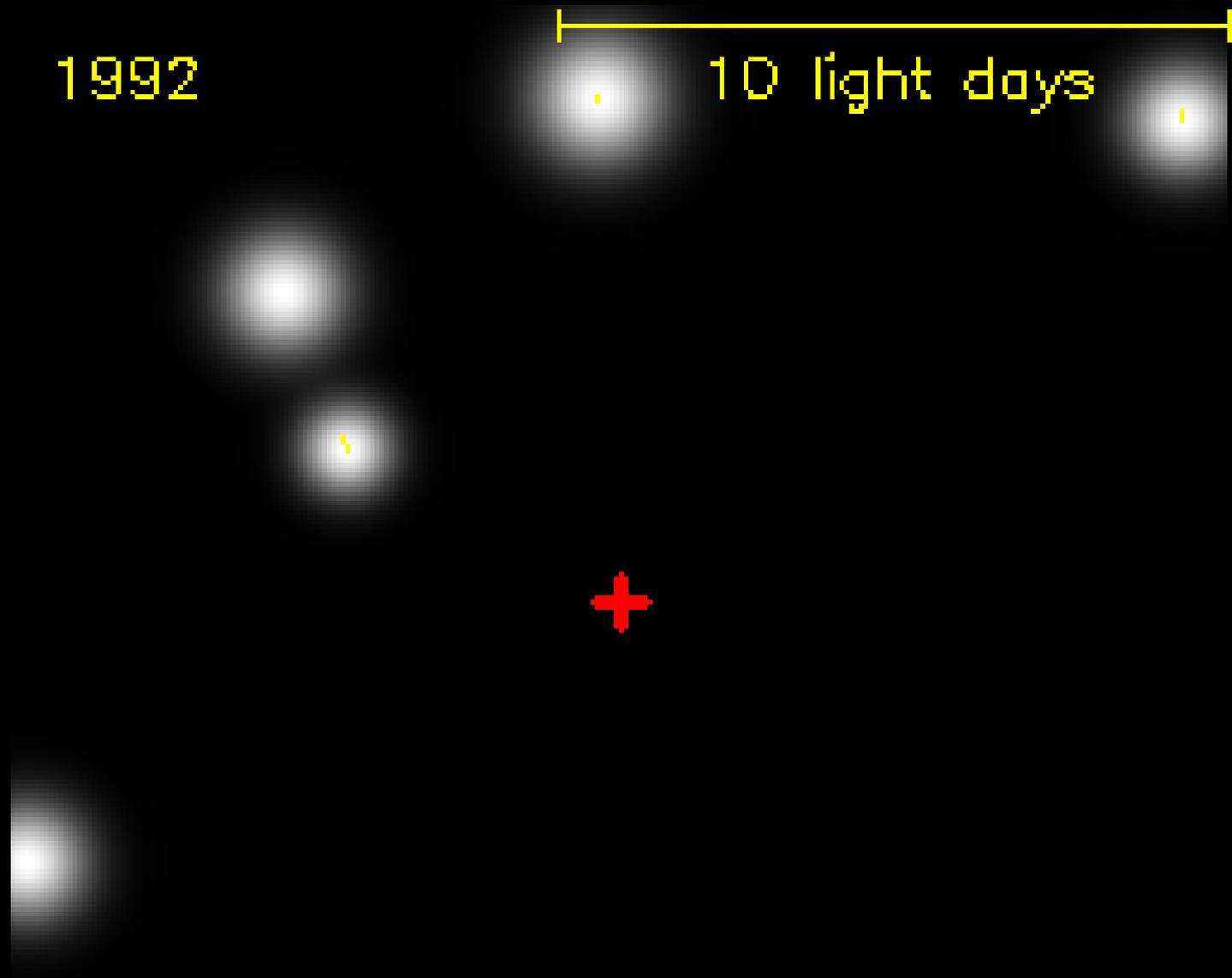


Ghez et al. (2003)

Schodel et al. 2002



Schodel et al. 2002

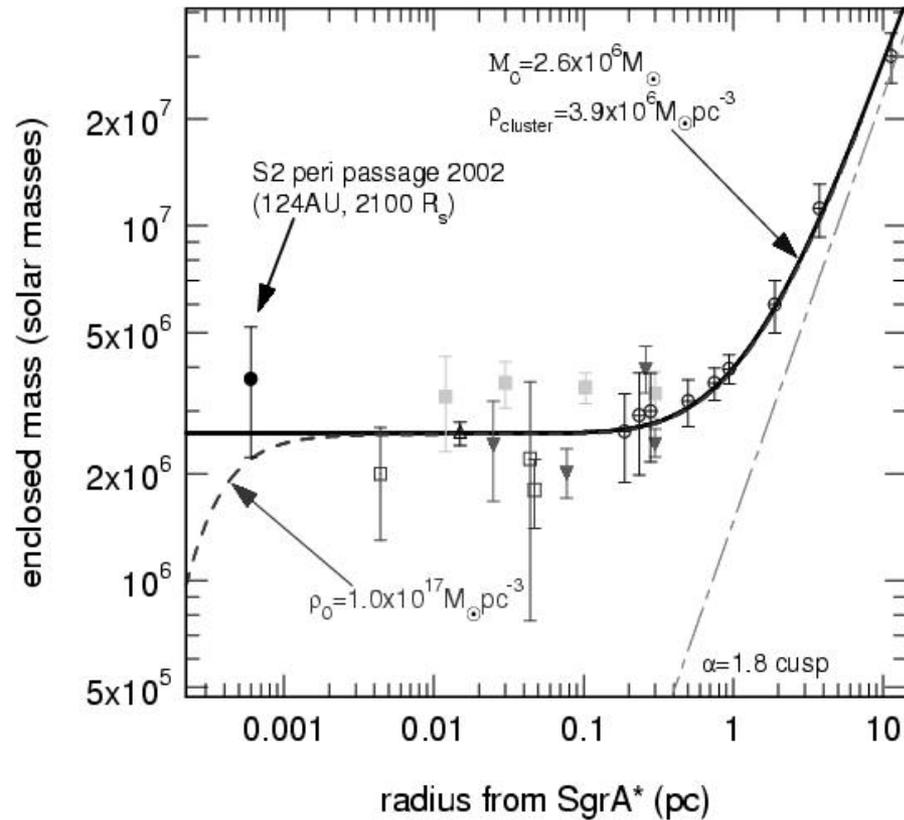


1992

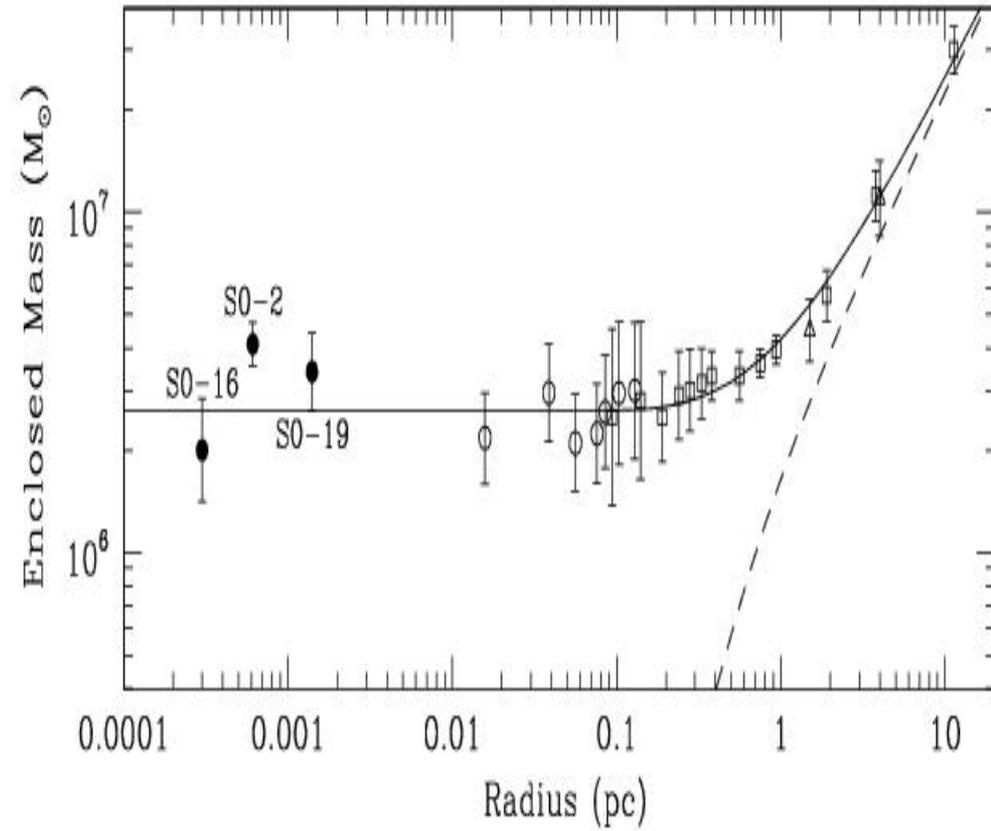
10 light days

Enclosed mass

$$M = 2.6 \times 10^6 M_{\odot}$$



Schodel et al. (2002)



Ghez et al. (2003)

Nonbaryonic dark matter

Familiar candidate: a neutralino

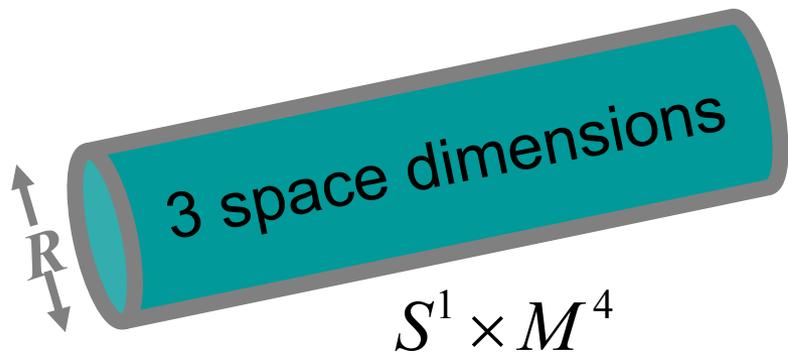
“a simple, elegant, compelling explanation for a complex physical phenomenon”

“For every complex natural phenomenon there is a simple, elegant, compelling, but wrong explanation.”

- *Tommy Gold*

Kaluza-Klein Particles

Kolb & Slansky (84); Servant & Tait (02); Cheng, Feng & Matchev (02)



Quantized Kaluza-Klein excitations

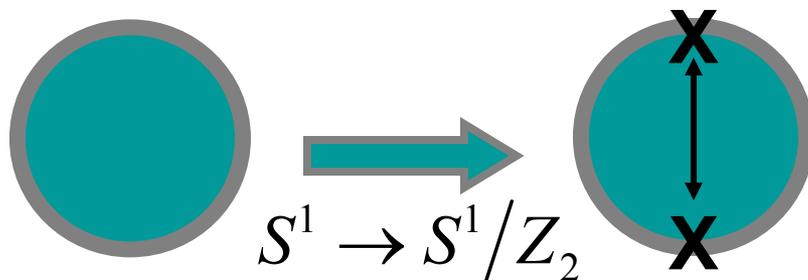
$$E^2 = \vec{p}^2 + p_5^2 \quad p_5^2 = n^2 / R^2$$

$$= \vec{p}^2 + M_n^2 \quad M_n^2 = n^2 / R^2$$

Conservation of momentum \longrightarrow conservation of KK mode number

First excited mode ($n=1$) stable, mass R^{-1}

need
chiral
fermions

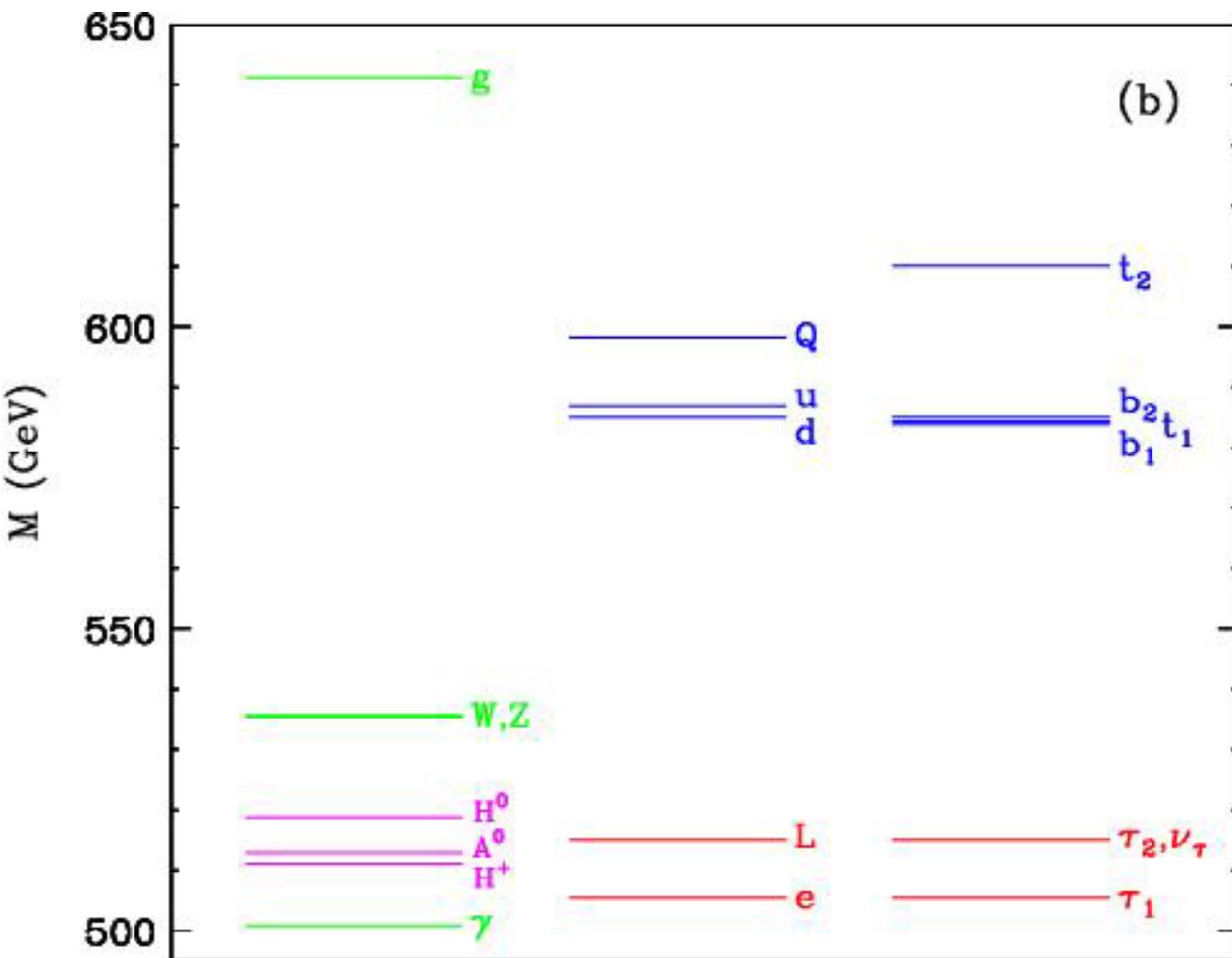


KK quantum number
 \longrightarrow KK parity

First excited mode ($n=1$) stable, mass R^{-1}

Kaluza-Klein Particles

$$R^{-1} = 500 \text{ GeV}$$



- LKP = KK photon
Cheng, Matchev & Schmaltz
- Looks like SUSY
Cheng, Matchev & Schmaltz
- Beware KK graviton
Kolb, Servant & Tait
- Direct detection
Servant & Tait
Cheng, Feng & Matchev
- Indirect detection
Bertrone, Servant, Sigl

Particle Dark Matter Candidates

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, sneutrino, ...) (cold dark matter)
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Axion dark matter Fischler et al.

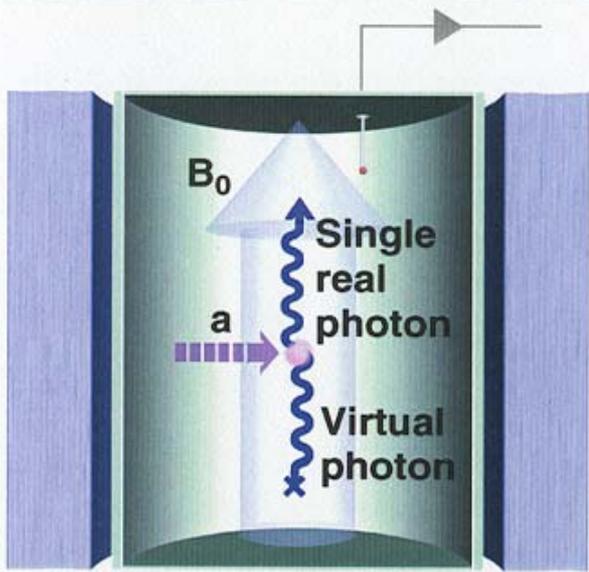
... about to be ruled out or closing in on detection

- Pseudo-Nambu-Goldstone boson

- Axion mass: $m_a = \frac{\Lambda_{QCD}^2}{f_{PQ}} = 1 \text{ eV} \frac{10^7 \text{ GeV}}{f_{PQ}}$

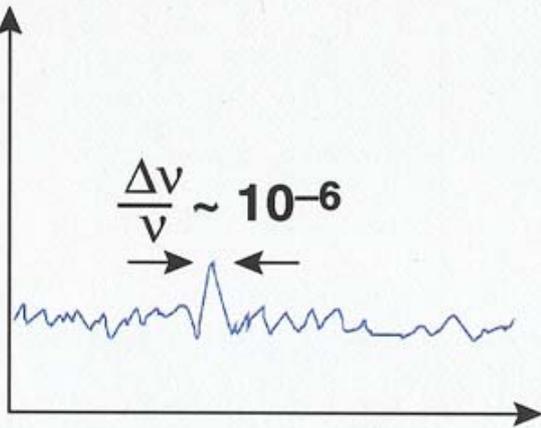
- Pseudoscalar
- Couples to two photons through the anomaly
- Very weakly interacting with matter
- Origin of axions
 - phase transition
 - decay of axion strings

Primakoff Conversion



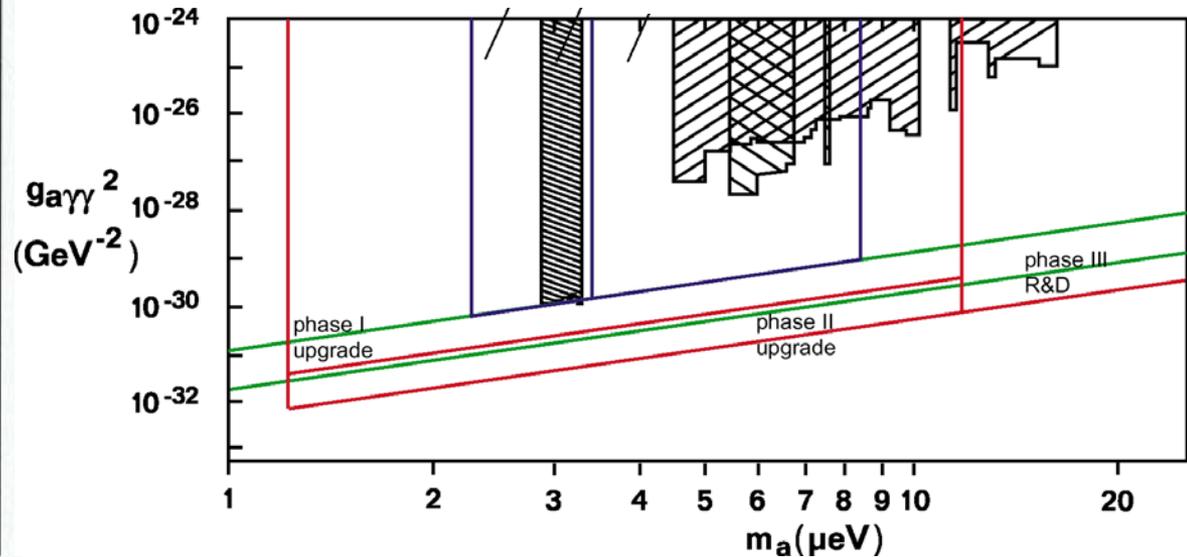
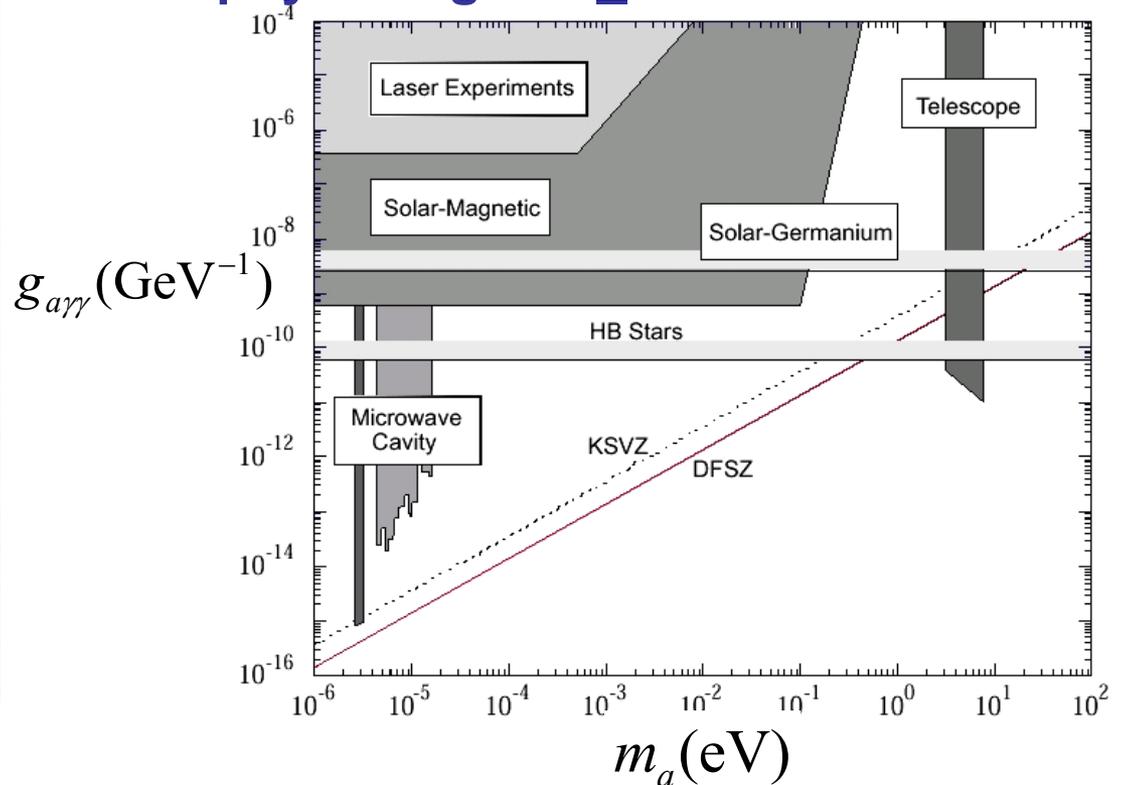
Signal

Power



Frequency (GHz)

www-phys.llnl.gov/N_Div/Axion/axion.html

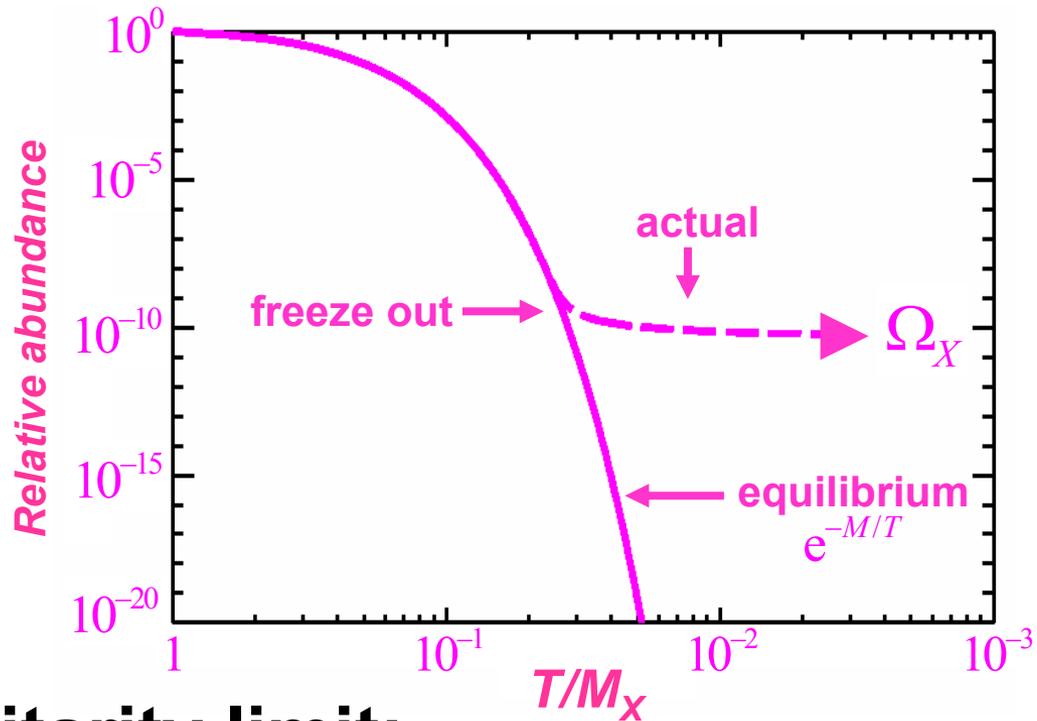


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Cold thermal relics



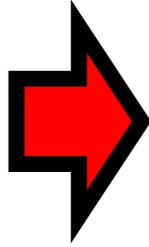
Unitarity limit:

- largest cross section: $\sigma_A \leq 8\pi/M^2$
- $M \leq 300$ TeV

Balls

- **Q-balls (non-topological solitons):** S. Coleman; T.D. Lee

Scalar field with conserved global charge “Q”



Ground state is a Q-ball, lump of coherent scalar condensate

$E \propto Q^{3/4}$: can't decay to Q free particles

- **Q-ball production and evolution:**

Solitogenesis

Frieman, Gelmini, Gleiser & Kolb

Solitosynthesis

Frieman, Olinto, Gleiser & Alcock; Greist & Kolb

Statistical fluctuations

Greist, Kolb & Massarotti

Condensate fragmentation

Kusenko & Shaposhnikov

Balls

- **Q-balls exist in MSSM**
scalars = squarks & sleptons

Kusenko, Shapashnikov & Tinyakov

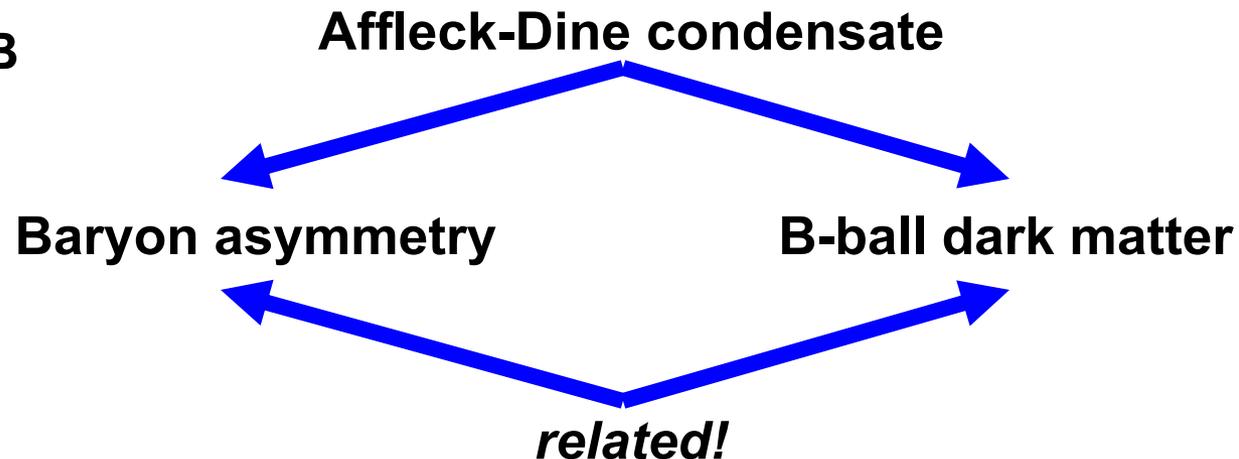
$$M_B \sim (1 \text{ TeV}) \times B^{3/4} \quad \left(\text{stable for } B \geq 10^{12} \right)$$

- **Fragmentation of Affleck-Dine condensate**

Kusenko & Shapashnikov

$$M_B \sim 10^{-3} \text{ g} \quad \left(B \simeq 10^{24} \right)$$

- **Relates Ω_{DM} to Ω_B**



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 - supermassive relics
 -
 -
 -
- 

Supermassive relics *(Nonthermal dark matter)*

Production Mechanisms:

- Reheating Chung, Kolb, Riotto
- Preheating Chung
- Bubble collisions Chung, Kolb, Riotto
- Gravitational Chung, Kolb, Riotto; Kuzmin & Tkachev

Expanding universe *particle creation*

Arnowit, Birrell, Bunch, Davies, Deser, Ford, Fulling, Grib, Hu, Kofman, Lukash, Mostepanenko, Page, Parker, Starobinski, Unruh, Vilenkin, Wald, Zel'dovich,...

It's not a bug, it's a feature!

first application: { **density perturbations from inflation**
gravitational waves from inflation

(Guth & Pi; Starobinski; Bardeen, Steinhardt, & Turner; Hawking; Rubakov; Fabbi & Pollack; Allen)

new application: **dark matter**

(Chung, Kolb, & Riotto; Kuzmin & Tkachev)

- **require (super)massive particle “X”**
- **stable (or at least long lived)**
- **initial inflationary era followed by radiation/matter**

Scalar field X of mass M_X

Fourier modes [$a(\tau)$ = expansion scale factor]

$$X(\vec{x}, \tau) = \int \frac{d^3x}{(2\pi)^{3/2} a(\tau)} \left[a_k h_k(\tau) e^{i\vec{k}\cdot\vec{x}} + a_k^\dagger h_k^*(\tau) e^{-i\vec{k}\cdot\vec{x}} \right]$$

Mode equation (τ = conformal time)

$$h_k''(\tau) + \left[k^2 + M_X^2 a^2 + (6\xi - 1) a''/a \right] h_k(\tau) = 0$$

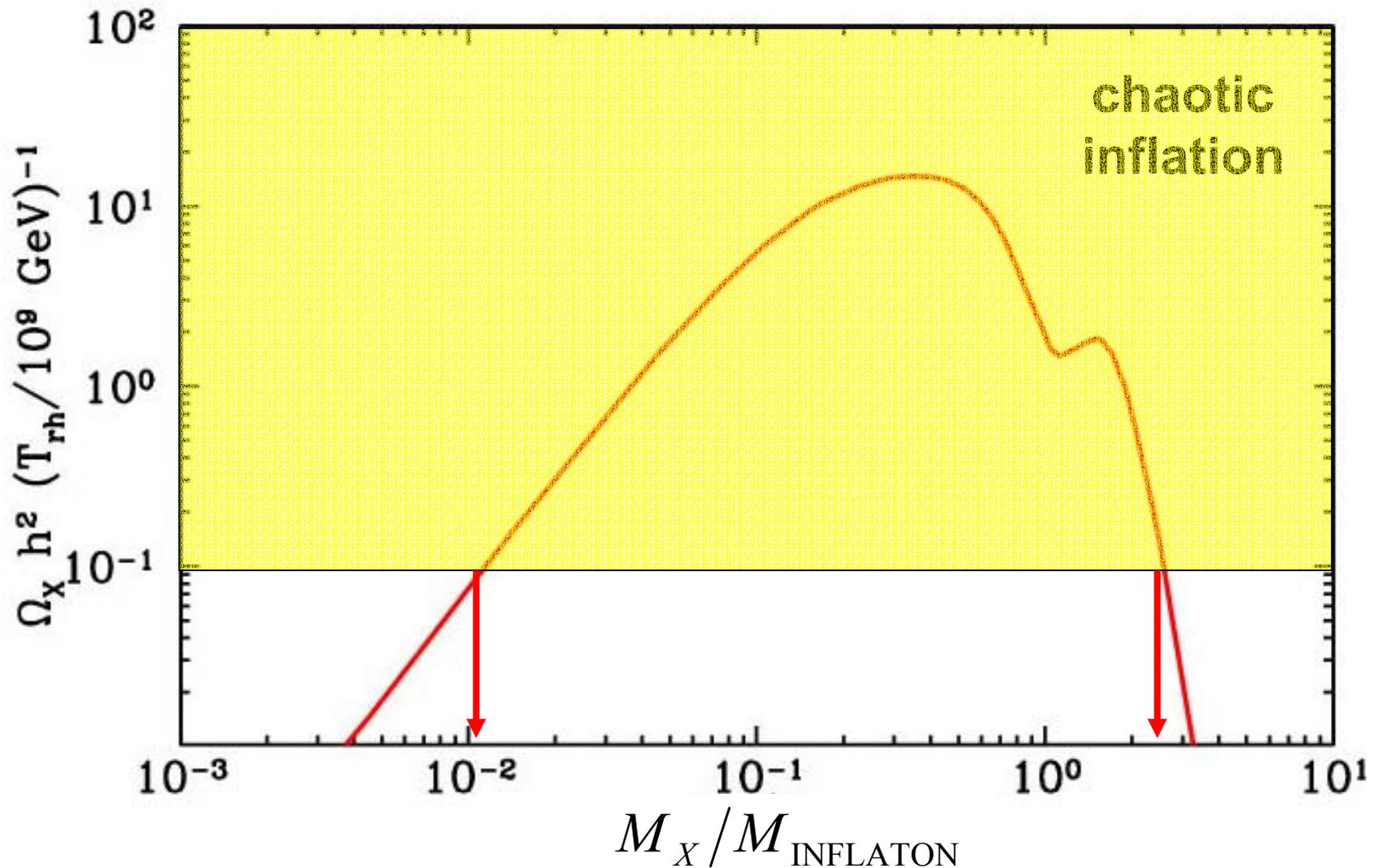
$$h_k''(\tau) + \omega_k^2(\tau) h_k(\tau) = 0$$

Particle creation in nonadiabatic region

$$\text{measure of nonadiabaticity} \propto \frac{\omega_k'}{\omega_k} \quad \text{or} \quad \frac{\dot{H}}{H^2}$$

Particle production

Chung, Kolb & Riotto; Kuzmin & Tkachev)



$$\Omega_X \approx 1 \quad \text{for} \quad M_X/M_{\text{INFLATON}} \approx 1 \Rightarrow M_X \approx 10^{10} \text{ to } 10^{15} \text{ GeV}$$

Superheavy particles

- Inflaton mass (in principle measurable from gravitational wave background, guess 10^{12} GeV), may signal a new mass scale in nature.
- Other particles may exist with mass comparable to the inflaton mass.
- Conserved quantum numbers may render the particle stable.

Gravitino production

Giudice, Riotto, Tkachev

Linde, Kallosh, Kofman, Van Proeyen

Nilles, Peloso, Sorbo

Nilles, Olive, Peloso

.....

(perhaps it is a bug after all...)

Dark Matter and Dark Energy

Rocky I: Evidence for dark matter and dark energy

Rocky II: Dark matter candidates

Rocky III: Dark energy reloaded

SLAC Summer Institute, August 2003

Rocky Kolb, Fermilab & The University of Chicago