# Cosmological Implications of Large Extra Dimensions

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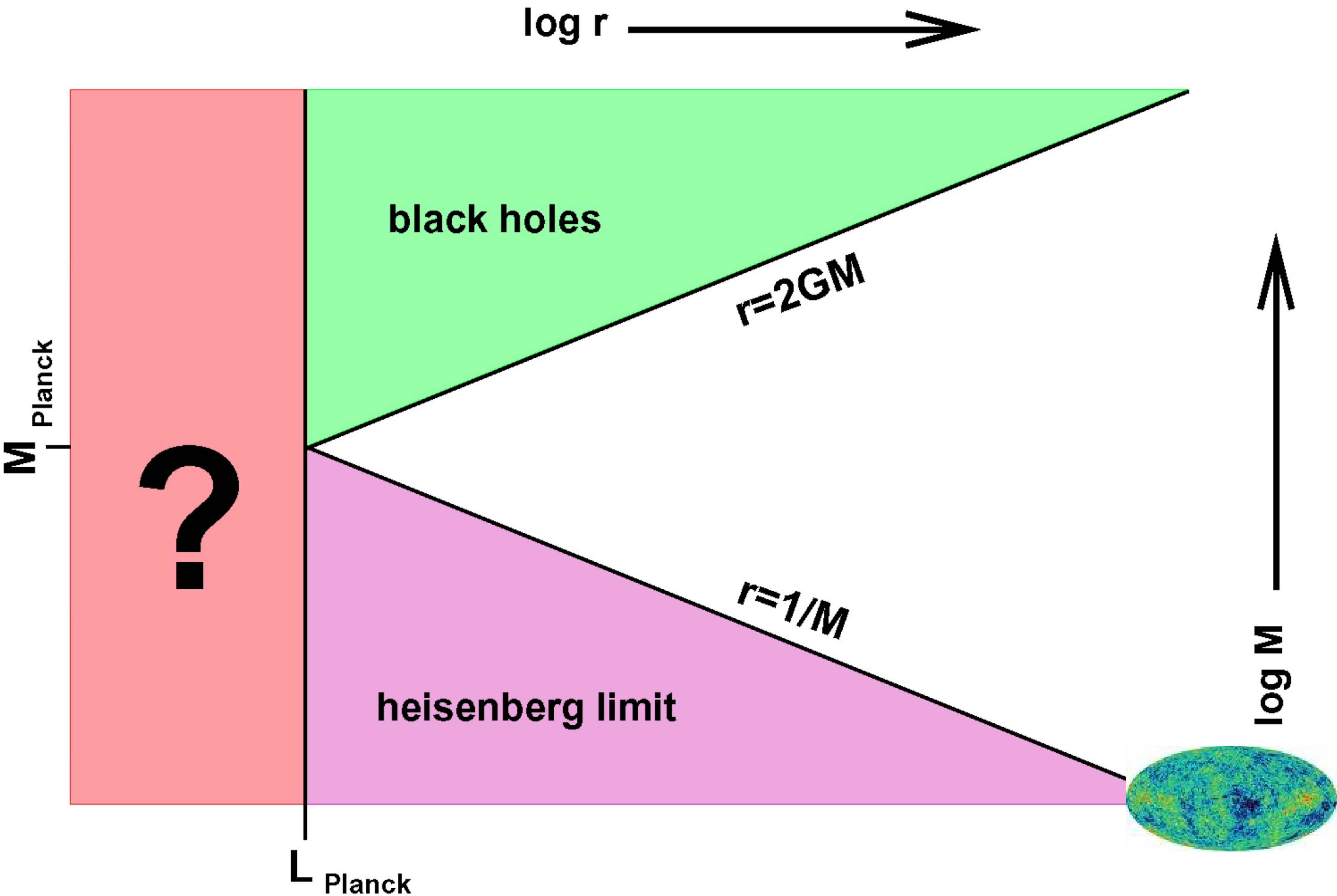
# Focus on…

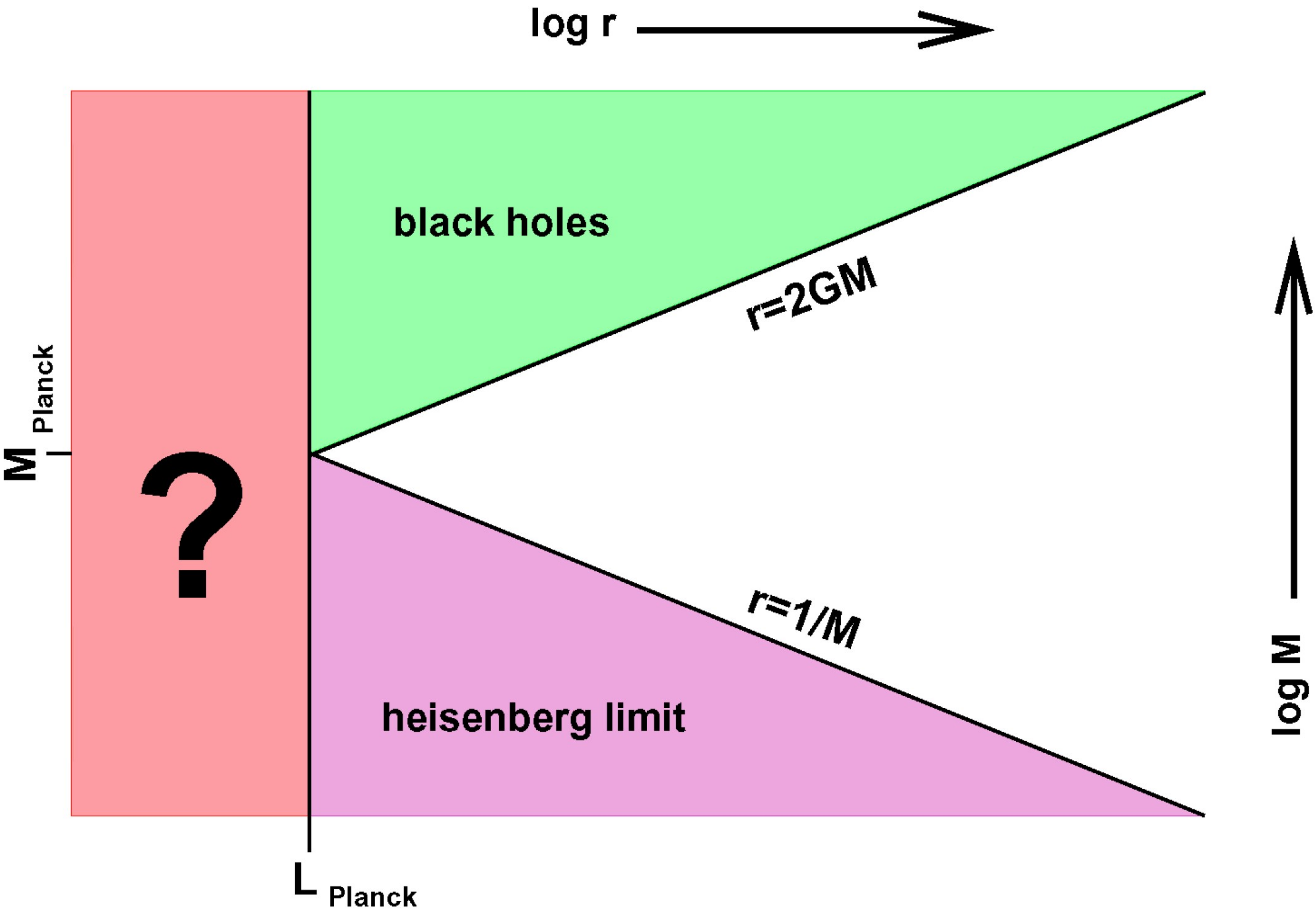
1. Cosmological constraints on large extra dimensions (ADD)

1. Universal extra dimensions  as Dark Matter (UED)

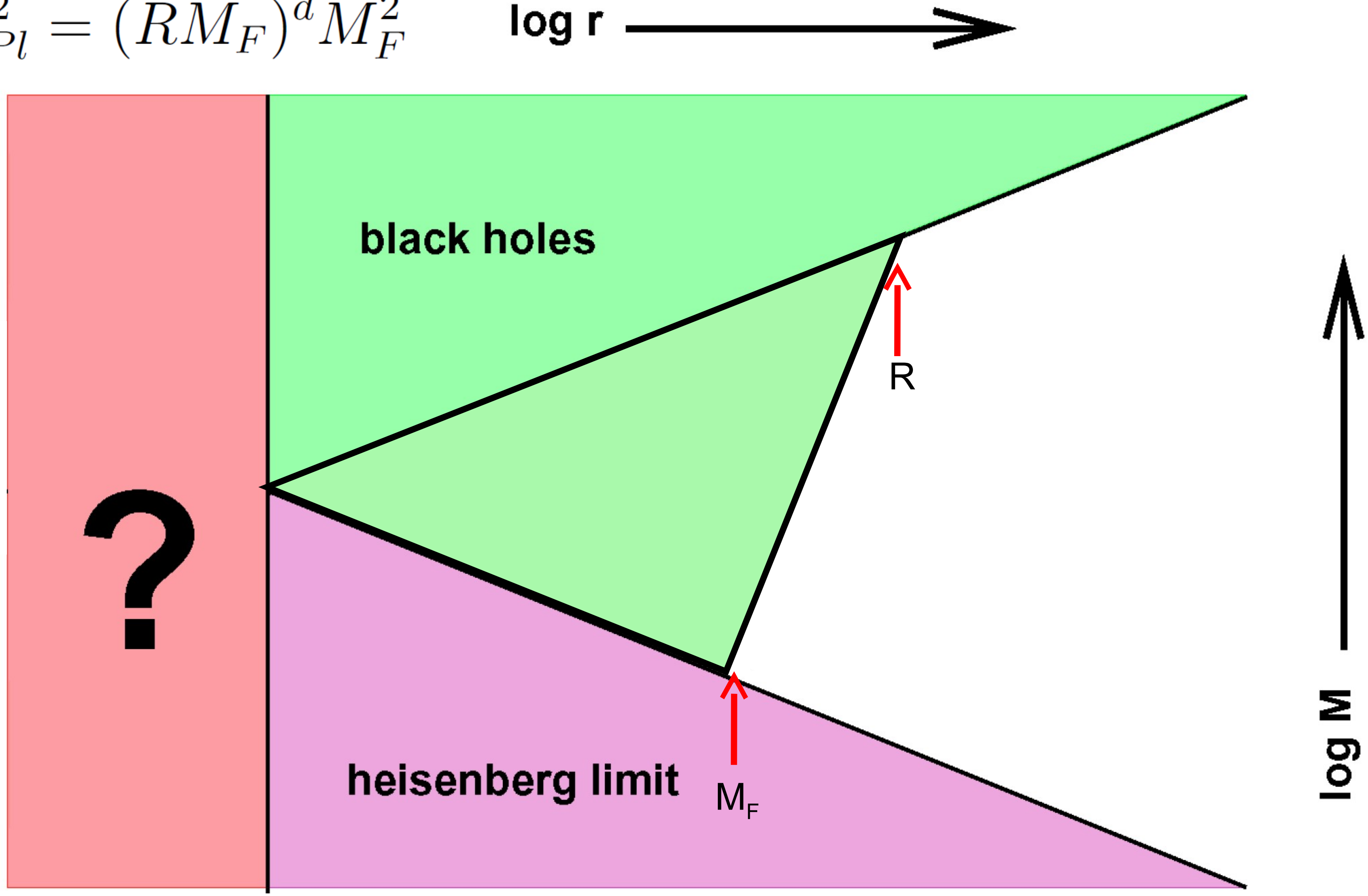


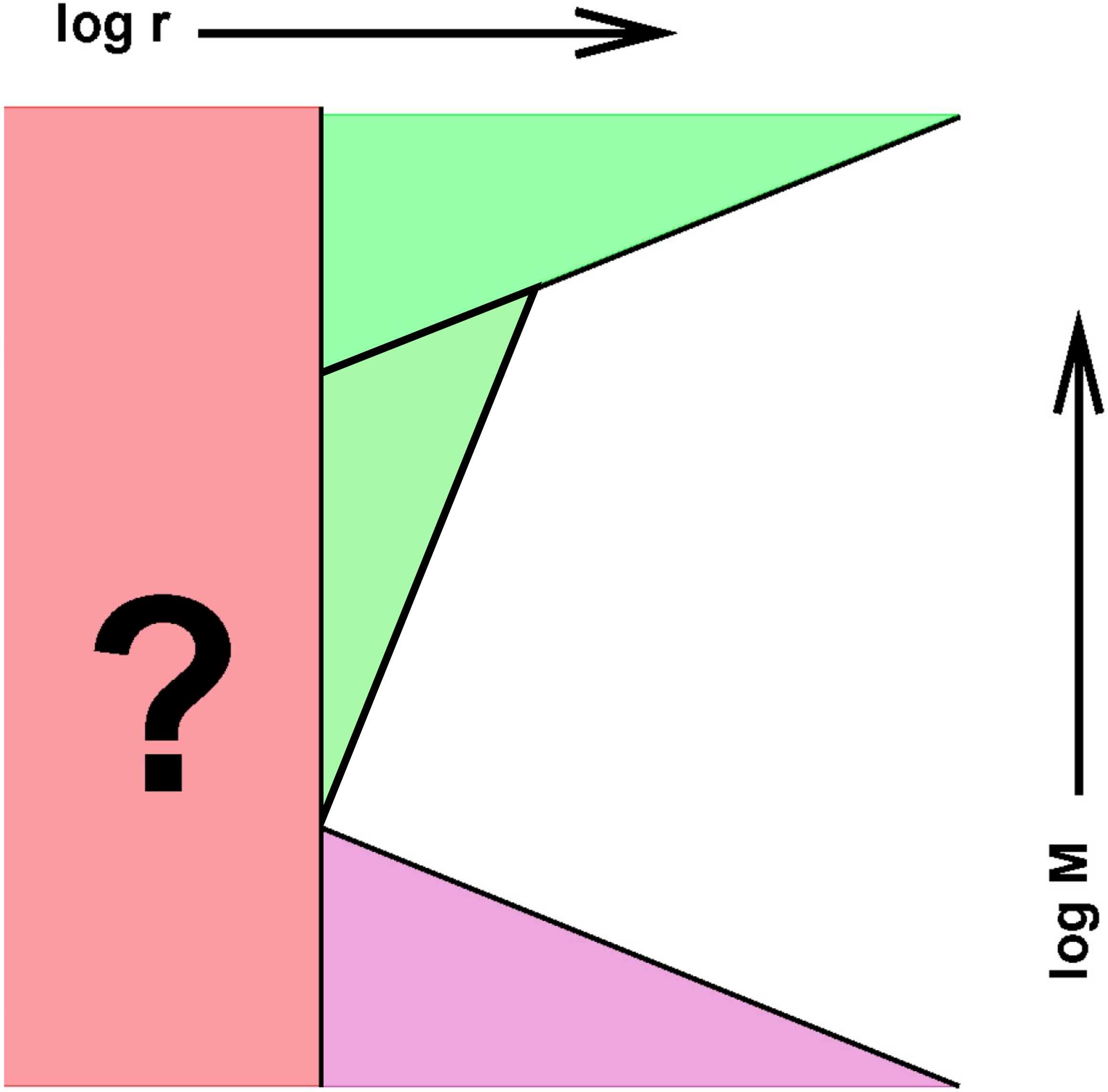
log r
black holes
r=2GM
$M_{Planck}$
?
r=1/M
heisenberg limit
log M
$L_{Planck}$

- homogeneous and isotropic
- flat
- big
- scale invariant spectrum of perturbations
- slight particle-antiparticle asymmetry
- observed ratio of light elements
- most of the universe is dark


log r
black holes
r=2GM
?
r=1/M
heisenberg limit
log M
M Planck
L Planck

$$M_{Pl}^2 = (RM_F)^d M_F^2$$



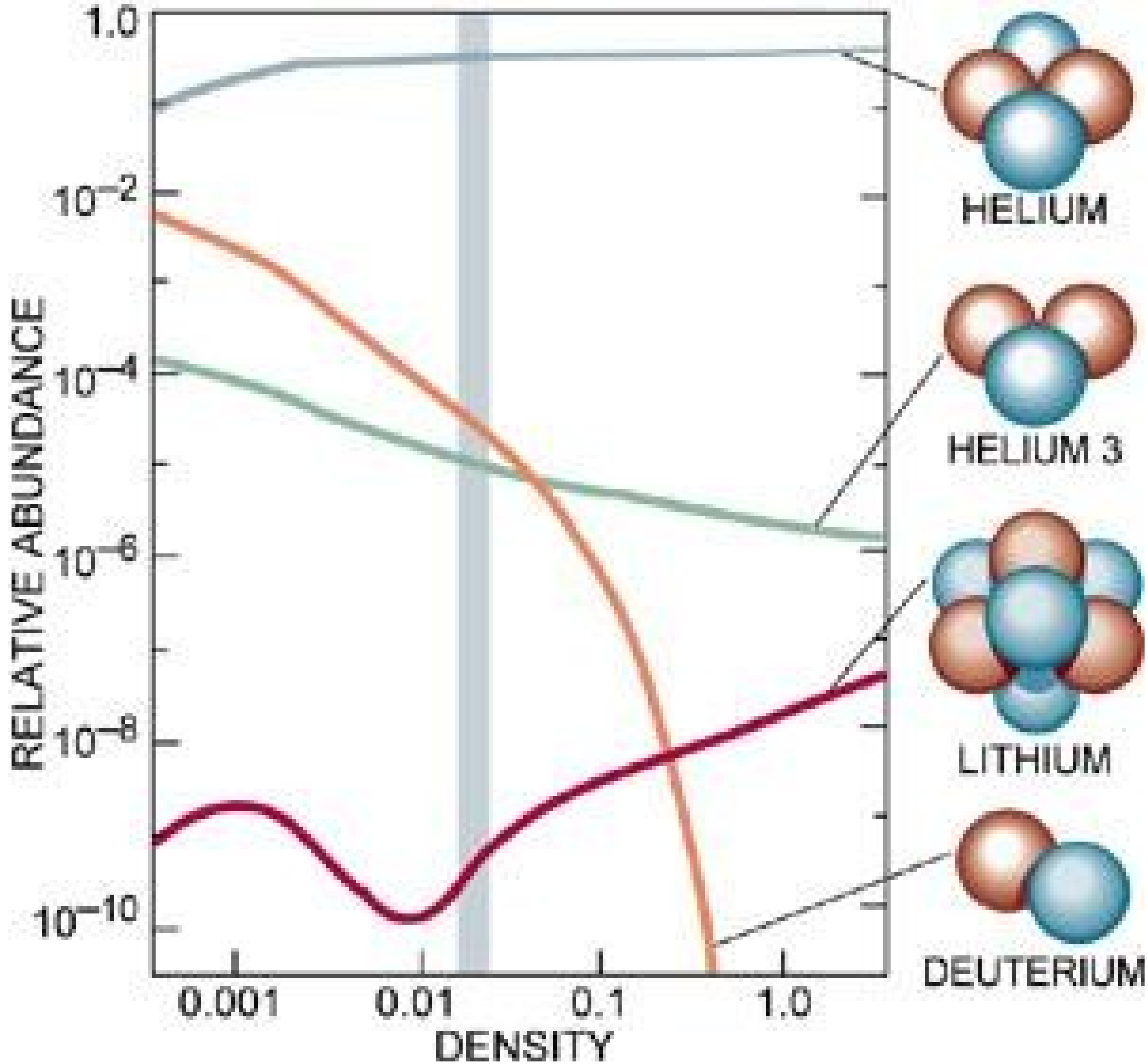

log r
?
log M

# Only Nucleosynthesis can be copied in the lab

$$n \leftrightarrow p$$

Due to weak interaction cuts off at T~MeV.

Need to be in thermal equilibirum at this time.



# Cosmological production of KK modes

Each KK mode only gravitationally coupled to the standard model

$$4\pi G = \frac{4\pi}{M_P^2} = \left(\frac{1}{RM_F}\right)^d \frac{1}{M_F^2}$$

$$\sqrt{\alpha_G} \sim \frac{E}{M_{Pl}} = \frac{1}{(RM_F)^{d/2}} \frac{E}{M_F}$$

However, at an energy E there are many KK modes with m < E

$$N_{KK}(m_{KK} < E) \sim (ER)^d$$

Emissivivity therefore goes like

$$\frac{d\epsilon}{dt} \sim \frac{(TR)^d}{(RM_F)^d} \left(\frac{T}{M_F}\right)^2 T^5 = \frac{T^{d+7}}{M_F^{d+2}}$$

# Cosmological production of KK modes

e.g. For photons....

$$\frac{d\epsilon_{\gamma\gamma\to KK}}{dt} = \frac{2^{d+3}\Gamma(\frac{d}{2}+3)\Gamma(\frac{d}{2}+4)\zeta(\frac{d}{2}+3)\zeta(\frac{d}{2}+4)}{(d+4)\pi^2}\frac{T^{d+7}}{M_F^{d+2}} = \mathcal{C}_{\gamma\gamma}\frac{T^{d+7}}{M_F^{d+2}}$$

And for electrons...

$$\frac{d\epsilon_{e^+e^-\to KK}}{dt} = \frac{2^d I(d)}{(d+4)\pi^2}\frac{T^{d+7}}{M_F^{d+2}}$$

$$I(d) = \int_0^\infty dx \int_0^\infty dy \frac{(xy)^{\frac{d}{2}+2}(x+y)}{[exp(x-\frac{\mu_e}{T})+1][exp(y+\frac{\mu_e}{T})+1]}$$

Evolution of density

Redshifts like matter

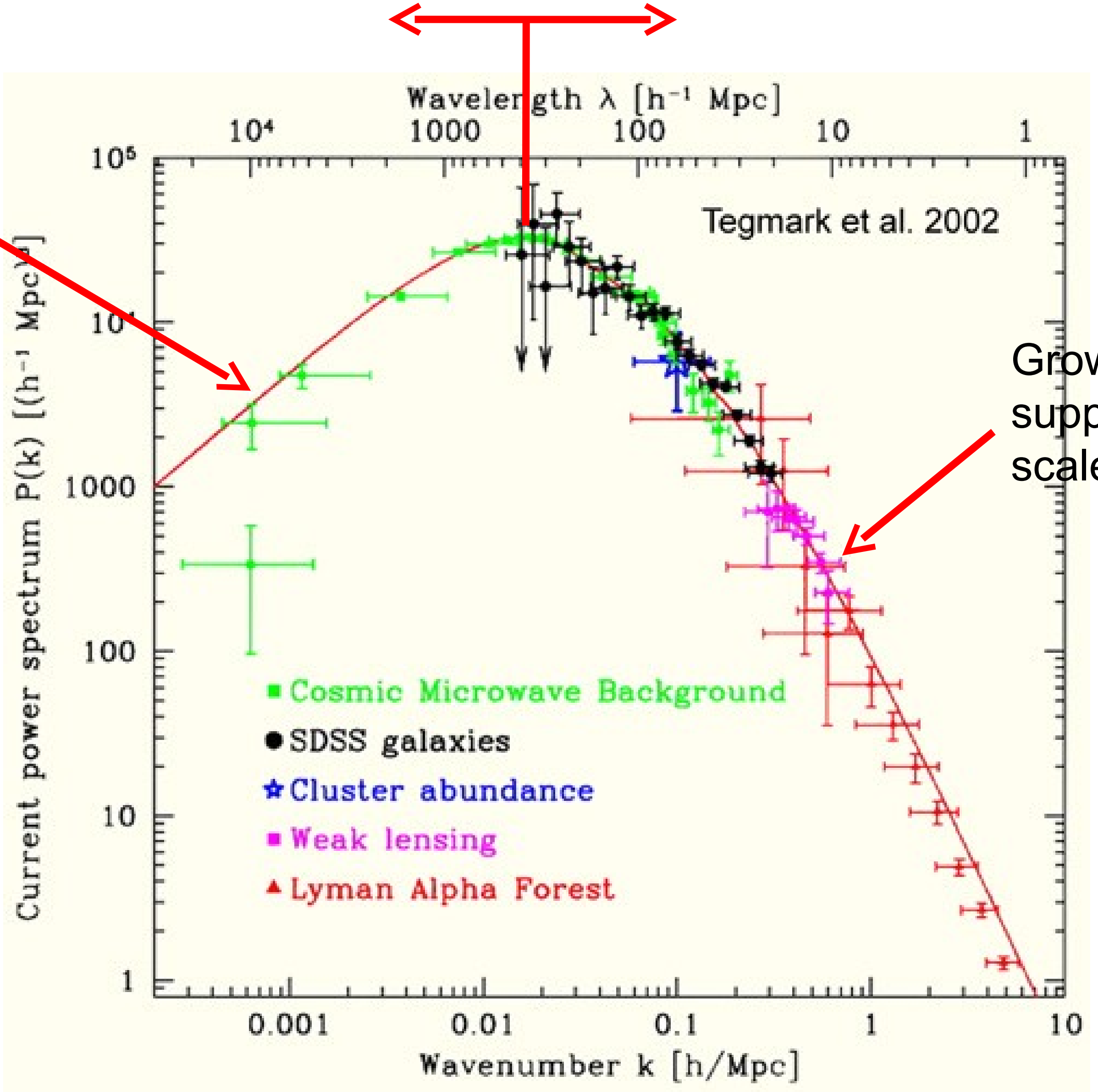
$$\frac{d\rho_{KK}}{dT} = \frac{-0.602}{\sqrt{g_* G}}\sum_i \mathcal{C}_i \frac{T_i^{d+4}}{M_F^{d+2}} + \frac{3\rho_{KK}}{T}$$

MF and Griffiths hep-ph/0111435

# Growth of perturbations

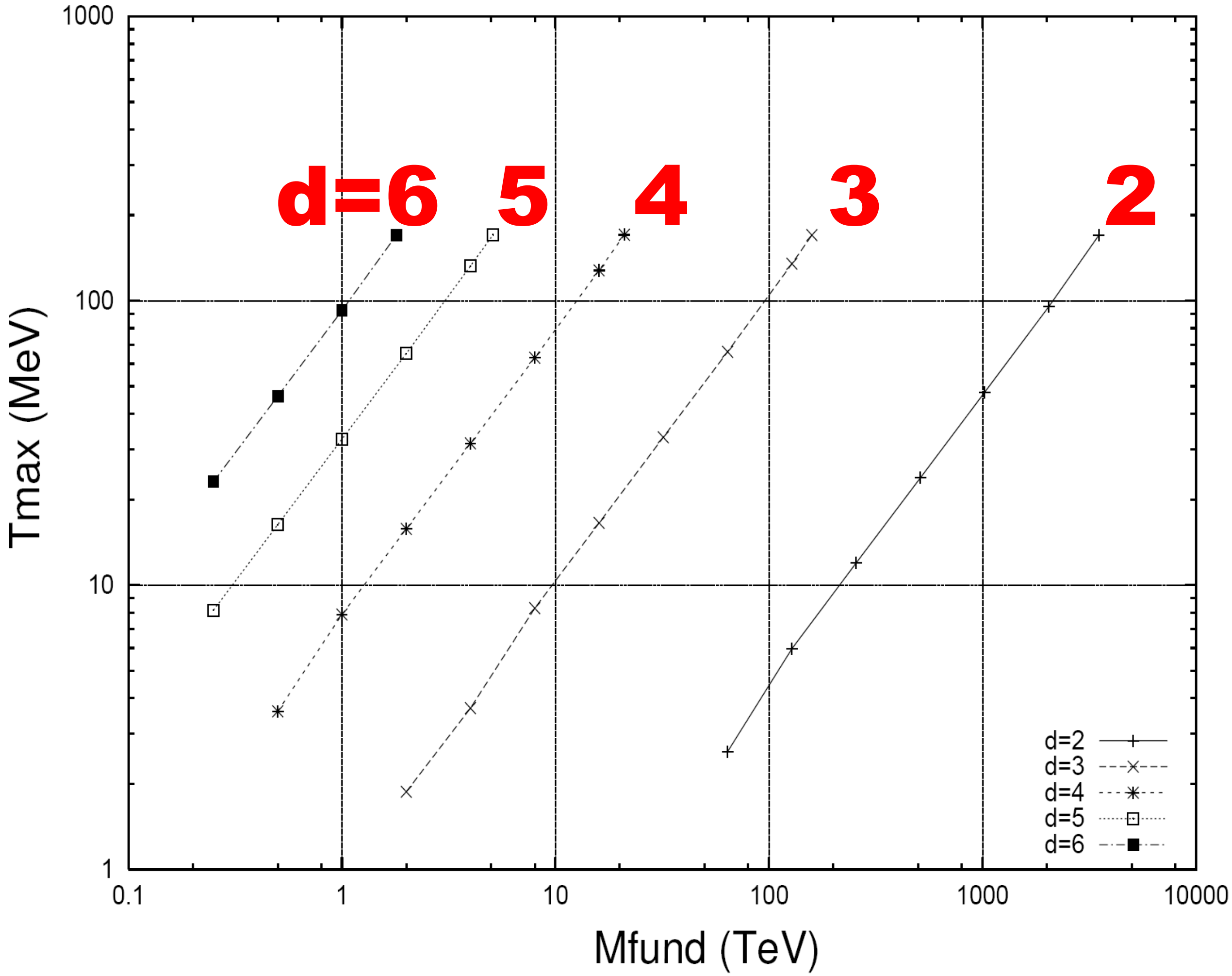
Position of peak depends on total density of matter at z~5000

P~k$^n$
(n=1 from
inflation?)




Growth of structure
suppressed on small
scales

# Constraints from Cosmological over-density of KK modes

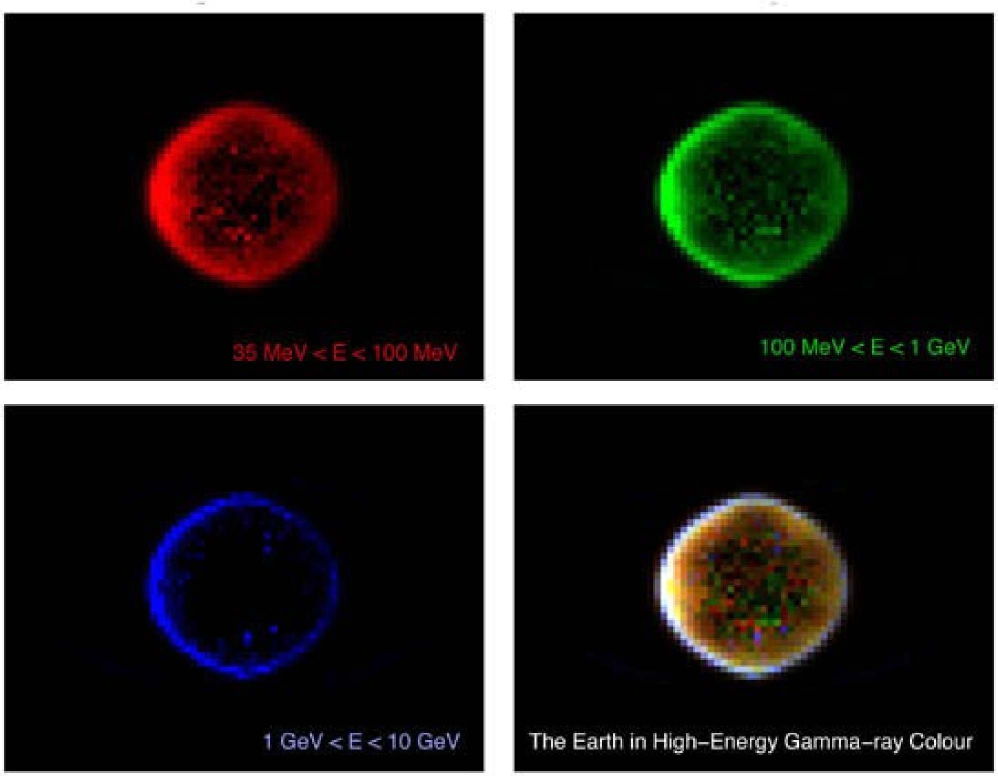



| d | Tmax (MeV) |
|---|---|
| 2 | forbidden |
| 3 | forbidden |
| 4 | 7.88 MeV |
| 5 | 32.6 MeV |
| 6 | 92.3 MeV |

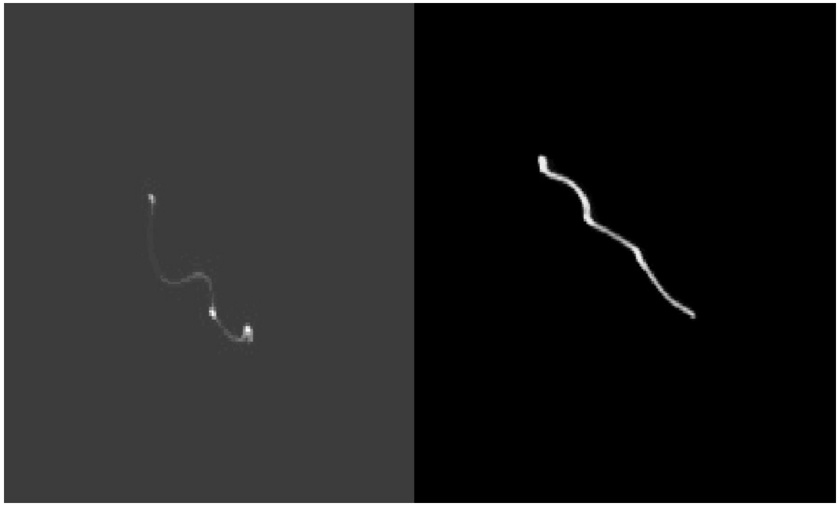
MF and Griffiths hep-ph/0111435

# Compton Gamma Ray Observatory

# 1991-2000



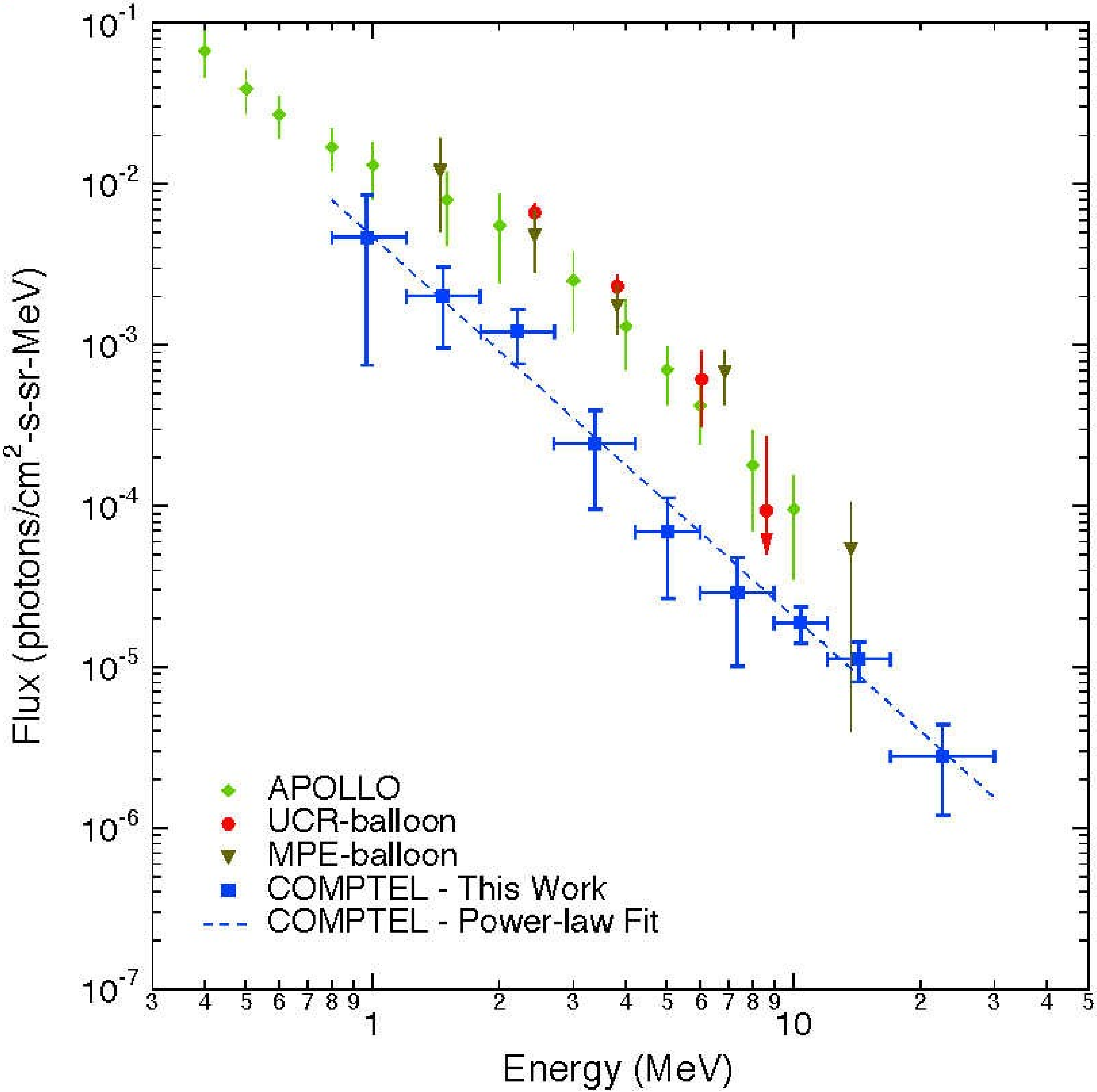

Dirk Petry, UMBC & NASA/GSFC, 2004



**Compton Gamma Ray Observatory**

**COMPTEL**

**Diffuse Background Radiation**



## Constraints from decay of KK modes into gamma rays

Decay rate

$$\Gamma(KK \to \gamma\gamma) = \frac{m_{KK}^3}{10 M_F^2}$$

Lifetime...

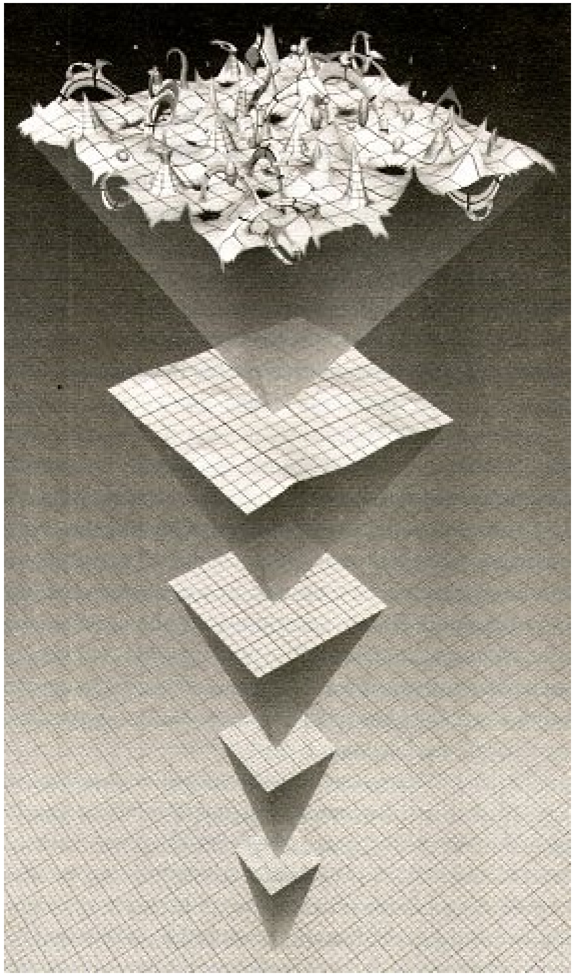
$$\tau(KK \to \gamma\gamma) = 3 \times 10^9 \mathrm{yr} \left(\frac{100\mathrm{MeV}}{m}\right)^3$$

Constraints on $M_F$ :-

| n | $T_{MAX} = 0.7$ MeV | 50 MeV | 100 MeV | 1 GeV |
|---|---|---|---|---|
| 2 | 73 | 161 | 165 | 167 |
| 3 | 3.9 | 16.0 | 18.6 | 21.7 |
| 4 | 0.47 | 2.96 | 3.75 | 4.75 |
| 5 | 0.10 | 0.89 | 1.19 | 1.55 |

Hall and Smith hep-ph/9904267 , Hannestad hep-ph/0102290

# Chaotic Inflation in Large extra Dimensions



Energy density has to be less than Fundamental scale

$$H \sim \sqrt{\frac{V}{M_{Pl}^2}} < \frac{M_F^2}{M_{Pl}}$$

For slow-roll, Inflaton mass must be less than H

$$m < H < \frac{M_F^2}{M_{PL}} \sim 10^{-4}\mathrm{eV}$$

Leads to density perturbations of magnitude

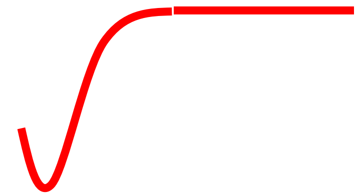
$$\frac{\delta\rho}{\rho} \sim 50\frac{m}{M_{Pl}} < 10^{-31}$$

Obviously, simplest models cannot work

Lyth hep-ph/9810320, Kaloper and Linde hep-ph/9811141

# Hybrid Inflation in Large extra Dimensions

Two field potential, inflaton field and waterfall field



$$V(\rho,\sigma) = \frac{1}{4!}(M^2 - \lambda\sigma^2)^2 + \frac{m^2}{2}\phi^2 + \frac{g^2}{2}\phi^2\sigma^2$$

$$\frac{\delta\rho}{\rho} = \frac{2\sqrt{6\pi}g}{5\lambda^{3/2}}\frac{M^5}{M_{Pl}^3 m^2}$$

If we choose most reasonable parameters

$$M \sim 1\ \mathrm{TeV},\ \lambda, g \sim \mathcal{O}(1)$$

$$\frac{\delta\rho}{\rho} \sim 5\times 10^{-5} \rightarrow m \sim 10^{-10}\mathrm{eV}$$

Difficult to understand without SUSY

Lyth hep-ph/9810320, Kaloper and Linde hep-ph/9811141

Need to invoke some new mechanism

## Possible Solution for Inflation with Large Extra Dimensions

- Universe starts with extra dimensions small, close to $M_F$
- Newton's constant $G \sim M_F^{-2}$
- $V \sim M_F^4 \rightarrow H \sim M_F^4 \rightarrow$ No problem to get large density perturbations
- Extra dimensions then grow after inflation
- Typically a problem with moduli field – requires extra phase of inflation

Mazumdar hep-ph/9902381, Arkani-Hamed at al hep-ph/9903224

# Effects of Low Reheat Temperatures

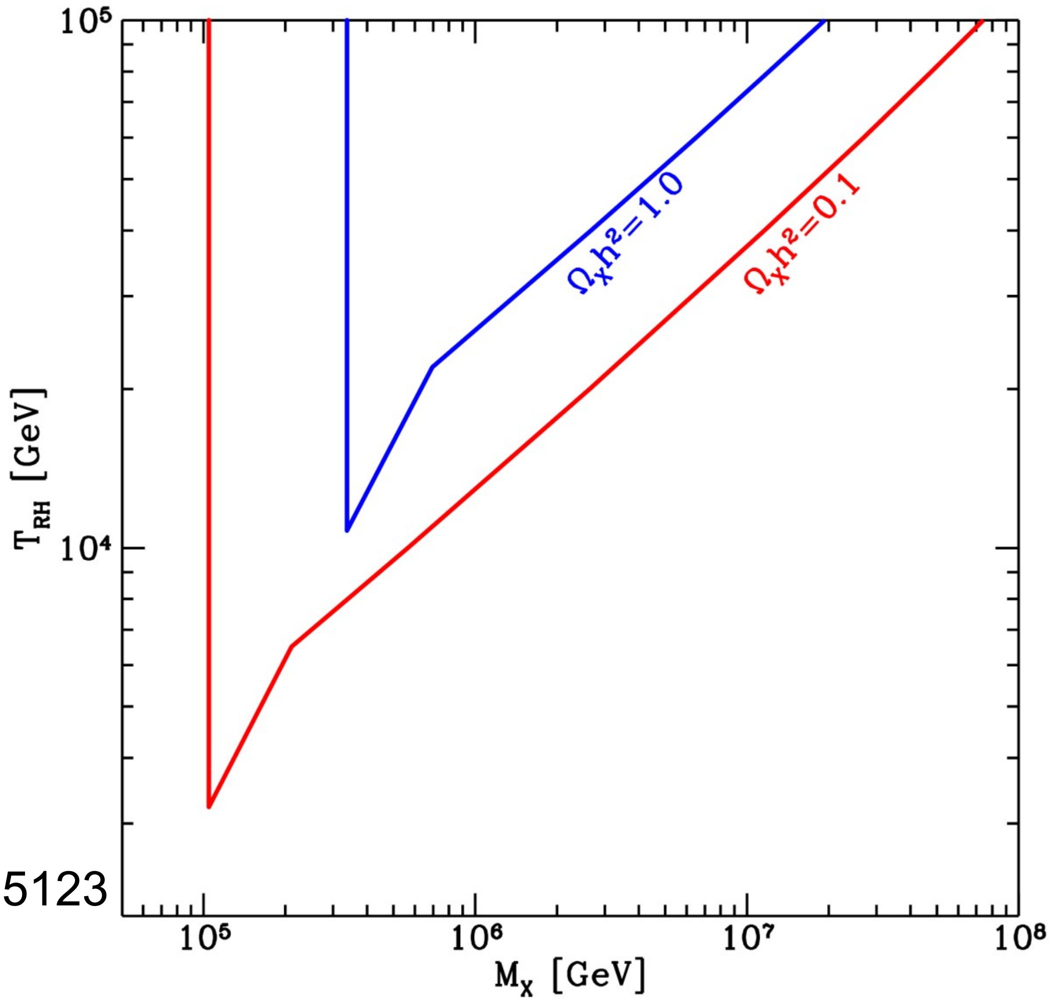
$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi \rho_\phi$$

$$\frac{d\rho_R}{dt} = -4H\rho_R + \Gamma_\phi \rho_\phi + \langle \sigma v \rangle 2 \langle E_X \rangle \left[ n_X^2 - (n_X^{eq})^2 \right]$$

$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma v \rangle \left[ n_X^2 - (n_X^{eq})^2 \right]$$

- Changes relic abundance

- Can make HDM particles like low mass axions CDM




Giudice, Kolb and Riotto, hep-ph/0005123

# Baryogenesis

Sakharov's three conditions need to be met:-

1. C and CP violation
2. B violation
3. Out of equilibrium thermodynamics

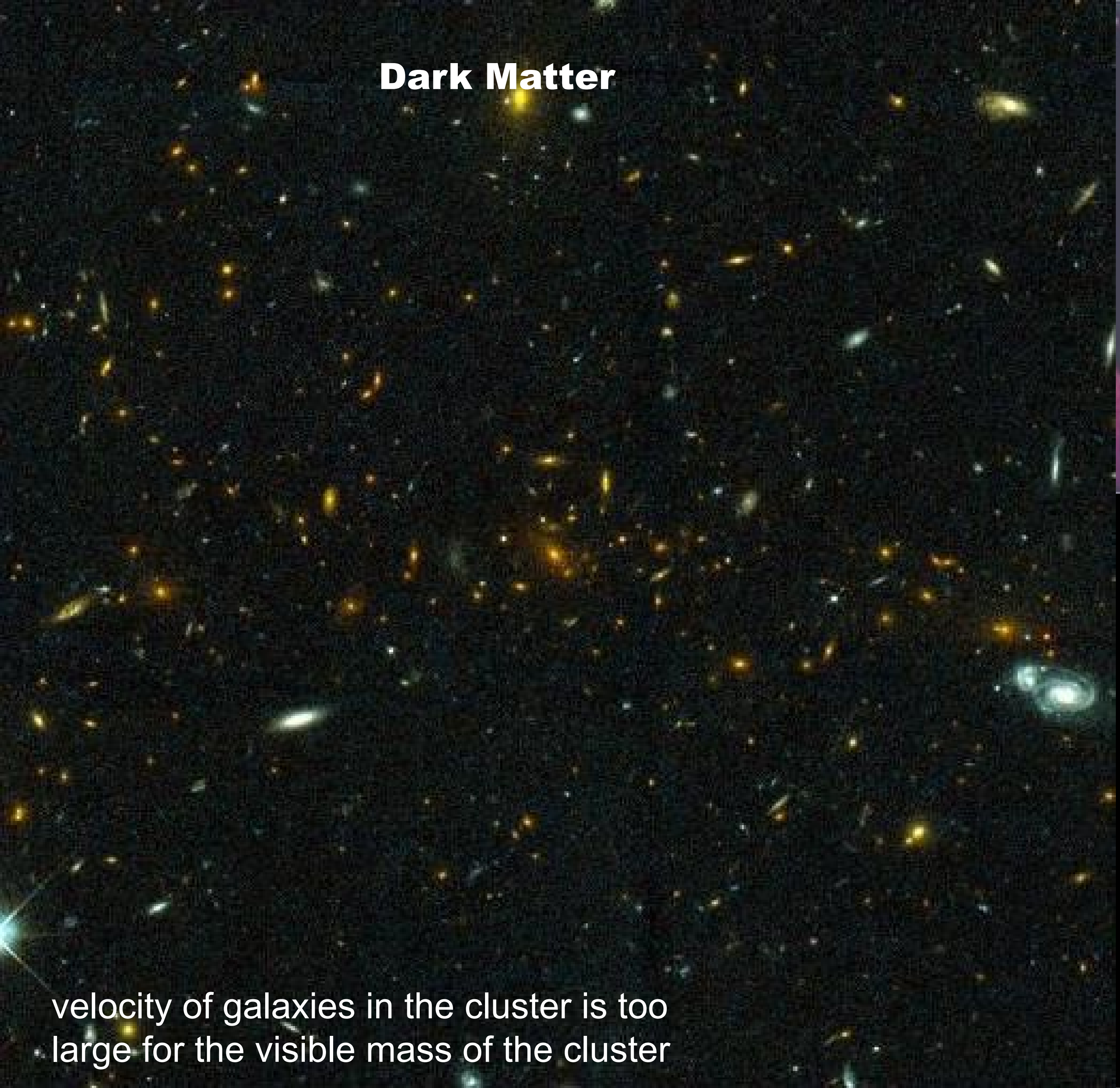
Condition 2 potentially met too easily in large extra dimension scenarios.

$$\Delta B = 1 \quad \leftrightarrow \quad M_F > 10^{12}\mathrm{GeV}$$ (Proton decay)

$$\Delta B = 2 \quad \leftrightarrow \quad M_F > 10^{5}\mathrm{GeV}$$ (neutron/anti-neutron mixing)

Gradual reheating can make sphaleron processes viable with low thermalisation temperature (Riotto et al)

## Dark Matter

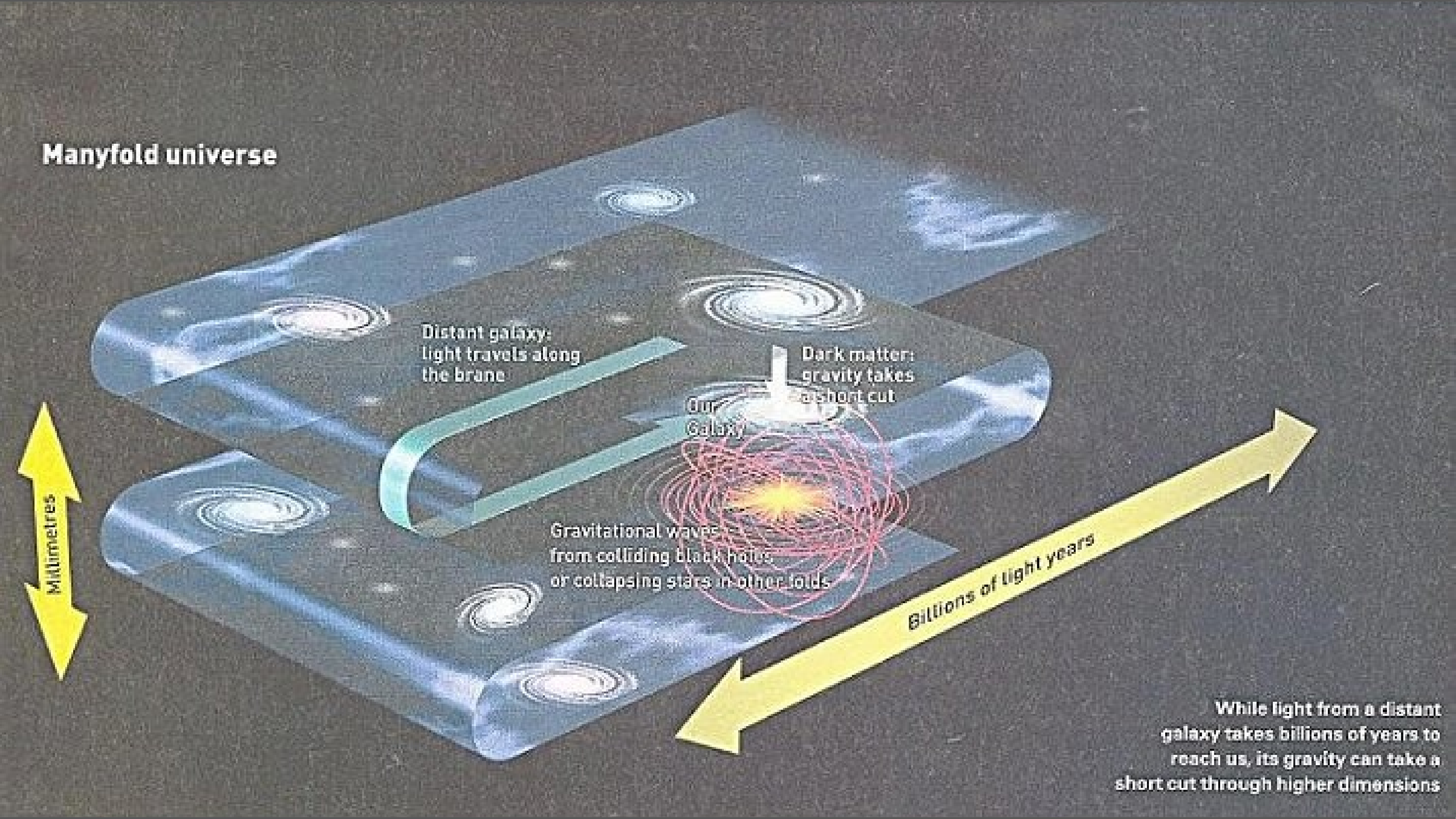


I have a good idea every two years. Give me a topic, I will give you the idea!

Fritz Zwicky
Coma Cluster 1933

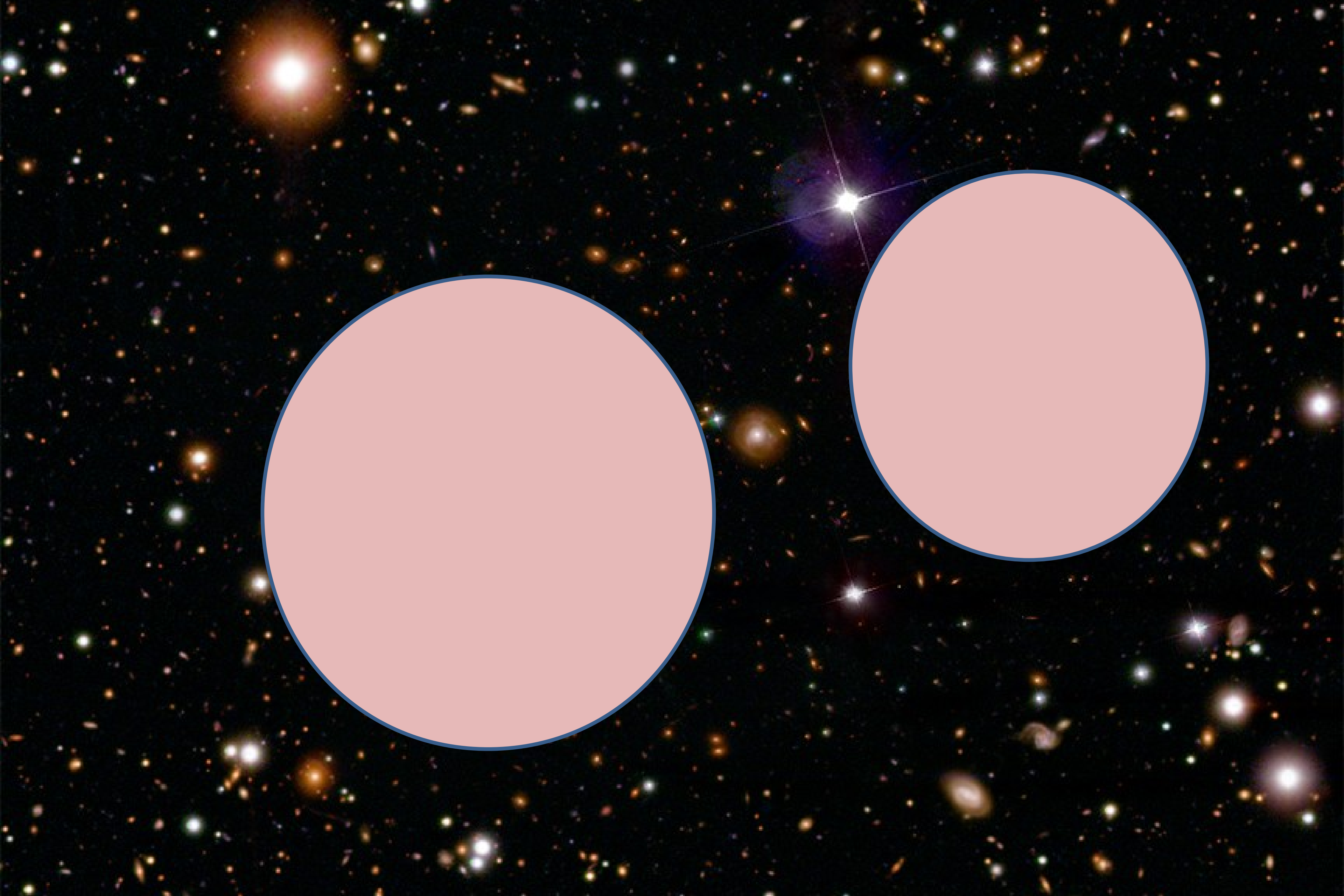
velocity of galaxies in the cluster is too large for the visible mass of the cluster

# Dark Matter: The Manyfold Universe

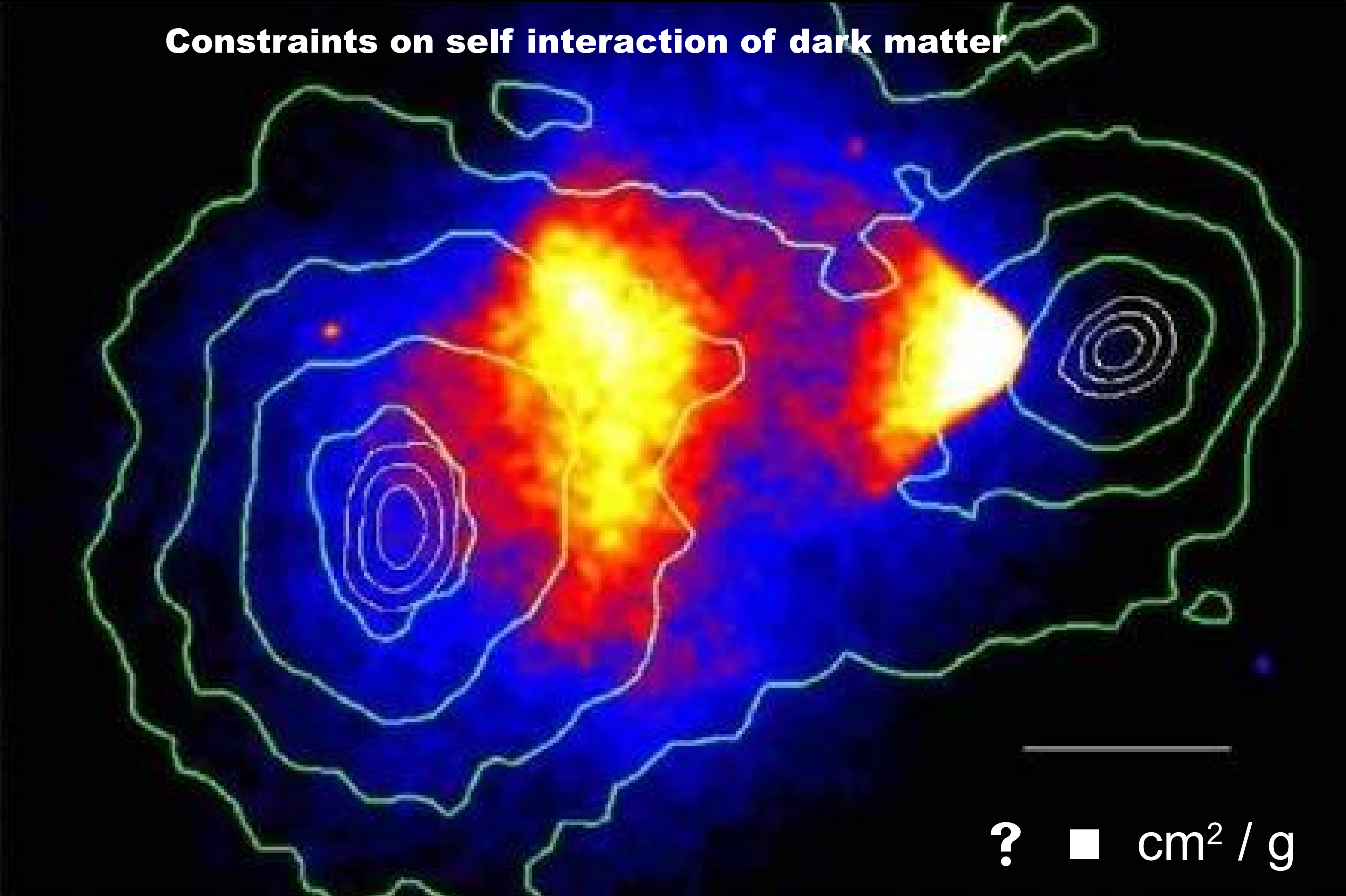



Arkani-Hamed et al. hep-ph/9811386

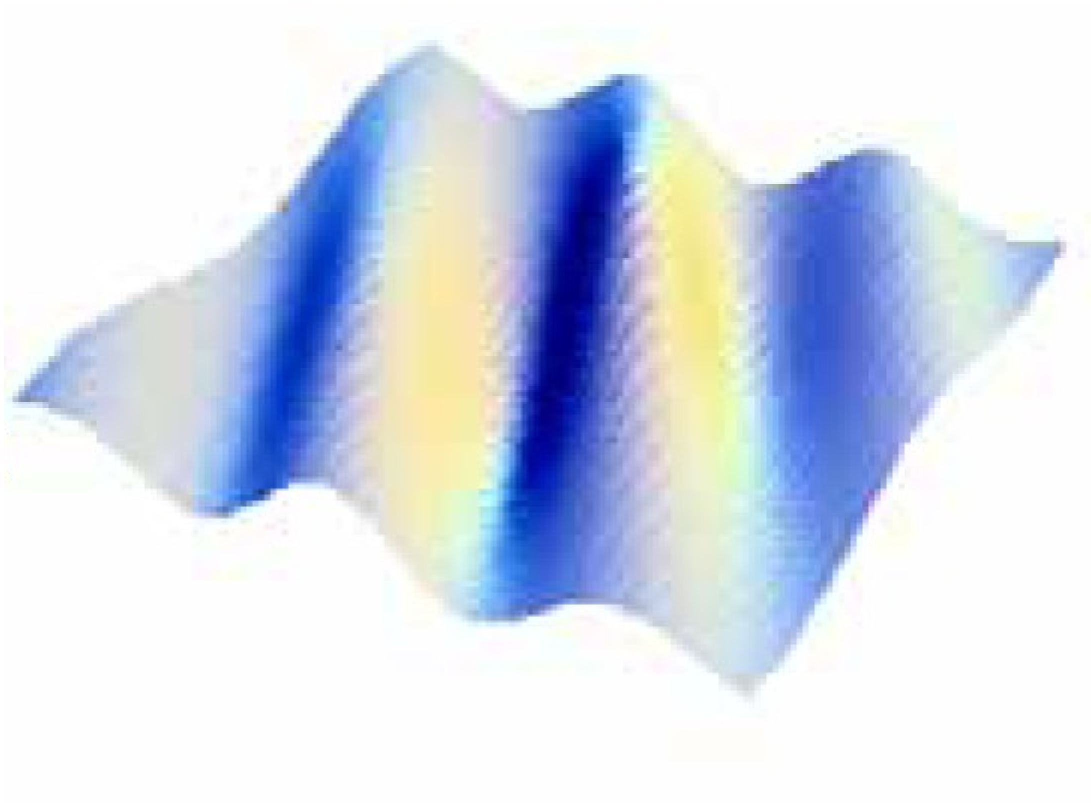
# Constraints on self interaction of dark matter



# Constraints on self interaction of dark matter



## Branon dark matter



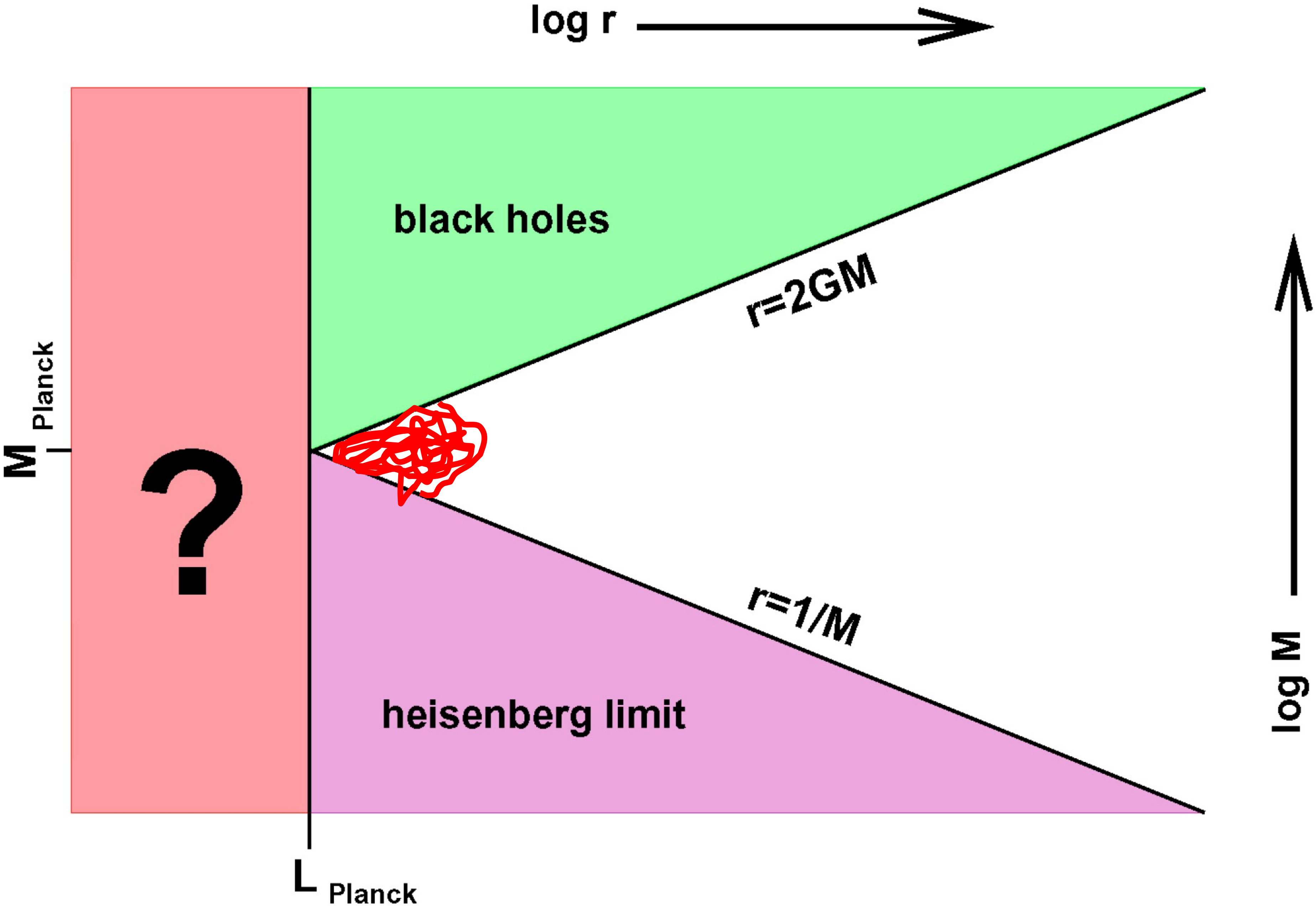
See Antonio Maroto's talk....

# Endpoint of black hole decay in string theory

Black hole undergoes phase transition to string ball

| Energy | Object | $\sigma(M)$ | Most probable size |
|---|---|---|---|
| $1 < Ml_s < 1/g$ | excited string doing random walk | $g^2 M^2 l_s^4$ | $M^{1/2} l_s^{3/2}$ |
| $1/g < Ml_s < 1/g^2$ | | unitarity prevents growth of cross-section beyond $l_s^2$ | |
| | self-gravity of excited string restricts growth | | $1/(g^2 M) < r < M^{1/2} l_s^{3/2}$ |
| $1/g^2 < Ml_s$ | black hole | $r_{BH}^2$ | $g^{2/(D-3)} l_s (l_s M)^{1/(D-3)}$ |

Bowick et al ’86, Amati et al ’89, Damour and Veneziano ‘99


log r
black holes
r=2GM
M Planck
?
r=1/M
heisenberg limit
log M
L Planck

# Modified Uncertainty Principle at Planck Scale ?

$$\Delta x \geq \frac{\hbar}{\Delta p} + L_p^2 \frac{\Delta p}{\hbar}$$

Heuristic argument then suggests modified Hawking temperature :-

$$T_{GUP} = \frac{Mc^2}{4\pi}\left[1 \mp \sqrt{1 - M_P^2 / M^2}\right]$$

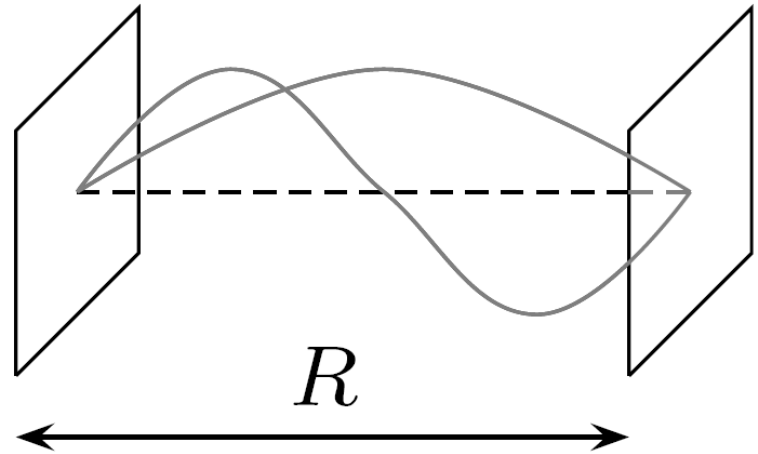
Temperature goes to zero close to the Planck scale.

Stable remnants at end point of black hole evaporation? Dark matter candidate?
(Pisin Chen)

N.B. This is not what string theory predicts…

# Universal extra dimensions

Appelquist et al. 2001




Extra dimensions of size
R ~ 1 / TeV into which
SM gauge fields propagate

Simplest scenario is 1 extra dimension orbifolded $S^1/Z_2$

Orbifolding leads to spectrum of Kaluza Klein (KK) modes such that the lightest KK mode is stable.

Potential dark matter candidate (Servant and Tait 2002)

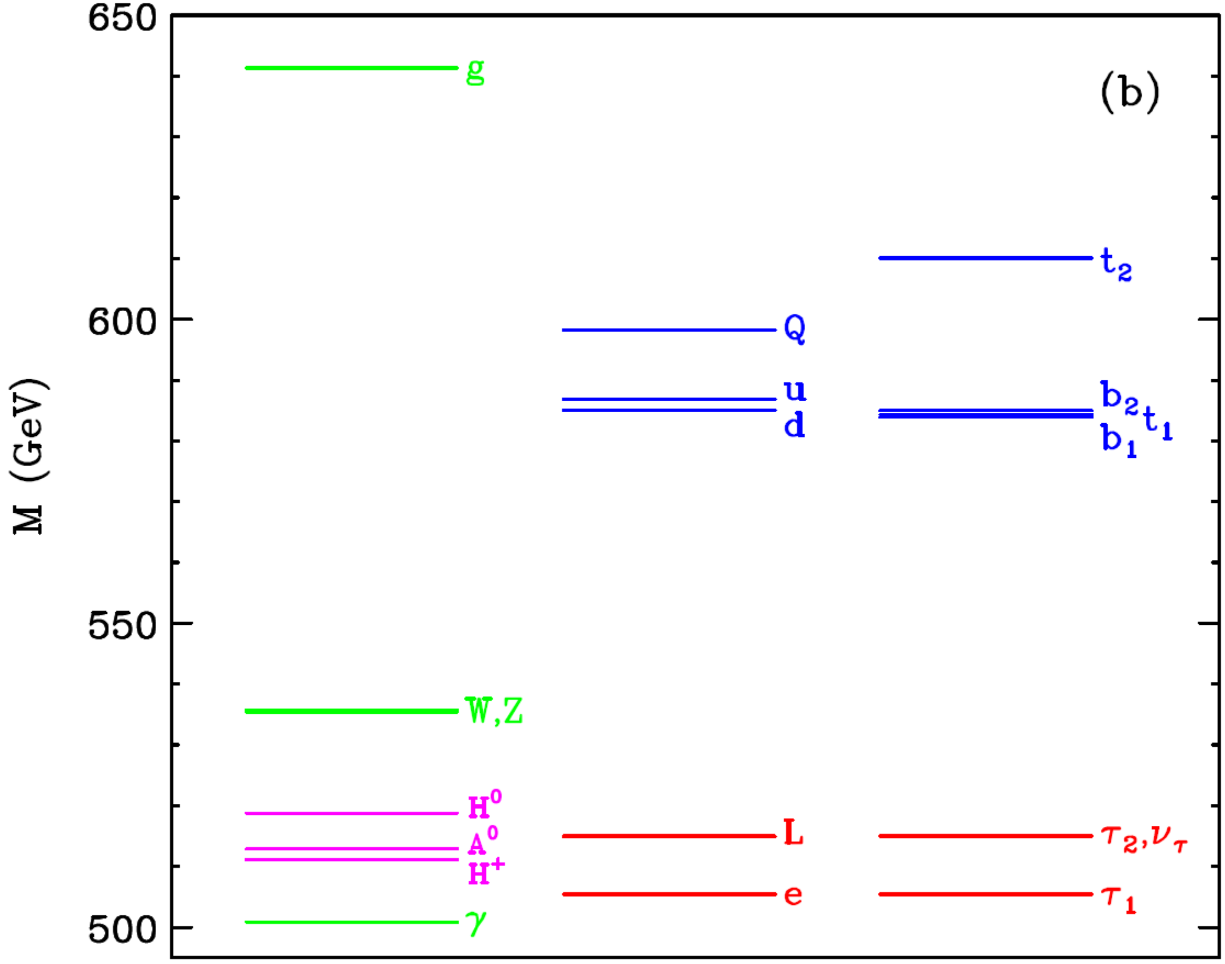
Simplest models fully determined by $R^{-1},\ m_h,\ \Lambda$

# Mass spectrum of KK particles

KK mass ~ 1/R + normal mass from higgs sector + radiative corrections, e.g. for higgs:-

$$\delta m_H^2 = \left(\frac{3}{2}g^2 + \frac{3}{4}g'^2 - \frac{m_h^2}{v^2}\right)\frac{\ln(\Lambda^2 R^2)}{16\pi^2}R^{-2}$$

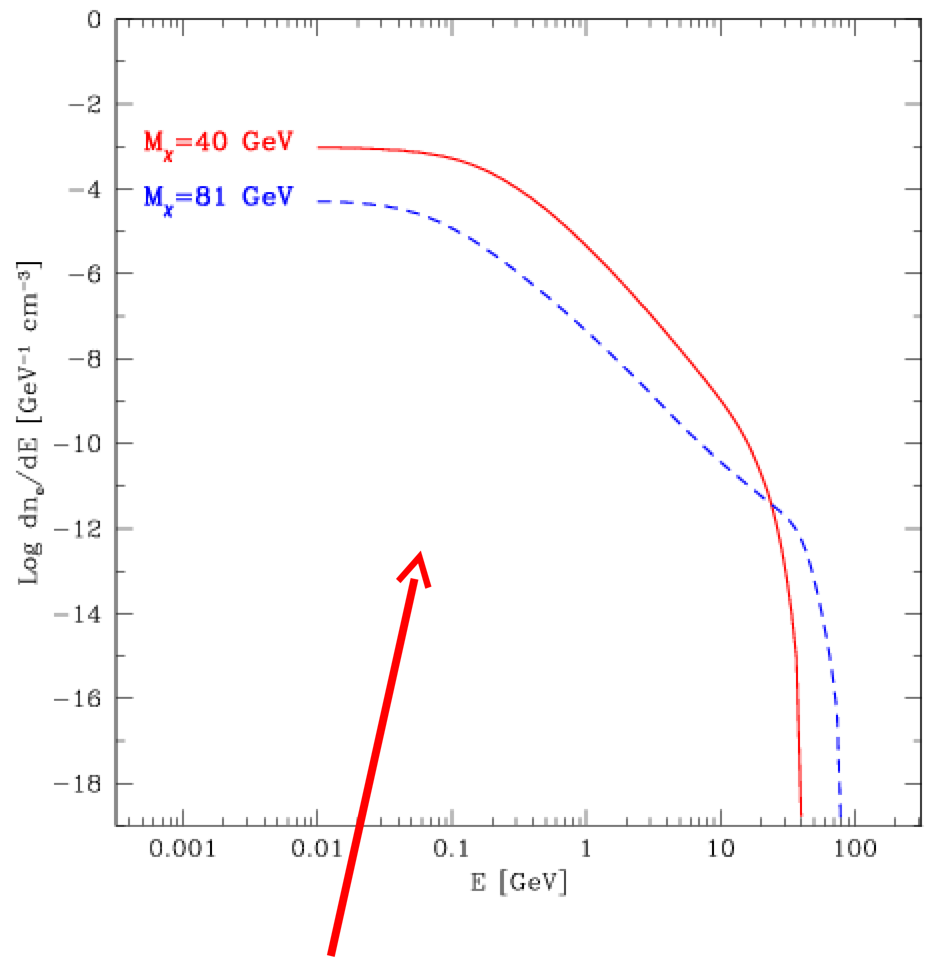
$$R^{-1} = 500 \text{ GeV},$$
$$\Lambda R = 20,$$
$$m_h = 120 \text{ GeV}$$



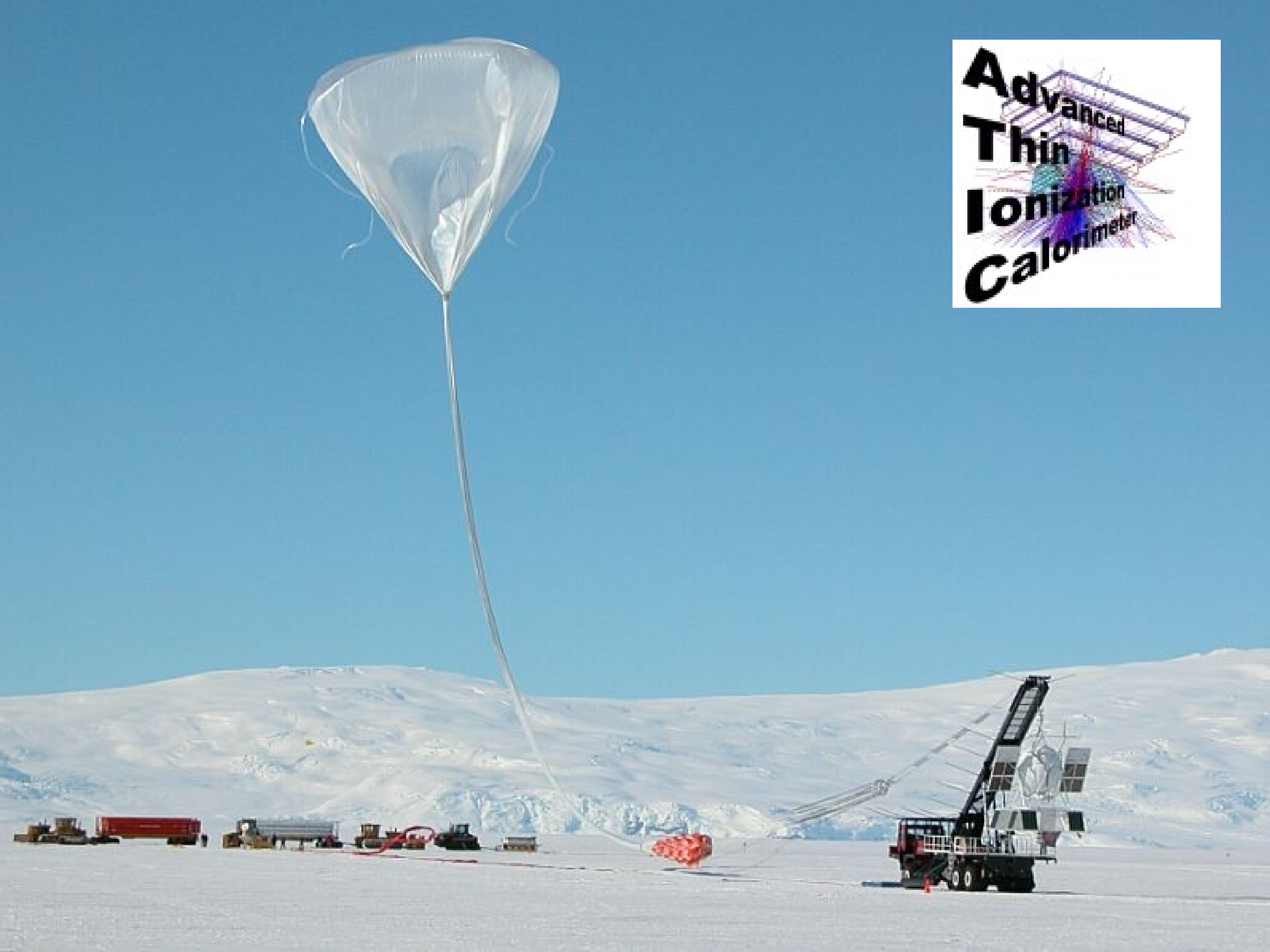

Cheng et al. 2006

# Annihilation of LKKP into electrons is direct, unlike neutralinos

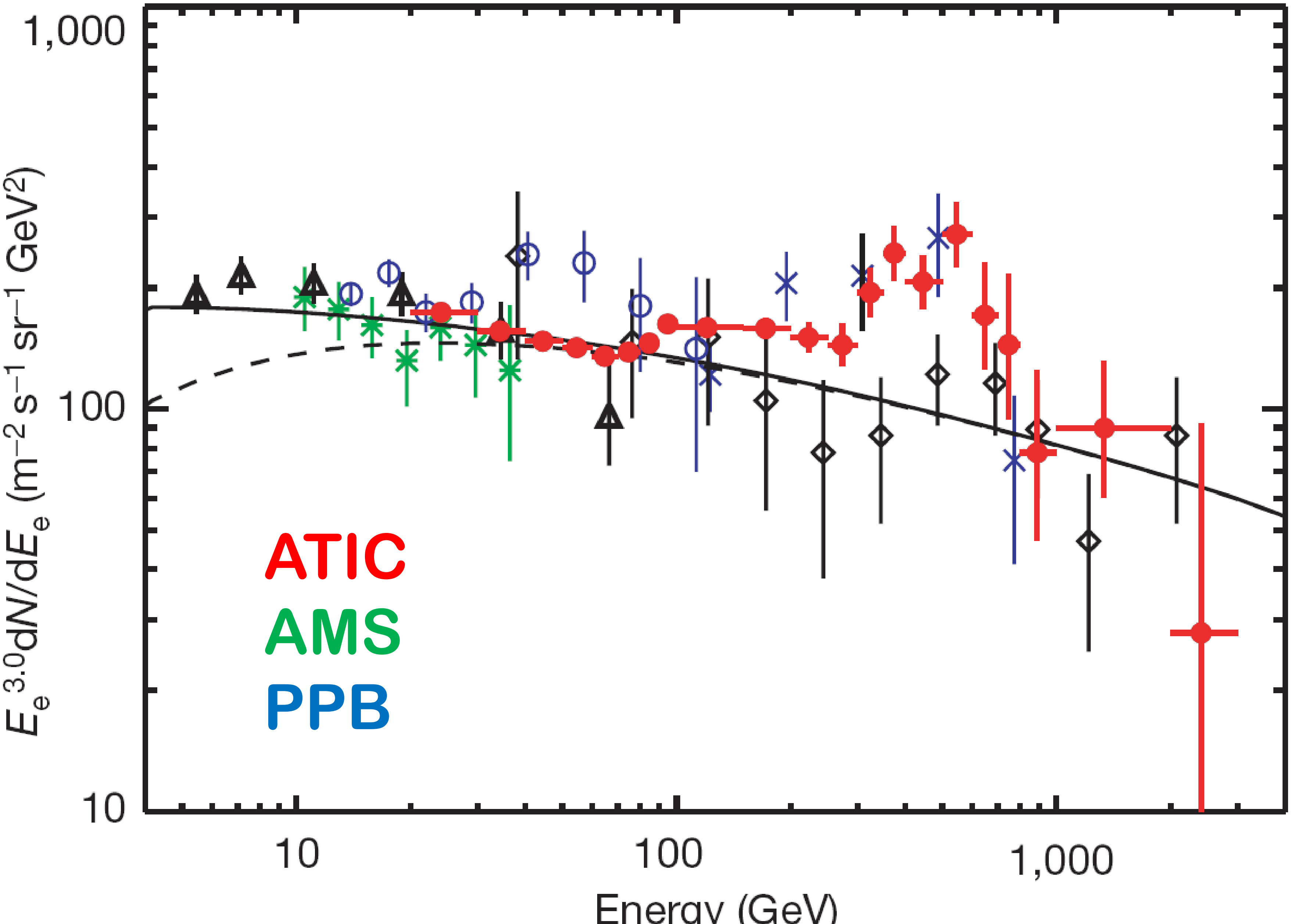
$$\frac{dn}{dt} = \langle \sigma v \rangle \left( \frac{\rho}{m_\chi} \right)^2$$



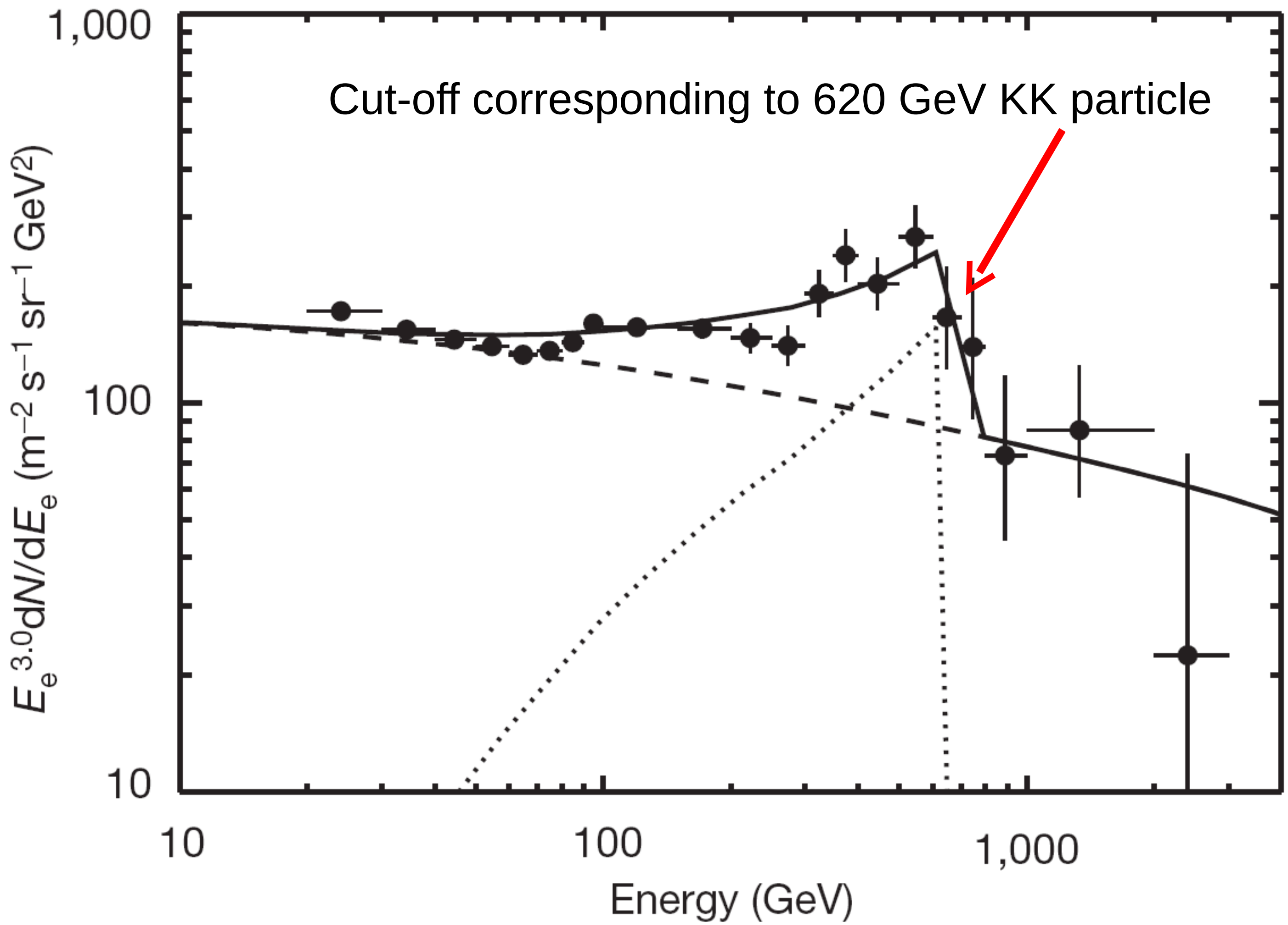

Neutralino annihilation into electrons
(goes via jets)


Advanced
Thin
Ionization
Calorimeter

**Chang et al. Nature 456, 362, 20th November 2008**



## Can be interpreted as Dark matter




However, need large boost factors,

B = ( 10, $10^2$, $10^3$ ) for $m_{DM}$ = ( 100 GeV, 1 TeV, 10 TeV) respectively

# Possible origins of the Boost Factor

**Thermally averaged self annihilation cross section today**

**Actual local density**

$$B \equiv Br_{e^+} \frac{\langle \sigma_A v \rangle \rho_{\rm DM}^2}{\langle \sigma_A v \rangle_F (\bar{\rho}_{\rm DM})^2}$$

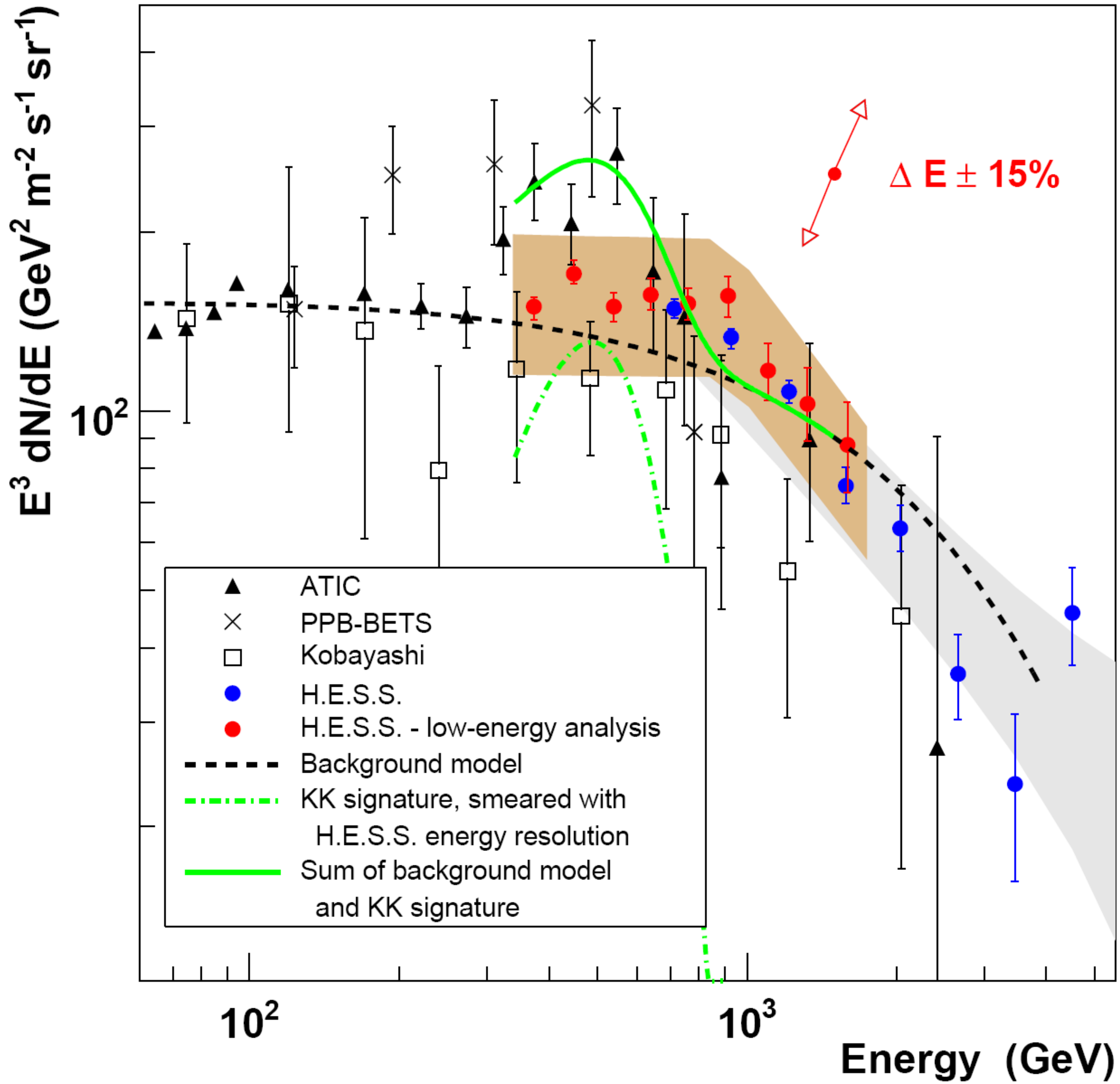
**Branching ratio into e⁺e⁻**

**Thermally averaged self annihilation cross section at freeze-**

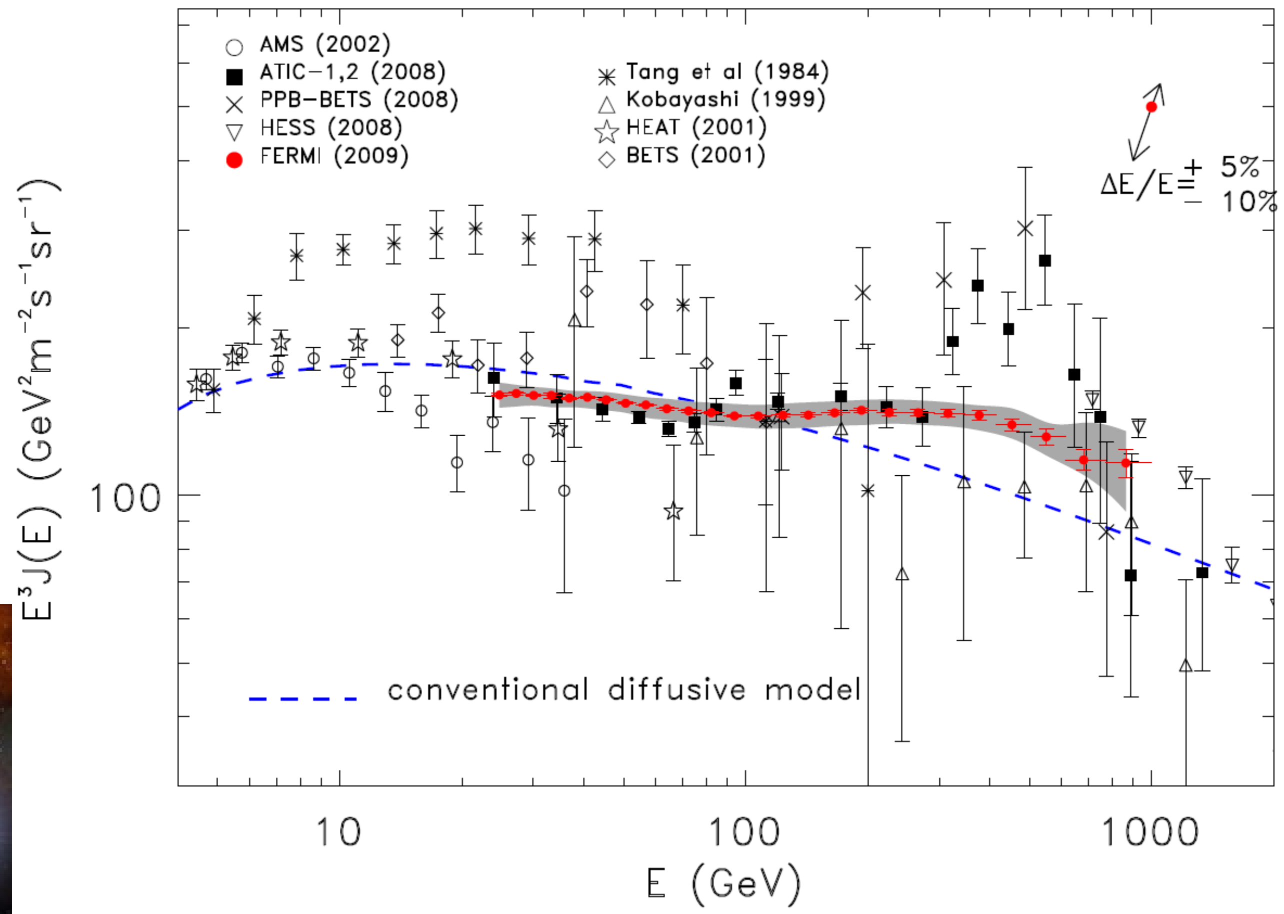
**Expected local density (0.3 GeV cm⁻³)**

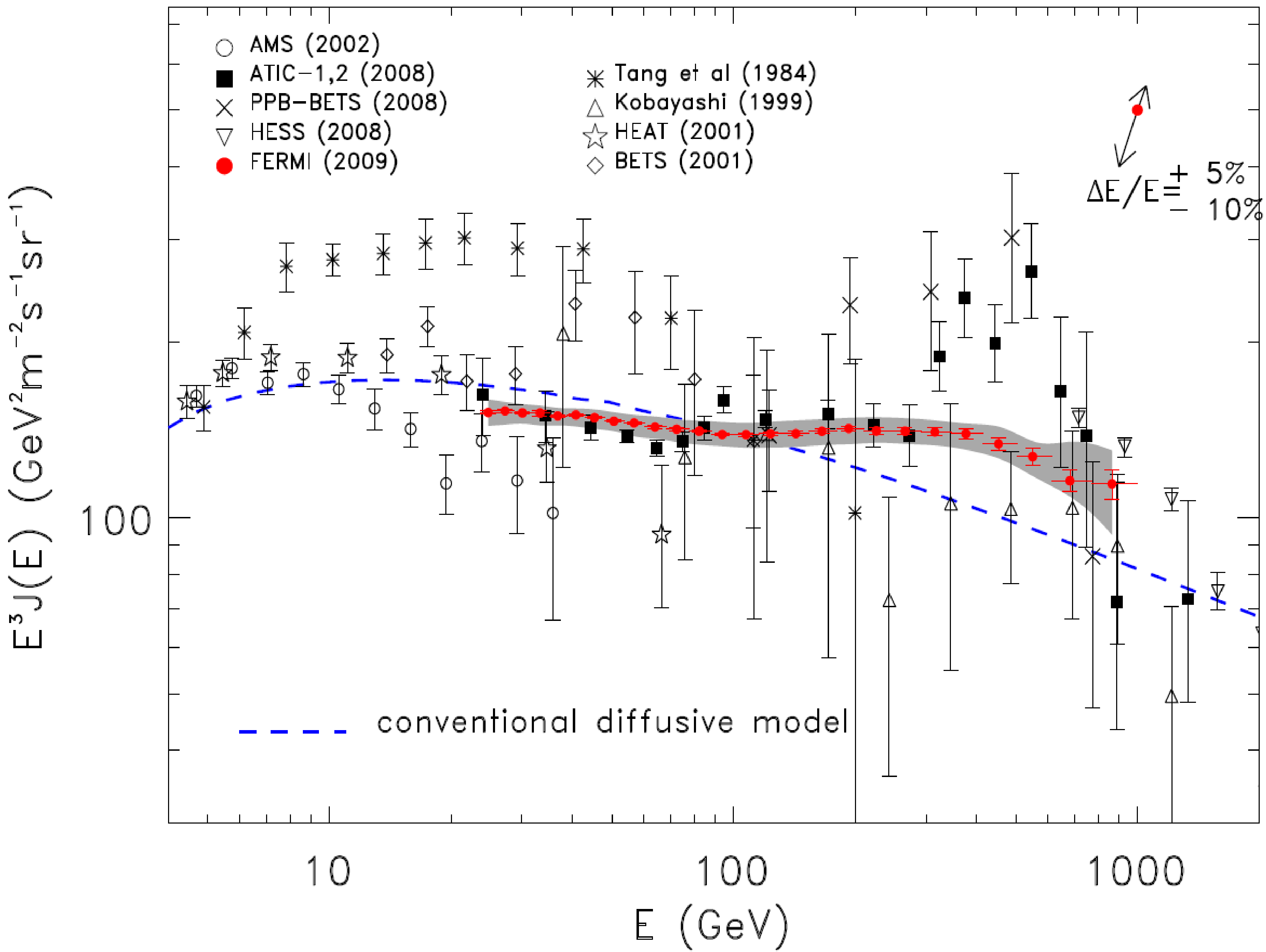
**New H.E.S.S. data**

**0905.0105**



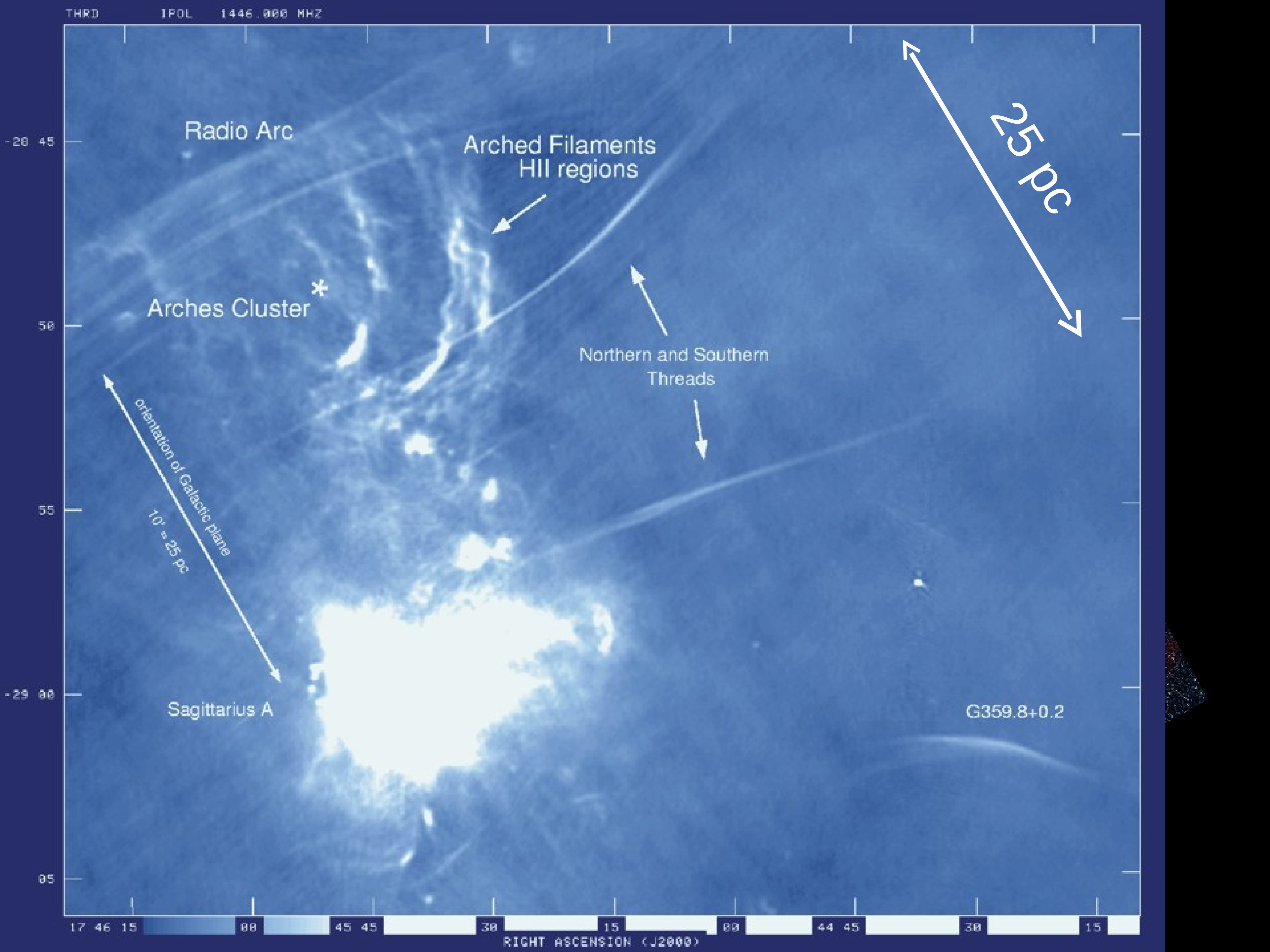
# New Fermi Data 0905.0025

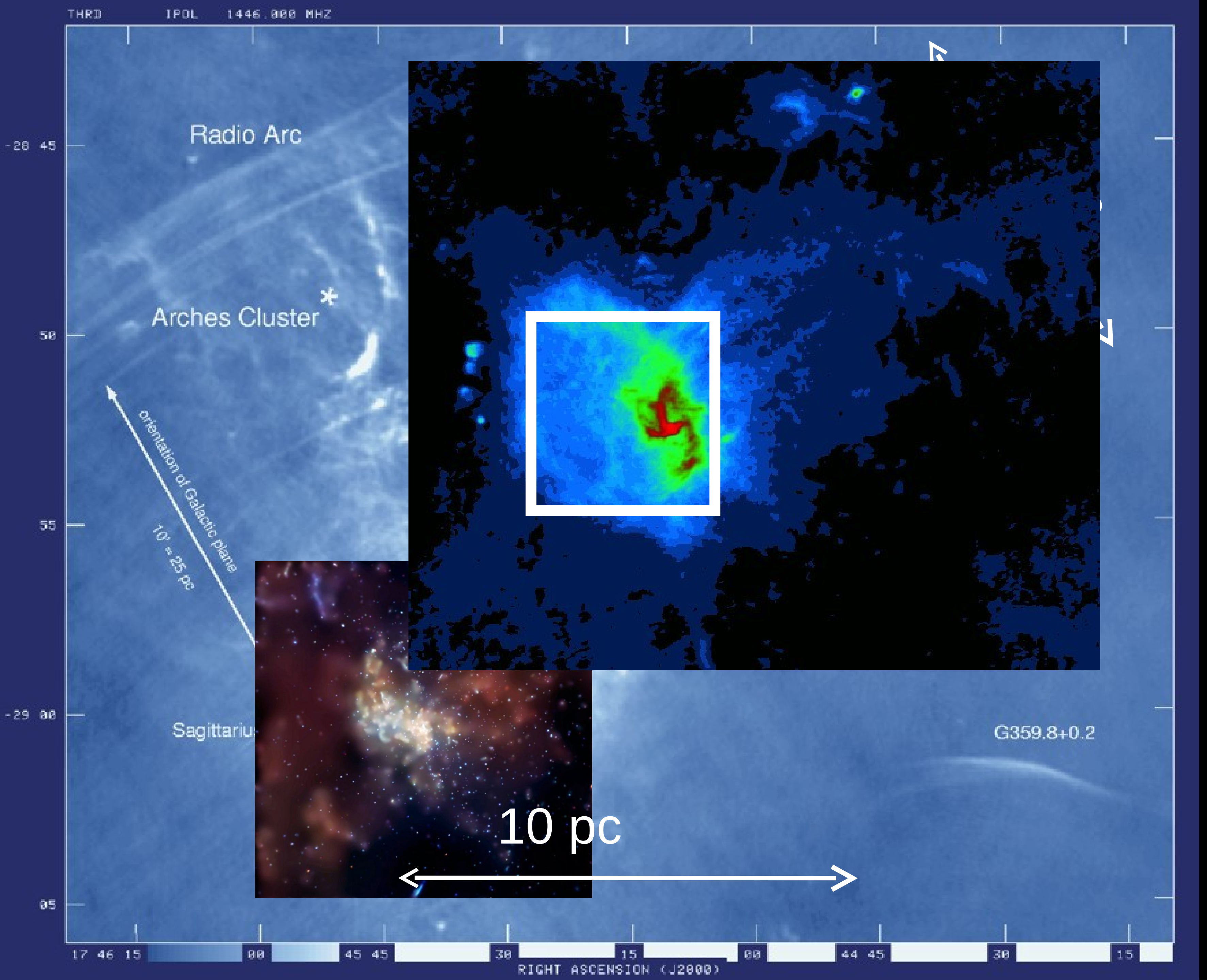




AMS (2002)
ATIC−1,2 (2008)
PPB−BETS (2008)
HESS (2008)
FERMI (2009)
Tang et al (1984)
Kobayashi (1999)
HEAT (2001)
BETS (2001)
ΔE/E=+ 5% − 10%
conventional diffusive model
100
10
1000
E (GeV)
E³J(E) (GeV²m⁻²s⁻¹sr⁻¹)


R 0.3+0.0
Feature:
Fane
alaxy
Mouse
359.0-00.9
Sgr E
SNR 359.1-00.5
Spitzer Infrared telescope
200 x 275 pc
Very La Array (radio)


THRD IPOL 1446.000 MHZ
Radio Arc
Arched Filaments
HII regions
25 pc
Arches Cluster
Northern and Southern
Threads
orientation of Galactic plane
10' = 25 pc
Sagittarius A
G359.8+0.2
-28 45
50
55
-29 00
05
17 46 15
00
45 45
30
15
00
44 45
30
15
RIGHT ASCENSION (J2000)



THRD IPOL 1446.000 MHZ
Radio Arc
Arches Cluster
orientation of Galactic plane
10' = 25 pc
Sagittariu
G359.8+0.2
10 pc
-28 45
50
55
-29 00
05
17 46 15
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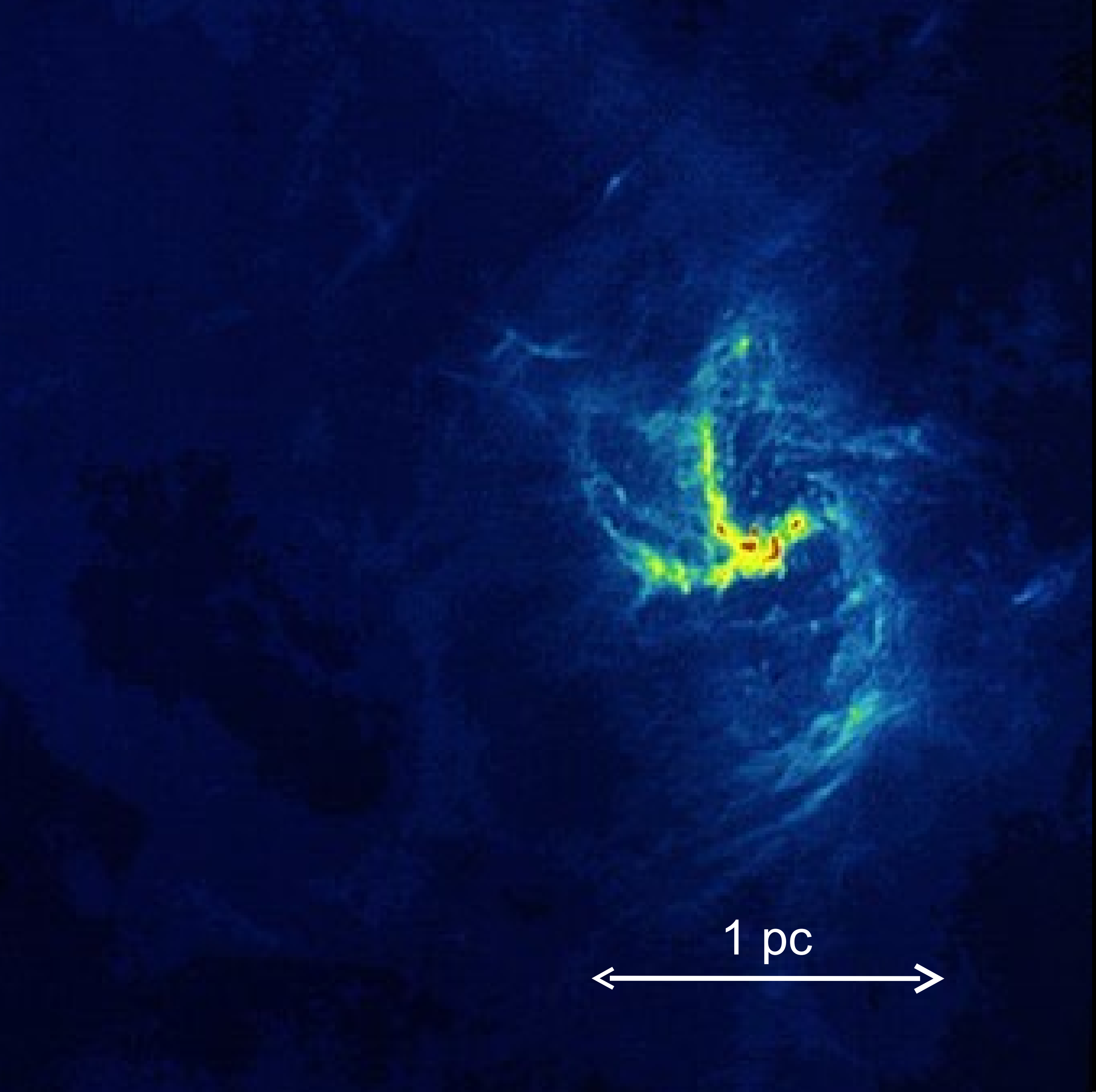
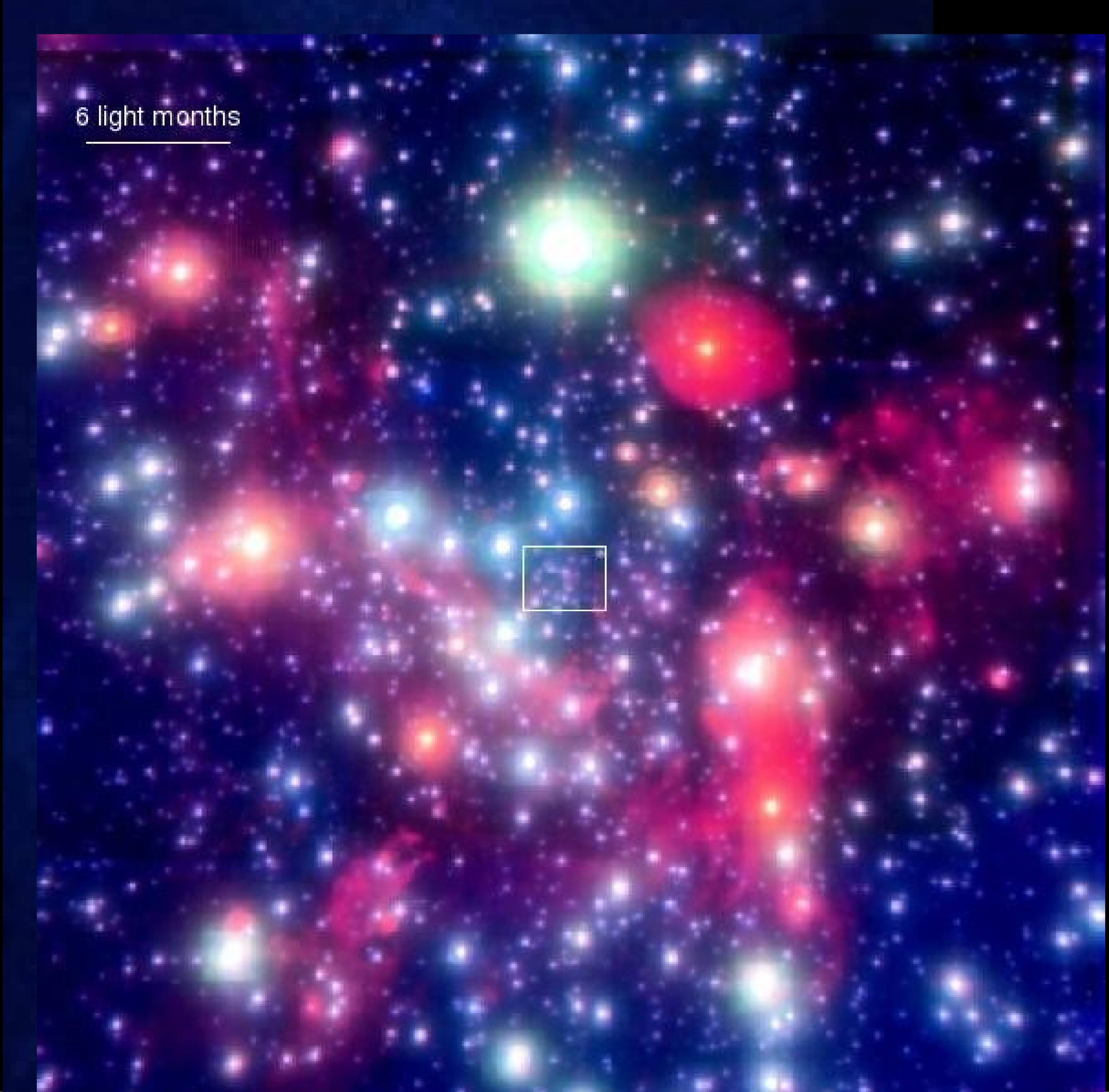
30
15
RIGHT ASCENSION (J2000)

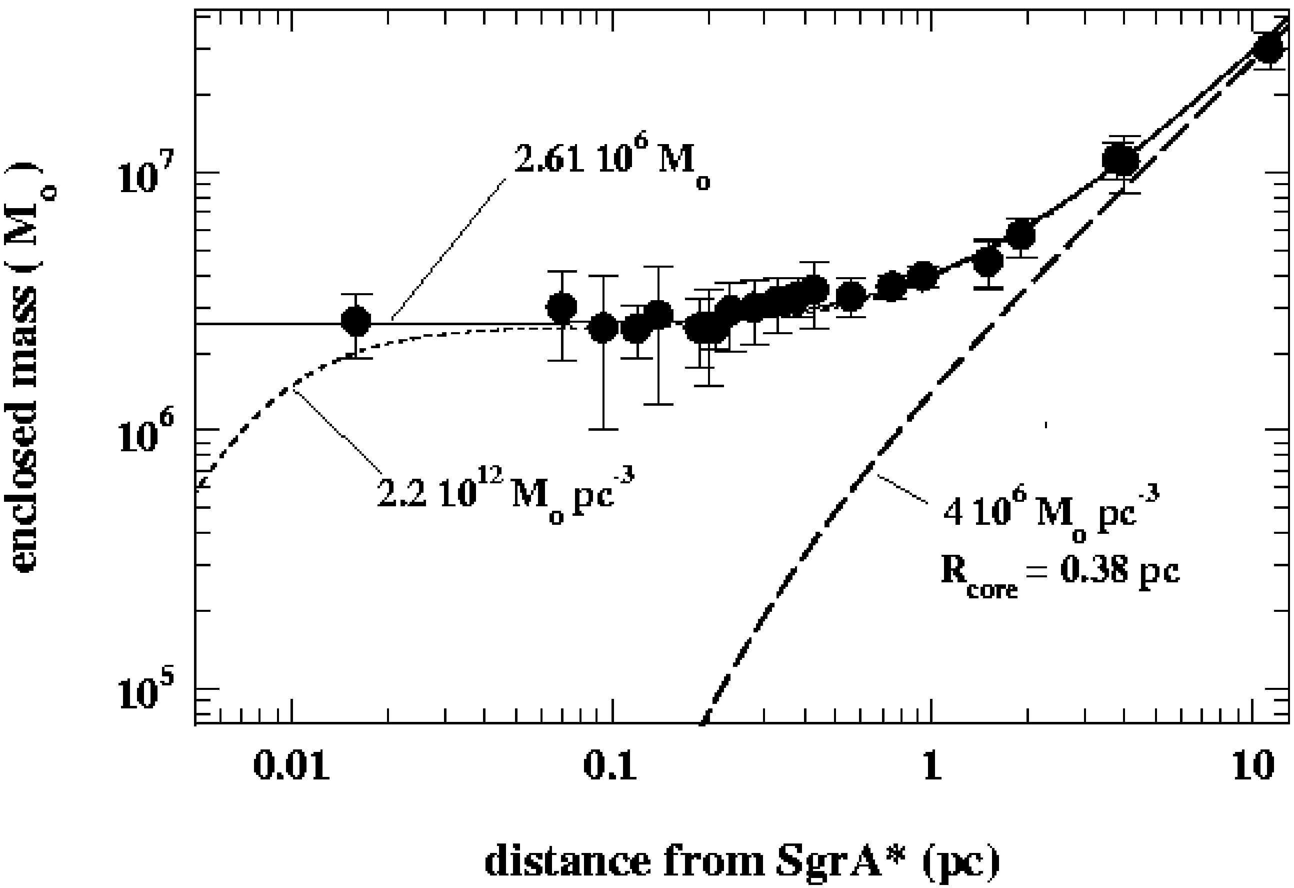



Sagittarius A*
Mini spiral

Original Motion
Picture Soundtrack
DIGITAL RECORDING
THE BLACK HOLE
Music by
JOHN BARRY

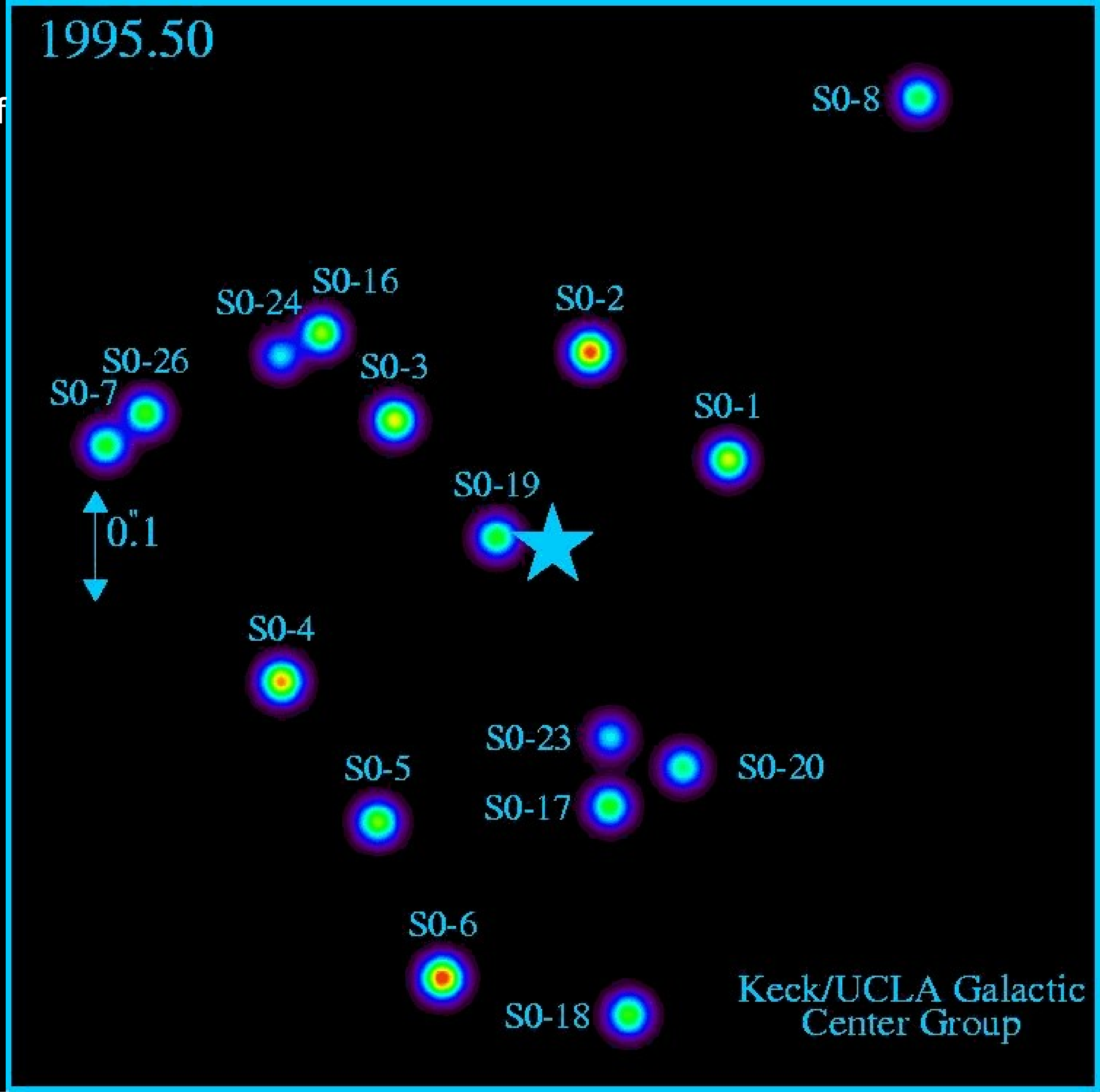

6 light months

# Mass contained within radius from stellar motions

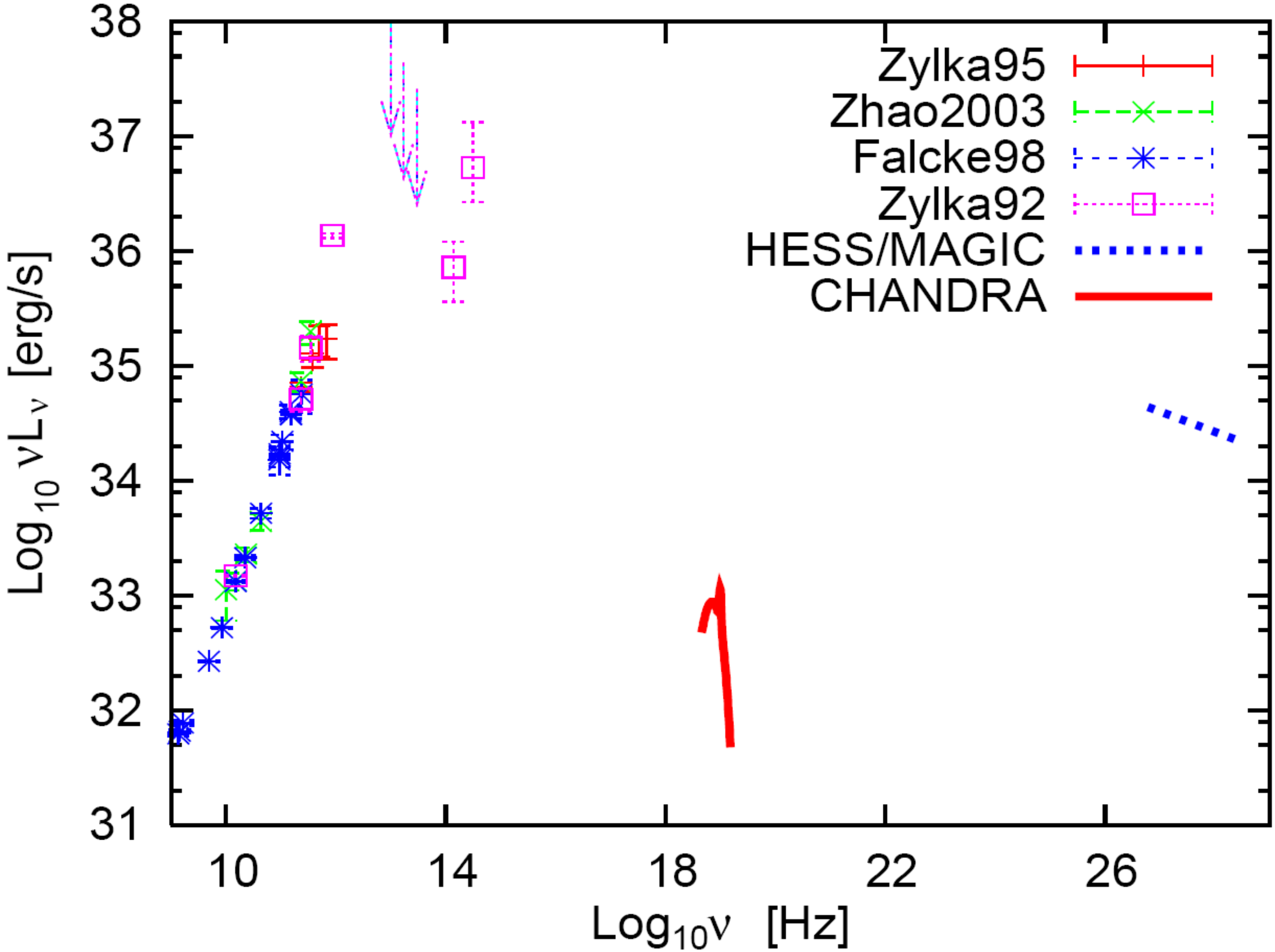


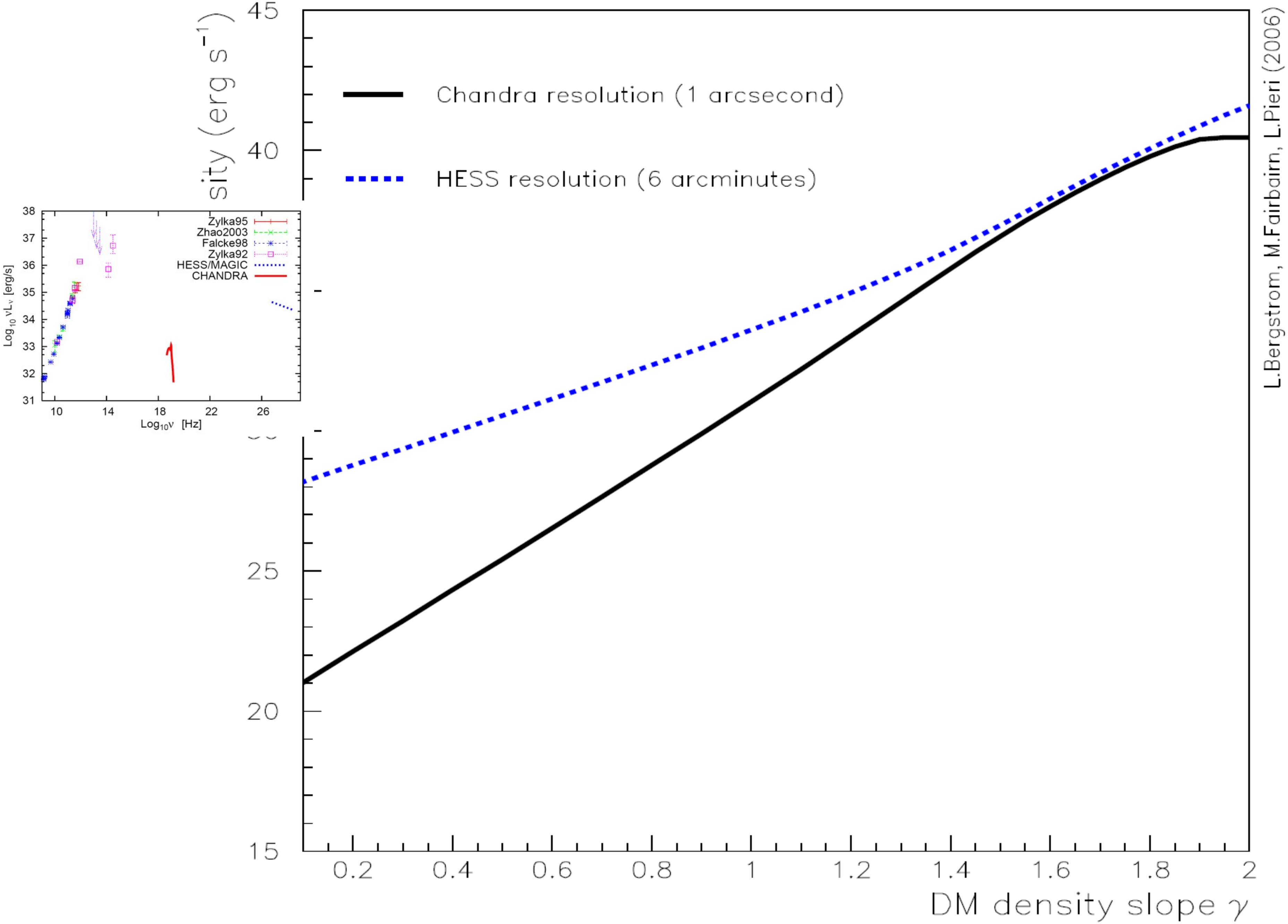
Closest approach of S0-16 is
0.0002 pc
=45 AU
=600 Rsch

0.04 pc



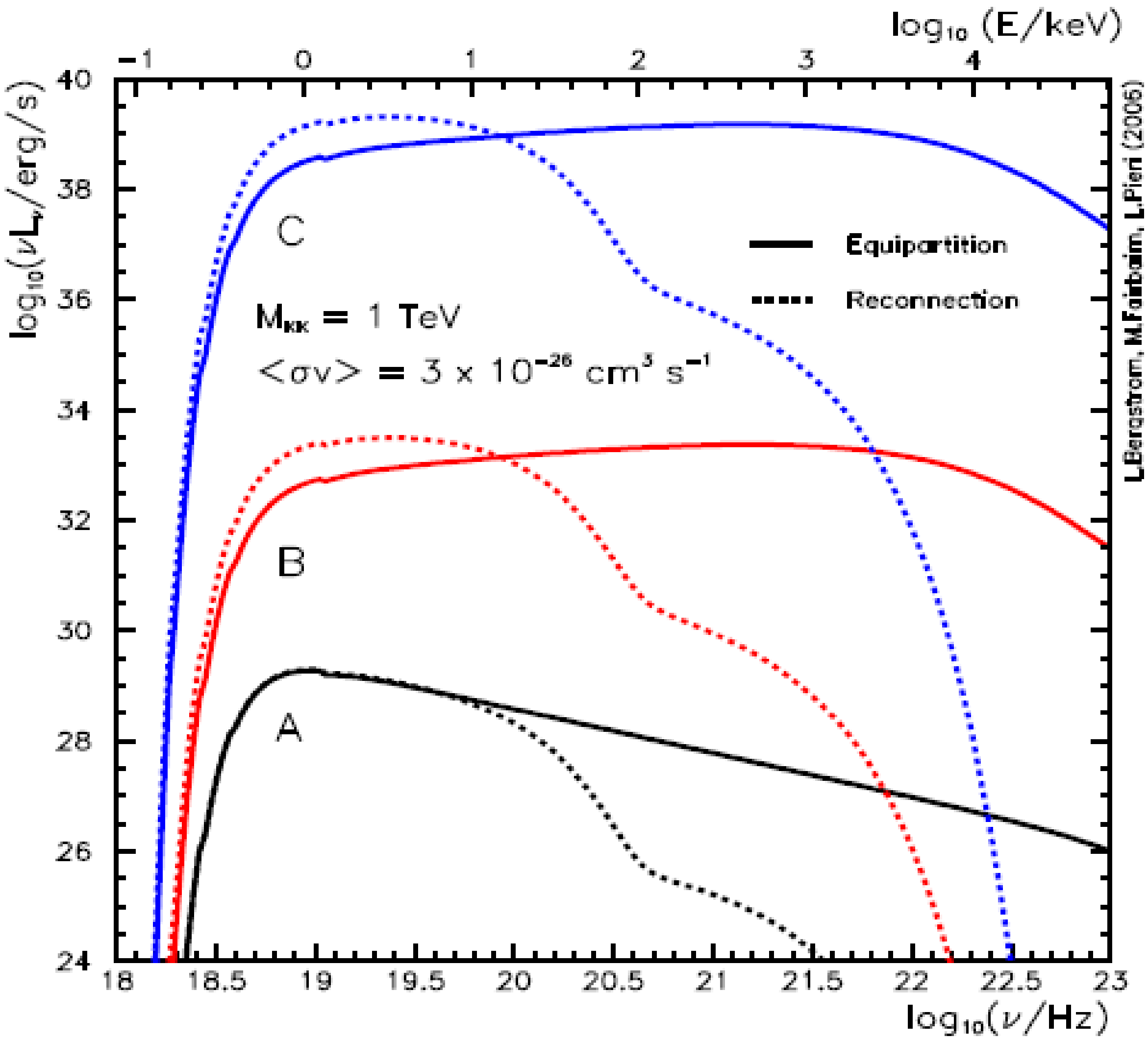
# Emission From Black Hole (best resolution at all frequencies)





sity (erg s^-1)
45
40
25
20
15
Chandra resolution (1 arcsecond)
HESS resolution (6 arcminutes)
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
DM density slope γ
L.Bergstrom, M.Fairbairn, L.Pieri (2006)
Zylka95
Zhao2003
Falcke98
Zylka92
HESS/MAGIC
CHANDRA
Log10 νLν [erg/s]
Log10ν [Hz]
38
37
36
35
34
33
32
31
10
14
18
22
26

UED predicts x-ray synchrotron rather than radio synchrotron!



# Conclusions

- Large extra dimensions tightly constrained by cosmology
- Many loose ends
- UED not reallly good explanation for ATIC/PAMELA signal
- UED does make interesting predictions for indirect DM searches