SUPERHEAVY DARK MATTER

A. RIOTTO,
CERN-THEORY GROUP

IN COLLABORATION WITH
R. KOLB & D. CHUNG

- PHYS. REV. D59 (1999) 023051
- PHYS. REV. LETT. 81 (1998) 4048
- hep-ph/9809454
- hep-ph/9810361
- SCIENCE (to appear this week)

OUTLINE:

☆ WHY DM ?

☆ WHO IS THE DM ?

COMMON LORE :
THERMAL RELICS, WEAK SCALE PHYSICS

UNBEATEN PATH :
INDICATED BY RECENT DEVELOPMENTS IN PARTICLE COSMOLOGY

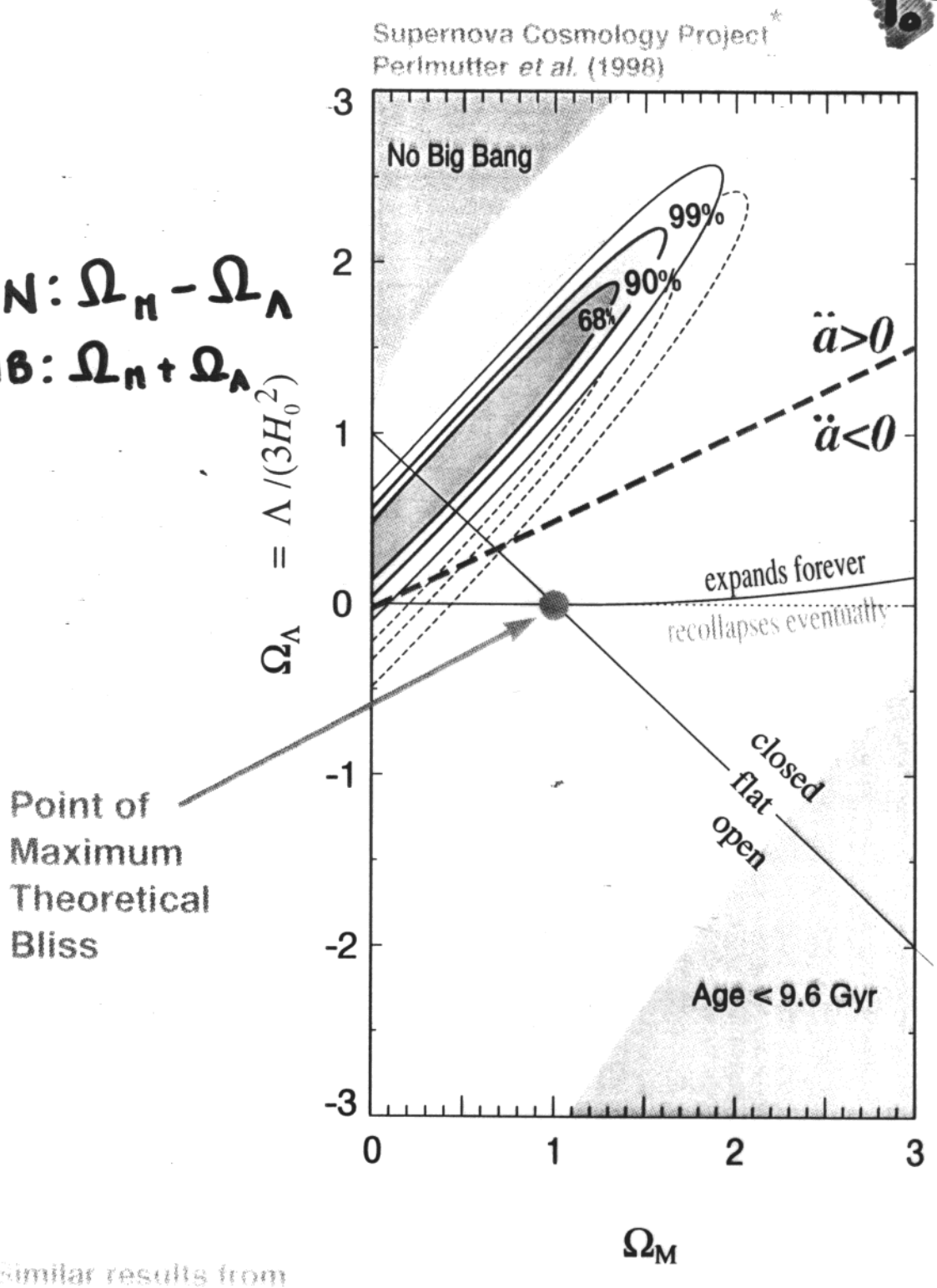
PANDORA'S BOX :
CHARGED DM, STRONGLY INTERACTING DM, GUT SCALE DM, ... , UHE COSMIC RAYS, ...

$$\Omega_\Lambda = 0.7 \quad \Omega_M = 0.3$$

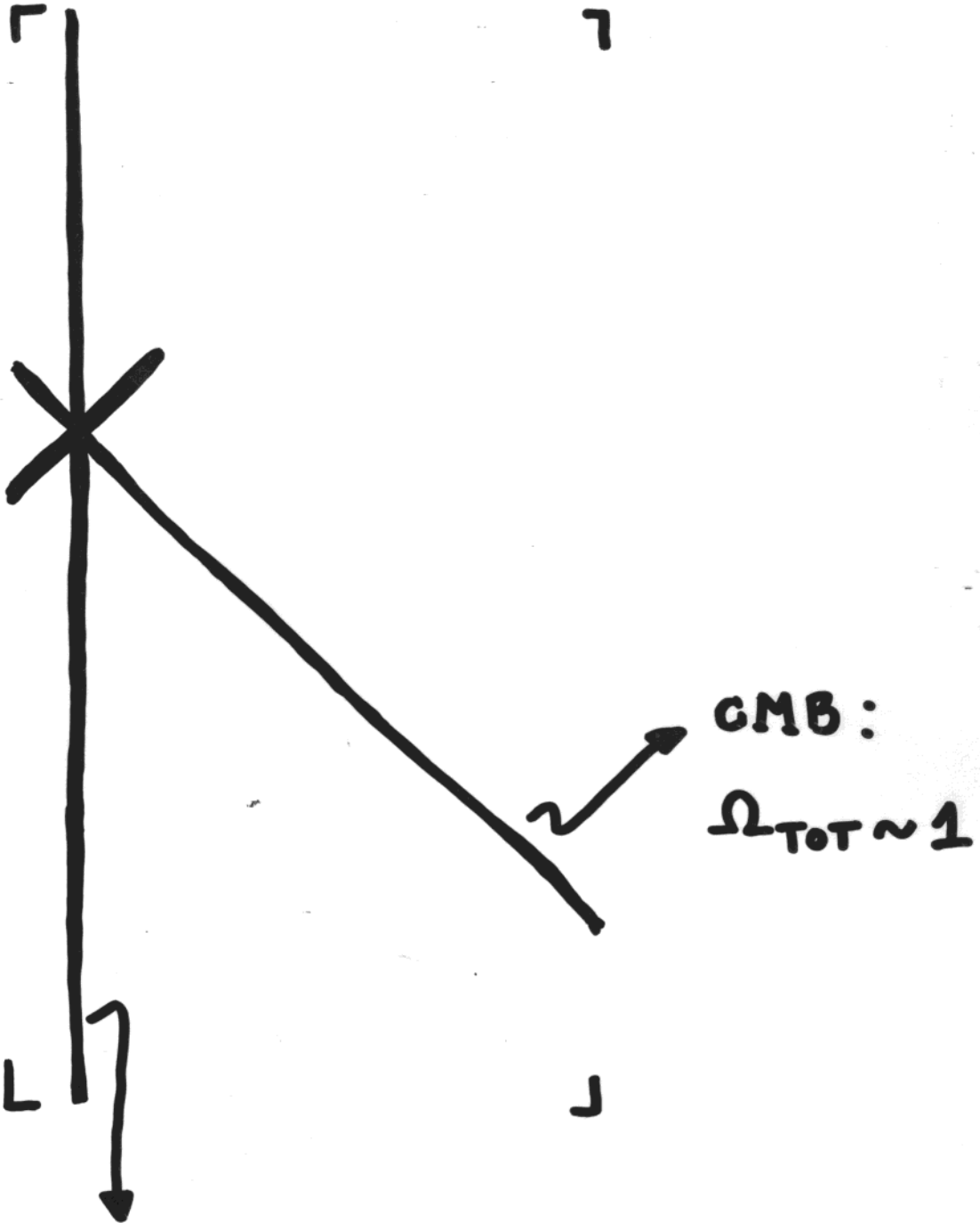
$q_0 = \Omega_{TOT}(1+3w)/2$

SN: $\Omega_M - \Omega_\Lambda$

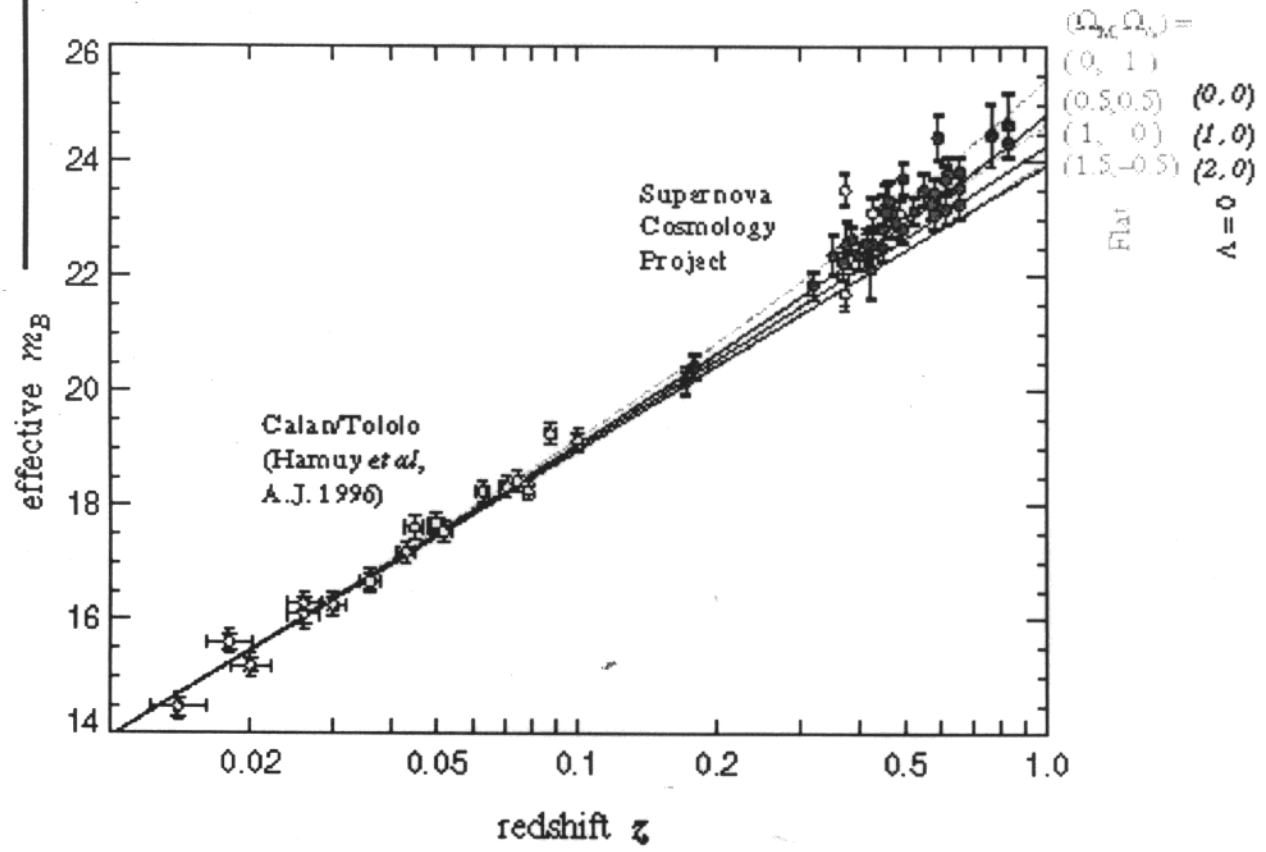
CMB: $\Omega_M + \Omega_\Lambda$



*Similar results from High-z supernova team


CMB :
$\Omega_{TOT} \sim 1$
LSS :
$\Omega_M \sim 0.3$

effective m_B ~ distance ~ $\ln d_L$



Perlmutter, et al.

$$H_0 d_L = z + \frac{1}{2}\left(1 - q_0\right) z^2 + \ldots$$

Space/Pictures.Colloquia/distance_redshift

HEWLETT PACKARD HEWLETT PACKARD HEWLETT PACKARD HEWLET PACKARI

WHO IS THE DM?

- INVISIBLE AXION [AXINOS]
- LIGHT NEUTRINO
- LSP - GRAVITINO
- MAGNETIC MONOPOLES
- PYRGONS
- QUARK NUGGETS
- PRIMORDIAL BLACK HOLES
- .....

- WHAT IS THE STANDARD LORE?

DM IS A THERMAL RELIC!

THERE EXISTS A NEW, YET UNDISCOVERED STABLE MASSIVE PARTICLE IN THERMAL EQUILIBRIUM

- $T \gg m_X$, $n_X \sim T^3$
- $T \ll m_X$, $n_X \propto e^{-m_X/T}$

- Ω_X IS DETERMINED BY ANNIHILATIONS INTO LIGTHER STATES: $X\bar{X} \to l\bar{l}$

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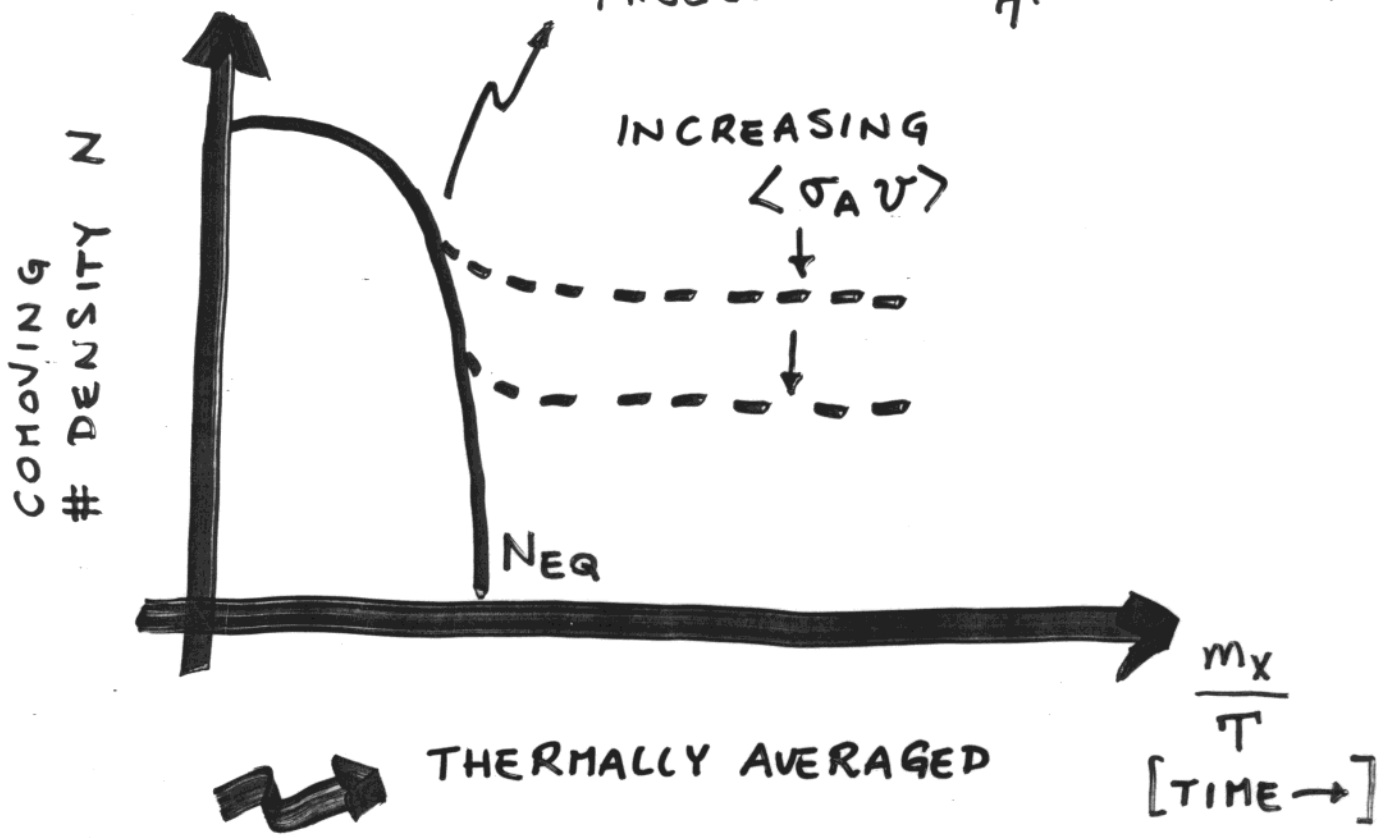
FREEZE OUT : $\frac{m_X}{T} \sim (10 \div 20)$



THERMALLY AVERAGED

$$\Gamma_A = \langle \sigma_A (X\bar{X} \to l\bar{l}) v \rangle n_X$$

$$H \sim T^2 / M_{PL} \quad \Rightarrow \quad \Gamma_A \lesssim H$$

X'S CEASE TO ANNIHILATE

$$\Omega_X h^2 = \frac{m_X n_X}{\rho_c} \simeq \frac{3 \times 10^{-27} \, cm^3 \, s^{-1}}{\langle \sigma_A v \rangle}$$

NICE COINCIDENCE:

v (@ FREEZE OUT) ~ FRACTION OF c

$\Omega_X h^2 \sim 1$ IF $\sigma_A \sim 10^{-9}\ \text{GeV}^{-2}$

$\Downarrow$

$\left\langle \sigma_{WEAK} \simeq \dfrac{\alpha^2}{m^2_{WEAK}} \right\rangle$ $\alpha \sim 10^{-2}$, $m_{WEAK} \sim m_Z$

"THIS COINCIDENCE SUGGESTS THAT IF A NEW, YET UNDISCOVERED, MASSIVE PARTICLE WITH ELECTROWEAK INTERACTIONS EXISTS, THEN IT SHOULD HAVE A RELIC DENSITY ~ 1 .... THIS ARGUMENT HAS BEEN THE DRIVING FORCE BEHIND A VAST EFFORT TO DETECT THESE PARTICLES IN THE HALO"

M. KAMIONKOSKI

hep-ph/9710467

HEWLETT PACKARD HEWLETT PACKARD HEWLETT PACKARD

MORE FORMALLY:

K. GRIEST
&
M. KAMIONKOWSKI
PRL 64 (90) 615

THE ANNIHILATION CROSS SECTION MUST SATISFY THE UNITARITY LIMIT:

$$\begin{cases} \sigma_A \leq \pi(2J+1)/p_i^2 \\ p_i^2 = E^2 - m_X^2 \approx m_X^2 v^2/4 \end{cases}$$

[REMEMBER $\Omega_X \propto \frac{1}{\sigma_A}$]

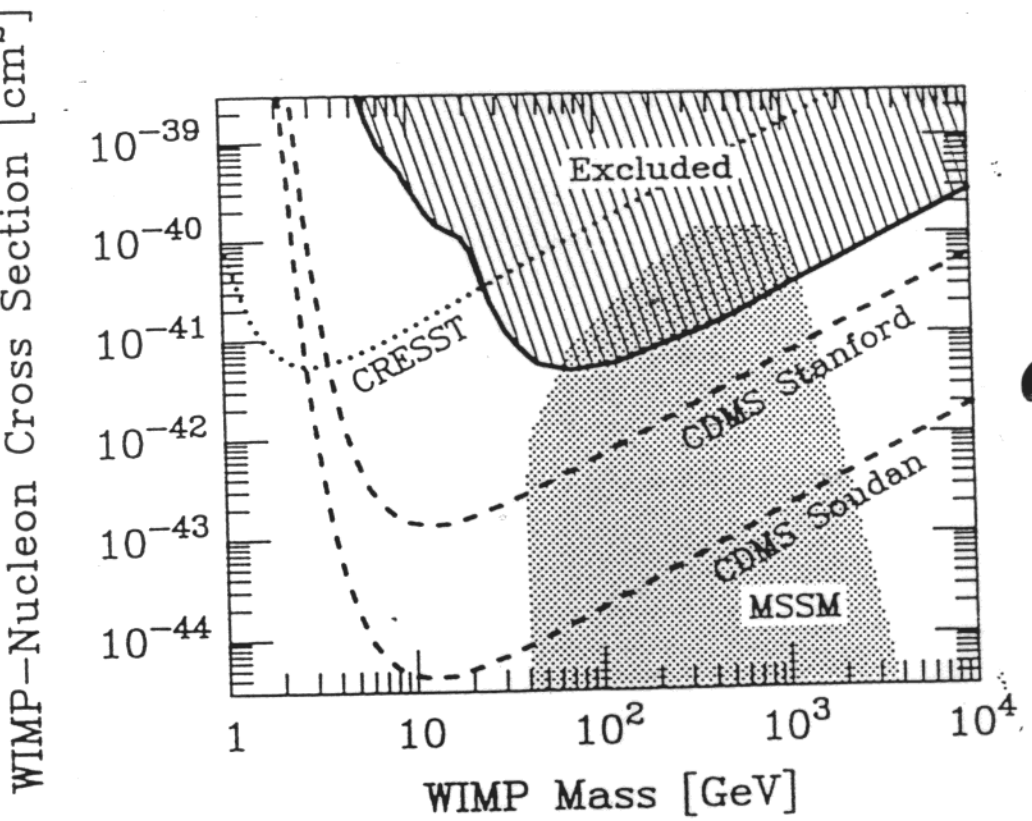
$$\Omega_X h^2 \lesssim 1$$

$$\left\{ m_X \lesssim 10^2 \text{ TeV} \right\}$$ IF THERMAL

LOCAL HALO DENSITY

$$\rho \sim 0.3 \text{ GeV cm}^{-3}$$

$$n_X \sim 3\,10^{-3} \left(\frac{100\,\text{GeV}}{m_X}\right) \text{cm}^{-3}$$



UV CUT OFF

IMPLICATIONS:

☆ RULES OUT DM WITH STRONG INTERACTIONS, $\sigma_{XN} \sim 10^{12} \sigma_{WEAK}$

☆ RULES OUT CHARGED DM, **CHAMP'S**

DE RÚJULA, GLASHOW, SARID, '89

$$\Omega_{CHAMP} \lesssim 1$$

$$\Downarrow$$

$$m_{CHAMP} \lesssim 10^2 \text{ TeV}$$

C^+ FORM SUPERHEAVY HYDROGEN WHOSE ABUNDANCE IN NATURAL WATER SHOULD BE MUCH LARGER THAN THE PRESENT BOUND

DARK MATTER

may be a

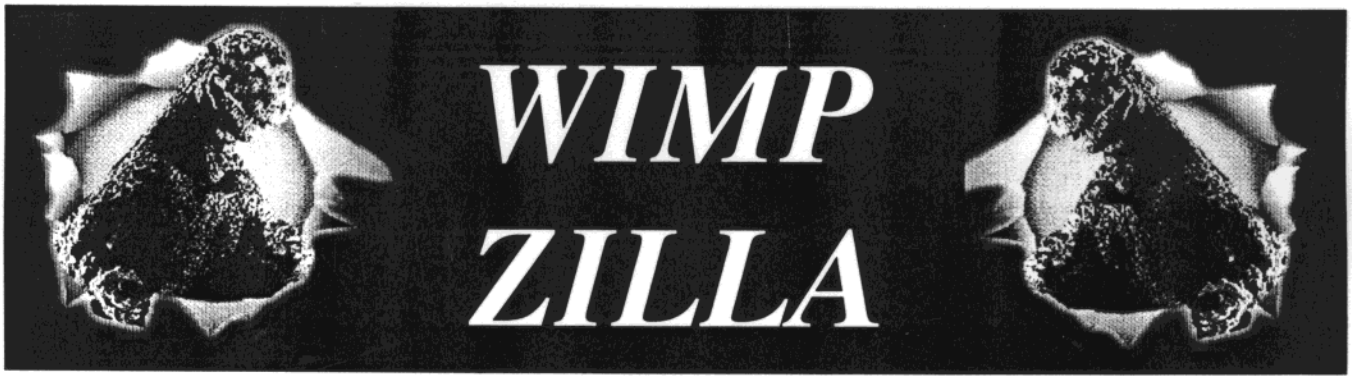
WIMP

thermal relic:

$\sigma \sim$ *weak scale*

M_X *undetermined*

or may be a



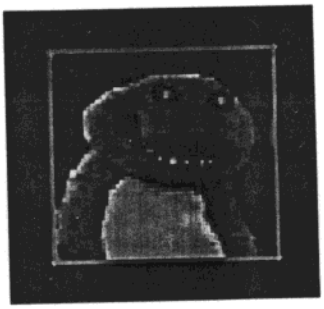
nonthermal relic:

σ *undetermined*

$M_X \sim H_{\text{end inflation}}$

- Old Dark Matter:

  – **axions,** $m \sim 10^{-5}$ eV.



  – **WIMP's,** $m \sim 100$ GeV.

- New Dark Matter:

  – **WIMPZILLA's,** $m \sim 10^{13}$ GeV.

HST picture of WIMPZILLA™

Wimpzilla™ is a registered trademark of Rocky Kolb and Co

THE KEY POINT:

THE SUPERHEAVY DARK MATTER IS PRODUCED AT SOME EARLY EPOCH IN A NON-THERMAL STATE

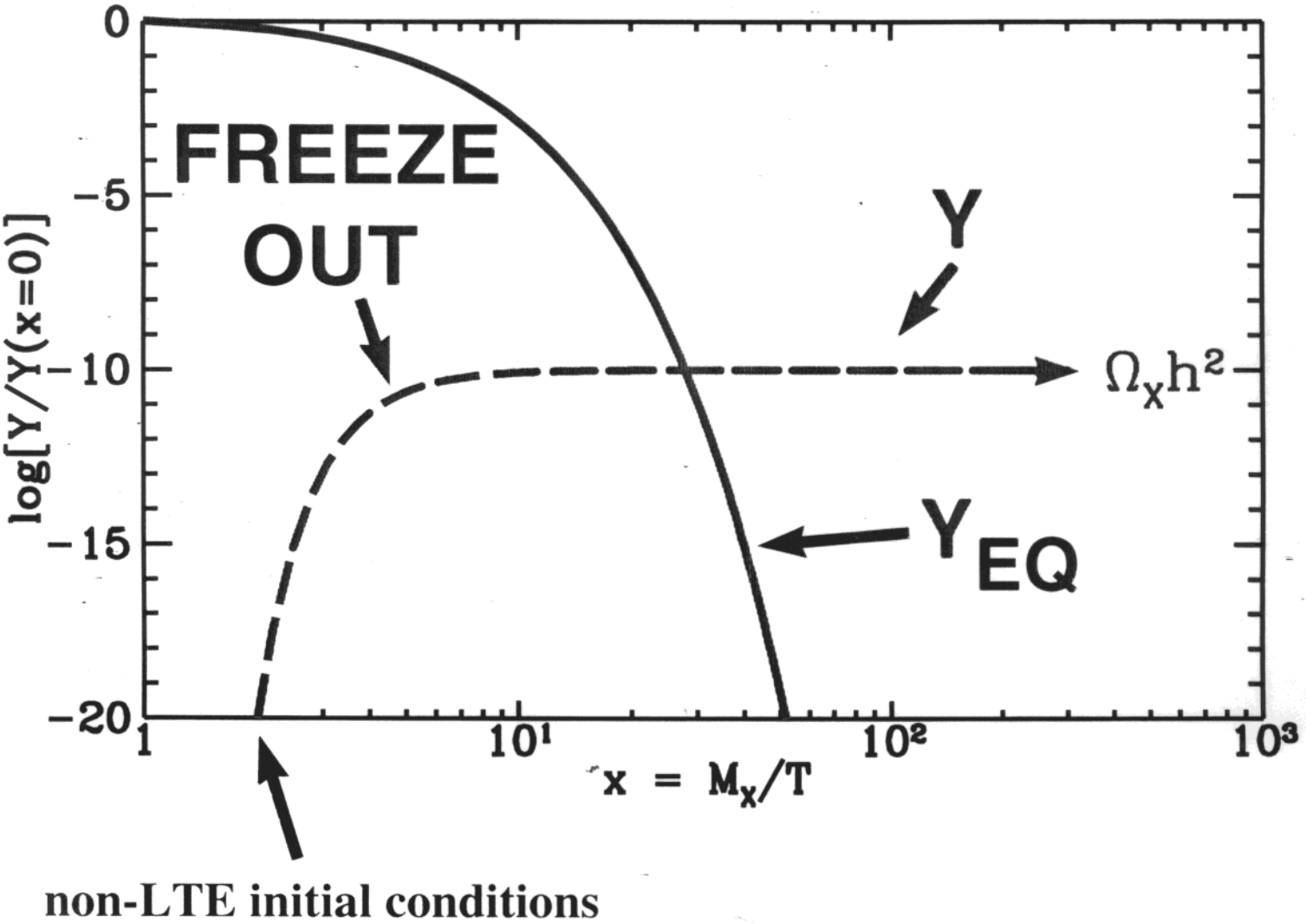
$$\&$$

$$\sigma_A \sim \frac{\alpha}{M_X^2}\,, \quad \Gamma_A \sim n_X \sigma_A \ll H$$

VALID THROUGHOUT ALL THE HISTORY OF THE UNIVERSE

Ω_X DEPENDS ONLY ON THE GENERATION MECHANISM!

NONTHERMAL RELICS



$$Y \equiv \frac{n_X}{s} \ll Y_{EQ} \quad \text{at freeze out}$$

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TWO EXAMPLES:

★ PRODUCTION OF NON-THERMAL MASSIVE STATES AT PREHEATING AFTER INFLATION

■ $m_X \sim 10^{15}$ GeV ■

WITH
A. LINDE,
R. KOLB,
I. TKACHEV

★ PRODUCTION OF NON-THERMAL MASSIVE STATES DURING THE TRANSITION FROM THE DE-SITTER EPOCH (OR INFLATION) TO THE MATTER/RADIATION ERA

■ $m_X \sim H$ ■

DOES NOT DEPEND ON THE COUPLING BETWEEN X & THE INFLATON(S)

WITH
D.J. CHUNG,
R. KOLB

The Cosmic Symphony (*Harmonice Mundi*)

tempo	movement	period	ρ	p	$\rho + 3p$
prestissimo	**string**	$t \sim 10^{-43}$s	**?**	**?**	**?**
presto	"vacuum" (inflation)	$t \sim 10^{-38}$s	ρ_V	$-\rho_V$	$-$
allegro	**inflaton oscilations**	$t \sim 10^{-36}$s	ρ_ϕ	**0**	**+**
andante	radiation	$t < 10{,}000$yr	T^4	$T^4/3$	+
largo	matter	$t > 10{,}000$yr	$\rho_{dark\ matter}$	0	+

da capo??

/Space/Pictures/Colloquium/movimenti_time

PROBLEMS SOLVED BY INFLATION

- HOMOGENEITY
- ISOTROPY
- FLATNESS [ENTROPY]
- MONOPOLE PROBLEM
- STRUCTURE FORMATION:

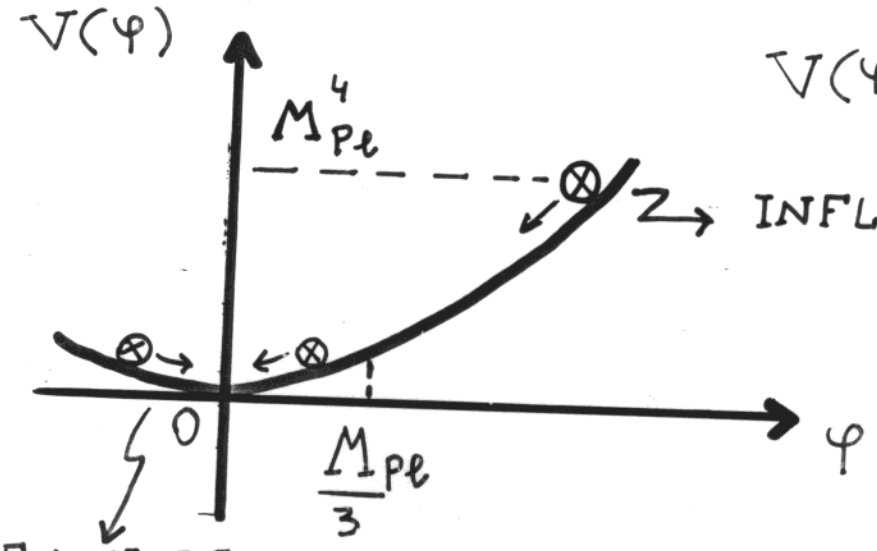
  INFLATION PRODUCES FLUCTUATIONS OF DENSITY WHICH LATER ON LEAD TO GALAXY FORMATION

REVIEW BY D. LYTH & A.R. TO BE PUBLISHED IN PHYS. REPTS. hep-ph/9807454

{ THIS IS AN UNEXPECTED BY-PRODUCT !

Simplest model

CHAOTIC INFLATION



$$V(\varphi) \sim \varphi^n$$

$$\begin{cases} \ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0 \\ H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_{Pl}^2}\left[V(\varphi) + \frac{1}{2}\dot{\varphi}^2\right] - \frac{K}{a^2} \end{cases}$$

GOES RAPIDLY TO ZERO: $\Omega = 1$

★ SOLUTION FOR $\varphi \gtrsim M_{Pl}$

$$a \sim e^{Ht}$$

$$H \sim \sqrt{\frac{8\pi}{3}}\, M_{Pl}^{-1}\, V(\varphi)^{1/2}$$

★ TYPICAL INFLATION:

$$\frac{a_f}{a_i} \approx 10^{10^{12}}$$

$10^{-33}\,cm \times 10^{10^{12}} \approx 10^{10^{12}}\,cm$

THE PART OF THE UNIVERSE WE SEE TODAY IS $\sim 10^{28}\,cm$

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AT THE END OF INFLATION:

- NO PARTICLES AROUND
- ZERO ENTROPY DENSITY
- NO TOPOLOGICAL DEFECTS
- ZERO TEMPERATURE
- ENERGY STORED IN THE INFLATON FIELD

REHEATING ⇄ REHEATING

STANDARD BIG-BANG THEORY

- PARTICLES AROUND
- NON-ZERO ENTROPY DENSITY
- THERMAL BATH
- ENERGY STORED IN THE THERMAL BATH

Gravitational production of dark matter at the end of inflation

Dan Chung, Rocky Kolb &Toni Riotto: hep-ph/9802238
(also Vadim Kuzmin & Igor Tkachev: hep-ph/9802304)

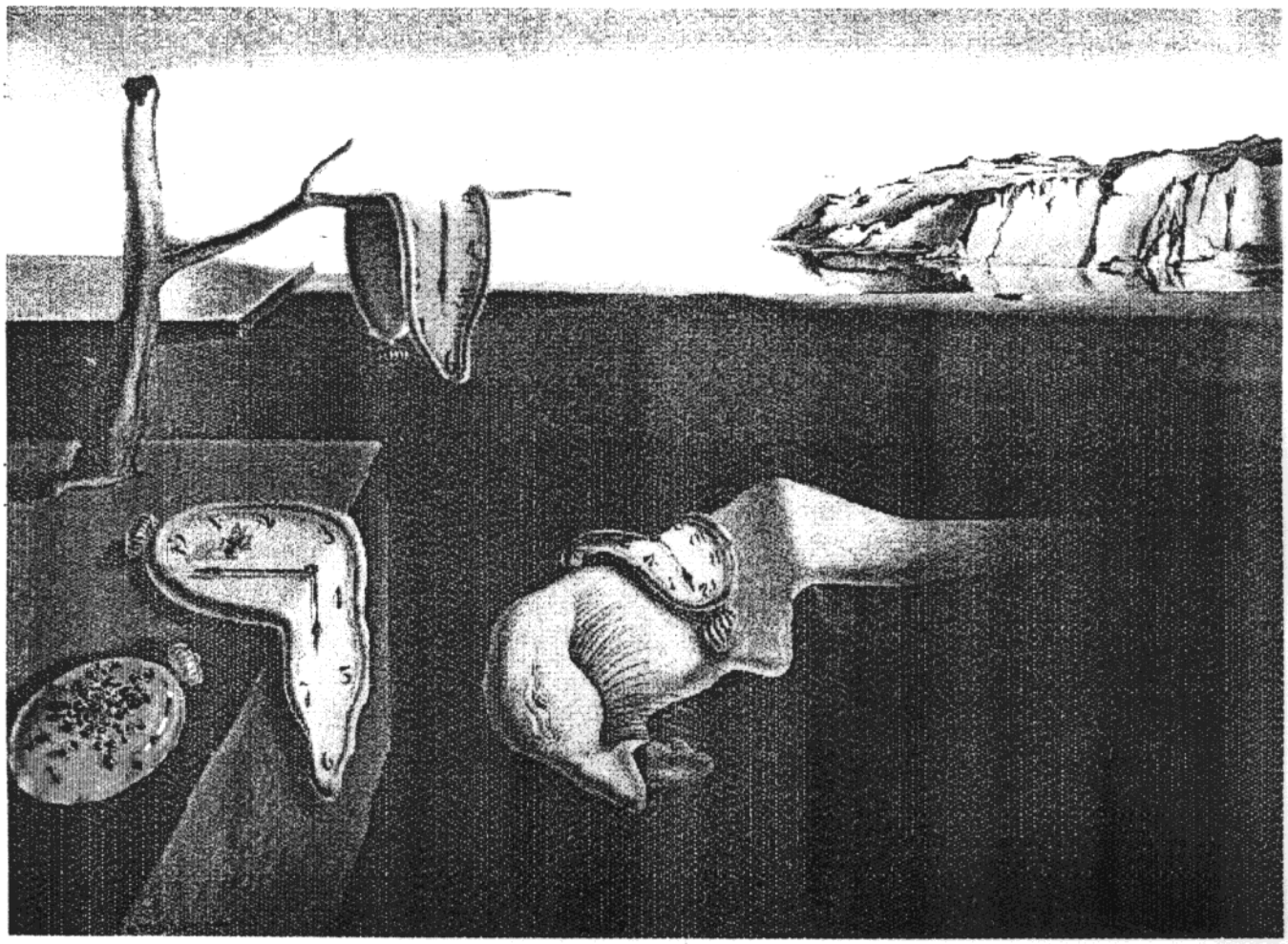
- **generic**
  (gravity is pretty generic)

- **independent of interaction strength**
  (strongly interacting to noninteracting)

- ***M* about 10^{12} GeV**
  (could be less---perhaps much less---but not much more)

Space Pictures Places Heidelberg/supermassive

Conformal Time



$$ds^2 = a^2(\eta)\left[d\eta^2 - d\vec{x}^2\right]$$

$$a^2(\eta)d\eta^2 = dt^2$$

ANALOGY
electric field

Consider scalar field X of mass M_X

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

Mode equation (η = conformal time)

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

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

Particle creation in nonadiabatic region

particle creation proportional to $\dfrac{\omega_k'}{\omega}$

Boundary Conditions

Inflation $\longrightarrow a_i; \eta_i \longrightarrow$ Matter/Rad.

Initial conditions early in inflation

$$\frac{a}{a_i} = \frac{1}{1 + H_V a_i (\eta_i - \eta)}$$

$$-\infty < \eta < \eta_i$$

Transition to matter/radiation era

$$\frac{a}{a_i} = \left(\frac{\eta}{\eta_i}\right)^2 \qquad \frac{a}{a_i} = \left(\frac{\eta}{\eta_i}\right)$$

matter radiation

$$\eta_i < \eta < \infty$$

No-particle state in past

$$h_k^0 \longrightarrow a_k^0 \qquad a_k^0|0\rangle = 0$$

$h_k(\eta)$ evolves as $\omega_k(\eta)$ changes

Bogoliubov transformation:

$$h_k = \alpha_k h_k^0 + \beta_k h_k^{0*}$$
$$a_k = \alpha_k a_k^0 - \beta_k a_k^{0\dagger}$$

Particle creation

$$N_k = \langle 0|a_k^\dagger a_k|0\rangle \propto |\beta_k|^2$$

Solve wave equation

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

$$\omega_k^2(\eta) = k^2 + M_X^2 a^2(\eta)$$

$$h_k^0 = 1/\sqrt{2\omega_k^0} \qquad h_k^{0\prime} = -i\sqrt{\omega_k^0/2}$$

Bogoliubov coefficient

$$|\beta_k|^2 = \frac{|h_k'|^2 + \omega_k^2 |h_k|^2 - \omega_k}{2\omega_k}$$

Number density proportional to

$$\int_0^\infty \frac{dk}{2\pi^2} k^2 |\beta_k(\infty, -\infty)|^2$$

Solve wave equation

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

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Number density proportional to

$$\int_0^\infty \frac{dk}{2\pi^2} k^2 |\beta_k(\infty, -\infty)|^2$$

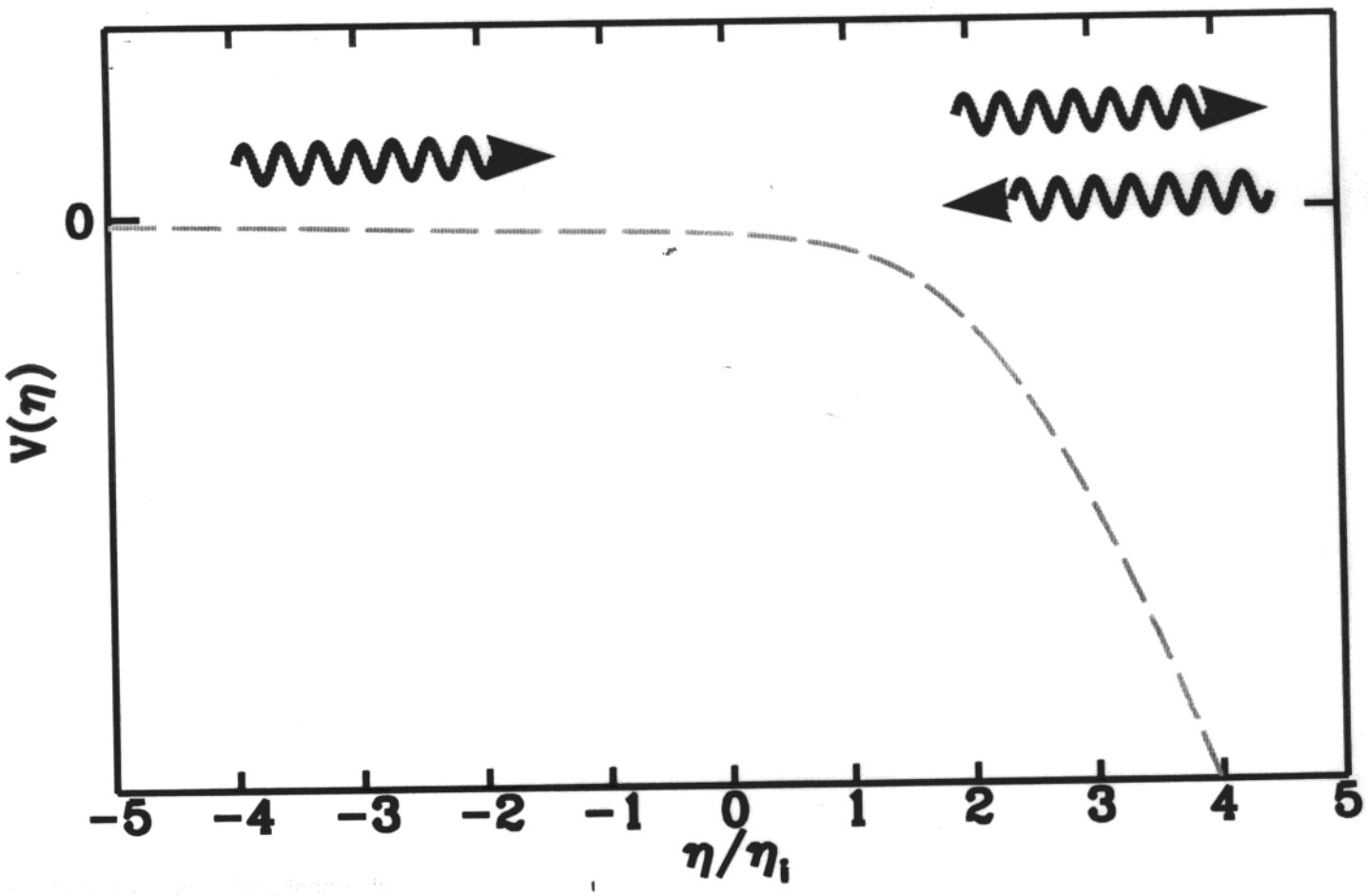
Mode Equation:

$$h''_{\tilde{k}}(\tilde{\eta}) + \left(\tilde{k}^2 + \frac{M_X^2}{H_i^2}\tilde{a}^2\right) h_{\tilde{k}}(\tilde{\eta}) = 0$$

$$\to x\ ; \quad h_{\tilde{k}}(\tilde{\eta}) \to \psi(x)\ ; \quad \tilde{k}^2 \to E\ ; \quad \frac{M_X^2}{H_i^2}\tilde{a}^2 \to -V(x)$$

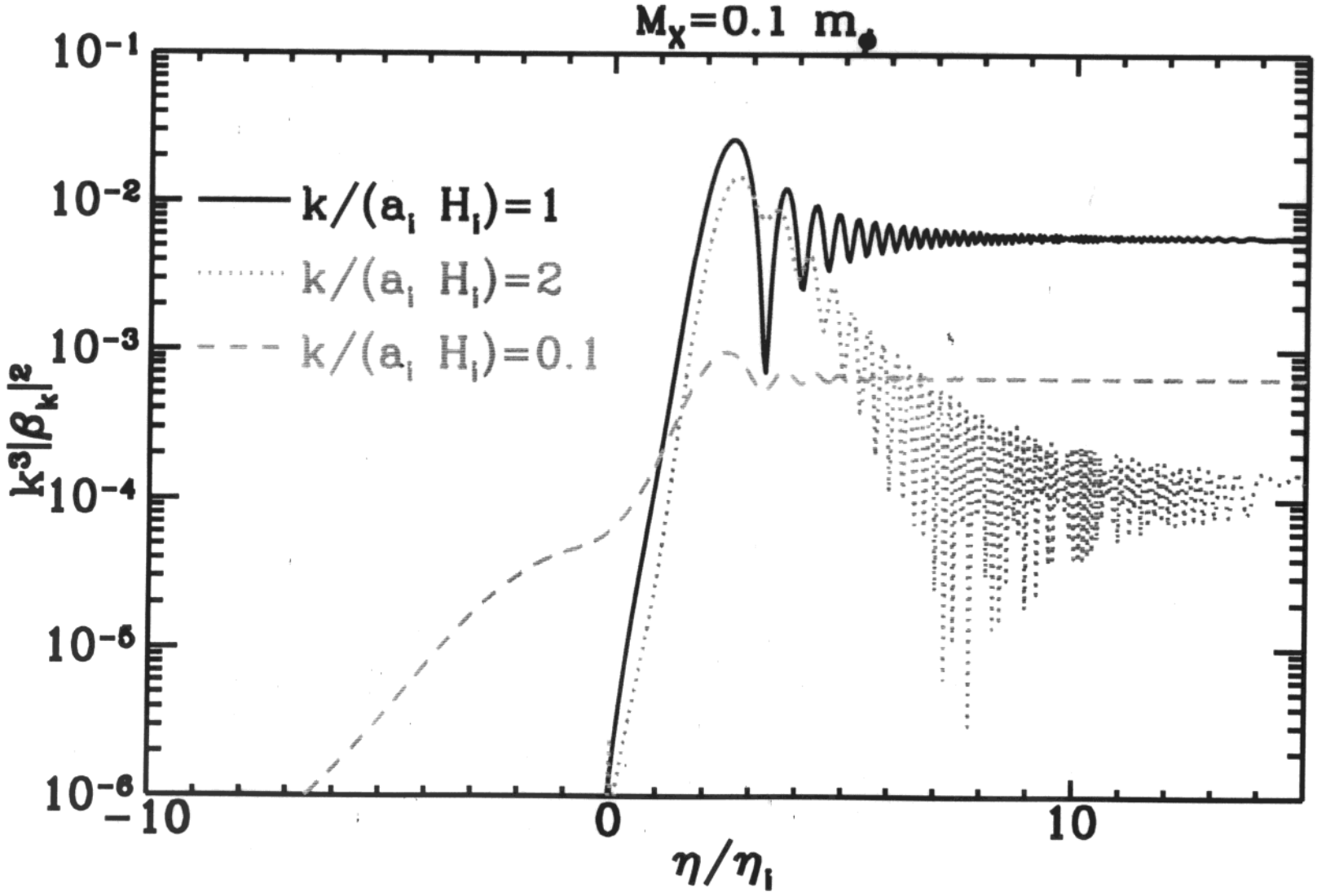
Wave Equation:

$$-\frac{\partial^2\psi(x)}{\partial x^2} + V(x)\psi(x) = E\psi(x)$$

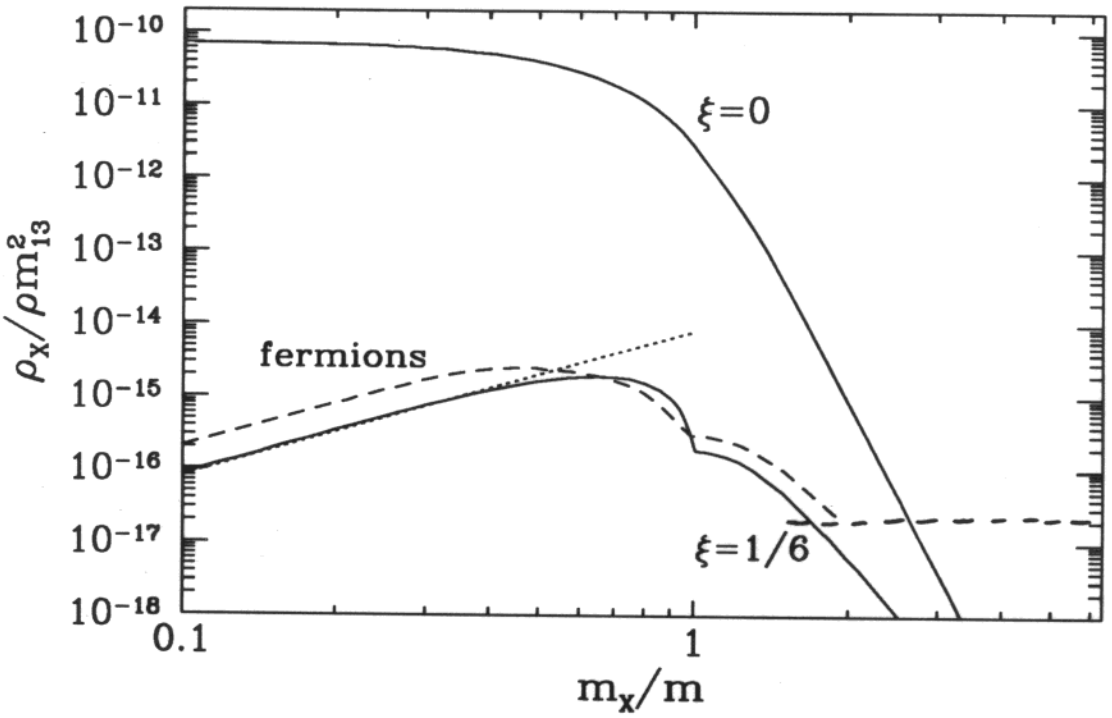


Action at transition out of inflation ($\eta/\eta_i \sim 1$)

Particles produced with momentum $k \sim aH$



There is no singularity and Hubble constant is limited, $H < m_\phi$, in inflationary cosmology. Production of particles with $m_X > H \sim 10^{13}$ GeV has to be suppressed.



Ratio of the energy density in X-particles to the total energy density at late times in a model with the massive inflaton, $V(\phi) = m^2\phi^2/2$. We defined $m_{13} \equiv m/10^{13}$ GeV. The dotted line is the Friedmann cosmology asymptotic.

To find the present day $\Omega_X h^2$ multiply this Fig. by

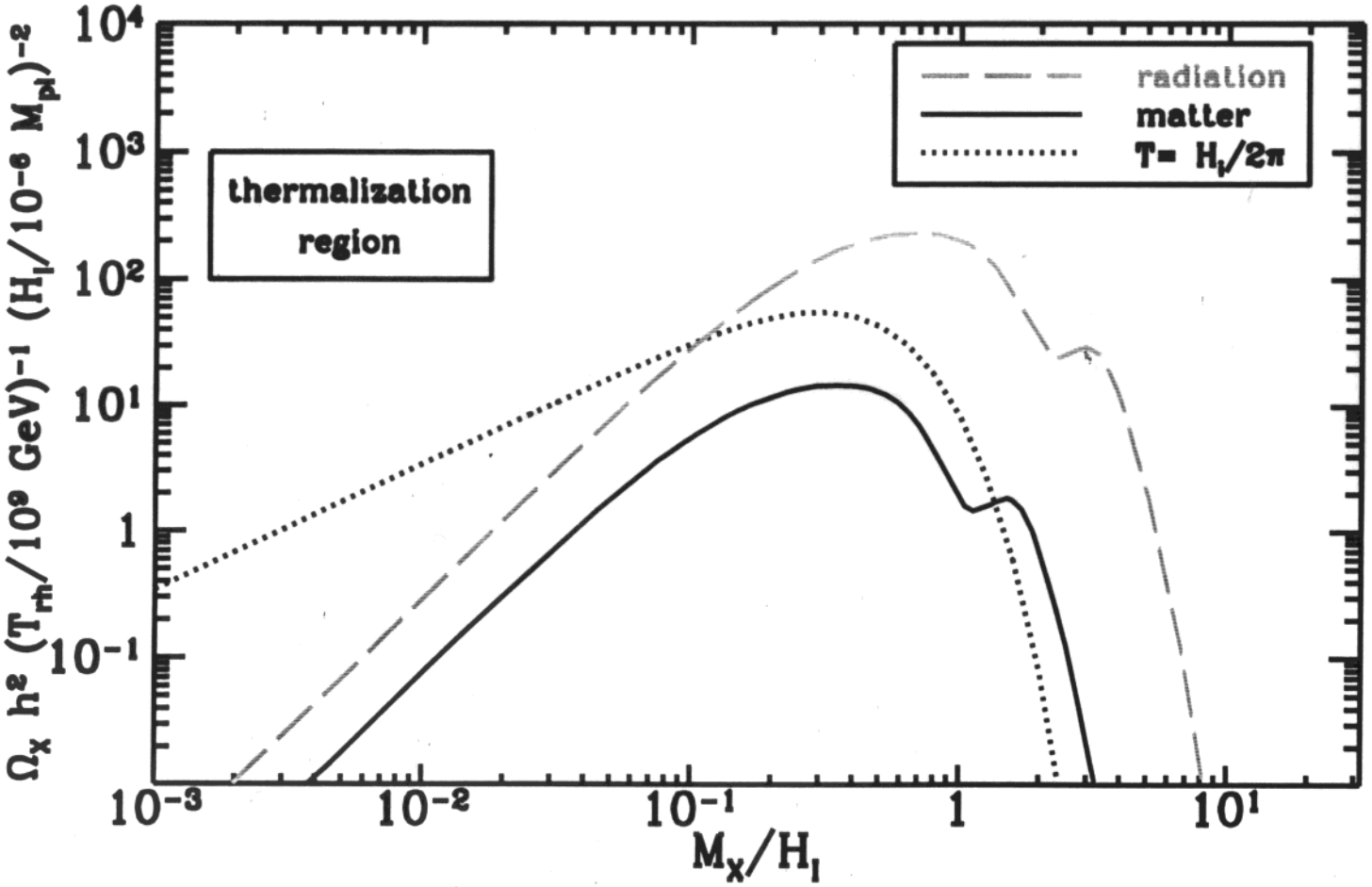
$$1.8 \times 10^{17}\ (T_*/\gamma 10^9\,\mathrm{GeV})\ m_{13}^2$$

ISSUES:

behavior of $a(\eta)$ (smooth or not)?

transition to matter-dominated or radiation-dominated?

thermalization?



Conclusions

Gravitational production of dark matter at the end of inflation

- **generic**
  (gravity is pretty generic)

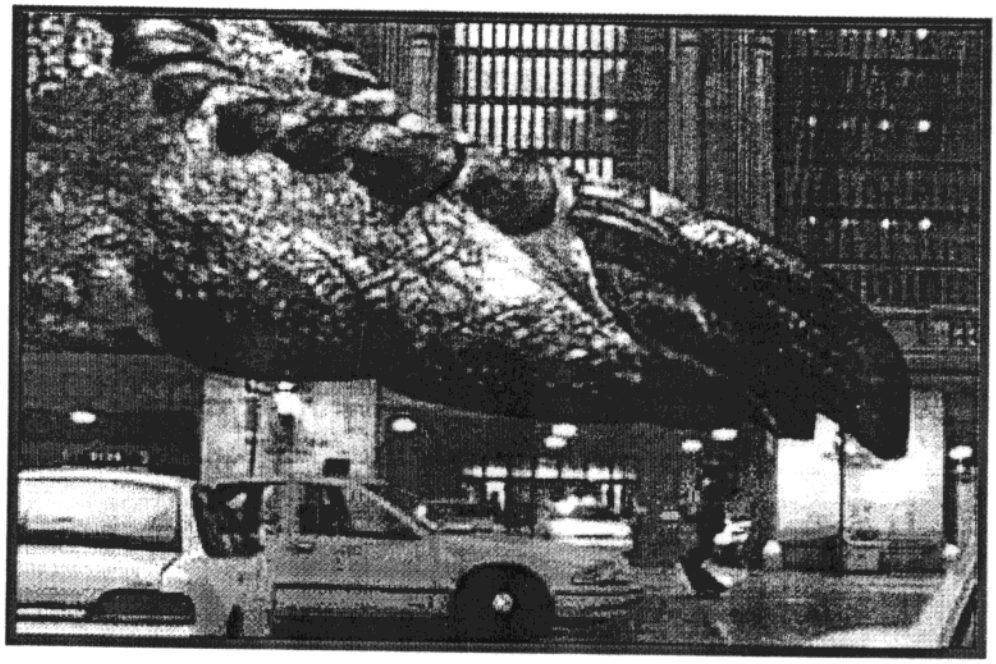
- **independent of interaction strength**
  (strongly interacting to noninteracting)

- ***M* about 10^{12} GeV**
  (could be less---perhaps much less---but not much more)

Implications and search strategy

Alvaro deRujula, Gian Giudice, Rocky Kolb & Toni Riotto:
work in progress

Wimpzilla Footprint:



Interaction strength: charged, hadronic, noninteracting?

UNDERGROUND DETECTORS ⇓ $M_X \geq 10^{11}$ GeV

Stability: stable, or decay (cryptons)

⟶ *UHE cosmic rays?*

Indirect detection?

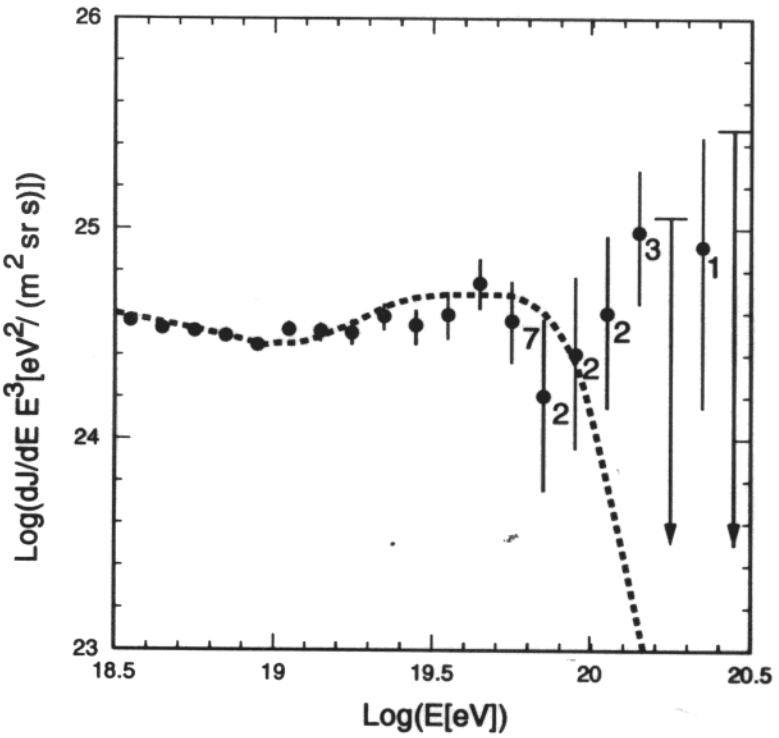
Space Pictures Placer COSMOS

GREISEN-ZATSEPIN-KUZ'MIN CUTOFF

UHECR protons or neutrons propagating in microwave background loose energy in photopion production, e.g., $p\gamma \rightarrow p\pi^0$. The mean free path is ≈ 5 Mpc. Detection of 3×10^{20} eV proton would require source within ~ 50 Mpc.

However, events above the cutoff were observed (!) by Yakutsk, Haverah Park, Fly's Eye and AGASA collaborations.

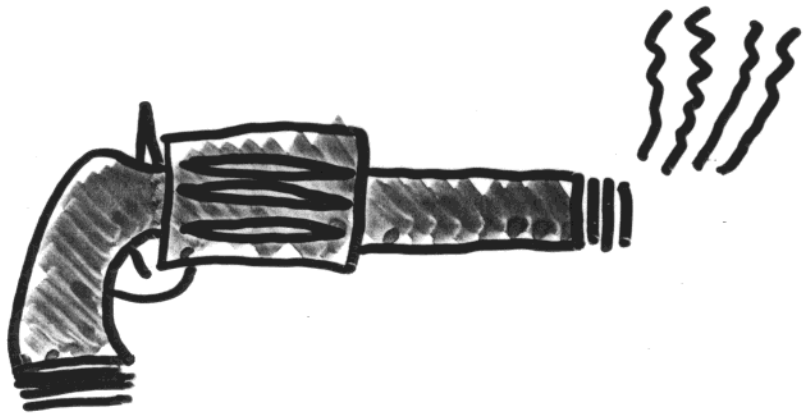
AGASA data set, February 1990 – October 1997,
adapted from M. Takeda et al., Phys. Rev. Lett. **81**, 1163-1166 (1998):



The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe.

No candidate sources are found in the directions of six 10^{20} eV events.

SMOKING GUN ?



- SUPPOSE THAT SUPERHEAVY DARK MATTER IS IN OUR GALAXY

- THE EARTH IS ~ 8.5 Kpc FROM THE CENTRE OF OUR GALAXY

↓

THE FLUX OF UHE COSMIC RAYS HAS ~ 20% EXCESS TOWARDS THE CENTRE OF OUR GALAXY !

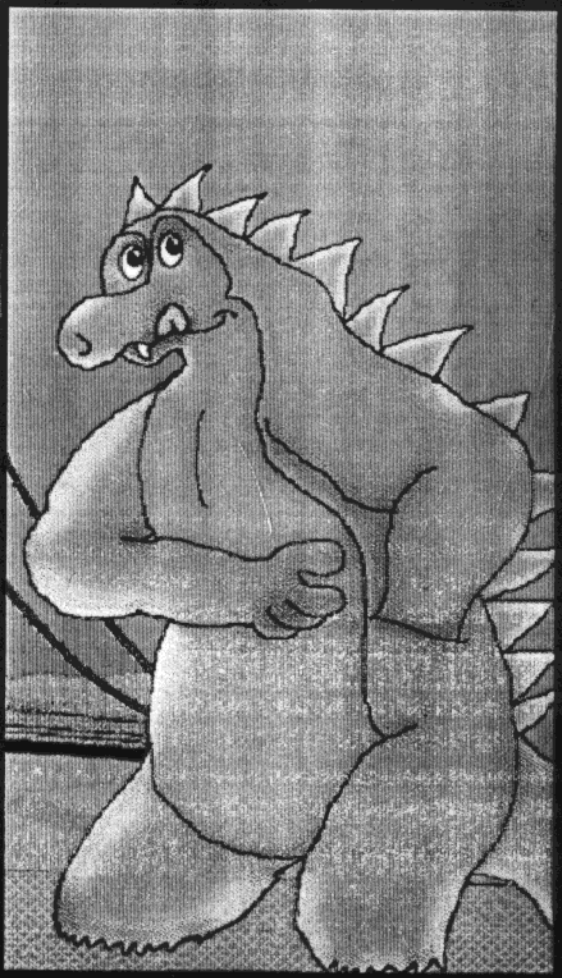
THE PIERRE AUGER PROJECT WILL DO THE JOB

DARK MATTER MAY BE A WIMPZILLA

SIZE DOES MATTER

$M_X =$

10^{12} GeV?



/Space/Pictures/Places/Sweden/wimpzilla

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DEFINE

$$\rho_c \equiv 3 H_0^2 / 8\pi G_N$$

$$\approx h^2 \, 10^{-29} \, g \, cm^{-3}$$

$$H_0 \equiv h \, 100 \, Km \, s^{-1} \, Mpc^{-1}$$

$$0.4 \lesssim h \lesssim 0.8$$

$$\Omega_i \equiv \rho_i / \rho_c$$

EX:

- Ω_B : IN BARYONS
- Ω_M : IN MATTER
- Ω_V : IN VACUUM

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WHY DM?

- DYNAMICAL EVIDENCE
  - ROTATION CURVES OF SPIRAL GALAXIES:
    $\Omega_{LUM} \lesssim 0.01$, BUT $\Omega_{HALO} \gtrsim 0.1$
  - CLUSTERS OF GALAXIES: $\Omega_M \sim 0.3$
    $\gg \Omega_{LUM}$
- BIG-BANG NUCLEOSYNTHESIS
  THE PREDICTED LIGHT-ELEMENT ABUNDANCES DEPEND ON
  $\eta \equiv n_B/n_\gamma$ or $\Omega_B h^2 \propto \eta$

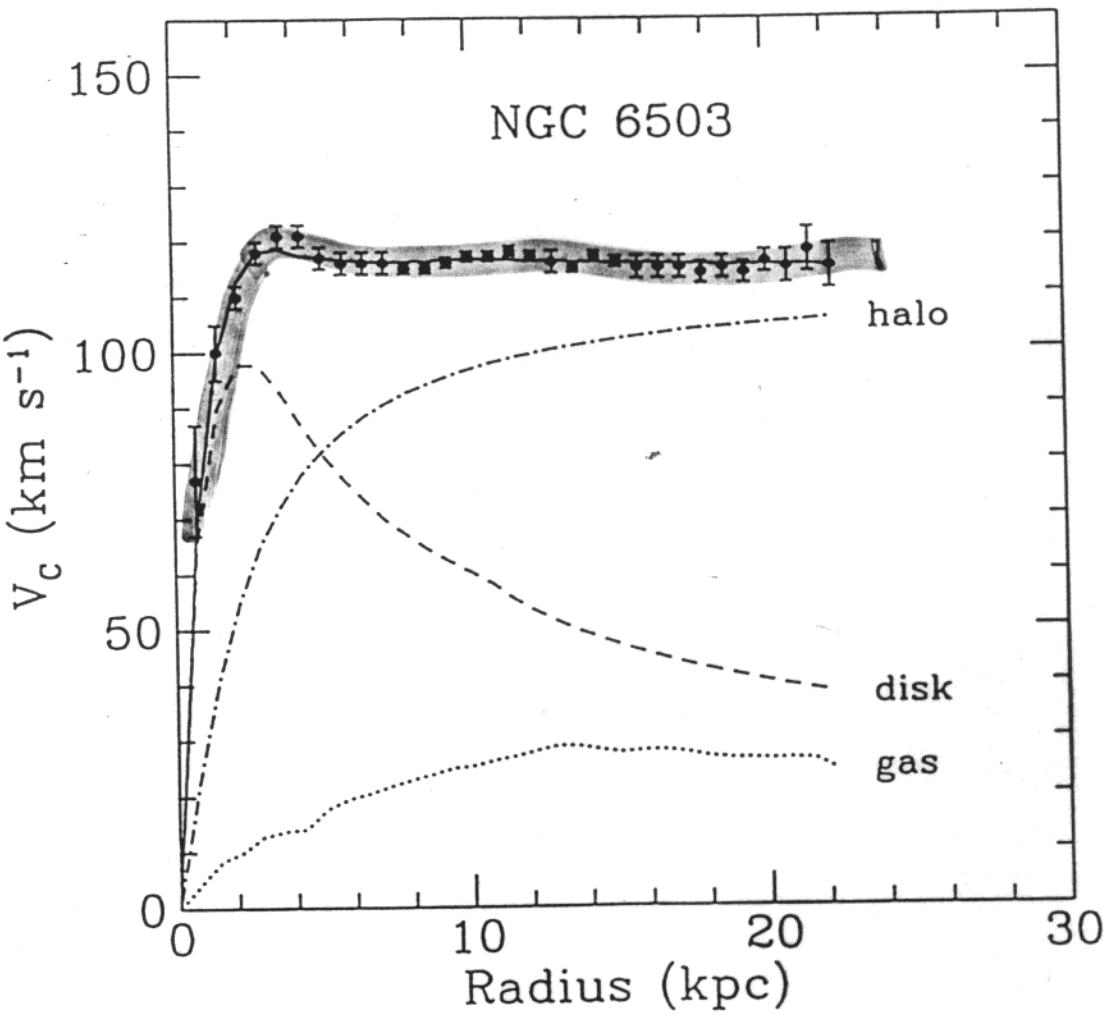
$$\left\langle 0.005 \lesssim \Omega_B h^2 \lesssim 0.024 \right\rangle \left(\frac{\eta}{10^{-10}}\right)$$

SURFACE LUMINOSITY OF THE DISK

$$I(r) = I_0 e^{-r/r_D} \Rightarrow v_{rot} \propto r^{-1/2}$$

BUT $v_{rot}(r)$ IS FLAT!

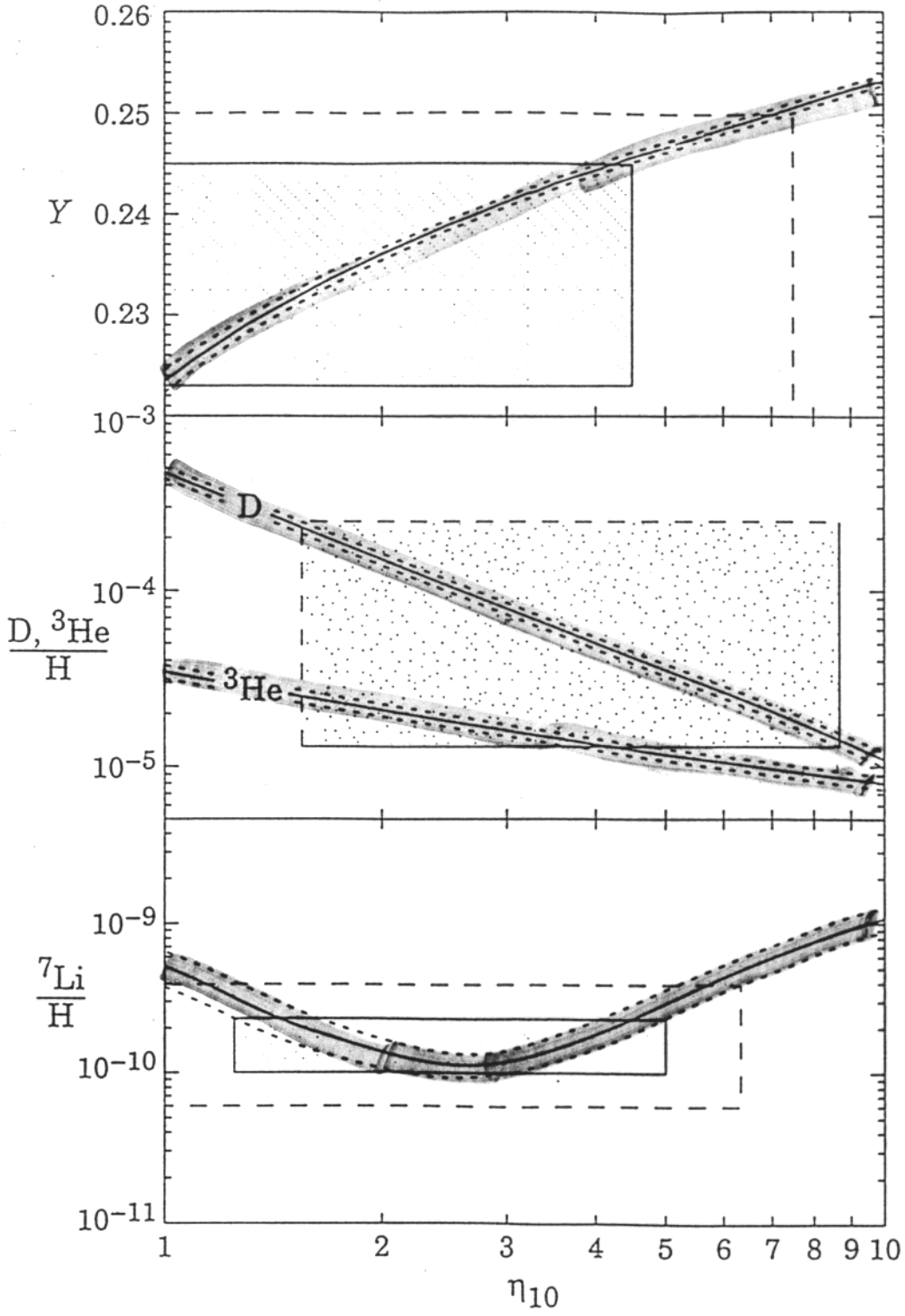
RADIO OBSERVATIONS:



$r_D = 1.73$ Kpc NGC 6503

LIGHT-ELEMENT ABUNDANCES FROM BBN

$1.5 \lesssim \eta_{10} \lesssim 6.3$



THE SUPERHEAVY DARK MATTER MUST BE STABLE:

- N=1 SUSY $SU(4) \otimes SU(2)_L \otimes SU(2)_R$ FROM WEAKLY COUPLED HETEROTIC SUPERSTRING, LEONTARIS & RIZOS, hep-ph/9901098
- DISCRETE GAUGE SYMMETRIES, YANAGIDA et al. hep-ph/9809426
- GAUGE MEDIATION & SUSY, T.HAN et al. hep-ph/9804228
- "CRYPTONS" FROM STRING and M-THEORY, J.ELLIS et al. / hep-ph/9803333; hep-ph/9809546
- ....

OR NEARLY STABLE ...

NONLTE:

radiation-dominated at freezeout: T_F

$$H^2 = \rho_\gamma(T_F)/M_{Pl}^2 = T_F^4/M_{Pl}^2$$

$$\frac{\Omega_X}{\Omega_\gamma} = \frac{M_X n_X(T_F)}{\rho_\gamma(T_F)} \frac{T_F}{T_0}$$

interaction rate << expansion rate

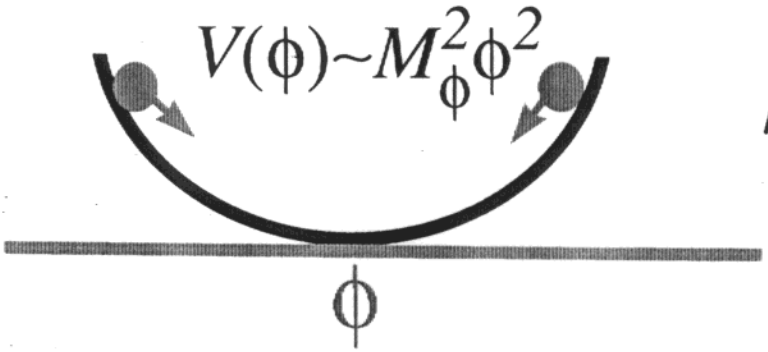
$$\frac{n_X(T_F)\langle\sigma_A|v|\rangle}{H(T_F)} = \frac{\Omega_X}{\Omega_\gamma} \frac{T_0 M_{Pl} T_F}{M_X}\langle\sigma_A|v|\rangle \ll 1$$

safe limits: $\langle\sigma_A|v|\rangle < M_X^{-2}$ $\Omega_X < 1$

$$\left(\frac{200\ \mathrm{TeV}}{M_X}\right)^2 \left(\frac{T_F}{M_X}\right) \ll 1$$

The End of Inflation

- After inflation universe frozen



$$\dot{\rho}_\phi + 3H\rho_\phi = 0$$

- Reheating (ca. early 1980s)

incoherent, nonresonant, linear
decay of inflaton field

$$\dot{\rho}_\phi + 3H\rho_\phi + \Gamma_\phi \rho_\phi = 0$$

$$\dot{\rho}_R + 4H\rho_\phi - \Gamma_\phi \rho_\phi = 0$$

- Preheating (ca. mid 1990s)

coherent, resonant, nonlinear
particle production

OLD PICTURE: $m_\varphi \sim 10^{13}$ GeV

$$V(\varphi) = \frac{1}{2} m_\varphi^2 \varphi^2 + h \varphi \bar{\psi} \psi + \frac{1}{2} g^2 \varphi^2 \chi^2$$

WHEN $\varphi \lesssim M_{PL}$, ENERGY IS TRANSFERRED TO THE PARTICLES ψ & χ

INFLATON ≡ CLASSICAL SCALAR FIELD, COLLECTION OF SEPARATE PARTICLES DECAYING INDEPENDENTLY

$m_\chi, m_\psi < 10^{13}$ GeV

ONCE PRODUCED, PARTICLES START THERMALIZING &

$$T_R \sim 0.1 \sqrt{\Gamma_\varphi M_{PL}}$$

$\Gamma_\varphi \equiv$ INFLATON DECAY RATE

Production of massive particles in reheating

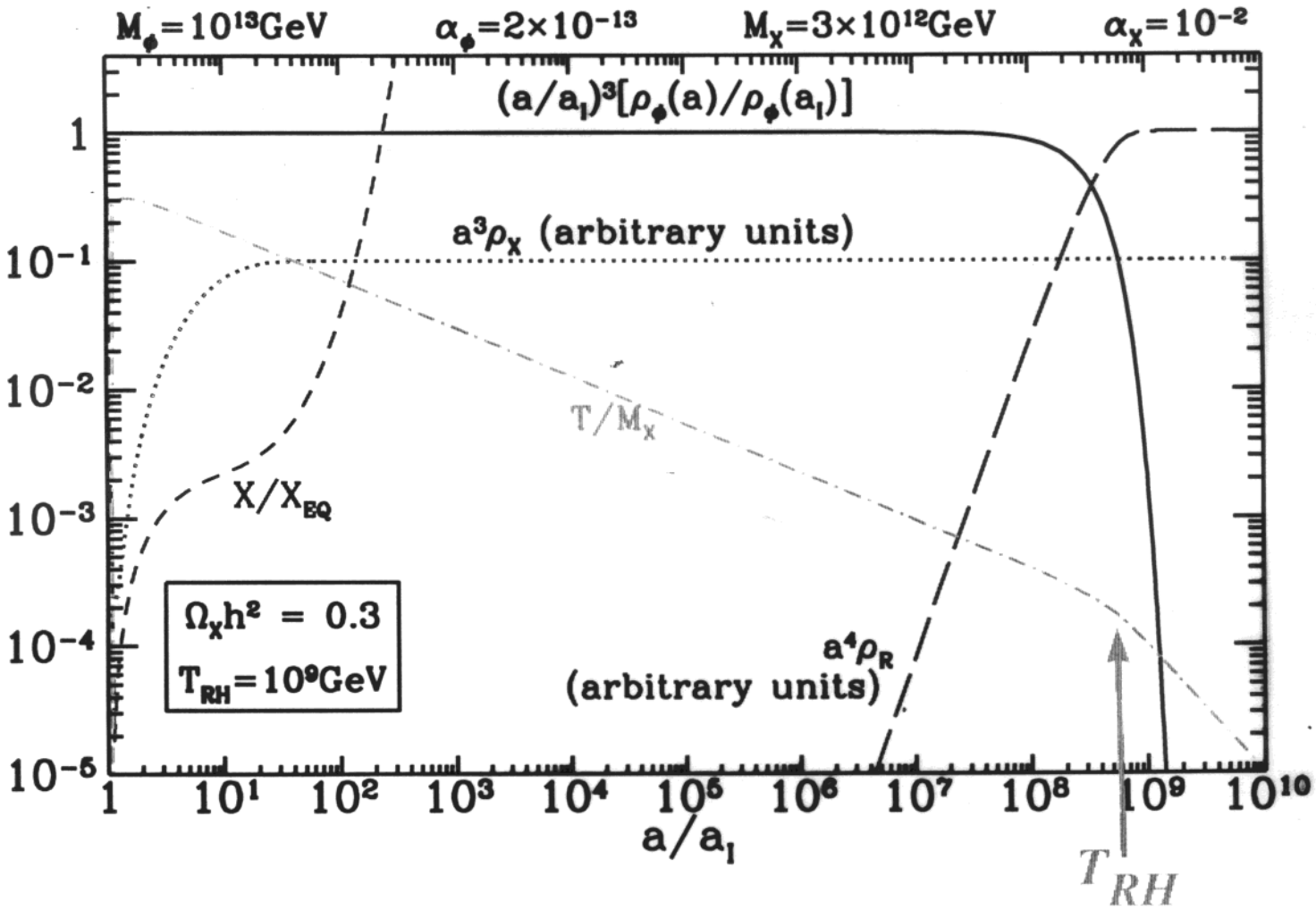
Chung, Kolb & Riotto '98

$\phi = \text{inflaton} \quad \Gamma_\phi = \alpha_\phi M_\phi$

$X = \text{wimpzilla} \quad \langle \sigma |v| \rangle = \dfrac{\alpha_X}{M_X^2}$

$$\Omega_X h^2 = \alpha_X \left(\frac{2000 T_{RH}}{M_X} \right)^7$$

not
exp(-M_X/T_{RH})!



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NEW WISDOM: $g^2\chi^2\varphi^2$

LINDE, HOFMAN, STAROBINSKY, '92

THE EQUATION OF MOTION FOR THE BOSON χ LEADS TO PARAMETRIC RESONANCE:

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left[\frac{\vec{k}^2}{a^2} + g^2\varphi_0^2\sin^2(m_\varphi t)\right]\chi_k = 0$$

$$\Downarrow$$

MATHIEU EQUATION

$$\ddot{\chi}_k + \left[A(q) - 2q\cos 2z\right]\chi_k = 0$$

$$A(q) \equiv \frac{\vec{k}^2}{a^2 m_\varphi^2} + 2q$$

$$q \equiv g^2\varphi_0^2/4m_\varphi^2 \gg 1$$

$$z \equiv m_\varphi t$$

STIMULATED DECAY

- EXPONENTIAL INSTABILITY: $\chi_k \sim e^{\mu_k^{(n)} z}$
- EXPLOSIVE STAGE: $n_{\chi_k} \sim e^{2\mu_k^{(n)} z}$

GAS OF NON-INTERACTING & NON-THERMAL BOSONS, $n_\chi/E_\chi^3 \ggg 1$, PREHEATING ERA

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PREHEATING OR DEFROSTING?

"I AM SURE ROCKY WILL USE IT IN ONE OF HIS BRILLIANT TALKS, BUT I ASSOCIATE IT WITH FROZEN CHICKEN BREASTS, WHICH I CANNOT STAND...."

A. LINDE ABOUT "DEFROSTING"

"TONI,

HOW DO YOU SAY IN ITALIAN

I BREAK YOUR LEGS?"

R. KOLB

Preheating relics

- defrosting may include a period of "preheating"

$$g^2\phi^2\chi^2$$

inflaton ← ϕ ; χ → dark matter

- can massive ($M_X > M_\phi$) bosons be made? **YES!**

  -analytic: Kolb, Linde, Riotto (PRL 96)

  -numerical: Kolb, Riotto, Tkachev (PRD 97)

- coherent process: $N\phi \longrightarrow X\bar{X}$

$$\langle E_X^2 \rangle \sim g\, M_{pl} M_\phi \sim g\, 10^{16}\,\mathrm{GeV}$$

$10^{19}\,\mathrm{GeV}$ ← → $10^{13}\,\mathrm{GeV}$

SUSY BREAKING! LINDE, ANDERSON & A.R. PRL 97

GUT BARYOGENESIS!

- GUT scale is the geometric mean of inflaton mass and Planck mass

  - g can't be too small

  - g can't be too large (unless SUSY)

- details in Dan Chung's thesis (wimpzilla ~ $10^3\, M_\phi$)

"RECENT PROGRESS IN BARYOGENESIS" M. TRODDEN & A.R., hep-ph/9901362, to be published in ANN. REV. NUCL. PART. SCIENCE

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ONCE PRODUCED, X'S DO NOT ANNIHILATE SINCE

$$\Gamma_A \sim n_X \sigma_A \sim \frac{\rho_X}{m_X^{EFF}} \frac{\alpha}{(m_X^{EFF})^2} \ll H \sim m_\varphi$$

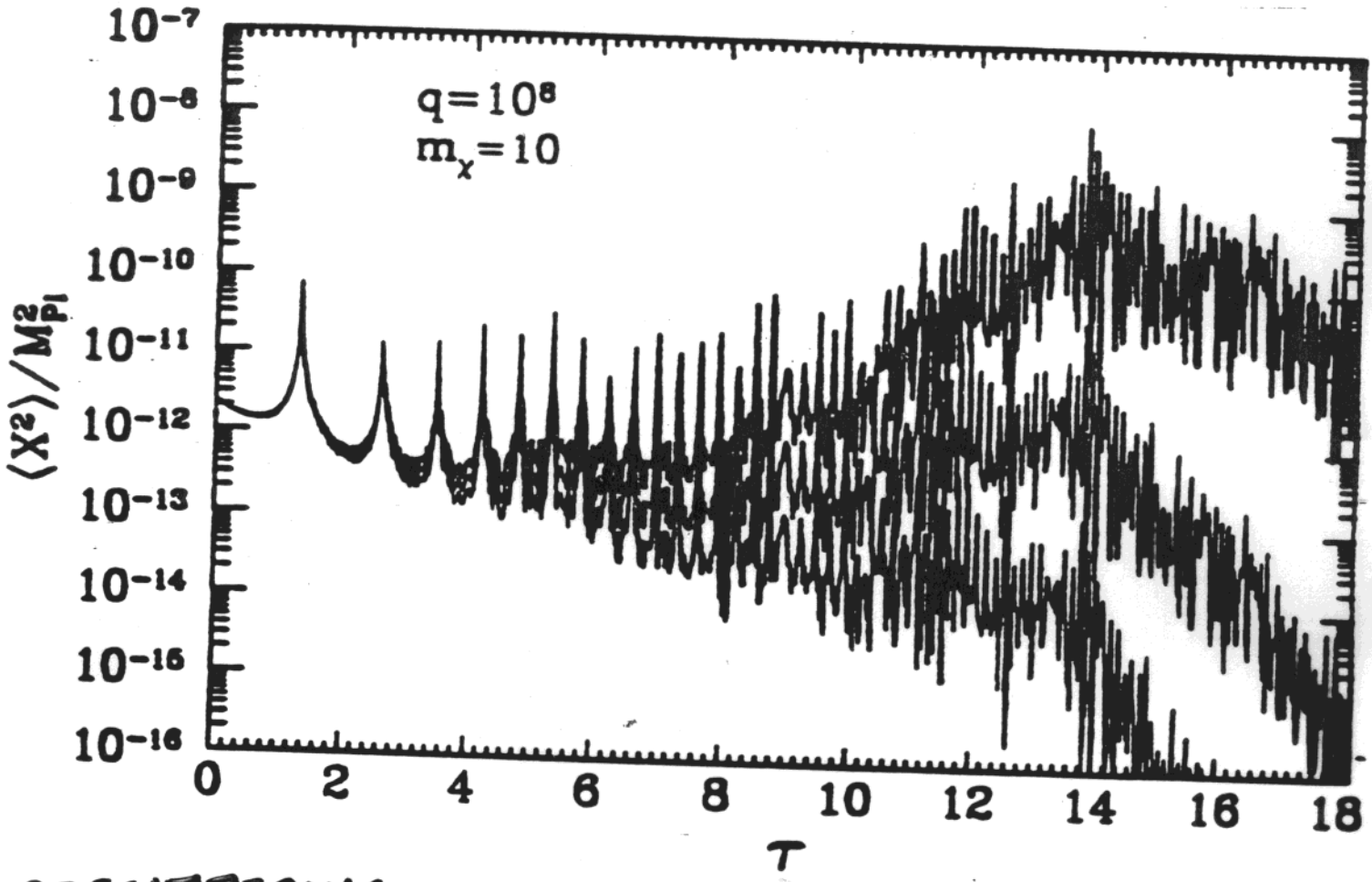
THE ENERGY DENSITY OF THE UNIVERSE IS DOMINATED BY QUANTA OF THE INFLATON $\delta\varphi$ CREATED DURING RESCATTERING, UNTIL THEY DECAY AND REHEAT THE UNIVERSE AT TEMPERATURE T_R

$$\Omega_X h^2_{TODAY} \sim 10^{+10} \left[\frac{T_R}{10^2\,GeV}\right] \frac{\rho_X(t_e)}{\rho_\varphi(t_e)}$$

$t_e \equiv$ TIME OF PRODUCTION

$$\Omega_X h^2_{TODAY} \sim 1 \quad \text{FOR} \quad \frac{\langle X^2 \rangle_{t_e}}{M_{PL}^2} \sim 10^{-12}$$

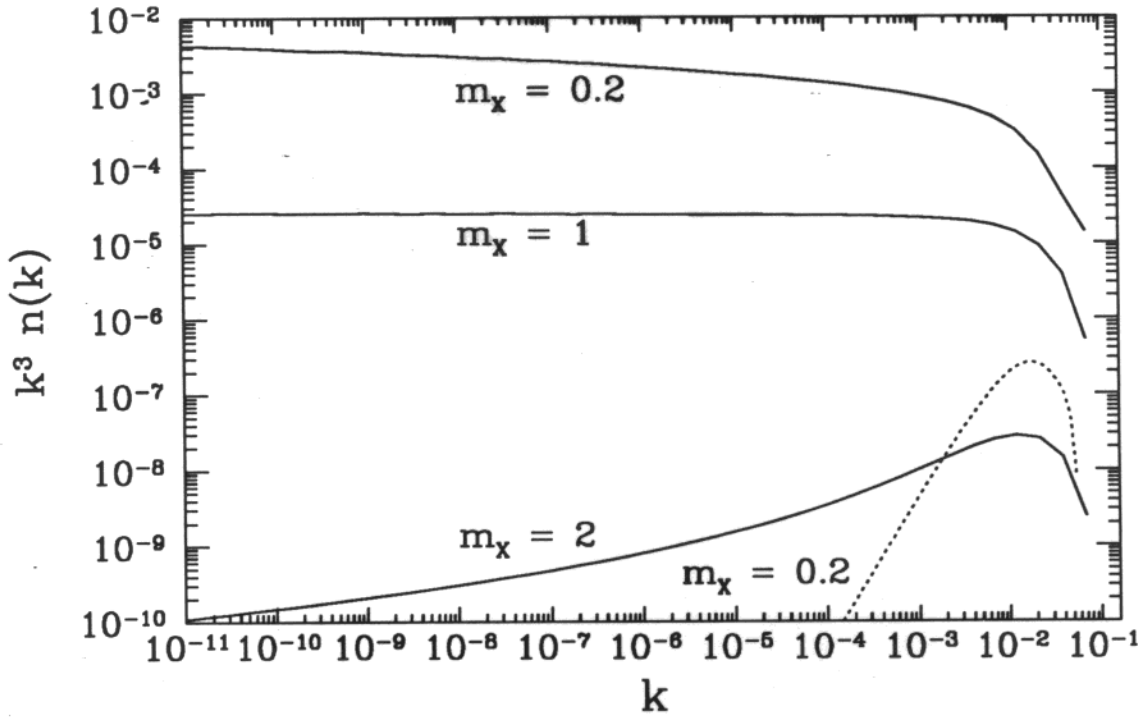
$M_X \sim 10^{14}$ GeV



RESCATTERING
&
BACK REACTION
INCLUDED

R. KOLB, I. TKACHEV
& A.R., PHYS. LETT. B423
(1998) 348

SPECTRUM



Spectrum of created particles in a model with massive inflaton for several choices of the mass of scalar X-particle with the minimal coupling (solid lines) and the conformal coupling (dotted line). Masses and momenta are given in units of the inflaton mass.

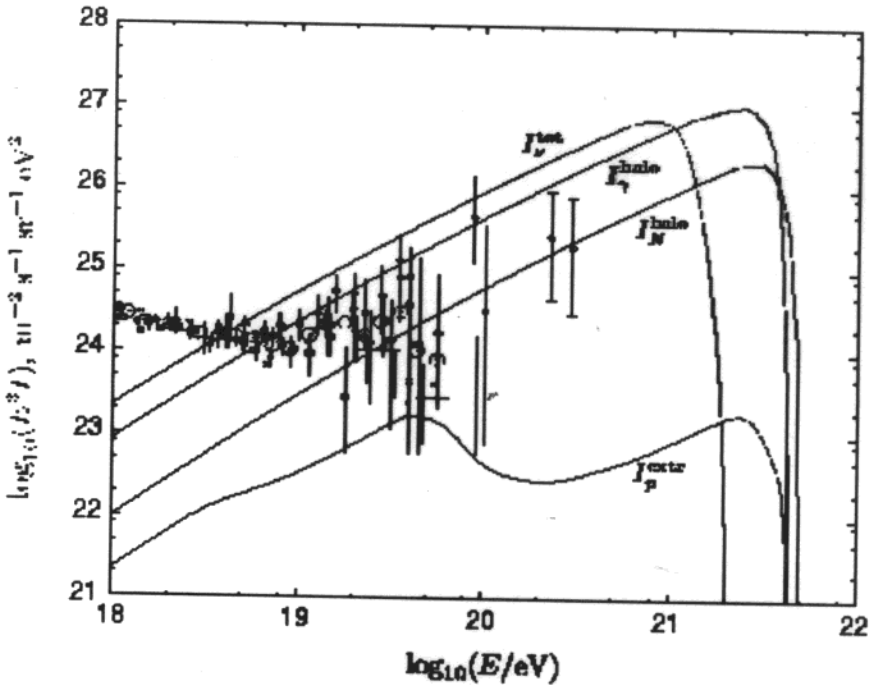
Magnitude of the density fluctuations induced in the process of X particle creation can correspond to the observable on the horizon scale, and be responsible for fluctuations in CMBR if $m_X/m \approx 2$ and $\Omega_X \approx 1$.

NEW PHYSICS ?!

Solutions to the puzzle were considered with the aid of:

- Particle which is immune to CMBR but produces normal air shower.
- Topological Defects:
  - Strings.
  - Superconducting strings.
  - Networks of monopoles connected by strings.
  - Magnetic monopoles.
- Heavy quasistable relic particles.

Particle has to be HEAVY, $m_X > 10^{12}$ GeV.



The fluxes shown were obtained for $m_X = 10^{13}$ GeV and $(\Omega_X/\Omega\text{CDM})(t_0/\tau_X) = 5 \times 10^{-11}$, V. Berezinsky, astro-ph/9801046.