Testing the Expansion History of the Universe with TeV Photons

Malcolm Fairbairn (with Arnaud deLavallaz)
King's College London

KING'S College LONDON

Agenda

- "Student" friendly introduction to dark energy
- Non-FRW universe, voids and effects of voids on cosmological observables
- Voids as alternatives to dark energy
- Using gamma rays to constrain void models
- Using gamma rays to constrain other models of dark energy
- Ultra high energy gamma rays and axions

Frieman Robertson Walker Model

Assume Isotropic/homogeneous Universe i.e. Robertson Walker Metric

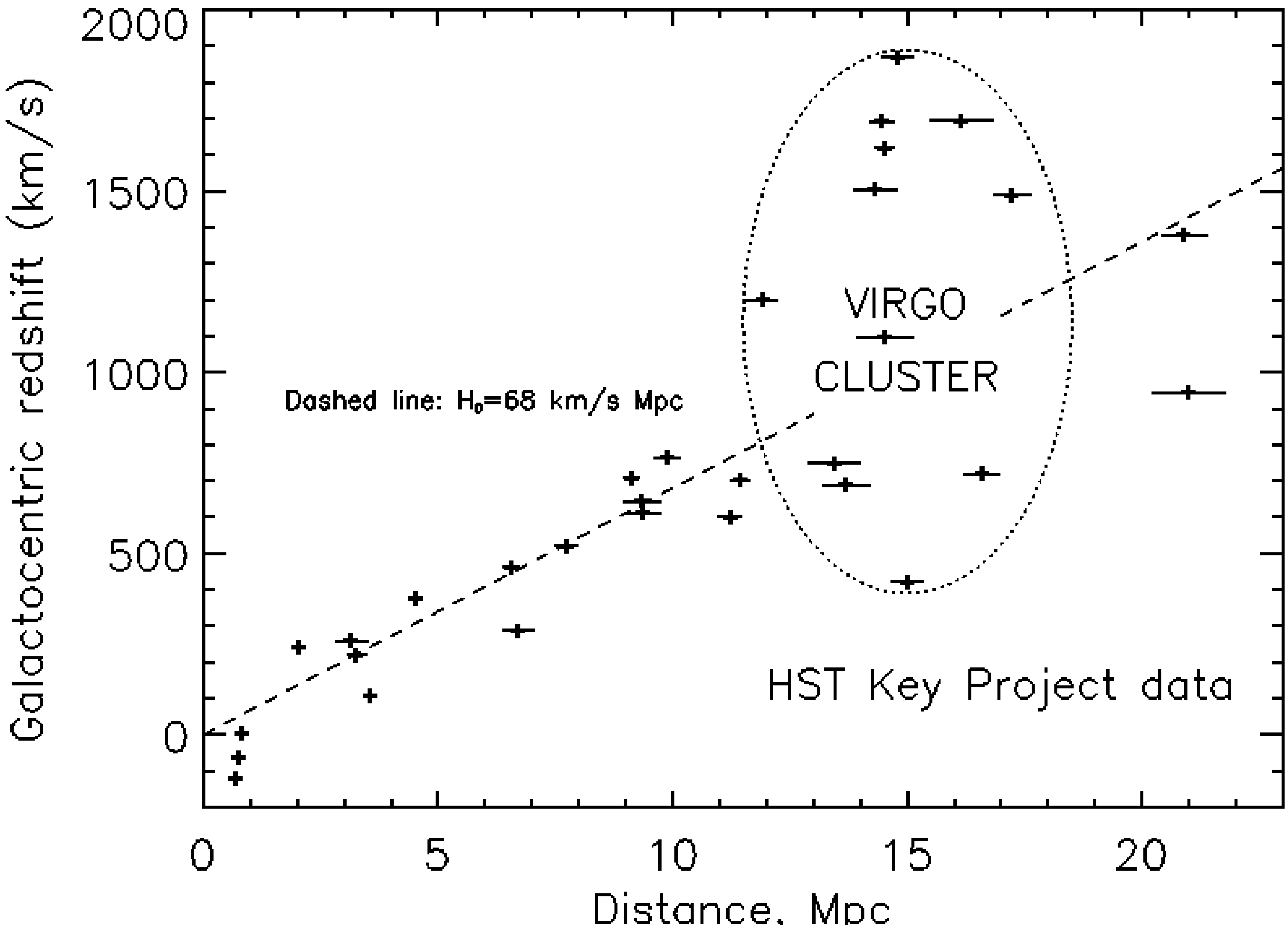
$$ds^2 = -c^2dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2d\theta^2 + r^2\sin^2\theta d\phi^2\right)$$

Comoving coordinate

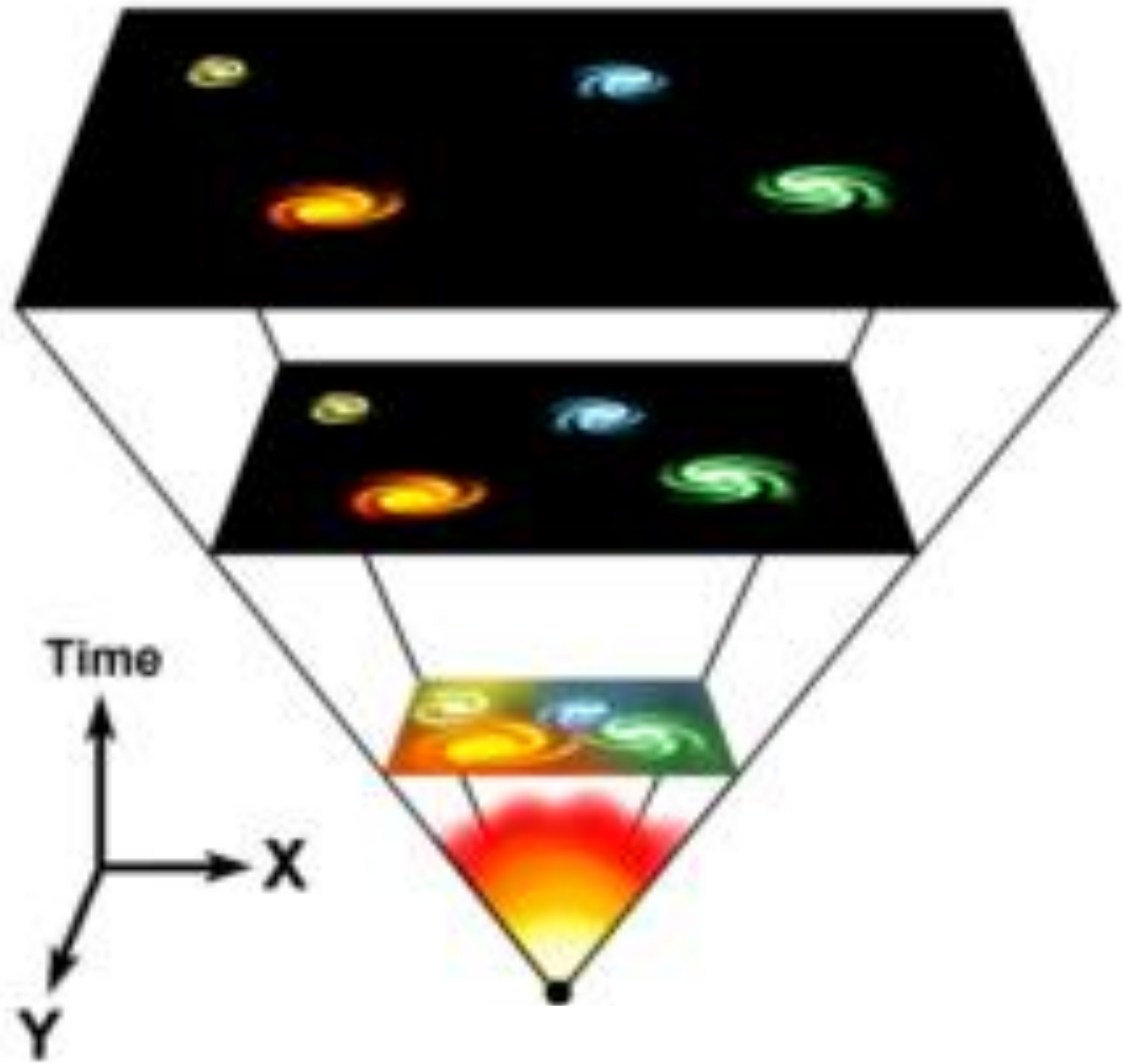
Leads to Friedman equation

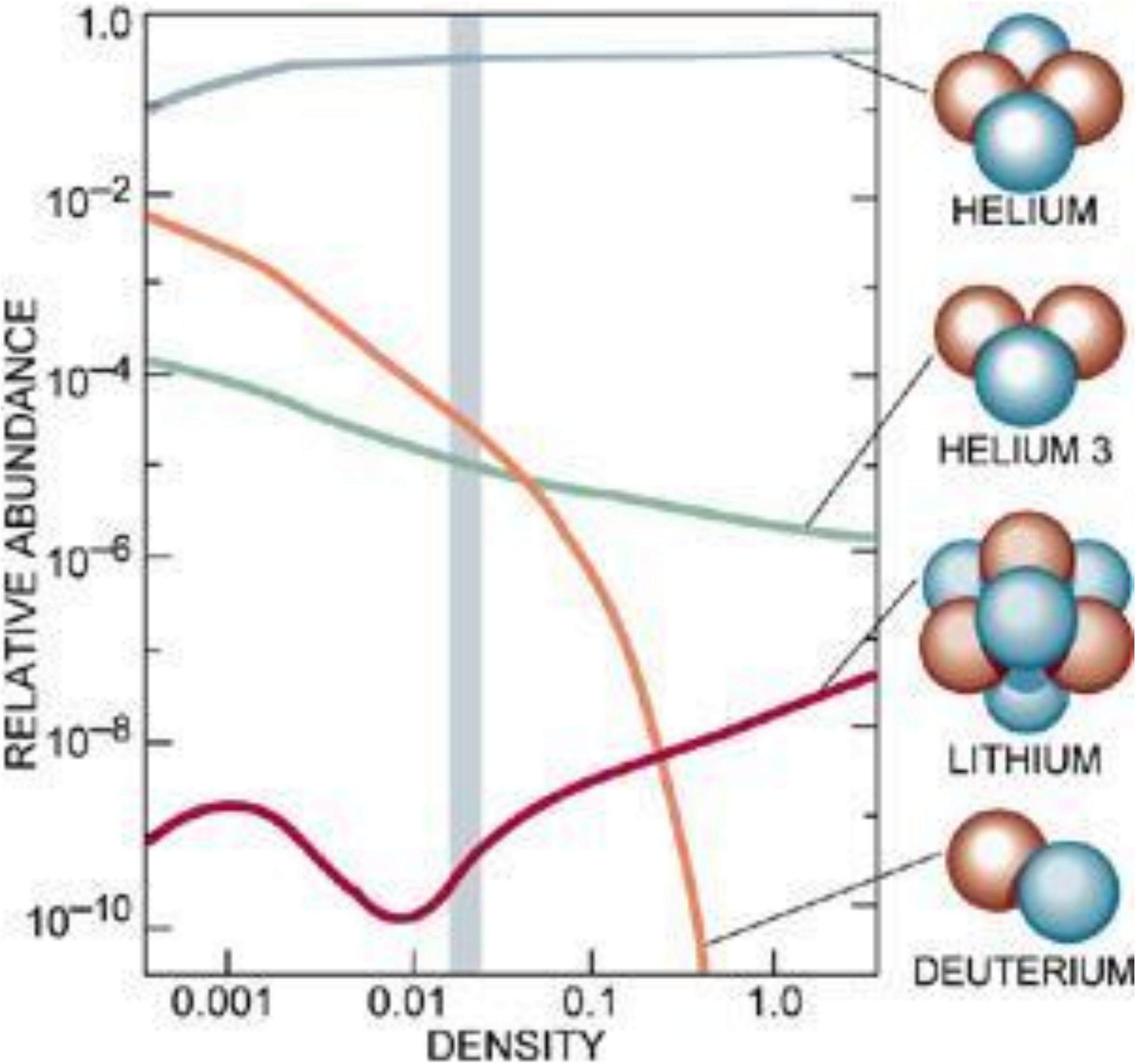
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

How fast is the Universe expanding?



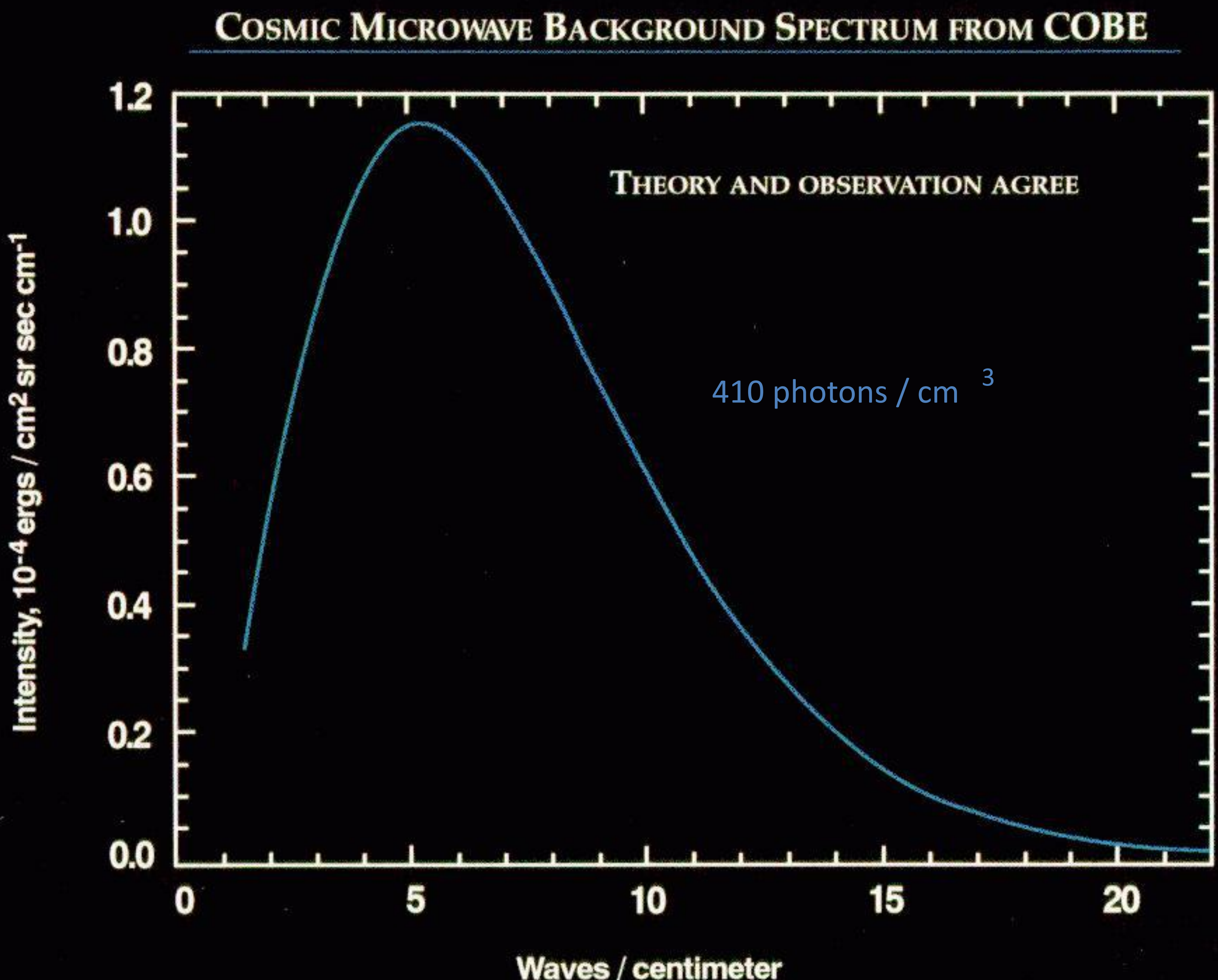
$$H = h \times 100 \mathrm{km s^{-1} Mpc^{-1}} \quad h = 0.65 - 0.75$$

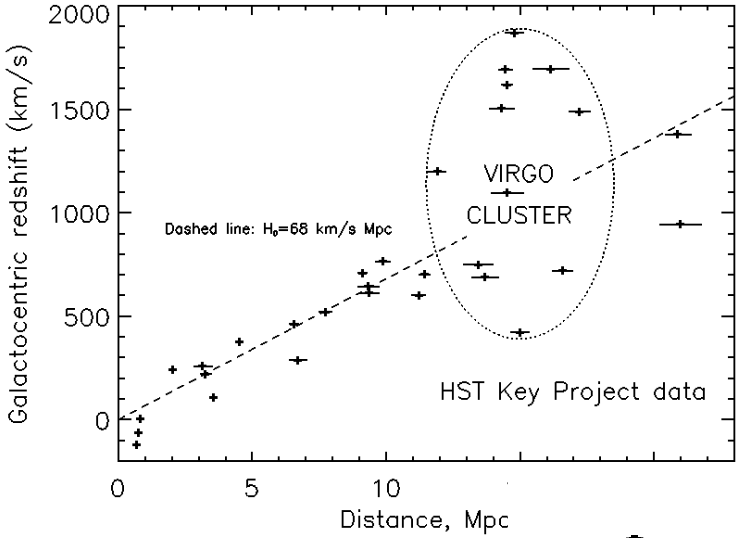

Time
X
Y

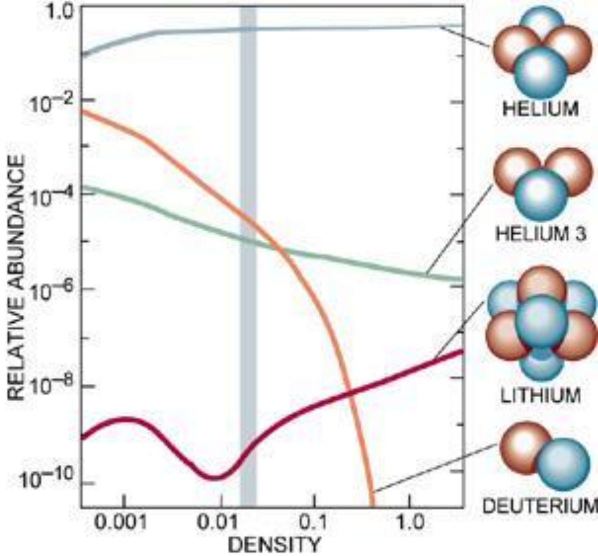


Baryon to photon ratio

Ratio of light elements gives baryon to photon ratio


COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
410 photons / cm 3
Intensity, 10-4 ergs / cm2 sr sec cm-1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter





$$H^2 = \frac{\dot{a}}{a} = \frac{8\pi G\rho}{3}$$

10^{-29} g cm^{-3}

4 x 10^{-31} g cm^{-3}

What's all the rest???

This tells us the Universe is not just full of baryons

(Or that it has a LOT of spatial curvature!)

Relationship between time and redshift

$$a_0/a(t) = 1 + z$$

$$dt = \frac{-1}{(1+z)} \frac{dz}{H}$$

$$t_0 - t_1 = \int_0^{z_1} \frac{dz}{(1+z)H(z)}$$

To get age of universe take $t_1 \to 0$

$$H^2(z) = H_0^2 \left[\Omega_\gamma (1+z)^4 + \Omega_M (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda\right]$$

So for example for matter

$$t_0 = \frac{2}{3H_0}$$

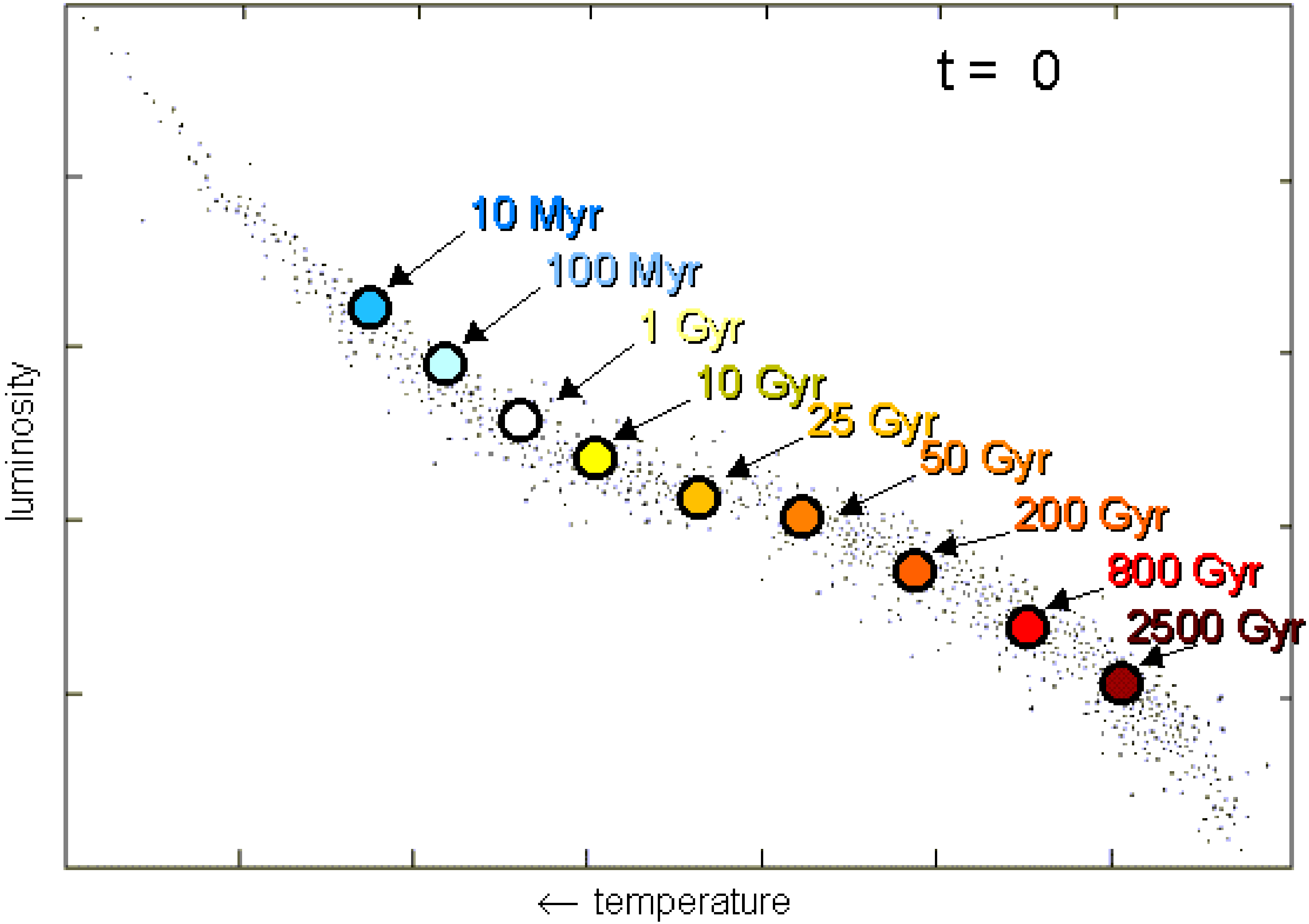
“The star which burns twice as bright burns half as long”
– from the film Bladerunner

A comparison of star sizes

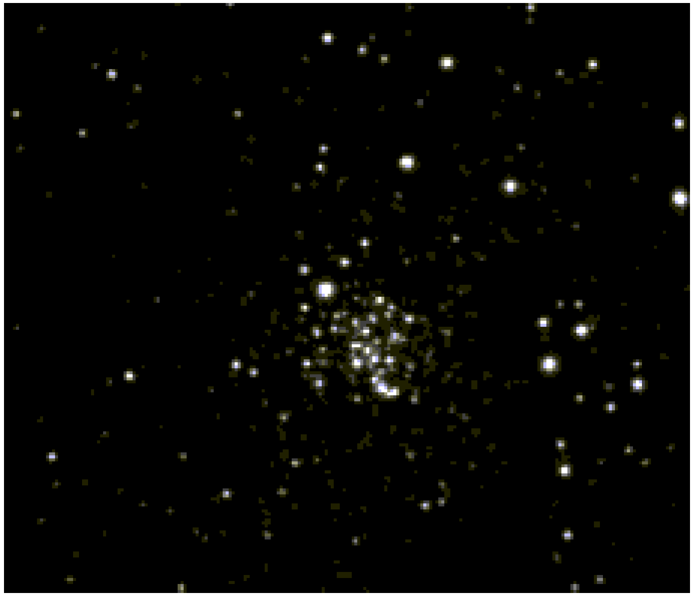
Star	Spectral Type	Mass, *M* (Solar Masses)	Central Temperature (10^6 K)	Luminosity, *L* (Solar Luminosities)	Estimated Lifetime (*M*/*L*) (10^6 years)
Spica B*	B2V	6.8	25	800	90
Vega	A0V	2.6	21	50	500
Sirius	A1V	2.1	20	22	1000
Alpha Centauri	G2V	1.1	17	1.6	7000
Sun	G2V	1.0	15	1.0	10,000
Proxima Centauri	M5V	0.1	0.6	0.00006	16,000,000

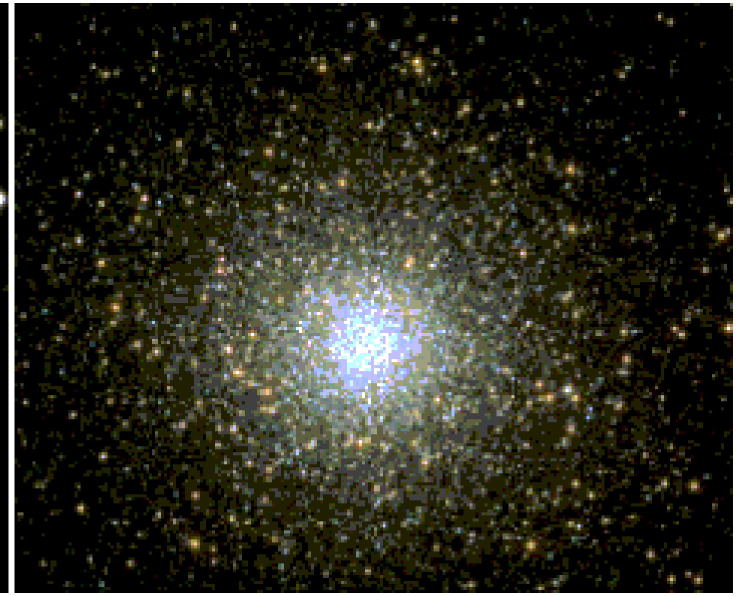
**The "star" Spica is, in fact, a binary system comprising a B1III giant primary (Spica A) and a B2V main-sequence secondary (Spica B).*

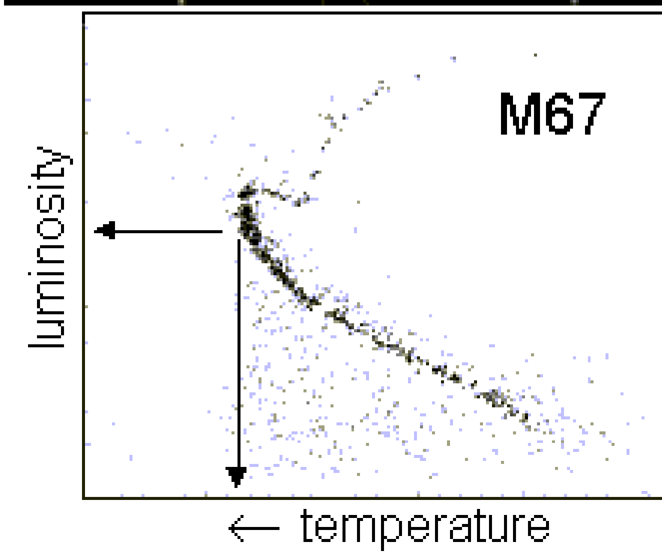
Time and the HR diagram

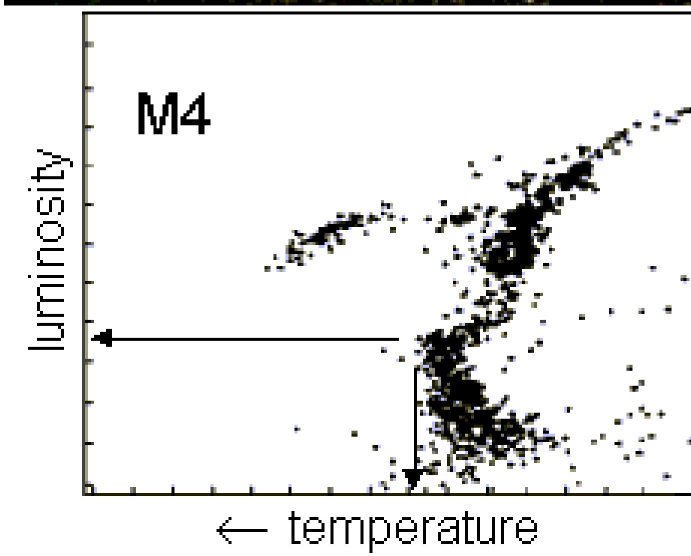


Age of the Universe from Globular Clusters



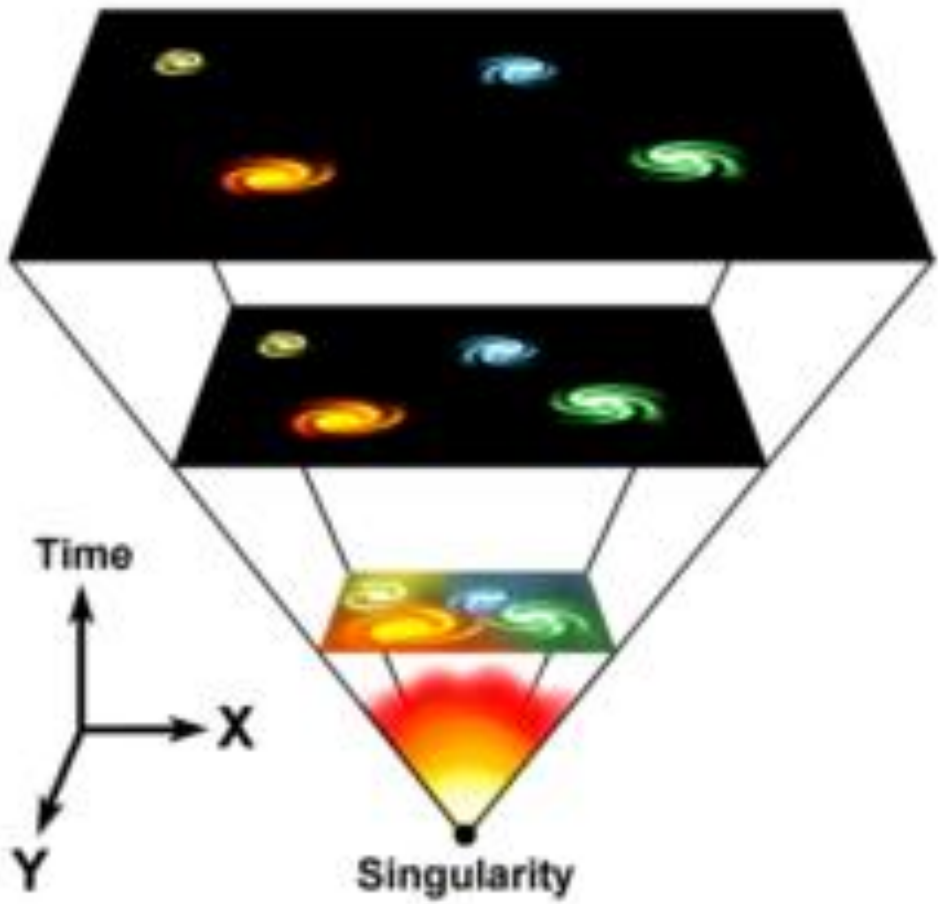






If the Universe just contained matter, its age would be about 9.2 billion years!!

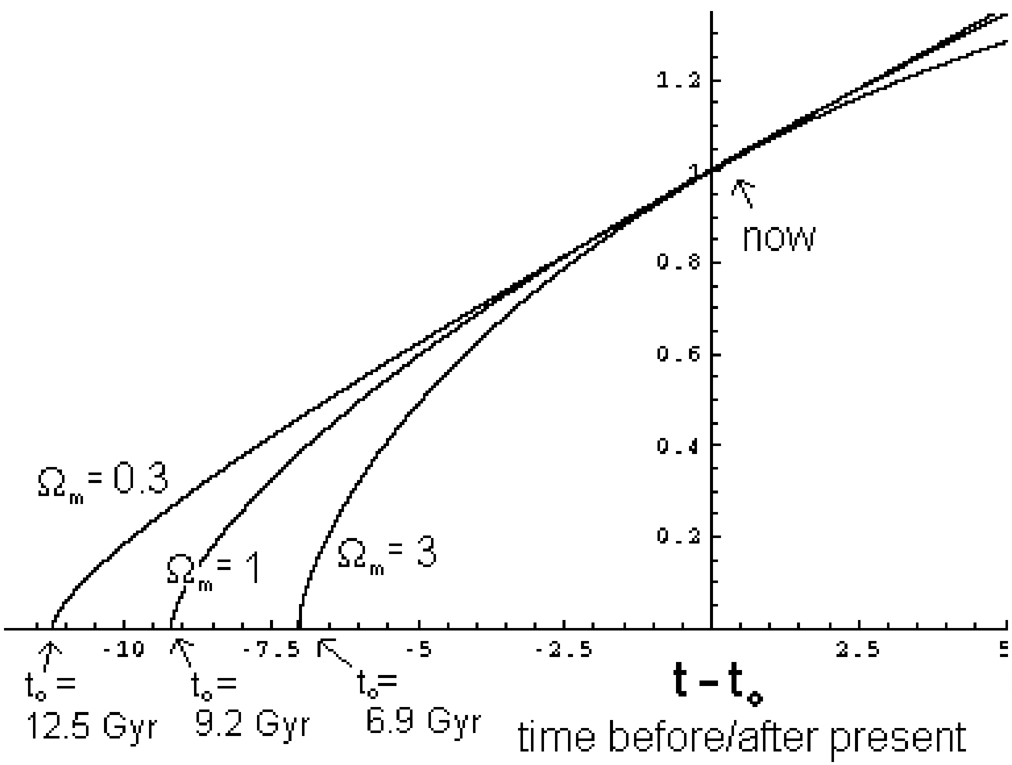
i.e. Not old enough to contain the stars inside it!

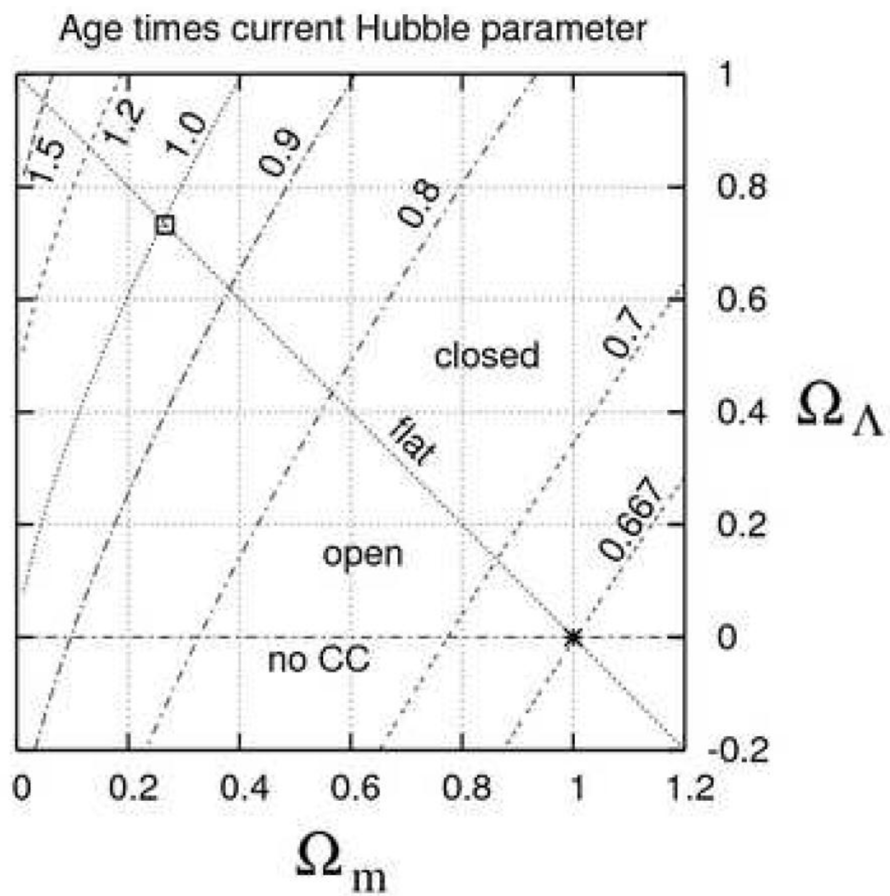


Constraint on Age of Universe

$$t_0 - t_1 = \int_0^{z_1} \frac{dz}{(1+z)H(z)}$$

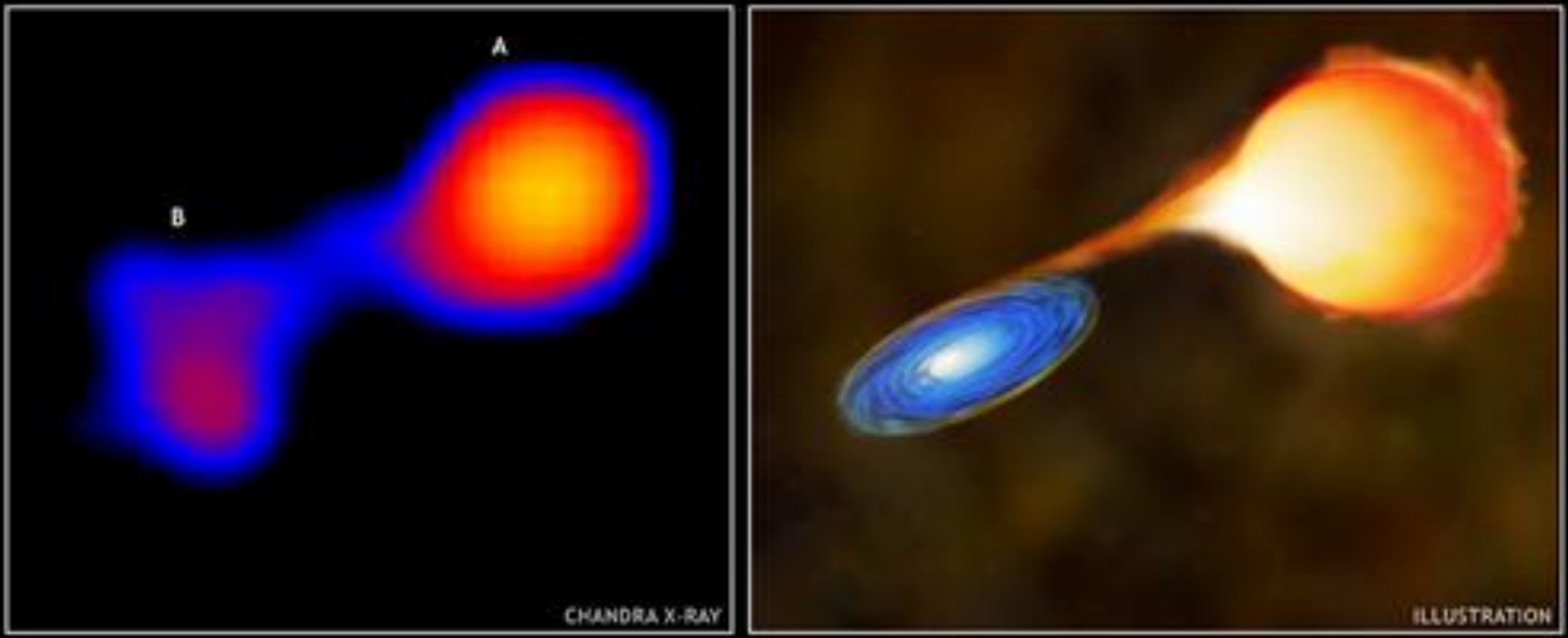
$$H^2(z) = H_0^2 \left[\Omega_\gamma (1+z)^4 + \Omega_M (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda\right]$$

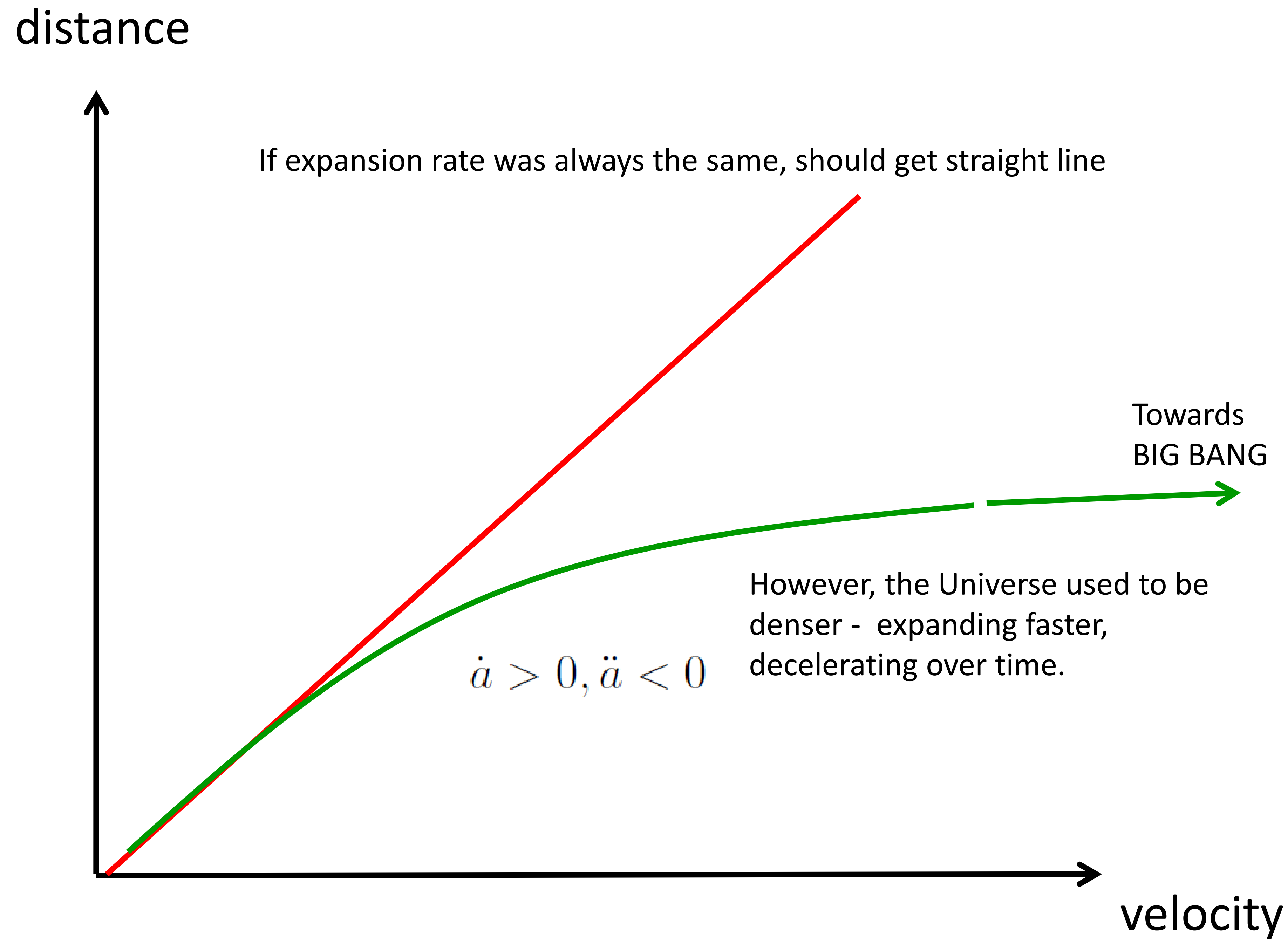




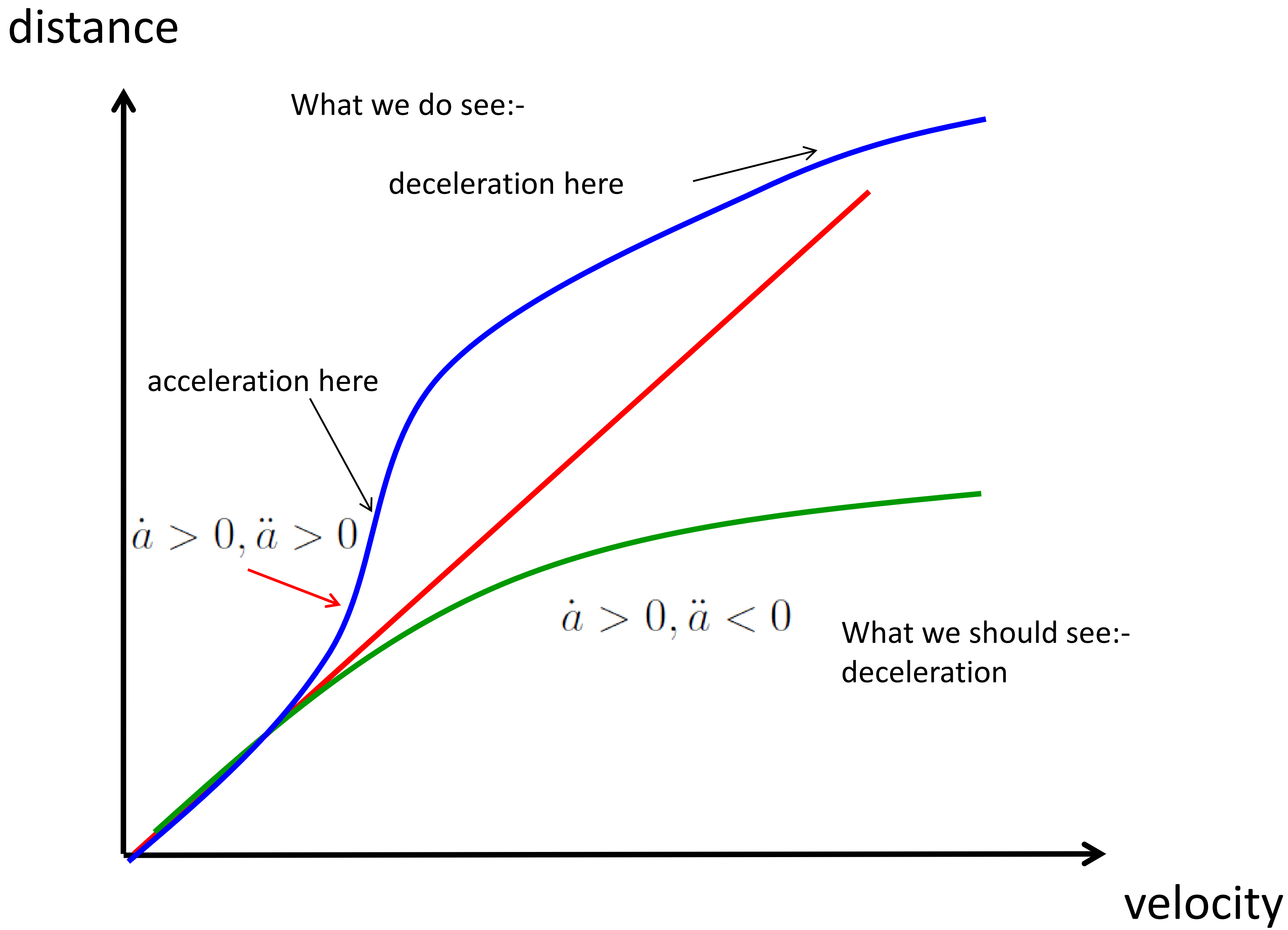
This tells us the Universe is not just full of matter

Type 1a supernovae as Standard candles

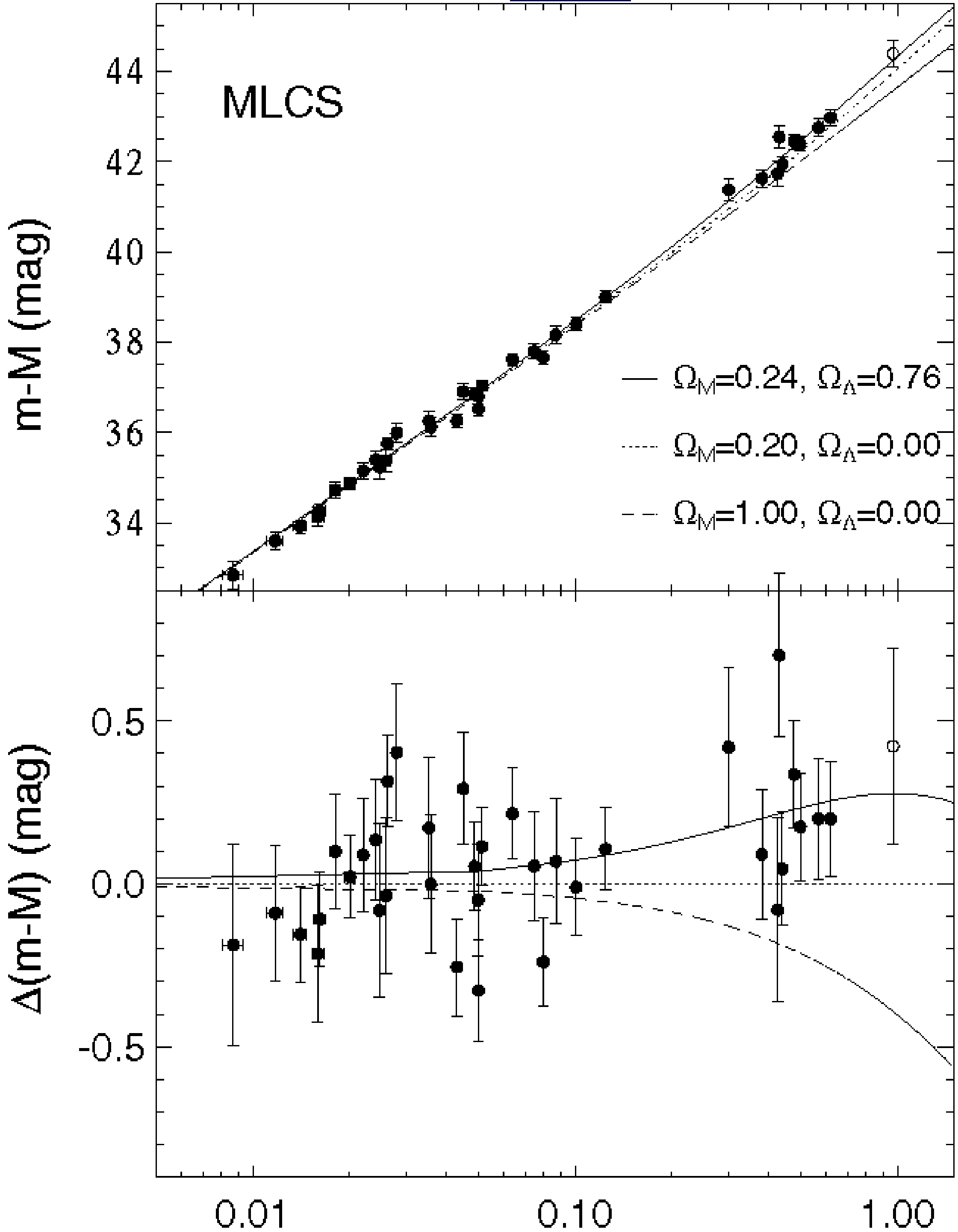


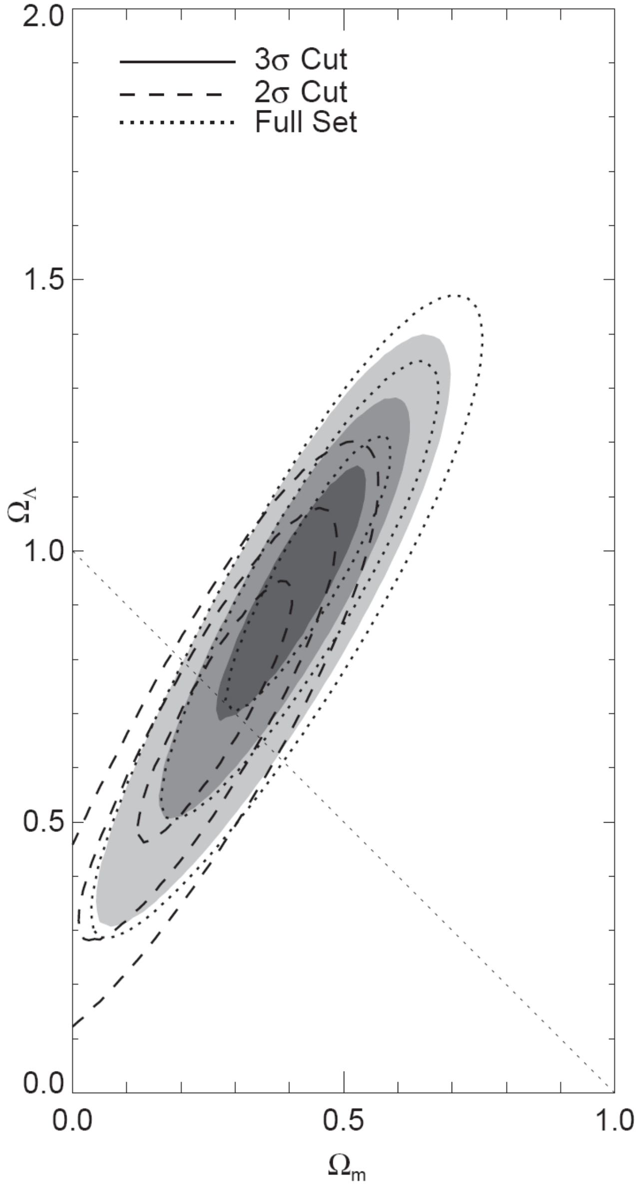


distance
If expansion rate was always the same, should get straight line
Towards
BIG BANG
However, the Universe used to be
denser - expanding faster,
decelerating over time.
$\dot{a} > 0, \ddot{a} < 0$
velocity

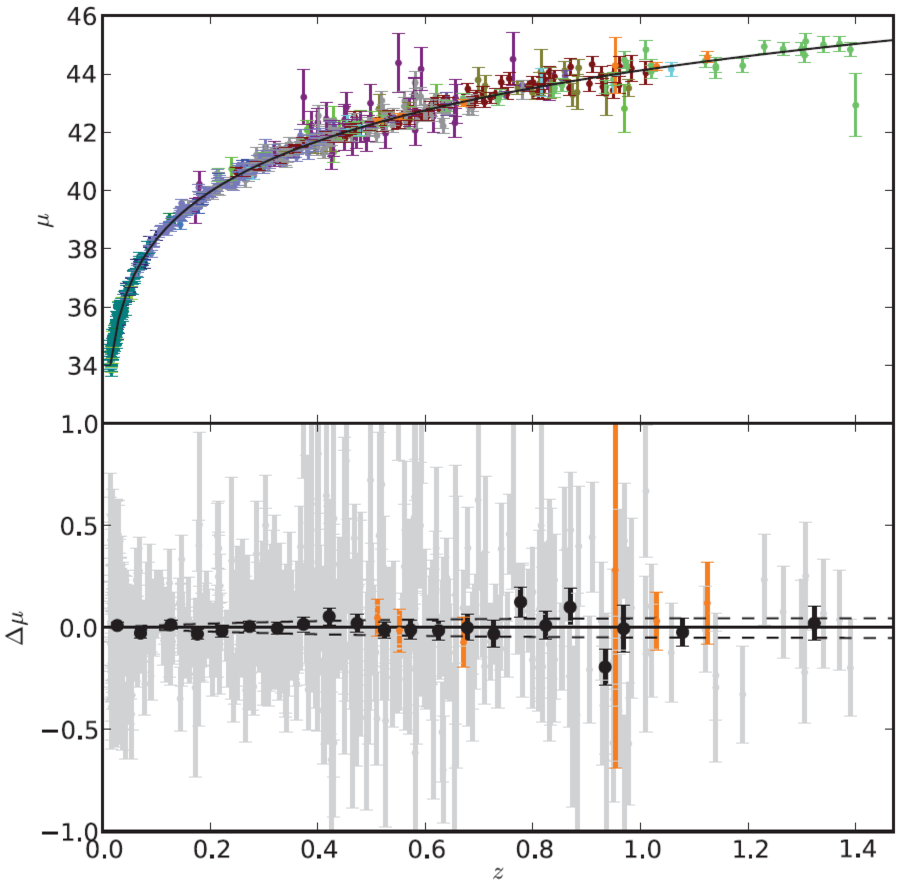

distance
What we do see:-
deceleration here
acceleration here
$\dot{a} > 0, \ddot{a} > 0$
$\dot{a} > 0, \ddot{a} < 0$
What we should see:-
deceleration
velocity

The actual data:-





Union supernova data set 0804.4142



Union2 Compilation1004.1711

Acceleration implies negative pressure

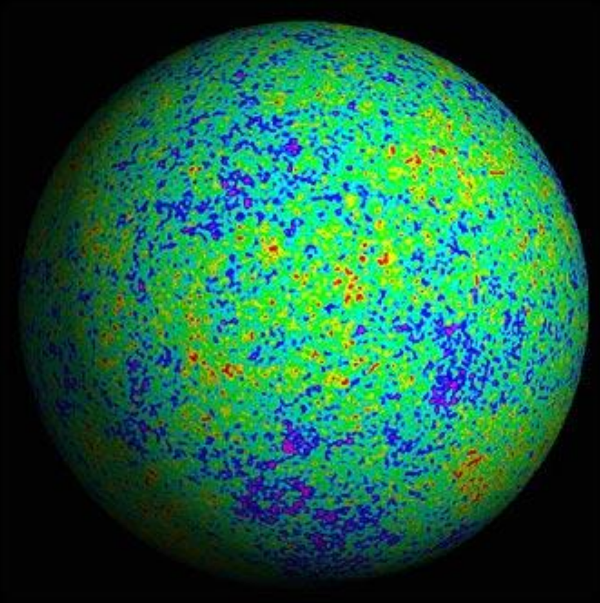
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P\right)$$

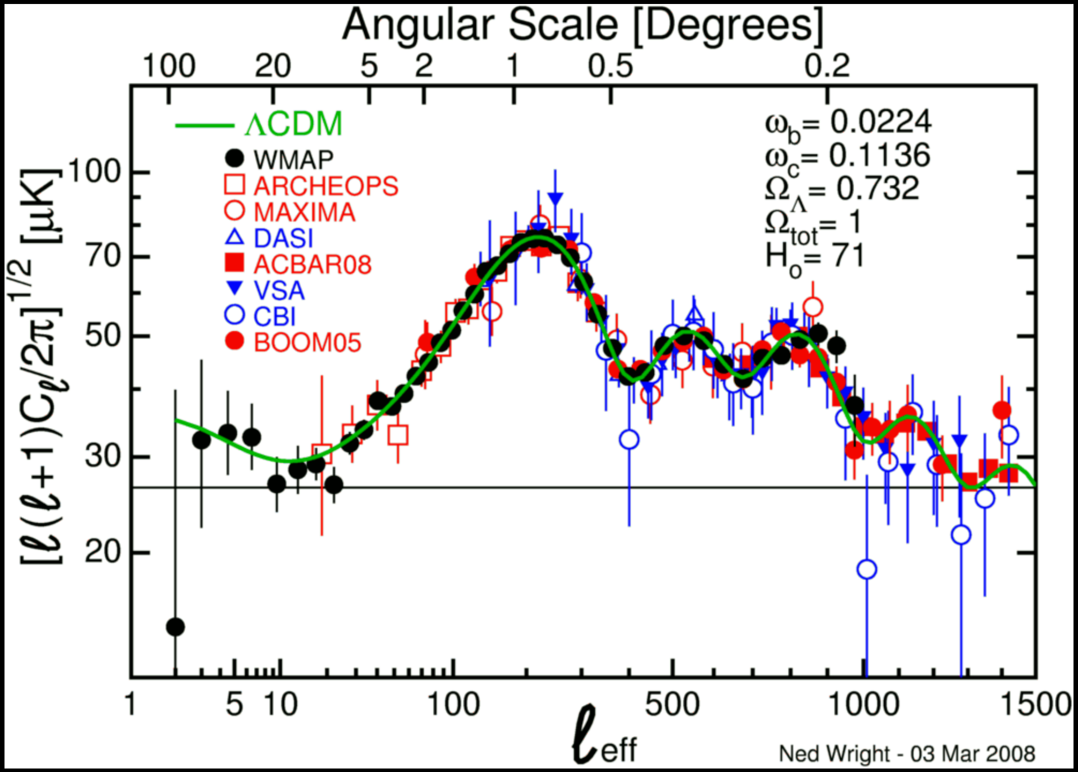
To get positive acceleration we need P < -ρ/3

In cosmology, pressure tells you how fast the density of something decreases as the Universe expands

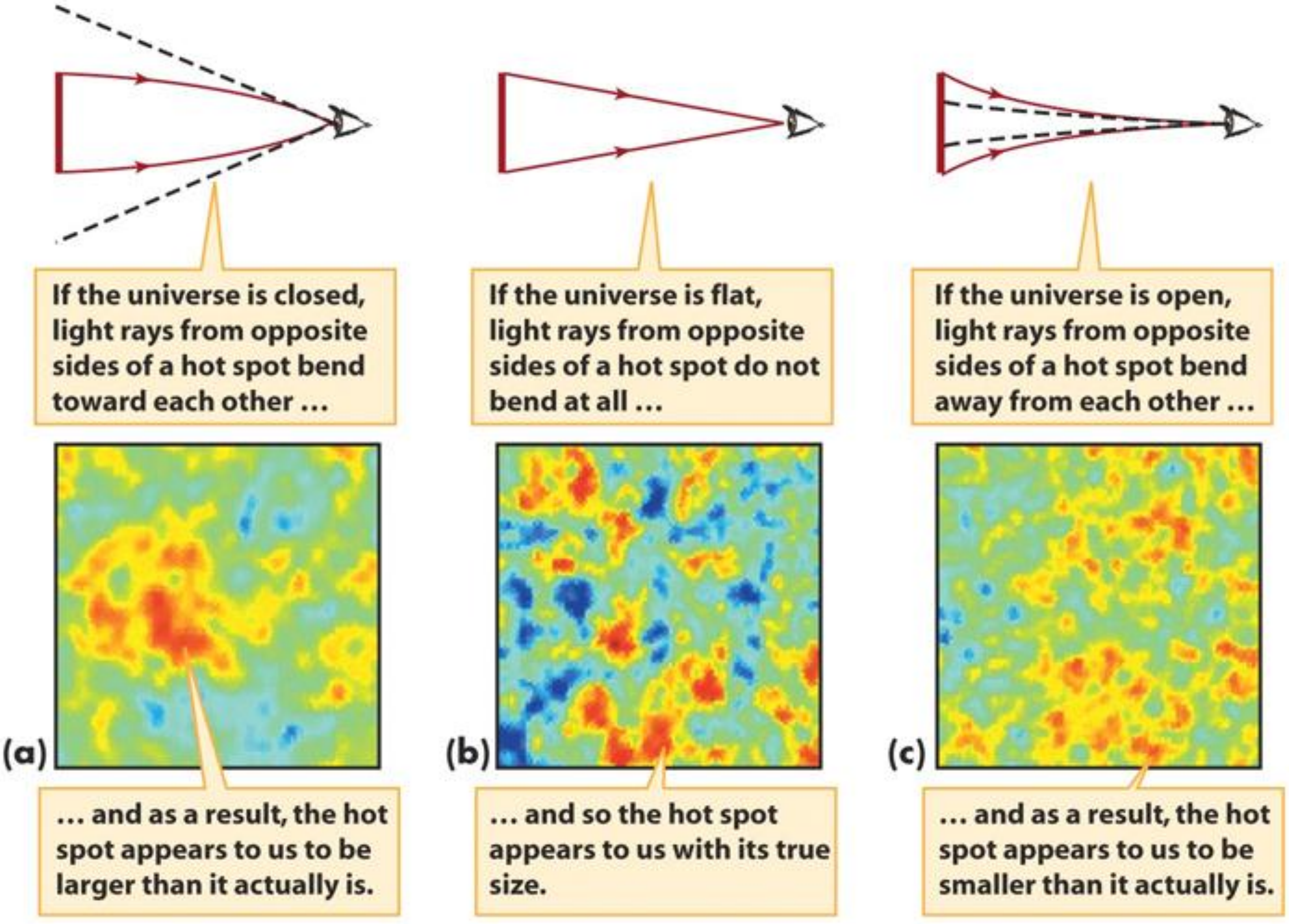
$$\dot{\rho} = -3H\left(\rho + P\right)$$

The CMB data



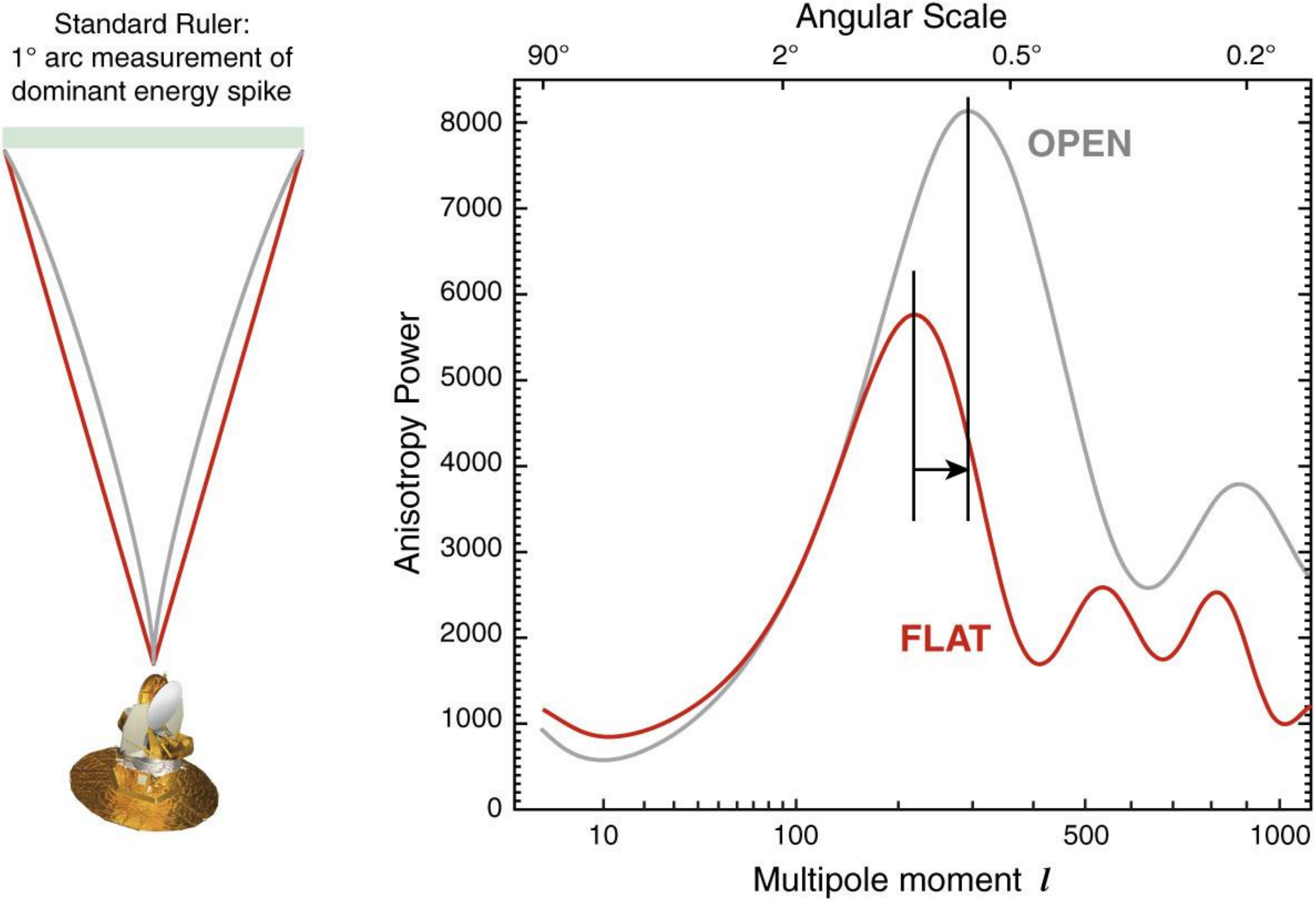


Angular Scale [Degrees]
100
20
5
2
1
0.5
0.2
ΛCDM
WMAP
ARCHEOPS
MAXIMA
DASI
ACBAR08
VSA
CBI
BOOM05
ω_b= 0.0224
ω_c= 0.1136
Ω_Λ= 0.732
Ω_{tot}= 1
H_o= 71
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ [μK]
100
70
50
30
20
1
5
10
100
500
1000
1500
ℓ_{eff}
Ned Wright - 03 Mar 2008

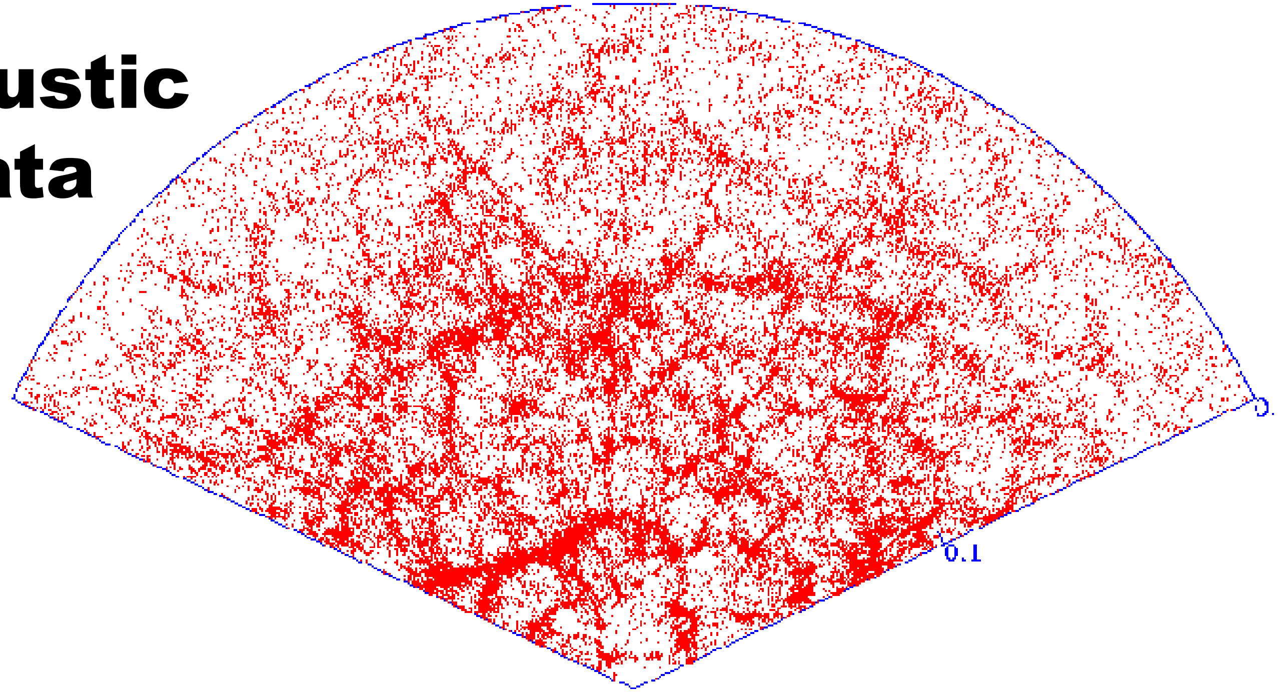


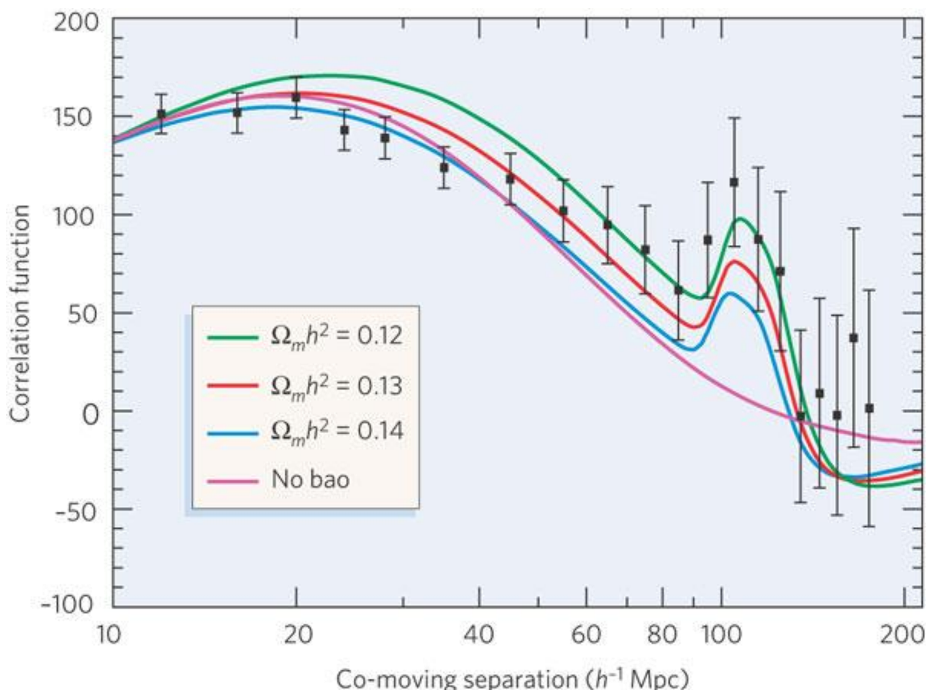
If the universe is closed, light rays from opposite sides of a hot spot bend toward each other …
If the universe is flat, light rays from opposite sides of a hot spot do not bend at all …
If the universe is open, light rays from opposite sides of a hot spot bend away from each other …
(a)
(b)
(c)
… and as a result, the hot spot appears to us to be larger than it actually is.
… and so the hot spot appears to us with its true size.
… and as a result, the hot spot appears to us to be smaller than it actually is.

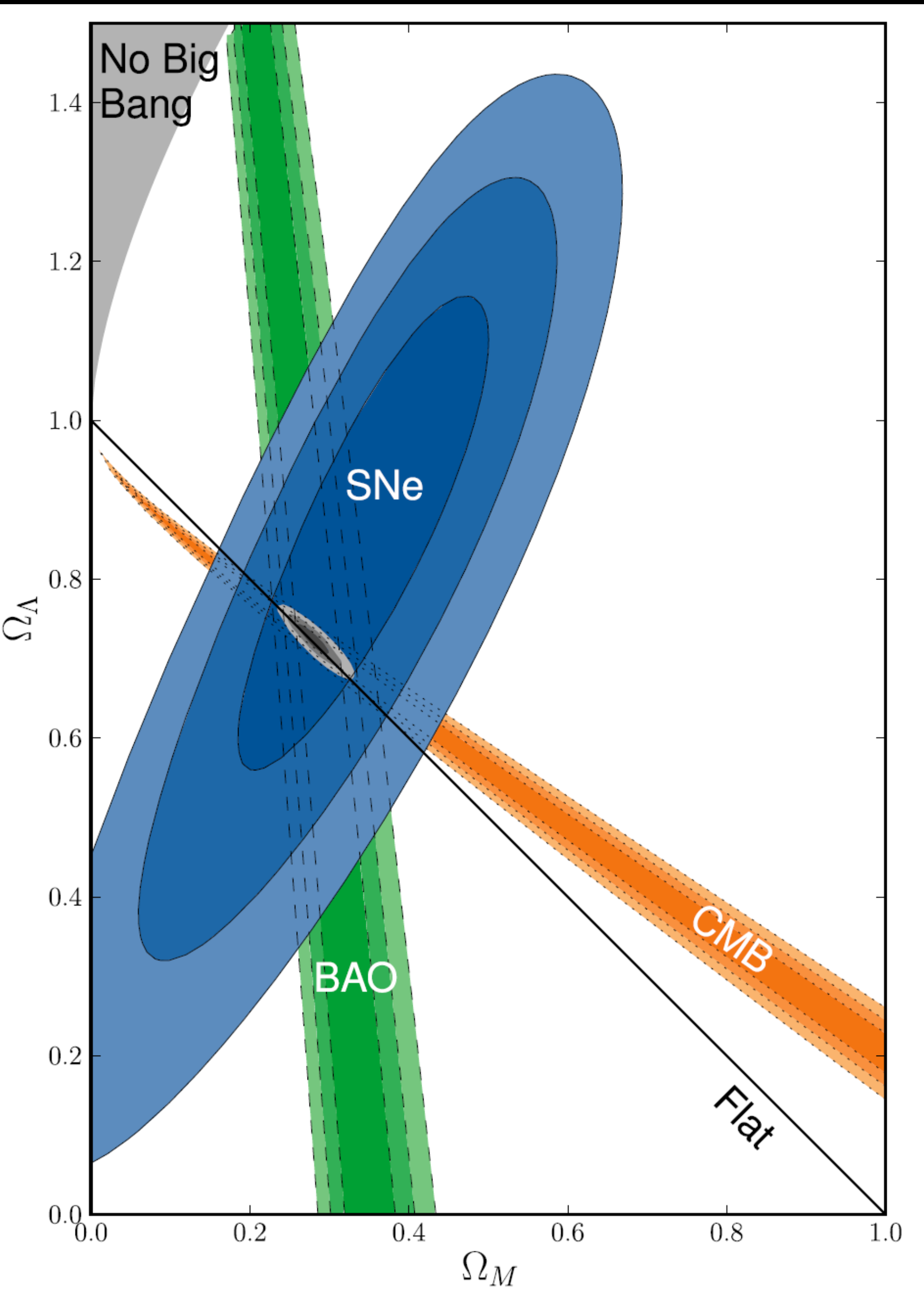
What it really looks like



Baryonic Acoustic Oscillation Data

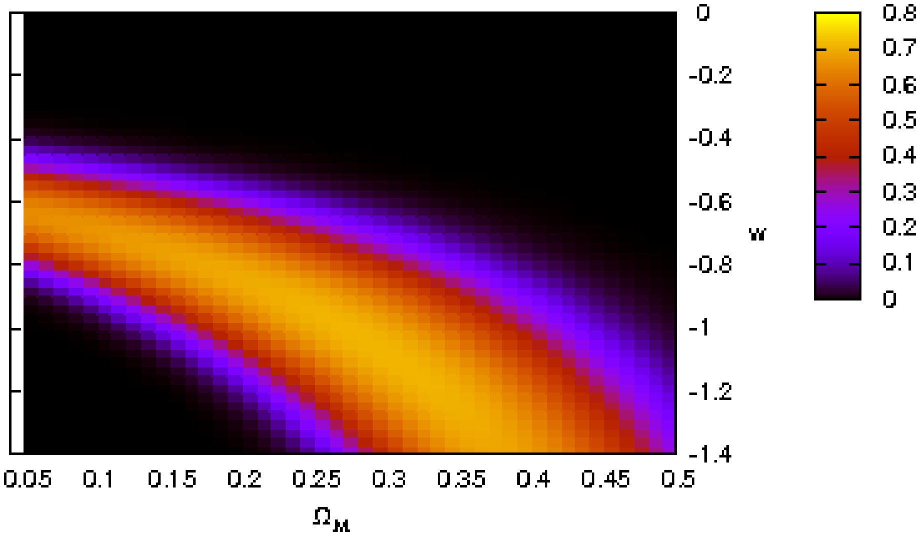




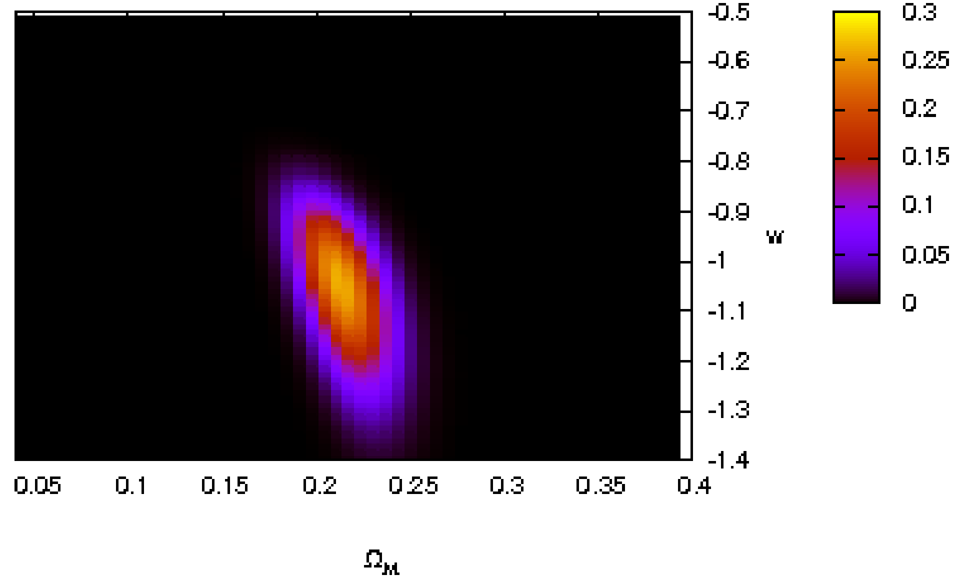

No Big Bang
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4


Dark Energy 73%
Atoms 4%
Cold Dark Matter 23%

Constraint on the Equation of State



With supernovae only



With supernovae, CMB and BAO

Note, this assumes the equation of state is constant.

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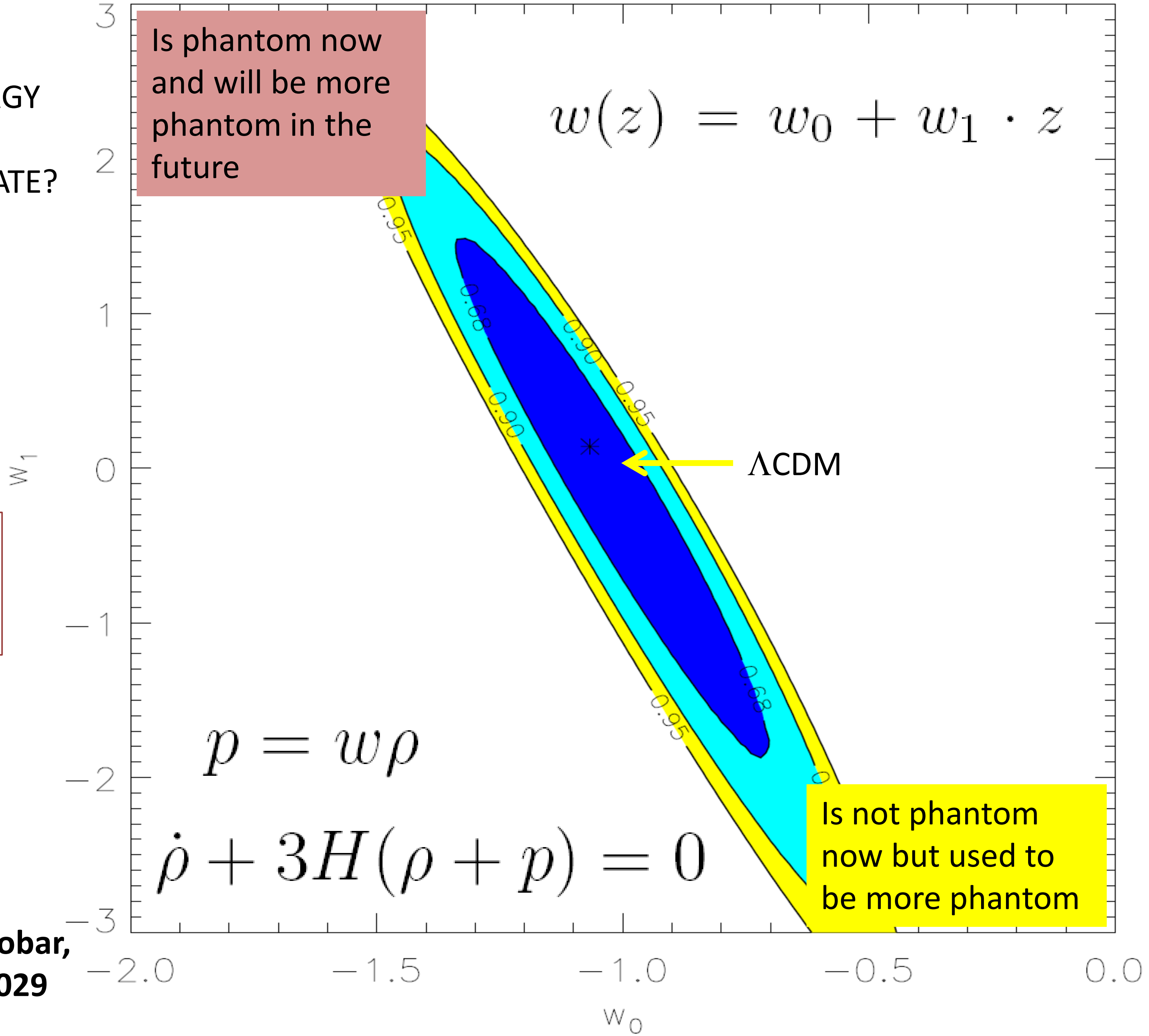
DOES DARK ENERGY HAVE CONSTANT EQUATION OF STATE?

Not neccessarily!

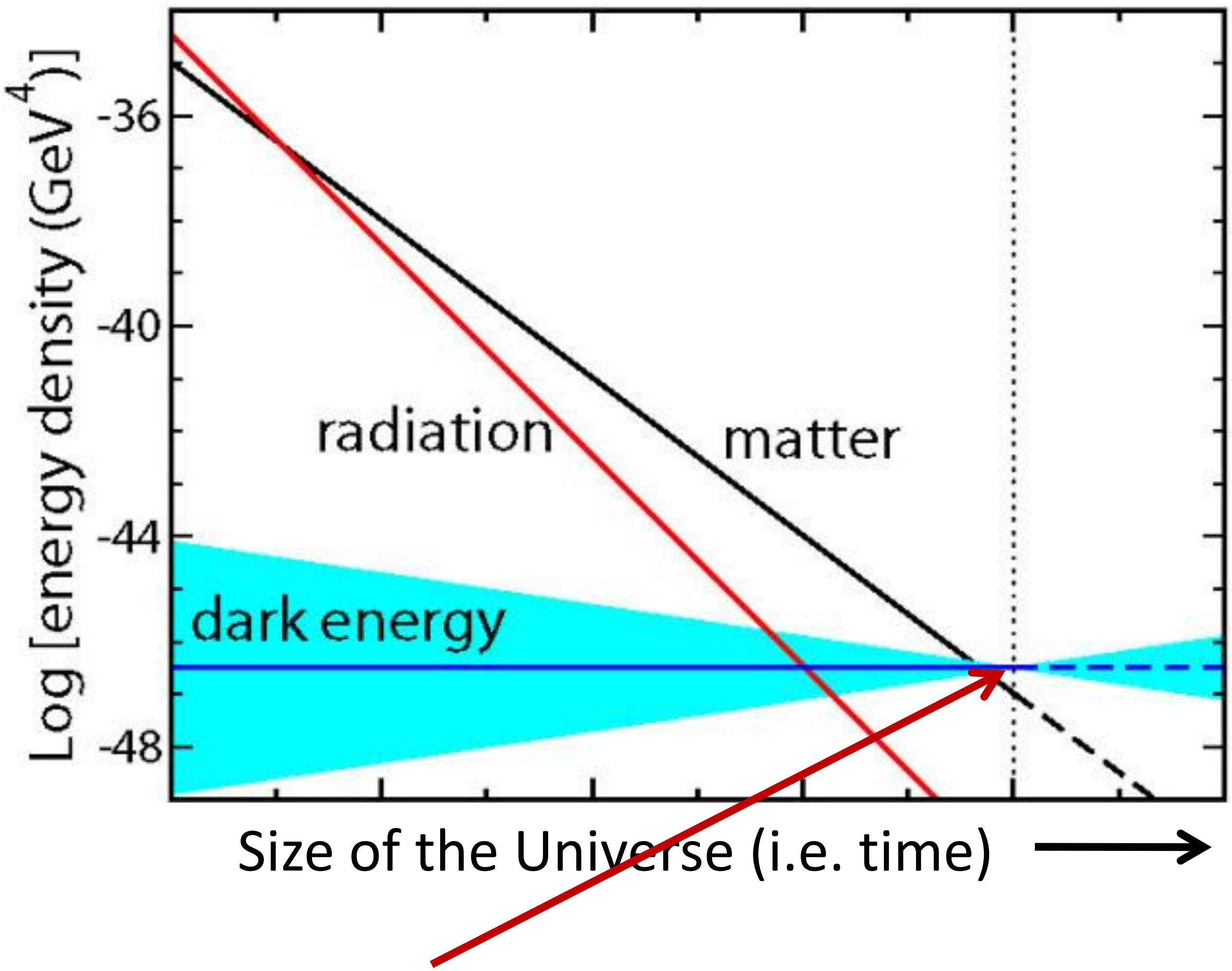
Phantom means

$$\dot{\rho} > 0$$



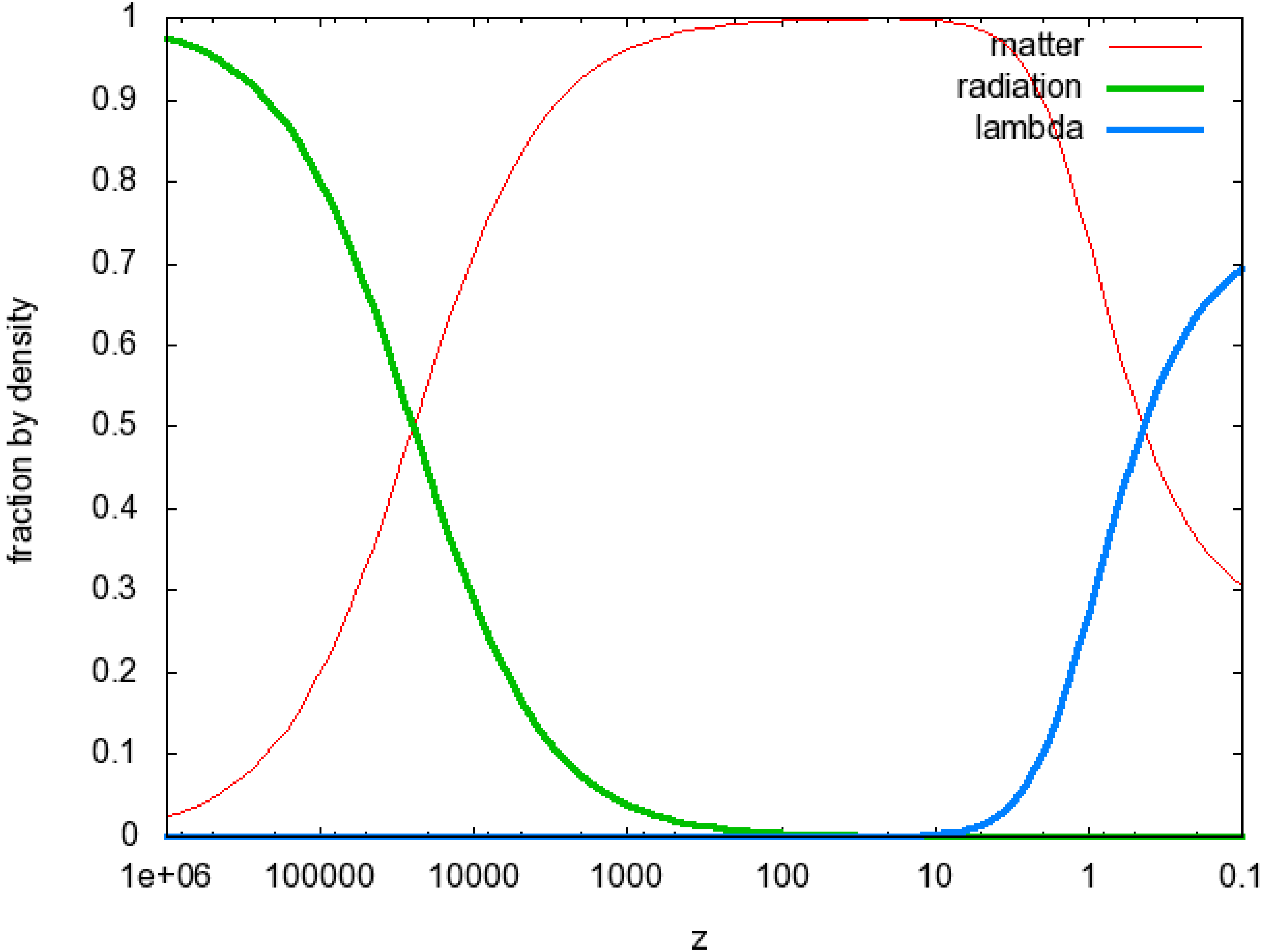
Fairbairn and Goobar, astro-ph/0511029

Different energies and how they dilute

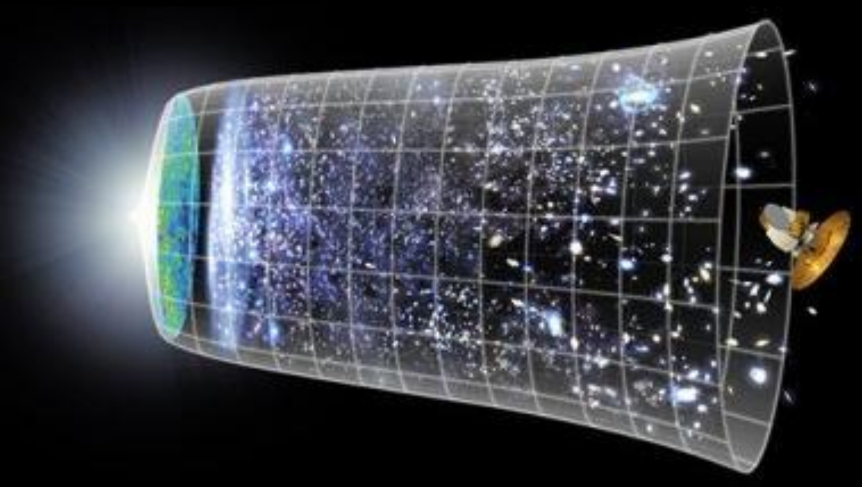


Why are we here? (cosmic coincidence problem)

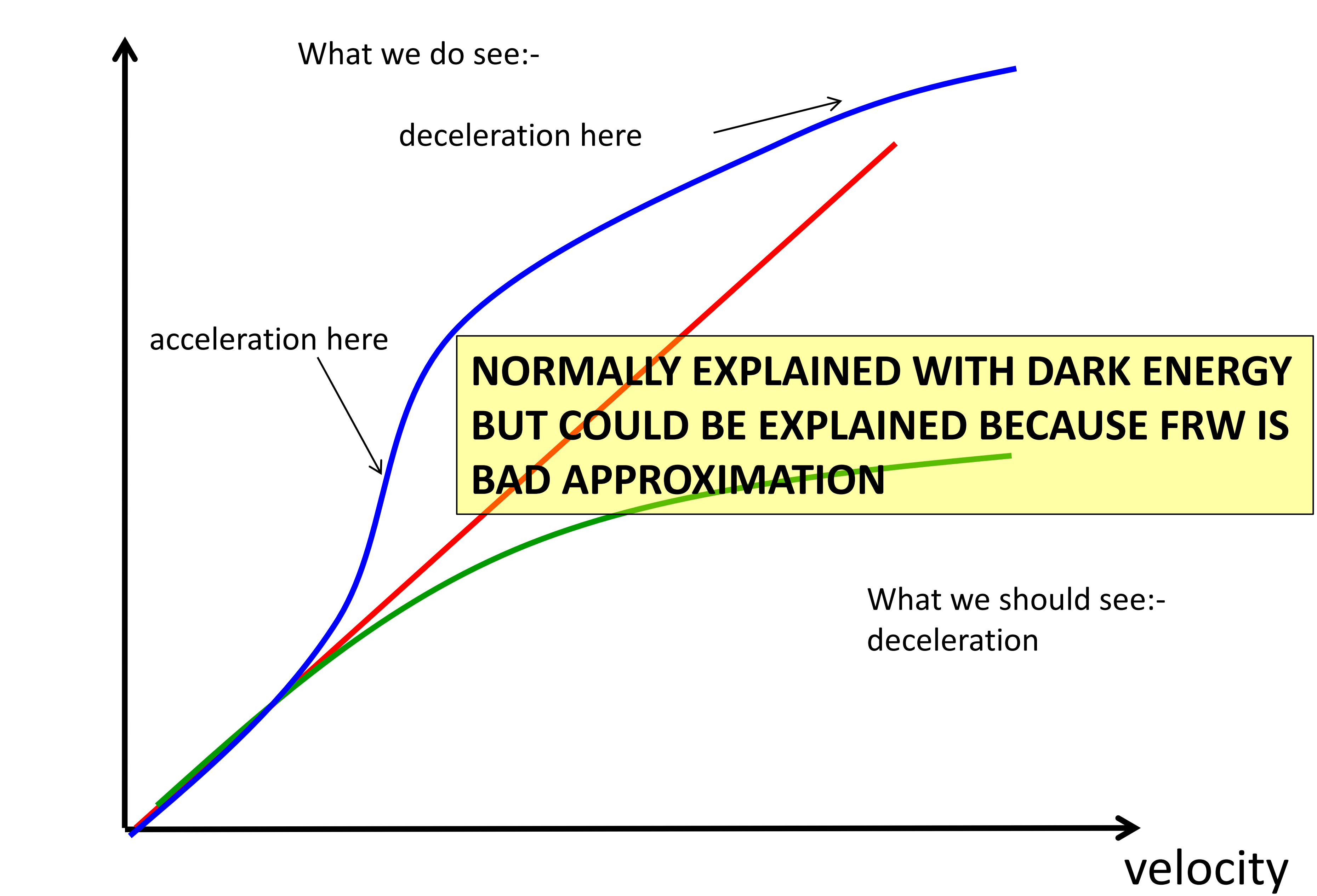
Cosmic Coincidence Problem

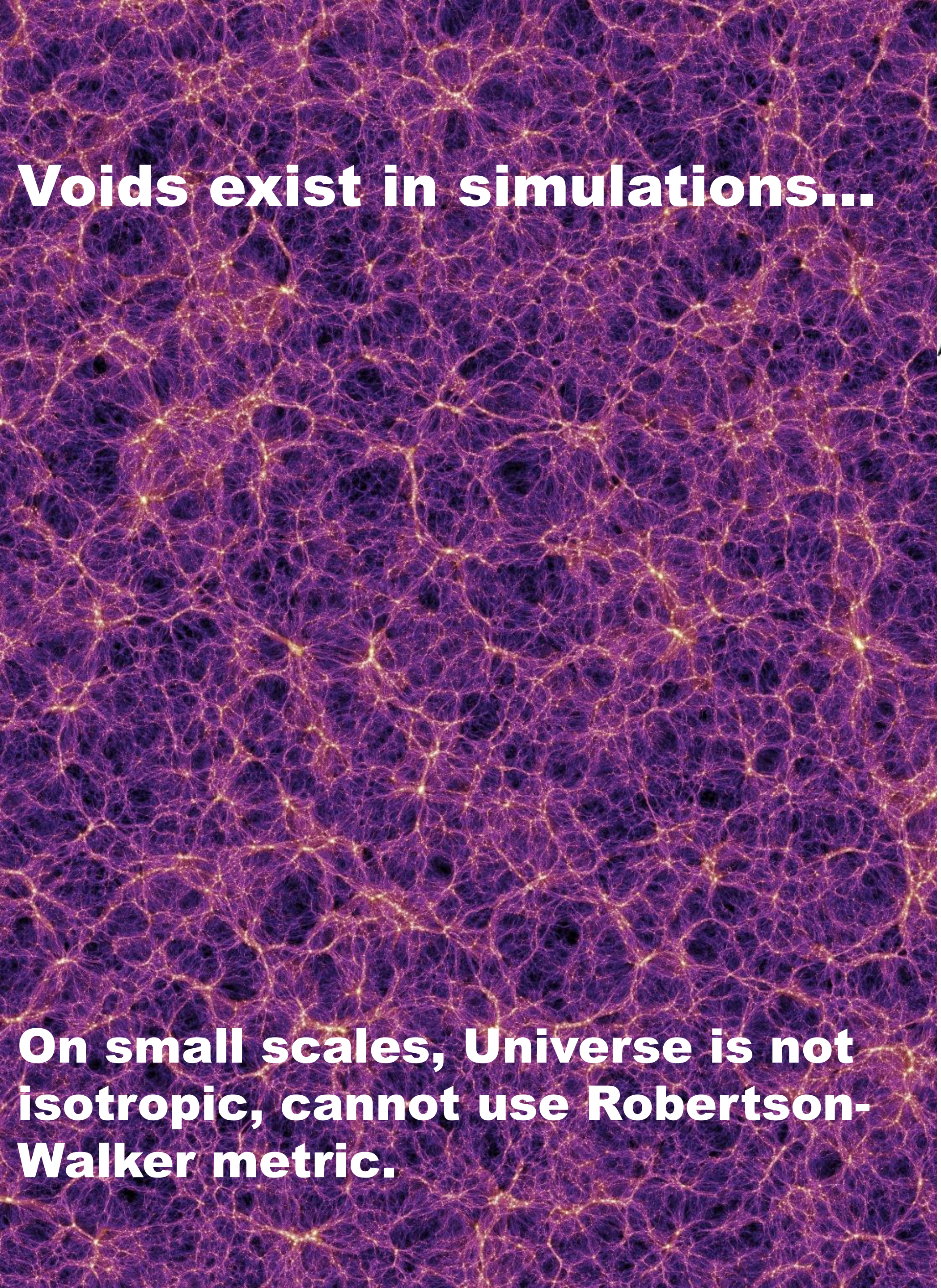


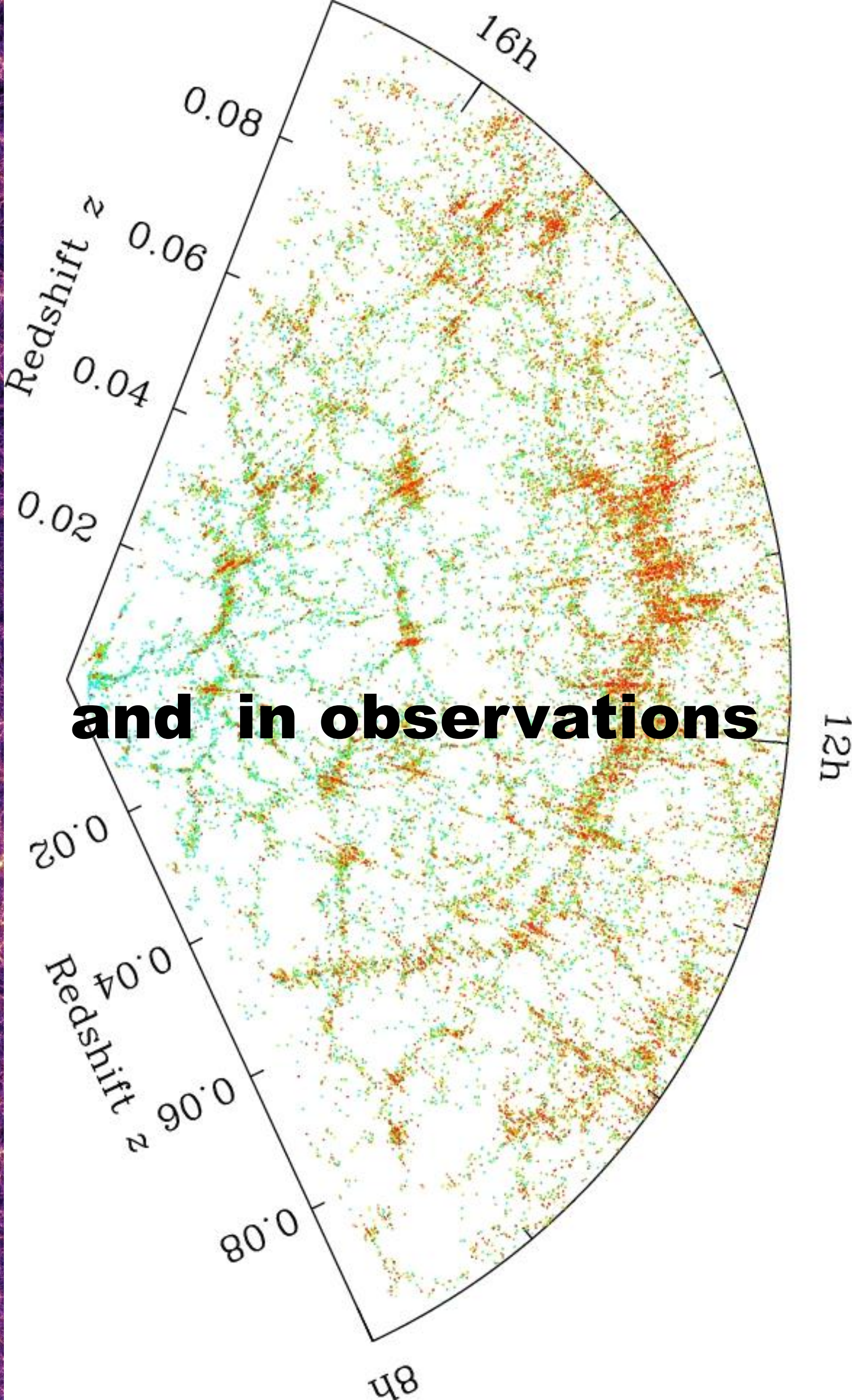
The energy content of the Universe

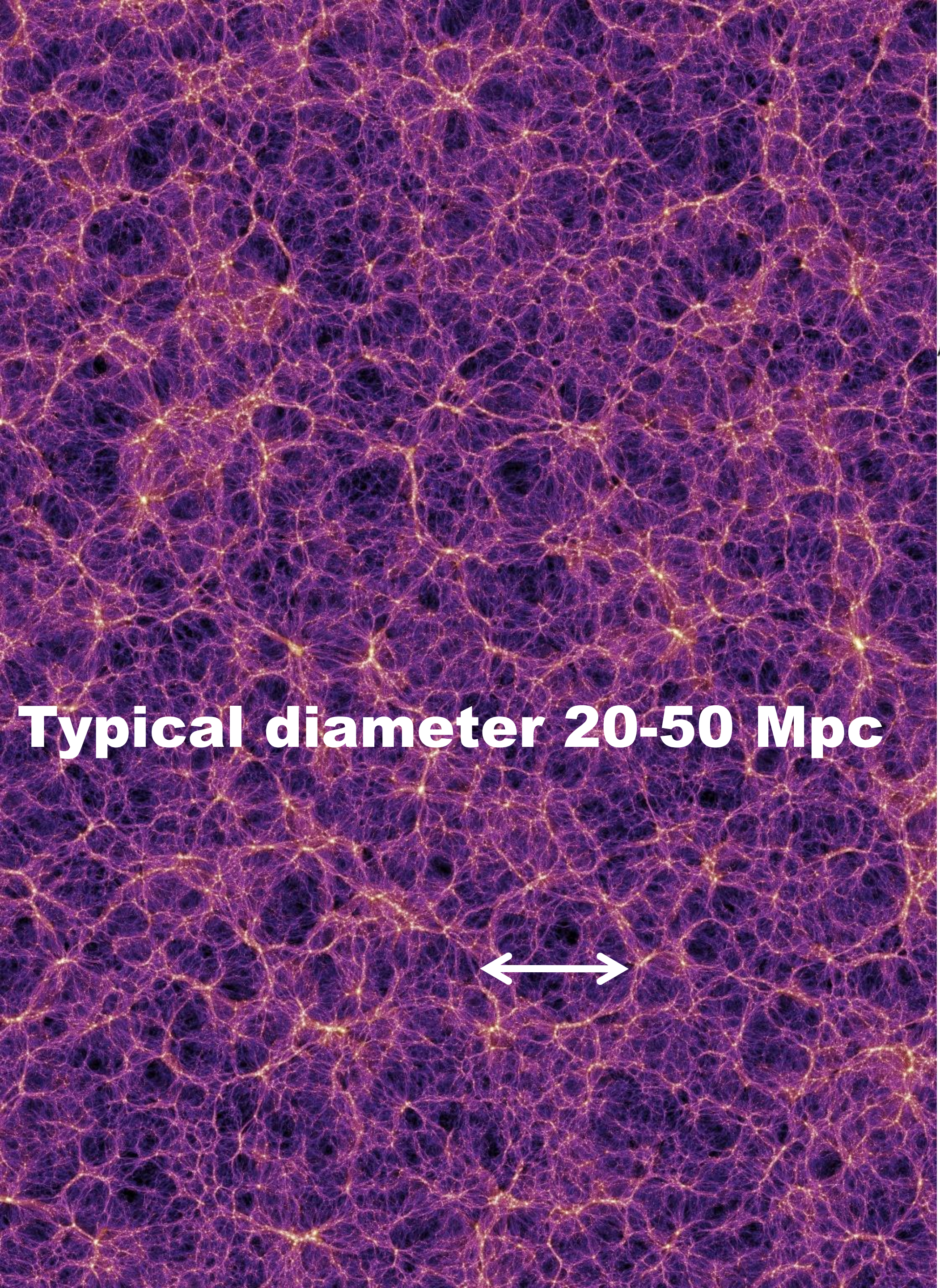


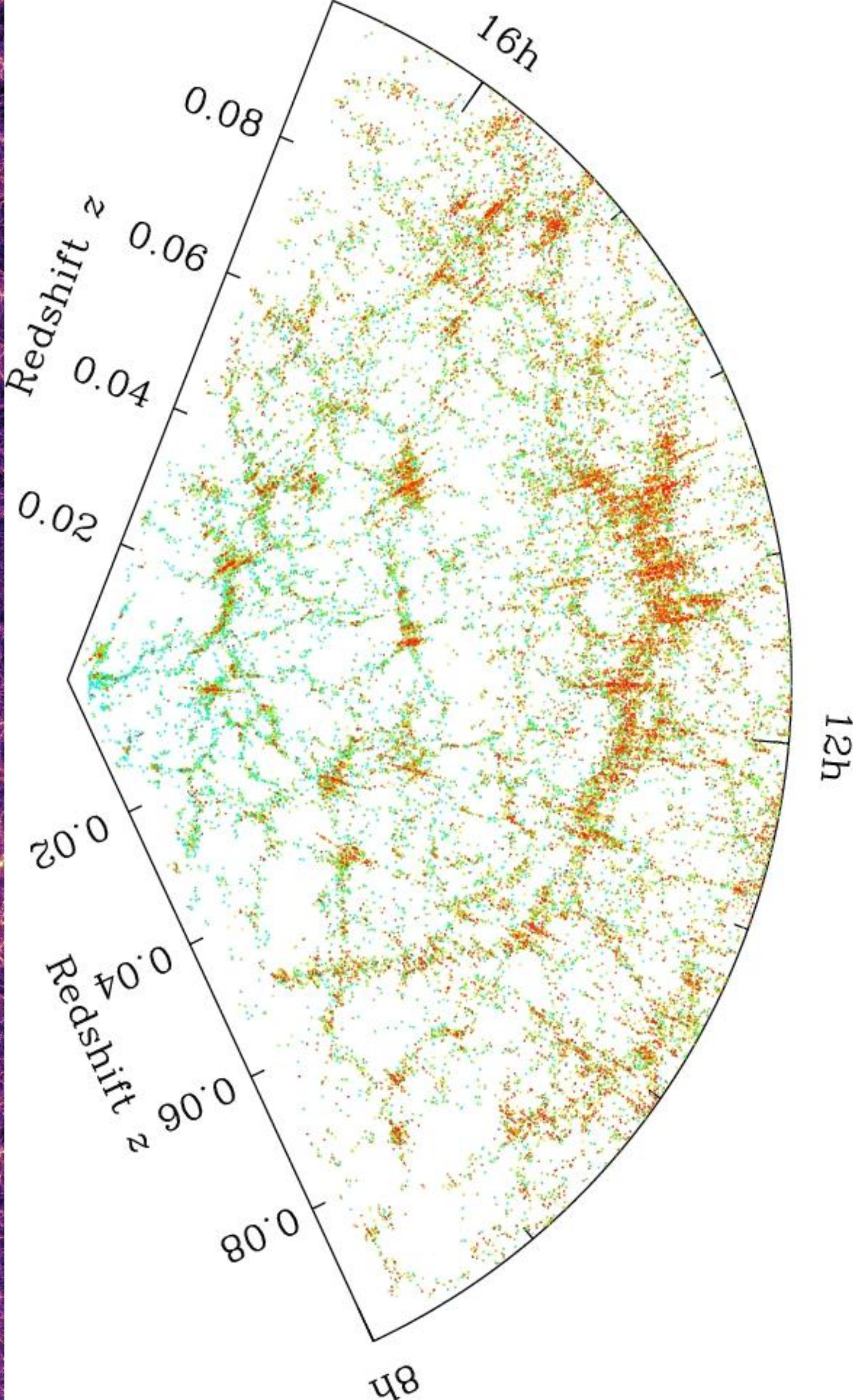
Basic Issue with Expansion History




Voids exist in simulations...
On small scales, Universe is not isotropic, cannot use Robertson-Walker metric.


and in observations
16h
12h
8h
Redshift z
0.08
0.06
0.04
0.02
Redshift z
0.02
0.04
0.06
0.08


Typical diameter 20-50 Mpc


16h
12h
8h
Redshift z
0.08
0.06
0.04
0.02
0.02
0.04
0.06
0.08
Redshift z

Evolution of a Spherical Void

We assume spherical void and use Lemaitre-Tolman-Bondi metric

$$ds^2 = -dt^2 + S^2(r,t)dr^2 + R^2(r,t)(d\theta^2 + sin^2\theta d\phi^2)$$

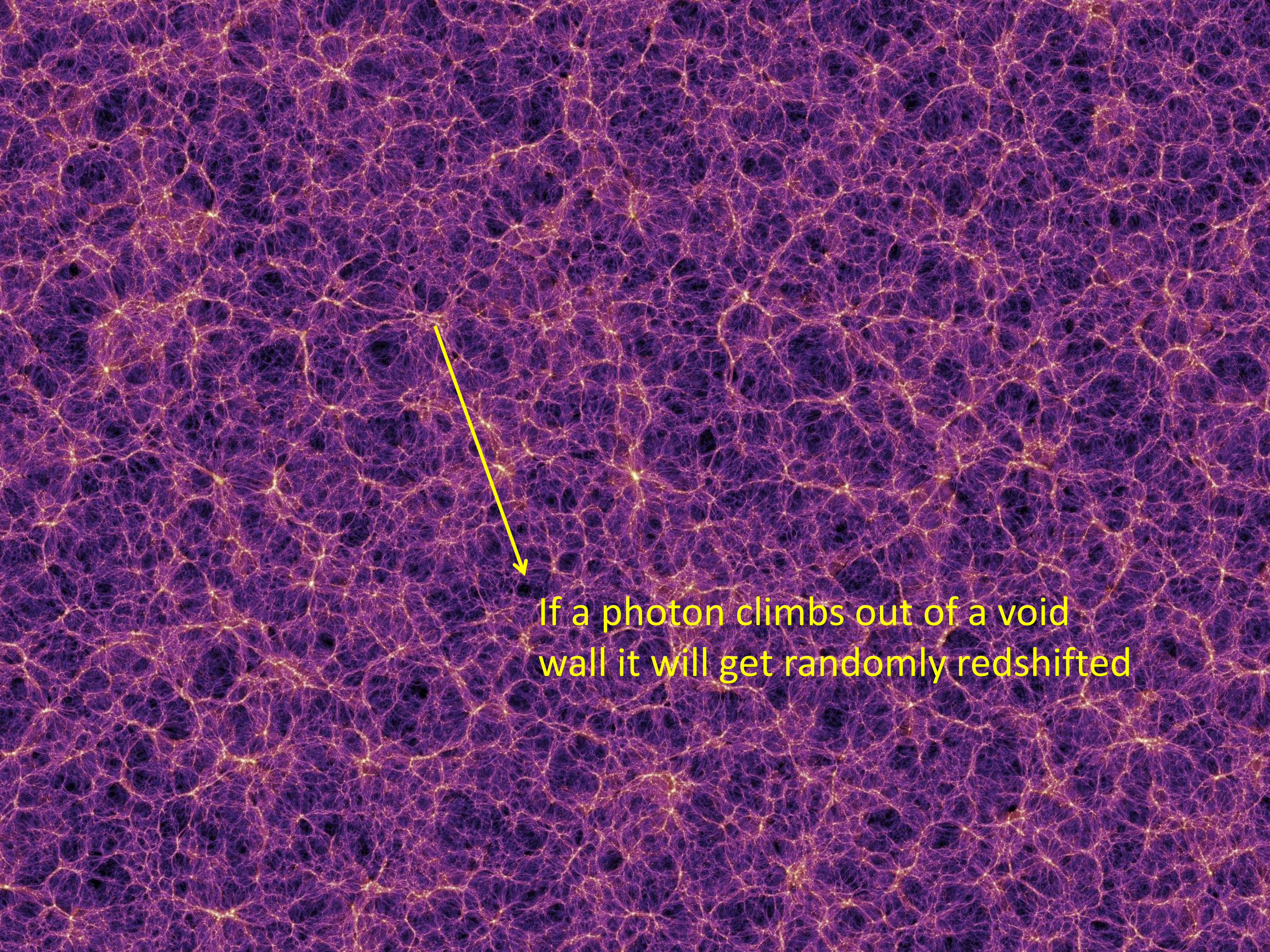
$$S^2(r,t) = \frac{R'^2(r,t)}{1 + 2E(r)}$$

curvature

'Friedman' equation for Lemaitre-Tolman Bondi metric

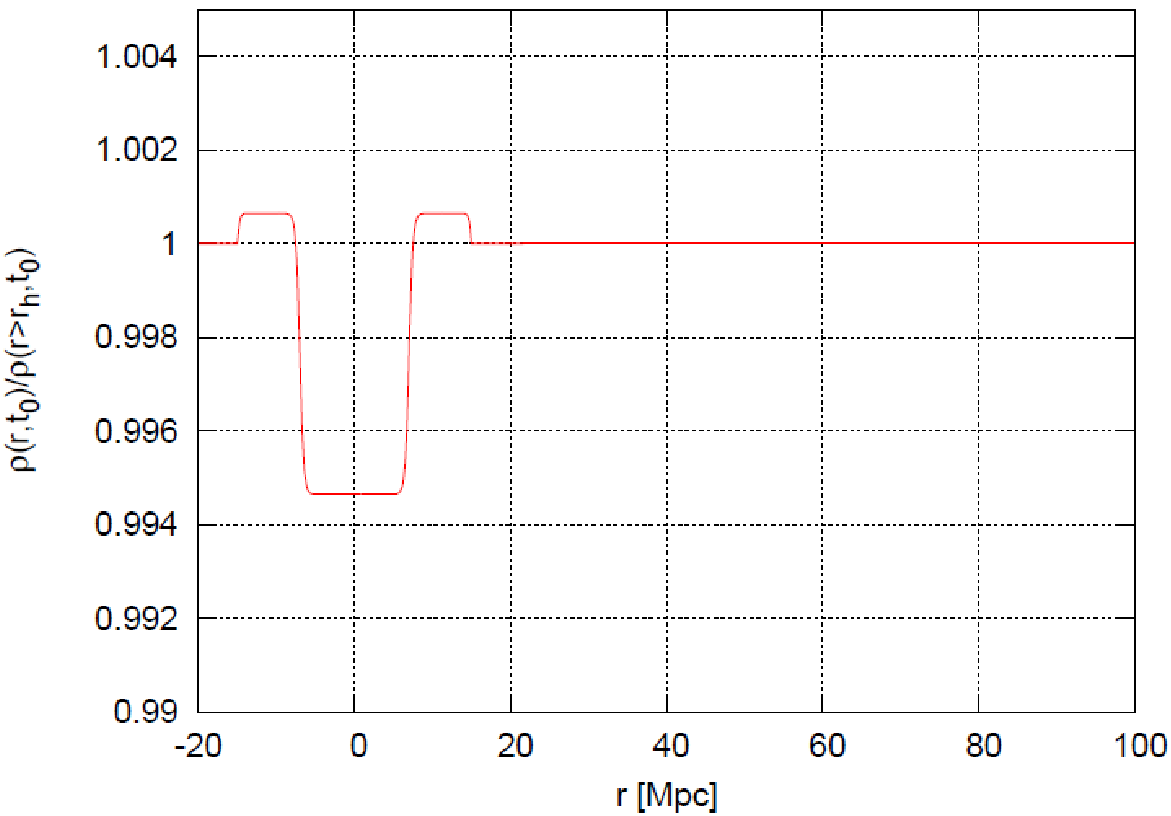
$$\frac{1}{2}\dot{R}^2 - \frac{GM(r)}{R(r,t)} - \frac{1}{3}\Lambda R^2 = E(r)$$

$$E(r) = \frac{1}{2}\frac{H^2_{\mathrm{LTB}}a^2_{\mathrm{LTB}}}{c^2}\left(r^2 - \frac{3}{4\pi}\frac{M(r)}{a^3_{\mathrm{LTB}}r\bar{\rho}(t_{\mathrm{LTB}})}\right)$$


If a photon climbs out of a void
wall it will get randomly redshifted

Modelling the Effect of Voids

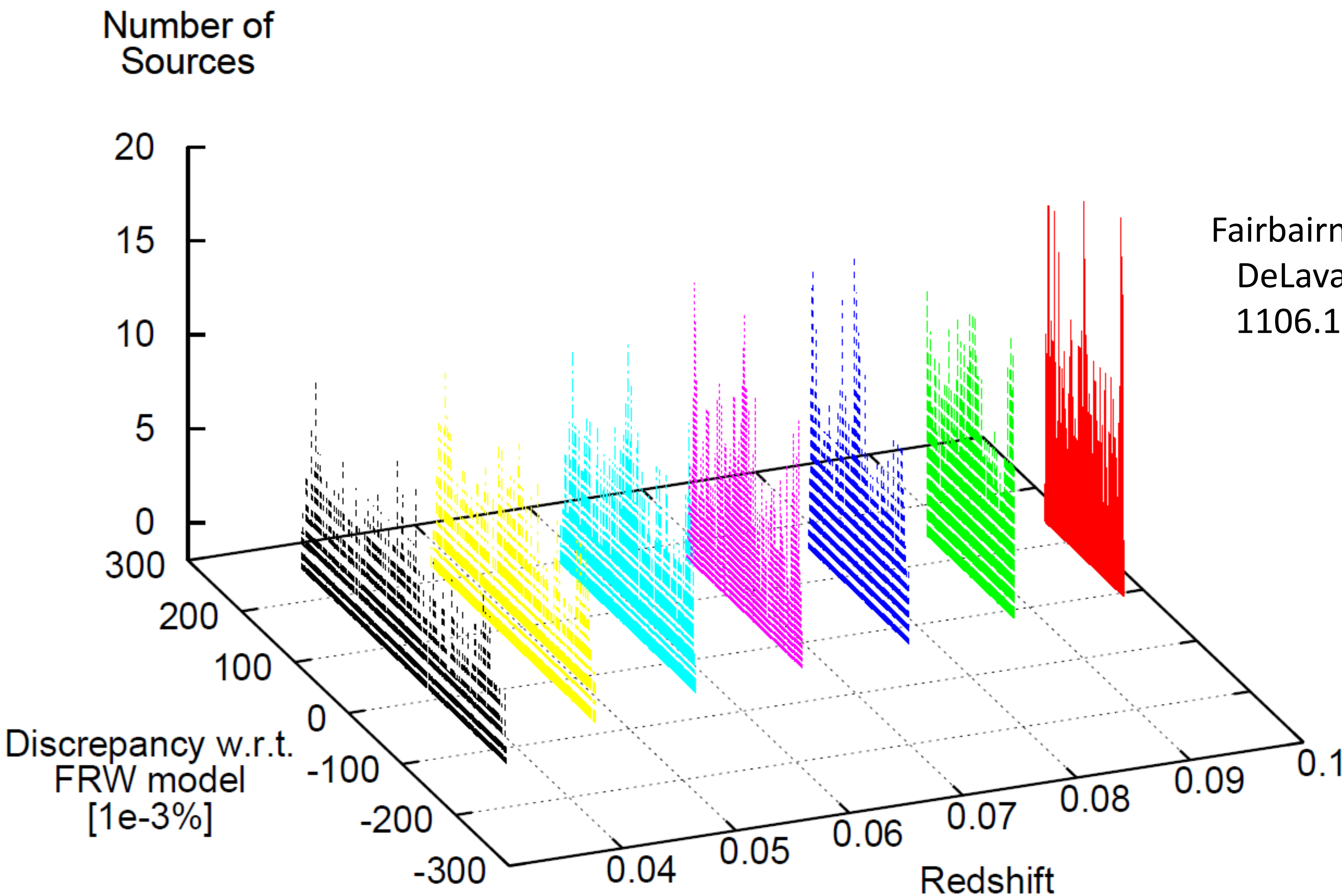
We chose a default void size to quantify the effects of the Voids



Density Profile Parameters	
r_1	4 Mpc
r_2	15 Mpc
A_1	9.97×10^{-1}
A_2	2.99×10^{-3}
A_3	1.70×10^{-4}
α	0.6
β	3.0

$$\rho(r, t_0) = \bar{\rho}(t_0) \times$$
$$\{A_1 + A_2 tanh\left[\alpha\left(r - r_1\right)\right] - A_3 tanh\left[\beta\left(r - r_2\right)\right]\}$$

Induced variance into luminosity distance due to voids.



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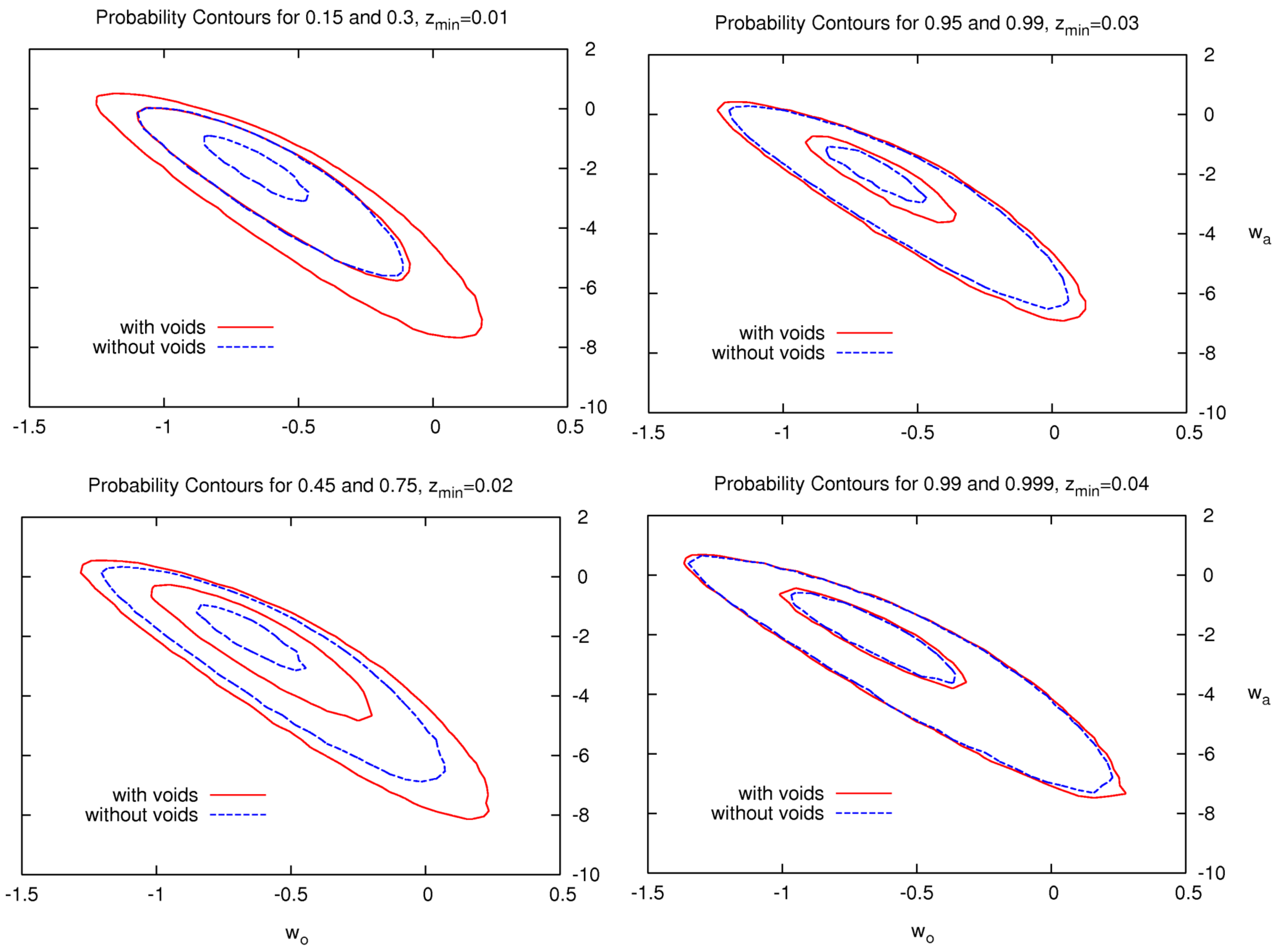
Constraints on the equation of State

Lets see how this additional error changes the conclusions we make about the history of the equation of state from the data.

We will use the more modern parametrisation

$$w = w_0 + w_a \frac{z}{1+z}$$



Probability Contours for 0.15 and 0.3, z_{min}=0.01
Probability Contours for 0.95 and 0.99, z_{min}=0.03
Probability Contours for 0.45 and 0.75, z_{min}=0.02
Probability Contours for 0.99 and 0.999, z_{min}=0.04
with voids
without voids
w_a
w_o
-1.5
-1
-0.5
0
0.5
2
0
-2
-4
-6
-8
-10

Concusions for that bit

Voids affect the way that supernovae appear but this is only significant at low redshifts

Non negligible effect because so much data at low redshift (100 sn1a out of about 550 at $z<0.04$)

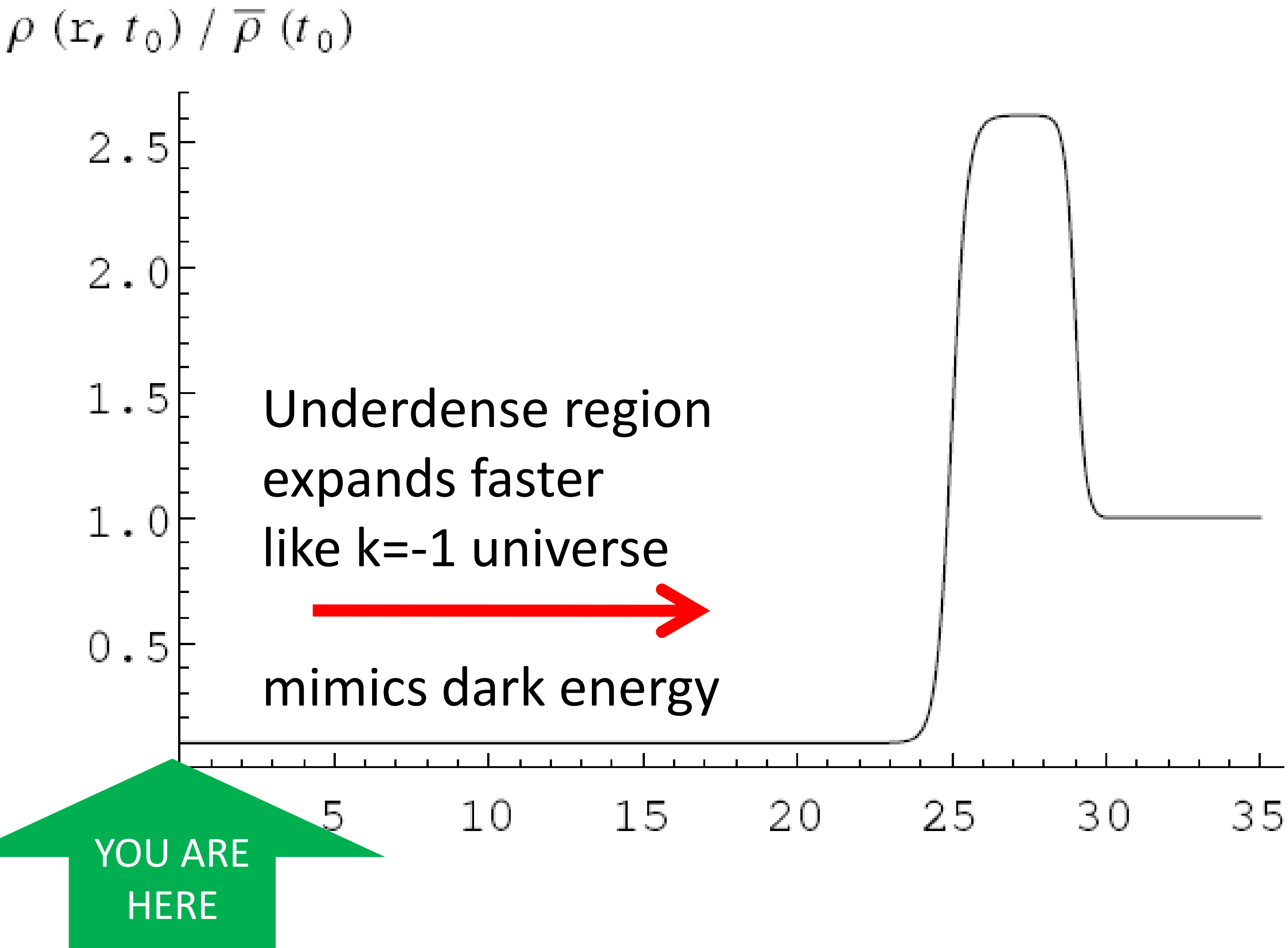
Acts as a powerful anchor on the data.

Still only a small effect on the constraint on the equation of state.

Can we use a really big void to explain the data without dark energy?

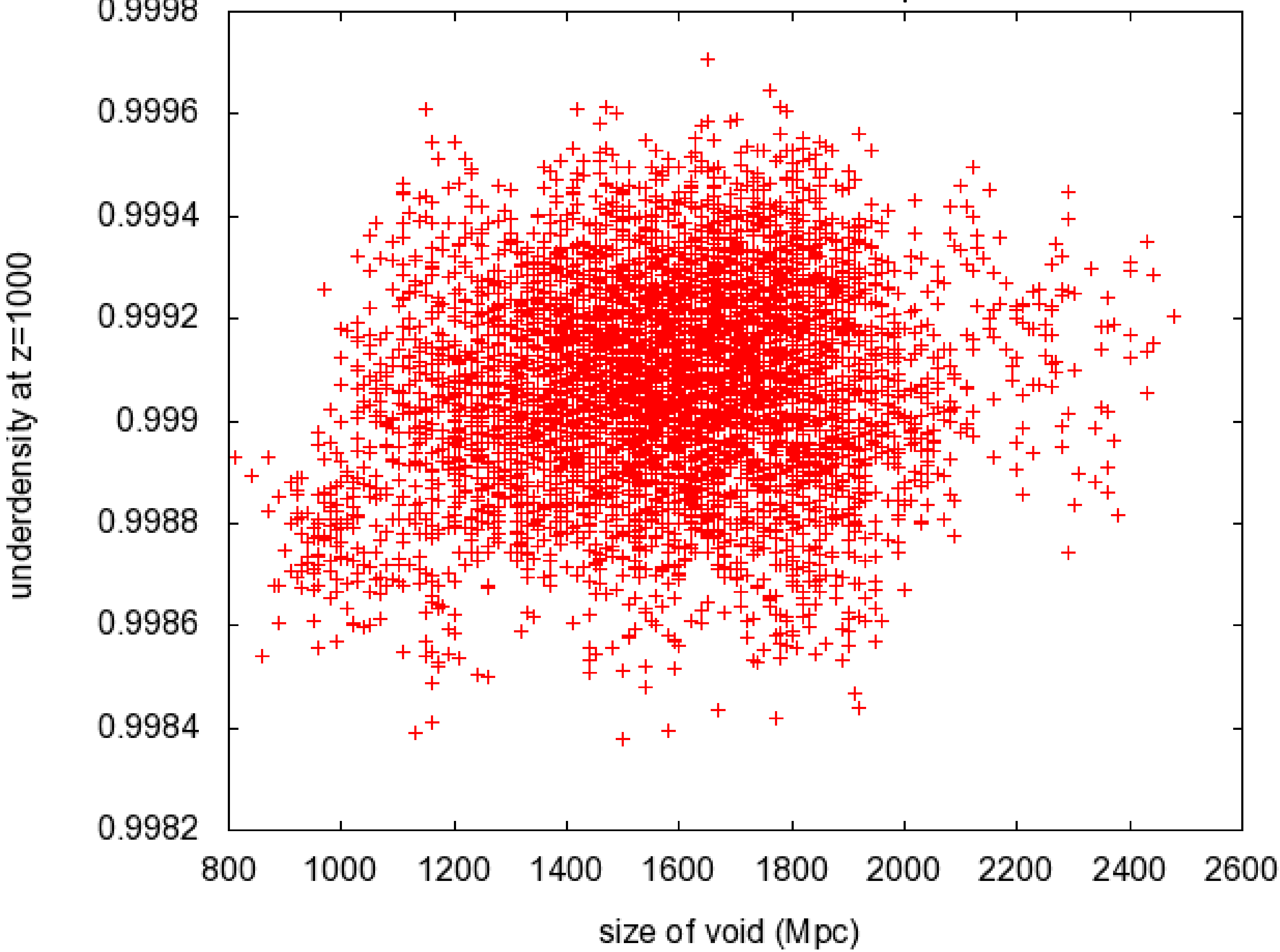
Void Models as Alternatives to Dark Energy

$$\frac{1}{2}\dot{R}^2 - \frac{GM(r)}{R(r,t)} - \frac{1}{3}\Lambda R^2 = E(r)$$

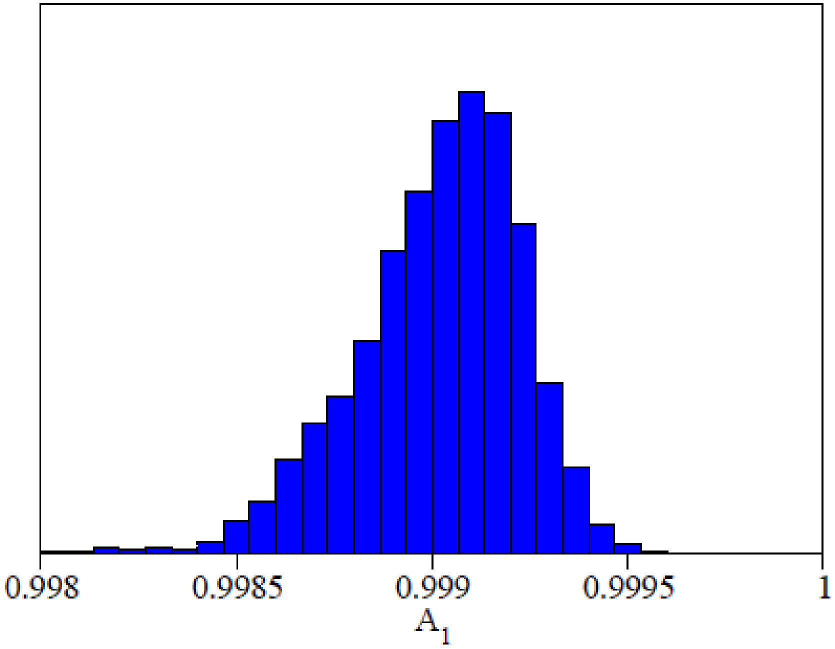


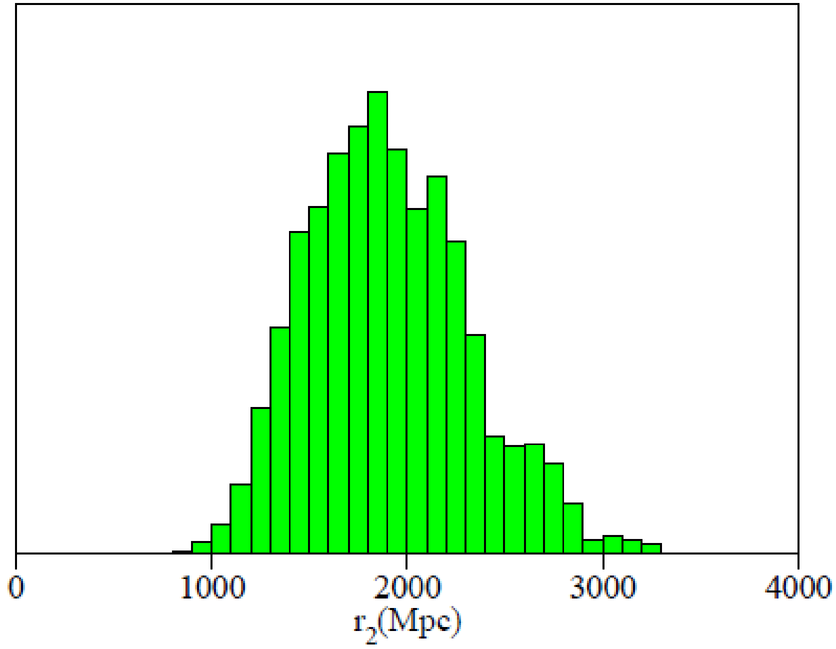
To explain expansion without dark energy we need bigger voids...

Results of numerical Code to fit supernova data

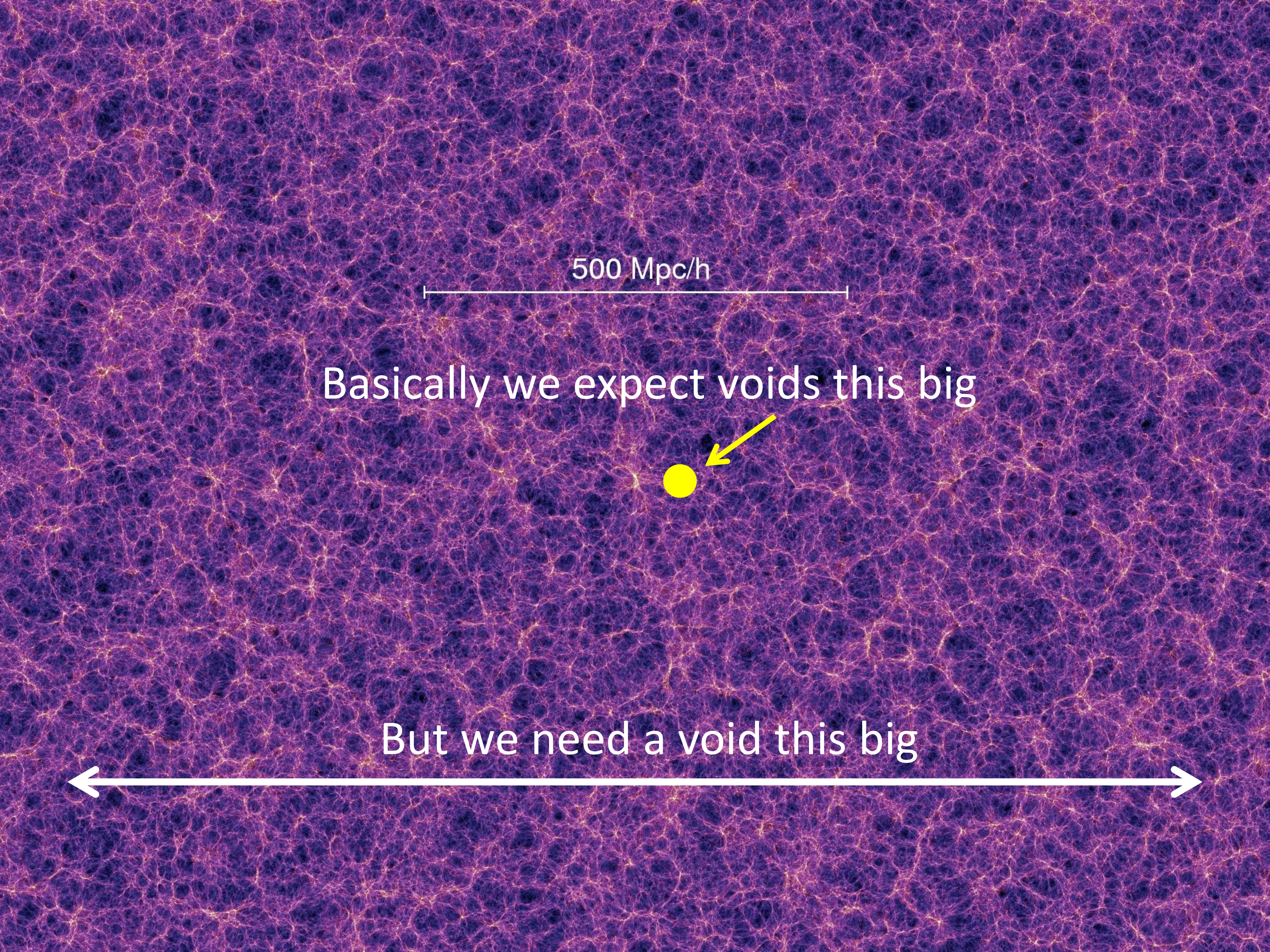


...really quite big voids indeed (although initial density contrast is not TOO bad)





$$\rho(r,t_0) = \bar{\rho}(t_0)\times$$
$$\{A_1 + A_2 tanh\left[\alpha\left(r - r_1\right)\right] - A_3 tanh\left[\beta\left(r - r_2\right)\right]\}$$

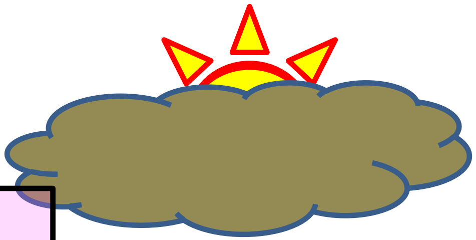

500 Mpc/h
Basically we expect voids this big
But we need a void this big

Pros and Cons of void models

Pros

- can explain supernovae without dark energy

Cons



- require complicated power spectra
- need to be near centre of void
- difficult to fit peaks in CMB
- usually still need local value of H to be low

PHILOSOPHICAL / OCCAM'S RAZOR TYPE ARGUMENTS -
NEED TO TRY HARDER TO KILL MODEL IN ORDER TO TEST IT

Testing void models with TeV Photons

A low level of extragalactic background light as revealed by γ-rays from blazars

Nature 440:1018 (2006)

Quasar 3C279

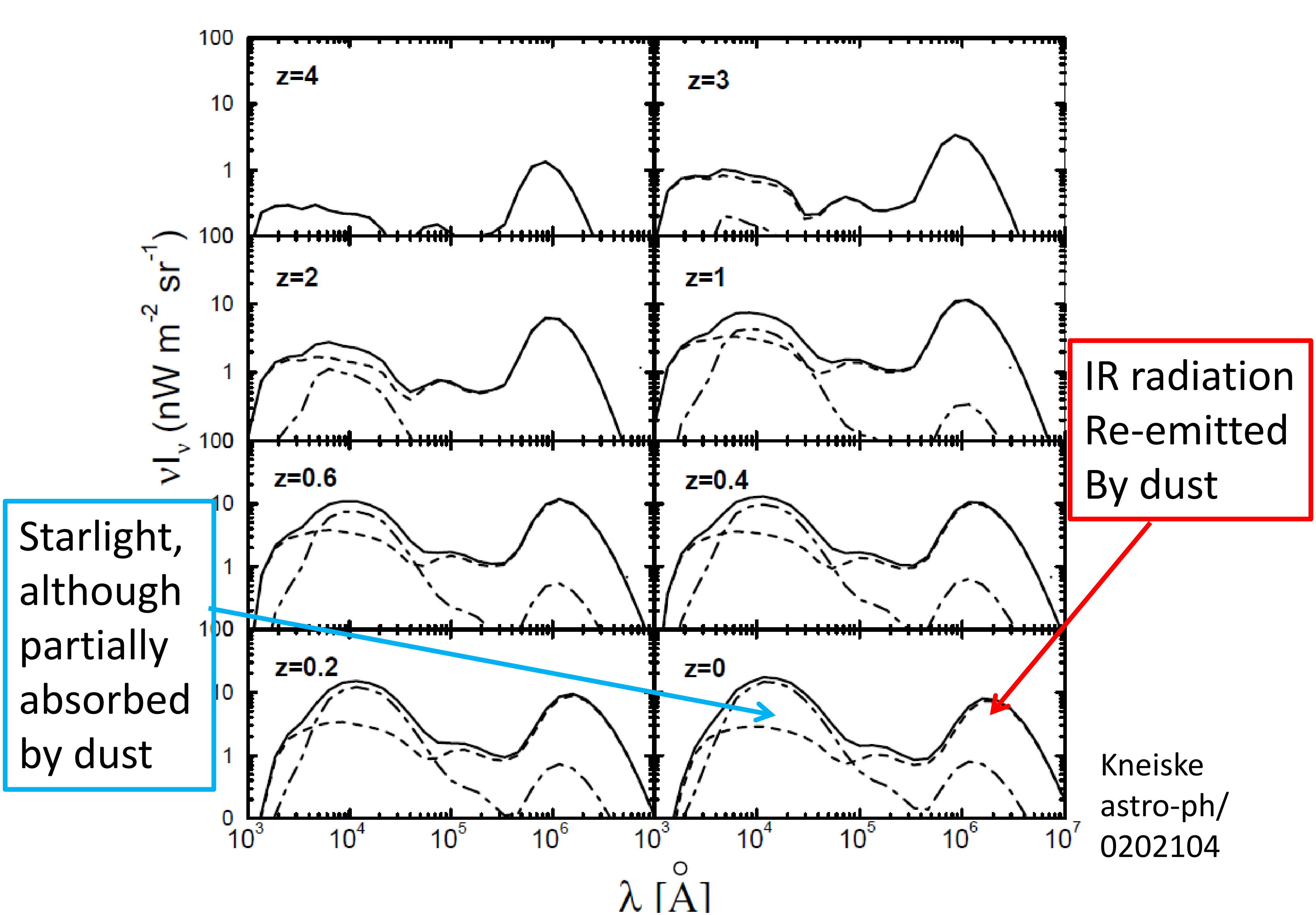
Z=0.536

Very-High-Energy Gamma Rays from a Distant Quasar: How Transparent Is the Universe?

The MAGIC Collaboration*

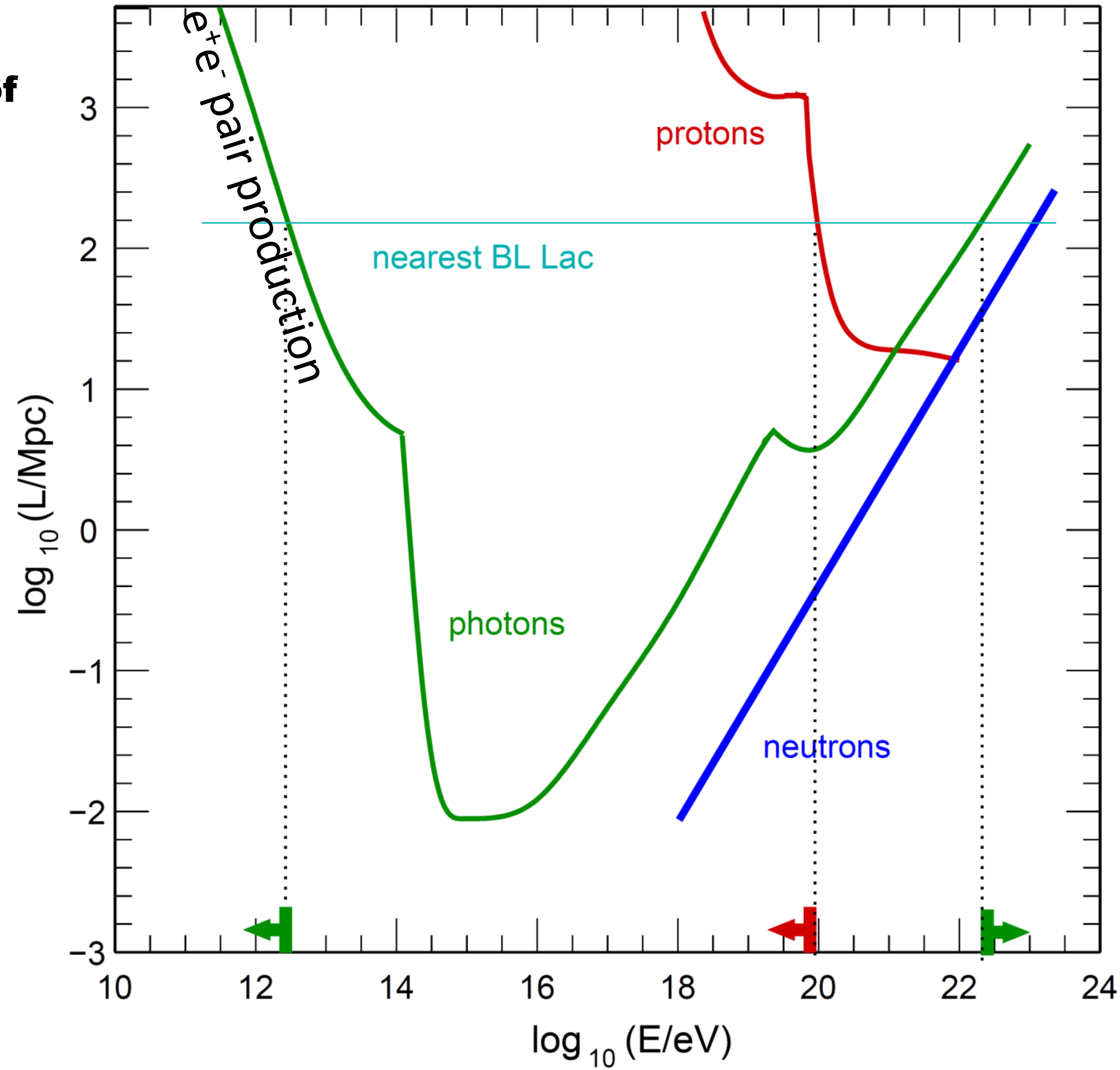
Science **320**, 1752 (2008); DOI: 10.1126/science.1157087

Extragalactic Background Light

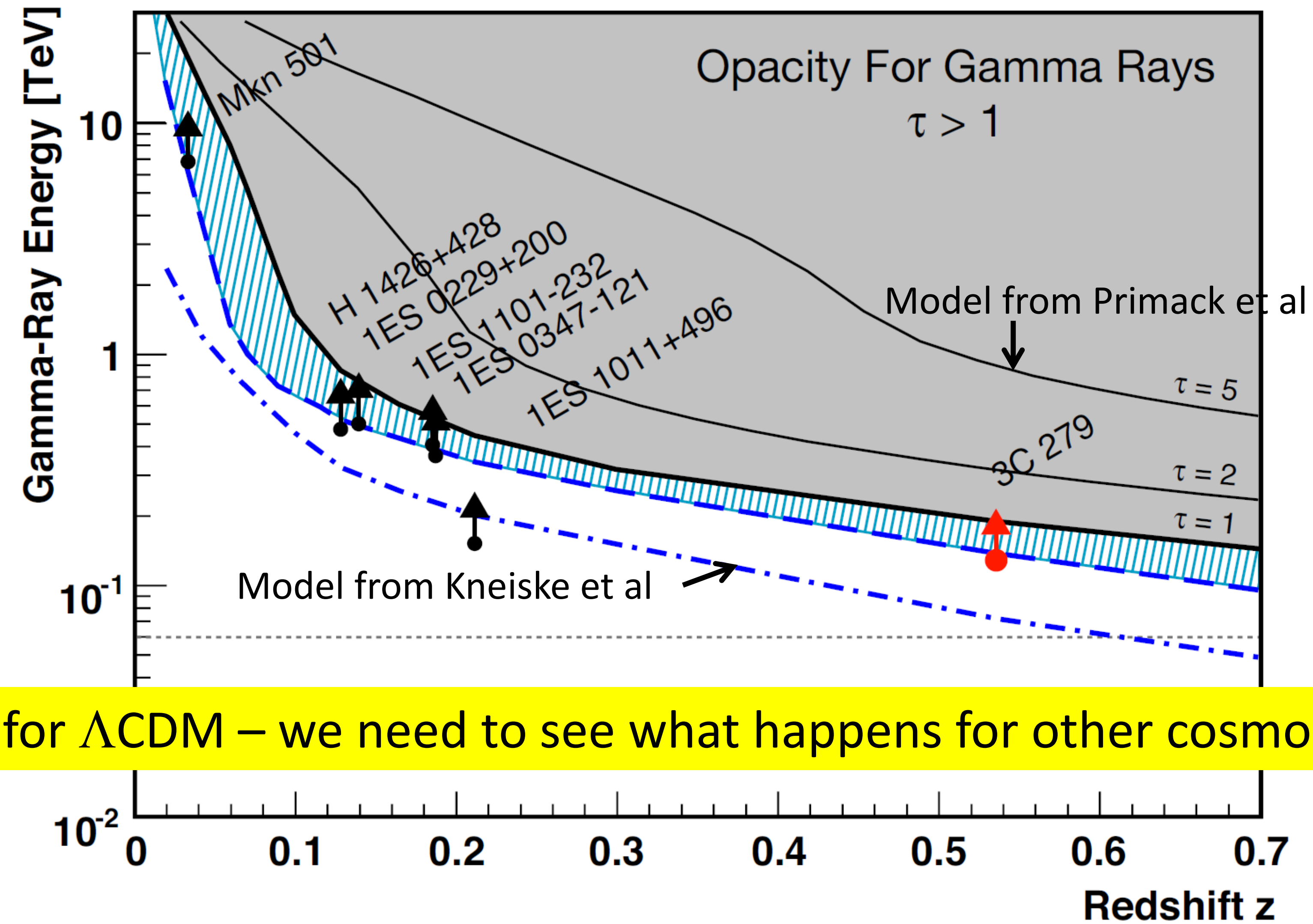


Kneiske astro-ph/ 0202104

Transparency of Universe at different wavelengths



Gamma Ray Horizon



This is for ΛCDM – we need to see what happens for other cosmologies

MAGIC COLLABORATION arXiv:0807.2822

Modelling the background light for different cosmologies

We followed quite closely the approach of Finke *et al.* arXiv:0905.1115

1. Treat stars as black bodies
2. Obtain approximate formulae for radius and temperature of star of mass M as a function of time (Eggleton, Fitchett and Tout provide us with this in the appendix of a paper on binaries from the end of the 1980s)
3. Assume an initial mass function, Salpeter will do for now, single power law.
4. Have stars being created at different rates throughout the history of the Universe.
5. Star light is partially absorbed, especially at high frequencies and re-emitted in the infra red and microwave
6. At any given redshift, light is due to combination of light being produced then, and light being produced at earlier times which is then redshifted.

Stellar Modelling

$$L_o = \begin{cases} \frac{1.107M^3+240.7M^9}{1+281.9M^4}, & \text{if } M < 1.0933 \\ \frac{13990M^5}{M^4+2151M^2+3908M+9536}, & \text{otherwise} \end{cases}$$

$M < 1.334$

$$\begin{aligned} R_o &= \frac{0.1148M^{1.25} + 0.8604M^{3.25}}{0.04651 + M^2} \\ \alpha &= 0.2594 + 0.1348\log_{10}(M) \\ \beta &= 0.144 - 0.833\log_{10}(M) \\ \alpha_d &= 0.0 \\ \beta_d &= 0.2226\log_{10}(M) \\ \gamma_d &= 0.1151 \end{aligned}$$

$M > 1.334$

$$\begin{aligned} R_o &= \frac{1.968M^{2.887} - 0.7388M^{1.679}}{1.821M^{2.337} - 1} \\ \alpha &= 0.09209 + 0.05934\log_{10}(M) \\ \beta &= 0.3756\log_{10}(M) - 0.1744\log_{10}(M)^2 \\ \alpha_d &= 0.1509 + 0.1709\log_{10}(M) \\ \beta_d &= -0.4805\log_{10}(M) \\ \gamma_d &= 0.5083\log_{10}(M) \end{aligned}$$

Stellar Modelling

$$t_{ms} = \frac{2550 + 669M^{2.5} + M^{4.5}}{0.0327M^{1.5} + 0.346M^{4.5}}$$

$$t < t_{ms}$$

$$\begin{aligned} L &= L_o 10^{\alpha\tau + \beta\tau^2} \\ R &= R_o 10^{\alpha_d\tau + \beta_d\tau^2 + \gamma_d\tau^3} \end{aligned}$$

Only continue if you leave the main sequence!

Stellar Modelling

High Mass stars are Wolf Rayet Stars...

$M > 25$ & $t < t_{ms} + t_{wr}$

$$\begin{aligned} L &= 10^5 \\ R &= 5 \end{aligned}$$

... or supernovae

$M > 25$ & $t > t_{ms} + t_{wr}$ $L = 0$

All other stars join giant branch after taking a time t_{hg} to cross the Herzprung Gap (hg) to the base of the giant branch (bgb)

$$t_{hg} = \frac{0.543 t_{ms}}{M^2 - 2.1M + 23}$$

$$\begin{aligned} L_{bgb} &= \frac{2.15M^2 + 0.22M^5}{1 + 0.014M^2 + 5 \times 10^{-6} M^4} \\ R_{bgb} &= (0.25 L_{bgb}^{0.4} + 0.8 L_{bgb}^{0.67}) M^{-0.27} \end{aligned}$$

$t_{ms} < t < t_{ms} + t_{hg}$

$$L = L_{t_m s} \left(\frac{L_{bgb}}{L_{tms}} \right)^{\frac{t - t_{ms}}{t_{hg}}}$$

$$R = R_{t_m s} \left(\frac{R_{bgb}}{R_{tms}} \right)^{\frac{t - t_{ms}}{t_{hg}}}$$

Stellar Modelling

$t_{ms} + t_{hg} < t$ Giant Branch phase lifetime equals 15% of t_{ms}. Then if Helium ignition doesn't start we have a white dwarf.

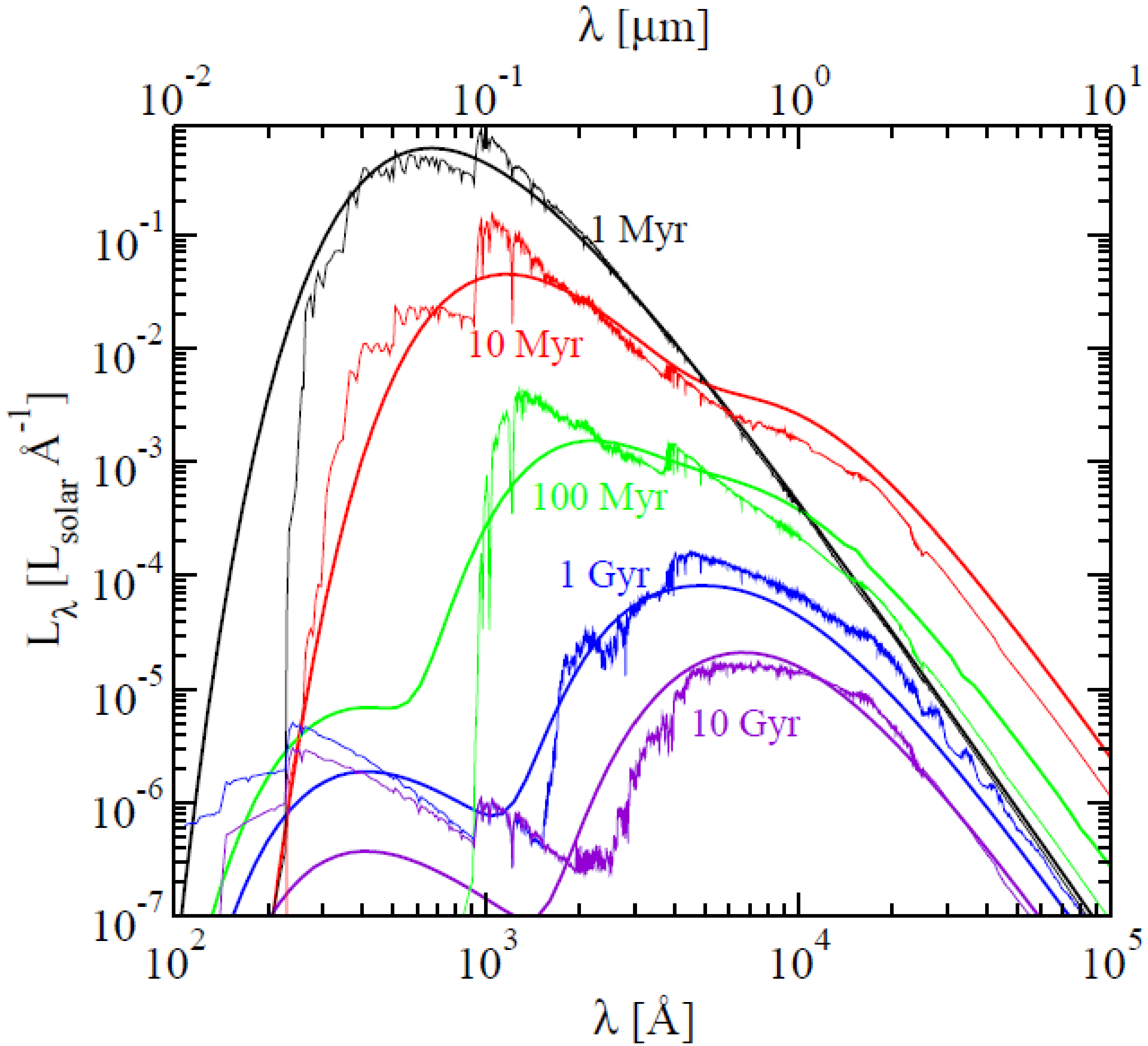
$$
\begin{aligned}
L_{gbmax} &= 4000M + 500M^2 \\
\tau &= \frac{1.15t_{ms} + t_{hg} - t}{0.15t_{ms}} \\
L &= \min\left(\frac{L_{bgb}}{\tau^{7/6}}, L_{gbmax}\right) \\
R &= (0.25L^{0.4} + 0.8L^{0.67})M^{-0.27d0}
\end{aligned}
$$

If we reach $L_{HeIG} = L_{bgb} + 2000$ before $1.15t_{ms} + t_{hg}$ then we have helium ignition.

Stellar Modelling: Helium Burning

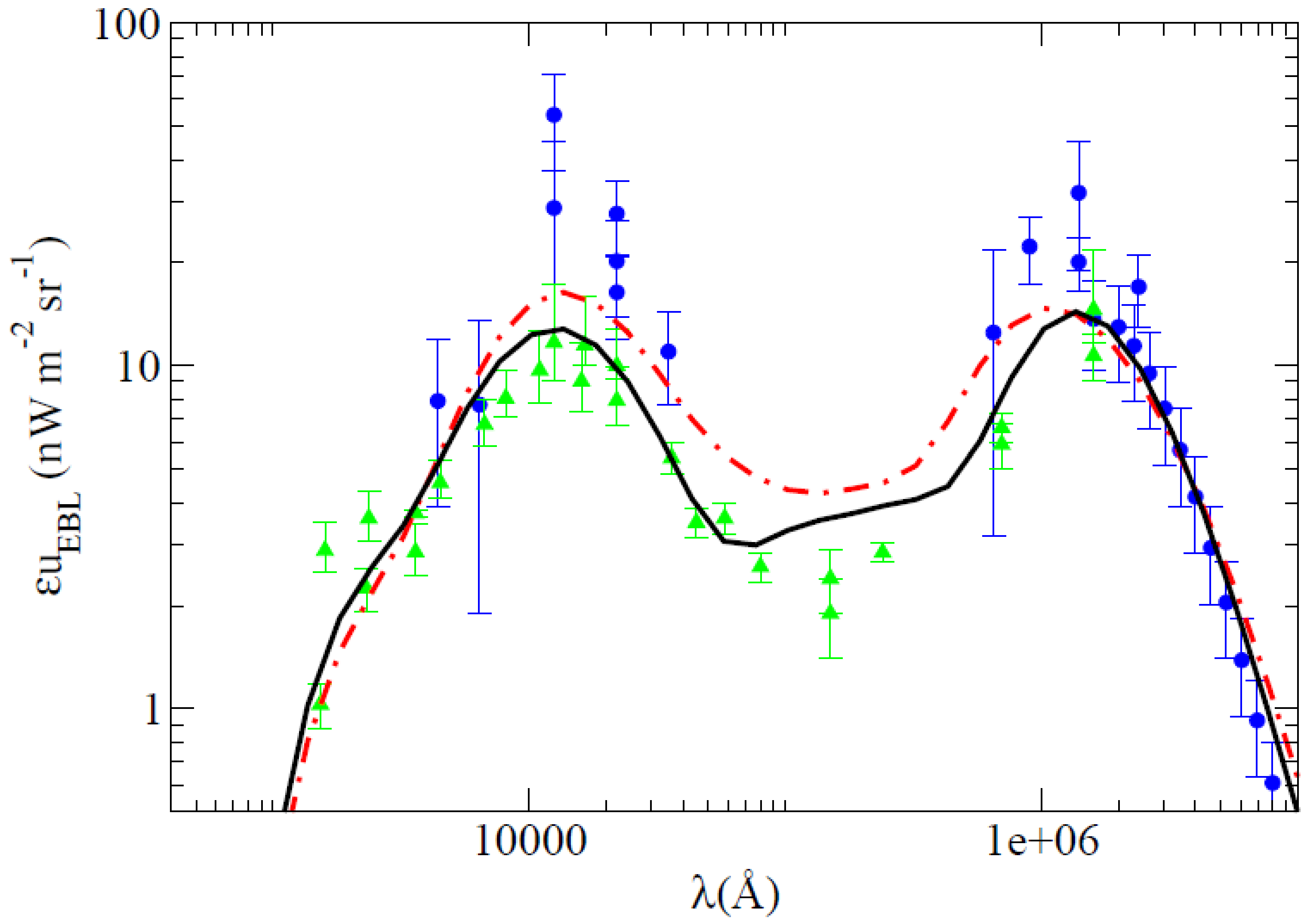
$$
\begin{aligned}
L &= 0.763 L_o M^{0.46} + 500 M^{-0.1d0} \\
t_{he} &= \frac{t_{ms} L_o}{L(M^{0.42} + 0.8)} \\
r_{ht} &= (0.25 L^{0.4} + 0.8 L^{0.67}) M^{-0.27d0} \\
\tau &= \frac{t - t_{HeIG}}{t_{He}} \\
r &= \min\left(25, r_{ht} \left\{ \frac{25}{r_{ht}} \right\}^{\tau} \right)
\end{aligned}
$$

Spectrum of stellar population created all at once
Data vs. observations



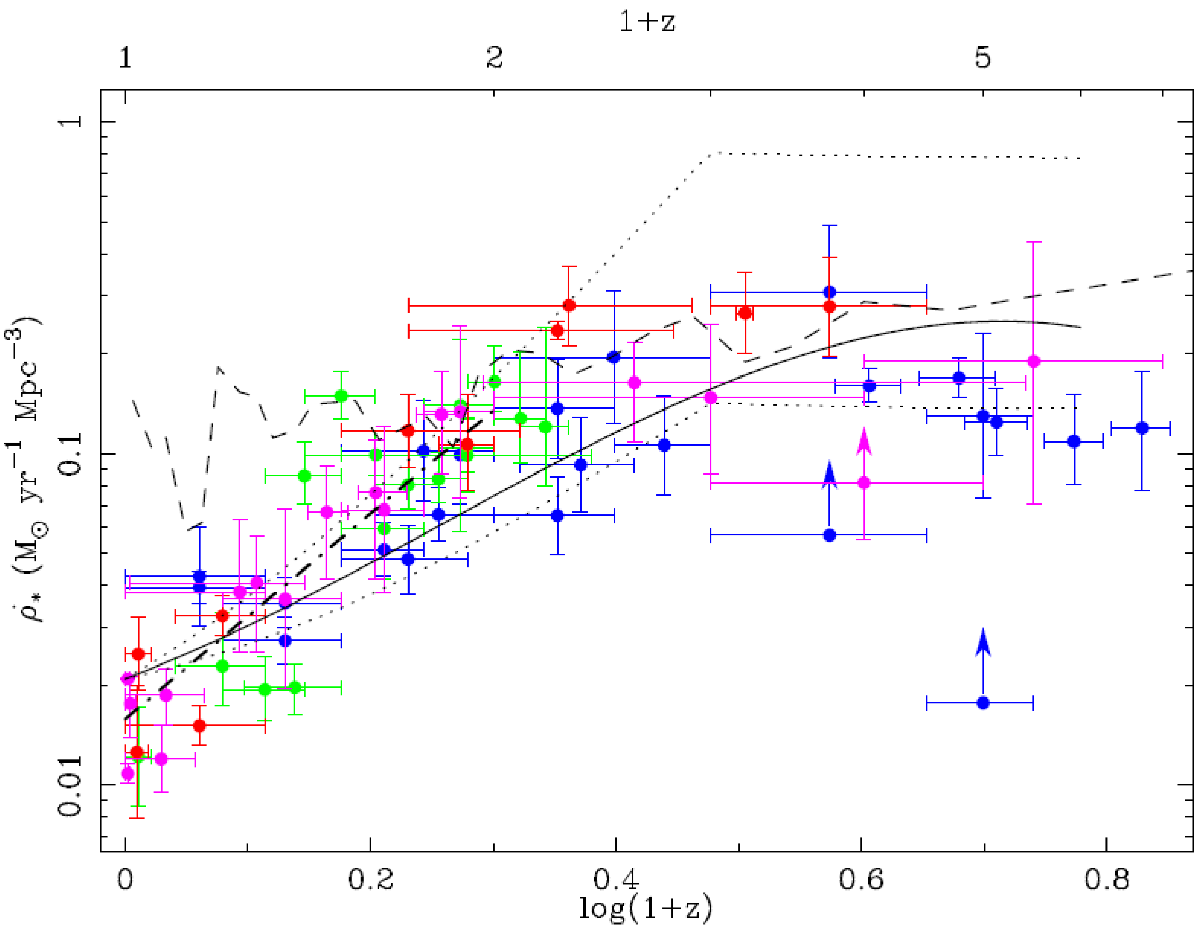
Plot from Finke *et al.* arXiv:0905.1115 . Ours is more or less the same.

Spectrum produced by our code



Data is from various sources, blue data is observed spectrum, green data is lower limits. Here we haven't fit this spectrum on the left, we just used the star formation rate data.

Star Formation Rate



Hopkins astro-ph/0407170

Can be fit with the expression

$$\dot{\rho}_* = \frac{a + bz}{1 + (z/c)^d}$$

$$\dot{\rho}_* \propto \frac{L(z)}{V_c(z, \Delta z)} \propto \frac{D_c^2(z)}{D_c^3(z + \Delta z) - D_c^3(z - \Delta z)}$$

Need to renormalise if you change underlying cosmology.

Our exact procedure

Evolve stellar population over time and put reddened spectrum into grid.
Put integral of luminosity lost to reddening at each time into a vector.

Pick a cosmology
Get z vs t

Rescale the SFR data for this cosmology

Fit the rescaled SFR data

Assign redshifts to each time bin in the stellar grid

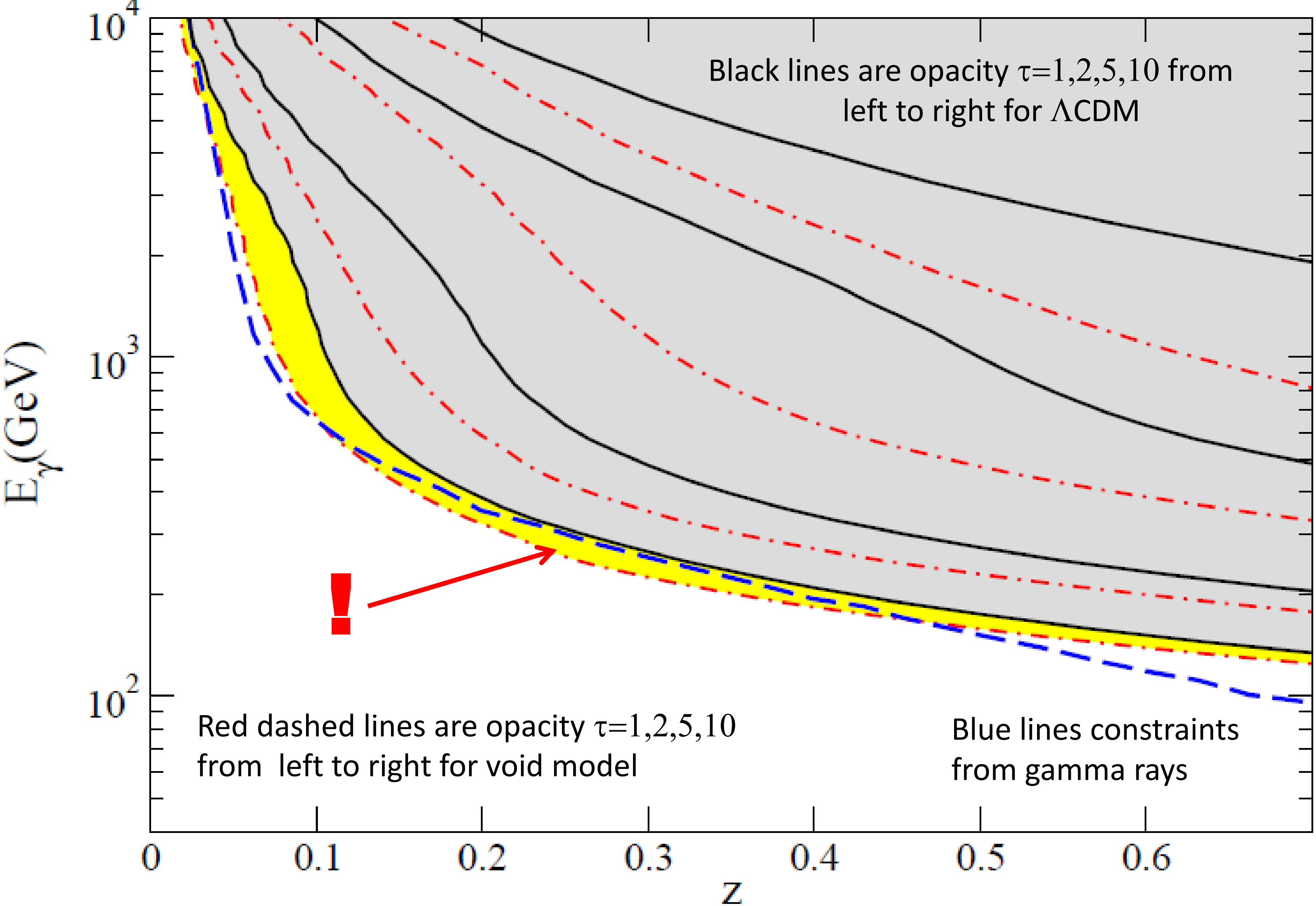
Integrate grid (redshift affects L and ν)

Send photon through the whole thing

See if it arrives at z=0, write paper

Results

arXiv:1111.4577



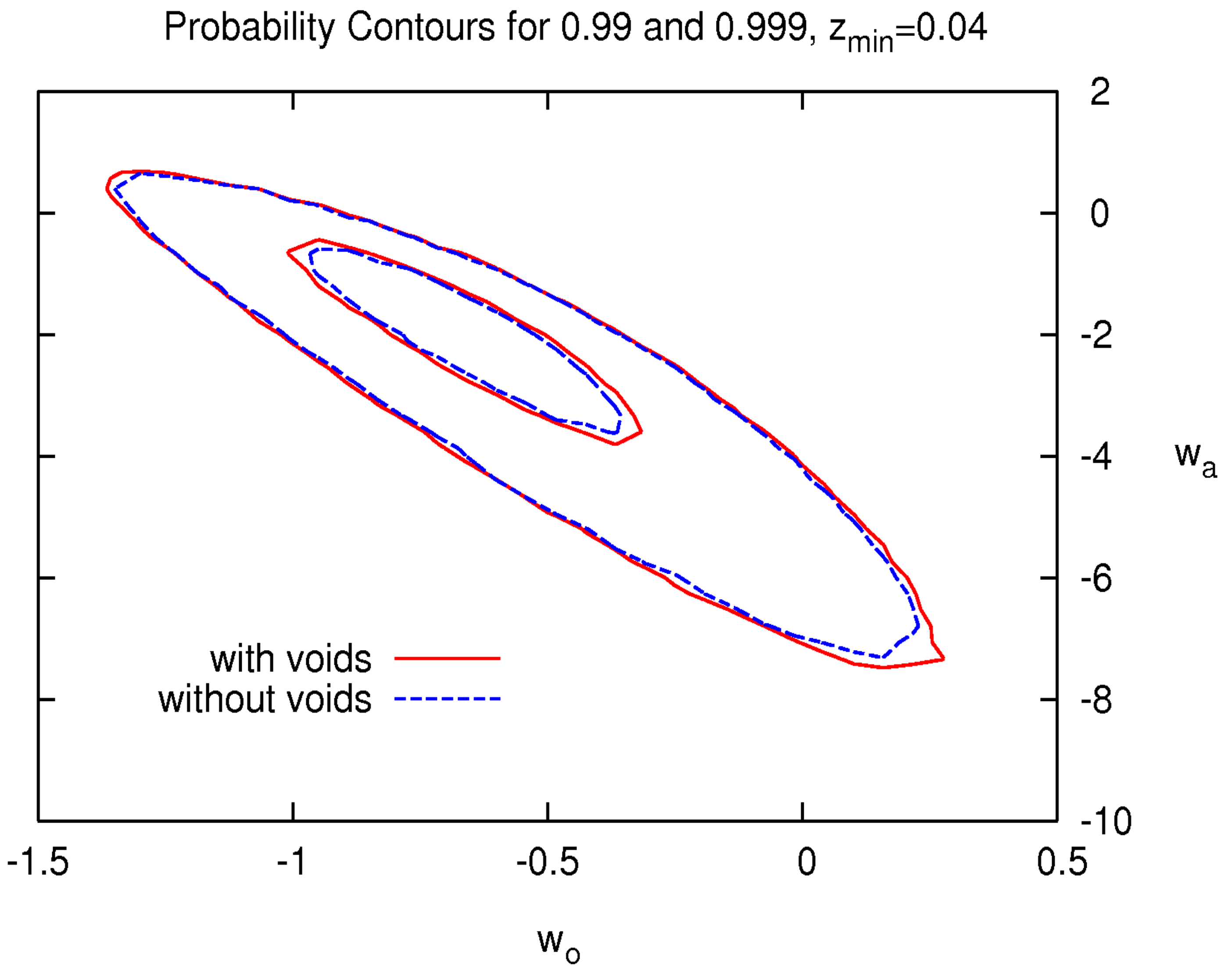
Can do the same thing for any cosmology, not just voids

Consider cosmologies with dark energy equation of states of

$$w = w_0 + w_a \frac{z}{1+z}$$

and see how the gamma ray opacity looks for them

Existing constraints on Dark Energy Equation of State.



What we need to do to investigate this further

- More data points! should get more in a matter of few weeks, to get great coverage maybe a month. Will see if I can speed up code.

- Errors! Many errors not yet taken into account. Need better grip on errors produced by gamma ray detectors. Also modelling errors, what is the error induced due to my assumptions, especially initial mass function and metallicity. Blue stage of high mass stars life very important for opacity. Also errors on fit to SFR data!

Axions

- Originally motivated as a solution to the strong CP problem
- Spin zero pseudo-scalar with induced coupling to the photon

$$\mathcal{L} = \frac{1}{2}(\partial^\mu a \partial_\mu a - m^2 a^2) - \frac{1}{4}\frac{a}{M} F_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Mixing in constant background

Mixing angle (strength)

$$\sin^2(2\theta) = \frac{4\Delta_M^2}{(\Delta_p - \Delta_m)^2 + 4\Delta_M^2}$$

When these terms dominate you have maximal mixing

Oscillation length

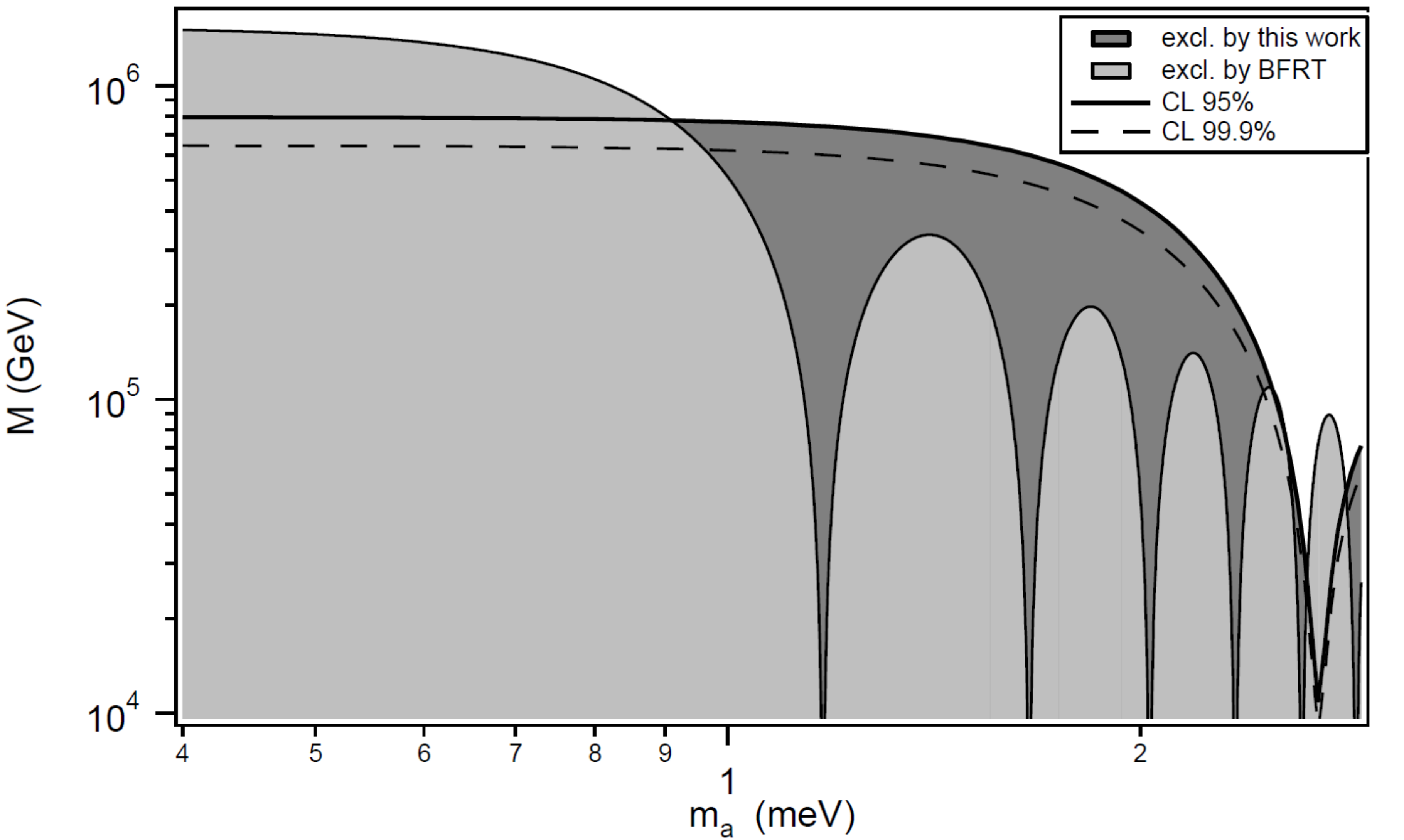
$$l_{osc} = \frac{2\pi}{\sqrt{(\Delta_p - \Delta_m)^2 + 4\Delta_M^2}}$$

$$\Delta_m = -\frac{m_a^2}{2\omega}$$

$$\Delta_M = \frac{B}{2M}$$

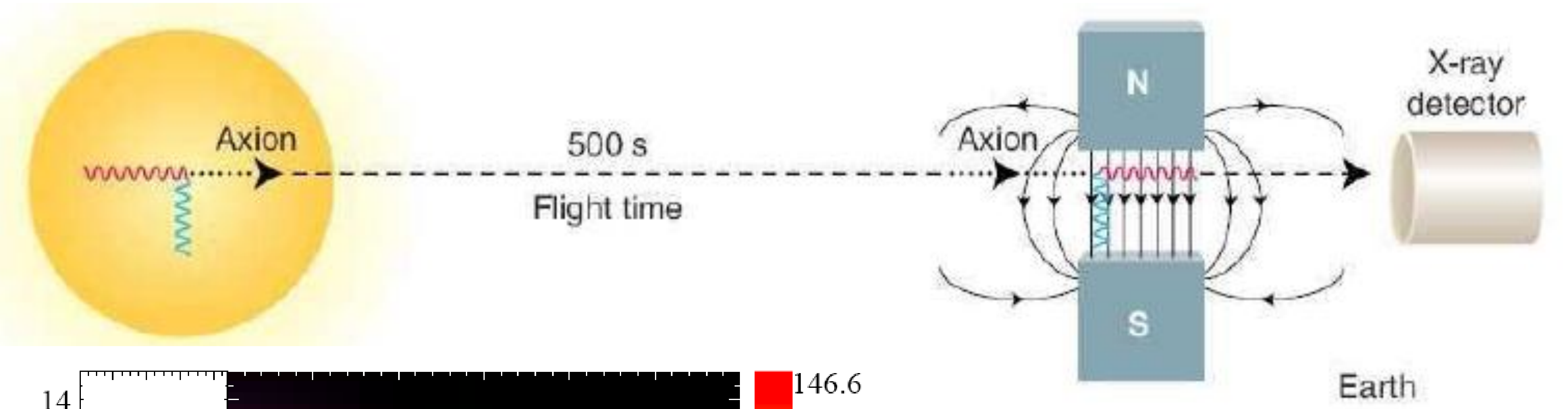
$$\Delta_p = -\frac{\omega_p^2}{2\omega}$$

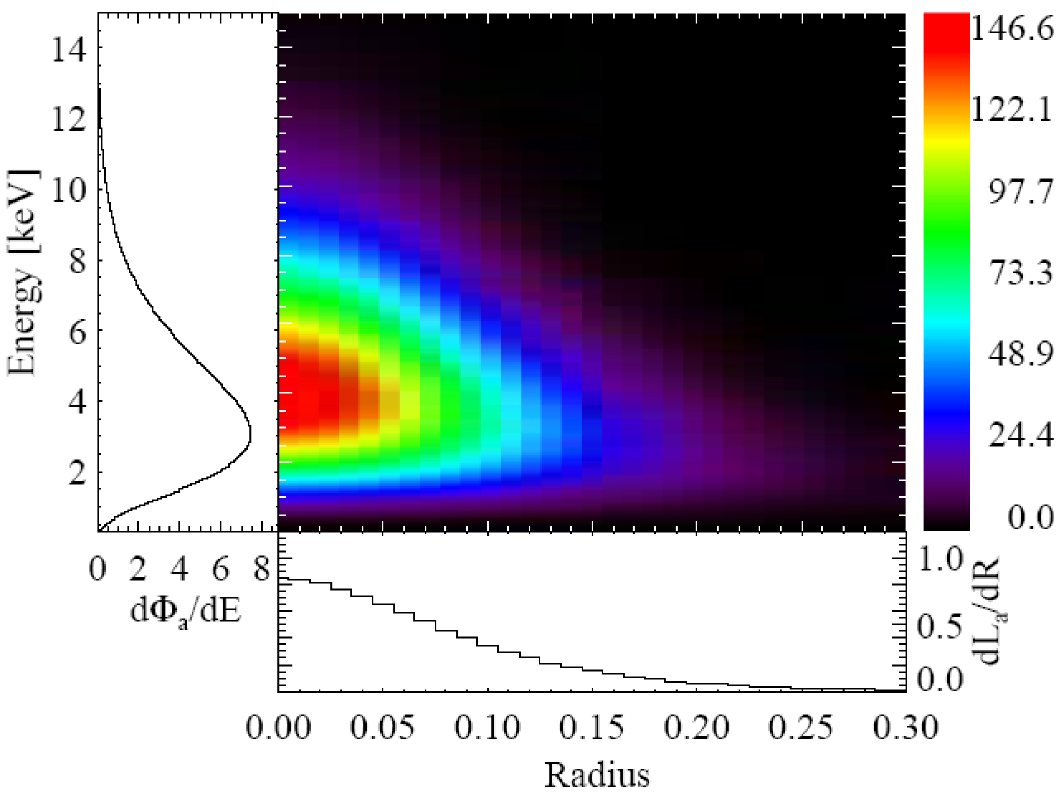
Shining light through walls



Robilliard et al, arXiv: 0707.1296

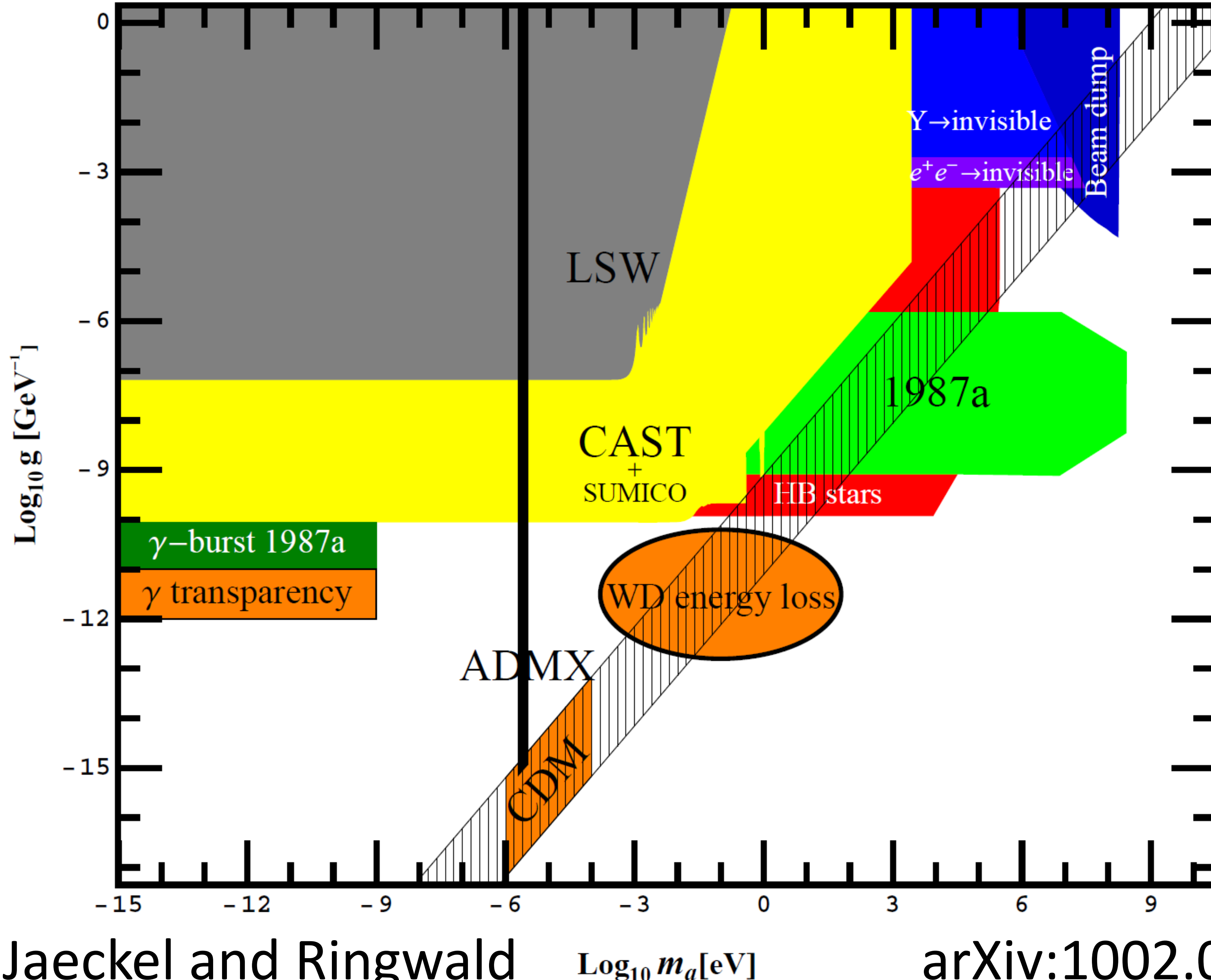
Search for Solar axions





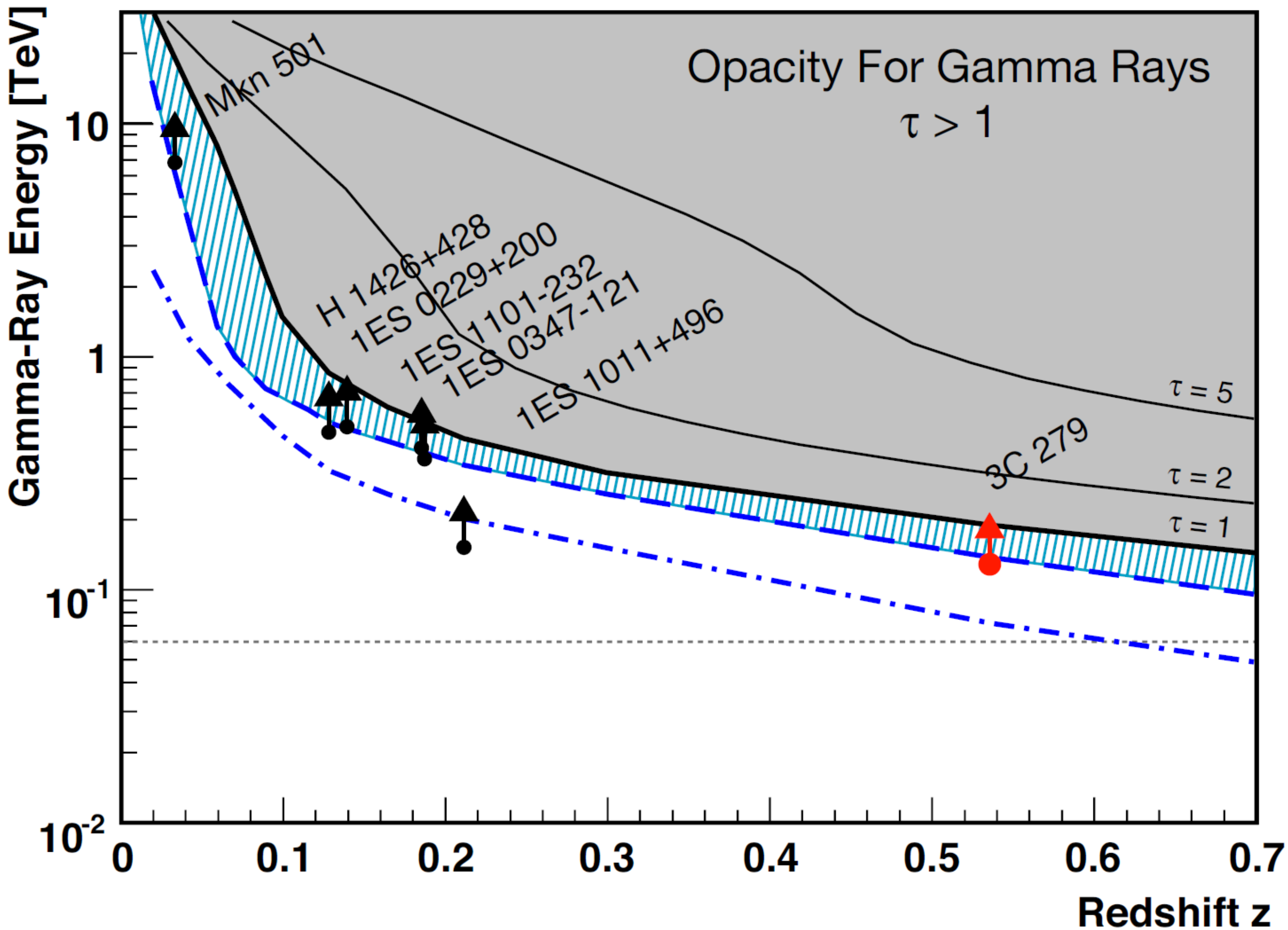
look for axions produced in the sun and turn them back into photons down here

CAST cern-axion-solar-telescope



Jaeckel and Ringwald arXiv:1002.0329

Gamma Ray Horizon

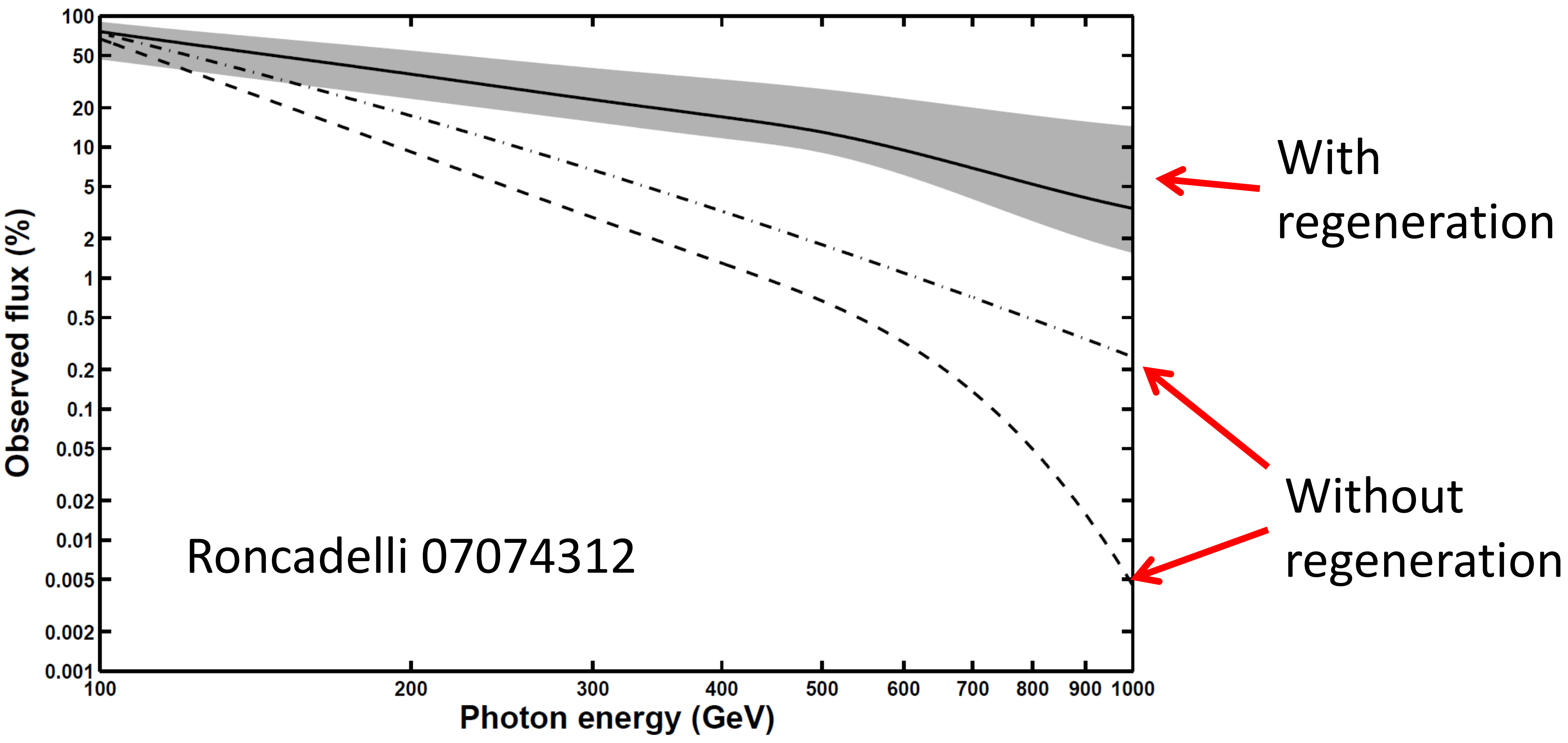


MAGIC COLLABORATION arXiv:0807.2822

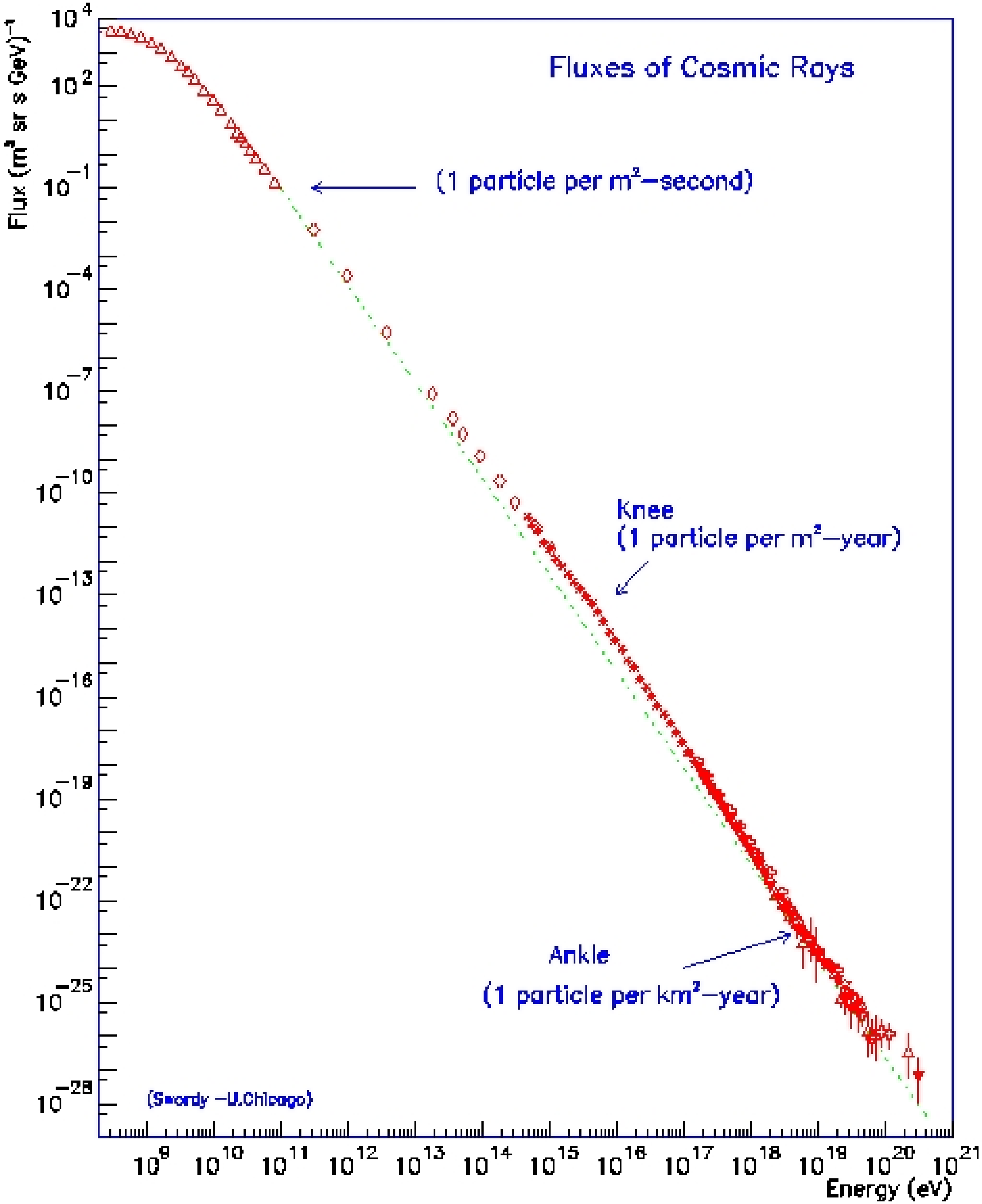
There isn't a problem with observed TeV photons, but if there was, there is a possible ALP explanation :

$$P^{(0)}_{\gamma\to\gamma}(y) \simeq \frac{1}{2}\, e^{-y/\lambda_\gamma} \left[1 + \cos^2\left(\frac{\delta y}{2\lambda_\gamma}\right)\right] \qquad P^{(0)}_{\gamma\to a}(y) \simeq \frac{1}{2}\, e^{-y/(2\lambda_\gamma)} \sin^2\left(\frac{\delta y}{2\lambda_\gamma}\right)$$

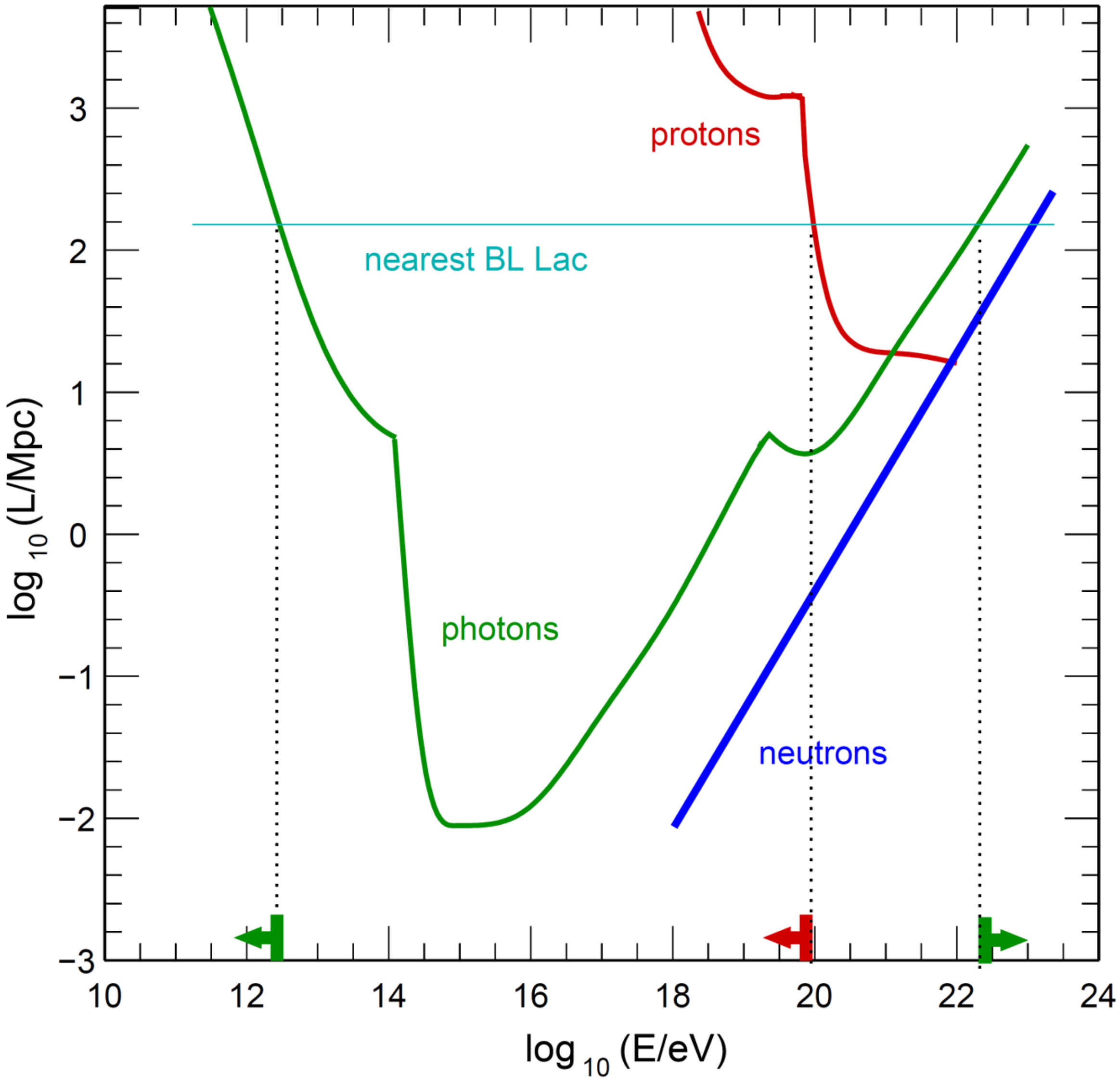
$$\delta \equiv \frac{B\,\lambda_\gamma}{M} \simeq 0.11 \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{M}\right)\left(\frac{\lambda_\gamma}{\mathrm{Mpc}}\right)$$



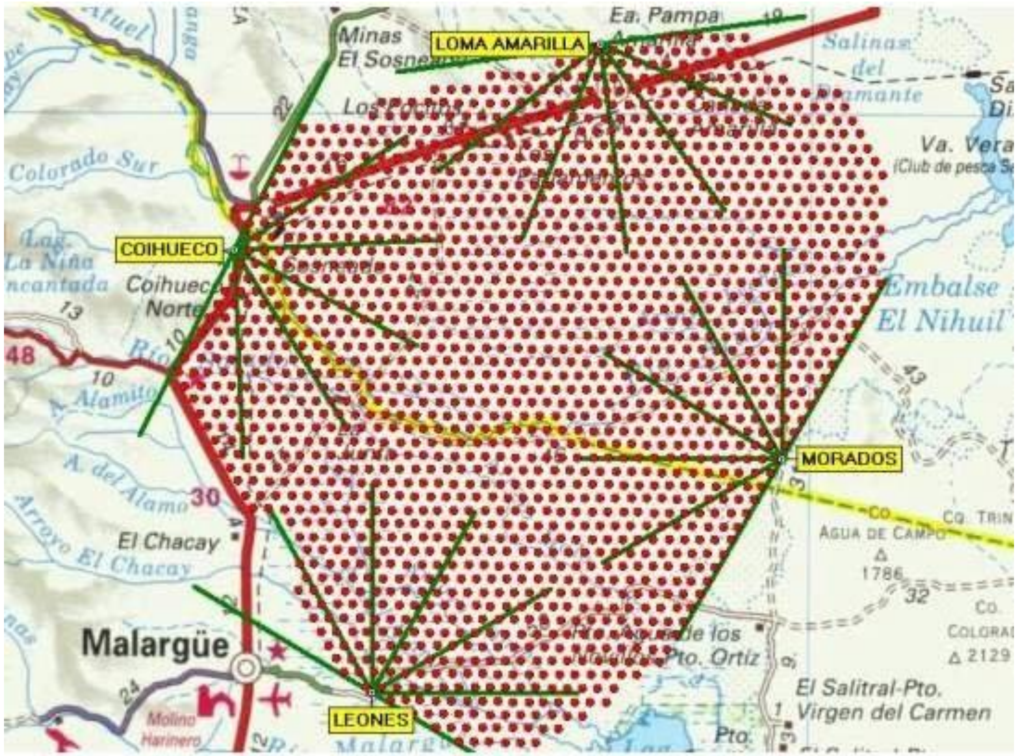
Cosmic rays exist with much higher energies



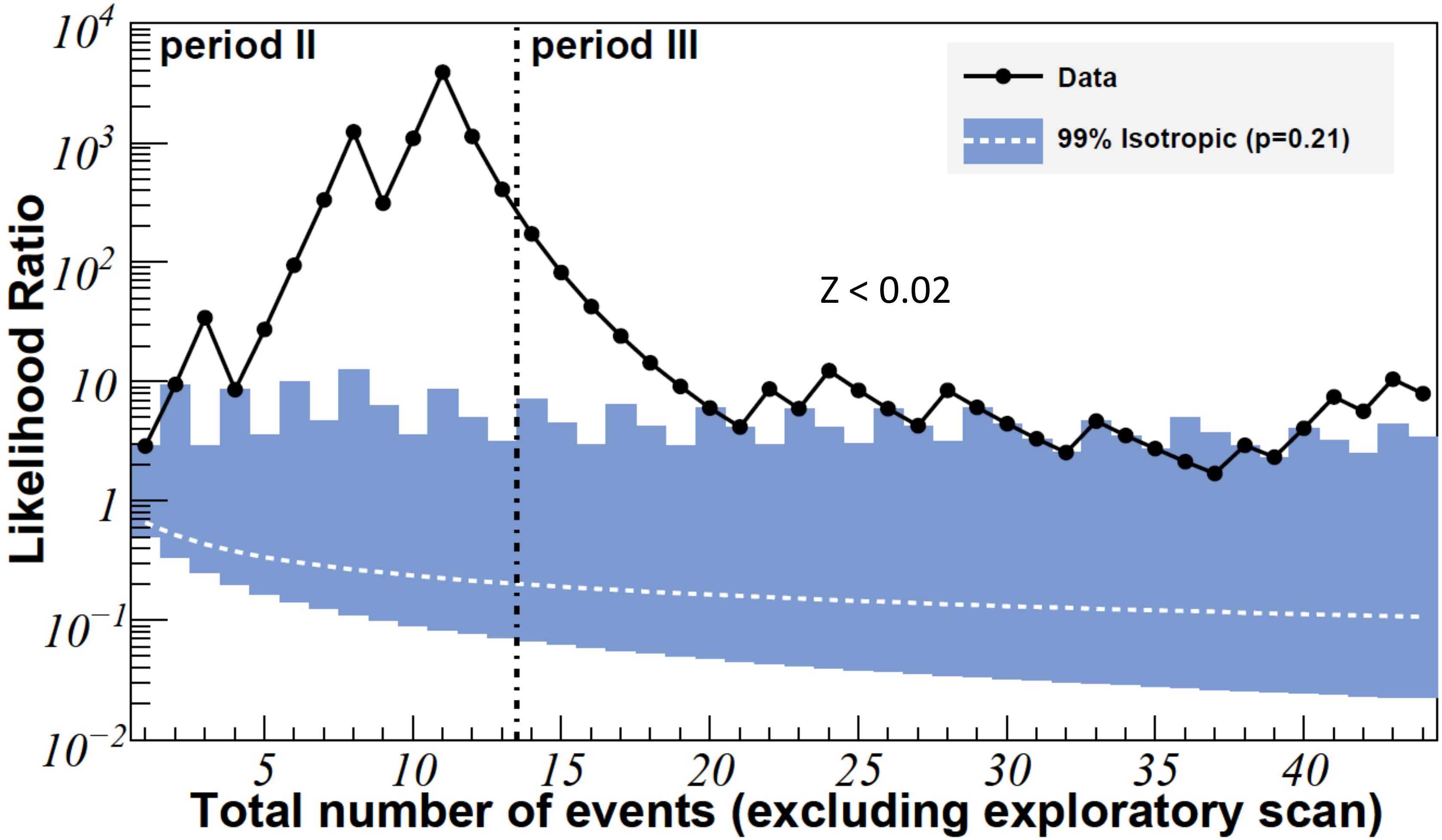
High energy protons must come from nearby



Pierre Auger Observatory, Argentina

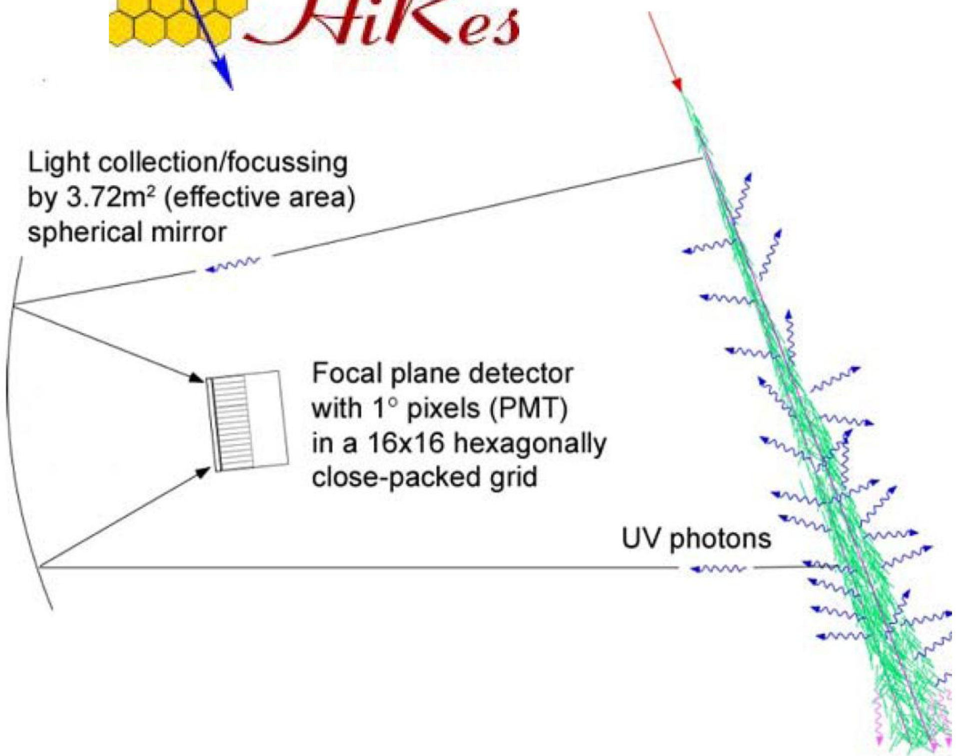


PA arrival coincidences with close objects



$$\delta \simeq 2.7^\circ \frac{60\ \mathrm{EeV}}{E/Z} \left| \int_0^D \left(\frac{d\mathbf{x}}{\mathrm{kpc}} \times \frac{\mathbf{B}}{3\ \mu\mathrm{G}} \right) \right|$$

Hague 0906.2347



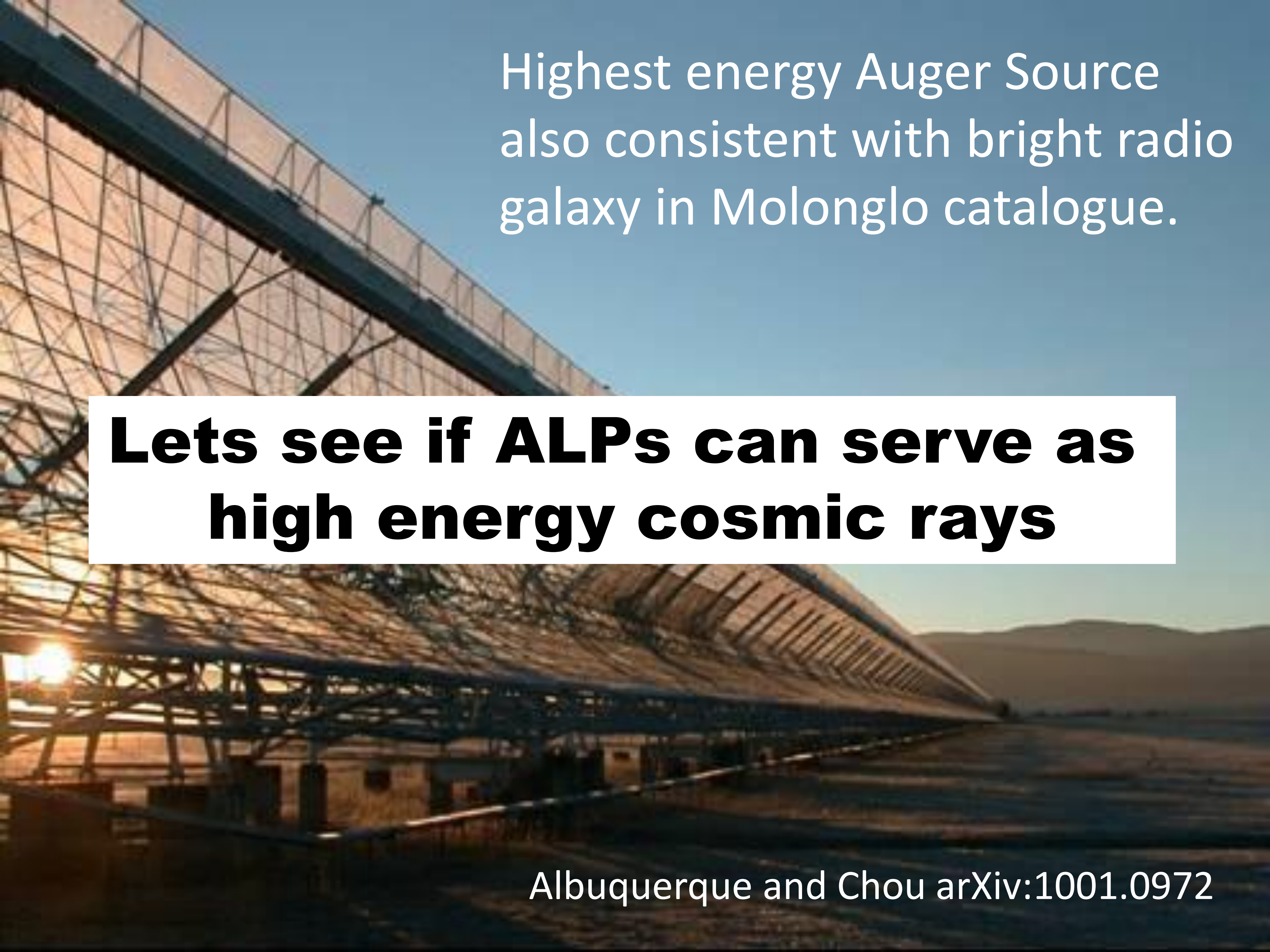
HiRes — BL Lac Correlation Results: Fraction $\mathcal{F}$ of simulated HiRes sets with stronger correlation signal.

Source Sample (# Obj.)	All Energies	$E > 10$ EeV
"BL" (157)	2×10^{-4}	2×10^{-4}
"HP" (47)	0.3	6×10^{-3}
"BL"+"HP" (204)	5×10^{-4}	10^{-5}

Note. — Correlations are with confirmed BL Lacs in Table 2 of the Veron 10th Catalog (Veron-Cetty & Veron 2001), classified as either "BL" or "HP," with $m < 18$.

astro-ph/0507120

Possible correlation with much more distant objects



Highest energy Auger Source also consistent with bright radio galaxy in Molonglo catalogue.

Lets see if ALPs can serve as high energy cosmic rays

Albuquerque and Chou arXiv:1001.0972

Old idea…

Super-GZK Photons from Photon-Axion Mixing

Csaba Csáki[a], Nemanja Kaloper[b], Marco Peloso[c] and John Terning[d]

hep-ph/0302030

Linearised wave equation

$$i\partial_z \Psi = -\left(\omega + \mathcal{M}\right)\Psi \qquad ; \qquad \Psi = \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix}$$

$$\mathcal{M} \equiv \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_M \\ 0 & \Delta_M & \Delta_m \end{pmatrix}$$

See, e.g. Raffelt and Stodolsky 1987

Mixing Matrix

$$\mathcal{M} \equiv \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_M \\ 0 & \Delta_M & \Delta_m \end{pmatrix}$$

$$\Delta_\perp = \frac{4}{2}\omega\xi \sin^2\Theta + \Delta_p$$

$$\Delta_\parallel = \frac{7}{2}\omega\xi \sin^2\Theta + \Delta_p$$

$$\xi = \frac{\alpha^2}{180\pi}\left(\frac{B}{m_e^2}\right)^2$$

$$\Delta_p = -\frac{\omega_p^2}{2\omega}$$

$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$

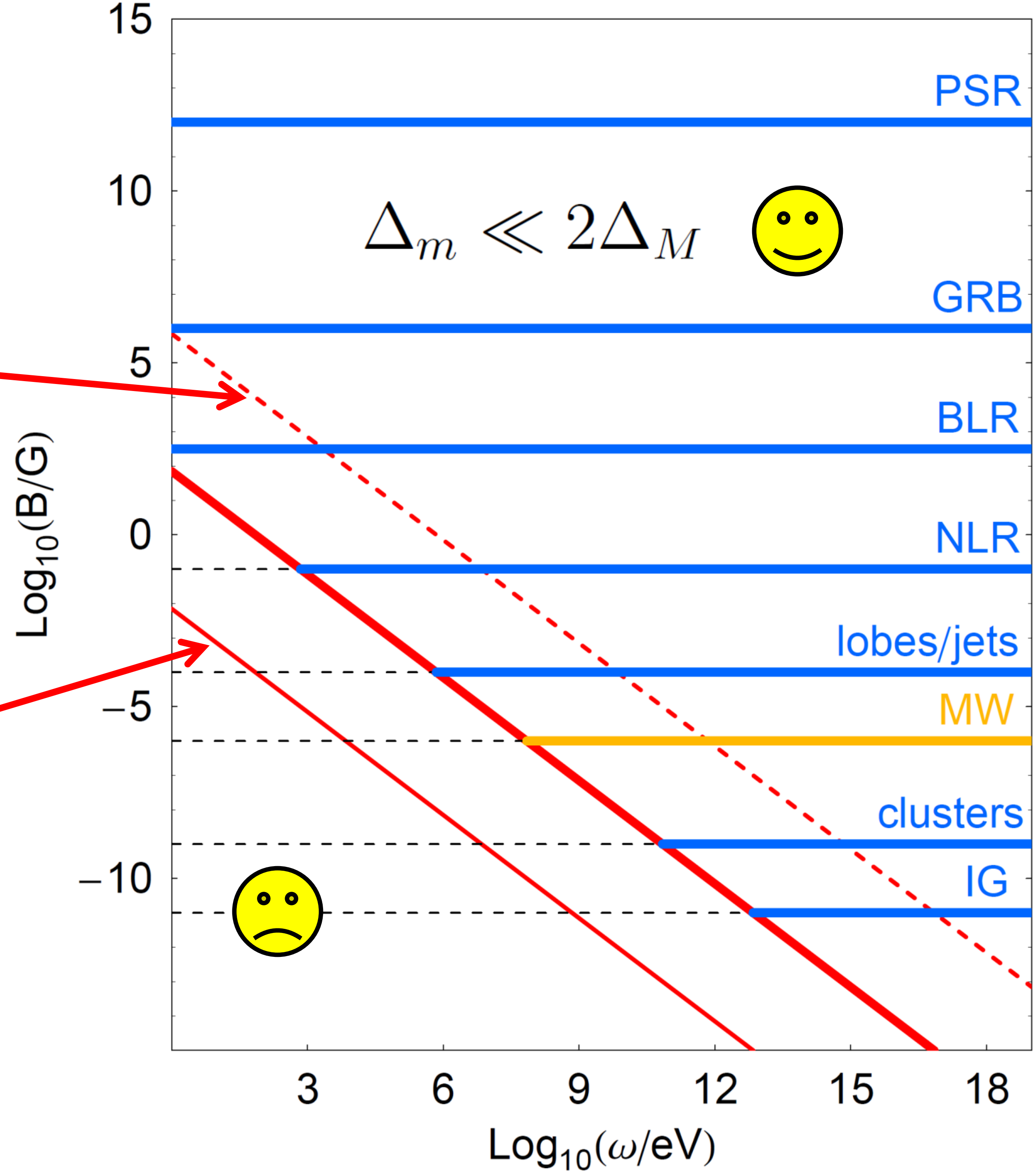
$$\Delta_m = -\frac{m_a^2}{2\omega}$$

$$\Delta_M = \frac{B}{2M}$$

Maximal Mixing 1

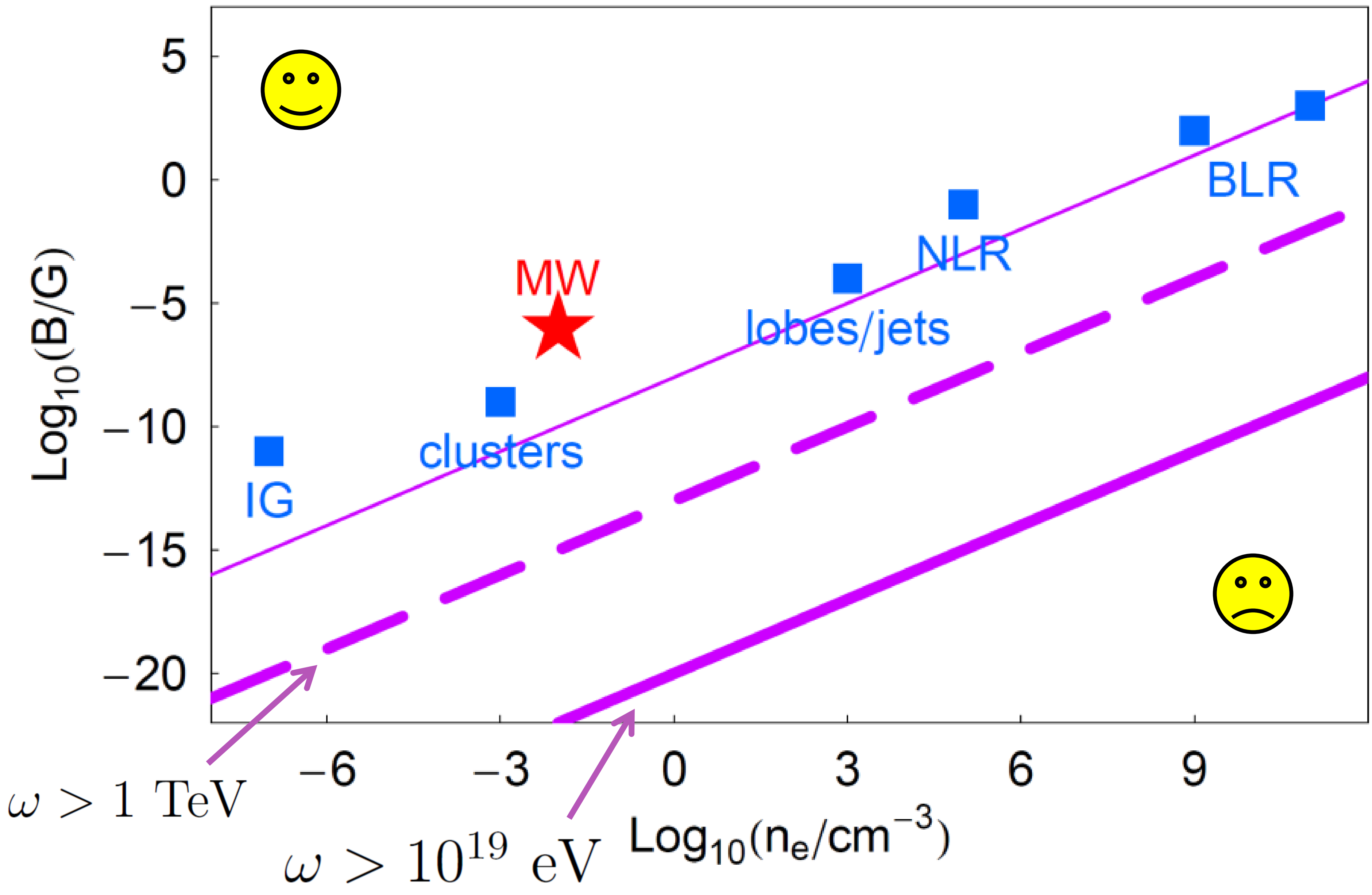
$m = 10^{-7}$ eV

$m = 10^{-11}$ eV

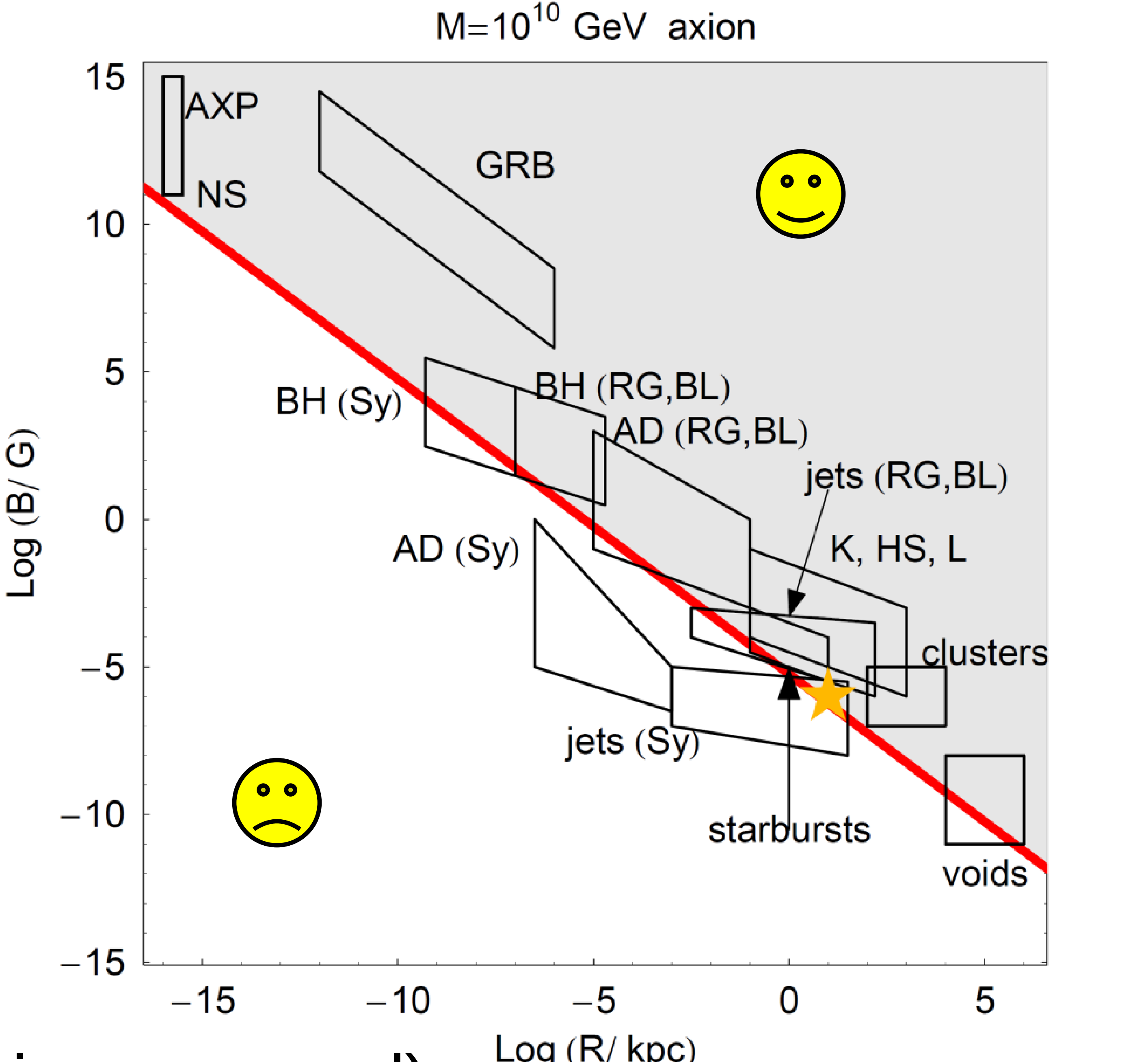


Maximal Mixing 2

$\Delta_p \ll 2\Delta_M$



Mixing Length in Source



(Maximal mixing assumed)

Different Mixing Scenarios

No.	m eV	IGMF G	ω eV	strong mixing in BL	fil	IG	MW	dominant conversion
1	$\sim 10^{-7}$	$\lesssim 10^{-11}$	10^{12}	+	−	−	+	source+MW
			10^{19}	−	+	−	−	fil+fil
2	$\sim 10^{-7}$	$\sim 10^{-9}$	10^{12}	+	−	−	+	source+MW
			10^{19}	−	+	+	−	IGMF+IGMF
3	$\sim 10^{-5}$	any	10^{12}	+	−	−	−	no explanation
			10^{19}	−	+	−	−	fil+fil (IGMF if strong)
4	$\lesssim 10^{-9}$	$\sim 10^{-9}$	10^{12}	+	+	+	+	IGMF+IGMF
			10^{19}	−	−	+	−	IGMF+IGMF

Most scenarios have a way of the photons getting through
Fairbairn, Rashba and Troitsky 0901.4085

Summary and Conclusions

- While contrived, void models can (just about) explain expansion history

- Would like another way of testing them

- γ-ray transparency of void Universes much less than ΛCDM

- Observations of blazars may rule out void models, if we can parametrise errors in our EBL models

- γ-ray transparency can also place constraints on other models of dark energy. I am quite excited about their potential.

- Transperency of the Universe also has interesting implications for the physics of axion-like particles.