Don’t try to teach your grandmother how to suck eggs

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釈迦に説法

Density Profile of Galaxy

Density Profile of Dark Matter Halos

- Universal Density Profile (Navarro, Frenk, White 1997)

$$\boxed{\rho(r) = \frac{\rho_s}{(r/r_c)(1 + (r/r_c)^2)}}$$

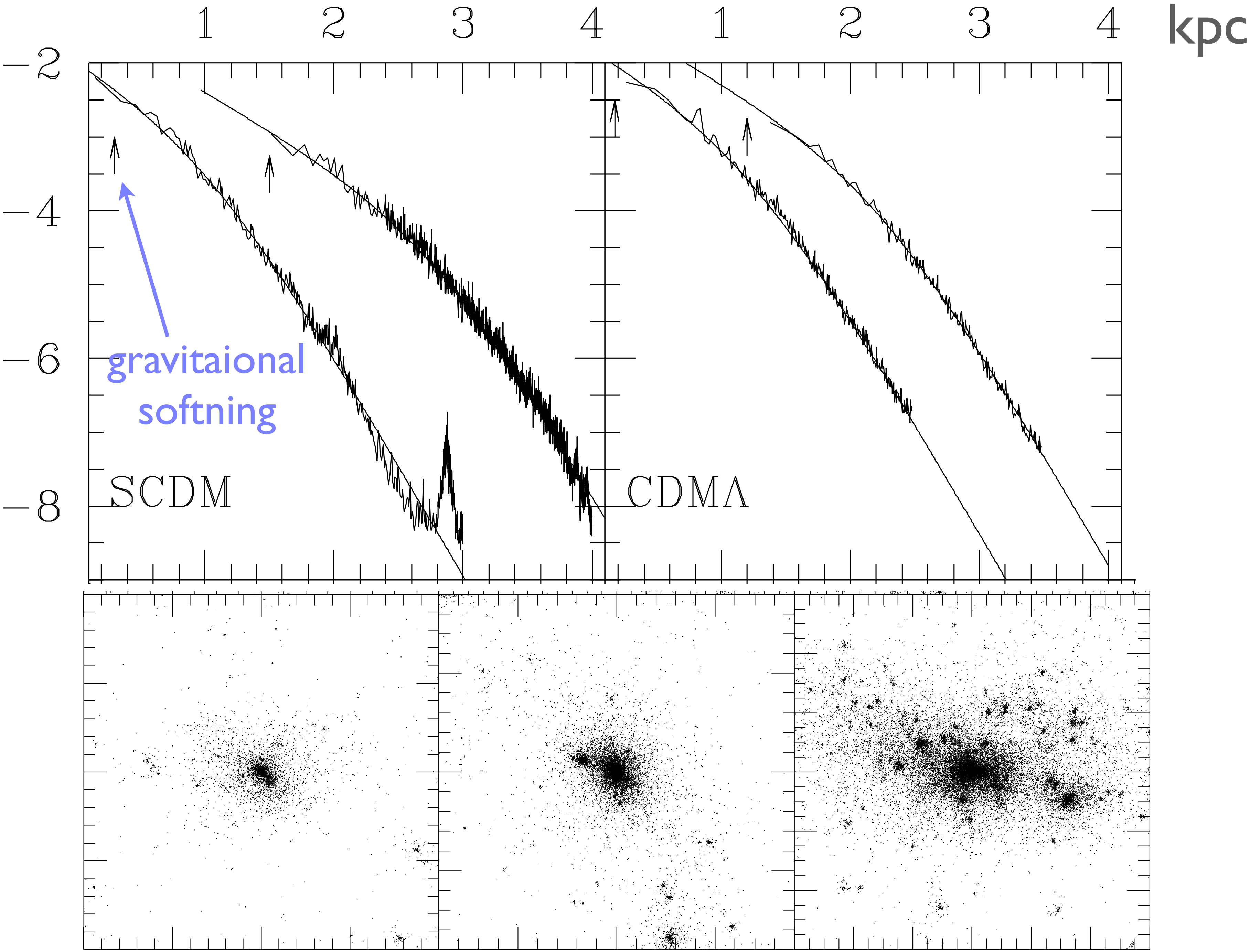
$$\rho \sim r^{-1} \quad (r \to 0)$$ central density cusp

- Moore et al (1999)

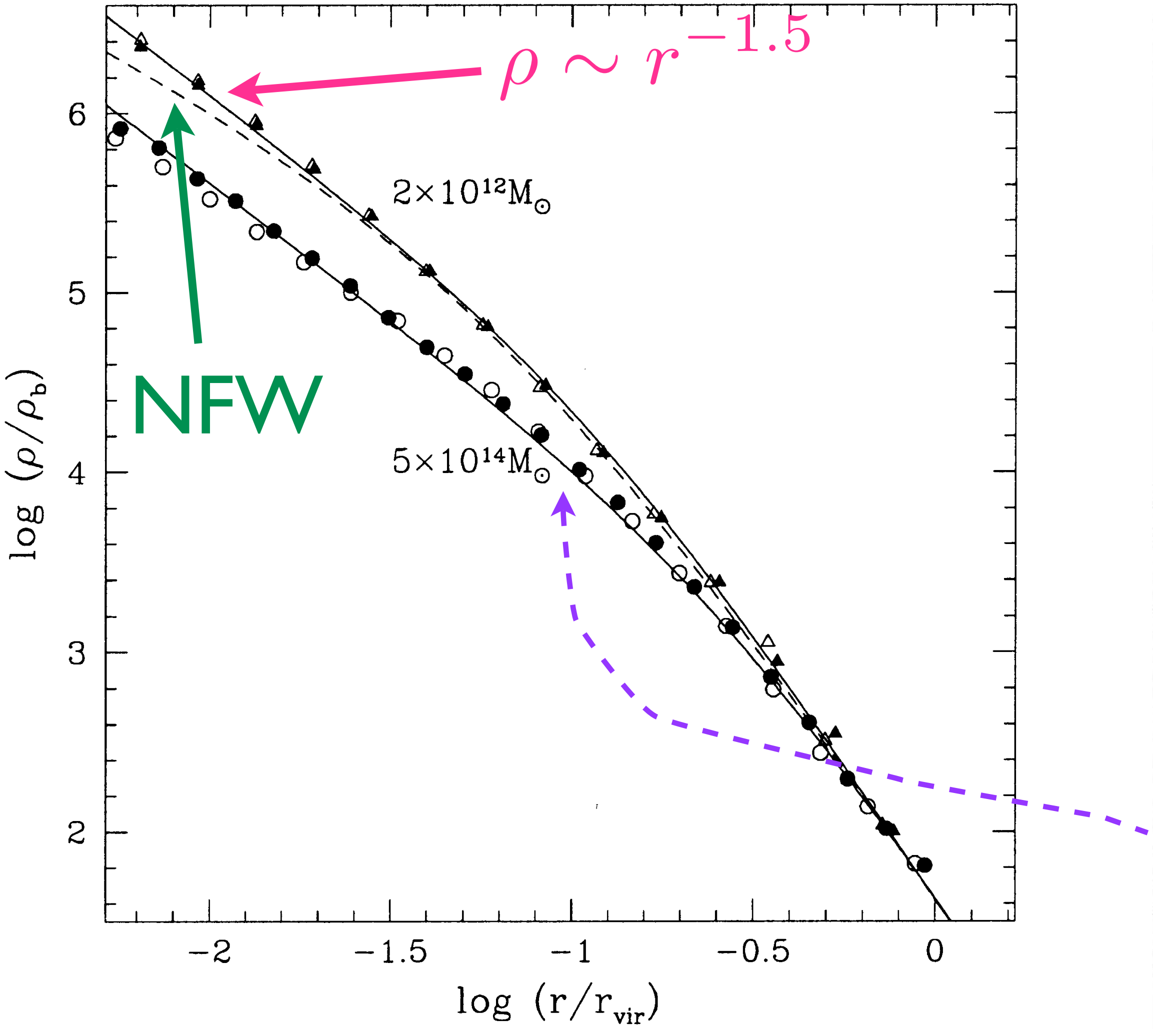
$$\boxed{\rho(r) = \frac{\rho_M}{(r/r_M)^{1.5}(1 + (r/r_M)^{1.5})}}$$

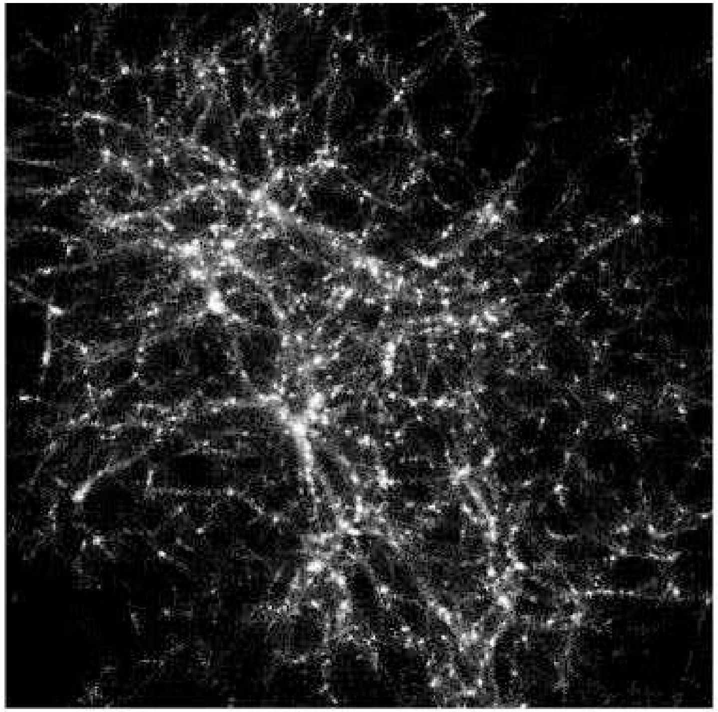
$$\rho \sim r^{-1.5} \quad (r \to 0)$$

Navvaro, Frenk, White (1997) [ApJ 490(1997)493]

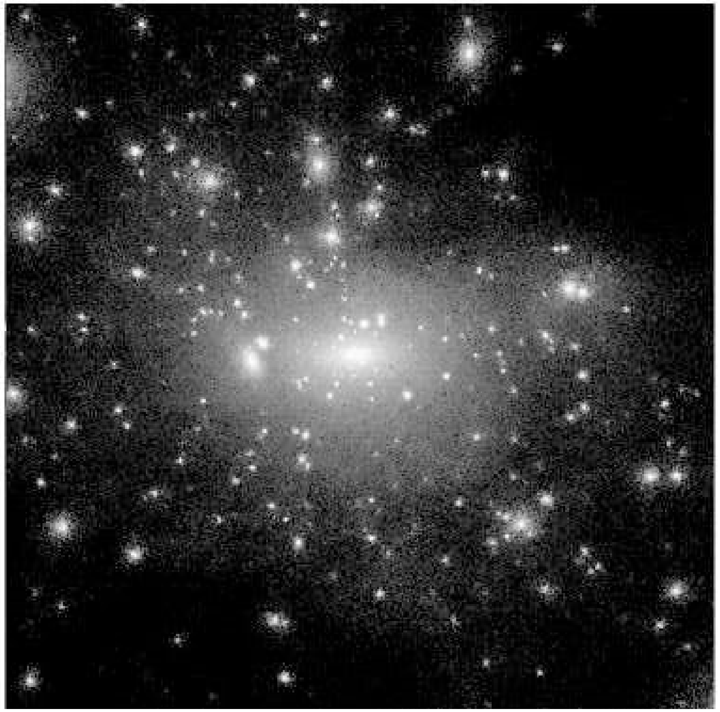


Moore et al (1999)





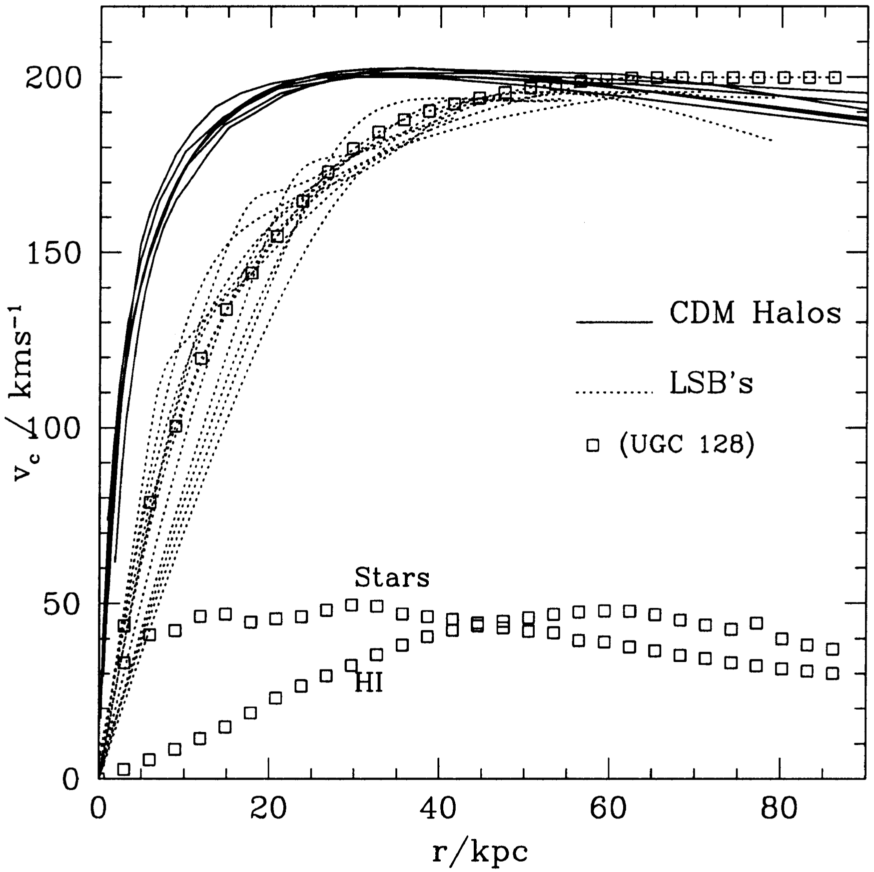
z=5

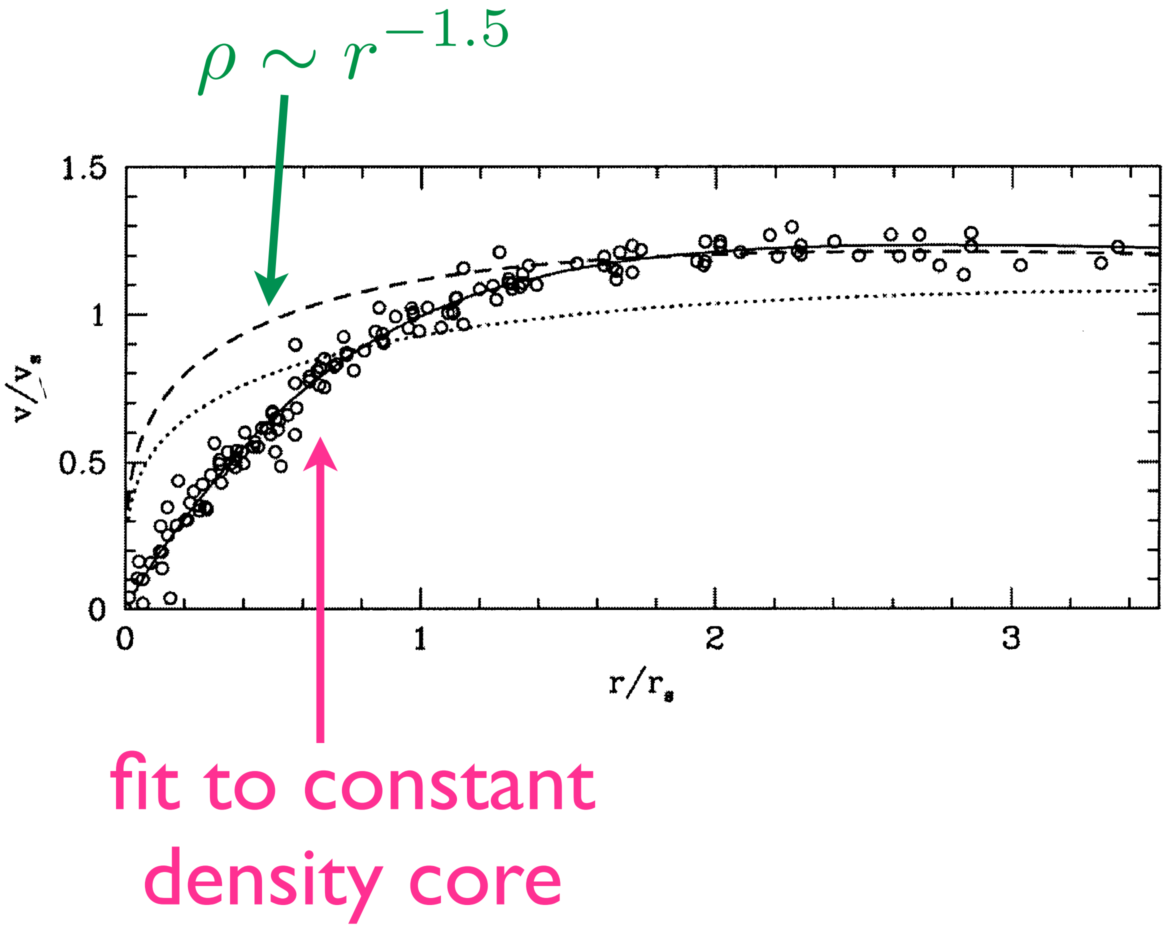


z=0

[MNRAS 310(1999)1147]

Rotation Curve





failure of CDM model?

[Moore et al MNRAS 310(1999)1147]

Improved N-body Simulation

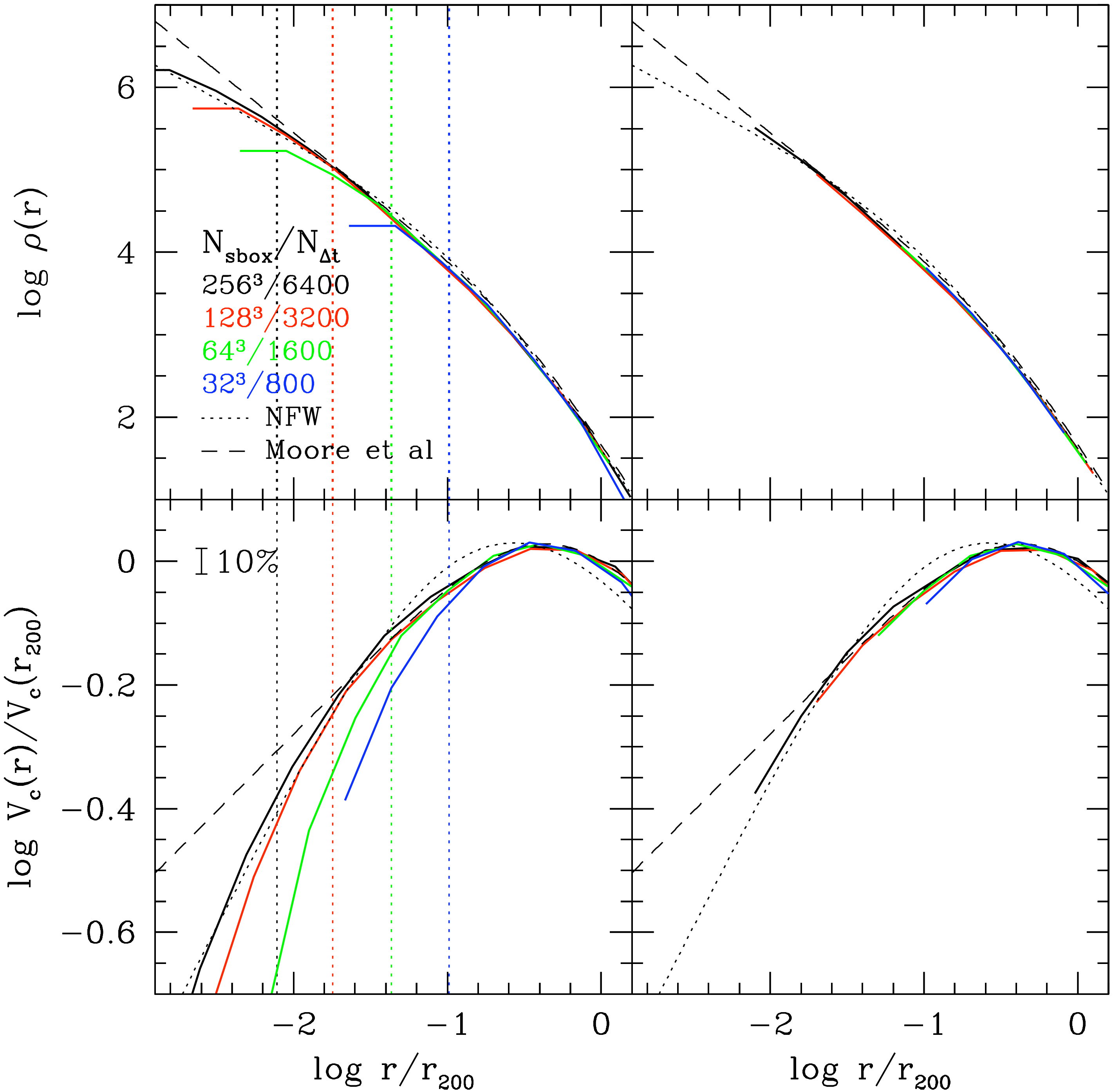
[Hayashi et al MNRAS 355(2004)794
Navvaro et al MNRAS 349 (2004)1039
Power et al MNRAS 338 (2003) 14]

- Central Cusp ?
  - Simulation with higher resolution

- Disagreement with rotation curves of LSB galaxies ?
  - Obs. improvement (long slit Hα observation)
  - Directly compared LSB rotation curves with simulations

Conversed Radius

[Hayashi et al MNRAS 355(2004)794]

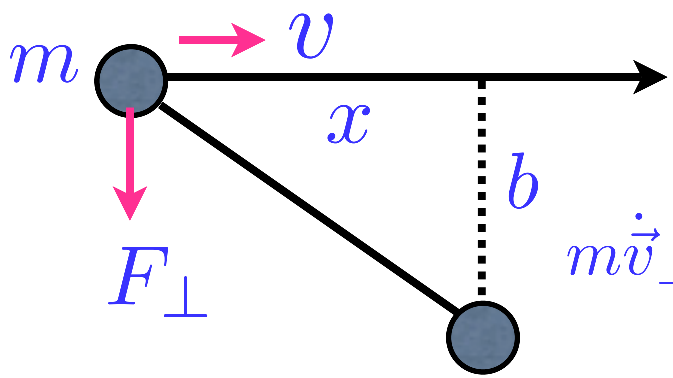


$N_{\Delta t}$ Total number of time steps

$$\frac{M(<r_{200})}{(4\pi/3)r_{200}^3} = 200\rho_{\rm crit}$$

Criteria for numerical convergence

- Particle collisions lead to changes of O(1) in energy in relaxation timescale



$$m\dot{\vec{v}}_\perp = \dot{F}_\perp = \frac{Gm^2 b}{(b^2+x^2)^{3/2}} \simeq \frac{Gm^2}{b^2}\left[1+\left(\frac{vt}{b}\right)^2\right]$$

$$\Rightarrow \quad |\delta v_\perp| \sim \frac{Gm}{bv}$$

Per one orbit time

$$\Delta v_\perp^2 \sim \int_\epsilon^r \delta v_\perp^2 \frac{N}{r^2} b\,db \sim N(r)\left(\frac{Gm}{rv}\right)^2 \ln(r/\epsilon) \sim \frac{1}{N}\ln(r/\epsilon) v^2$$

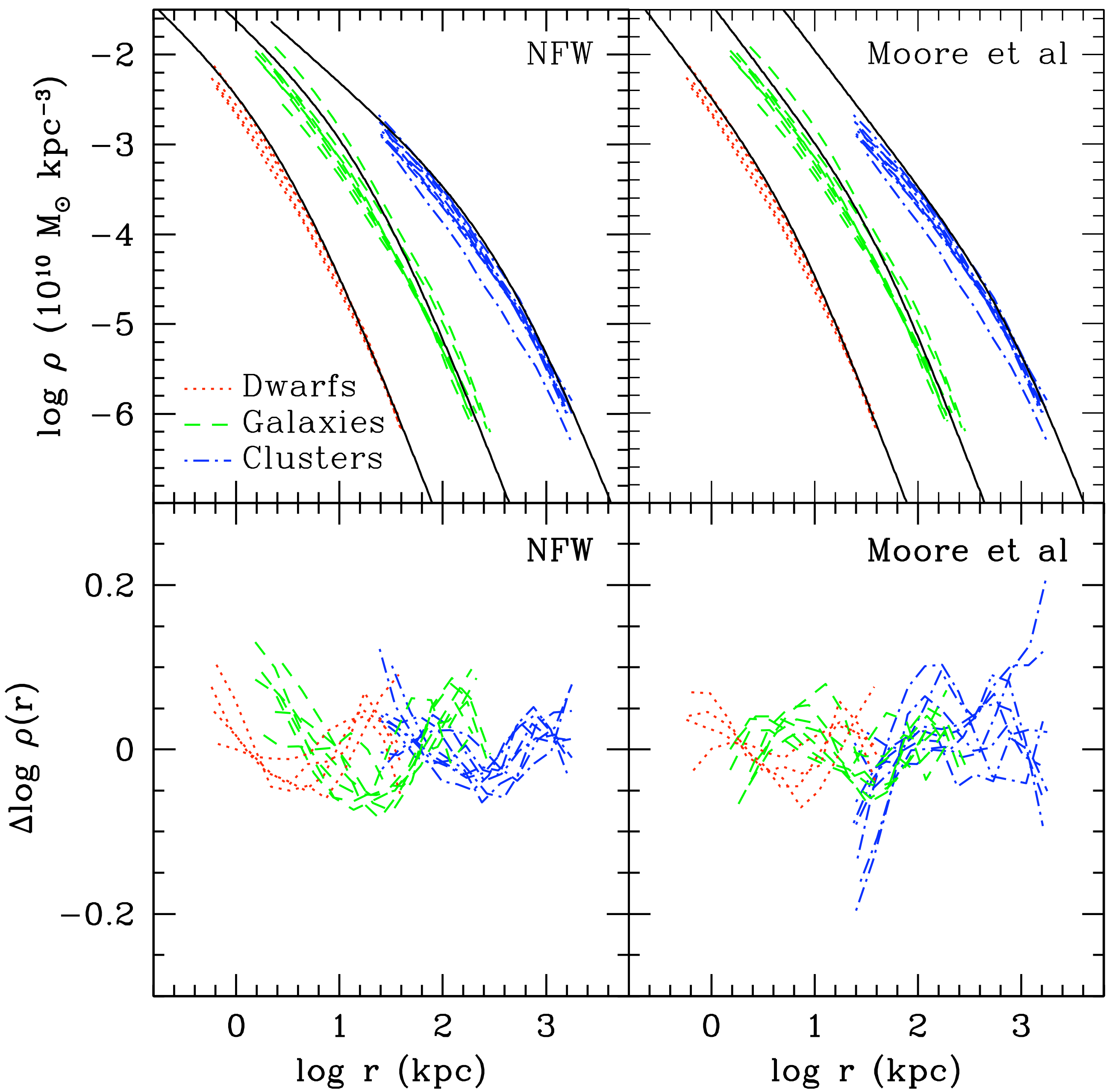
Relaxation time-scale

$$t_{\rm relax}(r) \sim (v^2/\Delta v_\perp^2)\, t_{\rm circ}(r) \sim \frac{N(r)}{\ln(r/\epsilon)} t_{\rm circ}(r) \qquad v^2 \sim \frac{GNm}{r}$$

$$\Rightarrow \quad \boxed{t_{\rm relax}(r) > t_0}$$

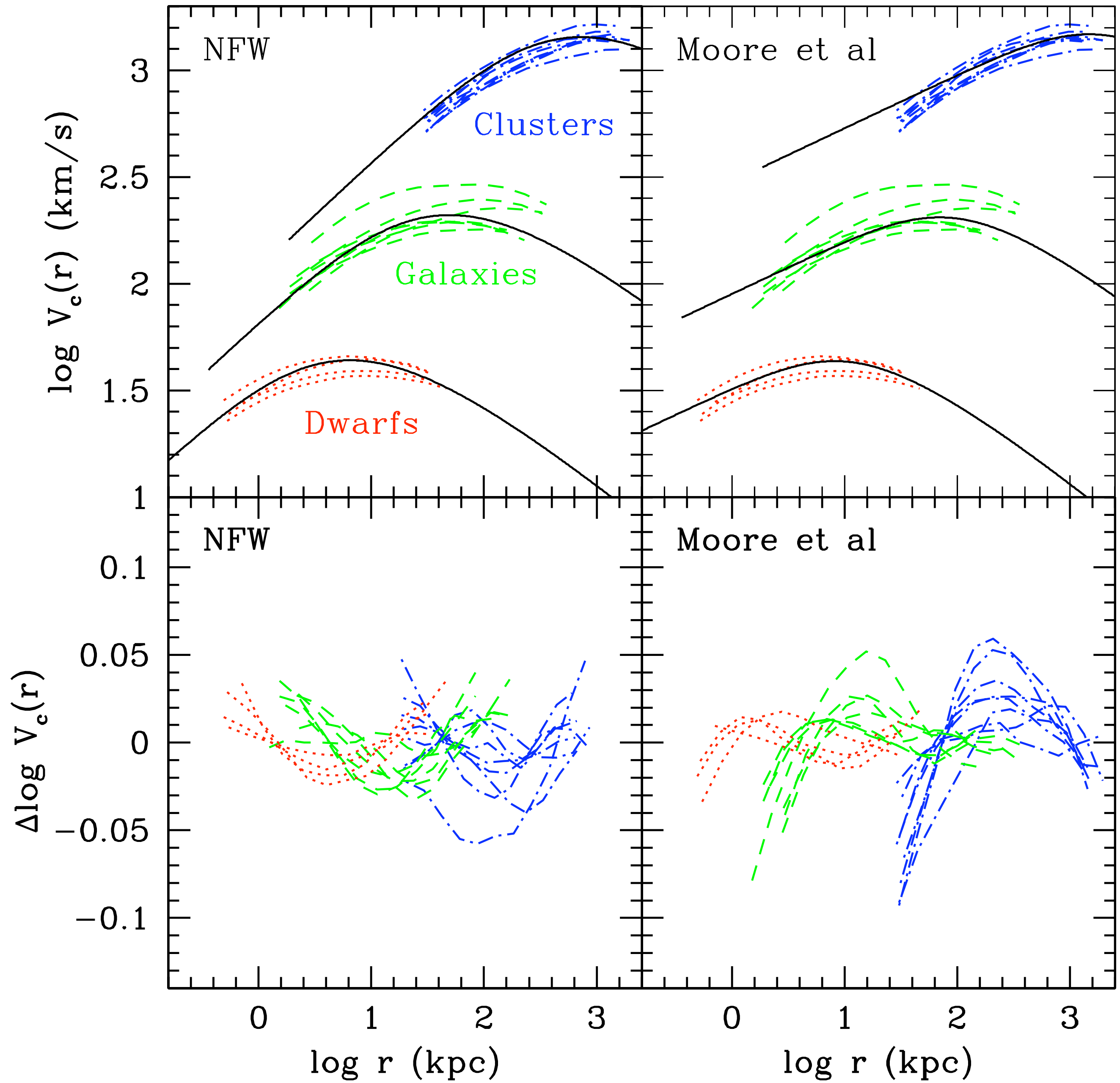
Density profile : NFW vs Moore et al

Navvaro et al MNRAS 349 (2004)1039

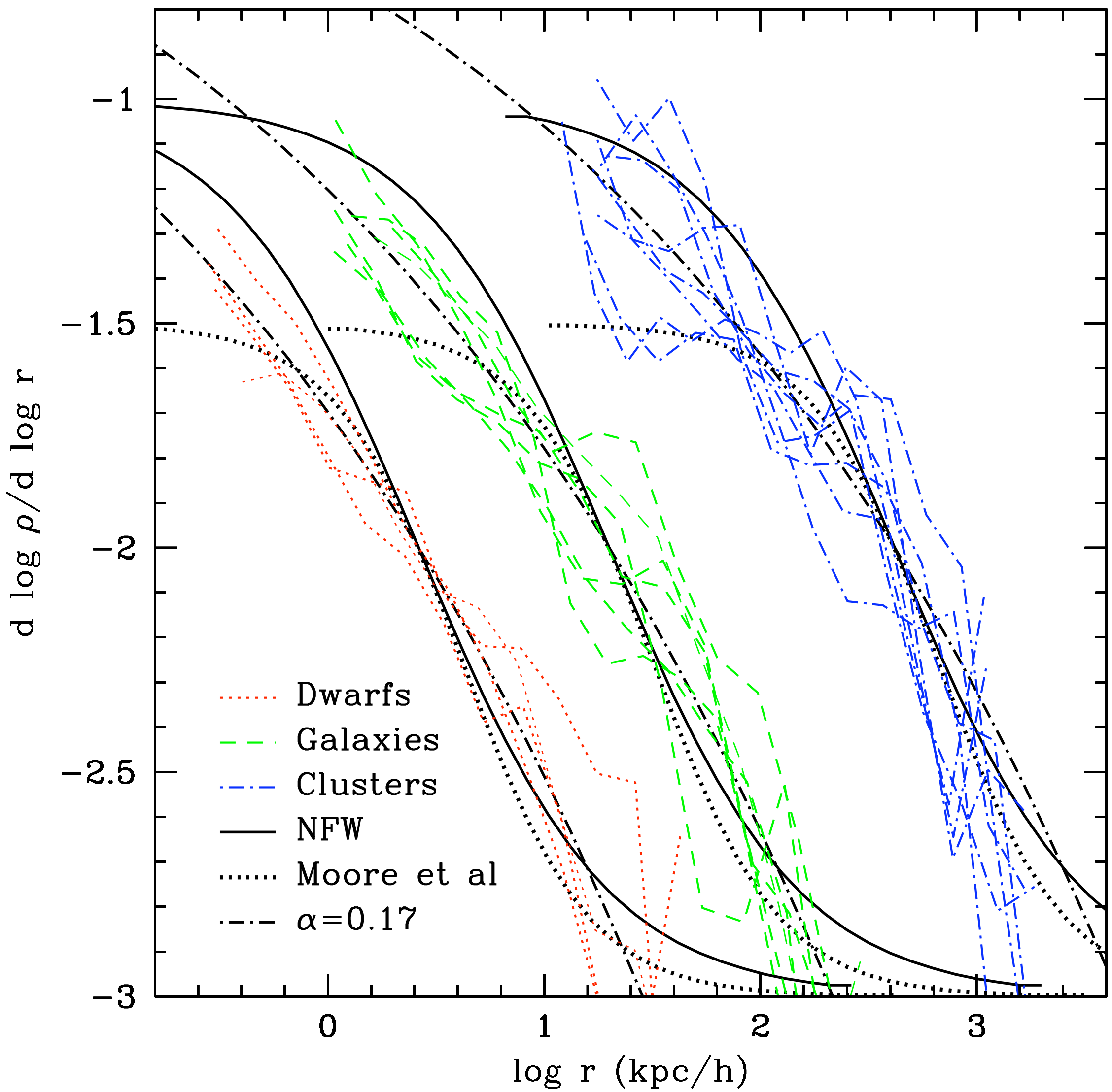


Rotaion curve : NFW vs Moore et al

Navvaro et al MNRAS 349 (2004)1039



Slope of the density profile



No indication for convergence to a well-defined aymptotic value

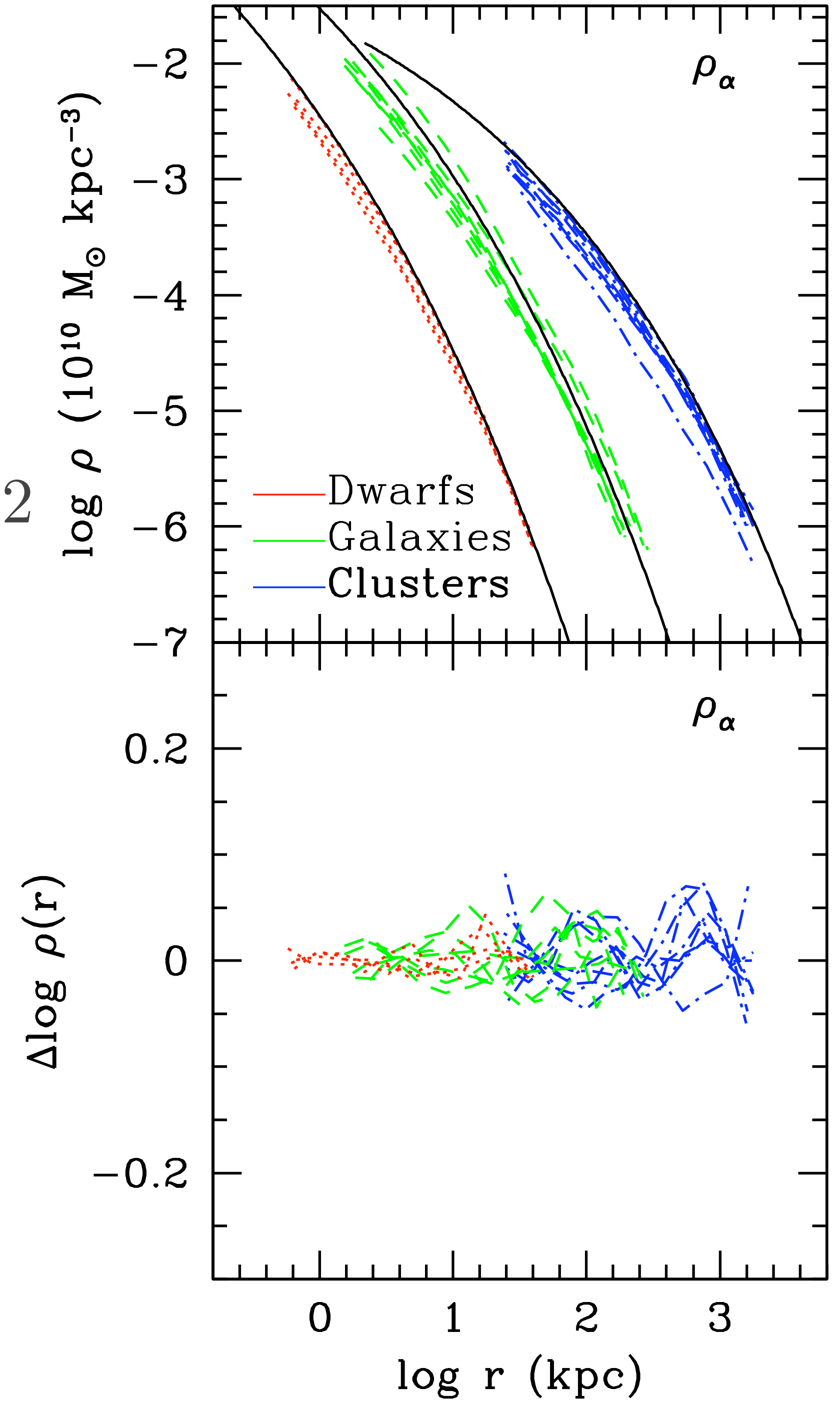
Improved fitting formula

α free

$$\beta_\alpha(r) = -d\ln\rho/d\ln r = 2(r/r_{-2})^\alpha$$

$$\ln(\rho_\alpha/\rho_{-2}) = (-2/\alpha)[(r/r_{-2})^\alpha - 1]$$

$\boxed{\alpha \sim 0.17}$ $\beta(r_{-2}) = -d\ln\rho/d\ln r = 2$



- CDM halos appear to be "cuspy"
- Gradual variation of the logarithmic slope

LSB rotation curve shape

- Hα rotation curve data set (67 galaxies)

  and simulated 266 halos

- χ^2 fit to

$$\boxed{V(r) = \frac{V_0}{(1 + (r_t/r)^\gamma)^{1/\gamma}}}$$

NFW : $\gamma \simeq 0.6$
ISO : $\gamma \simeq 2$

A. Best fit

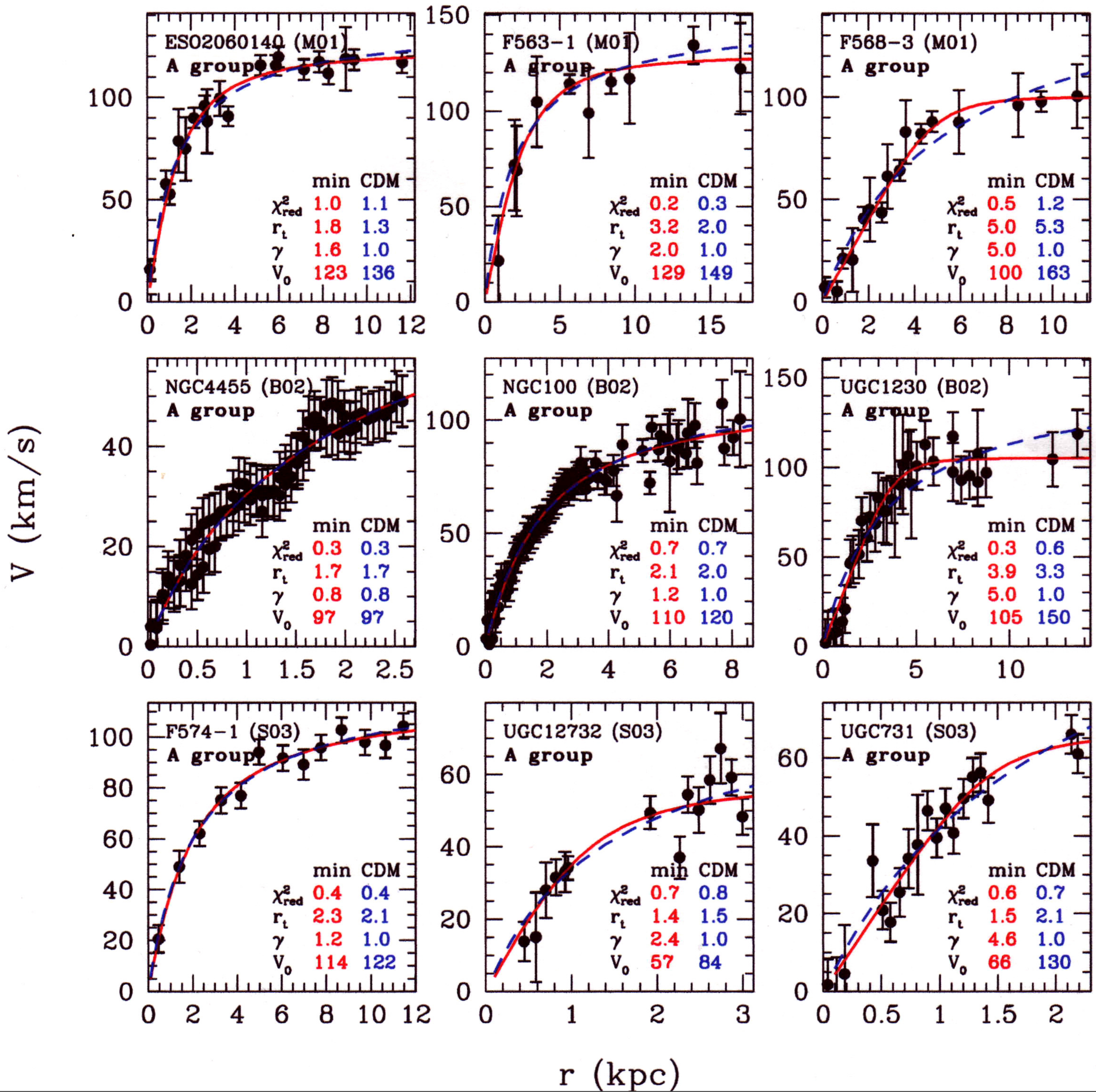
$$r_t > 0 \quad 0 \leq \gamma \leq 5 \quad V_0 \leq 2V_{\mathrm{max}}$$

B. ΛCDM fit

$$r_t > 0 \quad 0 \leq \gamma \leq 1 \quad V_0 \leq 2V_{\mathrm{max}}$$

$$|\log \Delta_{1/2} - \log \Delta_{1/2,\mathrm{CDM}}| \leq 0.7 \qquad \Delta_{1/2} = \bar{\rho}(r_{V_{1/2}})/\rho_{\mathrm{crit}}$$

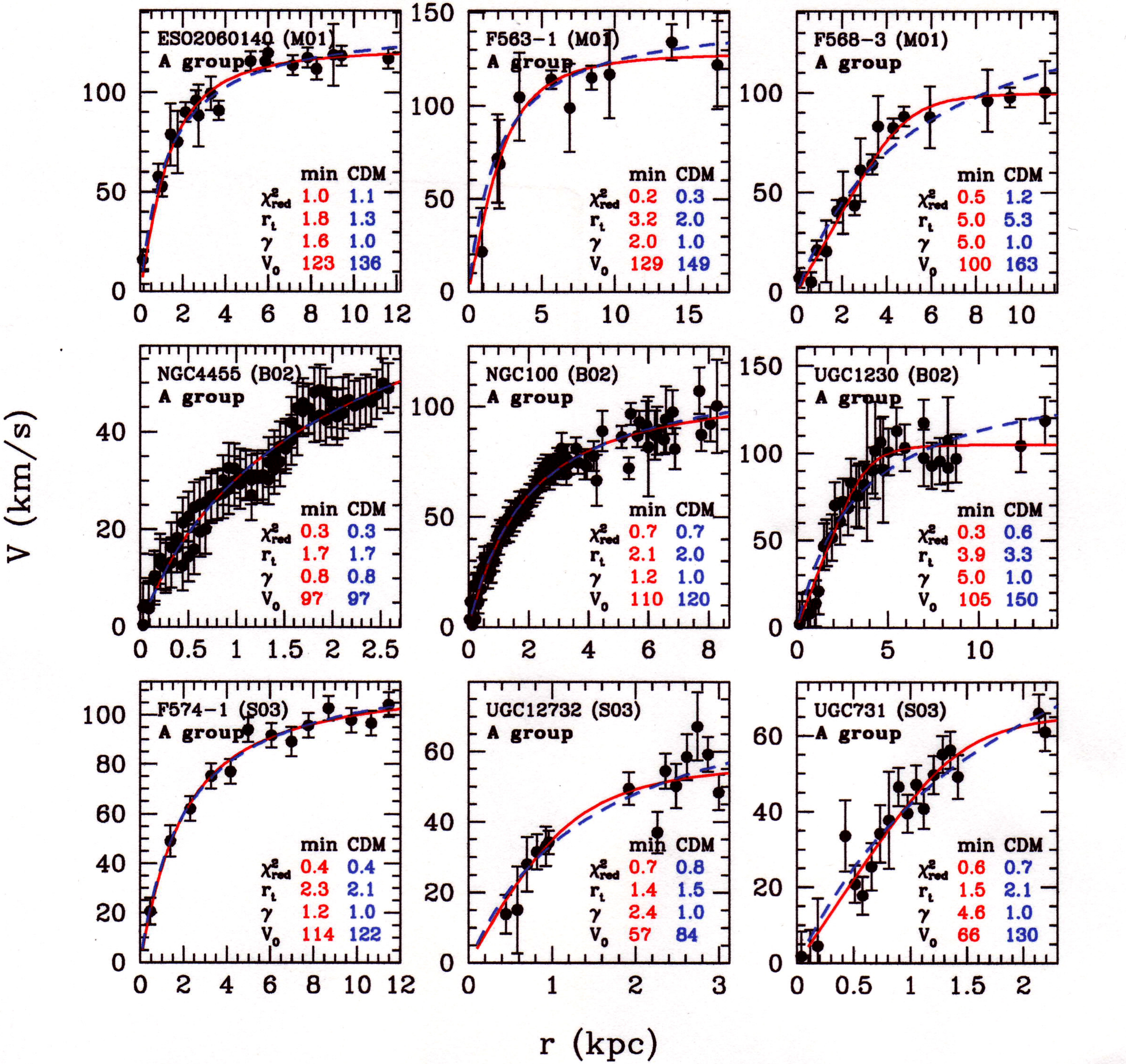
Rotation curves of LSB galaxies



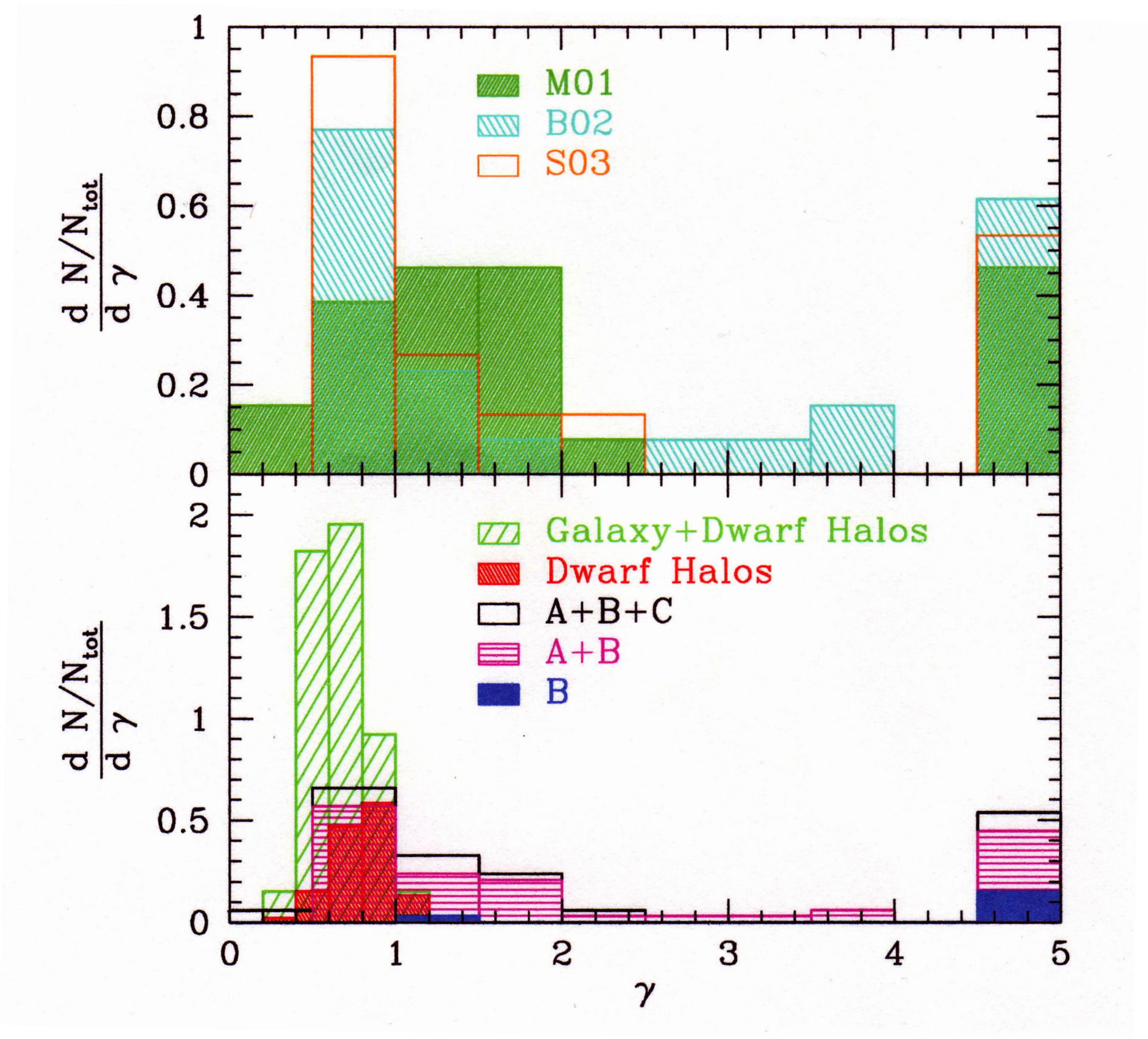
M01
McGaugh et al
AJ 122 (2001) 2381

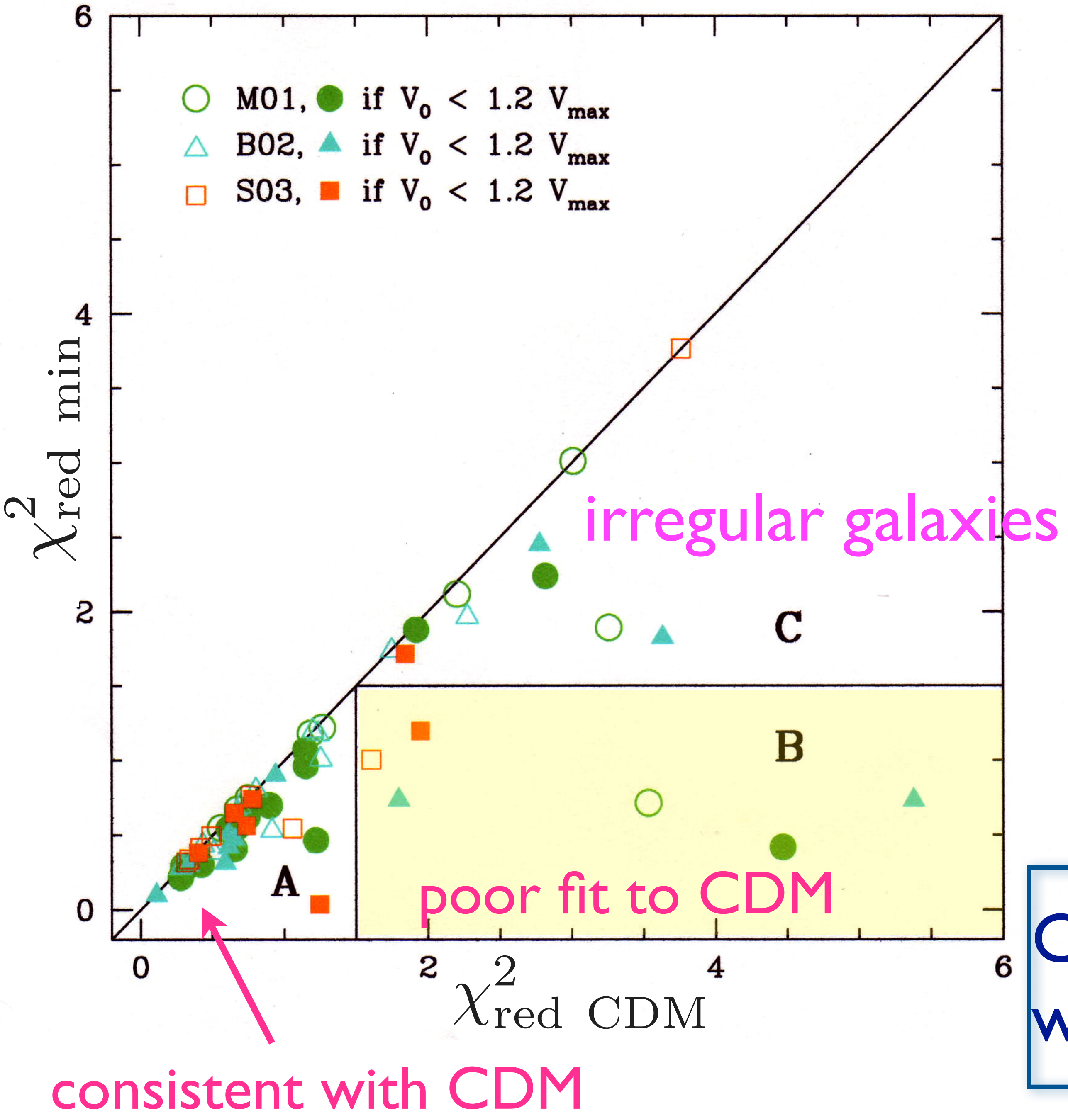
B02
de Block, Bosma
A&A 385 (2002) 816

S03
Swaters et al
ApJ 583 (2003) 732


ESO2060140 (M01)
A group
F563-1 (M01)
F568-3 (M01)
NGC4455 (B02)
NGC100 (B02)
UGC1230 (B02)
F574-1 (S03)
UGC12732 (S03)
UGC731 (S03)
min CDM
V (km/s)
r (kpc)

Distribution of γ





- 70% of LSB galaxies are consistent with CDM
- 20% have irregular rotation curves
- 10% is inconsistent with CDM (most of their rotation curves do not extend large enough radii)

CDM is not inconsistent with LSB rotation curve

Effect of galactic disks

Mo, Mao, White MNRAS 295 (1998) 319

Cooling of baryons $\Rightarrow$ Formation of galactic disk (and bulge)

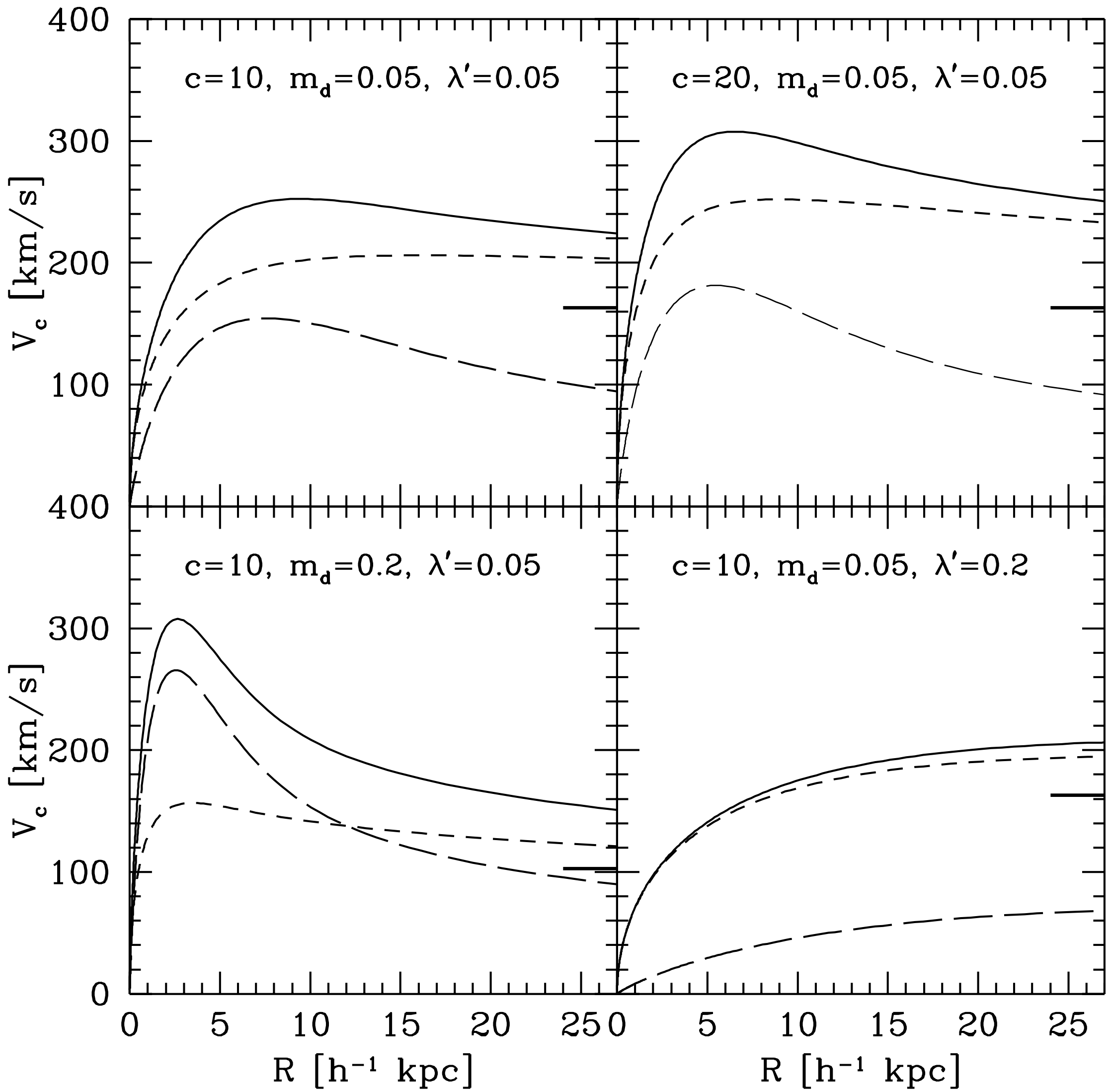
$\Downarrow$

NFW density profile may be deformed

- NFW halo + exponential disk
  - Fixed fraction of disk mass $M_d = m_d M$
  - Fixed fraction of disk angular momentum $J_d = j_d J$
  - Thin disk, exponetial surface density profile

$$\Sigma(R) = \Sigma_0 \exp(-R/R_d)$$

- Adiabatic contraction of halo
    - Spherical as it contracts
    - angular momentum conservation



$$GM_f(r)r = GM(r_i)r_i$$

$$M_f(r) = M_d(r) + M(r_i)(1 - m_d)$$

$$M_d(R) = M_d\left[1 - \left(1 + \frac{r}{R_d}e^{-r/R_d}\right)\right]$$

$$c \equiv \frac{r_{200}}{r_s}$$ concentration parameter

$$\lambda' \equiv \lambda\frac{j_d}{m_d}$$

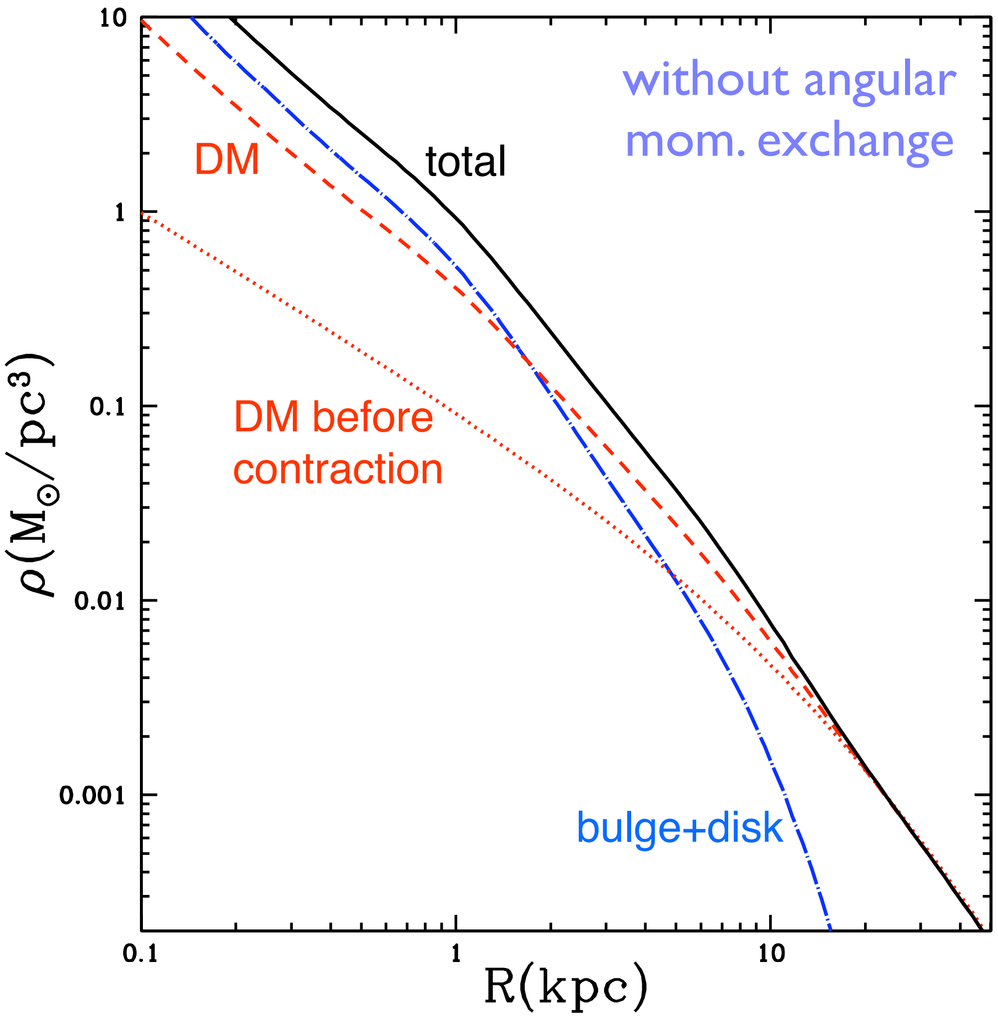
$$\lambda = J|E|^{1/2}G^{-1}M^{-5/2}$$

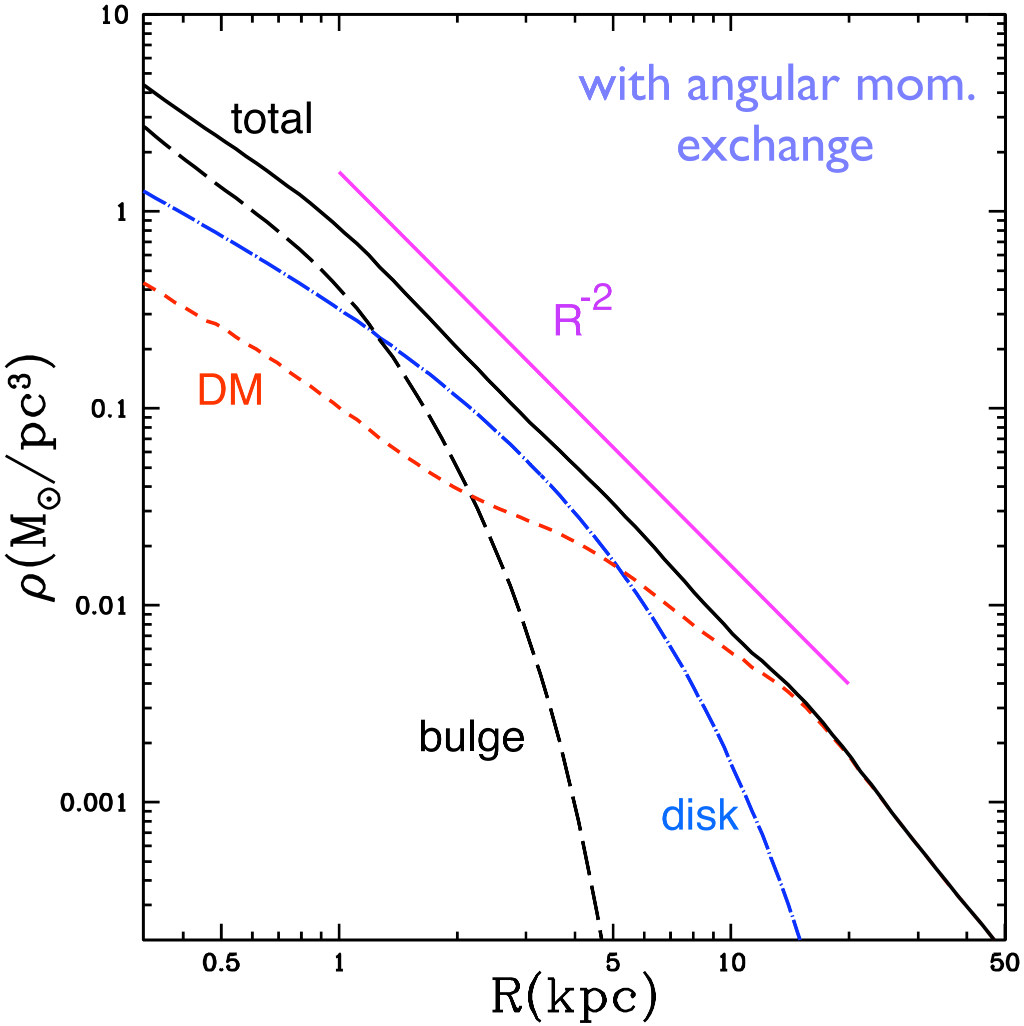
Spin parameter

Density profile of our Galaxy

Klypin, Zhao, Somerville ApJ 573 (2002) 397

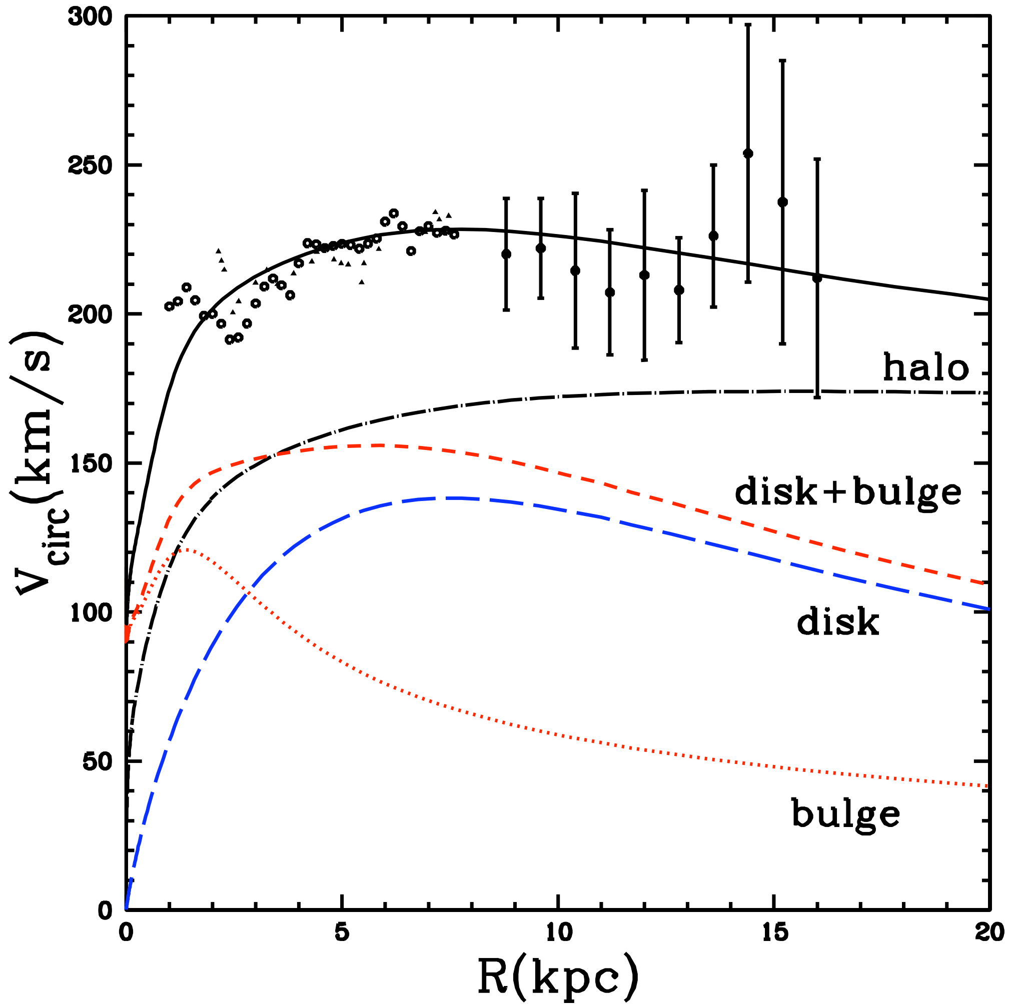
- NFW halo density profile
- three components (nucleus, bulge, disk)
- adiabatic contraction
- with/without angular momentum exchange



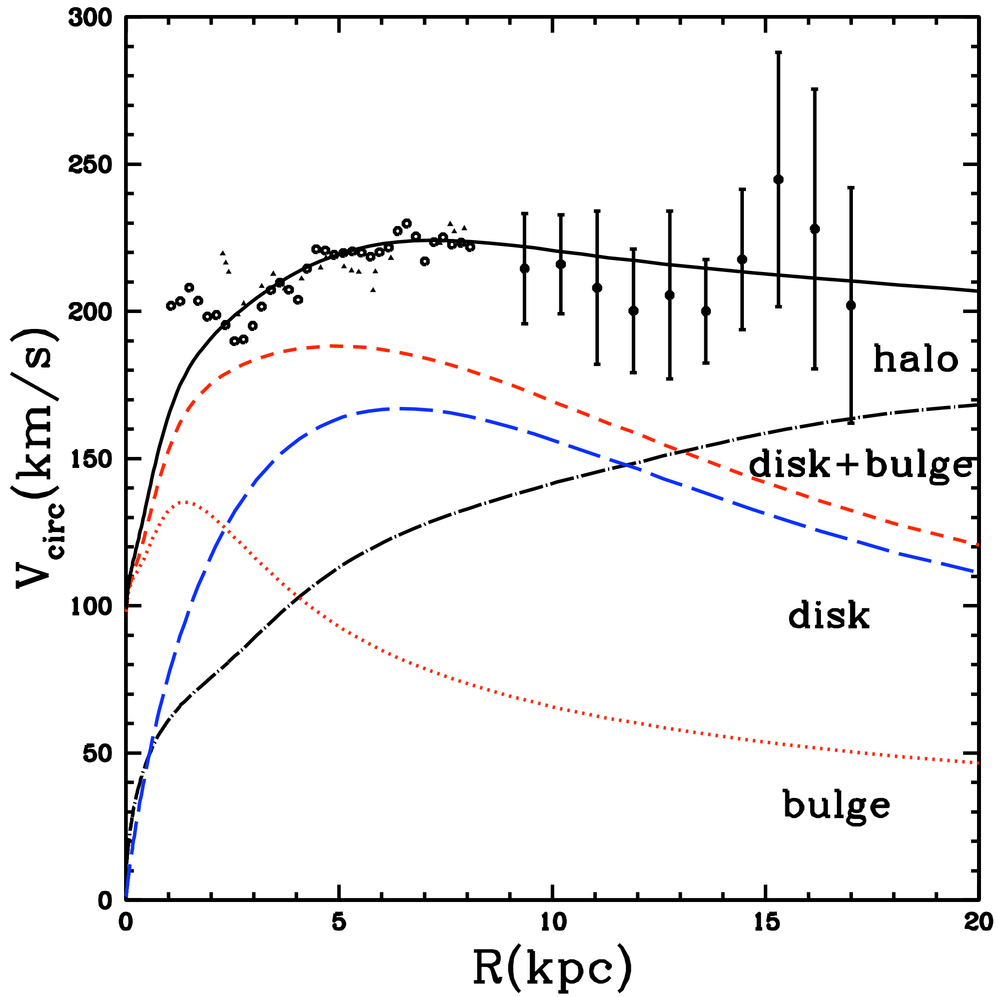


Rotation curve and ...

HII measurement by Knapp et al (circles) and Kerr et al (triangles)

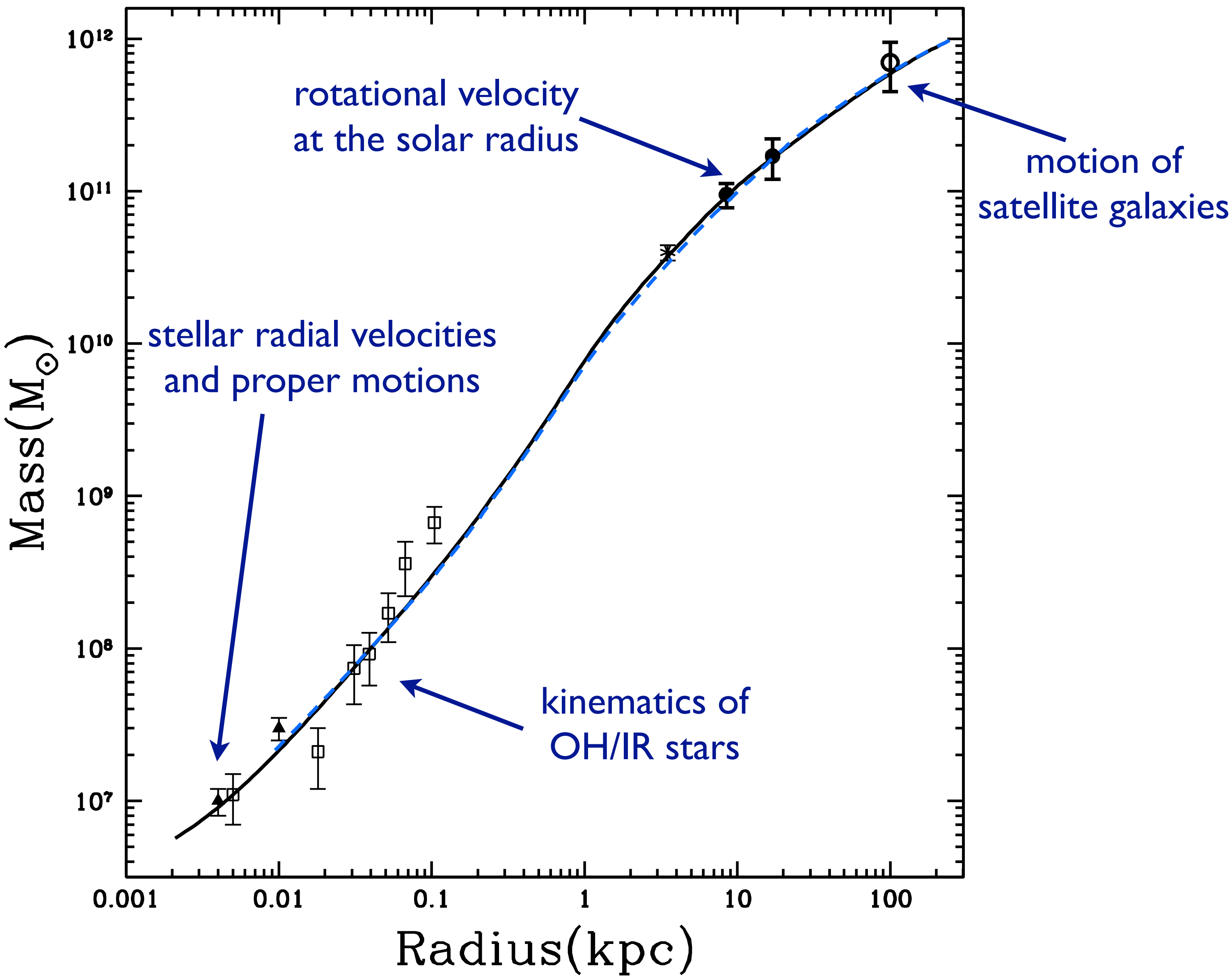


without angular mom. exchange



with angular mom. exchange

Mass distribution

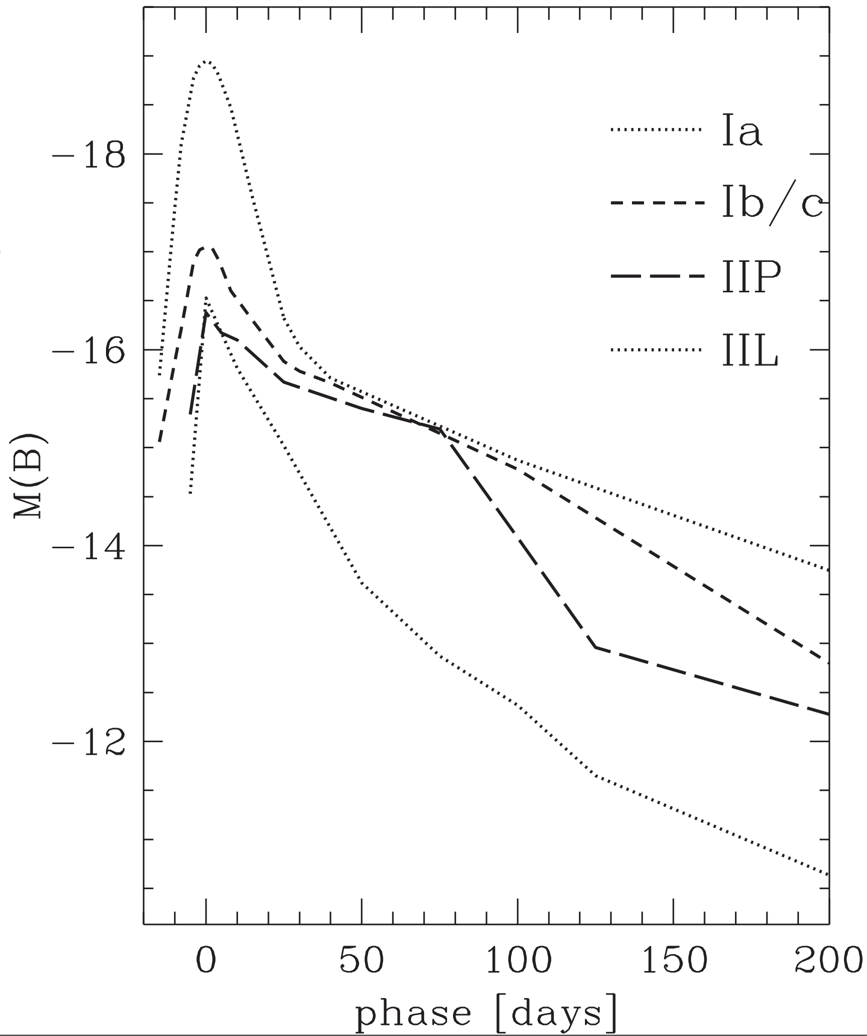


Supernova Rate

Supernova rate

- Type I no hydrogen line
  - Ia silicon line
  - Ib no silicon line, helium line
  - Ic no silicon line, w/wo weak helium line
- Type II hydrogen line

Light curve ⇒ SN & SN type



$$\text{SNR} = \frac{N_{\text{SN}}}{\sum_{j=1}^{N_G} \Delta t_j L_j}$$

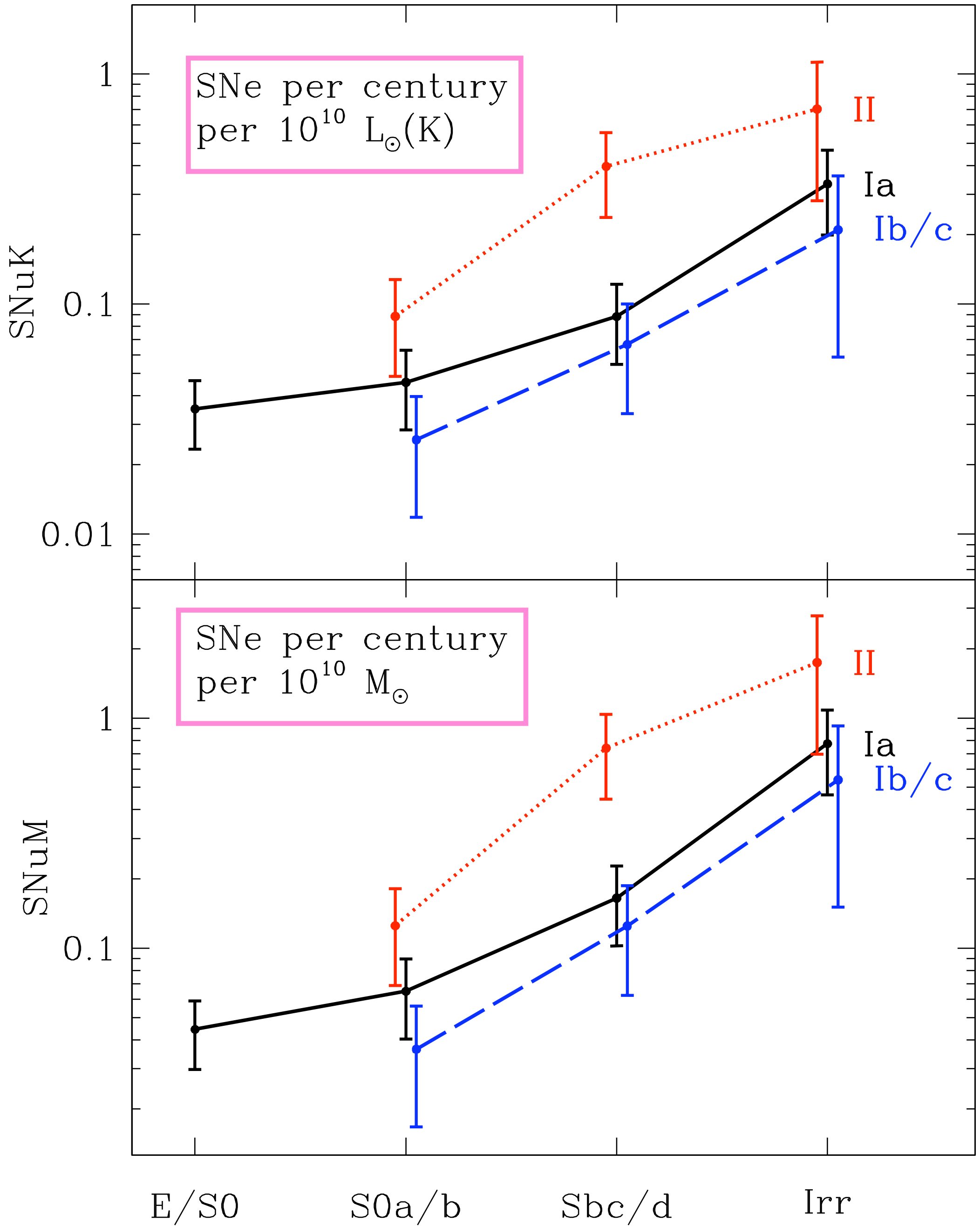
Δt_i : obs. time

L_j : $j-$th galaxy luminosity

N_{SN} : num. of discovered SN

The Present SN rate

[Mannucci et al A&A 433(2005)807]



Type	Ngal	Ia	Ib/c	II
E/S0	2048	21.0	0	0
S0a/b	2911	18.5	5.5	16.0
Sbc/d	2682	21.4	7.1	31.5
Irr	644	6.8	2.2	5.0

Type	Ia	Ib/c	II
SN rate per K-band luminosity (SNuK)			
E/S0	$0.035^{+0.013}_{-0.011}$	<0.0073	<0.10
S0a/b	$0.046^{+0.019}_{-0.017}$	$0.026^{+0.019}_{-0.013}$	$0.088^{+0.043}_{-0.039}$
Sbc/d	$0.088^{+0.035}_{-0.032}$	$0.067^{+0.041}_{-0.032}$	$0.40^{+0.17}_{-0.16}$
Irr	$0.33^{+0.18}_{-0.13}$	$0.21^{+0.26}_{-0.14}$	$0.70^{+0.57}_{-0.43}$
SN rate per Mass (SNuM)			
E/S0	$0.044^{+0.016}_{-0.014}$	<0.0093	<0.013
S0a/b	$0.065^{+0.027}_{-0.025}$	$0.036^{+0.026}_{-0.018}$	$0.12^{+0.059}_{-0.054}$
Sbc/d	$0.17^{+0.068}_{-0.063}$	$0.12^{+0.074}_{-0.059}$	$0.74^{+0.31}_{-0.30}$
Irr	$0.77^{+0.42}_{-0.31}$	$0.54^{+0.66}_{-0.38}$	$1.7^{+1.4}_{-1.0}$

SN rate of our Galaxy

Our Galaxy : Sbc

Ib/c + II $0.46 \pm 0.17 h_{75}^2$ SNuK

$$L_K = 8.9 \times 10^{10} L_\odot$$

SN rate = $4.1 \pm 1.5\ h_{75}^2/(100\mathrm{yr})$

$= 1/[(24 \pm 9)\ h_{75}^{-2}\ \mathrm{years}]$

Core Colapse SN rate

- E/S0 : Sa/b : Sbc/d: Irr = 0.32 : 0.28 : 0.34 : 0.06
- core collapse SN = SN Ib/c + SN II

$$\boxed{\begin{array}{r}(\mathrm{CC\ SNR}) = (0.44 \pm 0.13) h^2 \ \mathrm{SNuK} \\ \mathrm{SNuK} = 1/(100\mathrm{yr})/(10^{10} L_{K,\odot})\end{array}}$$

K-band luminosity density

$$j = (7.14 \pm 0.75) \times 10^8 h L_{K,\odot} \mathrm{Mpc}^{-3}$$

$$\boxed{\begin{aligned} R_{SN} \quad &= (3.11 \pm 0.96) \times 10^{-4} h^3 \ \mathrm{yr}^{-1} \mathrm{Mpc}^{-3} \\ &= (1.21 \pm 0.37) \times 10^{-4} \ \mathrm{yr}^{-1} \mathrm{Mpc}^{-3} \end{aligned}}$$

Star Formation Rate (SFR)

- Salpeter Initial Mass Function (IMF)

$$\phi(M) = \begin{cases} \frac{1}{3.532 M_\odot}\left(\frac{M}{M_\odot}\right)^{-1.35} & (M \geq 0.1\ M_\odot) \\ 0 & (M < 0.1\ M_\odot) \end{cases}$$

- From SFR to SN rate

$$R_{SN} = \boxed{\psi(t)} \int_{8M_\odot}^{100M_\odot} dM \frac{\phi(M)}{M}$$

- From Local SN rate to SFR (z=0)

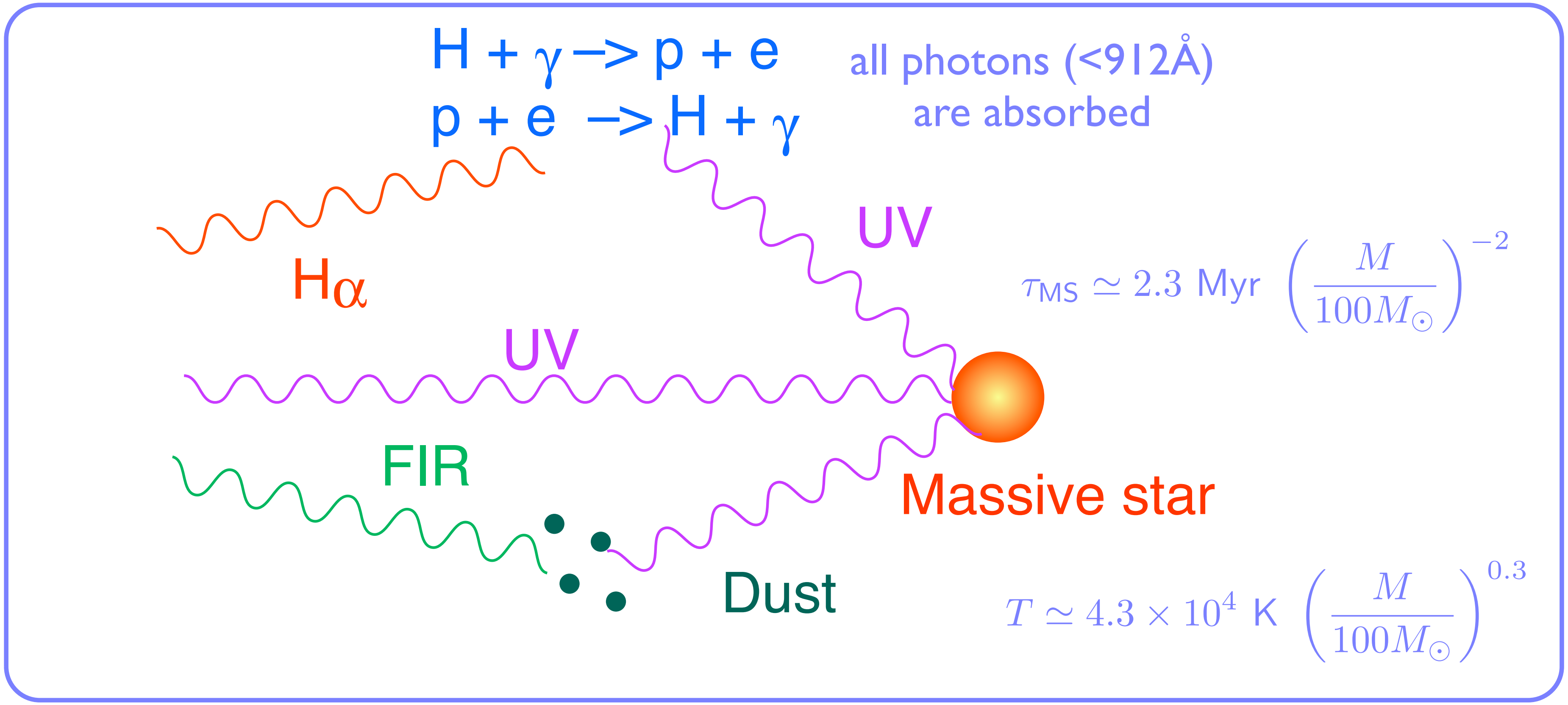
$$\psi(t) = 1.347 \times 10^2 M_\odot\ R_{SN}$$

$$\boxed{\log[\psi(z=0)/(M_\odot \mathrm{yr}^{-1} \mathrm{Mpc}^{-3})] = -1.79 \pm 0.15}$$

Hα $\log[\psi(z=0)/(M_\odot \mathrm{yr}^{-1} \mathrm{Mpc}^{-3})] = -1.79^{+0.13}_{-0.07}(stat) \pm 0.03(sys)$

[Hanish et al astro-ph/0604442]

Observations of SFR



High star formation rate

→ many massive stars

→ large UV flux

$$\mathrm{SFR} = L_{\mathrm{H}\alpha}/(1.25 \times 10^{34}\ \mathrm{W})$$

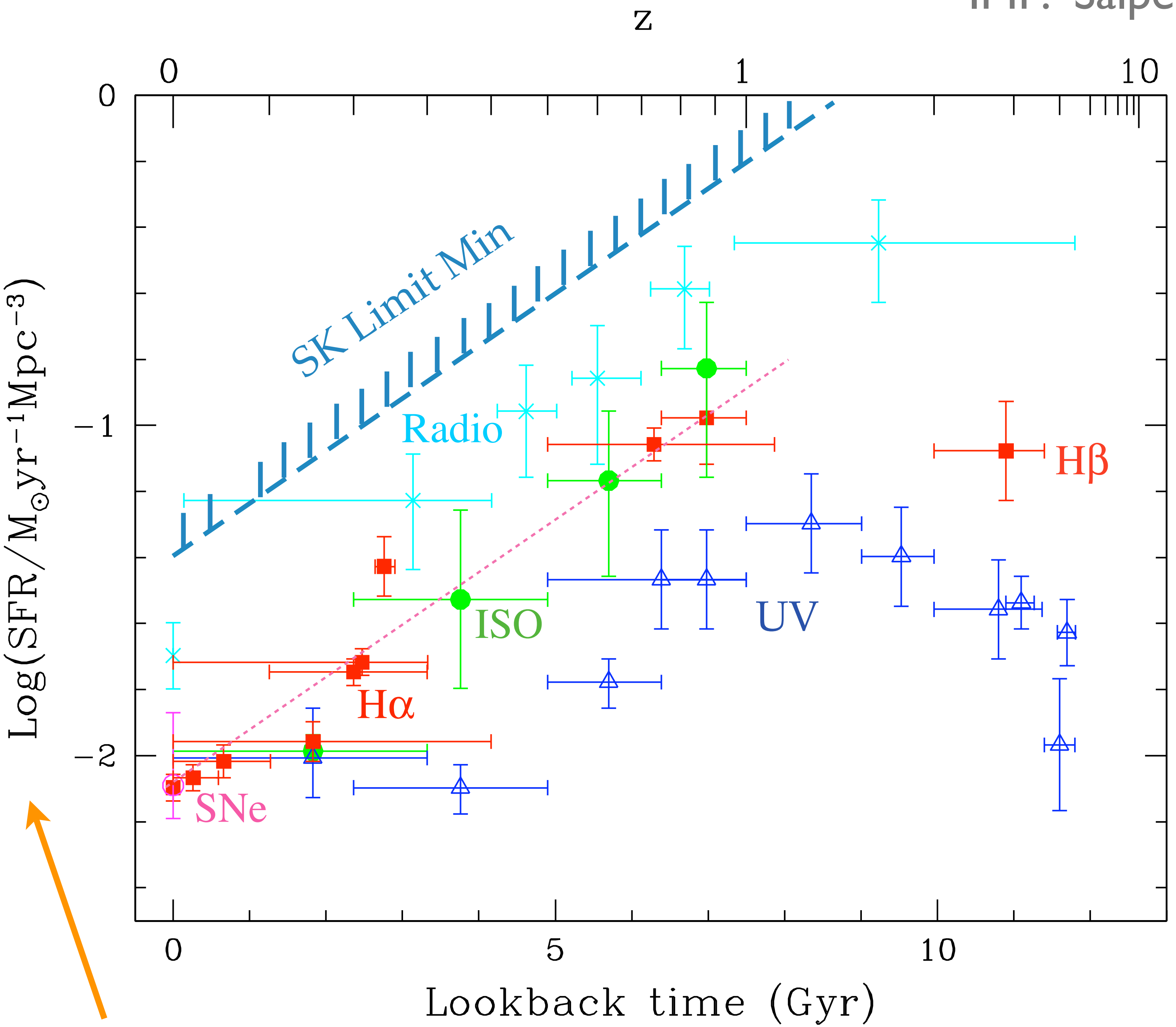
$$\mathrm{SFR} = L_{\mathrm{UV}}/(7.14 \times 10^{20}\ \mathrm{W\ Hz^{-1}})$$

$$\mathrm{SFR} = L_{\mathrm{FIR}}/(2.22 \times 10^{36}\ \mathrm{W})$$

SFR in units of $M_\odot \mathrm{yr}^{-1}$

Evolution of SFR

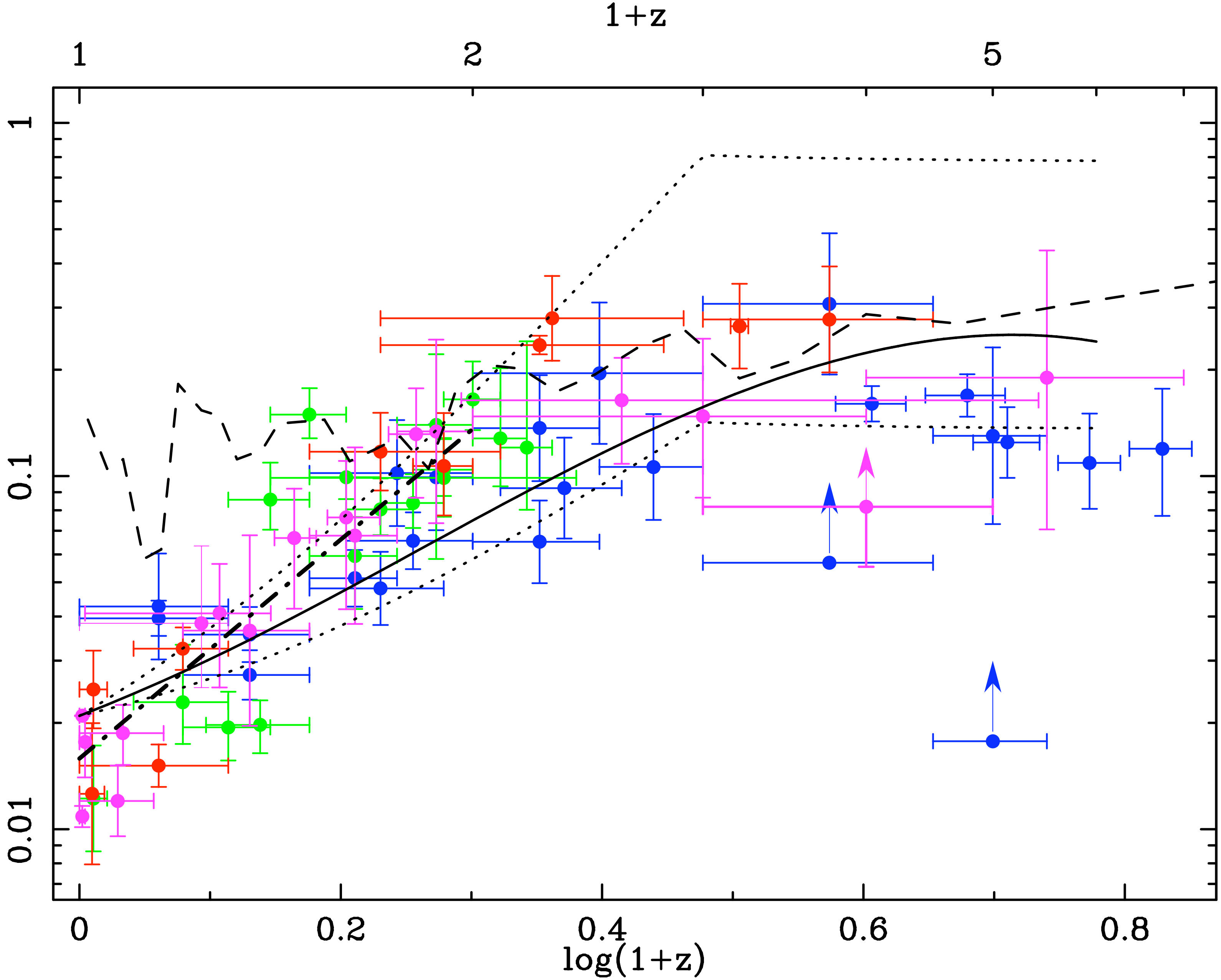
IMF: Salpeter+GBF



log SFR(Salpeter) - 0.22

[Fukugita MK MNRAS 340 (2003) L7]

SFR evolution



[Hopkins ApJ 615 (2004) 209]

GW Test of Gravitational Theory

Test of Gravitational Theory

metric theory of gravity $\Rightarrow$ non-gravitational fields respond only to the spacetime metric g

- Einstein gravity

$$\boxed{I = \frac{1}{16\pi G}\int R(-g)^{1/2} d^4x + I_m(\psi_m, g_{\mu\nu})}$$

- Scalar-tensor theories $\longleftarrow$ string theory

$$\boxed{I = \frac{1}{16\pi G}\int \left[\phi R - \frac{1}{\phi}\omega(\phi) g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \phi^2 V\right](-g)^{1/2} d^4x + I_m(\psi_m, g_{\mu\nu})}$$

Brans-Dicke $\quad \omega = \text{const}, \quad V = 0$

PPN parameters

$$\gamma = \frac{1+\omega}{2+\omega} \qquad \beta = 1 + \Lambda = 1 + \frac{d\omega/d\phi}{(3+2\omega)^2(4+2\omega)}$$

Post Newtonian Gravity

Einstein gravity

$$\gamma = \beta = 1$$

Oder of smallness $U \sim v^2 \sim \epsilon$

Metric

$$g_{00} = -1 + 2U - 2\beta U^2 + (2\gamma + 2)\Phi_1 + 2(3\gamma - 2\beta + 1)\Phi_2 + O(\epsilon^3)$$

$$g_{0i} = -\frac{1}{2}(4\gamma + 3)V_i - \frac{1}{2}W_i + O(\epsilon^{5/2})$$

$$g_{ij} = (1 + 2\gamma U)\delta_{ij} + O(\epsilon^2)$$

Brans-Dicke

$$\gamma = (1 + \omega)/(2 + \omega)$$

$$\beta = 1$$

Metric Potential

$$U = \int \frac{\rho'}{|\mathbf{x} - \mathbf{x}'|} d^3x' \quad \Phi_1 = \int \frac{\rho' v'^2}{|\mathbf{x} - \mathbf{x}'|} d^3x' \quad \Phi_2 = \int \frac{\rho' U'}{|\mathbf{x} - \mathbf{x}'|} d^3x'$$

$$V_i = \int \frac{\rho' v'_i}{|\mathbf{x} - \mathbf{x}'|} d^3x' \quad W_i = \int \frac{\rho'[\mathbf{v}' \cdot (\mathbf{x} - \mathbf{x}')](x - x')_i}{|\mathbf{x} - \mathbf{x}'|^3} d^3x'$$

Constraint on γ

- Deflection of light

  VLBI obs. of QSOs and radio galaxies

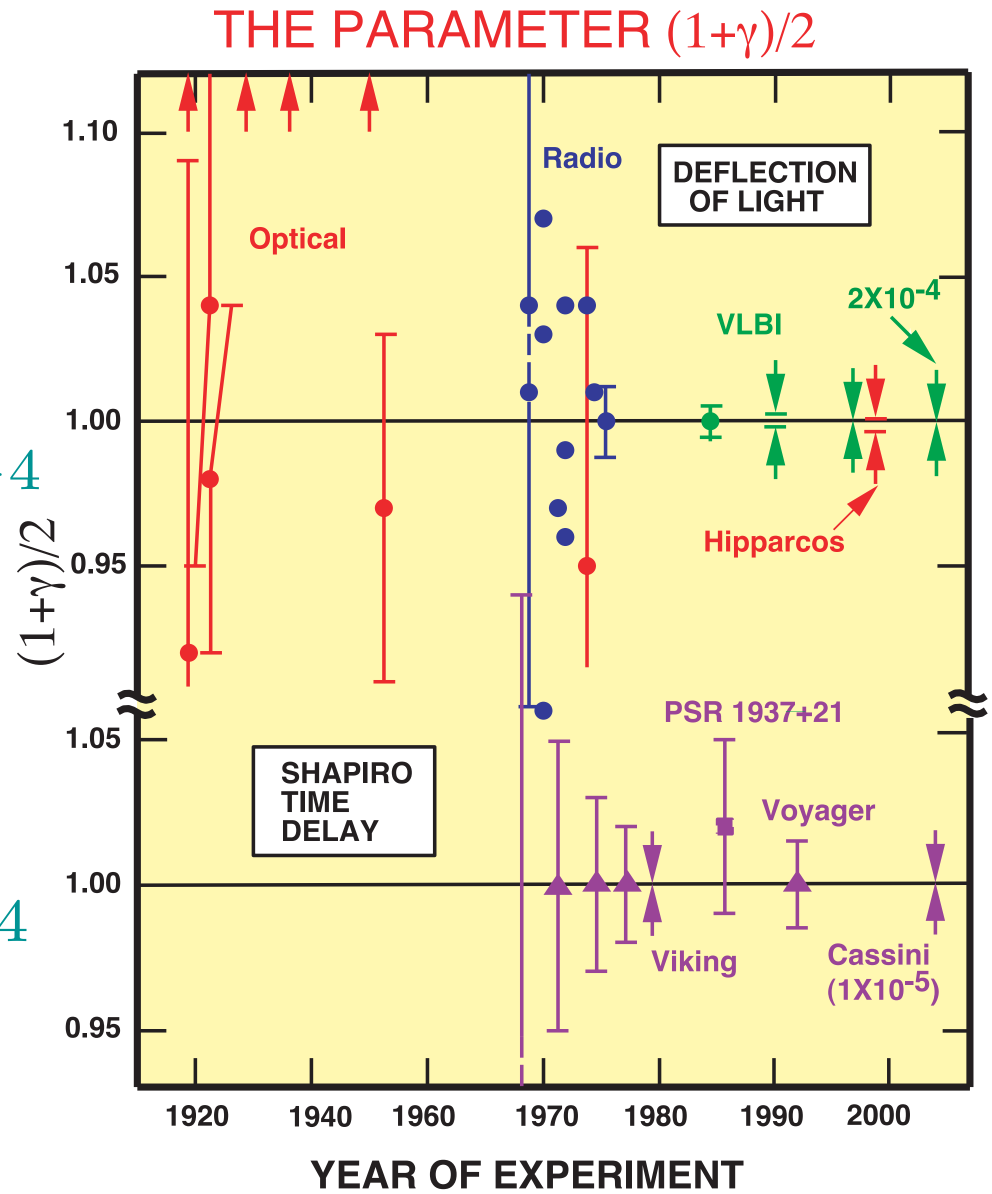
$$\gamma - 1 = (-1.7 \pm 4.5) \times 10^{-4}$$

- Time delay of light

  Cassini spacecraft

$$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-4}$$

→ $\omega > 40000$



Gravitational Wave tests of Gravitational Theory

- polarization of gravitational waves

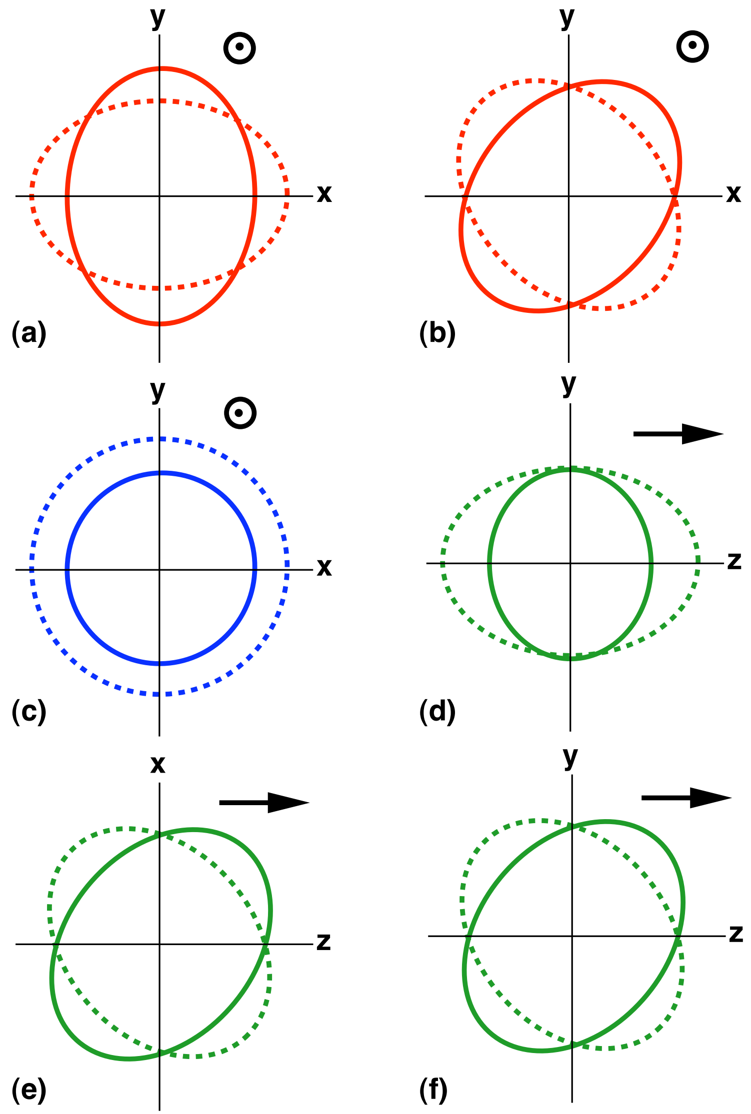
Scalar-tensor theory

⇨ 2 quadrupolar + 1 monopolar modes

3 modes + 2 direction cosines = 5 unknowns

➡ 5 detectors determine polarization

Gravitational–Wave Polarization



Gravitational Wave tests of Gravitational Theory

- gravitational radiation back-reaction

Scalar-tensor theory

⇨ Quadrupole + $\boxed{\text{dipole radiation}}$

⇨ change of motion of binary system

⇨ change of phase

Fourier transform of waveform

$$\tilde{h} = \frac{\sqrt{3}}{2}\mathcal{A}f^{7/6}e^{i\psi(f)}$$

$$\mathcal{A} = \frac{1}{\sqrt{30}\pi^{3/2}}\frac{\mathcal{M}^{5/6}}{D_L}$$

$G = 1$

$$\mathcal{M} = \eta^{3/5}(m_1 + m_2)$$

$$\eta = m_1 m_2/(m_1 + m_2)^2$$

phasing function

$$\psi(f) = \quad 2\pi f t_c - \phi_c + \frac{3}{128}(\pi\mathcal{M}f)^{-5/3}$$
$$\times\left[1 - \frac{5S^2}{84\omega}\eta^{2/5}(\pi\mathcal{M}f)^{-2/3} + \left(\frac{3715}{756} + \frac{55}{9}\eta\right)(\pi\mathcal{M}f)^{2/3}\right.$$
$$\left. -16\pi\eta^{-3/5}(\pi\mathcal{M}f) + 4\beta\eta^{-3/5}(\pi\mathcal{M}f)\cdots\right]$$

spin-orbit

$$v \sim (M/R)^{1/2} \sim (\pi\mathcal{M}f)^{1/3}$$

$S = \alpha_1 - \alpha_2 \quad \alpha_i$ "scalar charge"

$$\alpha_i = 1 - 2s_i = 1 - 2\left(\frac{\partial(\ln m_i)}{\partial(\ln G_{\mathrm{eff}})}\right)_N$$

BH: α=0 ← no-hair theorem

NS: α= 0.6-0.8

sensivity of mass to change of scalar field

⇨ BH-NS binary is the best

LISA BD bound

[Berti, Buonanno, Will, PRD71 (2005) 084025]

2PN, SNR = 10, 1 year observation time

TABLE IV. Errors and correlation coefficients in Brans-Dicke theory using 2PN templates, with and without the spin-orbit term. We consider one detector and set $\rho = 10$. In the first row we do not consider spin terms; in the second row we also include spin-orbit effects. When we include the spin-orbit term priors do not have an appreciable effect on parameter estimation. For each binary we also give the bound $\omega_{\rm BD,unc}$ that could be obtained (in principle) if all the binary parameters were known and not correlated with the BD term.

Δt_c (s)	$\Delta\phi_c$	$\Delta\mathcal{M}/\mathcal{M}$ (%)	$\Delta\eta/\eta$ (%)	$\omega_{\rm BD}$	$\Delta\beta$	$c^{\mathcal{M}\eta}$	$c^{\mathcal{M}\varpi}$	$c^{\mathcal{M}\beta}$	$c^{\eta\varpi}$	$c^{\eta\beta}$	$c^{\varpi\beta}$
$(1.4+400)M_\odot$, $\omega_{\rm BD,unc} = 43\,057\,645$											
3.82	23.2	0.000 243	0.293	765 014	⋯	−0.939	0.421	⋯	−0.705	⋯	⋯
7.95	76.7	0.00 657	2.50	39 190	0.0508	−0.997	−0.997	0.999	0.988	−0.993	−0.999
$(1.4+1000)M_\odot$, $\omega_{\rm BD,unc} = 21\,602\,414$											
3.79	16.7	0.000 189	0.116	211 389	⋯	0.845	−0.984	⋯	−0.926	⋯	⋯
7.99	58.4	0.00 764	1.86	21 257	0.0557	−0.996	−0.997	1.000	0.987	−0.998	−0.995
$(1.4+5000)M_\odot$, $\omega_{\rm BD,unc} = 6\,388\,639$											
4.60	12.5	0.000 600	0.0342	50 925	⋯	0.970	−0.998	⋯	−0.955	⋯	⋯
8.79	23.4	0.0114	1.33	6486	0.0550	−0.997	−0.997	0.999	0.988	−1.000	−0.992
$(1.4+10^4)M_\odot$, $\omega_{\rm BD,unc} = 3\,768\,347$											
6.59	13.8	0.000 877	0.0253	26 426	⋯	0.979	−0.998	⋯	−0.963	⋯	⋯
13.6	15.5	0.0178	1.61	3076	0.0706	−0.998	−0.998	0.999	0.991	−1.000	−0.993

Spin-Orbit term reduces BD bound

High Energy Neutrino

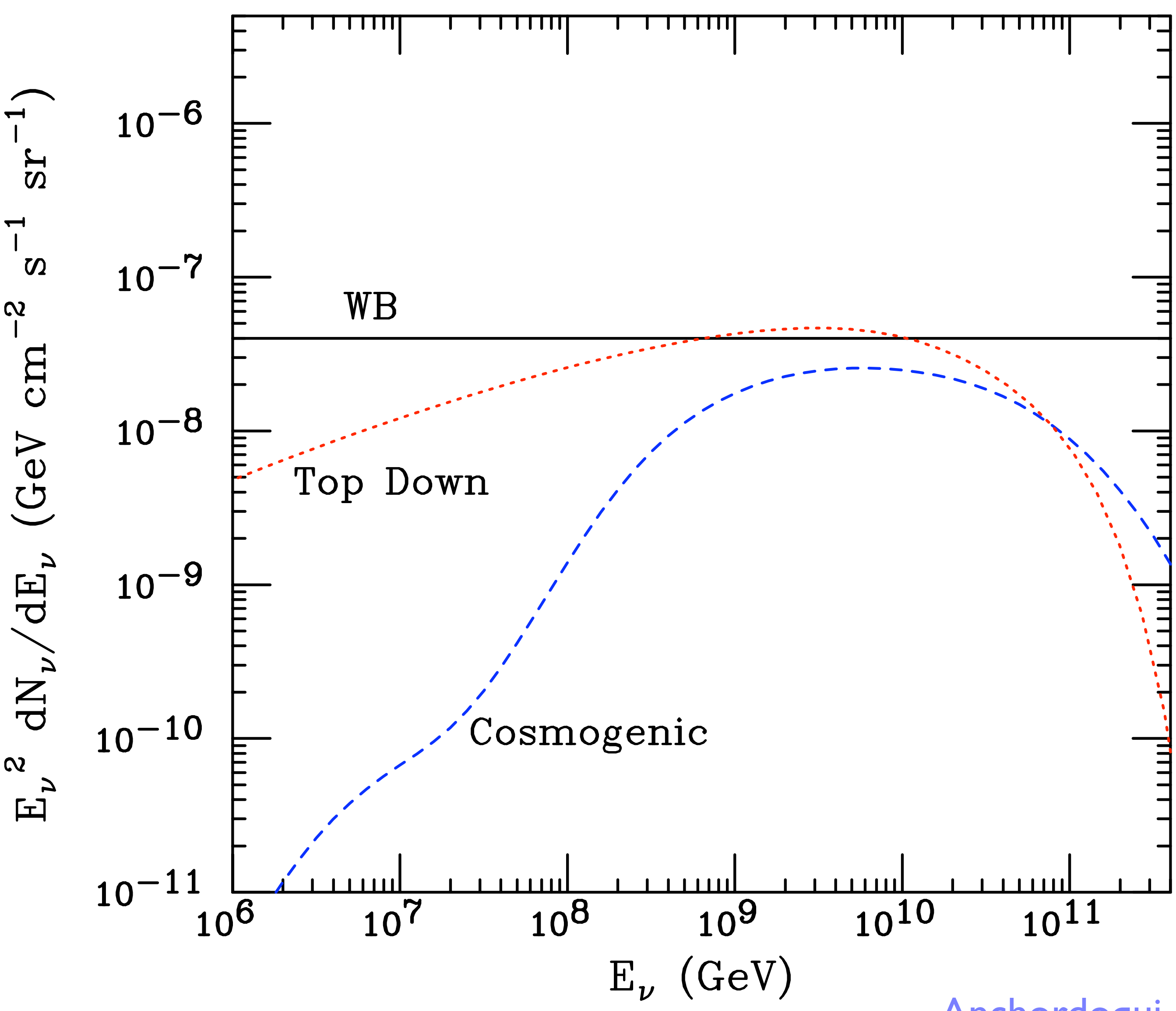
High Energy Neutrino

- Cosmogenic neutrino $p + \gamma_{\mathrm{CMB}} \to \pi + \cdots \to \nu + \cdots$
- Waxman and Bahcall

  optically thin to protons $E_\nu^2 dN_\nu / E_\nu \simeq 10^{-8}$ GeV $(\mathrm{cm}^2 \text{ s sr})^{-1}$
- EGRET bound

  optically thick to proton but thin to γ ~WB X 40
- Hidden source
- Top down (decay of superheavy particles…)

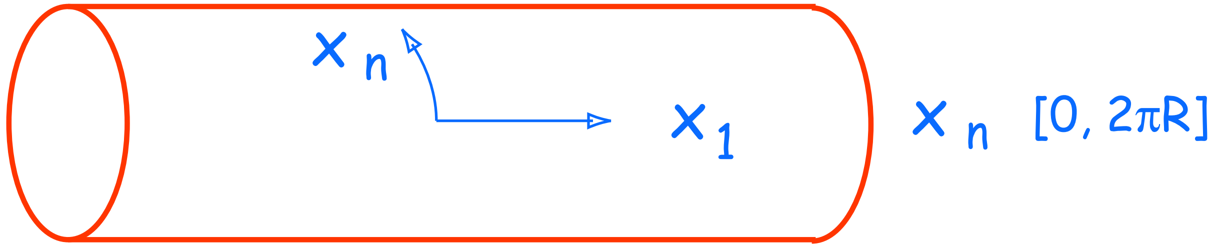
Ultra-high energy cosmic neutrino spectrum



Anchordoqui et al hep-ph/0508321

Black Hole Formation in TeV Gravity

Large Extra Dimension



Gravitational Force

$$\boxed{\begin{aligned} F &= G_N \frac{m_1 m_2}{r^2} && r \gg R \\ F &= \frac{1}{4\pi M_*^{n+1}} \frac{m_1 m_2}{r^{2+n}} && r < R \end{aligned}}$$

$$\Rightarrow \quad (4\pi G_N)^{-1} = R^n M_*^{n+2}$$

$$M_* = 1\ \text{TeV} \quad \Rightarrow \quad \boxed{R \sim 10^{\frac{30}{n} - 17}\text{cm}}$$

$$n = 2 \qquad R \sim 1\text{mm}$$

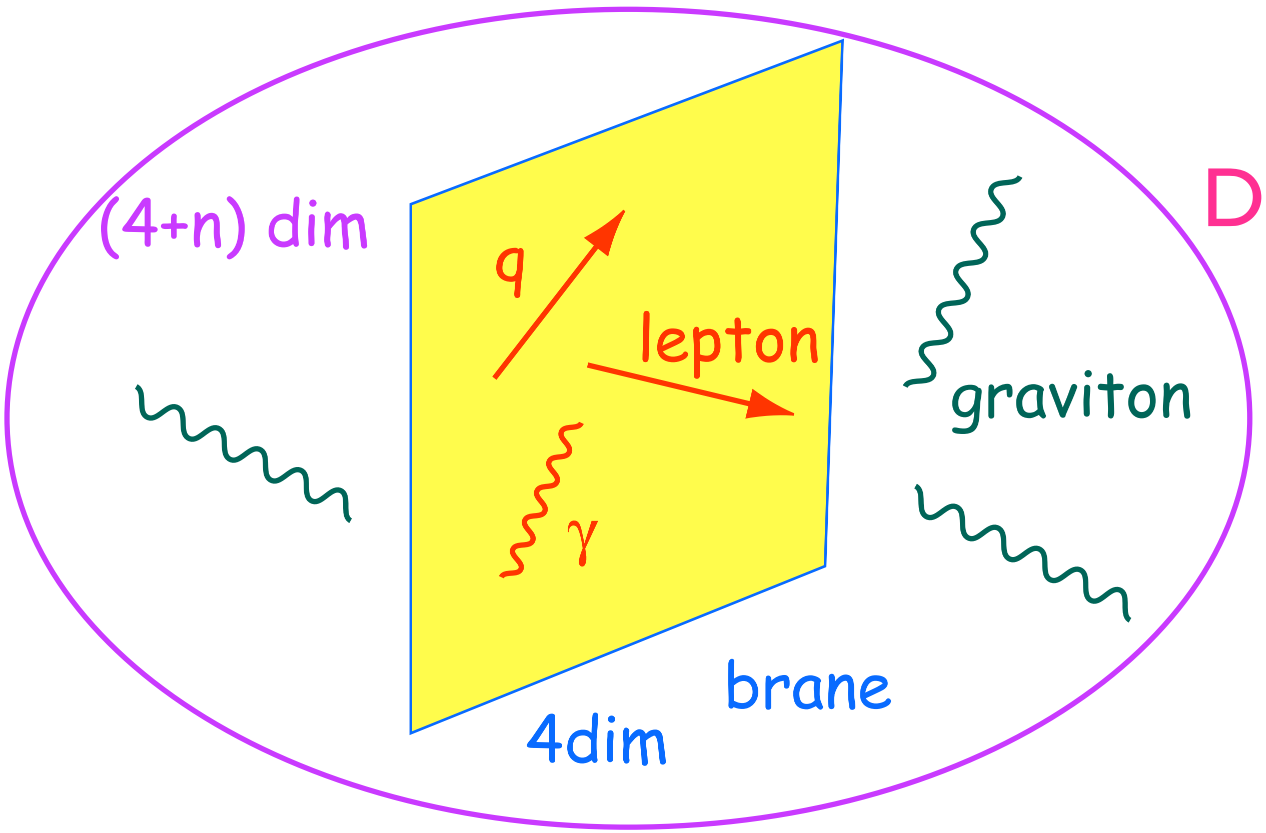
$$n = 7 \qquad R \sim 10^{-13}\text{mm}$$

LEP, TEVATRON

Strong, electroweak interaction

→ 4-dimensional for E < 1TeV

➡ Quarks, Leptons, Gauge Bosons are confined in 4-dim submanifold



D-Brane in Superstring Theory

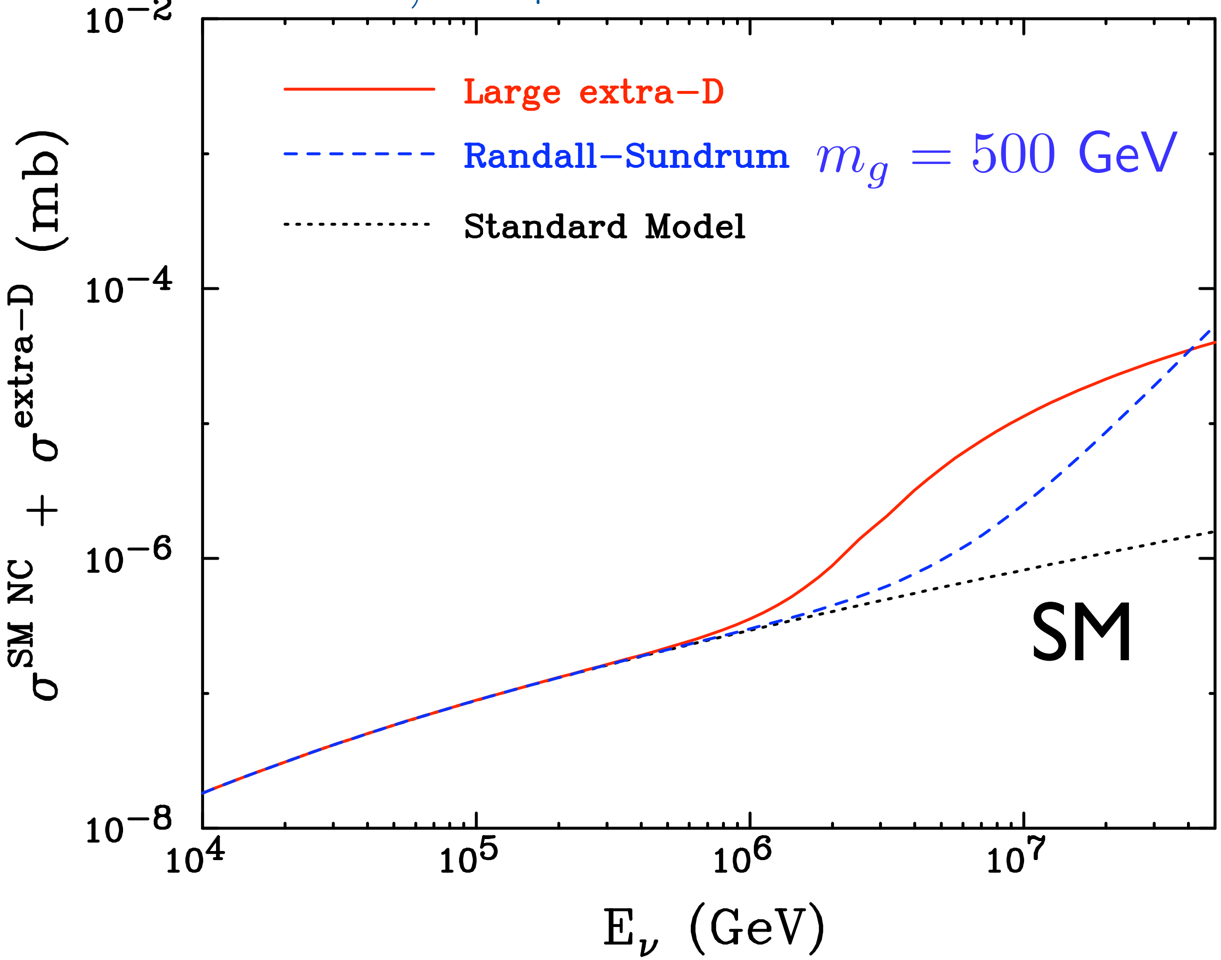
KK gravitons

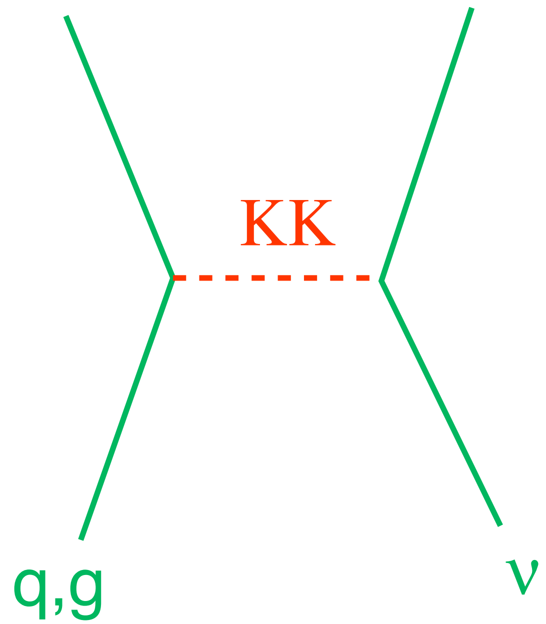
Extra-dimensions ⟹ KK-mode with mass 1/R

neutrino-nucleon scattering

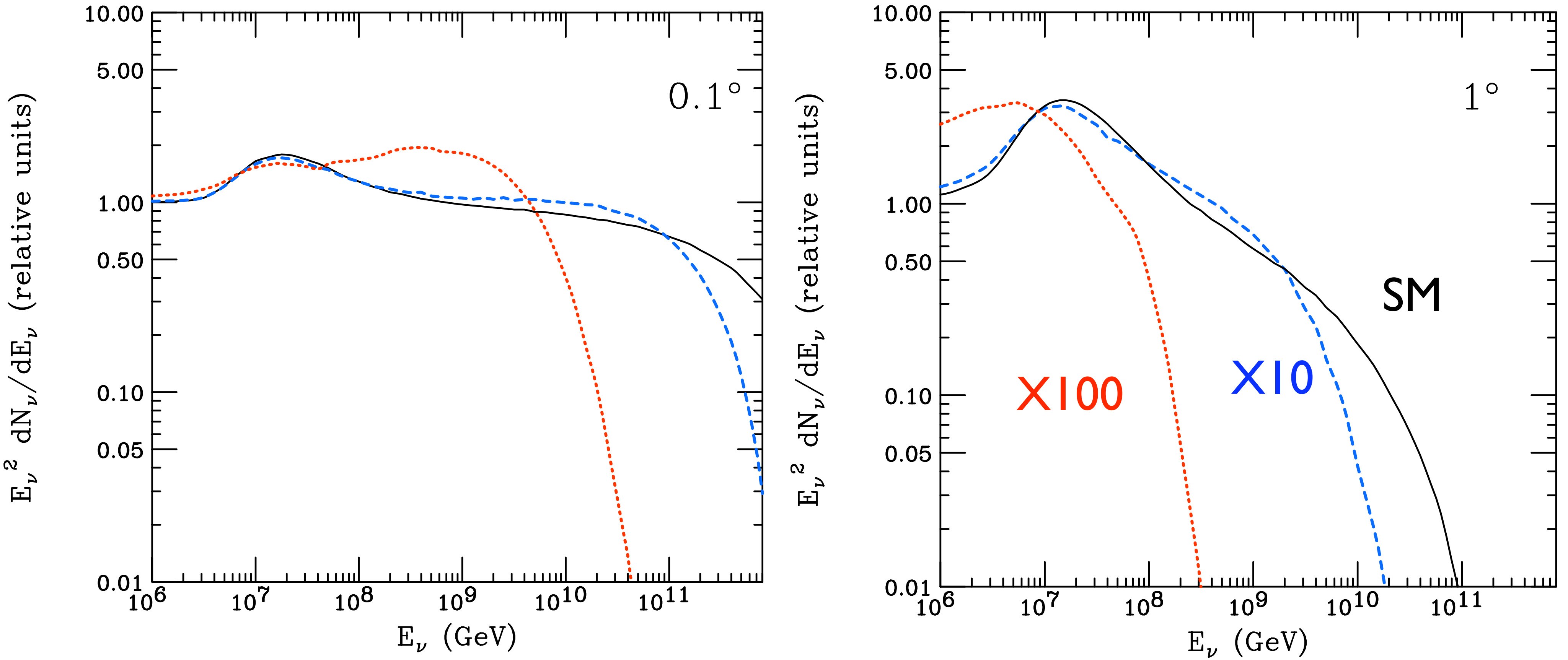
$$\boxed{\sigma \sim (ER)^n / M_{pl}^2 \sim E^n / M_*^{n+2}}$$

$n = 6,\ M_* = 1$ TeV





Earth-skimming tau spectrum at Auger



suppression of Earth-skimming tau spectrum

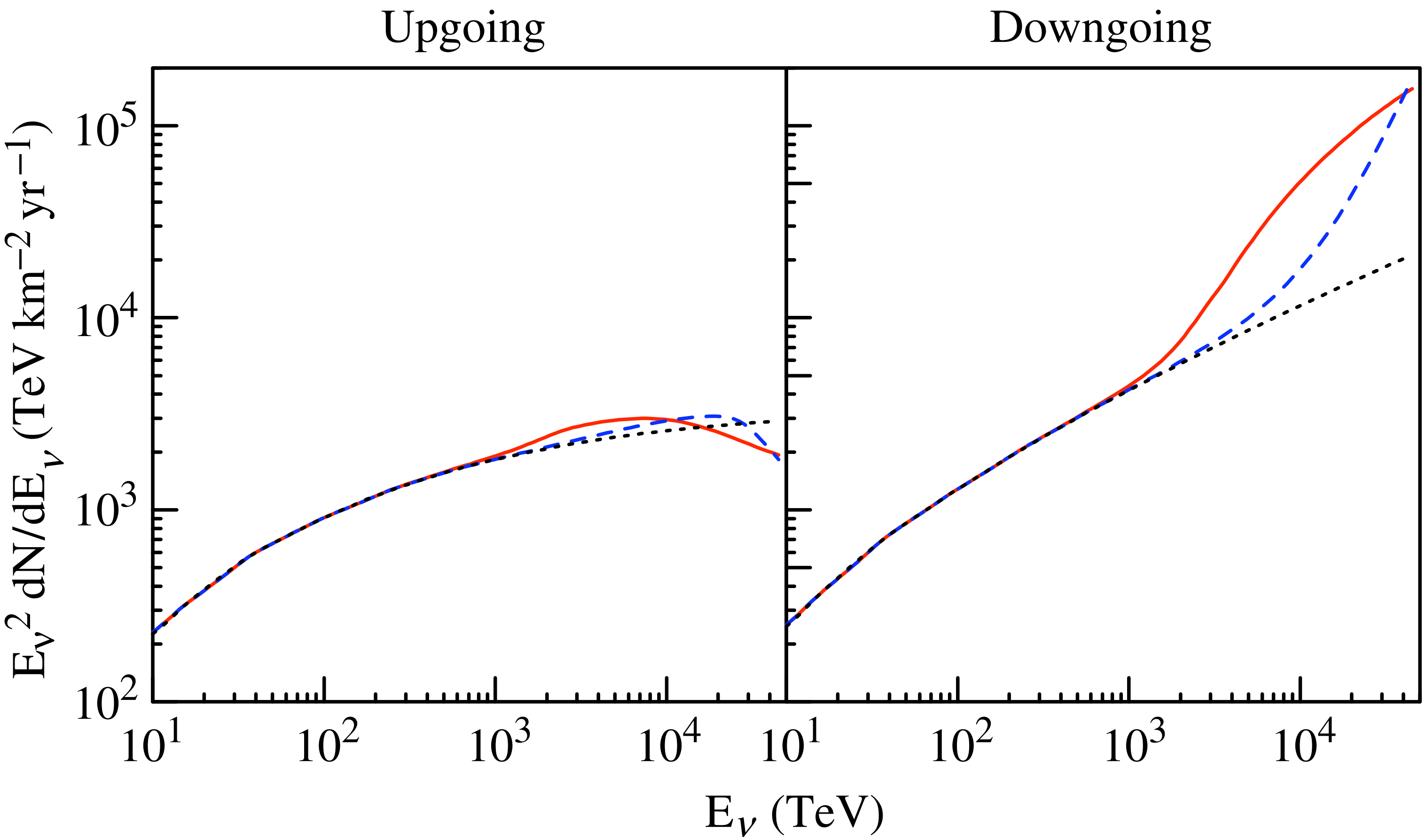
↕

enhance of quasi-horizontal showers

$\sigma_{\nu N}$	Quasi-horizontal	Earth-skimming ν_τ	Ratio
Standard Model	0.067	1.3	0.05
SM $\times$ 3	0.096	1.1	0.09
SM $\times$ 10	0.20	0.68	0.29
SM $\times$ 100	1.5	0.081	19

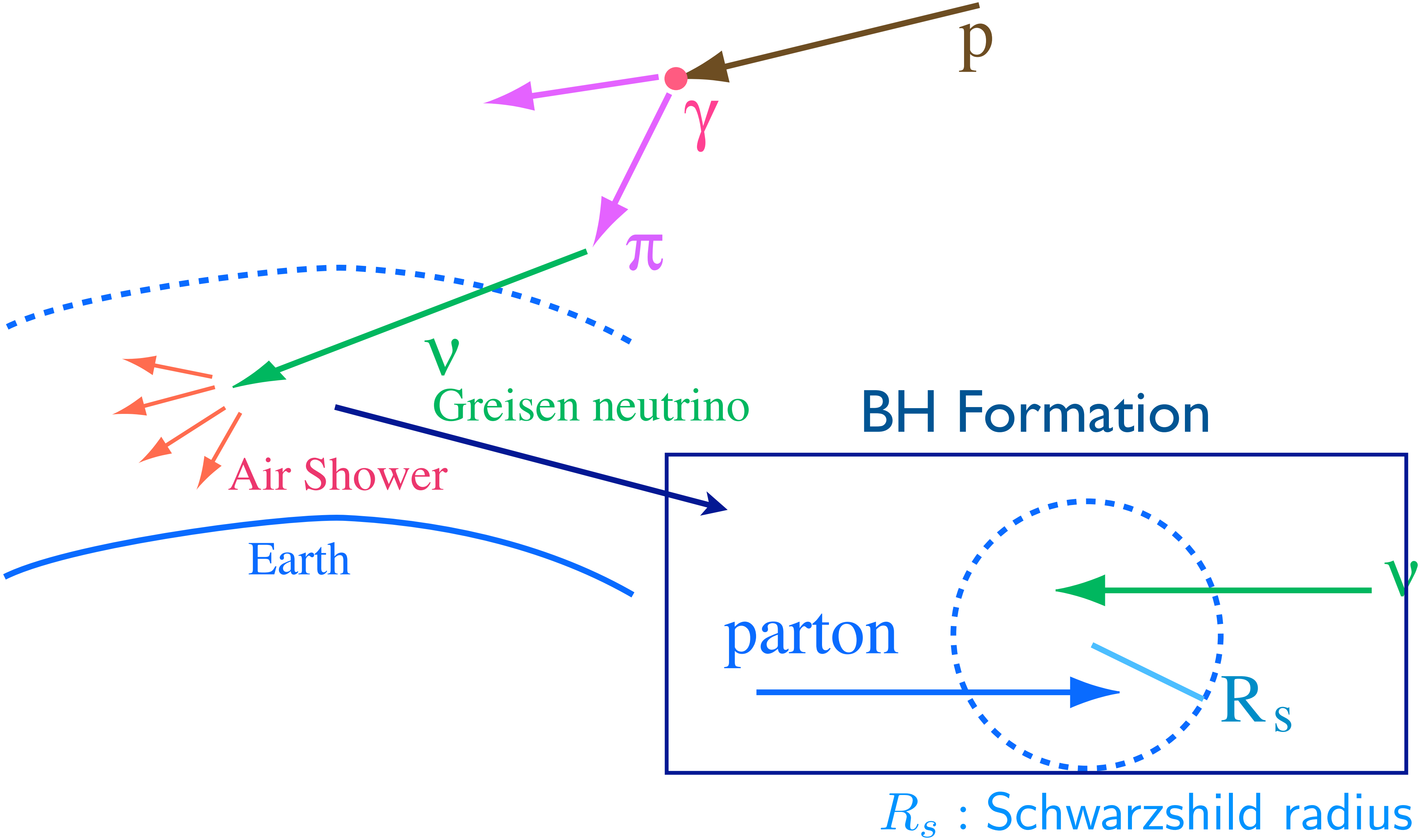
Anchordoqui et al hep-ph/0508321

$\nu_\mu + \bar{\nu}_\mu$ events in IceCube



[Alvarez-Muniz et al PRL 88 (2002) 021301]

BH Production by Cosmic Rays



Schwarzshild Radius in (4+n) dim.

gravitaional potential

$$U_{4+n}(r) \sim \frac{1}{M_*^{2+n}} \frac{M}{r^{n+2}}$$

Equating kinetic energy of a particle moving at the speed of light,

$$\frac{1}{2}mc^2 \sim \frac{mM}{M_*^{n+2} r^{n+1}} \Longrightarrow R_s \sim \frac{1}{M_*} \left(\frac{M}{M_*} \right)^{\frac{1}{n+1}}$$

$$\boxed{R_s = \frac{1}{M_*} \left[\frac{M}{M_*} \left(\frac{2^{n+1} \pi^{(n-3)/2} \Gamma((n+3)/2)}{n+2} \right) \right]^{\frac{1}{n+1}}}$$

Cross Section

geometric cross section

Parton-neutrino cross section

$$\sigma(i\nu \to BH) \simeq \pi R_s^2(xs) \quad i$$: i-th parton

$$s = 2m_N E_\nu$$ R_s : Schwarzshild radius

Nucleon-neutrino cross section

$$\boxed{\sigma(N\nu \to BH) = \sum_i \int_{M_{(BH,min)}^2/s}^{1} dx\ \sigma(i\nu\nu \to BH) f_i(x)}$$

$f_i(x)$: parton distribution function (PDF)

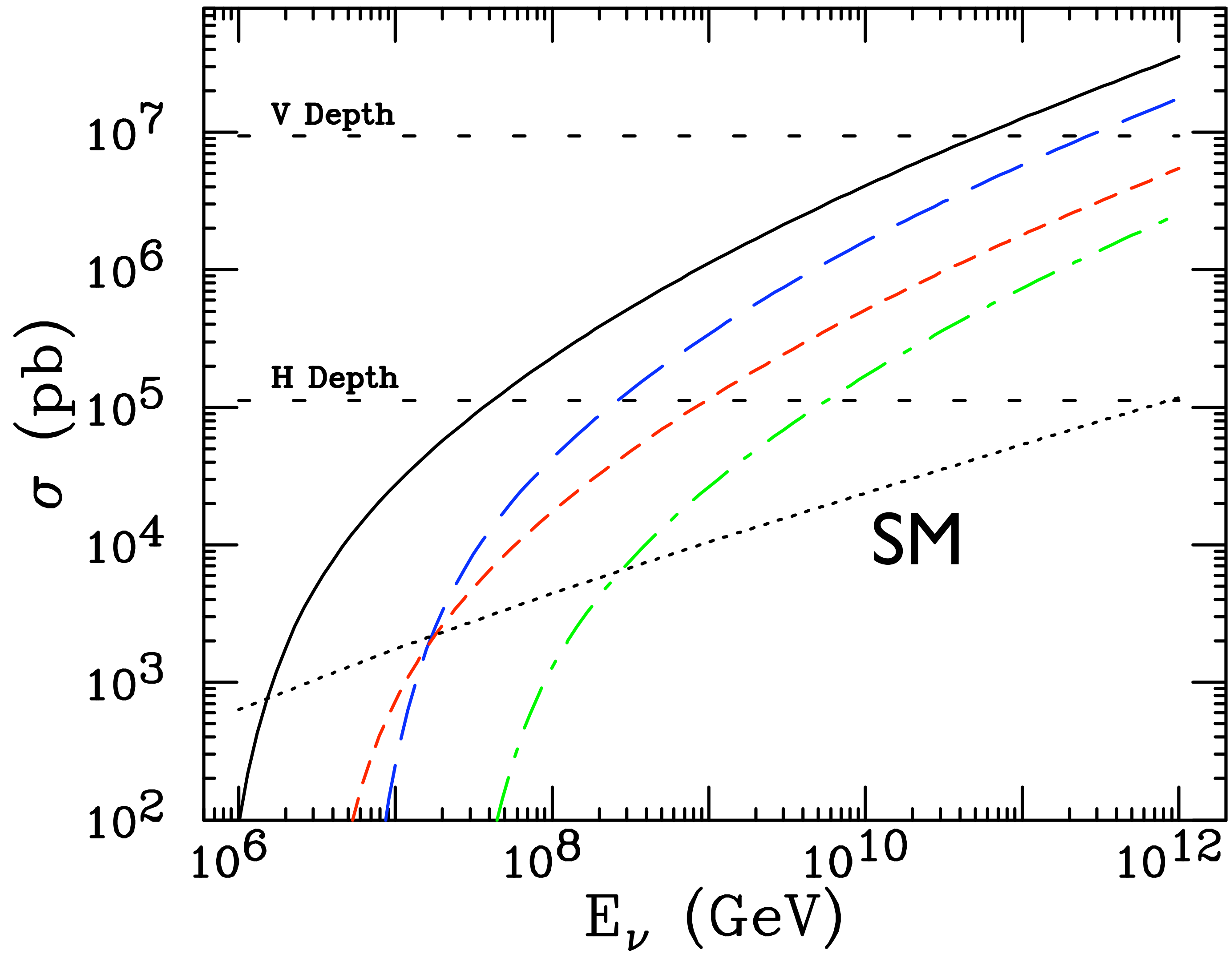
$$x_{\mathrm{min}} \equiv M_{B,\mathrm{min}}/M_*$$

$\longleftrightarrow$ SM Process $\nu N \to \ell N$

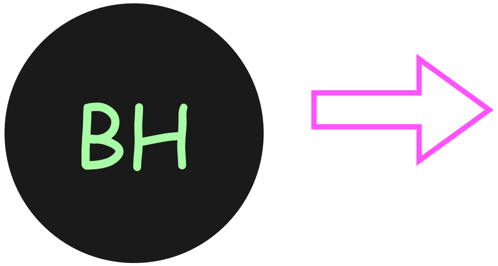
$\sigma_{BH} \gg \sigma_{SM}$ for high energy neutrino

$n = 6$

$(M_*, x_{\min}) = (1\text{TeV}, 1)$ $(1\text{TeV}, 3)$ $(2\text{TeV}, 1)$ $(2\text{TeV}, 3)$



Hawking Radiation



Hawking Radiation

- Temperature

$$T_H = M_* \left(\frac{M_*}{M_{BH}} \frac{n+2}{2^{n+1}\pi^{(n-3)/2}\Gamma((n+3)/2)} \right)^{\frac{1}{n+1}} \frac{n+1}{4\pi} = \frac{n+1}{4\pi R_s}$$

- Lifetime

$$\tau \sim \frac{1}{M_*} \left(\frac{M_{BH}}{M_*} \right)^{\frac{3+n}{n+1}} \sim 10^{-27}\text{sec} \left(\frac{M_{BH}}{M_*} \right)^{\frac{3+n}{n+1}}$$

- Average multiplicity

$$\langle N \rangle \sim \langle M_{BH}/T_H \rangle \quad 10 \text{ TeV BH} \Rightarrow \langle N \rangle \sim 50$$

Detection

BH decay $\Rightarrow$ 10% charged leptons
75% hadronic

- Neutrino telescope (IceCube, …)

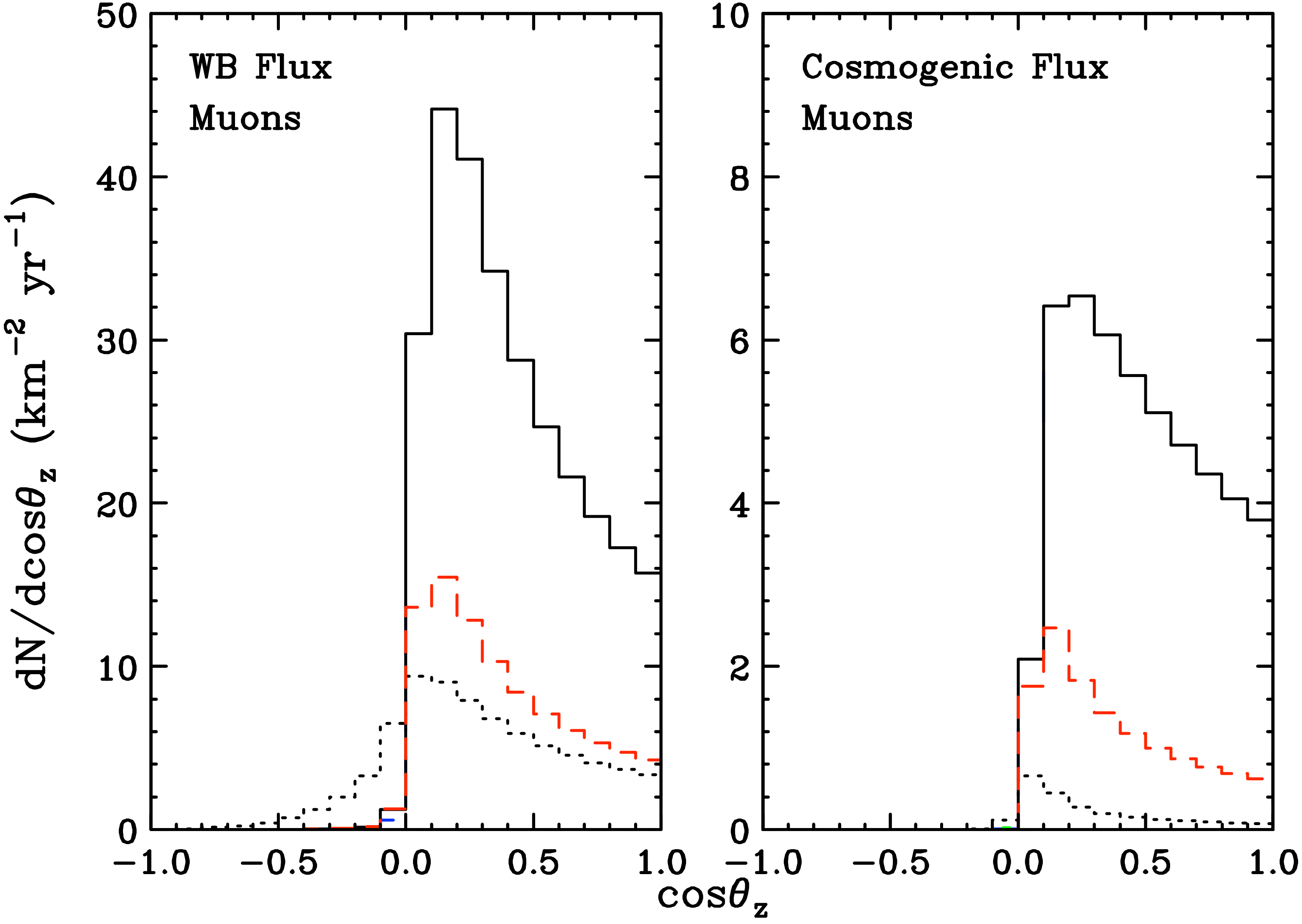
  muon track, tau event

- Air shower experiments (AGASA,…)

  neutrino-like event

Angular distribution of muon tracks above 500TeV

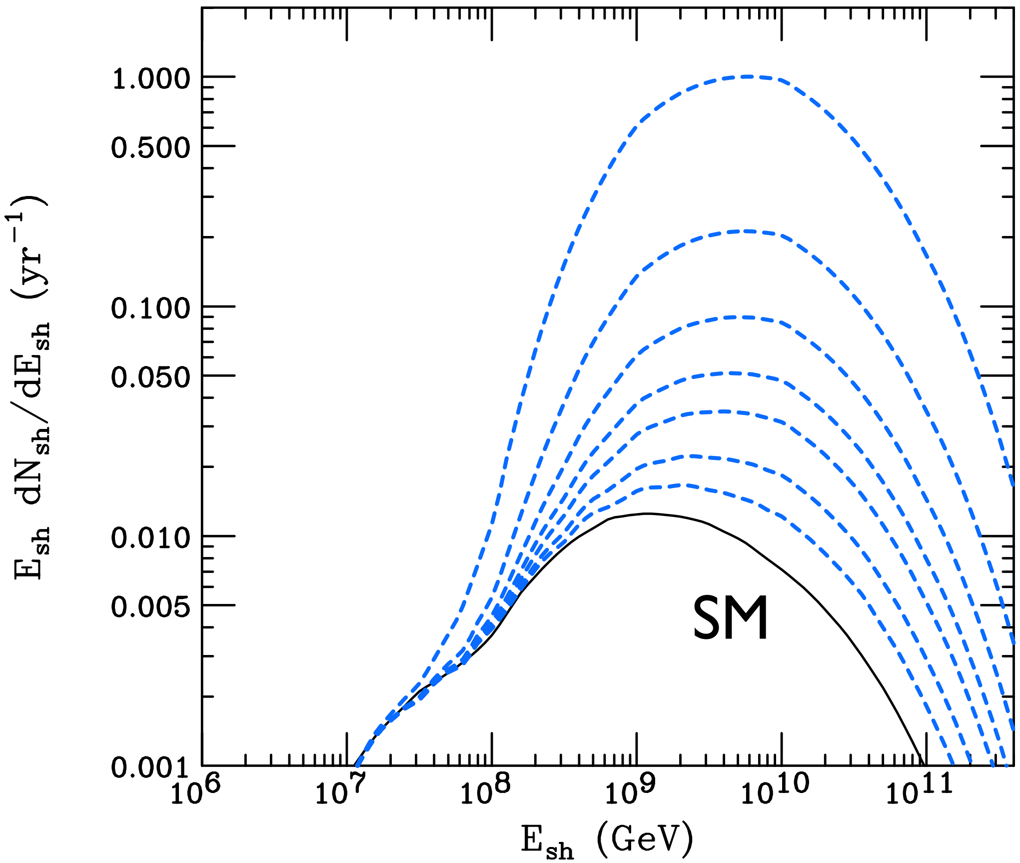
$M_* = 1$ TeV, $x_{\min} = 1$ $x_{\min} = 3$



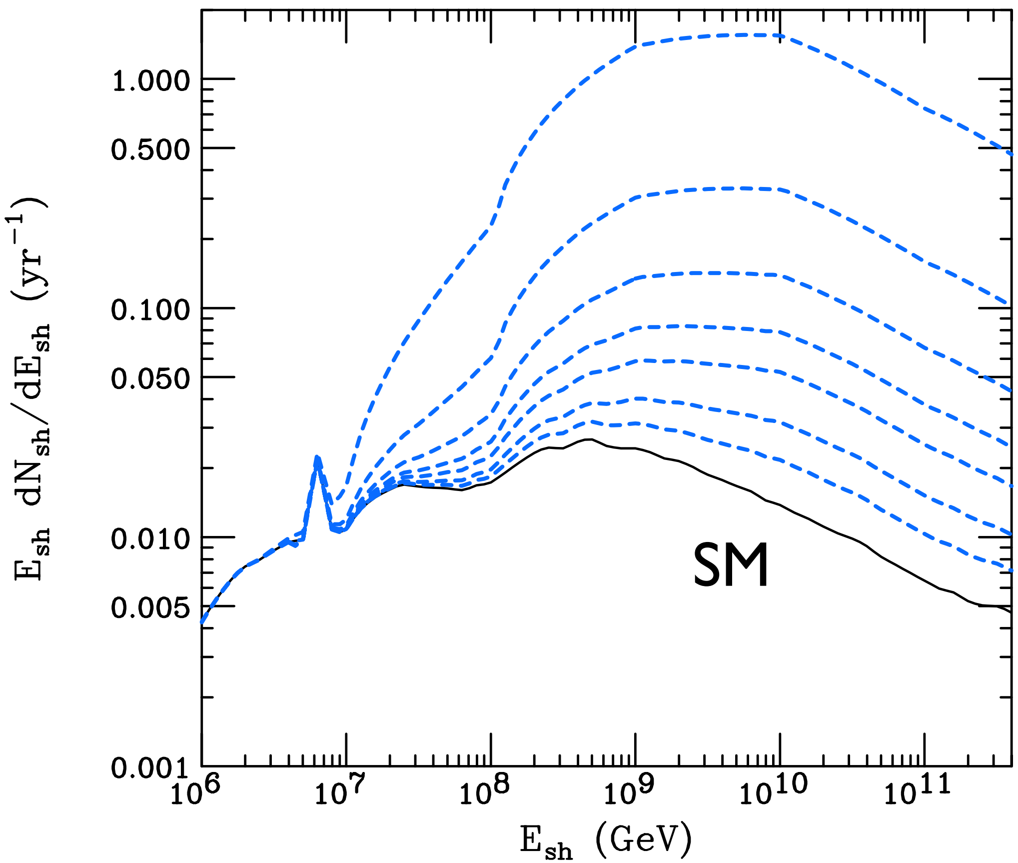
[Alvarez-Muniz et al PRD65 (2002) 124015]

Showers seen by Auger (quasi-horizontal showers)

cosmogenic



Waxman-Bahcall



$M_* = 10, 7, 5, 4, 3, 2, 1$ TeV (from below)

$x_{\text{min}} = 3$

[Anchordoqui et al hep-ph/0508312]

Showers seen by Auger (Earth skimming tau neutrino)

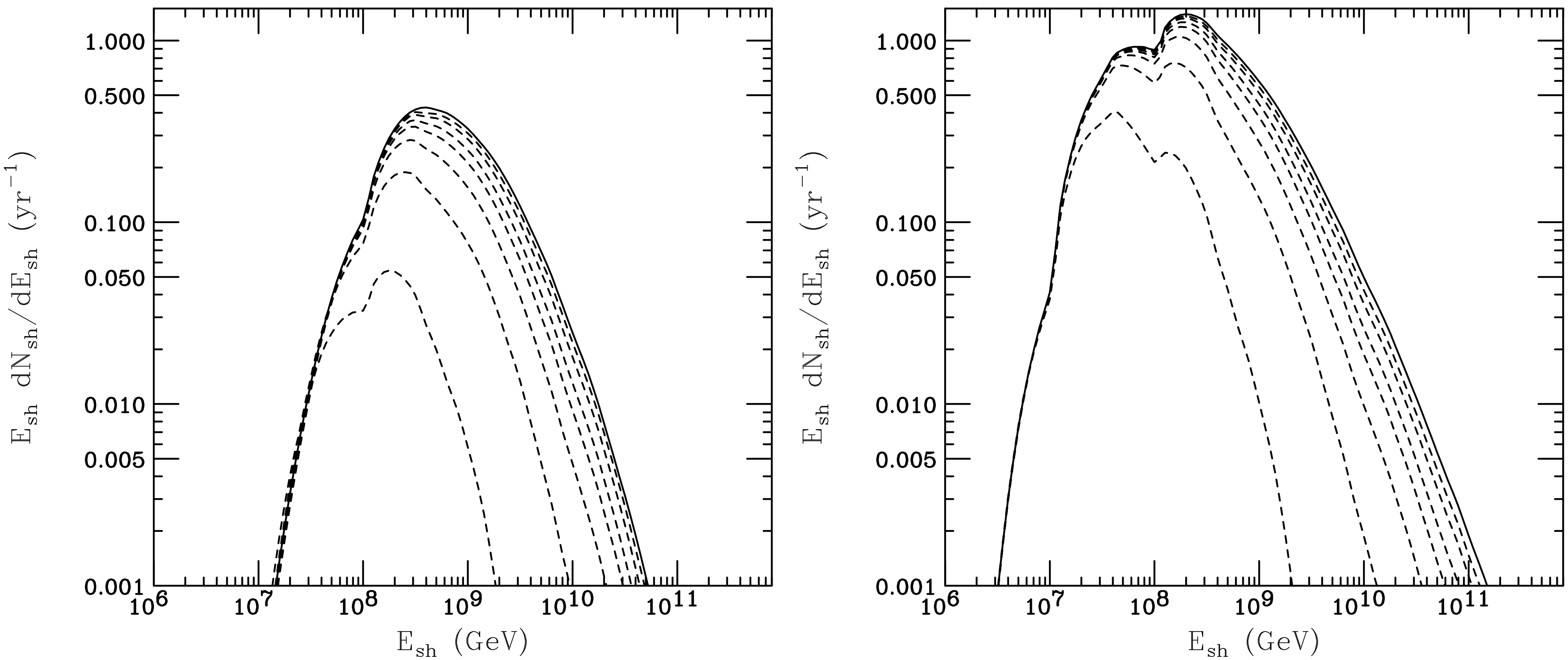


FIG. 13: The spectrum of Earth skimming, tau neutrino black hole induced showers as would be seen by Auger for the cosmogenic flux (left) and the Waxman-Bahcall flux (right). The dashed lines indicates different values of the fundamental Planck scale (from below M_{10} = 1, 2, 3, 4, 5, 7, 10 TeV; in all cases $M_{\rm BH,min} = 3M_{10}$), while the solid line is the SM prediction.

[Anchordoqui et al hep-ph/0508312]

Inflation Models

Inflation models

Inflation

- Chaotic Inflation
  - natural (no initial value problem)
  - take place at planck time
  - inflaton $\phi > M_G$
- Hybrid Inflation
  - initial value problem
  - cosmic string
- New Inflation
  - severe initial value problem
  - flatness (longevity) problem

Hubble

High

$\updownarrow$

Low

Flat Potential $\Rightarrow$ SUSY $\quad$ η problem

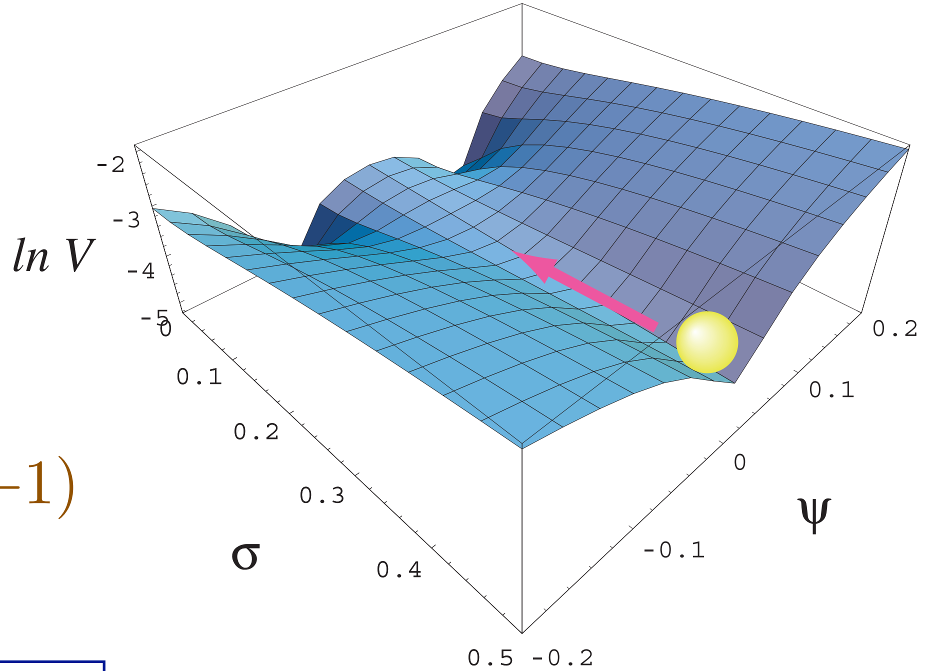
Hybrid inflation in supergravity

superpotential

$$\boxed{W = \lambda S \bar{\Psi}\Psi = \mu^2 S}$$

R charge $S(+2)\ \Psi\bar{\Psi}(0)$

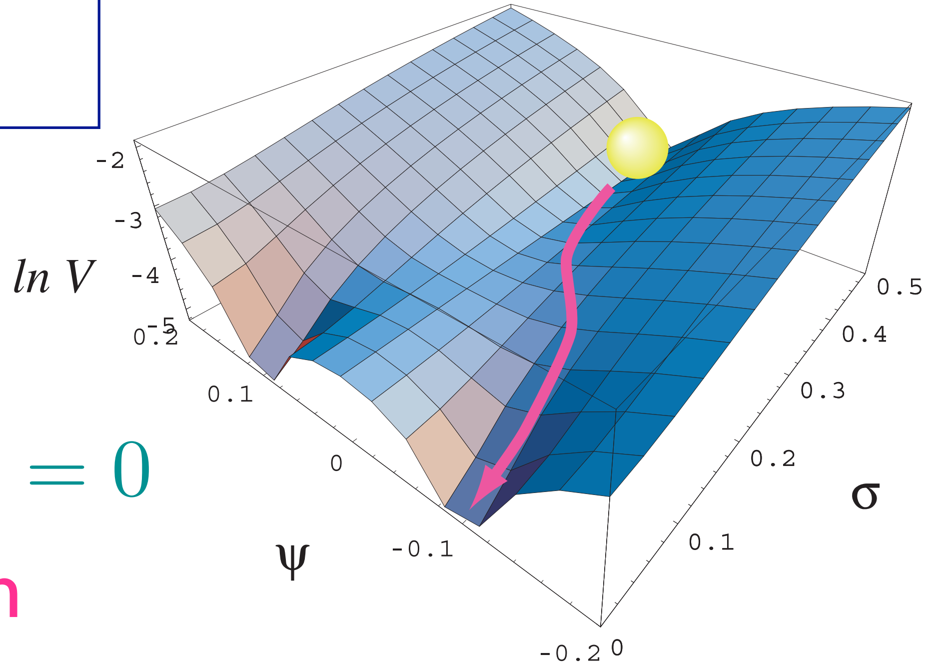
$U(1)$ gauge int $S(0)\ \bar{\Psi}(-1)\ \Psi(+1)$



Köhler potential

$$\boxed{K = |S|^2 + |\bar{\Psi}|^2 + |\Psi|^2}$$

scalar potential



$$\sigma = ReS/\sqrt{2}$$

$$\sigma > \sigma_c \sqrt{2}\mu/\lambda \ \Rightarrow\ \bar{\Psi} = \Psi = 0$$

flat potential ⇒ inflation

spectral index $n_s \simeq 0.98 - 1.0$

Chaotic Inflation in Supergravity

MK, Yamaguchi, Yanagida PRD63 (2001)103514

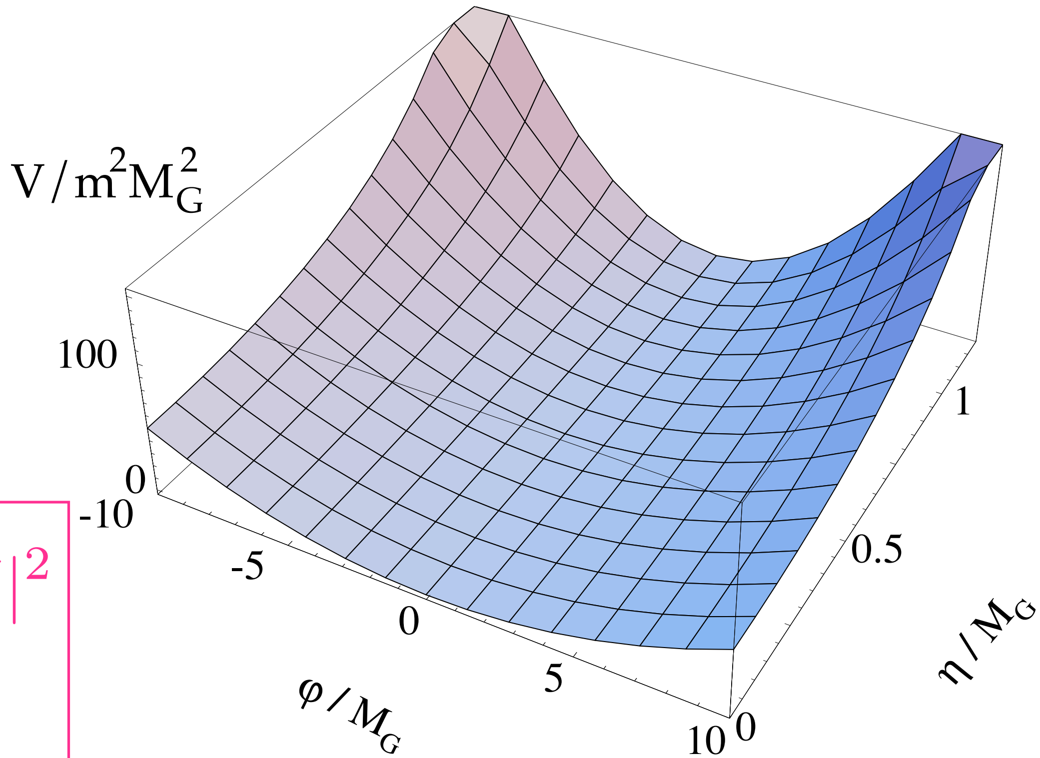
Shift symmetry $\Phi \rightarrow \Phi + iC$

Köhler potential

$$\boxed{K = (\Phi + \Phi^*)^2}$$

superpotential

$$\boxed{W = mX\Phi}$$

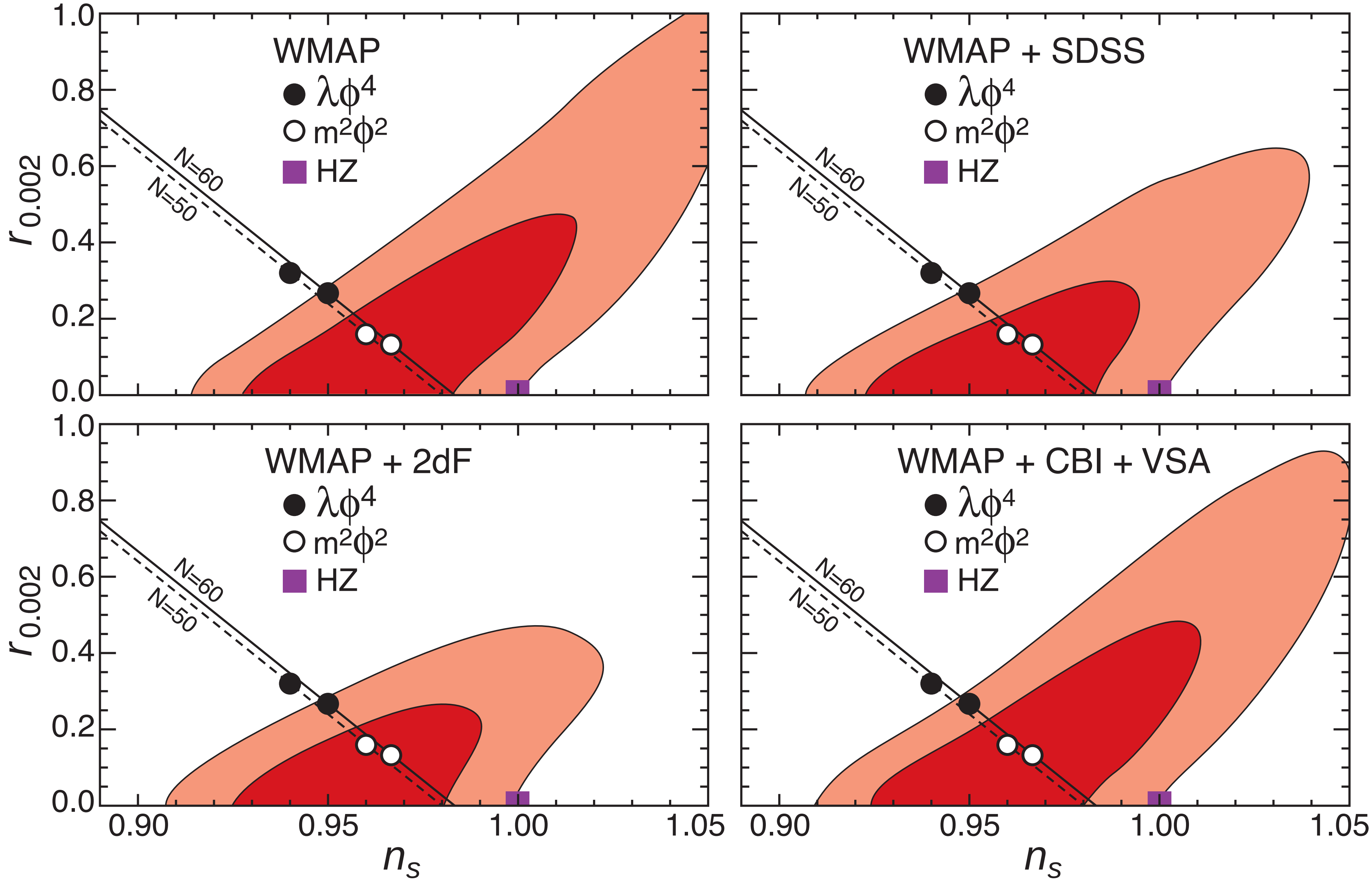


$$V(\eta = 0, \varphi, X) \simeq \frac{1}{2} m\varphi^2 + m^2|X|^2$$

$$\Phi = \eta + i\varphi$$

spectral index $n_s \simeq 0.96$

WMAP three years data



Spergel et al (2006)

Axion

Axion and Strong CP Problem

QCD $$\boxed{\mathcal{L} = \mathcal{L}_{\theta=0} + \theta \frac{g^2}{32\pi^2} F^{a\mu\nu} \tilde{F}^a_{\mu\nu}}$$

~~CP~~

Experiment $\Rightarrow$ $\theta \lesssim 10^{-9}$

Why is θ so small? $\Rightarrow$ strong CP problem

The only known solution to strong CP prob.

Peccei-Quinn Mechanism

$\Rightarrow$ AXION

Peccei-Quinn Mechanism

- Introduce U(1) and make θ dynamical variable

$$a \equiv F_a \theta \qquad \Phi_a = |\Phi_a| e^{i\theta} \qquad F_a : \text{PQ scale}$$

- Spontaneous symmetry breaking of U(1) at F_a

$$\langle \Phi_a \rangle \neq 0$$

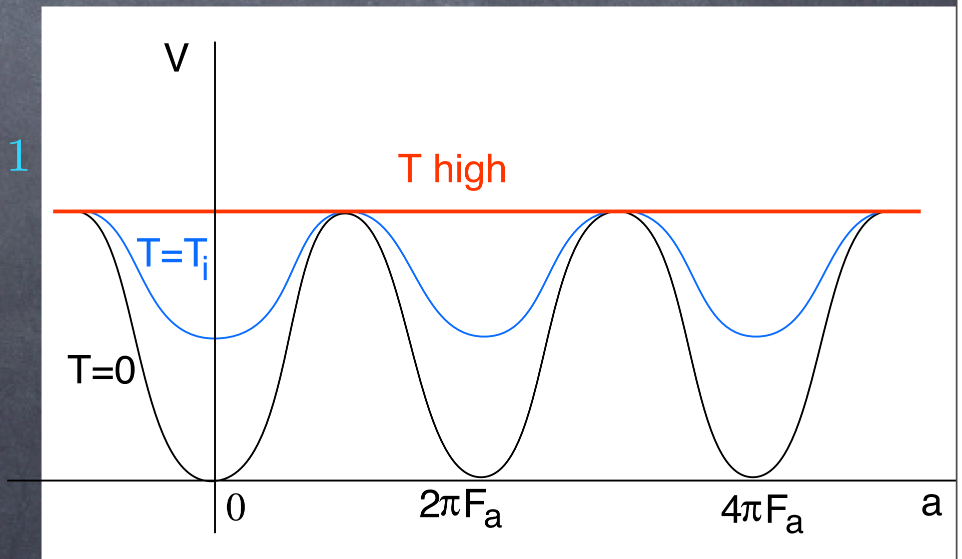
Nambu-Goldstone boson = AXION

- QCD instantton effect

$$m_a = 0.62 \times 10^{-5} \text{eV} \left(\frac{F_a}{10^{12} \text{GeV}} \right)^{-1}$$

- Minimum of θ potential

⇨ θ=0



Constraints on PQ scale

- Astrophysics SN198A Cooling

$$F_a \gtrsim 10^{10}\ \text{GeV}$$

- Cosmology (~~PQ~~ after inflation)
  - Coherent oscillation

$$F_a < (1-5)\times 10^{11}\ \text{GeV}$$

  - Axions from axionic strings

$$F_a < (2.4 \pm 1.4)\times 10^{11}\ \text{GeV}$$

Yamaguchi,MK,Yokoyama
PRL 82 (1999)4578

  - Axions from domain walls

$$\boxed{F_a \simeq (1-30)\times 10^{10}\ \text{GeV}}$$

Constraints on PQ scale

- Astrophysics   SN198A Cooling

$$F_a \gtrsim 10^{10}\ \text{GeV}$$

- Cosmology (~~PQ~~ before inflation)
  - Coherent oscillation

$$F_a < (0.3 - 1.4) \times 10^{12} \theta^{-1.7}\ \text{GeV}$$

$$\boxed{F_a \simeq (0.01 - 1.4\theta^{-1.7}) \times 10^{12}\ \text{GeV}}$$

Relax the cosmological bound on PQ scale

MK, Moroi, Yanagida PLB384 (1996)313

Entropy Production $\Rightarrow$ dilute axions

$$\Omega_a h^2 \simeq 5.3 \left(\frac{T_R}{\mathrm{MeV}}\right)\left(\frac{F_a\theta}{10^{16}\mathrm{GeV}}\right)^2$$

$$\Rightarrow \boxed{F_a\theta < 1.6\times 10^{15}\,\mathrm{GeV}\left(\frac{T_R}{\mathrm{MeV}}\right)^{-1/2}}$$

Even huge entropy production cannot dilute axions completely

PQ symmetry breaking before inflation

$$F_a \simeq (0.01 - 1.4\theta^{-1.7}) \times 10^{12} \text{ GeV}$$

⇒ Large isocurvature fluctuations

During inflation $$\frac{\delta a}{a} \simeq \frac{\delta\theta}{\theta} \simeq \frac{H}{2\pi}\frac{1}{F_a\theta}$$

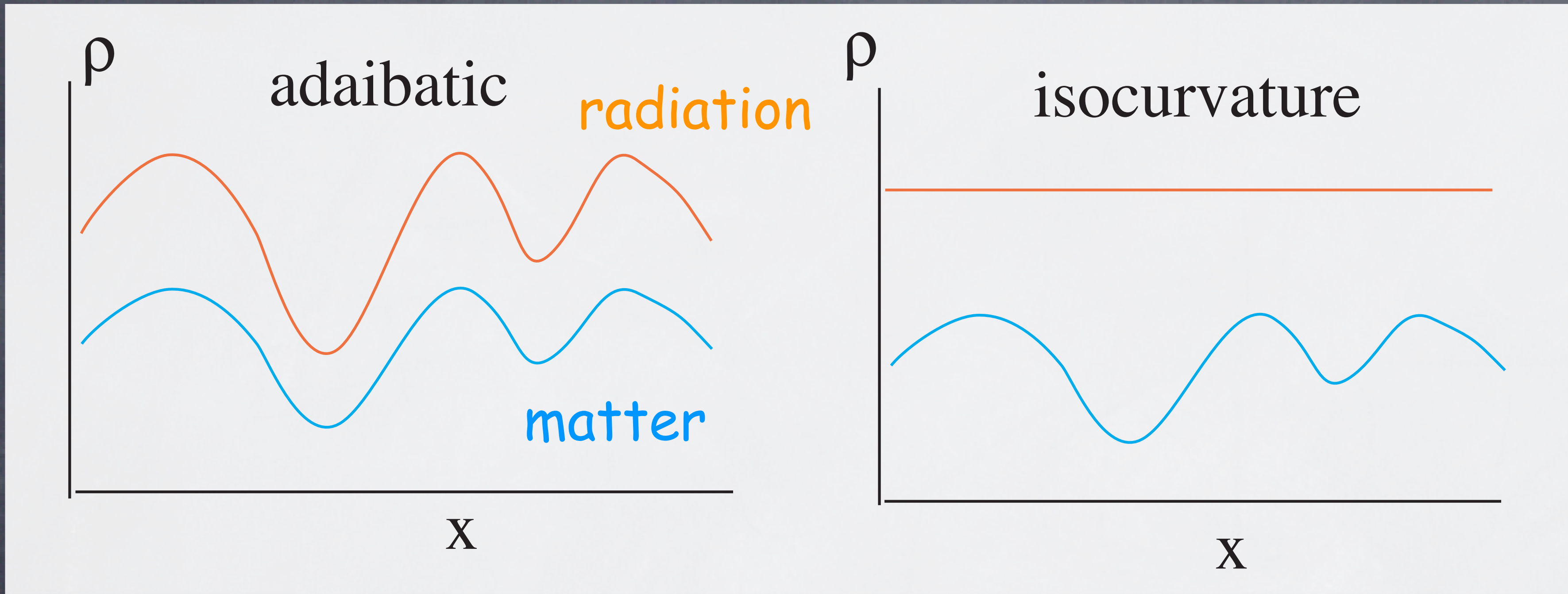
After QCD phase transition $$\frac{\delta\rho_a}{\rho_a} \simeq 2\frac{\delta\theta}{\theta} \simeq \frac{H}{\pi F_a\theta}$$

$$H \sim 10^{10} \text{ GeV} F_a \sim 10^{12}\text{GeV} \Rightarrow \delta_a \sim 10^{-2}$$

⇒ Axionic isocurvature can be observed in CBM spectrum

Isocurvature Perturbations

adiabtic vs isocurvature

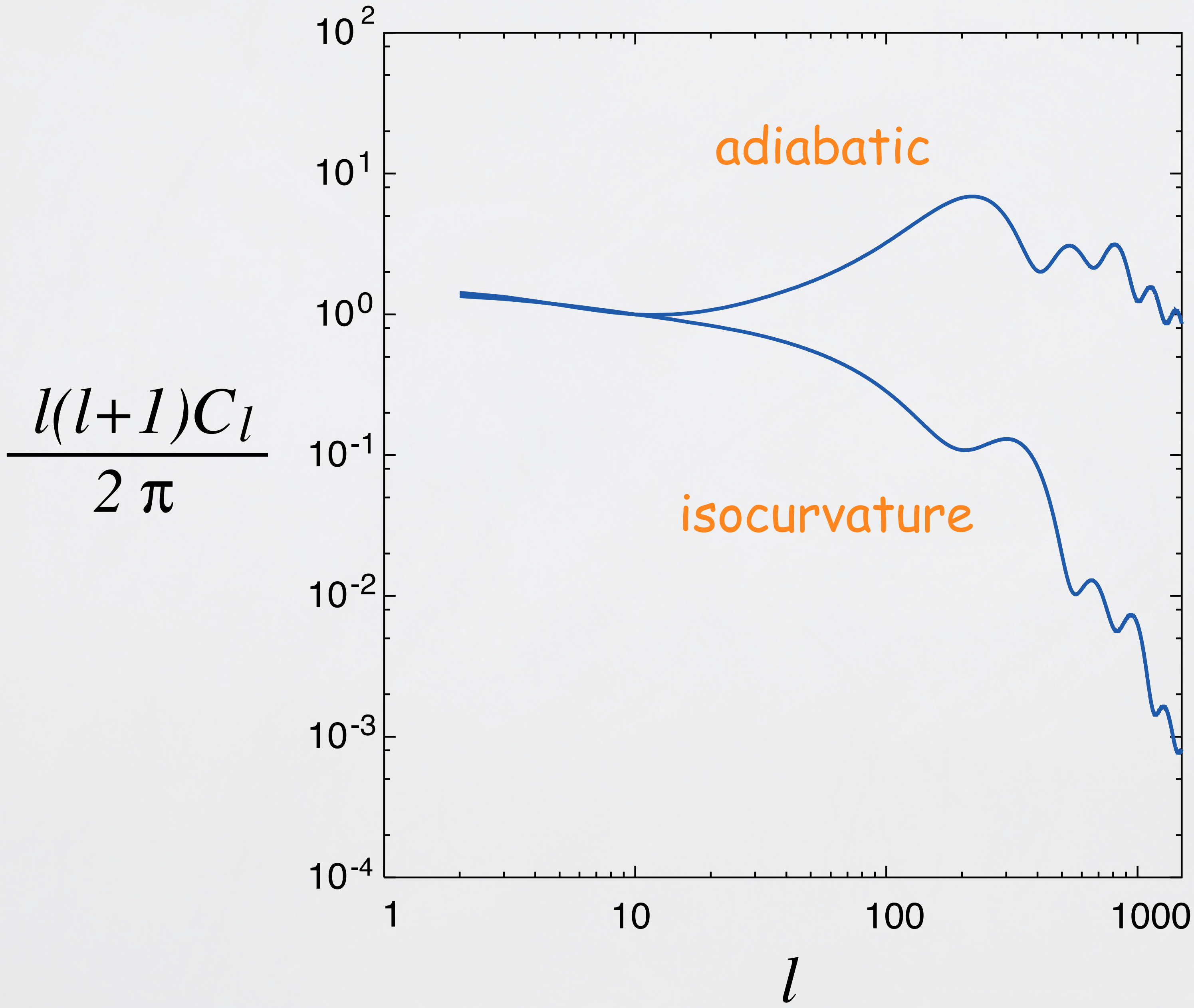


$$S_{m\gamma} = \frac{\delta(n_m/n_\gamma)}{n_m/n_\gamma} = \frac{\delta\rho_m}{\rho_m} - \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} = 0$$

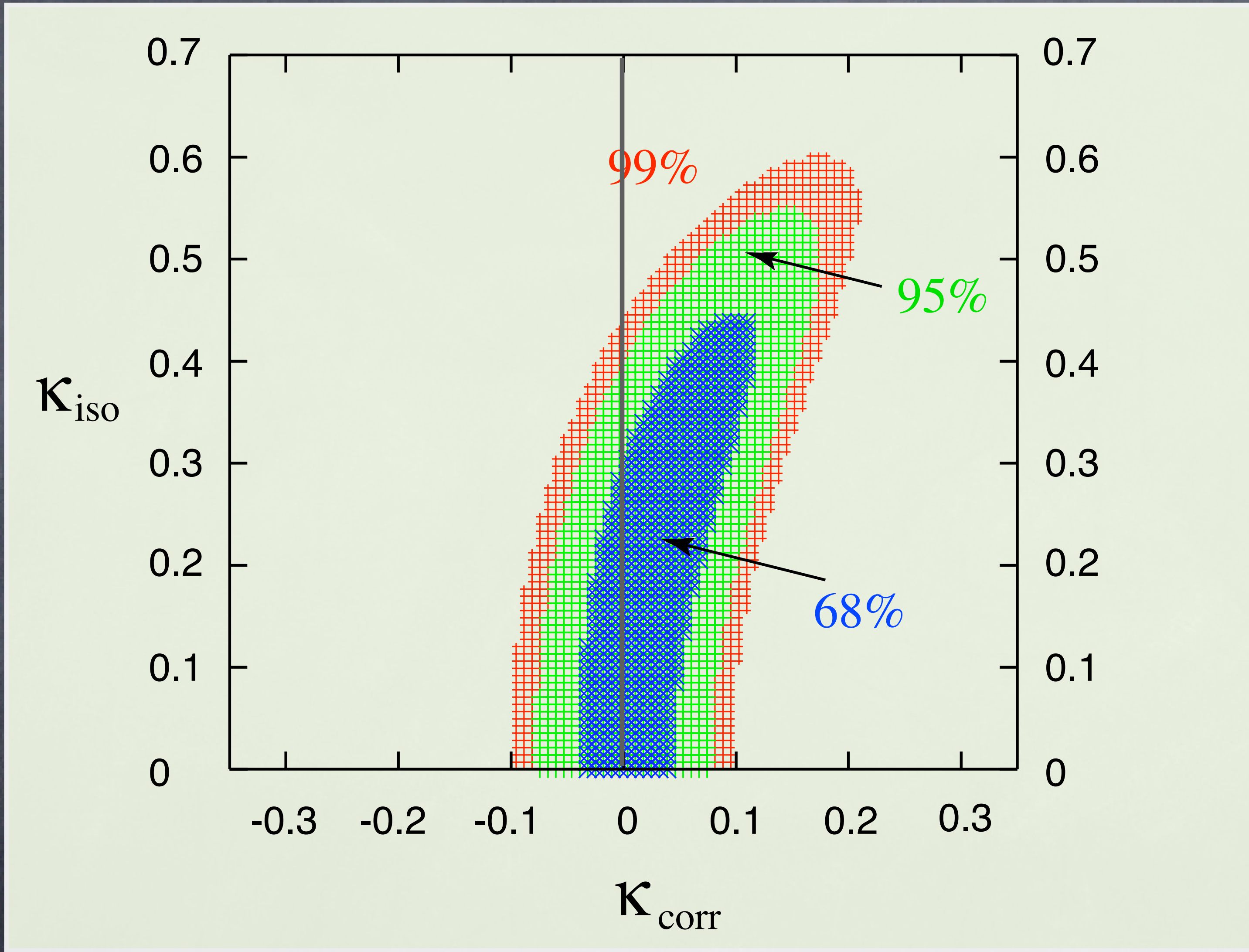
$$S_{m\gamma} \neq 0$$

$$\boxed{\kappa = \left(\frac{S}{\Psi}\right)_{\mathrm{RD}} = \frac{V'}{H_I^2 F_a \theta}}$$

TT correlation: adiabatic vs isocurvature



Constraint from WMAP 1st year



Hamaguch,MK,Moroi,Takahashi(2003)

Contribution of isocurvature < 30%

Expected isocurvature fluctuations

$$\boxed{\delta_a = \frac{\delta\rho_a}{\rho_a} \simeq 2\frac{\delta\theta}{\theta} \simeq \frac{H_I}{\pi F_a \theta} \simeq S}$$

chaotic inf. $\delta_a \sim 5 \times 10^{-2} \left(\frac{F_a \theta}{10^{15}\,\mathrm{GeV}} \right)^{-1}$

hybrid inf. $\delta_a \sim (10^{-7} - 3 \times 10^{-2}) \left(\frac{F_a \theta}{10^{15}\,\mathrm{GeV}} \right)^{-1}$

new inf. $\delta_a \sim 6 \times 10^{-11 \pm 1} \left(\frac{F_a \theta}{10^{15}\,\mathrm{GeV}} \right)^{-1}$

$\Updownarrow$

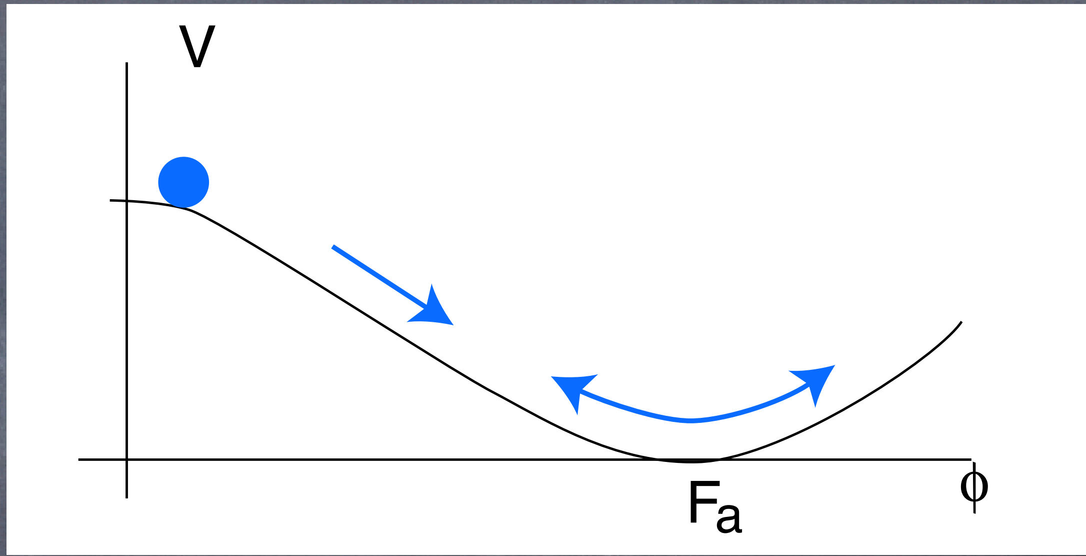
adiabatic fluctuation $\Psi \simeq 3 \times 10^{-5}$

Saxion

SUSY $\longrightarrow$ saxion + axino

$\searrow$ flat direction

$m_s \simeq m_{3/2}$ gravitino mass



$H \lesssim m_s$

$\boxed{\text{saxion oscillation}}$

$$\boxed{\Omega_s h^2 \simeq 1.6 \times 10^2 \left(\frac{F_a}{10^{12}\mathrm{GeV}} \right)^2 \left(\frac{m_s}{\mathrm{MeV}} \right)^{1/2}}$$

Dilution by entropy production

Saxion Decay

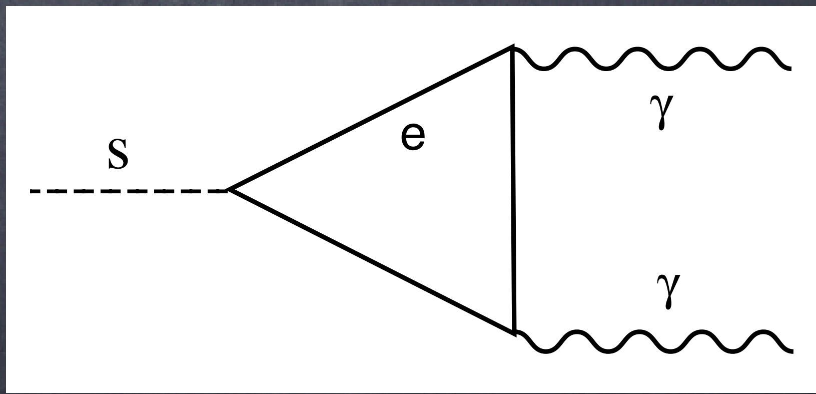
- Elecrron-positron pair $\mathcal{L} = \frac{m_e}{F_a}\bar{e}es$

$$\boxed{\tau(s \to e^+ + e^-) \simeq 2 \times 10^{11}\ \text{yr}\left(\frac{F_a}{10^{16}\text{GeV}}\right)^2 \left(\frac{m_s}{\text{MeV}}\right)^{-1}}$$

- two gammas

$$\boxed{\begin{aligned} \tau(s \to 2\gamma) &\simeq \left(\frac{\alpha^2}{256\pi^3} C \frac{m_s^3}{F_a^2}\right)^{-1} \\ &\simeq 3 \times 10^{17}\text{yr}C^{-2}\left(\frac{F_a}{10^{16}\text{GeV}}\right)^2 \left(\frac{m_s}{\text{MeV}}\right)^{-3} \end{aligned}}$$

$$C \sim O(1)$$



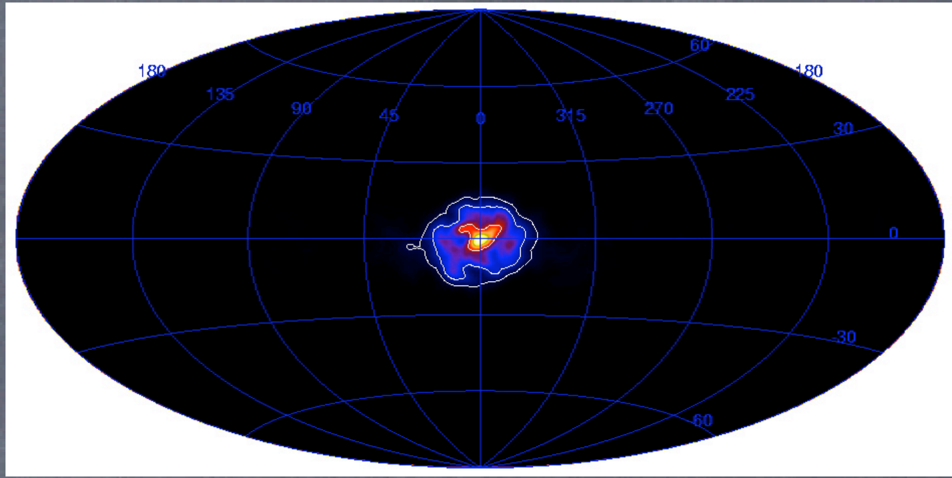
511 keV Gamma Ray from Saxion Decay

Recent INTEGRAL/SPI obs.

511keV line from Galactic bulge

$$\boxed{\Phi_{511} = 1.05 \pm 0.06 \times 10^{-3} \mathrm{cm}^{-2} \mathrm{s}^{-1}}$$

50σ significance



Knödlseder et al (2005)

Saxion decay

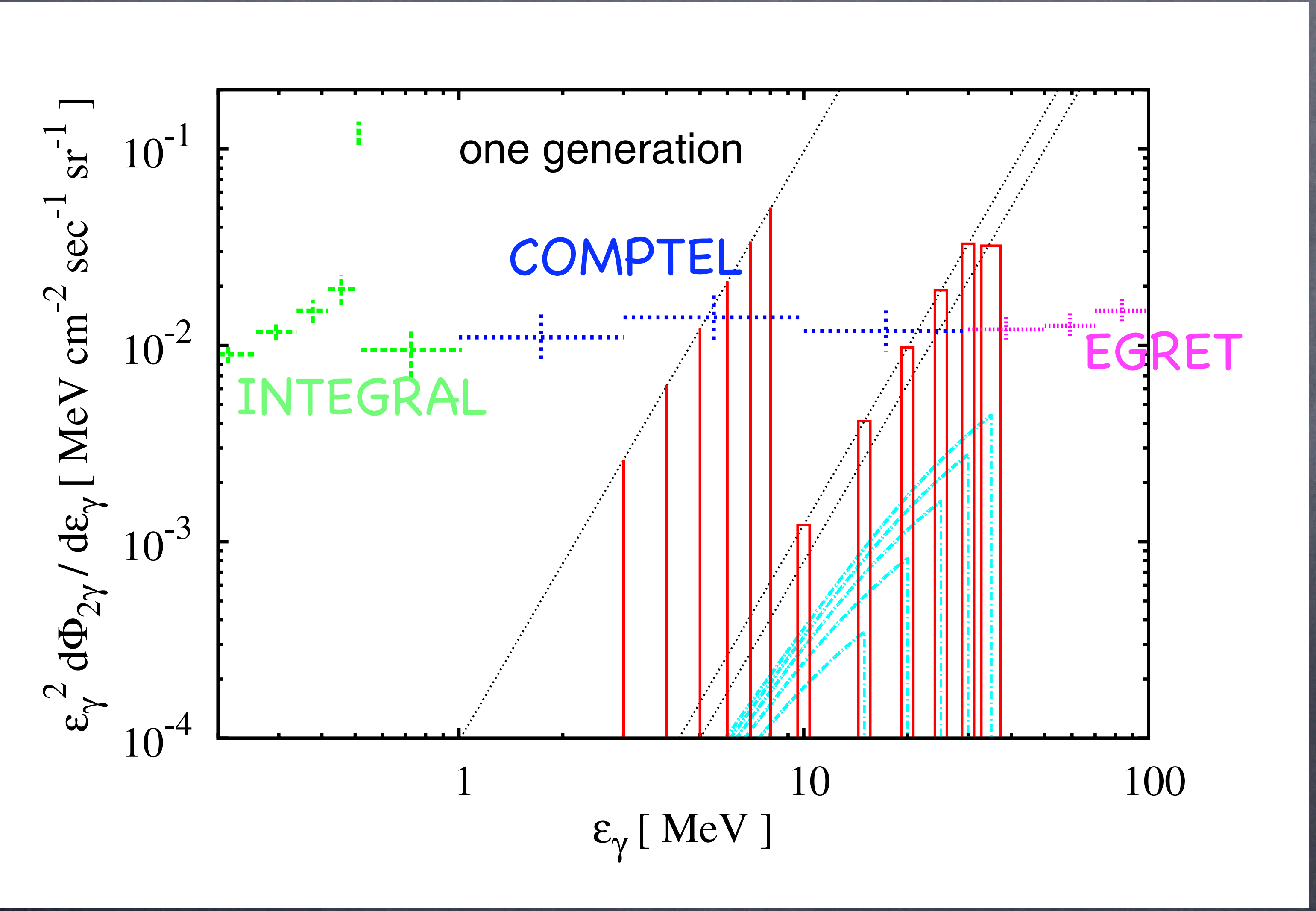
$$\Omega_s \simeq \left(\frac{\Phi_{511}}{10^{-3}\mathrm{cm}^{-2}\mathrm{sec}^{-1}}\right)\left(\frac{\tau_s}{10^{27}\mathrm{sec}}\right)\left(\frac{m_s}{\mathrm{MeV}}\right)$$

$$\simeq 6 \times 10^{-9} \left(\frac{\Phi_{511}}{10^{-3}\mathrm{cm}^{-2}\mathrm{sec}^{-1}}\right)\left(\frac{F_a}{10^{16}\mathrm{GeV}}\right)^2$$

Line Gamma

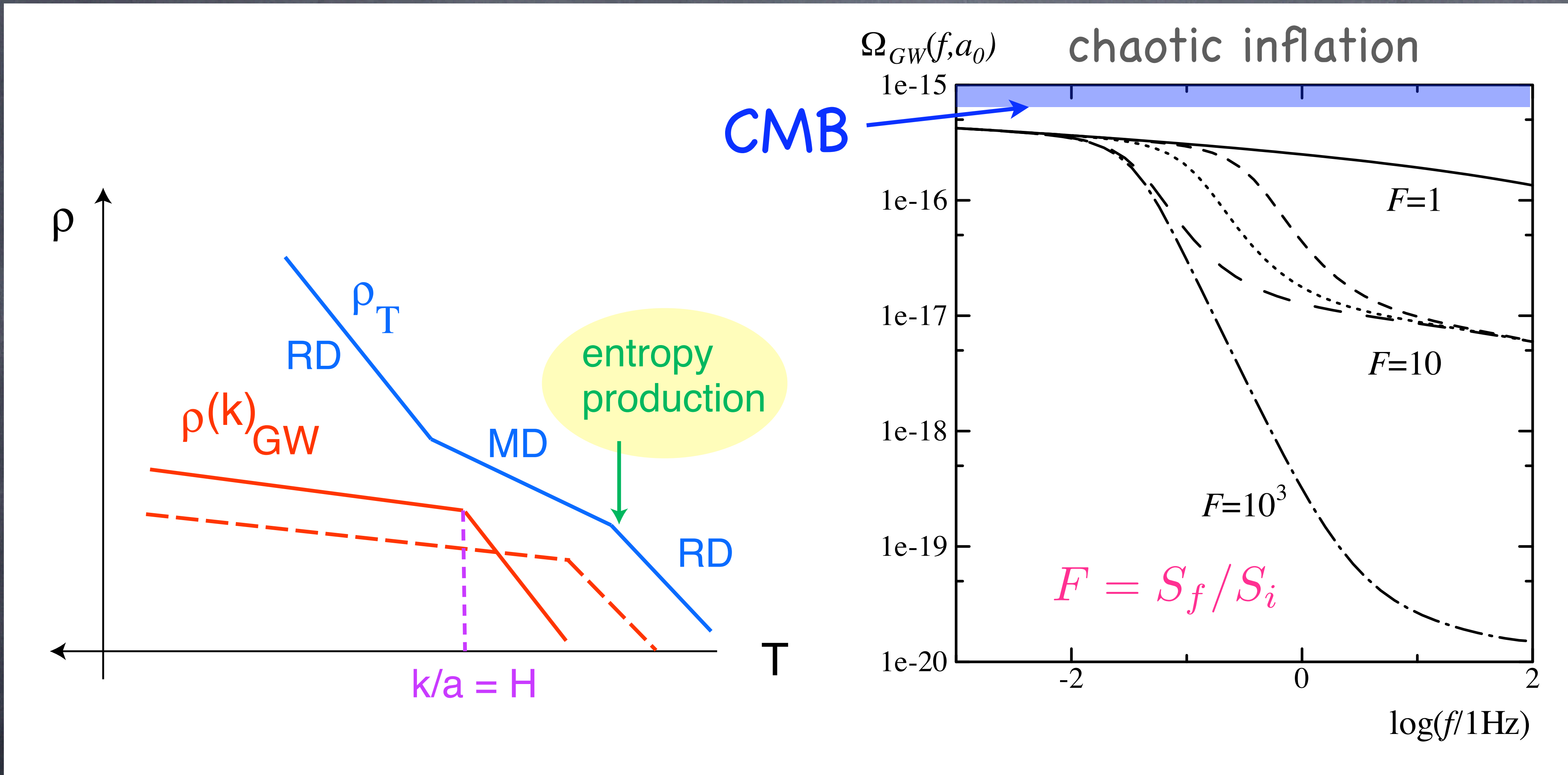
2 gamma flux is normalize to the $e^+ e^-$ flux observed by INTEGRAL

resolution =0.001, 0.08, 0.13



Kasuya, MK PRD73 (2006) 063007

Evidence for entropy production

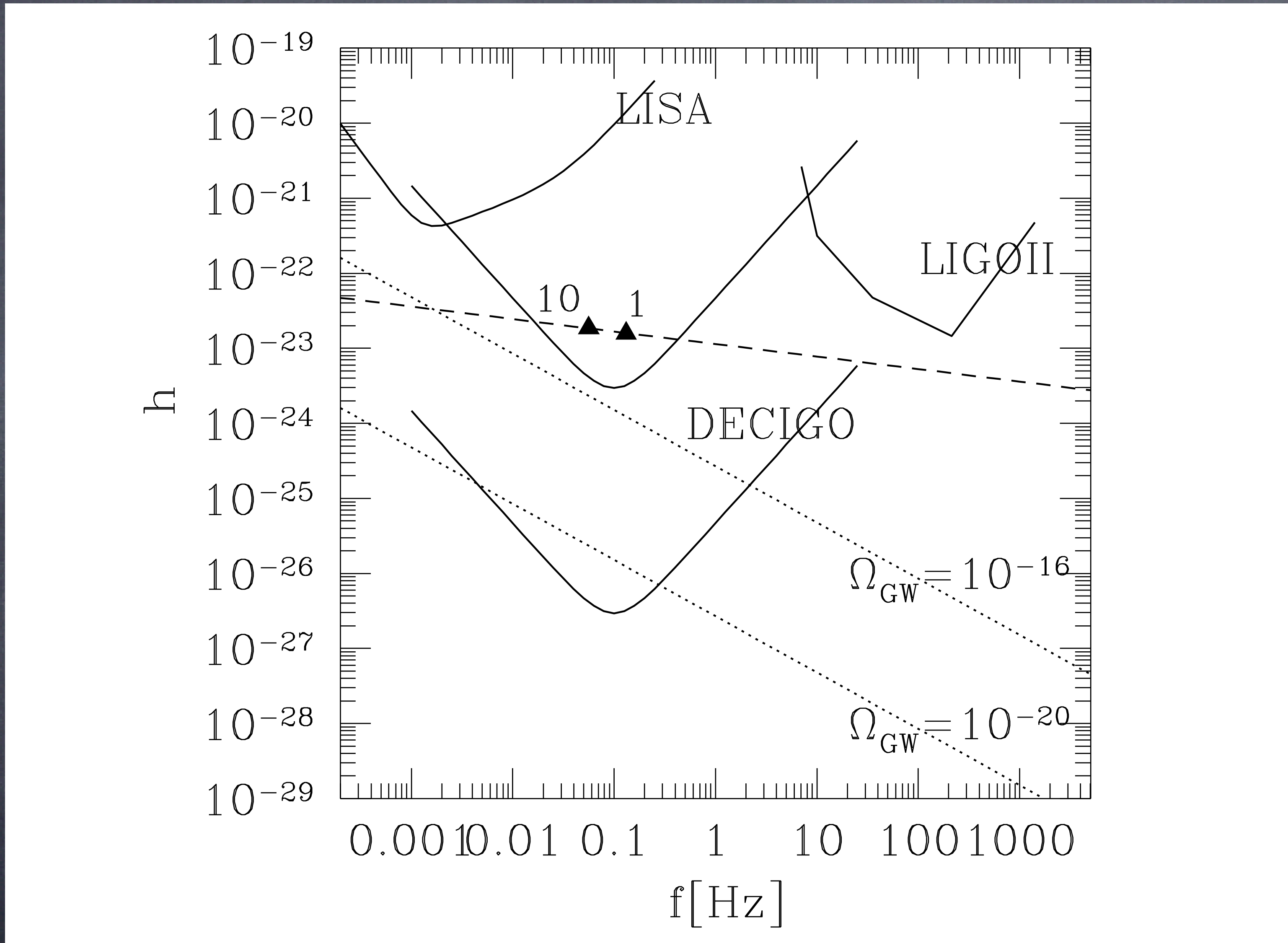


$$\rho_{GW}(f,a) = \frac{M_G^2 h^2(f,a)}{2}\left(\frac{2\pi f a_0}{a}\right)^2$$

$$h \simeq 10^{-18}\Omega_{GW}^{1/2}\left(\frac{f}{\text{Hz}}\right)^{-1}$$

$f \sim 1\text{Hz} \Rightarrow T \sim 3 \times 10^6$ GeV

Seto, Yokoyama J.Phys.Soc.Jpn 72 (2003) 3082



Seto, Kawamura, Nakamura PRL 87 (2001) 221103