



AS3 workshop, NAOC, Beijing, September 2012

cosmology with  
**Vacuum energy**

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DW, Josue De-Santiago & Yuting Wang, arXiv:1203.6776

Josue De De-Santiago, DW & Yuting Wang, arXiv:1209.0563

# Cosmology with large-scale structure

- two eras of cosmic acceleration
  - *Inflation in the very early universe*
    - *quantum vacuum fluctuations,  $P_\zeta$*
    - *primordial non-Gaussianity,  $f_{NL}$*
  - *Late-time acceleration*
    - *cosmological dynamics,  $H(z)$*
    - *growth of structure,  $D(z)$*

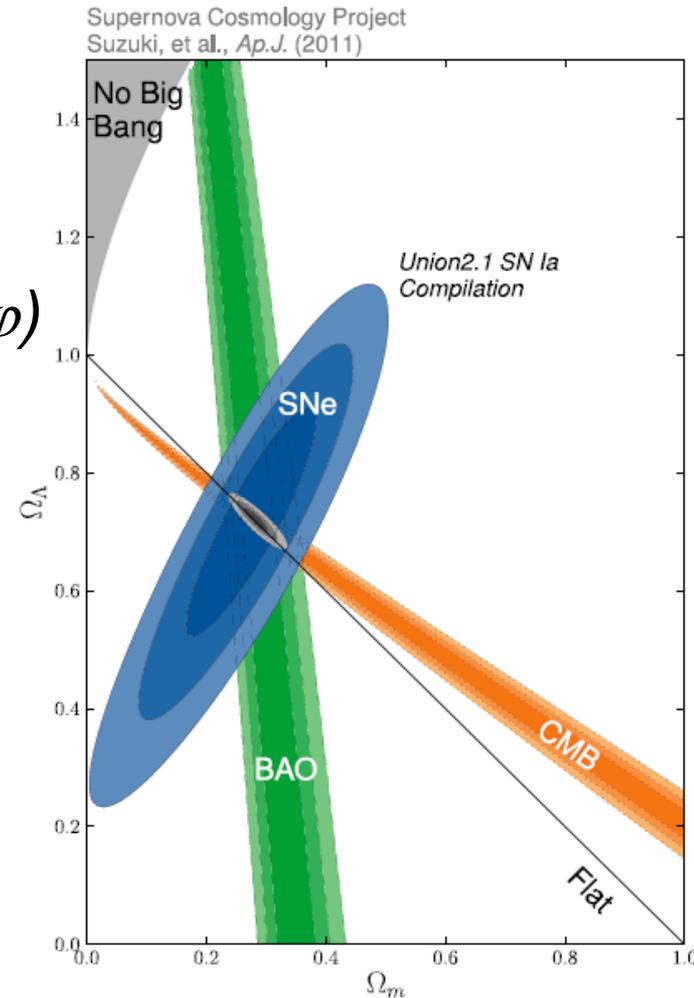
# outline

- **motivation**
- **vacuum energy + inhomogeneity + interaction**
- **vacuum cosmology + dark energy sound speed**
- **a worked example: decomposed Chaplygin gas**
- **conclusions**

# Dark energy models

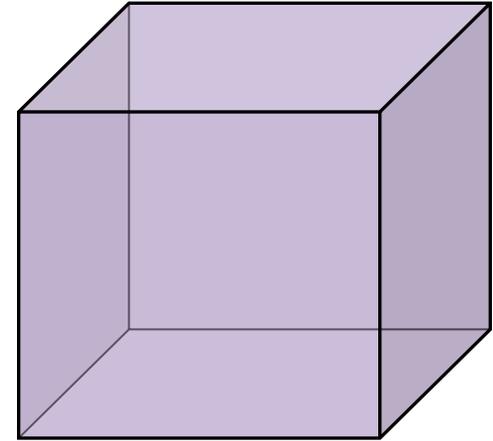
- **quintessence**
  - self-interacting scalar fields,  $V(\varphi)$
- **barotropic fluid**
  - exotic equation of state,  $P(\rho)$
- **interacting dark energy,  $\Gamma(t)$** 
  - coupled quintessence
  - *unified dark matter + energy*

*motivated by astronomical observations, but lacking persuasive physical model*



# Simplest model

- **vacuum energy,  $V$** 
  - nothing
  - undiluted by expansion
  - no new degrees of freedom



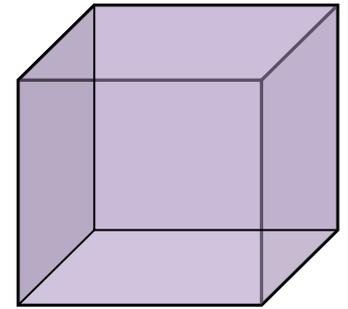
$$\check{T}_{\nu}^{\mu} = -V g_{\nu}^{\mu}$$

perfect fluid  $T_{\nu}^{\mu} = P g_{\nu}^{\mu} + (\rho + P) u^{\mu} u_{\nu}$

vacuum density = - pressure =  $\check{\rho} = -\check{P} = V$

*no particle flow, hence vacuum 4-velocity,  $u$ , undefined*

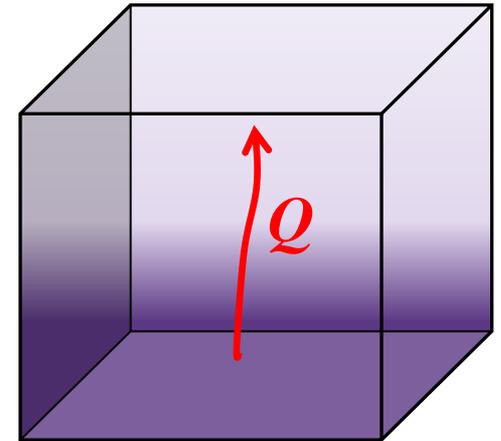
# Homogeneous vacuum



➤  $8\pi G V = \Lambda = \text{constant}$

- empirical value is cosmological constant problem

# Inhomogeneous vacuum



➤ interacting vacuum:

$$\nabla_{\mu} \check{T}_{\nu}^{\mu} = \nabla_{\mu} (-V g_{\nu}^{\mu})$$

$$= -\nabla_{\nu} V$$

$$\equiv Q_{\nu} \quad = \text{energy flow}$$

➤ total (matter + vacuum) energy-mtm conserved

# Time-dependent vacuum cosmology:

homogeneous 3D space  $\Rightarrow V=V(t)$

- Friedmann equation

$$H^2 = \frac{8\pi G_N}{3} (\rho + V) - \frac{K}{a^2}$$

- Continuity equations for matter + vacuum

$$\begin{aligned}\dot{\rho} + 3H(\rho + P) &= -Q, \\ \dot{V} &= Q.\end{aligned}$$

- e.g.,

Freese et al (1987); Berman (1991); Pavon (1991); Chen & Wu (1992); Carvalho et al (1992); Al-Rawaf & Taha (1996); Shapiro & Sola (2002); Sola (2011); ...

- Freedom to choose any  $V(t)$

- *more a description than an explanation? like  $V(\varphi)$ ?*

# Quintessence models of dark energy

- any dark energy cosmology can be decomposed into self-interacting scalar field + vacuum energy:

$$\rho_{de} = \frac{1}{2} \dot{\phi}^2 + V \quad , \quad P_{de} = \frac{1}{2} \dot{\phi}^2 - V \quad , \quad u_{\mu} \propto \nabla_{\mu} \phi$$

- and interaction:  $Q_{\mu} = V' \nabla_{\mu} \phi \propto u_{\mu}$

*but vacuum energy does not require any new fields or degrees of freedom, e.g., unified dark matter + dark energy*

# Vacuum models of dark energy

➤ *any* dark energy model can be decomposed into interacting vacuum+matter: Wands, De-Santiago & Wang (2012)

$$\rho_{de} = \rho_m + V \quad , \quad P_{de} = -V \quad , \quad u_\mu \propto u^{(m)}_\mu$$

➤ and an interaction:  $Q_\mu = \nabla_\mu V = -\nabla_\mu P_{de}$

# Generalised Chaplygin gas

Kamenshchik, Moschella and Pasquier (2001)

- exotic dark energy, barotropic equation of state:

$$P_{gCg} = -A\rho_{gCg}^{-\alpha}$$

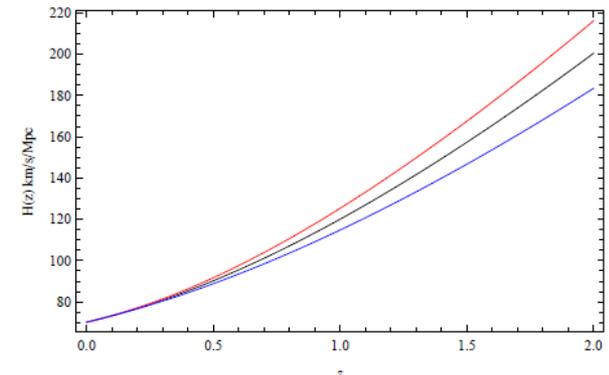
- two constants: dimensionless,  $\alpha$ , and  $A$
- unified dark matter + dark energy model

$$\rho_{gCg} = \left( A + Ba^{-3(1+\alpha)} \right)^{1/(1+\alpha)}$$

$$\rightarrow B^{1/(1+\alpha)} a^{-3} \quad (\text{matter}) \quad \text{as } a \rightarrow 0$$

$$\rightarrow A^{1/(1+\alpha)} \quad (\text{vacuum}) \quad \text{as } a \rightarrow \infty$$

- recover  $\Lambda$ CDM as  $\alpha \rightarrow 0$



# Decomposed Chaplygin gas

Bento, Bertolami and Sen (2004)

$$u_m^\mu = u^\mu, \quad \rho_m = \rho_{\text{de}} + P_{\text{de}}, \quad V = -P_{\text{de}}$$

➤ FRW interaction can be written as

$$Q = 3\alpha H \left( \frac{\rho_m V}{\rho_m + V} \right)$$

➤ *model has one dimensionless parameter,  $\alpha$*

➤ *late-time cosmological constant appears as an integration constant*

$$A = (\rho_m + V)^\alpha V$$

➤ decomposed model allows two independent perturbations:

$$\delta V, \delta \rho_m$$

# Structure in interacting vacuum model

DW, Josue De-Santiago & Yuting Wang (2012)

inhomogeneous 3D space  $\Rightarrow V(t, x^i) = V(t) + \delta V(t, x^i)$

➤ energy conservation:

$$\begin{aligned} \delta \dot{\rho} + 3H(\delta \rho + \delta P) - 3(\rho + P)\dot{\psi} + (\rho + P)\frac{\nabla^2}{a^2}(\theta + a^2\dot{E} - aB) &= -\delta Q - Q\phi, \\ \delta \dot{V} &= \delta Q + Q\phi. \end{aligned}$$

➤ momentum conservation:

$$\begin{aligned} (\rho + P)\dot{\theta} - 3c_s^2 H(\rho + P)\theta + (\rho + P)\phi + \delta P &= -f + c_s^2 Q\theta, \\ -\delta V &= f + Q\theta. \end{aligned}$$

*vanishing vacuum momentum requires vacuum pressure gradient balanced by force on vacuum*

$$\nabla_i(-V) = \nabla_i(f + Q\theta)$$

# Different sound speeds:

Josue De-Santiago, DW & Yuting Wang (2012)

➤ Barotropic (unified) model,  $V=V(\rho_m) \Rightarrow Q_\mu \propto \nabla_\mu \rho_m$

➤ **adiabatic sound speed:**

$$c_s^2 = \frac{\dot{P}_{\text{gCg}}}{\dot{\rho}_{\text{gCg}}} = \frac{\alpha V}{\rho_m + V}$$

➤ Non-adiabatic: e.g., energy flow along matter 4-velocity,  $Q_\nu \propto u_\nu$

➤ **zero sound speed:**

$$\delta \check{P}_{\text{com}} = 0 \Rightarrow c_s^2 = \left( \frac{\delta P}{\delta \rho} \right)_{\text{com}} = 0$$

# Barotropic $gCg$ power spectrum

[Harvard Sandvik](#),  
[Max Tegmark](#),  
[Matias Zaldarriaga](#),  
[Ioav Waga](#)  
[astro-ph/0212114](#)

$$-0.00000081 < \alpha < 0.00000079$$

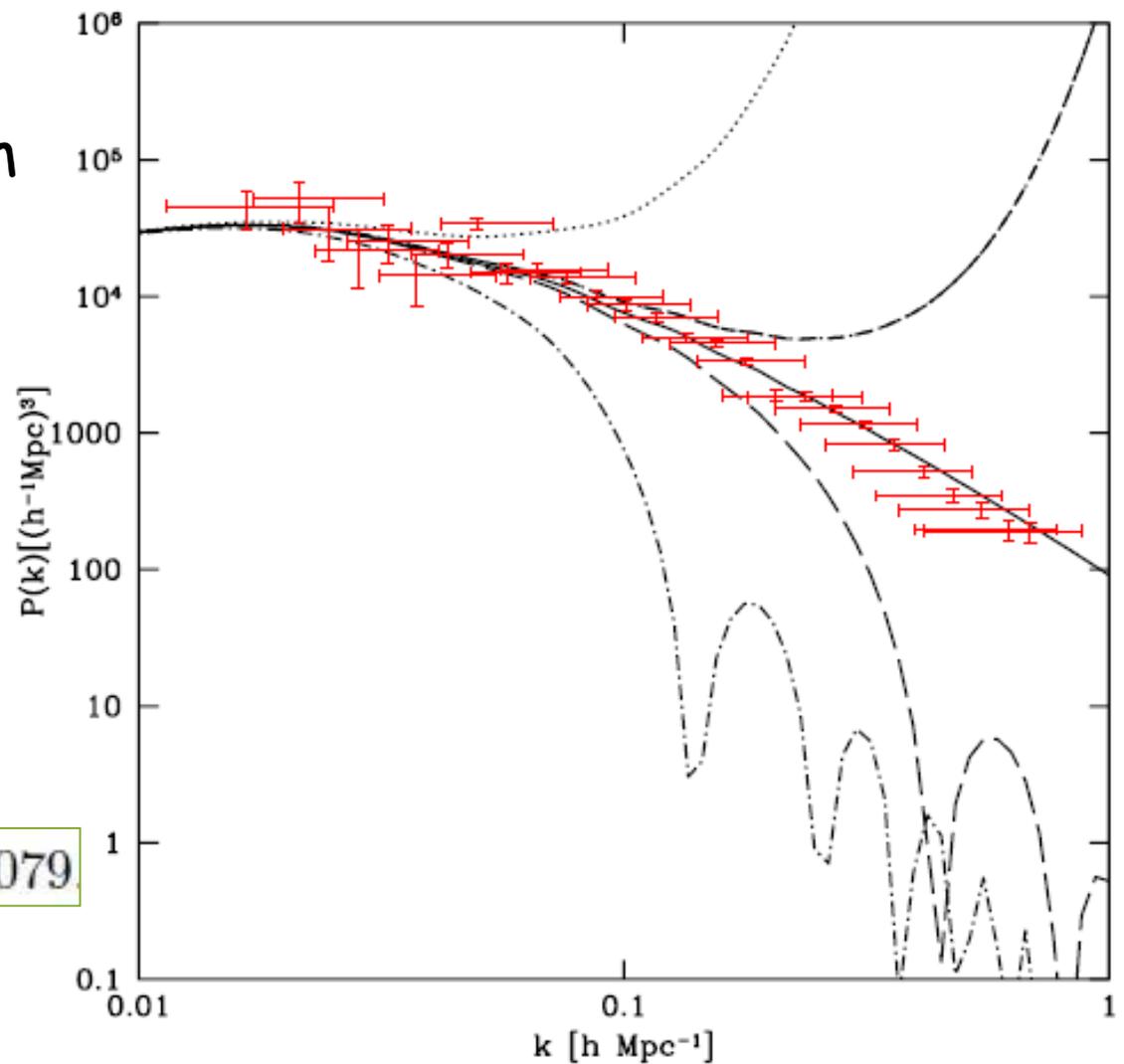


FIG. 1. UDM solution for perturbations as function of wavenumber,  $k$ . From top to bottom, the curves are GCG models with  $\alpha = -10^{-4}$ ,  $-10^{-5}$ ,  $0$  ( $\Lambda$ CDM),  $10^{-5}$  and  $10^{-4}$ , respectively. The data points are the power spectrum of the 2df galaxy redshift survey.

# Non-adiabatic $gCg$ matter power spectrum, $P(k)$

Yuting Wang, DW, et al, in preparation

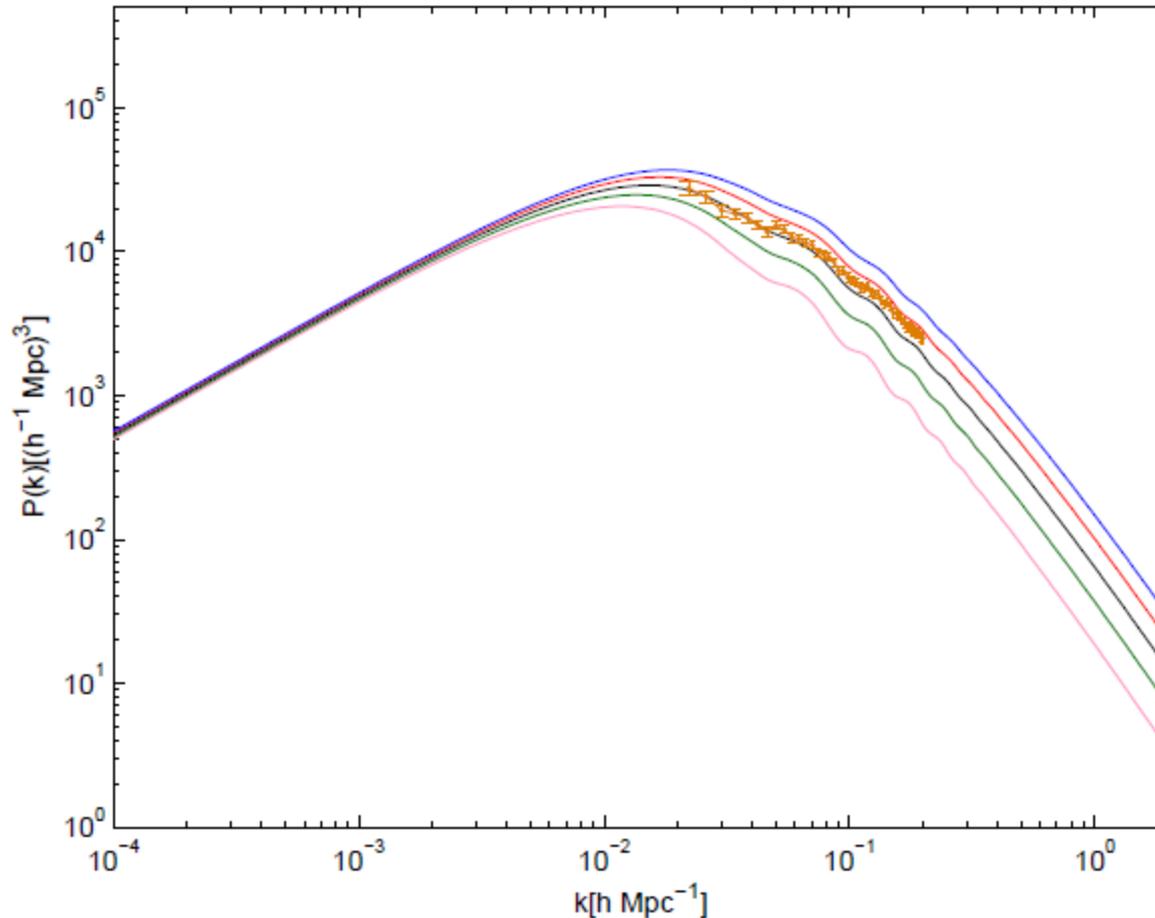
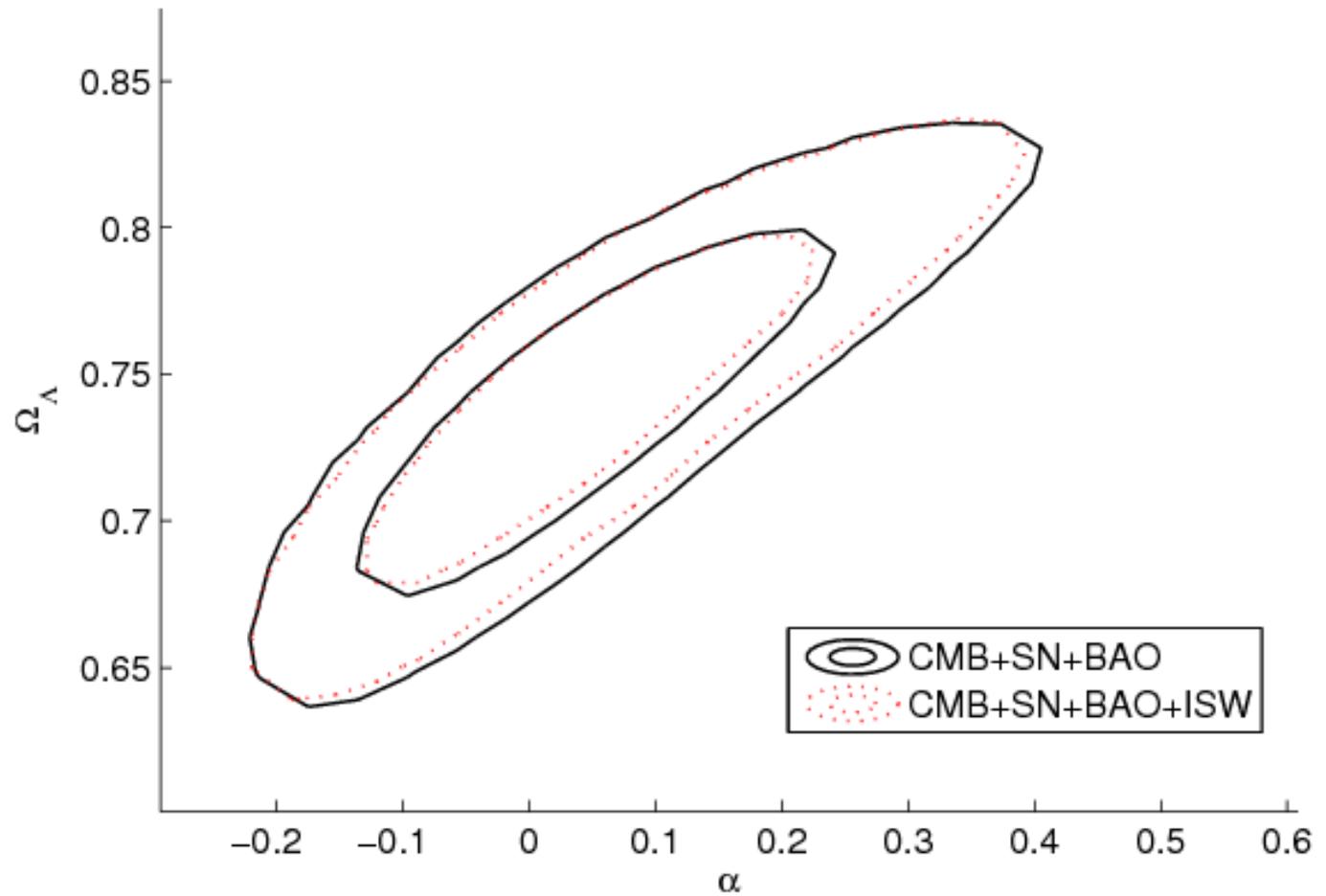


FIG. 7: The matter power spectra as a function of  $k$  for the geodesic model. The blue line, red line, black line, green line and pink line correspond to  $\alpha=0.2, 0.1, 0(\Lambda\text{CDM}), -0.1, -0.2$ , respectively.

# Results : Constraints on decomposed *GCG* model



# conclusions

- **vacuum energy is simplest model for acceleration**
  - no new degrees of freedom
- **any dark energy cosmology** can be decomposed into **interacting vacuum+matter** (like scalar field quintessence)
- **test interacting vacuum models through dynamics and growth of large-scale structure**
  - background cosmology distinguished by standard rulers (e.g., CMB+BAO+SN)
  - sound speed distinguished by growth of structure
  - worked example: (decomposed) Chaplygin gas