Cosmophysics Frontier

Accelerators in the Universe

- Four puzzles left over to the 21st century -

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宇宙分野での基本問題

宇宙モデル

- ✓ 宇宙の一様等方性，平坦性，宇宙年齢問題
  - ☞ 統一理論に基づく具体的なインフレーションモデル
  - ☞ ダークエネルギーの実体と起源
  - **Cf.** No-Go定理，Landscape問題，超対称性の破れ

宇宙物質

- ✓ CMBの温度・スペクトル，軽元素の起源と組成
  - ☞ メタルの起源（PopIII星の形成機構）
- ✓ バリオン数・レプトン数非対称性の起源
  - ☞ 初期宇宙進化とGUTの確定
- ✓ ダークマターの実体・存在量 (LHC, ILC)
  - ☞ 超対称モデルの確定と超対称性の破れの機構

宇宙構造

- ✓ (ΛCDM▸) CMBの非等方性・スペクトル，銀河分布の（超）大域的構造，相関関数，銀河形成機構，銀河タイプの起源・存在比，光度関数，回転曲線，銀河団の存在量，相関，X線銀河団の形成機構．．．
  - ☞ 球状星団の起源
  - ☞ 小スケールでの相関関数のずれ

天体物理学

- ✓ 星の構造と進化，銀河の構造と進化
- ☆ 星の形成機構（質量の決まるメカニズム）
- ☆ 超新星爆発の機構
- ☆ ガンマ線バースターの構造・成因・機構
- ☆ 活動的コンパクト天体・AGNの機構・形成過程

  - ☞ （相対論的）宇宙ジェットの形成機構
  - ☞ （超巨大）ブラックホールの形成機構
  - ☞ 中性子星・ブラックホール合体、崩壊による重力波放出の定量的推定

  - ☞ 超高エネルギー宇宙線の量と起源 (E¸ 10^{10} GeV)

惑星形成・生命の起源

- ☆ 惑星形成

  - ☞ 系外惑星探査

Contents

- Cosmology
  - Inflation
  - Dark Energy
- Astrophysics
  - UHE Cosmic Rays
  - Cosmic Jets
- Summary

Acceleration of the Universe

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa^2 T_{\mu\nu}$$

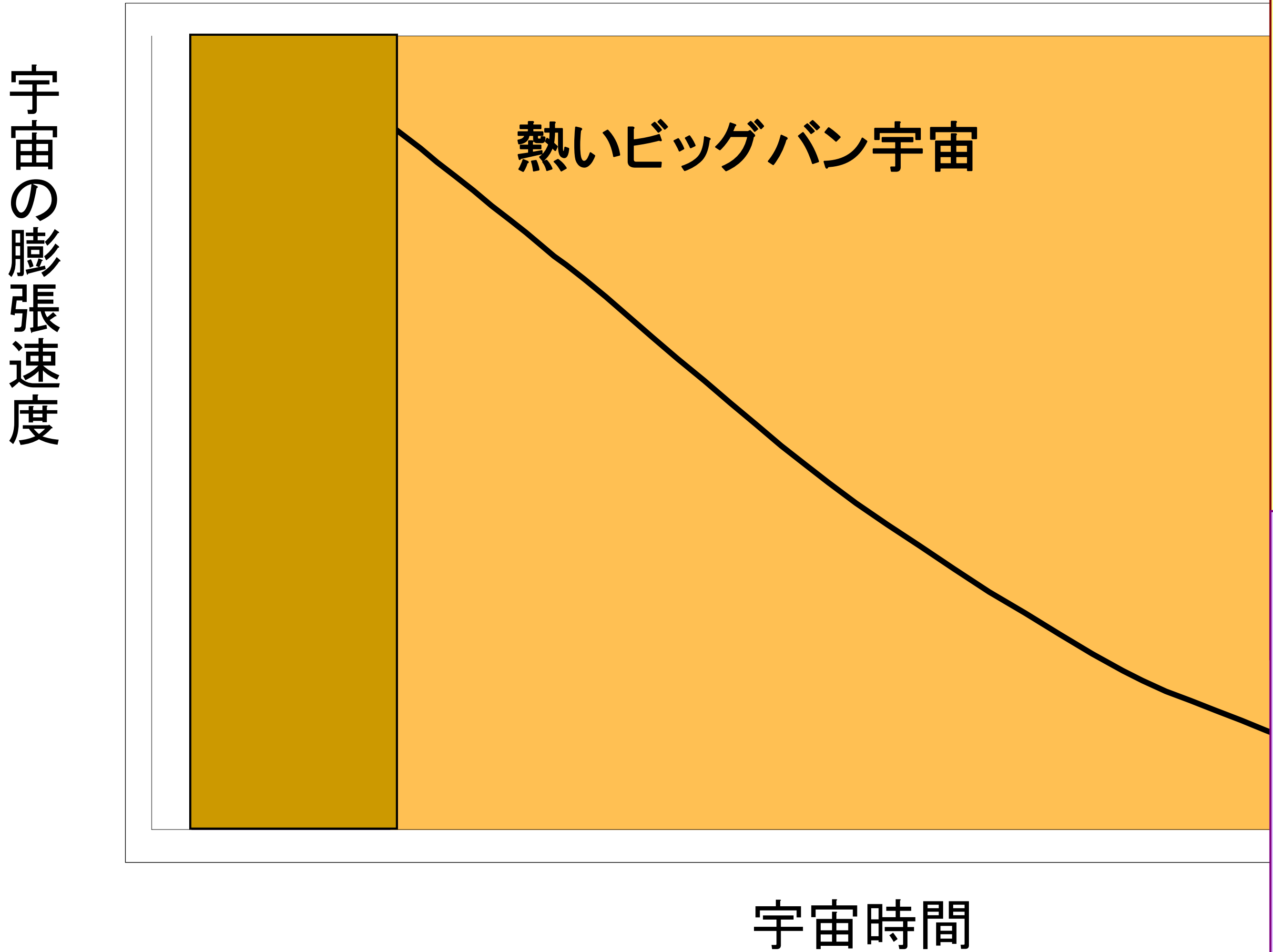
or

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \kappa^2 T_{\mu\nu} - \Lambda g_{\mu\nu}$$

or

$$R_{MN} - \frac{1}{2} R g_{MN} = \kappa_{11}^2 T_{MN}$$

Why is Our Universe Expanding?



1915 GR

1916 Static Einstein Universe model

1929 Hubble's law

1946 BBN (Gamov)

1965 Discovery of CMB

1981 Inflation model – flatness

1982 Origin of cosmic structures

1992 COBE DDR

1999 Boomerang

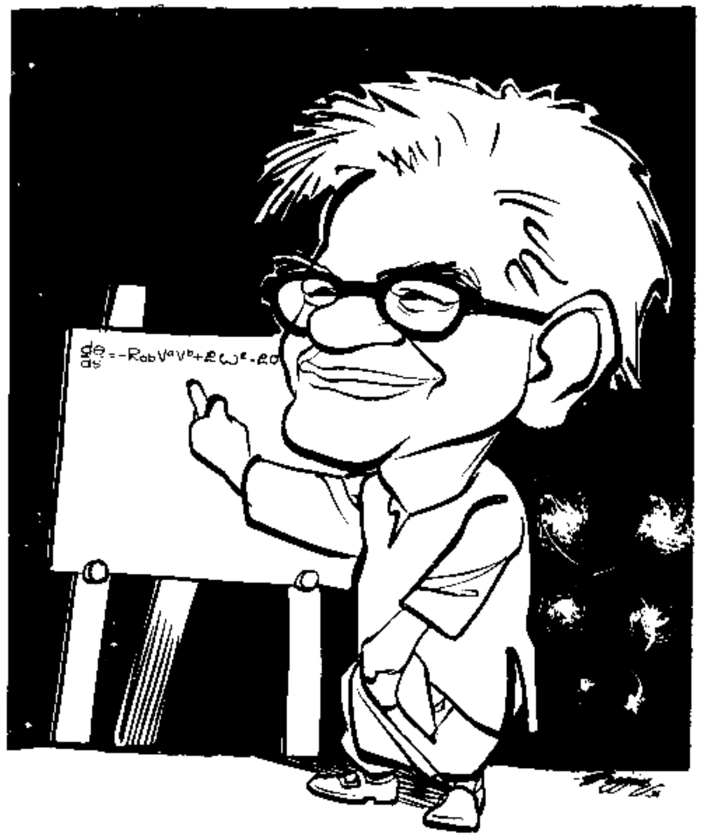
2003 WMAP

Why is the cosmic expansion accelerated?

重力が引力 ⇔ 宇宙膨張が減速

宇宙膨張が加速 ⇒ 重力が斥力

重力が斥力 ⇔ 圧力 $P < -\rho/3$



A. K. Raychaudhuri

The Cosmic Converger

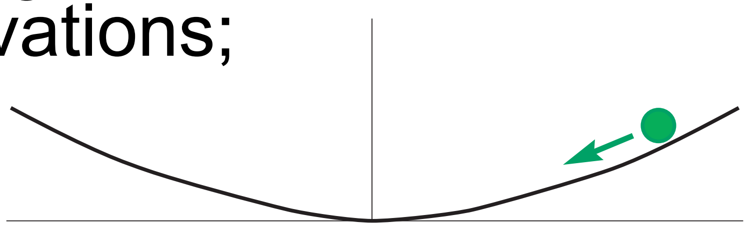
Raychaudhuri equation

$$\frac{3\ddot{a}}{a} \equiv \dot{\theta} + \frac{1}{3}\theta^2 = -R_{tt} - 2\sigma^2, \quad 2\kappa^2 R_{tt} = \rho + 3P$$

Inflation Problem

- It is easy to construct phenomenological models consistent with cosmological observations;

$$P = \frac{1}{2}\dot{\phi}^2 - V(\phi), \quad \rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$



  - They strongly suggest a unification of gravity and inflaton.
    - the inflation started around the Planck time.
    - the inflaton couples other fields only through gravity.

- However, no satisfactory model based on a unified theory has been constructed due to the No-Go theorem [Gibbons GW 1984] :

We cannot construct an accelerateting universe model by any compactification of a 10D or 11D *supergravity theory* with *stationary, compact and smooth* internal space.

Reacceleration of the Universe

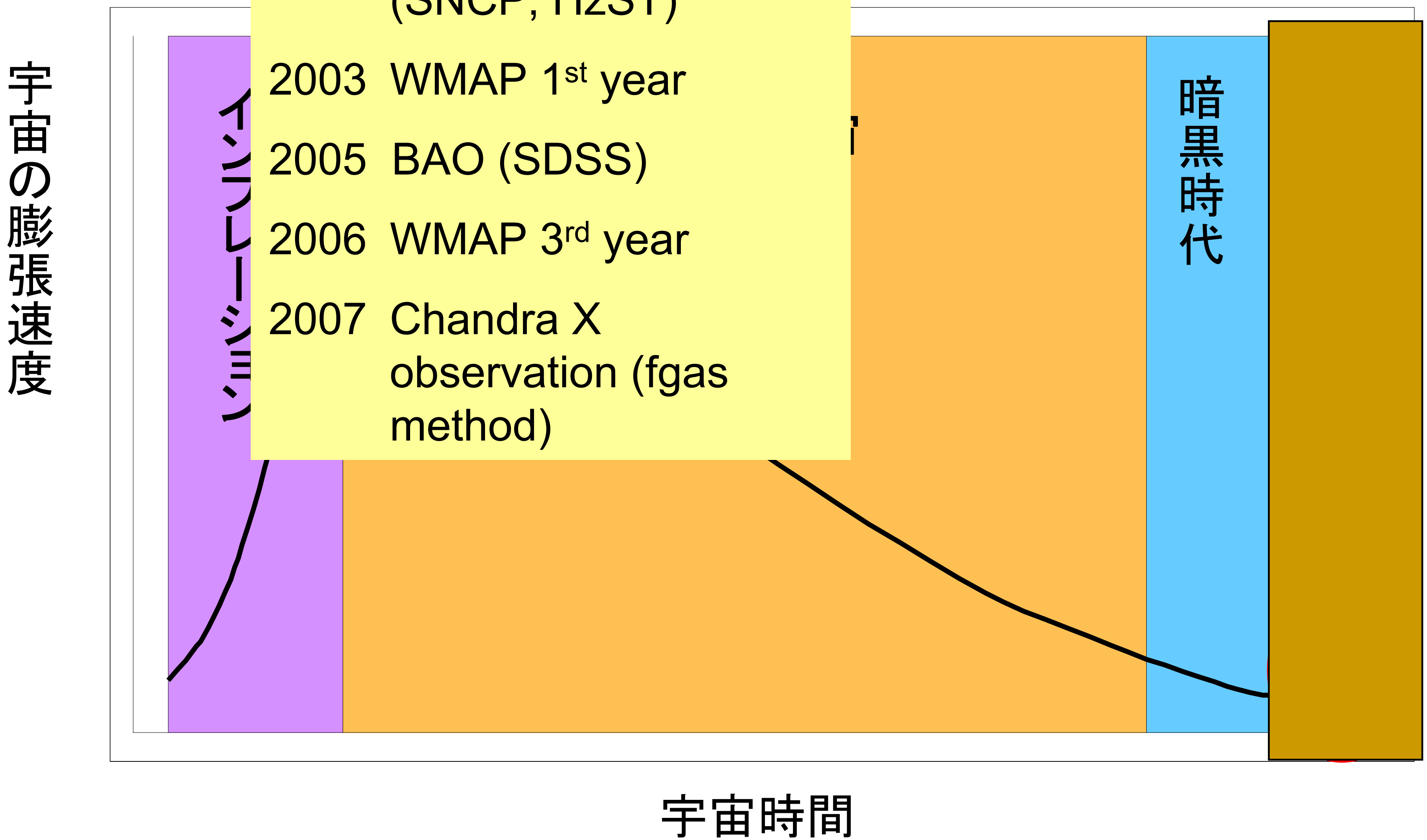
1998 Discovery by SNIa (SNCP, HzST)

2003 WMAP 1st year

2005 BAO (SDSS)

2006 WMAP 3rd year

2007 Chandra X observation (fgas method)



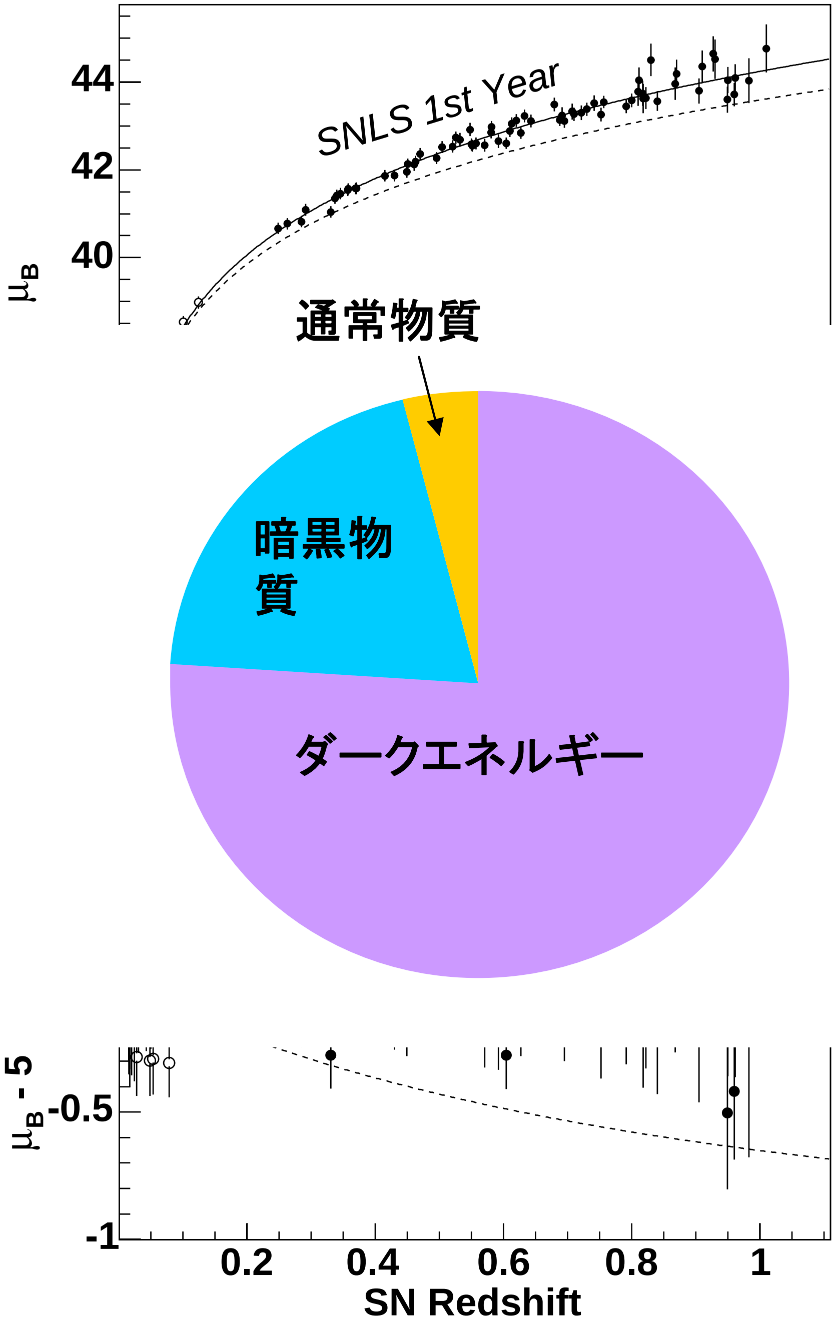
Cosmometry (測宇宙学)

- Measurement of distances to cosmic objects
  - Observed value + intrinsic value ⇒ distance
  - For example, the luminosity distance d_L is

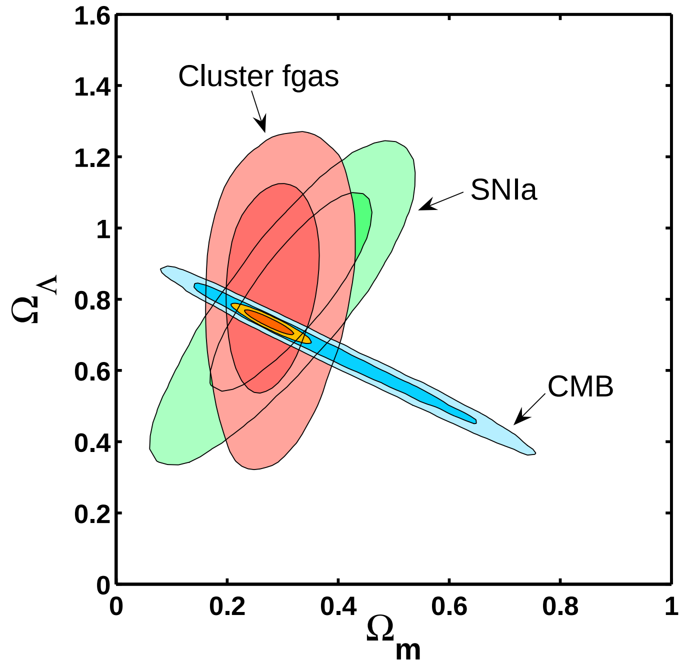
$$4\pi\, d_L^2 F_{\rm obs} = L$$

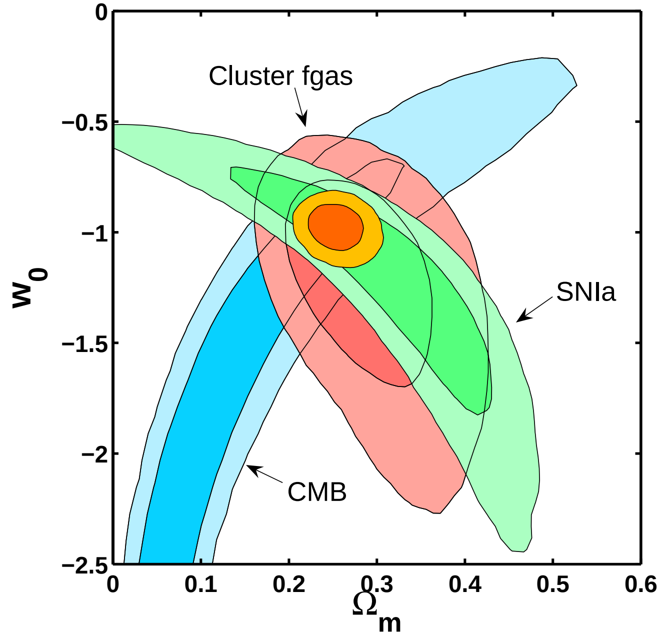
- Cosmological parameters
  - Distance-redshift relation depends on the geometry and expansion history of the universe
  - For example, d_L is related to $z = \delta\lambda/\lambda$ as

$$d_L = (1+z) R_K \sinh \frac{c\chi}{H_0 R_K}; \qquad \chi = \int_0^z \frac{H_0\, dz'}{H(z')}$$



SNLS: A&A447, 31(2006)





Allen et al: arXiv:0706.0033

Dark Energy Problem

$$\Lambda = \Lambda_{\mathrm{cl}} + \Lambda_{\mathrm{qn}} \simeq G \left(2 \times 10^{-3} \mathrm{eV}\right)^4$$

Provided that GR is valid on cosmic scales, the total dark energy density *including quantum contributions* is

- positive (Acceleration Problem),
- much smaller than typical characteristic scales of particle physics (Hierarchy/Λ Problem),
- of the order of the present critical density (Coincidence Problem).

Various Theoretical Approaches

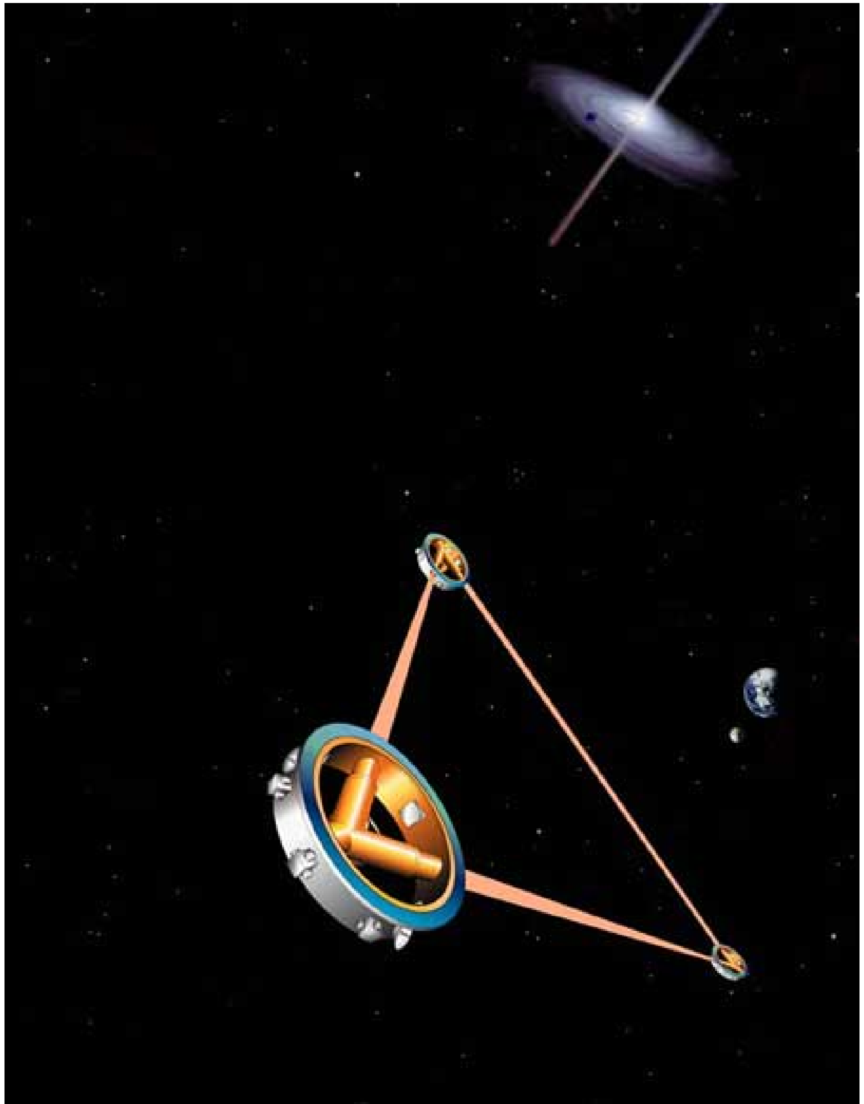
- Scalar Field Models
  - Quintessence, K-essence, phantom field, dilatonic ghost condensate, tachyon field(¾ Chaplygin gas),
- Quantum Gravity
  - Spacetime foams, EPI, baby universe
- Modification of Gravity
  - UV: string/M theory (→ brane(world), landscape)
  - IR: Lorentz SSB, $f(R,\phi,\mathbf{r}\phi)$-models, TeVeS theory, DGP model
- Anthropic Principle

Ref: Copeland, Sami, Tsujikawa: IJMPD15, 1753(2006)

Observatories of Fundamental Microphysics

- Large Scale Structures
  - CMB anisotropy
    (COBE, Boomerang, WMAP ⇒ Planck)
    Polarization measurements
    （e.g. 羽澄さん@KEK)
    ⇒ Tensor/Scalar ratio (inflation scaleの決定）
  - Galaxy/DM distribution statistics
    (CfA, 2dF, SDSS ⇒ DES)
  - Cosmometry by SNe
    (SCP, HzST, SSTC, SNLS ⇒ SNAP)
  - Weak lensing survey
    (CFHTLS ⇒ Subaru HSC/DENET, DUNE, SNAP)

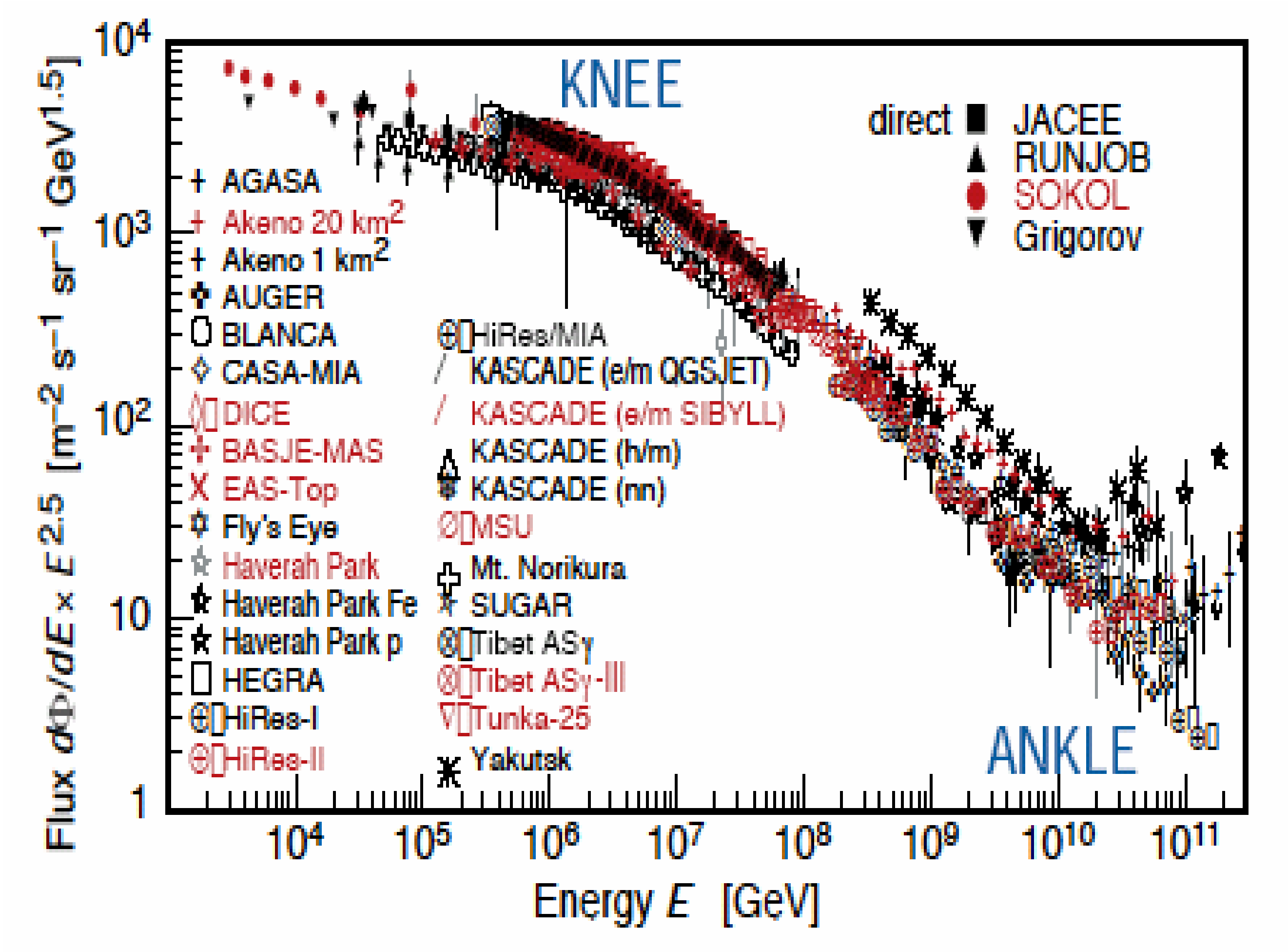
- Gravitational Waves
  - Laser-Interferometers in space
    (⇒>2020 BBO: LISA, DECIGO)
    L_{pl} at inflation ⇒ $L > 10\ R_E$



LISA (of Great Observatories), The Structure and Evolution of the Universe 2003 roadmap, "Beyond Einstein: From the Big Bang to Black Holes." (NASA)

Acceleration of Particles

High Energy Cosmic Rays



- $E_{max} > 10^{11}$ GeV
- Knee: E» 10^6 GeV
- Ankle E » 10^{10} GeV
- GZK limit = 5£10^{10} GeV

  $p + \gamma_{CMB}$! N + π
- Galaxy limit = 10^9 GeV

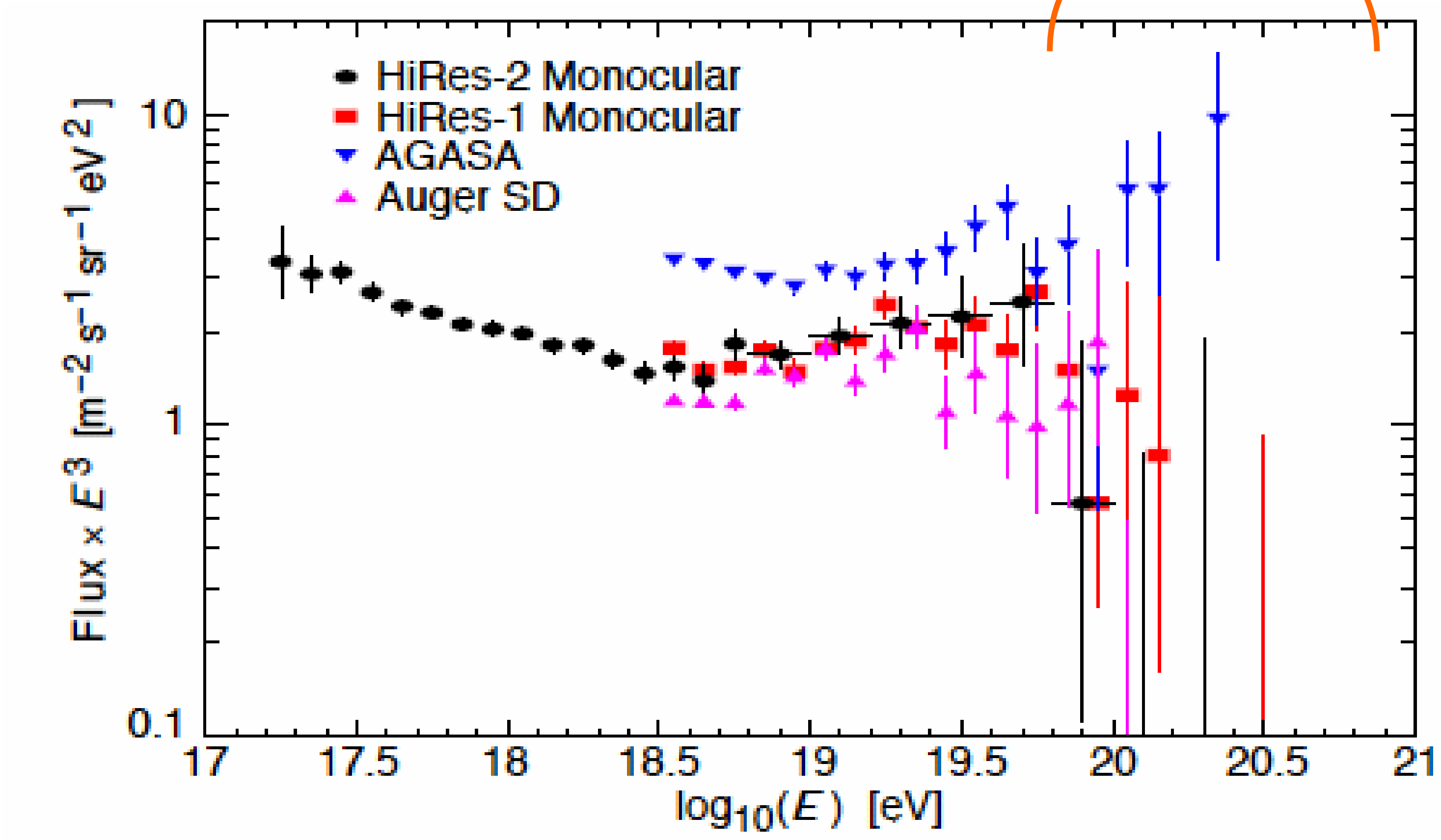
  R_L= pc/eB = 1 kpc

GZK=Greisen-Zatsepin-Kuzmin(1966)

From http://pdg.lbl.gov/

UHE Cosmic Rays

Lorentz不変性の破れ？



From http://pdg.lbl.gov/

Energetics

- Total energy
  - ρ_{CR} ¼ 1 eV/cm^3 ⇒ L_{CR}¼ 10^{41} erg/s per galaxy

    Cf. 3£ $E_{K,SN}$ / 100 yr ¼ 10^{42} erg/s
- Acceleration
  - 1st-Fermi acceleration by shocks gives

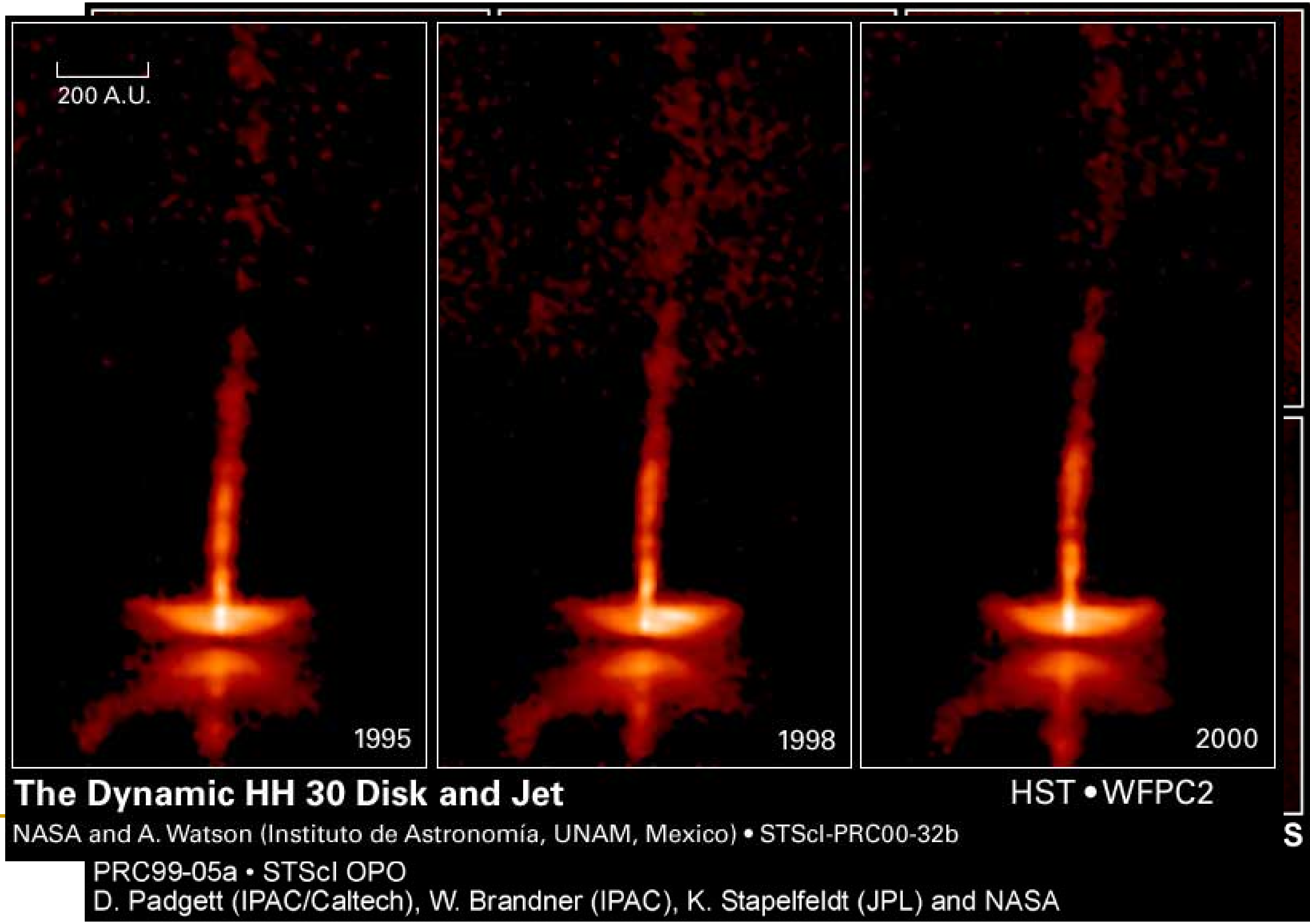
    E_{max} » Z£ 5¢10^6 GeV at SNRs

    This explains the galactic component and the appearance of Knee in the spectrum.
  - However, the UHE extragalactic components require other more powerful mechanisms:
    - GRBs, very massive DM, topological defects …

Cosmic Jets

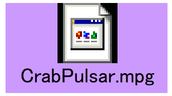
Jets are ubiquitous cosmic phenomena

Jets from young stars

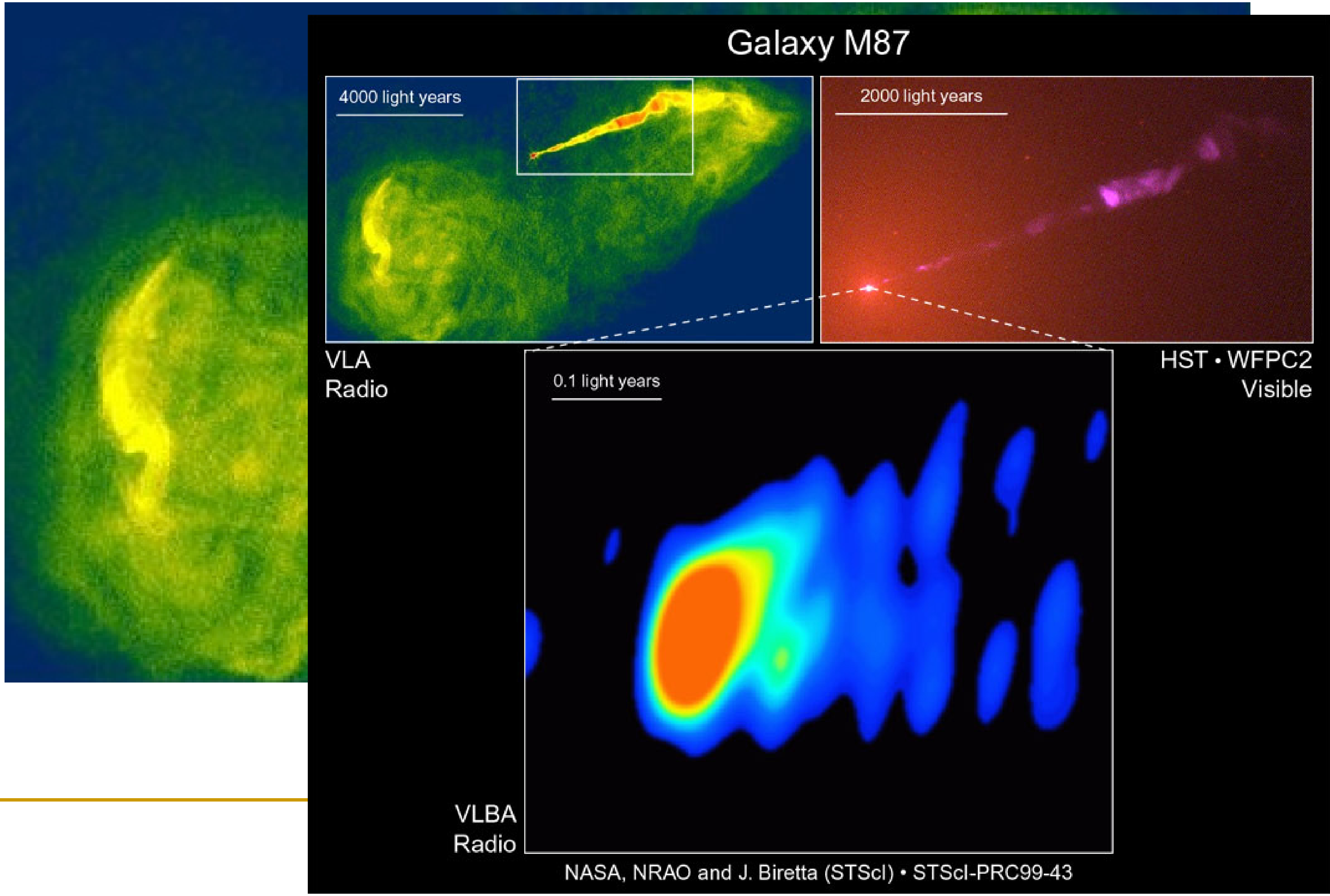


Neutron stars and stellar black holes

Crab Nebula (HST + Chandra) [HubbleSite]

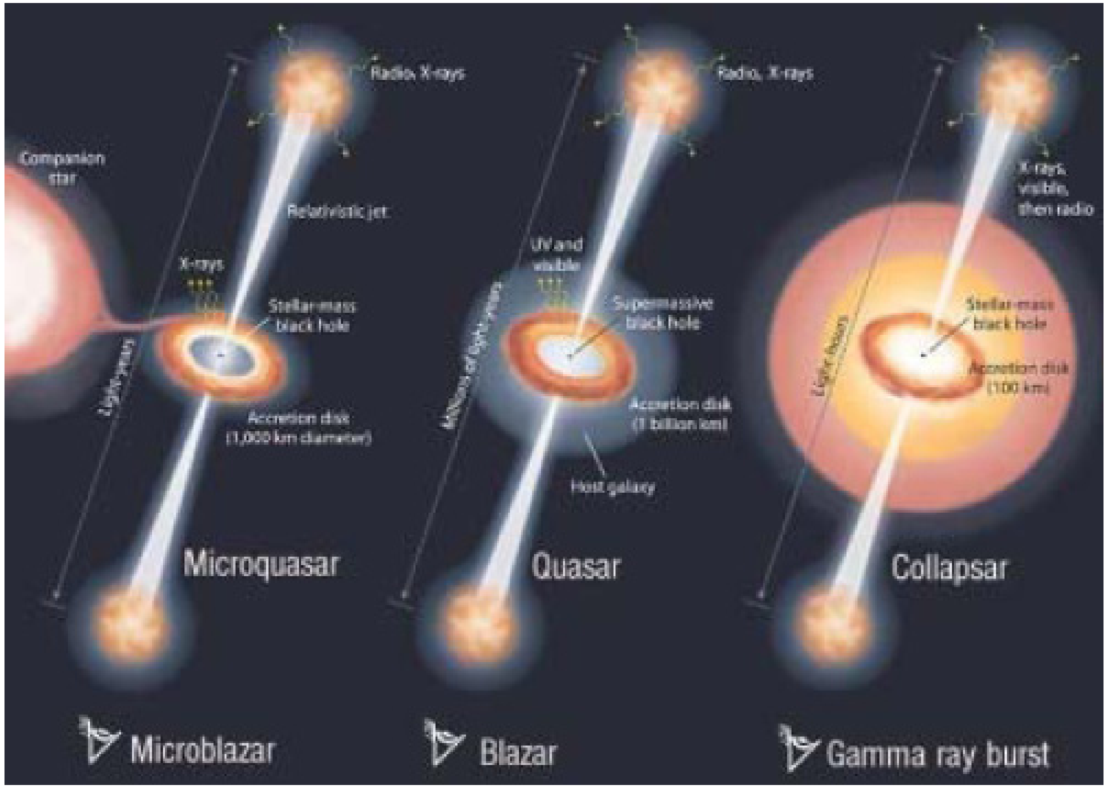


Supermassive black holes at the center of galaxies

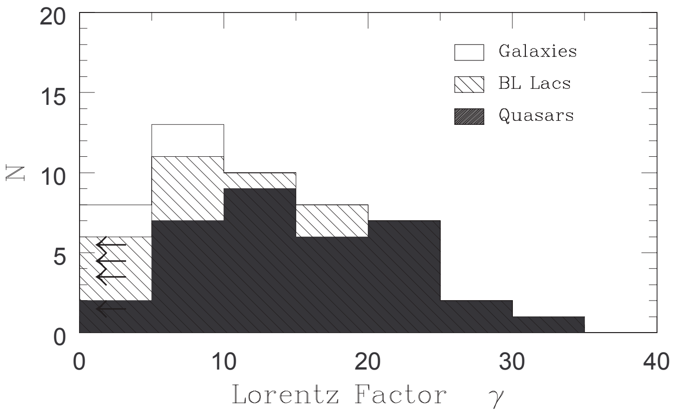


Relativistic Jets in Quasars, Microquasars and GRBs

Jets seem to be universally responsible for activities of AGNs/quasars, macroquasars and GRBs as well as SN explosions.



Mirabel IF, PTP Sup. 155, 71 (2004)

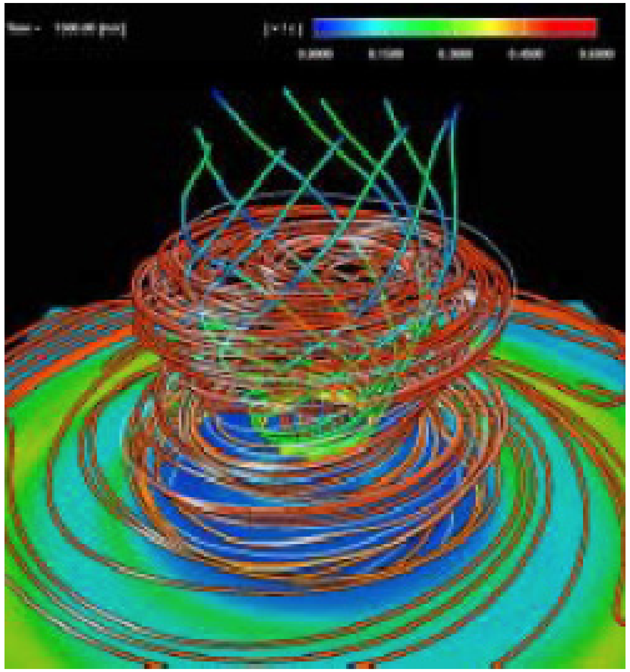


The Lorentz factor Γ of jets from black holes can exceed 30 for quasars and Γ ～100－300 for GRBs.

49 jet sources from 2cm multiepoch VLBA observations [Kellermann et al, ApJ609:539(2004)]

No Successful Theoretical Model

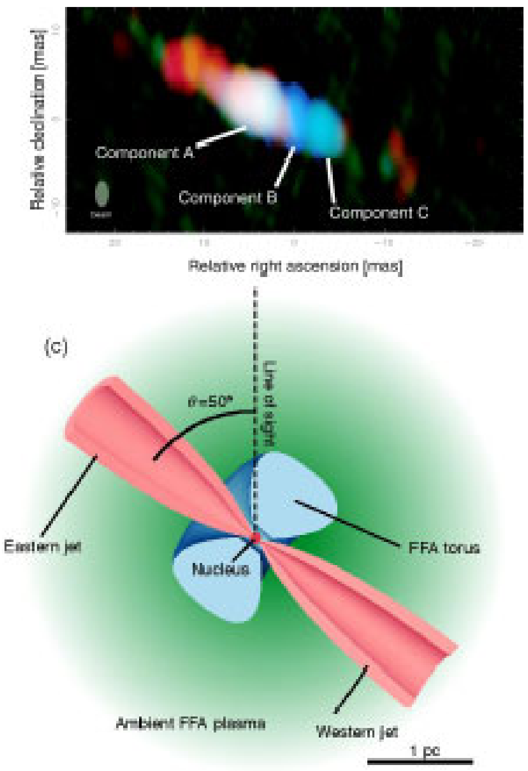
- MHD models are regarded as most promising, but there exists no numerical simulation producing a high Γ and stationary jet.
- Extremely strong magnetic fields (> 10^{15} G) are required even at the SN level theoretically.
- Numerical simulations indicate that GR effects such as the magnetic Penrose process in the ergo region (Punsky B, Coroniti F 1990) are crucial. [Nagataki S et al: ApJ, to be pub (2007)]
- Cosmic jets are strong candidates of acceleration sites for UHE cosmic rays.

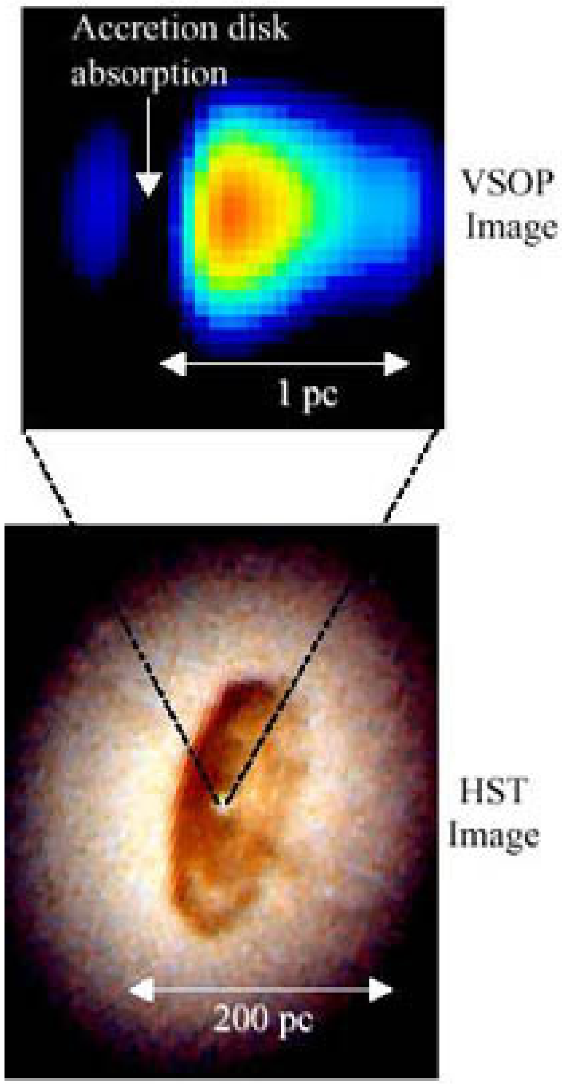


Kato et al: ApJ 605, 307 (2004)

Studies of cosmic jets will give valuable information on physics at extreme conditions as well as UHE particle physics and black hole structures.

Observatories of Extreme Physics





HALCA observations of
NGC1052 and NGC4261

Summary

新しい窓は新しい物理を生む

COBE, HST, SNLS, WMAP, SDSS

⇩

BBO, Space VLBI, ICECube

より高感度，より高解像度の観測

Cosmophysics Group Key Projects

- 重力を含む統一理論を宇宙初期進化で検証する
- 宇宙ジェットとブラックホールの高エネルギー物理

What's Cosmophysics ?

- At the turn of the millennium a new dictionary term, "**cosmophysics**", might have been coined to describe the quest to understand the universe at large as well as its individual components. [CERN Courier 40, No.5]

- **Cosmophysics** is a new term that Maurice Jacob initiates to us, showing how the New Physics and its most hot topics are closely related to astrophysical problems and its space laboratories. [European Astronomical Society, News Letter 23, June 2002]

Reviews and References

Inflation

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UHE Cosmic Rays

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