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清华天协 学术部

清华大学天文系

赵思逸

2022年秋季学期

活动简介

- 清华天协学术部 本学期特色微沙龙
  - 第一次 微·专业课层次·系列·沙龙——请多指教～
  - 主讲人带领的自由讨论
  - 希望讨论可以占到一半时间（及以上？）
- 天文系研究生课程 “物理宇宙学”
  - 拓展讨论?
- 每次1.5-2小时，穿插 “Dandan’s Crazy Friday” 讨论内容
  - 有穿插的时候会提前做时间分配并通知
  - 第一次在下周

活动简介

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- 天文系研究生课程 “物理宇宙学”
- 每次1.5-2小时，穿插 “Dandan’s Crazy Friday” 讨论内容
- 前置：大学物理
  - 希望可以做到“零基础”……
- **注重图象，但不止图象**
  - 事实上主要内容都是非常抽象的公式……
  - 所以要强调“物理图象”
  - *抽象和复杂的只是“语言”，“所指”应该是可理解的。*

大纲

一种熬粥方法……

- 基本集中于“如何加水”，
- 也讨论各种各样的“米”和“豆子”——*欢迎补充专题内容～*
- 每个专题1-2周，期中、期末周暂停。

时间	地点	内容	主讲人
9.18（周日）晚19：00–21：00	C楼C310B	Introduction	赵思逸
9.24（周六）晚19：00–21：00	C楼C309	GR	周晨曦
		FRW metric,Friedmann equation	唐昀毅
		红移，宇宙学相关距离、时间	杨晓睿
		宇宙热历史	王笑晗
		Inflation	
		CMB	冯睿哲
		BNN	
		LSS	
		21cm	
		perturbation	

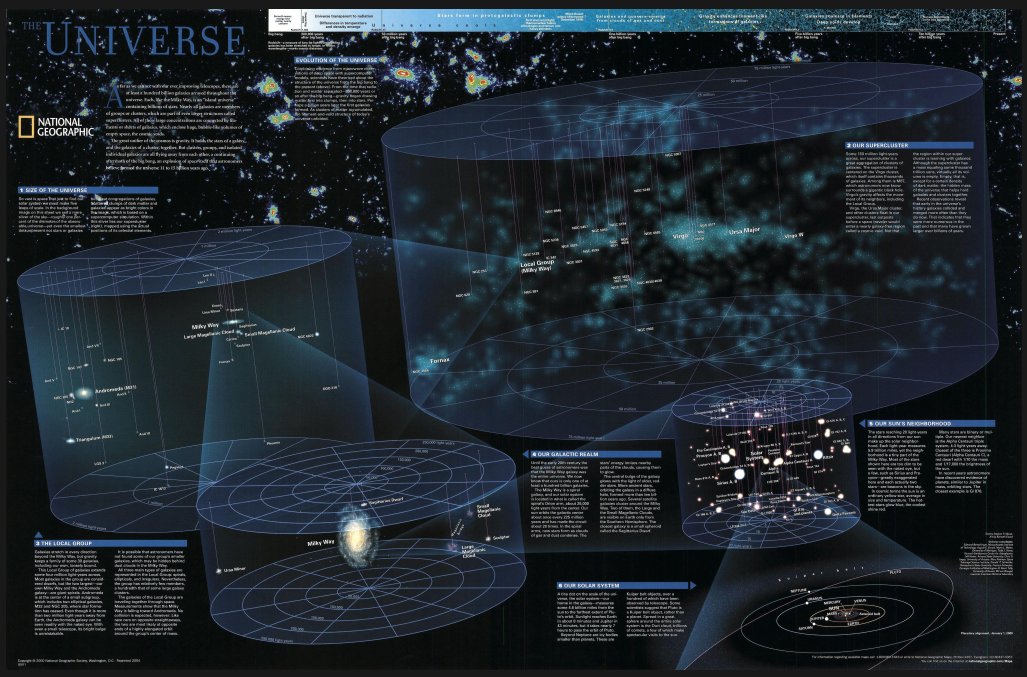
COSMOLOGY IN A NETSHELL

an incomplete and personal biased perspective

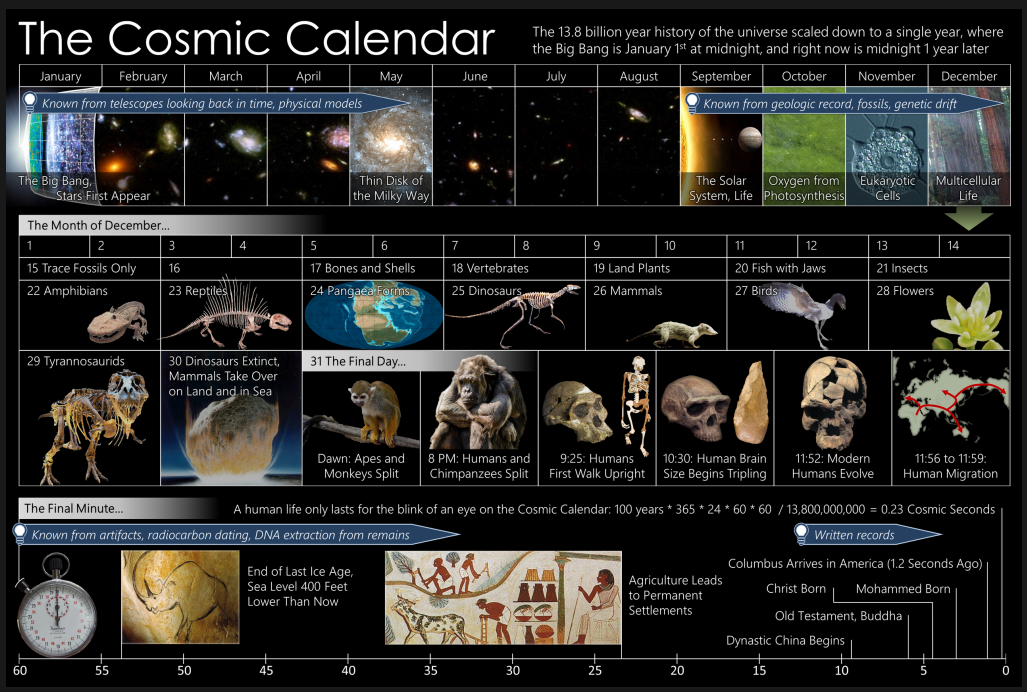
- homogenous
- inhomogeneous

- inhomogeneous
  - at small scales
  - beautiful and complete
  - abundant information
- homogenous
  - at large scales (~100Mpc)
  - rather simple ...
  - *we will focus here as beginning.*
- (JWST deep field)

OUR ADDRESS IN THE UNIVERSE (丹丹供图)



^Question: the satellite galaxies of MW have an anisotropic spacial distribution? Why?



observe from the last 'second' (wikipedia)

NATURAL UNIT

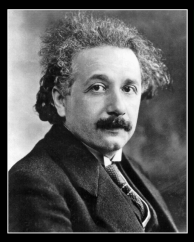
（开始抽象（X）

$$\hbar = c = k_{\mathrm{B}} = 1$$

- 自然单位制、量纲分析对于理论物理来说很重要，怎么熟悉都不为过——需要多练习同时加深理解。

时空结构：WHY?

A modern view of the Universe - I



Albert Einstein

Foundation of modern cosmology 1920s-1930s

- *Observation*: galaxy recession => a "hot & dense" start of the Universe.
- *Theory of GR*: the expansion speed is decided by the *energy density* and *spatial geometry*.

Edwin Hubble

然而，静态的宇宙是不稳定的!

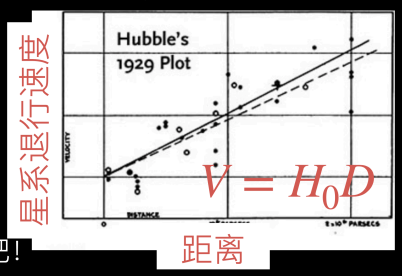
不怕！宇宙是膨胀的！

宇宙的"静止"如何来保持呢?

静态宇宙模型需要宇宙学常数Λ项

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

诶呀好啊！那我把宇宙学常数项扔掉吧！



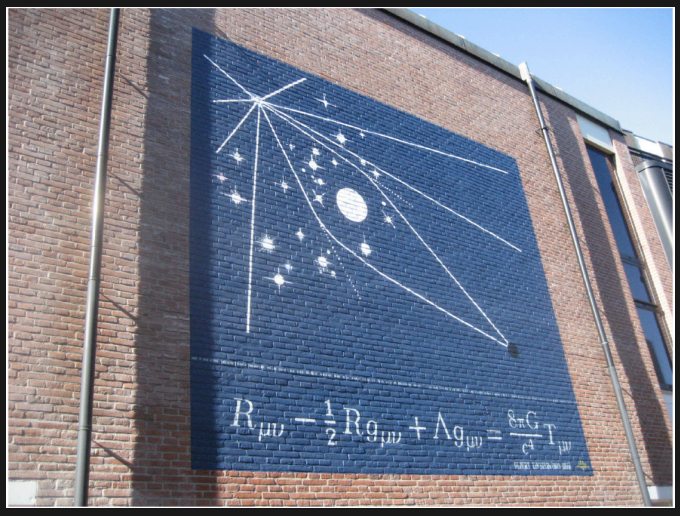
(丹丹的课件)

时空结构

我们的宇宙是广义相对论的一个解。

- spacetime -> GR
- 0 order / at background level -> FRLW metric
  - 宇宙学原理 (space)
    - homogenous
    - isotropic
- evolution -> Friedmann equation

GR: FROM METRIC TO FIELD EQUATION



- Metric / 度规
  - encode the information of spacetime
- Einstein field equation / 场方程
  - “物质告诉时空如何弯曲” ^ discuss: geodesic and field equation are independent?...

FRLW METRIC

$$
\begin{aligned}
ds^2 &\equiv g_{\mu\nu}(x)dx^\mu dx^\nu \\
&= -dt^2 + a^2(t)\left[\frac{dr^2}{1-Kr^2} + r^2 d\Omega\right]
\end{aligned}
$$

- $a(t)$, 膨胀或收缩
- 既适用于平直时空，也适用于弯曲时空 (K)
  - eg: inflation 期间的 de Sitter space
- isotropic
- homogenous (in case K=0, -1, +1?)

FRIEDMANN EQUATION

FRLW metric + Einstein field equation => Friedmann equations

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

$$
\frac{\ddot{a}}{a} + \frac{1}{2}\left(\frac{\dot{a}}{a}\right)^2 = -4\pi G P
$$

- The 2 equations is not independent with *energy conservation* equation.
- radiation / matter / Dark energy dominate
  - different stages of our Universe

OBSERVATION OF COSMOLOGY

distances

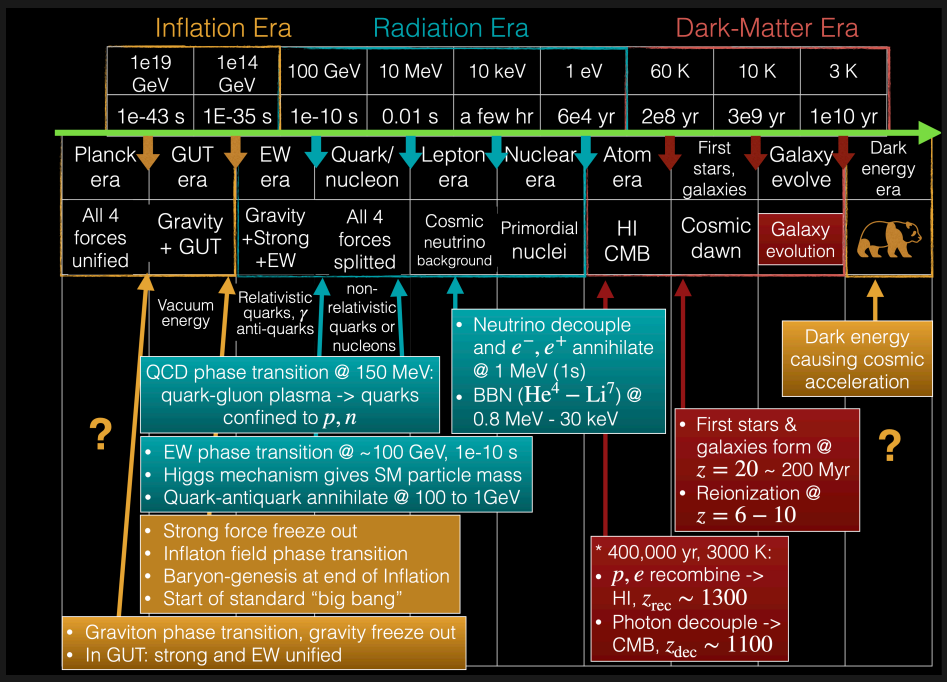
- *comoving distance*
- angular distance
- luminosity distance
- *Horizon*

times

- *conformal time*
- age
- look-back time

THERMAL HISTORY

- inflation (?)
- radiation era
- reheating / hot Big Bang
- "first three minutes"
- BBN
- matter era
- CMB
- dark age
- Cosmic Dawn: First stars and galaxies
- Reionization
- dark energy era
- We are here!

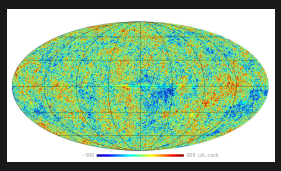


(丹丹的课件) ^discuss: inflaton looks like dark energy..

INHOMOGENEOUS UNIVERSE

- initial perturbation
- gravitational evolution

INFLATION



- *perturbed* initial condition
  - quantum fluctuation -> classical fluctuation ^discuss: 这一过程尚不清楚，几乎是一次“量子测量”。
  - Horizon
- Inflation itself ?
  - *cosmology beyond standard model*
  - Why we need Inflation?
  - inflaton potential and interactive: slow-roll single field and beyond.. ^（根据现场讨论改进）

STRUCTURE FORMATION

perturbation theory

super-horizon, sub-horizon

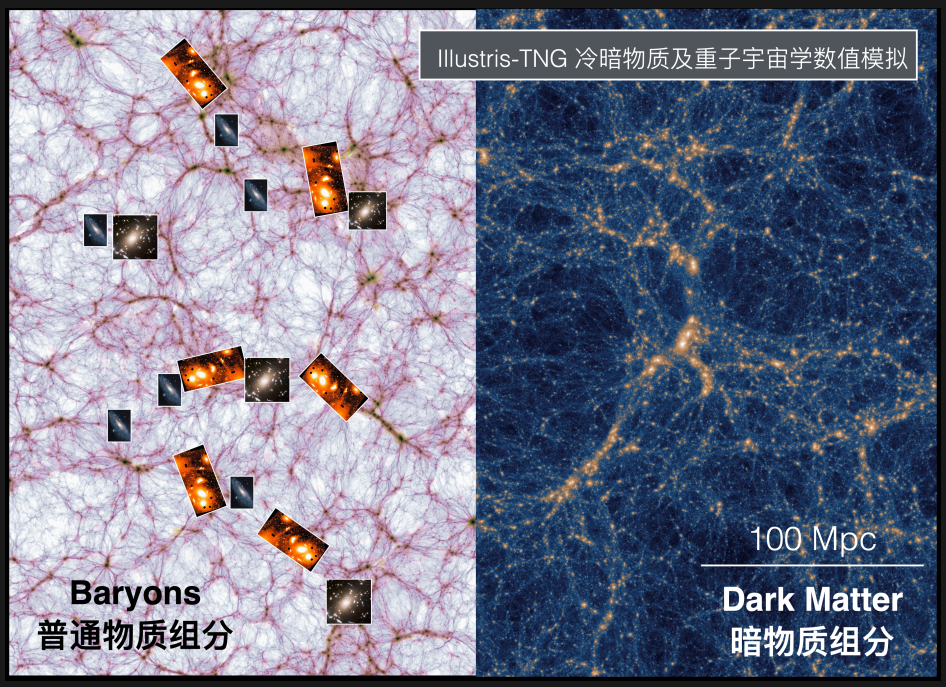
Euler perturbation, Lagrangian perturbation,

Zel'dovich approximation,

growth factor, transform function

dark matter / radiation / baryon dominate...

STRUCTURE FORMATION: SIMULATION



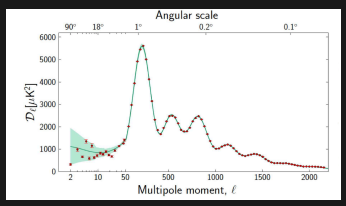
(丹丹的课件) ^吐槽：星系是一些贴图（雾）

宇宙学探针 TRACERS

-> constrain cosmology parameters

- CMB
- LSS
- 21cm

CMB： 宇宙学“第一探针”



- global signal and observation history
- monopole analysis -> power spectrum
  - BAO
- beyond horizon: SW effect...

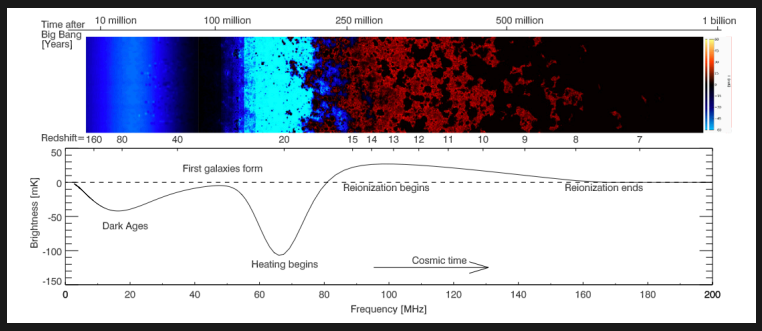
^大家可以看Wayne Hu的tutorial，有（功率谱随宇宙学模型参数变化的）动图，比如
http://background.uchicago.edu/~whu/intermediate/clcurvature.html

宇宙学探针： GALAXY SURVEY

星系在高密度区形成。

- 3D information!
- maybe significantly biased...

宇宙学探针：21CM



- also 3D
- overcome selection bias
- can be very clear at Dark Ages...
- hard to observe ...

宇宙学探针：……

- 中微子背景辐射?
- 原初引力波背景?

^ Question: 那个更难探测?

统计学方法

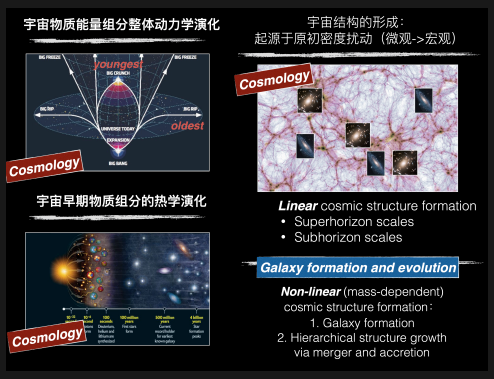
STATISTICS

- Power Spectrum
- High order statistic
  - skewness, kurtosis...
  - Bispectrum, Trispectrum...
  - ...
- Minkowski functional
- Scattering transform function (in machine learning?)
- ...

FORECAST

- Fisher ^需要给出parameters 的 fiducial value，所以比较依赖于先验
- MCMC ^在整个参数空间取样，不太依赖于先验，类似投针法测π（2米乘2米的正方形内接半径1米的圆形，随机投针看有多少比例落入圆形内……）
- ..

COSMOLOGY IN A NETSHELL



- homogenous
  - spacetime
  - expansion history
  - thermal history
- inhomogeneous
  - initial condition
    - -> inflation / fluctuations
  - structure formation
    - -> gravity / perturbation
  - how to observe inhomo.
    - -> tracers + Statistics
- (丹丹的课件)
- ^ summary , important!

再会，谢谢所有的🐟