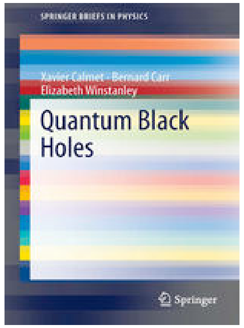
BLACK HOLES IN MACROPHYSICS AND MICROPHYSICS

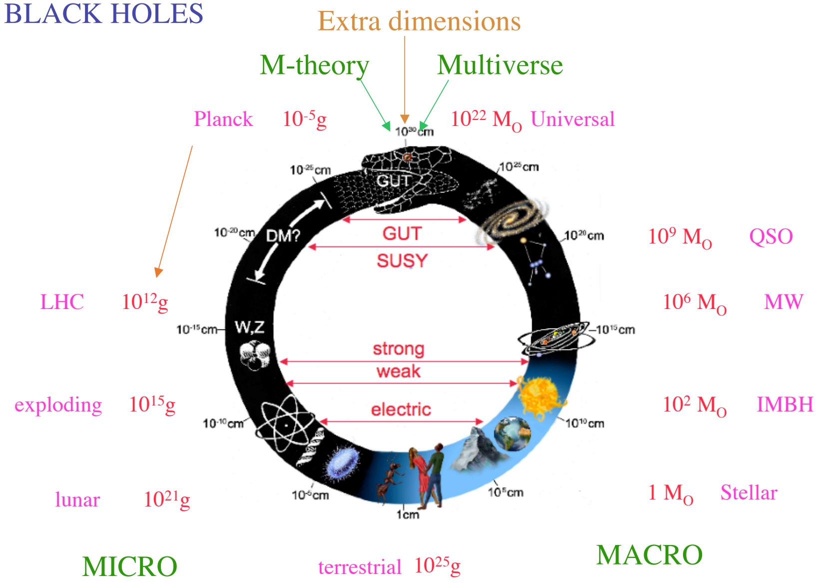
Bernard Carr
Queen Mary, University of London

- Introducing black holes
- Formation of primordial black holes
- Constraints on primordial black holes
- Some hot topics



Lectures at RESCEU summer school 2014

BLACK HOLES



BLACK HOLE FORMATION

$R_S = 2GM/c^2 = 3(M/M_O)$ km => $\rho_S = 10^{18}(M/M_O)^{-2}$ g/cm^3

Stellar BH ($M\sim10^{1\text{-}2}M_O$), IMBH ($M\sim10^{3\text{-}5}M_O$), SMBH ($M\sim10^{6\text{-}9}M_O$) may form at present or recent epochs.

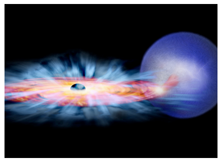
Small "primordial" BHs can only form in early Universe

cf. cosmological density $\rho \sim 1/(Gt^2) \sim 10^6(t/s)^{-2}$g/cm^3

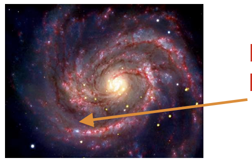
⇨ PBHs have horizon mass at formation

$$M_{PBH} \sim c^3t/G = \begin{cases} 10^{-5}\text{g at } 10^{-43}\text{s} & \text{(minimum)} \\ 10^{15}\text{g at } 10^{-23}\text{s} & \text{(evaporating now)} \\ 1M_O \text{ at } 10^{-5}\text{s} & \text{(QCD transition)} \\ 10^5M_O \text{ at 1s} & \text{(maximum)} \end{cases}$$

OVERWHELMING EVIDENCE FOR STELLAR BH ($M\sim10^{1\text{-}2}M_O$)

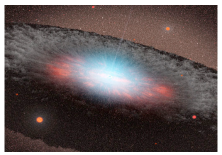


Cygnus X1

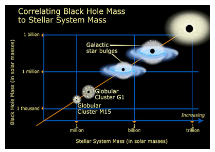


First observ' of BH birth (2010)

OVERWHELMING EVIDENCE FOR SMBH IN AGN ($M\sim10^{6\text{-}9}M_O$)



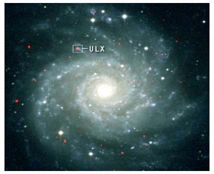
MW 4×10^6M_O
QSO 10^8M_O
Max 2×10^9M_O



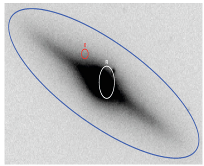
BH mass proport' to stellar mass?

POSSIBLE EVIDENCE FOR IMBH ($M \sim 10^{3-5} M_O$)

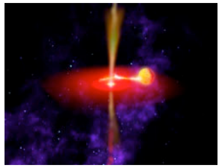
ULX source NGC1313 may have $500 M_O$ BH



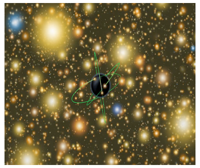
Spiral ESO 243-49 may have $M > 500 M_O$



QPO in NGC5408 X1 implies $2000 M_O$ BH

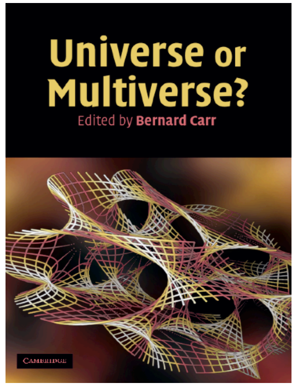


GC Omega Cen may have $4 \times 10^4 M_O$ BH



Gamma-ray bursts?

NO EVIDENCE FOR PRIMORDIAL BLACK HOLES!



NO EVIDENCE FOR ACCELERATOR BLACK HOLES!

BLACK HOLE EVAPORATION

Black holes radiate thermally with temperature

$$T = \frac{hc^3}{8\pi GkM} \sim 10^{-7} \left[\frac{M}{M_0}\right]^{-1} \text{K}$$ (Hawking 1974)

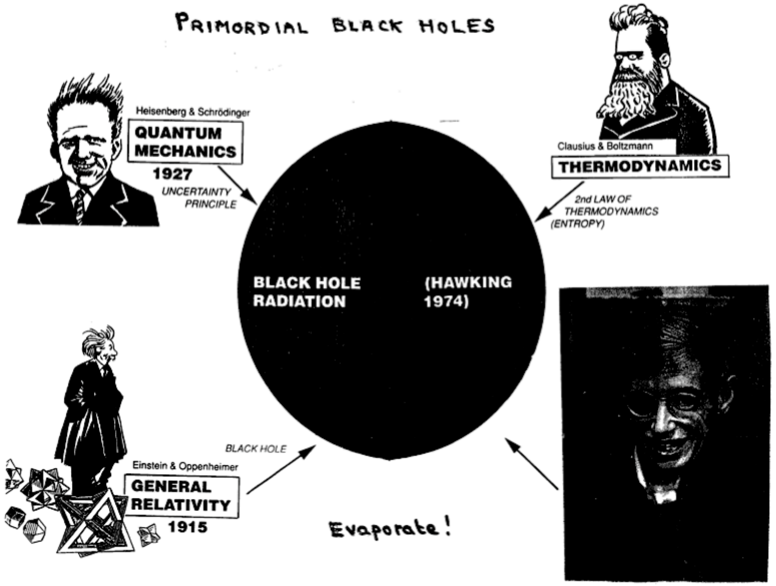
=> evaporate completely in time $t_{evap} \sim 10^{64} \left[\frac{M}{M_0}\right]^3$ y

$M \sim 10^{15}$g => final explosion phase today (10^{30} ergs)

This can only be important for PBHs

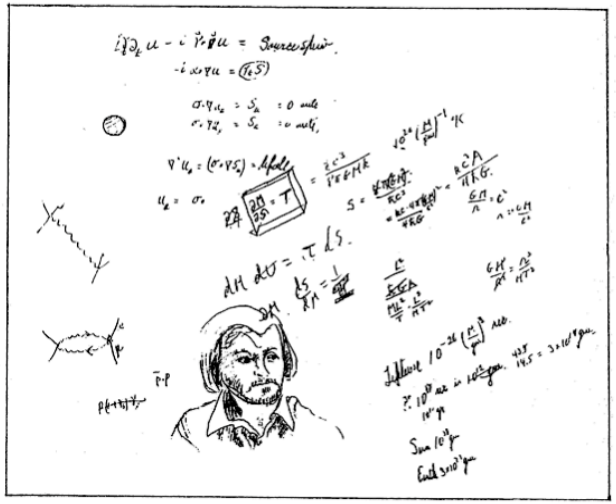
γ-ray bgd at 100 MeV => $\Omega_{PBH}(10^{15}\text{g}) < 10^{-8}$
(Page & Hawking 1976)

=> explosions undetectable in standard particle physics model



PBHs important even if never formed!

Feynman's envelope!

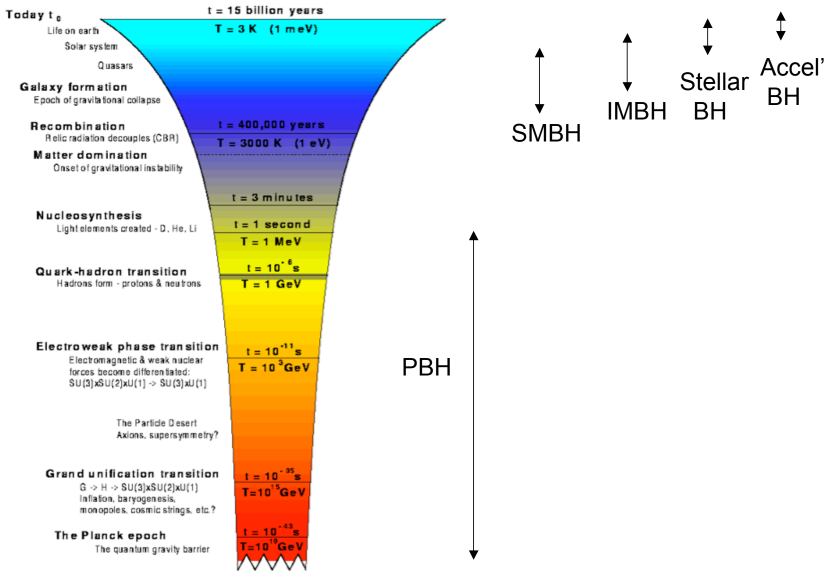


1975

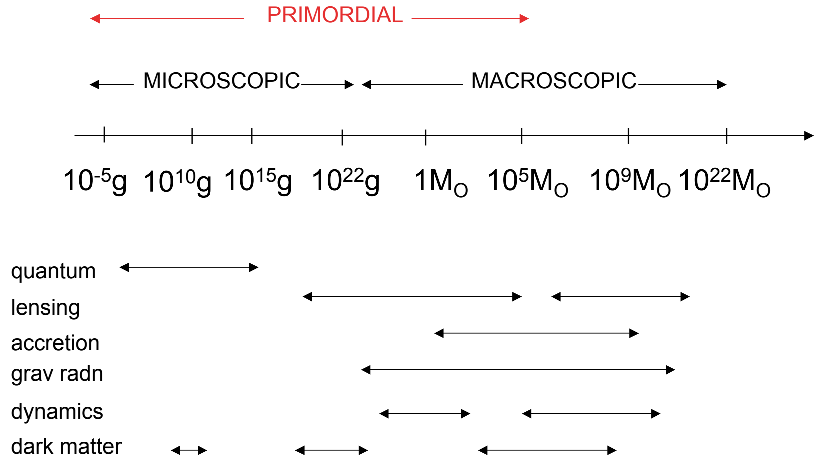
MODES OF BLACK HOLE FORMATION

Name	Mass/$M_\odot$	BH formation mechanism/stellar end-state	Location
SMO		Collapse to SMBH before H-burning from GR instability. Accretion onto/merger of IMBHs	Quasars/galactic nuclei Intergalactic/halo DM?
	10^5	Collapse to IMBH due to electron-positron instability during O-burning	GCs/ULXs/GRBs? Intergalactic/halo DM?
VMO	200	Explode due to electron-positron instability during O-burning (no remnant)	
	100	Prompt core collapse after nuclear burning or delayed collapse after failed supernova	Galactic discs
MO	25	White dwarf or neutron star remnant or total disruption at carbon ignition (no remnant)	
	1	Collapse from primordial fluctuations or at cosmological phase transition or in dust era	Intergalactic/halo DM?
PBH	10^{15}g	Same formation mechanism but evaporation completed and M* holes exploding today	Local GRBs?
	10^{-5}g	Planck mass relics of larger evaporated holes or remnants of Planck epoch	Intergalactic/halo DM?

WHEN BLACK HOLES FORM



QUANTUM & ASTROPHYSICAL EFFECTS OF BLACK HOLES



PART II: PRIMORDIAL BLACK HOLES

PBHs as probe of early Universe
inhomogeneities, phase transitions, inflation

PBHs as probe of high energy physics
PBH explosions, cosmic rays, extra dimensions

PBHs as probe of quantum gravity
Planck mass relics, Generalized Uncertainty Principle

HOW PBHS FORM

Inhomogeneities (discussed in more detail later)

Pressure reduction
Khlopov & Polnarev 1980, Widerin & Schmid 1998,
Jedamzik & Niemeyer 1999, Fuller et al 2000

Cosmic strings
Polnarev & Zemboricz 1988, Hawking 1989, Garriga & Sakellariadou 1993, Caldwell & Casper 1996, MacGibbon et al 1998

Bubble collisions
Crawford & Schramm 1982, Hawking et al 1982, La & Steinhardt 1989
Konoplich et al 1998, Khlopov et al 1999

Domain walls
Rubin et al 2000, Khlopov et al 2004

String necklaces
Matsuda 2006, Lake et al 2009

WHAT PRIMORDIAL BLACK HOLES DO

Probe fundamental physics **($M \sim 10^{-5}$g)**
Planck-mass relics
Extra dimensions and higher dimensional BHs
TeV quantum gravity

Probe early universe **($M < 10^{15}$g)**
Baryosynthesis/nucleosynthesis
Gravitino/neutrino/entropy production
Removing monopoles/domain walls

Probe high energy physics **($M \sim 10^{15}$g)**
Cosmological and Galactic γ-rays
Cosmic ray antiprotons and positrons
PBH explosions and gamma-ray bursts

Probe gravity **($M > 10^{15}$g)**
Non-baryonic cold dark matter candidate
Dynamical/lensing/gravitational-wave effects
Seed large-scale structure and SMBHs in galactic nuclei

Limit on fraction of Universe collapsing

β(M) **fraction of density in PBHs of mass M at formation**

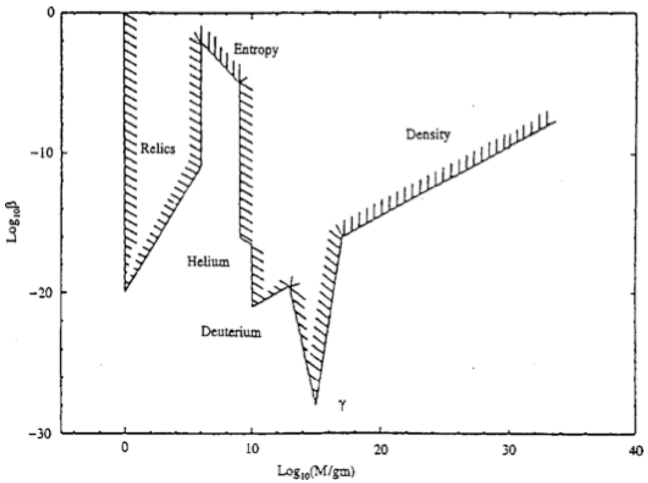
General limit

$$\frac{\rho_{PBH}}{\rho_{CBR}} \approx \frac{\Omega_{PBH}}{10^{-4}}\left[\frac{R}{R_0}\right] \Rightarrow \beta < 10^{-6}\,\Omega_{PBH}\left[\frac{t}{\text{sec}}\right]^{1/2} < 10^{-18}\,\Omega_{PBH}\left[\frac{M}{10^{15}\,g}\right]^{1/2}$$

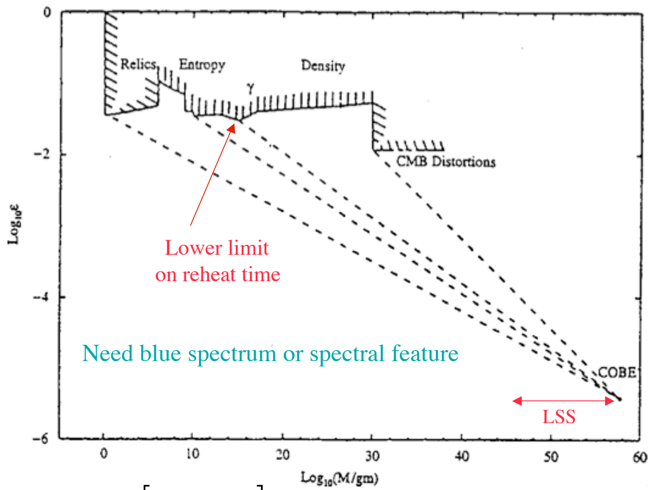
Unevaporated	**$M>10^{15}$g => $\Omega_{PBH} < 0.25$**	**(CDM)**
Evaporating now	**$M\sim10^{15}$g => $\Omega_{PBH} < 10^{-8}$**	**(GRB)**
Evaporated in past	**$M<10^{15}$g**	

=> constraints from entropy, γ-background, BBNS

Carr, Gilbert & Lidsey (1994)



Constraints on amplitude of density fluctuations at horizon epoch



$$\beta(M) \sim \varepsilon(M) \exp\left[-\frac{1}{18\varepsilon(M)^2}\right]$$

PBHs are unique probe of **ε** on small scales

PBH FORMATION => LARGE INHOMOGENEITIES

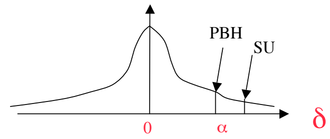
To collapse against pressure, need (Carr 1975)

$R > \sqrt{\alpha}\,ct$ **when** $\delta \sim 1$ **=>** $\delta_H > \alpha$ ($p=\alpha\rho c^2$)

Gaussian fluctuations with $\langle\delta_H^2\rangle^{1/2} = \varepsilon(M)$

⇒ fraction of PBHs

$$\beta(M) \sim \varepsilon(M) \exp\left[-\frac{\alpha^2}{2\varepsilon(M)^2}\right]$$



ε(M) constant => β(M) constant => $dN/dM \propto M^{-\left(\frac{1+3\alpha}{1+\alpha}\right)-1}$

ε(M) decreases with M => exponential upper cut-off

Separate universe for $\delta_H > 1$ **but recently disputed**

Analytic prediction ($\delta > 0.3$ **for** $\alpha = 1/3$**) confirmed by early numerical studies but pressure gradient means PBHs are somewhat smaller than horizon (Nadezhin et al 1978)**

CRITICAL PHENOMENA

Mass scaling => $M_{PBH} = k\, M_H(\delta-\delta_C)^\gamma$ **(Choptuik 1993)**

In Friedmann background (Niemeyer & Jedamzik 1998)

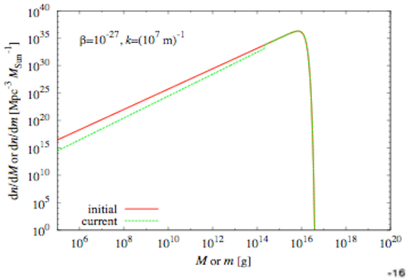
$2.4 < k < 11.9,\ 0.67 < \delta_C < 0.71,\ 0.34 < \gamma < 0.37$

⇒ PBH mass spectrum peaks at horizon mass but has extended low mass tail $dN/dM \propto M^{1/\gamma-1}\exp[-(M/M_f)^{1/\gamma}]$
(Yokoyama 1998, Kribs 1999, Green 2000)

Later studies => $0.43 < \delta_C < 0.47$ **(Musco et al 2005)**
Peak analysis versus Press-Schechter => $\delta > 0.3$ **again!**
(Green et al 2004)

Constraints on PBHs from near-critical collapse

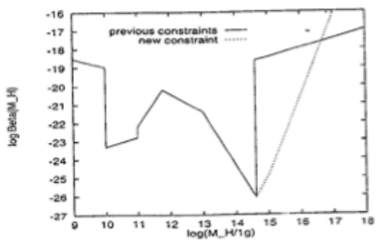
(Yokoyama 1998)



=> broad mass spectrum

=> strong constraints above 10^{14}g

GRBs and DM from 10^{16}g PBHs?
(Green 2000)



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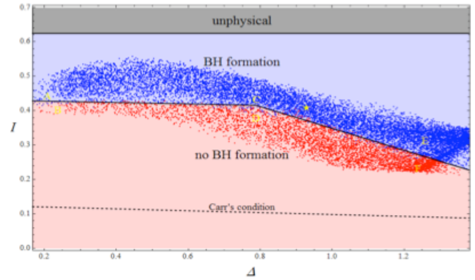
Identifying the most crucial parameters of the initial curvature profile for primordial black hole formation

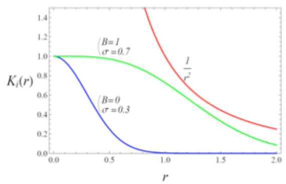
Tomohiro Nakama,[a,b] Tomohiro Harada,[c] A.G. Polnarev[d] and Jun'ichi Yokoyama[b,e]

Numerically solve evolution of spherically symmetric highly perturbed configuration using curvature profiles characterized by 5 parameters. Only two are important: average amplitude of central overdensity (I) and width of transition region at boundary (Δ).



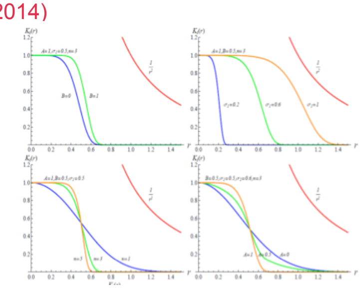
2-parameter curvature profile (Polanev & Musco 2007, Polnarev et al 2012))

$$K_i(r) = \left[1 + \frac{B}{2}\left(\frac{r}{\sigma}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{r}{\sigma}\right)^2\right]$$



5-parameter curvature profile (Nakama et al. 2014)

$$K_i(r) = A\left[1 + B\left(\frac{r}{\sigma_1}\right)^{2n}\right] \exp\left[-\left(\frac{r}{\sigma_1}\right)^{2n}\right] + (1-A)\exp\left[-\left(\frac{r}{\sigma_2}\right)^2\right]$$



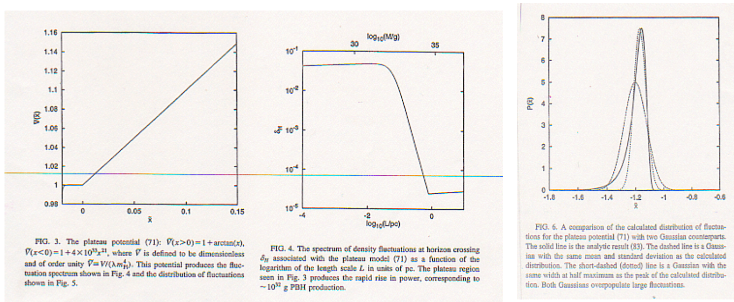
NON-GAUSSIAN FLUCTUATIONS

Expected whenever fluctuations are large
(Bullock & Primack 1997, Ivanov 1998, Hidalgo 2007, Young & Byres 2013)

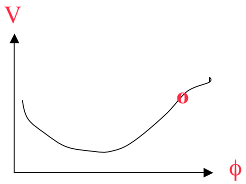
Quantum field theory => n-point correlation function
Slow-roll correction using inflation 3-point correlator

$$P(\delta) = \frac{1}{\sqrt{2\pi}\Sigma}\left[1 - \left(\frac{\delta^3}{\Sigma^6} - \frac{3\delta}{\Sigma^4}\right)\right]\exp\left[-\frac{\delta^2}{2\Sigma^2}\right]$$

(Seery & Hidalgo 2006)



PBHS AND INFLATION



PBHs formed before reheat inflated away =>

$$M > M_{min} = M_{Pl}(T_{reheat} / T_{Pl})^{-2} > 1 \text{ gm}$$

since CMB quadrupole => $T_{reheat} < 10^{16}$GeV

But inflation generates fluctuations $\frac{\delta\rho}{\rho} \sim \left[\frac{V^{3/2}}{M_{Pl}^{3} V'}\right]_H$

Can these produce PBHs?

Slow roll plus friction-domination

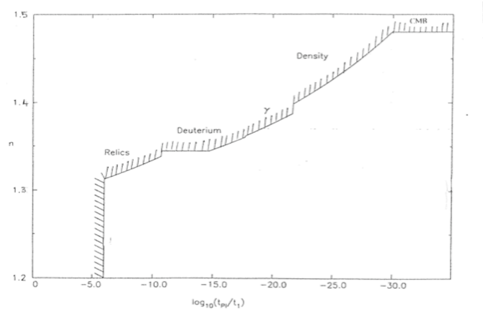
$$\xi = (M_{Pl}V'/V)^2 << 1, \qquad \eta = M_{Pl}V''/V << 1$$

=> nearly scale-invariant fluctuations

$$|\delta_k^2| \sim k^n, \ \delta_H \sim M^{(1-n)/4} \text{ with } \ n = 1 - 3\xi + 2\eta \approx 1$$

CMB => $\delta_H \sim 10^{-5}$ => n > 1 for PBHs => $V''V/V^2 > 3/2$.

PBH limits then constrain **n** for each reheat time t_R



Observe n < 1 on horizon scale => need running index for PBHs.

BICEP2 gives $\frac{d \ln n}{dk} \approx -0.02 \pm 0.01$ (wrong sign!)

Can reasonable inflation model allow n > 1 at large k?

Can we believe $\frac{\delta\rho}{\rho} \sim \left[\frac{V^{3/2}}{M_{Pl}^{3} V'}\right]_H$ at end of inflation?

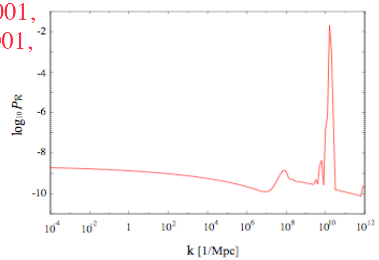
New sources of curvature fluct'ns at end of inflation
(Kolb et al 2005, Lyth 2005, Salem 2005)

PBH formation on sub-horizon scales (Lyth et al 2005)

Feature in V(ϕ) => discrete PBH mass spectrum on any scale
(Hodges & Blumenthal 1990, Ivanov et al 1994)

PBHs and preheating
(Easther & Parry 2000, Bassett &Tsujikawa 2001, Green & Malik 2001, Finelli & Khlebnikov 2001, Suyama et al 2005, Torres-Lomas et al. 2013)

Second inflationary phase can produce PBHs in any mass range
(Yokohama, Frampton et al. 2010)



PBH CONSTRAINTS ON INFLATION MODELS

Designer (Hodge et al 1990, Ivanov et al 1994,Yokoyama 1999, Blais et al 2003)

Chaotic (Carr et al 1994, Green & Liddle 1997, Kim et al 2000, Bringmann et al 2001, Lyth et al 2006, Zaballa et al 2007)

Supernatural (Randall, Soljacic & Guth 1996)

Supersymmetry/supergravity (Green et al 1997, Green 1999, Kanazawa et al. 2000)

Hybrid (Garcia-Bellido, Linde & Wands 1996, Kanazawa et al. 2000)

Multiple/oscillating (Yokoyama 1998, Taruya 1999, Saito et al 2008)

Running (Leach, Grivell & Liddle 2000, Kawasaki et al 2007, Kawaguchi et al 2008, Bugaev & Klimai 2009, Kohri et al 2009)

Locked/saddle (Easther, Khoury & Schalms 2004)

Hill top (Kohri, Lin & Lyth 2007, Alabidi & Kohri 2009)

Preheating (Easther & Parry 2000, Green & Malik 2001, Bassett & Tsukikawa 2001, Finelli & Khlebnikov 2001, Suyama et al 2005)