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Neutron stars and Black holes: Indirect probes for new physics

Lecture at

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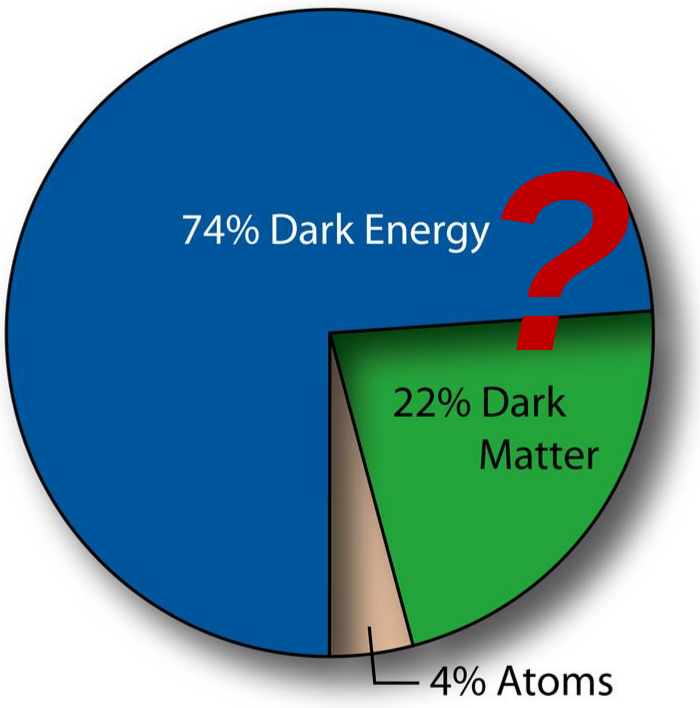
Dublin, Ireland, 20 June 2018

Outlines

- Physical basis of the modern cosmology – Physics beyond the Standard model
- Neutron Stars (NS) and Black Holes (BH) – ordinary matter in extreme conditions, natural sources for multimesenger High Energy Astrophysics
- Neutron Star probes for Dark Matter.
- Primordial Black Holes (PBHs) as cosmological reflection of particle symmetry.
- Strong Primordial nonhomogeneities and Massive PBH clusters from models of inflation.
- Antimatter as profound signature for nonhomogeneous baryosynthesis.

Composition of the Modern Unverse



$$\Omega \equiv \frac{\rho}{\rho_{cr}}$$

$$\Omega_{\mathrm{b}} \approx 0.044 \qquad \Omega_{\mathrm{CMB}} \approx 0.5 \cdot 10^{-4}$$

$$\Omega_{\mathrm{DM}} \approx 0.20$$

$$\Omega_{\Lambda} \approx 0.7$$

$$\boxed{\Omega_{\mathrm{tot}} \approx 1.0}$$

In the modern Universe dominate dark energy and dark matter – their nature is related to the new physics – physics beyond the Standard model, on which the bedrocks of modern cosmology are based

The bedrocks of modern cosmology

Our current understanding of structure and evolution of the Universe implies three necessary elements of Big Bang cosmology that can not find physical grounds in the standard model of electroweak and strong interactions. They are:

- Inflation
- Baryosynthesis
- Dark matter/energy

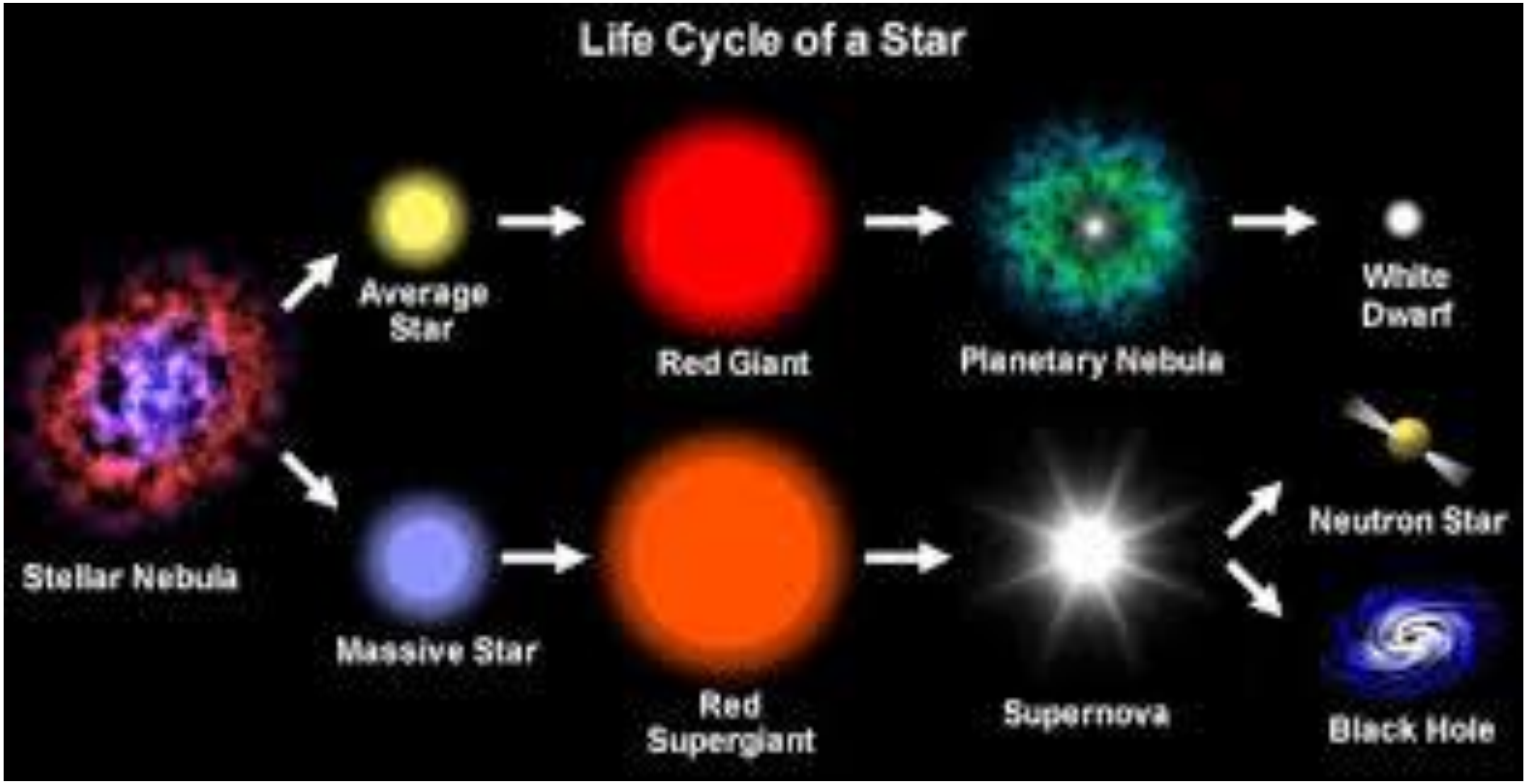
Physics beyond the Standard model, describing these phenomena inevitably predicts additional model dependent effects, in which NS and BH play important role.

Cosmological Reflections of Microworld Structure

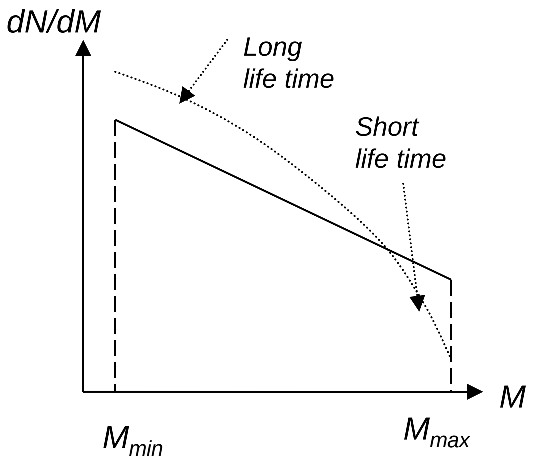
- (Meta-)stability of new particles reflects some Conservation Law, which prohibits their rapid decay. Following Noether’s theorem this Conservation Law should correspond to a (nearly) strict symmetry of microworld. Indeed, all the particles - candidates for DM reflect the extension of particle symmetry beyond the Standard Model.
- In the early Universe at high temperature particle symmetry was restored. Transition to phase of broken symmetry in the course of expansion is the source of topological defects (monopoles, strings, walls…).
- Structures, arising from dominance of superheavy metastable particles and phase transitions in early Universe, can give rise to Black Holes, retaining in the Universe after these structures decay.

NS AND BH FROM ORDINARY MATTER

NS and BH – final stages of a massive star



Stars in the Galaxy



Salpeter (1955) mass function:
$dN/dM \sim M^{-2.35}$

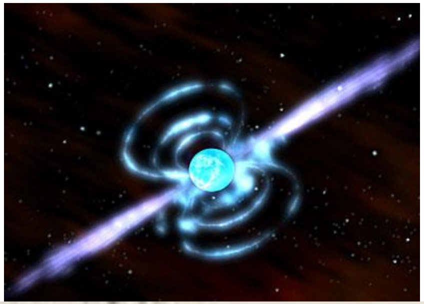
There are many modification (Miller-Scalo, Kroupa etc.).
At high masses the slope is usually steeper.
Note: it is initial mass function, not the present day!

It is possible to estimate the number of NS and BH progenitors.
Then using there average lifetime we can estimate the birth rate
and total numbers (with a given age of the Galaxy and assuming constant rate)
taking into account SFR~3 solar mass per year.
[see also Ch.1 in Shapiro, Teukolsky]

So, finally we have (0.3-1)10^9 NSs in the Galaxy.

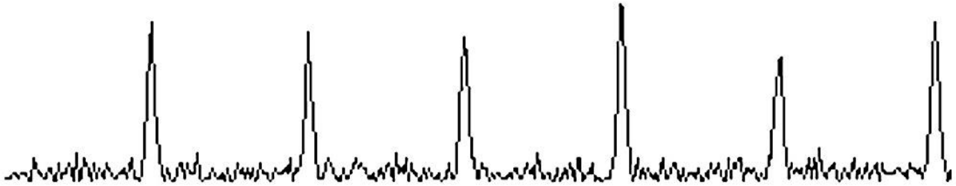
S.Popov. VIA lecture

Pulsars

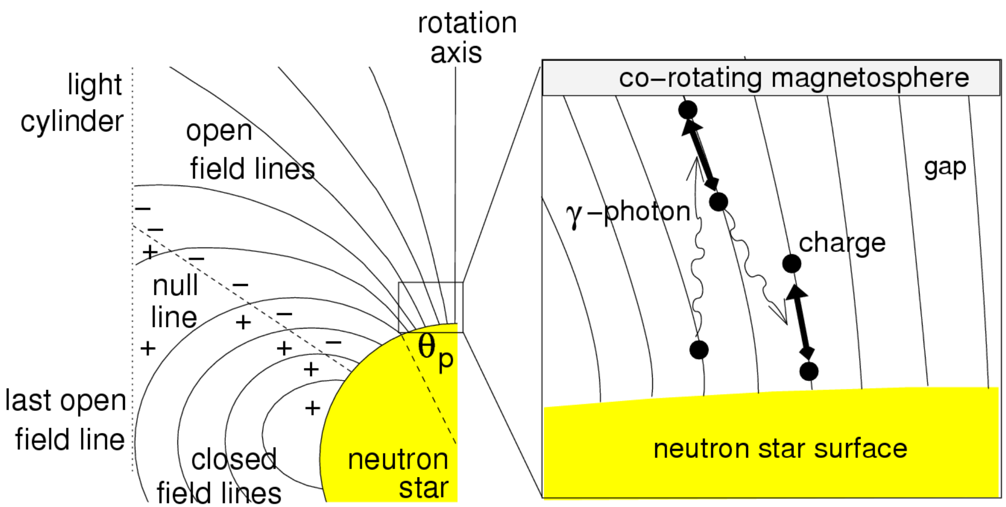


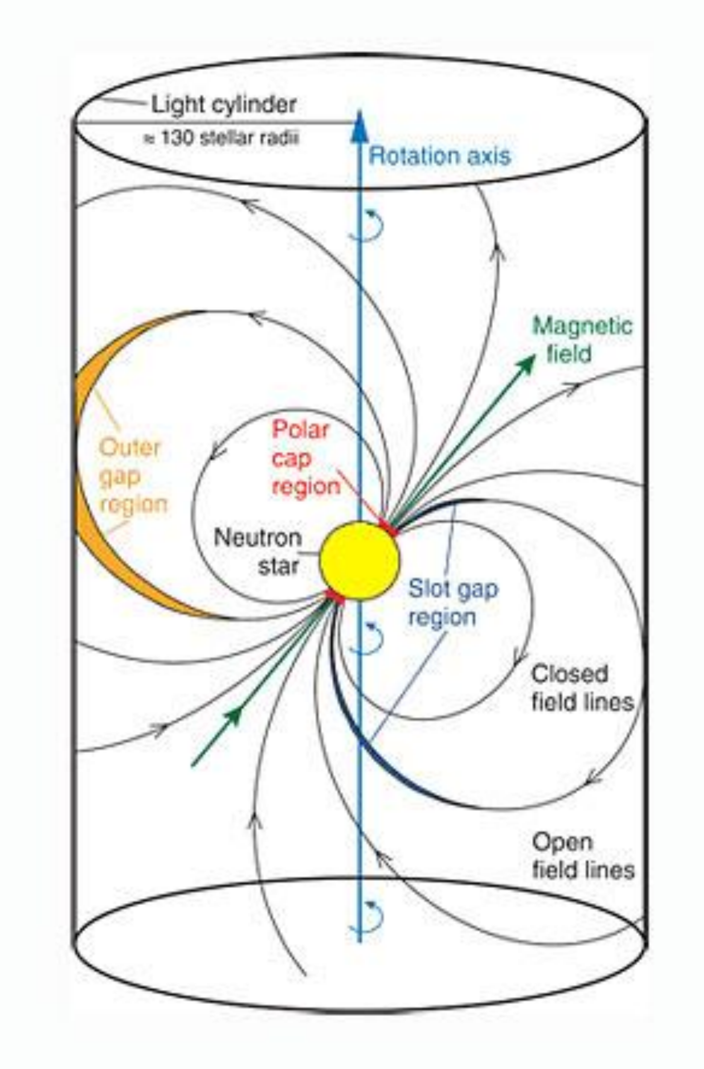
1967: Jocelyn Bell. Radio pulsars.

Serendipitous discovery of the observational feature of NS



How do pulsars work?



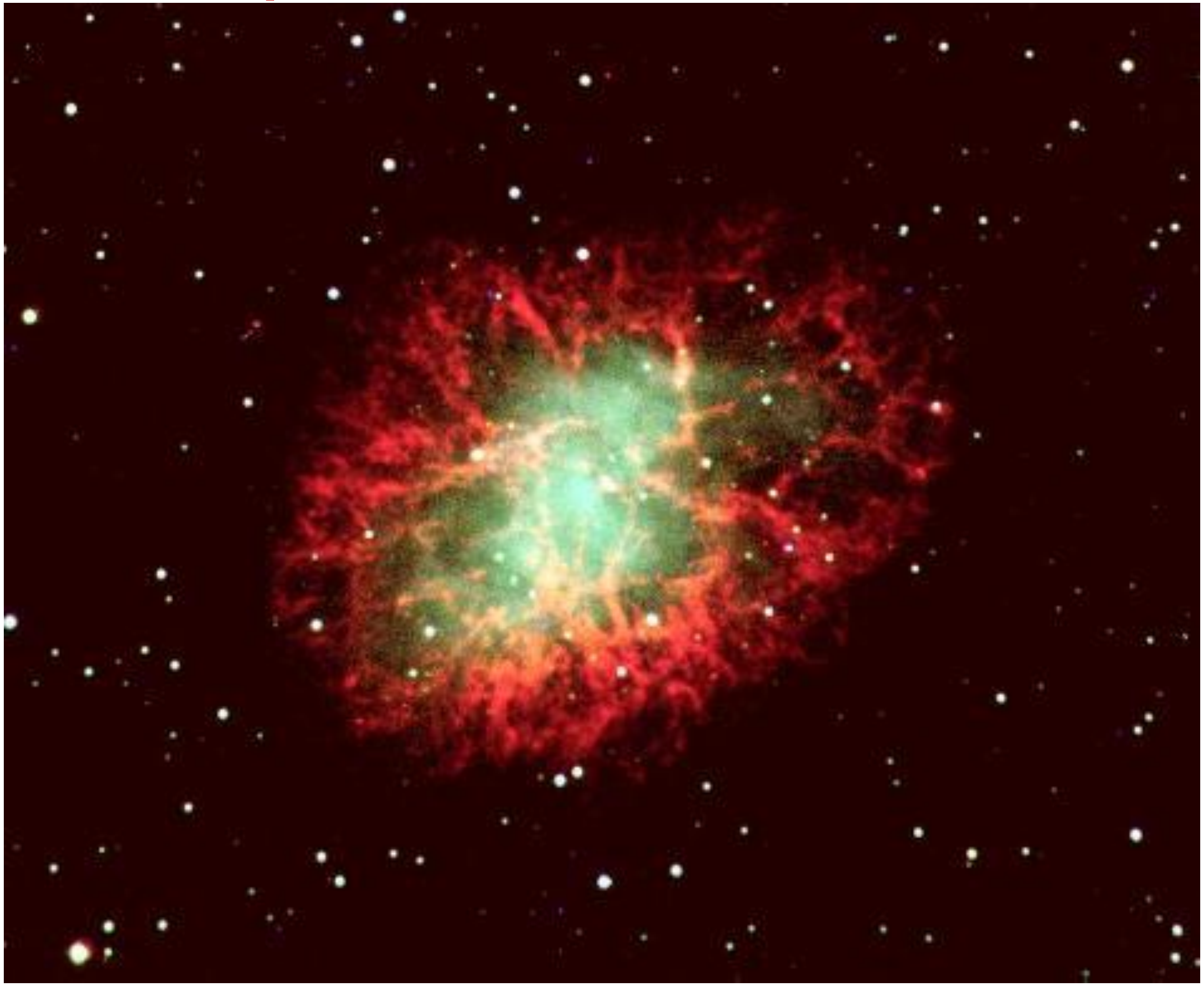


http://www.cv.nrao.edu/course/astr534/Pulsars.html

$$P_{\rm rad} = \frac{2}{3}\frac{m_\perp^2\Omega^4}{c^3} = \frac{2m_\perp^2}{3c^3}\left(\frac{2\pi}{P}\right)^4 = \frac{2}{3c^3}(BR^3\sin\alpha)^2\left(\frac{2\pi}{P}\right)^4,$$

Cascade of charged particles is formed in the magnetosphere. And then these particles move along curved field lines.

The pulsar in the Crab nebula



ANTF pulsar catalogue:
http://www.atnf.csiro.au/people/pulsar/psrcat/ and VIA lecture by S.Popov

How do pulsar loose their energy?

$$E_{\rm rot} = \frac{1}{2} I \Omega^2 = \frac{2\pi^2 I}{P^2} \,.$$

Rotation of PSRs is slowed.
Rotational energy is the main source of pulsar's energy.

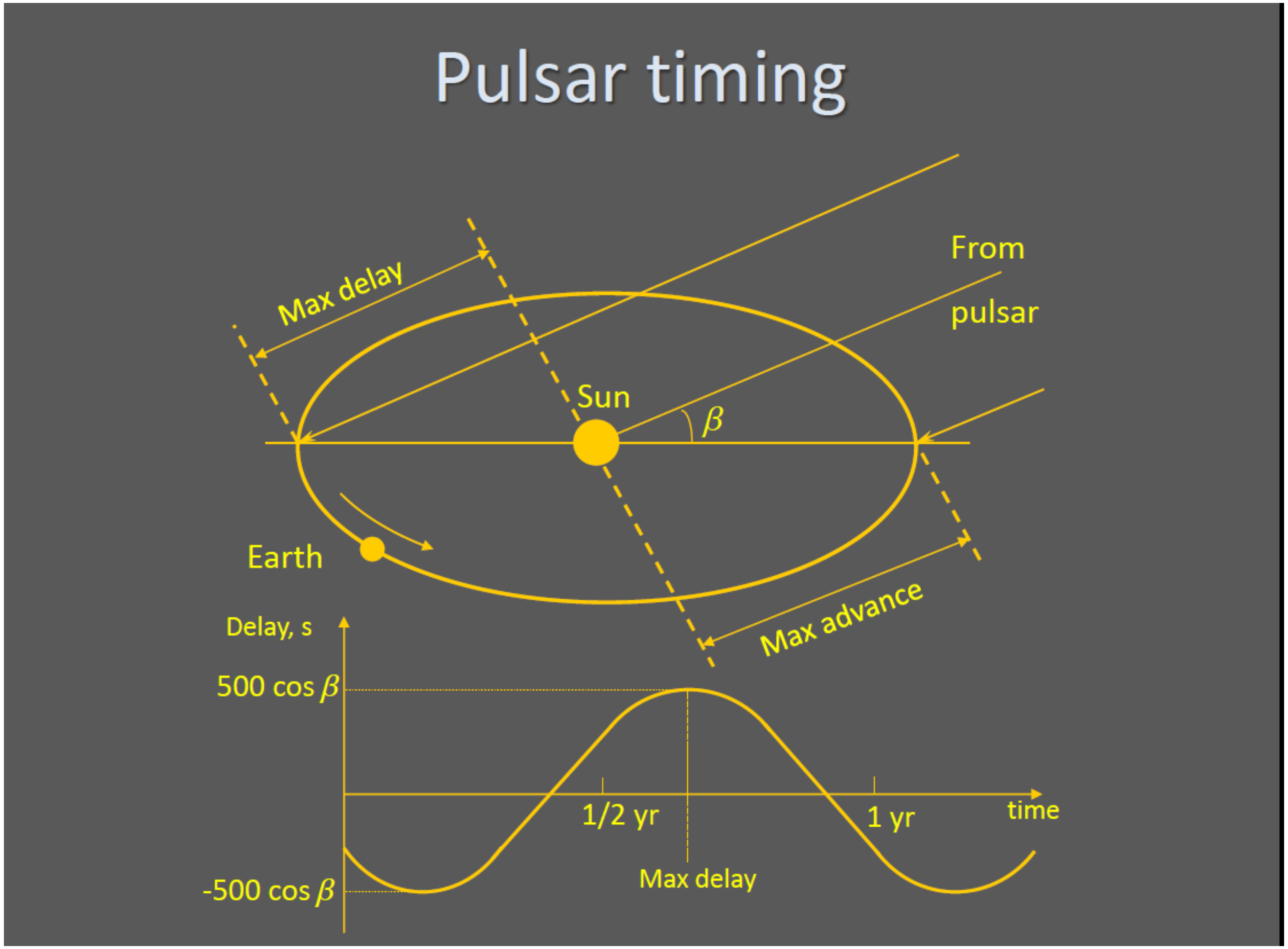
$$I = \frac{2}{5} MR^2 \approx \frac{2 \cdot 1.4 \cdot 2.0 \times 10^{33}\ \mathrm{g} \cdot (10^6\ \mathrm{cm})^2}{5} \approx 10^{45}\ \mathrm{gm\ cm}^2$$

$$E_{\rm rot} = \frac{2\pi^2 I}{P^2} \approx \frac{2\pi^2 \cdot 10^{45}\ \mathrm{g\ cm}^2}{(0.033\ \mathrm{s})^2} \approx 1.8 \times 10^{49}\ \mathrm{ergs}$$

$$\frac{dE_{\rm rot}}{dt} = \frac{d}{dt}\left(\frac{1}{2} I \Omega^2\right) = I \Omega \dot{\Omega}$$

http://www.cv.nrao.edu/course/astr534/Pulsars.html

Pulsar timing



Pulsar timing

Pulsar timing

Pulsar unit vector

Observer radius-vector

Shapiro delay

Dispersion measure

$$DM=\int_0^R n_e\,dl$$

$$c(t'-t)=-\vec{k}\cdot\vec{r}+\frac{1}{2R}[\vec{k}\times\vec{r}]^2+\delta t_{rel}+\frac{DM}{2.41\cdot10^{-16}}\frac{1}{f_{obs}^2}+\delta t_h,$$

observed time

calculated time

Pulsar distance

Observational frequency

$$t=t_0+P_0N+\frac{1}{2}P_0\dot{P}N^2-$$ time of arrival of Nth pulse to the Solar system barycenter

t_0 – initial epoch,

$P_0, \dot{P}$ – pulsar spin period and derivative,

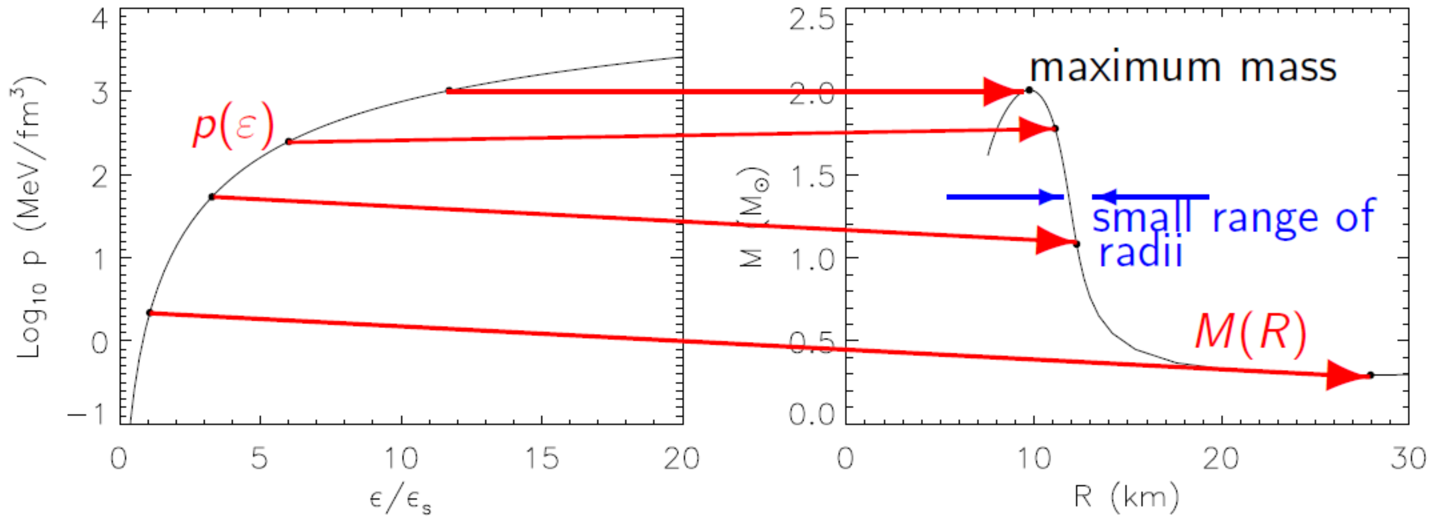
N – pulse number.

Neutron star structure

Tolman-Oppenheimer-Volkov equations

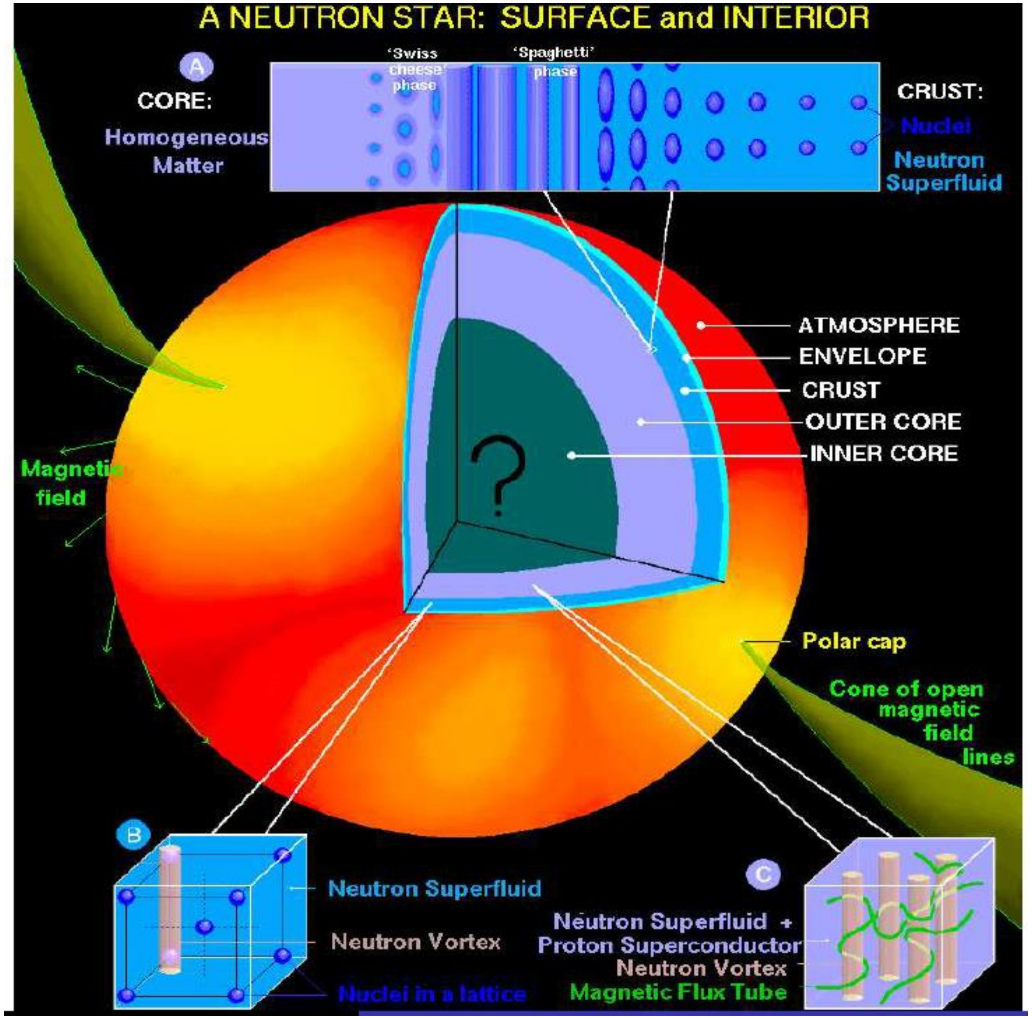
$$\frac{dp}{dr} = -\frac{G}{c^4}\frac{(mc^2+4\pi pr^3)(\varepsilon+p)}{r(r-2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi\frac{\varepsilon}{c^2}r^2$$



Equation of State ⟵ Observations

Neutron star structure



Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page D. & Reddy S., 2006, Annu. Rev. Nucl. Part. Sci. 56, 327

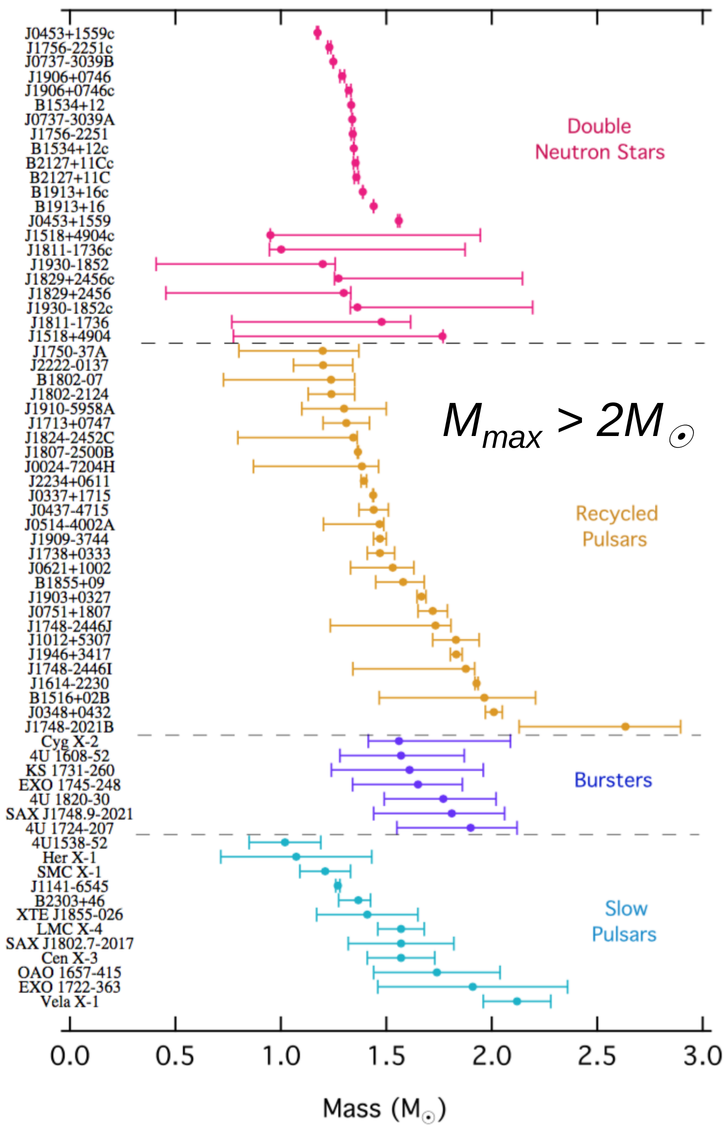
Limits on NS mass

- NS stability is supported by equality of pressures of gravity and degenerated matter.
- For mass exceeding 3 Solar masses degenerated neutron gas cannot prevent further collapse in Black hole (BH).
- NS also cannot have mass, much smaller, than Solar mass (neither by formation, nor by physical conditions)

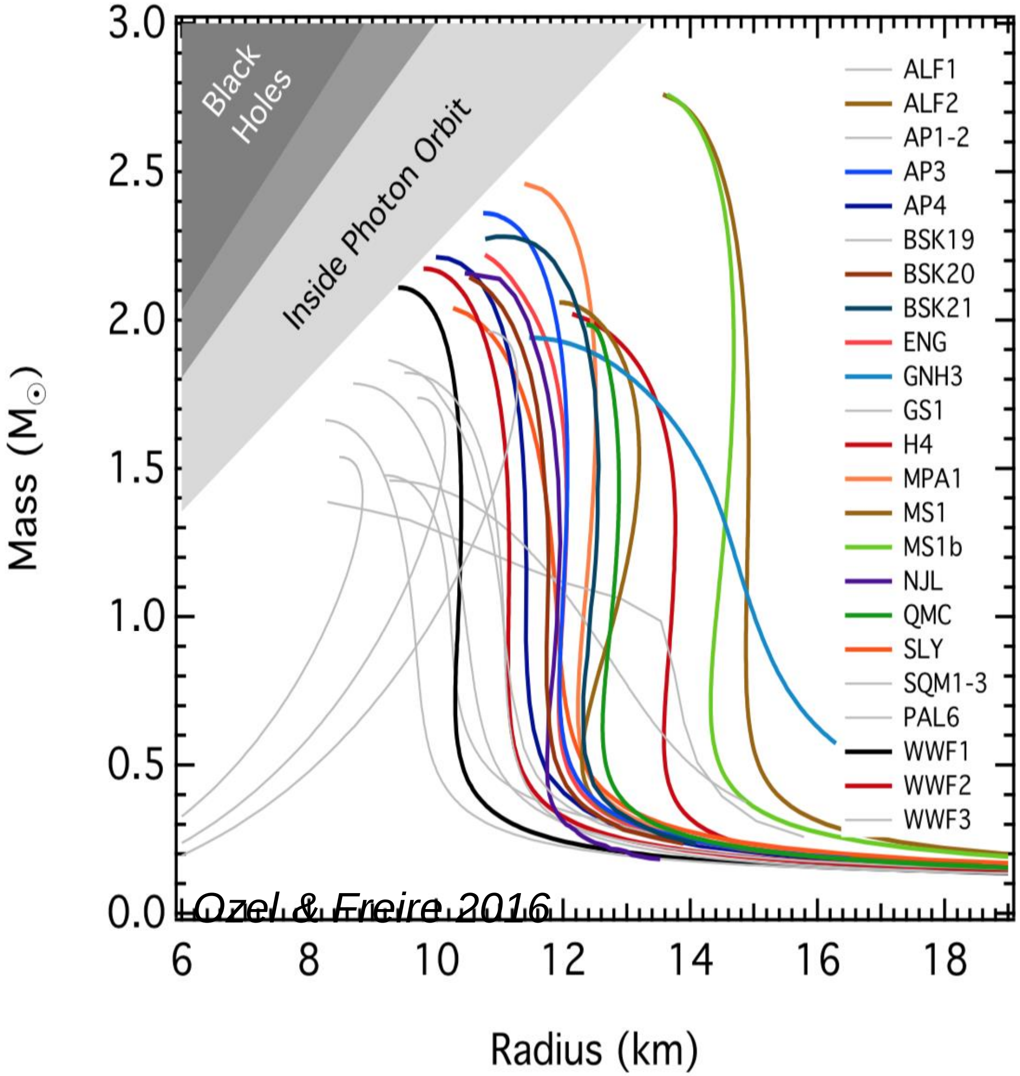
Neutron Stars: Open Questions

NS

Maximum mass?



Radius?



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Open problems of NS physics

- Role of nuclear forces in EOS
- Pion condensation
- Strange matter effect
- Quark matter effects…

And in addition to this set of problem related with nontrivial conditions of ordinary matter, described by SM physics

- Dark Matter effects

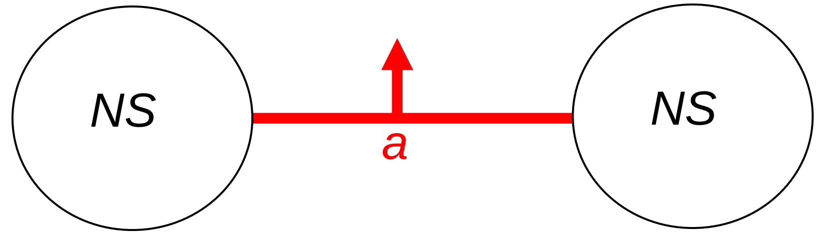
Compact objects for High Energy Astrophysics

- High matter densities
- High magnetic fields
- Acceleration of cosmic rays
- Neutrino radiation from collapse
- Gamma radiation
- Gravitational wave signal

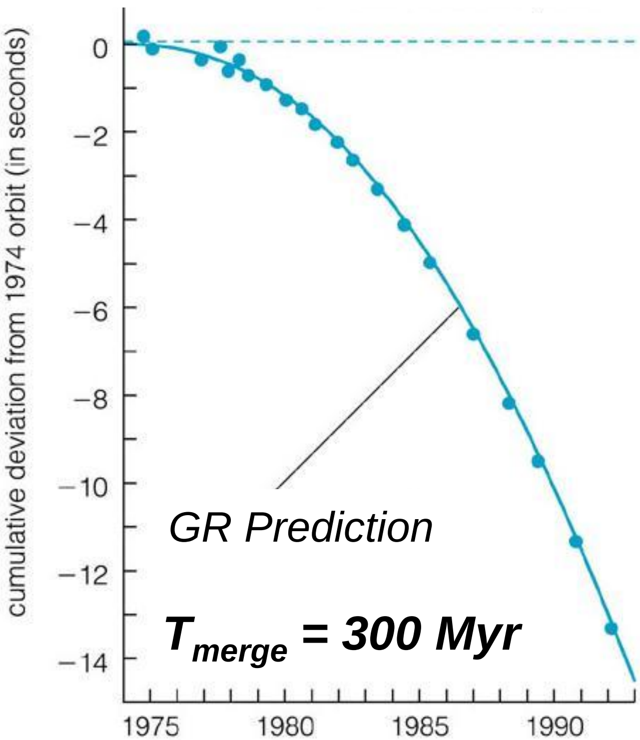
In the Universe dominated by new physics its impact can lead to observable effects

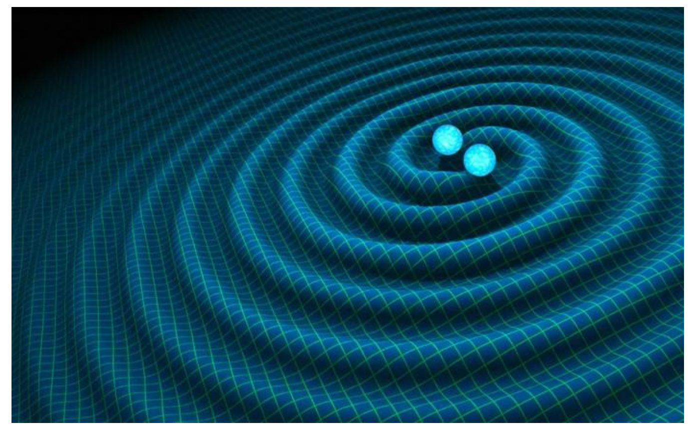
Binary Neutron Stars

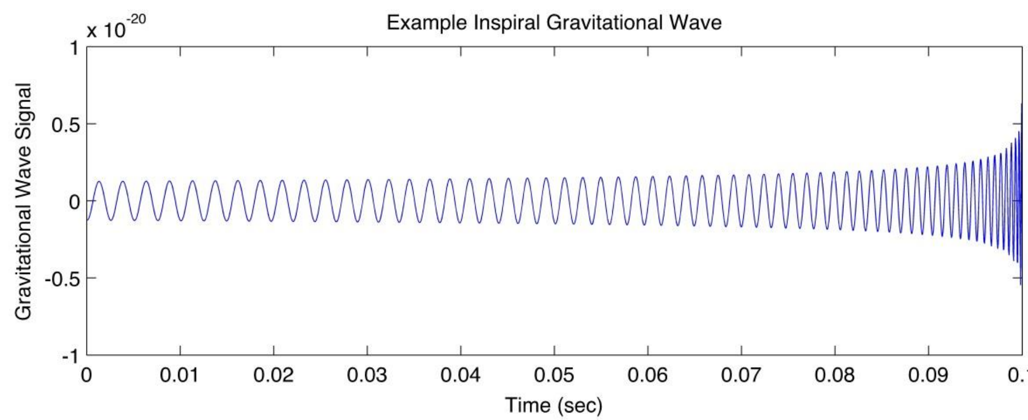
$$-\frac{1}{P}\frac{dP}{dt}=\frac{128}{15}\frac{G^3}{c^5}\frac{M^3}{a^4}$$



Hulse-Taylor Binary Pulsar







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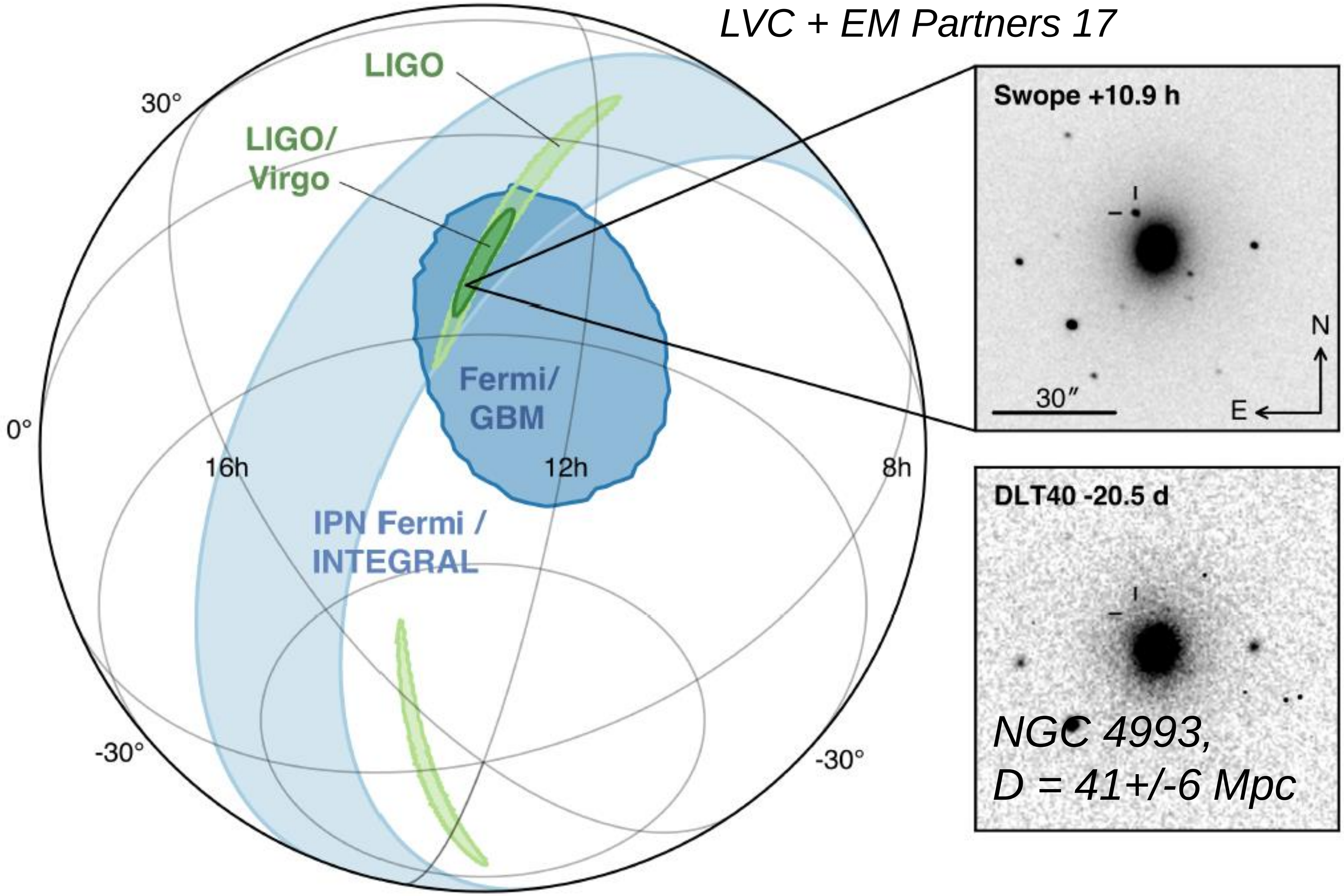
GW170817: the first BNS Merger

LVC + EM Partners 17



M_{ch} =1.118(3)$M_\odot$, M_1 =1.36-1.6$M_\odot$, M_2 =1.17-1.36$M_\odot$, $\mathbf{M_{tot}}$ **= 2.74-2.80** $\mathbf{M_\odot}$

Viewing Angle = 3° - 32°, D_{GW} = 26-48 Mpc

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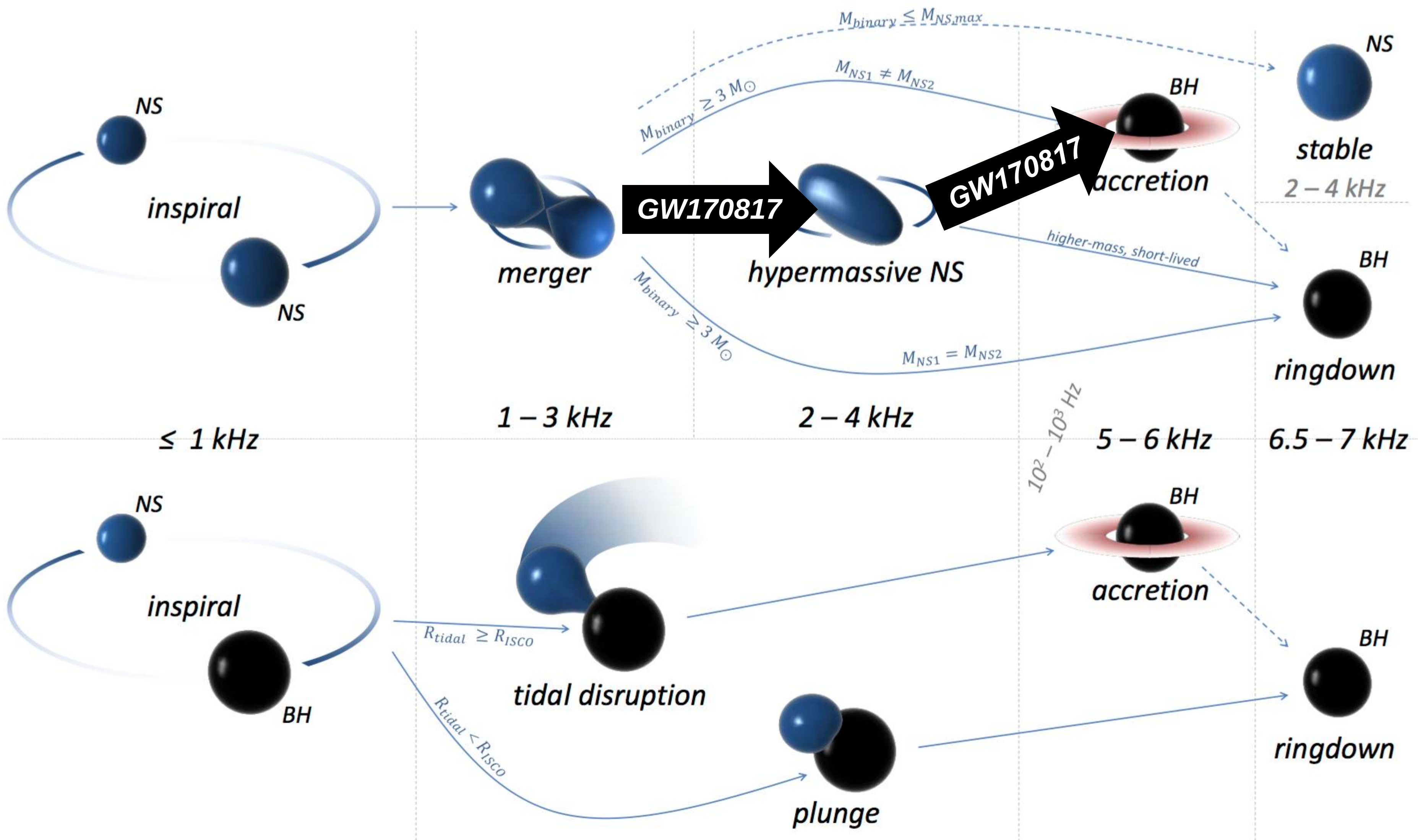
Neutron Star Binary Mergers



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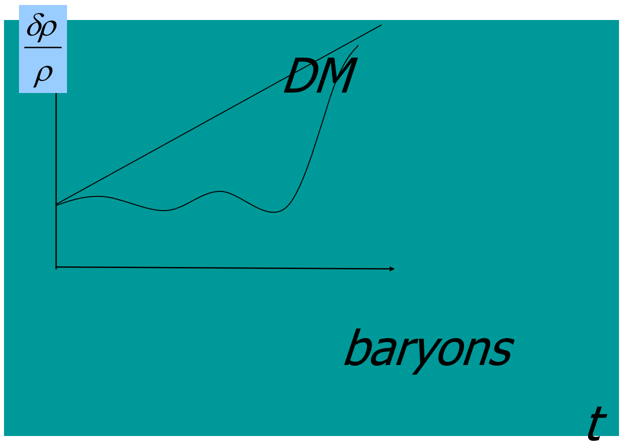
Bartos, Brady, Marka 2013
See Shibata et al. 2005, 2006

New physics in stars

- We live in the Universe, in which new physics dominates its evolution and modern content.
- I.Shklovsky (1980s): “No to ‘inos’, except for neutrinos. Physics of stars is well established by the nontrivial combination of laws of known physics and no new physics is possible”
- However in the Universe, dominated by new physics, it is hardly possible to prevent its impact on stellar structure and evolution.

NS PROBES FOR DARK MATTER

Cosmological Dark Matter



$$\frac{\delta\rho}{\rho} \Rightarrow \frac{\delta T}{T}$$

Cosmological Dark Matter explains:

- ***virial paradox in galaxy clusters,***
- ***rotation curves of galaxies***
- ***dark halos of galaxies***
- ***effects of macro-lensing***

But first of all it provides formation of galaxies from small density fluctuations, corresponding to the observed fluctuations of CMB

To fulfil these duties Dark Matter should interact sufficiently weakly with baryonic matter and radiation and it should be sufficiently stable on cosmological timescale.
Baryon density estimated from the results of BBN (mainly from Primordial deuterium) is not sufficient to explain the matter content of the modern Universe

Dark Matter – Cosmological Reflection of Microworld Structure

Dark Matter should be present in the modern Universe, and thus is stable on cosmological scale.

This stabilty reflects some Conservation Law, which prohibits DM decay.

Following Noether's theorem this conservation law should correspond to a (nearly) strict symmetry of microworld.

Dark Matter from Elementary Particles

By definition Dark Matter is non-luminous, while charged particles are the source of electromagnetic radiation. Therefore, neutral weakly interacting elementary particles are usually considered as Dark Matter candidates. If such neutral particles with mass m are stable, they freeze out in early Universe and form structure of inhomogeneities with the minimal characterstic scale

$$M = m_{Pl} \left(\frac{m_{Pl}}{m} \right)^2$$

- However, if charged particles are heavy, stable and bound within neutral « atomic » states they can also play the role of specific composite Dark matter (Dark atoms).
- Physical models, underlying dark matter scenarios, their problems and nontrivial solutions as well as the possibilities for their test will be the subject of the successive talks.

NS probe for dark matter

WIMP annihilation and Cooling of Stars

WIMP annihilation as a heating mechanism for
•neutron stars (CK '07, CK Tinyakov '10, Lavallaz Fairbairn '10)
•white dwarfs (Bertone Fairbairn '07, McCullough '10)

WIMP collapse to a Black Hole

WIMPs can be trapped inside stars and later collapse forming a black hole that destroys the star
(Goldman Nussinov '89, CK Tinyakov '10, '11,'13 McDermott Yu Zurek '11, CK'11,'12
Guver Erkoca Reno Sarcevic '12, Fan Yang Chang '12, Bell Melatos Petraki '13, Bramante Fukushima Kumar Stopnitzky '13)

New effects

WIMPs can slow down the rotation of a pulsar (Perez-Garcia,CK '14)

C,Kouvaris, VIA lecture

DM capture in stars

$$F = \frac{8}{3}\pi^2 \frac{\rho_{\rm dm}}{m} \left(\frac{3}{2\pi v^2}\right)^{3/2} \frac{GMR}{1-\frac{2GM}{R}} v^2 \left(1-e^{-3E_0/v^2}\right) f$$

Press Spergel '85, Gould '86, Nussinov Goldman '89, CK'07, CK Tinyakov '10

higher local DM density gives higher accretion

smaller velocities enhance capture

$f=1$ if $\sigma>\sigma_{\rm crit}$
$f=0.45\sigma/\sigma_{\rm crit}$ if $\sigma<\sigma_{\rm crit}$

$$f \simeq \frac{\sigma_\chi}{\sigma_{\rm crit}} \left\langle \int \frac{\rho}{M/R^3} \frac{dl}{R} \right\rangle$$

For typical NS

$$F = 1.25 \times 10^{24} {\rm s}^{-1} \left(\frac{\rho_{\rm dm}}{{\rm GeV/cm^3}}\right) \left(\frac{100{\rm GeV}}{m}\right) f$$

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Self interacting dark matter

Yukawa-type WIMP self-interactions $\alpha\phi\bar{\psi}\psi$ $V(r) = -\alpha \exp[-\mu r]/r$

If self-interactions attractive

$$2\langle E_k\rangle = \frac{8}{3}\pi G\rho m r^2 + \frac{GNm^2}{r} + \left\langle \sum_j \alpha \frac{e^{-\mu r_{ij}}}{r_{ij}} + \alpha\mu e^{-\mu r_{ij}} \right\rangle$$

$\mu r/N^{1/3} << 1$

$$E_i = \alpha \sum_j \frac{e^{-\mu r_{ij}}}{r_{ij}} \longrightarrow E_i = \alpha\mu/y^3$$

$$y = \mu r/N^{1/3}$$

Yukawa self-interactions can alleviate the effect of the Fermi pressure, leading to a gravitational collapse with dramatically lower amount of captured WIMPs

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NS probes for dark matter

Compact stars can reveal a lot of information about the nature of DM putting constraints on its properties complementary to direct searches.

- Observation of cold neutron stars can exclude thermally produced dark matter.
- Asymmetric dark matter:

1. keV to few GeV non-interacting bosonic dark matter is excluded.
2. Part of fermionic WIMP self-interactions excluded.
3. Constraints on WIMP-nucleon spin-dependent interactions.

- Millicharged dark matter could slow down pulsars faster than other mechanisms predict.

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PBH PROBES FOR PHYSICS OF EARLY UNIVERSE

Primordial Black Holes

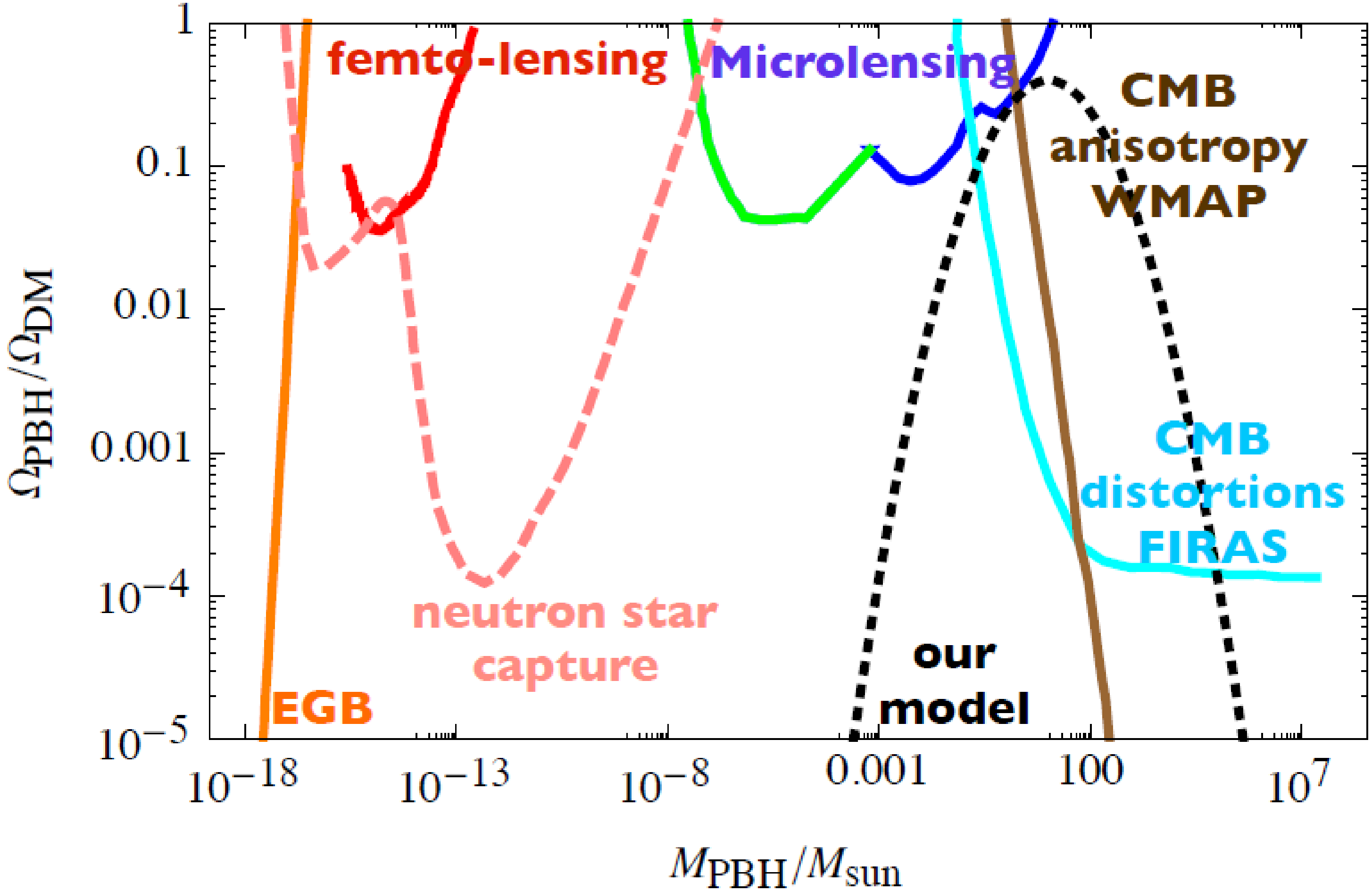
- Any object of mass M can form Black hole, if contracted within its gravitational radius.

$$\boxed{r \leq r_g = \frac{2GM}{c^2}}$$

- It naturally happens in the result of evolution of massive stars (and, possibly, dense star clusters).
- In the early Universe Black hole can be formed, if expansion can stop within cosmological horizon [Zeldovich, Novikov, 1966]. It corresponds to strong nonhomogeneity in early Universe

$$\delta \equiv \frac{\delta\rho}{\rho} \sim 1$$

Constraints on PBHs



S.Clesse, VIA lecture

PBHs as indicator of early dust-like stages

- In homogeneous and isotropic Universe ($\delta_0 << 1$) with equation of state $p = k\varepsilon$ probability of strong nonhomogeneity $\delta \sim 1$ is exponentially suppressed

$$P(\delta) = A(\delta, \delta_0)\exp\left(-\frac{k^2\delta^2}{2\delta_0^2}\right)$$

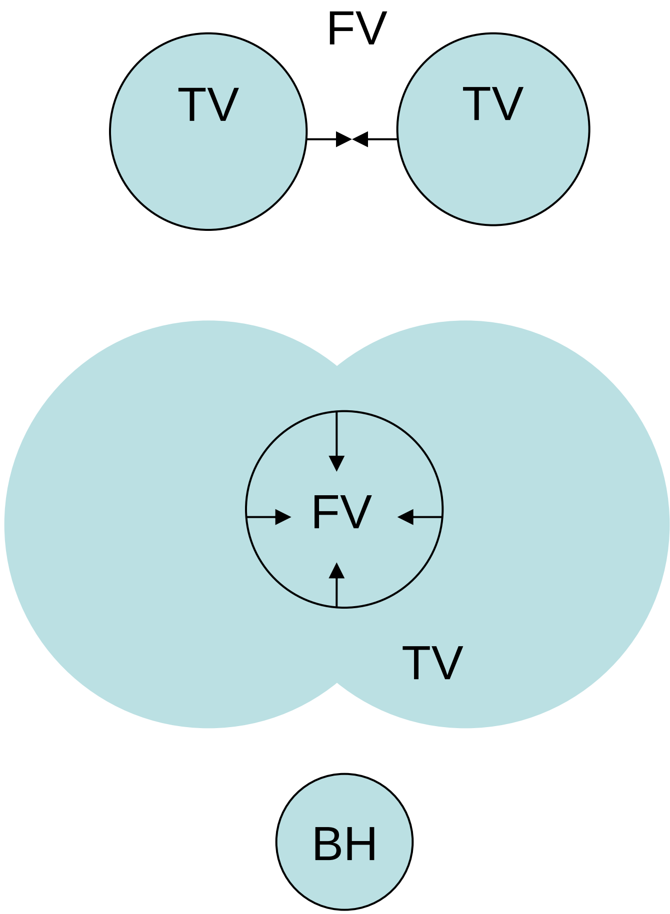
- At *k=0* on dust-like stage exponential suppression is absent. The minimal estimation is determined by direct production of BHs

$$A(\delta, \delta_0) \geq \left(\frac{\delta_0}{\delta}\right)^5 \left(\frac{\delta_0}{\delta}\right)^{3/2} = \left(\frac{\delta_0}{\delta}\right)^{13/2}$$

Dominance of superheavy particles

- Superheavy particles with mass *m* and relative concentration $r = n / n_\gamma$ dominate in the Universe at *T<r m.*
- Coherent oscillations of massive scalar field also behave as medium with *p*=0.
- They form BHs either directly from collapse of symmetric and homogeneous configurations, or in the result of evolution of their gravitationally bound systems (pending on particle properties they are like « stars » or « galaxies »).

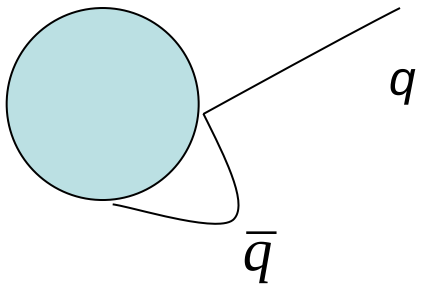
PBHs as indicator of first order phase transitions



- Collision of bubbles with True Vacuum (TV) state during the first-order phase transition results in formation of False Vacuum (FV) bags, which contract and collapse in Black Holes (BH).

PBH evaporation

- According to S. Hawking PBH with mass M evaporate due to creation of pairs by its nonstationary gravitational field. Products of evaporation have black body spectrum with



$$T_{PBH} \propto 1/r_g$$

$$T_{PBH} \approx 10^{13} GeV \left(\frac{1g}{M} \right)$$

- The rate of evaporation is given by

$$\frac{dM}{dt} = -\kappa T_{PBH}^4 r_g^2 \propto 1/r_g^2 \propto 1/M^2$$

- The evaporation timescale is

$$t_{PBH} \approx 10^{27} s \left(\frac{M}{1g} \right)^3$$

Any particle with $m \leq T_{PBH}$ is created – UNIVERSAL source

Effects of Primordial Black Holes

- PBHs behave like a specific form of Dark Matter
- Since in the early Universe the total mass within horizon is small, it seems natural to expect that such Primordial Black holes should have very small mass (much smaller, than the mass of stars). PBHs with mass $M < 10^{15} g$ evaporate and their astrophysical effects are similar to effects of unstable particles.
- However, cosmological consequences of particle theory can lead to mechanisms of intermediate and even supermassive BH formation.

STRONG PRIMORDIAL INHOMOGENEITY PROBES FOR INFLATION AND BARYOSYNTHESIS

Strong nonhomogeneities in nearly homogeneous and isotropic Universe

- **The standard approach is to consider homogeneous and isotropic world and to explain development of nonhomogeneous structures by gravitational instability, arising from small initial fluctuations.**

$$\delta \equiv \delta\rho / \rho << 1$$

- **However, if there is a tiny component, giving small contribution to total** $\rho_i << \rho$ **its strong nonhomogeneity** $\delta_i \equiv (\delta\rho/\rho)_i > 1$

is compatible with small nonhomogeneity of the total density

$$\delta = (\delta\rho_i + \delta\rho)/\rho \approx (\delta\rho_i/\rho_i)(\rho_i/\rho) << 1$$

Such components naturally arise as consequences of particle theory, shedding new light on galaxy formation and reflecting in cosmic structures the fundamental structure of microworld.

Strong Primordial nonhomogeneities from the early Universe

- Cosmological **phase transitions** in inflationary Universe can give rise to unstable cosmological defects, retaining a replica in the form of primordial **nonlinear** structures (massive PBH clusters, archioles).
- Nonhomogenous baryosynthesis (including spontaneous baryosynthesis and leptogensis) in its extreme form can lead to **antimatter** domains in baryon asymmetrical inflationary Universe.

Strong nonhomogeneities of total density and baryon density are severely constrained by CMB data at large scales (and by the observed gamma ray background in the case of antimatter). However, their existence at smaller scales is possible.

Cosmological Phase transitions 1.

- At high temperature $T > T_{cr}$ spontaneously broken symmetry is restored, owing to thermal corrections to Higgs potential

$$V(\varphi, T=0) = -\frac{m^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 \Rightarrow V(\varphi, T) = \left(C\lambda T^2 - \frac{m^2}{2}\right)\varphi^2 + \frac{\lambda}{4}\varphi^4$$

- When temperature falls down below

$$T = T_{cr} \cong \langle\varphi\rangle = \frac{m}{\sqrt{\lambda}}$$

transition to phase with broken symmetry takes place.

Cosmological Phase transitions 2.

- Spontaneously broken symmetry can be restored on chaotic inflationary stage, owing to corrections in Higgs potential due to interaction of Higgs field with inflaton

$$V(\varphi,\psi=0)=-\frac{m^2}{2}\varphi^2+\frac{\lambda}{4}\varphi^4 \Rightarrow V(\varphi,\psi)=\left(\varepsilon\psi^2-\frac{m^2}{2}\right)\varphi^2+\frac{\lambda}{4}\varphi^4$$

- When inflaton field rolls down below

$$\psi=\psi_{cr}\cong\frac{m}{\sqrt{\varepsilon}}$$

transition to phase with broken symmetry takes place.

Topological defects

- In cosmological phase transition false (symmetric) vacuum goes to true vacuum with broken symmetry. Degeneracy of true vacuum states results in formation of topological defects.
- Discrete symmetry of true vacuum $\langle\varphi\rangle = \pm f$ leads to domains of true vacuum with +*f* and -*f* and false vacuum wall on the border.
- Continuous degeneracy $\langle\varphi\rangle = f\exp(i\theta)$ results in succession of singular points surrounded by closed paths with $\Delta\theta = 2\pi$. Geometrical place of these points is line – cosmic string.
- SU(2) degeneracy results in isolated singular points – in GUTs they have properties of magnetic monopoles.

U(1) model

$$V(\psi) = \frac{\lambda}{2}\left(\psi^2 - f^2\right)^2$$

After spontaneous symmetry breaking infinitely degenerated vacuum

$$\psi = f e^{i\varphi/f}$$

experiences second phase transition due to the presence (or generation by instanton effects)

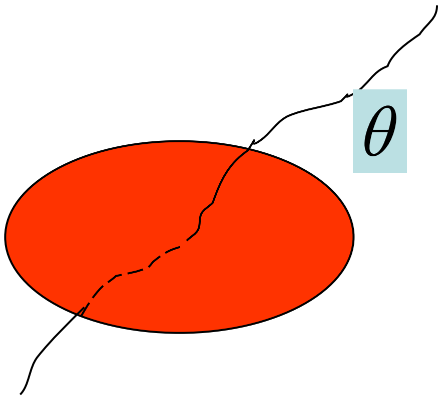
$$V(\varphi) = \Lambda^4\left(1 - \cos\left(\varphi/f\right)\right)$$

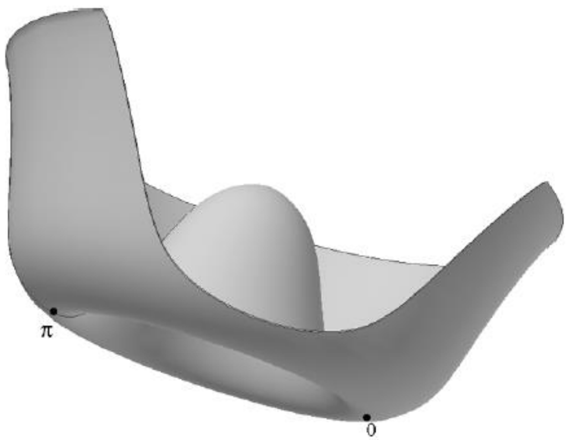
to vacuum states

$$\theta \equiv \varphi/f = 0, 2\pi, \ldots$$

In particular, this succession of phase transitions takes place in axion models

Topological defects



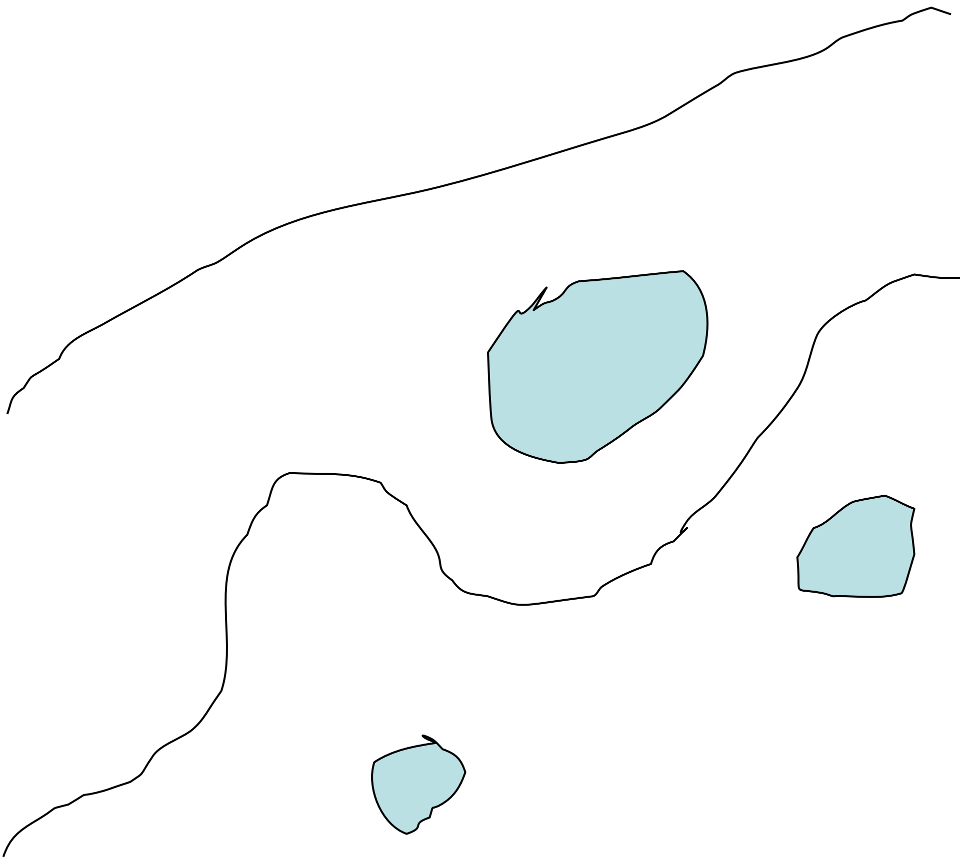


- Spontaneous breaking of U(1) symmetry results in the continuous degeneracy of vacua. In the early Universe the transition to phase with broken symmetry leads to formation of cosmic string network.
- The tilt in potential breaks continuous degeneracy of vacua. In the result string network converts into walls-bounded-by-strings structure in the second phase transition. This structure is unstable and decay, but the initial values of phase define the energy density of field oscillations.

Unstable topological defects

- This picture takes place in axion cosmology.
- The first phase transition gives rise to cosmic axion string network.
- This network converts in the second phase transition into walls-bounded-by-strings structure (walls are formed between strings along the surfaces $\alpha = \pi$), which is unstable.
- However, the energy density distribution of coherent oscillations of the field α follows the walls-bounded-by-strings structure.

Archioles structure

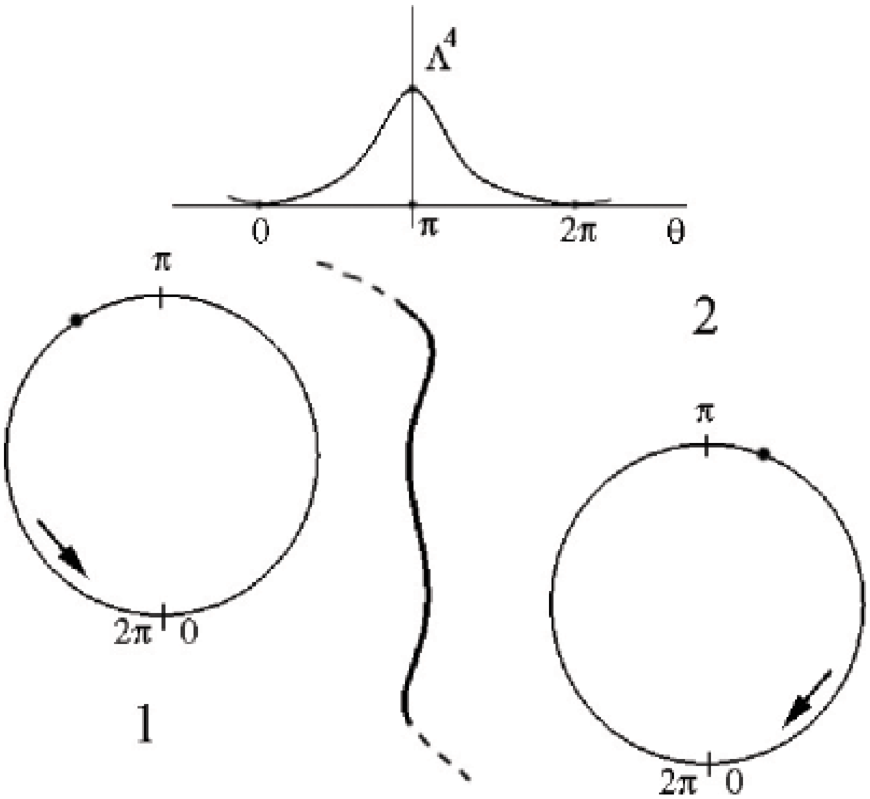


- Numerical studies revealed that ~80% of string length corresponds to infinite Brownian lines, while the remaining ~20% of this length corresponds to closed loops with large size loops being strongly suppressed. It corresponds to the well known scale free distribution of cosmic strings.
- The fact that the energy density of coherent axion field oscillations reflects this property is much less known. It leads to a large scale correlation in this distribution, called archioles.
- Archioles offer possible seeds for large scale structure formation.
- However, the observed level of isotropy of CMB puts constraints on contribution of archioles to the total density and thus puts severe constraints on axions as dominant form of Dark Matter.

Massive Primordial Black Holes

- Any object can form Black hole, if contracted within its gravitational radius. It naturally happens in the result of evolution of massive stars (and, possibly, star clusters).
- In the early Universe Black hole can be formed, if within cosmological horizon expansion can stop [Zeldovich, Novikov, 1966]. Since in the early Universe the total mass within horizon is small, it seems natural to expect that such Primordial Black holes should have very small mass (much smaller, than the mass of stars).
- However, cosmological consequences of particle theory can lead to mechanisms of intermediate and even supermassive BH formation.

Closed walls formation in Inflationary Universe



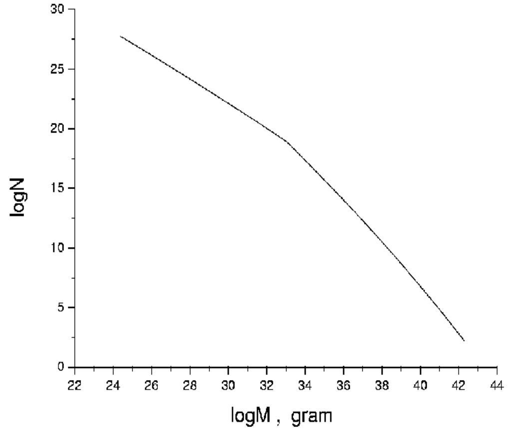
If the first U(1) phase transition takes place on inflationary stage, the value of phase θ , corresponding to e-folding N~60, fluctuates

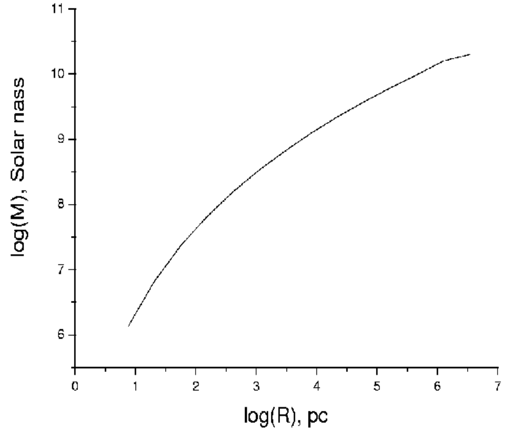
$$\Delta\theta \approx H_{\mathrm{infl}} / (2\pi f)$$

Such fluctuations can cross π

and after coherent oscillations begin,regions with $\theta > \pi$ occupying relatively small fraction of total volume are surrounded by massive walls

Massive PBH clusters





Each massive closed wall is accompanied by a set of smaller walls.
As soon as wall enters horizon, it contracts and collapses in BH.
Each locally most massive BH is accompanied by a cloud of less massive BHs.
The structure of such massive PBH clouds can play the role of seeds for galaxies and their large scale distribution.

Spectrum of Massive BHs

- The minimal mass of BHs is given by the condition that its gravitational radius exceeds the width of wall ($d \approx 2f/\Lambda^2$)

$$r_g = \frac{2M}{m_{Pl}^2} > d = \frac{2f}{\Lambda^2} \Rightarrow M_{\min} = f\left(\frac{m_{Pl}}{\Lambda}\right)^2$$

- The maximal mass is given by the condition that pieces of wall do not dominate within horizon, before the whole wall enters the horizon

$$R < \frac{3\sigma_w}{\rho_{tot}} \Rightarrow M_{\max} = f\left(\frac{m_{Pl}}{f}\right)^2\left(\frac{m_{Pl}}{\Lambda}\right)^2 \Rightarrow \frac{M_{\max}}{M_{\min}} = \left(\frac{m_{Pl}}{f}\right)^2$$

GW signals from closed wall collapse and BHs merging in clouds

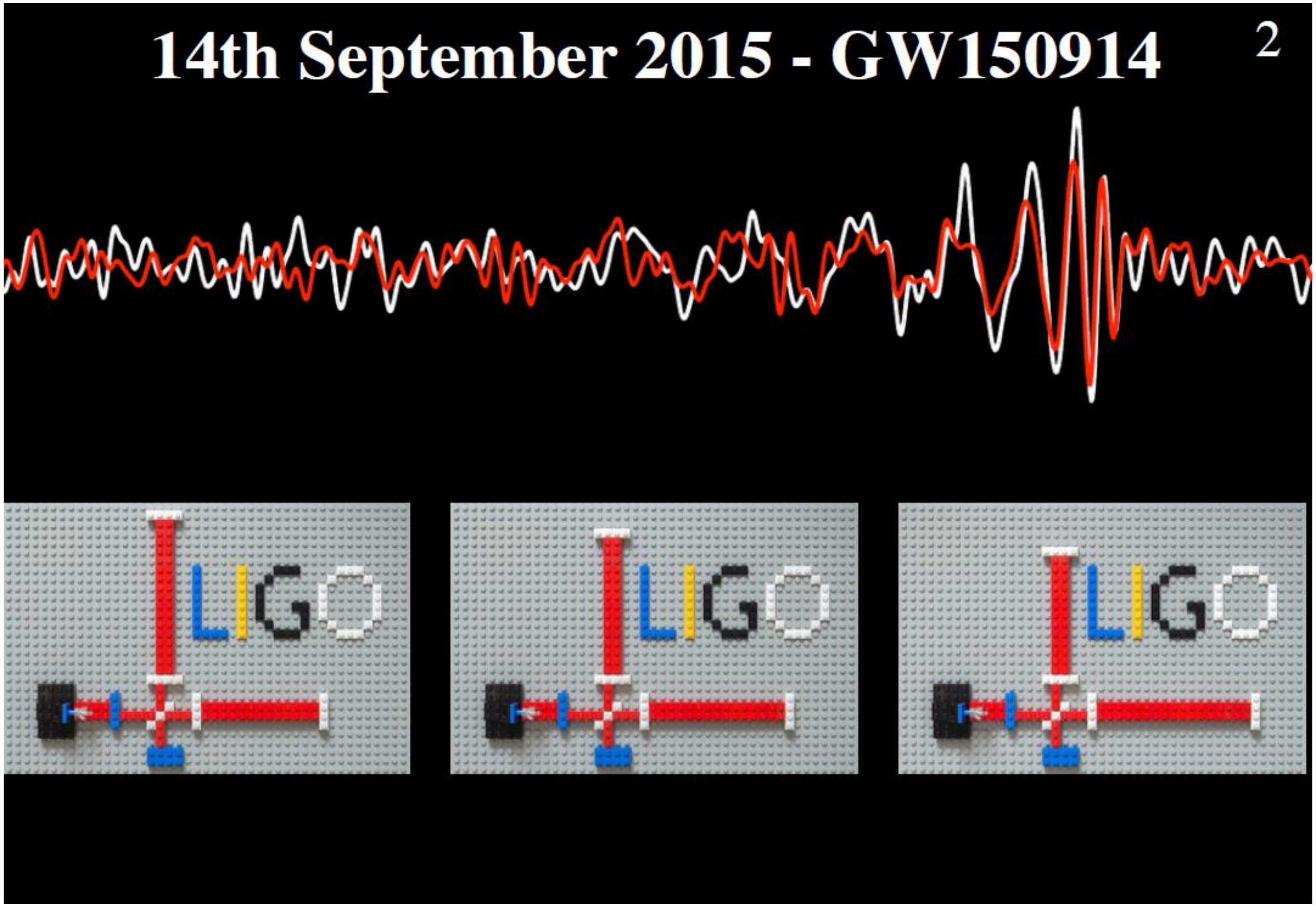
- Closed wall collapse leads to primordial GW spectrum, peaked at $\nu_0 = 3 \cdot 10^{11} (\Lambda / f) Hz$ with energy density up to

$$\Omega_{GW} \approx 10^{-4} \left(f / m_{Pl} \right)$$

- At $f \sim 10^{14} GeV$ $\Omega_{GW} \sim 10^{-9}$
- For $1 < \Lambda < 10^8 GeV$ $3 \cdot 10^{-3} Hz < \nu_0 < 3 \cdot 10^5 Hz$

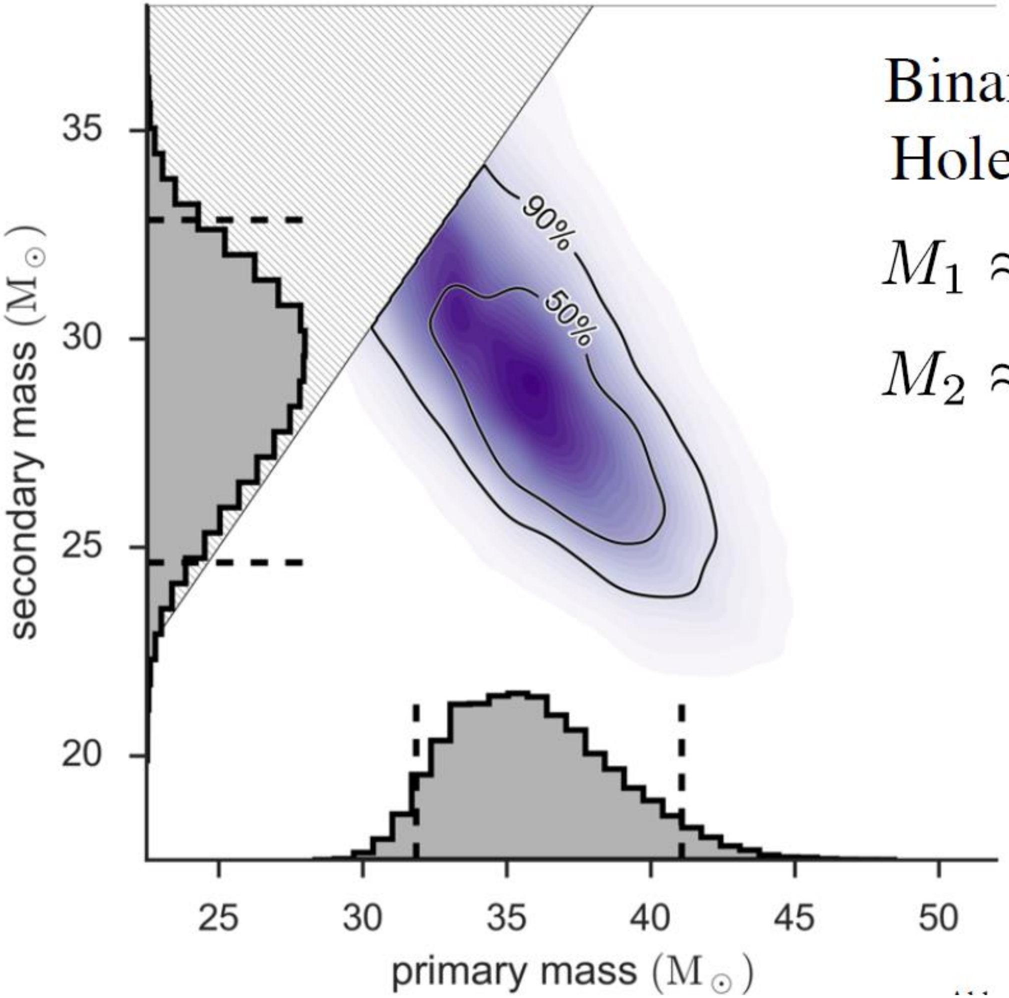
- Merging of BHs in BH cluster is probably detected by LIGO!.

The first GW signal!



From VIA talk 09.12.2016 by P.Lasky

Abbott et al. (2016) - GW150914



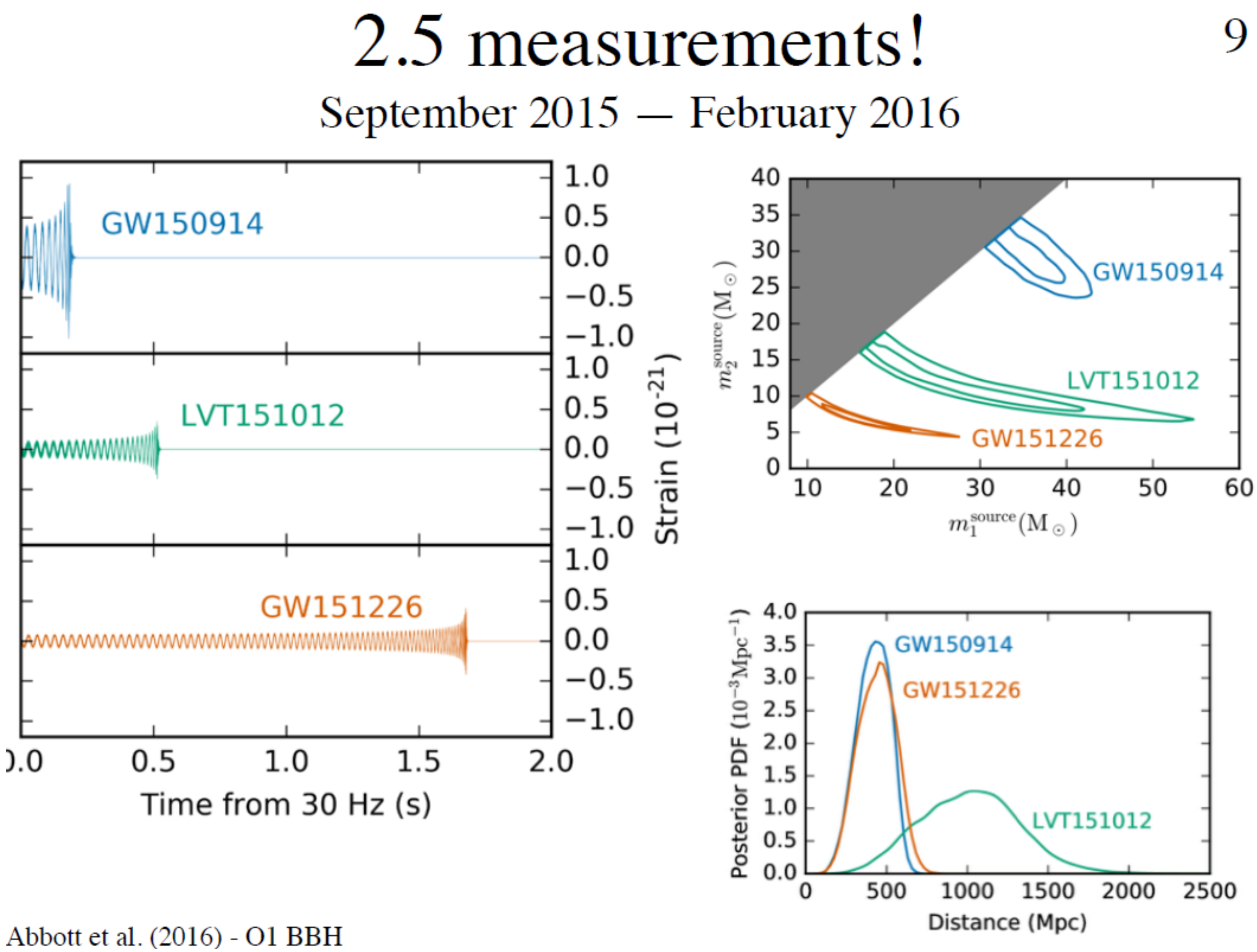
Binary Black Hole Merger

$M_1 \approx 36\, M_\odot$

$M_2 \approx 29\, M_\odot$

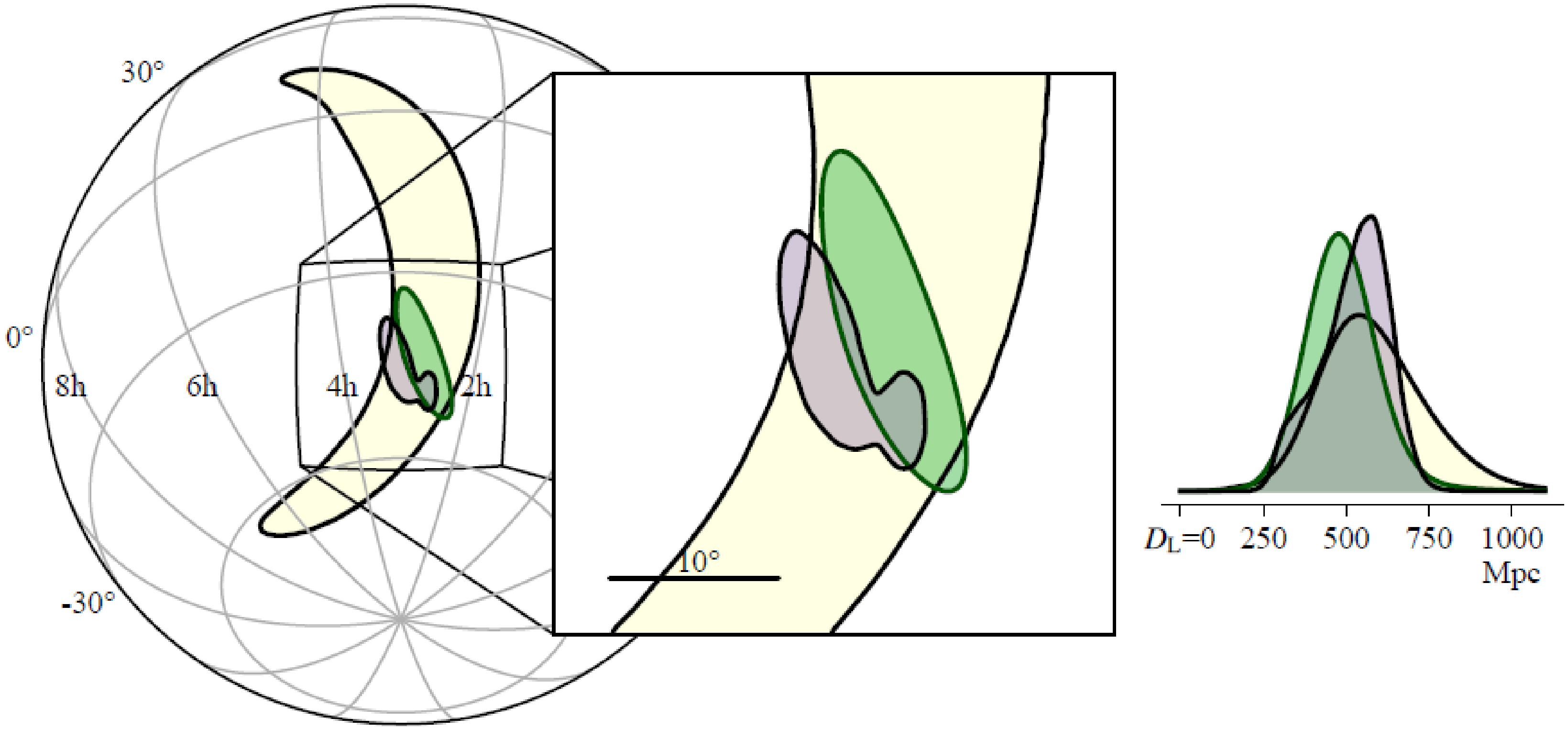
From VIA talk 09.12.2016 by P.Lasky

GW astronomy!



From VIA talk 09.12.2016 by P.Lasky

GW Astronomy:
Signal 170814 was registered by 3 detectors!



Joint detection of the GW signal 170814 by two LIGO detectors and VIRGO detector can provide localization of the source!

Binaries of massive PBHs?

- Massive PBHs are not distributed homogeneously in space, but are in clouds.
- It makes more probable formation of massive PBHs binaries.
- The problem of creation of stellar mass PBH clouds, their evolution and formation of BH binaries in them may be an interesting hot topic for a PhD thesis

ANTIMATTER STARS IN BARYON ASYMMETRIC UNIVERSE

Antimatter from nonhomogeneous baryosynthesis

- Baryon excess B>0 can be generated nonhomogeneously B(x).
- Any nonhomogeneous mechanism of BARYON excess generation B(x) leads in extreme form to ANTIBARYON excess in some regions.

Survival of antimatter domains

Diffusion of baryons and antibaryons to the border of domain results in eating of antimatter by surrounding baryonic matter.

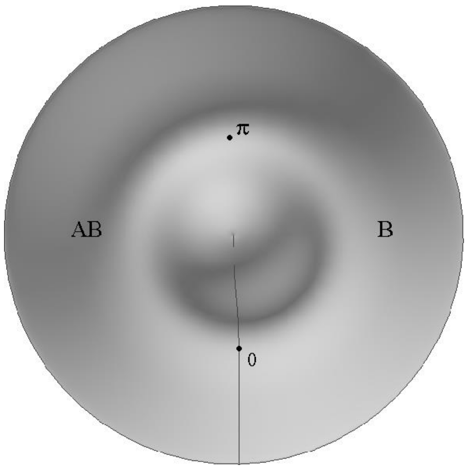
$$\partial n_b / \partial t = D(t) \partial^2 n_b / \partial x^2 - \alpha n_b$$ where $$D(t) \approx \frac{3T_\gamma c}{2\rho_\gamma \sigma_T}$$

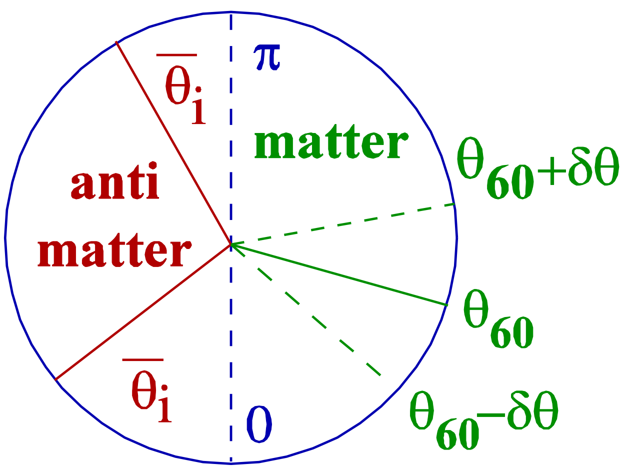
The minimal surviving scale is given by

$$d \approx \frac{c}{\sqrt{\frac{8\pi}{3} G\rho_0}} \frac{T_p}{m} \sqrt{\frac{m}{T_{rec}}} \int_{T_p/T_{rec}}^{1} \frac{dy}{y^{3/2}} = \frac{2c}{\sqrt{\frac{8\pi}{3} G\rho_0}} \sqrt{\frac{T_p}{m}}$$

which is about $d \sim 3/h$ kpc.

Nonhomogeneous spontaneous baryosynthesis





- Model of spontaneous baryosynthesis provides quantitative description of combined effects of inflation and nonhomogeneous baryosynthesis, leading to formation of antimatter domains, surviving to the present time.

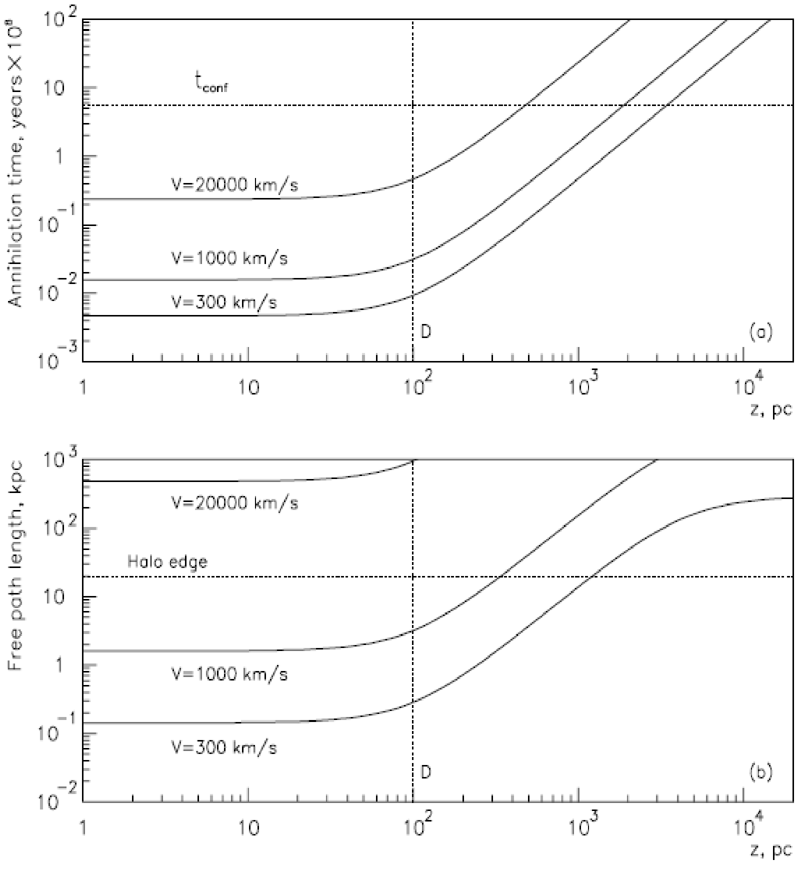
Antimatter in galaxies

Number of e-fold	Number of domains	Size of domain
59	0	$1103 Mpc$
55	$5.005 \cdot 10^{-14}$	$37.7 Mpc$
54	$7.91 \cdot 10^{-10}$	$13.9 Mpc$
52	$1.291 \cdot 10^{-3}$	$1.9 Mpc$
51	0.499	$630 kpc$
50	74.099	$255 kpc$
49	$8.966 \cdot 10^{3}$	$94 kpc$
48	$8.012 \cdot 10^{5}$	$35 kpc$
47	$5.672 \cdot 10^{7}$	$12 kpc$
46	$3.345 \cdot 10^{9}$	$4.7 kpc$
45	$1.705 \cdot 10^{11}$	$1.7 kpc$

Numerical simulations show that within the modern horizon possible amount of antimatter domains, with the size exceeding the survival scale and thus surviving to the present time, can be comparable with the total number of galaxies.

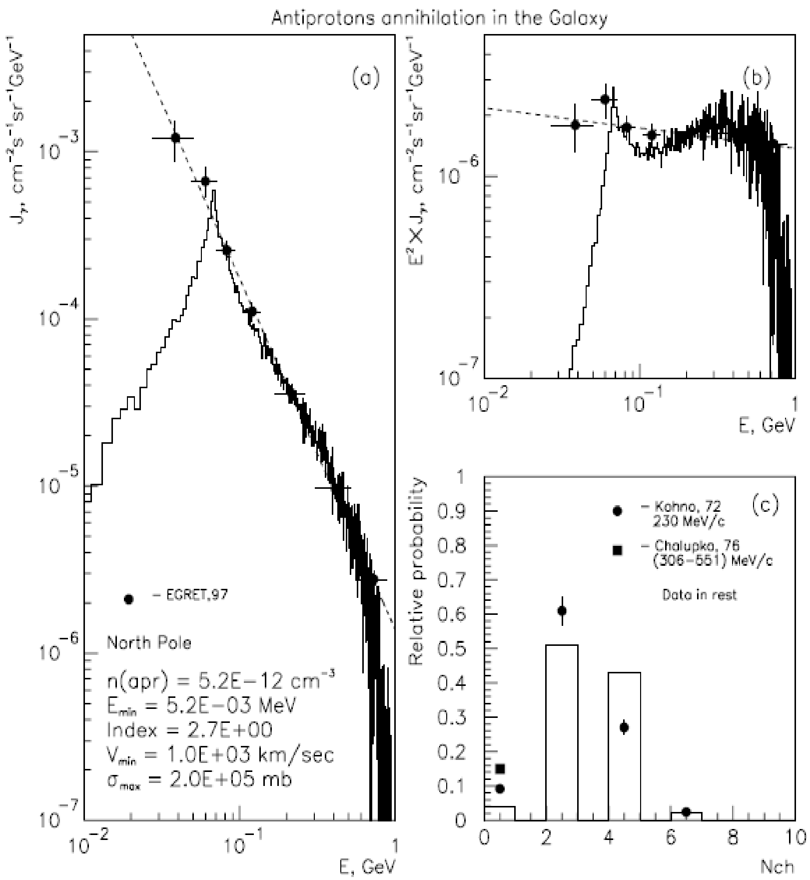
In our Galaxy from 1000 to 100000 antimatter stars can exist in a form of antimatter globular cluster (Khlopov, 1998). Being in halo, such cluster is a faint gamma ray source, but antimatter from it pollutes Galaxy and can be observed indirectly by annihilation, or directly as anti-meteorites or antinuclei in cosmic rays.

Antimatter pollution of Galaxy



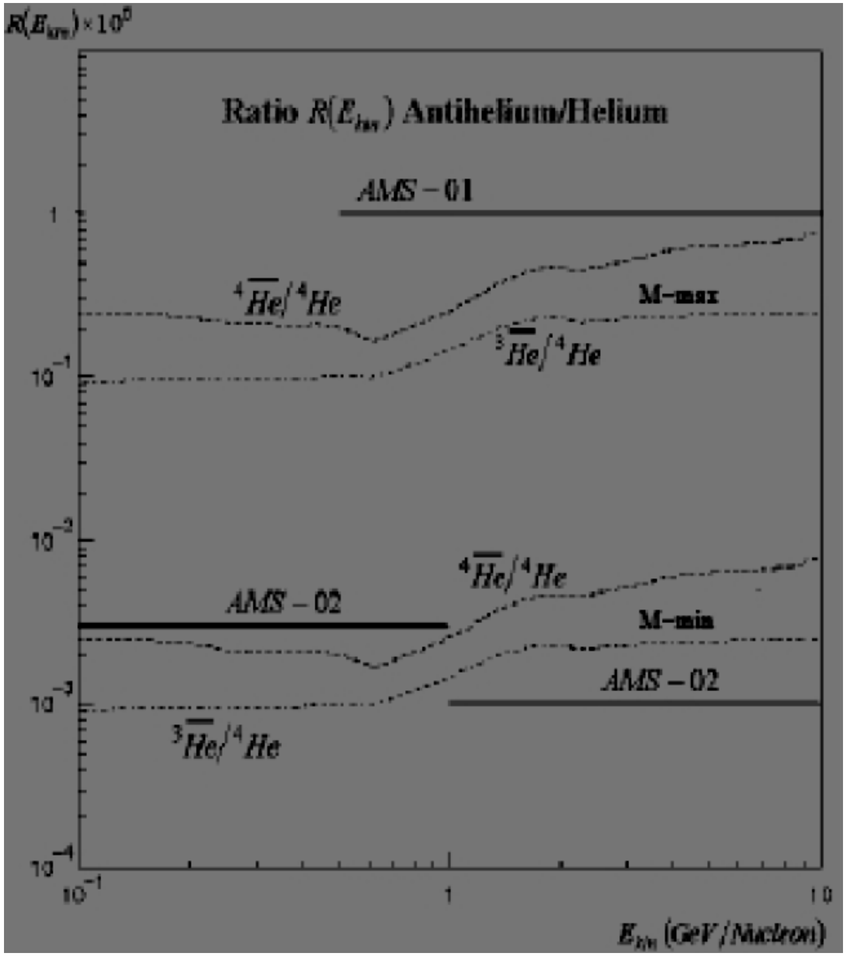
- Since antihydrogen is dominant in antimatter composition, the Galaxy is dominantly polluted by antiprotons.
- Their lifetime in Galaxy depends on their velocity and density of surrounding matter.

Gamma background from antimatter annihilation in Galaxy



- Antiproton annihilation can reproduce gamma background observed by EGRET in the range tens-hundreds MeV.
- It can not be considered as PROOF for existence of antimatter stars – only pieces of antimatter (antihelium nuclei, antimeteorites) can provide such PROOF.

Cosmic antihelium test for antimatter stars in Galaxy



- **Nonhomogeneous baryosynthesis in extreme form leads to antimatter domains in baryon asymmetrical Universe**
- **To survive in the surrounding matter domain should be sufficiently large, and to have sufficiently high internal antibaryon density to form stars. It gives minimal estimation of possible amount of antimatter stars in Galaxy**
- **The upper limit comes from observed gamma background**
- **Assuming that antihelium component of cosmic rays is proportional to the fraction of antimatter stars in the total mass of Galaxy, it is possible to test this hypothesis initially in PAMELA and then completely in AMS-02 experiment**

First signal from antimatter stars in AMS02?

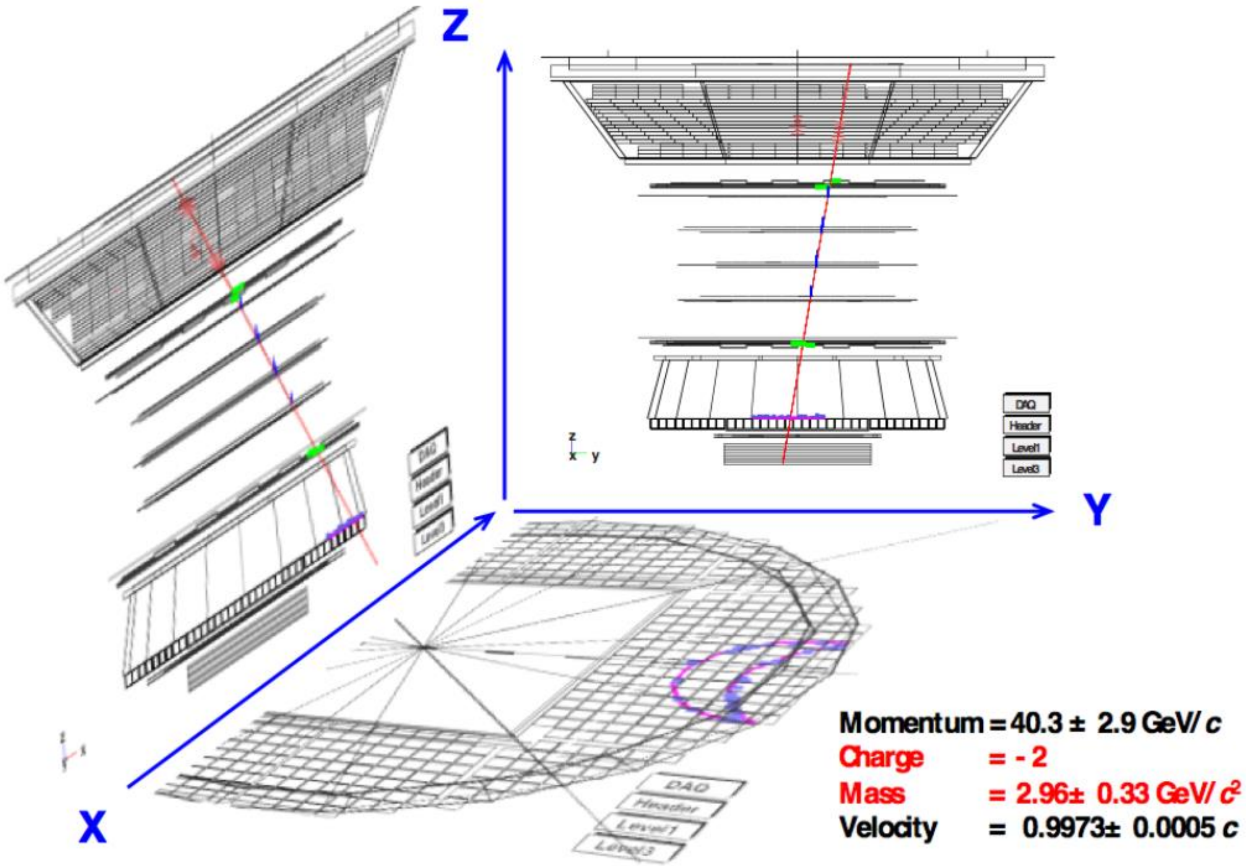


Figure 14. An antihelium candidate.

Presented in CERN on 08.12.2016 by Prof. S.Ting

Latest Results from the AMS Experiment on the International Space Station

ABSTRACT

In seven years on the Space Station, AMS has collected more than 115 billion charged cosmic rays with energies up to multi TeV. The measured positron spectra agrees well with dark matter models. The energy dependence of elementary particles (electrons, positrons, protons and antiprotons) as well as the rigidity dependence of primary cosmic rays and secondary cosmic rays are unique and distinct. These results require a new understanding of the cosmos.

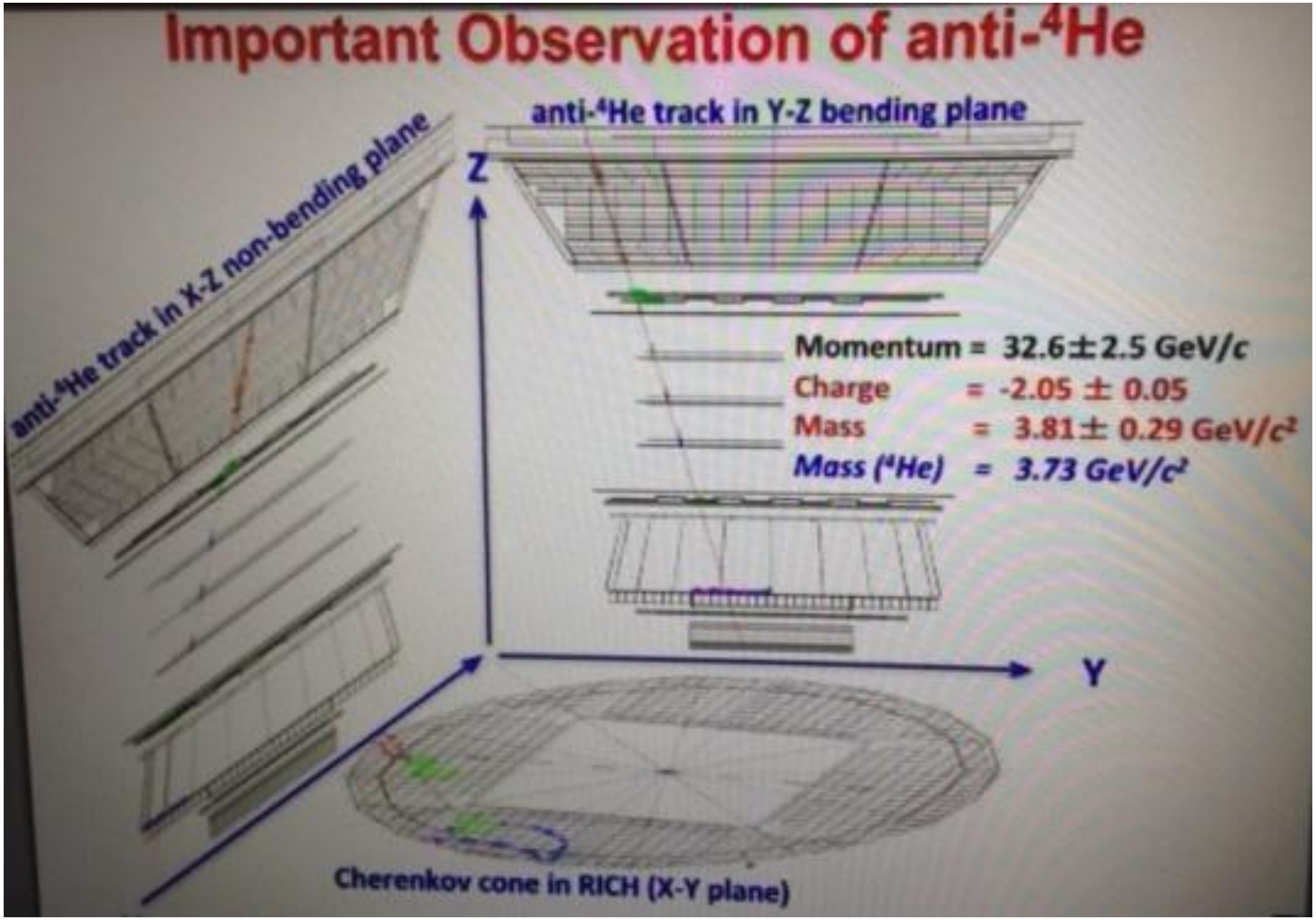
Samuel Ting

24 May 2018

Antihelium events

- 8 clear single track events with Z=-2 within helium mass region
- Momentum resolution better than 10%

Antihelium-4 candidates!



Samuel Ting 24 May 2018

Puzzle of antiHe-3 and antiHe-4 ratio

Two anti-Helium-4 events are announced on 24.05.2018 with background probability 1/300.

Continuing to take the data through 2024 would reduce background probability, putting such candidate events above 5-sigma significance

Though He3/He4 ratio is 0.1-0.2, the antiHe3/antiHe4 ratio looks now like 3. More data will resolve this puzzle

Conclusions

- Physical basis of the modern cosmology implies new physics, which inevitably enters the traditional fields of relativistic astrophysics – neutron stars and black holes.

- Possible range of neutron star masses is severely constrained by physics of degenerated neutron gas. Their features can constrain properties of dark matter.

- PBHs provide probes for physics of very early Universe

- Strong primordial nonlinear structures (massive PBH clouds, strong nonhomogeneities of baryonic matter and even antimatter stars) link structure of microworld to cosmological structures and lead to experimentally accessible effects.

- The impact of primordial particles and structures on observable properties of NS and BH give an example of fundamental relationship between micro- and macro worlds, studied by cosmoparticle physics.