(points), assumed to possess 'statistical weights' according to $|\Psi|^2$. In contrast to Bohm's time-dependent theory, this is *no longer an initial condition* that would have to be preserved by the presumed unobservable dynamics for the Bohm trajectories.

The structure of the Wheeler–DeWitt wave function in the range of applicability of a WKB approximation then statistically favors those classical states which lie on *apparent trajectories*. This result is very similar to Mott's (1929) description of α-particle tracks in a cloud chamber, where the 'stationary' (static) wave function suppresses configurations that describe droplets not approximately lying along particle tracks. Barbour calls these preferred states 'time capsules', since they represent consistent memories (without corresponding histories). In Barbour's words: "time is in the instant" (in the state) "– the instant is not in time" (in a history). If all classical states in the ensemble are regarded as 'real' (precisely as all past and future states are assumed to form a real one-dimensional history in the conventional block universe description), they now form a multi-dimensional rather than a one-dimensional continuum. One may even say that time is *replaced* by the wave function in this picture.

In contrast to the Everett interpretation, Bohm's theory presumes these classical configurations as part of fundamental reality, which must include observers. Each electron in a molecule, for example, is then assumed to possess a definite position in every actual state (though not any velocity or momentum). Since this particle position is *not* part of a memorized or documented (real or apparent) history according to this interpretation, we are only led to *believe* that it 'actually exists' as a wave function. The intrinsic dynamics of the static Wheeler-DeWitt wave function has the consequence that the electron's effects on measurement devices are dynamically 'caused' by *all* its positions in the support of the wave function (in dependence of the latter's amplitude) – not by a one-dimensional history. This picture would explain why the arena for the wave function is a classical configuration space, although most problems and disadvantages of Bohm's theory (see Zeh 1999b) persist, and even new ones may arise. Why should there be arbitrary global simultaneities representing actual elements of reality, while 'actuality' seems to be meaningful only with respect to local observers?

General Literature: Anderson 2006, Kiefer 2007.

6.2.3 Black Holes in Quantum Cosmology

During the early days of general relativity, the spacetime region behind a black hole horizon was regarded as meaningless, since it is inaccessible to observers in the external region. From their positivistic point of view, it would 'not exist'. Later one realized that world lines, including those of observers, can be smoothly continued beyond the horizon, where they would hit the singularity within finite proper time. The new conclusion, that the internal

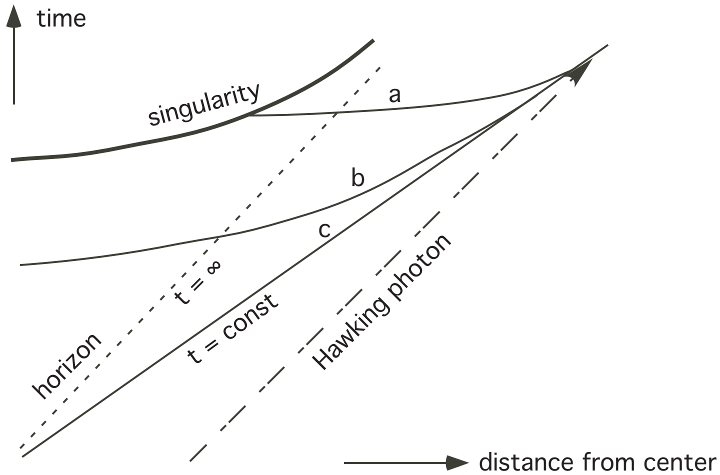

Fig. 6.4. Various kinds of simultaneities for a spherical black hole in a Kruskal type diagram: (a) hitting the singularity, (b) entering only the regular internal region, (c) completely remaining outside (Schwarzschild coordinate t). *Any* Schwarzschild time, for example $t = t_{turn}$, may be identified with $t = 0$ (a horizontal line in the diagram) regardless of the time of the observed collapse. No horizon forms on the Schwarzschild simultaneities, which are complete for the external universe. (From Zeh 2005c)

regions of black holes are physically 'regular' except at the singularity (hence for limited time only), seems to apply as well to Bekenstein–Hawking black holes until they disappear (see Sect. 5.1). However, arguments indicating a genuine (possibly dramatic) quantum nature of the event horizon have also been raised ('t Hooft 1990, Keski-Vakkuri et al. 1995, Li and Gott 1998).

While a consistent quantum description of black holes has not as yet been presented, attempts were mostly based on semiclassical methods. (For an overview see Kiefer 2007.) When combined with quantum cosmology, they may lead to important novel consequences, which seem to revive the early doubts in the meaning and existence of black hole interiors.

Consider the Schwarzschild metric (Fig. 5.1) as far as it is relevant for a black hole formed by collapsing matter, such that the Kruskal regions III and IV do not occur (Fig. 5.3a). Its dynamical (3+1) description in terms of three-geometries depends in an essential way on the choice of a foliation (see Fig. 6.4, or the Oppenheimer–Snyder model described in Box 32.1 of Misner, Thorne and Wheeler 1973). Three-geometries which intersect the event horizon may spatially extend to the singularity at $r = 0$, and thus render the global quantum states that they carry prone to dynamical indeterminism or consequences of a future theory that may avoid singularities. In contrast, a foliation according to Schwarzschild time t would describe regular three-geometries for $t < \infty$, which could be continued *in time* beyond $t = \infty$ by means of the new

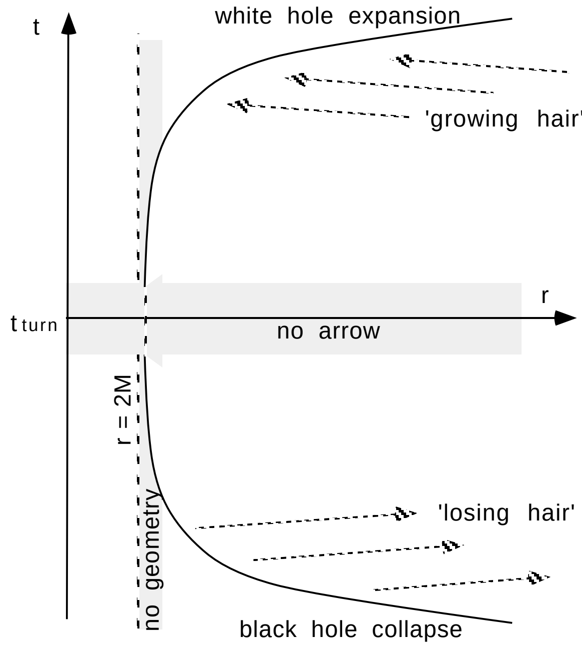

Fig. 6.5. Classical trajectory of a collapsing dust shell or the surface of a collapsing star (*solid curve*) in a thermodynamically symmetric recontracting universe. It is represented here in compressed Schwarzschild coordinates as used in Fig. 5.1, with the Schwarzschild metric now being valid only to the right of the star's surface. Because of the scale compression, light rays appear almost horizontal in the diagram. For $t > t_{\text{turn}}$, advanced radiation from the formal past would focus onto the black hole, which must now re-expand and grow hair in this scenario, while observers would experience time in the opposite direction. No horizon ever forms: the region $r < 2M$ (which is later than $t = \infty$) would arise only if gravitational collapse continued forever in a classical manner. Because of the drastic quantum effects close to the turning point of a Friedmann universe (see Fig. 6.3), there are in general only 'probabilistic' connections between quasi-classical branches in the expansion and contraction eras of the Universe. (From Kiefer and Zeh 1995)

time coordinate r (with physical time growing with decreasing r for $r < 2M$). According to this foliation, the black hole interior with its singularity would always remain in our formal future, and the singularity must be irrelevant for Hawking radiation. In the pair creation picture, the negative-energy partner is absorbed to the spacetime region close to what appears as a horizon until this is completely transformed into radiation. Therefore, this foliation seems to be appropriate for the formulation of a cosmological boundary condition (in superspace), that may explain the master arrow of time.

For further discussion now assume that the expansion of the classical universe on which this diagram is based is reversed at a finite Schwarzschild time

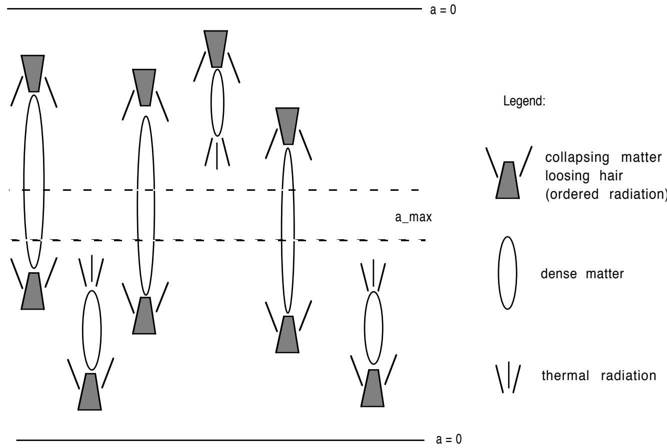

Fig. 6.6. Quasi-classical picture (using Schwarzschild coordinates) of a thermodynamically T-symmetric quantum universe which contains black holes, white holes, and black-and-white holes that re-expand by anti-causal effects. Instead of horizons and singularities, there are merely spacetime regions of large curvature ('dense matter') in this scenario. Because of their strong time dilation, they may serve as a short cut in proper time between big bang and big crunch (or between the presumed eras of opposite arrows of time). 'Information-gaining systems' could not thereby survive as such. In quantum cosmology there is no unique connection between quasi-classical histories (Everett branches) represented by the upper and lower halves of the figure, but there is no need for a violation of conservation laws

$t = t_{\rm turn}$ that is much larger than the time of the effective gravitational collapse (losing hair – see Fig. 6.5). No horizon yet exists on the Schwarzschild simultaneity $t = t_{\rm turn} < \infty$. If the cosmic time arrow does change direction (while the quasi-classical universe passes through an era of thermodynamical indefiniteness), the gravitationally collapsing matter close to the expected horizon will very soon (in terms of its own proper time) enter the era where radiation is advanced in the sense of Chap. 2. The black hole can then no longer 'lose hair' by emitting retarded radiation; it must instead 'grow hair' in an anti-causal manner (Fig. 6.6). According to a 'time-reversed no-hair theorem' it has to re-expand when the Universe starts recontracting (Zeh 1994, Kiefer and Zeh 1995).

This scenario does not contradict the geometrodynamical theorems about a monotonic growth of black hole areas, since no horizons ever form. A classical spacetime will not even exist close to the 'turning of the tide'. Here, decoherence is competing with recoherence before being replaced by it. Only region I of Fig. 5.1 is then realized. Events which appear 'later' than $t_{\rm turn}$ in the classical picture are 'earlier' in the sense of the intrinsic dynamics of the Wheeler–DeWitt equation (6.6) – and therefore also in the thermodynamical sense if this is based on an intrinsic initial condition. This quantum cosmological model describes an *apparent* (quasi-classical) two-time Weyl tensor or similar condition (see Fig. 6.6). In quantized general relativity, the two apparently different boundaries are identical, and thus represent *one and the same* boundary condition. The problem of their consistency (Sect. 5.4) is reduced to the intrinsic 'final' condition of normalizability for $a \to \infty$.

The description used so far in this section does not apply directly to a forever-expanding universe, where the arrow would preserve its direction along a complete quasi-trajectory from $a = 0$ to $a = +\infty$. The Wheeler–DeWitt wave function is then *not* normalizable for $a \to \infty$. However, one may require this wave function to vanish on *all* somewhere-singular three-geometries by a symmetric generalization of the Weyl tensor hypothesis. Such a condition has been confirmed to apply to a simple quantum model of a collapsing thin spherical matter shell (Hájíček and Kiefer 2001). In more realistic cases it would again lead to important thermodynamical and quantum effects close to event horizons (Zeh 1983), and drastically affect (or even exclude) the possibility of continuing a quasi-classical spacetime beyond them. These consequences would be unobservable in practice by external observers, since the immediate vicinity of a future horizon remains outside their backward light cones for all finite future. In order to receive information from the vicinity of a future horizon, one has to come dangerously close to it, and thus participate in the extreme time dilatation (see Fig. 5.2, where the light cone structure is made evident, while distances are strongly distorted).

These conclusions seem again to throw serious doubts on the validity of a classical continuation of spacetime into black hole interiors (see also Kiefer 2004 or Zeh 2005a). Event horizons in classical general relativity may signal the presence of drastic thermodynamical and quantum effects rather than representing 'physically normal' regions of spacetime. While their observable consequences depend on the world lines of detectors or observers (their acceleration, in particular), global quantum states, such as a specific 'vacuum', are invariantly defined – though not invariantly observed (Sect. 5.2). These global states may define an objective arrow of time, including 'quantum causality' (responsible for decoherence), by means of a fundamental boundary condition for the Wheeler–DeWitt wave function.